Characteristics of 9mm Metallic Triple-Beam Tuning Fork Resonant Sensor

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Abstract. This paper describes the design and testing of the first miniaturised metallic triple-beam tuning fork resonant sensors for use in force, pressure and torque measurement applications. The new devices with 9mm length vibrating tines have resulted in over a 40% in size when compared to previously tested resonators. The four fold increase in operating frequency to 26 kHz, with Q factors in air up to 4000, provides additional benefits for resolution, accuracy, range and overload capability. Measurement repeatability of at least 0.02% of span levels for torque transducers employing the sensors are quoted. Results of characterisation over the temperature range -30°C to +90°C are given.

1. Introduction

Resonant sensors have been used in a wide range of sensing applications, such as load, pressure, torque and fluid flow characteristics [1]. The key element of these sensors is the resonator, an oscillating structure, which is designed such that its resonance frequency is a function of the measurand. The most common sensing mechanism is for the resonator to be stressed as a force sensor. The applied stress effectively increases the stiffness of the resonator structure, which results in an increase in the resonator's natural frequency. The resonator provides a virtual digital frequency output, which is less susceptible to electrical noise and independent of the level and degradation of transmitted signals, offering good long-term stability. The frequency output is also compatible with digital interfacing and no analogue-to-digital conversion is required, therefore maintaining inherent high accuracy and low cost.

The first successful metallic triple-beam tuning fork (TBTF) resonant sensor with thick-film drive/pickup elements [2, 3, 5] has a resonating 'tine' element length of 15.5mm and an overall sensor length of 23.5mm, a thickness of 0.25mm and beam widths of 1mm, 2mm and 1 mm. The gap between the beams was 0.5mm. However, this device is too large for current force/torque and pressure sensing applications. The challenge has been to reduce the sensor dimensional footprint and if possible enhance sensor performance.

2. Design and Fabrication

The combination of processes used in the resonator fabrication, photo-etched TBTFs with drive and pick-up piezoelectric elements printed directly onto the device surface, presents low-cost manufacturing opportunities for mass batch production. Figure 1 shows a plan view of the resonator structure with PZT drive and detection elements. The thick-film screen-printing process deposits relatively thick layers of material, typically between 50 and 100µm. The magnitude of the output of the lead zirconate titanate (PZT) element depends upon the piezoelectric properties of the deposited layer, its thickness and the stress or voltage applied. In trying to reduce the size of the sensor there is a danger that the piezoactuator might not be able to excite the stiffer tines, so PZT printing is a physical limitation in size reduction. Finite element analysis (FEA) was employed to simulate the modal behaviour and stress distribution of the resonator in order to optimise the positioning of the thick-film PZT elements on the structure.

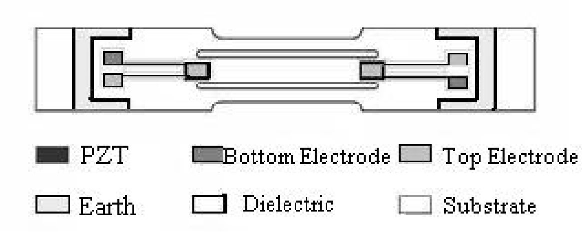


Figure 1. Plan view of the resonator structure with PZT drive and detection elements.

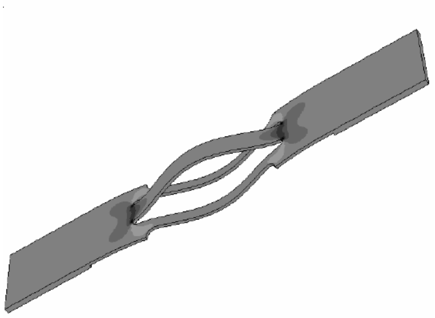


Figure 2. Stress contour plot for the resonator in mode 3.

The triple beam tuning fork has a planer structure and is inherently more dynamically balanced when compared to a single beam or an out-of- plane double beam structure vibrating in flexural modes. Balanced structures dissipate less energy through their supports and therefore possess an intrinsically higher mechanical quality factor. The sensor is designed to oscillate in a differential mode, where the central beam vibrates in anti-phase with the outer beams (mode 3) to minimise mechanical energy losses from the resonator. Figure 2 shows the operational modal behaviour of the sensor modelled by FEA.

Frequency of operation is proportional to $1/L^2$, where L is the tine length, thus a reduction in length will lead to an increase in operating frequency (in this case from 5-6 kHz to 25-27 kHz). However, the reduction in size allows a larger application range-ability (i.e. 9mm tine device could be used for torque applications from 10 Nm to 1000 Nm, depending on the torque shaft diameter). It is true to say that longer tines are more sensitive than shorter tines. However, when comparing the old 15.5mm device with new 9mm device in terms of sensitivity and other performance characteristics, care was taken to make sure that both devices were compared under the same micro-strain conditions, that means to consider total frequency excursions, designed usually at 5-10% of workable range [5].

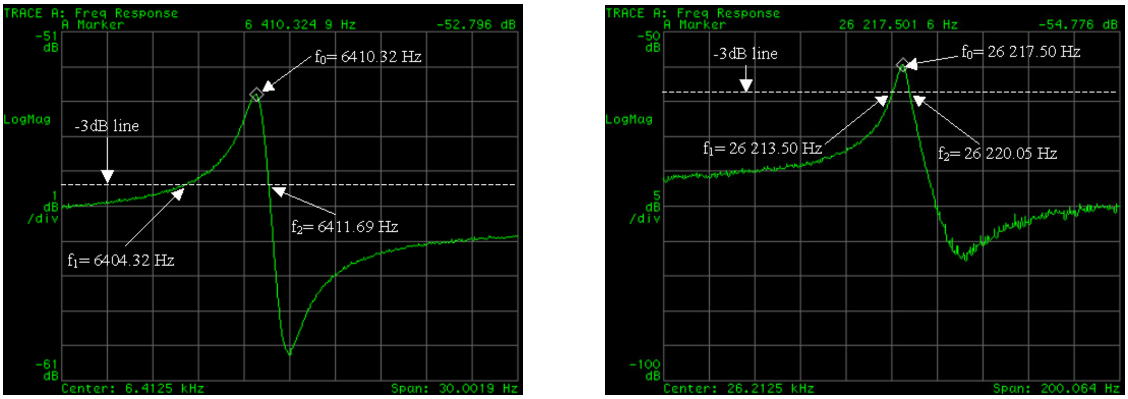
3. Resonator Operation

3.1. Open-loop configuration

The aim of the experiments was to compare the performance of resonators designed with different beam lengths. One resonator is 23.5mm long with a tine length of 15.5mm (Type 1) and a natural frequency between 5 – 7 kHz and the new resonator is 15.5mm long (Type 2) with a tine length of 9mm with a natural frequency between 25-27 kHz. Both resonating elements have the same beam thickness of 0.25mm and beam widths of 2mm for the middle beam and 1mm for each of the outer beams.

The first tests on the resonators are realised in an open-loop configuration. The PZT element at one end of the resonator is driven by a periodic chirp signal of 1V peak-peak from a Hewlett-Packard 89410A Vector Signal Analyser, which swept the frequencies around the resonant frequency. The PZT element on the other end of the resonator was connected to a Kistler 5011 Charge Amplifier, which has an adjustable low pass filter, and the output from the charge amplifier was fed back to the signal analyser for frequency response analysis of the resonator. Figure 3 shows the amplitude-frequency response for the third mode of vibration for both resonator types.

From these results the values for the centre frequencies and quality factor (Q) for the two devices are as follows: resonator Type 1 has a centre frequency of 6,411Hz and Q-factor of 870, while resonator Type 2 has a centre frequency of 26.220kHz and Q-factor of 4002.



(a) Resonator Type 1 (b) Resonator Type 2

Figure 3. Resonator frequency response from HP89410A Vector Signal Analyser

3.2. Closed-loop configuration

The custom-built electronics for the TBTF resonators operates in a feedback closed loop mode. The receiving PZT element is connected to a charge amplifier circuit, followed by a digital 90° phase shift circuit. For optimised performance the feedback signal passes through a second adjustable phase shifter and a second stage of amplification all on one circuit board. The output from the second stage amplification is fed back to the driving PZT element. The resonant frequency is displayed on the Agilent 54621A oscilloscope, which is connected to the output of a Phased Locked Loop circuit. Additionally the frequency output can be connected to an analogue input of the data acquisition card DAQ6035E that imports the data to the LabView software. In this software the Fourier transformation is obtained for the amplitude-frequency analysis of the resonators.

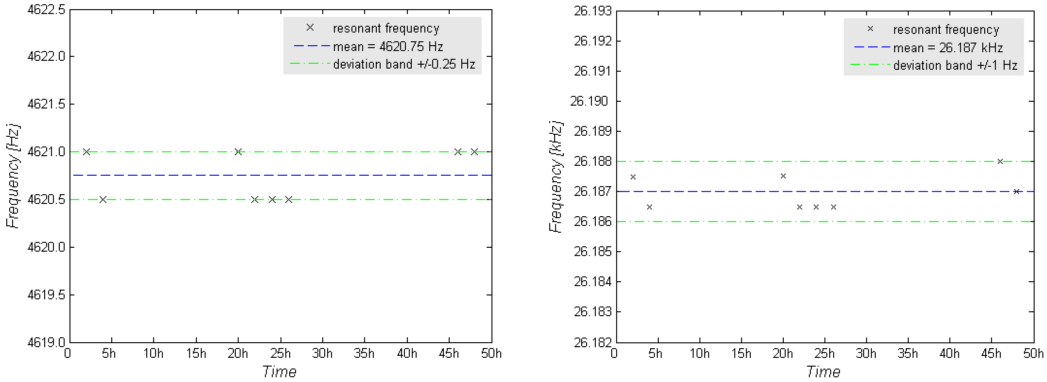
4. Characteristics

4.1. Stability

Stability is the ability of a measuring system to maintain constant its measurement characteristic with time. For this investigation the environmental conditions, such as temperature, humidity and pressure, have to be constant. This was achieved by using a climatic test chamber Montford Mini-Mech-B set to 25°C. The resonators were operated in the open-loop configuration. Over a time period of 48h the amplitude-frequency response was recorded in unequal time steps. The default frequency resolution for this experiment was 0.5Hz.

Figure 4a displays the test result of resonator Type 1 over a time period of 48h. The maximum deviation from the mean value of 4,620.75Hz was 0.25Hz. In practical terms, for a measured torque sensitivity of 40 Hz/Nm [4] for this resonator type, the maximum error converted to torque is 0.00625 Nm, hence the stability for a torque range of 0-20 Nm is 0.03 percent.

The maximum deviation for resonator Type 2 (figure 4b) from the mean value 26.187kHz was 1Hz. The torque sensitivity of this new designed resonator, tested under static torque conditions, with an expanded torque range of 0-100 Nm, is 26.6 Hz/Nm. Hence the maximum error converted to torque is 0.0375Nm or, calculated for this torque range, gives a stability of 0.04 percent.



(a) Resonator Type 1 (b) Resonator Type 2

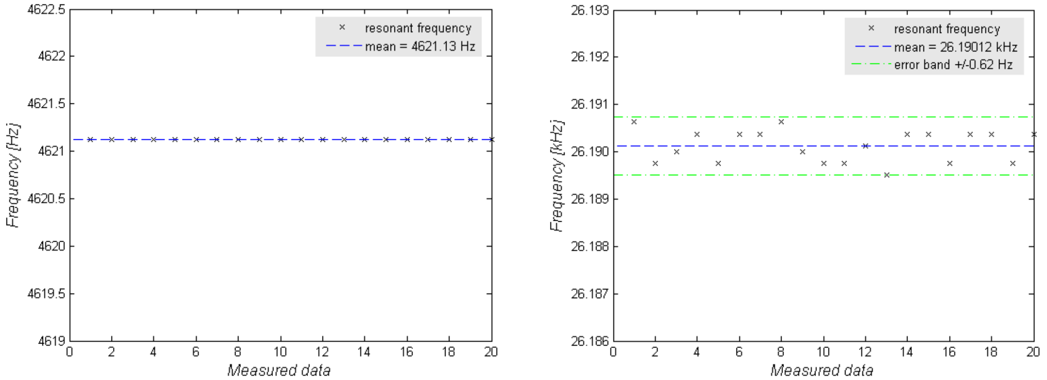
Figure 4. 48h Stability test results

4.2. *Repeatability*

This investigation illustrates the measurement precision under conditions of repeated measurements over a short period of time. The experimental set-up was similar to that for the stability investigation, except that the period of measurement was shortened to about 5 minutes and the resolution was adjusted to 0.1Hz.

Figure 5a shows, that the deviation of the resonance frequency of resonator type 1 is less than the resolution of 0.1Hz. Hence the maximum error converted to torque is less than 0.0025Nm as the torque sensitivity is 40 Hz/Nm. The repeatability for the measurement range 0-20 Nm, is better than 0.01 percent.

The maximum deviation for resonator Type 2 (figure 5b) is 0.62Hz with respect to the mean value 26.190kHz. Hence the error in torque is 0.023Nm at the torque sensitivity of 26.6 Hz/Nm and the repeatability for the expanded torque range 0-100 Nm is 0.02 percent.



(a) Resonator Type 1 (b) Resonator Type 2

Figure 5. Repeatability Test Results

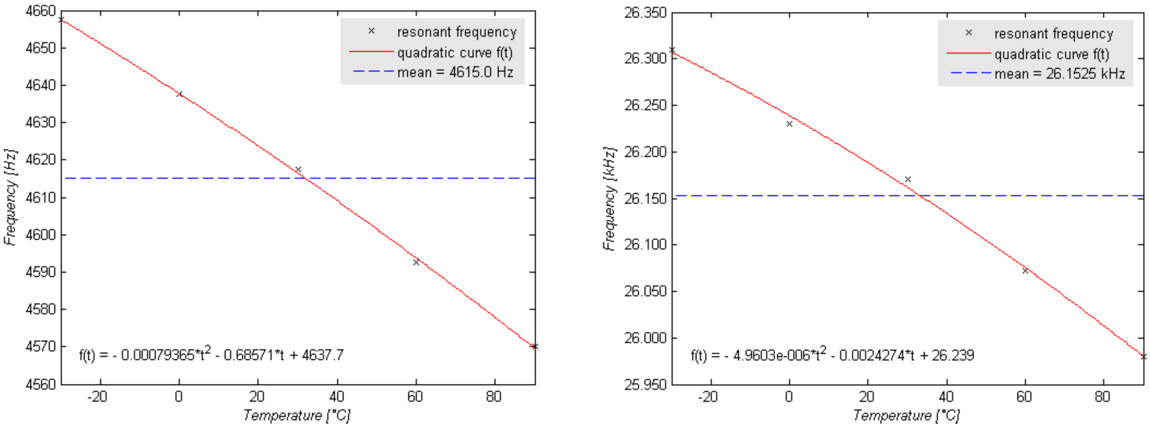
4.3. Temperature

Industrial monitoring applications require a satisfactory measurement capability over a temperature range of -30°C up to 85°C. To increase the application field of the resonant sensor by having even larger temperature ranges requires that the compensated temperature range should be as large as possible. On account of this the temperature characteristic needs to be known so that strategies for temperature compensation can be employed.

The experimental set-up was similar to that for the stability and repeatability tests. The drive and pickup PZT elements of the sensor were connected by two coaxial cables to the open-loop electronics outside the climatic test chamber. The temperature was increased from -30°C to 90°C in steps of 30°C. At each temperature point the frequency response of the respective resonator was recorded after two hours delay, required to establish stable conditions inside the climatic test chamber.

The temperature characteristic of resonator Type1 is displayed in figure 6a. Without any kind of temperature compensation the maximum deviation from the mean 4,615.0Hz is 45Hz in the temperature range between -30°C and 90°C (approximately 0.75Hz/^{o}C). Converted to torque it is 1.125Nm or 5.6 percent for the torque range of interest. After fitting a quadratic polynomial (see equation f(t) in figure 6a), the maximum deviation could be reduced to 1.5Hz. This is 0.038Nm or 0.2 percent of the maximum torque value.

Figure 6b shows the characteristic of resonator Type 2. The trend of this resonator is similar with a maximum deviation from the mean 26.1525kHz of 172.5Hz (approximately 2.5Hz/^{o}C). Converted to torque it is 6.48Nm or 6.48 percent. After fitting a quadratic polynomial f(t), (figure 6b), the maximum deviation is 10Hz or in torque 0.385Nm. This is about 0.4 percent deviation in the complete temperature range.



(a) Resonator Type 1 (b) Resonator Type 2

Figure 6. Temperature test results

5. Discussion of Results

The 9mm tine TBTF has a performance comparable to the 15.5mm device. However, the 9mm device under test has a 500Hz frequency excursion (range or span) for every +/- 25Nm, which is only 2% of the base frequency. Therefore, under the same strain conditions as tested on the 15.5mm device [5], the 9mm element could measure up to 1000Nm.

Range is approximately 500Hz for 50 Nm (+/- 25 Nm).
Sensitivity is better than 25 Hz/Nm.
Linearity is better than 2% of the range (worse case)..
Repeatability (Max/Min. load) is +/- 0.04% of the range (maximum change 2Hz): given that the temperature during the tests was varying by +/- 1^{o}C, this is a good result.
Stability is better than +/- 0.04% of the range (though temperature effect must be considered).
Max. Hysteresis is less than 1%

The temperature coefficient of these 9 mm devices is approximately 2.5 Hz/°C, which translates to 0.08Nm torque. There are several reasons for this effect, which should be investigated further: (a) material of TBTF, stainless steel 430 S17 with a temperature coefficient of 12 ppm; (b) temperature mismatched between TBTF and shaft material (stainless steel 17-4 Ph hardened), which has a temperature coefficient of 16 ppm; (c) temperature characteristic of the PZT paste and dielectric is not known (there is an effect although not quantified).

6. Conclusion

Reduced size metallic triple-beam tuning fork resonant devices, resulting in a 42% reduction in critical dimensions, have been successfully fabricated and tested. The main characteristics can be summarised as follows:

(a) The stiffer 9mm device are less sensitive than the longer 15.5 mm device but they have an increased operating range.
(b) Unstressed frequency of operation occurs at 26 kHz, with a variation of +/-5% in the resonant frequency, from device-to-device through all fabricated batches, due to etching tolerances and variations printed PZT activity factor.
(c) Unstressed frequency variation within a given batch is less than +/- 2%.
(d) Q-factors are generally greater than 2,000 (maximum of 4,000 although some are as low as 1500).
(e) Robust devices with good stability and repeatability, having high overload capability and suitable for laser spot welding to transducer structures.
(f) Performance characteristics of the 9mm devices are encouraging, so that future plans for further miniaturization can be implemented.
(g) Improvements in yield (etching results, and printing PZT drive and pick-up) will lead to better device performance and further cost reduction.

7. References

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