A STUDY OF TYMPANIC MEMBRANE DISPLACEMENT

by

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SUMMARY

Presented in this thesis is a study relating to the measurement of tympanic membrane displacement. Contributions have been made under three broad headings: firstly, following a review of techniques used to measure various audiological parameters, particular emphasis is given to the design and development of a new method, the Tympanic Membrane Displacement (TMD) system; secondly, consideration is given to the techniques of signal processing, including the separation of the desired signal from the noise, which is both environmental and physiological in origin; thirdly, the physiology of the ear and the acoustic reflex are examined in detail.

The TMD system was conceived to overcome various shortcomings of other measurement techniques. This device measures extremely small volumetric displacements, of the order of a few nanolitres, over a relatively wide bandwidth and under near free field conditions.

Audiological aspects of the present work include comprehensive studies of the background noise level within the external ear canal, the displacement of the tympanic membrane in connection with the Eustachian tube function, and the steady state and dynamic characteristics of the acoustic reflex. An hypothesis is postulated which relates the latter reflex characteristics to the resting position and dynamics of the stapes footplate in the oval window, the interface between the middle and inner ear.

It is thus shown that the TMD system enhances the physical understanding of the hearing mechanism, and so has a potential for identifying abnormalities pertaining to pathological conditions.

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Nomenclature

Abbreviation

ADC Analogue to digital converter.

DAC Digital to analogue converter.

DC A constant amplitude or ultra low frequency.

EAI Electroacoustic impedance: used in respect of the EAI bridge measurement technique.

TM Tympanic membrane.

TMD Tympanic membrane displacement: used in respect of the TMD system measurement technique.

dB Decibel: used in respect of sound pressure levels and system attenuation characteristics. (Eg. such as for filter network attenuations).

HTL Hearing threshold level, ISO 389 (1975).

μl Microlitres: that is 1×10^{-9} cubic metres.

nl Nanolitres: 1×10^{-9} litres. (Metric units used throughout dissertation).

SPL Sound pressure level.

α A parameter expressing the degree of overshoot of a system response.

$\sum$ Mathematical notation expressing a summation of terms.

Abbreviation

ζ Damping ratio parameter.

σ Signifies a standard deviation specified by a subscript.

τ_0 Oscillation decay rate parameter.

ω Parameter expressing a system oscillation frequency. Subscripts 'd' and 'n' denote a damped and natural frequency respectively.

CHAPTER 1

INTRODUCTION

The study of the anatomy and physiology of the ear has been the subject of investigations for several centuries. Research studies on the ear are made to obtain an improved understanding of how it functions, and to aid the diagnosis of hearing disorders. In recent years, investigations in the field of audiology, have become increasingly concerned to show how the hearing response is related to the physical structure and behaviour of the hearing mechanism. These investigations have an important bearing on the work reported in this thesis.

The topic of the present study is the measurement of displacement of the tympanic membrane, and the application of contemporary technologies to facilitate a high integrity of displacement measurement under transient conditions. Evaluation of the tympanic membrane movement is a relatively old idea for obtaining information on the ear. As early as 1860, Politzer sealed a glass capillary tube into external ear canals of his subjects. In these experiments tympanic membrane displacements caused by swallowing, rapid respiration or voluntary tensor tympani muscle contractions were indicated by movements of a coloured liquid within the capillary tube (Politzer 1869, 1908). However, Politzer's device had an extremely slow response time, a problem which has been partially overcome during the past two decades by the advent of intricate electronics and the development of sensitive pressure and flow measurement transducers. Even so, substantial shortcomings in the measurement techniques could still be identified.

This thesis is primarily concerned with how further improvements in measurement can be achieved as a result of a new system - described here as the 'Tympanic Membrane Displacement System'. This system is capable of evaluating extremely small volume displacements and producing results which, to the author's knowledge, are unsurpassed in detail and integrity by any other noninvasive method currently available.

1.1 BACKGROUND TO THE PRESENT RESEARCH

During 1974, a short study was conducted into the feasibility of measuring movement of the tympanic membrane (Marchbanks 1975). It was shown that minute displacements of the membrane, as caused by the acoustic reflex (section 2.2), could be monitored by sealing a purpose built flowmeter into the external ear canal. However, the device was difficult to calibrate and the results indicated that the reflex transient was masked by a large amount of noise, both physiological and extraneous in nature. Furthermore, as with similar flow and pressure measurement devices, this technique unfortunately did not yield free field measurments (section 3.2.2.).

New techniques which could be classified as free field were conceived during August 1976, and as described later in this dissertation, were incorporated in the 'Scanning Capacitance Probe' and the 'Tympanic Membrane Displacement System', known for brevity as the TMD system (chapter 4). The present programme of research was initiated shortly after this date in September of the same year.

1.2 OBJECTIVES AND AIMS OF THE PRESENT INVESTIGATION

Hearing dysfunction diagnosis and research has, in the last decade, relied to a large extent on data obtained with the electroacoustic impedance bridge (section 3.1). This instrument measures the ear's acoustic impedance to a tone of a known frequency, but is unable to provide data concerning the direction and magnitude of tympanic membrane movement. The primary objective of the present research is, therefore, to develop a means by which the membrane movement may be measured directly.

The principal aims of this research are: i) To review the current state of tympanic membrane displacement measurement. ii) To exploit the unique 'Tympanic Membrane Displacement System' in order to advance the understanding of the physical structure and dynamics of the ear. iii)To investigate the contraction characteristics of the acoustic reflex in relation to the physical configuration of the tympanic membrane, middle ear mechanism and its interface with the inner ear.

The main objectives of the study are: i) To establish the 'Tympanic Membrane Displacement System' as an effective device for measuring dynamic displacements of the tympanic membrane. ii) To quantify steady state displacements and dynamic characteristics of the tympanic membrane, such as those due to respiration, cardiovascular pulsations, and in particular the acoustic reflex.

1.3 ORGANISATION OF THE DISSERTATION

The present dissertation may be thought of as consisting of four main areas. The first three chapters provide, in a broad sense, an introduction to the complete work. These chapters discuss the background to the present research and its aims. They also afford an introduction to the anatomy and physiology of the human ear, and finally review the state of the art of measuring tympanic membrane movement prior to the present research.

The first three chapters set the scene for the next area which discusses two original techniques for measuring movement of the tympanic membrane, namely the 'Scanning Capacitance Probe' and, in particular, the 'Tympanic Membrane Displacement System'. Out of these two techniques, the TMD system was fully developed during the present research, and is the principal subject of discussion.

Any information on the movement of the tympanic membrane contained in the signal from the TMD system is unavoidably corrupted by a large amount of noise, originating both from other physiological processes and from the environment. Therefore, the third area of this dissertation classifies the TMD signal, and presents the statistical techniques which are introduced to improve the signal to noise ratio. This is followed by chapter 7, which indentifies and quantifies the relevant noise sources. In so doing, this chapter acts as a link to the next three chapters which concern various aspects of the ear physiology investigated with the TMD system. These chapters include discussions on the Eustachian tube function, swallowing, the steady state and dynamic characteristics of the acoustic reflex, as well as presenting an hypothesis which explains the configuration of the tympanic membrane displacement in terms of the resting position and dynamics of the stapedial footplate.

The final chapter discusses the conclusions of the present investigation, and the future of the TMD system. This is followed by a list of references and the appendices.

The organisation of this dissertation is such that the first three chapters provide a fairly general discussion of various aspects relevant to the present investigation, leaving a more detailed discussion of any points to be made in the appropriate chapters. In the main, each chapter begins with a short introduction to the topics to be discussed.

CHAPTER 2

ANATOMY, PHYSIOLOGY AND PATHOLOGIES OF THE HUMAN EAR

This chapter provides an introduction to the human ear. The first section deals with anatomy and physiology, and is followed by a discussion of the middle ear reflexes and their diagnostic importance. The final section concerns the function and dysfunction of the Eustachian tube. Mention is made in the last section of the relationship between the Eustachian tube function, swallowing and the tensor tympani muscle. This is of particular relevance to the discussion in Chapter 8 which is concerned with the measurement of the Eustachian tube function.

2.1 ANATOMY AND PHYSIOLOGY OF THE EAR

The anatomy of the ear is best considered in three parts, the external, middle and inner ear, as shown in figure 2.1. The tympanic membrane (ear drum) provides the boundary between the external and the middle ear. Likewise, the oval and round windows form the boundary

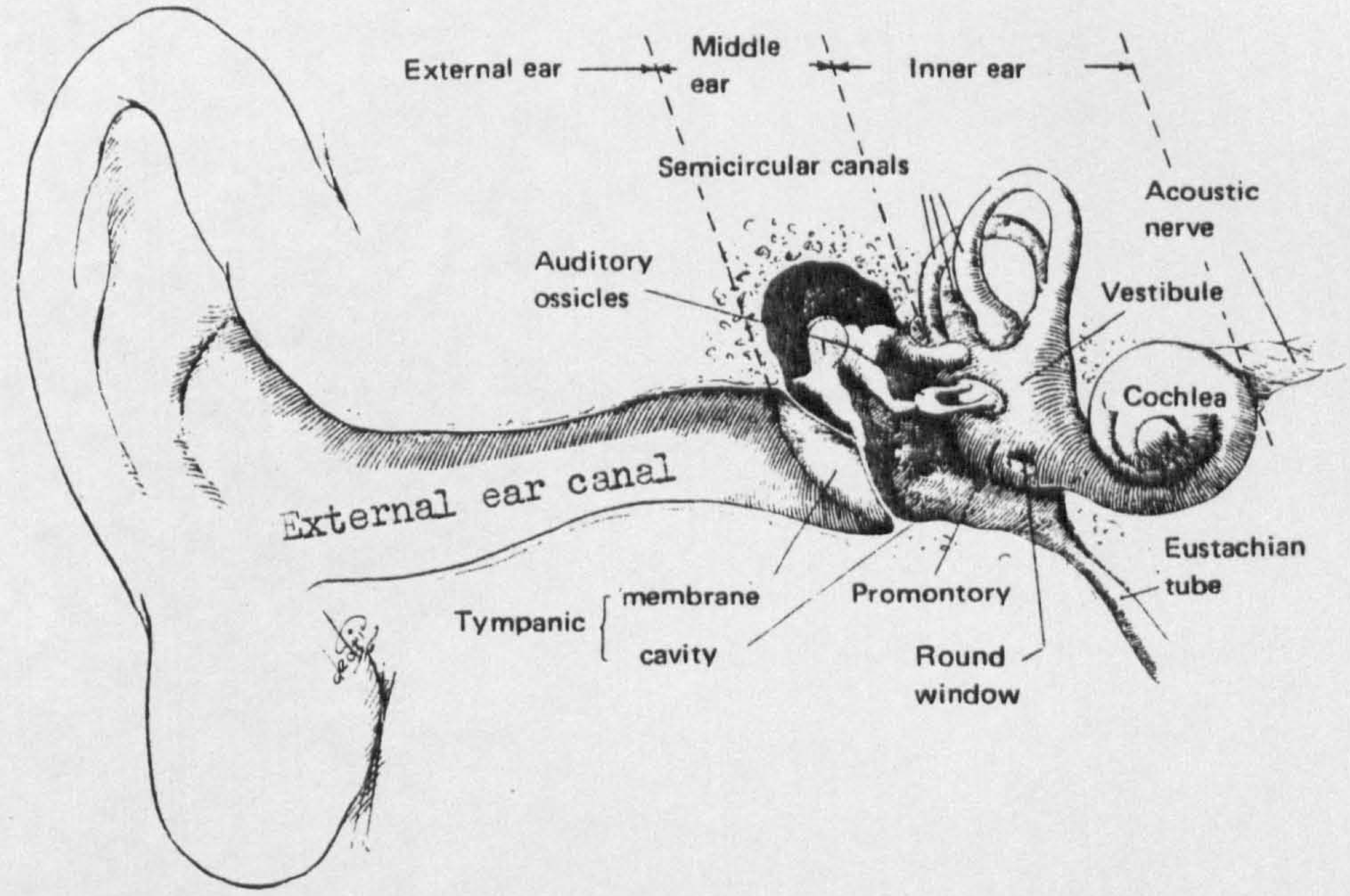


FIGURE 2.1 <u>Schematic of the human ear</u> Sanders (1977)

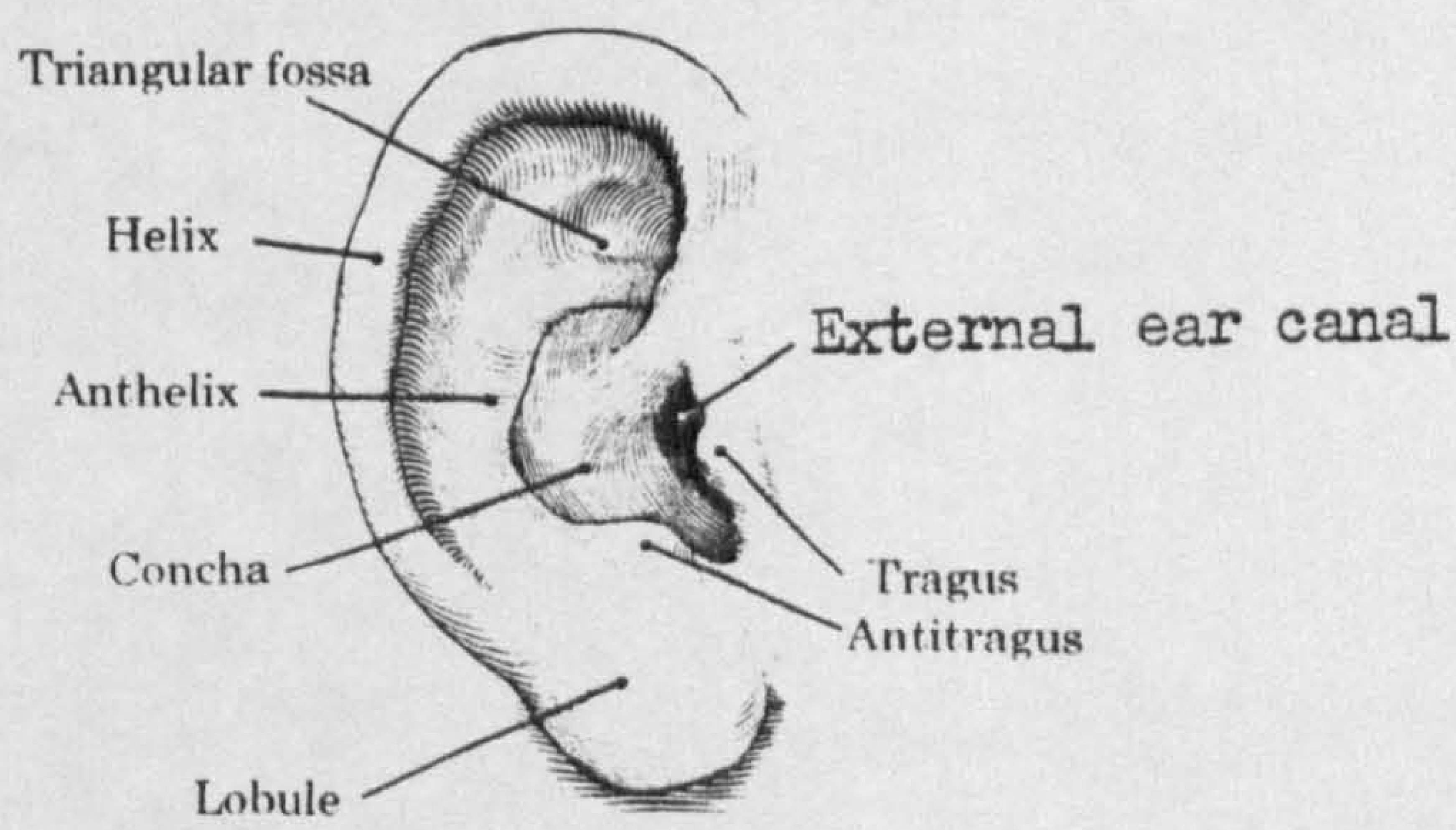


FIGURE 2.2 <u>The pinna</u> Dorland (1974)

between the middle and inner ear. This section discusses the anatomy of the ear. An additional description of the oval window and stapes is given in section 10.4.

2.1.1 The external ear

The function of the external ear is to communicate airborne sound to the middle ear mechanism. At its outermost extent it is an intricately shaped flap of skin and cartilage, known as the pinna, which is attached to the side of the head. It has been suggested that the structure of the pinna, shown in figure 2.2, plays an important role in an individual's ability to localise sound (Sanders 1977). Leading from the pinna is the external ear canal, which continues in a slightly curved manner to the tympanic membrane. The length of this canal in adults is approximately 23 millimetres from the membrane to the outer surface of the tragus (figure 2.2). The tympanic membrane, often referred to in this dissertation as the TM, lies obliquely to the longitudinal axis of the external ear canal at an angle of approximately 55 degrees.

2.1.2 The tympanic membrane

The tympanic membrane divides the external ear from the middle ear. Its purpose is to extract sound energy from the air and transmit it to the middle ear mechanism with a minimum of energy loss. The tympanic membrane, shown in figure 2.3, is roughly oval in outline, measuring between 9.0 and 10.2 mm along the major axis, and between 8.5 and 9.0 mm along the minor axis (Lim 1970). With the exception

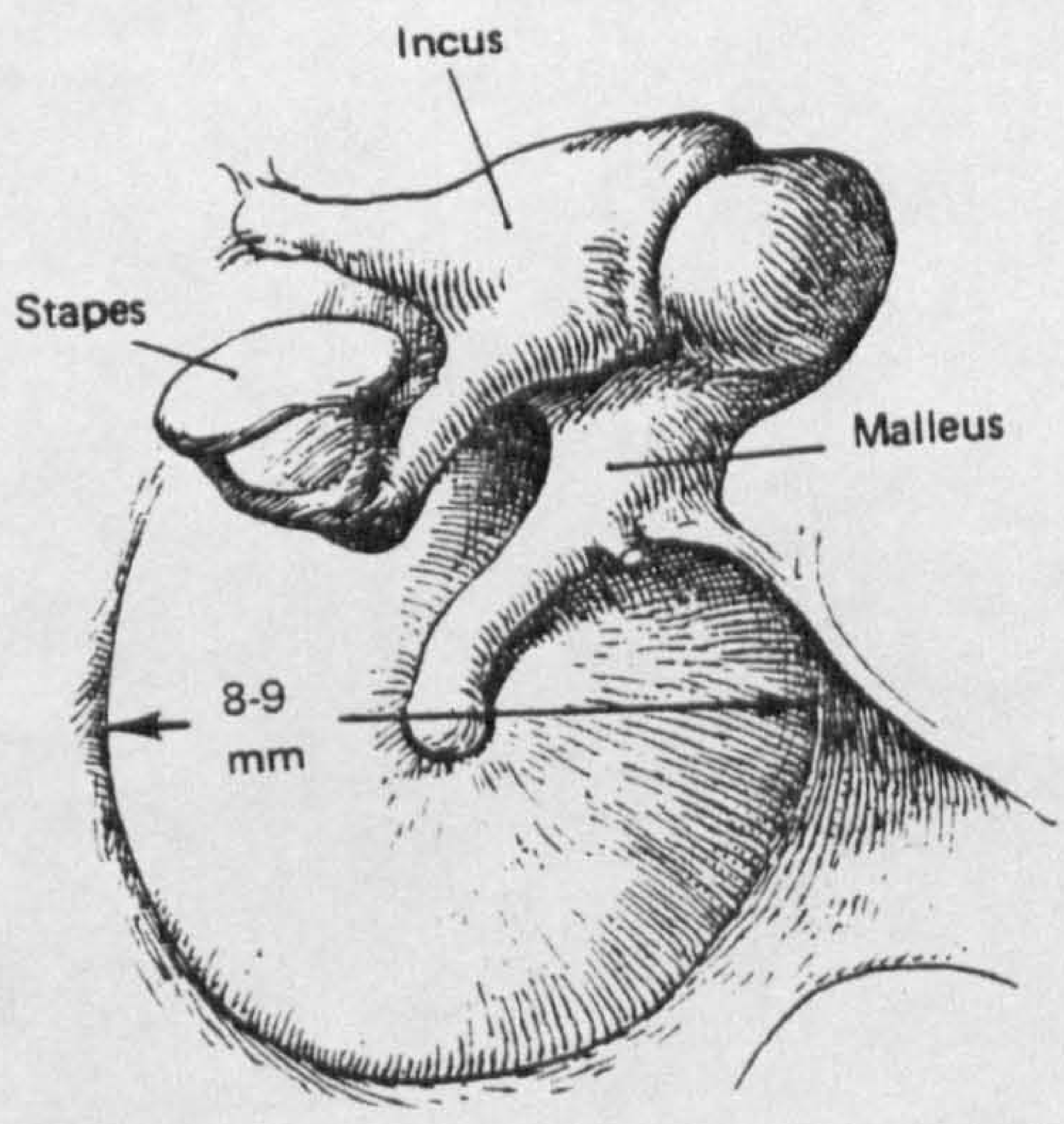


FIGURE 2.3 The tympanic membrane and malleus attachment
Sanders (1977)

of a small sector, the notch of Rivinus, the membrane is attached to a circular groove in the bony wall of the external ear canal.

Fixed to the tympanic membrane is the manubrium or handle of the malleus, which is connected along a radius of the uppermost sector of the membrane, as shown in figure 2.3. In the normal resting position, this ossicle draws the centre (umbo) of the TM inwards, so forming the TM into a shallow conical shape. The majority of the TM is held under tension in a region which constitutes the pars tensa. However, there also exists a small triangular section bounded by the notch of Rivinus, which being flaccid in nature is known as the pars flaccida. The skin of this particular region is a continuation of the skin of the external ear canal.

2.1.3 The middle ear

Behind the tympanic membrane is the middle ear cavity. This cavity, elongated in cross-section, is an air filled volume of 1 to 2 cubic centimetres. At the base of the cavity is the Eustachian tube which is directed downwards at an angle of about 30 degrees to the horizontal. This feature is approximately 36 mm long in an adult. It provides the means by which the middle ear may be vented to the atmosphere, so enabling equalization of the middle ear and atmospheric pressures. At its lowest extent, the tube connects into the pharyngeal part of the throat at the level of the nose (nasopharynx).

The middle ear cavity contains the ossicles, the outermost of which is the malleus. The head of the malleus is connected to the next ossicle, the incus, by an articular capsule, as shown in figure 2.3 and 2.4. In turn, the incus is connected by another articular capsule to the head of the innermost ossicle, the stapes. The footplate of the stapes, figure 2.4, is fixed into the oval window of the inner ear by an annular ligament and by this connection the sound energy is transmitted to the cochlea.

In addition to the previously mentioned attachments, other restraints to the ossicular mechanism are provided by the superior and anterior ligaments of the malleus, and the posterior ligament of the incus. (Not all of these ligaments are shown in the figures for the sake of clarity). Further restraints are provided by the two muscles, the tensor tympani and stapedius muscles. The stapedius muscle is the smallest in the body, having a length of only about 6.3 mm, and is connected to the head of the stapes, whereas the tensor tympani measures approximately 200 mm and is connected to the anterior medial aspect of the neck of the malleus (Love and Stream 1978). Innervation of the stapedius is from a branch of the facial or VIIth cranial nerve, and the tensor tympani, from the mandibular branch of the Vth cranial nerve.

The function of the tympanic membrane and the ossicular chain is to transfer airborne sound energy to the fluid contained within the inner ear. It achieves this more successfully than a direct transfer of the energy from the air to the fluid, by providing impedance matching between the air-tympanic membrane and the oval window-fluid

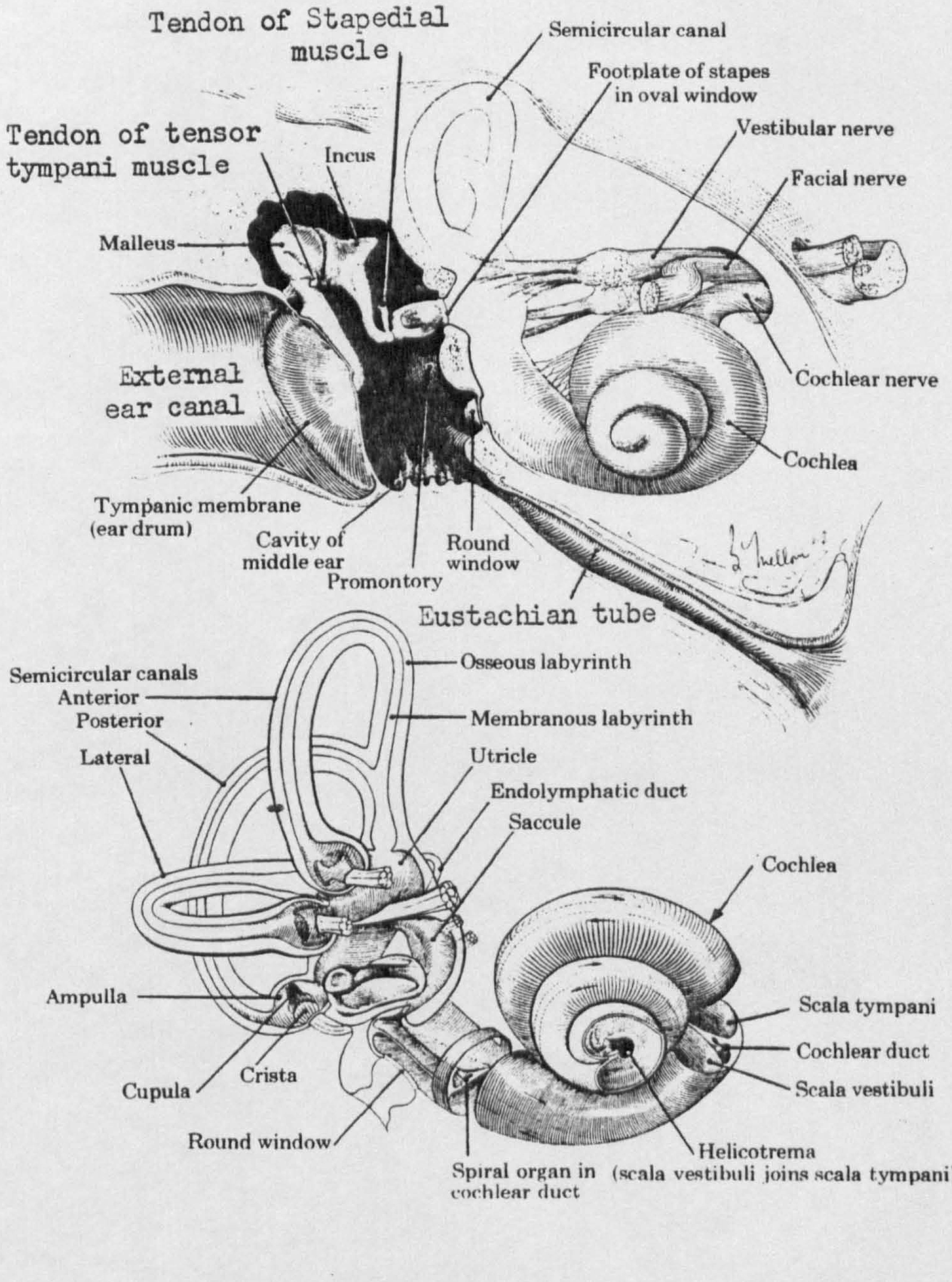


FIGURE 2.4 <u>External and internal structures of the ear</u>
Dorland (1974)

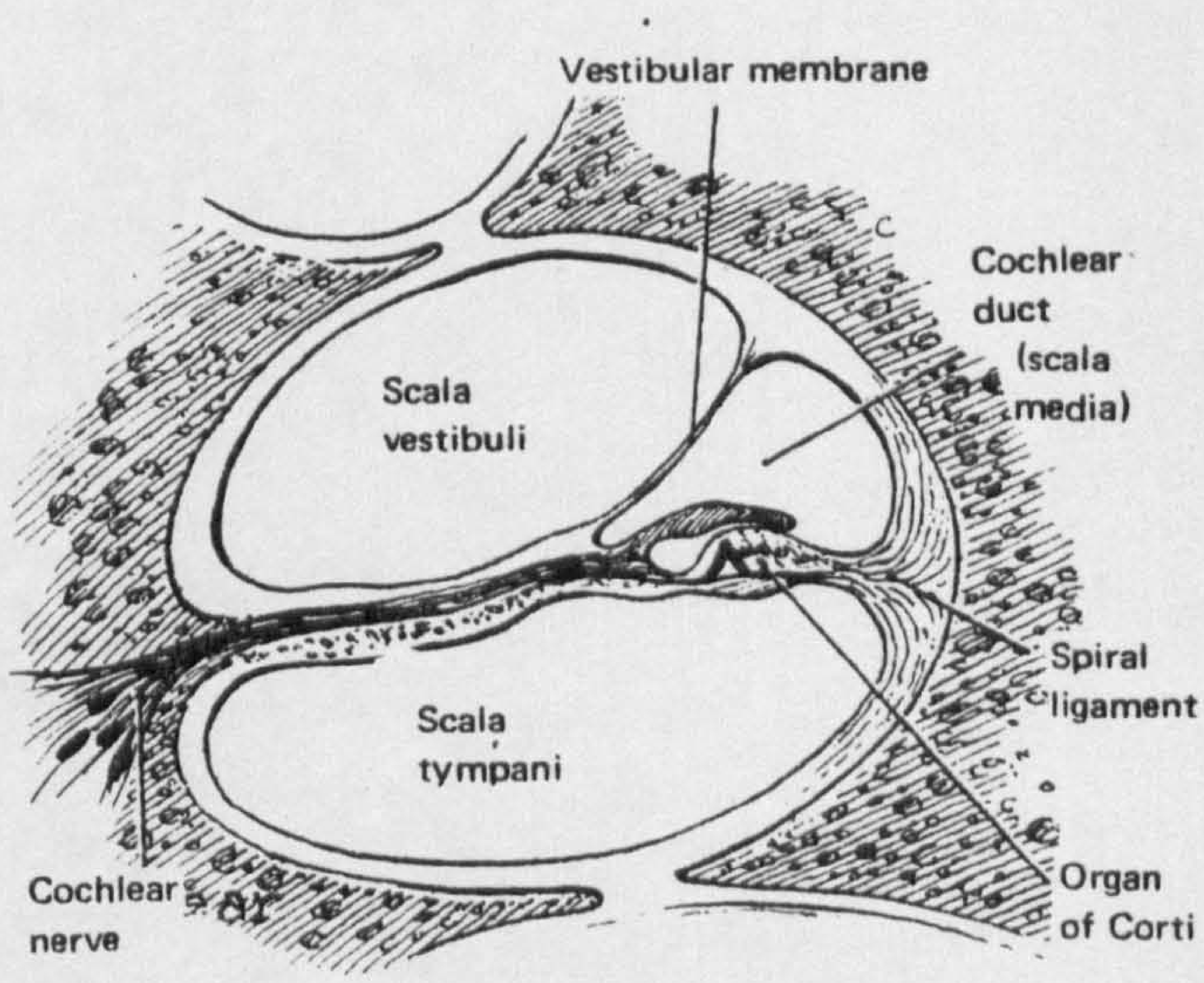


FIGURE 2.5 A diagram of a cross section of the cochlea
Sanders (1977)

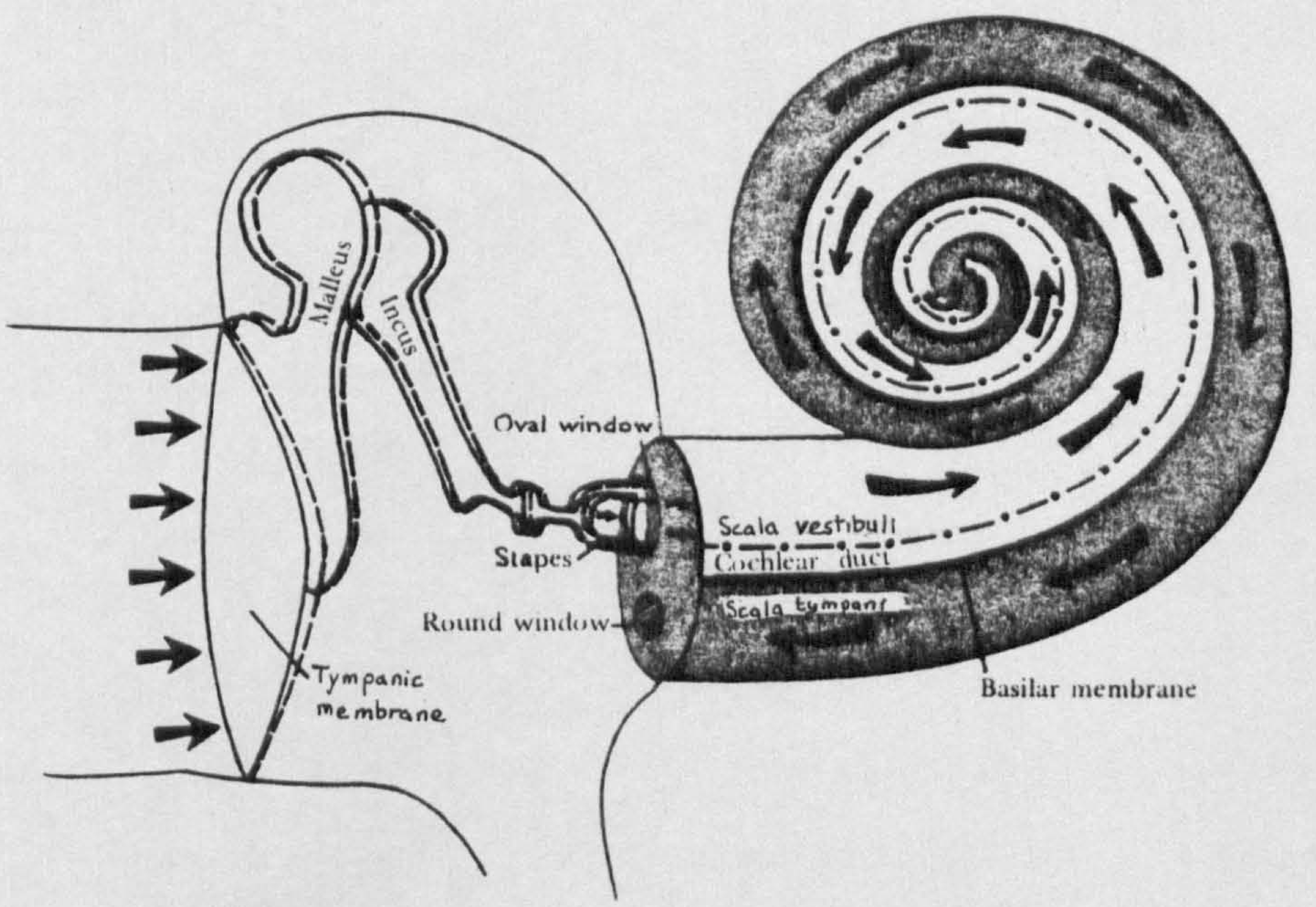


FIGURE 2.6 Schematic of the hearing process
Lindsay and Norman (1977)

interfaces *. The effectiveness of the middle ear mechanism is demonstrated by a claim by Wever and Lawrence (1954), who note that in the absence of the middle ear mechanism and tympanic membrane, there is about a 30 dB reduction in the energy transferred to the inner ear. This claim is substantiated by Harris (1974), who calculated that the total mechanical advantage of the middle ear mechanism is about 25 to 27 dB. The impedance matching is partly due to the middle ear mechanism acting as a complex lever, although it is principally as a result of the large difference in the area of the TM to that of the oval window.

2.1.4 The inner ear

Immediately behind the oval window is a relatively large egg shaped cavity known as the vestibule. Attached to this is an extensive structure buried within the temporal bone of the skull, as shown in figure 2.4. Upwards from the oval window are the semicircular canals, which contain part of the balance regulating apparatus, whereas downwards from this window is a snail shaped passage which houses the sound receptors, the cochlea.

Along the length of the cochlea spiral two membranes, the vestibular or Reissner's membrane, and the basilar membrane. The basilar membrane provides a base for the organ of Corti, which is the sensory organ of hearing with its related structure, shown in figure 2.5. These two membranes divide the cochlea into three passages: the scala vestibuli, cochlear duct and the scala tympani. The

* Wever and Lawrence (1954), have calculated that the impedance mismatch between air and water results in only 0.1 % of the airborne energy being transferred to the water. That is 99.9 % of the energy is reflected at the interface.

cochlear duct is sealed from the other two passages and contains a fluid, the endolymph. The scala vestibuli and tympani contain the fluid, the perilymph, and connect at the apex of the cochlea via a small opening (helicotrema). At the end adjacent to the middle ear cavity, the scala vestibuli terminates at the oval window, and the scala tympani at the membrane covered round window.

Figure 2.6 shows a greatly simplified diagram of the function of the cochlea. Sound energy arriving at the stapes is transfered to the scala vestibuli. The energy is conducted by a travelling wave along this passage to the apex of the cochlea and back down again along the scala tympani, where pressure variations within the perilymph are relieved at the round window. During this passage of sound energy, the displacement sensitive organ of Corti is stimulated in specific regions, which facilitates the perception of sound.

2.2 THE MIDDLE EAR MUSCLES

One of the main aspects of the present investigation is the study of the displacement of the tympanic membrane as caused by contraction of the two middle ear muscles, the stapedius and tensor tympani. This section considers the physiology of these muscles. Subsequently their significance is considered in respect of the Eustachian tube function (chapter 8), and their direction of pull on the middle ear mechanism (chapter 10).

2.2.1 Contraction of the middle ear muscles

Contraction of the two middle ear muscles may be stimulated in a number of different manners, such as; tactile methods by touching or electrical stimulation of the auditory canal walls. (Gunn 1973; Bosatra et al 1975); a startle reaction, by blowing towards the eyes (Klockhoff and Anderson 1960, 1961; Djupesland 1967; Lidén et al 1970; Greison and Neergaard 1975); or defensive reactions by sudden forcible opening of the eyelids and in anticipation of loud sounds such as from a firearm (Coles and Knight 1965; Bench 1971). In addition, spontaneous contractions sometimes occur when the subject is suffering from anxiety (Djupesland 1975), and in a few subjects voluntary contraction is possible.

The stapedius muscle contracts due to reflex activity elicited by acoustic stimulation. The reflex is bilateral even to a unilateral stimulus. This is due to a complex pathway of nerves in the brain stem which interconnect the muscles and cochlea of the two ears, normally referred to as the acoustic reflex arc, see figure 2.7. An ipsilateral reflex refers to muscle activity measured in the same ear as stimulated. A contralateral reflex refers to stimulation and measurements made in opposing ears.

In the last few decades, there has been a degree of controversy concerning whether or not the tensor tympani muscle can be acoustically stimulated. Terkildsen (1957,1960), and Lidén et al (1970) claim that acoustic stimulation of this muscle is possible. Contrary views are

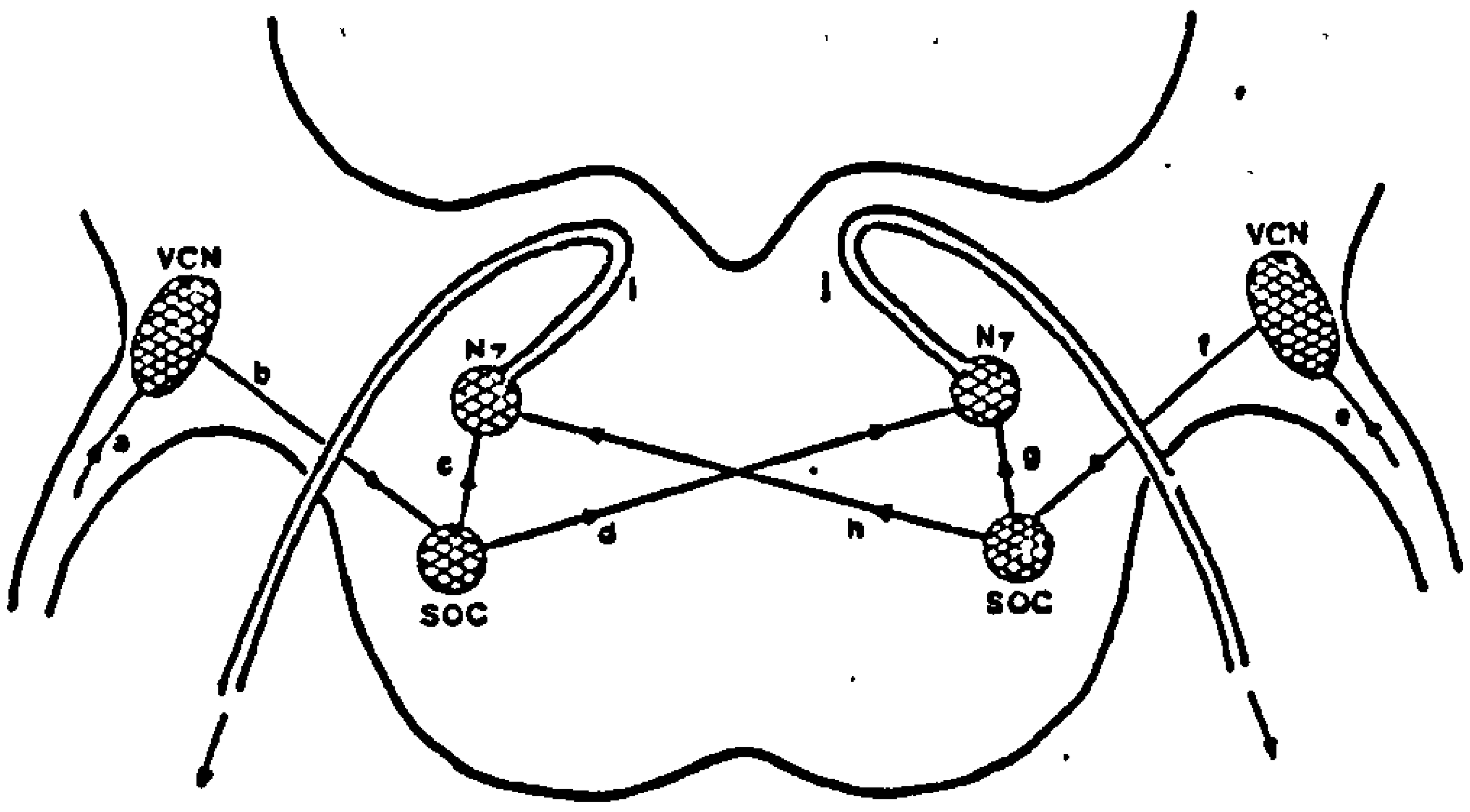


FIGURE 2.7 <u>Simplified schematic illustration of the probable acoustic stapedius reflex pathways in the brain stem</u>

a and e: the primary acoustic neuron (the eighth cranial nerve). VCN: ventral cochlear nucleus. b and f: second neurons through the trapezoidal body. SOC: superior olivary complex. c and g: third homolateral neurons to the motor nucleus of the seventh cranial nerve. d and h: third contralateral neurons to the motor nucleus of the seventh cranial nerve. N : motor nucleus of the seventh cranial nerve. i and j: the seventh cranial nerve.

Reproduced from Brask (1978)

expressed by Klockhoff (1961) and Djupesland (1965). These authors consider that if the tensor tympani muscle does respond to sound, then it is merely a part of the startle response. Further investigations are necessary before it can be established whether or not acoustic stimulation of this reflex is possible.

2.2.2 Functions of the middle ear muscles

An important function of the middle ear muscles is their contribution to the suspension of the middle ear mechanism. However, specific functions of the muscles have not been unequivocally established.

Contractions of the stapedius muscle dislodge the stapes footplate from the oval window (chapter 10), and in so doing reduce the sound energy transmitted from the tympanic membrane to the cochlea. A possible function of this reflex may be to protect the inner ear from over-stimulation (Borg et al 1979). In this particular role the effectiveness of the acoustic reflex depends on it responding sufficiently quickly to prevent harmful energy being transmitted; not decaying too rapidly with time; and having an adequate rate of recovery. The value of the protection afforded by the reflex is disputed by several authorities mainly due to its ineffectiveness against impulsive sounds and high frequency noise.

The stapedius has been shown to be active during vocalization and speech reception (Djupesland 1965; Borg and Zakrisson 1975). It is suggested that this action aids the understanding of speech by reducing the masking effect of the lower frequencies on the higher frequency components. This selective filtering is due to the reflex attenuation being greater at the lower frequencies (Gunn 1973). The tensor tympani muscle has also been shown to be active during vocalization. Djupesland (1965) found EMG activity in this muscle 40 to 450 msec before the initiation of vocalization, and this persisted 200 to 300 msec after the vocalization had ceased.

Bursts of EMG activity have been measured from the tensor tympani muscle during swallowing and opening of the Eustachian tube (Salomon and Starr 1963; Djupesland 1965). Salomon and Starr (1963) conclude that the tympani muscle is integral in the act of swallowing and so may consequently play a role in the ventilation of the middle ear cavity (section 2.3.4).

2.2.3 Threshold of the acoustic reflex

The threshold of the acoustic reflex is the minimum sound pressure level of a particular stimulus which causes observable muscle activity. The level varies with the duration, spectral content and mode of presentation of the stimulus. For pure tone stimulation with a duration greater than 500 msec, the normal contralateral reflex threshold varies between 70 and 100 dB above the hearing threshold level (HTL) of the subject (Jerger et al 1972; Wilson and McBride 1978; Brask 1978). A lower threshold is obtained for white noise stimulation, occuring at approximately 65 dB HTL (Jepsen 1963).

There is a scarcity of documentation on the reflex threshold for ipsilateral stimulation. The ipsilateral threshold level is generally considered to be lower than the contralateral. Møller (1962) reported an average difference of 3 dB between the intensity of stimulation for these two types of reflex configurations. Later the findings of Fria et al (1975) suggest the differential is greater, averaging 6 dB.

Decreasing the stimulus duration below a certain value will result in the reflex threshold being elevated. Woodford et al (1975) discuss the thresholds for stimulus durations ranging from 10 to 500 msec, for which the level was found to vary by up to 30 dB. The threshold tends to remain at a constant level for stimuli which extend over 500 msec.

2.2.4 Diagnostics and the acoustic reflex

The behaviour of the acoustic reflex is important in the diagnosis of hearing pathologies. It is often successfully used to differentiate between conductive, sensorineural and retrocochlear hearing losses. The degree of elevation of the reflex above normal threshold may indicate the stage of development of certain pathologies, for example otosclerosis or otitis media (section 2.3).

The reflex is a good indication of the presence or absence of a conductive component in a hearing loss. If the reflex is present for contralateral stimulus levels no higher than 95 to 100 dB above the hearing threshold then there is a high probability that the middle ear is functioning normally. Elevation or partial absence of the acoustic reflex will occur in cases of otosclerosis, where partial or total fixation of the ossicular joints is present. Another disease of the middle ear is otitis media (section 2.3). This disorder may result in the presence of fluid within the middle ear, which will be detected as an absence or drastic reduction in the magnitude of the reflex (Jerger 1975).

Sensorineural dysfunctions result from lesions of the cochlea or VIII nerve. A sensorineural loss will give a reflex threshold closer to the hearing threshold than normal (Jerger 1975). This phenomenon, known as loudness recruitment, is often more marked at certain frequencies, and so sometimes only substantiated if the reflex is tested over the entire audiometric range. Other characteristics of the reflex in cases of sensorineural dysfunctions have been studied in more detail by Norries et al (1974), and Letin and Bess (1975). These authors reason that since the presence of the acoustic reflex is directly dependent upon the integrity of the cochlea, then lesions of this organ should alter some aspects of reflex behaviour. Both groups of investigators conclude that the response of the reflex to pulse stimuli differentiate normals from patients with sensorineural problems. In particular the reflex recovery rate is more rapid for normal subjects.

Abnormal reflex decay rates, latencies, or elevated reflex thresholds are possible signs of retrocochlear lesions such as an acoustic neuroma (Bosatra et al 1975). With this type of condition, stimulation of the contralateral ear with a tone of 500 or 1000 Hz, of 10 dB above the reflex threshold, will result in a reflex which decays rapidly. With a normal ear the muscle will remain contracted for a longer period of time (Olsen et al 1975). For these frequencies Anderson et al (1970) noted a stable reflex with normal subjects, but a decay to less than 50% within 5 seconds for cases of acoustic neuroma. They conclude that reflex decay tests are important, since they are sensitive enough to identify retrocochlear lesion at an early stage. The site of a retrocochlear lesion may sometimes be located by a comparison of the reflex behaviour for contralateral and ipsilateral stimulation of both ears. Abnormality of one or more of these tests indicates that the lesion is in the vicinity of particular reflex pathways (Brask 1978).

2.3 THE EUSTACHIAN TUBE

This section provides an introduction to the anatomy, physiology, function and dysfunction of the Eustachian tube. Also included is a discussion of the physiological relationship between the Eustachian tube, swallowing, the tensor tympani muscle and the regulation of the middle ear pressure. This relationship is particularly relevant to the contents of chapter 8, which deals with the measurment of the Eustachian tube function as exemplified by swallowing and gas absorption from the middle ear cavity (section 8.3). A more extensive description of this function and its measurement is given in section 8.1.

2.3.1 Anatomy and physiology of the Eustachian tube

At the base of the middle ear cavity is the internal opening (aural orifice) of the Eustachian tube. From this opening, the Eustachian tube projects downwards at an angle of approximately 30 degrees to the horizontal, until it terminates in the pharyngeal part of the throat at the level of the nose (nasopharyngeal orifice). The middle ear opening of the Eustachian tube leads initially to a bony section, which connects to a cartilaginous portion forming the middle or isthmus part of the tube. This region then gradually widens into a membranous portion connected to the nasopharynx.

The isthmus is of diameter 1 to 2 millimetres in an adult and is normally in a collapsed state until it is opened by swallowing or yawning. The opening mechanism is facilitated by the tensor veli palatini muscle, the muscle fibres of which lie in two fairly distinct bundles situated laterally to the Eustachian tube.

2.3.2 Functions of the Eustachian tube

There are three principal functions of the Eustachian tube:

i) It provides a means by which secretions produced within the middle ear cavity may be drained into the nasopharynx.

ii) It prevents nasopharyngeal secretions entering into the middle ear cavity, such as by a reflux action during swallowing.

iii) It provides a means by which the middle ear cavity may be intermittently ventilated to produce an equilibration of pressure across the tympanic membrane.

Without adequate ventilation a negative gauge pressure will develop in the middle ear cavity. This pressure is detrimental to the efficiency of the sound transmission properties of the middle ear mechanism, and occurs as a result of oxygen being continuously absorbed by the walls of the middle ear cavity (section 8.1.1).

2.3.3 Dysfunction of the Eustachian tube

Dysfunction of the Eustachian tube occurs when either the tube remains continuously in an open or patulous state, or when due to a blockage or constriction it provides inadequate ventilation of the middle ear cavity. Its open state may be detected clinically using acoustic impedance bridge measurements, which will indicate a lower than normal impedance value, and impedance changes which are synchronous with respiration.

Sealing of the Eustachian tube commonly occurs due to swelling of the adenoids; in the presence of a tumour; or because of an infection or allergy. Bluestone (1975) considers such dysfunction as one of the main factors which promotes disease of the middle ear. Negative pressure due to sustained closure causes retraction of the tympanic membrane, and eventually effusion from the tissue linings of the middle ear. The liquid from these linings is initially a light watery fluid, a condition diagnosed as a stage of a pathology known as otitis media, (serous otitis). In more serious situations, this liquid becomes viscous (chronic serous otitis), and if untreated adhesions may form on the tympanic membrane or ossicles which will result in the immobilization of the middle ear mechanism, (chronic adhesive otitis). At a very advanced stage of this pathology sclerotic bone may develop on the ossicles. Left untreated, otitis media is likely to result in an irreversible degeneration of the middle ear system.

<u>2.3.4 Swallowing and the function of the tensor tympani muscle</u>

Swallowing is an act directed by the central nervous system. It is closely linked with the opening of the Eustachian tube which facilitates ventilation of the middle ear cavity. Salén and Zakrisson recorded bursts of EMG activity from the tensor tympani muscle, having a duration of about 300 msec, during every act of swallowing. They concluded that the tensor tympani muscle is integral in the act of swallowing and so may consequently play a role in the ventilation of the middle ear cavity. Further evidence for their proposal is both experimental and embryological in nature (Misurya 1978, Kamer and Rood 1978).

Experimental evidence for a relationship between swallowing and contraction of the tensor tympani muscle is provided by Ingelstedt and Jonson (1966). These authors proposed that the over pressure in the middle ear, caused by a contraction of the tensor tympani muscle, may facilitate the opening of the Eustachian tube by breaking away the mucous membranes glued together within the isthmus portion. Although they do not make special reference to contractions of the tensor tympani in relation to swallowing, they note that during all their experiments that once or twice every hour there is a particularly strong contraction of this muscle which often results in the opening of the Eustachian tube.

Embryological evidence for a relationship between swallowing and the tensor tympani muscle is proposed by Salén and Zakrisson (1978). These authors point out that this muscle is embryologically related to the tensor palati muscle which is known to function during swallowing, and has a common motor innervation with this muscle, the trigeminal nerve (Hamilton et al 1959). Similar conclusions and results were given in publications by Djupesland (1965), and Salomon and Starr (1963).

Chapter 8 discusses the measurement of the displacement of the tympanic membrane during swallowing. This information may be used to aid assessment of the normality of the Eustachian tube function.

CHAPTER 3

ALTERNATIVE TECHNIQUES FOR STUDYING THE EAR MECHANICS

A number of different measurement techniques are available for studying middle ear mechanics. The techniques discussed in this chapter include probably the most well known, the electroacoustic impedance bridge, as well as a variety of other methods. Some of these, such as pressure and flow methods, are also sensitive to changes in the pressure of the perilymphatic fluid within the middle ear. Particular mention is made of pressure and flow measurement procedures employed to sense volume displacements of the tympanic membrane. Results obtained by these methods are especially relevant, as these devices are the predecessors of the TMD system used during the present investigation.

This chapter also discusses the advantages and disadvantages of the various measurement techniques. Details of the results obtained with these devices are given in appropriate chapters throughout this dissertation.

3.1 THE ELECTROACOUSTIC IMPEDANCE BRIDGE

The electroacoustic impedance bridge (EAI bridge) is probably the most commonly used device for studying the mechanics of the middle ear, both in clinical and research environments. A brief discussion of this device is given in this section. A more extensive description of its operational details and diagnostic powers are given in bibliographies by Lilly (1973) and Jerger (1975).

3.1.1 Historical review

The concept of acoustic impedance was first introduced by Webster in 1919. However, it was not until 1946 that Metz developed a practical electromechanical impedance bridge which was used to monitor stapedius muscle contraction in subjects with sensori-neural hearing loss and loudness recruitment (Jerger 1975).

The forerunner of the present day electroacoustic impedance bridge (EAI bridge), was pioneered by Terkildsen and his colleagues during the 1950s. Details of this device are given by Terkildsen and Scott-Nielsen (1960). During the very early stages of development, publications on acoustic impedance investigations were almost exclusively from the Scandinavian countries, from notable researchers such as Jepsen (1951, 1953) and Møller (1958, 1960) and at a later stage Liden who developed the tympanometry technique (Northern 1975).

Outside Scandinavia, Zwislocki (1975 a,b) in America developed an electromechanical impedance bridge and designed a device which measured the absolute impedance value of the middle ear mechanism. Nevertheless, the electroacoustic impedance principle remained by far the most popular for clinical applications.

The publications on EAI bridge investigations are too numerous to be given in this section, but may be found with reference to bibliographies by authors such as Møller (1972), Lilly (1973), Jerger (1975) and Borg (1976).

3.1.2 The acoustic impedance of the ear

The term impedance is in common usage in disciplines which are concerned with electrical, mechanical or acoustic systems. In each case, impedance is a complex ratio between two vector quantities, which in respect of acoustic impedance is the ratio of applied sound pressure to a vector quantity defined as the volume velocity. Expressing acoustic impedance in more physical terms, it is the vector sum of a resistance component, which is in-phase with the input, together with an out of phase reactive component, dependent on the dynamic mass and stiffness of the system. The unit of acoustic impedance is the acoustic ohm, which is directly analogous with the electrical equivalent.

Acoustic impedance is essentially a vector quantity. However for reasons of simplicity, only the vector magnitude of the impedance is normally used for audiological work, a quantity inversely related to the energy transmitted by the middle ear mechanism. Often this quantity is referred to as "impedance", whereas strictly speaking it is the "impedance vector magnitude", that is a scalar quantity.

How then does acoustic impedance relate to dysfunction of the hearing mechanism? Normally the ear is highly efficient, with the tympanic membrane and middle ear offering a relatively low acoustic impedance to the transmission of energy to the inner ear. In the case of abnormal ears, the amount of energy transmitted, and therefore the value of the acoustic impedance is often found to vary. For example, less energy will reach the cochlea if there is fluid within the middle ear, serous otitis, or perhaps disease has caused the joints of the ossicular chain to become less mobile or locked as with otosclerosis. In this situation there will be an increase in the acoustic impedance. In contrast, a discontinuity in the ossicular chain will result in the tympanic membrane becoming more mobile and a reduction in acoustic impedance.

The instrument normally employed to measure the acoustic impedance is the electroacoustic impedance bridge, the principle of which is subsequently described in this section. The clinical applications of acoustic impedance is discussed in detail in a bibliography under the title of "Clinical Impedance Audiometry", edited by Jerger (1975).

3.1.3 The principles of the EAI bridge

The main components of the EAI bridge are shown schematically in figure 3.1. A probe is connected to three tubes and sealed into the subject's external ear canal. At the end of one of these tubes is a miniature telephone transducer which produces a tone, normally 220 Hz in the subject's external ear canal. The driving signal to this transducer is from a voltage oscillator, the amplitude of which can be varied by a variable attenuator. Connected to one of the other tubes is a microphone which monitors the sound pressure level within the ear canal produced by the probe tone. The output from this microphone is filtered, amplified and rectified, and is then fed to one side of a centre balance volt meter. The other side of the meter is connected to a constant DC voltage which is adjusted to produce a null meter reading when the microphone is monitoring a specific sound pressure level. A variation in this sound pressure level, such as caused by a change in the impedance of the ear, is indicated as an out of balance of this meter.

The third tube leading from the probe, is connected to a small pump and pressure gauge, capable of producing and measuring a pressure in the ear canal within the range of ±400 mmH_2O. This enables the acoustic impedance to be determined for varying canal pressures, a study known as tympanometry, which is commonly employed for aiding the evaluation of the middle ear function.

The acoustic impedance bridge may be used to monitor reflex activity of the middle ear muscles, an application

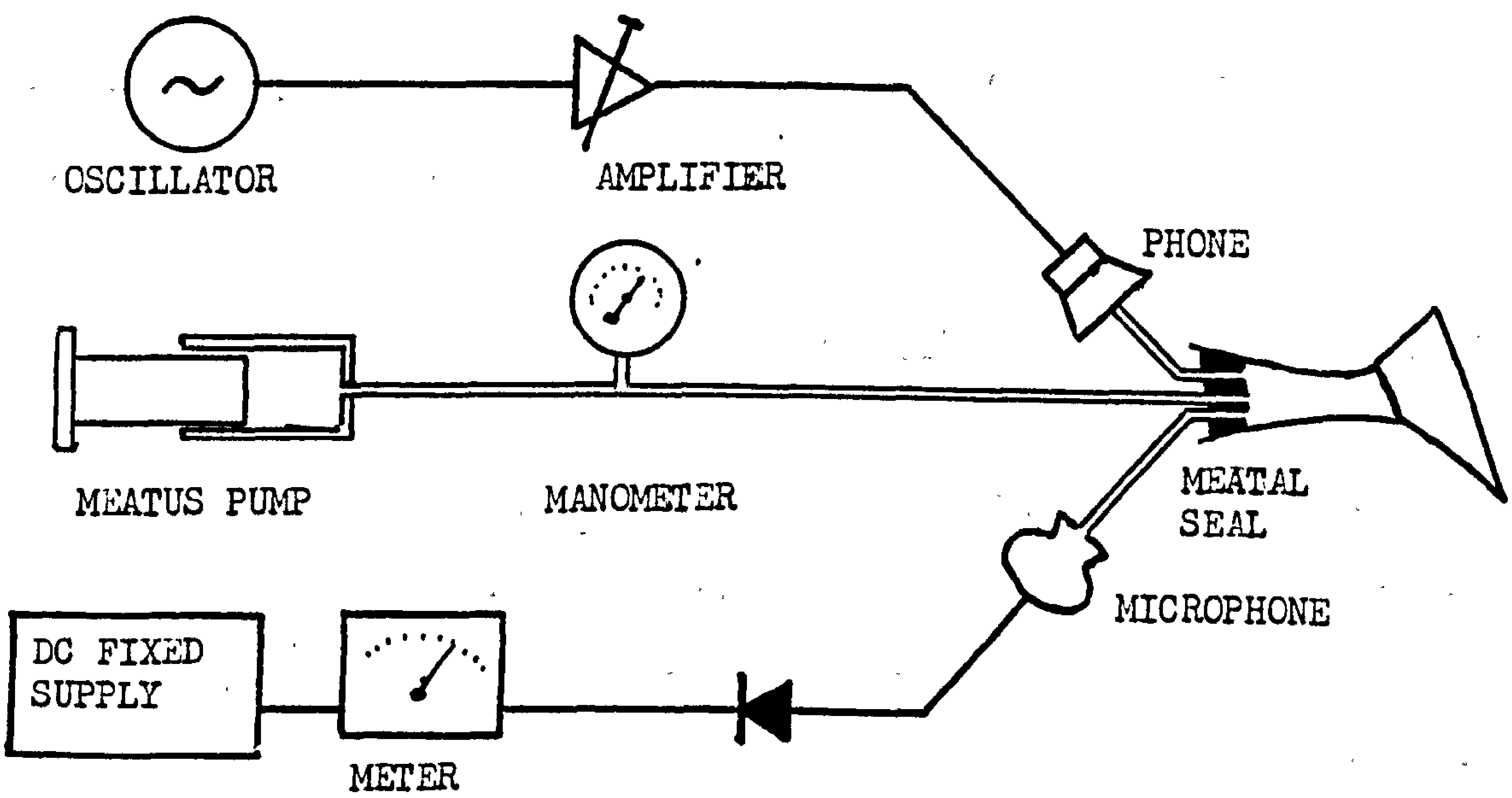


Figure 3.1 <u>Schematic of the electroacoustic impedance bridge</u>

which provides a valuable aid for diagnosing hearing disorders (section 2.2.4.). Reflex activity is identified as a change in the acoustic impedance of the ear, since muscle contraction affects the transmission of energy by the middle ear mechanism. The EAI bridge reflex threshold is the minimum stimulus intensity which produces reflex activity capable of causing a measurable fluctuation in the ear's acoustic impedance.

3.1.4 The influence of the probe tone on the reflex threshold

Essential to the operation of the EAI bridge is the probe tone, which has a known frequency and intensity below the reflex threshold. Brask (1978) performed experiments to determine if the probe tone affected the reflex threshold. He used a tone of 250 Hz with an intensity of 95 dB SPL, which is similar to probe tones employed in commercially available impedance apparatus. All his experiments indicate that the threshold is influenced by the probe tone in such a manner that it was lowered to produce what is known as the sub-reflex threshold. The degree of this influence depends on; i) the intensity of the probe tone, ii) the intensity of the stimulus, iii) the difference between the stimulus and the probe tone frequencies, and also whether the stimulus is ipsilateral or contralateral. Brask concludes that "the ordinary clinical impedance measurements are not the result of a "pure" contralateral or ipsilateral stimulation".

3.1.5 Concluding comments on the EAI bridge

The EAI bridge is a powerful device for both research purposes and clinical studies of the middle ear mechanism. It has a world wide popularity for aiding clinical diagnosis of hearing pathologies, which in part is due to it being fairly easy to operate. However, it is difficult to relate acoustic impedance with the physical configuration of the middle ear mechanism and reflexes. For example, the direction of movement of the tympanic membrane can not be obtained from impedance information. On the other hand, methods which measure the volume displacement of the tympanic membrane, such as pressure and flow techniques discussed in the following sections, yield data which are more closely related to the physical ear.

Impedance information is essentially different from that of TM displacement data, the former being related to energy absorption properties of the ear, and the latter to its physical configuration. Furthermore, impedance data are more complicated to interpret than that of TM displacement. This is because impedance measurements are dependent on the probe tone frequency and intensity. In particular, reflex impedance relates to the stimulus parameters as well as those of the probe tone. With TM displacement techniques the time course depends only on the stimulus parameters.

3.2 PRESSURE MEASUREMENT TECHNIQUES

Changes in the volume of the external ear canal, such as caused by contraction of the middle ear muscles, are measured using sensitive pressure transducers which have been airtightly sealed into the canal. These devices may range from simple 'U' tube manometers to sophisticated ultra low frequency capacitance microphones. Pressure techniques have not been used extensively in clinical environments. Nevertheless they are useful for research purposes, as they yield information which is closely related to the physical configuration of the middle ear mechanism and reflexes.

This section gives a historical account of the pressure techniques, as well as their advantages and disadvantages. Table 1 provides a list of relevant investigations with the associated equipment.

3.2.1 Historical review

Mangold and Eckstein (1913) successfully recorded reflex response as a result of voluntary and acoustic elicitation, using a type of photomanometer. Although their device worked on completely different principles to that used by Wagner (1924), both methods relied on a pressure variation deflecting a thin membrane. Allowances must be made for the volume displacement characteristics of this membrane, if a true pressure measurement is to be obtained. This typifies a problem of measuring pressure within a small enclosed cavity, namely that the pressure sensing device

TABLE 1 TYPES OF PRESSURE MEASUREMENT DEVICES UTILIZED BY PREVIOUS INVESTIGATORS

INVESTIGATION	TYPE OF DEVICE
Mangold and Eckstein (1913)	Form of photomanometer
Wagner (1924)	Diaphragm manometer
Mendelson (1957)*	Capacitance manometer
Mendelson (1961, 1966)	Improved capacitance manometer
Holst et al (1963)	Elema-Schönander EMT 573
Weiss et al (1963)	Western Electronic 64 OAA
Møller (1964)	Elema-Schönander EMT 573 Also Brüel and Kjaer 4131 AC microphone.
Neergaard and Rasmussen (1966, 1967)	AC microphone
Lidén et al (1970)	Elema-Schönander EMT 32 and 31.
Yonovitz and Harris (1976)	Sanborn Model 270
Brask (1978)	Brüel and Kjaer microphone 4132
Marchbanks (1980) (present investigation)	Brüel and Kjaer 2631 DC microphone

* In which applied pressure differences changed the transconductance of an ionisation tube.

must ideally have a very high input impedance, so as not to affect the pressure by itself varying the cavity volume.

Later Mendelson (1957) utilized a form of capacitance manometer, and was able to observe reflex responses in 25 subjects tested for acoustic stimulation (400 to 8000 Hz). Subsequently in 1961 and 1966, he improved on his technique and was able to detect muscle contraction in a higher percentage of subjects. It was also noted that the reflex may cause inward, outward or inward-outward deflections of the tympanic membrane.

Reflex experiments with both tactile and acoustic stimulation, were also performed by Holst et al (1963) with another type of pressure transducer. Both the results of this investigation, as well as Mendelson (1957, 1961, 1966) are qualitative in nature, yielding principally only information on the direction of the TM displacement. As found by these investigators, the magnitude and dynamic characteristics are normally masked by noise, such as that due to cardiovascular pulsations. This problem was overcome by Weiss et al (1963) by averaging sets of up to 100 reflex responses. This improved the signal to noise ratio by about 20 dB, and for the first time histories of the onset and offset characteristics of the reflex were obtained, for example see figure 3.2.

Other investigations, around this time, include the application of manometer systems in studies of the TM volume displacement for varying middle ear pressures, Flisberg et al (1963), as well as for measuring reflex activity in young cats and rabbits, Møller (1964). The

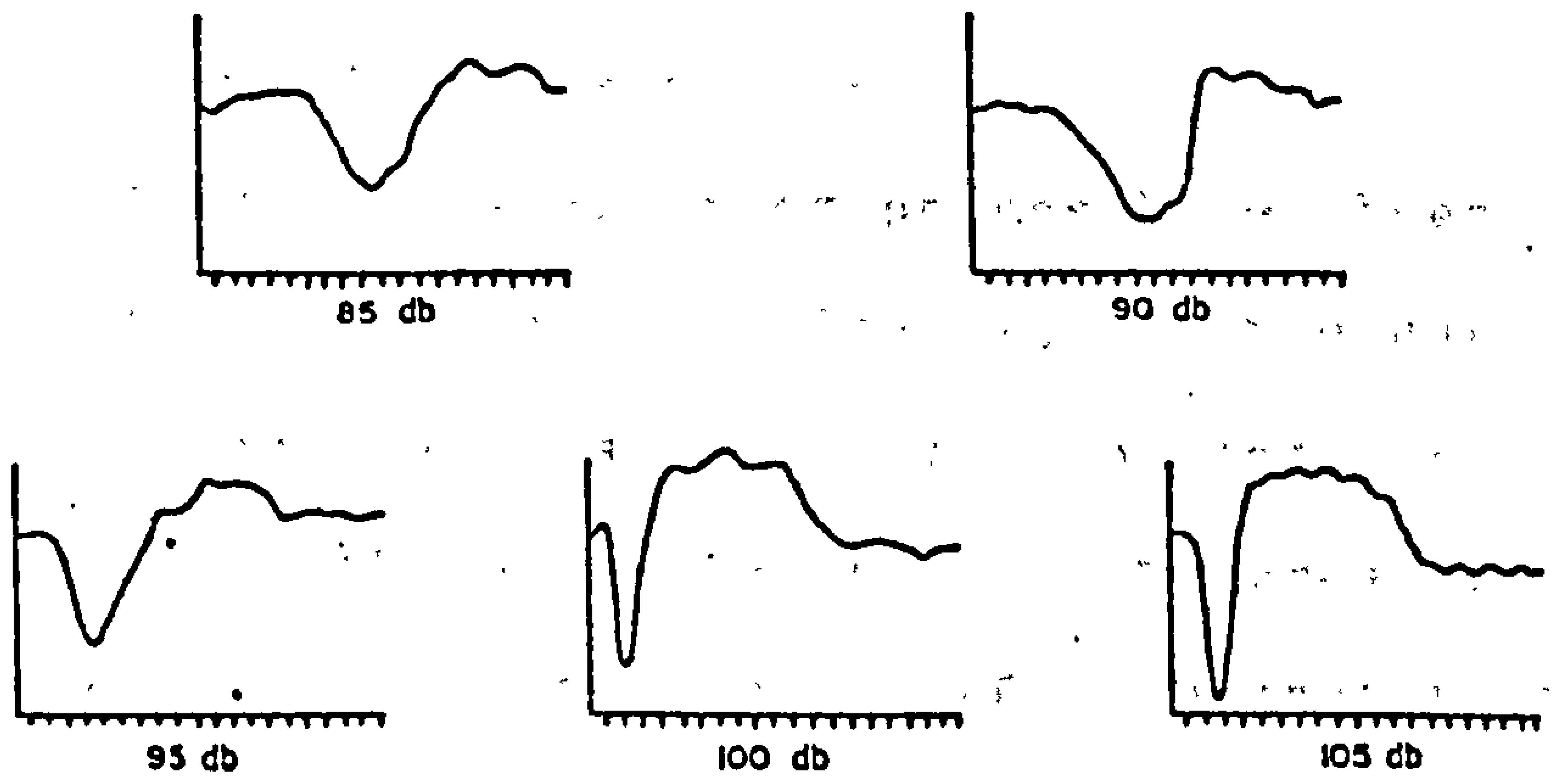


FIGURE 3.2 <u>The onset and offset characteristics of the reflex as recorded by Weiss et al (1963)</u>.
Ensemble average of 50 records, analysis time 2 seconds, stimulus 800 Hz 1 second ramp signal.

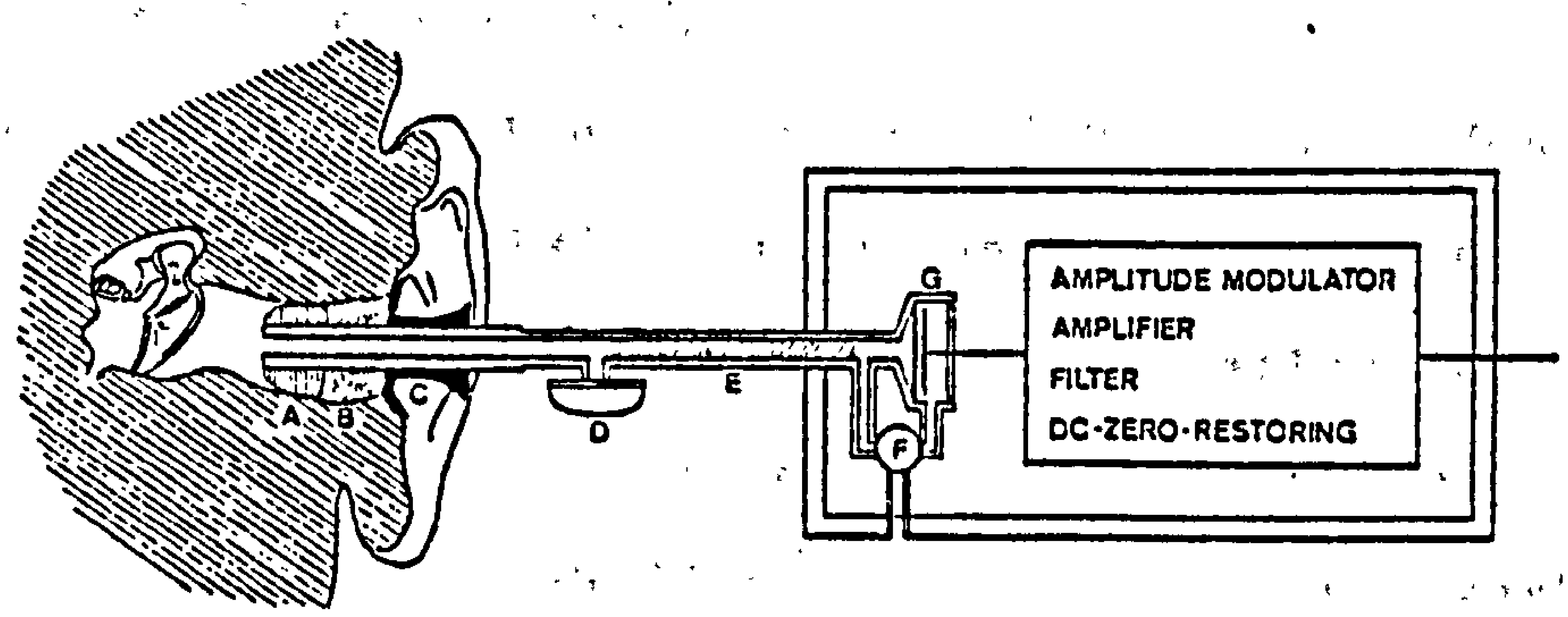


FIGURE 3.3 <u>Schematic drawing of Brask (1978) manometer system and the ear plug</u>
A: closed-pore sponge cuff. B: carbowax. C: movable "soft piston". D: earphone. E: acoustic low-pass filter. F: electromagnetic valve. G: condensor microphone.

results of the latter author indicate that the tensor tympani muscle always displaces the TM inwards, whereas a stapedius contraction could cause either inward, outward or inward-outward displacements.

Standard laboratory microphones have been utilized to study AC pressure variations within the ear canal (Møller 1964). These devices have a superior sensitivity when compared with most types of DC pressure tranducers. However, because of their AC characteristics, these microphones provide only limited information on reflex activity, which is essentially low frequency and outside the bandwidth of these devices. Nevertheless, AC microphones were successfully employed by Neergaard and Rasmussen (1966, 1967) to determine the latency of the stapedius muscle (results given in section 9.2). Their investigation of 1967 produced interesting results, in that for 6 pathological ears no reflex activity could be found using the EAI bridge, although reflex pressure variations could still be observed.

More recently, Lidén et al (1970) and Yonovitz and Harris (1973 and 1976), simultaneously recorded changes in pressure and impedance for various reflex contractions. These works were followed by probably the most extensive investigation published to date, written by Brask (1978). This investigation utilized a electromanometer detailed in figure 3.3. Brask improved the signal to noise ratio with the ensemble averaging technique (chapter 6) in a similar manner to Weiss et al (1963). With this method he investigated the stapedius reflex response for normal conditions, varying ear pressures and for different subject postures.

3.2.2 Backpressure on the tympanic membrane

A disadvantage of the pressure measurement technique is that any displacement of the tympanic membrane is resisted by the resulting pressure change within the closed ear canal. The magnitude of this resistance is dependent on the volume enclosed within the ear canal and measurement transducer; the smaller the volume then the greater the change in pressure. This backpressure will affect both the dynamic characteristics of the TM, as well as its steady state resting position. Evidence to quantify the significance of this interaction is scant; what data there are coming from studies of the compliance of the tympanic membrane (Flisberg 1963, Elner et al 1971a, Casselbrant et al 1977) and the influence of ear canal pressure on the stapedius reflex amplitude (Casselbrant et al 1977).

Casselbrant et al (1977) measured the compliance of the TM for varying differential pressures between the ear canal and middle ear cavity. Their results, shown in figure 3.4, indicate that when the TM is in its neutral position, its volume displacement for varying pressures is approximately 20 nanolitres per N/m^2. This may be seen to be fairly significant when related to a contraction of the stapedius muscle which produces a pressure increase of typically 8 N/m^2, for a corresponding TM volume displacement of about 200 nl (Brask 1978) *. Considering these values it is to be expected that the dynamic characteristics of the reflex

* The TM volume displacement magnitude is for a 500 Hz stimulus of intensity 10 dB above the reflex threshold, section 9.3. The pressure increase is from the results of Brask (1978) for a similar stimulus.

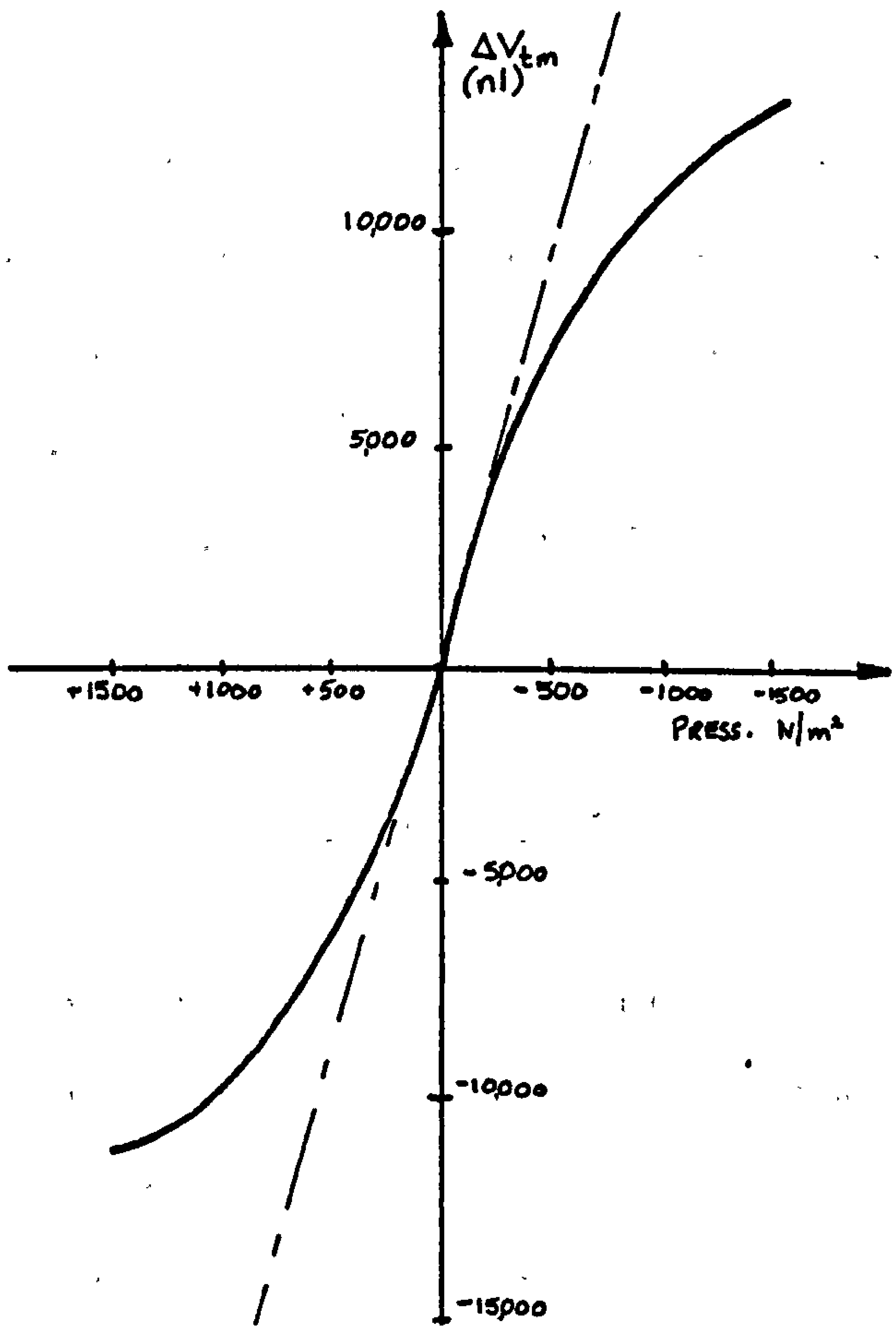


FIGURE 3.4 Differential pressure across tympanic membrane and resulting membrane displacement
Reproduced from Casselbrant et al (1977)

are altered. However, since the compliance of the TM will be different after the contraction, no quantitative conclusions may be drawn from them.

Further evidence for the interaction between the ear canal pressure and the magnitude of the TM volume displacement is given by Casselbrant et al (1977). Their results show that the maximum reflex response occurs at an over-pressure within the middle ear of about $200 N/m^2$. At this pressure the TM displacement was found to decrease at a rate of approximately 1 nl per N/m^2, as shown in figure 3.5.

3.2.3 Concluding discussion on pressure measurement techniques

Pressure measurement techniques are probably the simplest methods available for monitoring displacements of the tympanic membrane. In comparison with the electroacoustic impedance bridge, these provide more information in respect of the physics of the middle ear mechanism. In several instances of tests on pathological ears where no EAI bridge responses were apparent, muscle contraction was detected using pressure techniques (Neergaard and Rasmussen 1967).

As with the flowmeter techniques described in the following section, pressure measurements are subject to high noise levels so that, if the reflex dynamic characteristics are to be resolved, ensemble averaging must be adopted (Brask 1978).

The pressure measurement techniques have principally two

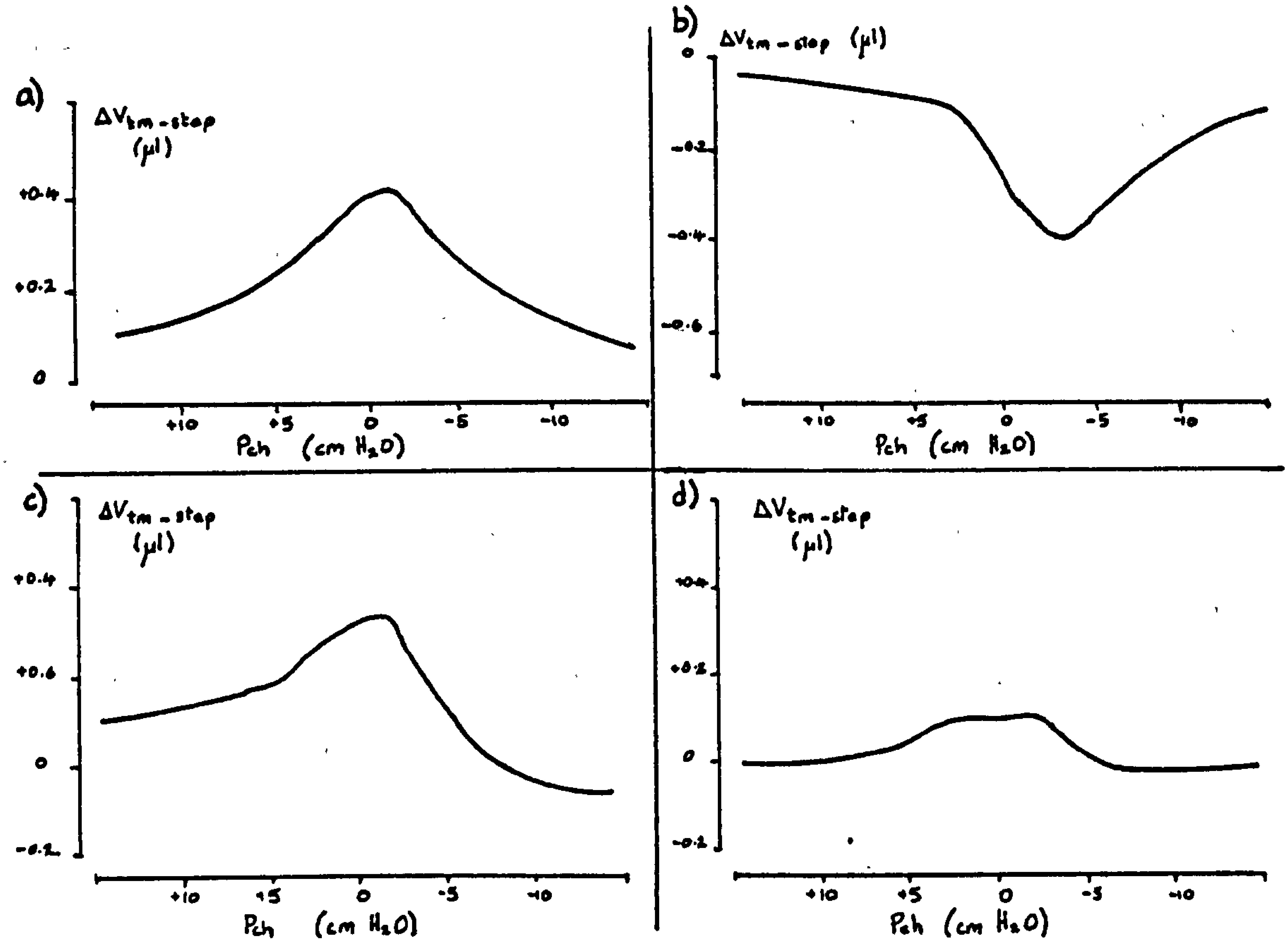


FIGURE 3.5 <u>The acoustic reflex volume displacement of the tympanic membrane for varying differential pressures across the membrane</u>

The stimulus presented to the contralateral ear, 1 KHz, 105 dB.

a) Only outward movements at the stapedius reflex contraction, irrespective of the pressure across the tympanic membrane.

b) Only inwards movements.

c) and d) Outward and inward movements at the stapedius reflex contraction depending on the pressure across the tympanic membrane.

Reproduced from Casselbrant et al (1977)

disadvantages. Firstly, they are fundamentally non-free field measuring devices, in that backpressures are produced which resist movements of the TM. Although unproven, it is likely that this effect will modify the dynamic characteristics of the tympanic membrane. A further disadvantage is that this technique does not provide a direct measure of the volume displacement of the TM. This displacement may only be estimated if the enclosed volume within the ear canal and measuring device is known. However, it is not possible to exactly evaluate this parameter because the walls enclosing the volume are not perfectly rigid. These two disadvantages are alleviated by the use of flow measurement techniques described in the following section.

3.3 TM VOLUME DISPLACEMENT MEASUREMENT TECHNIQUES

Any movement of the tympanic membrane displaces a minute volume of air into or out of the external ear canal. This volume displacement may be measured by one of several techniques. The simplest method is by airtightly sealing a small bore capillary tube into the ear canal. Inside this tube is placed a minute thread of liquid, so that when the TM moves its steady state volume displacement is related to the distance moved by the liquid column. Because of the high effect of surface tension, the distance travelled is often less than expected (Terkildsen 1957).

A more sophisticated technique involves employing a micro-flowmeter. This device is sealed into the ear canal so that any TM volume displacement is measured as a flow of air into or out of the canal. The volume of the air displaced is extremely small (typically less than 1 cubic millimetre) and will fluctuate over relatively short periods. Consequently careful consideration must be given to the design and calibration of such flowmeters.

3.3.1 Historical review

A technique for measuring the TM volume displacement was used in 1860 by Politzer (1869, 1908), who sealed a 2 to 3 mm bore glass capillary tube into the external ear canal. Volume variations caused by swallowing, rapid respiration and voluntary tensor muscle contraction, were indicated by movements of a coloured thread of liquid within a 'U' shaped section of the glass tubing. Wojatschek (1909) used a similar principle and recorded volume displacement by projecting an image of the fluid onto a rotating cylinder covered with photographic paper.

Almost five decades later, Terkildsen (1957, 1960) again adopted a capillary type volume measuring device, as shown in figure 3.6. He chose the liquid to have a low surface tension, so enabling it to respond more readily to a TM displacement. Terkildsen demonstrated that it was possible to measure the TM displacement as a result of acoustic elicitation of the reflex, which he estimated to be less than 1 cubic millimetre. The reflex threshold was similar to that measured with the then available impedance bridge.

The earliest publication on the use of a flowmeter for

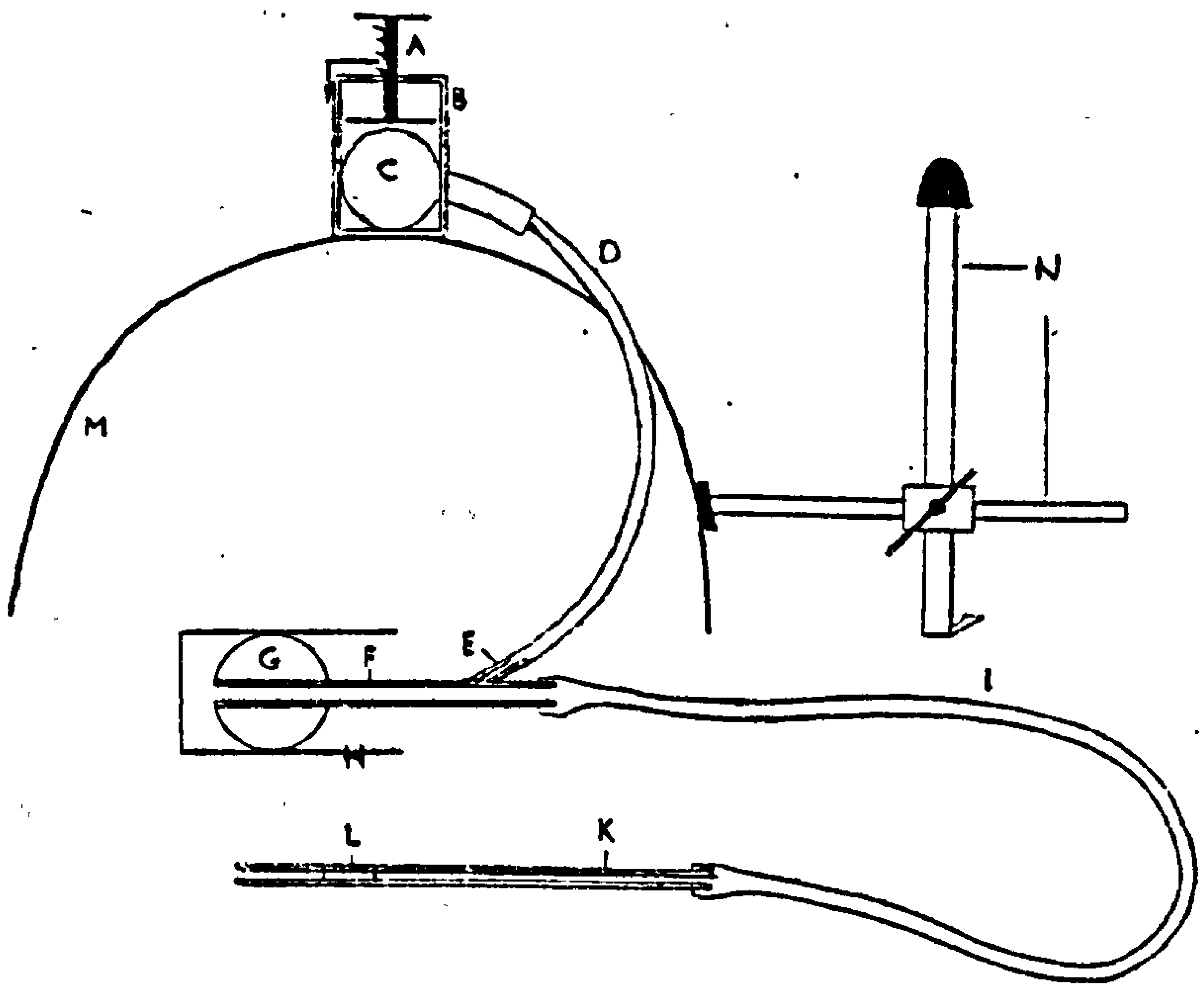


FIGURE 3.6 <u>Diagram of Terkildsen's (1957) capillary tube volume displacement measuring device</u>

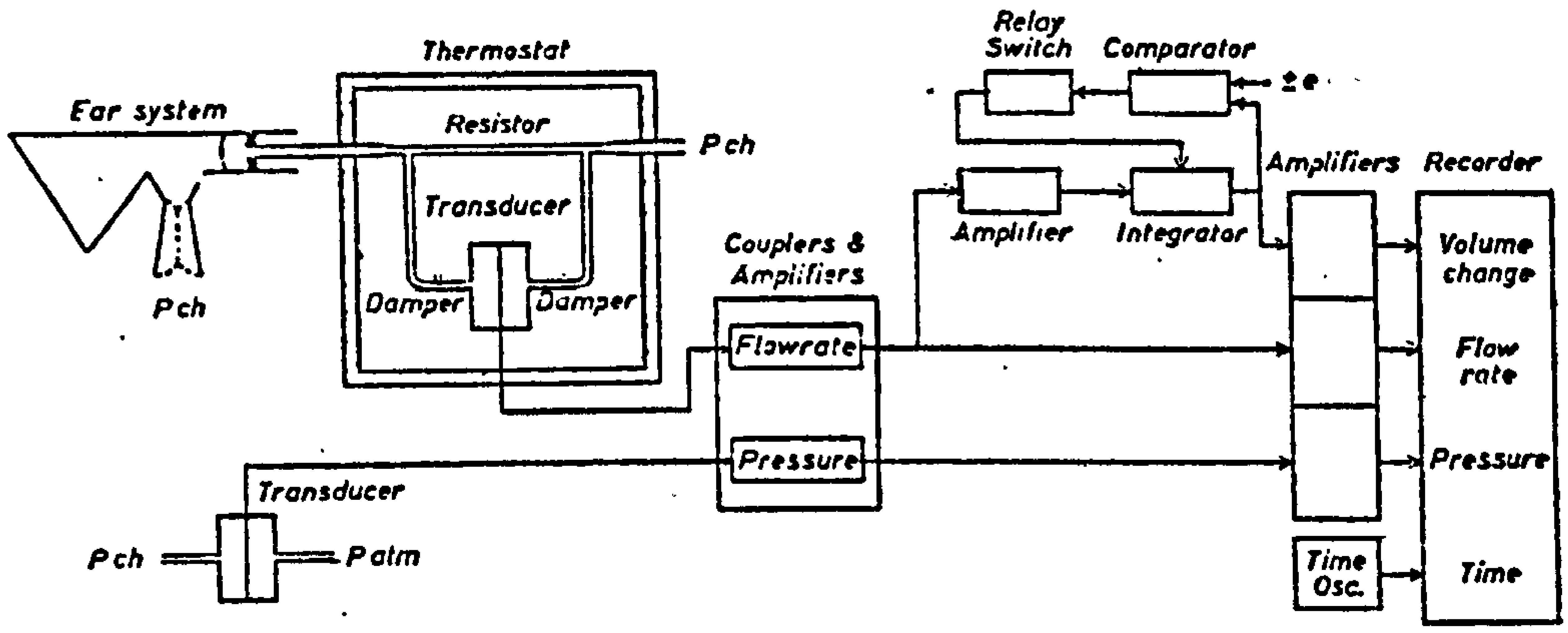
A. plunger: B. metal housing: C. compressible rubber bag: D. rubber tube: E. metal side tube: F. earpiece: G. latex rubber cuff: H. external ear canal: I. rubber tube: K. glass-tube gauge: L. fluid drop: M. flexible headband: N. adjustable fixture.

measuring TM displacement, appears to have been written by Holst et al (1963). They measured the pressure drop across a capillary tube caused by the volume flow, using a pressure transducer of type Elema-Schönander EMT 573. With this flowmeter and pressure techniques, they were able to give qualitative assessments on the magnitude and direction of reflex TM displacement. Subsequently publications from a programme of research using flowmeters were forthcoming from the Departments of Oto-laryngology and Clinical Physiology at the University of Lund, Sweden. These investigations account for most of the research performed with flowmeters.

The research at Lund University was performed using a capillary flowmeter design, based on an Elema-Schönander EMT 32 differential gas pressure transducer, the specifications of which are given by Ingelstedt et al (1967) and show that the device has a frequency response which is flat over 0 to 11 Hz, as shown in figure 3.7. Over the past two decades, this research has been conducted by a group which has included Holst, Ortegren, Ingelstedt, Jonson, Ivarsson, Elner and later Casselbrant, Densert and Pederson.

Ingelstedt and Jonson (1966) and Elner (1977), published papers concerning a flowmeter technique which measured the gas absorption rate from the middle ear (section 8.3). Ingelstedt et al (1967) and Elner et al (1971 a,b,c) employed similar techniques to study the mechanics of the human ear, the Eustachian tube function and to indirectly determine the middle ear pressure. In a similar manner, Elner et al (1971a) studied the elastic properties of the

a) Block diagram of the equipment for pressure, flow and volume determinations.



b) Characteristics of the flow-volume device.

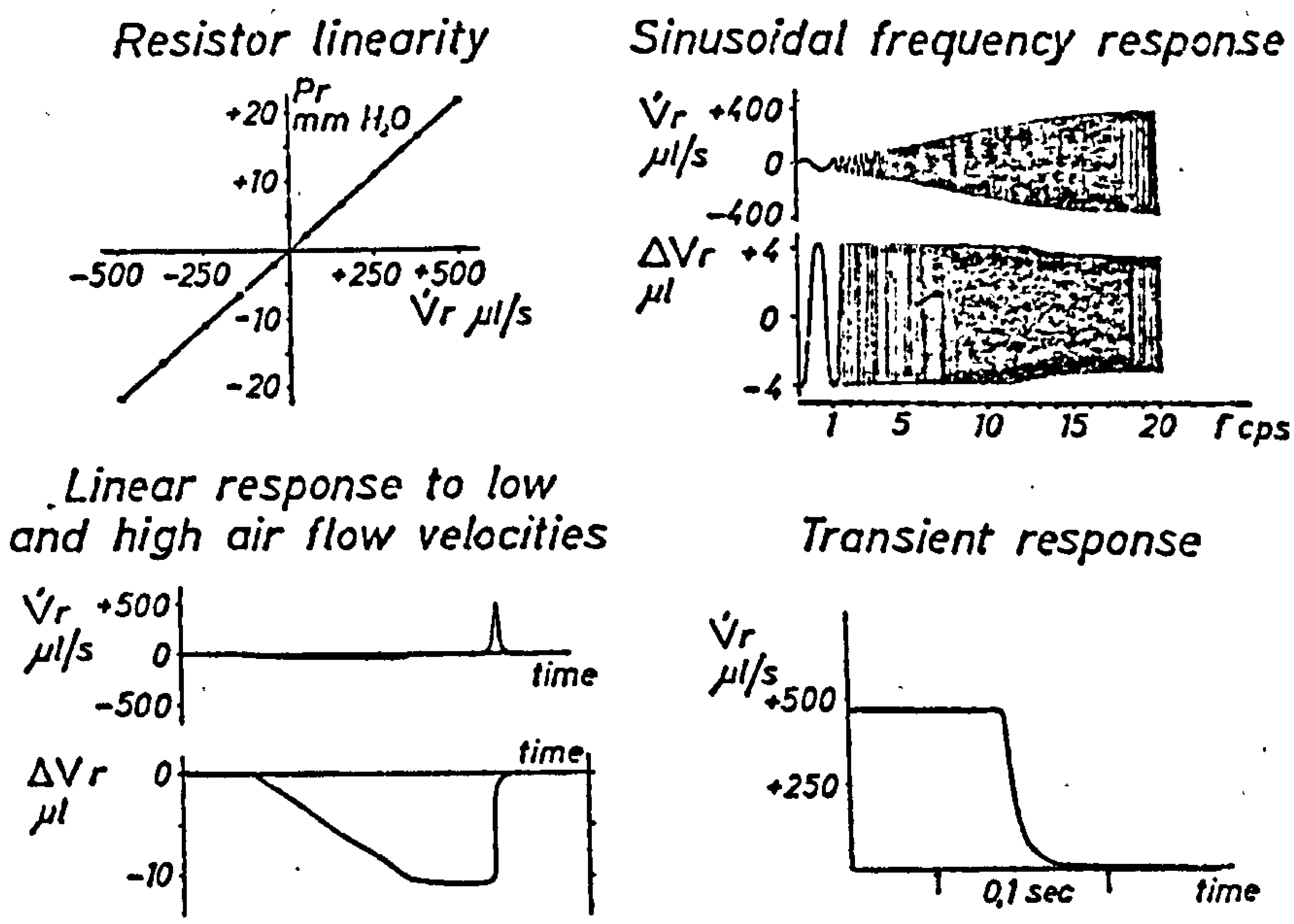


FIGURE 3.7 <u>The flowmeter used for research at Lund University, Sweden</u>
Reproduced from Ingelstedt et al (1967)

tympanic membrane. More recently the research at Lund University has resulted in publications concerning the reflex TM displacement and the effects of changes in the perilymphatic pressure (chapter 10), Casselbrant (1977, 1978) and Densert et al (1977).

In an unpublished document, Marchbanks (1975) gives an account of a flowmeter for measuring the TM volume displacement resulting from contractions of the middle ear muscles. This investigation, as with those at Lund University, does not use averaging techniques to improve the signal to noise ratio, see figure 3.8. Consequently the information from these results is more or less limited to the values of steady state TM displacements.

3.3.2 Concluding comments on TM displacement measuring techniques

Out of the two types of TM volume displacement measuring techniques mentioned in this section, only the flowmeter developed at Lund University has successfully been utilized for measurements over a reasonable frequency bandwidth. A good feature of this technique is its capability of measuring volume displacements of the tympanic membrane, independent of the volume enclosed within the external ear canal. Furthermore, the backpressure imposed on a moving TM is less than with pressure measurement methods. However, flowmeters are fundamentally non-free field devices, since to operate they rely on a pressure differential between their inlet and exhaust. The larger the pressure differential, then the greater is the

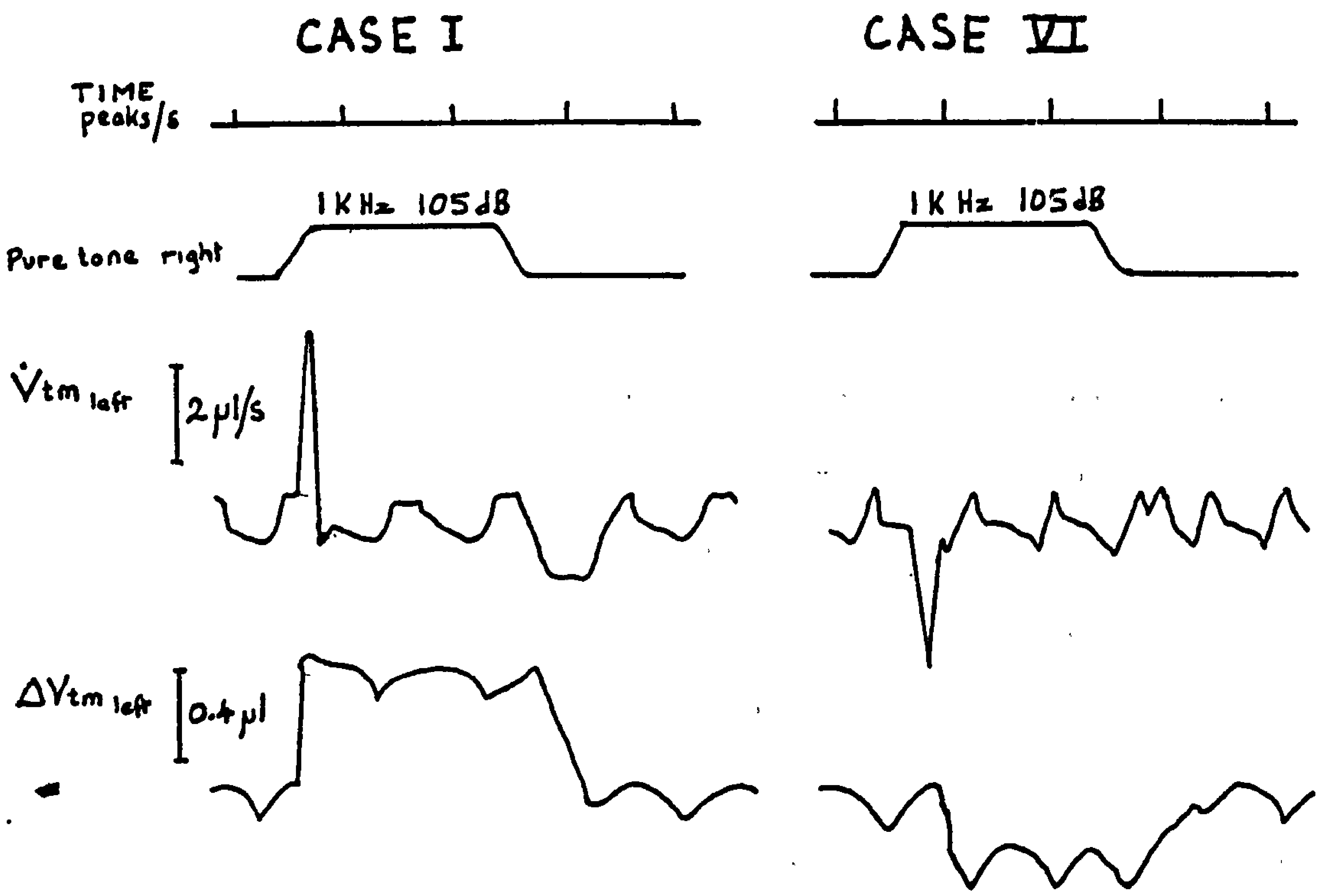


FIGURE 3.8 Tympanic membrane displacement recordings made by Casselbrant et al (1977)

$\dot{V}_{tm}$ represents the recorded flow velocity and ΔV_{tm} the volume displacement of the tympanic membrane. Notice that information from this data is more or less limited to values of steady state displacements.

Reproduced from Casselbrant et al (1977)

sensitivity of the flowmeter. In relation to measuring volume displacements within the ear, this implies that the sensitivity may only be improved at the expense of increasing the backpressure on the tympanic membrane.

3.4 CAPACITANCE PROBE TECHNIQUES

Capacitance probes can be used to measure very small displacements of the tympanic membrane, of the order of Ångström units *. The principle of the capacitance probe technique relies on the probe being placed close to the moving part of the ear mechanism under study. Any displacement of this member can then be measured as a change in electrical capacitance, the probe constituting one plate of a capacitor and the ear member the other. If the displacement amplitude is small compared with the distance between the probe and the part of the ear under study, then the change in capacitance is approximately a linear function of the displacement amplitude. This principle is described in detail in section 4.1.

The change in capacitance is normally measured by one of two different methods. Rubinstein et al (1964) and Fischler et al (1967) connected the moving member of the ear to the output of a high frequency 200 KHz oscillator and the probe was connected to the input of a wide band amplifier. A change in capacitance caused an amplitude modulation of this 200 KHz carrier frequency, so that the envelope of the carrier waveform becomes a function of the

* An Ångström unit is equivalent to 1 x 10^{-10} metres.

displacement. Møller (1963) and Hoeff et al (1964) utilized the capacitance of the probe in an oscillator tank circuit, so that a variation in distance resulted in a change in the frequency of oscillation. The degree by which the frequency is changed is a measure of the displacement of the ear member.

3.4.1 Historical review

A capacitance probe is occasionally employed either to determine the modes of vibration of the tympanic membrane or to measure the displacement of specific members of the middle ear mechanism. Probably the earliest investigation to measure the modes of vibration was made by Von Békésy (1941) using a capacitance probe. He performed the experiment on a fresh human cadaver specimen, which he subjected to a tone of 2000 Hz. With the aid of the capacitance probe he mapped the vibration amplitudes at specific regions of the tympanic membrane. Later Møller (1963) used the same principle to evaluate the transfer function of the middle ear in an anaesthetized cat. He measured the amplitude and phase variations for vibrations of the incus, malleus, and round window for constant sound pressure levels at the TM.

Hoeff et al (1964) utilized a probe to make a direct measurement of the displacement of the guinea-pig TM when acted upon by tones in the range 200 to 600 Hz. They placed the probe about 1 mm in front of the malleus and as close to the centre of the tympanic membrane as possible. Later Fischler et al (1967) also used a probe to estimate the magnitude of motion at several locations on the TM and the stapedial footplate in human cadaver preparations.

3.4.2 Concluding comments on the capacitance probe

The advantage of the capacitance probe is that very small displacements can be measured without mechanically loading the ear mechanism. The disadvantage of this device is the need for critical positioning of the probe within the external ear canal. It requires to be fixed at a distance of about a millimetre from the ear member under study for it to function correctly. This needs to be performed by professional operators if damage to the ear is to be avoided. It is difficult to see that the capacitance probe can ever be used to obtain routine clinical measurement of TM displacement, such as caused by the acoustic reflex. Normally the positioning problems are not so critical in research situations, since experiments are conducted on anaesthetized animals or human cadaver specimens, for which the external ear canal may be specially prepared or even removed.

3.5 LASER HOLOGRAPHIC INTERFEROMETRY

The technique of laser holographic interferometry has been adopted, in several different modes, to obtain information concerning movement of the tympanic membrane. Tonndorf and Khanna (1968) used interferometry for observing displacements of a chosen point on the TM of the cat. They achieved this by attaching a small object mirror to the tympanic membrane and a second reference mirror to the temporal bone around the entrance to the external ear canal. Light from a laser was reflected from both mirrors to a point at the face of a photomultiplier, see figure 3.9. At this position, the amplitude of vibrations of the membrane is recorded as an interference pattern produced by the interaction of the two beams. With this method, Tonndorf and Khanna were able to determine the vibration of a particular part of the membrane in response to tones of varying frequency.

During 1971 and 1972 Tonndorf and Khanna published papers concerning the application of a technique known as 'time averaged' holography, reported earlier by Powell and Stetson (1965). Tonndorf and Khanna adapted this technique for recording the modes of vibration of the TM for tones of varying frequencies. This method requires that the TM has a reflective surface, which is accomplished by coating it with a fine bronze powder. As with the previous techniques, the TM is illuminated with a laser such that the interference between the reflected laser light and the reference beam provides a hologram. Essentially, a series

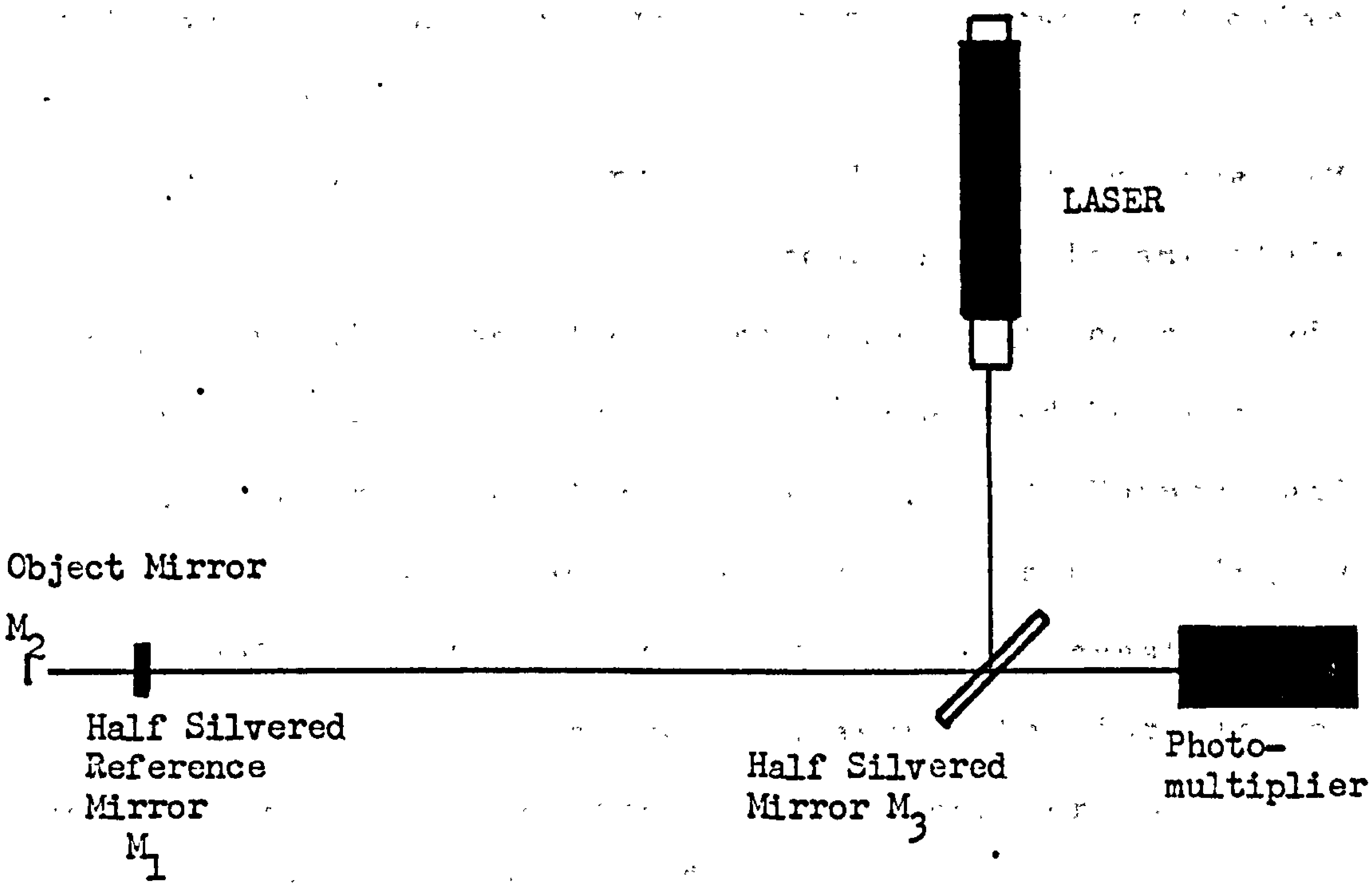


FIGURE 3.9 Schematic diagram of the interferometer used by Tonndorf and Khanna (1968)

None of the focusing lenses, apertures, filters, mechanical alignment devices, etc., are included. For details on these latter items cf. Khanna et al (1968)

Reproduced from Tonndorf and Khanna (1968) of holograms are recorded for each position of the vibrating membrane. Since the TM spends most of its time in positions of maximum displacement, these particular maxima are emphasised.

The image reconstructed from the hologram shows the TM superimposed by fringes which represent isoamplitude contours, from which the TM deformation may be calculated, see figure 3.10. With this time averaged holographic technique, Tonndorf and Khanna (1971), and Khanna and Tonndorf (1972) performed experiments on both living as well as freshly sacrificed cats. The same investigators also employed this technique to measure the vibration of the tympanic membrane in fresh human cadaver specimens (Tonndorf and Khanna 1972).

The holographic interferometry techniques so far described are incapable of measuring the displacement of the tympanic membrane at a particular instant of time, such as required for studying the deformation caused by the middle ear reflexes or an acoustic impulse. Such transients can be determined using a laser which emits pulses of very short duration. If the interference hologram is recorded at an instant before the transient and at an instant during or after the transient; then the resulting hologram contains information on the movement of the TM between these two instances. This technique was described and applied on guinea-pigs by Smigielski et al (1975), who investigated the TM response to acoustic impulses.

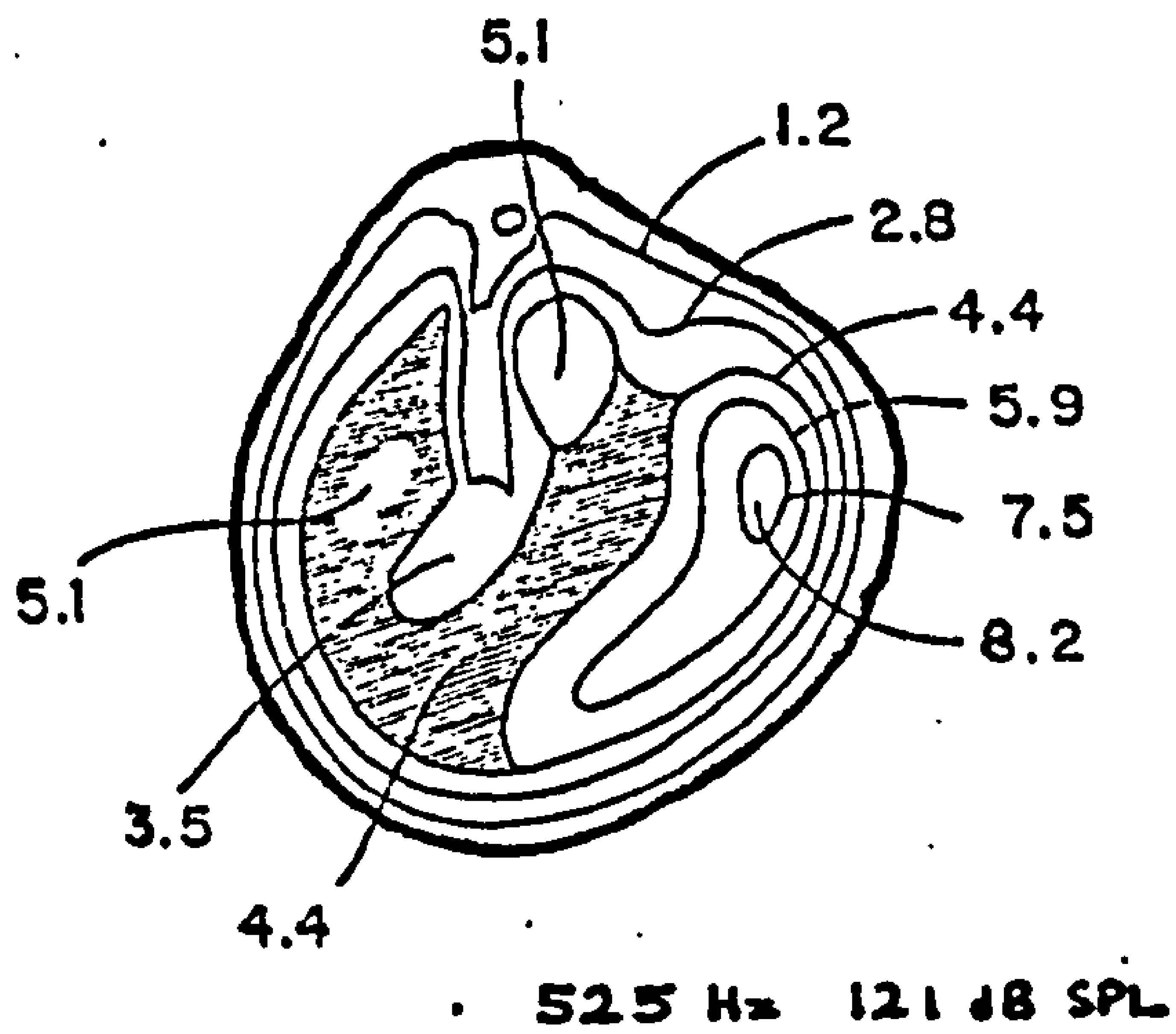


FIGURE 3.10 <u>Diagrammatic reconstruction of a time averaged hologram of the human tympanic membrane</u>

For TM subjected to an acoustic field of 525 Hz, 121 dB SPL. The numerals indicate the amplitude of each isoamplitude contour and must be multiplied by 10^{-7} metres.

Reproduced from Tonndorf and Khanna (1972).

3.5.1 Concluding comments on laser holography

Laser interferometry provides a very accurate means of measuring submicroscopic displacements of the tympanic membrane. At present this technique is limited to animals which can be sacrificed before or after the experiment, or on human cadaver specimens. This is due to the need for modification of the external ear canal so as to obtain direct visual access to the TM, as well as the necessity of clamping the specimen so as to maintain rigidity between the mirrors and laser. At the present stage of holographic development these limitations make it unlikely that this technique could be routinely used on living humans to monitor middle ear reflex activity or other TM displacements.

3.6 OTHER TECHNIQUES FOR MEASURING MOVEMENT OF THE TYMPANIC MEMBRANE

This section outlines several less well known procedures which have been adapted to evaluate displacement of the TM.

As long ago as 1874, Mach and Kessel utilized the principle of stroboscopic illumination to monitor the vibration of the tympanic membrane in response to acoustic stimulation. The same principle was later adopted by Kobrak (1943), and Guinan and Peake (1967). However this technique is only applicable for acoustic TM vibrations and not for displacement transients.

The Mössbauer effect discovered in 1957, has been applied by Gilad et al (1967) to the measurement of vibrations of guinea-pig TM in response to sound stimulation. This technique, described in detail by Gilad et al (1967), requires that a radioactive gamma source is placed on the vibrating ear member, and that a gamma absorber is positioned between it and a gamma counter. The radioactivity absorbed in the absorber will depend upon the velocity of the source, and can be estimated from the change in the gamma particle count rate. The displacement is calculated from this velocity. As with the stroboscopic illumination, this technique is suited to sound vibrations of the TM but not to single transients, such as with reflex activity.

Kohler (1909) and Kobrak (1957) measured the middle ear reflex activity by monitoring the angular rotation of a light beam reflected from a tiny mirror glued to the tympanic membrane. This method is sufficiently sensitive for Kobrak (1957) to be able to observe minute movements caused by the pulse, respiration, stimulus tones as well as reflex activity. Although this and the other methods described in this section provide useful information for research purposes, the degree of subject preparation and rigidity of the set up, currently excludes these techniques from routine clinical applications.

CHAPTER 4

TWO NEW CONCEPTS FOR MEASURING TYMPANIC MEMBRANE DISPLACEMENT

At the outset of the present research, the methods which were then available for measuring tympanic membrane displacement were investigated. Time was also spent in attempting to devise new techniques which have advantages over the conventional methods outlined in chapter 3. As a result, the two devices described in this chapter were conceived, namely the 'scanning capacitance probe' and the 'tympanic membrane displacement (TMD) system'. Both of these devices were scrutinized by the National Research and Development Corporation (NRDC).*

The scanning capacitance probe was not developed beyond the early prototype stage and consequently was not patented by the NRDC. This was because only limited effort was available and the TMD system posed the most promising avenue of research on several counts:

i) The TMD system was the easiest of the two alternatives to develop within the given 3 years.

ii) The scanning capacitance probe possessed unknown

* A UK patent application has now been filed on the TMD system by the NRDC. Patent application number 80 14390.

problems in respect to its positioning in the external ear canal.

iii) The TMD system was felt to be easier to operate and calibrate.

4.1 THE SCANNING CAPACITANCE PROBE

The scanning capacitance probe utilizes the same capacitance principle as the conventional probes discussed in section 3.4. In addition it incorporates a unique focusing feature which enables it to sense the movement in very specific regions of the tympanic membrane, as detailed in this section.

4.1.1 The principle of the conventional capacitance probe

A capacitance probe is often used to monitor the displacement of a moving surface. The principle of operation is that the fixed probe and the moving surface form the two plates of a capacitor, the capacitance of which is an inverse function of the separation of the plates. By applying a sinusiodally varying voltage to the probe and by earthing the moving surface, the distance between the two can be measured as a function of time.

Considering the circuit of figure 4.1. If a sinusoidally varying voltage, $V(t)=V_0 \sin\omega t$, is applied between the two electrodes, then the current flowing in the circuit (assuming capacitance impedance only) is $I(t)=Cj\omega \sin\omega t$ where C is the capacitance between the

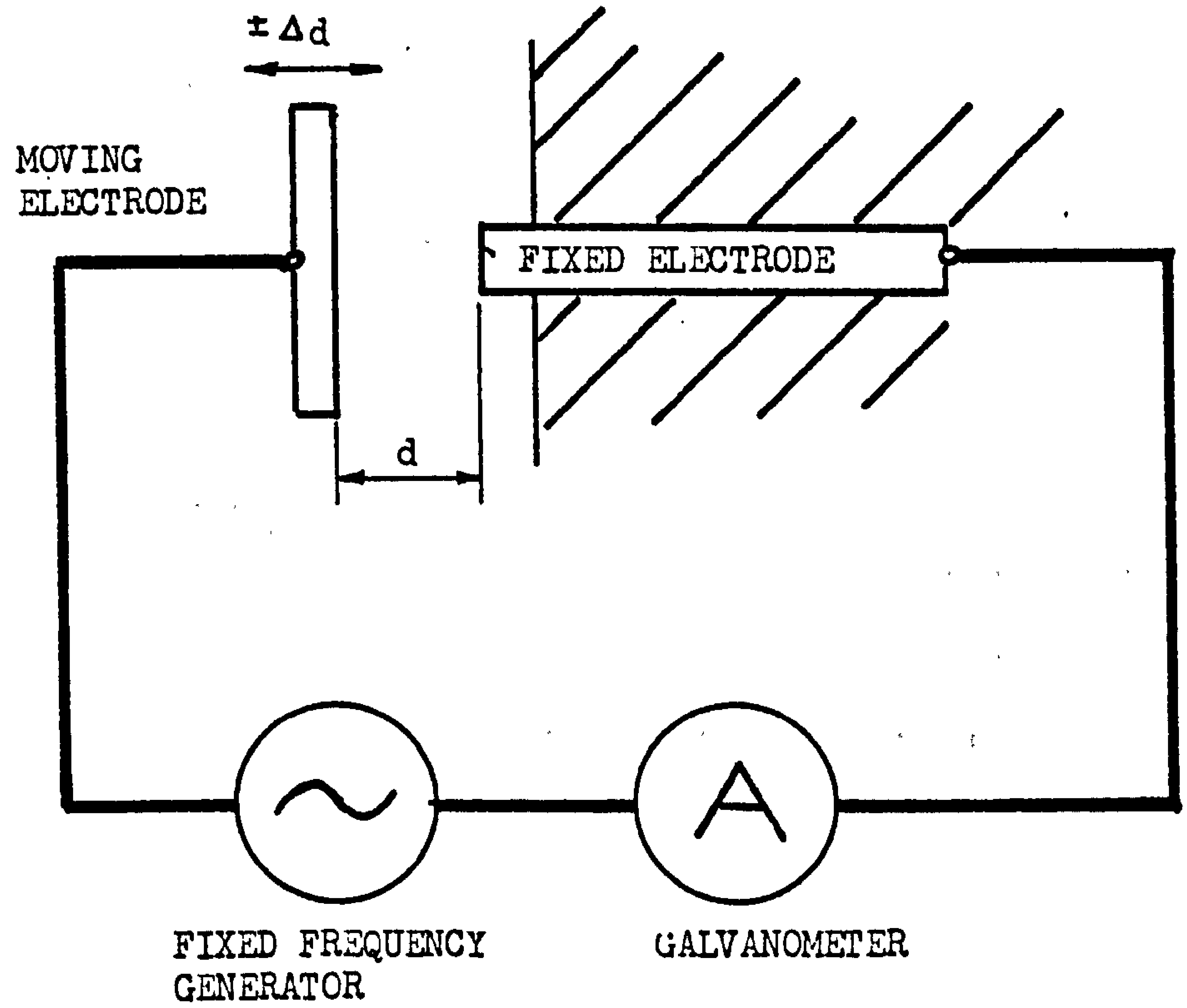


FIGURE 4.1 Principle of the capacitance probe

electrodes and ω is the frequency (rads/sec) of the voltage source. The peak current flowing in the circuit I_o is related to the peak voltage applied across the electrodes V_o by

$$I_o = CV_o\omega$$

The capacitance is related to the distance between the electrodes $(d + \Delta d(t))$ by

$$C = \frac{K}{(d+\Delta d(t))}$$

where d is the nominal distance between the electrodes, $\Delta d(t)$ is a small magnitude variation from d and K is a constant of proportionality. So that

$$I_o(t) = \frac{K V_o \omega}{(d+\Delta d(t))}$$

that is the displacement $\Delta d(t)$ is related to the current flowing in the circuit.

If an electrode is inserted into the ear canal and a sinusoidally varying voltage is applied between it and the tympanic membrane, movement of the TM can be calculated from the current in the circuit (Koidan 1953; Lothar et al 1963; Wilson et al 1975).

Limitations of the conventional capacitive probe are:

i) The probe can only measure the distance between it and a single region on the surface. It must be mechanically realigned to measure the movement of other regions. This process is slow and complicates the measurement of the relative displacements and phase relationship.

ii) The region of the surface over which the capacitance effect is measured is fairly large and it is often desirable to measure the displacement of a more specific region.

4.1.2 Principle of the scanning capacitance probe

The scanning capacitive probe measures the capacitance of different regions of a moving surface in a scanning action; the probe remaining stationary during this operation. This scanning is achieved by surrounding a capacitive probe by electrodes of differing electrical potentials to that of the probe. The scanning and focusing of the capacitive effect to a specific region of the moving surface, is accomplished by varying the potentials on the four 'directing electrodes' (see figure 4.2), which vary the probe's electrostatic field. If the capacitance of a region is compared with that of the same region a small interval of time later, then the distance moved in a direction perpendicular to that of the probe's surface may be deduced.

A two dimensional electrostatic field analysis has been performed and the results indicate that the capacitive probe does effectively scan surfaces if the field is varied in a precise manner, see figure 4.3.

The concept of directing electrodes is:

i) To enable scanning of surfaces to detect

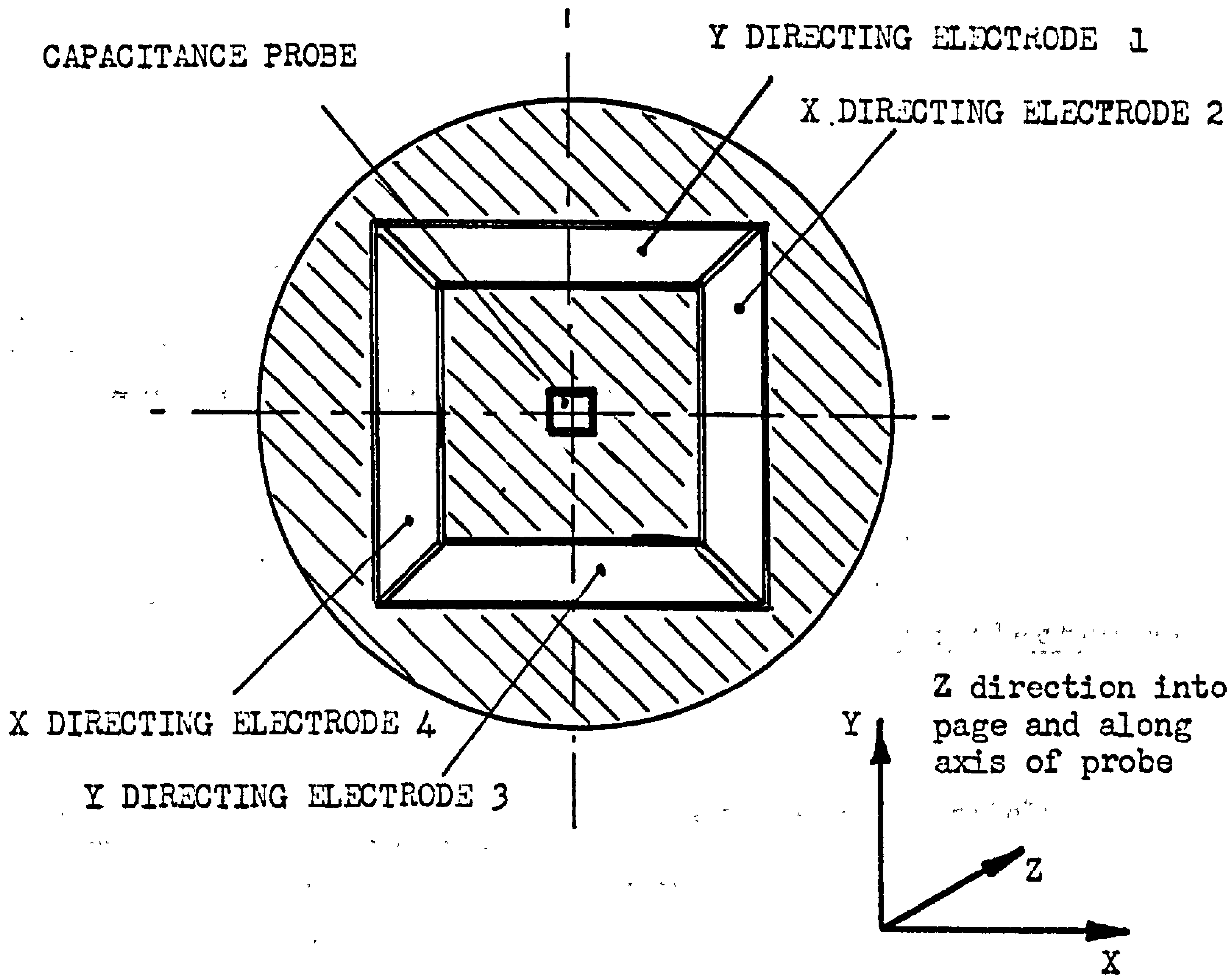
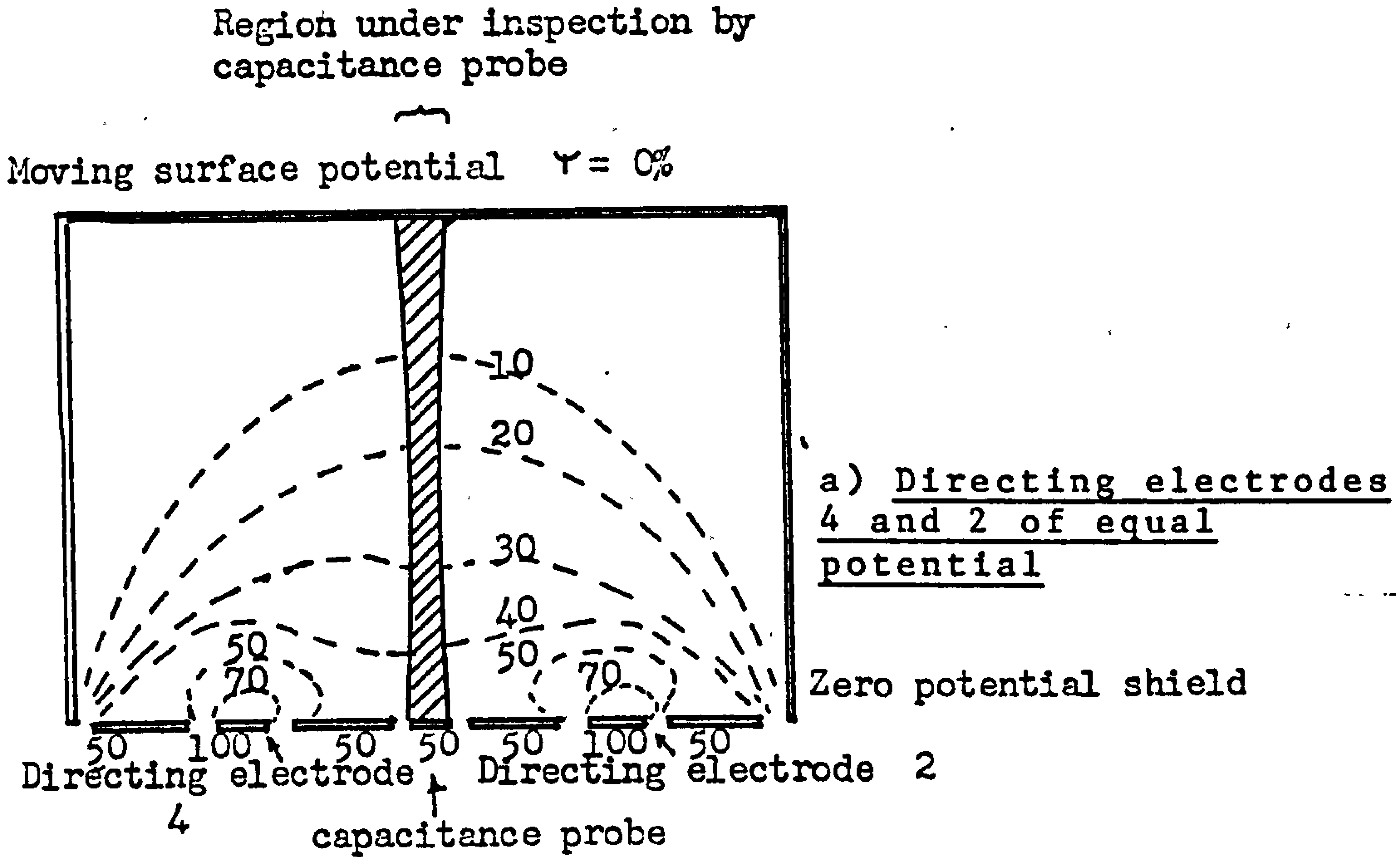


FIGURE 4.2 The scanning capacitive probe with surrounding electrodes

This is a view of the capacitive probe surface with the surrounding electrodes. By varying the potential of the four directing electrodes the electrostatic field around the probe will be changed. (Figure 4.3) The shaded areas, although insulated from the probe, are kept at probe potential.



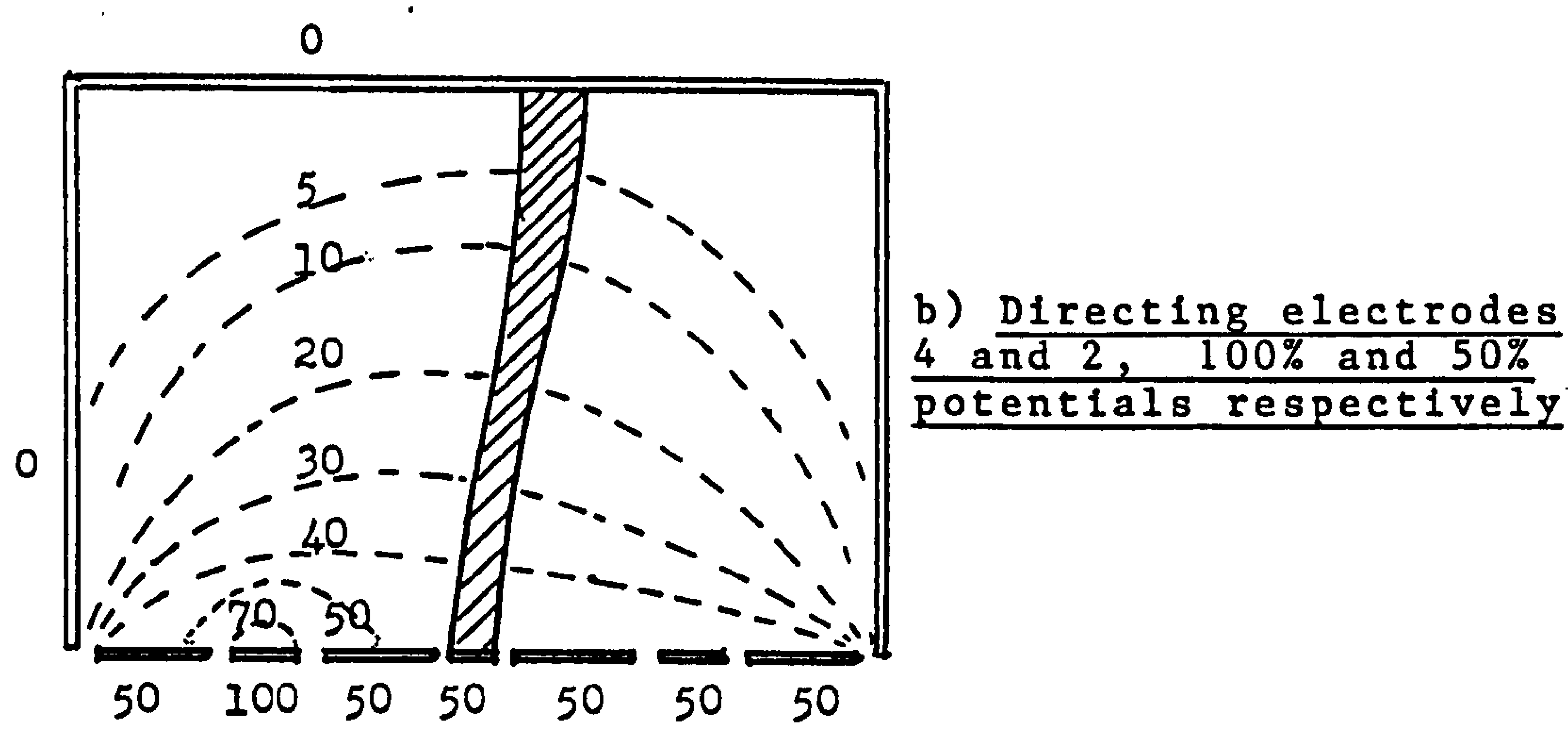
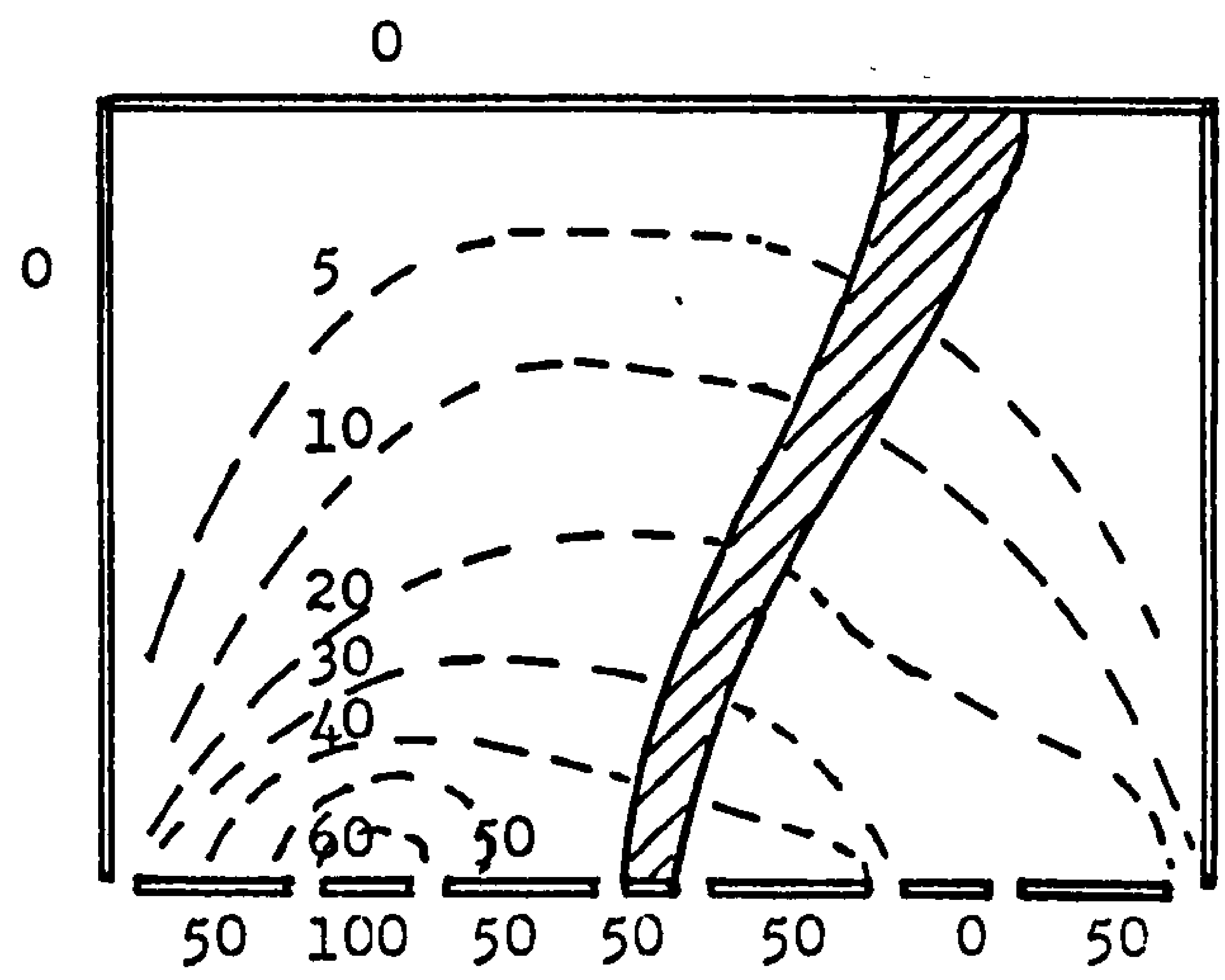


FIGURE 4.3 Capacitance probe scanning and equal potential lines in the X - Y plane

For orientation of X - Y plane see figure 4.2.

FIGURE 4.3 (Continued)



c) Directing electrodes 4 and 2, 100% and 0 potentials respectively

These figures demonstrate capacitive probe scanning by varying the immediate electrostatic field. The surface potential and field line potentials, as obtained from a two dimensional field analysis, are expressed on the figures as percentages of the maximum surface potential. Note that one of the two electrodes remains at maximum potential whilst the other is varied between maximum and zero. The probe and remaining surfaces are always at a potential of 50% of maximum.

The shaded area is the region through which the probe's electric flux lines flow and link with the moving surface. The probe measures the capacitance of the area on the moving surface where these lines intersect.

Electric flux lines are orthogonal to lines of equal potential.

displacements; eg. to obtain modes of vibration of a small membrane.

ii) To enable 'focusing' of the probes effective measuring area onto a specific region of a surface, see figure 4.3a.

The latter enables greater precision than is available from the conventional capacitance probe.

4.1.3 Measurement of TM displacement with the scanning capacitance probe

During the conceptualization stages of the scanning capacitance probe, thought was given to the difficulties which would occur if the device was applied for measuring tympanic membrane displacement. It was felt that the main problems were twofold. Firstly, there was the question of the safety of a technique based on an electrical phenomenon, i.e. capacitance. Secondly, difficulties might arise during the positioning of the probe within the external ear canal.

The safety problem was resolved by measuring the capacitance at a frequency of 10 MHz. For such a high frequency the probe and electrodes may be completely insulated from the subject, enabling the maximum current flowing in the surrounding tissues to be limited to 10^{-6} amperes. A current of such a low magnitude is unlikely to cause any problems (Grassie 1974).

The positioning of the probe within the external ear canal threatened to be more problematic. During the early experimental stages, it was proposed that the device would be focused onto the handle of the malleus. This could be achieved by varying the potentials of the four 'directing electrodes' and so avoiding the physical alignment necessary with other capacitance devices. A displacement of the TM would then be measured as a variation in the capacitance between the probe and malleus handle. At a later stage of development, the 'directing electrodes' would facilitate scanning across the surface of the TM. The achievement of sufficiently high scanning rates enables the dynamic movement of various regions of the tympanic membrane to be measured. Thus the reflex characteristics could also be determined.

The focusing facility on the scanning capacitance probe enables far more freedom in its positioning relative to the tympanic membrane, when compared with more conventional devices. Nevertheless, it is essential that the probe is situated within 5 millimetres of the membrane's surface. Although the scanning capacitance probe has the potential for producing more information on the TM displacement than the TMD system, it was strongly felt that the simplicity of operation of the latter device was the more important factor.

4.2 THE TYMPANIC MEMBRANE DISPLACEMENT SYSTEM.

The 'tympanic membrane displacement system', known as the TMD system, measures minute variations in the volume of the external ear canal. Of particular interest are changes as a result of movement of the tympanic membrane, which are quantified by the system in terms of a TM volume displacement. The forerunners of the TMD system are the extra tympanic pressure (e.g. Brask 1978) and flow measurement (e.g. Casselbrant 1977) methods. In comparison, this new technique possesses a unique feature, in that measurements are made without exerting a backpressure on the membrane. Such free field characteristics are considered essential if accurate TM dynamics are to be determined.

This section discusses the principle of the TMD system. Factors such as the hardware of the system, its dynamic response and noise level are described elsewhere (sections 5.1, 5.2 and 6.1 respectively).

4.2.1 The principle of the TMD system

The TMD system monitors tympanic membrane displacement independent of the external ear canal volume, over the bandwidth of approximately DC to 200 Hz. This measurement is made in effectively free field conditions. To achieve this, the subject's ear canal is airtightly connected to the TMD servo cavity, see figure 4.4. In this cavity is a microphone (Brüel and Kjaer type 2631), and also a diaphragm in the form of a TDH 39 headphone. The diaphragm

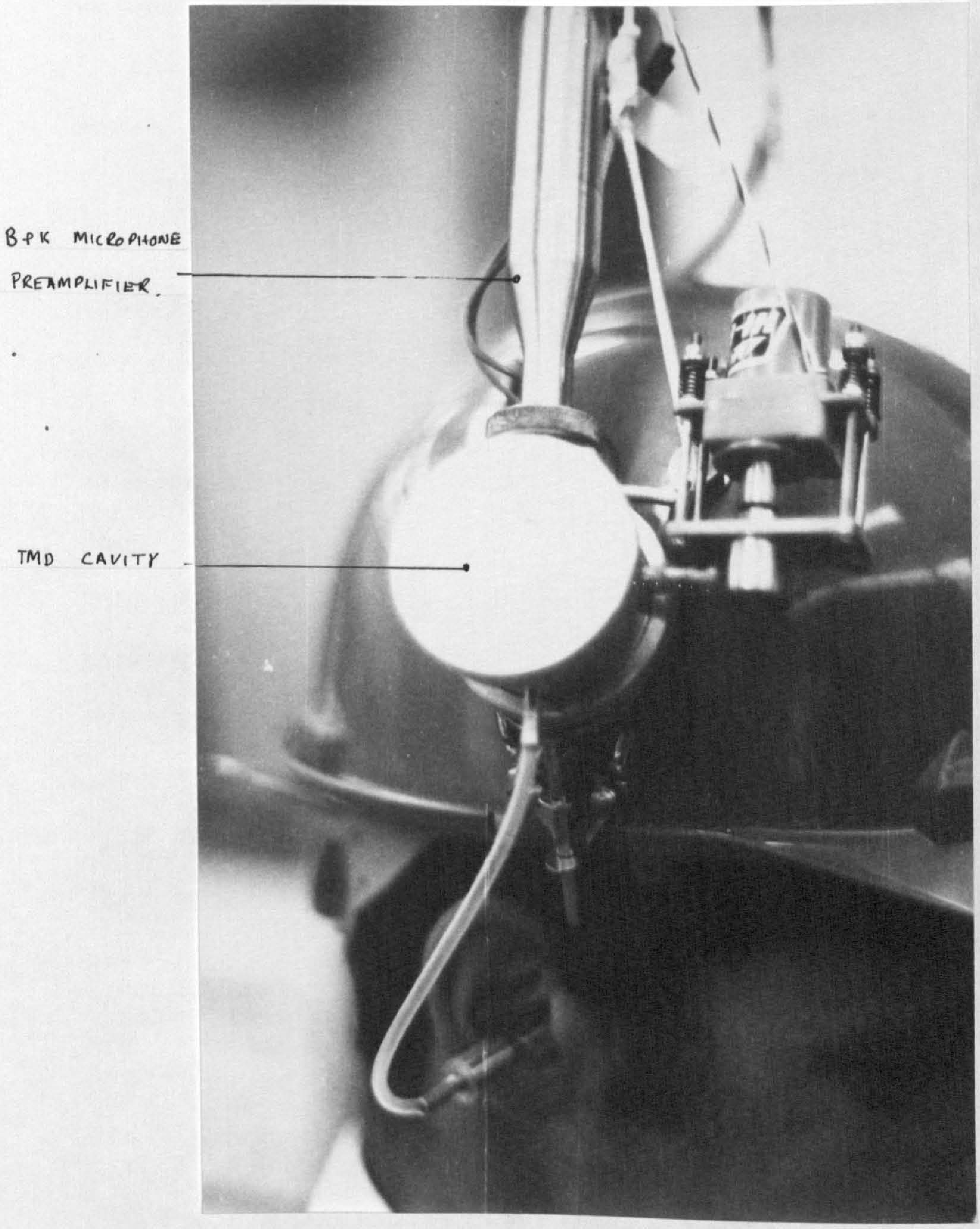


FIGURE 4.4 Photograph of the TMD system cavity connected to the subject's external ear canal

is capable of changing the ear canal/TMD system cavity volume by approximately ±4μl (microlitres).

The microphone has a response which extends from the audio down into the infra sonic frequencies. Such a microphone is commonly used to measure shock waves emitted from aircraft. The microphone of the present TMD system monitors any pressure variations within the sealed external ear canal and servo cavity. Of particular interest is the induced pressure caused by movements of the tympanic membrane. Such pressure fluctuations are cancelled out by the reference diaphragm driven by the microphone output in such a manner that the cavity pressure remains constant across the bandwidth of the system. This implies that any volume displacement of the tympanic membrane, or external ear canal, is matched by an equal but opposite volume displacement of the reference diaphragm, see figure 4.5. The voltage supplied to the reference diaphragm, being a measure of the ear canal/TM displacement, is fed to an analogue to digital converter of a digital computer for real time processing, storage and display.

4.2.2 Advantages of the tympanic membrane displacement system.

Probably the most popular technique of studying the middle ear function is by utilizing one of the several commercially available electroacoustic impedance bridges (EAI bridge). The TMD system is fitted to the subject in an identical manner to the commercially available EAI bridges and requires no additional patient co-operation.

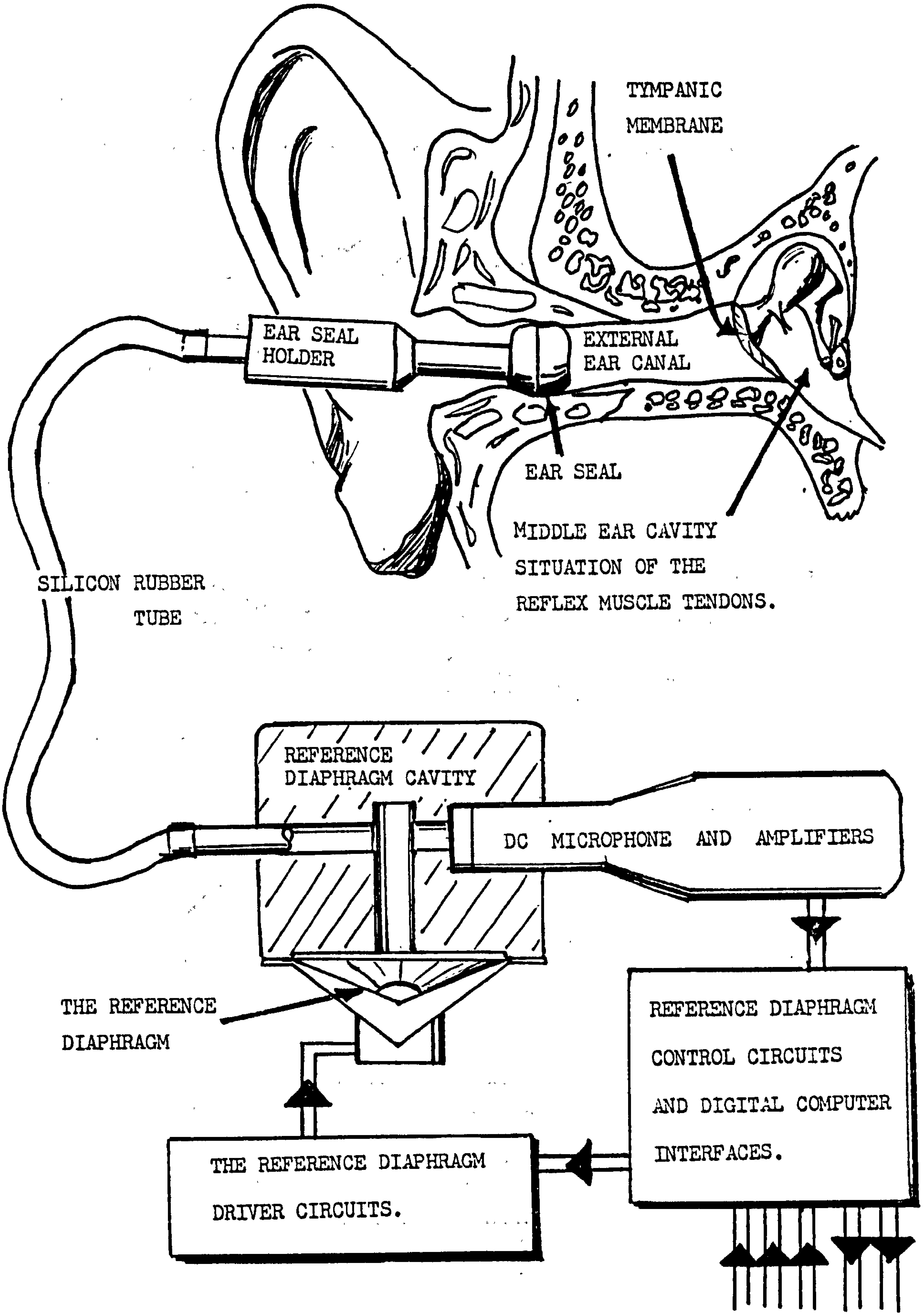
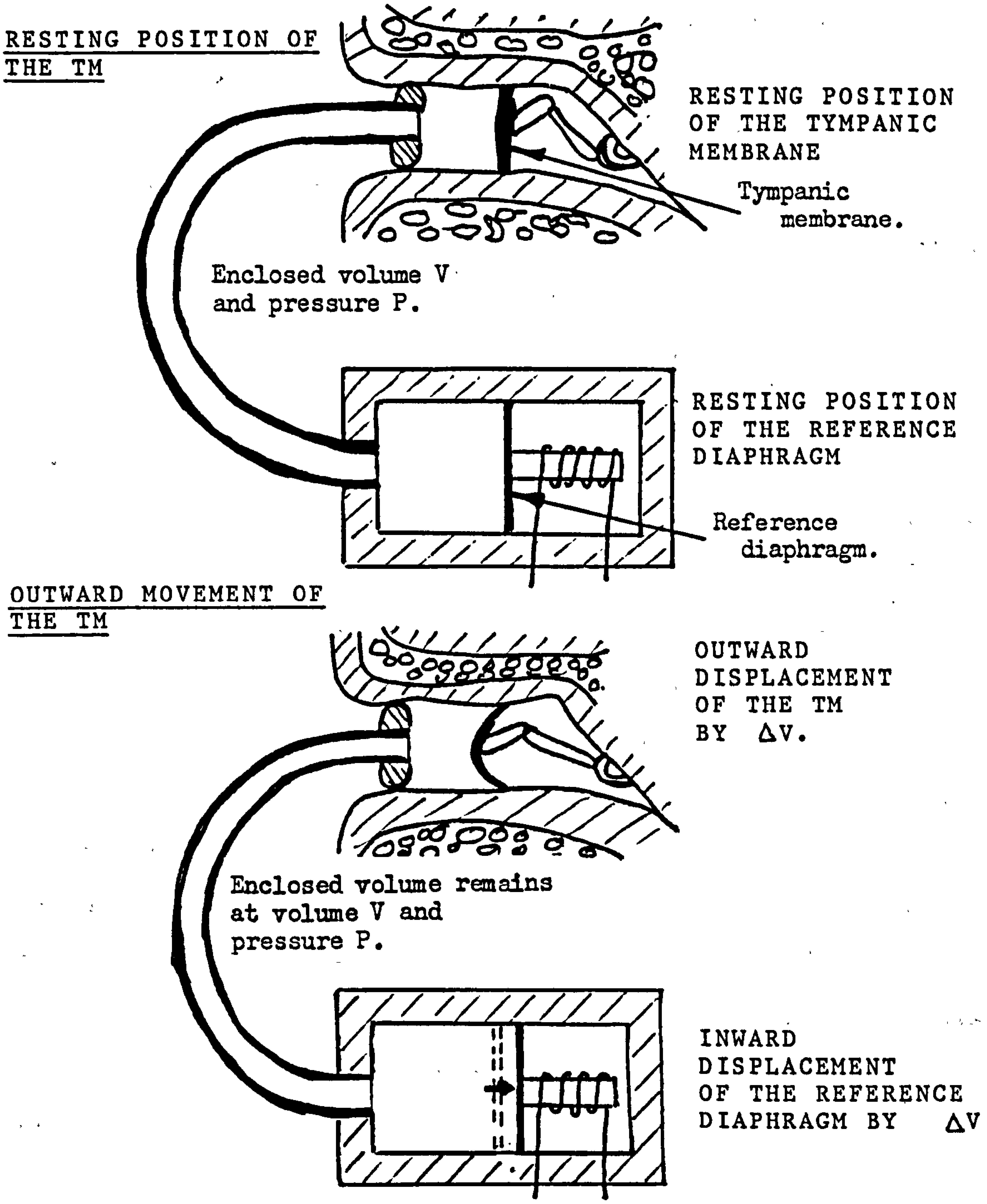


FIGURE 4.5 Principle of the tympanic membrane system servo
a) Control of the TMD system servo and connection to the external ear canal

FIGURE 4.5 (Continued)

b) Corresponding displacements of the tympanic and the reference membrane



The voltage applied to the reference diaphragm, necessary to ensure constant volume, is a direct measure of the volume displacement of the tympanic membrane.

Provided an airtight seal is obtained in the ear canal, the TMD system is as stable in operation as the EAI bridge.

Since most audiology workers are familiar with the EAI bridge, it is constructive to give a detailed comparison of the TMD servo system with this method:

i) The TMD system yields a direct measure of the volume displacement of the tympanic membrane which is far easier to relate in mechanical terms to the middle ear function than are the acoustic impedance measurements.

ii) The TMD system effectively evaluates the movement of the TM under free field conditions. Since the tympanic membrane is a flaccid membrane, closed system methods such as the EAI bridge, exert a backpressure on the membrane which may modify its response.

iii) The TMD system measurement is independent of the external ear canal volume, unlike impedance.

iv) The reflex response measurement with the EAI bridge depends on the parameters of the reflex stimulus, as well as the probe tone frequency. The reflex response with the TMD system depends only on the stimulus parameters (section 3.1.4).

v) Unlike the EAI bridge, the TMD system has been developed to measure rapid displacements of the TM, such as reflex transients.

Other methods are available for monitoring movements of the TM, such as with capacitance probes, laser holography, stroboscopic illumination, EMG and Mössbauer effect, but at present none of these are suitable for routine patient examination because of the stringent conditions under which these methods operate (chapter 3).

CHAPTER 5

THE TYMPANIC MEMBRANE DISPLACEMENT SYSTEM

This chapter discusses the TMD system, chosen for the present investigation. The first section is an account of the TMD system configuration on the City University hybrid computer. The second and third sections consider the dynamic characteristics of the system.

The dynamic limitations of equipment are often specified in terms of a frequency bandwidth. Sections 5.2 and 5.3 discuss the bandwidth of the TMD system as well as limiting factors. Section 5.2 provides sufficient information to allow a working understanding of the dynamics of the TMD system, whereas the final section studies in more detail factors which affect the stability of the TMD servo, and provides data for further development or optimization of the servo design.

5.1 THE 680 TYMPANIC MEMBRANE DISPLACEMENT SYSTEM CONFIGURATION

5.1.1 The hybrid computer

The TMD measuring system was programmed onto the City University EAI 680 Hybrid computer. This computer being hybrid, provides digital computer interfacing, easily accessible analogue components, logic circuits and displays, necessary to set up the system. The digital computer is programmed to provide control of the system, test sequencing, data processing, storage and control of the output peripherals. The analogue computer provides signal amplification, sequence timing, also a high gain integrator and a track store required for driving the reference diaphragm. It further provides filtering of the outputs from the digital computer interface before the data are displayed on the VDU or recorded on the X-Y plotter.

The logic section of the hybrid is driven from the digital computer's control register. It provides the hardware logic necessary for controlling the analogue sequence timers, and switching of the TMD servo and stimulus. It also yields logic control of the X-Y plotter and VDU.

Once the desired system parameters have been set from the teletype terminal, the hybrid facility enables total automation of the system, including plotting and calibration of the plots on the X-Y plotter.

5.1.2 The stimulus generated by the audiometer

The stimulus used to elicit the reflex is generated by a standard audiometer which gives a range of tones of differing frequencies and intensities. Several small modifications have been made to this instrument so that the stimulus may be controlled by the computer. In addition, the input to the left hand headphone has been fed to an amplifier and then to the input power amplifier of the reference diaphragm. This facilitates ipsilateral reflex elicitation. The other audiometer headphone is used in a normal manner and elicits contralateral reflex activity. That is, the stimulus is presented to the ear opposite to which the displacement is being measured, see Figure 5.1.

The audiometer stimulus has a latency period from the time of switching the stimulus generator on, to the first signs of an input to the headphones. This latency is allowed for in the software of the programme, so that effectively the stimulus appears to switch on exactly when required. The stimulus is discussed further in Appendix V. The audiometer is connected to the hybrid through a purpose-built 19 inch interfacing rack.

5.1.3 The interfacing rack

A 19 inch rack has been chosen to house several modules which interface the hybrid computer to the peripheral equipment, namely: the Brüel and Kjaer 2631 microphone carrier system, the audiometer and the reference diaphragm. The modules include two power amplifiers which drive up to two reference diaphragms if required. These devices

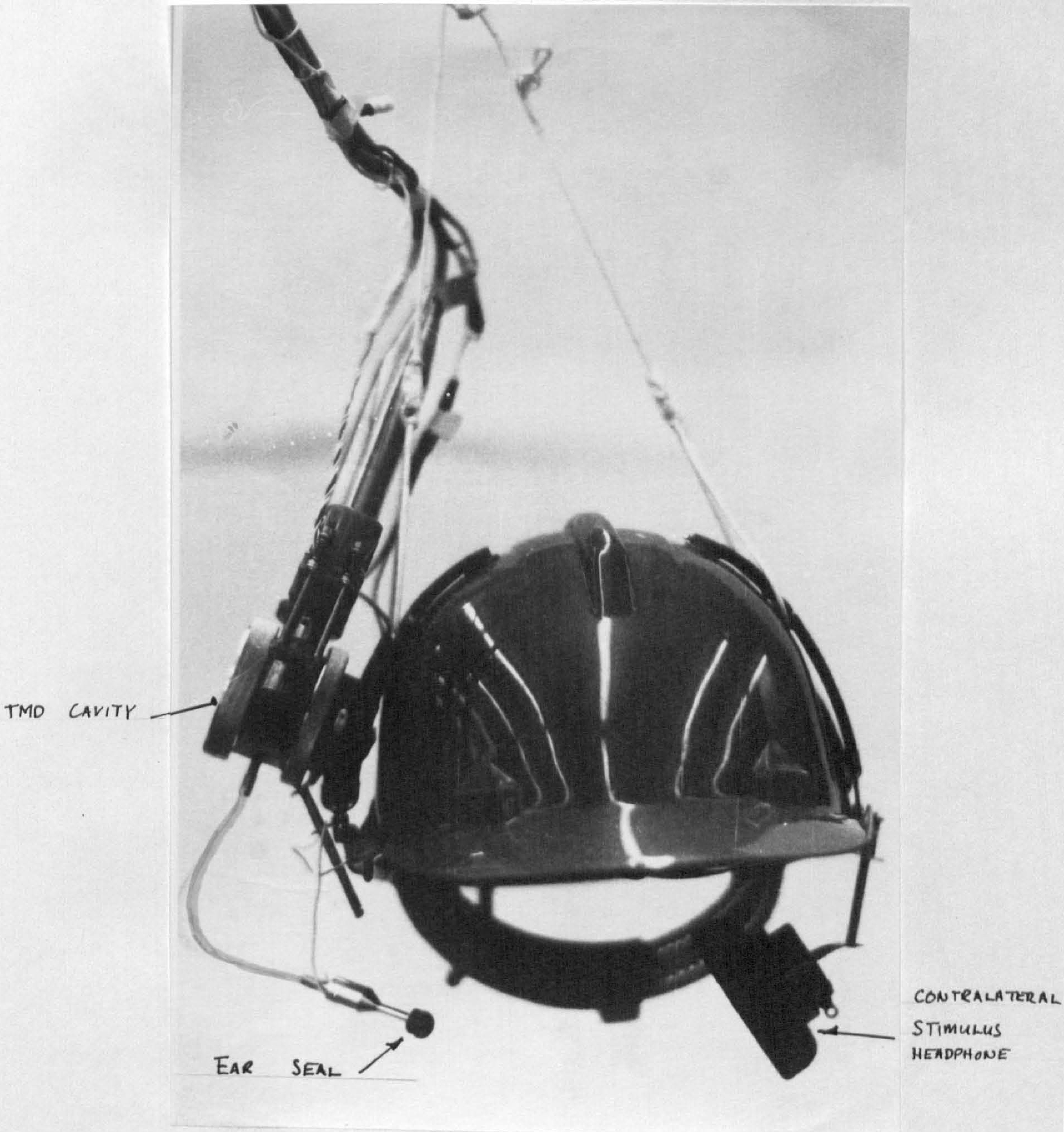


FIGURE 5.1 Photograph of the helmet, TMD cavity and the contralateral stimulus headphone

incorporate LEDs which indicate if the voltage to the diaphragm has exceeded set tolerances. These amplifiers are driven from two matched power supplies which provide ±5 volt outputs.

Another module provides the switching of the stimulus, and a further module incorporates a second order low pass filter, which filters the diaphragm volume displacement signal input to the ADC computer interface. Such filtering is necessary to prevent aliasing the data.

5.1.4 The reference diaphragm cavity and microphone carrier system

As previously described, the reference diaphragm cavity incorporates a Brüel and Kjaer DC microphone connected to a 2631 microphone carrier system, as well as the reference diaphragm which is capable of ±5μl (microlitres) volumetric displacement. Also connected is an actuator valve which vents the cavity to atmosphere and a rubber tube connected to the ear seal, see Figure 5.2.

The purpose of the actuator valve is twofold. Firstly, it vents the cavity to atmosphere when the ear seal is being fitted or retracted from the subject's ear canal. This prevents relatively large pressure variations being produced in the cavity which may damage or stretch the condenser microphone diaphragm. Secondly, the valve allows the subject's external ear canal to be vented just prior to a volume displacement measurement. It has been shown (Casselbrant 1978), that slight pressure variations in the external ear canal will alter the resting position of the

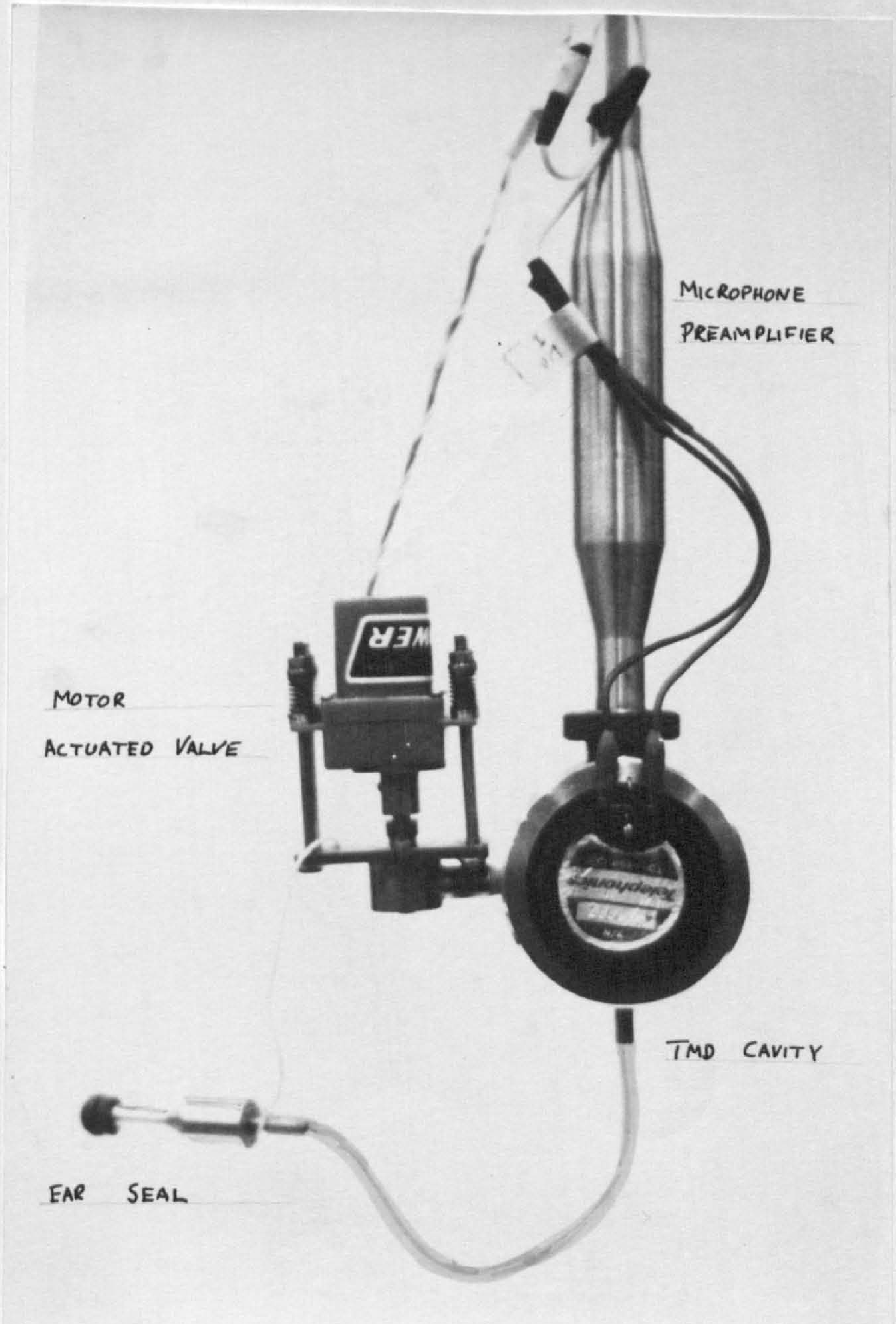


FIGURE 5.2 Photographic close up of the TMD cavity, valve and ear seal

middle ear mechanism and tympanic membrane. In so doing, it can affect the membrane's displacement on elicitation of the reflex.

5.1.5 Connecting the cavity to the subject's ear canal

The cavity is firmly mounted on the subject's head by means of a helmet. The cavity is positioned just above the subject's ear, enabling easy interconnection between the cavity and the external ear canal. The ear seals chosen are a standard type commonly fitted to the Madsen Impedance Bridges and are available in varying sizes to suit different ear canal apertures.

The headphone for contralateral reflex stimulation, is also connected to the helmet on the opposite side to the reference diaphragm cavity. The headphone and cavity are easily interchangeable so enabling reflex measurements to be made on both ears.

Since the helmet with cavity and microphone are reasonably heavy, they are partially supported by suspending them from a boom with a counterbalancing weight. This boom is positioned directly above the subject's head by means of a stand. The weight should be adjusted so that the helmet is just heavy enough to seat firmly on the subject's head.

This arrangement of boom and helmet, allows the subject a certain degree of freedom to move his or her head during the experiment. Consequently the subject is more relaxed than if the head is firmly constrained. The subject should still be encouraged to remain as still as possible, but not at the expense of tensing the muscles. If the subject is tense then an acoustic stimulation may produce a startle reaction, which could invalidate any results.

5.2 THE BANDWIDTH OF THE TMD SYSTEM

This section considers the flow of the TMD signal from its measurement to its final output on the X-Y plotter, shown in figure 5.3. Where necessary the bandwidth of the signal has been limited with filters so that it remains linearly related to the TMD dynamic. This approach to the signal processing ensures that the signal is not unnecessarily confused with noise introduced by nonlinearities within the system.

The section concludes with a discussion of the backpressure exerted on the tympanic membrane by the TMD system and the frequency range over which the system may be considered to be acting as a free field measuring device.

5.2.1 Bandwidth of the servo

The bandwidth of the TMD servo has been obtained from frequency response experiments with the equipment shown in figure 5.4. This figure shows the TMD servo cavity connected to the calibrator cavity, on to which has been sealed a headphone diaphragm identical to that used for the reference diaphragm. For frequency response purposes, the calibrator cavity and diaphragm may be considered as constituting the ear canal and the tympanic membrane

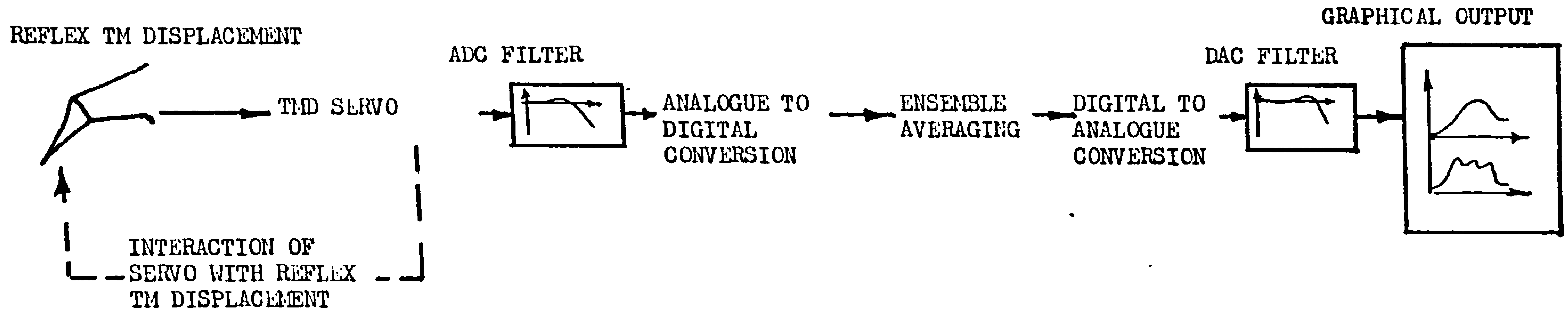


FIGURE 5.3 <u>The TMD system and the flow of information</u>

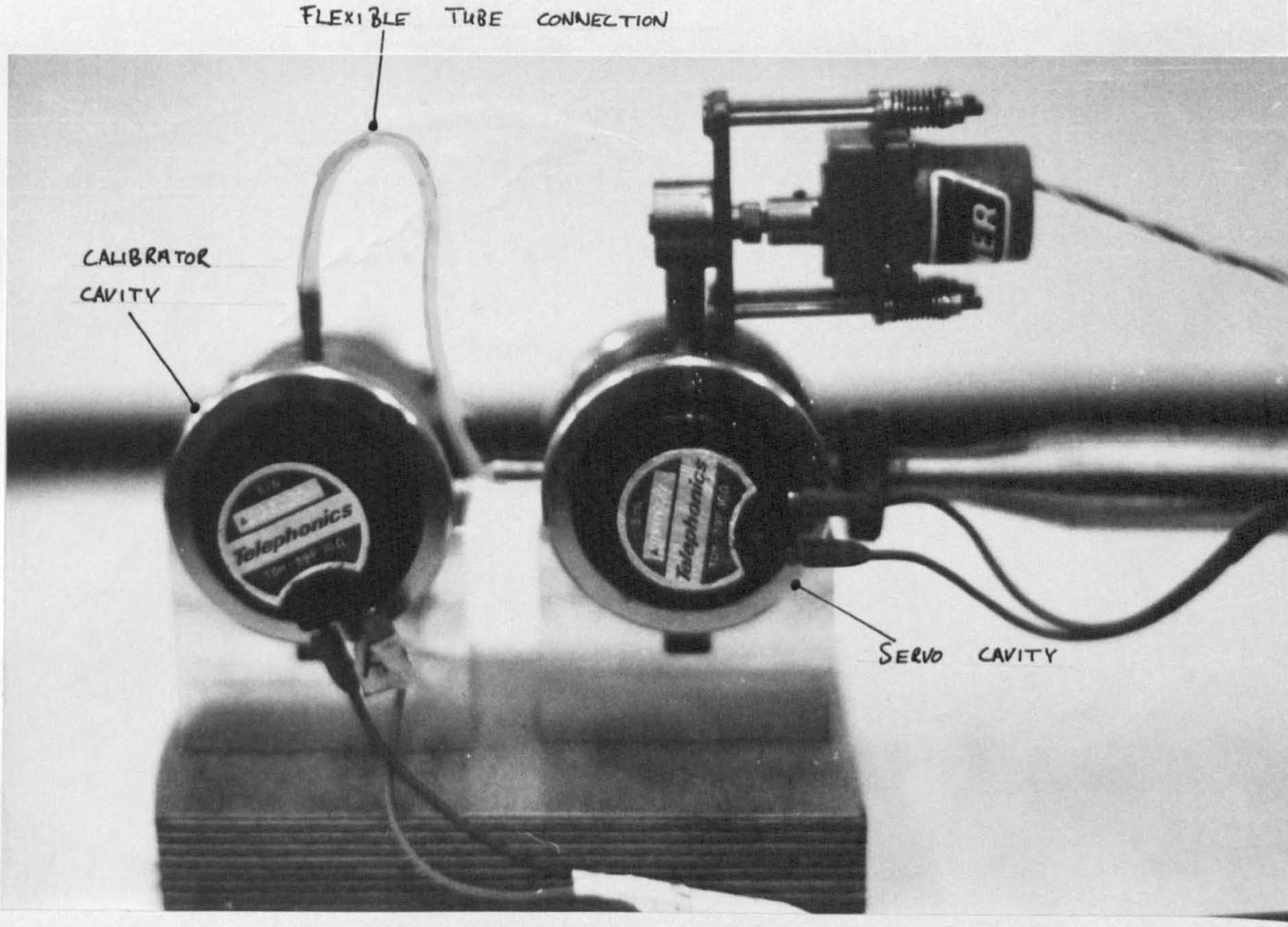


FIGURE 5.4 The calibrator and servo cavities

respectively. The frequency response is obtained by placing a known sinusoidally varying voltage on the calibrator diaphragm and measuring the corresponding voltage applied to the reference diaphragm when the servo is operative. Figure 5.5 displays the resulting Bode diagram. Also shown in this figure, is the attenuation characteristic of the flexible tube connection between the ear seal holder and the servo cavity. It is subsequently shown that the attenuation characteristics of this tube limit the bandwidth of the present TMD servo.

The bandwidth of the servo may be seen to be DC to 180 Hz. Over this frequency range the servo responds with an accuracy of better than ±3 dB. In practice this bandwidth will depend on the ear canal volume. The greater the volume, then the smaller the bandwidth. However, the volume of the calibrator cavity is adjusted to be larger than the normal ear canal volume, so that a conservative estimate of the servo bandwidth is obtained from the tests. The volume of the calibrator cavity with diaphragm is approximately 2000 to 2700 mm^3 which compares with 1400 mm^3 for the standard artificial ear, such as the Brüel and Kjaer type 4152 coupler cavity.

To ensure that the output from the TMD servo is totally independent of variations in the ear canal volumes of the subjects, the signal is fed into a second order low pass filter having a lower bandwidth than that of the servo. The output of the filter is then fed to the analogue to digital converter (ADC).

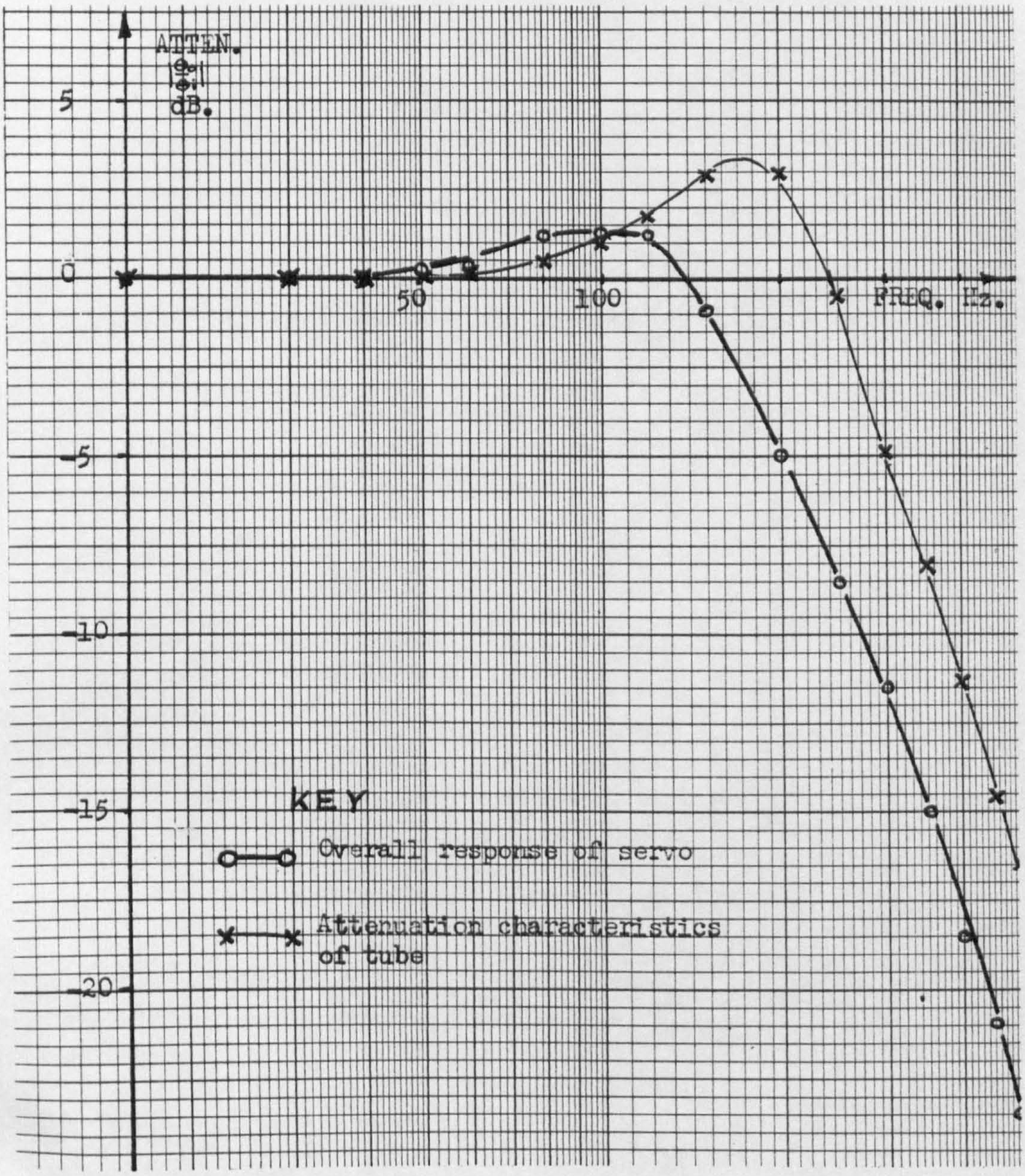


FIGURE 5.5 Comparison of the servo response with the attenuation characteristics of the flexible tube and connection. (Excluding ADC filter)

5.2.2 The ADC filter

The filter mentioned in the previous subsection is known as the ADC filter. It has a bandwidth of 130 Hz (-3 dB point), with a -12 dB per octave cut off above this frequency. (Bode plot shown in appendix I).

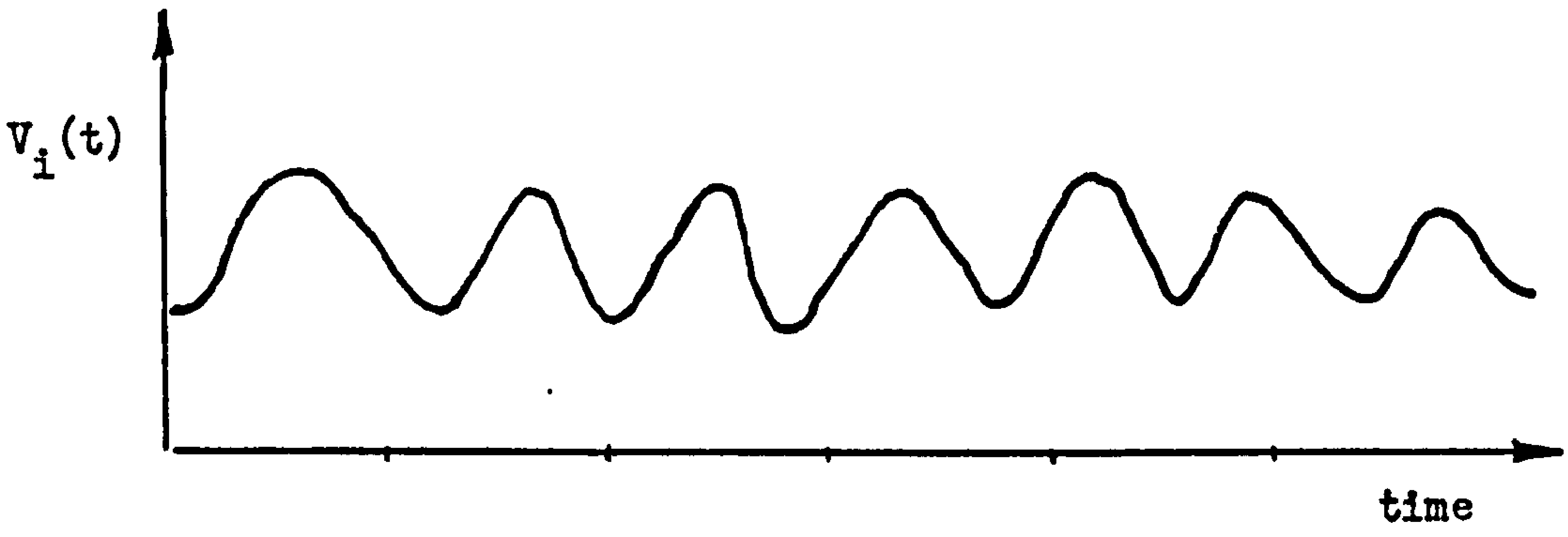
The purposes of the ADC filter are threefold. Firstly, as described in section 4.2.1, it ensures that the TMD is independent of the volume of the subject's ear canal. Of equal importance, it prevents aliasing and furthermore, reduces high frequency noise components (Beauchamp 1973). Aliasing is shown in figure 5.6. If an analogue signal is not filtered prior to digitization, then the signal components of frequencies greater than half of the ADC sampling rate, will be reconstructed at the digital-to-analogue converter as noise of a lower frequency.

The output characteristics from the servo including the ADC filter is given in figure 5.7, which shows a bandwidth of 140 Hz (-3 dB point). Above this bandwidth there is a rapid attenuation of the signal, initially at a rate of -24dB per octave.

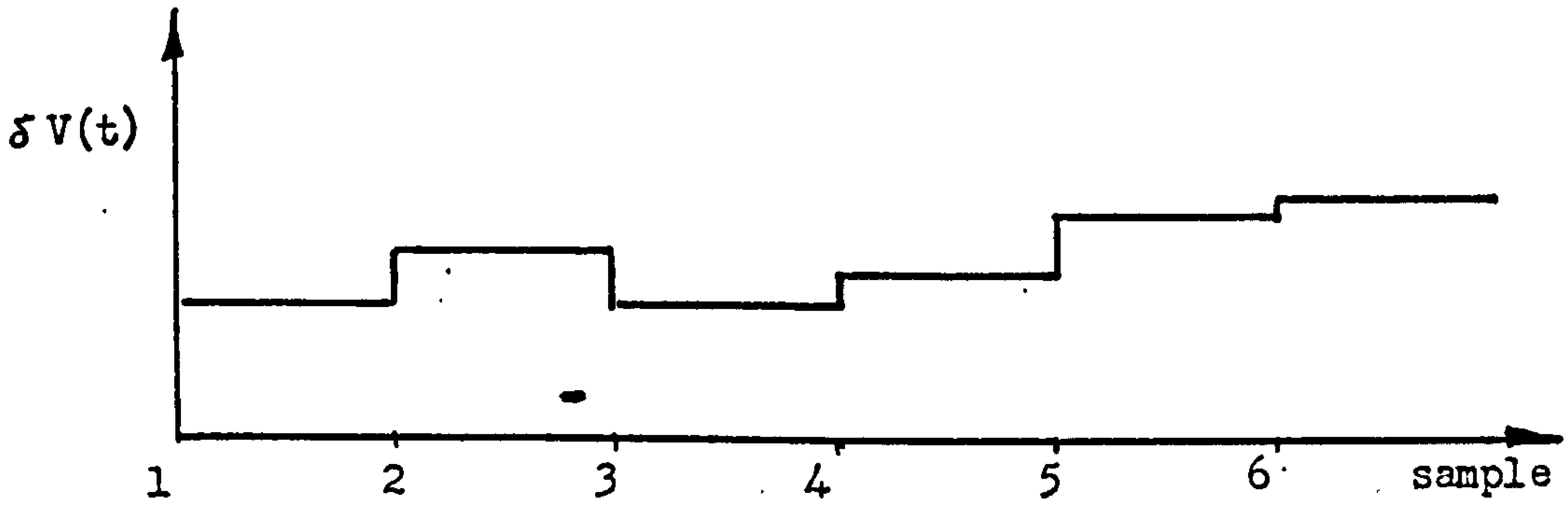
5.2.3 Damping of the TMD servo response

The flexible tube connection between the ear seal and the servo cavity is plugged with a small wad of wire wool, which damps the response of the servo. Figure 5.8 compares the damped with the undamped servo response not including ADC filtering. It may be seen that the undamped response amplifies the signal at frequencies just below the cut off

a) The signal prior to digitizing contains components of frequencies greater than half the sampling rate.



b) The digitized signal.



c) Reconstruction of the digitized signal produces a lower frequency waveform.

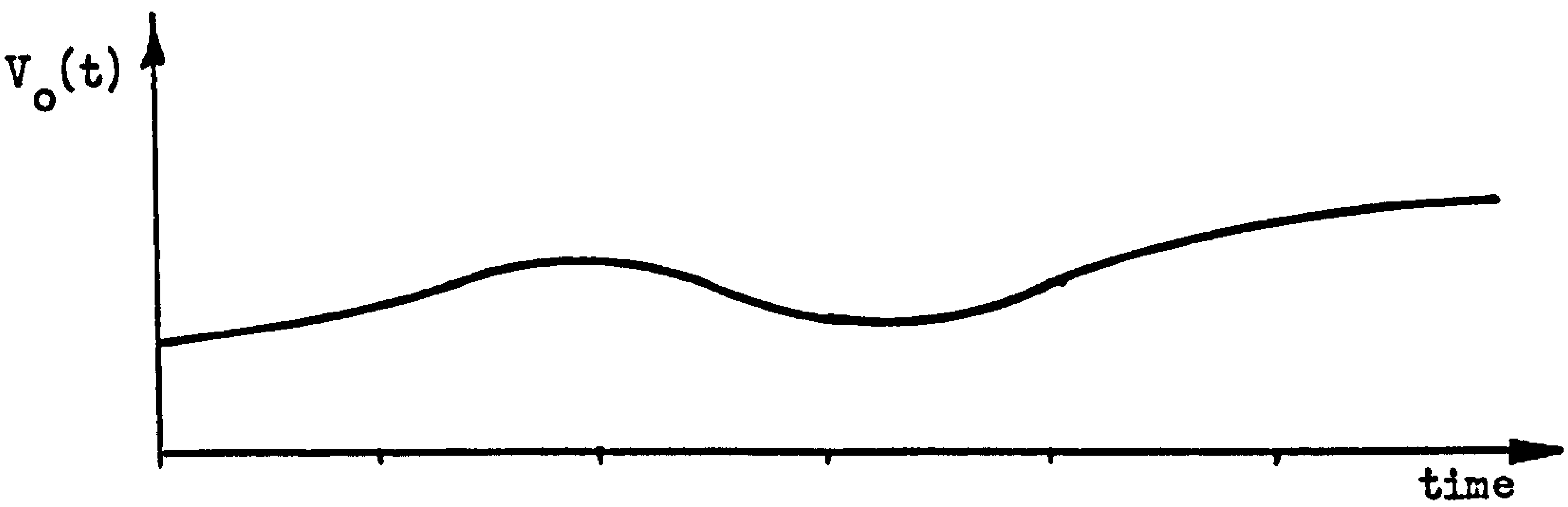


FIGURE 5.6 The aliasing effect

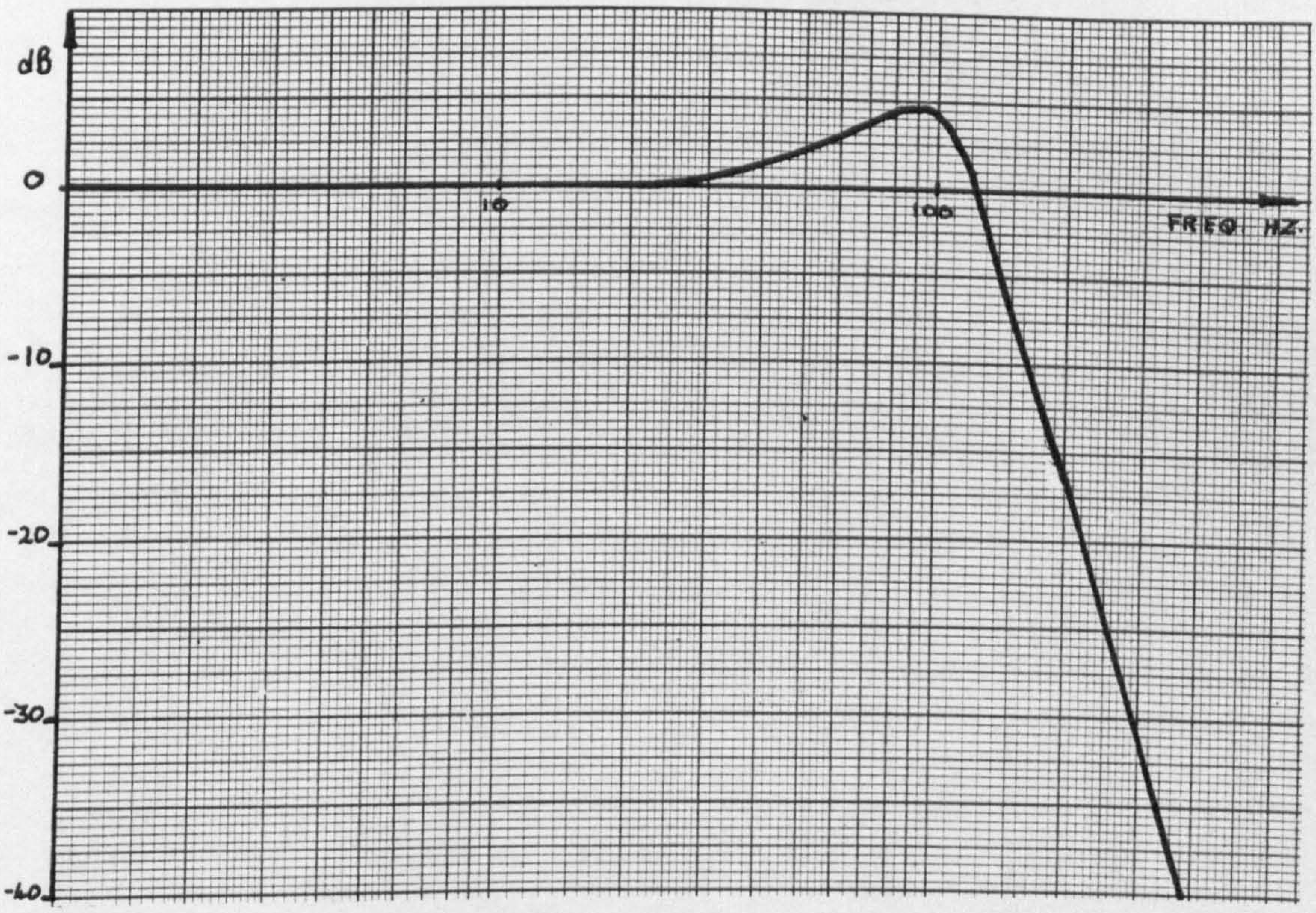


FIGURE 5.7 The TMD system response including ADC filter

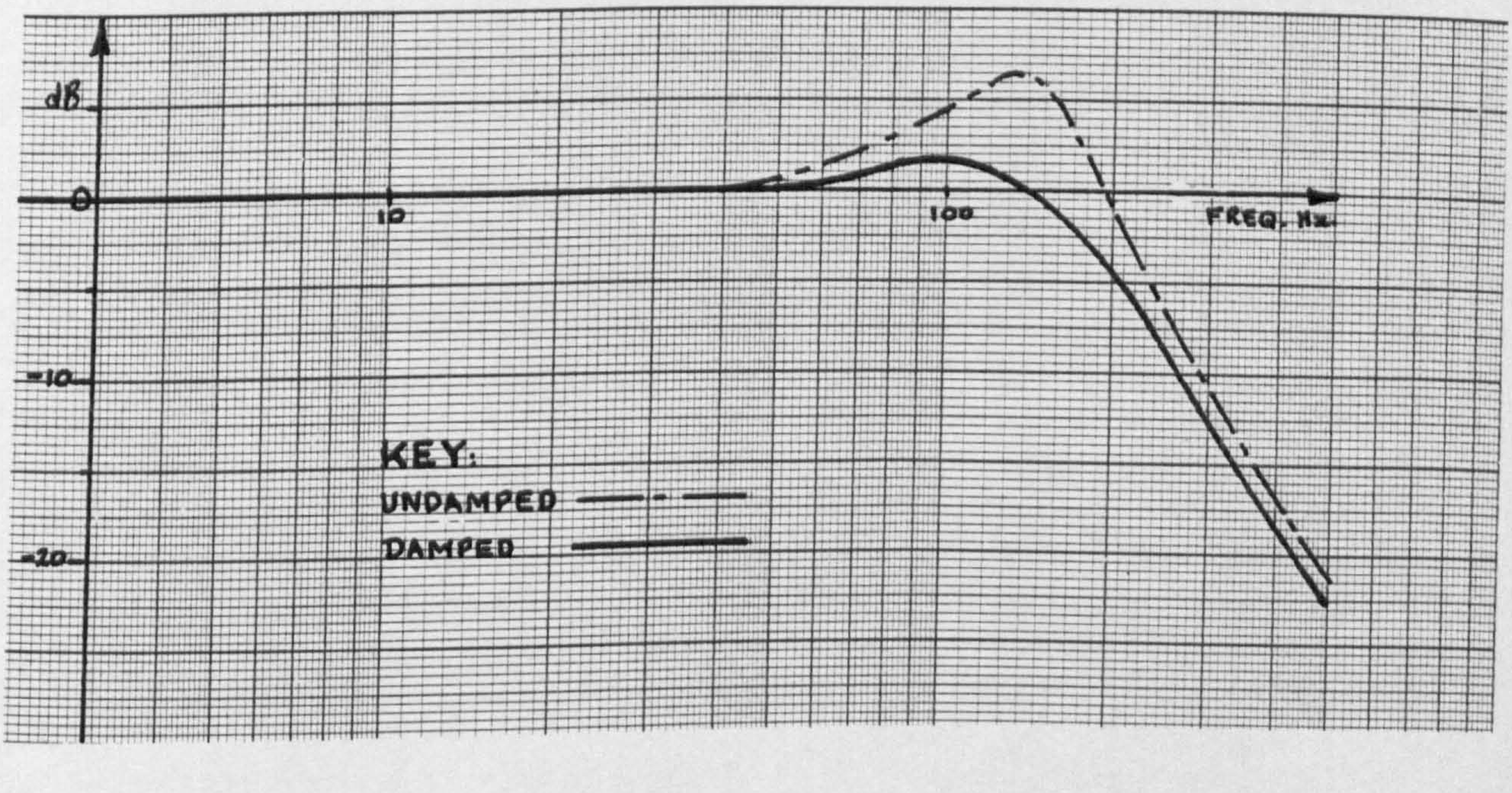


FIGURE 5.8 The overall response of the TMD servo:-Damped compared with undamped response.(Excluding ADC filter)

frequency of the tube. This resonance point is reduced in magnitude by the wire wool damping, so ensuring a flatter frequency response. This also increases the stability of the servo, so allowing higher forward loop gains to be set.

5.2.4 The forward loop gain of the TMD system

Changing the forward loop gain of any servo will alter the system's stability and bandwidth. In the case of the TMD servo, the forward loop gain of the electronics is set to 4.0×10^4. Increasing this to 5.0×10^4 only produces a marginal change in the servo bandwidth, due to the dominating effect of the attenuation characteristics of the flexible tube connection. The servo response for varying forward loop gains is shown in figure 5.9.

If the gain of the electronics * exceeds 5.9×10^4, then the servo will become unstable. This value compares with a critical forward loop gain of 4.7×10^4 for the servo undamped with wire wool.

5.2.5 Bandwidth of the TMD graphical output

Often much effort is spent in ensuring that the bandwidth of the measuring equipment is an optimum, but the bandwidth of the final output device is totally ignored. With the TMD system, the final record of the TMD transient is made on a X-Y plotter recorder. X-Y plotters typically have a restricted frequency response, and the signal should be presented to the plotter at a rate slower than actual, so allowing a more accurate reproduction of the signal to be made. Furthermore, this type of plotter has a nonlinear

* With reference to figure 5.12, this gain is denoted as K_I.

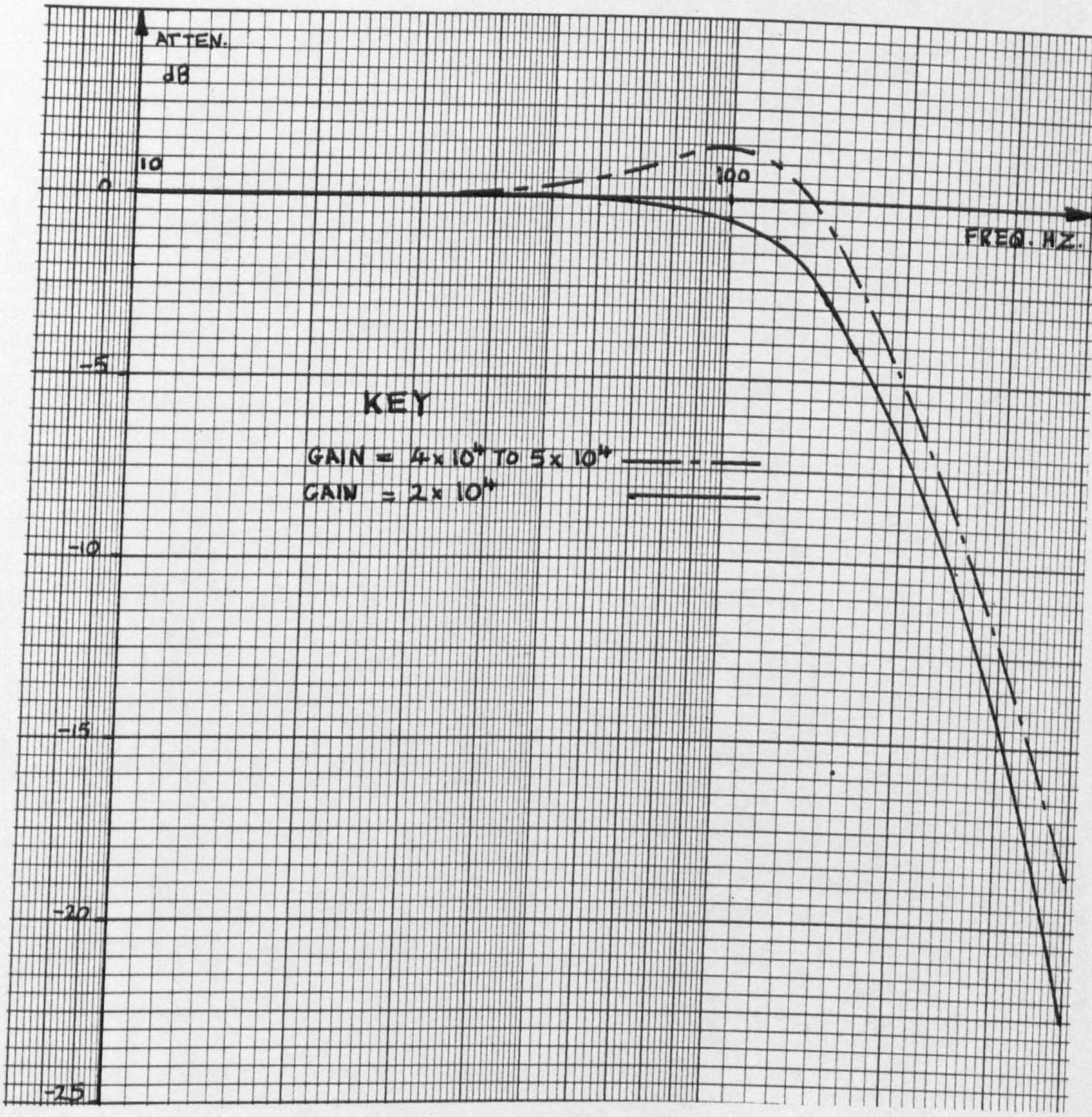


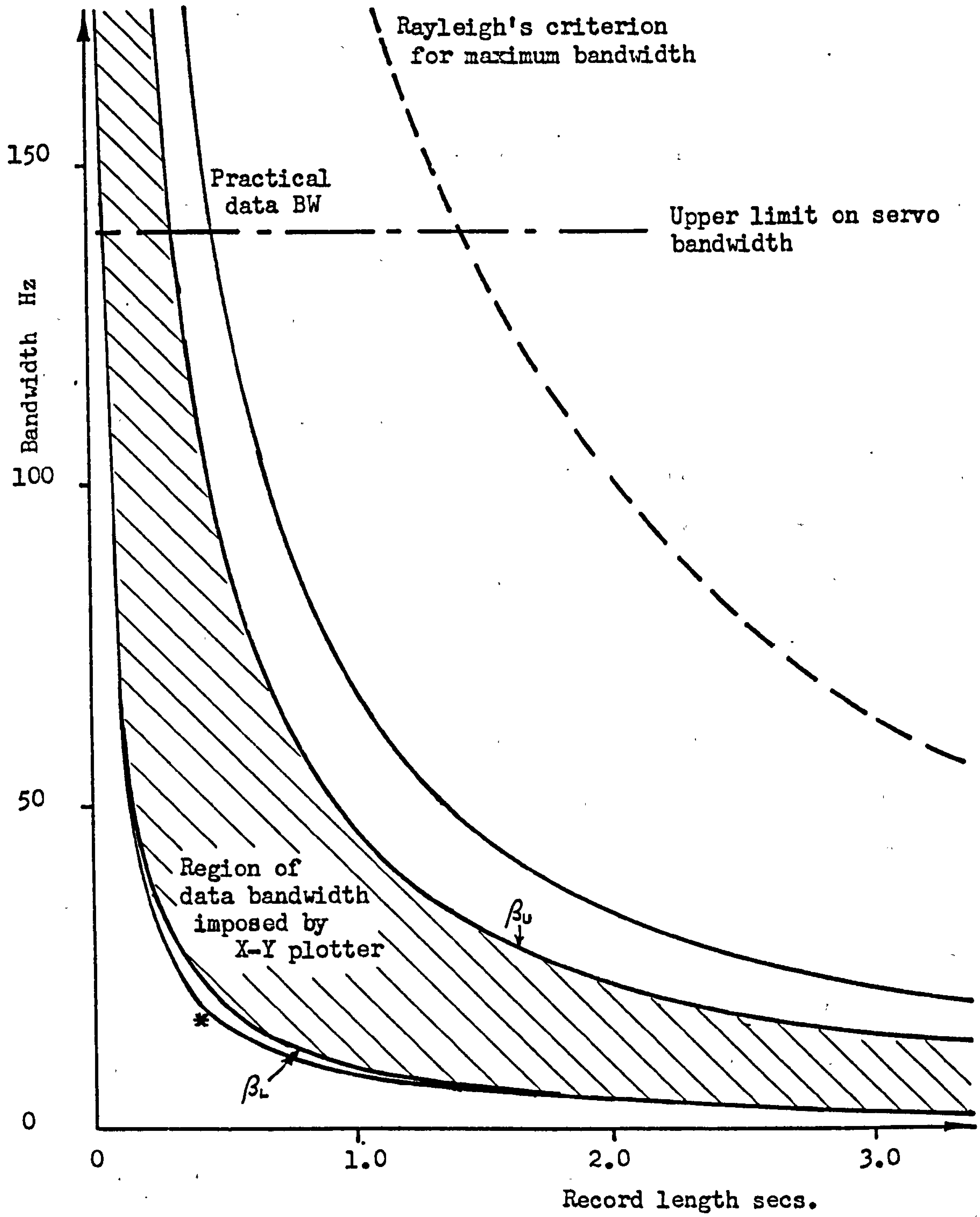
FIGURE 5.9 The TMD servo response for varying forward loop gains. (Excluding ADC filter)

frequency response. This is due to the limitations on the speed at which the plotter can respond, normally specified as the maximum writing speed, and it results in the effective bandwidth of the plotter decreasing with increasing amplitude of the output.

The time taken for the plotter to plot a graph is constant, regardless of the original length of the TMD record. Therefore the frequency bandwidth of the TMD plot will depend on both the bandwidth of the plotter and the record length. The shorter the record length, then the greater is the bandwidth of the plot, up to a maximum determined by the TMD servo. Figure 5.10 displays the signal bandwidth for varying record lengths. Rayleigh's criterion (Beauchamp 1973) gives the maximum theoretical bandwidth of the signal for 400 samples per record. Also shown in this figure, is a more realistic limit for the bandwidth of the information contained within the TMD signal (Beauchamp 1973).

As previously mentioned, the bandwidth of the X-Y plotter depends on the amplitude of the signal. The range of this bandwidth is shown in figure 5.10 as a region, the boundaries of which are derived in appendix I. As can be seen, the plotter reduces the bandwidth of the signal, consequently it effectively filters out some of the potentially useful information. This may be alleviated by one or more of the following methods:

i) By choosing the shortest possible length for the TMD record. For example, to study the onset reponse in more detail, the record length is



* Actual bandwidth limited by plotter DAC filter

FIGURE 5.10 Variations in data bandwidth with record length chosen to be just sufficient to record this dynamic.

ii) By slowing down the rate at which the X-Y plotter records the results.

iii) By choosing a means of plotting the data which has a more rapid response time.

In the TMD system the signal is filtered just prior to input to the plotter, which ensures that the signal bandwidth coincides with that of the lower limit of this device. This plotter filter, placed on the output of the digital to analogue converter DAC, ensures that the output of the plotter is linearly related to the TMD dynamic. Another function of this filter is to smooth the output from the DAC, which consists of a number of discrete signal levels, typical of sampled data.

5.2.6 Free field characteristics of the TMD system

Any closed system measuring device, such as pressure or impedance techniques, imposes a backpressure on the tympanic membrane when it displaces. This can modify the TMD response. However, the TMD system was devised to overcome this problem. Figure 5.11 shows the reduction in the backpressure when the servo is operating. It demonstrates that at the servo cut off frequency of 140 Hz, there is approximately a 40% reduction in the backpressure. Below this frequency the backpressure reduces at a rate of 6 dB per octave, so that at 1.0 Hz there is about a 99.5% reduction. Therefore, it may be seen that the servo has the effect of reducing the backpressure for the higher frequency components of the TM transient and acting as a

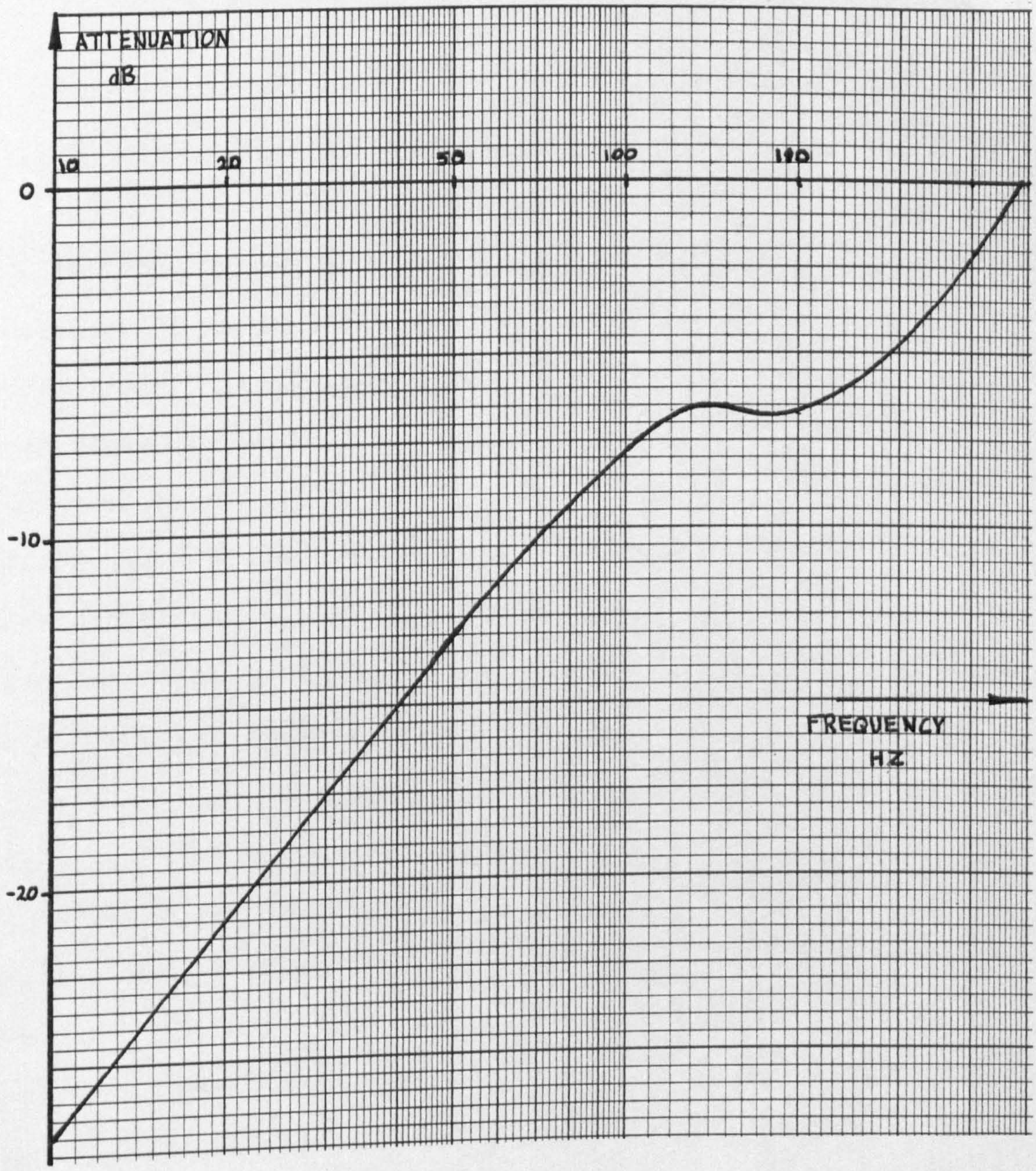


FIGURE 5.11 Free field bandwidth of the TMD servo

free field measuring device for the lower frequencies.

5.3 FACTORS AFFECTING THE TMD SERVO RESPONSE AND STABILITY

The TMD response will depend on several nonlinear components, such as the finite time required for the pressure variations at the tympanic membrane and the reference diaphragm to be sensed by the microphone. A further factor is the output impedance of the reference diaphragm, which is related to the shape and size of the servo cavity. In the following section, each of these factors will be discussed in respect of their influence on the TMD servo response and stability.

5.3.1 Loop gains of the TMD servo.

A block diagram of the TMD servo is shown in figure 5.12. The factors affecting the response of the servo are; the cavity impedance to the reference diaphragm, the acoustic time delays, the controller and the system loop gain. The forward loop gain K_F is related to the pressure variation in the servo cavity per unit change in the internal volume, such that:

$$K_F = K_I \cdot K_P \cdot K_D \cdot K_M \qquad \text{............ eq 5.1}$$

where gains K_I, K_P, K_M, are defined in figure 5.12. The forward loop gain is dependent on the total enclosed volume, consequently it

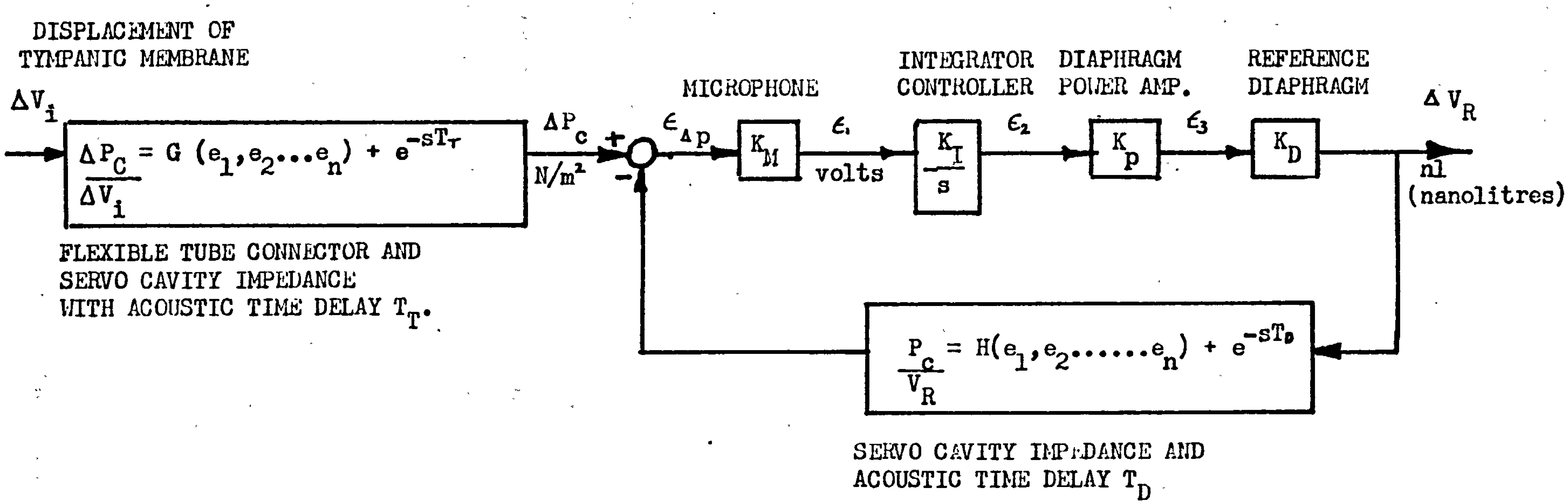


FIGURE 5.12 BLOCK DIAGRAM OF TMD SERVO WITH FLEXIBLE TUBE CONNECTOR

GAINS: $K_M = 1.26\times10^{-2}\,\frac{\text{volts}}{N/m^2}$, $K_I = 4.0\times10^{4}\,\frac{\text{volts/sec}}{\text{volts}}$, $K_p = 8.10\times10^{-2}\,\frac{\text{volts}}{\text{volts}}$, $K_D = 5.63\times10^{3}\,\frac{\text{nl}}{\text{volts}}$

varies with the volume of the subject's ear canal.

5.3.2 The servo controller

An integral controller was placed in the forward loop of the TMD servo. A more sophisticated controller was unnecessary because the system's stability is largely dependent on factors other than those of the controller's characteristics (section 5.2.4). If integration was the only term involved in the servo loop, then the closed loop transfer function would be

$$\frac{\Delta V_{OUT}}{\Delta V_{IN}} = \frac{1}{(\tau s + 1)} \quad \text{..... eq 5.2}$$

The frequency response of such a system is shown in figure 5.13. As can be seen the phase lag never exceeds 90 degrees, which implies inherent stability. However in reality the servo becomes unstable for too high a gain setting. The impedance of the servo cavity and acoustic time delays must therefore be taken into account when considering the system's stability.

5.3.3 Cavity impedance

The impedance of the servo cavity is important in two respects. Firstly, the cavity impedance as seen at the position of the tympanic membrane, will determine the pressure change within the servo cavity for a given volume displacement of the TM. This factor is dependent on the attenuation characteristics of the flexible connection from

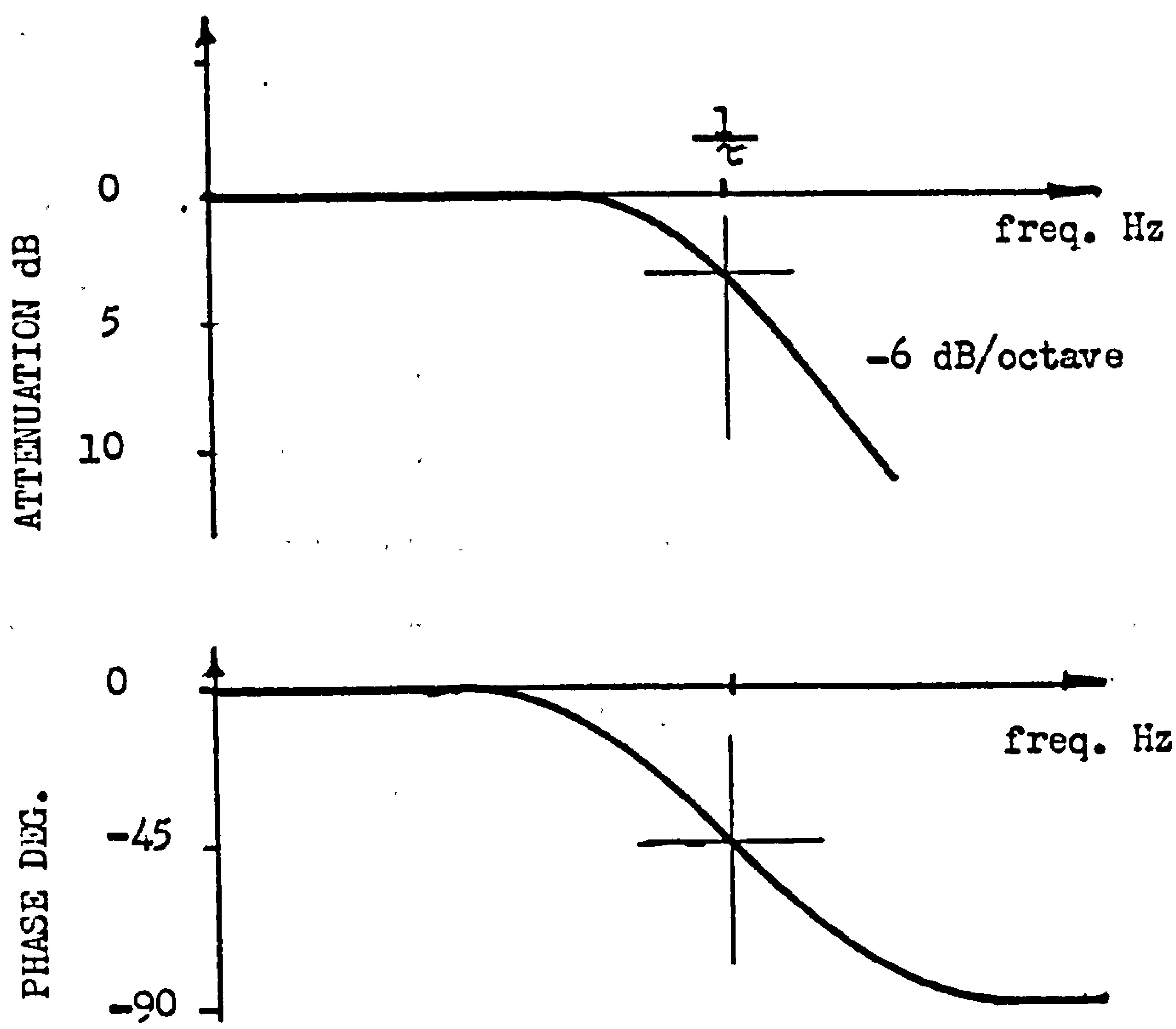


FIGURE 5.13 A Bode plot showing the closed loop frequency characteristics of an integrator controller

the ear seal holder to the servo cavity. Secondly, the cavity impedance, as seen at the position of the reference diaphragm, is important in respect to the frequency response and stability of the servo.

Figure 5.14 displays the variation with frequency of the pressure within the servo cavity, measured for a constant amplitude input to the calibrator cavity diaphragm. It shows that at 200 Hz there is a rapid attenuation of the pressure within the servo cavity. This reduction corresponds to the cut off frequency of the flexible tube connection. In contrast to this, figure 5.15 shows the pressure variation with frequency for a constant amplitude input to the reference diaphragm. It can be seen that the pressure increases around 200 Hz by approximately 6 to 8 dB. At this frequency the attenuation of the tube connection is so great that the servo cavity volume has in effect been isolated from that of the ear canal. Calculations confirm that an isolation of the two volumes results in a 7 dB pressure variation within the servo cavity.

The cavity impedance, as seen by the reference diaphragm, determines the feedback characteristics and will therefore influence the stability of the servo. At very low frequencies the feedback may be represented by a simple gain K_G which is calculated as having the value of 2.2×10^{-2} N/m^2 per nl. With reference to figure 5.12, this gives a loop gain of 5.1×10^{-3} N/m^2 per nl.* At the cut off frequency of the tube connection, the gain increases by approximately 7 dB so that the loop gain becomes

* This gain is calculated as $K_M.K_I.K_P.K_D.K_G$, where K_G is estimated at low frequencies according to $\Delta p/\Delta V = -\gamma p_0/V$ for $\gamma = 1.4$, where γ is the ratio of the specific heat capacities.

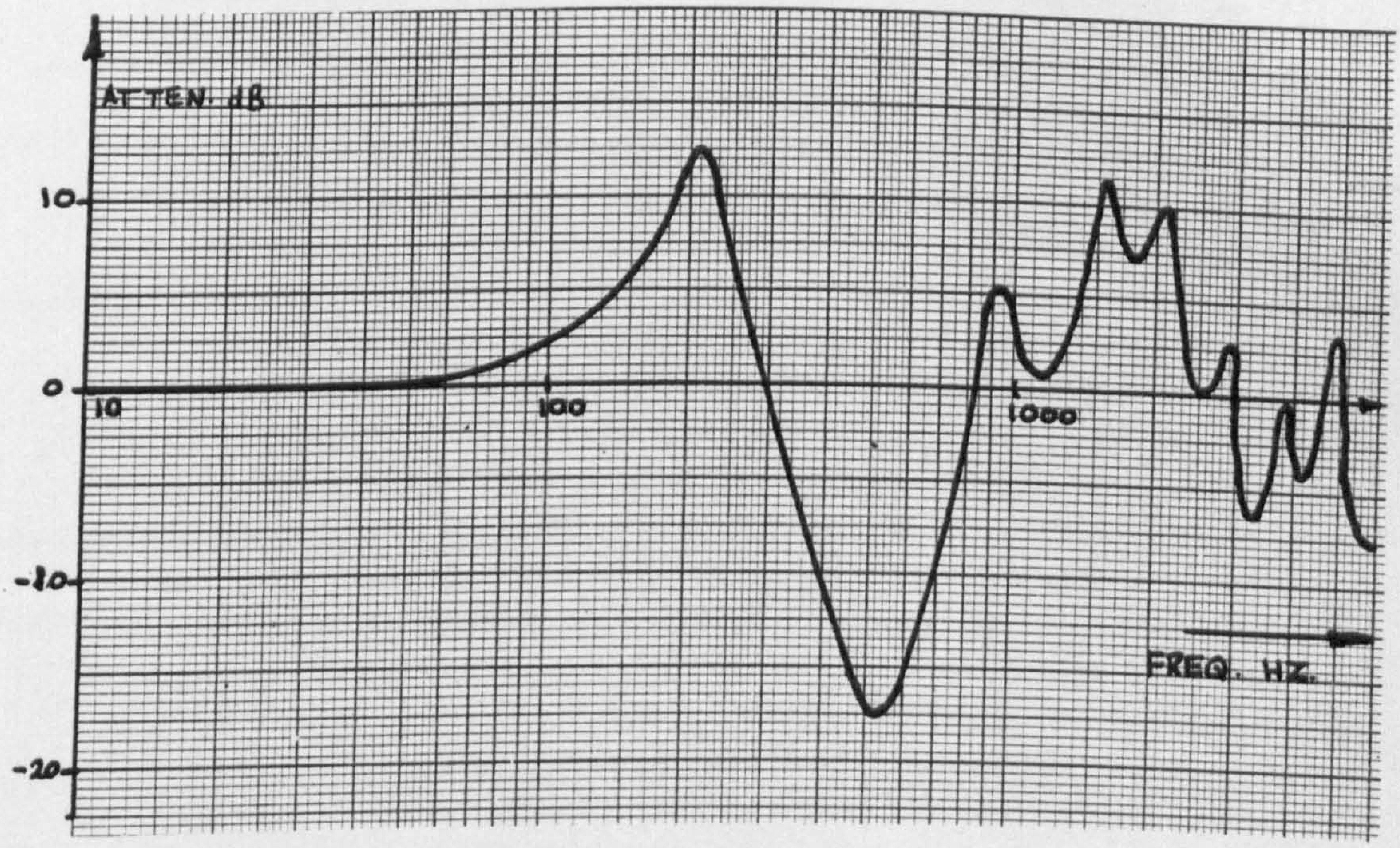


FIGURE 5.14 Frequency characteristics of the servo cavity for a constant amplitude input to the calibrator diaphragm

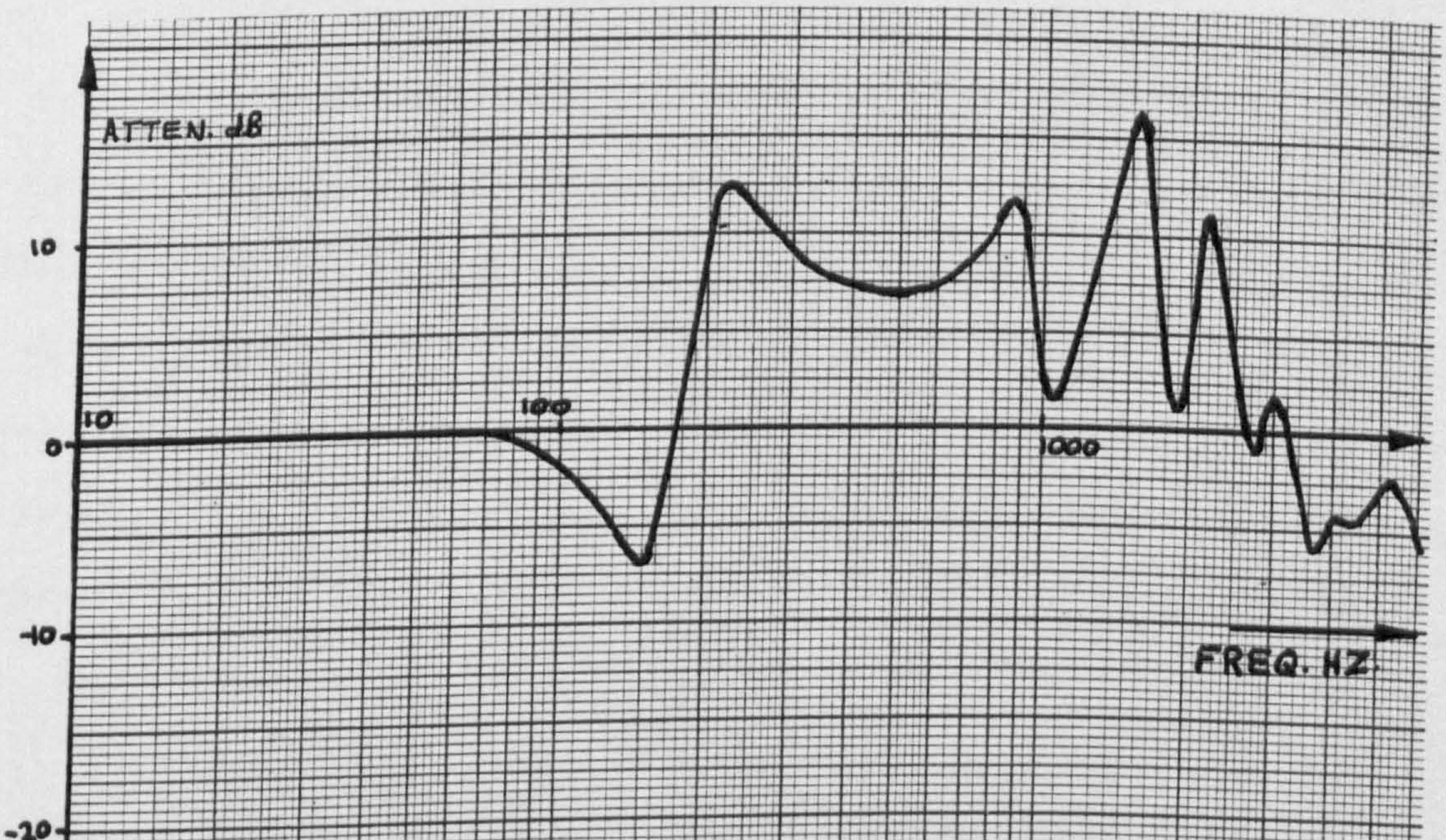


FIGURE 5.15 Frequency characteristics of the servo cavity for a constant amplitude input to the servo diaphragm

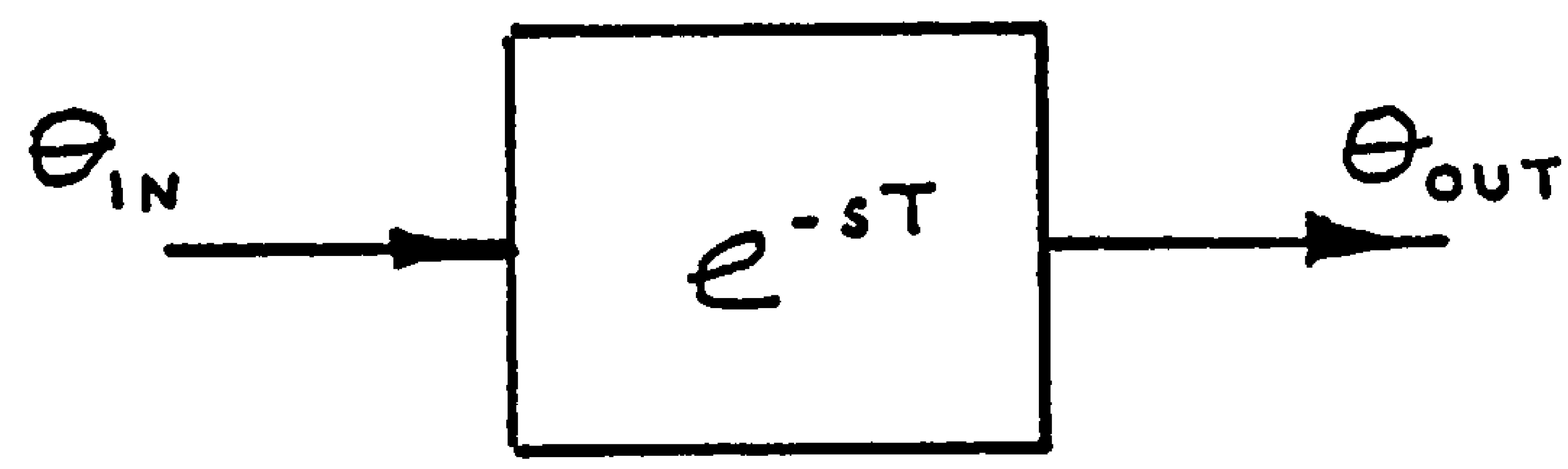
11.0×10^3 . Since an increase in this gain corresponds to a decrease in stability, this implies that the servo stability is not determined by the low frequency gain but by that at a frequency above the cut off value of the tube connection.

5.3.4 Acoustic time delays

Pressure waves originating from either the tympanic membrane or the reference diaphragm, take a finite amount of time before being detected by the microphone. This time is proportional to the local sonic velocity and inversely proportional to the distance between the pressure source and the microphone. Such a time lag may be represented as shown in figure 5.16. In general, any open loop responses including a time lag, will have a Nyquist diagram of the form shown in figure 5.17. For the system to be stable, the complex coordinate, $-1 + j0$, must not be encircled by the spiral contour (Elgerd 1967).

The time delay within the feedback loop T_D, may be estimated from a Bode diagram of the phase difference between the input to the reference diaphragm and corresponding output from the microphone (figure I.5 appendix I). T_D has a value of 0.09 degrees lag per Hz that is approximately a 250 microsecond delay. The delay T_T, is the time required for a pressure wave to travel from the tympanic membrane to the microphone. This may likwise be estimated from a Bode diagram for the phase difference between an input to the calibrator diaphragm and the microphone output (figure I.6 appendix I). This has the

a) Block diagram representation of an acoustic time delay. Letter s denotes the Laplace operator and T_d is the acoustic time delay such that $T_d = x/c$ where x is the distance between microphone and reference diaphragm and c is the sonic velocity.



b) Nyquist representation of a pure time lag. Where ω is the frequency of the signal subjected to the time delay.

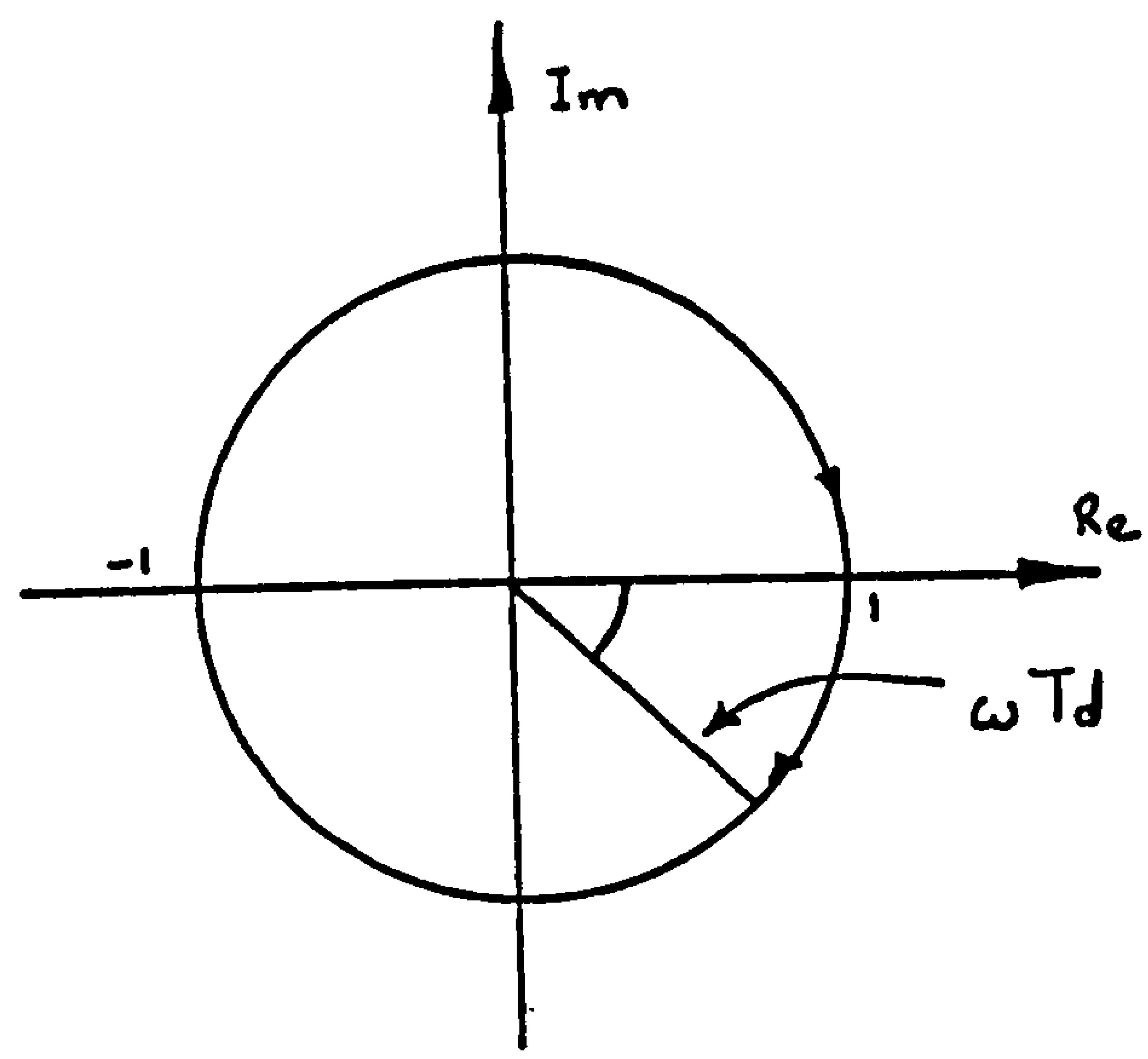


FIGURE 5.16 <u>Representation of pure time delays</u>
Note that the amplitude does not vary with frequency and a pure time delay only results in a phase angle lag.

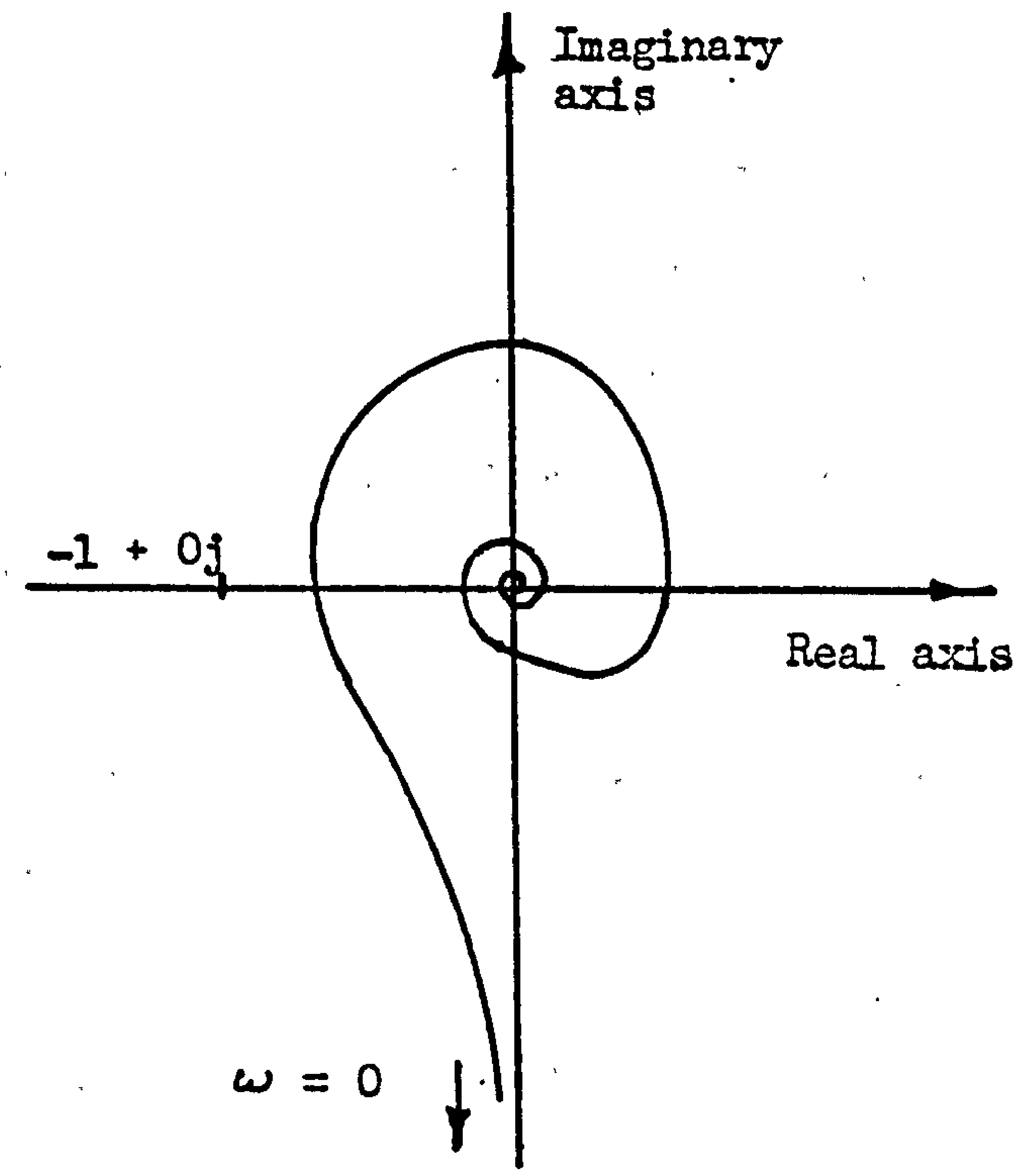


FIGURE 5.17 A Nyquist plot including a pure time delay

A spiral Nyquist plot characteristic of a transfer function including a pure time delay term.

value of approximately 0.27 degree per Hz, which corresponds to a 750 microseconds delay. The stability of the servo is not dependent on the value of T_T, but it is on the time delay T_D.

5.3.5 Optimum servo cavity design

An optimum design of the servo cavity is a compromise between two factors; the stability of servo and the signal to noise ratio of the reference diaphragm output. The stability of the servo is affected by the magnitude of the acoustic time delay between the reference diaphragm and the microphone , as well as by the volume of the cavity. The latter factor influences the degree by which movements of the tympanic membrane and reference diaphragm are impeded by the cavity. A sufficiently large cavity volume is necessary to reduce this impediment to an acceptable level. However, contrary to this requirement, the smaller the cavity volume, then the better is the signal to noise ratio of the output from the reference diaphragm. The reason for this is that for a given TM displacement, the smaller the cavity volume, then the greater the output from the microphone, the device which limits the system's signal to noise ratio (section 7.1.4).

As can be seen, careful design of the cavity, especially in respect of its volume, is necessary if adequate servo stability as well as signal to noise ratio are to be obtained.

CHAPTER 6

CLASSIFICATION AND STATISTICAL ANALYSIS OF THE TMD SIGNAL

Terminology : Before discussing the signal from the TMD system, it is prudent first to define some items of the terminology used in this chapter.

A record is defined as a single recording of the process under study. In general the recording will be time variant and consist of both the processed signal and noise. A collection of records is known as an ensemble. An ensemble average is an average taken across the ensemble.

In the context of this chapter, a signal is a stream of potentially useful information from the TMD system, whereas noise is an undesirable phenomenon which corrupts this signal.

One of the principal applications of the TMD system is to measure the volumetric displacement of the tympanic membrane resulting from acoustic stimulation of the middle ear reflex. In a similar manner to 'evoked response audiometry' (ERA), the reflex response to a particular stimulus is obtained by averaging an ensemble of records.

Although each response is recorded for the same stimulus and test conditions, no two responses will be exactly identical. The causes for these variations between records are twofold. Firstly, as a result of noise both from extraneous origins and from other biological processes, such as respiration. Secondly, as with other physiological measurements, there are neurological and physical reasons why the reflex response itself will vary from record to record. Similar inconsistencies between records occur when the TMD system measures other physiological processes, such as swallowing.

A thorough analysis of any signal from the TMD system requires that an ensemble of records is subjected to various statistical techniques. Not only are these techniques chosen to improve the signal to noise ratio of the TMD signal, but also to quantify how closely an ensemble average approximates the actual reflex response.

Before considering the integrity of an average, it is first essential to formulate the properties of the records which constitute the ensemble.

6.1 STATISTICAL PROPERTIES OF THE TMD RECORDS

Individual records from the TMD system are composed of an additive mixture of a signal component $s_i(t)$ and a noise component $n_i(t)$. That is, if the ith record is denoted by $x_i(t)$ then

$$x_i(t) = s_i(t) + n_i(t)$$

Both the signal and noise are considered to be nonstationary, that is their statistical properties are variant with time. In respect of the signal, both its mean and standard deviation vary with time, and in respect of the noise the standard deviation is time variant (section 7.4).

The noise present with the reflex TM displacement records originates from several sources, including cardiovascular pulsations, respiration and swallowing. At stimuli intensities near the reflex threshold, this noise completely masks the TM displacement transient.

6.1.1 Record independence

It is important to know how the statistical properties vary between the records of an ensemble. Signals may be classified depending on whether or not they are: 1) independent, 2) dependent or 3) correlated. Classes 1) and 2) are in fact the two extremes of the more general correlated classification.

In relation to the TMD records of reflex activity, if throughout a test no reflex adaptation or fatigue occurs, then the records are independent; that is they are invariant with the number of stimuli. Alternatively if these processes do take place, then the sample records will be dependent on the number of stimuli and therefore their positions in the ensemble.

It is often the case in physical situations involving nonstationary data, that some correlation exists between signals in different records, or in other words neither dependence nor independence of the signal can be proven.

As later described, the duration of the interval between the reflex stimulation used throughout the present investigation, was chosen to be long enough to avoid adaptation and fatigue. The records were therefore assumed to be independent. It is shown in appendix II that whether or not the records are independent is relevant to the properties of the ensemble statistics, and in particular the accuracy to which the TMD signal may be recovered from the noise.

6.1.2 Inter-stimulus duration and reflex recovery

Only if the TMD records are independent, will an averaged TM displacement history be a true representation of an actual TM transient. The factors affecting the independence may be reflex adaptation and/or fatigue. It is therefore essential for the duration of the inter-stimulus period to be sufficient for the reflex to fully recover.

Reflex fatigue and adaptation have been observed by a number of investigators. It has been shown for example, that a continuous stimulus tone of frequency above 1000 Hz, and of an intensity greater than the reflex threshold, will cause these physiological processes to occur (Habener and Synder 1974, Borg 1976). If the stimulus is interrupted for a short period, then the reflex will rise to a higher value after the pause than immediately before. This recovery phenomenon has been noted by Kobrak et al (1941), Metz (1951), Wersäll (1958), Habener and Snyder (1974) and Borg (1976, 1979). The degree of reflex recovery is dependent on the length of the pause between presentations of the stimulus.

There is a lack of literature on reflex recovery, so that references have been made to other experiments which continually repeated stimuli of intensities above the reflex threshold. Habener and Snyder (1974) performed experiments to determine the reflex decay rates and these authors state that "No studies were available to show what length of time was necessary for a reflex recovery". They performed tests and were satisfied that for 1000, 2000 and 4000 Hz stimulus tones, a ten-second rest after each ten-second stimulus was an adequate period of time to ensure a complete recovery of the reflex. Similarly Borg (1976) from his own observations, notes that for a 2000 Hz tone and stimulus duration of approximately 8 seconds, the reflex requires an inter-stimulus interval of 5 to 10 seconds for it to retain its initial amplitude.

In a correspondence with Borg (1978), it was confirmed that 10 second rest periods were sufficient for the reflex to fully recover from 1 second stimuli. During the present investigation a minimum 10 second interval was allowed between each stimulus tone.

6.2 THE ENSEMBLE AVERAGING TECHNIQUE

6.2.1 Discussion

Often a signal needs to be extracted from a background noise. In many applications, bandpass and notch filters can be used to filter out the unwanted noise. However, the problem becomes more complex if the noise is of a similar frequency bandwidth and of an amplitude comparable to or greater than the magnitude of the signal. In this circumstance, filters cannot successfully be applied, since they also attenuate the required signal and cause phase distortions. The signal averaging techniques can often be applied under such conditions without impairing the quality of the signal. This is achieved by summating correlated samples of the signal and noise. Desired signals sum coherently, whilst the uncorrelated noise sums to a small value. The result is an improvement in the signal to noise ratio.

A distinction here should be made between the terms 'time average' and 'ensemble average'. The more familiar term 'time average' is only meaningful for stationary ergodic data and is not valid for non-stationary data, such as those for the tympanic membrane transient (appendix II). However, non-stationary data do have an 'ensemble average'. In particular, the ensemble average is used for data for which the statistical properties, mean and variance, vary with time. Clearly this is so with the TM transient, or in fact any transient. In contrast the time average is applied to data which may be considered to be in a steady state condition, so that the statistical properties are constant with time.

Much of the literature on signal averaging considers only time averaging. This is because the stationarity hypothesis greatly simplifies the analytical work necessary for the derivation of the signal's statistical properties. The fact that 'time averaging' will improve the signal to noise ratio by approximately the square root of the number of repetitions of the signal, is often misinterpreted as implying that any class of signal averaging will result in the same improvement. Bendat (1963) is one of the authors who has considered the mathematical analysis of the signal averaging of non-stationary data. Such analysis is dealt with in Appendix II.

The ensemble averaging technique can be applied to the TM transient provided three prerequisite conditions are satisfied:

i) The transient signal must be repetitive.

ii) Each repeat of the transient must be preceded by a flag pulse which acts as the signal precursor.

iii) The transient and flag pulse must be synchronized with each other.

The method known as 'multipoint' or 'multi-sweep' averaging was adopted for analysis of the TM transient as opposed to the 'boxcar' or 'single-sweep' averaging processes (Beauchamp 1973). The multipoint technique is detailed in section 6.3.1.

6.2.2 Standard deviations and ensemble averaging

The relationship between the ensemble, sample, signal and noise standard deviations for statistically independent samples is derived in appendix II as

$$\sigma_x^2(t) = \frac{1}{N}\left[\sigma_s^2(t) + \sigma_n^2(t)\right] = \frac{1}{N}\,\sigma_f^2(t) \qquad \ldots\text{eq. } 6.1$$

The terms σ_x, σ_s, σ_n, σ_f, are the standard deviations of the ensemble average, signal, noise and sample records respectively. A finite value for the signal standard deviation clearly implies that the signal component varies with different samples. This is particularly relevant for physiological signals. For instance, with TM transients it is unlikely that two identical responses may be obtained due to, for example, minor variations in the pressure within the ear or the resting position of the middle ear mechanism. Furthermore, there may be neurological reasons for inconsistencies between records. These aspects have been studied by various investigators who have obtained results that demonstrate that the variance in the reflex response increases with frequency and decrease with intensity (Djupesland et al 1967; Ruth and Niswander 1976; Barry and Resnick 1976).

With reference to equation 6.1, it can be seen that the signal variance $\sigma_s^2(t)$ may be expressed in terms of the variances of the noise $\sigma_n^2(t)$ and samples $\sigma_f^2(t)$ such that

$$\sigma_s^2(t) = \sigma_f^2(t) - \sigma_n^2(t) \quad \text{.......... eq 6.2}$$

Both the variances of the samples $\sigma_f^2(t)$ and the noise $\sigma_n^2(t)$ may be obtained during the reflex experiments, so allowing an estimation of the signal variance $\sigma_s^2(t)$. Strictly this relationship only holds for a large number of records, so that only an approximation may be obtained.

Confidence limits can be estimated for the ensemble averaged transient using the ensemble average standard deviation given by equation 6.1 as

$$\sigma_z(t) = \sqrt{\frac{1}{N}}\,\sigma_f(t) \quad \text{...............eq 6.3}$$

This equation indicates that for a large number of records the ensemble variance theoretically tends to zero, implying that the transient ensemble mean may be precisely obtained. In practice there is a limit to the improvement obtained by ensemble averaging. Beauchamp (1973) considers that the maximum improvement in the signal to noise ratio is about 60 dB, which is set by the performance of the analysis equipment.

6.3 IMPLEMENTATION OF THE ENSEMBLE AVERAGING TECHNIQUE

This section deals with practical considerations on how the multi-sweep averaging technique may be implemented on a digital computer. Principally there are two methods; either all the records of the ensemble are recorded and then averaged, or the averaging is performed whilst the data are being collected. The former will be classed as off-line processing and the latter as on-line processing. The difference between the two is mainly that with the on-line processing data reduction is performed as the data are being recorded, whereas with the other approach this operation occurs after all the data have been collected. For most applications on-line analysis should be used if possible. Both methods have their advantages and disadvantages, but on-line analysis is normally the more convenient method.

Comparing off-line with on-line data analysis, off-line data computations require more storage space and is far slower. On the other hand, it may be cheaper to implement since the data may be recorded on a tape recorder and then analysed later on a computer at a different location. Also there is a permanent record of the raw data which may be further analysed at a later date.

On-line processing usually requires a dedicated digital computer. The computer must be fast enough to perform the ensemble averaging and any other processing whilst the data are still being recorded. This requirement normally implies that the computer uses a language which is compiled before use, such as 'Fortran'. From experience, uncompiled 'Basic' tends to be too slow. In order to obtain an optimum speed, in some applications it will be necessary for the programme to be written in an assembler language and then compiled to machine codes.

The advantage of on-line processing is that it yields results which are almost immediately available after completing the data input, which facilitates a rerun of the test if necessary. Also a visual display unit may be used to show the state of the data processing throughout the test.

The on-line processing method was adopted for ensemble averaging the data produced by the TMD system because of its distinct advantages with this application.

6.3.1 Computer Programming

Off-line analysis

The off-line ensemble averaging programme is slightly simpler in its operation than the on-line analysis. A possible method is to store each successive record of the ensemble in an array of dimension equal to the number of data points in the record. After the entire data input is completed, all the arrays are summed together and the result is divided by the number of records in the ensemble. Thus the ensemble average is completed and it only remains to subtract the first value of the array from all the other values to remove any DC bias. The data may then be displayed on a VDU, and printed out on a graph plotter to produce a hard copy of the results.

This analysis is shown diagrammatically in figure 6.1.

On-line analysis

On-line ensemble averaging may be performed simply by adding the incoming record in a sequential manner to the sum of earlier records already stored in an array, see figure 6.2. After the final record has been summed, it then only remains to divide by the number of records in the ensemble and compensate for any DC bias as previously described for the off-line processing. A VDU display of this process shows a plot of the instantaneous sum of the records, which increases in amplitude with the number of records summed. Often a better alternative to this method is to write a programme which calculates the running ensemble average of the data, that is, the instantaneous average as opposed to the sum of the data. The running average is more meaningful for a step-by-step visual display of the processing.

The running average method was adopted for the TMD system and is shown in figure 6.3. This type of processing, in its simplest form, normally requires two arrays of dimensions equal to the number of data points in the record. Sometimes it is possible to use a single array, in which case the incoming data are immediately processed and stored in the array during the sampling. This approach may only be used with relatively slow data sampling rates. Often, as in the case of tne TMD system, the computer can only cope with the data input and storage,

FIGURE 6.1 <u>Diagrammatic representation of off-line ensemble averaging</u>

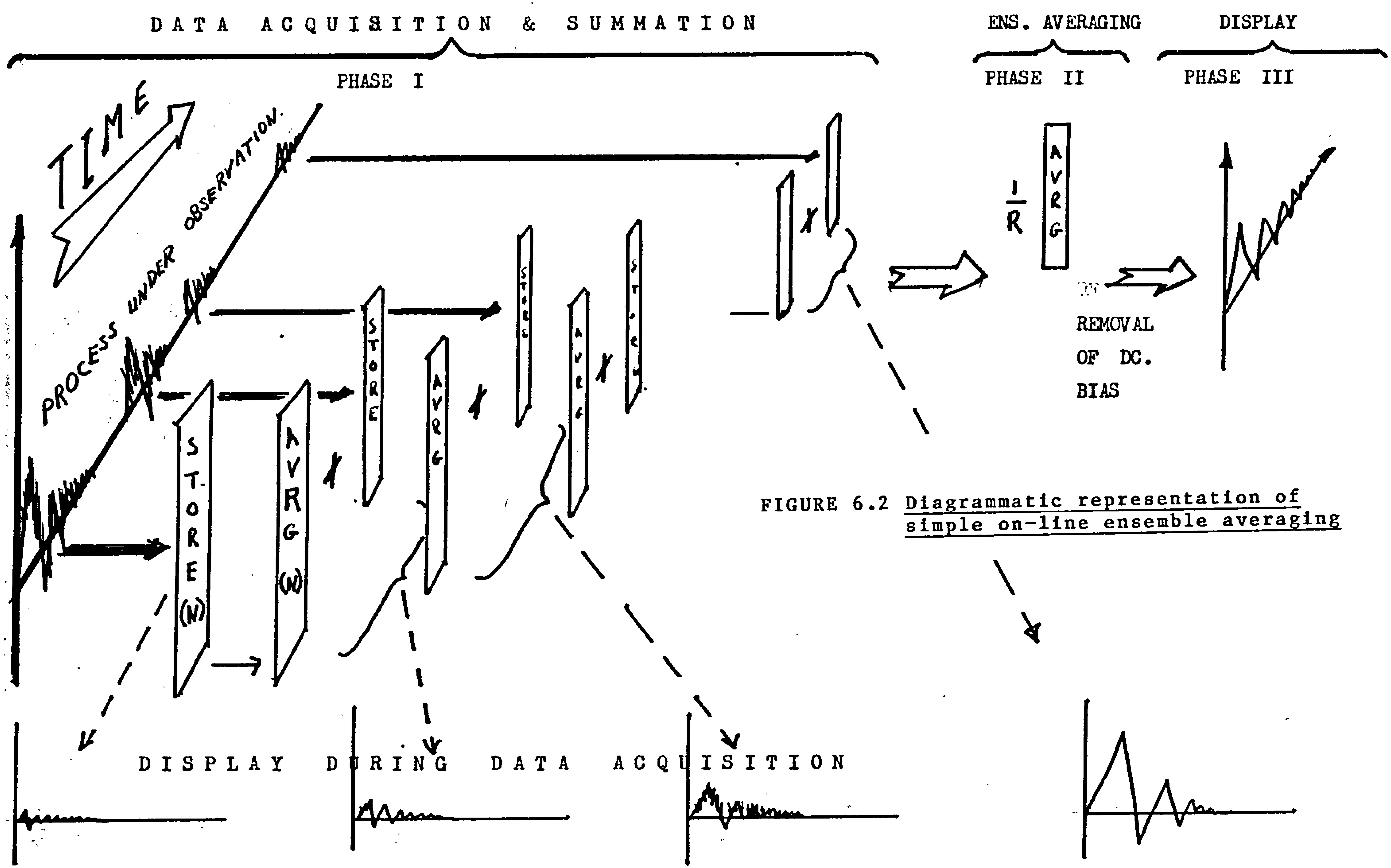


FIGURE 6.2 <u>Diagrammatic representation of simple on-line ensemble averaging</u>

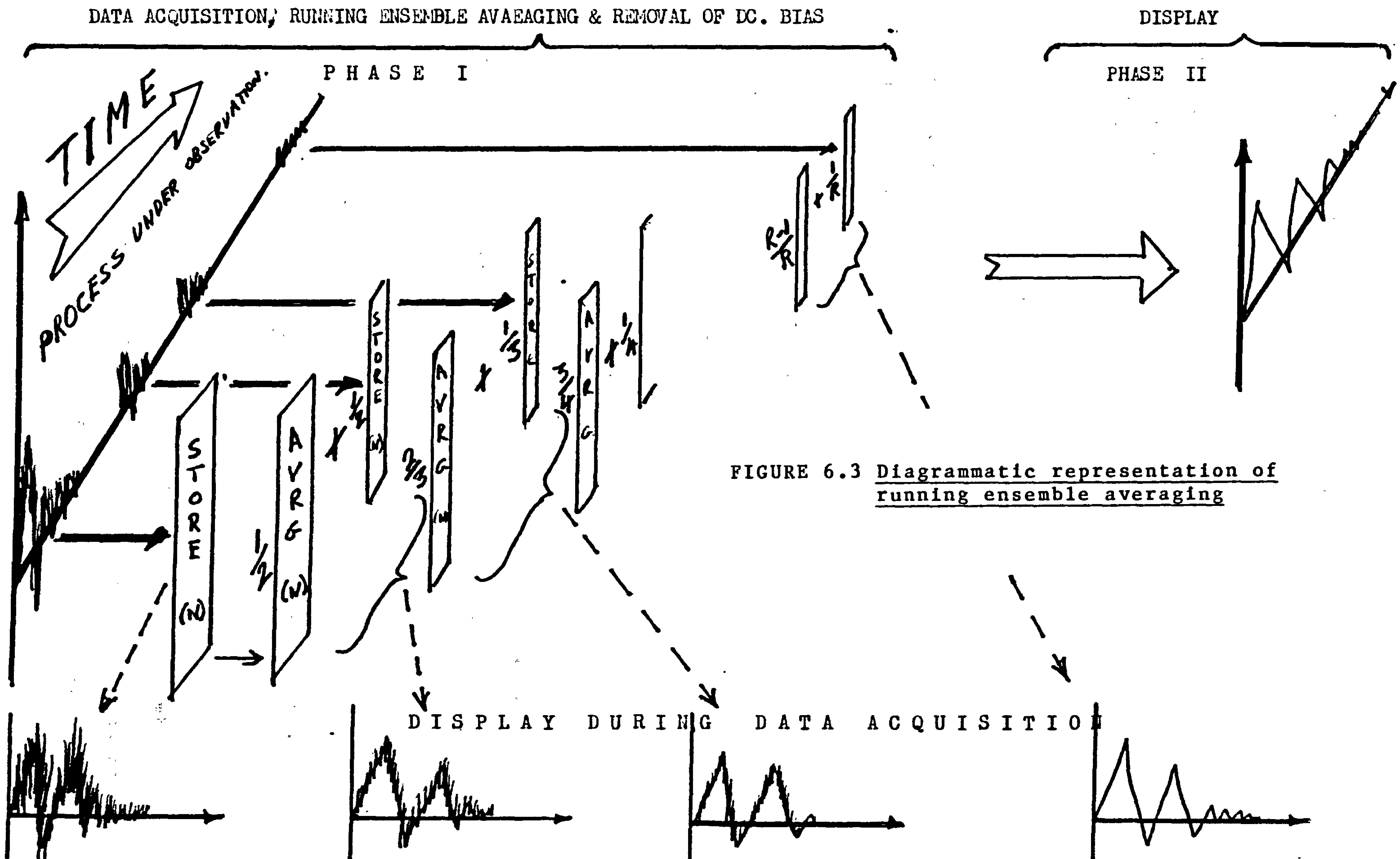


FIGURE 6.3 Diagrammatic representation of running ensemble averaging

and is programmed to process the information immediately after the last data point of the record. The routine employed to calculate this running average for the TMD system, is discussed in the following paragraphs.

Let the data sampled by the computer be immediately stored in the array

$$STORE\ (N) = STORE\ (S_1, S_2, S_3, \ldots\ldots\ldots S_n, \ldots\ldots\ldots S_N).$$

This array has a dimension of N, which corresponds to the N data points in each of the records. Let the elements of the array be denoted by $S_1, S_2, \ldots S_n, \ldots S_N$ such that the nth data point in the record corresponds to the S_nth element.

Let the running average be stored in the array

$$AVRG(N) = AVRG(A_1, A_2, A_3, \ldots\ldots A_n, \ldots\ldots A_N)$$

Likewise the nth data point corresponds to the A_nth element. The running average of the arrays is calculated as

$$\text{RUNNING AVERAGE OF nth ELEMENT} = \frac{(STORE(S_n) - STORE(S_1)) + ((K - 1) \times AVRG\ (A_n))}{K} \ldots\text{eq. } 6.4$$

where K is the number of data records just prior to calculating the ensemble average. Thus the value of K will initially be '1' immediately after the first record has been stored in STORE, and will increase in value until finally it becomes equal to the number of records in the complete ensemble.

Note that the first element of the array, STORE(S_1), is subtracted from all the other elements so as to eliminate the quiescent component of the incoming signal, Equation 6.4 is expressed in normal programming terms as

$$AVRG(A_n) = (STORE(S_n) - STORE(S_1) + (K-1)*AVRG(A_n))/K \quad \text{....eq 6.5}$$

This equation performs the averaging and restores the new value in the array element AVRG(A_n).

6.3.2 Calculation of the record and ensemble standard deviations

In addition to calculating the ensemble average, it is often desirable to compute the ensemble standard deviation. In so doing, a more comprehensive description of the process under observation is obtained. As with the ensemble averaging computation, the data required to calculate the standard deviation are best reduced between samples, so economizing on the storage space required.

The method of calculating the standard deviation in the programme for the TMD system, was to use an array, SDEV(N), of dimension equal to the number of data points in each record. This array stored the sums of the squares of the normalized sample values. That is, shortly after the record had been stored in STORE(N) the computer performed the instruction

$$SDEV(D_n) = (STORE(S_n) - STORE(S_1))^2 + SDEV(D_1) \quad \text{.....eq 6.6}$$

where D_n is the nth element of the SDEV array. Finally, after all the records have been averaged, their standard deviation $\sigma_f(t)$ was calculated in the following manner:

STANDARD DEVIATION $\sigma_f(t)$ =

$$\sqrt{\frac{SDEV(D_n) - TRANS*AVRG(A_n)^2}{(TRANS - 1)}} \quad \text{..............eq 6.7}$$

where TRANS is the total number of transient records in the ensemble.

An estimation of the standard deviation of the ensemble average $\sigma_x(t)$ was obtained using equation 6.3. That is

$$\sigma_x(t) = \sqrt{\frac{1}{TRANS}}\,\sigma_f(t)$$

The TMD system also calculates the standard deviation of the background noise in the external ear canal $\sigma_n(t)$. This was measured from the control records and allows an approximation to the standard deviation of the signal $\sigma_s(t)$ to be made, equation 6.2.

These standard deviations were displayed in various ways on the TMD graphical output, as described in the following section.

6.4 THE TMD SYSTEM GRAPHICAL OUTPUTS

The final section of the TMD system output routine controls the X-Y plotter. With reference to figure 6.4, it can be seen that there are a number of different plots displayed about three horizontal axes. Above each axis there is a calibration mark, which is equivalent to a volume displacement noted on the line printer, normally 0.04 µl. The scaling of the top two graphs is varied automatically so as to encompass the large variations in the TM displacement transient amplitudes. The calibration mark is changed accordingly. The vertical dashed line gives the instant at which the stimulus is switched off. The various plots are subsequently described.

6.4.1 Plot 1. TM volume displacement

The topmost plot of figure 6.4 displays the TM volume displacement resulting from reflex stimulation. The solid contour is the ensemble average of the reflex transient and the dashed lines show the range of one standard deviation of this average. The closer the standard deviation limits approach each other, the more certainty there is that the ensemble average is a true representation of the actual TM transient.

a) The graphical output showing the TM volume displacement.

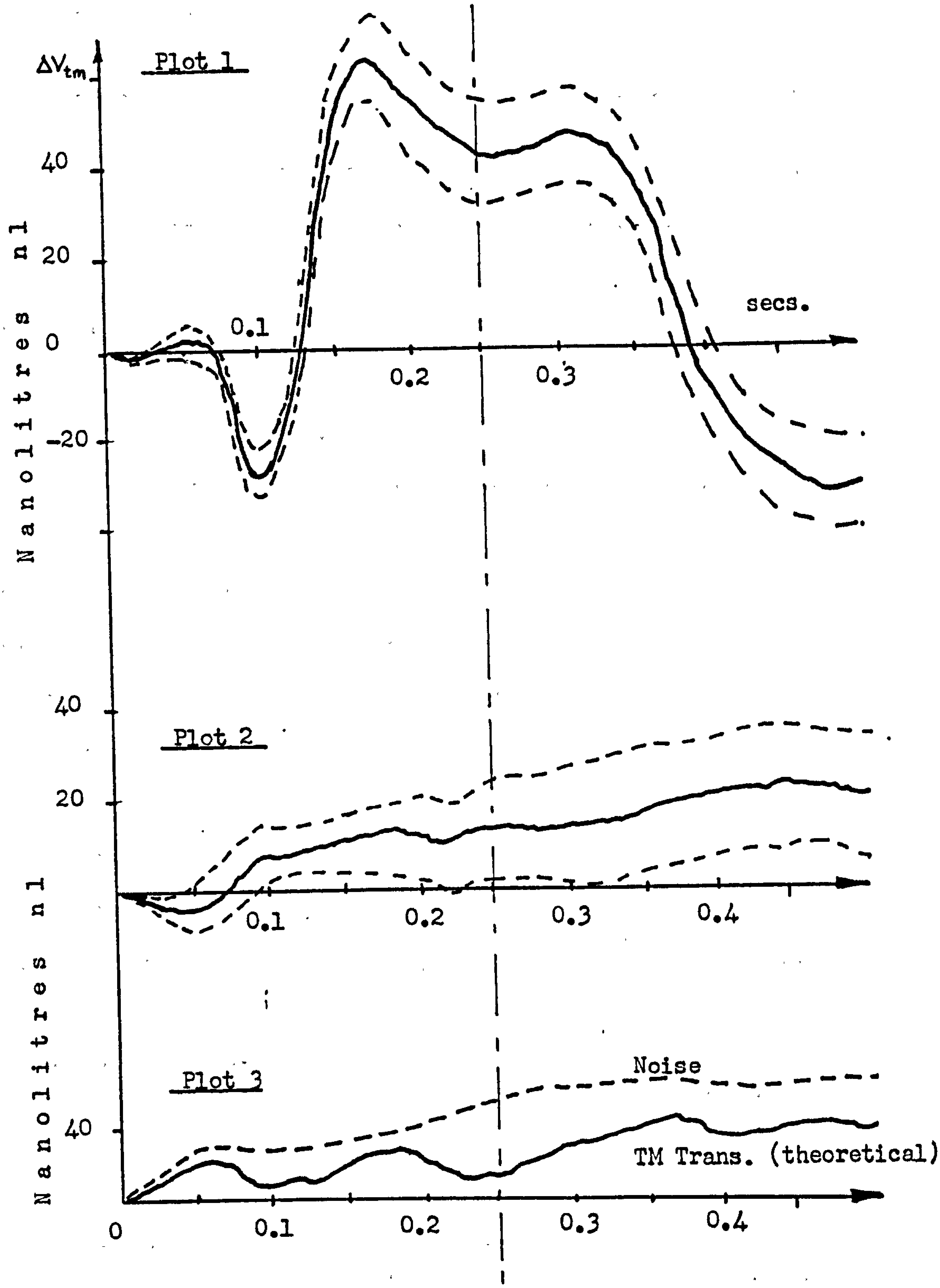


FIGURE 6.4 <u>The TMD system output</u>

FIGURE 6.4 (Continued)
b) The alpha-numeric output giving details of the test

```
CITY UNIVERSITY 690 HYBRID COMPUTER

*************************************************
*                                               *
*   MEASUREMENT  OF  EAR  DRUM  DISPLACEMENT    *
*   DATE 15TH AUGUST 1979 ←                     *
*                                               *
*************************************************

TEST NUMBER   18

SUBJECT S IDENTITY IS R.J.

A DRUM DISPLACEMENT MEASUREMENT OF THE RIGHT EAR IPSILATERAL

STIMULUS FREQUENCY 1000 HZ

STIMULUS INTENSITY IS 90 DB UC

STIMULUS SWITCH OFF TIME 1 TO 10 IS    5

INTERSAMPLE INTERVAL SECS. IS    8

NUMBER OF RECORDS   20

RECORD LENGTH IS      .50000 SECONDS

FORWARD LOOP GAIN P031 IS  .4001    CAL.MARK 0.040 CU.MM.

ADDITIONAL COMMENTS -
TESTS ON FEASIBILITY OF IPSILATERAL REFLEX TESTS ←

TIME  AVERAGE  STATISTICS  FOR  COMPLETE  ENSEMBLES CU.MM.
**************************************************

                           MEAN      STANDARD DEVIATION

NOISE                      .0125     .0078

DRUM DISPLACEMENT          .0150     .0323
```

6.4.2 Plot 2. Control volumetric displacement

The centre plot displays the control volumetric displacement within the ear canal. Again the dashed lines are the standard deviation of the noise ensemble average *. This plot yields a visual comparison by which one can judge whether or not the tympanic membrane moved due to reflex activity.

6.4.3 Plot 3, Actual standard deviation of records

The bottommost plot shows the actual standard deviation of the noise with time $\sigma_n(t)$, displayed as the dashed line, and the TM signal standard deviation $\sigma_s(t)$, as a continuous line. Whether the plot of $\sigma_s(t)$ is of any diagnostic value remains to be seen. However if any significant variations in the latency of the reflex occur , this will be shown as an increase in this standard deviation after a time approximately equal to the reflex latency. Figure 6.5 shows this effect in a simulation of varying latencies.

* The standard deviation of the noise ensemble average is estimated in an identical manner to that of the TM displacement transient.

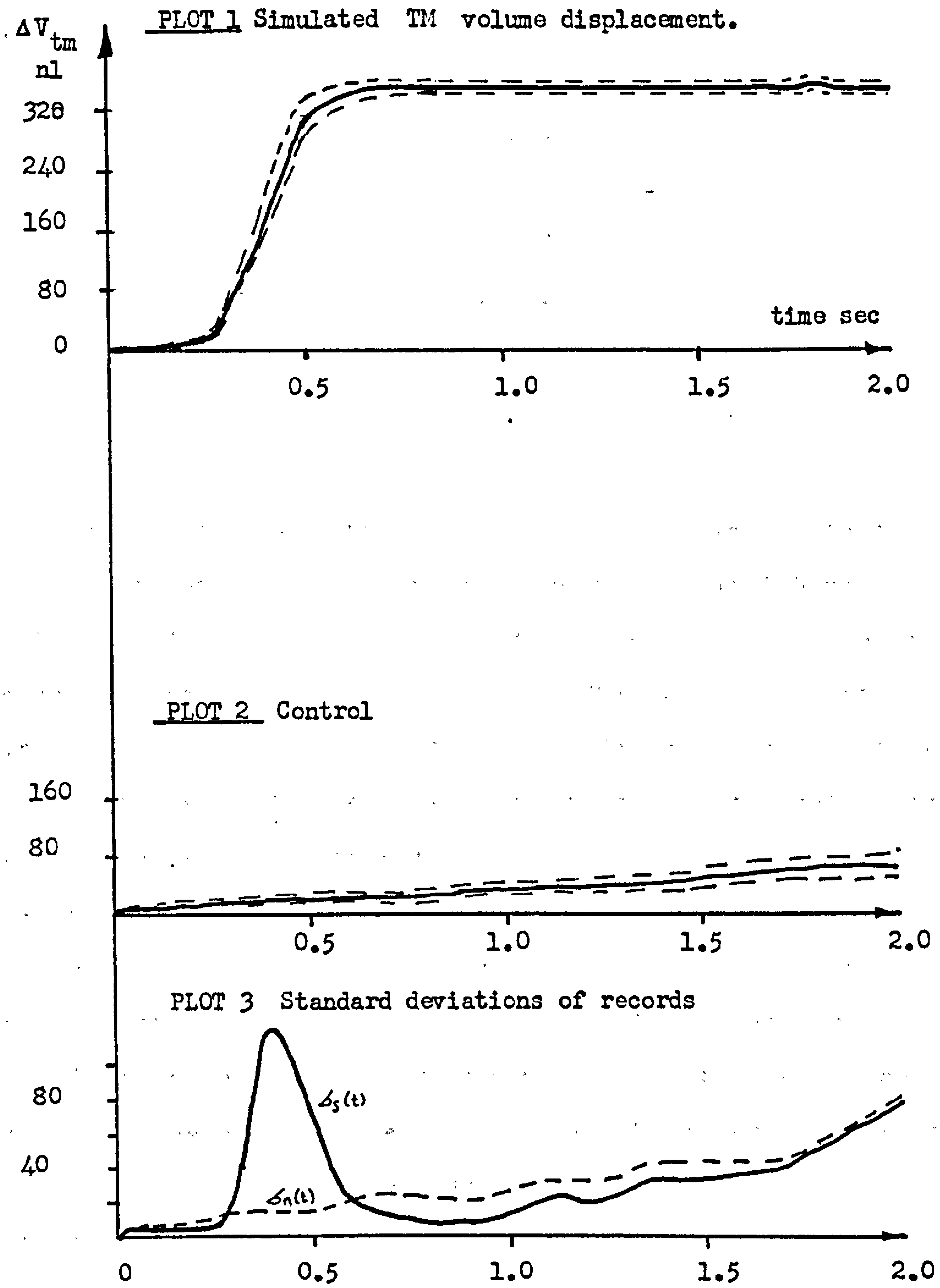


FIGURE 6.5 Simulation of the effects of varying reflex latencies

CHAPTER 7

NOISE AND THE TMD SYSTEM

Consideration of the origins, types and effects of noise, allows a better understanding of the TMD system as well as aids the interpretation of the TM displacement results obtained with the system. The origins of the noise are both intrinsic and extrinsic. The extrinsic noise may be sub-classified according to whether it originates from the TMD system circuitry or local ambient pressure variations.

This chapter initially discusses extrinsic noise, and then intrinsic noise of physiological origins. It concludes with a section which presents experimental results showing the effectiveness of the ensemble averaging technique for improving the signal to noise ratio of the TMD records.

7.1 LOW FREQUENCY NOISE AND THE TMD SYSTEM

A degree of correlation exists between the records of an ensemble due to ultra low frequency noise. Local ambient pressure and temperature variations as well as DC equipment drift, are all contributing factors. Because of the correlation between records, this noise is difficult to remove with the ensemble averaging technique, and therefore should be reduced or avoided if possible before the records are averaged.

7.1.1 The low frequency stability of the TMD system

Low frequency noise caused by drifts and instabilities in the servo control loop, are detectable by measuring the pressure variations within the cavity whilst the servo is operating. By this method, it has been shown that the DC drift and low frequency noise of servo origins is less than $5 \times 10^{-3} N/m^2$ per second, measured over a period of 5 seconds. Relating this to an equivalent volume displacement of the reference diaphram, this is better than 0.2 nanolitres per sec. Comparing this value with a typical reflex displacement of 100 nl, it can be seen that the servo has an extremely good closed loop low frequency stability. However, the overall noise level of the TMD system falls short of these figures, being limited by other factors such as atmospheric and microphone noise.

7.1.2 Effects of atmospheric noise

The TMD system is sensitive to local variations in atmospheric pressure. The power spectral density of this noise increases towards the low frequencies and is therefore, difficult to reduce using ensemble averaging techniques. A typical average of the pressure noise within the sealed TMD cavity, measured over a period of 5 seconds, is shown in figure 7.1. The 10 transients of this ensemble were insufficient for reducing the mean noise level to zero. There is a tendency for the average to drift away from the initial pressure with increasing time, indicative of very low frequency noise. The pressure drift may equally be in the opposite direction to that shown and in addition, the amplitude of the pressure variations will vary from day to day. Typically however it has been shown to vary with a mean standard deviation of approximately 0.8 N/m^2, averaged over a period of 5 seconds *.

Local pressure variations are transmitted to the enclosed air volume within the cavity, because the cavity walls are not perfectly rigid. In particular the back of the reference diaphram is open to the atmosphere, so that this, with the rubber tubing connection to the ear seal, will flex with pressure variations. Although small, this flexing produces significant changes in the internal volume. The effect of an ambient pressure increase on the system may be seen in figure 7.2, where the flexing of a wall has been greatly exaggerated. Considering diagram a), the cavity pressure is initially equal to that of the local atmospheric pressure. On an increase of the local

* Inclusive of the low frequency noise of the microphone specified in section 7.1.4.

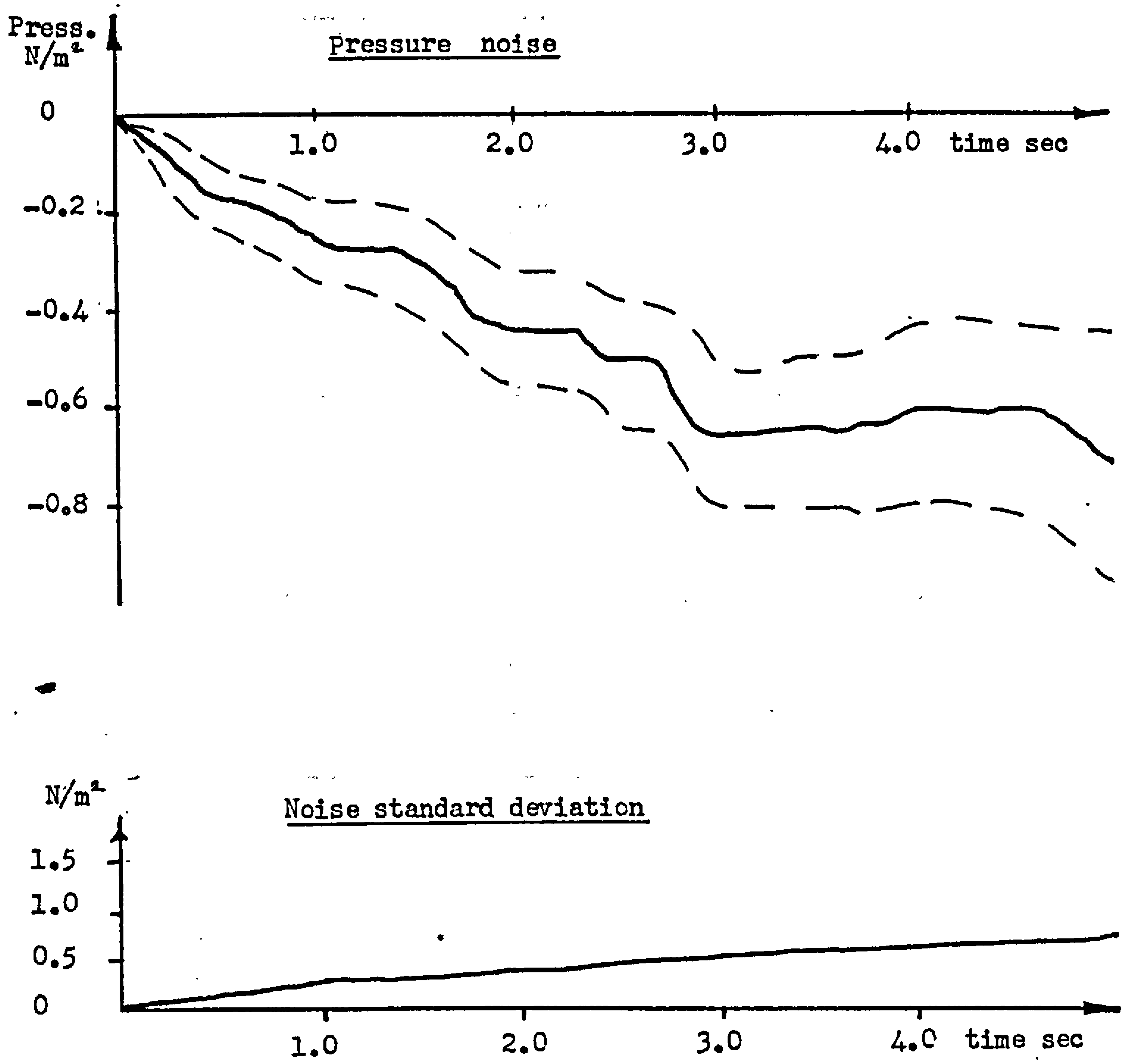
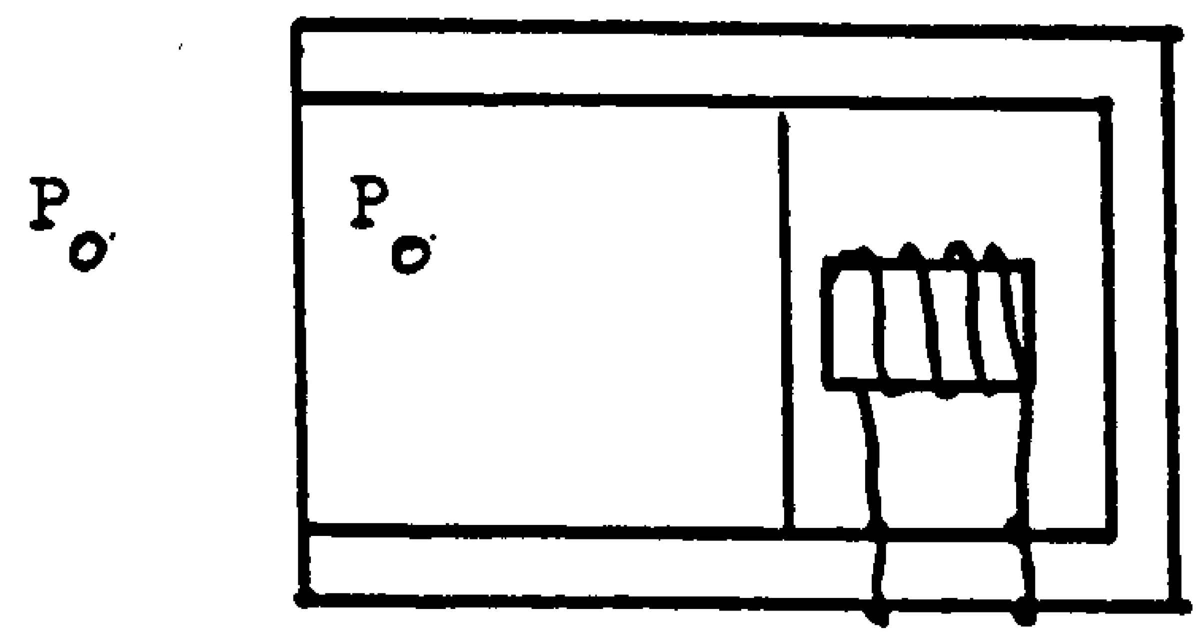
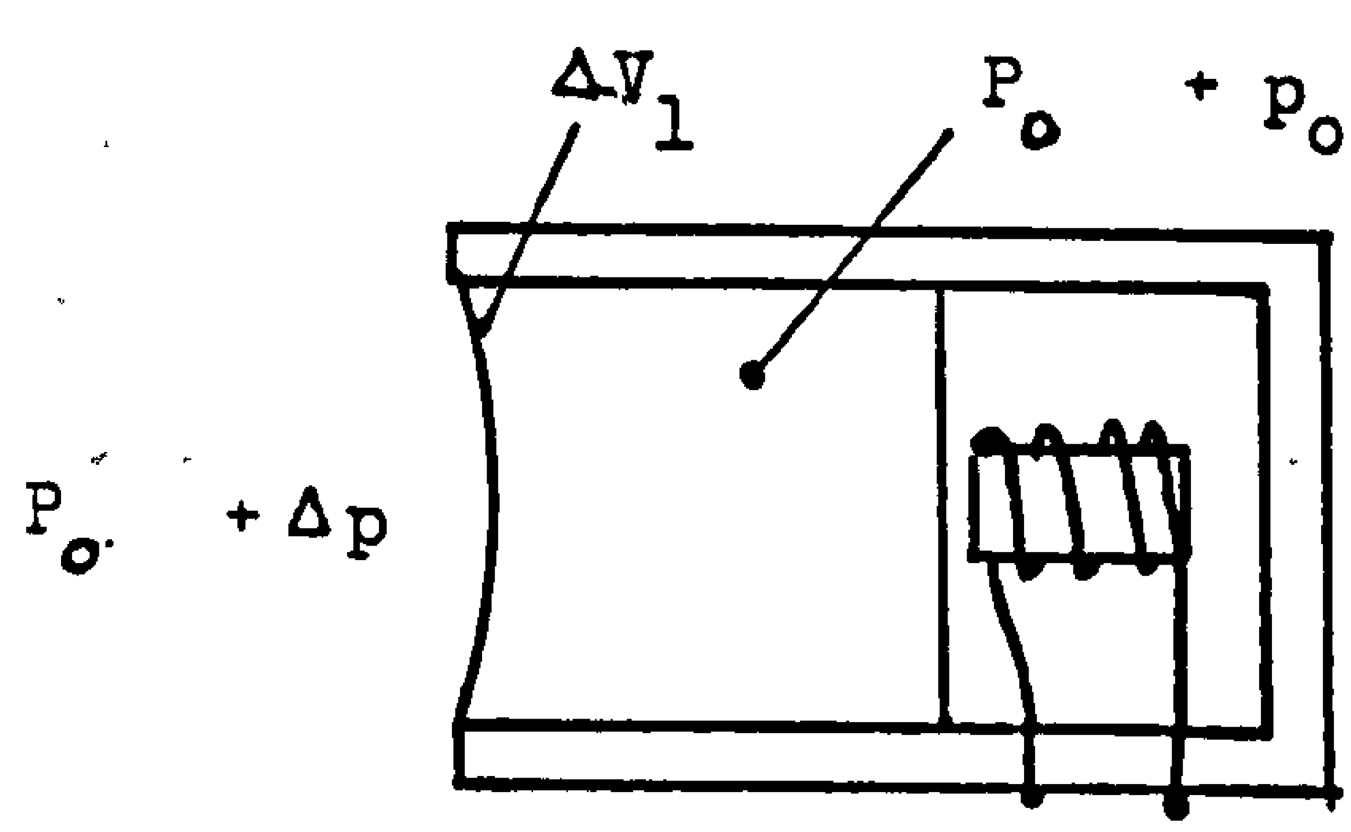


FIGURE 7.1 Pressure noise within the sealed TMD cavity

(a) Equilibrium conditions



b) A pressure increase Δp with servo inoperative



$$\Delta V_1 = K \left(\Delta p - p_o \frac{\gamma \Delta V_1}{V}\right)^*$$

where

$$\Delta V_1 \left(\frac{1}{K} + p_o \frac{\gamma}{V}\right) = \Delta p$$

c) A pressure increase Δp with servo operative. Note that $\Delta V_2 > \Delta V_1$ due to the greater differential pressure across the diaphragm.

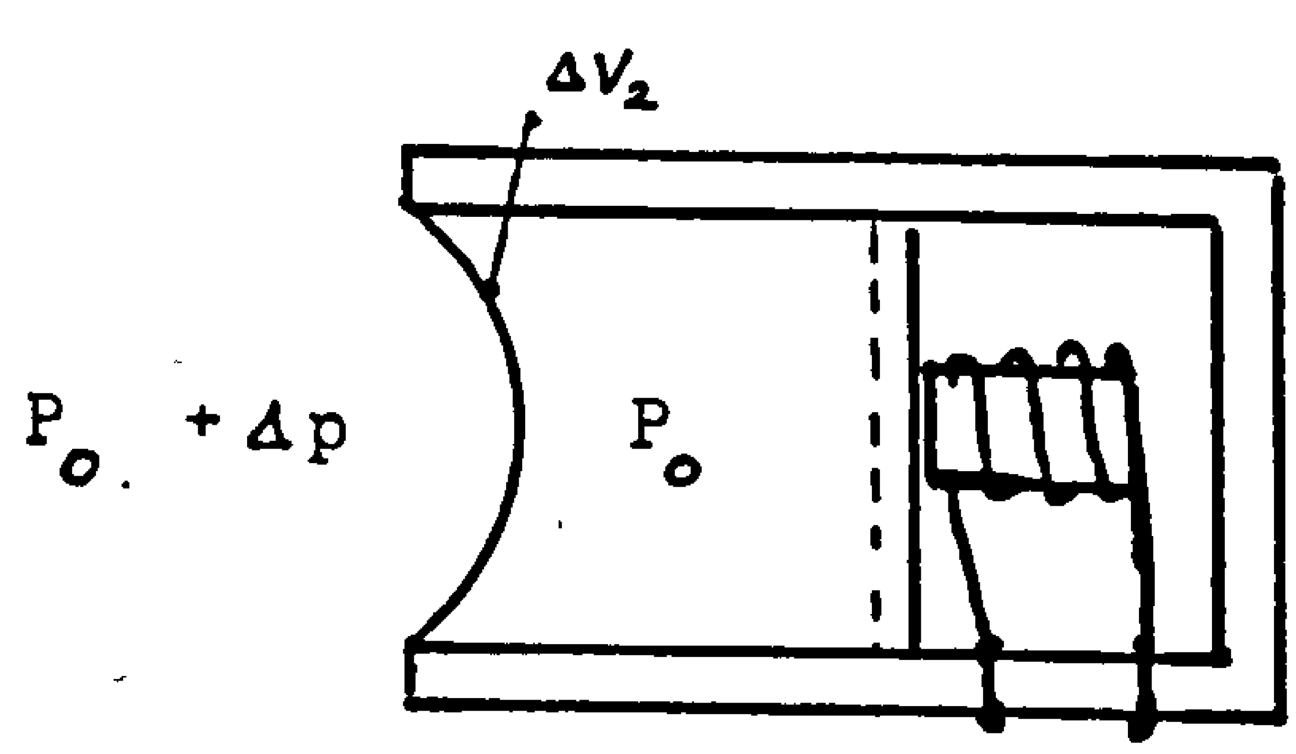


FIGURE 7.2 Atmospheric pressure variations and the servo cavity
The effects of pressure variations are shown by assuming a flexible membrane is attached to the cavity

* Assuming a linear relationship between the differential pressure and ΔV.

pressure, shown in b), the cavity walls tend to flex inwards, so causing a momentary increase in cavity pressure. Almost instantaneously, the servo increases the cavity volume by an amount necessary to restore the initial pressure, see c). It can be seen in this figure that the servo exaggerates the volume displacement of a flexing wall. This is because by maintaining a constant internal pressure, it increases the differential pressure across this wall (Compare b and c).

It has been shown in the previous section, that the servo has a negligible DC and low frequency noise level. Therefore, this local atmospheric pressure and microphone noise may be measured in terms of a volume displacement of the reference diaphragm, by operating the servo with the cavity sealed at the ear cuff. As with the atmospheric pressure, this noise level correspondingly varies from day to day, but typically its standard deviation increases at a rate of 16 to 24 nanolitres per second, averaged over a 5 second period. This may be seen to be fairly significant when compared with a reflex TM displacement of 100 nl or less.

7.1.3 Meteorological pressure variations

Depending on the time of year, the meteorological atmospheric pressure may change up to 20 mbar to 60 mbar per day. That is about 2000 to 6000 N/m^2 per day. On average, this variation gives a maximum rate of change of 0.023 to 0.069 N/m^2 per second. However, experimentation shows that the pressure variation measured over short periods have typically a maximum rate of change of 0.48 N/m^2 per second. As is to be expected, this value is much larger than the meteorological rate of change as it includes environmental noise, such as from; air-conditioning ducts, lifts and wind induced internal pressure fluctuations within the laboratory.

7.1.4 Stability and noise level of the low frequency microphone

A Brüel and Kjaer type 4147 Low Frequency Microphone Cartridge and type 2631 Microphone Carrier System, are used to sense pressure variations within the reference diaphragm cavity (section 5.1.4). The lower frequency limit of the microphone utilized during the present research (serial number 337980), has been estimated as being 1.8 x 10^{-3} Hz (-3 dB point). This limit exists because all microphones include some form of static pressure equalization, which allows any low frequency ambient pressure variations to be equalized both sides of the microphone diaphragm, see figure 7.3. This feature reduces the microphone's sensitivity to ambient pressure noise. With this low frequency microphone, the time constant of this equalization process is far greater than that of normal microphones, so giving it a lower cut off frequency.

Unfortunately, the noise levels of DC microphones are unavoidably greater than those of other microphones in general use. For the microphone incorporated in the TMD system, the noise level is specified as being about 0.1 N/m^2 RMS over a frequency band of 2 to 200 KHz. This

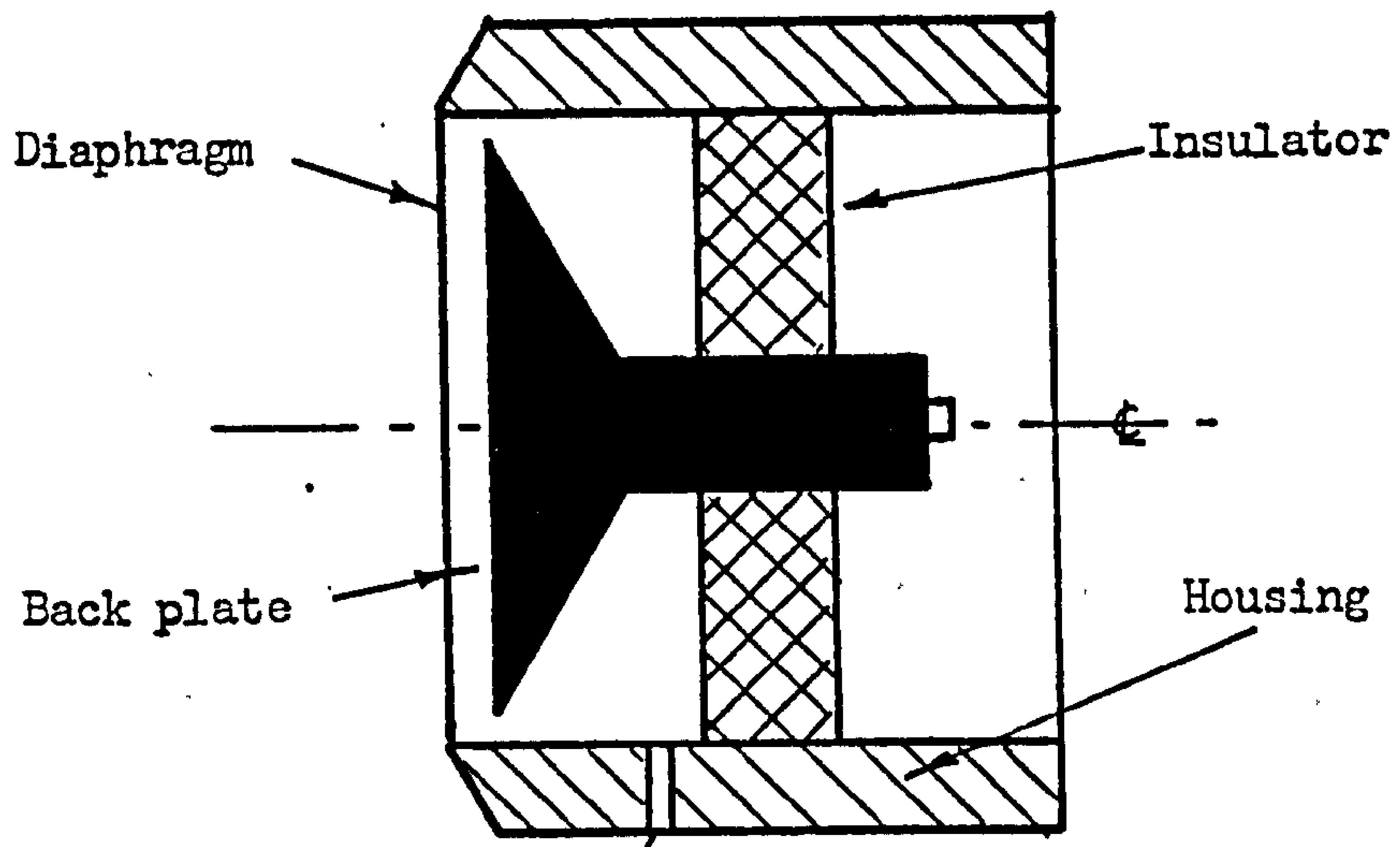


FIGURE 7.3 Diagram of a condenser microphone Reproduced from Brüel & Kjaer microphone 4144/45/46/61 instruction manual

is of the same order of magnitude as local ambient pressure noise and is similarly displayed as noise on the signal from the reference diaphragm.

7.2 NOISE OF PHYSIOLOGICAL ORIGINS

In addition to noise caused by local ambient pressure variations, the TMD records are subjected to noise from physiological origins, such as due to respiration, swallowing, gas absorption from the middle ear and the pulsing of blood. The first three sources are dealt with in this section and the cardiovascular pulse is discussed in detail in section 7.3. The respiration causes a low frequency noise; the blood pulse is a noise of a higher frequency; the swallow tends to produce a large amplitude but infrequent pulsing; and gas absorption a drift of the TMD record in one direction.

Figure 7.4 shows the spectral density of the pressure noise within the external ear canal. It can be seen that most of the noise is below 10 Hz and increases towards the lower frequencies. The peaks in the graphs are caused by the cardiovascular pulse, the fundamental frequency of 1.2 Hz corresponding to the heart rate. The other peaks are the harmonics of this frequency.

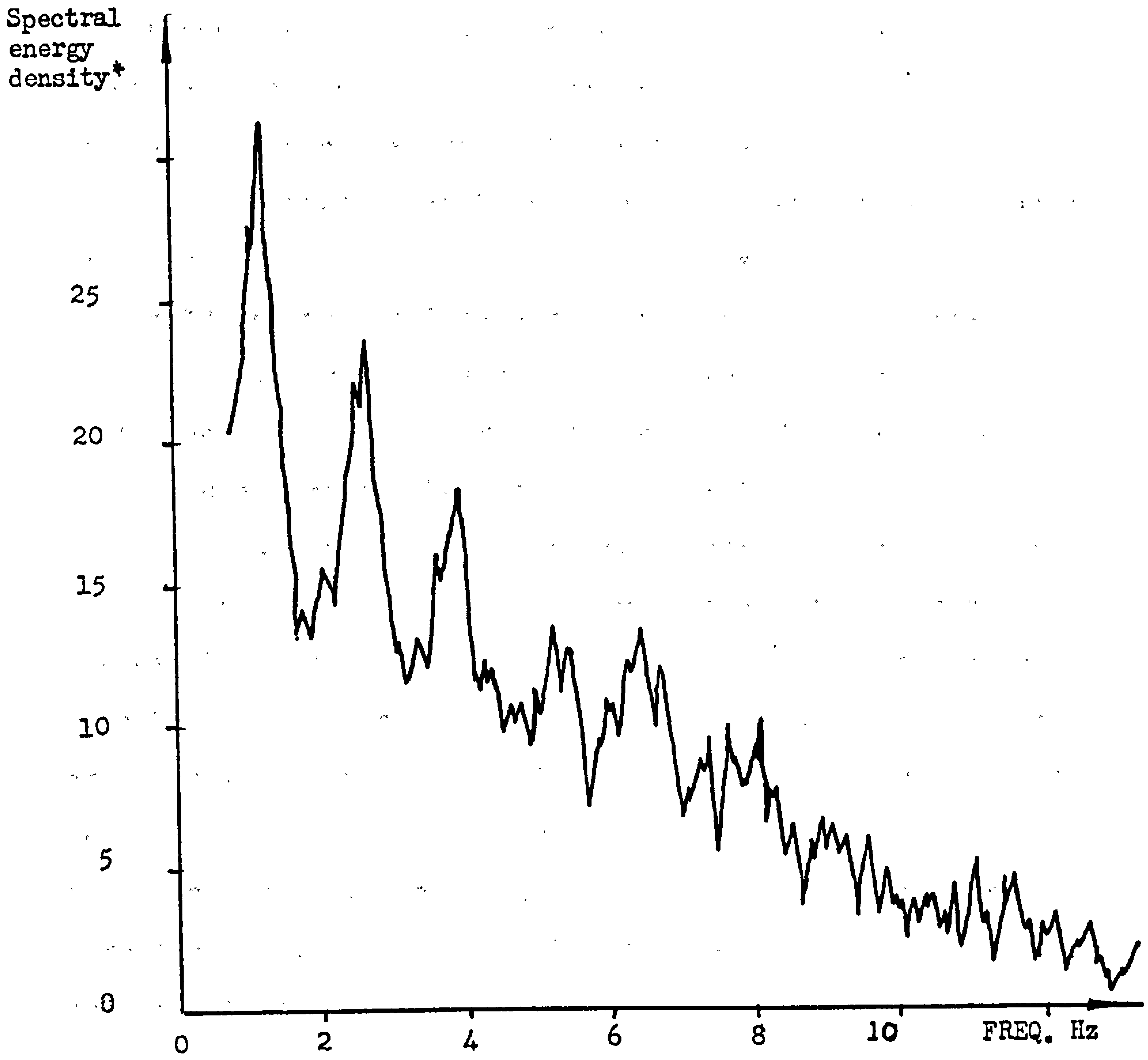


FIGURE 7.4 Spectral density of the pressure noise within the external ear canal

* Arbitrary datum.

7.2.1 Respiration noise

Respiration in the normal subject causes a change in volume of the external ear canal. This is probably due to small movements of the tympanic membrane resulting from variations in the middle ear pressure. Inspiration causes a decrease in the volume of the ear canal and expiration an increase. The normal rate of respiration for an adult is 16 to 20 breaths each minute, so that the noise has a fundamental frequency of 0.27 to 0.37 Hz.

The TM volume displacement characteristics and amplitude of respiration were obtained by ensemble averaging data collected during respiration cycles. To ensure that the cycles were summed coherently, the subject was prompted with a low intensity tone to breath at a predetermined instant and rate. The peak to peak respiration amplitude varies between subjects, but is typically 200 nl for deep breathing shown in figure 7.5, and 20 nl for normal breathing, figure 7.6. Since the respiration cannot be separated from other low frequency noise, it is difficult to quantify it. However, from the results of the present investigation, a peak to peak amplitude of about 200 nl appears to be the upper limit of the noise level and 60 nl a more typical value.

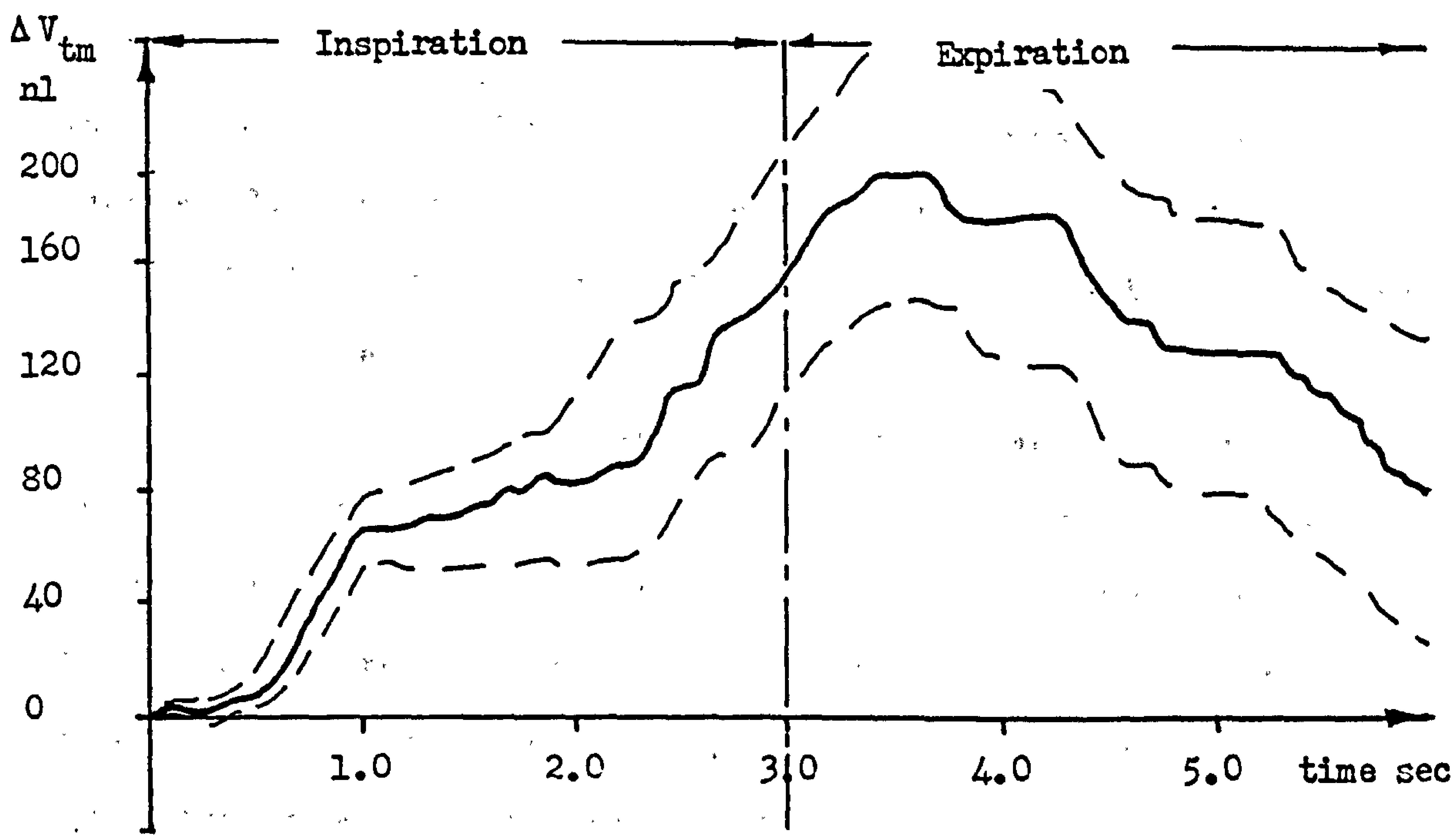


FIGURE 7.5 <u>Deep Respiration</u> Subject JM

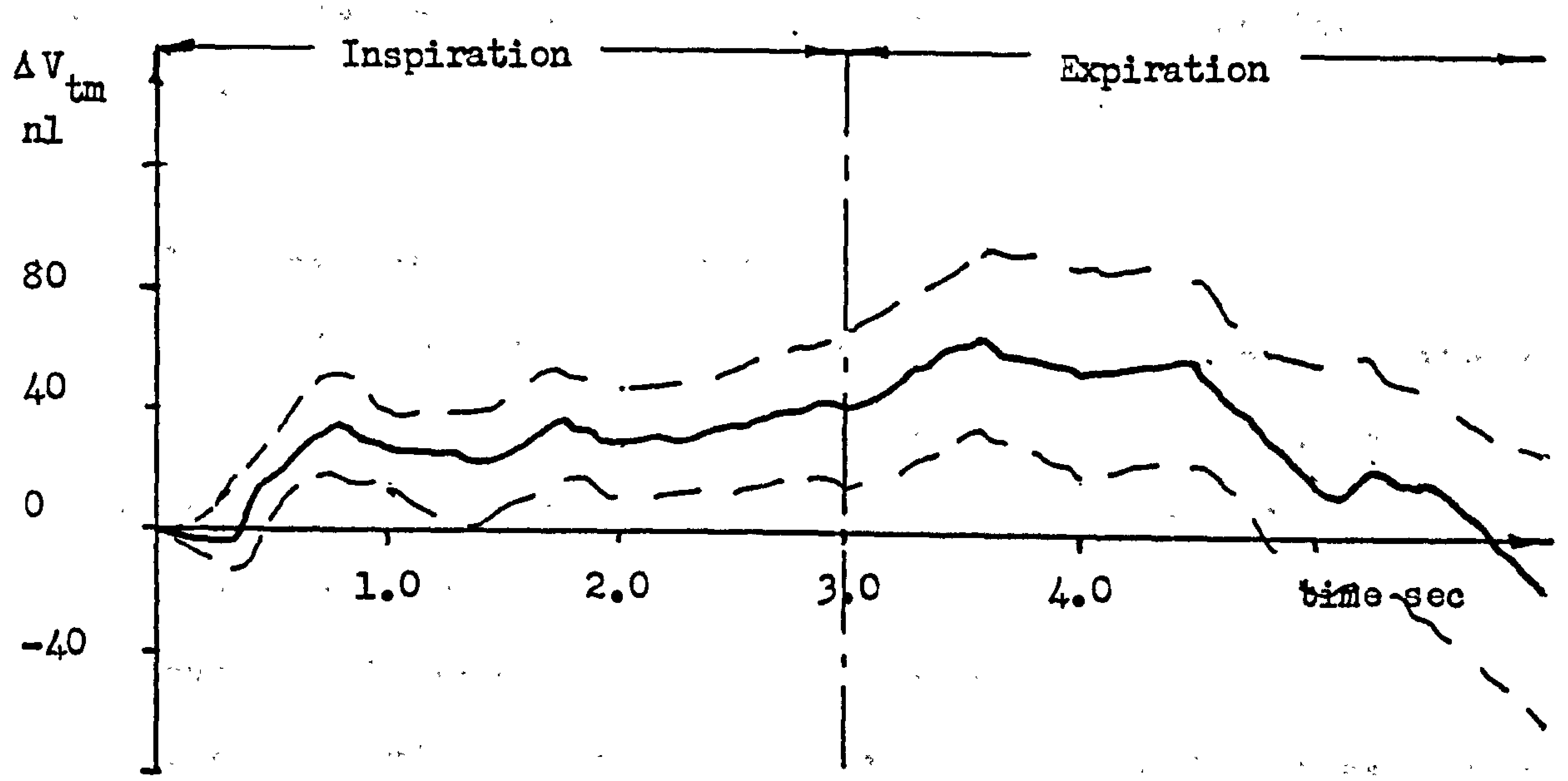


FIGURE 7.6 <u>Normal respiration</u> Subject JM

7.2.2 Noise caused by gas absorption from the middle ear

The physiological nature and measurement of the gas absorption from the middle ear is discussed in detail in chapter 8. In principle, however, air is absorbed into the walls of the middle ear cavity, which is normally closed to the atmosphere. This gas absorption will result in a continuous inward displacement of the tympanic membrane at an average rate of 0.8 to 4.3 nanolitres per second, depending on the middle ear cavity volume (section 8.3). This displacement is greater than the maximum drift rate of the TMD servo, estimated at 0.2 nl/sec (section 6.1.1) but is considerably smaller than the noise level due to atmospheric pressure variations which has a range of up to 48 nl/sec.

The middle ear gas absorption rate, being an order of magnitude less than fluctuations in the atmospheric pressure, is not considered to be a major contributor to the overall noise level.

7.2.3 Noise due to swallowing

Swallowing occurs fairly infrequently, approximately once or twice every second minute. Assuming that the TMD system output consists of 20 reflex records and 20 control records both of duration 1 second, with an inter-stimuli interval of 10 seconds, then the probability of a swallow interfering with the output may be calculated as being about unity for every set of plots.

As described more fully in chapter 8, a swallow causes a substantial inward displacement of the tympanic membrane.

The magnitude of the displacement may be of the order of 1000 nl, and the effect of the swallow may last in the region of one or more seconds, figure 7.7. In addition, there will normally be a variation in the resting position of the TM before and after the swallow of the order of 200 nl.

If a swallow does occur during the recording of a record, then the ensemble averaging technique will tend to average it out. It may, however, be shown as a larger than normal standard deviation about the ensemble average. The swallow noise could be avoided if the subjects were instructed not to swallow during the tests. Such a course of action was not taken because it was felt to have done so might have introduced further errors due to resulting abnormal middle ear function.

7.3 THE CARDIOVASCULAR NOISE

A main source of noise within the external ear canal is that due to the pulsing of blood through the blood vessels, known in this thesis as the cardiovascular pulse. The magnitude of this noise is variant with the choice of subject and often with the same subject from minute to minute. Unfortunately, the pulse is of a similar frequency content as the reflex transients, and consequently it may not be removed by simple filtering techniques. The effect of the noise is of most significance when measurements are being made near the reflex thresholds. At higher

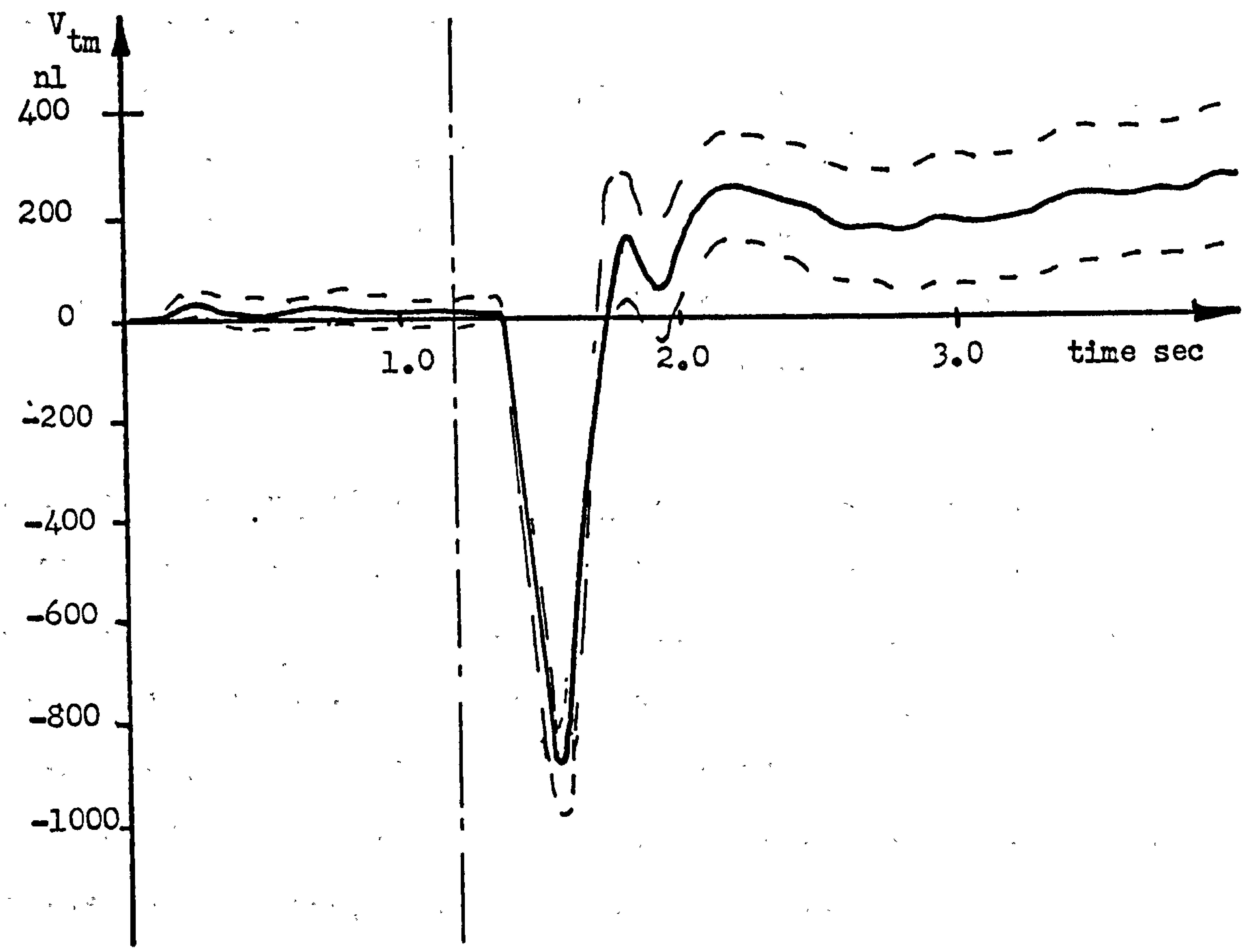


FIGURE 7.7 Volume displacement during swallowing
Subject JM

intensities, the significance varies with different subjects, being dependent on the relative magnitudes of the cardiovascular noise to the reflex magnitude. For subjects with large reflex displacements, the vascular noise is essentially insignificant. If its magnitude is similar to or greater than that caused by the reflex, then difficulty may be experienced in obtaining accurate TMD plots, so that the number of records in the ensemble average may require increasing to 40 or more.

The following section considers the historical accounts of the cardiovascular pulse, its magnitude and reduction with ensemble averaging. Also included is a means of extracting this noise from the TMD records, with the result that the signal to noise ratio is improved.

7.3.1 An historical account of the cardiovascular pulse

The cardiovascular pulse has been observed with either pressure or flow measurement techniques by Weiss (1962), Neergaard and Rasmussen (1966), Yonovitz and Harris (1976), Casselbrant et al (1977) and Brask (1978).

Brask (1978) notes that during his pressure measurements of reflex activity, that out of all the noise sources within the ear canal, the vascular pulsation is the most problematic. Firstly he comments that with some subjects the amplitude of the pulsation is greater than that of the TM displacement as caused by acoustic reflex stimulation, and secondly, he observed that with some subjects the pulse rate is not independent of the repetition rate of the stimuli. He attributes the latter pheonomenon to the fact that rhythmic sounds can influence the "rythme" of the automonic nervous system such as the heart rate and respiration. However, if the ensemble averaging technique is to be used effectively, then it is essential that the noise is independent of the stimuli rate. Brask (1978) ensured this by randomly varying the duration of the interstimuli period.

Brask (1978) not only observed that the pulse amplitude varied greatly between different ears, but he also demonstrated that it varied even in the same ear during a single experiment. Usually the amplitude was found to be the greatest at the beginning of the test period, and nervousness was thought to be one possible reason for this. Brask also suggested that the cardiovascular noise originates mainly from the external ear, although pulsations from the TM, middle ear and inner ear, are also transmitted to the external ear by the osscicles and tympanic membrane.

There is further evidence to suggest that the cardiovascular pulse must at least in part originate from movement of the tympanic membrane (Kobrak 1957; Møller 1963). Kobrak (1957) in his paper "Objective Audiometry" uses a minute mirror attached to the TM to reflect a light beam onto a screen; as the TM moves the reflected beam is rotated through a small angle. He observes that the subject's pulse and respiration produce undesirable movements of the mirror, although movements caused by the reflexes are substantially larger. Furthermore, Møller (1963) using a capacitance probe on live cats to measure TM displacements, also observed small movements of the TM due to respiration or blood pulsation.

7.3.2 The waveform of the cardiovascular pulse

A brief study of the waveform of the cardiovascular pulse has been undertaken during the present investigation. Part of this study involved the acquisition of an averaged pulse from subject JM, as shown in figure 7.8. This was obtained by averaging 8 pulse histories in such a manner that each was expressed in terms of a percentage of the heart beat period, as opposed to using a time base. It is plotted in this form, due to the constantly varying period of the pulse as discussed in section 7.3.4.

It was observed during the present investigation, that the amplitude of the pulse varied between different subjects, a result previously noted by Brask (1978). An indication of the range of this intersubject variation is provided by the study of the external ear canal noise level, given in section 7.4.

7.3.3 Reduction of cardiovascular noise with ensemble averaging

It is difficult, if not impossible, to consider the cardiovascular noise in isolation from other noises within the external ear canal. Nevertheless, for the sake of completeness of the present discussion on ear canal noise, an estimation of the reduction in the vascular noise with ensemble averaging is required. To facilitate this aim, the vascular pulse waveform, shown in figure 7.9a, is

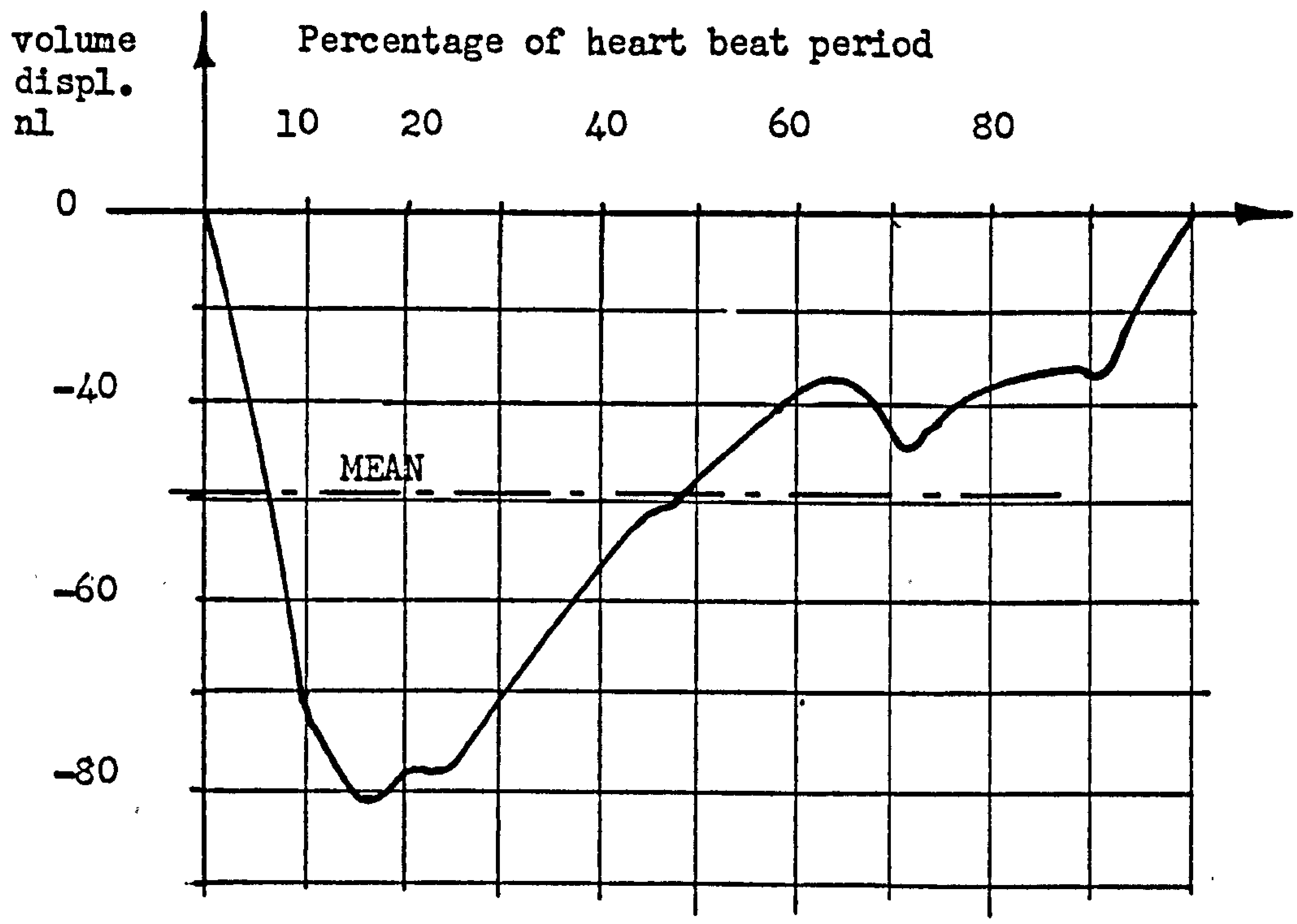
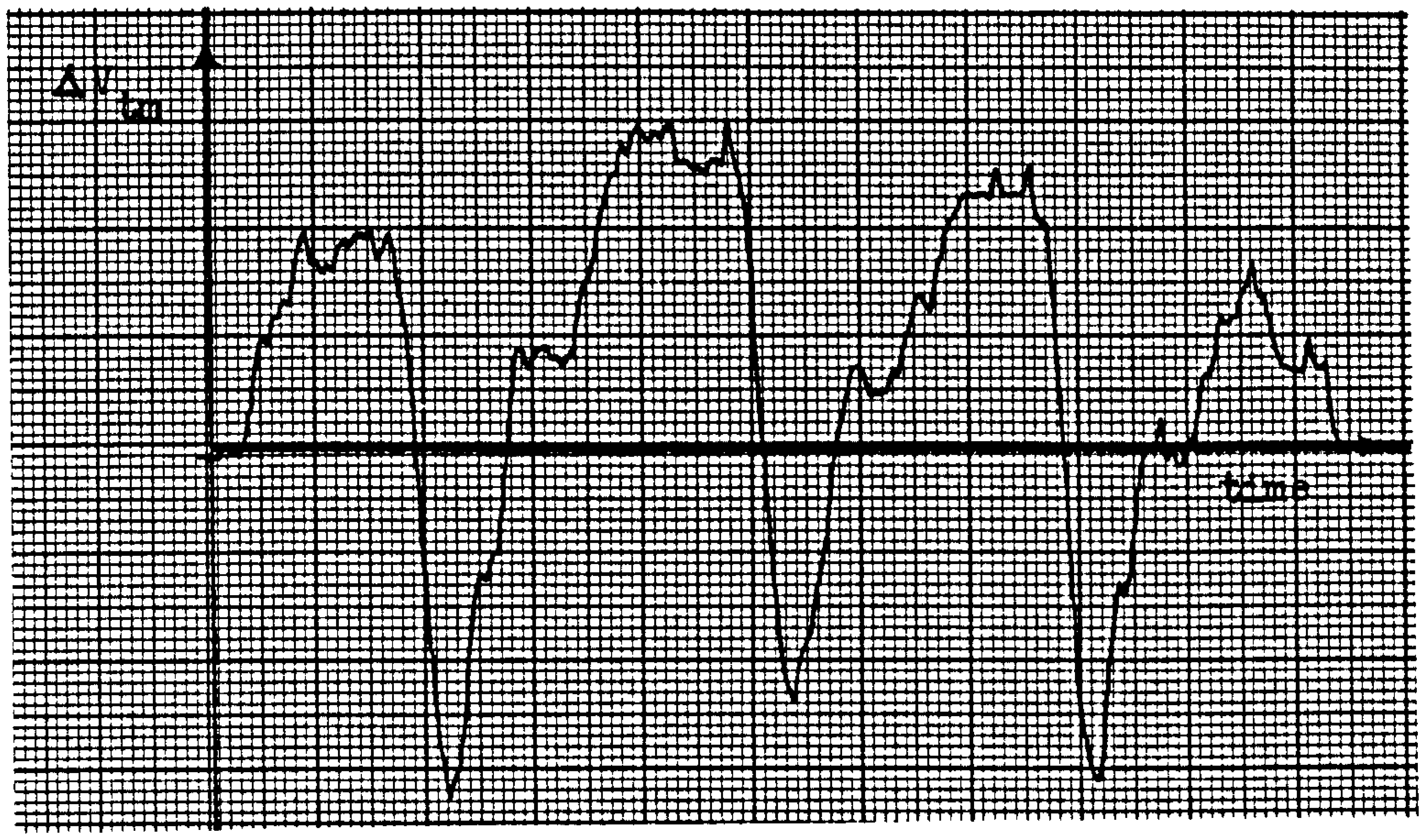


FIGURE 7.8 <u>An averaged cardiovascular pulse</u>
An average of 8 beats from subject JM

a) The actual cardiovascular pulse



b) The full-wave rectified sine wave used to model the pulse

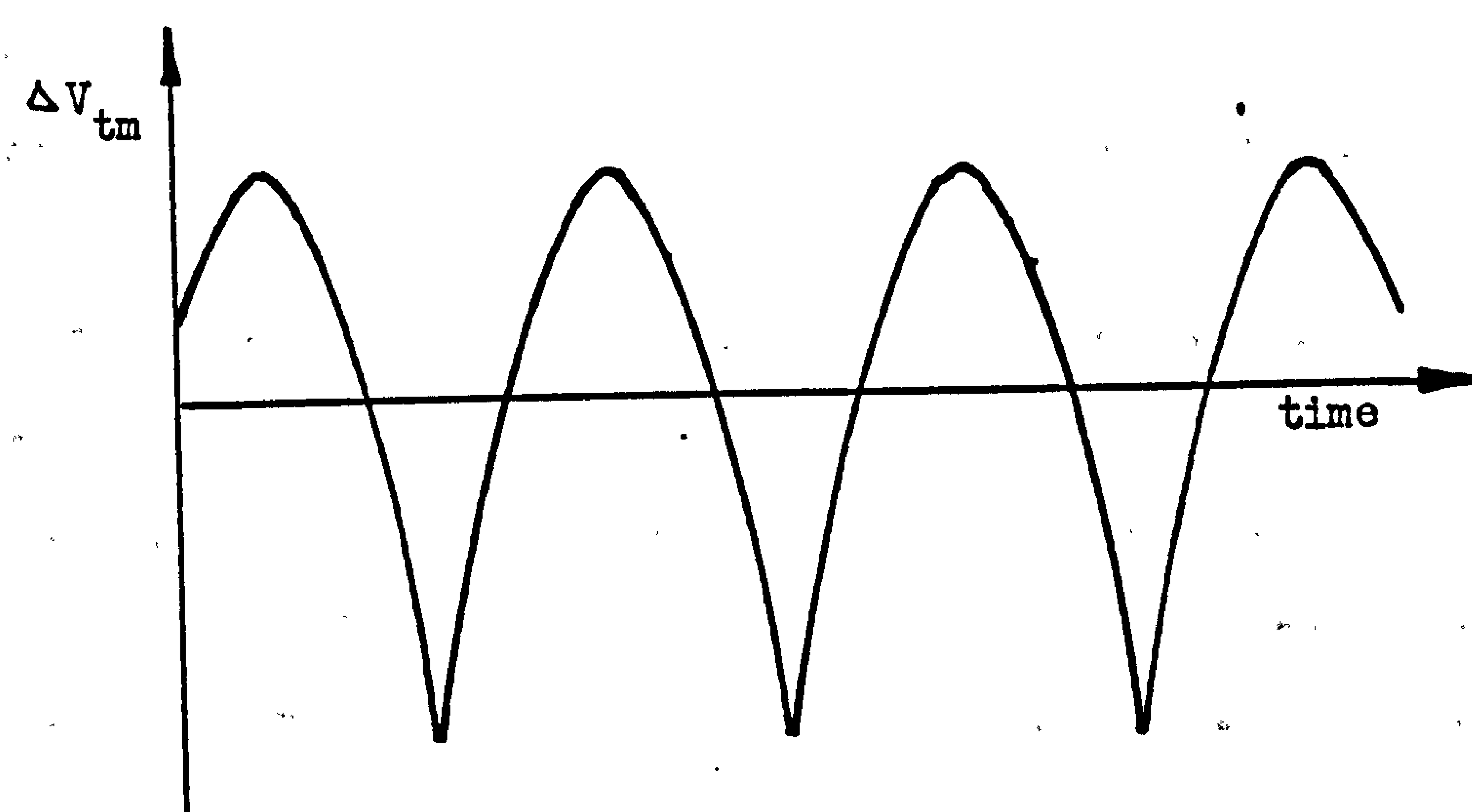


FIGURE 7.9 Reduction of cardiovascular noise with ensemble averaging

approximated with a full-wave rectified sine wave, figure 7.9b. A predetermined number of records of this waveform are averaged so that the reduction in the noise level, with the number of records in the ensemble, may be estimated. The noise level is expressed as a standard deviation of the signal from its mean . The phase of the waveform is varied randomly between records, as in the real situation.

The results of this analysis are shown in figure 7.10. In this figure, the mean standard deviation of a set of 10 ensemble averages is expressed as a ratio of the standard deviation of the waveform, and this is plotted against the number of records in a single ensemble. Also plotted is the theoretical reduction in the noise level, given as $1/\sqrt{N}$, where N is the number of records in the ensemble (appendix II). It may be seen from the graph that the experimental points cluster about this theoretical reduction and the results show, if anything, a noise reduction slightly better than given by the theory.

7.3.4 Further improvements in the signal to noise ratio

An improvement in the noise level resulting from the cardiovascular pulse, may be obtained by subtracting the pulse waveform from the TMD records prior to ensemble averaging. This is achieved by digitally deducting in phase cardiovascular pulses from those in the TMD records. Prerequisites of this method are:

i) A means of identifying and marking a specific point during the pulse cycle. This is used as a precursor to synchronize the phase of the prerecorded pulse

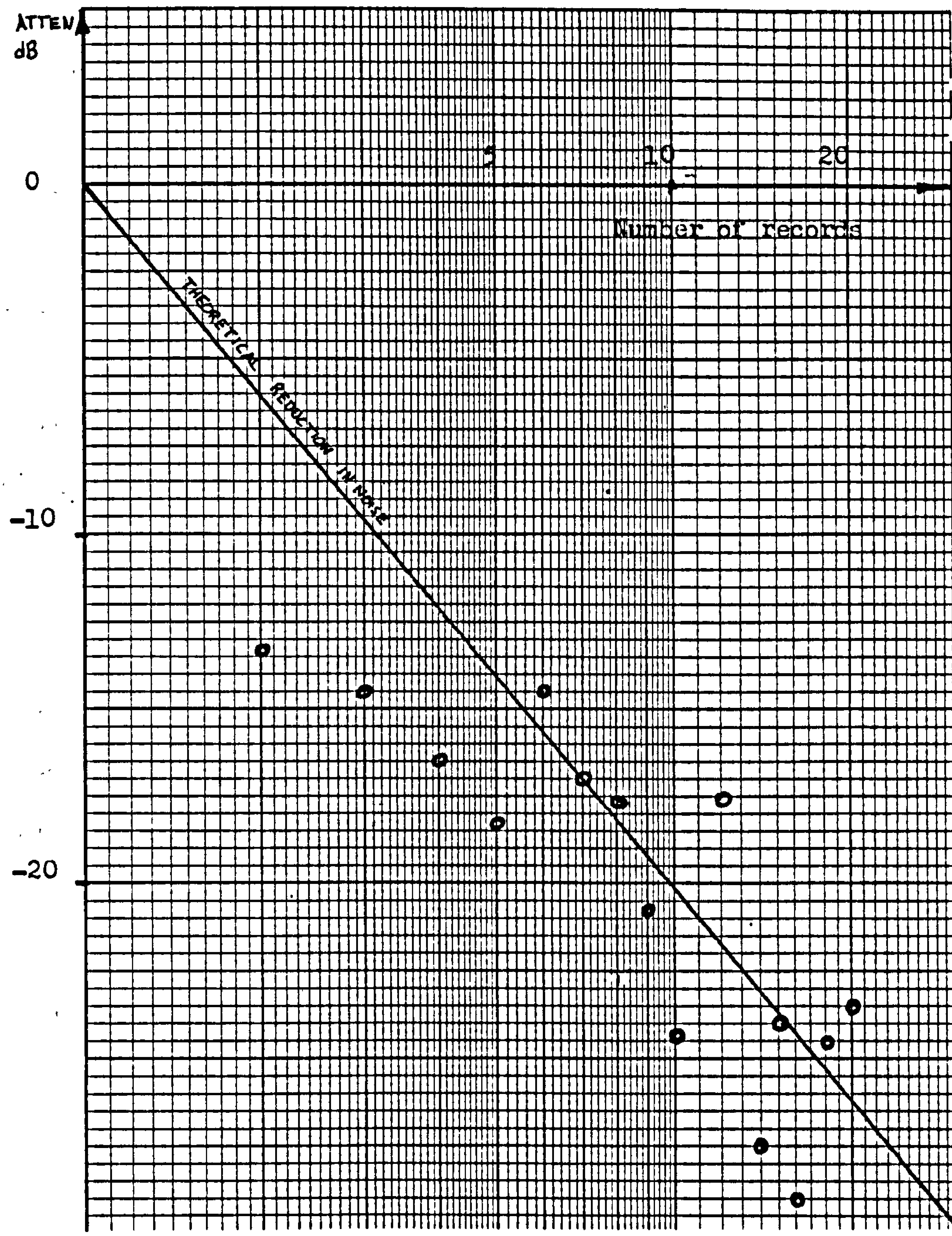


FIGURE 7.10 <u>The reduction of noise level on ensemble averaging simulated cardiovascular pulses</u>

with those in the TMD records.

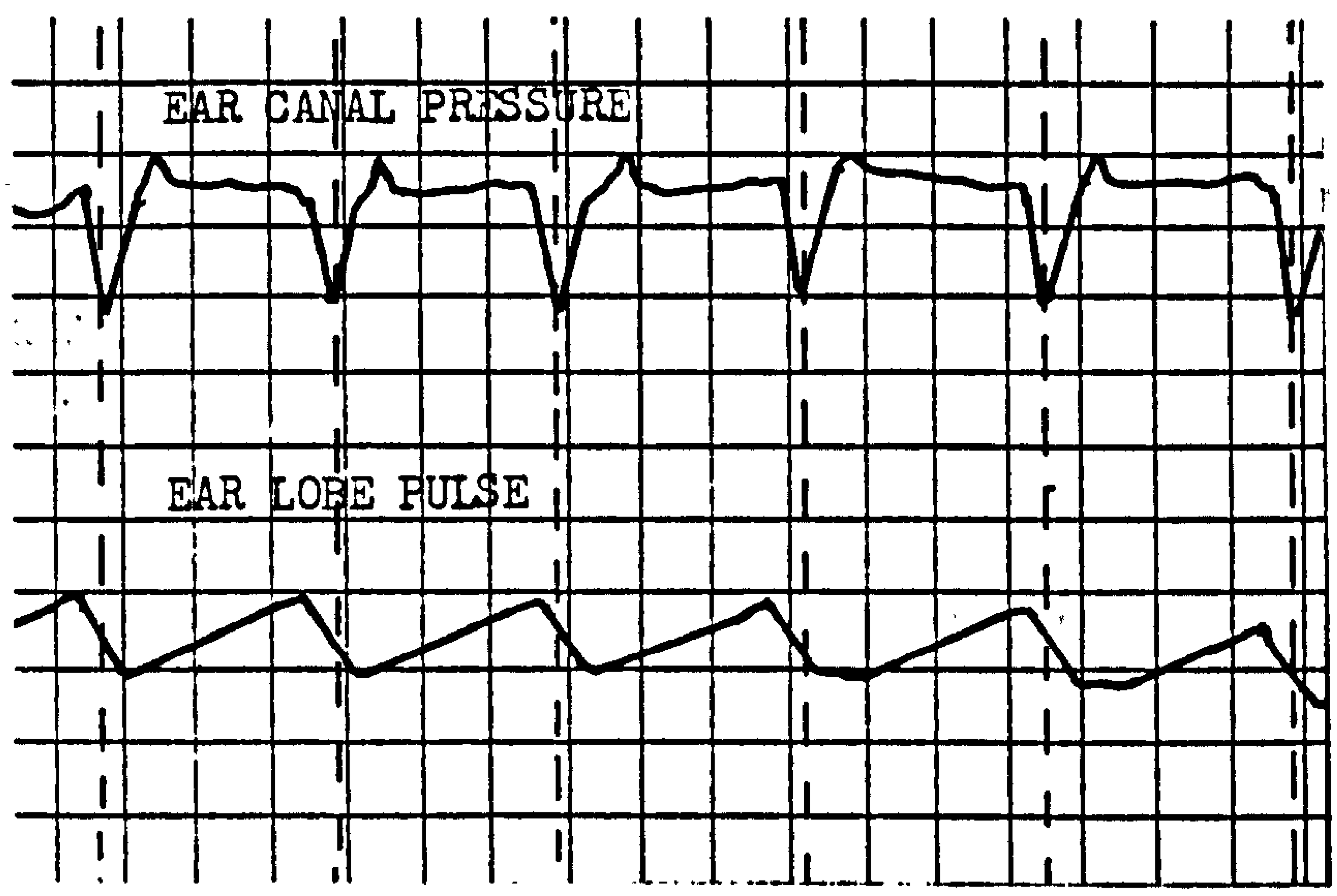
ii) A means of adjusting the period of the prerecorded pulse to equal those in the TMD records.

During the present investigation the precursor for synchronization was triggered at the position in the pulse cycle indicated in figure 7.11. This location is detected by a specially designed electronic circuit, which uses a differentiator to detect the zero slope of this triggering position, and a gating arrangement which rejects spurious synchronization precursors. There are several options for a source of the pulse suitable for triggering the precursor, the least favourable probably being from the ear canal itself, since any TM displacement interacts with the pulse recording. Other sources are from the ear lobe and electrocardiac activity. Examples of pulse traces from these are shown in figure 7.12.

Variations in the heart beat period dictate that the prerecorded pulse waveform must be tailored to fit the cardiovascular activity during the TM displacement recording. The inter-beat variations have been measured utilizing the pulse from the ear canal as well as an electrocardiograph. The results are tabulated in table 2 and indicate, for this small sample, that the standard deviation of the period varies from about 4 to 7 per cent of its total duration. One of the main causes of the variation in the pulse period, is the Sinus Arrhythmia (Womack 1971). This is a fluctuation in the instantaneous heartbeat rate which is dependent on the respiration cycle, such that the heart beat accelerates on inspiration and

FIGURE 7.11 <u>Synchronized pulse triggering from cardiovascular pulse</u>

a) Simultaneous traces of the ear-lobe pulse and pressure within the external ear canal. The ear-lobe pulse is measured using a Becton and Dickinson pulse monitor. This device incorporates an infra red source and sensor mounted either side of the ear lobe.



b) An electrocardiogram.

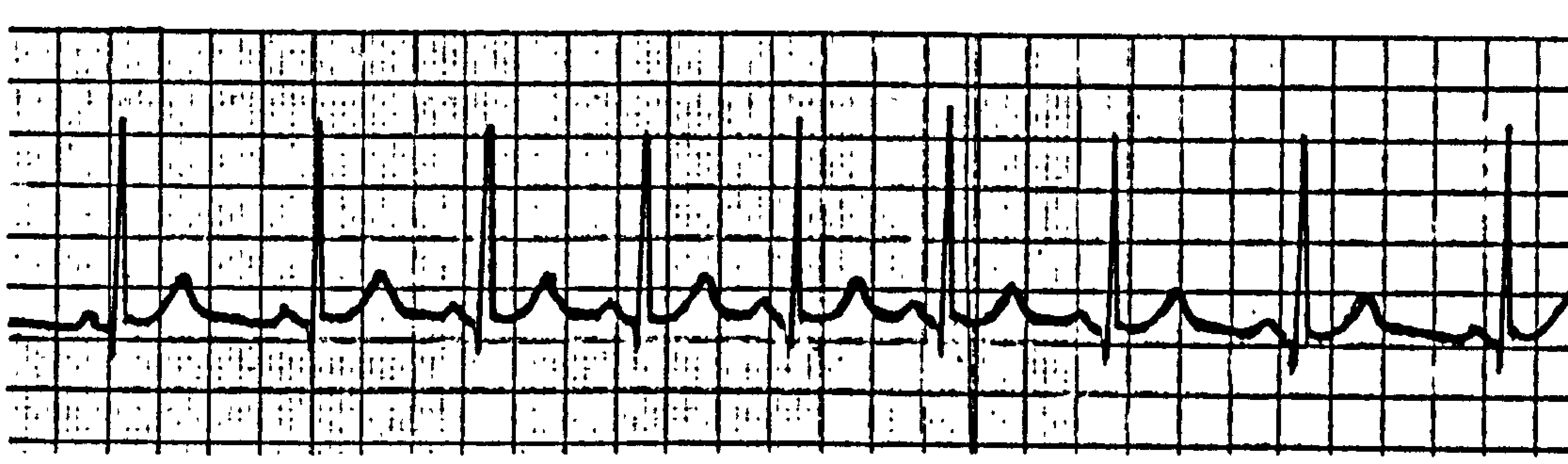


FIGURE 7.12 <u>Sources of a synchronization pulse</u>

TABLE 2 CARDIOVASCULAR ARRHYTHMIA

SUBJECT	NUMBER OF PULSES	STAND.DEV.% OF PERIOD	SOURCE OF PULSE
RM	150	6.2	Ear canal pressure
RM	138	4.6	Ear canal pressure
MJ	170	5.4	Ear canal pressure
CE	6	4.0	E.C.G.
CE	27	5.4	E.C.G.
CE	12	5.4	E.C.G.
CE	23	4.9	E.C.G.
RM	28	7.4	E.C.G.
JL	24	3.3	E.C.G.
JL	30	7.2	E.C.G.

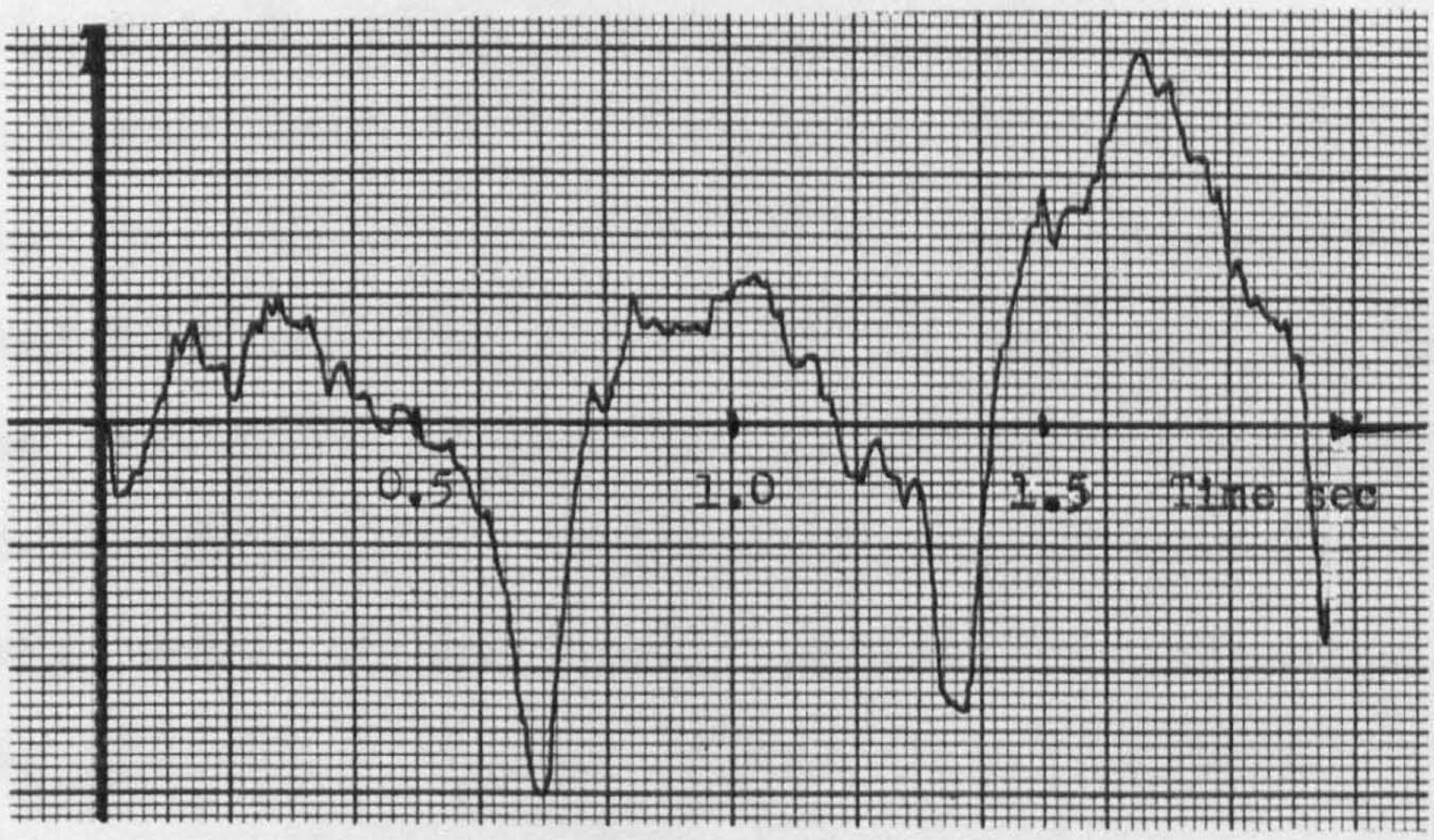
slows on expiration.

Experiments were performed on subject JM to determine the improvement in the ear canal noise level on subtraction of the cardiovascular pulse. Figure 7.13 shows a typical two second TMD record as well as similar prerecording. The result of deducting one from the other, as shown in this figure, is a reduction in the standard deviation of the noise by about 40 per cent, corresponding to a 4 dB improvement in the signal to noise ratio. This reduction in the noise level will vary between different subjects and ears, being dependent on the degree to which the cardiovascular activity contributes to the overall noise level.

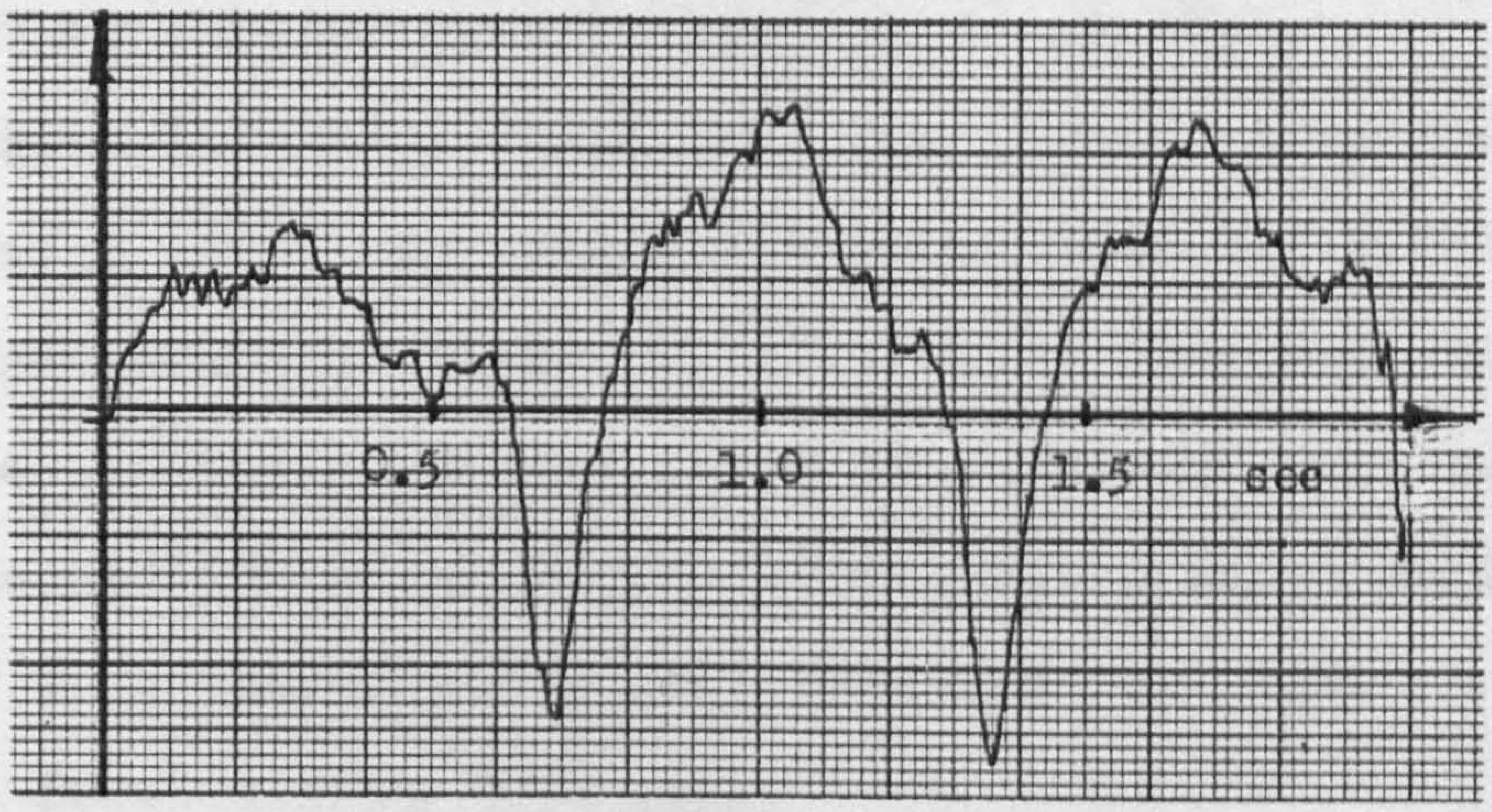
7.4 THE EXTERNAL EAR CANAL NOISE LEVEL AND ENSEMBLE AVERAGING

This section considers the variations of the external ear canal noise levels between different subjects. Also discussed is the effectiveness of the ensemble averaging technique as well as its time dependent characteristics.

a) A trace of the cardiovascular pulse.



b) Another trace in phase with a).



c) The result of subtracting trace a) from b).

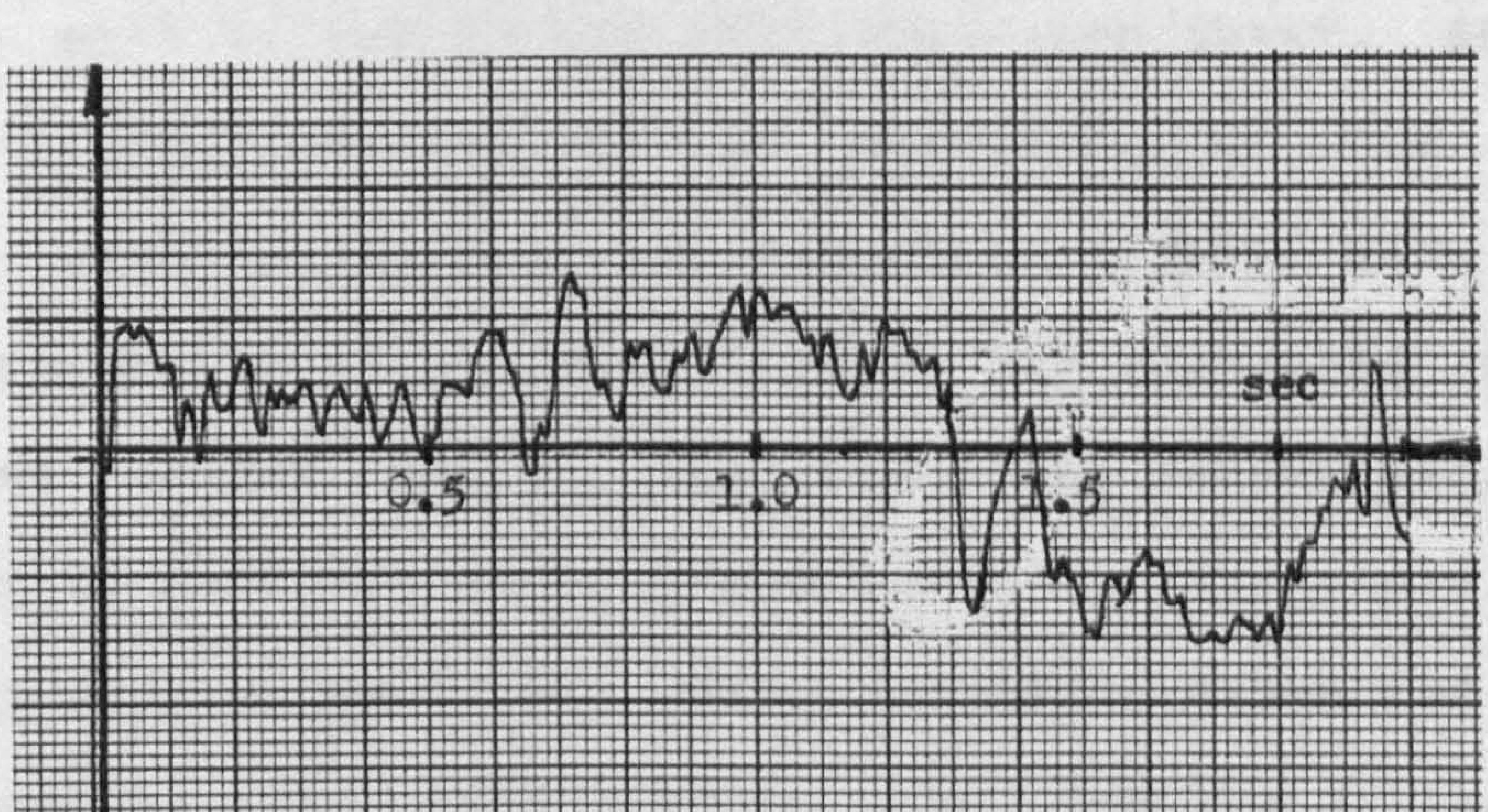


FIGURE 7.13 Subtraction of the cardiovascular noise

7.4.1 Inter-subject ear canal noise levels

The noise level in the external ear canal varies from subject to subject. The level of this noise has been obtained from the TMD plots, and is expressed as the value of the standard deviation of the noise, averaged over a period of one second. Table 3, lists 18 ears (9 subjects) and the mean noise level within the ear canal, for 80 records per ear. Figure 7.14 is a relative frequency histogram of these results, which shows a mean noise level of 130 nanolitres with a range of 61 to 308 nl.

Figure 7.15 is a plot of the noise level within a subject's left ear plotted against that in the right ear. It expresses the degree of correlation between the noise levels within opposite ears of subjects. The regression factor is 0.88 for a 1 to 1 correlation, which implies that there is a tendency for the subjects to have a similar noise level within both ears.

A large component of the noise within the external ear canal will be due to the cardiovascular noise. Andreasson et al (1978) investigated the magnitude of the vascular pulse with a number of subjects. They note that the pulsations are larger than normal for subjects who have serious otitis media, and that the pulsations are even larger in patients with glomus tumours. Therefore, greater than normal noise levels are possible signs of hearing dysfunction and furthermore, the results of the present investigation indicate that large discepancies between the noise in a subject's opposite ears should be a pointer to unilateral disorders.

TABLE 3 MEAN NOISE LEVEL IN THE EXTERNAL EAR CANAL

SUBJECT	RIGHT EAR	LEFT EAR	MEAN NOISE LEVEL 1 second period Nanolitres
EC	X		67
EC		X	87
CT	X		78
CT		X	67
JH	X		104
JH		X	147
JR	X		190
JR		X	227
KH	X		195
KH		X	308
JM	X		72
JM.		X	64
PC	X		61
PC		X	113
TJ	X		91
TJ		X	96
SL	X		197
SL		X	178

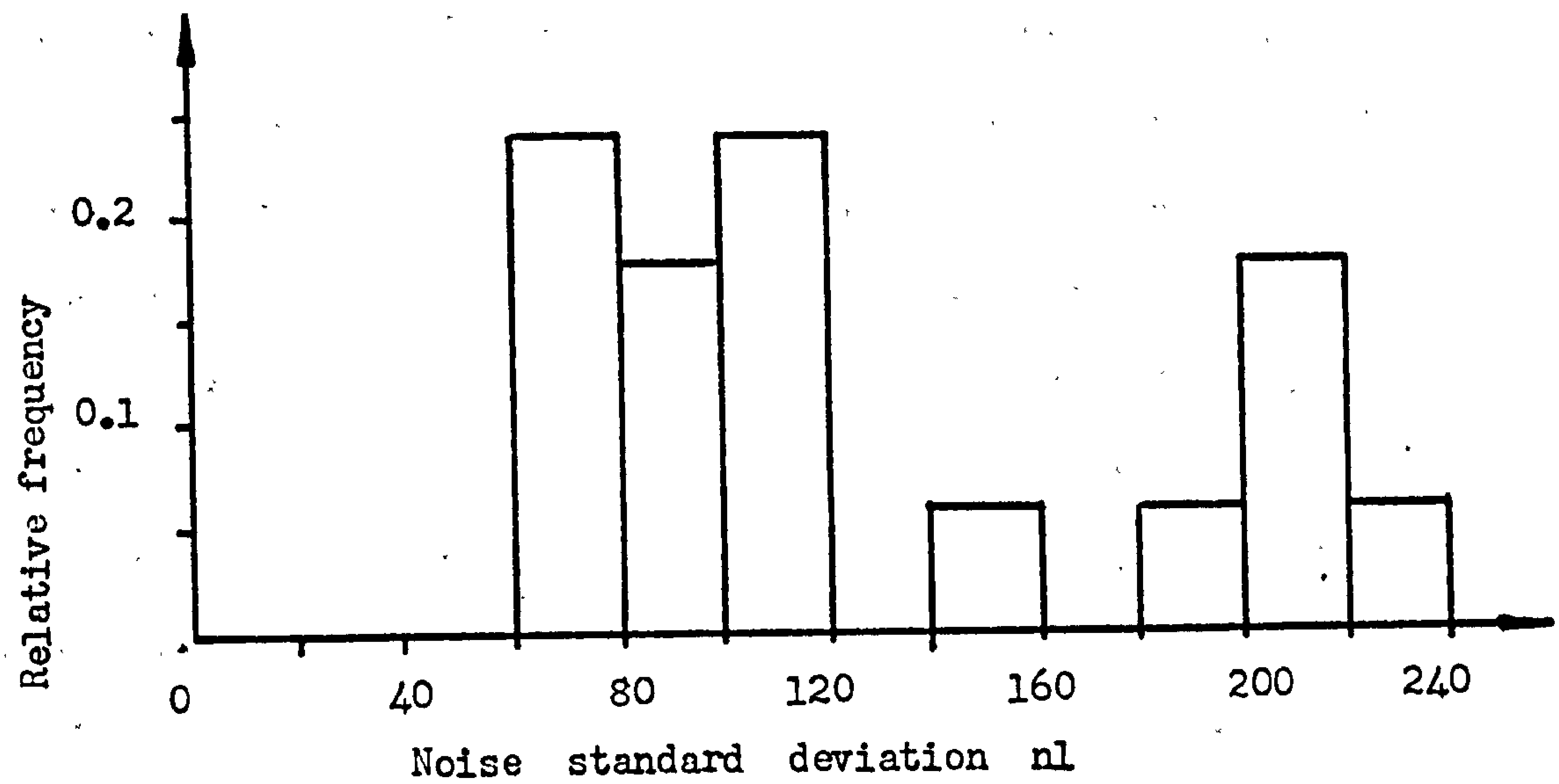


FIGURE 7.14 Relative frequency histogram of external ear canal noise levels A sample of 17 ears.

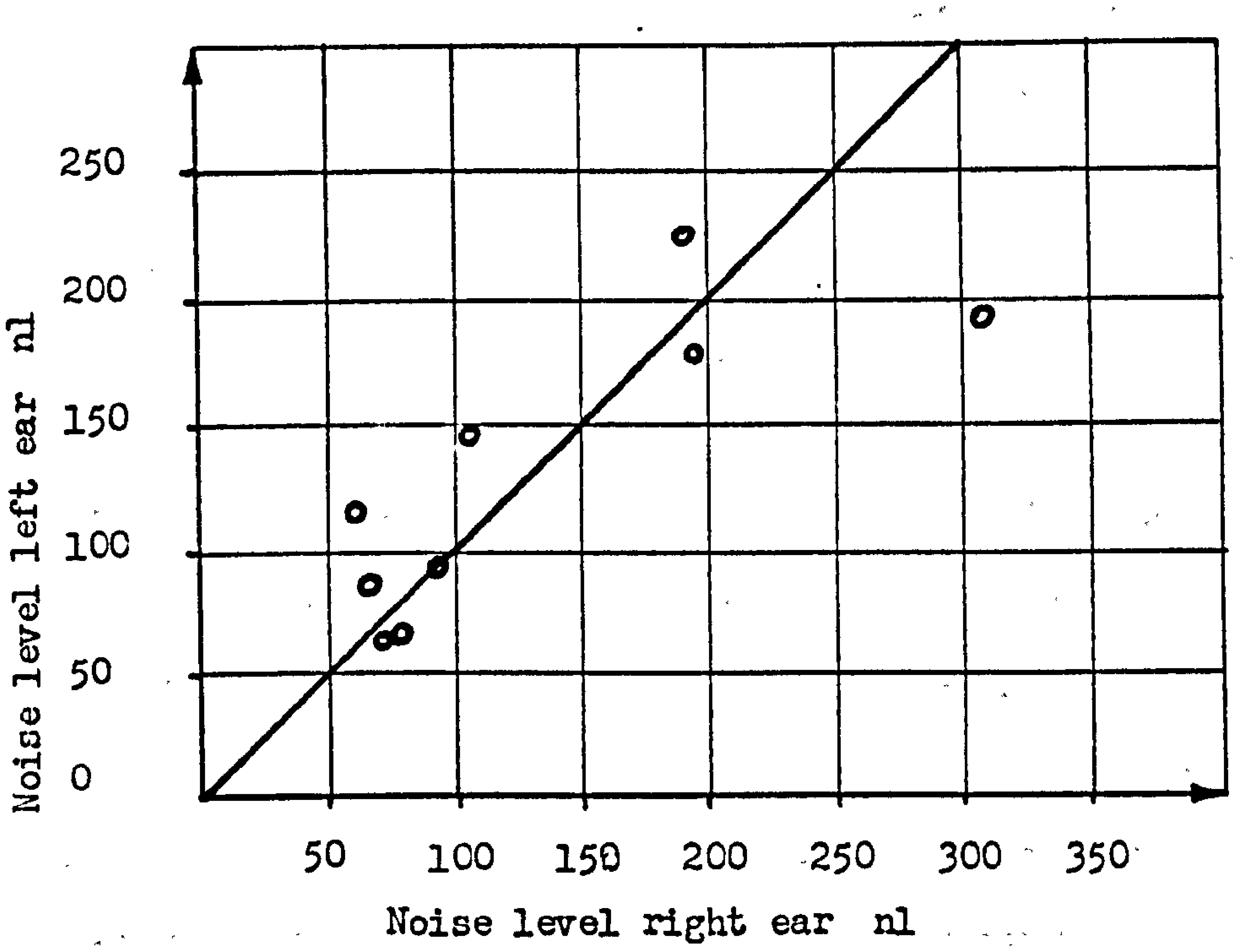


FIGURE 7.15 Correlation between noise levels in the subjects left and right ear canals From a sample of 9 pairs of ears.

7.4.2 Reduction of TMD noise with ensemble averaging

The theoretical improvement of noise level with ensemble averaging is $1/\sqrt{N}$, where N is the number of records in the ensemble (section 6.2.2). This assumes that all the records are independent of each other. However, a degree of correlation is expected between the TMD records due to very low frequency pressure noise (section 7.1). Such correlation will reduce the effectiveness of the ensemble averaging technique as demonstrated in the following analysis.

The alpha-numeric TMD system output was programmed to include values which give the time averaged mean and standard deviation of the control ensemble averages. These values were calculated for each increase in the number of records in the ensemble (as shown in figure III.3, appendix III). Of particular interest are the time averaged standard deviations which express the variation in the noise level with the number of ensemble records averaged. The actual noise level was estimated by drawing at random 20 sets of TMD results, chosen from a batch of values for 18 ears (9 subjects). The record length was 1 second. These results are plotted in figure 7.16 and are expressed as a proportion of the noise level before ensemble averaging. For comparison purposes, this figure also displays the noise levels for a different set of 20 TMD results. It may be seen that both sets are in fairly close agreement and show an actual noise improvement with ensemble averaging of consistently less than the theoretical, shown by the continuous line.

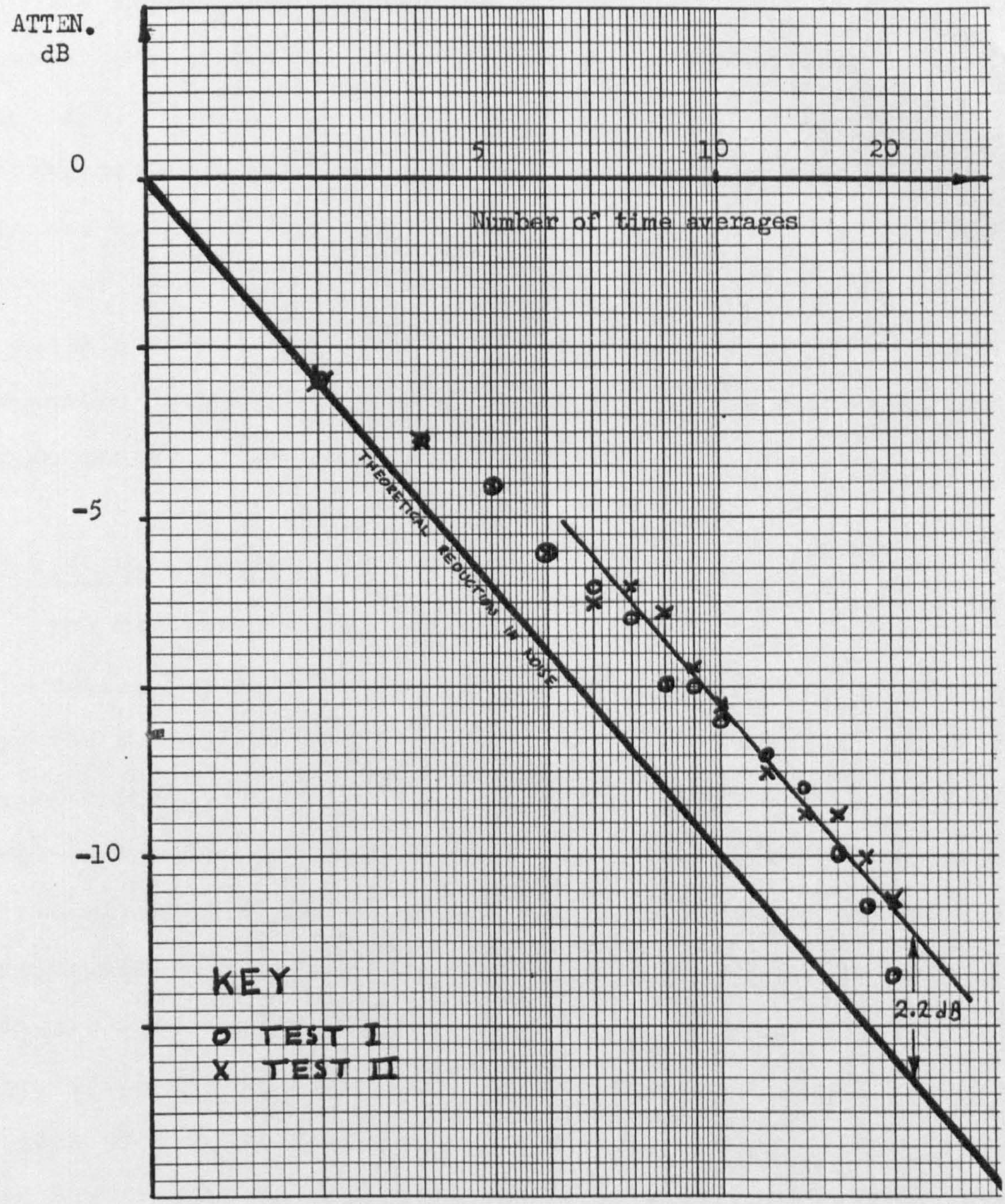


FIGURE 7.16 Reduction of noise level on ensemble averaging

The discrepancy between the actual and the theoretical noise level reductions, will vary between ears and from day to day, depending on the relationship of the atmospheric noise level to that of any other sources of noise present in the external ear canal. However on average, for between 10 and 20 records, the difference can be seen to be approximately 2.2 dB, that is an actual improvement with ensemble averaging of approximately 0.78 of that predicted theoretically for independent records (appendix II).

7.4.3 Time variance of the noise standard deviation

The TMD noise level, expressed as a standard deviation, increases with time to a steady state value. This is due to the removal of the quiescent component of the TMD signal (section 6.3.1), which has the effect of constraining both the ensemble average and the standard deviation to an initial value of zero. A comparison of constrained and unconstrained initiation of ensemble averaging is given in figure 7.17. The time taken for the noise standard deviation to reach a steady state value will depend on the shape of the noise power spectrum. The greater the power at low frequencies, then the longer the time required for a steady state to be achieved, see figure 7.18.

For sampling times of several seconds or more, the low frequency noise caused by local variations in atmospheric pressure have a dominating influence on the settling time of the standard deviation. In such cases, the deviation increases almost linearly with time without obtaining a steady state value. Figure 7.19 displays this

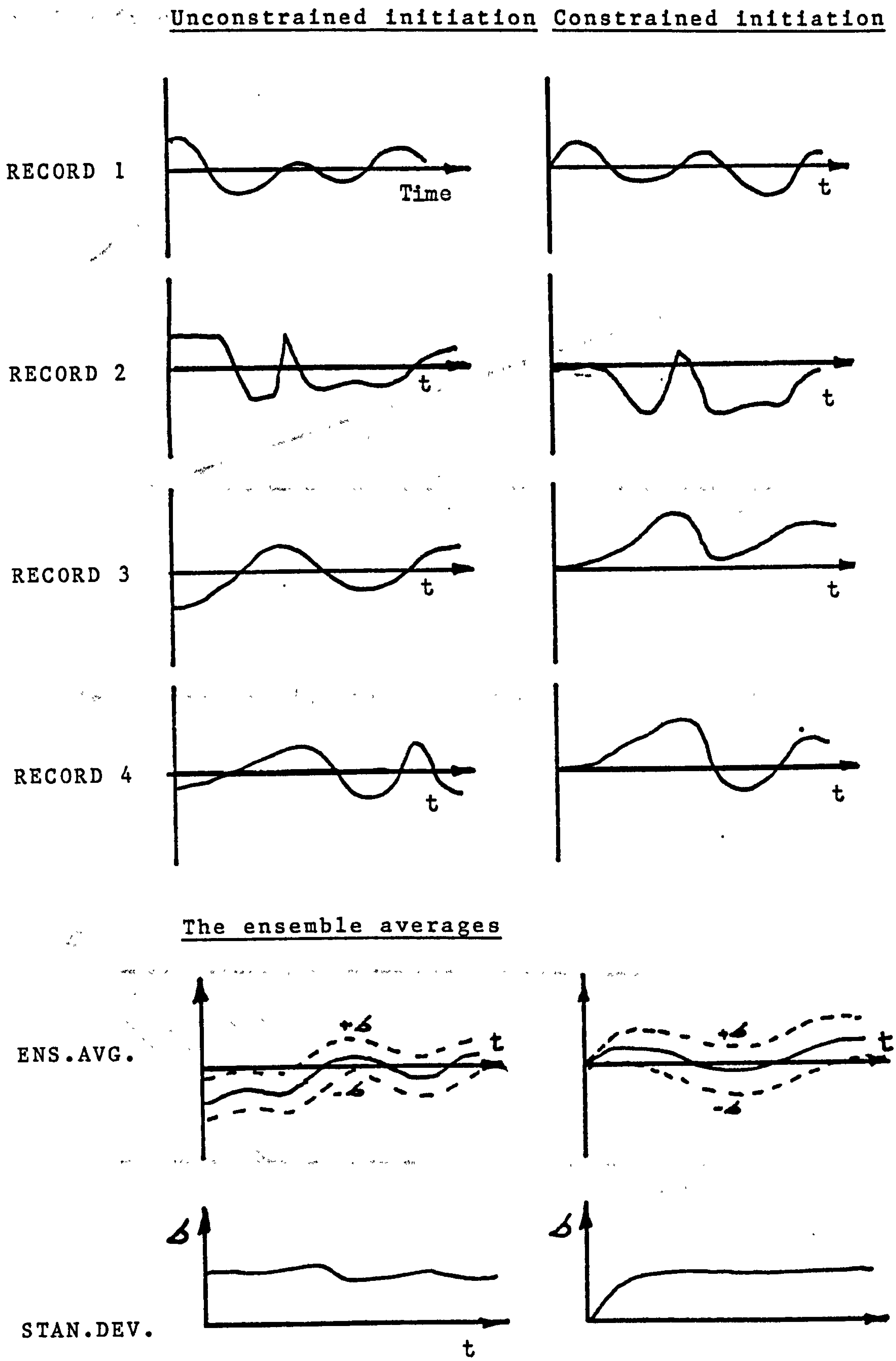
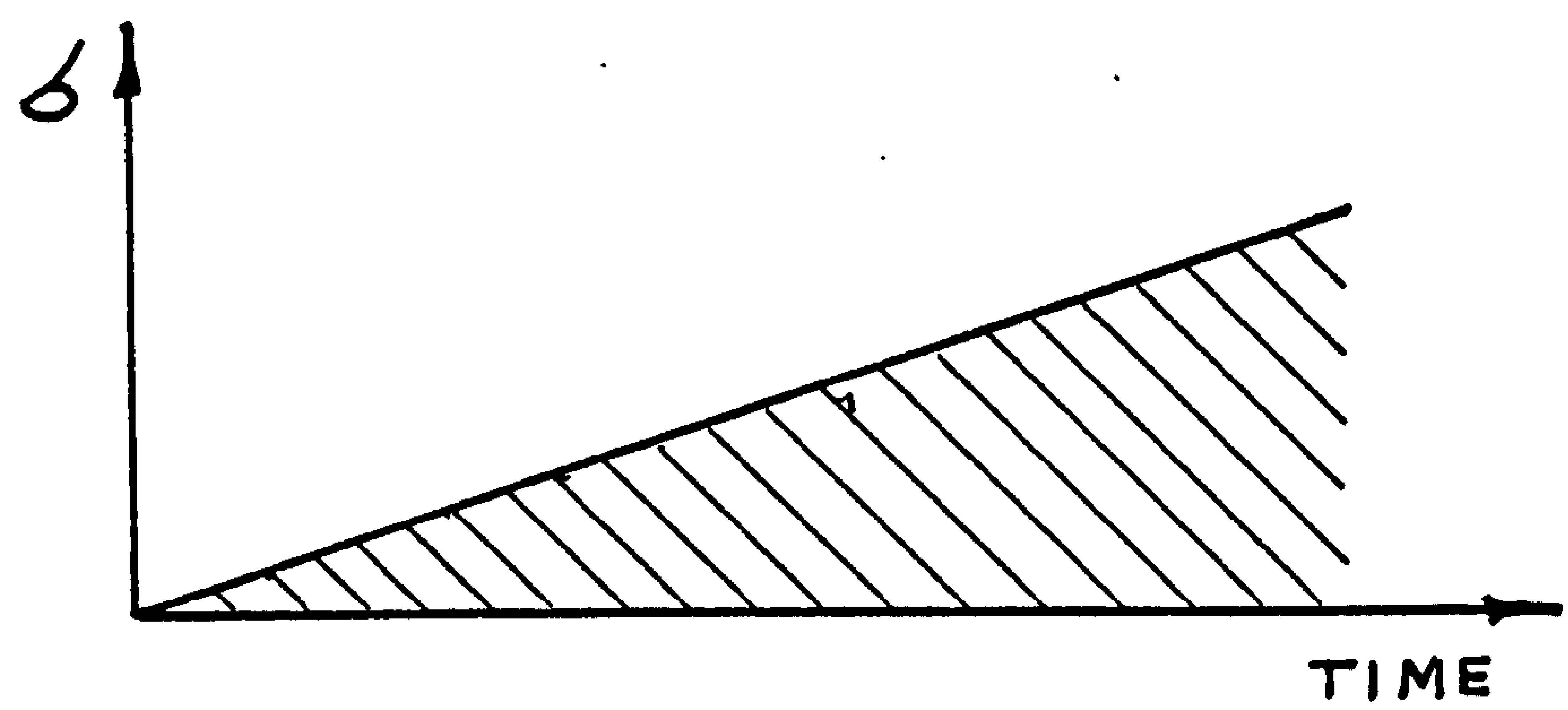


FIGURE 7.17 Removal of the quiescent component of the TMD records and the noise standard deviation

a) Low frequency dominance in the power spectrum



b) High frequency dominance in the power spectrum

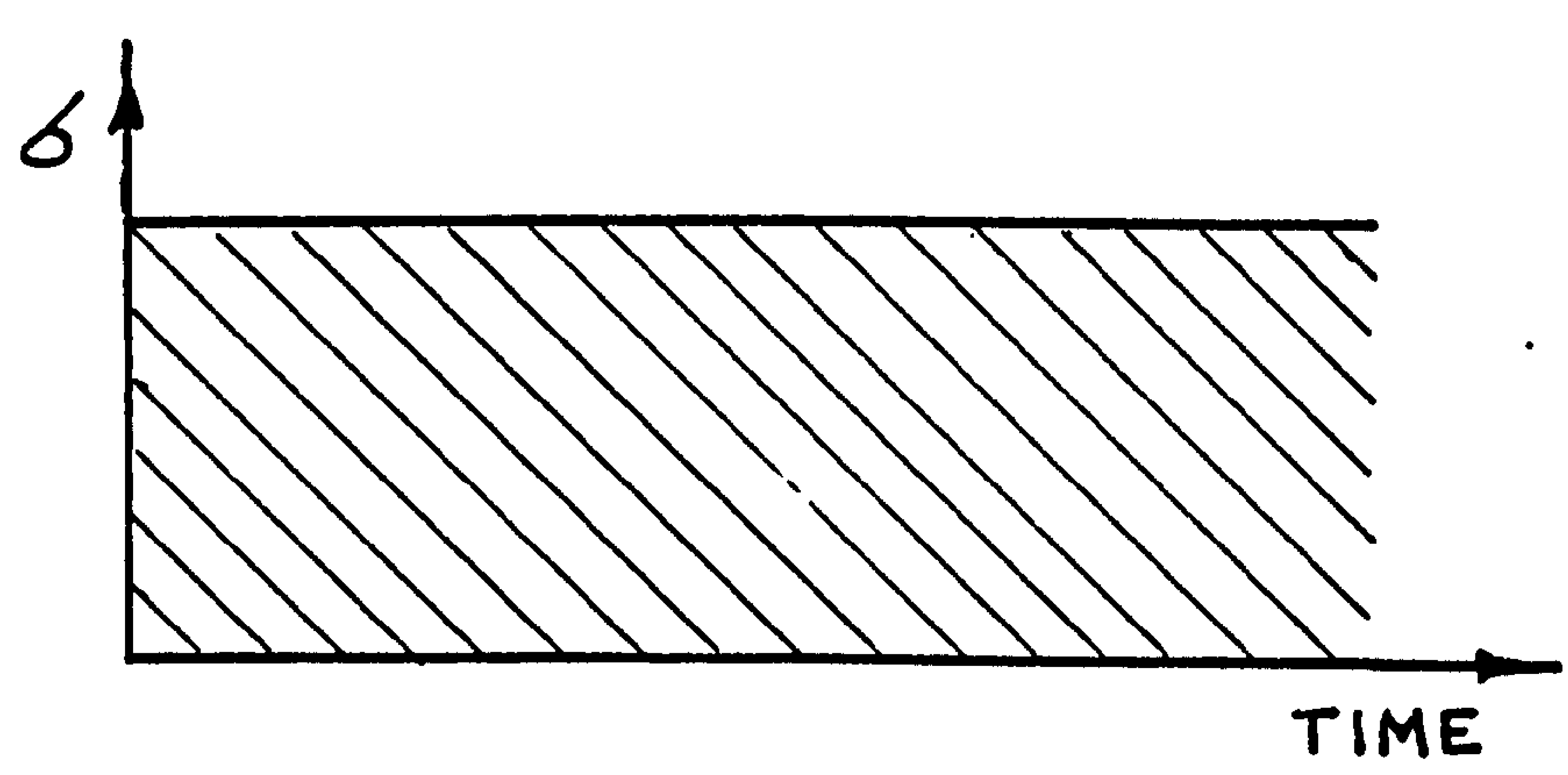


FIGURE 7.18 Variation of the noise standard deviation with time

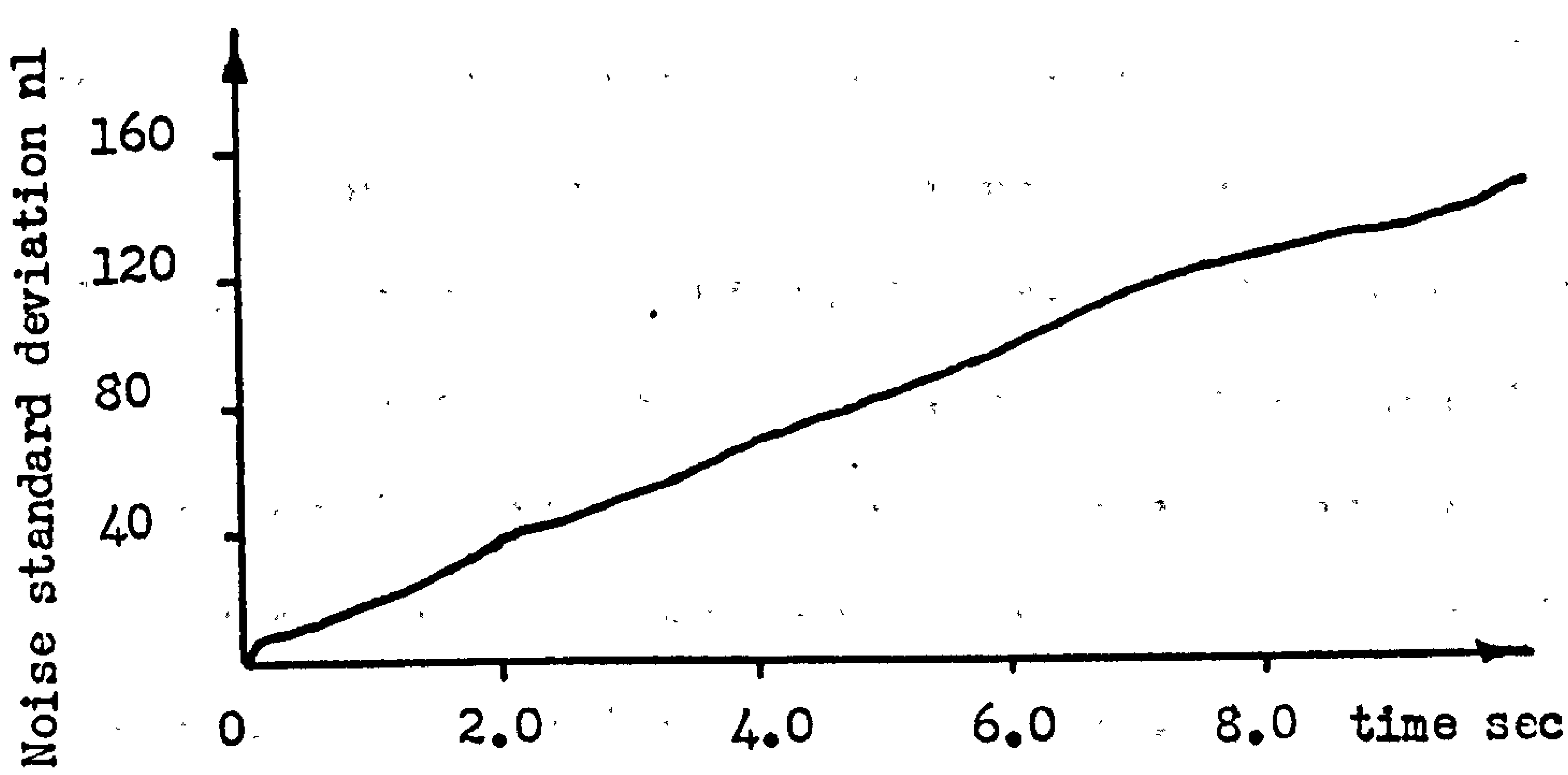
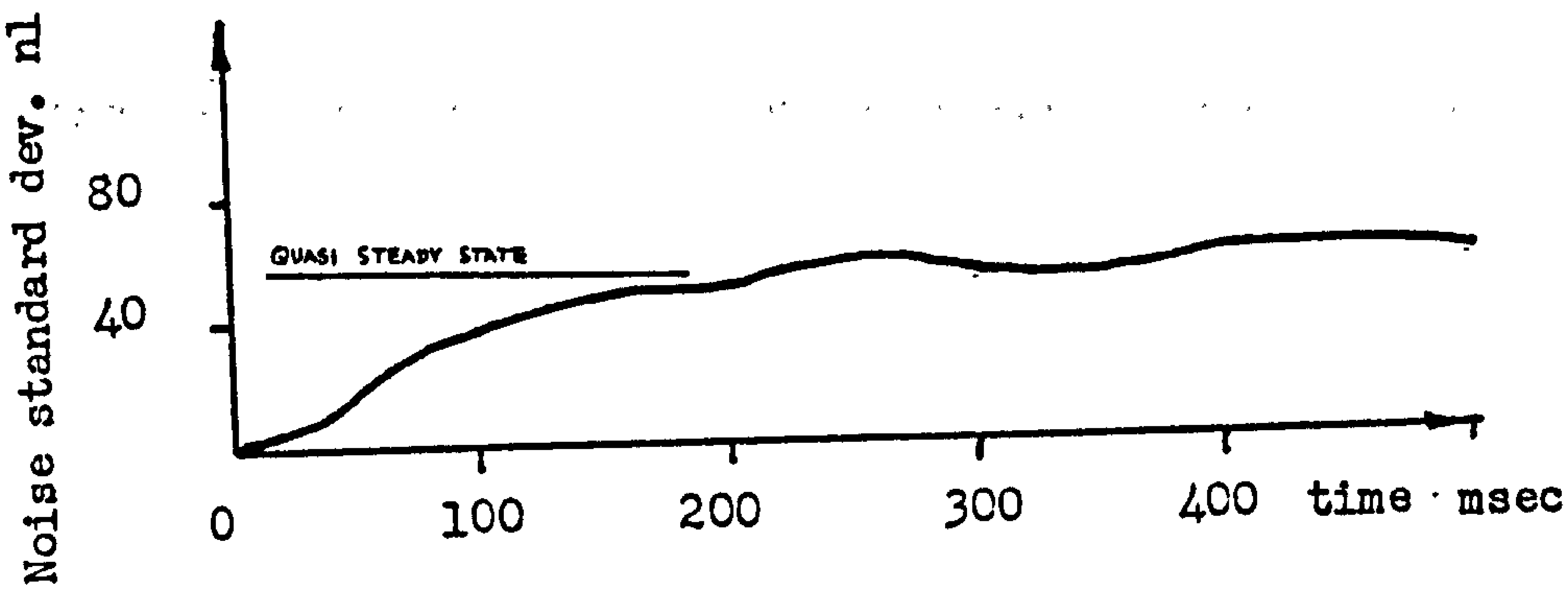


FIGURE 7.19 The noise standard deviation for predominant low frequency ambient pressure noise

characteristic for the ensemble average of 40 ten second records. These were obtained by sealing the TMD cavity at the ear cuff, so that the records show the noise induced by local atmospheric pressure variations. The rate of change of the standard deviation (measured on 2 separate days for 120 records), has a mean of 18 nanolitres per second, with a range of 16 to 24 nl/sec.

Samples of TM displacements of duration of a second or less are proportionately richer in higher frequencies than the previously considered records, which is mainly due to the cardiovascular noise. The tendency is, therefore, for the standard deviation to reach a quasi steady state within the period of the sample, shown in figure 7.20a. However, for a sample of a longer duration, figure 7.20b, it may be seen that after an initial rapid growth in the standard deviation, the deviation tends to increase linearly with time. This phenomenon is caused by a dominance of the low frequency noise, as previously discussed. The increase occurs with a mean rate of change of 24 nl/sec, with a range of 20 to 29 nl/sec (measured on 2 separate days for 120 records). Since there is a component of low frequency noise within the external ear canal, these values are slightly greater than the previously quoted values for the rate of change of the standard deviation with the TMD servo disconnected from the ear canal (section 7.1.2).

a) Noise measured over a short period obtains a quasi steady state condition.



b) Noise measured over a long period shows both characteristics of high and low frequency components.

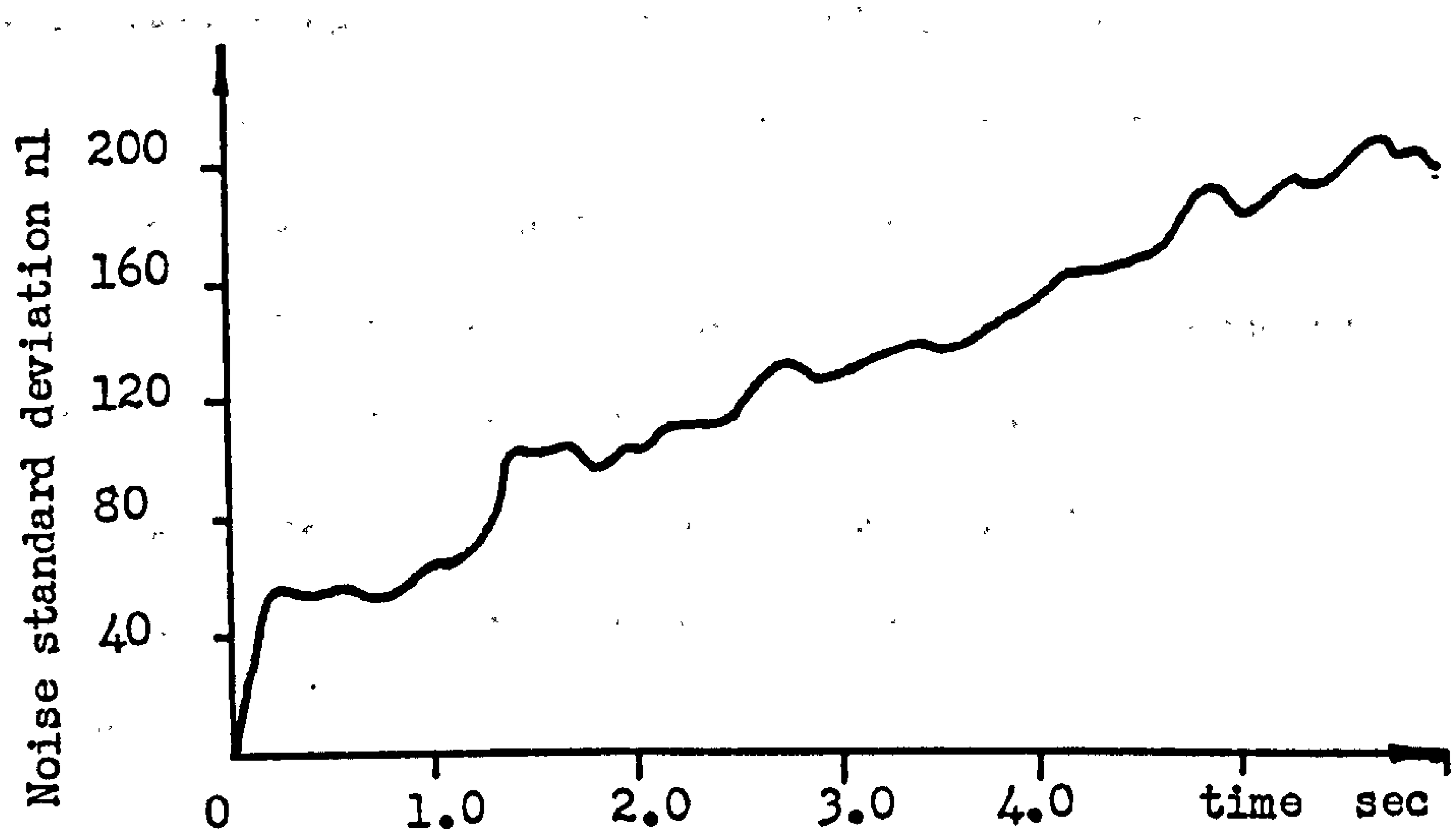


FIGURE 7.20 <u>The TMD standard deviation of the noise within the external ear canal</u>

CHAPTER 8

THE EUSTACHIAN TUBE FUNCTION AND THE TENSOR TYMPANI MUSCLE

8.1 INTRODUCTION

During the present research a small set of experiments was performed to measure the Eustachian tube function (chapter 2), and related physiological processes. The aims of these experiments were threefold. Firstly they were to study any contractions of the tensor tympani muscle which might accompany swallowing (chapter 2). Secondly, they examined the Eustachian tube function and commented on the feasibility of using the TMD system for such studies. The final objective was to study the feasibility of measuring the gas absorption rate from the middle ear also using the TMD system.

8.1.1 The Eustachian tube and middle ear pressure regulation

Most of the time, the middle ear forms a closed soft walled cavity having no connection with the air of the surrounding environment. Whilst closed, the gas mixture within the middle ear is continuously being absorbed into the walls of the cavity. This absorption results in a sub-atmospheric pressure being developed within the middle ear.

An equilibrium condition is maintained between the middle ear and atmospheric pressures by the Eustachian tube which intermittently ventilates the cavity to the surrounding environment. Elner (1977) remarks that the word ventilation should be used with reservations, since this term may imply a gross mixing of atmospheric air with the middle ear gases. In actual fact, the volume of the air which passes through the Eustachian tube is so minute, compared with the volume of the middle ear, that the opening is best considered as a pressure regulation rather than ventilation.

Regulation of the middle ear pressure occurs as a result of several different physiological processes. In a paper by Salén and Zakrisson (1978), the authors conclude that under normal conditions the middle ear will be ventilated by the opening of the Eustachian tube during, either yawning, belching or swallowing. Swallowing is the most frequent means of ventilation which occurs about 30 to 60 times an hour.

Controlled swallowing was used in the present experiments to study the Eustachian tube function, contractions of the tensor tympani muscle and the feasibility of measuring the middle ear gas absorption.

8.1.2 Present clinical methods of assessing the Eustachian tube function

Dysfunction of the Eustachian tube results in abnormal ventilation of the middle ear cavity. Failure of adequate ventilation is a very important factor in the promotion of middle ear pathologies (Misurya 1978). Consequently, a number of techniques have been developed which measure various characteristics of the Eustachian tube function. In the opinion of Bluestone (1975), tests which check the pressure regulation of the middle ear provide the optimum approach for establishing the normality of the Eustachian tube function. This process may be investigated clinically using the electroacoustic impedance bridge, by one or more of the following tests: 1) measuring the resting middle ear pressure, 2) inflation - deflation, 3) Toynbee and Valsalva manoeuvres.

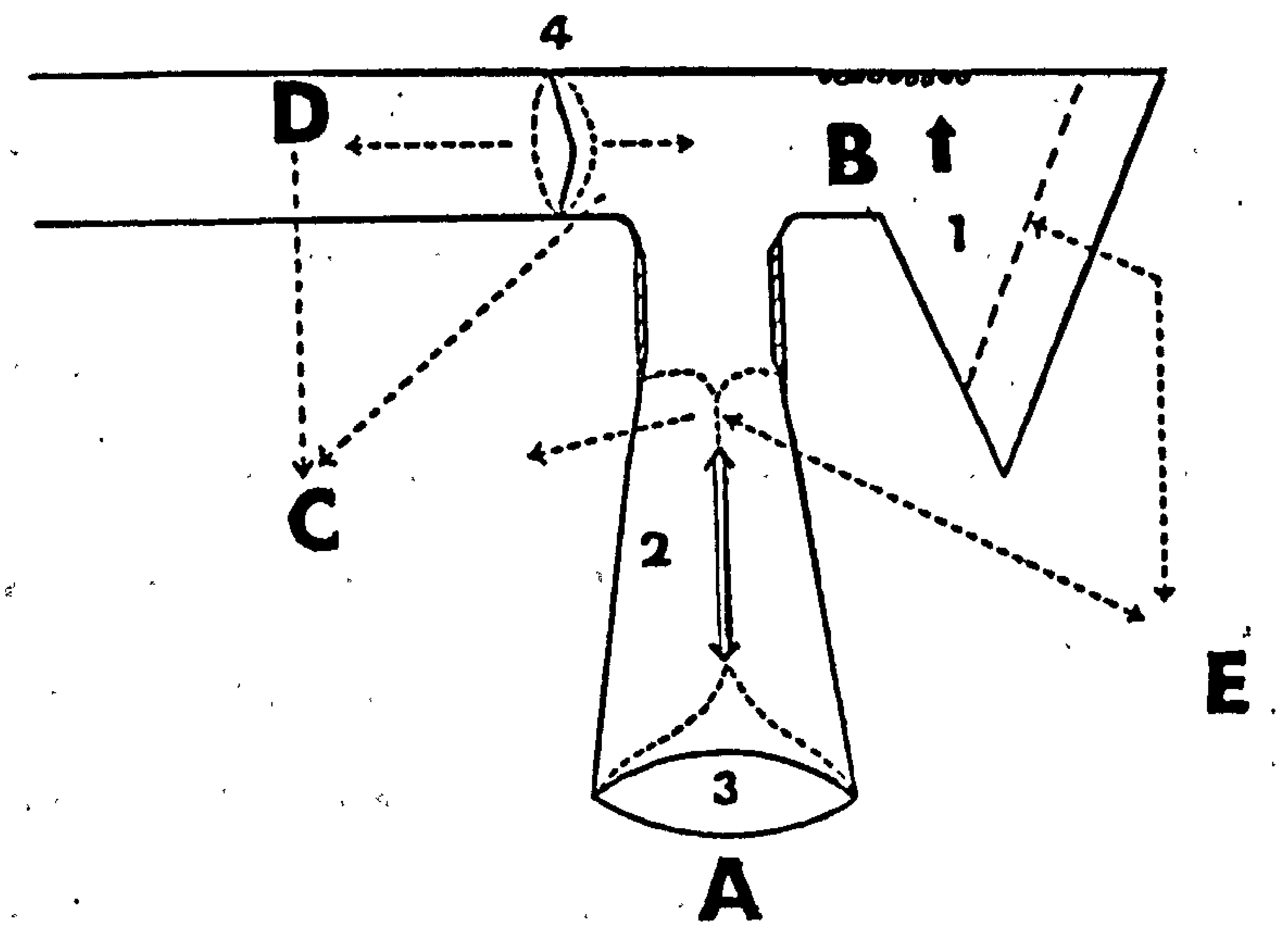
These methods are described in detail by Bluestone (1975).

8.1.3 Tympanic membrane displacement and the Eustachian tube function

Variations in the pressure or mass of the gas mixture within the middle ear, are reflected as movements of the tympanic membrane. Consequently, volume displacements of the TM may be used to investigate the ability of the Eustachian tube to ventilate the middle ear cavity. The relationship between the TM volume displacement and the middle ear pressure is the subject of a number of investigations. The exact form of this relationship is complicated due to the middle ear being effectively a 'soft walled' cavity (figure 8.1), as well as by the elastic properties of the tympanic membrane.

At the present time, the most accurate method of obtaining this pressure/ volume relationship is by using a technique, referred to by Ingelstedt et al (1967) as the 'direct method'. This method requires a free air passage from the middle ear space to a pressure measurement system, which involves surgical intervention such as puncturing of the TM or the mastoid process in man or the bulla of animals (Flisberg et al 1963). The technique normally used with human subjects is classified as the 'indirect method', which does not require surgical intervention, only that the TM is moveable and its displacement reflects the middle ear pressure.

Flisberg et al (1963), using a direct method, presented a graph of the volume displacement of the tympanic membrane against the volume of gas evacuated from the middle ear cavity for different cavity volumes, figure 8.2. In



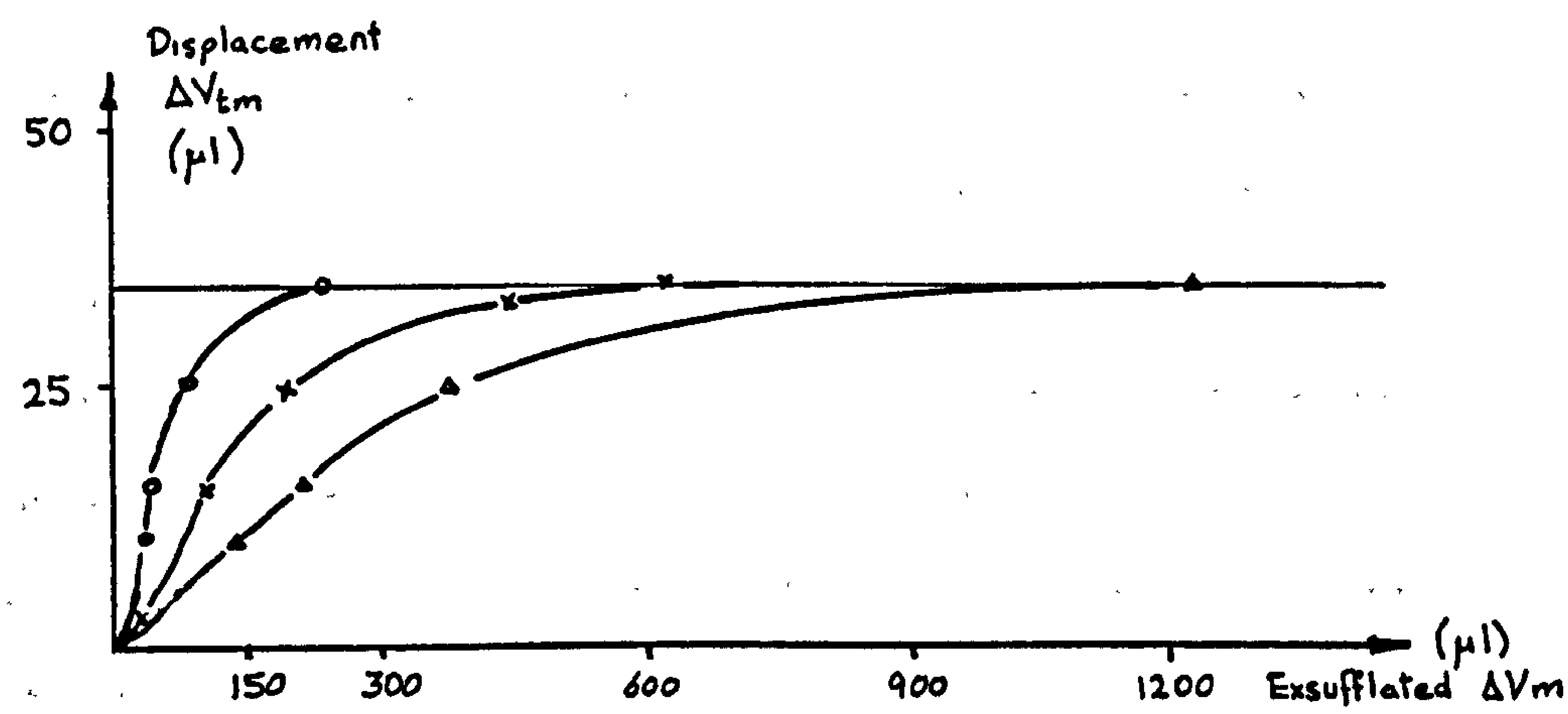
Main factors:
Tubal ventilation (A)
Gas diffusion (B)
Ear drum mobility (D)

Vacuum effects (C) on:
hearing
transudation
tubal "locking"

Accessory factors (E):
Variation in air space volume
Tubal factors:
secretion
surface tension
ciliary activity

(1. Air-filled ear space
2. Eustachian tube
3. Rhinopharynx
4. Ear drum)

FIGURE 8.1 Factors regulating the middle ear pressure
Flisberg et al (1963)



Middle ear air evacuation – drum volume displacement relation

1) o—o—o 3 ml. air space system
2) x—x—x 9 ml. " " "
3) Δ—Δ—Δ 18 ml. " " "

FIGURE 8.2 Volume displacement of the TM ΔV_{tm} for varying volume exsufflated from the middle ear cavity ΔV_m
Flisberg et al (1963)

calculating the points for this graph, they ignored the effect of a pressure increase causing an increase in the blood content and, therefore, volume of the vascular network of the mucosa. However, Ingelstedt and Jonson (1966) performed tests which tend to show that the blood volume content changes will only result in a 3 to 8 per cent error. Figure 8.2 is used later in this chapter to relate the TM volume displacement to changes in the specific volume of the gas within the middle ear cavity.

8.2 STUDY OF THE TYMPANIC MEMBRANE DISPLACEMENT DURING SWALLOWING

The TMD system method of studying the Eustachian tube function is classified as 'indirect' because no direct access to the middle ear cavity is required. To the author's knowledge, there are no publications which specifically relate to the magnitude of TM volume displacement during swallowing, and any consequential opening of the Eustachian tube. However, some quantitative information on the tensor tympani reflex, swallowing, and the Eustachian tube function is given in the following section.

8.2.1 Quantitative data on the tensor tympani reflex and the Eustachian tube function

Previous studies of the physiology of the Eustachian tube and the tensor tympani reflex have been discussed in chapter 2. However, there is a scarcity of quantitative data on displacements of the tympanic membrane resulting from these processes. Some data are given in a paper by Ingelstedt and Jonson (1966), who during experiments observed spontaneous contractions of the tensor tympani muscle which sometimes result in the opening of the Eustachian tube. Their examples of this are shown in figure 8.3. They estimated, with a sample of 8 subjects, that the mean volume displacement of the TM resulting from this contraction was 7.6 microlitres with a range of 6.0 to 8.5 microlitres. These data provide the order of magnitude of TM displacement resulting from contraction of the tensor tympani muscle. There is not, however, any evidence to suggest that the tensor tympani will cause the same volume displacement as a result of swallowing.

Salén and Zakrisson (1978), in their studies of the electromyograph activity of the tensor tympani muscle during swallowing, provide more relevant information. These investigators 'note that swallowing was always accompanied by EMG activity which had a duration of about 300 msec.

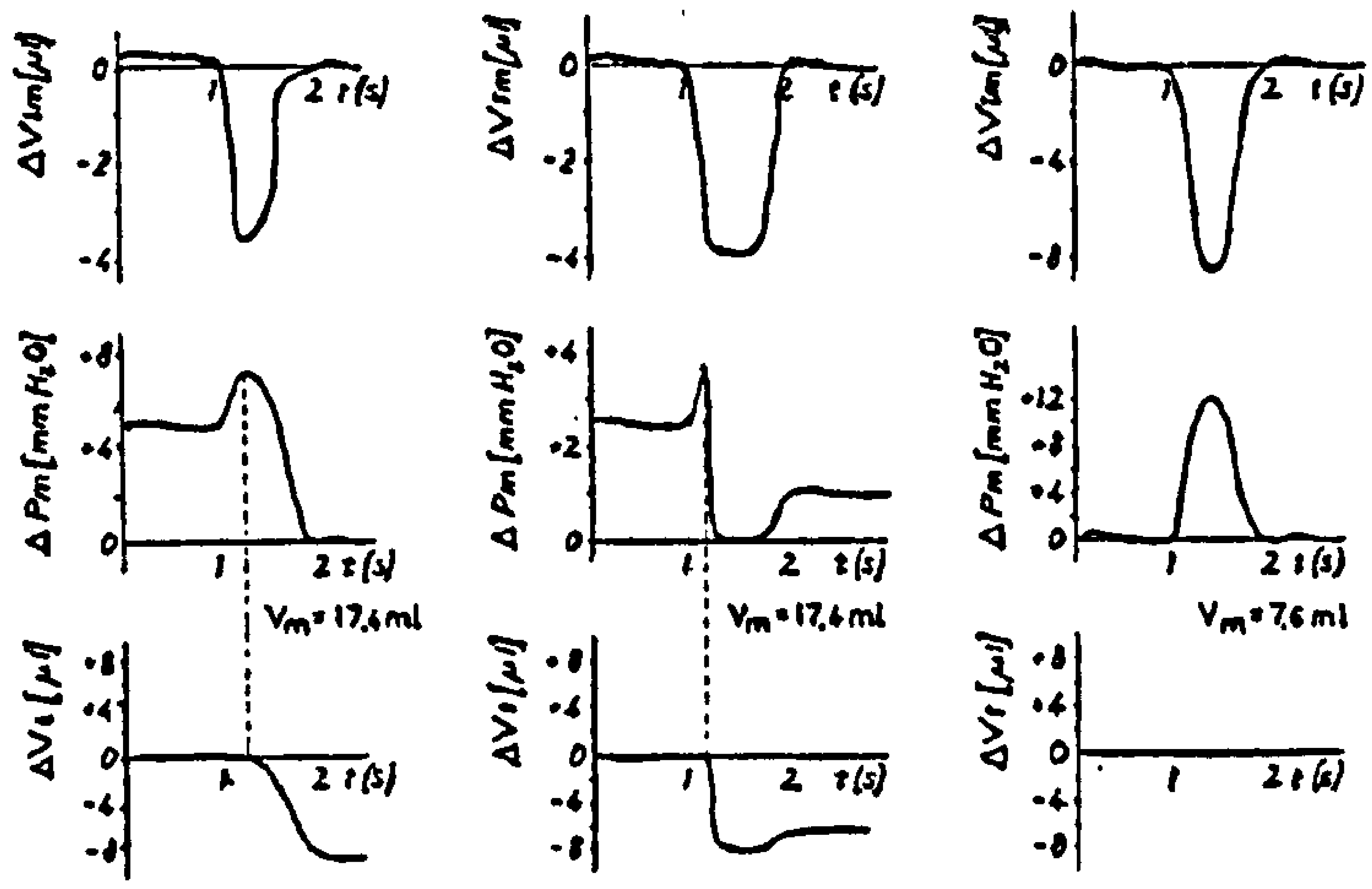


FIGURE 8.3 Tympanic membrane displacement ΔV_{tm} and the middle ear pressure changes induced by contractions of the tensor tympani muscle
On the tracing to the left and in the middle of the figure the tube opens during tensor contractions, to the right the tube remains closed. From Ingelstedt and Jonson (1966)

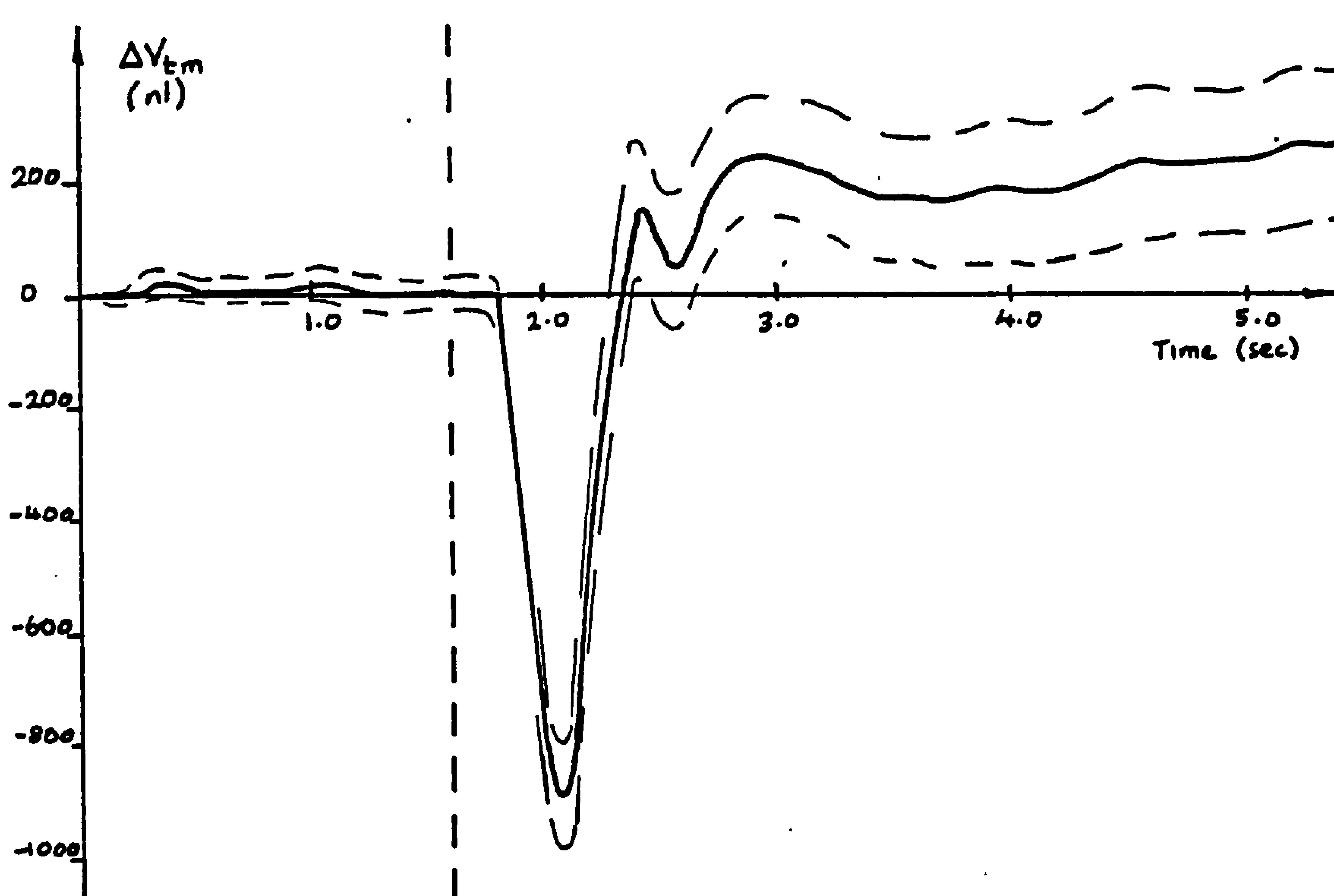


FIGURE 8.4 The TM displacement during swallowing: I Subject JM

8.2.2 Method of obtaining TMD records during swallowing

The swallowing experiments of the present investigation, were performed using the standard TM displacement programme as described in appendix III, which was set to produce displacement records of a 6 second duration. A stimulus of intensity well below the reflex threshold was presented for 2 seconds at the beginning of each record, and the subject was instructed to swallow when the stimulus stopped. This was repeated 10 times to yield 10 records for the ensemble average. Such prompting of the subject's swallowing allowed coherent summing of the TM displacement resulting from the opening of the Eustachian tube. The duration of the interstimuli interval was 60 seconds, which was chosen to correspond to a fairly typical rate of swallowing. Only normal hearing subjects (appendix IV) were used for the swallowing experiments. Some of these subjects were instructed to swallow normally during the tests, whilst others swallowed water from a beaker.

8.2.3 Discussion of results

The results of the swallowing experiments, obtained from a small sample of 5 subjects, consistently show that the tympanic membrane moves rapidly inwards on the initiation of the swallow. This pulse like characteristic, shown in figure 8.4, has a duration of up to one second, and according to several authorities is due to contraction of the tensor tympani muscle (Misurya 1978; Kamerer and Rood 1978). The magnitude of this inward displacement was studied in detail for subject JM, both for swallowing dry and with water. This subject's results indicate a peak inward displacement of 650 nl (mean of 20 swallows) for swallowing dry and 1100 nl (mean of 40 swallows) for swallowing with water. This inward displacement, presumably due to contraction of the tensor tympani muscle, is up to 3 times greater than the maximum displacement caused by the stapedius reflex of this subject (105 dB HL, 500 Hz).

Also shown in the swallow records (figure 8.4), is a variation in the resting position of the tympanic membrane before and after the swallow. This is due to the equilibration of any ambient or gas absorption pressure differentials across the TM, which occurs on the opening of the Eustachian tube. As mentioned later in section 8.3, with certain precautions this phenomenon may be used to estimate the rate of gas absorption from the middle ear.

8.2.4 Concluding comments

Results presented in this section are little more than a cursory look at the tensor tympani reflex and the Eustachian tube function. However, the results are sufficient to prove the viability of studying swallowing and the Eustachian tube function with the TMD system. The method adopted for the present study of prompting the subject to swallow at a desired instant, is not precise enough to ensure that the records of the ensemble are summed coherently. An improvement in the coherence and therefore ensemble resolution, may be achieved by detecting the time of peak TM displacement, and using this as a cursor for the summing of the records.

Ingelstedt et al (1967) commented on the importance of tympanic membrane displacement studies for providing data on the dysfunction of the Eustachian tube. It is felt that useful information may be obtained from further studies of the Eustachian tube with the TMD system.

8.3 FEASIBILITY OF USING THE TMD SYSTEM TO STUDY THE RATE OF GAS ABSORPTION FROM THE MIDDLE EAR CAVITY

The rate of gas absorption from the middle ear was not measured during the present research. However, the feasibility of doing so with the TMD system is discussed in the following sections. An interesting finding of this study is that middle ear pressure fluctuations, caused by gas absorption, are of a similar magnitude as drifts in the ambient pressure. The implication of this is that, in normal ears the Eustachian tube function plays an equally important role in compensating for ambient pressure variations, as for equilibrating the effects of gas absorption.

8.3.1 Previous studies of gas absorption rates from the middle ear.

The middle ear gas absorption has been studied by a number of investigators. Riu et al (1966) found the gas absorption to be 0.8 ml daily, Ingelstedt and Jonson (1966) 1 to 2 ml and Elner et al (1971c) 0.7 to 1.1 ml daily. Results from these investigations consistently indicate that the normal rate of gas absorption from the middle ear is about 1 ml per day.

8.3.2 Using the TMD system to measure the gas absorption rate

With reference to data obtained by Flisberg et al (1963), figure 8.2, it may be estimated that the normal 1 ml per day rate of gas absorption, corresponds to an average rate of TM displacement ranging from 0.8 to 4.3 nl per second, depending on the middle ear cavity volume.

Fundamental to obtaining the gas absorption rate, is that it must be distinguishable from long term pressure variations. It is stated in section 7.1.3 that the pressure measured over a period of a day may vary at a rate of up to 0.023 to 0.069 N/m^2 per second. From a graph given by Ingelstedt and Jonson (1966), figure 8.5, the TM displacement with ambient pressure is approximately 12 nl per N/m^2 ($0.12 \mu l/mmH_2O$). Therefore, the TM displacement as caused by long term ambient pressure variations is approximately 0.3 to 0.8 nl per sec, which is unfortunately of the same order of magnitude as the rate of displacement caused by gas absorption.

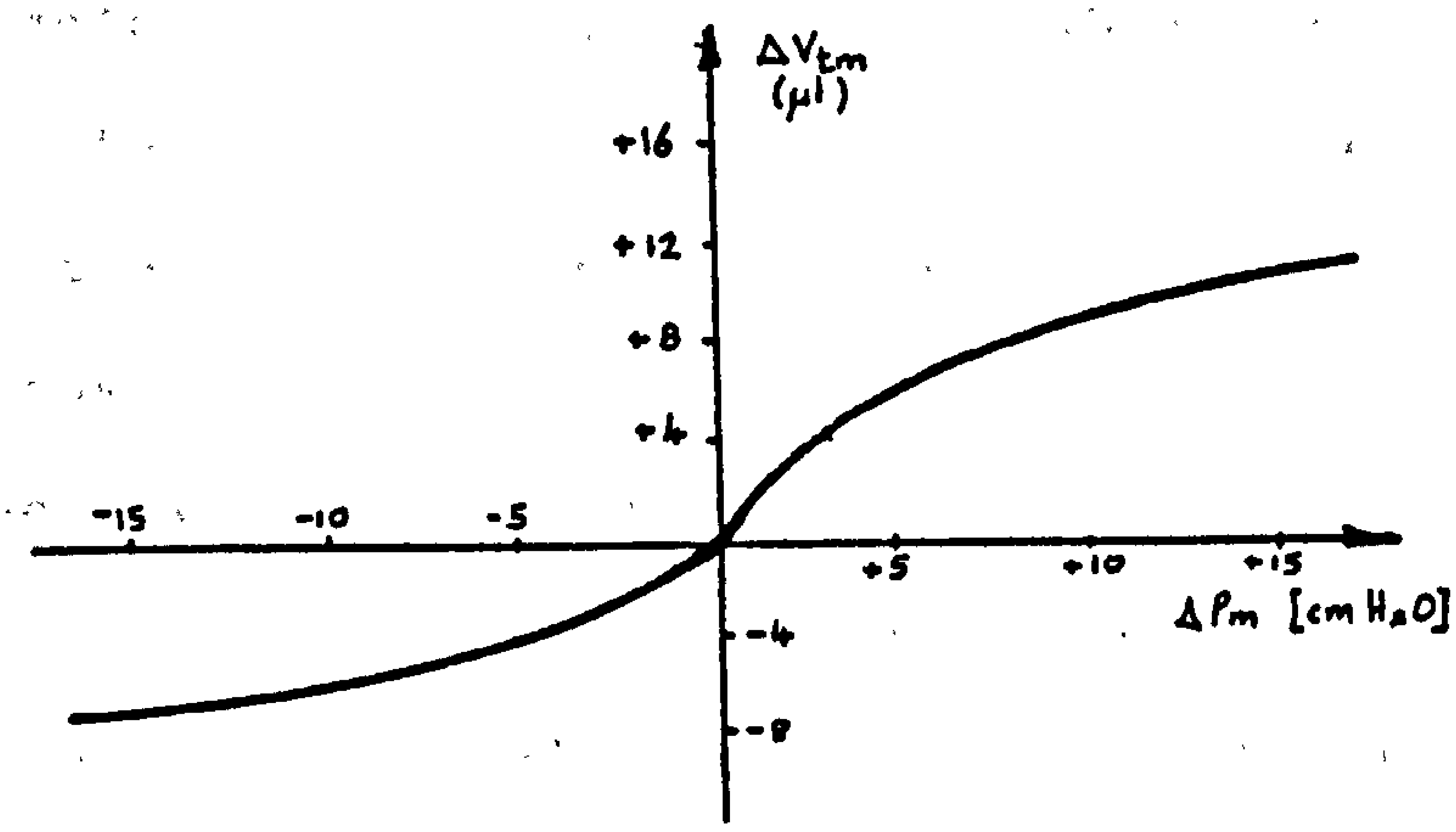


FIGURE 8.5 The static volume relationship of the tympanic membrane determined on 9 normal ear cases
Reproduced from Ingelstedt and Jonson (1966)

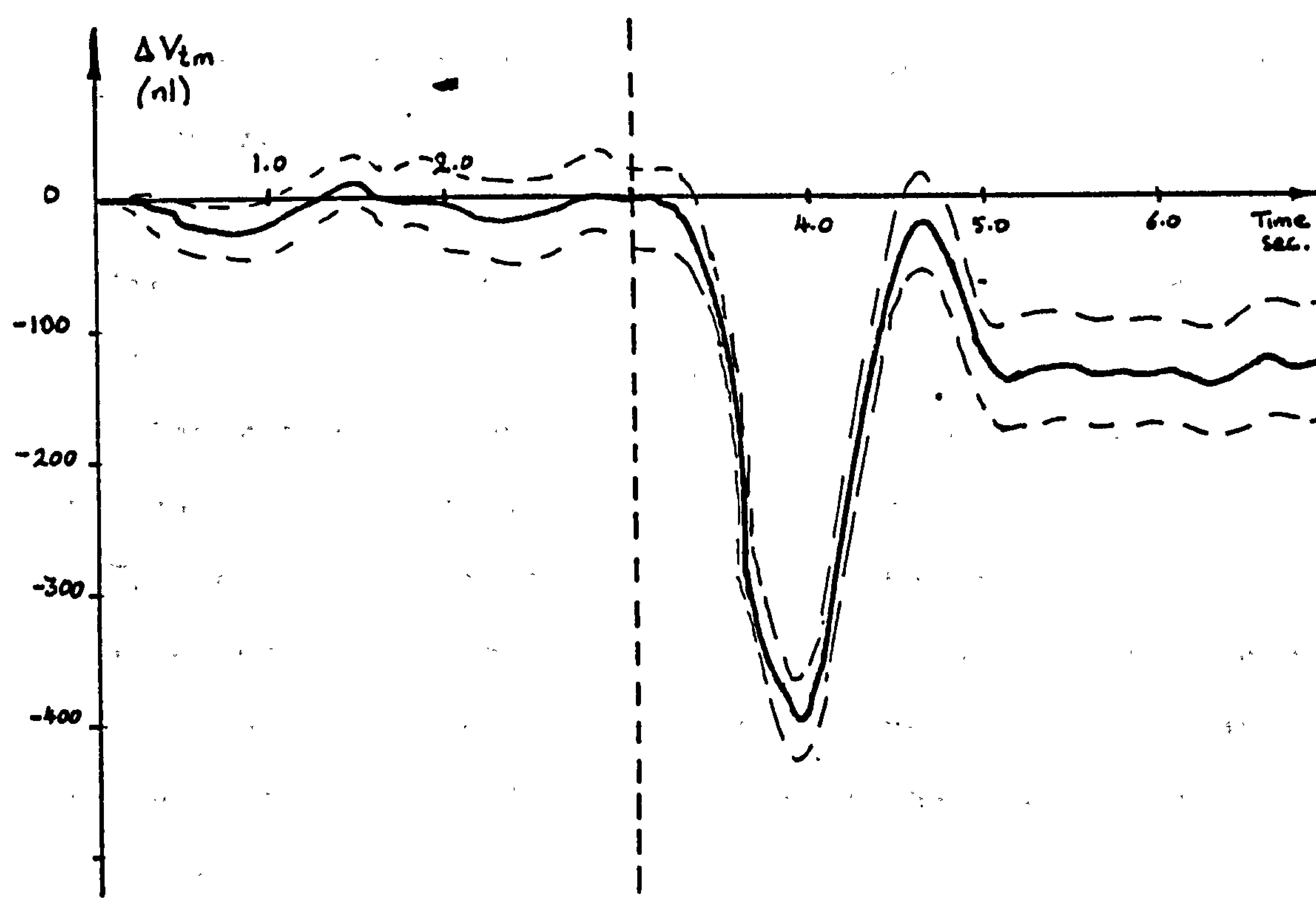


FIGURE 8.6 The TM displacement during swallowing: II

Subject JM

To enable measurement of the gas absorption rate, it is essential that the measurement technique adopted takes into account the ambient pressure noise. Therefore to measure the gas absorption rate either:

i) The environmental pressure and temperature must be controlled, that is by some form of specially constructed climate room (Ingelstedt and Jonson 1966).

ii) Sets of gas absorption TM displacement results taken on different days must be averaged. The ambient pressure variations will then be incoherent and so will be averaged out.

iii) The ambient pressure and temperature variations are measured so that the errors in the TM displacement results may be corrected for when calculating the gas absorption rate.

For reasons of expense, the first method is probably impracticable. Considering the second method, the signal to noise ratio will be improved if N independent records are summed together, approximately according to a rate of $1/\sqrt{N}$. However it is stressed that the records must be independent. In respect of the very low frequency noise, all the records in any one ensemble average will have a degree of correlation and cannot be taken as being indepedent.

The third of these three options seems to be the most practical, and instead of monitoring the rate of gas absorption directly, the change in the resting position of the TM before and after the opening of the Eustachian tube, as caused by swallowing, may be used. (A characteristic mentioned in section 8.2.3). Such TM volume displacements may be related to the rate of gas absorption provided that the compliance of the TM is known (Flisberg et al 1963).

8.4 CONCLUDING COMMENTS ON THE EUSTACHIAN TUBE FUNCTION

Both the studies of the Eustachian tube function during swallowing, and the middle ear gas absorption rate, highlight an interesting fact usually neglected by most authors. That is, fluctuations in the ambient pressure are of a similar magnitude to the rate of change of the middle ear pressure as caused by gas absorption. Therefore, one of the functions of the Eustachian tube is to compensate for ambient pressure variations. On occasions of decreasing ambient pressure, a net flow of air through the Eustachian tube from the middle ear cavity is possible; a direction contrary to that normally expected. Confirmation of this phenomenon is given in figure 8.6, which shows an overall increase in the middle ear pressure on repeated opening of the Eustachian tube during swallowing.

CHAPTER 9

CHARACTERISTICS OF THE STAPEDIUS REFLEX

This chapter considers the TM volume displacement characteristics of the stapedius reflex, such as its latency, threshold and magnitude. The final section discusses the dynamic response of the reflex. The main aims of the chapter are:

i) To document investigations and data on the characteristics of the middle ear reflex.

ii) To compare these data with those obtained using the TMD system.

iii) To present new data obtained with the TMD system, in particular, information on the reflex TM displacement magnitude and its oscillatory characteristics.

iv) To investigate the worth of the TMD system for measuring characteristics of the stapedius muscle reflex.

Most of the TMD system results presented in this section have been acquired from about 80 tests on 10 normally hearing subjects. These were performed for stimuli frequencies of 500 Hz and 1000Hz, and of an intensity of 10 dB above the reflex threshold as measured by the impedance bridge method. Both ipsilateral and contralateral reflexes are studied.

9.1 STAPEDIUS REFLEX THRESHOLDS

The thresholds of the stapedius reflex were determined for all the subjects tested during the present research, for two reasons: firstly as a part of a larger batch of tests to check the normality of the subjects' hearing and secondly, so that the TMD tests could be performed at 10 dB above the threshold. The thresholds were measured using a Madsen Z073 Electroacoustic Impedance (EAI) Bridge. Since the thresholds were found by adjusting the Z073 in increments of 5 dB, the values obtained may be up to 5 dB greater than the minimum reflex threshold obtainable with the EAI bridge *.

In a few cases, thresholds measured using the EAI bridge were compared with those measured with the TMD system. These results are discussed at the end of this section.

* That is by visual inspection of the balance meter. Lower threshold values may be obtained by using signal averaging techniques.

9.1.1 Measurement of reflex thresholds

The middle ear reflex threshold was determined as early as 1913 by Kato who performed experiments on cats and rabbits, but he was unable to give an absolute threshold value. He did state that the threshold was the lowest in the range from 640 to 3400 Hz, which was later confirmed by similar observations made by Philip (1932), Tsukamoto (1934) and Kobrak (1930). In 1929 Lüscher observed the stapedius tendon through a perforation in the TM, and he investigated the reflex threshold for various stimuli. By the same method Potter (1936), Lindsay et al (1936) and Kobrak (1938) observed the threshold of the stapedius tendon as ranging from 70 to 90 dB hearing threshold level (HTL).

The stapedius reflex threshold is now normally measured using EMG, electroacoustic impedance, or TM displacement methods. The impedance method is by far the most frequently used, so that the threshold obtained by other methods are normally compared with impedance results.

Some of the first impedance threshold measurements were obtained by Jepsen (1951, 1955) and Metz (1952), who found that the threshold in humans ranged from 70 to 90 dB HTL in the frequency range of 1000 to 2000 Hz. Later, several investigators compared results obtained using the impedance method with those obtainable with flow and pressure measurement techniques. Casselbrant et al (1977), using flow measurement, found that their method had approximately the same sensitivity as the impedance method. Over the frequency range of 250 to 2000 Hz, their results gave a threshold of 89.8 dB HTL with a standard deviation of 8.2 dB, which compares with a threshold of 85 dB HTL with a standard deviation of 8 dB, obtained by Jerger et al (1972) using the impedance method.

Later, Brask (1978) performed tests on 22 normally hearing subjects (44 ears). His results also show that the threshold was approximately equal for both pressure measurement and impedance methods. For a stimulus frequency of 1000 Hz, he found that the threshold for the contralateral reflex was a mean of 87.6 dB HTL with a standard deviation of 6.8 dB for the impedance method and 90.6 dB HTL, standard deviation 6.9 dB, for the pressure measurement method. The range of thresholds in both cases was 75 dB to 105 dB HTL. Neergaard and Rasmussen (1966) also confirmed that impedance and pressure measurement methods had approximately the same sensitivity for determining the stapedius reflex threshold.

Table 4 gives a summary of the reflex thresholds obtained from other investigations using TM volume displacement measuring techniques. Most of these researchers compared their thresholds with those obtained using the impedance bridge.

TABLE 4 REFLEX THRESHOLD VALUES FROM TM VOLUME DISPLACEMENT INVESTIGATIONS

AUTHOR(S)	METHOD	THRESHOLD OBTAINED BY TM DISPLACEMENT METHODS COMPARED WITH IMPEDANCE
Terkildsen (1960)	V	Difference less than 5 dB
Weiss et al (1962)	P	Less sensitive than Impedance. Average threshold about 92 dB HTL ±4 dB.
Holst et al (1963)	F	Slightly less than impedance.
Neergaard and Rasmussen (1966)	P	Approximately the same.
Yonovitz and Harris (1976)	P	Less sensitive than impedance. 100 dB HTL ±6 dB.
Casselbrant et al (1977)	F	Approximately the same. 89.9 dB HTL ±8.2 dB.
Brask (1978)	P	Approximately the same. 87.6 dB HTL ±6.8 dB.
Present study (1978)	TMD	Approximately the same.

N.B. The limits on the threshold values refer to one standard deviation.

D - Volumetric displacement P - Pressure
F - Flowmeter

9.1.2 The subjects' reflex thresholds

The reflex thresholds for all the subjects used during the present research, were checked for normality across the entire frequency range (250 to 8000Hz). Thresholds for ipsilateral and contralateral reflexes, found using a Z073 EAI bridge, were used to estimate the 10 dB above threshold levels required for the TM displacement tests.

The distributions of the subjects' thresholds are shown in figure 9.1. Mean threshold levels for ipsilateral stimulation of 500 and 1000 Hz were 93 and 89 dB SPL, with a standard deviation of 6 and 4 dB respectively. Mean threshold levels for contralateral stimulation of 500 and 1000 Hz were both 88 dB HTL, with standard deviations of about 5 and 4 dB respectively. These results compared very favourably with those found by previous researchers such as Chiveralls and FitzSimons (1973).

9.1.3 Reflex thresholds with the TMD system

Detecting the reflex threshold with the present TMD system is a relatively lengthy process when compared with the EAI bridge method. For this reason it was determined only for a small number of subjects. However out of over 100 tests, 20 transient records each, only 3 tests did not have a discernable and measurable TMD response at 10 dB above the threshold as given by the impedance bridge. In all three cases this was due to a high background noise level in the external ear canal, so that a TM displacement result was obtainable by increasing the number of records averaged from 20 to 40.

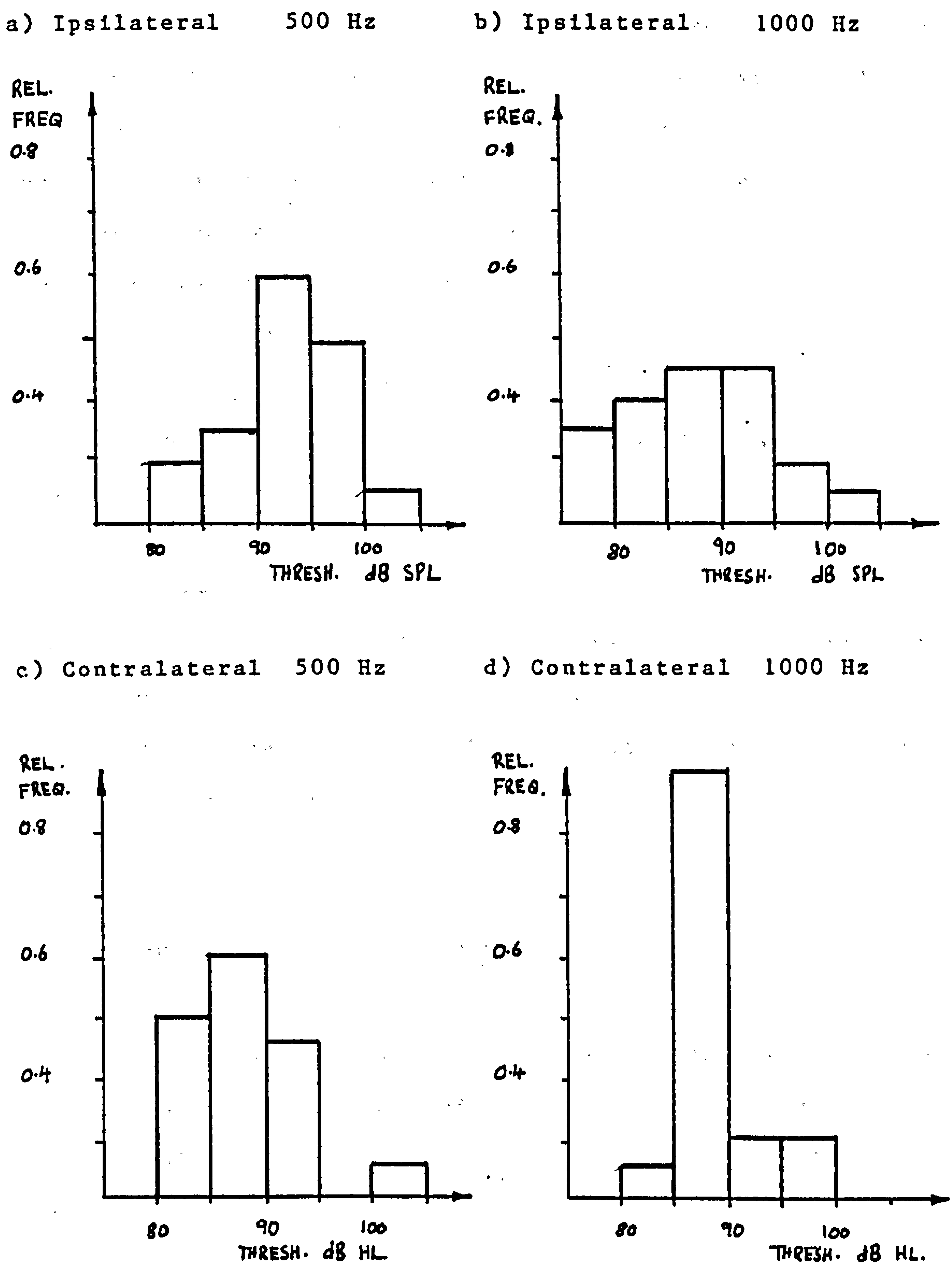


FIGURE 9.1 Acoustic reflex thresholds
Relative frequency histograms of impedance thresholds.

For the subjects for whom the TM displacement thresholds were determined, displacements could be discerned at the impedance bridge threshold and in some cases at 5 dB below this level. The accuracy of the TM displacement threshold varies greatly between subjects, being dependent on the background noise level of the external ear canal, and the number of records in the ensemble average.

9.1.4 Concluding comments

Results of the present and previous research, show that techniques which measure the volume displacement of the tympanic membrane are at least as sensitive as impedance methods for monitoring reflex activity. Furthermore, the fact that the reflex TM displacement thresholds are approximately the same as those obtainable with the impedance bridge is good evidence that the TM displacement is due to the acoustic reflex.

9.2 LATENCY OF THE STAPEDIUS REFLEX

As with other muscle reflexes, the middle ear reflex has a state of apparent inactivity which occurs between the instant of the stimulation, and the beginning of the muscle response. This period is known as the muscle latency. It is the latency of the stapedius reflex which is of particular interest in this section. A comparative study of the latencies for contralateral and ipsilateral stimulation of both ears of a patient, can provide evidence for the presence and location of lesion of the brain stem. Brask (1978) used a similar study of the decreased function of the reflex pathways, to locate the position of a tumour.

The present research was not specifically designed to measure the stapedius reflex latency. The TMD plots chosen to display the overall characteristics of the reflex do not provide sufficient resolution for accurate estimations of the latency. However, this section reviews the techniques of latency measurement with their pitfalls and limitations. Furthermore, a method of using the TMD system for determination of latency is discussed and estimations of the latencies obtained from the TMD plots are presented.

9.2.1 Techniques for measuring the muscle latency

The latency of the middle ear muscle reflexes are measured by several different methods. Over a century ago Hensen (1878) made a direct observation of the tensor tympani reflex in the Dog species, and he estimated the latency as being 92 msec. Later Kato (1913) made optical recordings of the muscle contractions in the Rabbit and Cat, from which he observed latencies of 20 msec for the stapedius muscle. Other methods used to measure the latency are:

i) Electromyographic (EMG) observations by means of electrodes implanted in the muscle or tendon.

ii) By vibrating the skull at audio frequencies and then measuring changes in the sound transmission of the middle ear mechanics, by recording cochlea microphonics or the variations in the sound pressure level within the external ear.

iii) Monitoring variations in the acoustic impedance of the ear.

iv) Detection of TM displacement by measuring pressure variations within the external ear canal or air displaced by the movement of the membrane.

A comparison of these techniques, shows that the EMG method generally yields the lowest reflex latencies.

When measuring the latencies, care must be taken over the choice of suitable equipment. Some investigators, including Ruth et al (1976), used the Madsen Z070 electroacoustic impedance bridge to monitor reflex latency. The validity of the latency results of these experiments are highly questionable because the Z070 Bridge has a response which is too slow for this application. The latency and initial response obtained, is more indicative of the Z070 Bridge characteristics than those of the stapedius muscle!

Care must also be exercised over correct interpretation of the results. Evidence from several investigators indicate that the degree of dependence of the stapedius reflex latency varies with the experimental method used. The EMG methods indicate only a weak dependence on the stimulus intensity, whereas acoustic impedance and pressure/flow methods show a strong intensity dependence. Hung et al (1972) using the acoustic impedance method, found that their results showed that the reflex latency increases as the stimulus intensity approaches that of the reflex threshold. At these stimulus intensities, they noted that this latency was difficult to measure accurately, but was of the order of a few hundred milliseconds. The latency was found to decrease rapidly as the SPL was increased, and it nearly became constant at sound pressure levels over 110 dB. The shortest latency measured was about 20 msec for wide-band noise, and this increased for pure tones, the longest being for tones with frequencies less than 300 Hz.

The variation in the degree of dependence of the latency on intensity is not too surprising when one considers the differences in measuring techniques. EMG monitors reflex activity by means of an electrode implanted in the muscle or tendon. The electrode measures the EMG activity which is effectively a series of rapid pulse changes within the motor units of the muscle, see figure 9.2. This activity causes the muscle to tension, the effect of which may be recorded by indirect techniques such as acoustic impedance or pressure/flow methods. If one considers the signal to noise ratio of the different methods at near reflex threshold levels, then it is very poor for the indirect methods, and in comparison extremely good for the EMG method. Consequently the EMG technique will register muscle activity before the muscle response signal is distinguishable from the noise with the indirect methods. Figure 9.2 shows the increase of EMG activity for increasing stimulus intensity. It can be seen from this figure that if the amplitude of the first EMG pulse is taken as the signal, then the signal to noise ratio is almost independent of the stimulus intensity. The fact

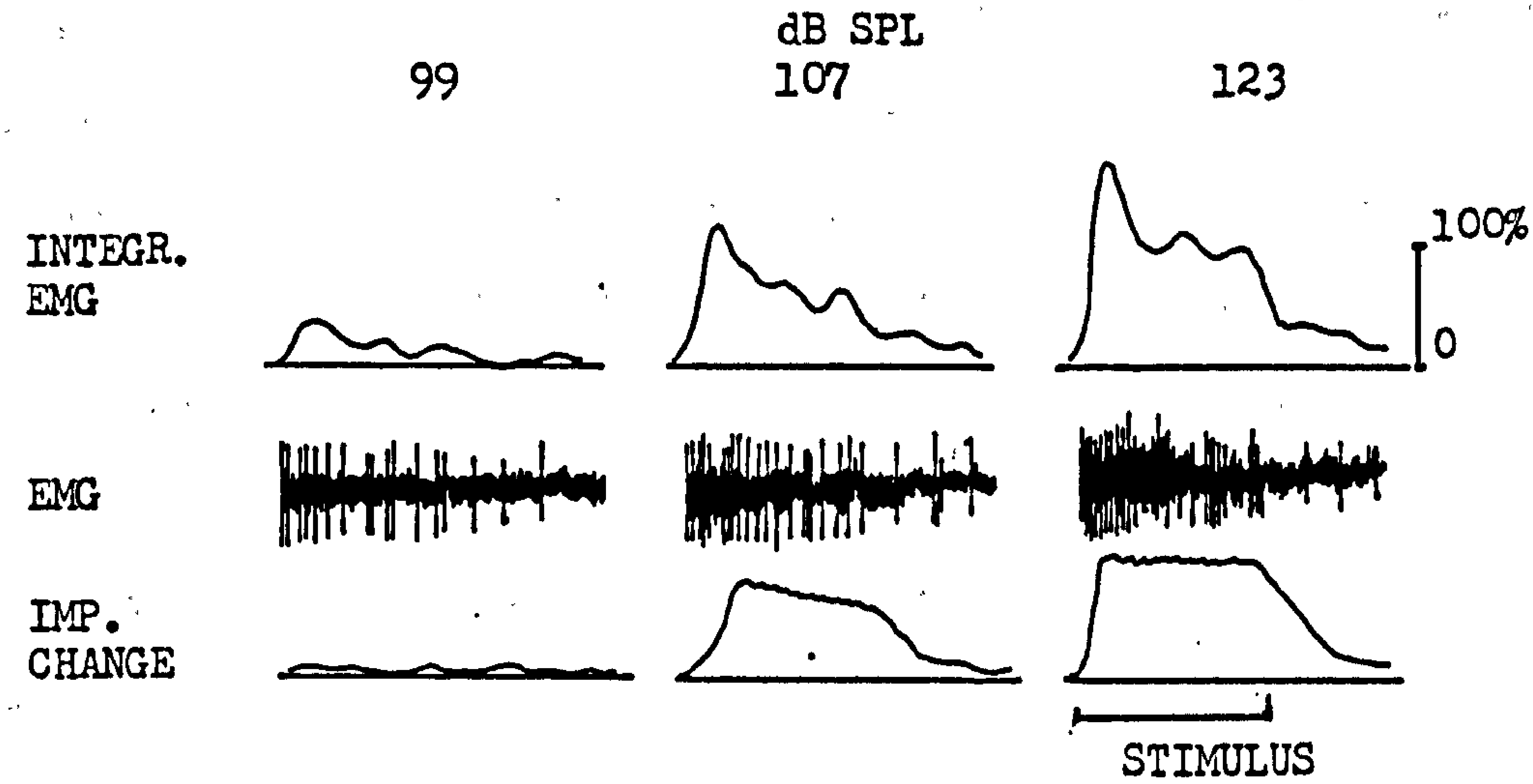


FIGURE 9.2 Simultaneous recordings of EMG and impedance
Simultaneous recordings of EMG of the stapedius muscle of the left ear and impedance change in the right ear, in response to 2.0 KHz pure tone stimulation of one second duration in the right ear. Integrated EMG (rectified and low-pass filtered at 3.9 Hz) is also shown. Reproduced from Zakrisson et al (1974).

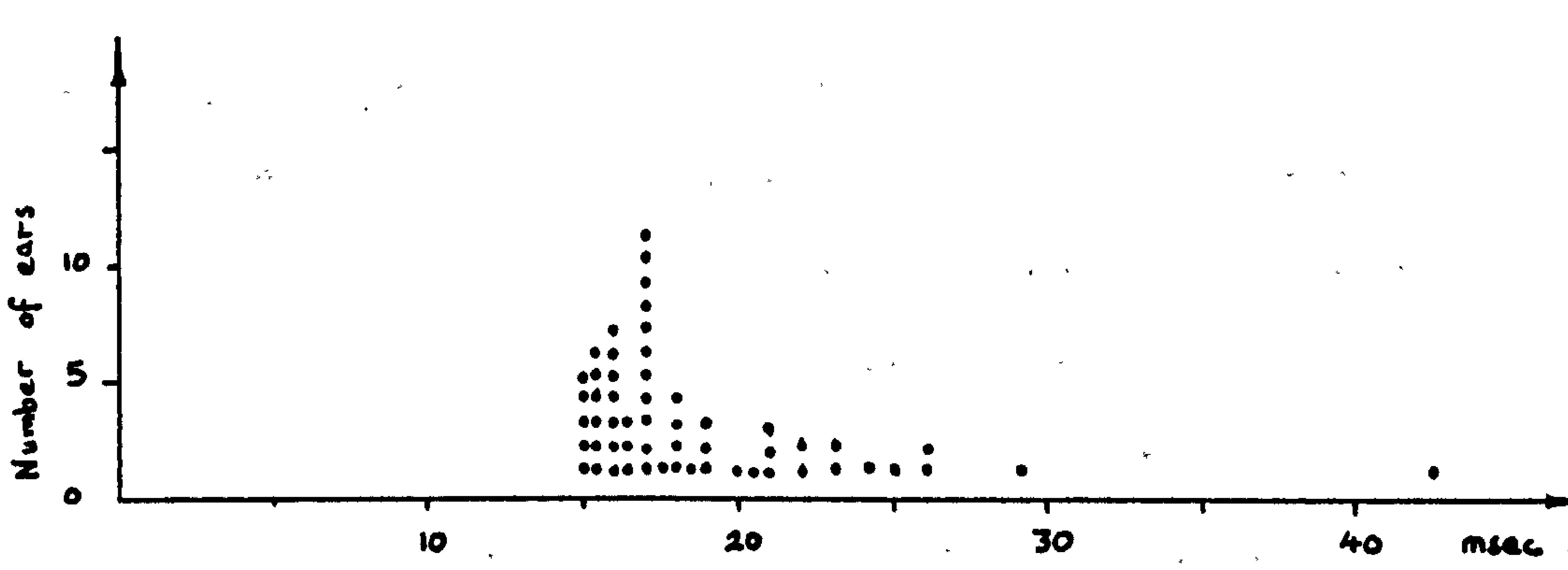


FIGURE 9.3 Distribution of latency in 56 normal ears
Reproduced from Neergaard et al (1966)

that far better signal to noise ratios may be obtained with systems communicating by pulses, pulse coded modulation (PCM), rather than analog methods (i.e. frequency or amptitude modulation) is well known in the telecommunication technologies. It is also possible that the lowest degree of EMG activity is not accompanied by a pull in the tendon and so being unobservable using indirect measurement techniques.

The signal to noise ratio of methods such as acoustic impedance and pressure/flow methods could be improved by filtering and ensemble averaging techniques, so allowing better assessment of the muscle latencies.

9.2.2 The magnitude of the middle ear reflex latency

The magnitude of the stapedius muscle latency tends to vary with the measurement technique. Generally, as previously mentioned, the EMG methods yield the shortest values. Perlman and Case (1939), Fisch and Schilthess (1963) and Djupesland (1965) consistently gave stapedius muscle latencies in man of 10 msec, using EMG.

Metz (1951) used changes in acoustic impedance to measure the muscle latency and observed a minimum latency of 35 msec, and for stimulus intensities approaching the reflex threshold, the latency was about 150 msec. These are similar results to those obtained by Møller (1958), who using an electroacoustic measuring device found latencies ranging between 25 and 130 msec. Terkildsen (1960b) employed a similar method to Møller (1958) and produced comparable results. Later impedance measurements, Klockhoff (1961), McRobert et al (1968) and Liden et al (1974), gave similar latency values ranging between 30 and 200 msec.

Neergaard et al (1966), using pressure measurements designed their experiments to specifically determine the stapedius muscle latency, and their results were comparable to those obtained using the EMG methods. They measured the latency in 56 ears, and the results show a characteristic asymmetric distribution having a sharply defined lower limit of 15 msec and a distribution median of 17 msecs. The distribution tails off for longer latencies but with no apparent limit. The results of Neergaard et al (1966) are shown in figure 9.3. The stimulus used for these experiments was 1000 Hz at a level of 100 dB above the hearing threshold.

The tensor tympani muscle reflex has a longer latency than the stapedius. This fact is sometimes used to identify whether a particular reflex response is caused by the stapedius or tensor reflex. Solomon and Starr (1963) using EMG methods, found reflex latencies ranging between 90 and 300 msec, results which were almost identical to the range observed by Djupesland (1965). In both cases the reflex seemed to be present only as a component of a general startle reaction, and was therefore attributed to the tensor tympani reflex. Casselbrant et al (1977), in their reflex studies, observed a reflex which occurred with varying latency. They noted that this reflex caused a large inward movement of the tympanic membrane. The mean latency value was 650 msec and the range was 300 to 1200 msec. This reflex was also interpreted as being due to the tensor tympani muscle.

9.2.3 The present method

There is a choice of several definitions for the stapedius reflex latency when measured with indirect techniques, such as the TMD system. The most commonly applied definitions are:

i) The time taken from the stimulus onset until the first detectable reflex response.

ii) The time taken from the stimulus onset until 10 percent of the maximum response magnitude has been obtained.

In this section the first definition is used, which was also adopted by Neergaard and Rasmussen (1966) and Brask (1978). The main drawback of this definition is that the latency is difficult to measure if the response leaves the baseline asymptotically. This problem prevails at near reflex threshold intensities.

The TMD system of the present research is not particularly suited for latency measurements on two accounts. Firstly, the rise time of the stimulus generator is far too slow and secondly, the system does not resolve the initial reflex 'on' response very accurately. Improvements could be made by sampling over the minimum time possible, that is 80 msecs, as well as passing the signal through a high pass filter prior to signal averaging. Filtering greatly reduces the low frequency noise.

The optimum resolution of the latencies from the existing TMD plots is ± 12.5 msec, and only results within these limits are analysed in the following sections. These results are for stimulus intensity of 10 dB above the reflex threshold and from normally hearing subjects.

9.2.4 The results of the present study

Within the resolution of the TMD plots, there is no significant difference between latency values for 500 Hz, 1000 Hz, ipsilateral or contralateral reflex * so that, for the purpose of the present preliminary study, all these results have been combined to give the overall spread of latency values.

With reference to the onset characteristics of the stimulus, appendix V, it may be seen that because of the slow stimulus rise time, at least 30 msecs are required for its intensity to approach that of the reflex threshold. Subtracting this value from the latency measured from the plots, yields an estimate of the muscle latency for 10 dB above reflex threshold. The spread of the results are shown in figure 9.4.

Out of a sample of 13 ears and 46 tests, the range of the latency values was from 20 msecs to 95 msecs, with a mode value of 30 to 40 msecs. The onset of the muscle contraction is often very well defined, as shown in figure 9.5, but for accurate results a stimulus with a more rapid rise time is essential. Nevertheless, the latency values obtained in this study are in close agreement with those measured by other investigators. Since this latency is

* For detailed studies of latencies, distinction should be drawn between results for ipsilateral and contralateral stimulation. The latency will be different due to the varying lengths of the reflex neural pathways.

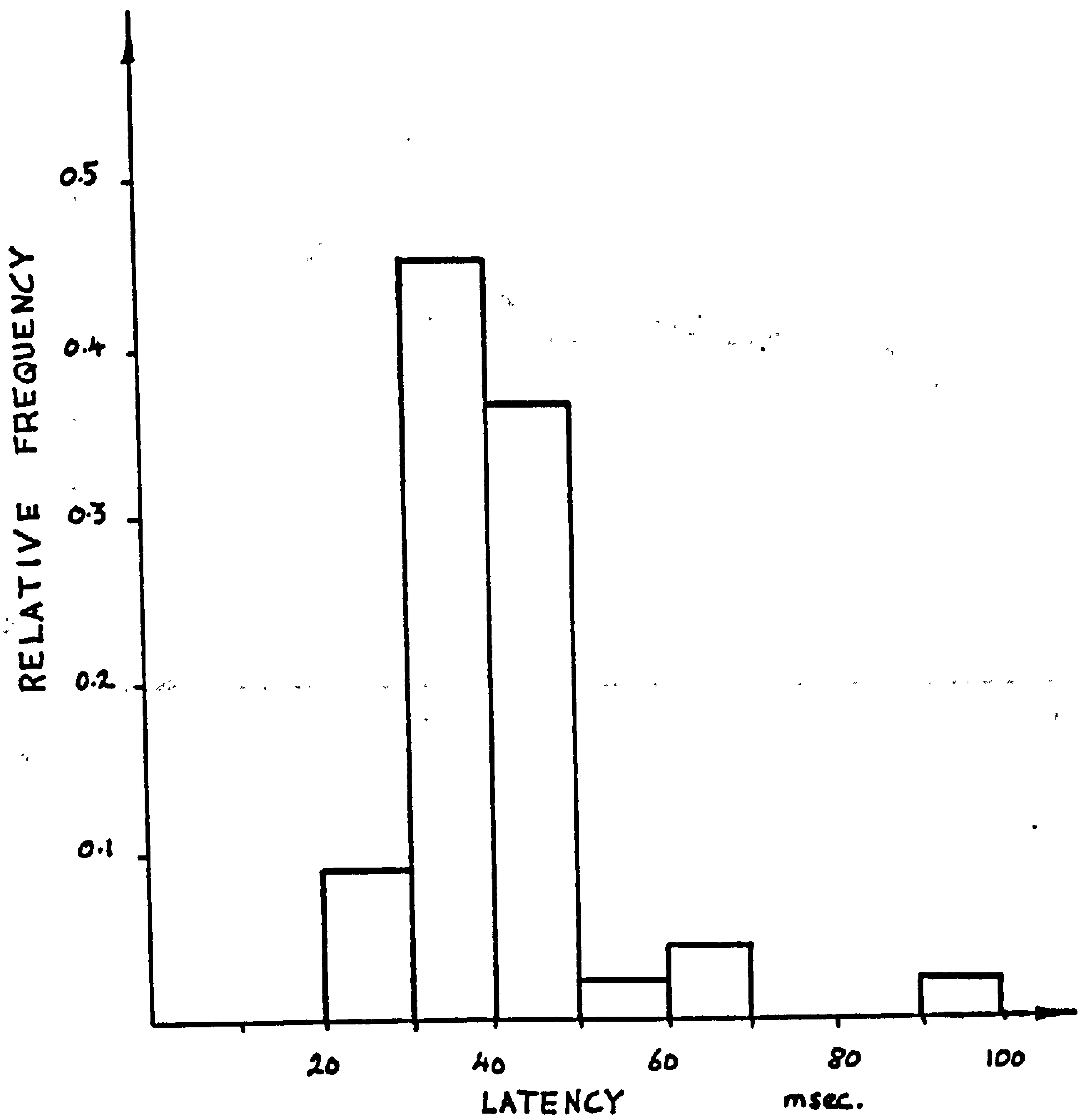


FIGURE 9.4 Relative frequency histogram of reflex latencies

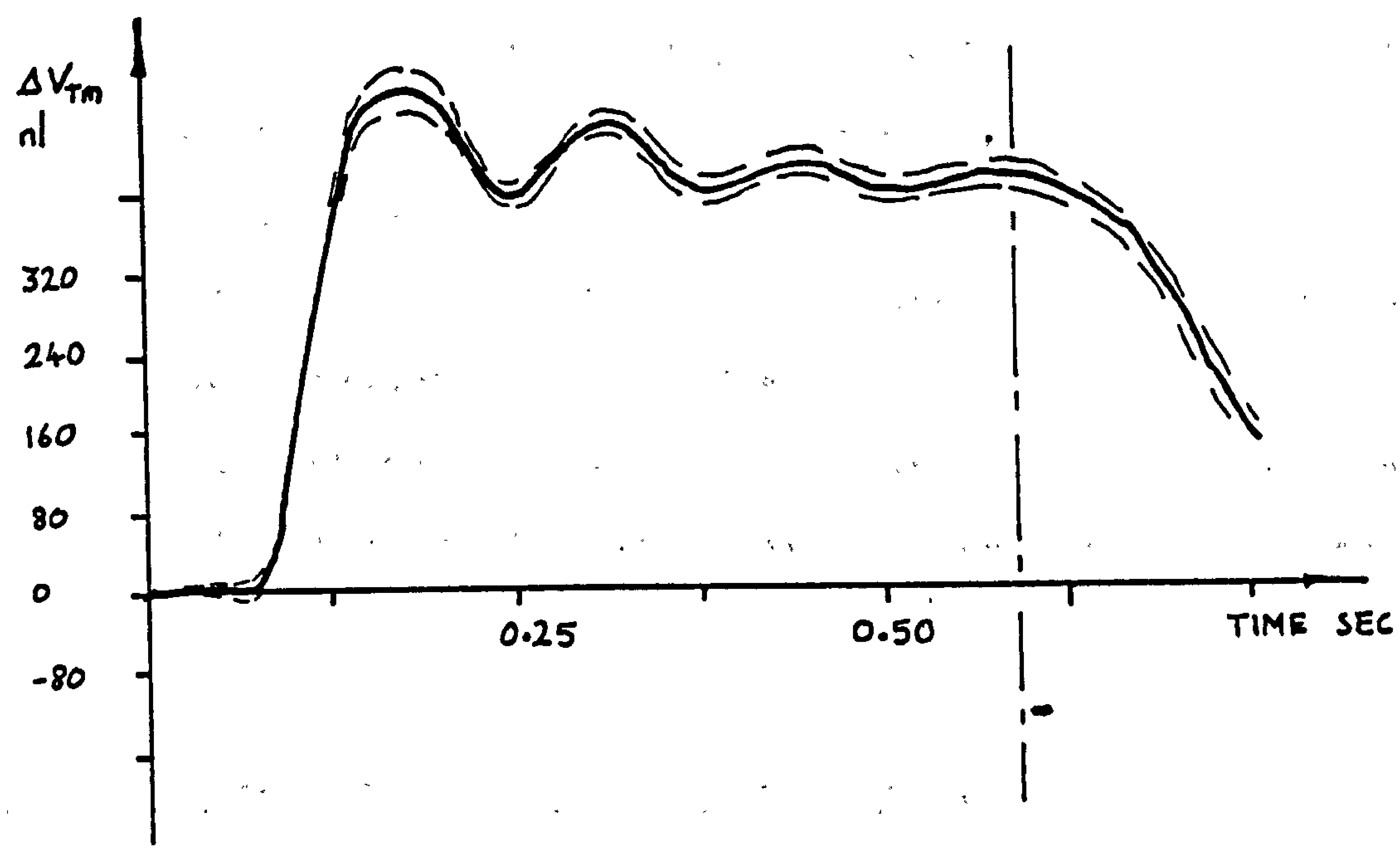


FIGURE 9.5 A TM displacement plot

The TM displacement plots often display very definite onset charateristics as shown by this plot.

Subject EC: Ipsilateral reflex, stimulus 1000 Hz at intensity of 10 dB above the reflex threshold.

shorter than that of the tensor tympani reflex, it provides evidence to show that the TMD system is in fact measuring the response of the stapedius muscle.

9.3 AMPLITUDE OF THE TYMPANIC MEMBRANE DISPLACEMENT

During the present research, the magnitudes of the TM displacements induced by the acoustic reflex were investigated. The stimulus intensity chosen was 10 dB greater than the subject's reflex threshold as determined by impedance measurements. The results compare very closely with those of a similar investigation (Casselbrant et al 1977), details of which are given later in this section.

9.3.1 Measurement of the reflex magnitude

Both the steady state and peak volume displacement of the tympanic membrane were studied in the present investigation. The definitions of parameters which relate to these particular displacements are shown in figure 9.6. In actual fact, these parameters are more closely related to the mean distance travelled by the TM, than its linear displacement. They were chosen to take into account both inward and outward, as well as inward followed by outward volume displacements of the TM. These parameters, designated as ΔV_{ss} and ΔV_{pk} for the steady state and peak displacements respectively, are used throughout this dissertation.

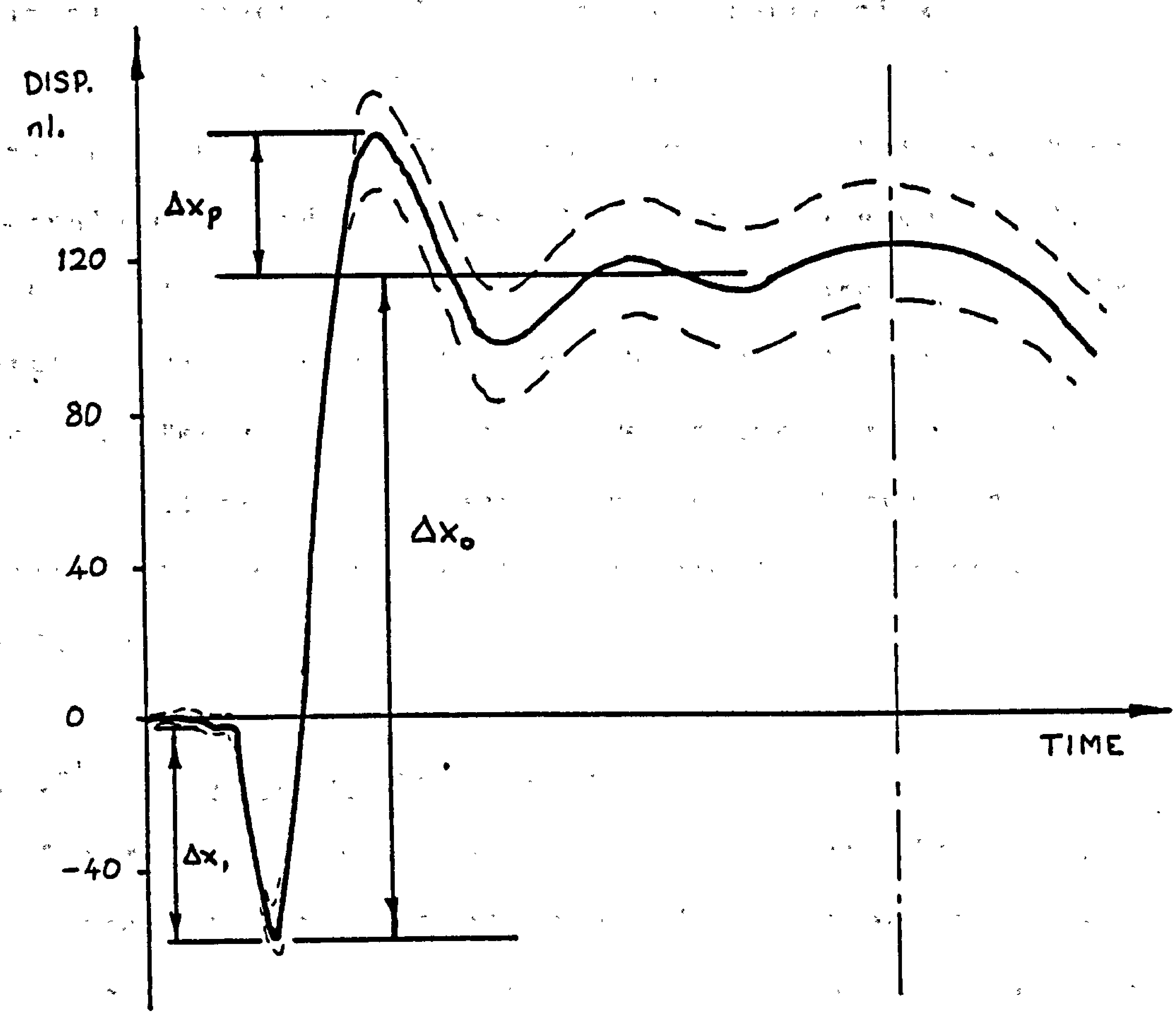


FIGURE 9.6 Measurement of parameters ΔV_{ss} and ΔV_{pk} from a TM displacement plot

$$\Delta V_{ss} = \Delta x_i + \Delta x_o$$

$$\Delta V_{pk} = \Delta x_i + \Delta x_o + \Delta x_p$$

9.3.2 The subjects and the tests

The results were obtained from 19 ears of 10 normally hearing subjects. The stimulus frequencies were 500 and 1000 Hz, of intensity 10 dB above the reflex threshold as obtained from a Madsen Z073 Impedance Bridge. Both the contralateral and ipsilateral reflexes were measured.

Each TMD plot consisted of 20 TMD records. The stimulus duration was 0.5 seconds and the record length was 1.0 second. Ten seconds were allowed between each presentation of the stimulus to avoid reflex fatigue and to give sufficient time for the TM to return to its normal resting position.

9.3.3 Discussion of the results

The mean of all the subjects' steady state TM displacements are plotted as a relative frequency histogram in figure 9.7. Likewise, the peak TM displacements are plotted in figure 9.8. These histograms show that the greatest relative frequency is within the limits of 200 to 300 nanolitres.

To the author's knowledge, Casselbrant et al (1977) is the only investigation that studies the TM volume displacement quantitatively in any detail. Comparisons of their results with the present data are difficult, because their measurements are not relative to the subject's reflex threshold as determined with an impedance bridge. They also did not use any averaging techniques to resolve the dynamics of the TM displacements; consequently their measurements are only approximately equivalent to the peak

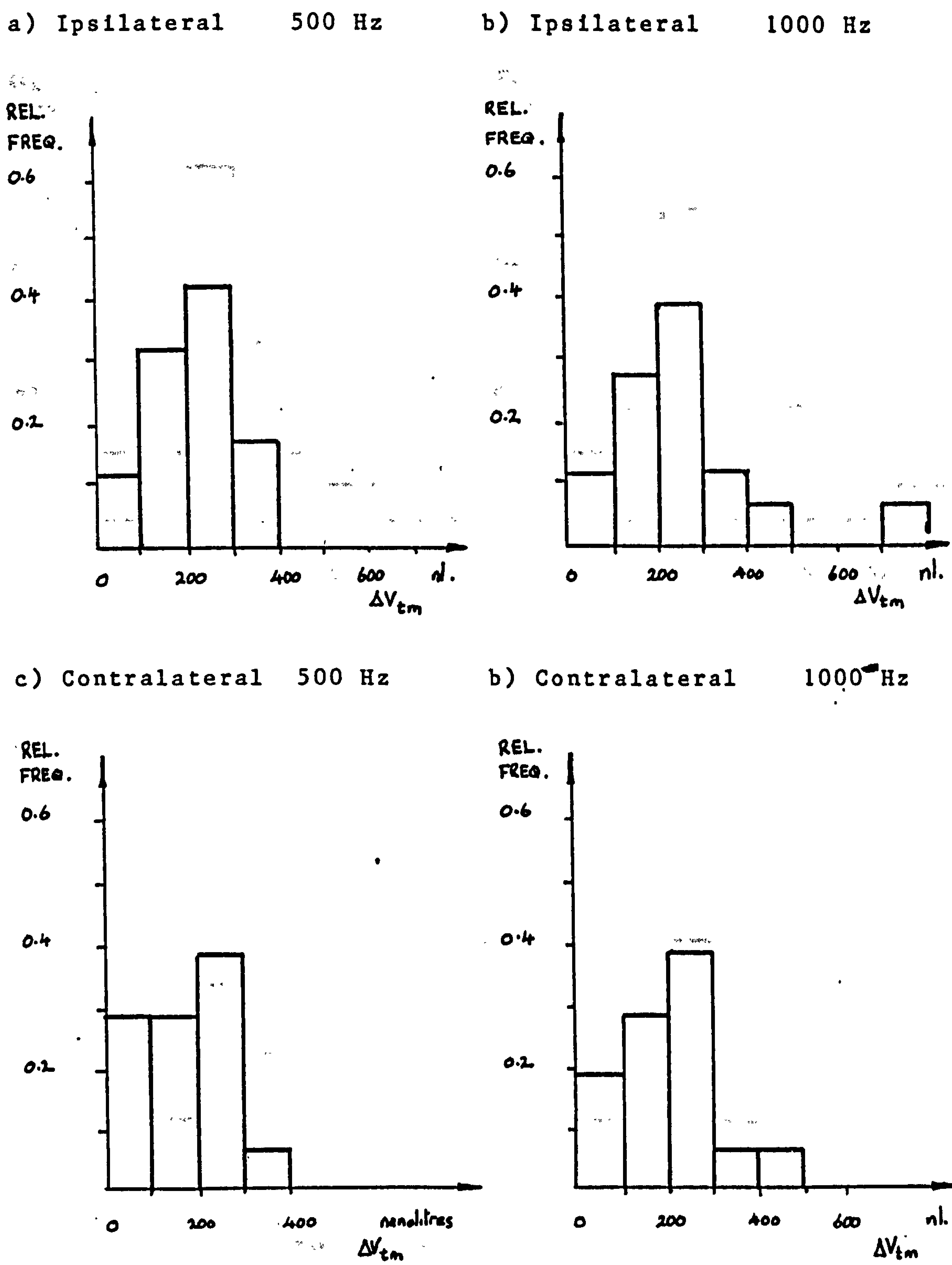


FIGURE 9.7 Acoustic reflex steady state amplitudes
Relative frequency histograms of steady state values.

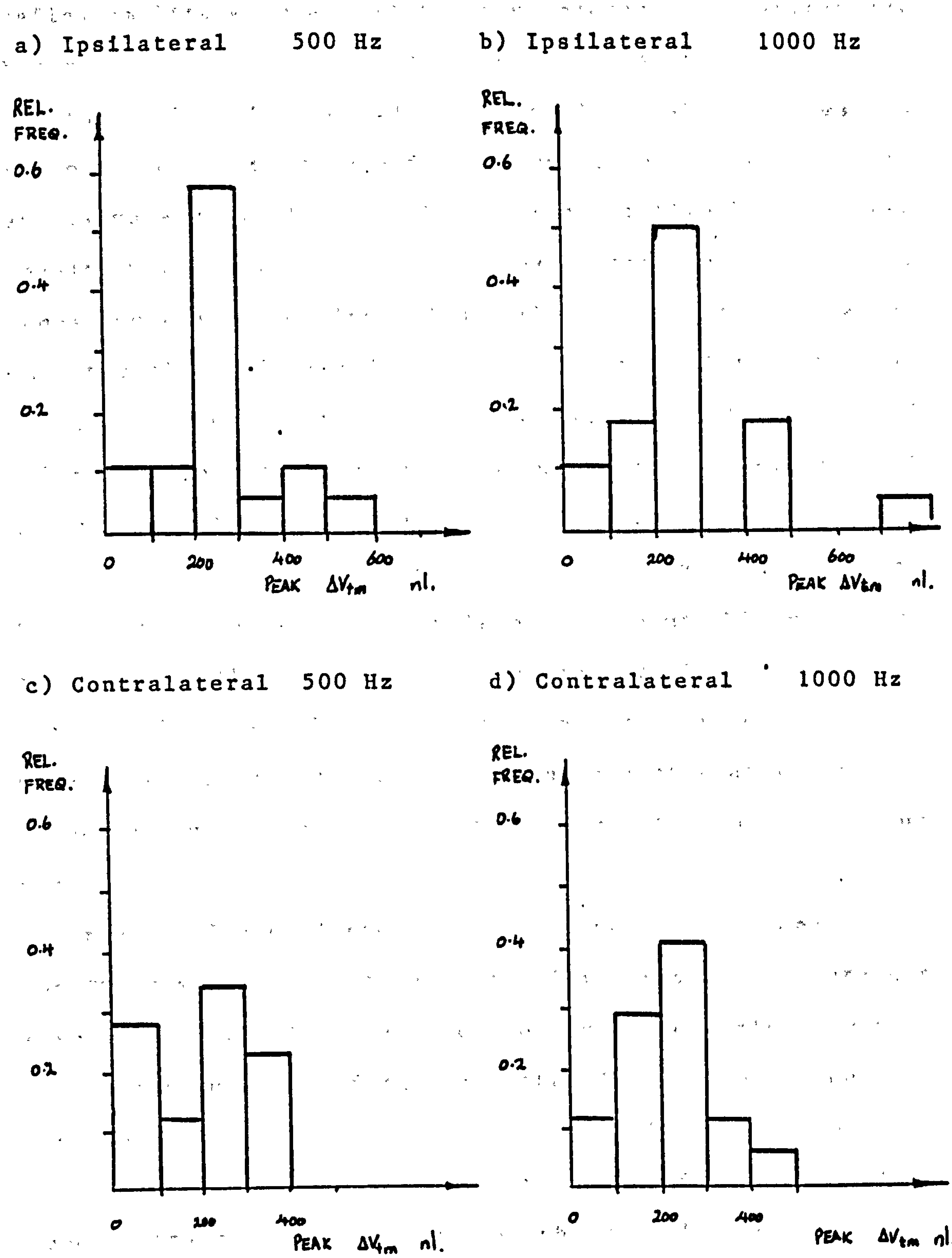


FIGURE 9.8 <u>Acoustic reflex peak amplitudes</u>
Relative frequency histograms of peak displacements.

reflex amplitudes measured in the present investigation. Nevertheless, using their volume displacement thresholds for the reflex, figure 9.9 was compiled which gives an estimate of the volume displacement, for 10 subjects, at approximately 10 dB above this particular threshold. These results were obtained for a 1000 Hz contralateral stimulus. Comparing these results with those of the present investigation, figure 9.8d, it may be seen that their mean displacement value of 210 nl, and standard deviation of 107 nl, compares very closely with the present mean of 214 nl, and standard deviation of 107 nl.

The present results show that the magnitude of the ipsilateral reflex is consistently about 20 per cent greater than that of the contralateral reflex (Table 5). Brask (1978) similarly observed this phenomenon, which he thought was probably due to the longer contralateral reflex pathways causing greater attenuation of the stimulus signal.

Brask (1978) estimated the mean linear displacement of the TM from some of his results. Similarly for the present results, if the TM is assumed to move like a piston with a utilized diameter of 8 mm, then the linear displacement of the TM is of the order of 0.004 mm, for 10 dB above the reflex threshold. In actual fact the TM forms a shallow cone, attached along its periphery. It is therefore expected that the displacement of the umbo region will be somewhat greater than calculated by this piston-like model.

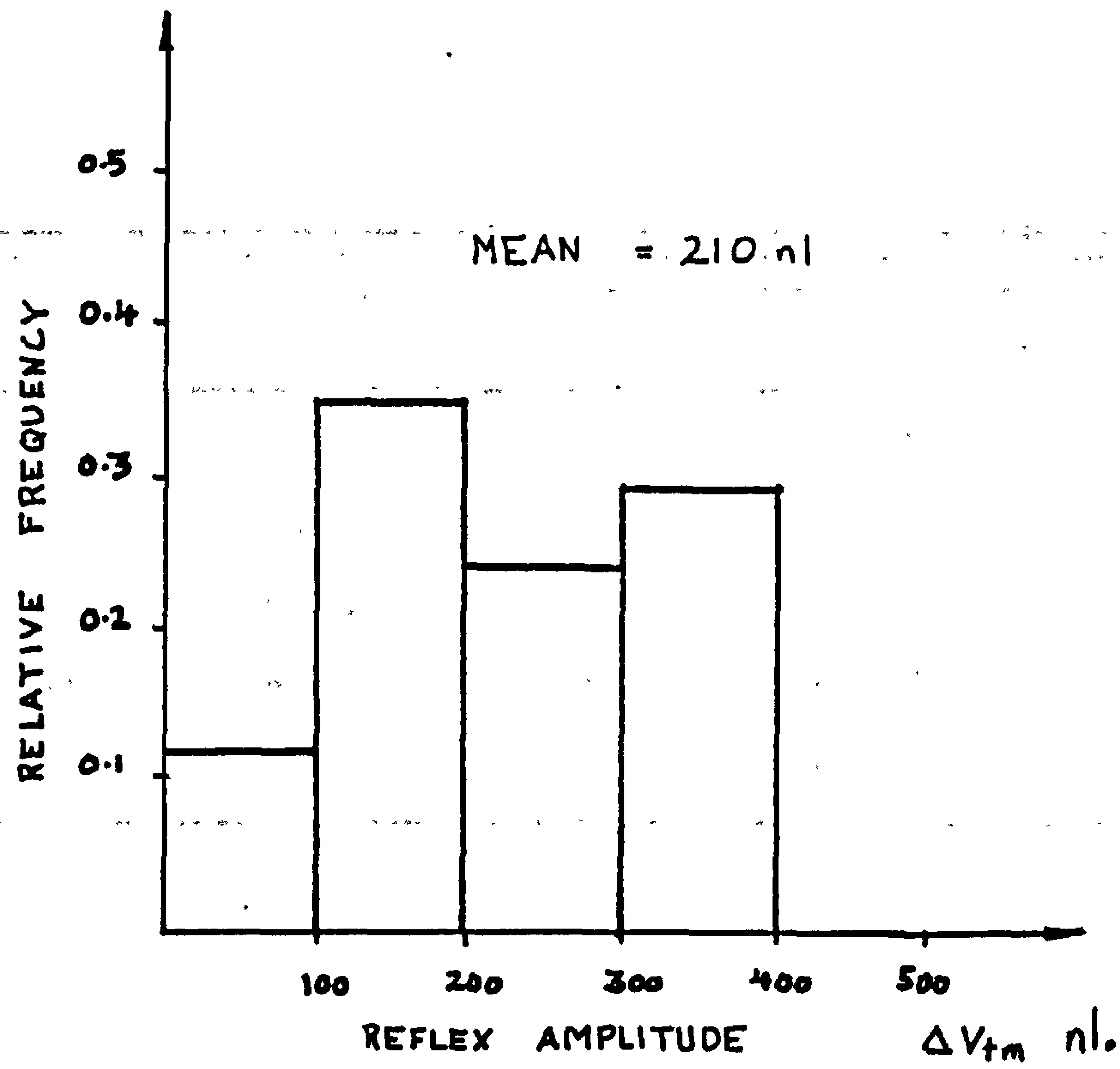


FIGURE 9.9 Reflex amplitudes at 10 dB above reflex threshold* as measured by Casselbrant et al (1977) Sample 17 ears, contralateral 1000 Hz stimulus.

* TM volume displacement threshold

TABLE 5 COMPARISON OF IPSILATERAL AND CONTRALATERAL REFLEX AMPLITUDES

FREQUENCY Hz	PEAK/STEADY STATE AMPL.	MEAN TM DISPLACEMENT CONTRAL. nl	IPSIL. nl	PERCENT. IPS>CONT %
500	S.S.	175	204	17
1000	S.S.	199	244	23
500	PEAK	196	253	27
1000	PEAK	214	265	24

9.4 DYNAMIC CHARACTERISTICS OF THE STAPEDIUS REFLEX

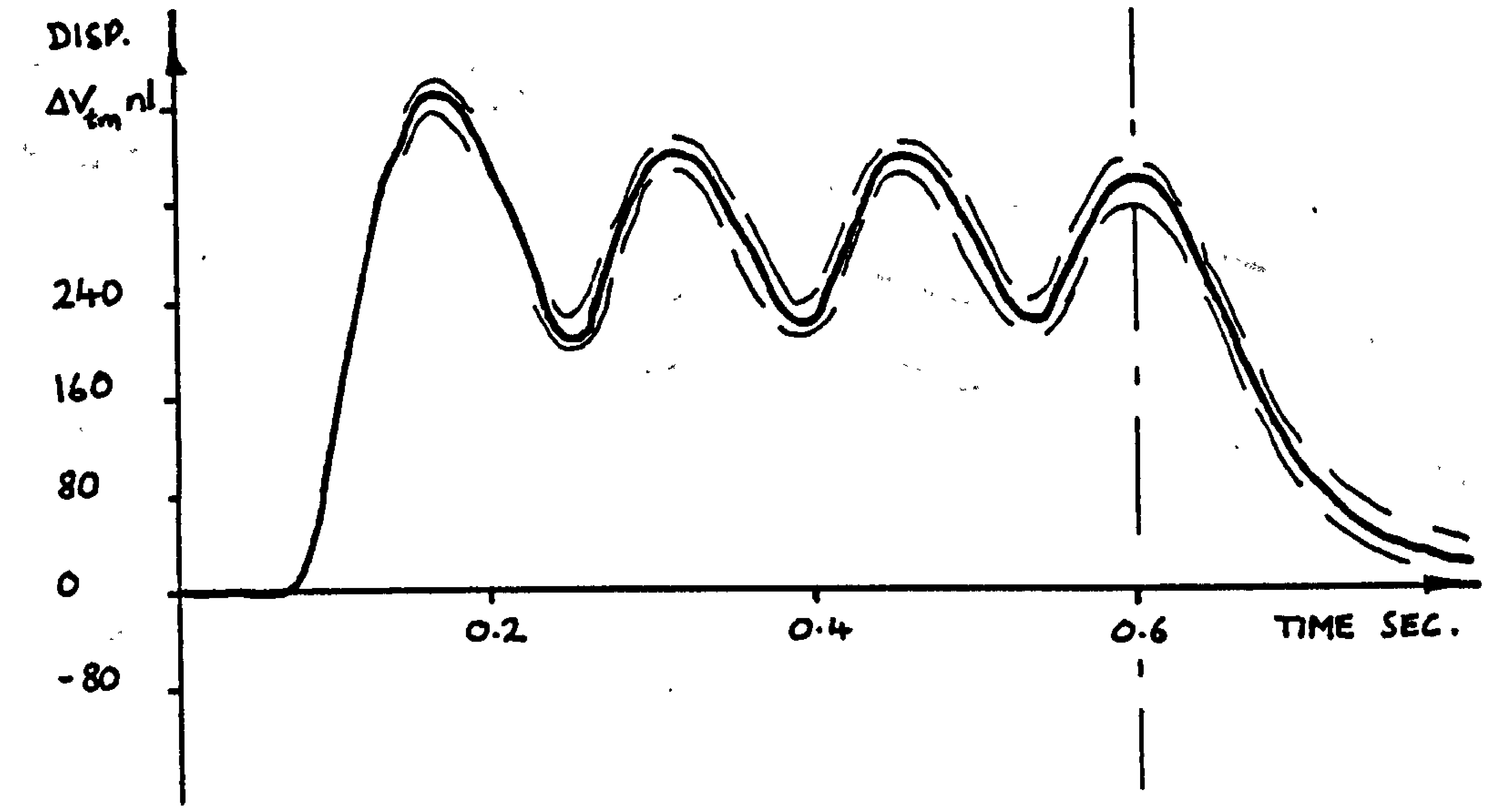
A large number of the results from the TMD system, show that, on contraction of the stapedius muscle, the tympanic membrane initially oscillates about the steady state position. This charateristic, shown in figure 9.10, is particularly noticeable at frequencies below 1500 cycles per second. Similar oscillations have been observed by previous researchers, and are presumably due to variations in the contraction tension of the stapedius muscle.

This section investigates these dynamic characteristics of the stapedius reflex, as found using the TMD system, and compares them with results from other investigations.

9.4.1 Reasons for the oscillatory characteristics of the reflex

An effect of the stapedius reflex is to reduce the sound energy transmitted by the middle ear mechanism to the inner ear (Brask 1978). Consequently, the intensity of the stimulus which elicits the reflex, is itself attenuated by the reflex; i.e. there is a closed loop response. If the middle ear/reflex system is underdamped, then this negative feedback will inevitably cause oscillations as the system hunts to obtain a steady state condition. The reflex is more efficient at attenuating the lower auditory frequencies, so that if the frequency is sufficiently high, the reflex causes little or no attenuation of the stimulus. In this case the reflex may be considered as having open loop characteristics and no forced oscillations will occur.

a) Subject EC, Contralateral reflex, stimulus 500 Hz at intensity of 10 dB above reflex threshold.



b) Subject JH. Contralateral reflex, stimulus 500 Hz at intensity 10 dB above reflex threshold.

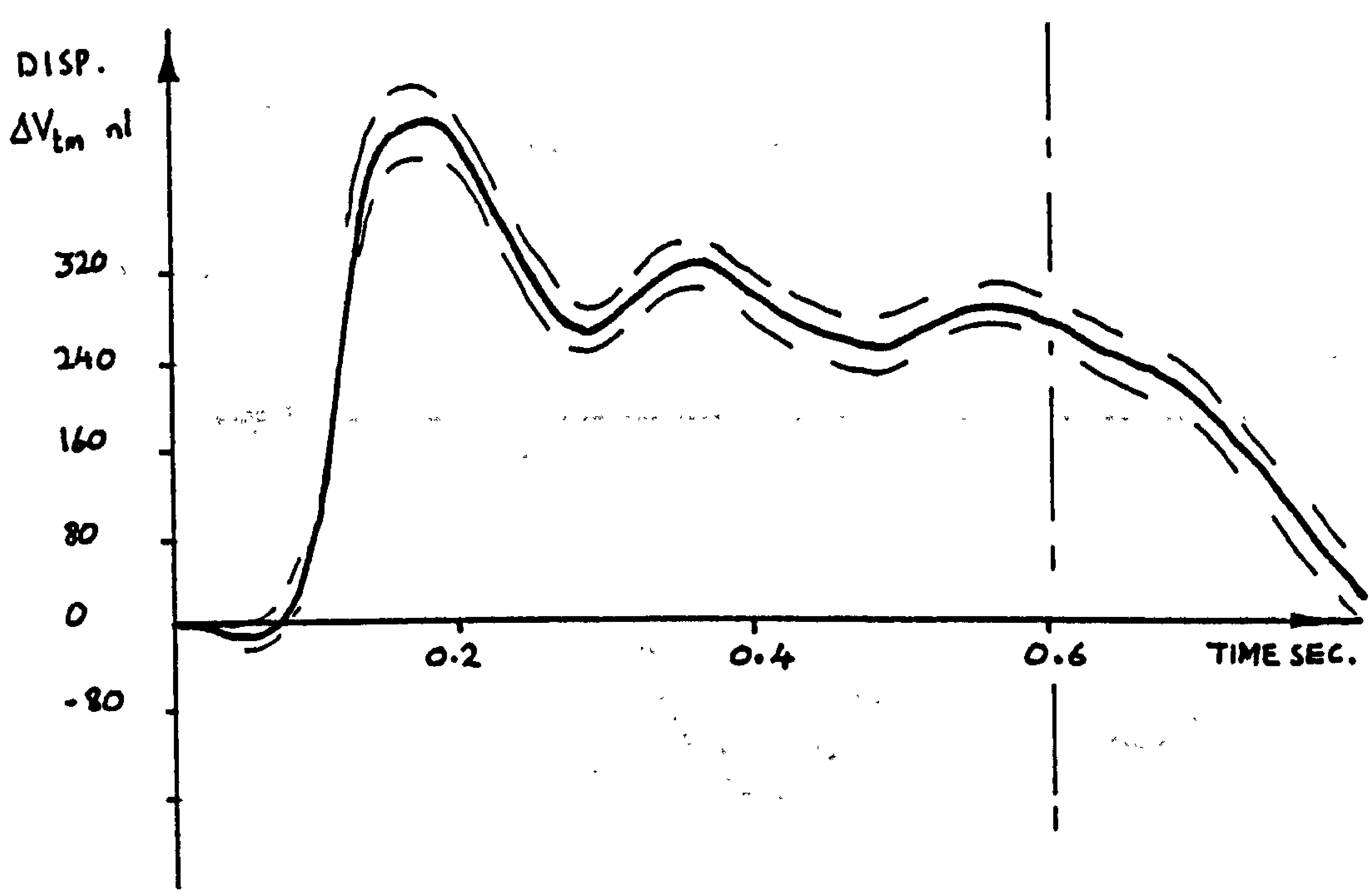
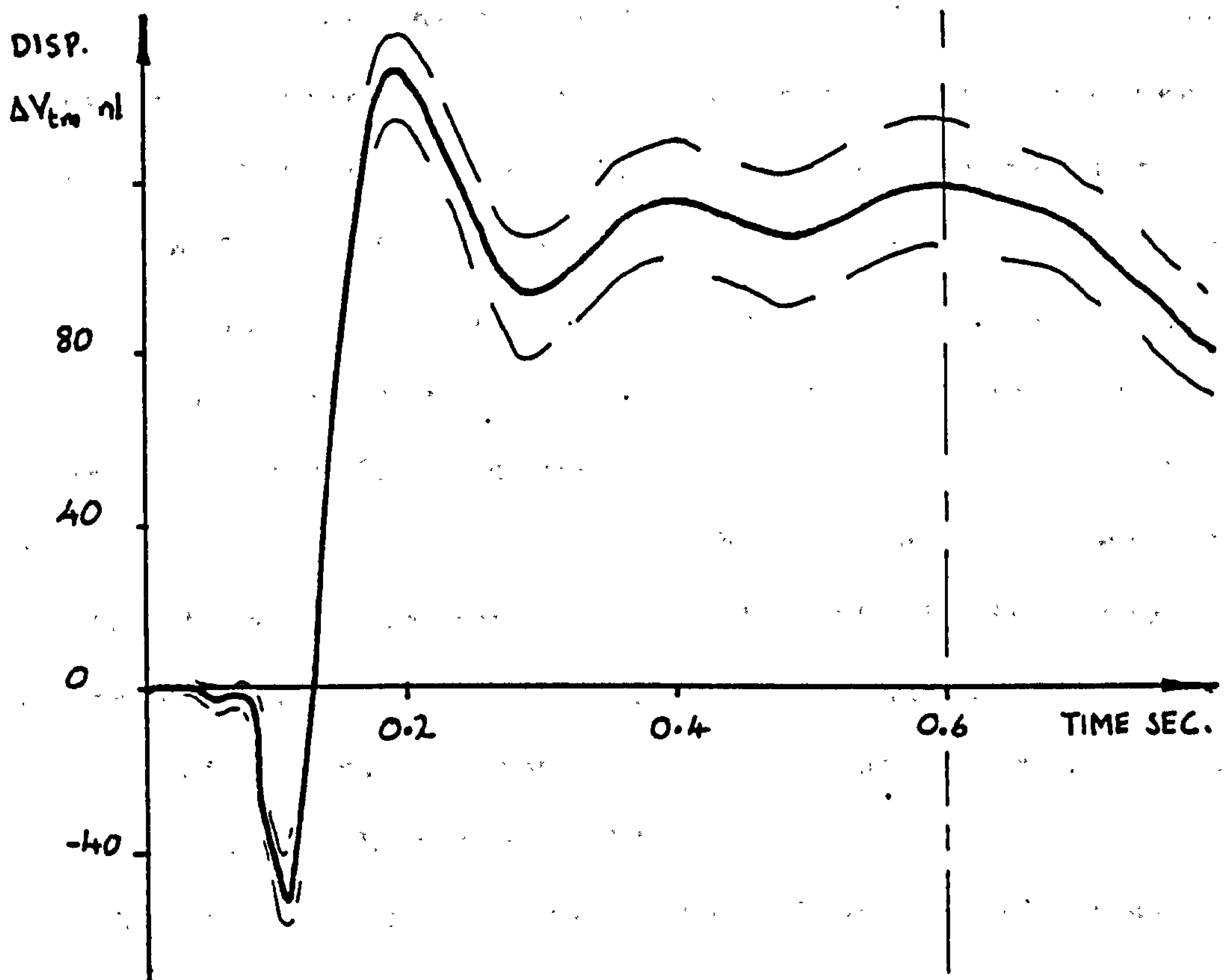


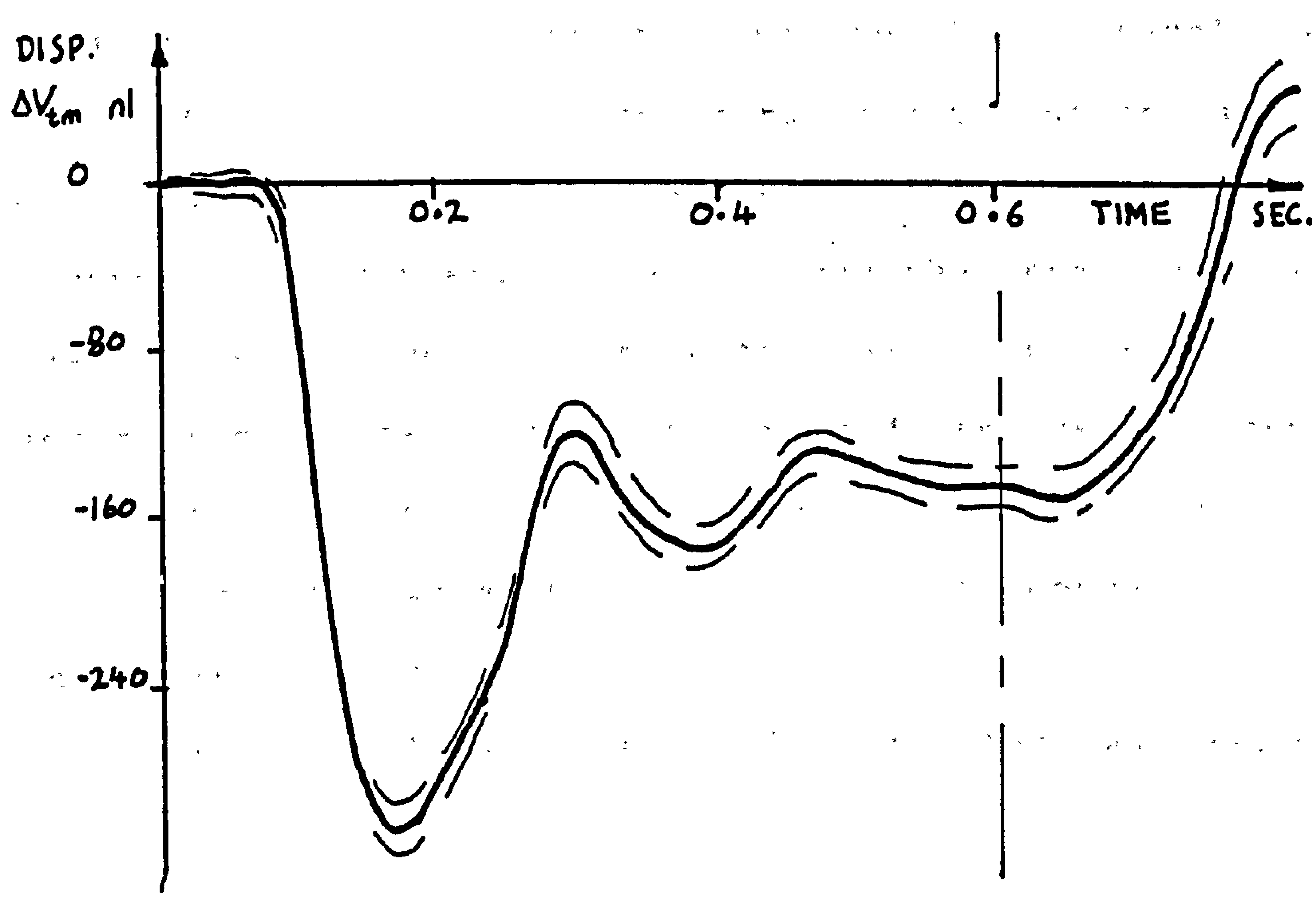
FIGURE 9.10 Four examples of TMD plots displaying oscillatory characteristics

FIGURE 9.10 Continued

c) Subject CT. Ipsilateral reflex, stimulus 500 Hz at intensity of 10 dB above reflex threshold.



d) Subject PC. Contralateral reflex, stimulus 500 Hz at intensity 10 dB above reflex threshold.



Møller (1962), Borg (1968), Hung and Dallos (1972), and Brask (1978), attributed the oscillations solely to the negative feedback of the reflex. However various authors such as Lorente De Nó (1935) and Wersäll (1958) disregard negative feedback as a total explanation, and propose that the oscillations have their origins in the reflex arc. Evidence for this hypotheseis is provided by Wersäll (1958), using electromyography to study contractions of the middle ear muscles, who noted that these oscillations continued even for the open loop case; i.e. when the reflex does not attenuate the stimulus intensity. He achieved open loop contractions by stimulating the reflex contralaterally on rabbits, with cut muscle tendons in the stimulation ear. He comments that such findings support the results of Lorente De Nó (1935).

The evidence presented by Borg (1968) and Brask (1978) to support the case that the oscillations are due to the attenuation characteristics of the reflex is as follows. Both investigators compared the contralateral responses from a subject suffering from unilateral peripheral facial paralysis. This disability, paralyses the stapedius muscle so allowing measurements of the open loop response of the contralateral reflex. In both cases the oscillations and overshoots did not appear in the open loop tests, but were again present when the subject had recovered from the paralysis. These authors, therefore, concluded that these characteristics were due to the negative feedback effect of the reflex.

Negative feedback is generally accepted as being the main cause of the oscillatory characteristics of the reflex. Whether or not any secondary effects exist, as reported by Lorente De Nò (1935) and Wersäll (1958), still remains to be more fully investigated.

9.4.2 Quantification of the dynamic characteristics

This investigation quantifies the dynamic characteristics with three parameters: (i) the damped natural frequency ω_d, which is the frequency of oscillation of the response; (ii) the decay rate of the oscillations τ_D; (iii) a parameter α, which expresses the degree of the initial response overshoot as a proportion of the steady state value. These parameters are shown in figure 9.11.

The oscillation frequencies as found by other investigators are summarized in table 6. It may be seen from the investigations, that the oscillations vary in frequency between about 3 and 8.5 Hz. These results have been obtained from a very small sample of subjects. It is an aim of the present research to provide more information on the variability of the oscillation frequencies, from ear to ear.

The dependency of the oscillation frequency and magnitude of overshoot on stimulus intensity and frequency, has only been investigated by a few researchers. Hung and Dallos (1972), using impedance measurements, observed overshoots when the eliciting stimuli had frequencies between 400 and 800 Hz, but none outside this frequency band. The amplitudes of the overshoot initially increased

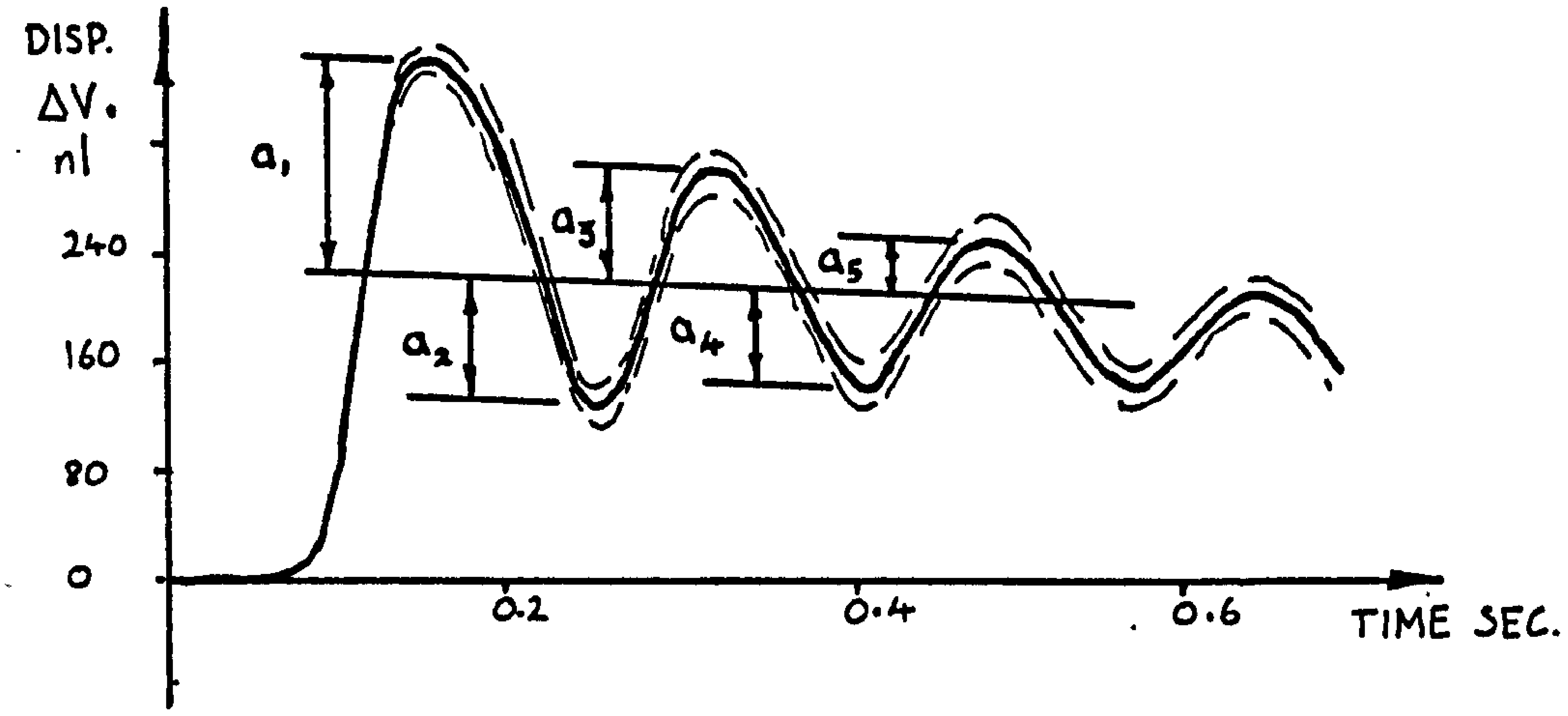


FIGURE 9.11 Measurement of reflex oscillatory parameters
Measurement of the parameters which express the damped natural frequency ω_d , the oscillation decay rate τ_D and the overshoot magnitude α .

If N equals the number of complete oscillations then

$$\omega_d = \frac{N}{\Delta T} \quad \text{and} \quad \tau_D = \frac{1}{2\omega_d \log_e A}$$

where $$A = \frac{1}{2N}\sum_{i=1}^{i=2N} a_{(i+1)} / a_i$$

with reference to figure 9.6

$$\alpha = \frac{\Delta V_{pk} - \Delta V_{ss}}{\Delta V_{ss}} = \frac{\Delta x_p}{\Delta x_f - \Delta x_o}$$

TABLE 6 OSCILLATORY CHARACTERISTICS OF THE STAPEDIUS REFLEX

AUTHOR(S)	METHOD	FREQUENCY OF OSCILLATION Hz
Møller (1962)	I	Approximately 5 Hz.
Weiss (1962)	P	Oscillations up to 8.5 Hz.
Borg (1968)	I	Approximately 5 Hz.
Hung and Dallos (1972)	I	From 3.0 to 6.0 Hz.
Brask (1978)	P	From 5 to 8 Hz.
Present study (1980)	TMD	From 4 to 8.5 Hz.

P - Pressure technique I - Impedance bridge with intensity, and decreased again at high intensity levels until ultimately they disappeared. Their results also indicated that the oscillation frequency decreases with decreasing stimulus intensity. Further features were observed by Borg (1968), also with impedance methods, who noted that the oscillations were more pronounced with low frequency ipsilateral stimulation than using contralateral stimulation. This observation was later verified by Brask (1978) with pressure measurements.

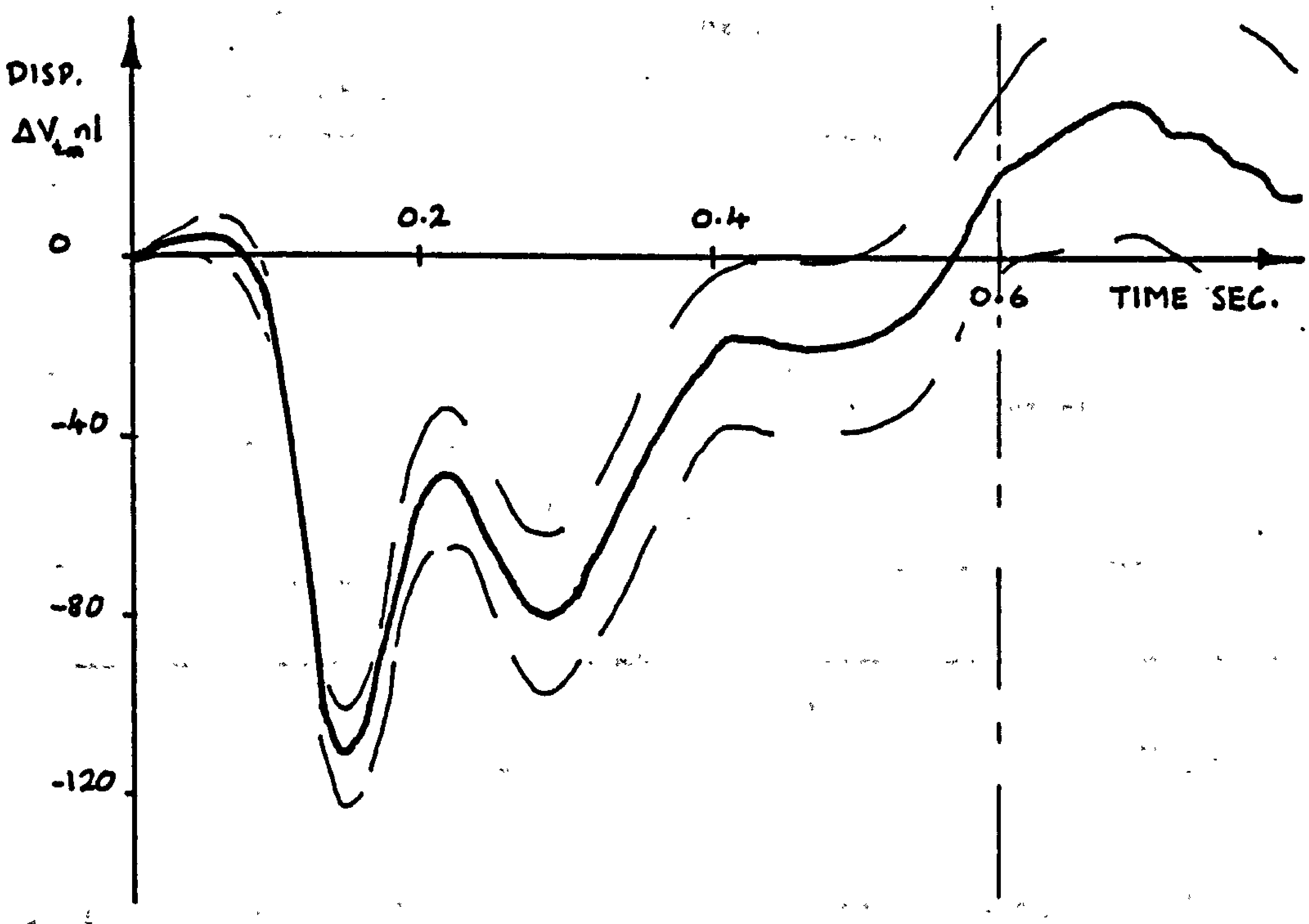
The results for this investigation were obtained from TMD plots, from 10 normally hearing subjects. Both ipsilateral as well as contralateral stimuli of frequencies 500 and 1000 Hz were used, at an intensity of 10 dB above the reflex threshold.

9.4.3 The results of the investigation.

All the subjects tested displayed overshoot or oscillatory characteristics for one or more of the tests. However, only 28 of the 75 tests performed, displayed measurable oscillatory characteristics. This in part was due to the difficulty experienced in measuring the frequency of oscillation of inward TM displacements and also because many results obtained a steady state value immediately after the first oscillation. (Figure 9.12).

Figure 9.13 shows the distribution of the overshoot magnitudes. Also given are the means and standard deviations of the distributions, not including zero overshoot values, and the percentage of zero values in the sample.

a) Oscillatory characteristics of the TM inward displacement phase.



b) A TM displacement response with only one complete oscillation.

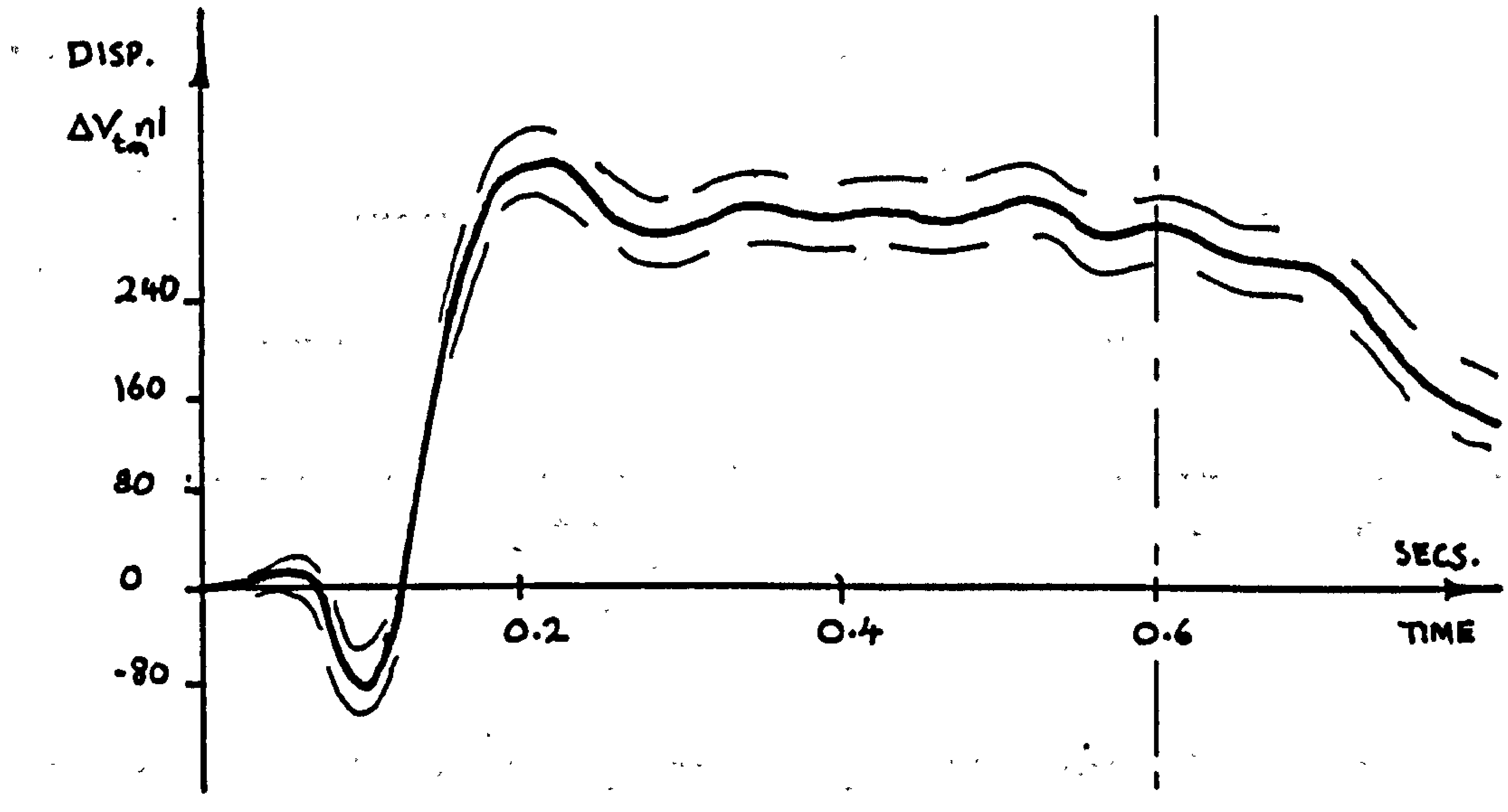


FIGURE 9.12 Underdamped TM displacement plot

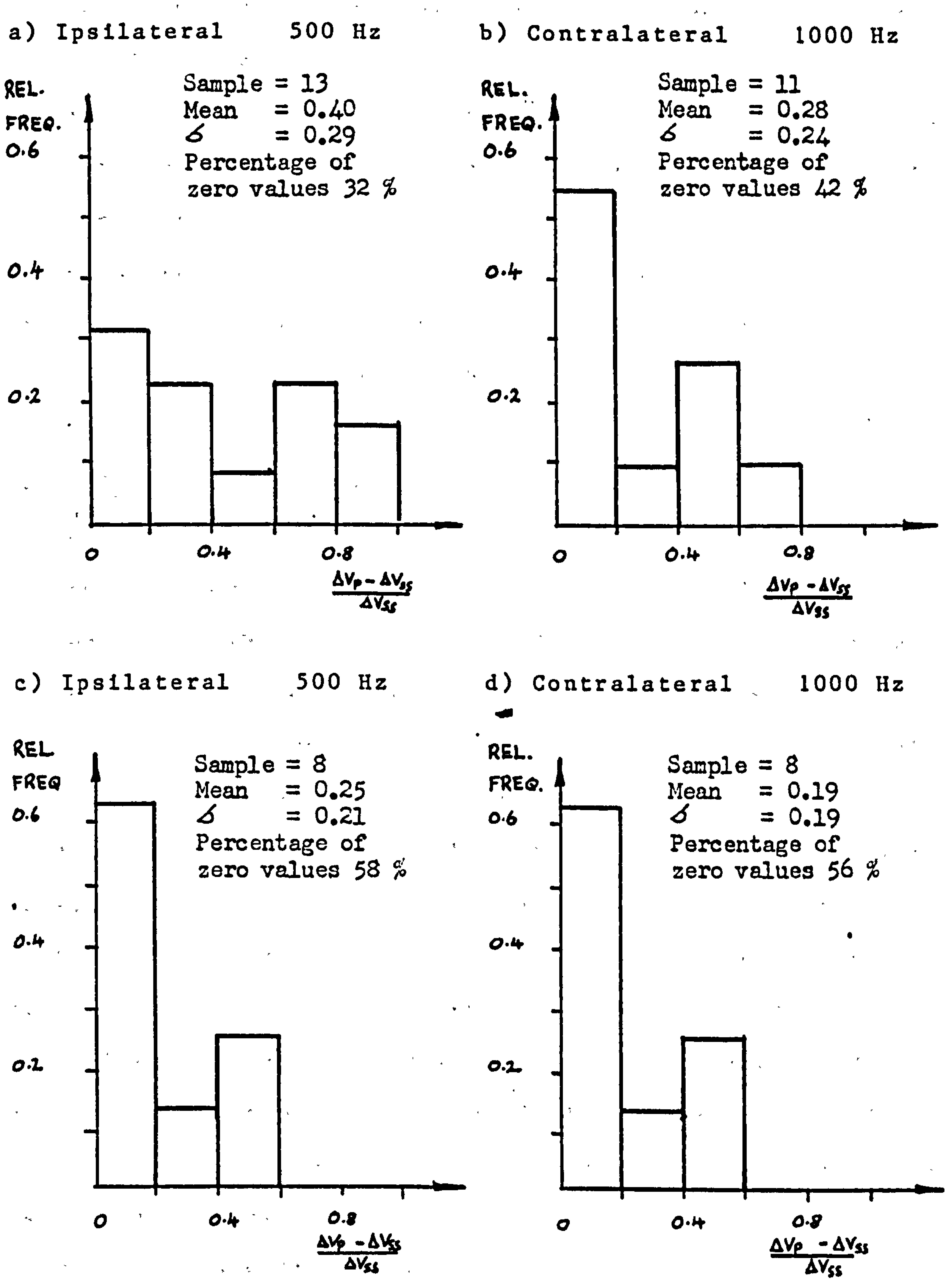


FIGURE 9.13 Relative frequency histograms of reflex overshoots

Sample numbers, means and standard deviations are exclusive of zero values.

The magnitudes of oscillation frequencies and oscillation decay rates are shown in figures 9.14 and 9.15 respectively. There are insufficient data to allow analysis of the variability of these parameters with frequency and type of reflex, whether ipsilateral or contralateral. Consequently, all the data have been combined to provide information on the overall distributions and ranges of these parameters.

9.4.4 Discussion of the results

Results from 28 tests which display oscillatory characteristics, indicate that the frequency of oscillation ranges from about 4 to 8.5 Hz. These results compare favourably with those observed in previous investigations which have a range of 3.0 to 8.5 Hz (Table 6). The oscillation frequencies, of this investigation, are fairly evenly distributed about the mean value of 6.4 Hz, figure 9.14, unlike the oscillation decay rates, which form a skew distribution ranging from 0.05 to 0.70 seconds, figure 9.15. Because of the skewness of this distribution, a typical sample value is given by the median, 0.13 sec, rather than the mean. On considering these results, it is felt that the parameter τ_D adequately expresses the oscillation decay charateristics of the reflex.

Borg (1976) writes that in the closed loop situation, and with low frequency stimulation, the occurrence of oscillations depend on several factors such as the reflex attenuation of the stimulus, the speed of the muscle response, the muscle latency time and offset time. Large

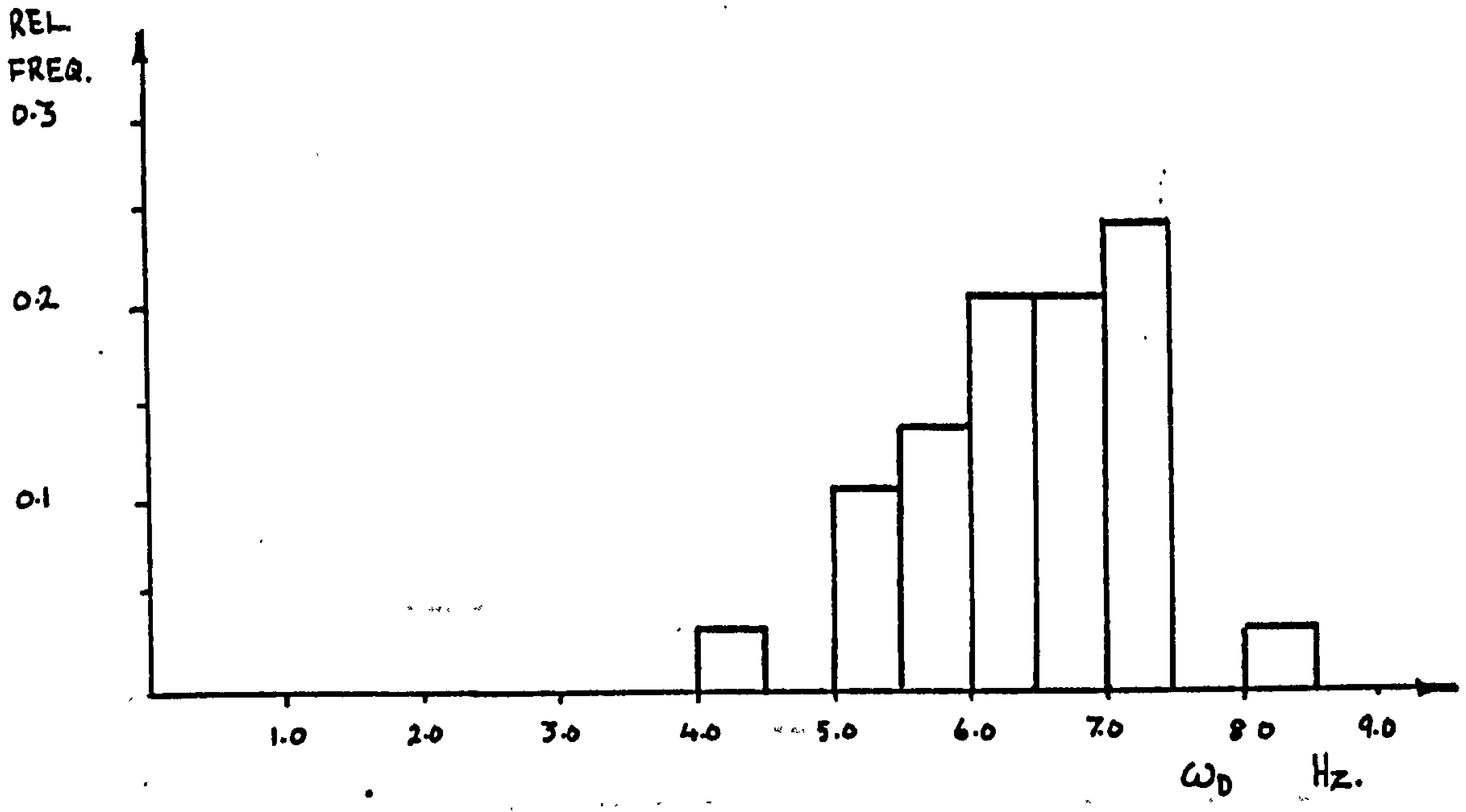


FIGURE 9.14 Relative frequency histogram of damped natural frequency

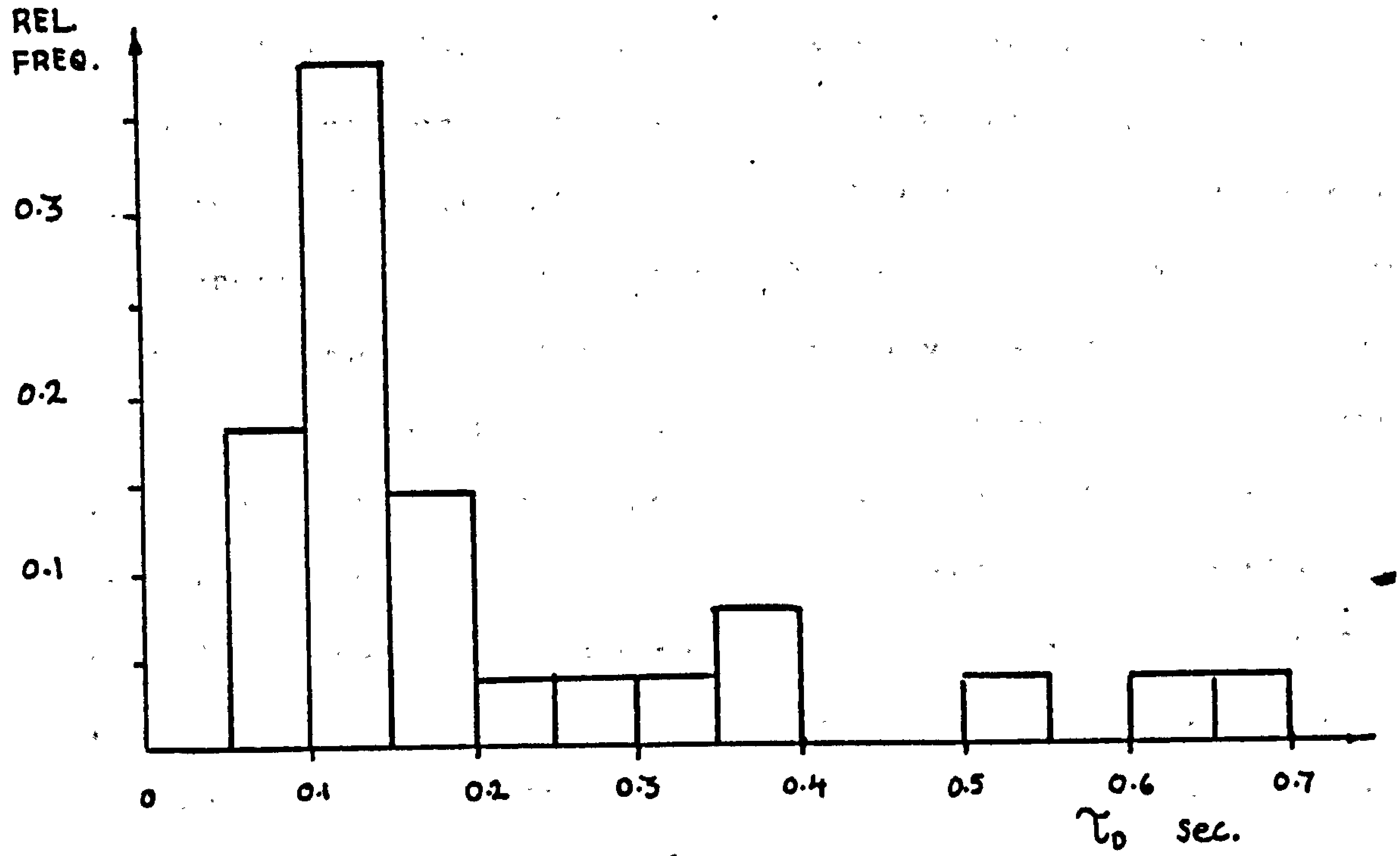


FIGURE 9.15 Relative frequency histogram of oscillation decay rates

degrees of attenuation, long latency, great onset speed and short offset time will potentiate the oscillations. Intuitively this reasoning seems correct; nevertheless, further investigations of an empirical nature are required before these hypotheses are proven.

A number of results which do not exhibit measurable oscillations do, however, display measurable overshoots. The distributions of the overshoot parameter α, displayed in figure 9.13, tend to indicate that the overshoot is more pronounced at 500 Hz than at 1000 Hz. This trend is shown both by a smaller percentage of zero values at 500 Hz and the larger mean values at this frequency. Greater overshoots at 500 Hz are expected, as this implies a greater attenuation of the 500 Hz stimulus than the 1000 Hz. This trend is supported by the research of Borg (1968) and Gunn (1973), which suggests that the attenuation afforded by the reflex was greater for low frequency tones than for high frequencies.

The overshoot results at 500 Hz also tend to show that the ipsilateral reflex is more pronounced than the contralateral, as indicated by the mean and percentage of zero values in the sample. For such a small sample, the proof of this trend is not conclusive but it does support the findings of Borg (1968) and Brask (1978).

9.4.5 Second order approximations

Hung and Dallos (1972) chose to quantify the oscillatory characteristics by approximating them to a second order response, and then calculating the damping ratio, ζ, and natural frequency, ω_n. It is conceivable that such a second order approximation may be useful, but by observation there is no doubt that this provides only a crude approximation to the actual dynamics. For instance Hung and Dallos (1972), as well as the present observations, show that the amplitude of the overshoot increases to a maximum value, decreases, and finally disappears on increasing the stimulus intensities from the reflex threshold value to a point where reflex saturation occurs.

The parameters ω_n and ζ derived by fitting a second order equation to the oscillations of the present results, have a larger variability than ω_d and τ_D. It was calculated that parameter ω_n had a range of about 5.8 to 19.0 Hz compared with 4.0 to 8.0 Hz for ω_d. Therefore, it seems pointless to adopt second order approximations when direct measurements are more accurate. Furthermore, since the system is not second order, there is no reason to imply that ω_n is any closer to the actual natural frequency of the reflex system than ω_d.

The frequency ω_d is measured for a damped reflex response. Therefore, it should be smaller in magnitude than the natural frequency of the reflex system, and as the damping decreases (as τ_D increases) the damped natural frequency should tend to the value of the natural frequency. Results from Hung and Dallos (1972) tend to support this prediction but more data are necessary before the hypothesis may be considered proven.

CHAPTER 10

THE MAIN CONFIGURATIONS OF THE REFLEX RESPONSE

A deeper understanding of the middle ear mechanism and reflex is achieved if the displacement motion of the tympanic membrane, caused by stapedius muscle contraction, can be explained in terms of the geometry and anatomy of the ear. Generally the TM displacement responses fall into one of three configurations

an inward, an outward displacement or an inward followed by an outward displacement. Examples of these are given in figure 10.1. The latter motion is known as a diphasic TM displacement. With all the subjects tested, an initial inward TMD configuration developed into a diphasic displacement when the intensity of the stimulus was increased.

Several investigators have studied the direction in which the middle ear muscles pull on the ossicles. With reference to figure 10.2, it may be seen that the direction of pull of the tensor tympani muscle is almost perpendicular to the plane of the tympanic membrane. Therefore, a contraction of this muscle will cause an

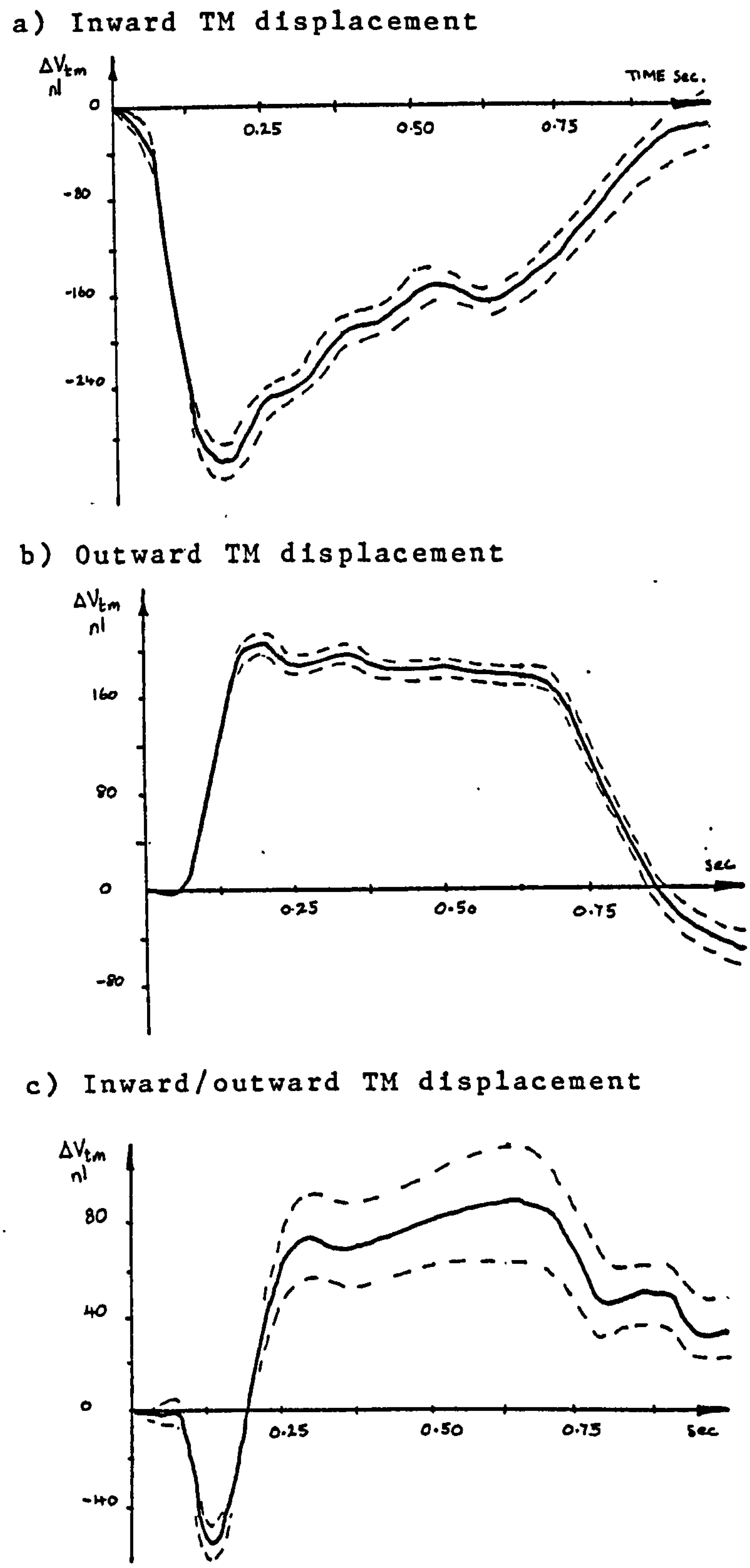


FIGURE 10.1 <u>Reflex TM displacement configurations</u>

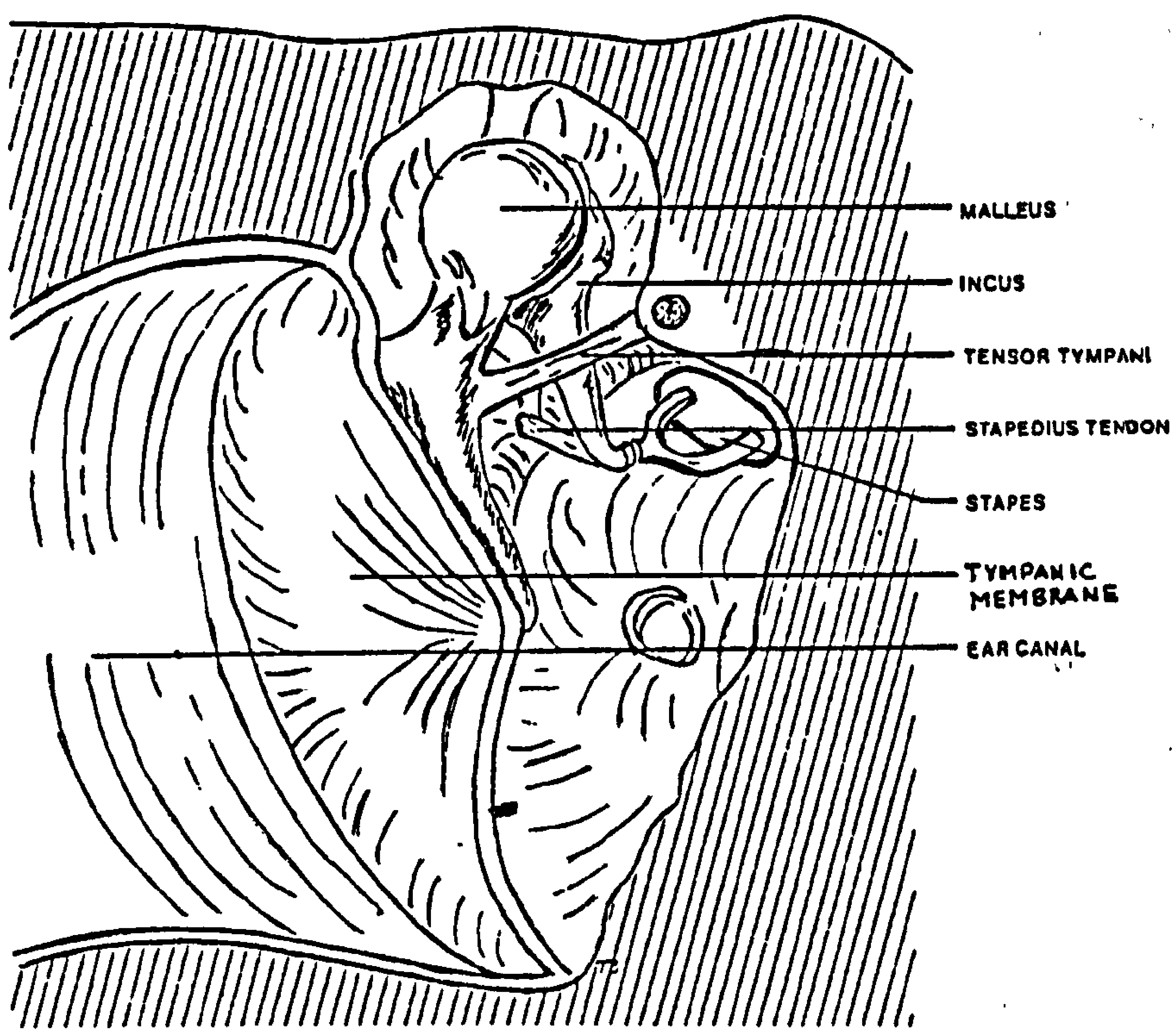


FIGURE 10.2 Frontal section through the middle ear
Reproduced from Brask (1978)

confirmed by Ingelstedt and Jonson (1966), Casselbrant (1977) and the results of section 8.2 which relate the inward displacement of the TM caused by swallowing to contraction of this muscle. However, the direction of the TM displacement caused by contraction of the stapedius muscle, is not so apparent. This displacement is complicated due to the pull of the muscle tendon being almost parallel to the plane of the TM. Noting, as previously mentioned, that the stapedius muscle causes the TM to move, i) outwards, ii) inwards or iii) inwards/outwards, and since the muscle pulls only in one direction, then a mechanical explanation of this phenomenon must be sought.

The following sections discuss, firstly, the variability of the main TMD configuration and, secondly, some hypotheses which have been proposed to explain these configurations.

10.1 INFLUENCE OF PERILYMPHATIC PRESSURE ON THE DISPLACEMENT OF THE TYMPANIC MEMBRANE

Investigations have shown that the variation in the inner ear pressure, that is the perilymphatic pressure, have drastic effects on the reflex TM configuration. Densert et al (1977) performed a quantitative study on the influence of variations in this pressure using preparations of human temporal bones. Stapedius muscle contraction was simulated by applying various tensions to the tendon of this muscle. The application of a negative pressure to the perilymphatic space caused the volume displacement of the TM, following a pull on the tendon, to become greater. Correspondingly, at positive pressures the TM displacement became regularly less pronounced. For one case, at negative pressures the TM moved outwards, whilst at positive pressures the TM moved inwards. These trends are consistent with results obtained by Casselbrant et al (1978) and Brask (1978).

Casselbrant et al (1978) observed that TM displacement configurations varied with the posture of the subjects during tests. They note that the sitting posture emphasized outward displacements, and the recumbent posture, inward displacements. They attributed their findings to the increase in the perilymphatic pressure as the subjects moved from the sitting to the recumbent position. Brask (1978) obtained similar results, and in one particular case, an outward TMD response in the sitting position changed into an inward response in the recumbent posture, figure 10.3. He also observed that it took approximately 20 to 25 minutes for the TM configuration to become stable when the pressure was increased by moving the subject from sitting to recumbent position. However, with a decrease of pressure, stability was obtained almost immediately.

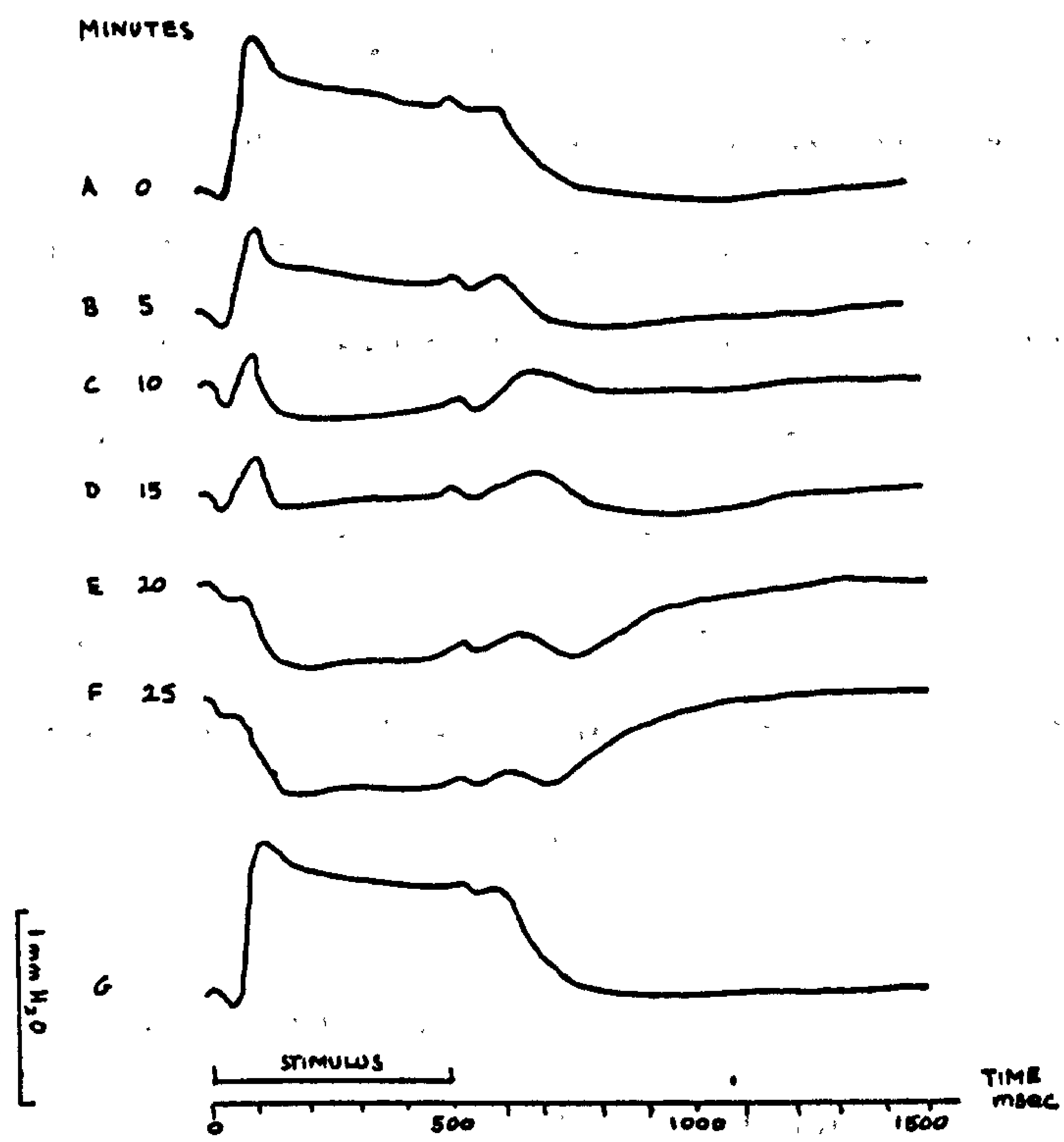


FIGURE 10.3 Variation of TM displacement configurations with posture

Ipsilateral reflex. A: the subject was in a sitting position. B-F: the subject was in a recumbent position. The main response developed into an inward configuration. G: the subject was again in a sitting position. Reproduced from Brask (1978).

10.2 VARIABILITY IN THE INWARD DISPLACEMENT OF THE TYMPANIC MEMBRANE

It was found that 9 out of 10 of the subjects tested during the present investigation, exhibited an initial inward displacement of the tympanic membrane on contraction of the stapedius reflex. Inward displacement magnitudes were measured, from a sample of 19 normally hearing ears, with the intention of providing qualitative information on its variability between the subjects and tests. Also studied on several ears, is the relationship between the magnitude of the inward displacement phase and the overall intensity of the reflex response.

10.2.1 Other investigations

The inward displacement of the tympanic membrane, on contraction of the stapedius muscle, has been observed by a number of investigators but to the author's knowledge no detailed quantitative studies have been undertaken. Casselbrant et al (1977,1978), using a flowmeter technique, measured the inward displacement, but their technique was only capable of measuring the gross displacement. Consequently the magnitude of the inward phase was not isolated from the outward phase.

Brask (1978), using a pressure measuring technique, found that with some subjects, the magnitude of the inward displacement increased with decreasing stimulus intensities.

10.2.2 Results of the present investigation

Altogether 72 sets of results were studied for inward TM displacements at stimulus intensities of 10 dB above the reflex threshold. These tests were performed on 19 ears for both ipsilateral and contralateral reflexes, at frequencies of 500 and 1000 Hz. About 32% of these results did not show any measurable inward displacements. Out of the remaining results, only those which show an inward followed by an outward displacement were analysed, as only responses with completed inward displacement phases are of interest. These 44 sets of results were preliminarily analysed in four categories, according to the stimulus frequency and whether it was a contralateral or ipsilateral stimulation. It was found that the displacement distributions for each of these categories were similar, so consequently they were combined to give an overall distribution, as shown in figure 10.4.

10.2.3 Discussion of the results

The sample mean of the inward displacement distribution (figure 10.4) is 91 nanolitres. However because of its skewed nature, the median value of 60 to 70 nl is more representative of an expected sample value.

A small number of tests were further analysed to determine if the magnitude of the inward phase varied with the intensity of the reflex response. Figures 10.5 a,b,c, show the magnitudes of the inward, Δx_i, plotted against the outward, Δx_o, phases of the TMD plots, for three subjects. For these subjects, the results show that there is a

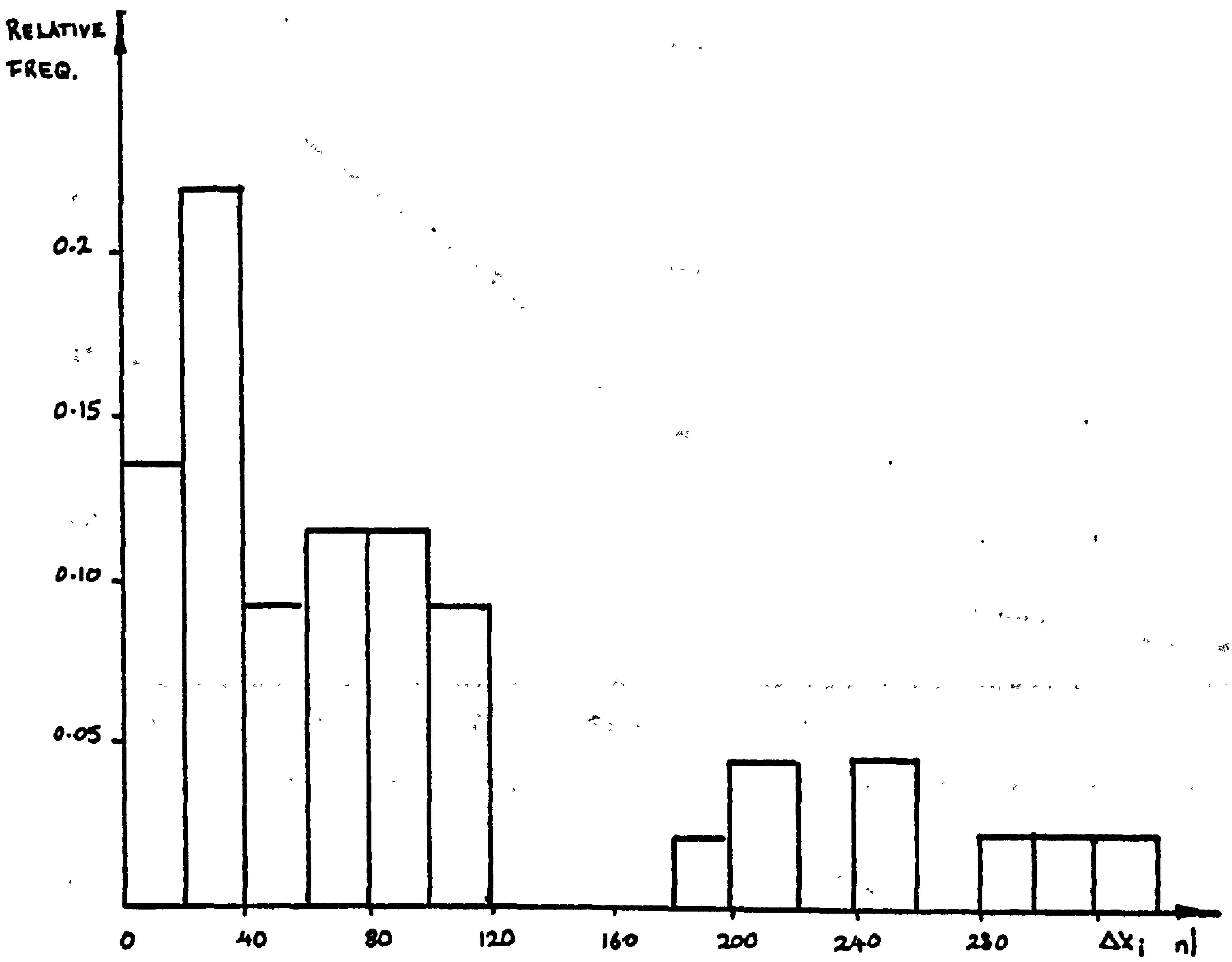


FIGURE 10.4 TM inward displacement phase amplitudes
Sample of 44 ears. Mean diplacement 91 nl+

+ Exclusive of zero values.

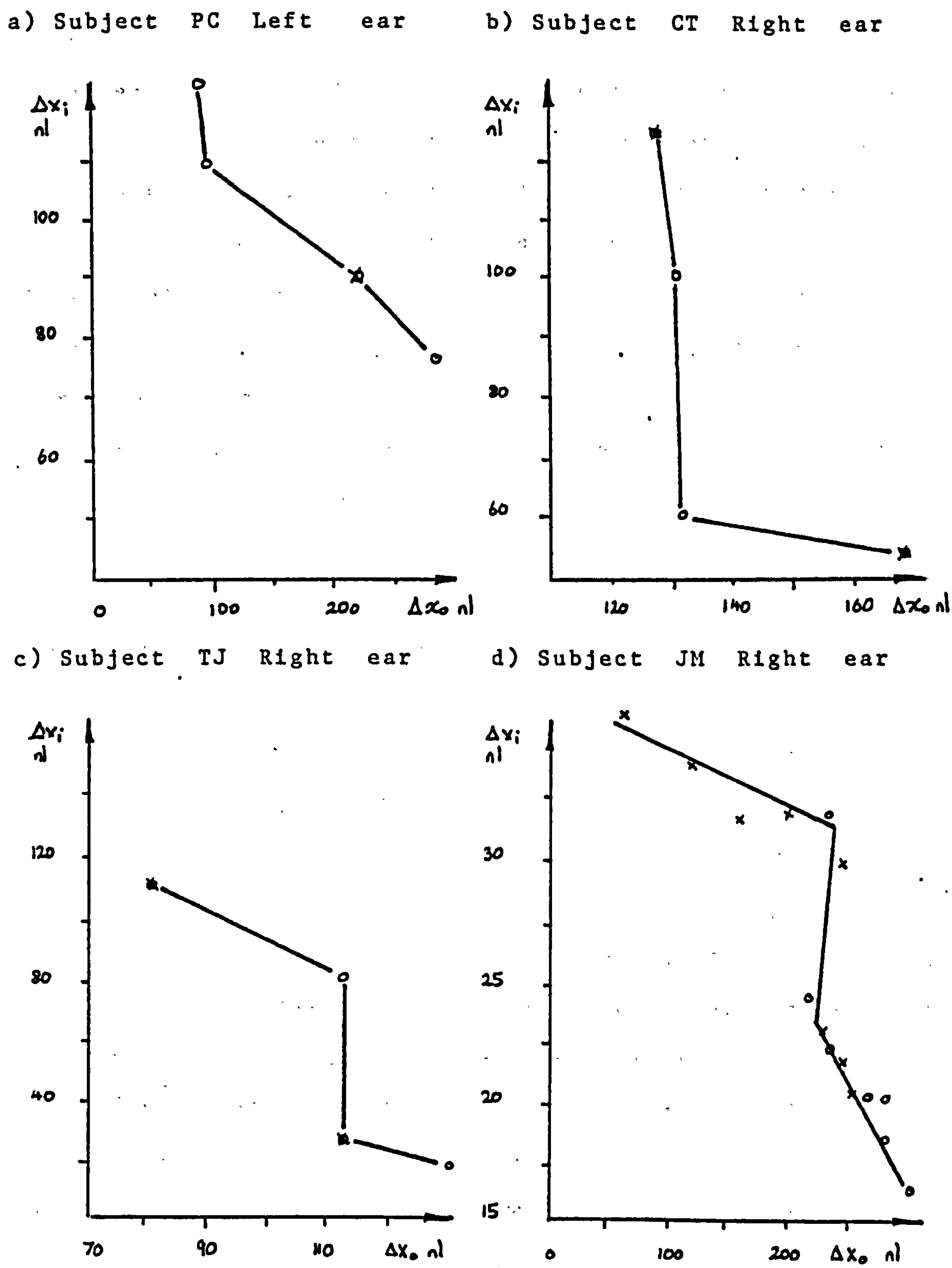


FIGURE 10.5 <u>Inward TM displacement vs outward displacement</u>
Key: × - 500 Hz o - 1000 Hz

tendency for the magnitude of the inward displacement to decrease with the intensity of the reflex response, as observed by Brask (1978). For one subject, this trend was studied in more detail by analysing further test results, see figure 10.5 d. This graph clearly shows that when the outward displacement becomes equal to about 220 nl, there is a rapid decrease in the inward displacement for increasing TM displacement intensities. However, the cause for this phenomenon is not apparent.

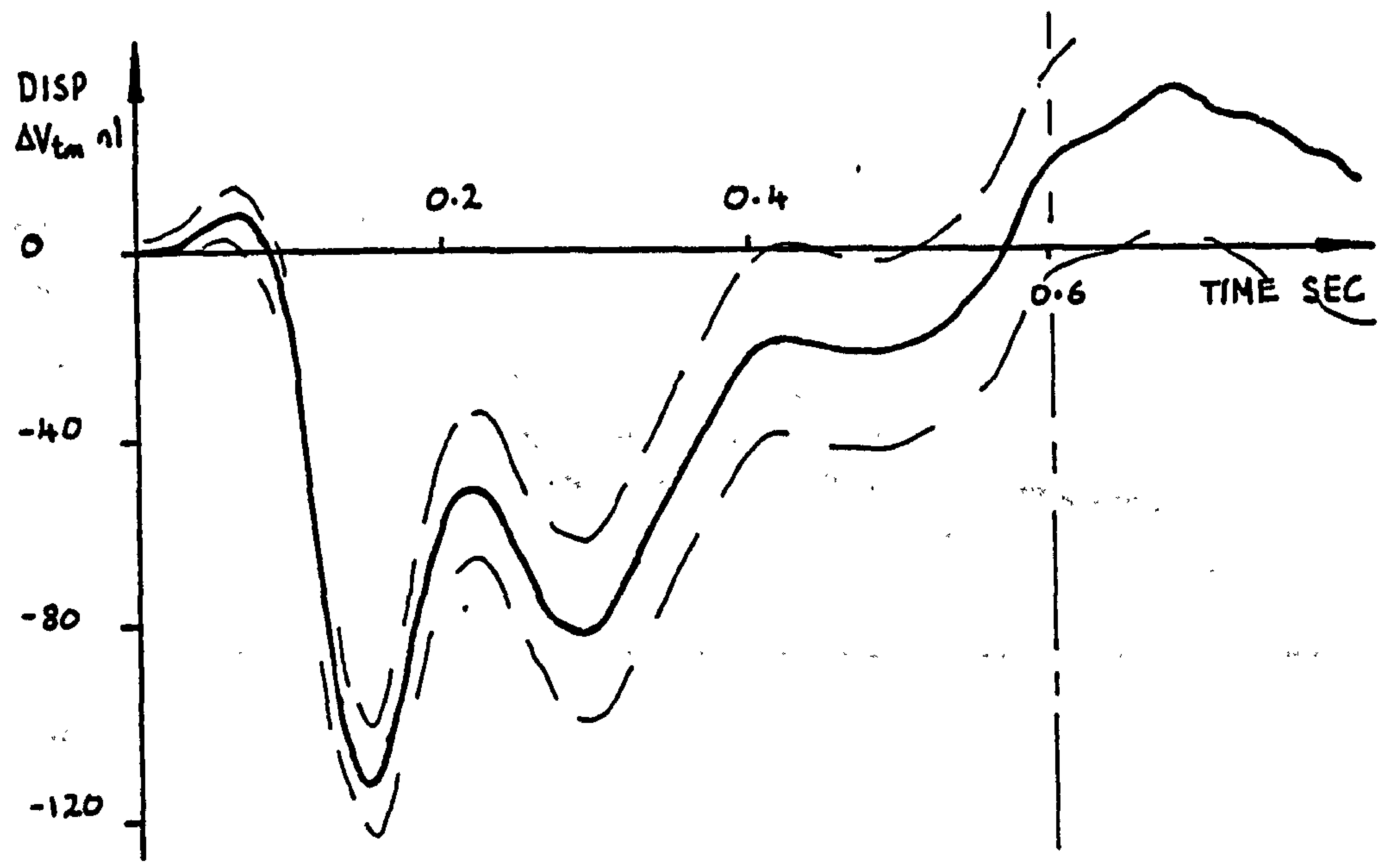
Figure 10.6 shows some of the TMD plots corresponding to the results of figure 10.5.

10.3 CONSISTENCY OF TM RESPONSES

Brask (1978) noted that, provided certain precautions were adhered to, the TM responses remained consistent over periods of days or weeks. Figure 10.7 shows the TM displacement responses, for the same subject under similar conditions, over a period of several days. It is, however, important to perform the tests with the subject in similar positions of posture. Several investigators, Casselbrant et al (1977,1978), Brask (1978) and Densert et al (1978), found that the TM displacement configuration varies with posture due to resulting variations in the pressure within the inner ear (see section 10.1).

All the tests of the present investigation were performed with the subjects in an upright sitting position.

a) Test TN12 2 OCT 1979



b) Test TN10 2 OCT 1979

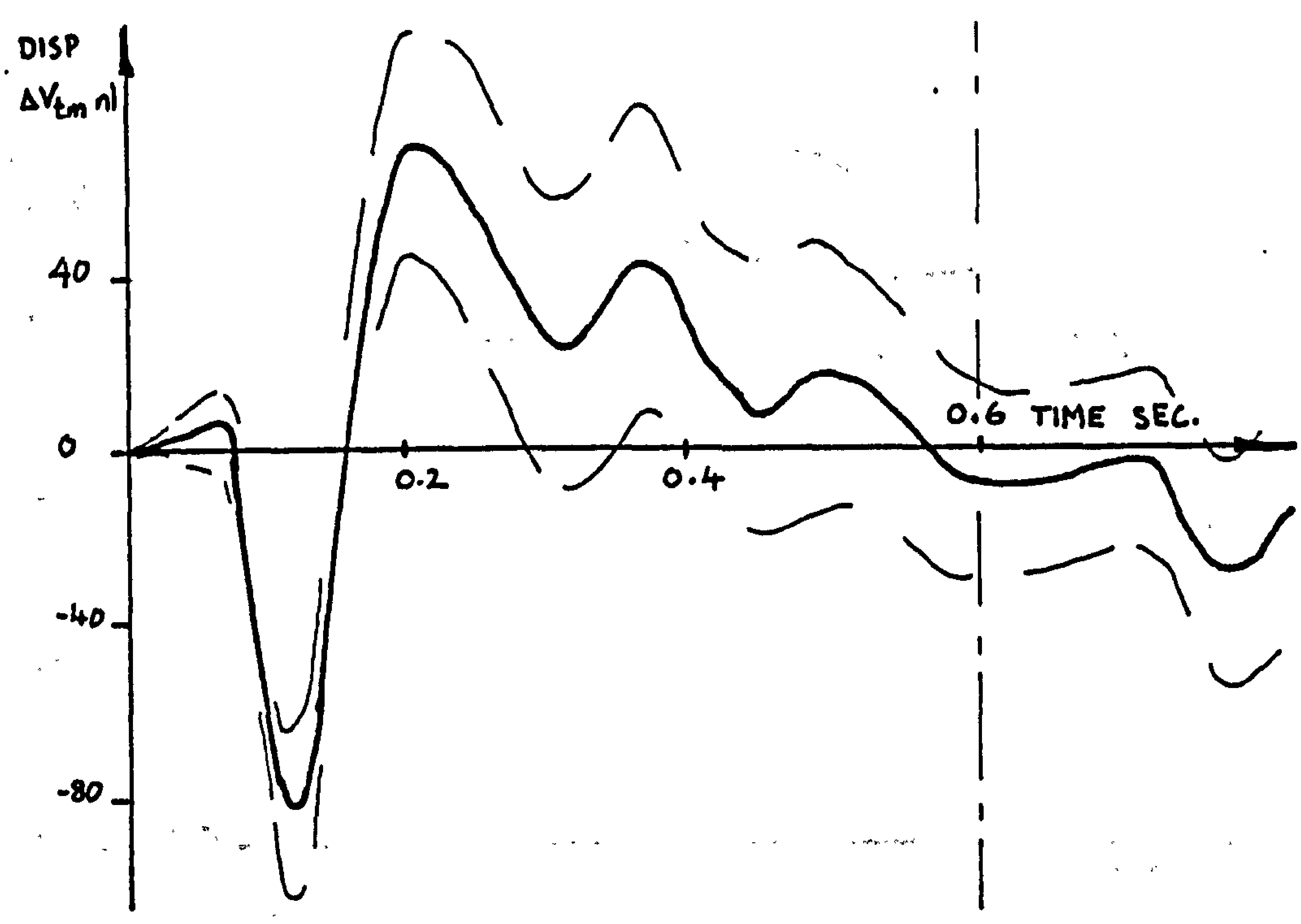
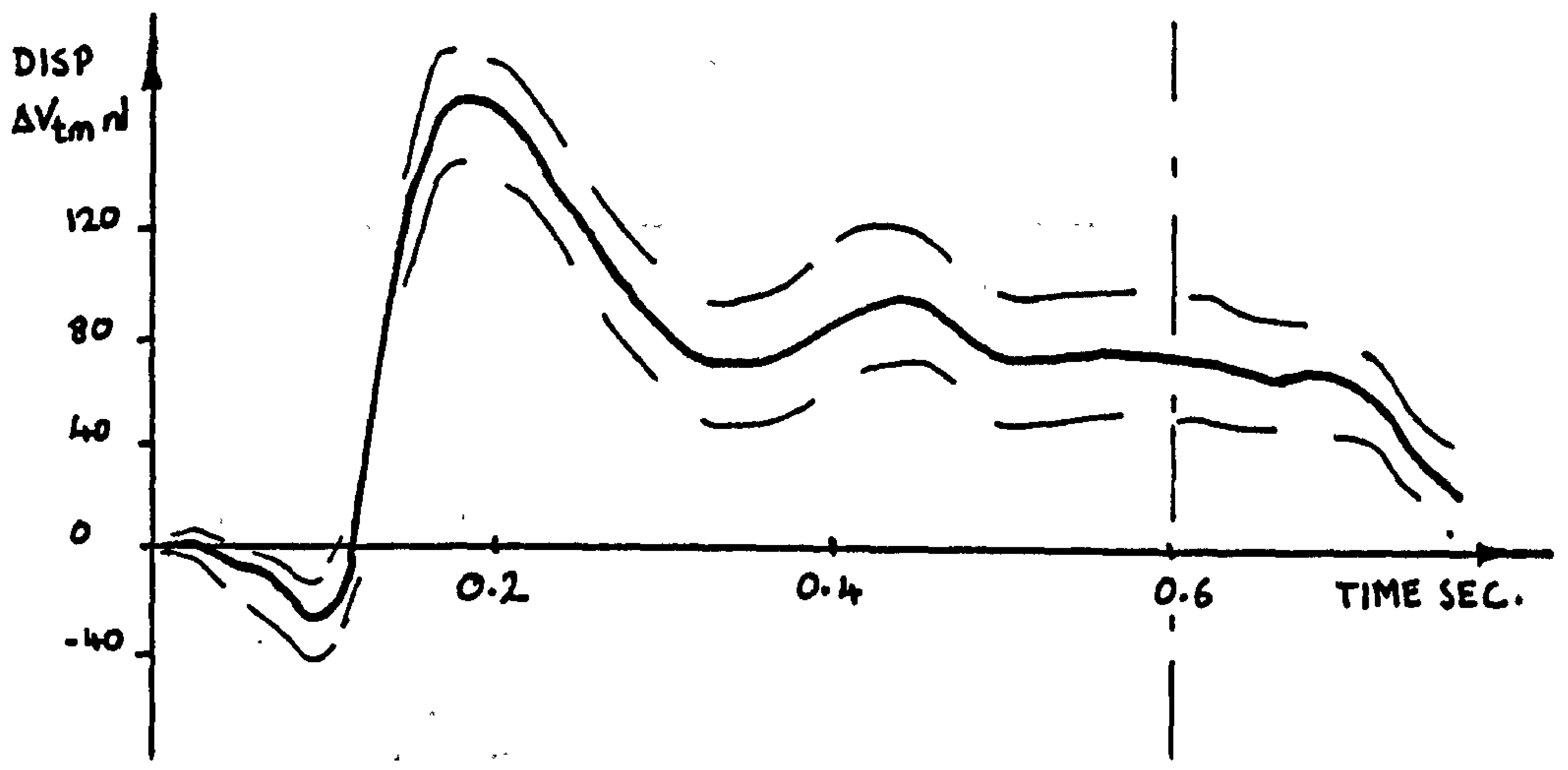
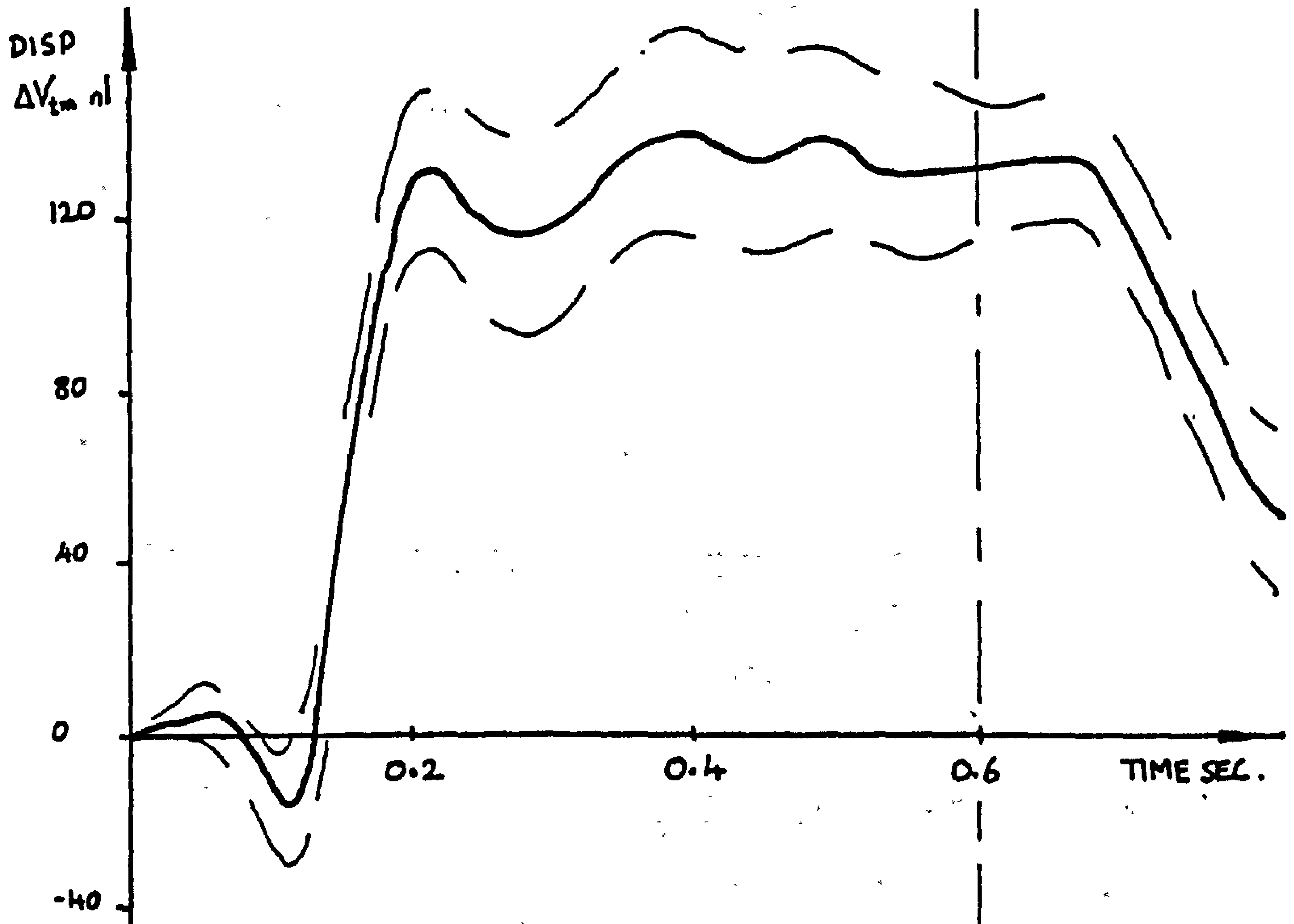


FIGURE 10.6 Four reflex results showing decreasing inward displacement with increasing reflex intensity
Subject TJ

FIGURE 10.6 Continued

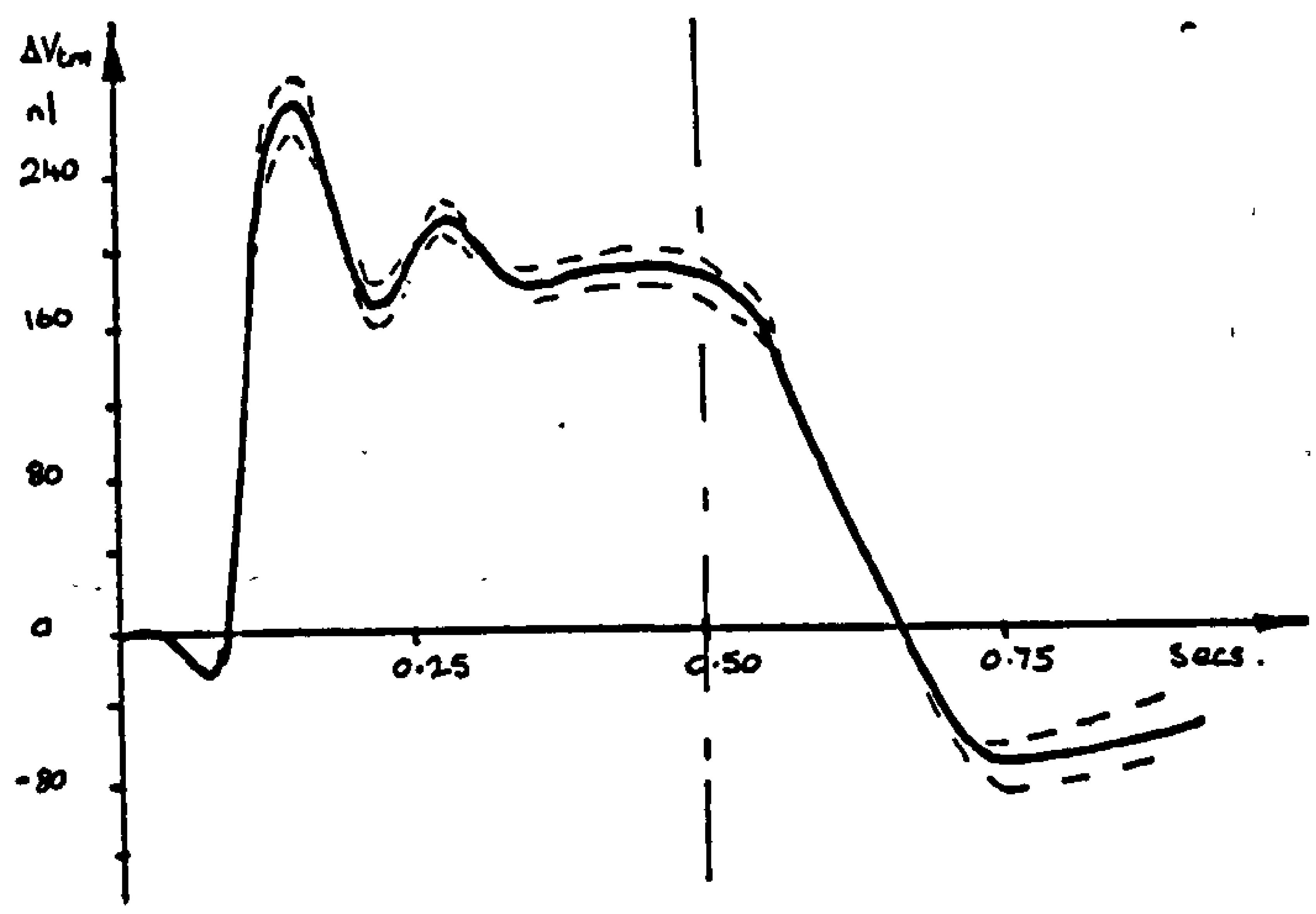


c) Test TN9 2 OCT 1979

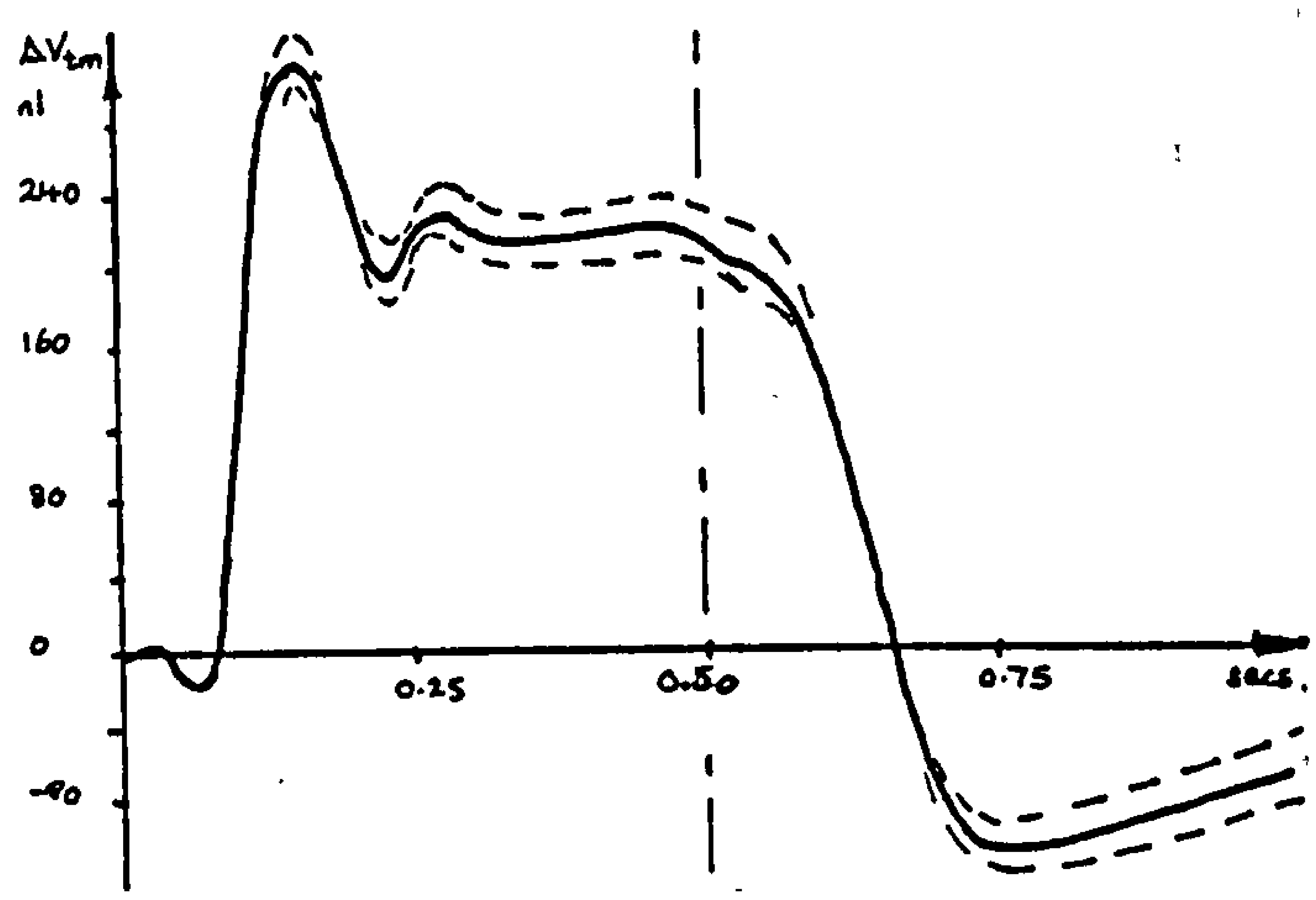


d) Test TN11 2 OCT 1979

a) Test TN17 15 AUG 1979



b) Test TN2 5 SEP 1979



c) Test TN2 17 SEP 1979

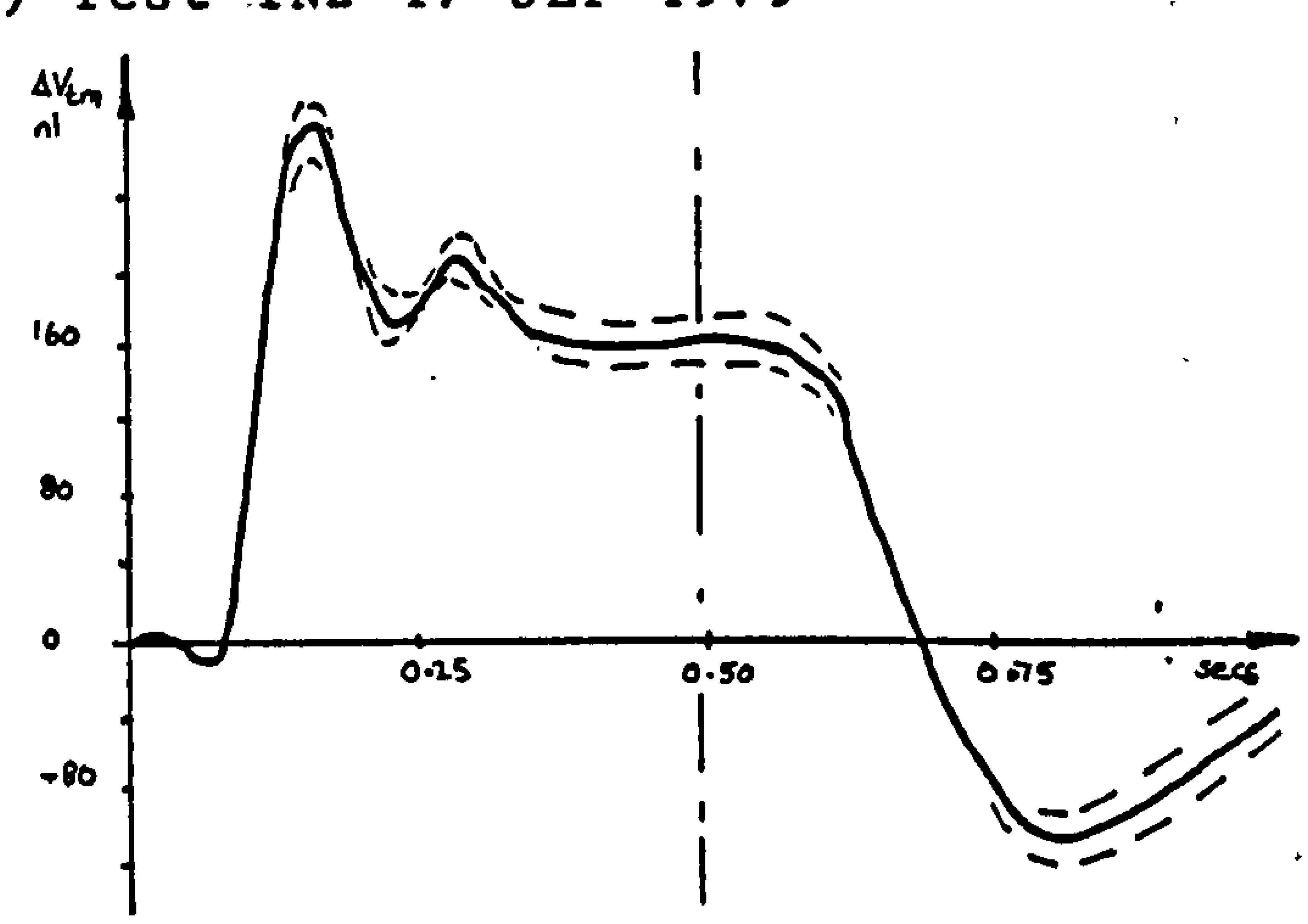


FIGURE 10.7 <u>Consistency of TM displacements over a period of a month</u>
Subject JM, right ear ipsilateral, 1000 Hz, 90 dB SPL.

10.4 VARIOUS HYPOTHESES FOR THE DIPHASIC DISPLACEMENT OF THE TYMPANIC MEMBRANE

Several investigators have proposed various hypotheses to explain the diphasic displacement of the tympanic membrane on contraction of the stapedius reflex. These propositions have been made as results of both pressure and volume displacement measurements (eg Weiss et al 1962; Casselbrant et al 1978; Brask 1978), as well as impedance bridge measurements. Often impedance measurements of the reflex show an initial decrease followed by an increase in impedance. Whether or not the diphasic impedance response relates to that of the TM displacement remains to be investigated. However, several authors have assumed that it does (Love and Stream 1978) and therefore have attempted to hypothesize on the mechanism for the diphasic TM displacement as a result of impedance studies.

The hypotheses for the diphasic displacement generally fall into one of three categories:

i) Relaxation followed by contraction of the stapedius muscle.

ii) Combined tensor tympani and stapedius contraction.

iii) Geometric configuration and dynamics of the stapedius muscle with the middle ear mechanism.

These three categories will be discussed in the following sections.

10.4.1 Stapedius muscle relaxation and contraction hypothesis

The stapedius muscle relaxation and contraction hypothesis is probably the least favoured of the three categories, and it is shown in this section to be an inadequate explanation of diphasic TM displacement observations.

Some investigators, including Hung and Dallos (1972) suggest that the initial inward movement is due to relaxation of the stapedius muscle. In an attempt to explain diphasic impedance observations, they relate the muscle relaxation to a phenomenon known as muscle latency relaxation described by Sandow (1944). This relaxation was reported to be of a duration of approximately 3 msec and of a magnitude of about 0.2% of the maximum tension of the muscle contraction.

Since this muscle latency relaxation is said to occur immediately before the main tensioning phase of the muscle, it provides an inadequate mechanism for the inward TM displacements, which sometimes last for several seconds or more. Therefore, this category of hypothesis does not adequately explain the main configuration of the TM response.

10.4.2 Stapedius and tensor tympani muscle interaction hypothesis

Several investigators have hypothesized that bilateral displacement is due to the interplay of the two middle ear muscles. In particular, it is suggested that they often work in an antagonistic manner, such that the tensor tympani pulls the TM inwards, and the stapedius pulls the membrane outwards. Weiss et al (1962) proposed this possible explanation to account for their pressure measurements. Love and Stream (1978) proposed such an hypothesis to explain bilateral impedance measurements, and further suggested that the tensor tympani is the main contributor to the acoustic reflex.

This hypothesis does not suitably account for the results obtained during the present investigation or during other pressure or TM volume displacement investigations. This hypothesis postulates that the initial decrease in impedance is due to stapedius, followed by the tensor tympani reflexes. However, TMD results show if anything, an inward followed by an outward displacement. If this were the action of two antagonistic muscles, then it would require that the tensor was followed by the stapedius muscle, and also that the tensor tympani had the shortest latency. Such conditions are contrary to the widely accepted view that the tensor has the longest latency. Even if the tensor did have the shortest latency, then the TMD results provide further evidence against this hypothesis. That is the TMD results show that the magnitude of the inward displacement initially increases to a certain maximum value, and then remains constant or decreases with any further increase in the stimulus intensity (section 10.2). This maximum inward displacement is of an order of magnitude smaller than the saturation displacement value for the tensor tympani.

The TMD results also refute the postulate of Love and Stream (1978), which states that the tensor tympani is the main contributor to the acoustic reflex. For the subjects tested, the results show that for high stimulus intensities the TM will always displace outwards. According to all the existing evidence, an outward displacement is due to stapedius muscle contraction and not tensor tympani as required by the hypothesis of Love and Stream (1978).

<u>10.4.3 Middle ear geometric configuration and dynamics hypotheses</u>

Casselbrant et al (1978) and Brask (1978) hypothesized that the diphasic TM displacement is caused by the geometry, and dynamics, of the middle ear mechanism in relation to the stapedius muscle. These hypotheses vary in that Casselbrant considers the motion to be due to the relative positioning of the stapedius muscle, to the position of its attachment to the stapes. Brask on the other hand, considers it to be due to the motion of the stapes footplate in the oval window. The results of the present investigation are in general agreement with the hypothesis of Brask (1978) and are dealt with in this respect in the present section.

The results of Casselbrant et al (1978) are only accurate enough to show the gross volume displacement of the TM and not the diphasic characteristic, so that on considering the effect of a pull from the stapedius muscle on the stapes, they were only attempting to explain why:

i) The TM apparently moves in different directions for different subjects.

ii) The direction may be reversed by varying the perilymphatic pressure (section 10.1).

Their hypothesis relies on the direction of pull of the stapedius muscle being critically related to the resting position of the stapes, see figure 10.8. That is, in certain positions, the muscle contraction results in an inward movement and in other positions, an outward movement. The main drawback of this hypothesis is that it does not allow for diphasic TM responses. The movement may only be unilateral. Furthermore, one may question any hypothesis which relies on such critical positioning of the stapes and stapedius muscle.

The present investigation has provided additional information on the TM displacement as caused by the stapedius muscle reflex. It is, therefore, possible to propose a mechanism to account for the main configurations of the reflex response. This mechanism is principally an elaboration of the hypothesis made by Brask (1978), who proposed that the principal factors influencing the configurations were:

i) The force and velocity of the stapedius muscle contraction.

ii) The ratio between the elasticity of the anterior

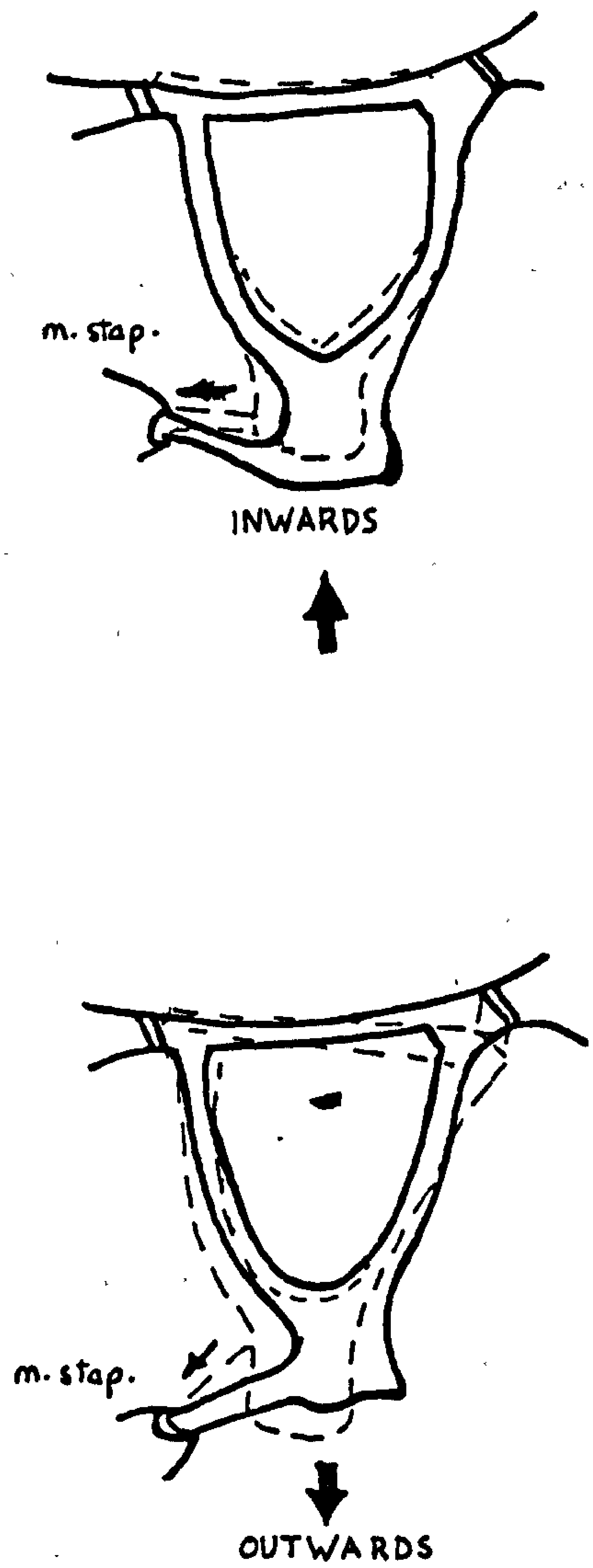


FIGURE 10.8 Configuration hypothesis of Casselbrant et al (1978)

Explanation of the different movement directions of the tympanic membrane at stapedius reflex contraction. Reproduced from Casselbrant et al (1978).

and posterior parts of the annular ligament surrounding the footplate of the stapes.

iii) The resting position of the stapes.

These factors are subsequently discussed in more detail.

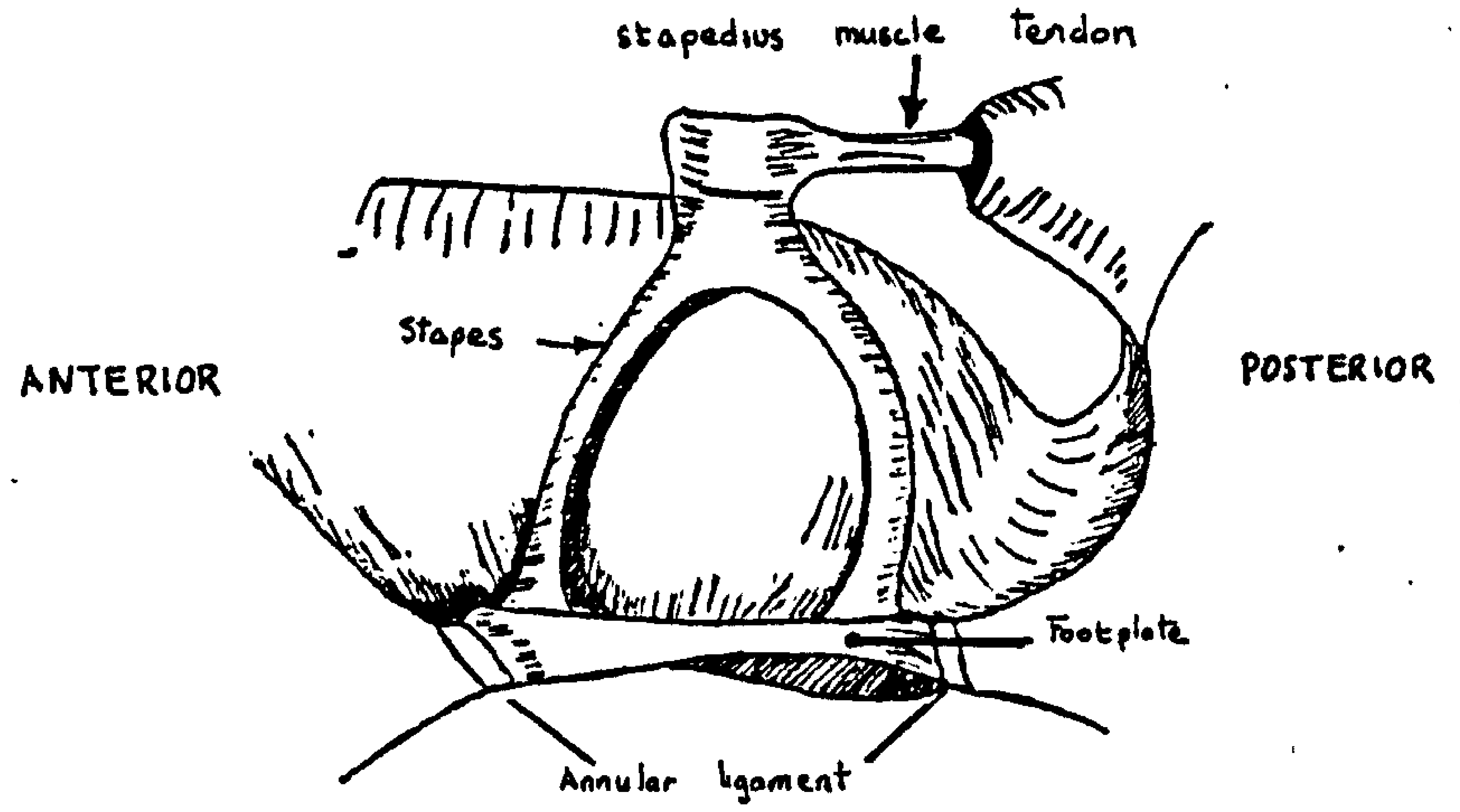
Before hypothesizing on a possible mechanism, one must first consider the means by which the stapes is suspended in the oval window as well as its modes of displacement. These are outlined in the following section and are also dealt with in detail by Brask (1978).

10.5 Suspension of the stapes in the oval window

The innermost ossicle is the stapes, shown in figure 10.9. The stapes transmits vibrations from the other ossicles and tympanic membrane into the inner ear. This is accomplished by the footplate of the stapes being suspended in the oval window by the annular ligament. This ligament is shown in a photomicrograph of a section through a human stapes, presented by Békésy (1957), figure 10.10. Being a flexible attachment to the oval window, the stapes is free to move and vibrate in modes determined by the ligament and the incudo-stapedial joint.

Several investigators have studied the modes of vibration of the footplate for sounds of varying amplitude and frequency. Békésy (1960) isolates the stapes vibration into three modes as shown in figure 10.11. He notes that the stapes rotates about an axis at the posterior end of the footplate, for low frequency stimulation and sound

a) Figure showing the attachment of the stapes footplate to the oval window.



b) The anterior and posterior regions of the annular ligament.

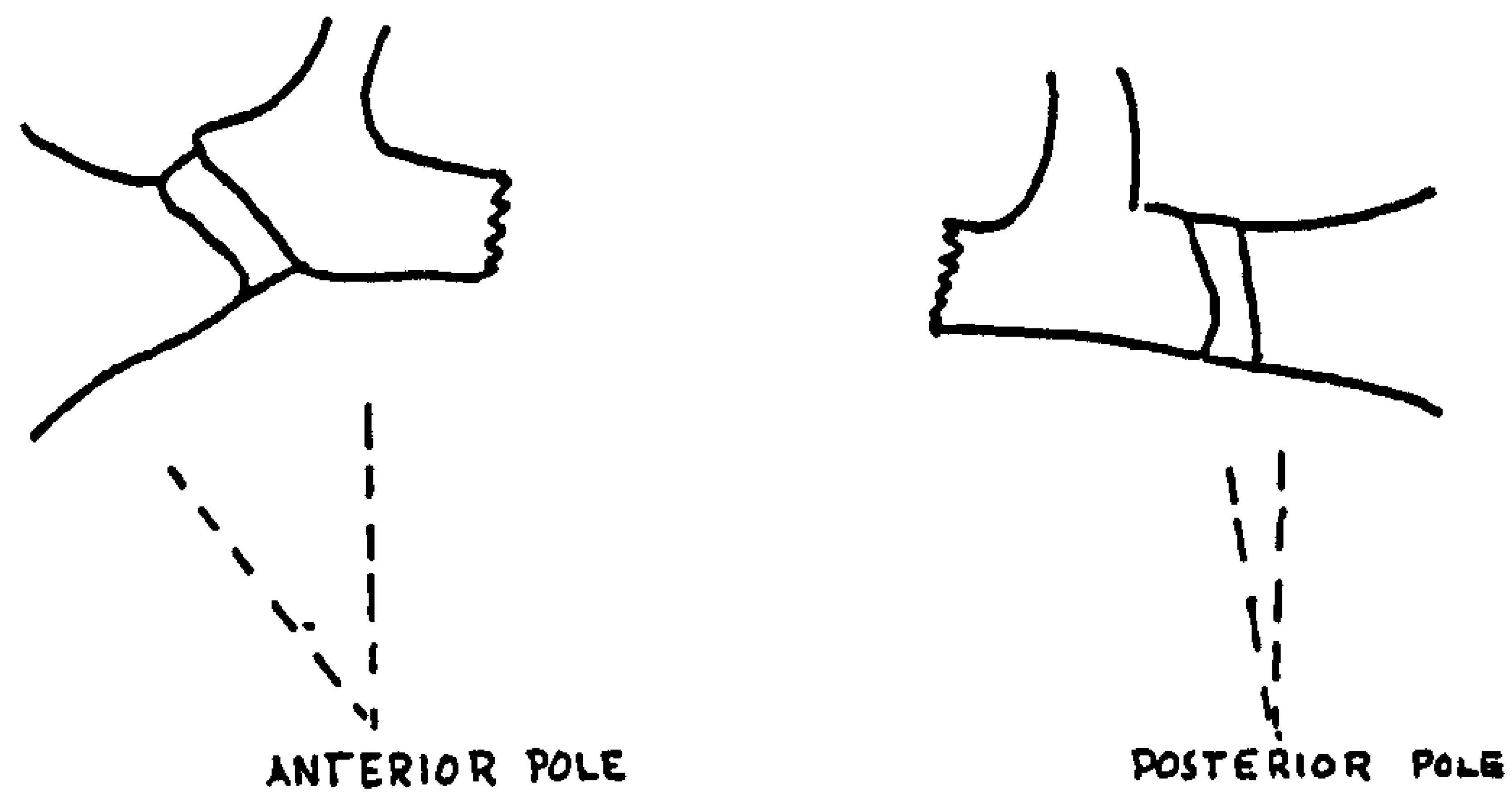


FIGURE 10.9 The stapes and annular ligament
Reproduced from Bel et al (1976)

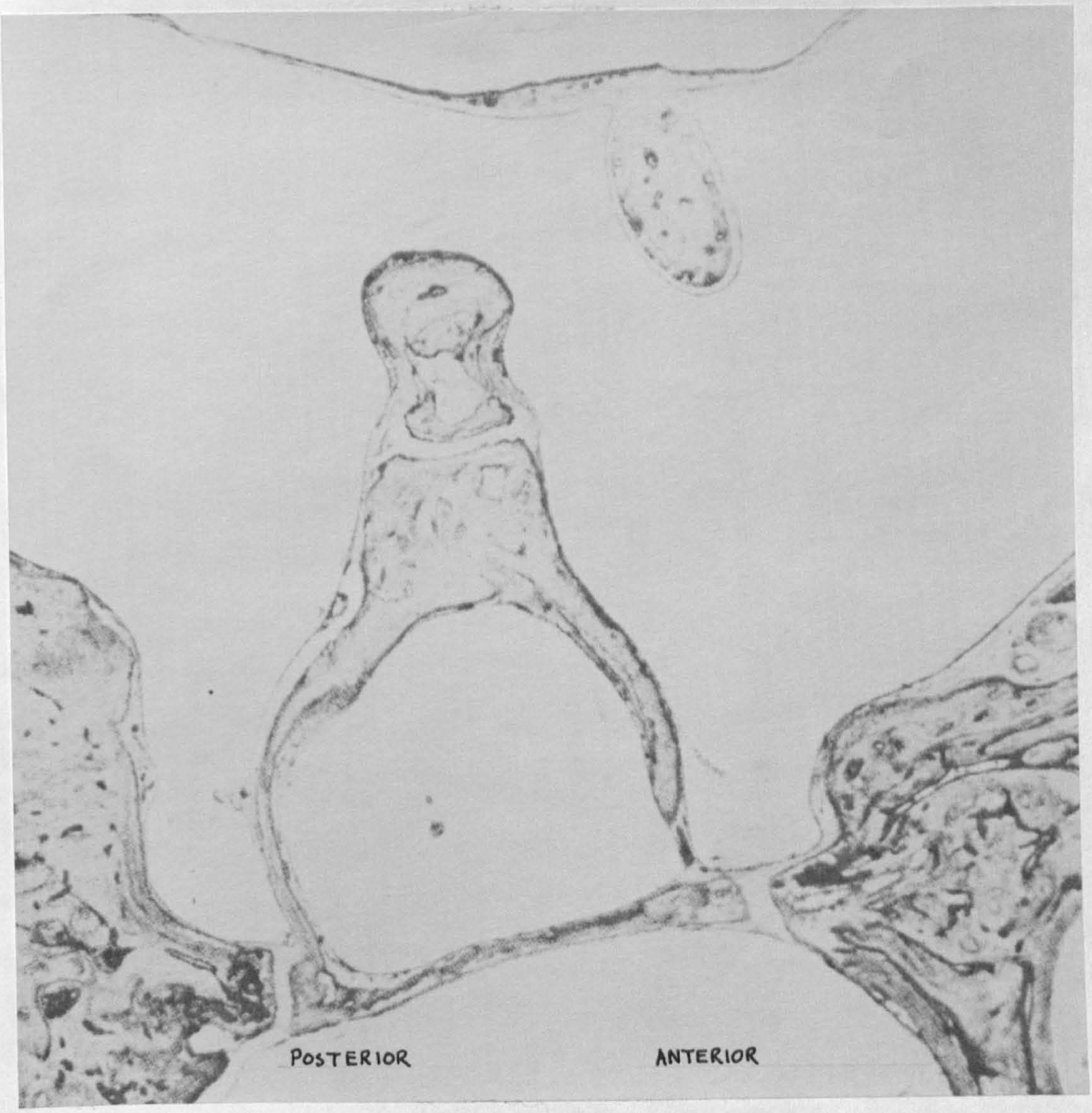


FIGURE 10.10 Photomicrograph of a section through a human stapes and oval window

The stapes of a normal human ear enlarged 19 times. The thin line at the top of the page is the tympanic membrane. The annular ligament may be seen as a translucent area between the footplate and the surrounding bone.

From Békésy (1957).

FIGURE 10.11 Modes of vibration of the stapes proposed by Békésy (1960)

The dashed lines represent the axes of rotation. a) Rotation about an axis through the posterior end of the footplate. b) Rotation about the long axis of the footplate. c) "Pistonlike" motion.

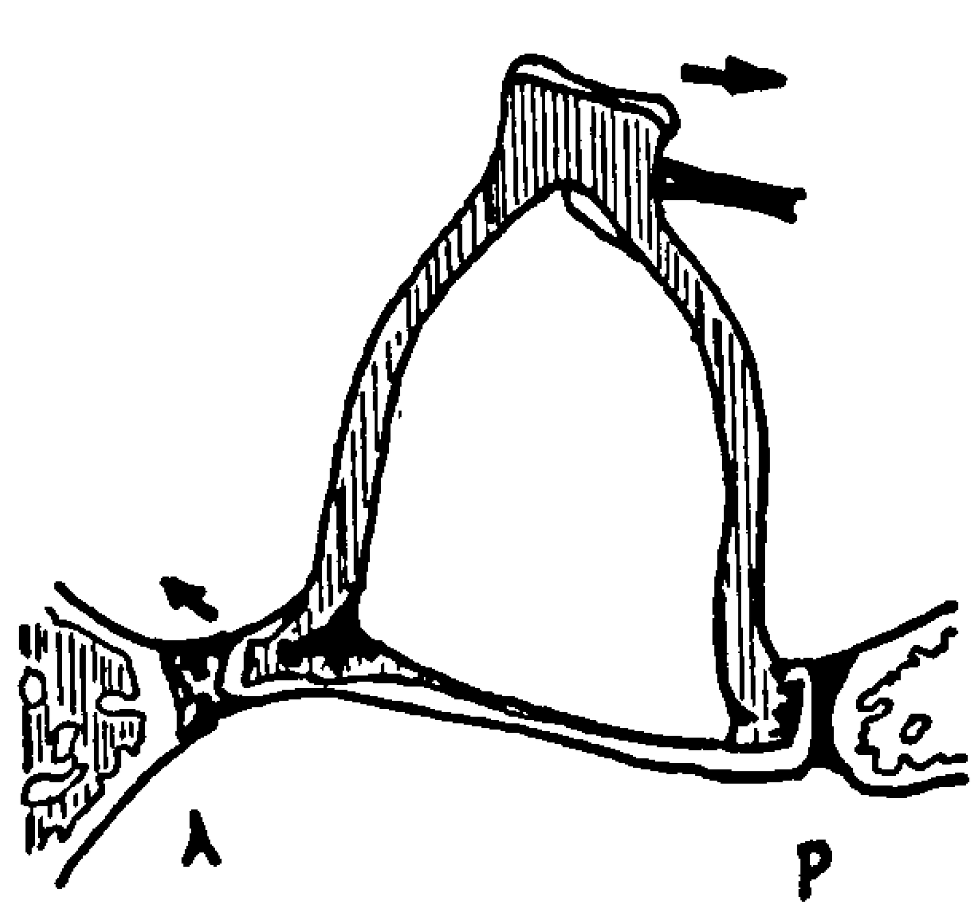


FIGURE 10.12 Reflex displacement of the stapes as observed by Kobrak (1948)

A sketch from cinematographic records made by Kobrak (1948). The sketch shows that on stapedius muscle contraction there is an elongation of the annular ligament in the region of the anterior pole.

pressure levels below the threshold of feeling. This work was performed on cadavers. Guinan and Peake (1967), however, measured the footplate displacement on living cats. They observed, for frequencies below 3000 Hz and intensities of up to 130 dB SPL, that the motion of the stapes was predominantly piston-like with little or no rocking. Exceptions to this description were at sound pressure levels above 150 dB and at higher frequencies, when the motion became more complex and included rocking of the footplate. They also noted that at higher intensities, flexing of the incudo-stapedial joint occurred. In an attempt to explain the differing results of various investigators, many of whom performed experiments on cadaver specimens, they also studied the footplate vibration on cat cadavers. They noted that the vibration amplitude diminished in a chronic manner from the time of death, presumably due to the drying of the annular ligament.

Whether one accepts the piston or the rocking motion of the footplate as being a correct description of the motion, it is apparent that the footplate has a relatively flexible attachment to the oval window. Kobrak (1948) studied the stapes displacement on contraction of the stapedius muscle. He calculated that the contraction produced an outward displacement of 0.16 millimetres in the region of the anterior pole of the footplate. His sketch of the motion is shown in figure 10.12. As can be seen, the stapedius muscle tendon is attached to the head of the stapes.

According to Bel et al (1976), a contraction of the stapedius muscle causes a pedal movement of the footplate in the oval window. Furthermore, Møller (1964) notes that the contraction causes a substantial movement of the stapes, although very little movement of the tympanic membrane. This is because the muscle pulls in a direction nearly perpendicular to the inward/outward motion of the stapes. Similar motions were described by Guinan and Peake (1967), who stated that contraction of the stapedius muscle caused the head of the stapes to be abruptly pulled posteriorly, whilst the incus remained relatively stationary. They observed that articulating surfaces of the incus and stapes were caused to slide over each other in an anterior-posterior direction.

10.6 The present reflex TM displacement hypothesis

It is proposed that the configurations of the stapedius reflex TM displacements depends upon:

i) The resting position of the middle ear mechanism and stapes footplate in the oval window.

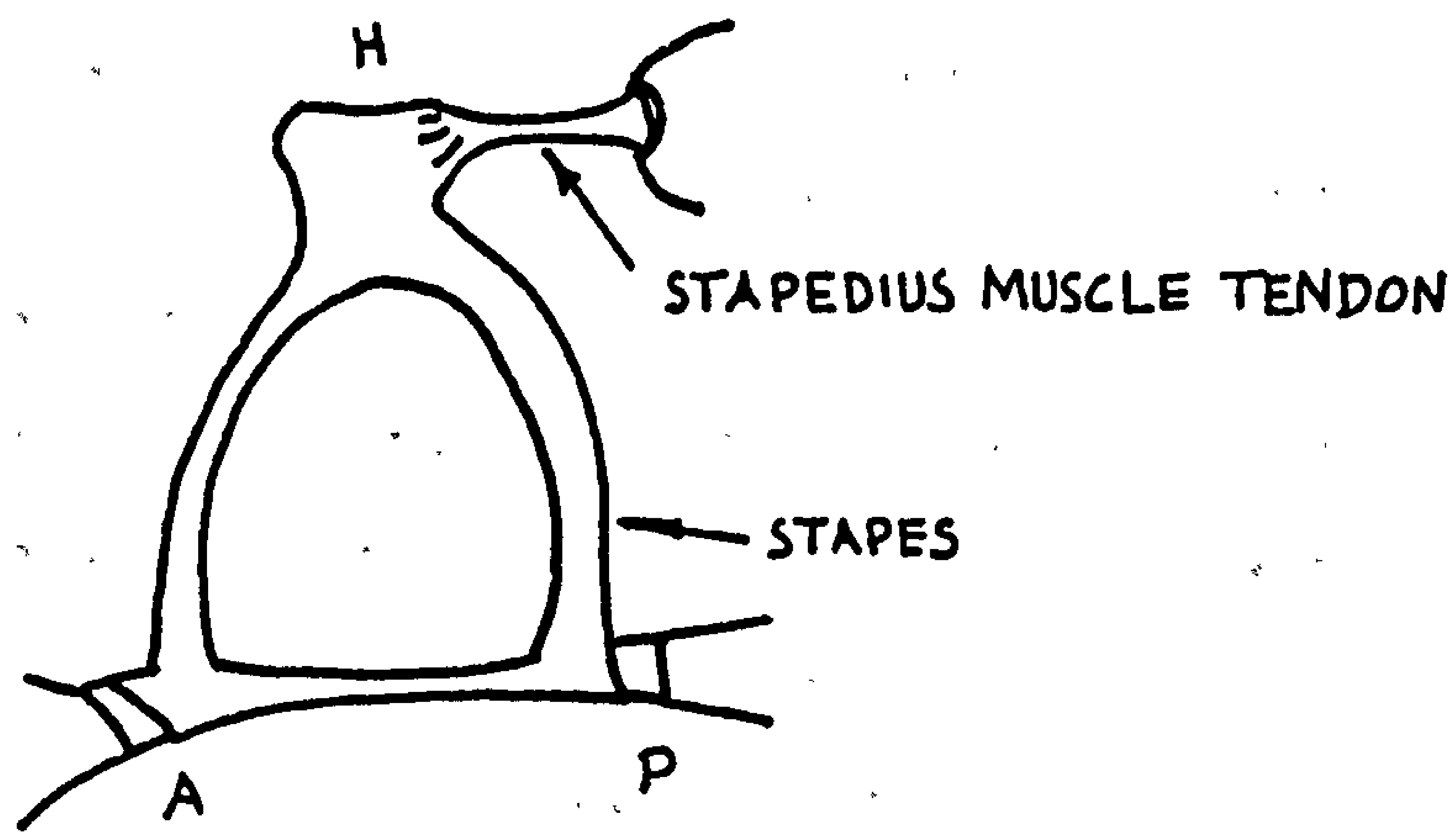
ii) The dynamic characteristics of the stapedius reflex contraction.

iii) The relative impedance to displacement of the anterior and posterior parts of the annular ligament surrounding the footplate of the stapes.

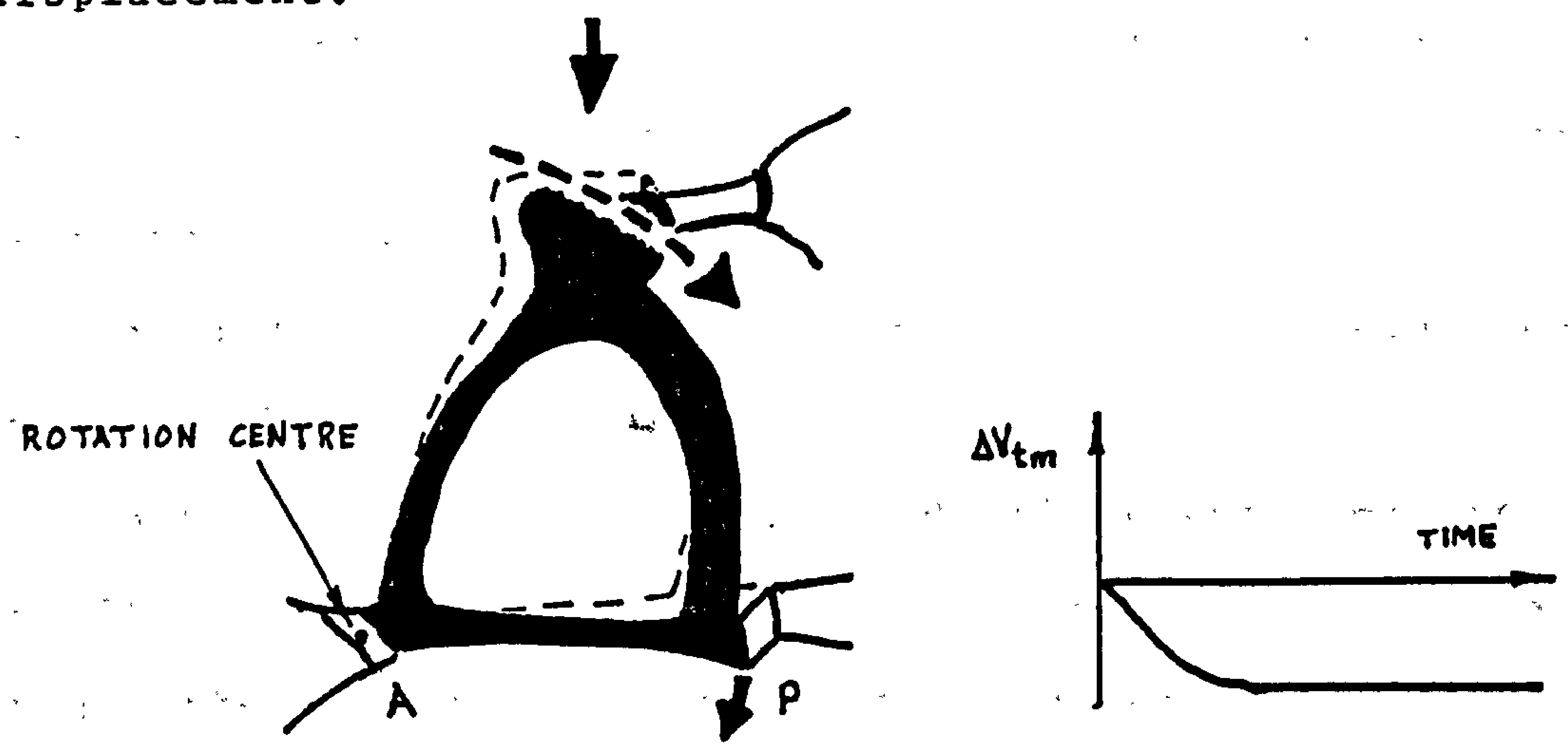
This hypothesis follows along lines similar to those of Brask (1978), the main difference being that the present hypothesis considers that the reflex configurations are due to the relative impedance to displacement of the anterior and posterior regions of the stapes footplate. On the other hand, Brask proposed that the configurations were due to the ratio of the elasticities of the annular ligament in these regions. The impedance, however, takes into account the elasticity as well as other factors which will affect the footplate displacement. For instance, the footplate interfaces with the inner ear via a fluid, the perilymph. Since the fluid is incompressible, the impedance will include an inertial component to allow for movement of the fluid. It is also reasonable to expect some form of dynamic damping plays a part in shaping the TM displacement configuration.

Consider the dynamics of the stapes and footplate in the oval window. Let the anterior region of the footplate be denoted by A and the posterior region by P, see figure 10.13a. The head of the stapes is denoted by H. The kinematics of the stapes and tympanic membrane are said to be such that an inward movement of the stapes head will cause an inward displacement of the TM. Correspondingly, an outward movement of H will cause an outward displacement of the TM. This is dealt with in detail by Brask (1978). It is hypothesized that any displacement of the stapes may be approximated by considering that the stapes is constrained to rotate about a centre lying on a locus approximately running between the postions A and P. The position of this centre will depend on the relative displacement impedances at the positions A and P.

a) Normal resting position of the stapes.



b) Rotation about the anterior region:- Inward TM displacement.



c) Rotation about posterior region:- Outward TM displacement.

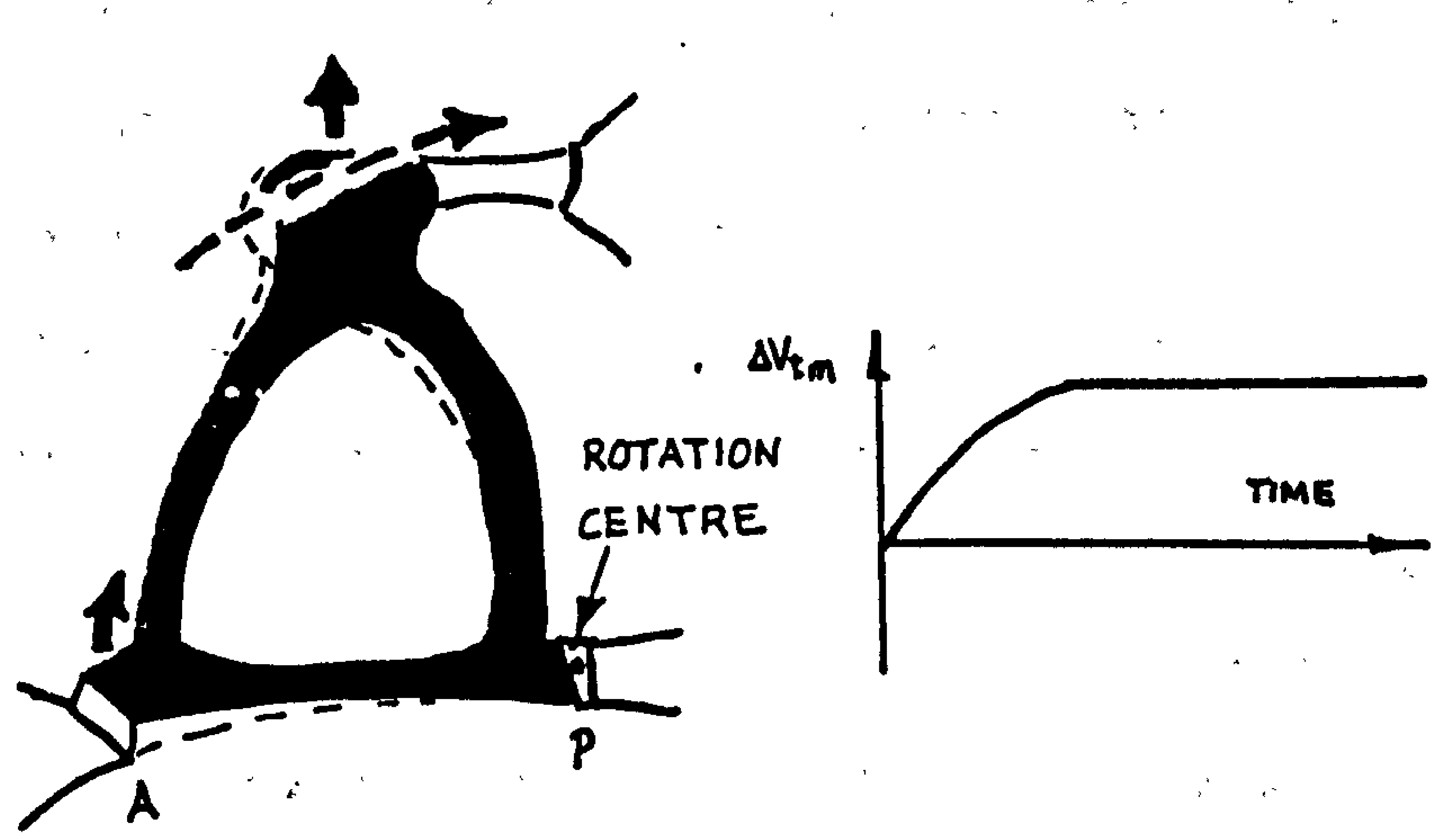
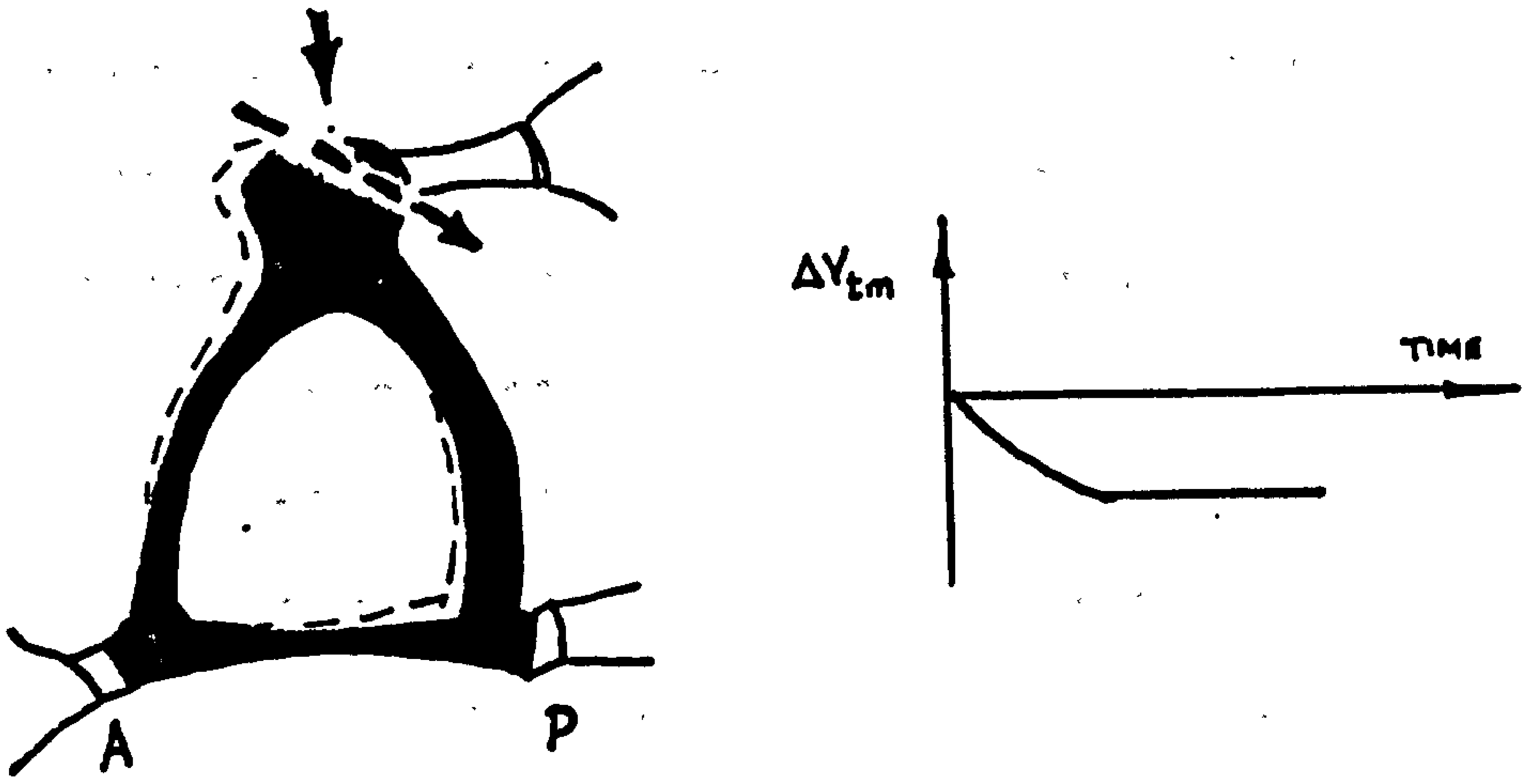


FIGURE 10.13 Rotation of the stapes about the anterior and posterior regions of the annular ligament

The TM displacement configurations are probably best explained by first considering two extreme cases. Suppose that the impedance at A is far greater than at P. Then on contraction of the stapedius muscle, the stapes will be constrained to rotate about A which causes the stapes head H to move through an arc in an inwards direction, see figure 10.13 b. This will result in a inward displacement of the TM. On the other hand, consider the case where the impedance at P is far greater than at A. Then on muscle contraction the stapes will be constrained to rotate about P, which causes H to move through an arc in an outward direction and so causing the TM to be displaced outwards, see figure 10.13 c.

An inward-outward displacement of the TM is explained by the hypothesis as follows. If the resting position of the footplate is such that the displacement impedance of position A is relatively large compared with that at P, then the centre of rotation is situated towards A. On contraction of the stapedius muscle, H will rotate inwards causing an inward displacement of the TM, see figure 10.14 a. However, this motion causes position P to move inwards and the ligament in this region to be stretched and so to become less elastic. The impedance at this point will increase, causing the centre of rotation to move along the locus towards P. If the contraction is great enough, then the centre will be such that point H will rotate in an arc in an outward direction. This will then cause the TM to be correspondingly displaced outwardly. This motion will continue until the forces in the muscle tendons equal

a) The initial TM displacement phase.



b) The outward displacement phase.

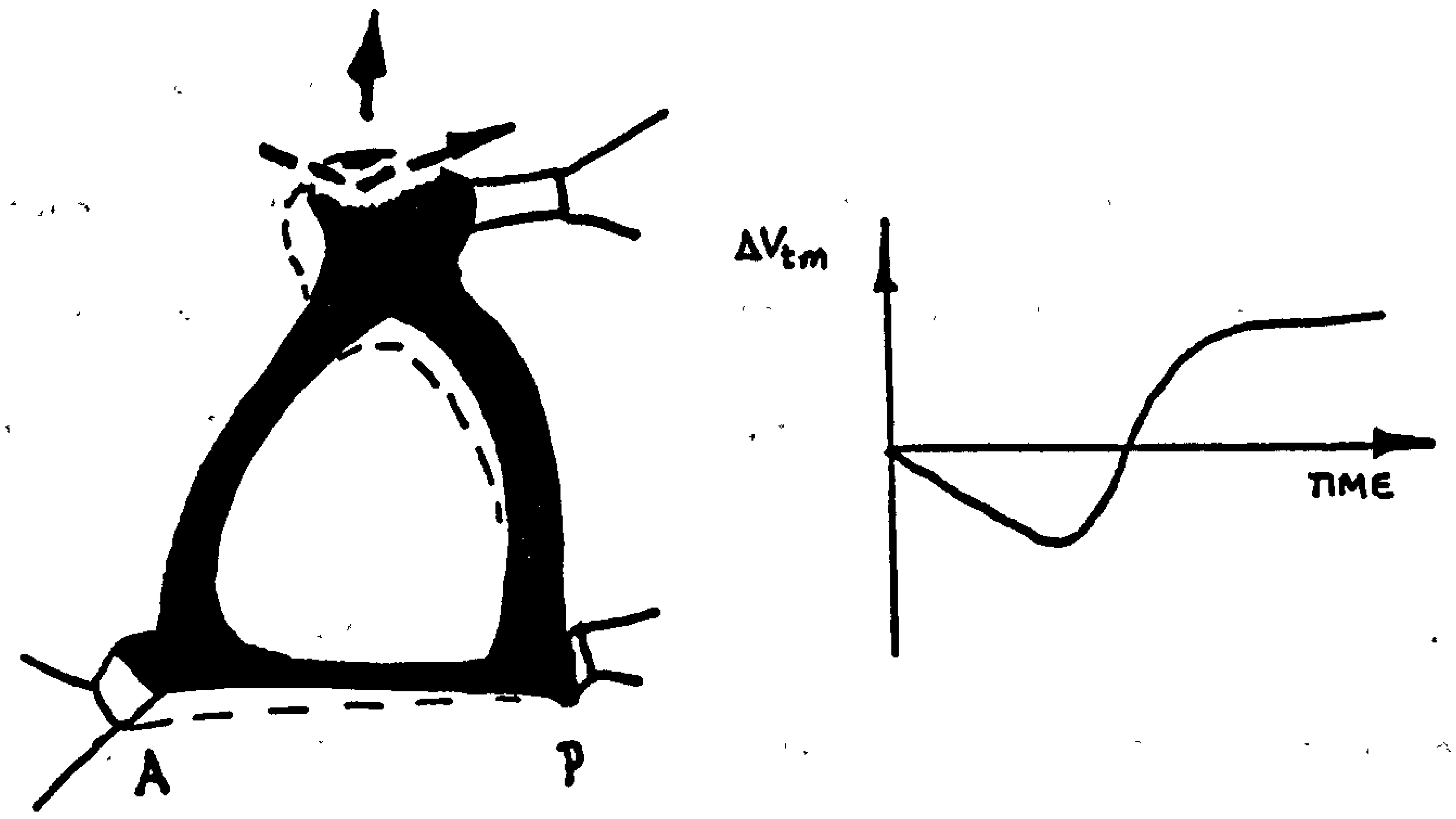


FIGURE 10.14 <u>The inward/outward TM configuration</u>

those acting upon the stapes, at which instant the TM will obtain a new steady state resting position.

The locus of H during this contraction is determined by the relative impedance at P and A, which is dependent on the dynamics of the muscle contraction. This implies that:

i) The TM displacement configuration is dependent on the intensity of the muscle contraction.

ii) In general H will follow a different displacement profile on contraction than on relaxation of the muscle, the dynamics of the muscle being different for the two situations.

Both of these characteristics are displayed in the present TMD results. The former characteristic is discussed in section 10.2 and an example of the latter is shown in figure 10.15.

Some TMD results only display an outward TM displacement. This is explained if the resting position of the stapes is such that the relative impedance at P is greater than at A, so that the rotation centre is positioned towards P. This causes only an outward TM displacement.

This hypothesis agrees with the experimental results presented in the preceding sections. It also explains the outward and diphasic TM displacements as well as the characteristic noted in section 10.2, that the TM configuration varies with the intensity of the reflex contraction. Furthermore, as found experimentally, the

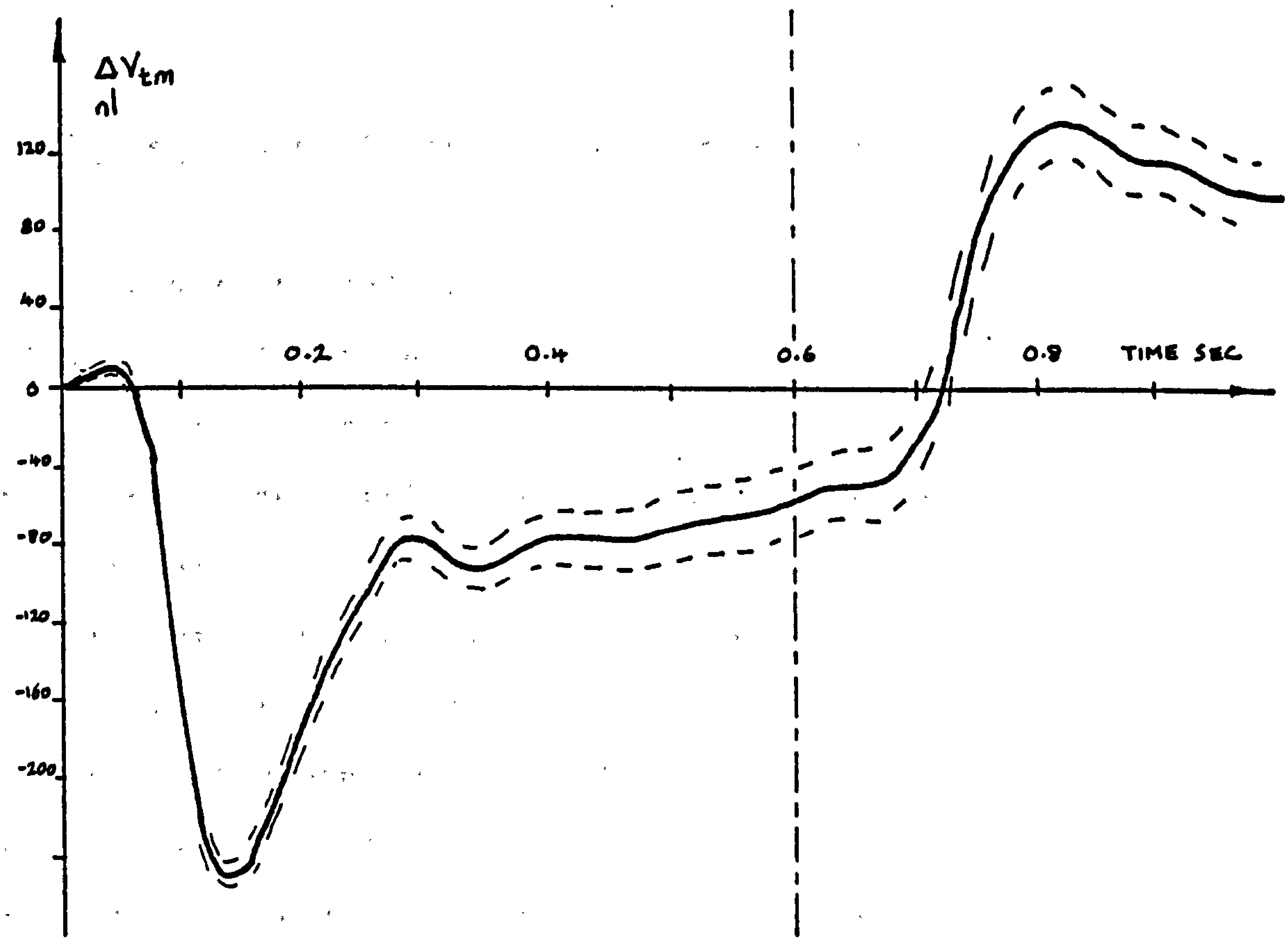


FIGURE 10.15 Reflex contraction and relaxation configuration

Subject PC, right ear, contralateral. Stimulus 1000 Hz, 105 dB HTL.

hypothesis predicts that the onset characteristics of the reflex are fundamentally different from the offset.

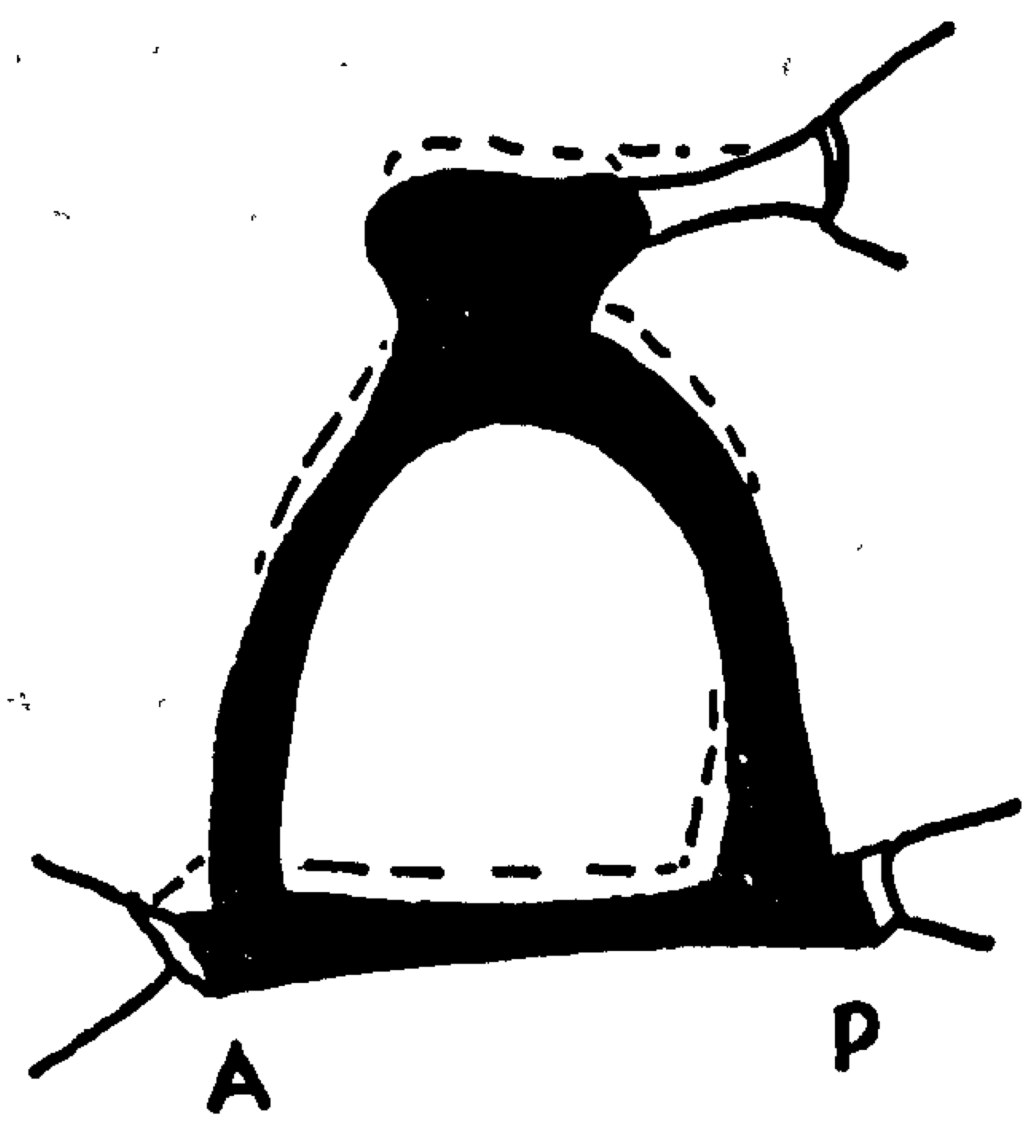
10.7 The hypothesis and effects of varying ear pressures

It was mentioned in section 10.1 that variations in the middle or inner ear pressures may drastically affect the reflex TM displacement configuation. The present hypothesis adequately explains this phenomenon.

Any variation in the differential presssure between the outer ear canal and the middle ear, or the middle ear and the inner ear will change the resting position of the stapes in the oval window. A slight increase in the middle ear pressure, or decrease in the perilymphatic pressure, will cause the resting position to be displaced inward and so stretching the annular ligament. On contraction of the stapedius muscle, the impedance to displacement of the footplate at the posterior edge will be relatively greater than that at the anterior edge. Consequently the hypothesis predicts that such a pressure variation will reduce, sometimes to zero, the initial inward displacement phase of the TM, see figure 10.16 a.

Conversely a decrease in the middle ear pressure, or an increase in the perilymphatic pressure, will cause the resting position of the footplate to be displaced outwards. On contraction of the stapedius muscle, the impedance to the footplate displacement in the anterior region will be relatively greater than that in the posterior region. In

a) Inward displaced resting position of the footplate caused by an increase in the middle ear or decrease in inner ear pressure.



b) Outward displaced resting position of the footplate caused by a decrease in middle ear or an increase in inner ear pressures.

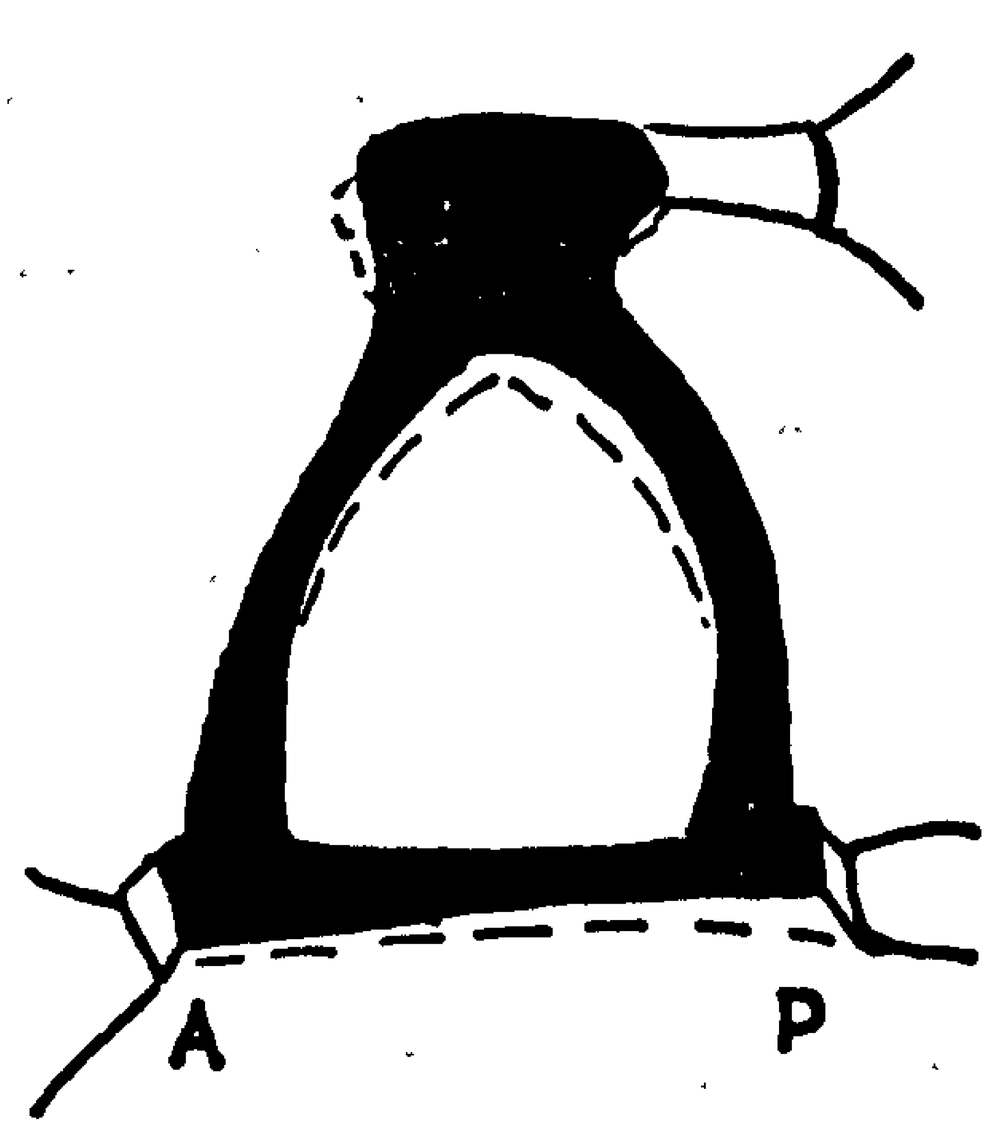


FIGURE 10.16 Changing resting positions of the stapes as caused by ear pressure variations.

this case, the hypothesis predicts that such a pressure variation will tend to favour inward or reduce outward displacements of the tympanic membrane. See figure 10.16 b.

The TM configurations predicted by the hypothesis are in complete agreement with the experimental observations made by Densert et al (1977), Casselbrant et al (1977,1978) and Brask (1978). The effects of varying the ear pressures on the configuration are also described by Brask (1978).

10.8 Physical models of the TMD reflex configurations

During the present investigation a model, made with scaled dimensions from a photomicrograph of a section through the stapes and oval window, was constructed to provide further evidence for the present hypothesis. This model was constructed from perspex with a rubber-band to simulate the posterior and anterior ligaments, as shown in figure 10.17. Brask (1978) produced a similar but more elaborate model. With the aid of it, he was able to simulate the effects of variations in the footplate resting position on the reflex configuration. Both models demonstrate that a pull on the stapes, in the direction of a contracting stapedius muscle, can produce a diphasic displacement of the tympanic membrane as predicted by the present hypothesis.

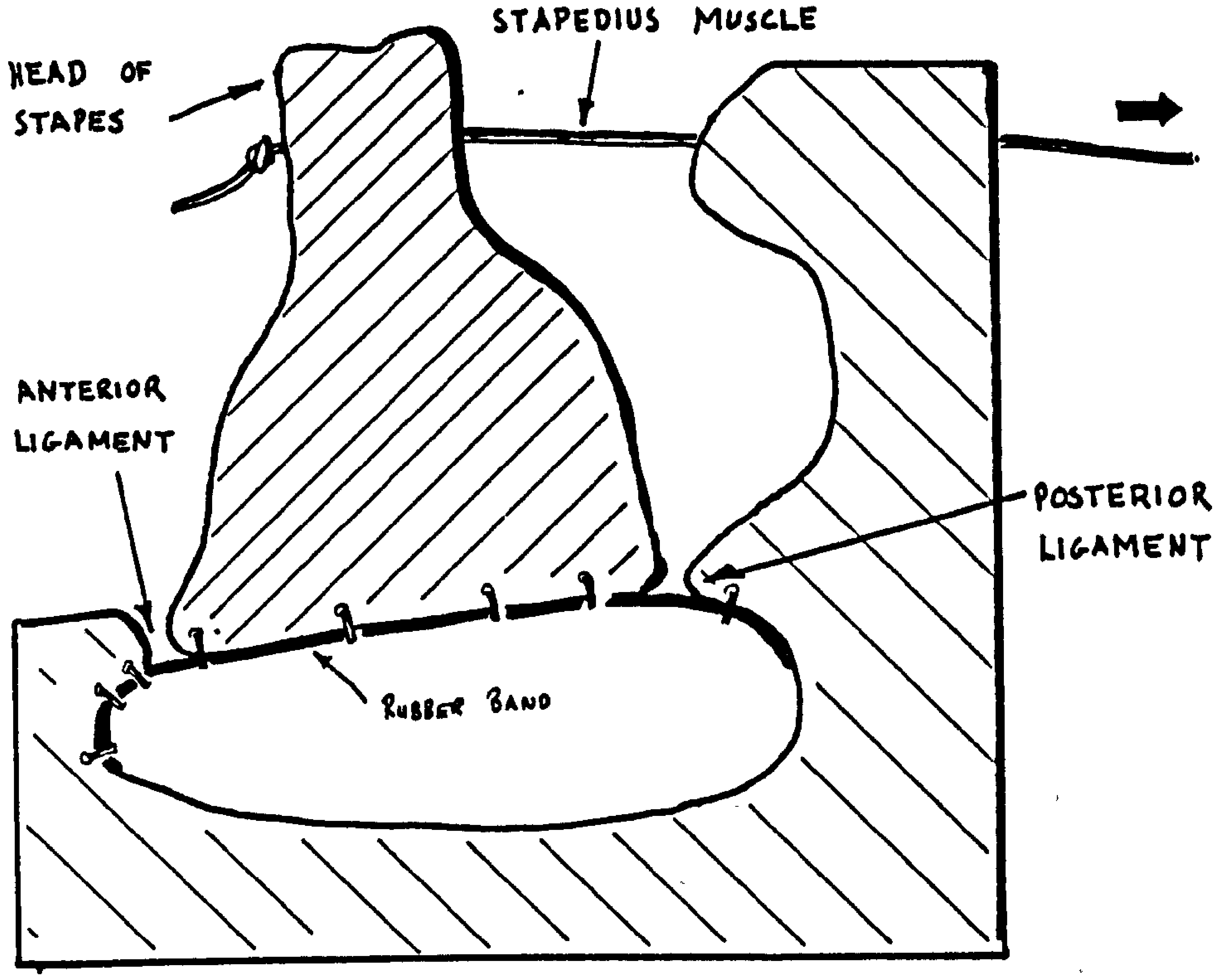


FIGURE 10.17 Physical model of the stapes and footplate attachment in the oval window.

CHAPTER 11

CONCLUDING REMARKS AND FUTURE DEVELOPMENT

The detailed subject matter of the present dissertation may be considered under three broad headings. The first is concerned with the techniques used to measure various audiological parameters, with particular emphasis on the design and development of a new method, the TMD system. The second aspect of the work is that of signal processing; how to deal with a noisy signal and one which is also time variant. The third and final aspect concerns those findings of the present research which relate to the physiology of the ear. A number of new results have been obtained as a result of the present study. It has also proved possible on a number of occasions, to provide data which confirm the results of earlier investigations.

This current chapter is divided into sections which discuss these three aspects outlined above, and includes a section concerning the future of the TMD system.

11.1 VARIOUS TECHNIQUES FOR STUDYING THE PHYSIOLOGY AND DYSFUNCTION OF THE EAR

One of the devices most frequently utilized for studying and diagnosing disorders of the ear is the electroacoustic impedance bridge. Over the past decade, impedance information has revolutionized the diagnosis of hearing dysfunctions. Nevertheless, it still remains difficult to relate this information to the physical structure and dynamics of the ear. In particular, information on the dynamic response of the ear mechanism to the middle ear reflex must be sought from other techniques which are sensitive to displacements of the tympanic membrane, for instance, pressure and flow measurement devices. These techniques, although not frequently used in a clinical environment, have been shown in some cases to be sensitive to middle ear muscle contractions which are undetectable with the impedance bridge (Neergaard and Rasmussen 1967).

A disadvantage of both pressure and flow measurement techniques is that they are fundamentally non-free field devices, since to operate, they rely on a differential pressure between the external ear canal and the surrounding environment. Thus it is demonstrated that existing devices have fundamental disadvantages, and these problems have been overcome by the concept and development of a new device, the TMD system.

The TMD system is capable of making direct measurements of changes in the volume of the external ear canal, and in particular volume displacements of the tympanic membrane.

The measurement device incorporated in this system is extremely sensitive, resolving volume variations of a few nanolitres. Characteristics of transient displacements of the tympanic membrane may be evaluated due to the wide bandwidth of this device (DC to 140 Hz). Besides this important fact, a unique feature of this system is that measurements are made without exerting a backpressure on the tympanic membrane. It has been shown that the dynamic response of the measuring device affords a 99.5 percent reduction in the backpressure on the membrane at a frequency of 1 Hz, and for higher frequencies the backpressure increases at a rate of 6 dB per octave.

A noteworthy feature of techniques which measure TM displacement, including the TMD system, is their sensitivity to fluctuations in the resting position of the stapedial footplate, which reflects variations in the perilymphatic pressure. This pressure cannot be measured by any other noninvasive technique, so that TM displacement measurements have a potential for providing new information which relates to pathologies of the inner ear.

11.2 SIGNAL PROCESSING AND ENSEMBLE AVERAGING

Special attention is given in this dissertation to the processing of the signal from the TMD system. Statistics, performed on ensembles of TMD records, are used to analyse data from various physiological processes. It is stressed that the purpose of these techniques is not only to improve the signal to noise ratio, but also to provide parameters, such as the signal variance, which are essential if the physiological process is to be more fully understood. Parameters such as the variance are important because the signal from these processes, generally classified as nonstationary, will vary from record to record due to physiological and neurological reasons. This variance, itself, is an important property of the process.

A detailed study is included of the practical aspects of the ensemble averaging technique. Section 7.4.3 considers the deterioration of the signal to noise ratio with time, and an interesting point of this discussion is that the rate of change in the signal to noise ratio is related to the spectral content of the noise. The greater the energy at the higher frequencies, then the greater the rapidity at which the signal to noise ratio reaches a steady state value. Conversely for noise with an ultra low frequency content, the rate of change of this ratio is effectively constant with time.

It is often wrongly assumed that the ensemble averaging technique reduces the noise by a factor of $1/\sqrt{N}$, where N is the number of records in the ensemble. This theoretical value is derived for an average obtained from records which are totally independent of each other. In practice a certain degree of correlation exists between the records of most ensembles, which results in a reduction in the effectiveness of the ensemble averaging technique. Analysis of the signal and noise from the TMD system shows that the actual improvement in the signal to noise ratio is about 0.78 of that predicted by theory, due to ultra low frequency noise, mainly from fluctuations in the ambient pressure.

Also studied in detail are the physiological processes which affect the volume of the external ear canal. It has been noted that the canal volume is influenced by reflex activity, respiration, swallowing, cardiovascular pulsations and to a much lesser extent, gas absorption from the middle ear cavity. Depending on which process is under study, and constitutes the signal, the remaining processes produce noise which corrupts the information contained within the signal.

11.3 DISCUSSION OF THE PRESENT AUDIOLOGICAL INVESTIGATION

Audiological results collated during the present investigation may be considered in four categories depending on whether they; relate to the background noise level in the ear canal; concern the Eustachian tube function and associated physiological processes; express the dynamic and steady state characteristics of the acoustic reflex; or provide evidence for an hypothesis which explains the main displacement configuration of the reflex and associated mechanism.

11.3.1 The background noise level within the external ear canal

Various authors have shown that larger than normal external ear canal noise levels occur in subjects with pathologies such as, serous otitis media or a glomus tumour (Andreasson et al 1978). Greater than normal noise levels, therefore, are possible signs of hearing dysfunction. Tests on 18 ears, performed during the present investigation, highlight a tendency for subjects to have a similar noise level within both ears (correlation regression factor 0.88, section 6.4.1). Consequently, it is proposed that a large discrepancy between the noise level in one ear of a subject when compared with that in the other, is a possible sign of unilateral disorders.

Throughout the present study, noise levels are expressed as a standard deviation of the noise measured over a particular interval of time. For the 18 ears tested, the mean noise level within the external ear canal was 130 nanolitres with a range of 61 to 308 nl (section 6.4.1).

11.3.2 The Eustachian tube function

Results presented in section 8.2 prove the viability of studying swallowing and the Eustachian tube function with the TMD system. An interesting fact which has emerged from this particular study is that fluctuations in the middle ear pressure, caused by gas absorption into the walls of the cavity, are of a similar magnitude to drifts in the ambient pressure. The implication of this is that, contrary to what is normally expected, a net flow of air through the Eustachian tube from the middle ear cavity may happen during times of decreasing ambient pressure. With normal subjects, therefore, the Eustachian tube plays an equally vital role in compensating both for ambient pressure variations and for gas absorption.

11.3.3 Characteristics of the acoustic reflex

Chapter 9 details the results of tests specifically designed to study both the steady state and the dynamic characteristics of the acoustic reflex. With the aid of these tests, it was demonstrated that the reflex threshold obtained with the TMD system was approximately the same as that measured using impedance bridge techniques.

The steady state displacements, both ipsilateral and contralateral, were found to occur with a mode value ranging between 200 to 300 nl for 10 dB above the reflex threshold, and stimuli of 500 or 1000 Hz (section 9.3). These results generally agree with those of a similar investigation performed by Casselbrant et al (1977), and correspond to a mean linear displacement of the tympanic membrane in the order of 0.004 mm.

The TMD tests gave reflex latency values ranging from 20 to 95 msec, with a mode value of 30 to 40 msec, and also showed that the magnitude of the contralateral reflex was consistently about 20 percent smaller than that of the ipsilateral reflex. This latter phenomenon was similarly observed by Brask (1978), who proposed that it was due to the longer contralateral reflex pathways causing greater attenuation of the stimulus signal than the ipsilateral pathways.

Reflex results show that, immediately following muscle contraction, the new resting position of the tympanic membrane may be obtained with no overshoot, some overshoot, or after sustained oscillations. The overshoot was found to be more pronounced at 500 Hz than at 1000 Hz, and it is suggested that this trend indicates a greater attenuation of the stimulus by the reflex at 500 Hz than at 1000 Hz, results supported by Borg (1968) and Gunn (1973). It is also suggested that the attenuation of the stimulus by the reflex, causes the observed oscillatory characteristics which were found to have frequencies ranging from about 4 to 8.5 Hz, with a mean of 6.4 Hz, and a decay rate ranging from 0.05 to 0.7 seconds.

Chapter 10 relates to the displacement configuration of the tympanic membrane as caused by contraction of the acoustic reflex. Tests showed that the membrane movement was either inwards, outwards, or often initially inwards followed by an outward movement. The physical mechanism for this displacement configuration has been the subject of various hypotheses. The results of the present investigation generally support the hypothesis proposed by Brask (1978). An elaboration on this hypothesis is that the relative impedance to displacement of the anterior and posterior regions of the annular ligament surrounding the footplate has an important influence on the reflex configuration. In contrast, Brask proposed that the configuration was only affected by the relative elasticities of these regions of the annular ligament. Consistent with the present hypothesis, are results from tests performed for varying levels of stimulus. A comparison of these results show that on increasing the stimulus intensity from the reflex threshold, the inward displacement phase of the reflex initially increases to a maximum value, and then decreases with increasing intensity. The amplitude of the maximum inward phase occured with a median value of 60 to 70 nl, measured from a sample of 18 ears.

11.4 THE FUTURE OF THE TMD SYSTEM

The future of the TMD system, and its underlying principles, have been secured over the next 18 months by two separate sources of financial backing, which in total provide some £22,000 for the development and application of the system. One of the supporting bodies is the Science Research Council (SRC), who have provided £5,000 for a feasibility study into other applications of the volume measurement principle incorporated in the TMD system. The study will consider work by Gunther (1976), who stresses the importance of flow measurements in the nanolitre range for determining osmotic and hydraulic permeabilities of membranes. On further investigation, it is anticipated that additional applications for this principle will be forthcoming.

Part of the SRC study will involve the interfacing of the volume measuring device with a microprocessor or an inexpensive microcomputer. This will reduce the cost of the present system and provide a portable device which is more suitable for applications in the applied sciences.

The second source of funding has been provided by the National Research and Development Corporation (NRDC) who have filed a patent on the TMD system. The support of this Corporation amounts to £17,000 , for a study on the commercial viability of the TMD system in the field of audiology. This study will involve the interfacing of the present TMD system with an LSI 11 computer, manufactured by 'Digital Corporation'. This computer will provide the analysis and storage capability necessary to evaluate the TMD system in a clinical environment.

In respect of the NRDC research, a pathology which merits special attention is Ménière's disease. Very little information is available on the causes of this condition, although there is a view that some of the symptoms relate to an increase in the inner ear pressure and its influence on the ear's sensory mechanism. Since the TMD system is potentially very sensitive to variations in the resting position of the stapedial footplate, and therefore, the inner ear pressure, it is hoped that some correlation between fluctuations in the perilymphatic pressure and the occurence of Ménière's disease will be discovered.

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APPENDIX I

DYNAMIC CHARACTERISTICS OF THE TMD SYSTEM

This appendix supplements the contents of chapter 4 by providing more details on particular elements of the TMD system. Further, it includes a discussion on the nonlinear response of X-Y plotters.

THE X-Y PLOTTER

A permanent record of the processed TM displacement transient is made on an X-Y plotter (type Bryans 26051 A3). Care must be taken to ensure that the plotter has a suitable bandwidth to adequately record the transient. A simplified diagram of the principle of an X-Y plotter is shown in figure I.1. The instrument servos, used in plotters, regularly have high static accuracy. However due to the inertia of moving parts, their frequency bandwidth is limited to 5 Hz or less. Furthermore they possess a non-linear frequency response which may be flat within 1

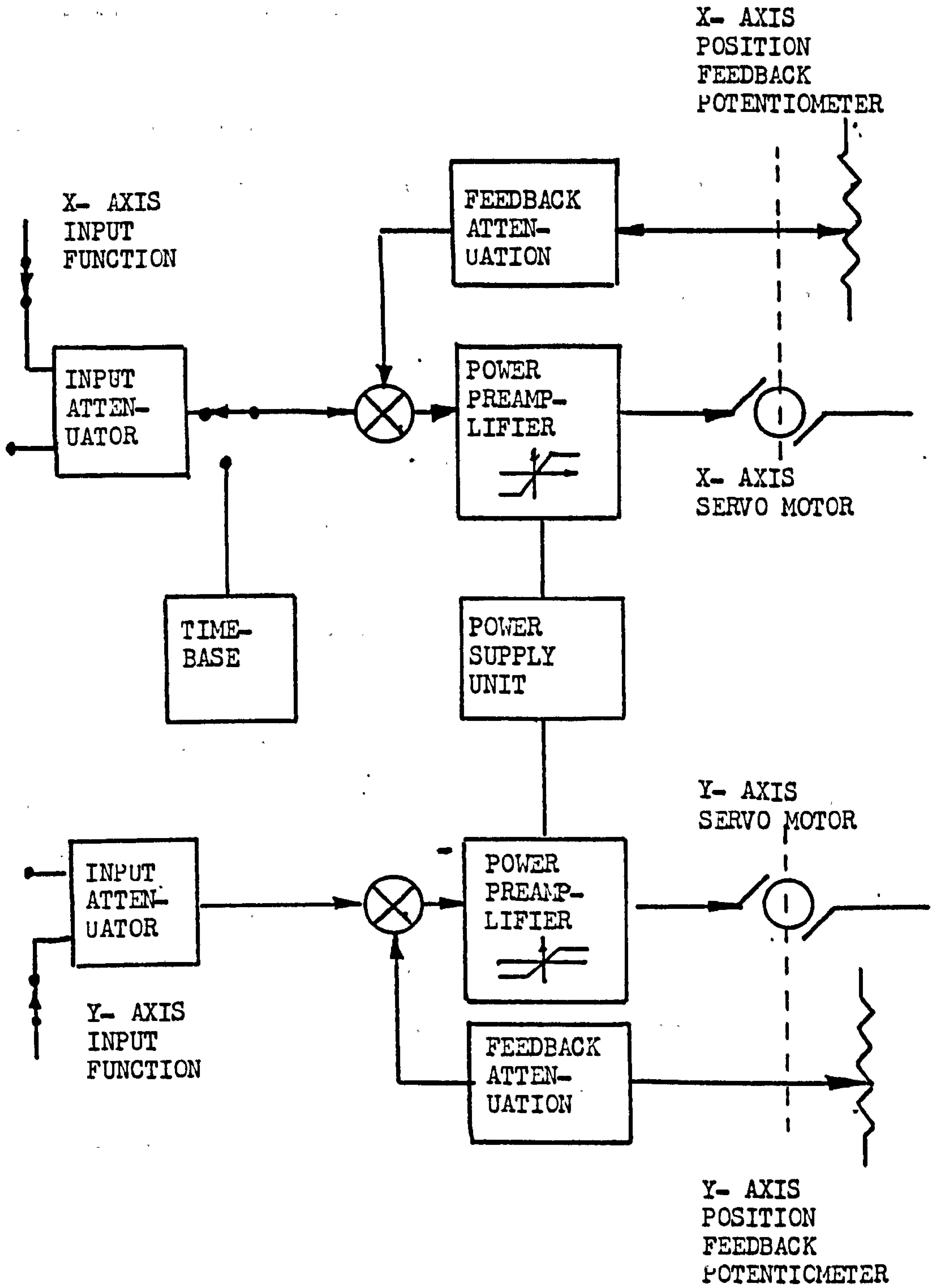


FIGURE I.1 Schematic diagram of an X-Y plotter percent to 5 Hz for inputs that are 10 percent of full scale, but if the inputs are near full scale a reduction in frequency response will result. This is a consequence of the finite limits on the power used to drive the servo motor, shown in figure I.1 as non-linear elements. Considering a power amplifier, such as used to drive the servo motor, its frequency response will become a function of the input signal amplitude once the difference between the input signal and plotter position signal exceeds certain limits. Due to non-linearities, plotter manufacturers normally specify the plotter response characteristics in terms of a maximum writing speed and maximum acceleration, as opposed to quoting the specification in terms of frequency.

The inertia of the plotter's positioning mechanism is normally less in the y direction that the x direction: it therefore follows that the writing speed is normally greater in the y direction. Nevertheless with the TMD system, the test results were plotted with the time axis in the direction of the plotter's y axis, for the sake of convenience.

Estimation of the bandwidth of the X-Y plotter

Given a signal of a known maximum amplitude, the bandwidth of a plotter may be estimated using the value for the maximum writing speed.

Suppose that we wish the plotter to reproduce a sinusoidal waveform of frequency ω (rads/sec) and amplitude A_o. The waveform is described by the equation

$$S(t) = A_o \sin \omega t \qquad \text{..........eq. I.1}$$

where S(t) is the plotter's displacement along the axis under consideration. The velocity of the plotter in the same axis is given as

$$\frac{dS}{dt} = A_o \omega \cos \omega t \qquad \text{..............eq. I.2}$$

and the maximum velocity is given by $A_o \omega$. If W_{max} is the maximum writing speed, then

$$W_{max} \geqslant A_o \omega \qquad \text{..............eq. I.3}$$

for the waveform to be accurately reproduced.

Figure I.2 gives the maximum bandwidth of the plotter used in the TMD system, for various plotter output amptitudes, figure I.3 shows the step response of the plotter for varying step amplitudes. Notice that unlike a second order step response, the maximum slope is constant, being limited by the value of the writing speed.

The frequency bandwidth of the TM transient will normally be better than these values indicate, because the signal is usually played to the plotter at a slower rate than at which it was recorded. The plotter completes a single plot in just over nine seconds (9.07 sec). Therefore, for a signal transient duration of less than 9 seconds there will be an improvement in signal bandwidth,

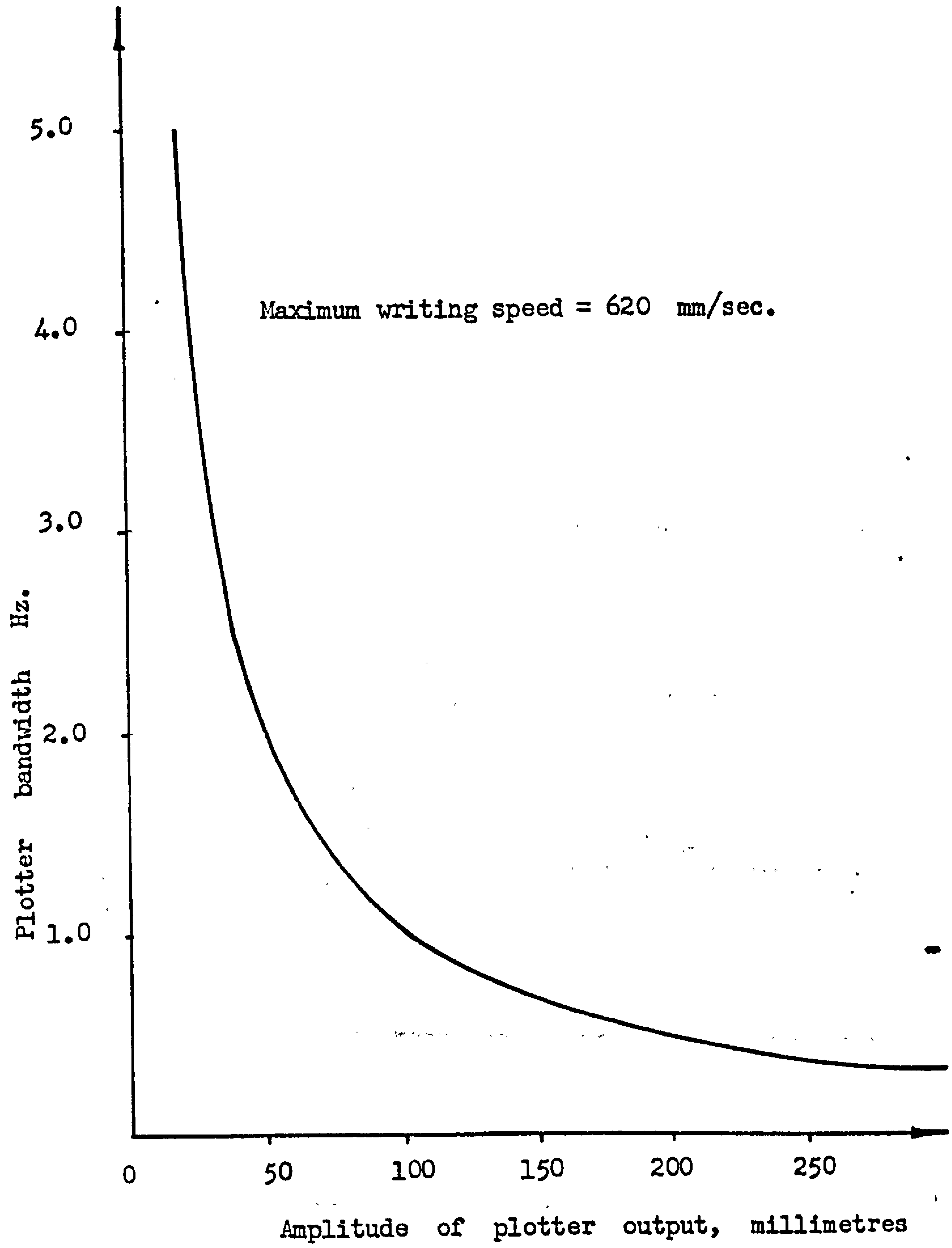


FIGURE I.2 Frequency bandwidth of the plotter vs amplitude of the plotter output

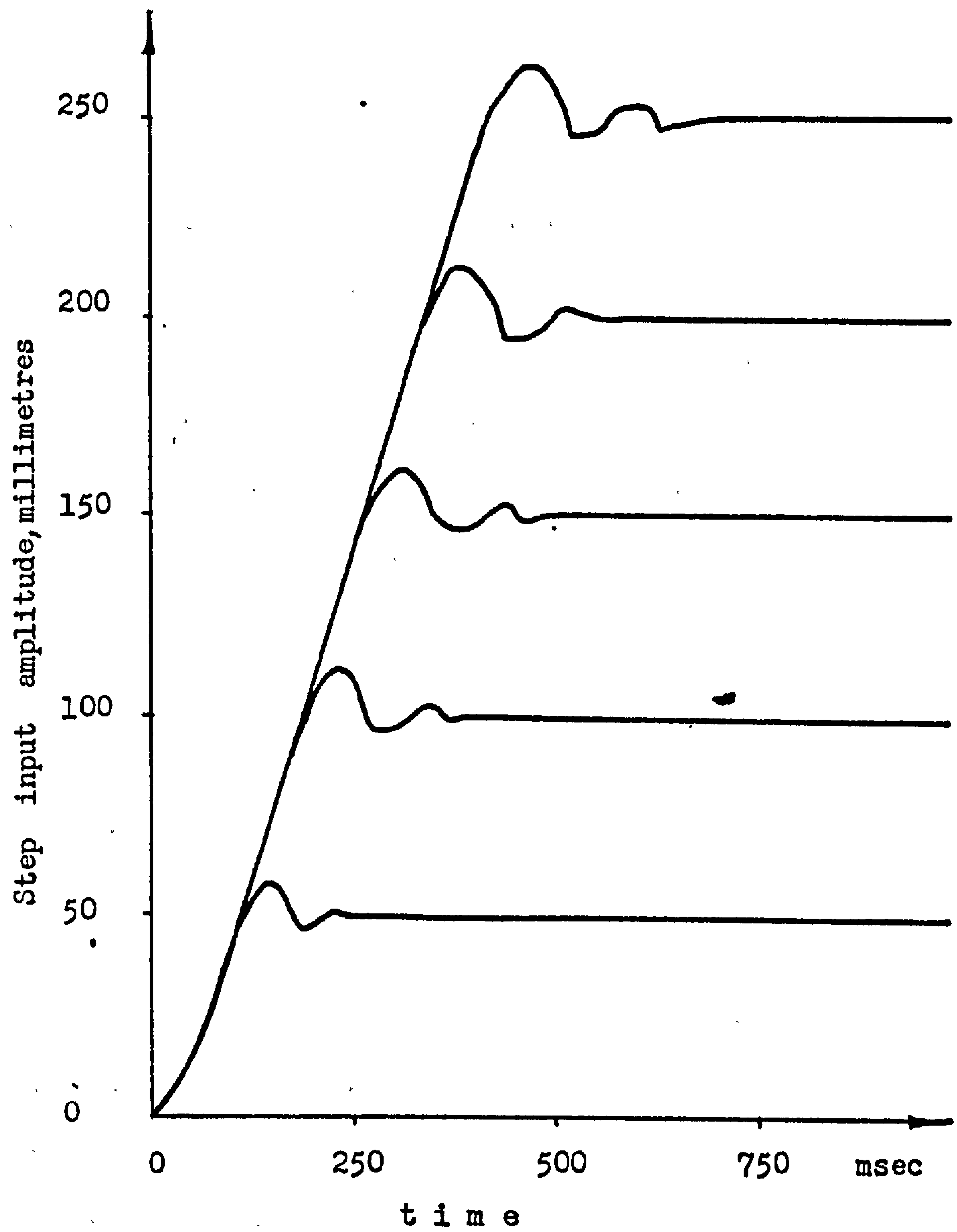


FIGURE I.3 Response of the Bryans X-Y recorder for varying amplitude step inputs and for a duration greater than 9 seconds a deterioration, on that given in figure I.2.

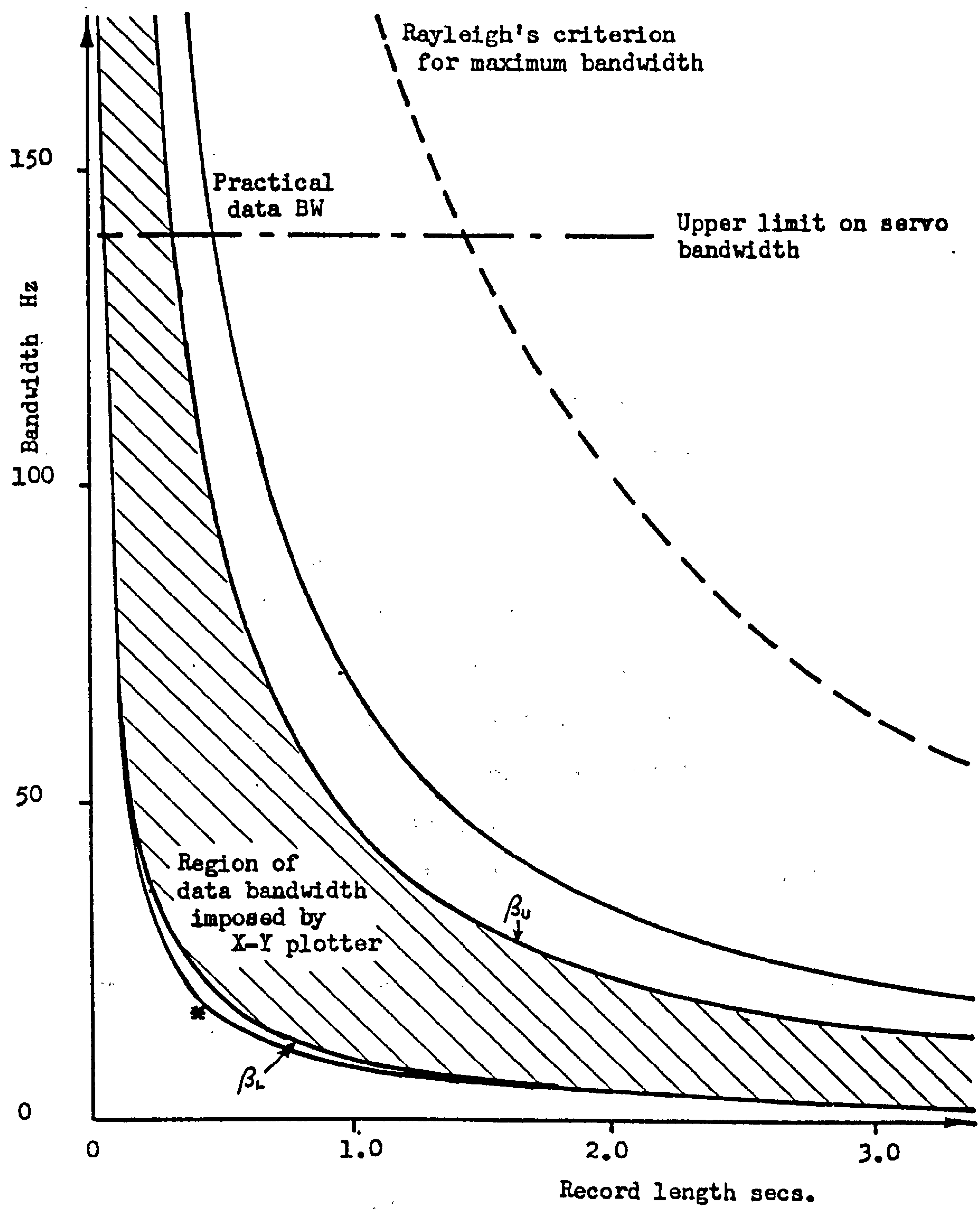
The limit on the amount of information contained in sampled data is related to the sampling rate. In this respect Rayleigh's criterion (Beauchamp 1973) gives the maximum theoretical bandwidth of the data. However, a sampling rate of at least six times the highest frequency of interest is necessary in most practical situations (Beauchamp 1973). Variations in these bandwidths with record length are shown in figure I.4, which also displays the actual bandwidth of the TMD system data as limited by the X-Y plotter. The upper limit on the actual bandwidth β_u is estimated from the natural frequency of the plotter ω_n (rads/sec) *. That is

$$\beta_u = \frac{\omega_n T}{2\pi L} \quad \text{Hz} \qquad \text{.......eq. I.4}$$

where L is the transient record duration, and T the time taken to plot one graph. The lower limit on the actual bandwidth β_L, is estimated from the criterion that the maximum deviation of the plotter A_{max} is plus or minus 0.1 m from the zero axis of the graph. Using equation I.3

$$\beta_L = \frac{W_{max} T}{2\pi A_{max} L} \quad \text{Hz} \qquad \text{.......eq. I.5}$$

* Estimated as 31 rads/sec, Doeblin (1975).



* Actual bandwidth limited by plotter DAC filter

FIGURE I.4 Variations in data bandwidth with record length

Substituting for ω_n, T, W_{max} and A_{max};

$$\beta_U = \frac{45}{L} \text{ Hz}$$

$$\beta_L = \frac{9}{L} \text{ Hz} \qquad \text{.......... eq. I.6}$$

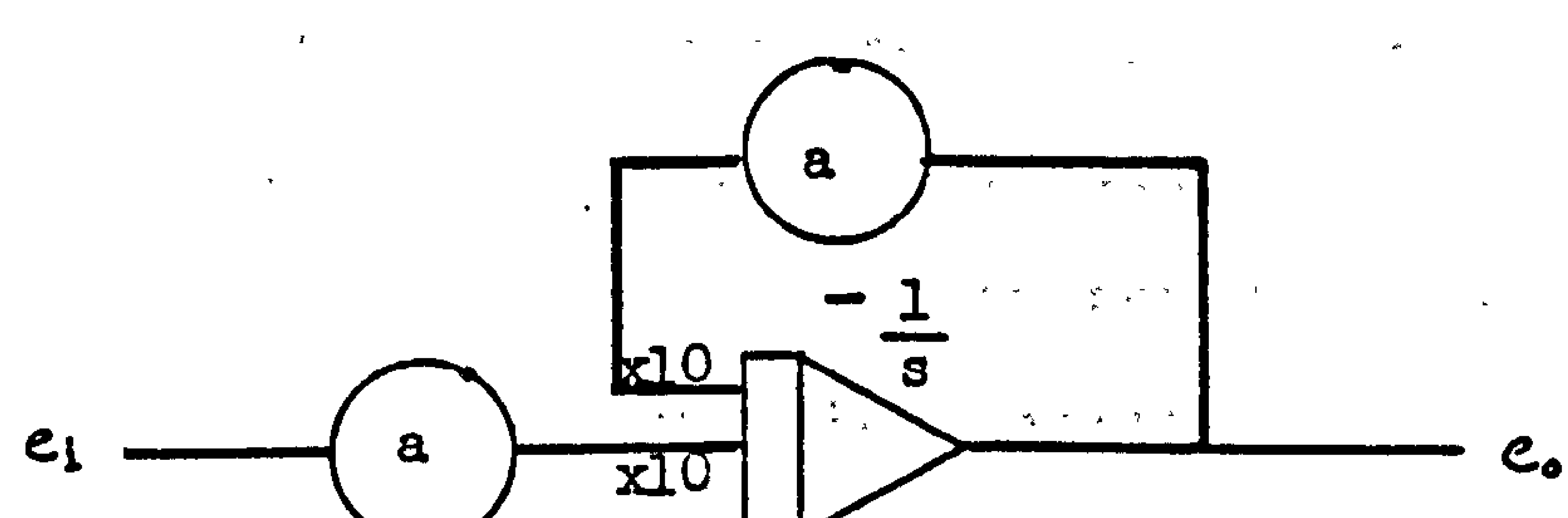
Response of the graph plotter filter

A graph plotter filter is placed on the output of the DAC which feeds the Y axis of the X-Y plotter. It has principally two purposes:

i) To smooth the output from the DAC, which consists of a number of discrete voltage levels, typical of sampled data.

ii) To ensure that the bandwidth of the data is compatible with the maximum writing speed of the X-Y plotter, since it is pointless feeding the plotter with information it cannot respond to.

The filter is a first order low pass device with the circuit shown below.



The transfer function is

$$\frac{e_o}{e_i}(t) = -\frac{1}{(\tau s + 1)} \qquad \text{where } \tau = \frac{1}{10\,a}$$

The potentiometer setting a = 0.5, so that τ = 0.2 sec which yields a bandwidth of 0.8 Hz (-3 dB point). Given that 9.07 seconds are required for the ouput of the TMD record which consists of 400 data points, and that the TMD record length is T seconds, then the bandwidth of the data fed to the graph plotter is given as

$$B.W. = \frac{69.07 \times 0.8}{T} = \frac{7.3}{T}$$

The bandwidth of the information is chosen to approximately coincide with the lower limits of the graph plotter bandwidth. This ensures that the output of the plotter is always linearly related to the output from the DAC, and therefore linearly related to the TMD displacement dynamic.

The non-linear X-Y plotter response

If a X-Y plotter is fed with a signal which has not been band-limited to suit the bandwidth of the plotter, then because of its non-linear response, it will tend to produce a plot covered with low amplitude spikes. This is due to the limitations on the value of its maximum writing speed, which results in it producing high frequency components over small amplitudes. Besides being redundant information, these spikes tend to confuse the profile of the plot.

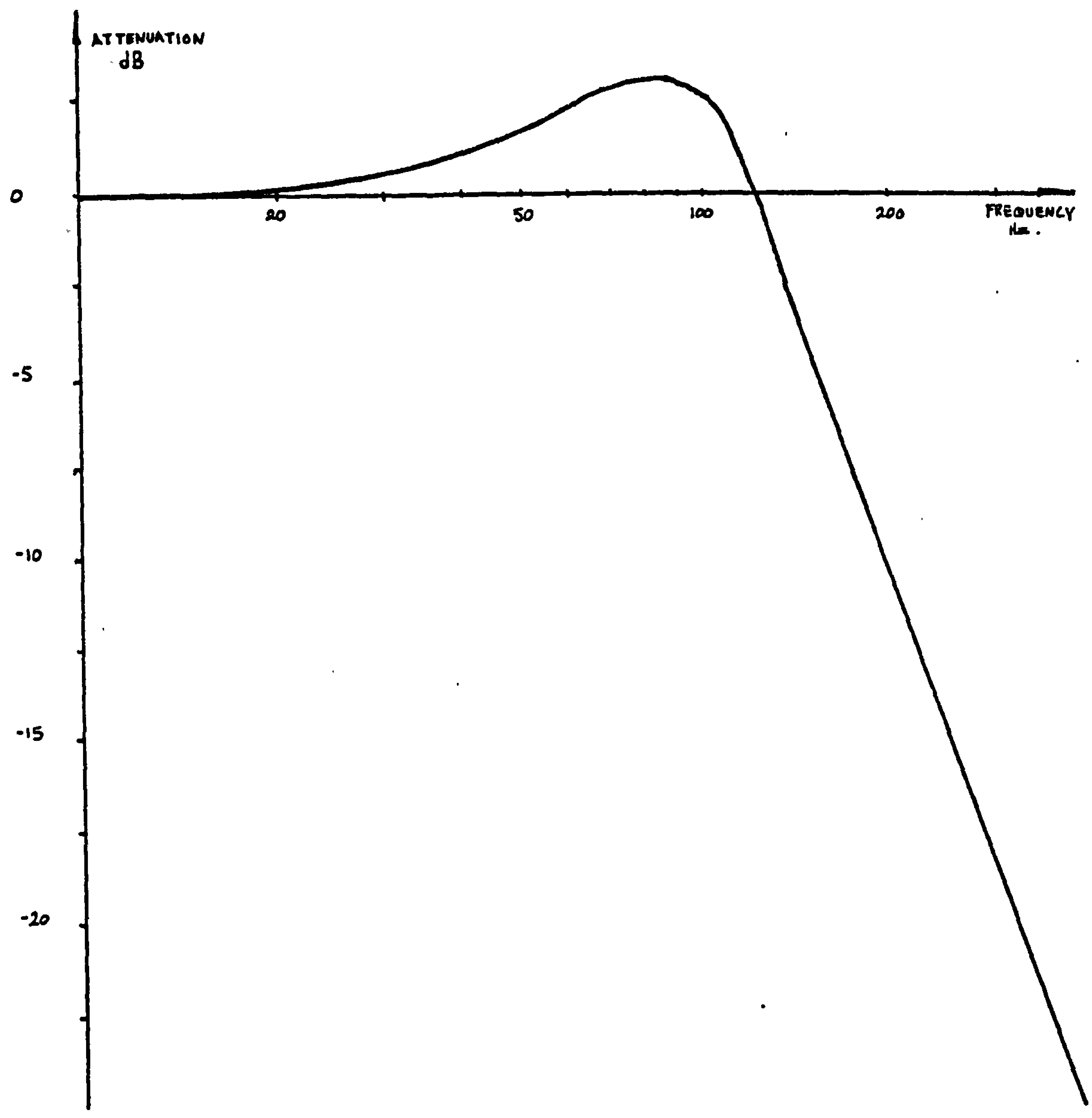


FIGURE I.5 Frequency response of ADC filter

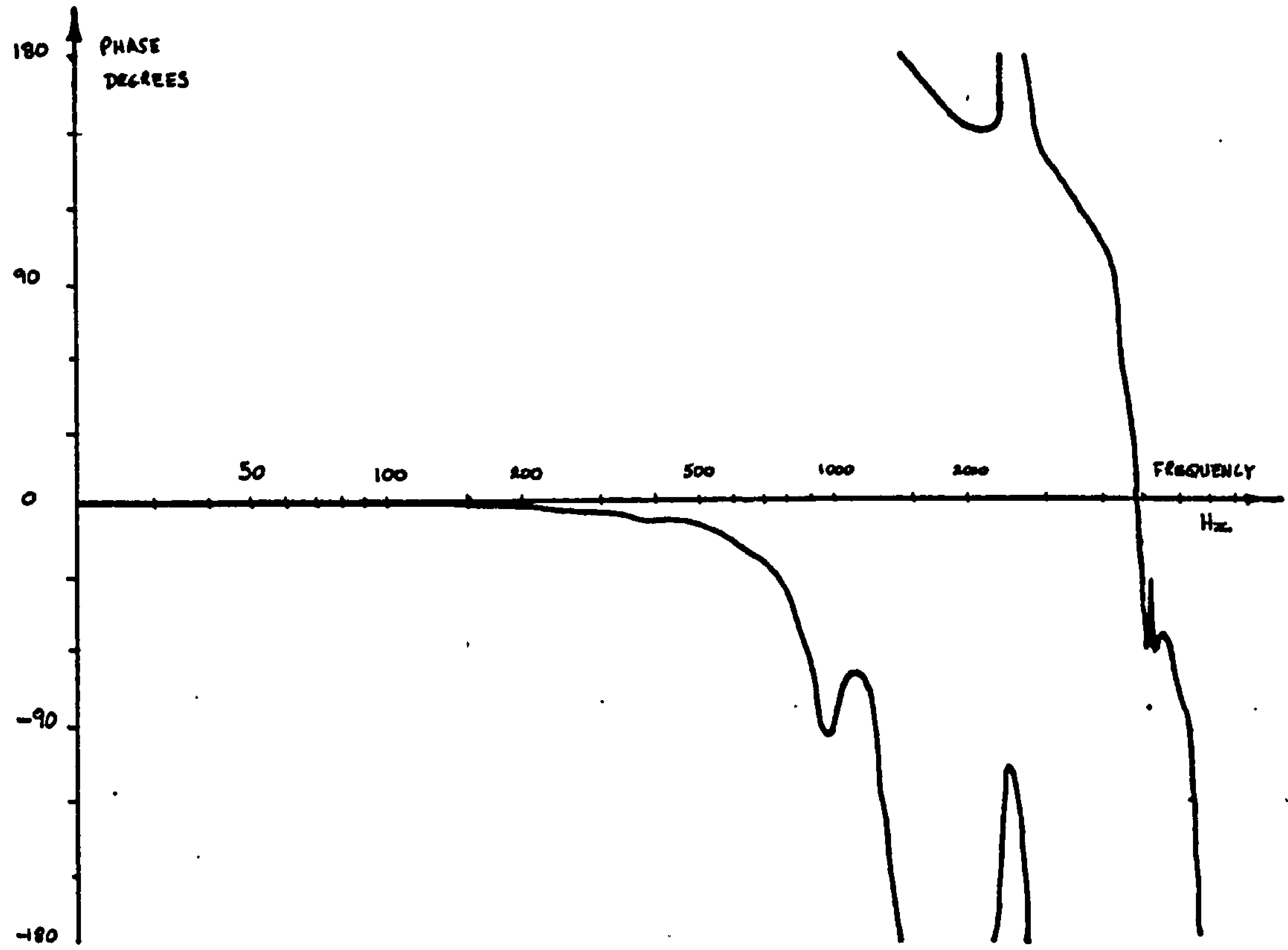


FIGURE I.6 Phase difference between an input at the reference diaphragm and that measured by the microphone

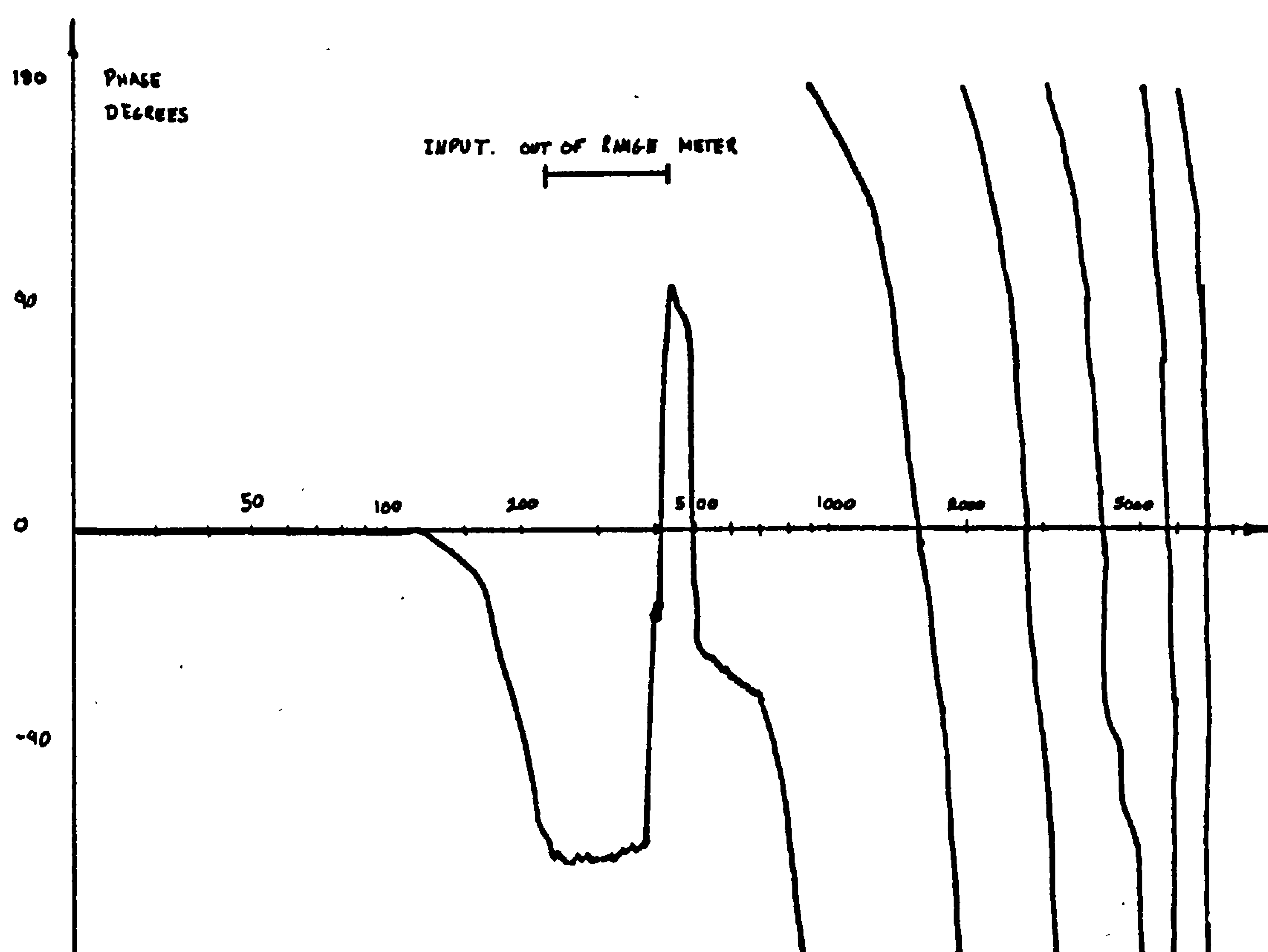


FIGURE I.7 Phase difference between an input at the calibrator diaphragm and that measured by the microphone

APPENDIX II

SIGNAL STATISTICS AND ENSEMBLE AVERAGING

This appendix provides background information on signal classification, statistics and the ensemble averaging technique. In particular it supplements the discussion of chapter 6, which is concerned with the statistical analysis of the TMD signal.

SIGNAL AVERAGES

Consider a set of N signal time histories, denoted by $x_1(t)$, $x_2(t)$,.....$x_N(t)$, which describe a process, see figure II.1. Such a set of records is known as an ensemble. The statistical averages describing the ensemble can be two distinct types.

i) ensemble averages, which use sets of amplitude values, $x_1(t_i)$, $x_2(t_i)$,.....$x_N(t_i)$, taken from the whole ensemble at a fixed time t_i.

ii) time averages, which use sets of amplitude

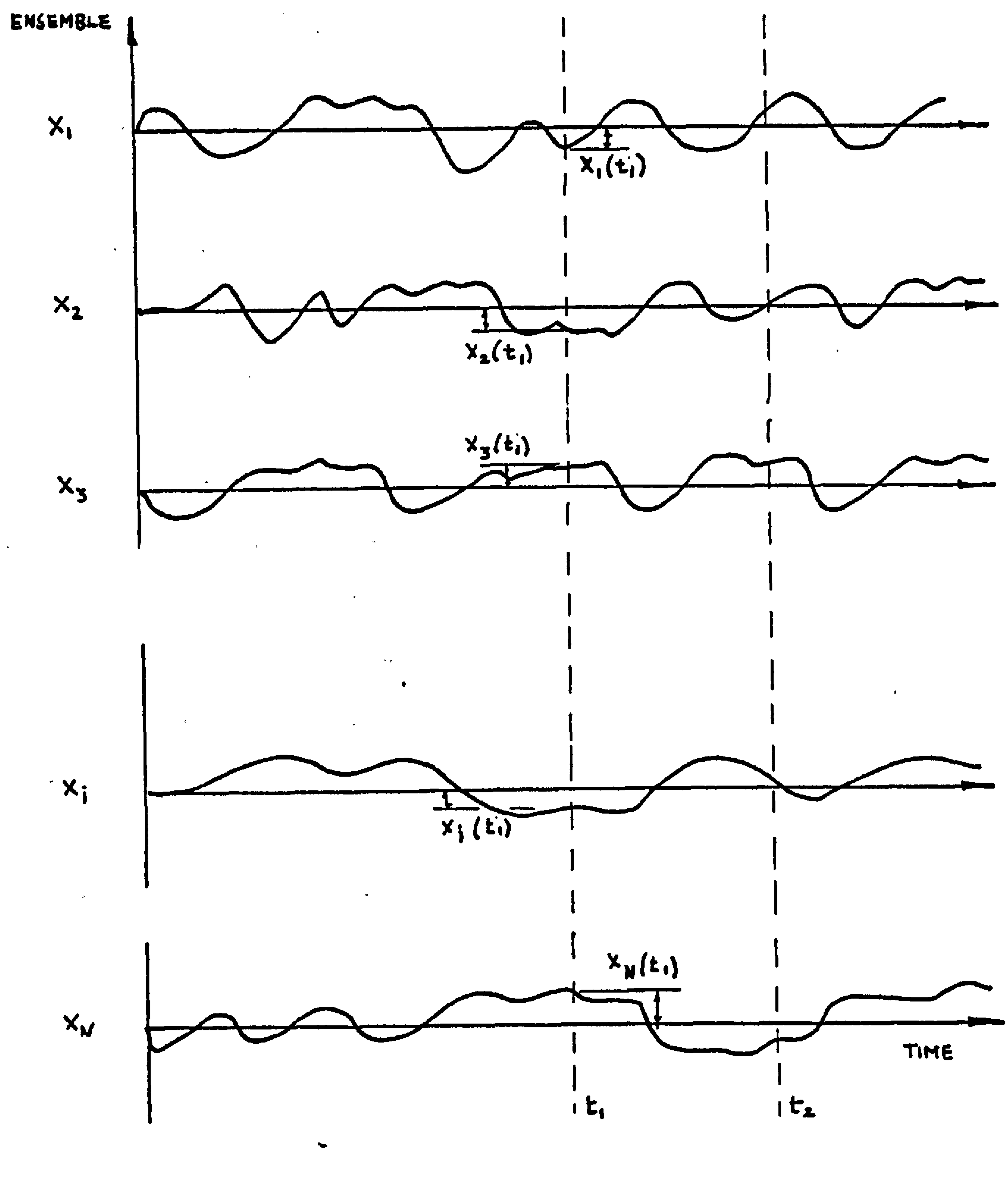


FIGURE II.1 An ensemble of records

values, $x_i(t_1)$, $x_i(t_2)$,.....$x_i(t_n)$, taken over a time period, for one fixed record x_i.

The simplest form of ensemble average is given mathematically as

$$\tilde{x}(t_1) = \frac{1}{N}\left[x_1(t_1) + x_2(t_1) + \ldots x_i(t_1) + \ldots x_N(t_1)\right]$$

or more concisely

$$\tilde{x}(t_1) = \langle x(t_1)\rangle = \lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} x_i(t_1) \quad \text{......eq.II.1}$$

This is familiarly known as 'the ensemble average' but to avoid confusion with higher order ensemble averages, it is strictly the 'first order ensemble average'. The 'second order ensemble average' is known as the 'Auto-correlation Function' $\tilde{x}(t_1, t_2)$ *. This is an average value of the product of two sample values, $x_i(t_1)$, $x_i(t_2)$, taken at two separate times t_1 and t_2, over the entire N records of the ensemble. Mathematically that is

$$x(t_1,t_2) = \langle x(t_1).x(t_2)\rangle = \lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N} x_i(t_1).x_i(t_2) \quad \text{....eq.II.2}$$

Higher order ensemble averages are obtained by an extension of the previous definition. The third and higher order averages become increasingly more difficult to obtain with random records, but normally only the first and second order averages are required.

* Sometimes denoted by $R(t_1,t_2)$ or $R(\tau)$, where $\tau = t_2 - t_1$ for stationary processes for which the average is independent of the particular time but a function of the time difference.

These ensemble averages are theoretically only correct for a very large number of records N. In practice a smaller number of records have to be used and in general the statistical properties will vary with different choices of N.

A process is defined as being <u>stationary</u> if <u>all</u> the statistical ensemble properties are invariant with time. However in practice, reference is only normally made to the first order average.

The time average of a process is defined mathematically as

$$\bar{x}(t) = \frac{1}{T} \int_0^T x(t)\, dt$$

where theoretically T should tend to infinity, but in practice a good approximation to the time average is made, provided T is great enough.

If the ensemble average of a stationary process equals the time average;

$$\tilde{x}(t) = \bar{x}(t)$$

then the process is classed as being <u>ergodic</u>. Ergodicity implies that <u>all</u> the statistical properties of a process are invariant with time, and can be determined from measurements made on a single record length. Whether or not a process can be assumed to be ergodic is particularly important for processes which yield only a single realization.

Mathematical analysis of non-stationary data

The non-stationary characteristic of the TM transient has been previously discussed in section 6.1. Bendat (1963) considers the analysis of non-stationary data. He notes that only ensemble averaging, as opposed to time averaging, is appropriate for the analysis.

The form of an ensemble average, given in equation II.1, is

$$\tilde{x}(t_i) = \langle x(t_i) \rangle = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} x_i(t_i) \qquad \text{......eq.II.3}$$

where $x_i(t_i)$ is the amplitude value at time t_i for the ith record and N is the total number of records in the ensemble.

In the following analysis, it is assumed that the individual records $x_i(t)$ are composed of an additive mixture of a signal component $s_i(t)$ and a noise component $n_i(t)$, that is

$$x_i(t) = s_i(t) + n_i(t) \qquad \text{.....eq II.4}$$

The noise records are assumed to be non-stationary and independent with respect to the signal and other noise records. The signals are assumed to be non-stationary. Two cases will be considered depending on whether the sample records $x_i(t)$ are;

1) independent or 2) dependent. Bendat (1963) considers

a third case where the records are correlated. The first two cases are in actual fact the two extremes of the correlated case. The independent case is of particular interest in respect to the TMD transient records. However the mathematics of the dependent case are also given for comparison purposes.

Ensemble averaging analysis

To determine the 'true' ensemble average of an ensemble of non-stationary records, $\tilde{x}(t) = \langle x(t) \rangle$, then the average should be taken over a very large number of records, that is $N \to \infty$. Practically, however, this cannot be achieved and N will have a finite value such that

$$z(t) = \frac{1}{N} \sum_{i=1}^{N} x_i(t) = \frac{1}{N} \sum_{i=1}^{N} \left[s_i(t) + n_i(t) \right] \quad \text{..eq.II.5}$$

where z(t) is an approximation to the ensemble average $\langle x(t) \rangle$. For a large collection of finite ensembles, $z_k(t)$ where k = 1,2......N, it is possible to estimate the ensemble average $\langle x(t) \rangle$.

$$\langle x(t) \rangle = \langle z(t) \rangle = \lim_{M \to \infty} \frac{1}{M} \sum_{k=1}^{M} z_k(t) \quad \text{.....eq.II.6}$$

The brackets $\langle \; \rangle$ denote an ensemble averages so that $\langle z(t) \rangle$ implies an ensemble average of a collection of M finite ensemble averages z(t).

The approximation z(t) will vary depending on the choice of N records. It is therefore necessary to determine the variance $\sigma_z^2(t)$, for a set of finite ensemble averages $\{z_k(t)\}$. The variance is defined as

$$\sigma_z^2(t) = \langle z^2(t)\rangle - \left[\langle z(t)\rangle\right]^2 \qquad \text{........eq II.7}$$

Note that $\sigma_z(t)$ is the standard deviation. This is a measure of how closely the set of measurements z(t) clusters about its mean value $\langle z(t)\rangle$.

The mean value $\langle z(t)\rangle$ has been defined in equations II.6 and may also be determined by

$$\langle z(t)\rangle = \frac{1}{N}\sum_{i=1}^{N}\langle x(t)\rangle = \frac{1}{N}\sum_{i=1}^{N}\left[\langle s_i(t)\rangle + \langle n_i(t)\rangle\right]$$
$$\text{.....eq.II.8}$$

From equations II.5 and II.6 the mean square value is given by

$$\langle z^2(t)\rangle = \frac{1}{M}\sum_{K=1}^{M}\left[\frac{1}{N}\sum_{i=1}^{N} x_{Ki}(t)\right]^2 \qquad \text{.......eq.II.9}$$

This is a double summation expression which using the ensemble averaging terminology is

$$\langle z^2(t)\rangle = \frac{1}{N^2}\left\langle\left[\sum_{i=1}^{N} x_i(t)\right]^2\right\rangle$$
$$= \frac{1}{N^2}\left[\sum_{i=1}^{N}\langle x_i^2(t)\rangle + \sum_{\substack{i,j=1\\ i\neq j}}^{N}\langle x_i(t).x_j(t)\rangle\right] \qquad \text{...eq.II.10}$$

This expression has N terms in the first summation and $(N^2 - N)$ in the double summation where $i \neq j$. Evaluation of the double summation depends on whether 1) independent,

2) dependent or 3) correlated records, is being considered.

Properties of the signal and noise

In the following analysis of ensemble averaging of non-stationary records, it will be assumed that the noise process $\{n_i(t)\}$ will have at any time t an ensemble mean of zero, and a variance of $\sigma_n^2(t)$, that is

$$\langle n(t)\rangle = \frac{1}{N}\sum_{i=1}^{N}\langle n_i(t)\rangle = 0 \qquad \text{...eq.II.11}$$

$$\sigma_n^2(t) = \frac{1}{N}\sum_{i=1}^{N}\langle n_i^2(t)\rangle \qquad \text{...eq.II.12}$$

It will also be assumed that the signal process $\{s(t)\}$ at any time t has an ensemble mean value of m(t) and a variance of $\sigma_s^2(t)$, that is

$$\langle s(t)\rangle = \frac{1}{N}\sum_{i=1}^{N}\langle s_i(t)\rangle = m(t) \qquad \text{...eq.II.13}$$

$$\sigma_s^2(t) = \frac{1}{N}\sum\langle s_i^2(t)\rangle - m^2(t) \qquad \text{...eq.II.14}$$

This analysis considers non-stationary processes, so that as indicated, both the properties of the signal and noise are functions of time. The mean m(t) is therefore the desired value of the signal at time t less the unwanted noise component. The fact that the signal $s_i(t)$ is considered to have a mean and standard deviation is important. This implies that besides an unwanted noise component $n_i(t)$, there is a degree of randomness inherent in the signal itself.

It has been assumed that the noise component is independent of the signal, so that there is no correlation between these components. Expressing this mathematically

$$\langle s_i(t)\, n_j(t)\rangle = \langle s_i(t)\rangle \langle n_j(t)\rangle = 0 \qquad \text{.....eq II.15}$$

for all i and j.

Similarly all the noise components are independent of each other, so that

$$\langle n_i(t)\, n_j(t)\rangle = \langle n_i(t)\rangle \langle n_j(t)\rangle = 0 \qquad \text{.....eq II.16}$$

for $i \neq j$.

Case 1: Independent Samples

The statistical properties, mean $m(t)$ and variance $\sigma_x^2(t)$ are derived for statistically independent samples as follows. If samples $x_i(t)$ and $x_j(t)$ for all $i \neq j$ are statistically independent, then the ensemble average is such that

$$\langle x_i(t)\, x_j(t)\rangle = \langle x_i(t)\rangle \langle x_j(t)\rangle \qquad \text{.....eq II.17}$$

Likewise for the signal ensemble average

$$\langle s_i(t)\, s_j(t)\rangle = \langle s_i(t)\rangle \langle s_j(t)\rangle = m^2(t) \quad \text{....eq II.18}$$

with reference to equation II.13.

The mean is given by equation II.8 as

$$\langle z(t)\rangle = \frac{1}{N}\sum_{i=1}^{N}\left[\langle s_i(t)\rangle + \langle n_i(t)\rangle\right]$$

$$= \frac{1}{N}\left[\sum_{i=1}^{N}\langle s_i(t)\rangle + \sum_{i=1}^{N}\langle n_i(t)\rangle\right]$$

and substitution of equation II.11 and II.13 yields:

$$\underline{\langle z(t)\rangle = m(t)} \quad \text{....eq.II.19}$$

This implies that for a large number of samples the ensemble average $\langle z(t)\rangle$ is an unbiased estimate of the mean value of the signal m(t).

The ensemble variance is given by equation II.7 as

$$\sigma_z^2(t) = \langle z^2(t)\rangle - \left[\langle z(t)\rangle\right]^2$$

Substitution equations II.10 and II.19.

$$\sigma_z^2(t) = \frac{1}{N^2}\left[\sum_{i=1}^{N}\langle x_i^2(t)\rangle + \sum_{\substack{i,j=1\\ i\neq j}}^{N}\langle x_i(t).x_j(t)\rangle\right] - m^2(t)$$

Evaluating the first term:

$$\sum_{i=1}^{N}\langle x_i^2(t)\rangle = \sum_{i=1}^{N}\langle (s_i(t) + n_i(t))(s_i(t) + n_i(t))\rangle$$

$$= \sum_{i=1}^{N}\langle s_i^2(t)\rangle + \sum_{i=1}^{N}\langle n_i^2(t)\rangle$$

using independence relationship II.15.

Hence:

$$\sum_{i=1}^{N} \langle x_i^2(t)\rangle = N\left[\sigma_s^2(t) + m^2(t) + \sigma_n^2(t)\right] \quad \text{..eq.II.20}$$

on substituting equations II.14 and II.12. Evaluating the second term by substitution of equation II.4 and expanding:

$$\sum_{i,j=1}^{N}\langle x_i(t).x_j(t)\rangle$$

$$= \sum_{\substack{i,j=1\\ i\neq j}}^{N}\left[\langle s_i(t).s_j(t)\rangle + \langle n_i(t).s_j(t)\rangle + \langle n_j(t).s_i(t)\rangle + \langle n_i(t).n_j(t)\rangle\right]$$

$$= \sum_{\substack{i,j=1\\ i\neq j}}^{N}\langle s_i(t).s_j(t)\rangle$$

on using independence relationship II.15 and II.16.

Hence

$$\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \left\langle x_i(t).x_j(t) \right\rangle = (N^2 - N).m^2(t) \qquad \text{....eq.II.21}$$

from equation II.18.

Finally substituting equation II.20 and II.21 in the equations for the ensemble variance yields

$$\sigma_z^2(t) = \frac{1}{N} \left[\sigma_s^2(t) + \sigma_n^2(t) \right] = \frac{1}{N} \sigma_x^2(t) \qquad \text{....eq.II.22}$$

This proves that the variance for statistically independent samples at time t, $\sigma_z^2(t)$, equals the sample variance $\sigma_x^2(t)$ divided by the sample size N. In the limit as N tends to infinity the sample variance $\sigma_z^2(t)$ tends to zero, so that for large samples it is possible to estimate the mean signal value m(t) quite accurately.

Case 2: Dependent Samples

The statistical properties mean m(t) and variance $\sigma_z^2(t)$ are derived for statistically dependent samples as follows:-

For M sets of amplitude records, the records are statistically dependent if for all sets $\{f_i(t)\}$ and $\{f_j(t)\}$

$$f_i(t) = s_i(t) + n_i(t)$$

$$\text{......eq.II.23}$$

$$f_j(t) = s_i(t) + n_j(t)$$

That is s (t) is a common in both f (t) and f (t). As with case 1 the noise terms n (t) and n (t) are independent of each other and of the signal.

The ensemble mean is identical to that of the independent case for which equation II.19 gives

$$\langle z(t) \rangle = m(t)$$

Likewise the ensemble variance is given by equation

$$\sigma_z^2(t) = \langle z^2(t) \rangle - \left[\langle z(t) \rangle \right]^2$$

which on substitution of equation II.10 and II.19 yields

$$\sigma_z^2(t) = \frac{1}{N^2} \left[\sum_{i=1}^{N} \langle x_i^2(t) \rangle + \sum_{\substack{i,j=1 \\ i \neq j}}^{N} \langle x_i(t).x_j(t) \rangle \right] - m(t)^2$$

As previously mentioned the dependent varies from the independent case only in the evaluation of the second double summation term:

$$\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \langle x_i(t).x_j(t) \rangle = \sum \langle s_i(t).s_j(t) \rangle \qquad \text{for } i \neq j$$

which now becomes

$$= N \sum_{i=1}^{N-1} \langle s_i^2(t) \rangle$$

using dependence relationship II.23.

So that

$$\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \left\langle x_i(t).x_j(t) \right\rangle = N(N - 1)\left[\sigma_s^2(t) + m^2(t) \right] \qquad \text{..eq.II.24}$$

using equation II.14.

Finally substituting equations II.20 and II.24 in the equation for the ensemble variance yields

$$\sigma_z^2(t) = \sigma_s^2(t) + \frac{\sigma_n^2(t)}{N} \qquad \text{......eq II.25}$$

Equation II.25 states that for large N the ensemble variance $\sigma_z^2(t)$ tends towards the sample variance $\sigma_s^2(t)$ which in general will have a value other than zero. However, as with the independent case the ensemble average $\langle z(t) \rangle$ is an unbiased estimate of the mean value of the signal m(t), equation II.19.

APPENDIX III

MEASURING TYMPANIC MEMBRANE DISPLACEMENT

The process of measuring tympanic membrane displacements may be considered in four sequential stages. These are:

i) Pre-test stimulus and subject preparation

ii) The operator interrogation section, during which time the following are entered; a) the system parameters, such as the stimulus duration, b) other details which do not affect the performance of the system, but are printed out with the test results on the line printer, for example the subject's identity or the date.

iii) The reflex test. During this period the digital computer controls stimulus presentation and displacement measurements. The resulting data are processed, for example ensemble averaged, and the evolving average of the TM transient is displayed visually on the VDU.

iv) The output of the results. During this period; a) the information and results concerning the test are printed out on the line printer, and b) the TM transient and other information are plotted on the X-Y plotter.

Each of these four sections will subsequently be discussed in more detail.

PRE-TEST STIMULUS AND SUBJECT PREPARATION

Before commencing the test it is necessary to perform the following procedure:

i) Select the stimulus, a) intensity, b) frequency, c) the ipsilateral or contralateral reflex configuration. All these requirements are satisfied by adjusting the appropriate dials on the audiometer.

ii) Next the cavity and headphone are placed on the helmet so that they correspond to the ear under test, and the helmet is adjusted to fit the subject's head. The counterbalance weight is then adjusted as previously prescribed (chapter 5).

iii) With the valve venting to atmosphere, the ear seal is fitted airtightly into the subject's ear canal. The valve is then closed, and is checked for air tightness by operating the reference diaphragm servo. If a perfect seal has not been obtained, then this fault will be rapidly indicated as an overload on the reference diaphragm power amplifier. Once the seal has been obtained, the valve is opened so that the cavity is vented.

NOTE BEFORE INSERTION, ADJUSTMENT OR REMOVAL OF THE EAR SEAL, IT IS IMPORTANT TO ENSURE THAT THE VALVE IS OPEN.

THIS PREVENTS SUBJECTING THE MICROPHONE DIAPHRAGM TO EXCESS PRESSURE.

iv) Finally the subject is briefed. He or she is told that a sound will be generated by the equipment, which is subsequently demonstrated using the audiometer interrupter key. By warning the subject in this manner, the possibility of startling the subject with the first stimulus is reduced.

THE OPERATOR INTERROGATION

The first stage of the test programme interrogates the operator on the teletype to obtain: a) the system parameters, b) the test details. This interrogation has been so arranged that only the details which differ from the preceding test are altered. For example, the date is only entered for the first test of the day.

The system parameters

The system parameters are:

i) NUMBER OF RECORDS? This integer dictates the number of records collected to form the ensemble average.

ii) INTERSAMPLE INTERVAL SECS? This integer gives the time in seconds between presentations of the stimulus to the subject. The interval should be large enough to avoid fatiguing the reflex (Borg 1976). If the interval is too short to allow for the operation of the valve, data processing and display, then the teletype will request a longer intersample interval.

iii) RECORD LENGTH SECONDS? The real number entered here will give the length of the records in seconds. The minimum sample length is 80 milliseconds.

iv) STIMULUS SWITCH OFF TIME 1 TO 10? The integer in the range 1 to 10 entered will dictate the length of the stimulus in proportion to the record length. For example '1' will cause the stimulus to be turned off after one tenth of the record length has elapsed. Entering '5' will cause the stimulus to be turned off after half the record length.

<u>The test details</u>

As previously mentioned, these details do not affect the running of the test, but will be printed out on the line printer with other details and system parameters. The test details are:

i) THE DATE?

ii) SUBJECT'S IDENTITY?

iii) TEST NUMBER AMENDMENT? Each test performed on a particular day has a test number starting from '1'. This number is automatically incremented on each run of the test. However, the subsequent test numbers may be renumbered by entering an integer number in response to this request.

iv) A DRUM DISPLACEMENT OF THE? Enter here the ear under test, left or right, and whether the test is ipsilateral or contralateral.

v) STIMULUS FREQUENCY?

vi) STIMULUS INTENSITY?

vii) ADDITIONAL COMMENTS?

Once the interrogation section has been completed the computer will continue with the test.

THE REFLEX TEST

The test cycle is shown in figure III.1. Immediately following the operator interrogation, the system waits for ten seconds before continuing with the test cycle. Approximately two seconds before the end of this period the actuator valve is instructed to close. At 166 milliseconds before the initiation of the tympanic membrane displacement sampling, the hybrid interface rack is instructed to switch on the stimulus. As previously mentioned the stimulus generator has a 166 msec latency time.

At 100 msec, before sampling commences, the reference diaphragm servo is switched on. This ensures that a steady state has been obtained before ear displacement sampling is initiated.

Next the TM displacement sampling is performed over the period of time prescribed for the record length. During this time the stimulus is switched off at the appropriate

FIGURE III.1 Flow diagram displaying one cycle of the tympanic membrane displacement measurement instant. Following this sampling period three operations are performed simultaneously:

i) The valve is opened to allow venting of the cavity.

ii) The servo is switched off.

iii) The intersample interval timer is initiated.

Next follows the data processing and then the display of the evolving ensemble average on the display screen.

Approximately two seconds before half of the intersample interval has elapsed, the valve will once again be instructed to close, and at 100 msec before this time, the servo will again be activated.

During the following period of time, equal in length to the TM displacement record, another record will be made of the volume displacement activity in the subject's ear canal. This record, being without stimulus, is a component of the control ensemble average. As with the previous sampling period, this is followed by servo deactivation, the valve opening to allow venting, data processing and a repetition of the TM transient display until the intersample interval has elapsed.

The next cycle begins again with the closing of the valve two seconds before the stimulus is switched on.

Once the prerequisite number of records have been obtained for the ensemble average, the system proceeds to the data output routine after first opening the actuator valve.

THE DATA OUTPUT ROUTINE

This routine is displayed in the flow diagram, figure III.2. The first part of this routine controls the printing of the system parameters and test details on the line printer. Also, during this period, the gains of critical amplifiers are checked and recorded. Any other information required by the operator is printed out on the line printer. The output in figure III.3 shows data concerning the ensemble averaging technique which is relevant to the operator's research.

The final section of the output routine controls the X-Y plotter. With reference to figure III.4, it can be seen that there are a number of different plots, plotted about three horizontal axes. Above each axis there is a calibration mark, which is equivalent to a volume displacement noted on the line printer output, normally 0.04 µl. The scaling of the top two graphs is varied automatically so as to encompass the large variations in the amplitude of the TM displacement transient, and the calibration mark is changed accordingly. The vertical dashed line gives the instant at which the stimulus is switched off. The various plots are described in section 6.4.

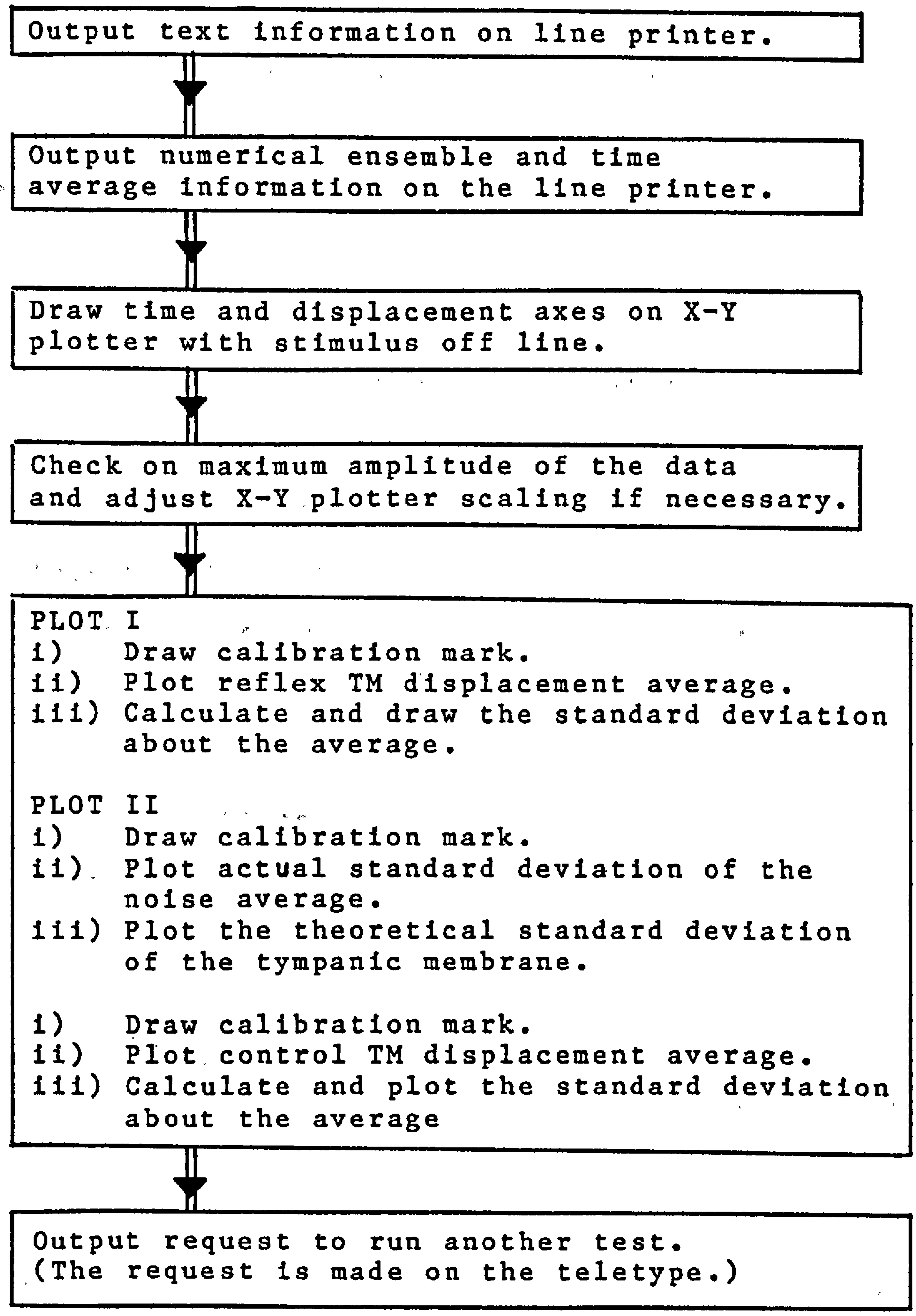


FIGURE III.2 Diagram of data output routines

CITY UNIVERSITY 690 HYBRID COMPUTER

```
**************************************************
*                                                *
*   MEASUREMENT  OF  EAR  DRUM  DISPLACEMENT     *
*   DATE 15TH AUGUST 1979 +                      *
*                                                *
**************************************************
```

TEST NUMBER 18

SUBJECT S IDENTITY IS R.J.

A DRUM DISPLACEMENT MEASUREMENT OF THE RIGHT EAR IPSILATERAL

STIMULUS FREQUENCY 1000 HZ

STIMULUS INTENSITY IS 90 DB UC

STIMULUS SWITCH OFF TIME 1 TO 10 IS 5

INTERSAMPLE INTERVAL SECS. IS 8

NUMBER OF RECORDS 20

RECORD LENGTH IS .50000 SECONDS

FORWARD LOOP GAIN P031 IS .4001 CAL.MARK 0.040 CU.MM.

ADDITIONAL COMMENTS -
TESTS ON FEASIBILITY OF IPSILATERAL REFLEX TESTS +

TIME AVERAGE STATISTICS FOR COMPLETE ENSEMBLES CU.MM.
****

	MEAN	STANDARD DEVIATION
NOISE	.0125	.0078
DRUM DISPLACEMENT	.0150	.0323

FIGURE III.3 Example of line printer output

TIMF AVERAGES CU.MM.
* DATE 15TH AUGUST 1979 *

TEST NUMBFR 18

NUMBER	MEAN	STD.DEV	MEAN	STD.DEV	MEAN	STD.DEV	MEAN	STD.DEV
1	-.06368	.04457	-.01639	.02050	-.02405	.02214	-.01433	.01833
5	.00661	.00789	.01091	.00703	.01032	.00664	.01134	.00550
9	.00742	.00435	.00498	.00546	.01093	.00478	.00815	.00444
13	.00865	.00425	.00365	.00380	.00749	.00433	.00762	.00568
17	.01181	.00707	.01279	.00674	.01203	.00786	.01249	.00781
21	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108
25	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108	1111.11108

RATE OF CHANGE OF CONTROL .04994 CU.MM.PER.SEC.

SIGNIFICANCE FACTOR IS 10.00 SFCONDS

FIGURE III.3 Continued

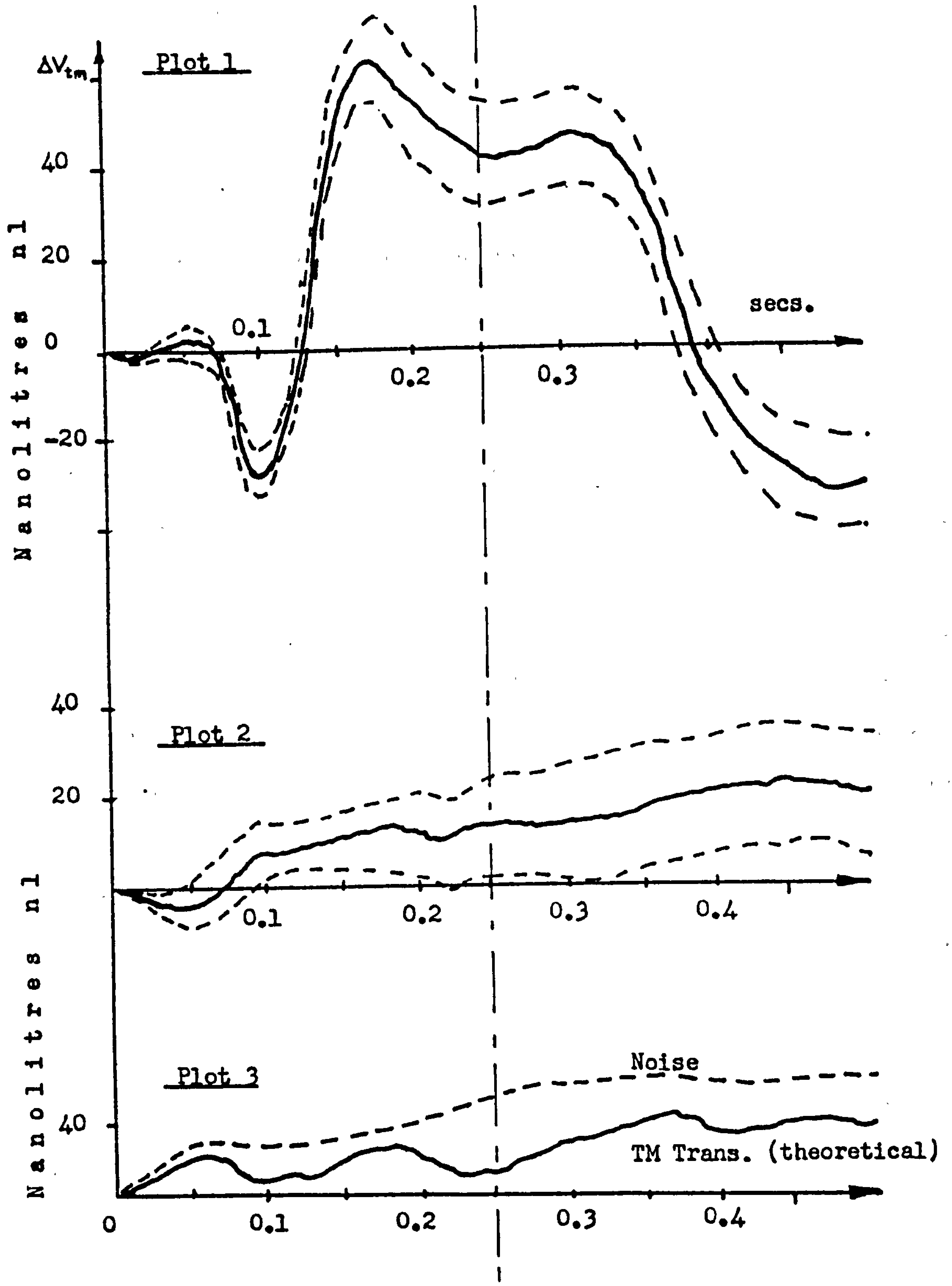


FIGURE III.4 <u>A typical graphical output from TMD system</u>

APPENDIX IV

THE SUBJECTS EMPLOYED FOR THE PRESENT INVESTIGATION

During the present investigation results were obtained from a sample of 20 ears, from a total of 10 normal hearing subjects. All these subjects had a hearing threshold of at least 15 dB HTL or better for the frequencies of 250,500, 1000, 2000, 4000 and 8000 Hz. The middle ear function of the subjects was evaluated using a Madsen Z073 acoustic impedance bridge, from which it was demonstrated that all the middle ear pressures were within ± 25mmH_2O and that the static compliance values ranged between 0.3 to 1.7 cubic centimetres. The acoustic reflex threshold ranged between 80 to 95 dB HTL for contralateral tones of 250, 500, 1000, 2000 and 4000 Hz.

All the subjects tested had no history of ear disease, or subjective or objective signs of catarrhal infections.

APPENDIX V

STIMULUS CHARACTERISTICS

Tests were performed to determine the envelope, and latency, of the tone generated by the audiometer incorporated in the TMD system. It was discovered that there is a considerable latency from the time of switch on of the stimulus generator, to the first appearance of the output. This lag was compensated for by operating the audiometer 166 msec before the stimulus was required, and also switching off 18 msec early to allow for a further latency on cessation of the tone.

The standard TMD system programme was modified to measure the envelope of the tone. The result is displayed in figure V.1, which shows that the stimulus has a time constant of approximately 62 msec. This time constant is greater than the onset latency of the stapedius muscle (approximately 20 msec). Therefore, if the muscle latency is to be accurately determined, a stimulus with a more rapid rise time is required.

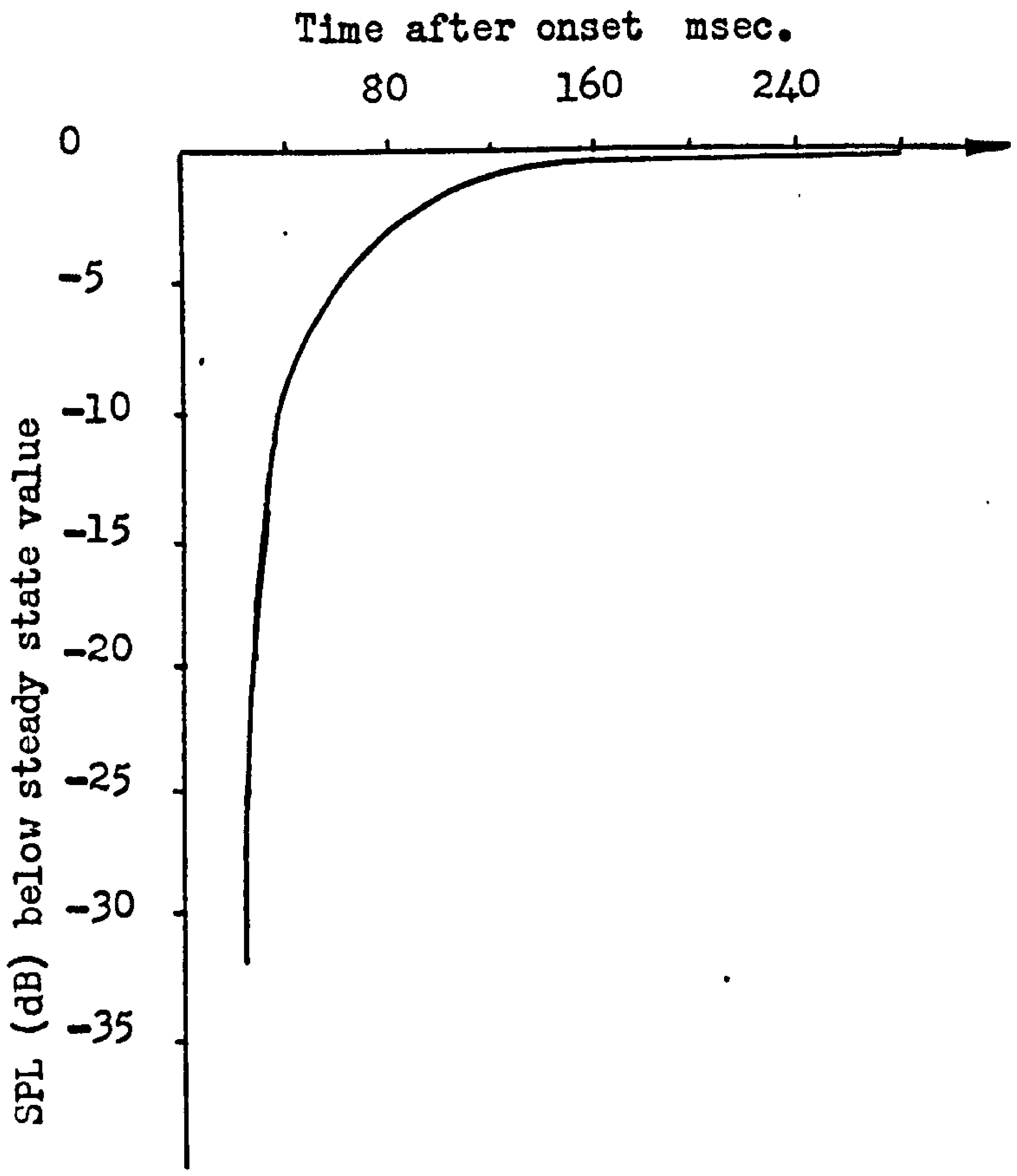


FIGURE IV.1 Onset characteristic of audiometer stimulus