The Tumble Mode - Where Test Pilots Fear To Tread

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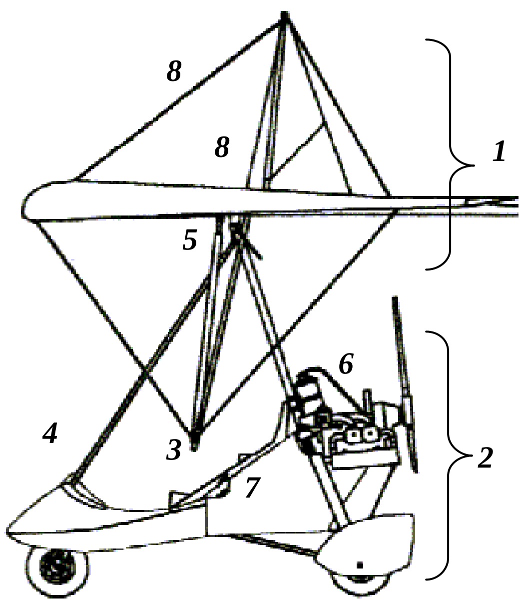
Introduction

Following a fatal accident in 1997 **[1]**, and identification of common patterns in several (usually fatal) previous accidents **[2, 3, 4, 5, 6, 7, 8, 9]** the AAIB (United Kingdom Air Accidents Investigations Branch) asked the BMAA (British Microlight Aircraft Association) to pursue a course of investigation into the tumble mode, which had been attributed as the primary cause of that fatal accident. Through an ongoing collaboration, the University of also Southampton became involved in this investigation,

The tumble mode is a peculiarity of weightshift controlled aircraft – that is flexwing microlights and hang-gliders. It is a departure from controlled flight leading to a nose-down pitch autorotation: pitch rates of 400°/s are known. When a tumble occurs in a microlight aeroplane, it is rare for the crew to survive and loss of the aircraft is universal. Prior to work starting in the UK to try and eliminate the tumble, one type had suffered 7 fatal tumble accidents in a service history of less than 200,000 hours, and the total number of fatal tumble accidents was somewhat greater.

Some readers may not be fully familiar with the design of weightshift controlled aircraft and wish to familiarise themselves in order to fully understand. The best available general description is in reference **[10]** whilst the most commonly used pilot briefing material is in reference **[11]**. **Figure 1** also shows the main parts of the aircraft class that are mentioned in this paper.

Figure 1, Labelled illustration of typical flexwing aircraft (Mainair Blade 912)



1 Wing
2 Trike
3 Basebar
4 Front Strut
5 Hangpoint
6 Engine
7 Seats (tandem seating, 2 crew)
8 Landing wires

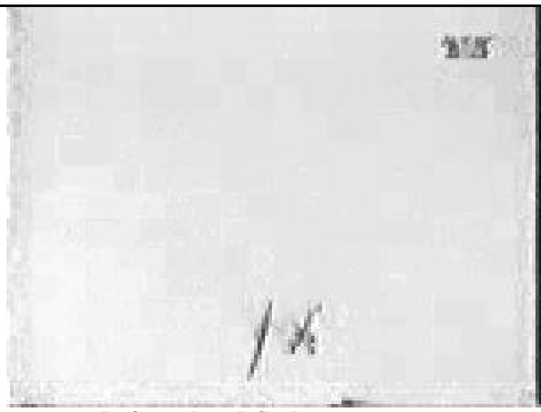
Illustrating the tumble

The following sequence of photographs is the best known photographic evidence of a genuine tumble accident, the accident occurred at an airshow in Europe, and the type is identifiable as a French "Cosmos" aircraft. The accident is believed to have been fatal.

Figure 2, Illustration of a fatal tumble after a failed loop

Note: The origin of this piece of video is uncertain. The exact date, location and source cannot be verified.

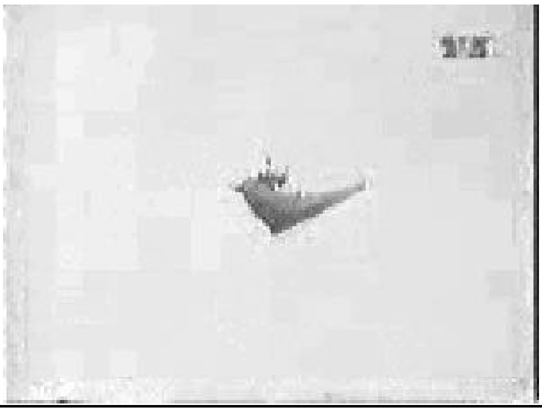
3 seconds from level flight 50° nose up



4 seconds from level flight, 80° nose up

6 seconds from level flight, 45° beyond vertical

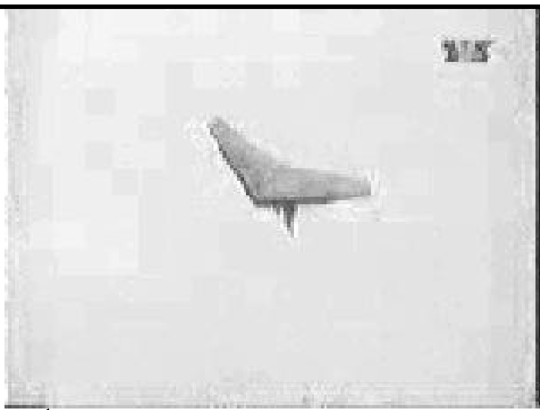
7 seconds from level flight, inverted.



8 seconds from level flight, inverted with nose approximately 45° below the horizon. At this point the “nose-up” (in aircraft axes) motion pauses.	9 seconds from level flight, pitch rotation has reversed and the aircraft has rotated “nose down” (in aircraft axes) back to inverted.
 9 ½ seconds from level flight, the wing is continuing to pitch “nose-down”, note that the trike can be seen to be very “nose down” compared to the wing. It is likely that the front strut or basebar has failed at this point.	 10 seconds from level flight, the wing is now pointed almost straight upwards.
 10 $^{1}/_{3}$ seconds from level flight, the aircraft passes through a level attitude. It can be seen that the pitch rate between this frame and the previous is over 400°/s	 10 $^{2}/_{3}$ seconds from level flight, the aircraft is now pointed downwards. Pitch rate must at this point be 200 - 300°/s

Menu

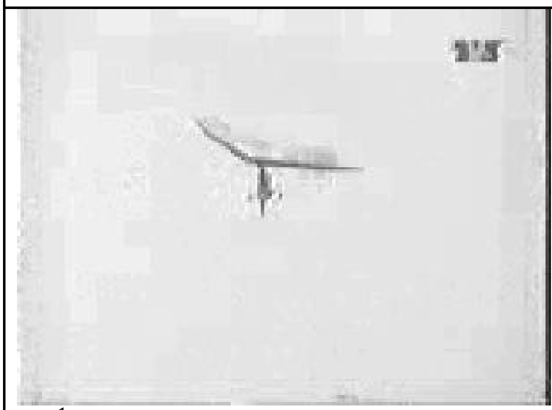
11 seconds from level flight, the aircraft passes through inverted.



$11\ ^{1}/_{3}$ seconds from level flight, 45° nose down.

$11\ ^{2}/_{3}$ seconds from level flight, the trike can be see very nose down compared to the wing - also there is considerable wing distortion.

12 seconds from level flight, inverted. Pitch rate appears to be slowing, note very large washout at tips.



$12\ ^{1}/_{3}$ seconds from level flight, passing through a level attitude.

$12\ ^{2}/_{3}$ seconds from level flight, aircraft is pointed downwards.   Wing planform can be seen still intact.


13 seconds from level flight, passing through a level attitude.


13 ½ seconds from level flight, passing through a vertical nose-down attitude.


14 ½ seconds from level flight, impact with the ground.

<u>Conflicting evidence</u>

An analysis was carried out of the information available from known accidents, which had occurred in the UK over about 20 years. These reports showed the following common factors:

- A departure from controlled flight either following gross mishandling, flight to the stall, or during flight in potentially highly turbulent conditions.
- In most cases, the aircraft was being flown at a comparatively low weight (typically ~$^{2}/_{3}$ MTOW)
- Damage to the aircraft consistent with very large negative g overload of the wing (usually failure of the landing wires and failure downwards of the wing-tips)
- Impact of the basebar with the front strut, usually resulting in a failure of one of these two components, causing the propeller subsequently to impact the keel tube. Where a pilot has survived the departure it is normal that they have subsequently reported the basebar being “snatched from their hands”. [Note: the term “trike” describes all of the aircraft that is not the wing, or the hangbolt. The wing and trike are hinged in pitch and roll at the hangpoint, of which the hangbolt is the central component, whose removal allows the two to be separated for derigging.]
- Autorotation of the aircraft in nose-down pitch, at a rapid rate (in excess of 300°/s), generally followed by…

- Break-up of the aircraft in flight, preventing it from sustaining flight and usually resulting in a fatality.

Note: Sycamoring failure mode. It has been recorded in a number of accidents that the wing basebar has failed following impact with the front strut. The result of this would appear to have been that immediately following this failure, the loss of structural integrity has caused a subsequent failure of the wing leading edge (and cross-tube), at the root on one side only. This has resulted in a new wingform that is approximately "L-shaped" as seen in forward view. It is reported that a wing which has failed in this way develops a spiral motion that tends to arrest the aircraft's descent, in the manner of a sycamore leaf (hence the accepted term, "sycamoring" which has become adopted to describe the nature of descent). It is believed from anecdotal evidence, although documentary evidence to either support or dispute this case is weak, that all tumble accidents which have been survived have involved basebar failure and sycamoring descent. Similarly there does not appear to be any recorded tumble accident, where the front strut failed, which was survived. For this reason, all British microlight manufacturers eliminated any previous use of re-enforcing cables within the basebar from the late 1980s**[12].**

Understanding the aircraft's behaviour

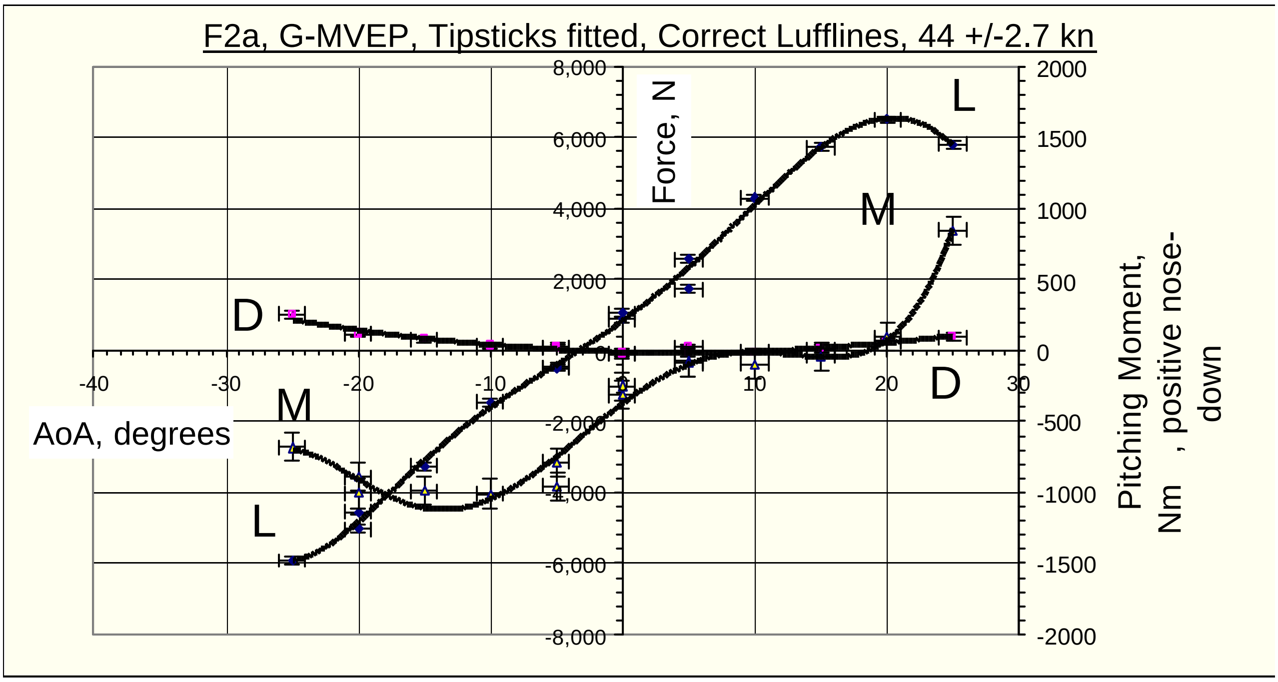
The investigation was presented with a problem of some significance – we knew that there was a departure from controlled flight, it appeared to be in pitch, and was unrecoverable. There did not seem to be a single entry mode, and there was conflicting information as to how the mode occurred.

It was an obvious starting point to consider longitudinal static stability, since one consistent piece of information was that the aircraft and/or the wing was rotating about the lateral axis. The weightshift nature of the aircraft class means that there is a complicated relationship between "apparent" LSS characteristics, and true "aerodynamic" LSS, and it was felt that obtaining a realistic understanding of the aerodynamic LSS characteristics would be helpful. In addition, much of the speed / AoA envelope of the wing could not be explored in flight without endangering the aircraft, whilst simultaneously only obtaining results from transient conditions Therefore use was obtained of the British Hang-gliding and Paragliding Association (BHPA) test rig at Rufforth in Yorkshire. The equipment, essentially a V6 Chevrolet truck, with a large instrumented "sting" such as might be fitted into a wind-tunnel, except considerably larger and incorporating a hydraulic mechanism for altering pitch attitude of the wing. Power is augmented with a nitrous oxide injection system into the V6 engine. Operating this equipment is a complex multicrew environment in itself, normally requiring a crew of 2 although 3 is more normal (a driver, instrumentation operator, and test engineer) for microlight work. Data logging is via conventional force and displacement instrumentation feeding a PC through a conventional A/D converter. Whilst none of this hardware legally requires flight proving, it nonetheless carries human beings and has, on occasion, become inadvertently airborne; this requires conventional flight test safety planning and inspection practices to be applied. It is normal for at-least two of any operating crew to be either microlight or hang-glider test pilots or flight test engineers.

Figure 3, BHPA hang-glider test facility at Rufforth, Yorkshire

This produced a great deal of data, and demonstrated well the extremely non-linear C_M.v.AoA characteristics of this class of wing, as well as their susceptibility to minor adjustments in configuration. **Figure 4** is a typical data presentation. As may be seen, the lift and drag characteristics are unremarkable, but the pitching moment characteristics different to those of a conventional rigid wing.

Figure 4, Characteristics of Mainair Flash 2 alpha wing



Nonetheless however, this curve (nor any other curve generated) in itself showed no characteristic which in itself indicated a risk of pitch autorotation. Therefore a further model was developed (not included in this paper, but may be found at Reference **[13]**. This model showed that the main player was not the wing characteristics alone, but the combination of wing and trike. This is counter-intuitive, since the hangpoint design is such that "stick free" no significant pitching (or rolling) moment(s) should be transmitted between the wing and trike, and the forces applied by the pilot to the basebar produce a relatively small pitching moment. However, the main evidence which brought this together was the video of a nose-down autorotation (

Figure 2) which shows the basebar and front strut apparently in continuous contact, together with the evidence from numerous wreckage inspections, which showed damage of both the basebar and front strut where they had struck each other.

This led to the following explanation of tumble entry:-

?? Departure occurs from a steep nose-up attitude. If power was used to achieve this condition, the throttle is likely to have been closed.

?? The airspeed decreases rapidly, towards a stalled condition.

?? At the point of stall, the wing aerodynamic pitching moment becomes strongly nose down (**Figure 4**).

?? Simultaneously however, the trike pitches nose-down, initially rotating about the hangpoint until the front strut locks against the basebar, creating a rigid system upon which a net nose-down pitching moment is acting.

?? The aircraft is then rotating nose-downwards, with the entire system rotating about the whole aircraft CG (rather than the wing alone rotating about the hangpoint).

?? This creates what we have termed "induced flow", where the angle of attack becomes strongly positive at the leading edge and strongly negative at the trailing edge. This is illustrated in **Figure 5**, and creates effectively a wing with a large negative camber.

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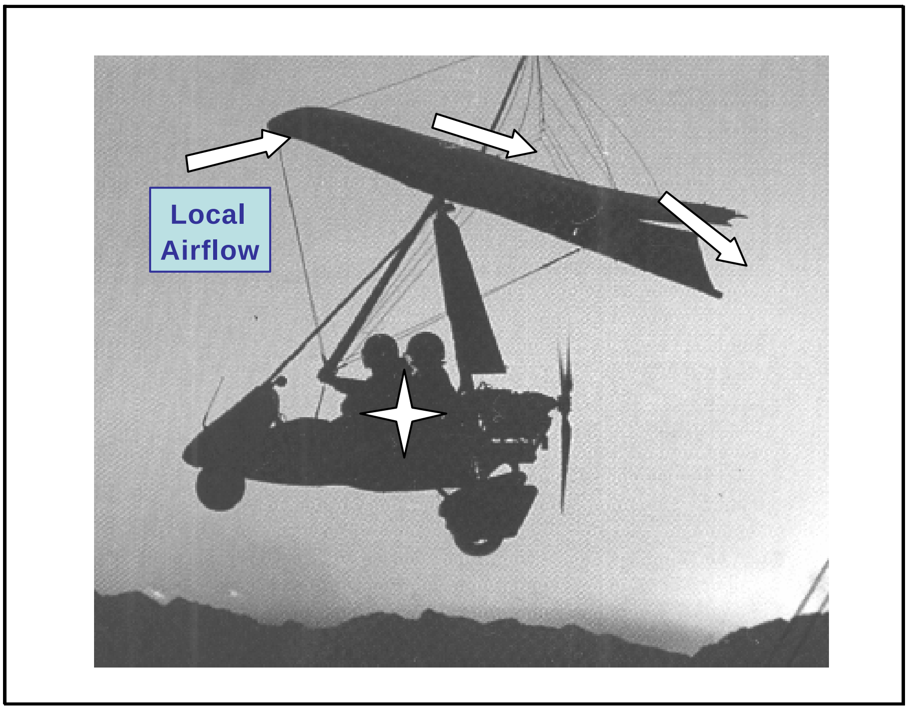
Figure 5, Illustration of induced flow, superimposed upon aircraft image



- ?? This "induced camber" locks the aircraft into the nose-down autorotation, which continues until the aircraft either hits the ground or breaks up.

Avoiding Tumble entry

Further investigation, through a combination of flight testing and analysis of accident reports have shown four main entry routes. Apart from developing design tools to avoid the combination of wing and trike characteristics described above (work on this is still ongoing), determination of these entry routes, and education of pilots in their avoidance has been the main thrust of the teams efforts.

The four main entry routes that have been identified are:-

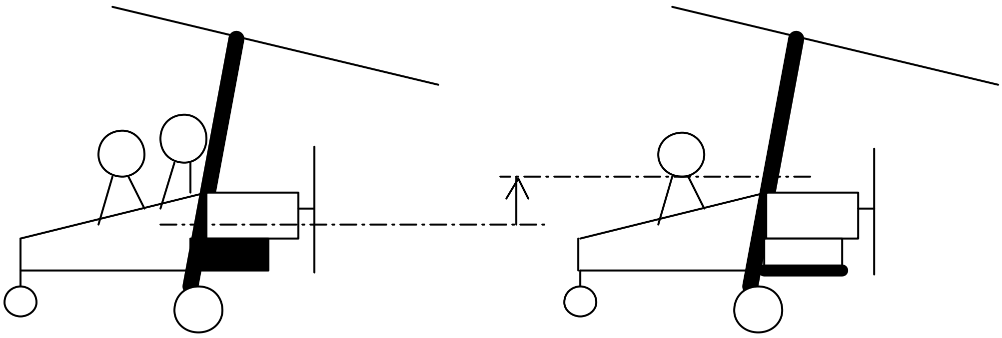
First mechanism – the whip stall

This occurs when the aircraft is climbed at too steep an attitude, and then at this steep attitude, the thrust is removed (either by engine failure or via throttle closure). This causes a rapid deceleration towards the stall whilst simultaneously creating a tendency for the trike to swing nose-down. So, the mechanism described above occurs.

Related to this, it is known from the history of tumble accidents, that the more highly loaded the trike is, the less the aircraft will tend to tumble. Once the nose-down pitch departure occurs, a more lightly loaded trike will result in a whole-aircraft CG closer to the wing, and thus a greater angle of inflow into the wing – this is illustrated in **Figure 6** below. So, at a lower trike mass, the induced camber at the wing will be greater since the point of rotation will be closer to the wing. Also at lower trike mass, the rotational inertia in pitch will be less, causing a greater initial response to the induced flow.

Figure 6, Illustrating the shift in vertical CG with passenger and fuel loading changes.

(a) High trike load (b) Low trike load



With due caution (this is high risk testing) the susceptibility of a type to whip-stalling may be evaluated through flight testing, **Figure 7** is an extract from one of BMAA's standard flight test schedules that might be used, for example, in evaluating a flexwing aircraft which has been fitted with a new powerplant. It is usual for this to be evaluated initially at cruise conditions (serial #38 below), then repeated progressively towards best-rate climb conditions (serial #39) until either the best rate climb speed is achieved, or commonly a speed is achieved at which an acceptable margin is achieved before whipstalling will occur – this will then be promulgated in operating limitations as either a maximum nose-up climbing attitude, or as a minimum safe climb speed.

Figure 7, Extract from BMAA Standard Flight Test Schedule (No. AW/010b issue 1)

Title:
Performance and handling (Section S issue 2 compliance): Flexwing, Vd not exceeding 140 kn CAS

Serial No.	**Test Conditions**	**Test(s) Required**	**Data Required**
#38	Minimum 1500ft agl, Power for Level Flight, cruise trim, aft hangpoint, nil turbulence	Simulated sudden engine failure, maintain height by increasing pitch attitude until stall, recovery from stall to best glide speed	Height, stall warning(s) - nature and speeds, stall symptom, cruise speed, stall speed, weight, stall characteristics, height loss until a glide was established using Pitch control only, control responses at low speed, pitch authority during recovery, maximum nose-up and nose-down pitch seen, wing drop (if any), time from throttle closure to stall, rate of descent at best glide speed
#39	Minimum 1500ft agl, Climb Power, best climb speed, aft hangpoint, nil turbulence	Simulated sudden engine failure, followed by stall in climb attitude (with bar locked in climb position) and recovery to best glide speed.	Height, stall warning(s) - nature and speeds, stall symptom, stall speed, weight, stall characteristics, height loss until a glide was established using Pitch control only, control responses at low speed, pitch authority during recovery, maximum nose-up and nose-down pitch seen, wing drop (if any).

Second mechanism, Spiral instability combined with loss of visual horizon.

Weightshift Microlight aircraft are approved only for flight in Visual Meteorological Conditions (VMC). This implies a guaranteed visual horizon which the pilot may use as a reference when correcting small rolling departures. However, it is possible through ill-luck or poor judgement for an aircraft to enter Instrument Meteorological Conditions (IMC), where a defined horizon cannot be guaranteed. If the pilot is unable to extract the aircraft rapidly from this situation it is almost inevitable that some cause (most likely turbulence) will initiate an undemanded rolling manoeuvre. Many weightshift microlight aircraft are spirally unstable (particularly at higher power settings); thus, an initial small bank angle is likely to increase without (unless a horizon reference is available) the pilot's knowledge or ability to control it. The aircraft would roll, potentially past 90° of bank to a condition where the pendulum stability which keeps the trike below the wing ceases to act – inevitably causing some loss of control. It is then *possible* that the aircraft will find itself in an unsustainably steep nose-up attitude. It is noticeable that some tumble accident reports, particularly that to G-MVEP **[1]**, have occurred in conditions where the horizon was known to be poor, and where the subsequent damage to the aircraft showed that the basebar had fractured (in contact with the front strut) at the end. This implies a rolling component to the departure from controlled flight, which would be consistent with this mechanism.

Table 1 shows the results of a brief test carried out to demonstrate the spiral instability of a weightshift aircraft. A Raven-X weightshift microlight (**Figure 9**) was trimmed in moderately turbulent conditions and the controls released. The resultant bank angle was estimated based upon a visual horizon and the time to reach given bank angles. This demonstrates that following flight into IMC such a departure could readily happen within 60 seconds (obviously, the presence of spiral instability will vary between aircraft types, and with power setting).

Table 1, Results of test to demonstrate weightshift spiral instability

Aircraft:	Southdown Raven-X (Rotax 447 SCSI engine / 2.58:1 A-type gearbox) + 60” 3-blade Ivoprop propeller @ 9° pitch (Propeller approved by MAAN 1076)
Registration:	G-MNKZ
Crew:	Gratton (solo)
Conditions:	CAVOK, light turbulence, nil Wx, OAT +5°C, No.3 from front hangpoint setting giving 48 mph IAS trim.
Date:	13 Feb 2001
Test:	Aircraft flown in light but perceptible turbulence over woodland, nominal 1000ft on QFE 1024 hPa

Results:

Power	Time at 30° bank	Time at 45° bank	Time at 60° bank
3000 rpm (Flt Idle)	25 seconds	40 seconds	Test abandoned due to ground proximity
5000 rpm (PLF)	10 seconds	20 seconds	25 seconds
6,500 rpm (MCP)	10 seconds	15 seconds	20 seconds

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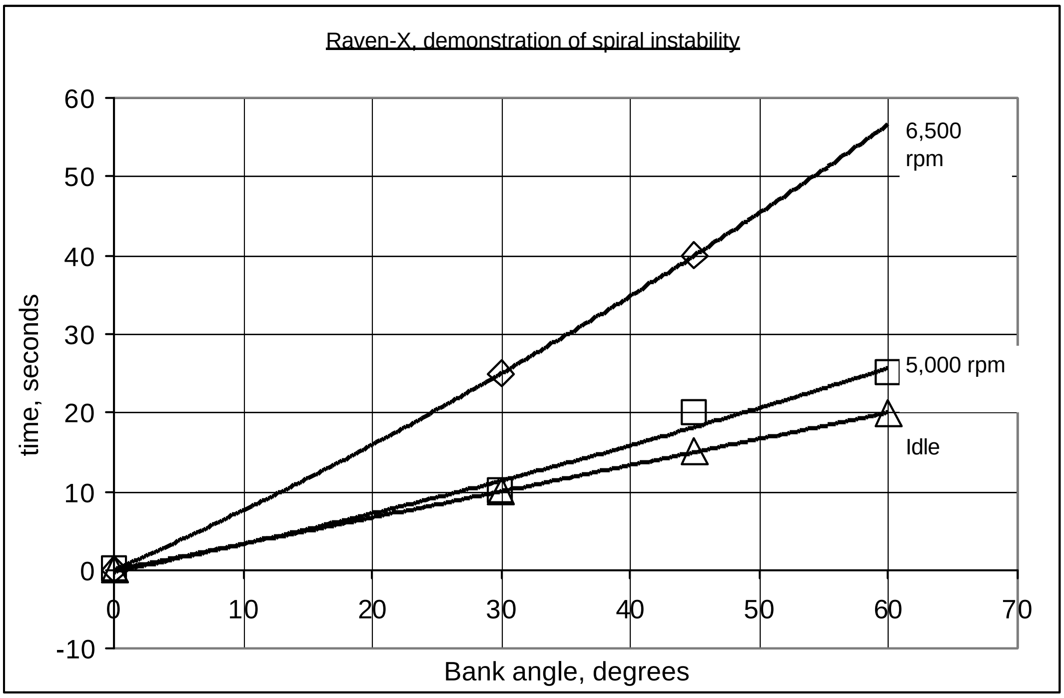
Figure 8, Illustration of spiral instability as a function of engine power: Raven-X



In the case of G-MVEP **[3]** (not an identical type, but one with similar handling qualities to the Raven), it would be a reasonable deduction that having lost the visual horizon the pilot (who was still under training) might have rolled beyond permissible limits in under 60 seconds.

A further comment may be made concerning the results above. This is that given that aircraft in this class appear to show the greatest spiral stability at low power settings, pilots should be taught, in the event of inadvertent flight into IMC, to descend out of it in idle power where possible, rather than attempting to climb out or maintain level flight.

Figure 9, Southdown Raven-X with Rotax 447 engine.

Third mechanism – failed loop manoeuvre.

Whilst weightshift microlight aircraft are neither approved, nor should be, for aerobatics, it is occasionally known for a misguided pilot to attempt aerobatic manoeuvres. There are several reported instances of pilots attempting to conduct a loop in such an aircraft. If positive normal acceleration is maintained throughout this manoeuvre then it can be executed as safely as in any other aircraft. However, as with any other aircraft, if the aircraft runs out of kinetic energy near to the top of the loop, then the pilot finds himself inverted without sufficient airspeed to complete the manoeuvre. In this case, the inevitable consequence will be a negative N_Z, leading potentially to a tumble. This is adequately demonstrated in

Figure 2.

Fourth proposed mechanism, flight through own wake vortex.

It is well known that a minimum safe separation should be ensured between landing aircraft, particularly behind larger aircraft which tend to generate very large vortex wakes that can normally be expected to remain for up to 80 seconds **[14, 15]** in normal conditions, rather longer in very still air. The weightshift microlight, using as it-does a delta wing, tends to generate a particularly large wake vortex for the size of the aircraft capable of generating considerable upset **[16]**. Pilots of weightshift aircraft should be taught that level turns should never be continued beyond 270° and preferably not beyond 180° without climbing or descending during the turn. Whilst for reasons of comfort and control such advice has always been part of flexwing pilot training, the significance of this with regard to the tumble (and consequent far more serious implications) have only become apparent during the course of this investigation.

Considering a typical steep turn at 45 kn CAS, 60° bank, 2000ft it can be shown that the turn rate will be 40°/s. Hence, if the pilot were to fly a continuous tight balanced turn, the aircraft's own wake vortex would be met in less than 9 seconds - scarcely time for the vortex to have significantly dispersed in even moderately disturbed airflow. It is known that aircraft flying through the wake vortex of another can suffer a large magnitude undemanded roll. It is then reasonable to assume that the same mechanism, as was described above, for a loss of visual horizon may also occur – although it is likely that the onset will be more rapid.

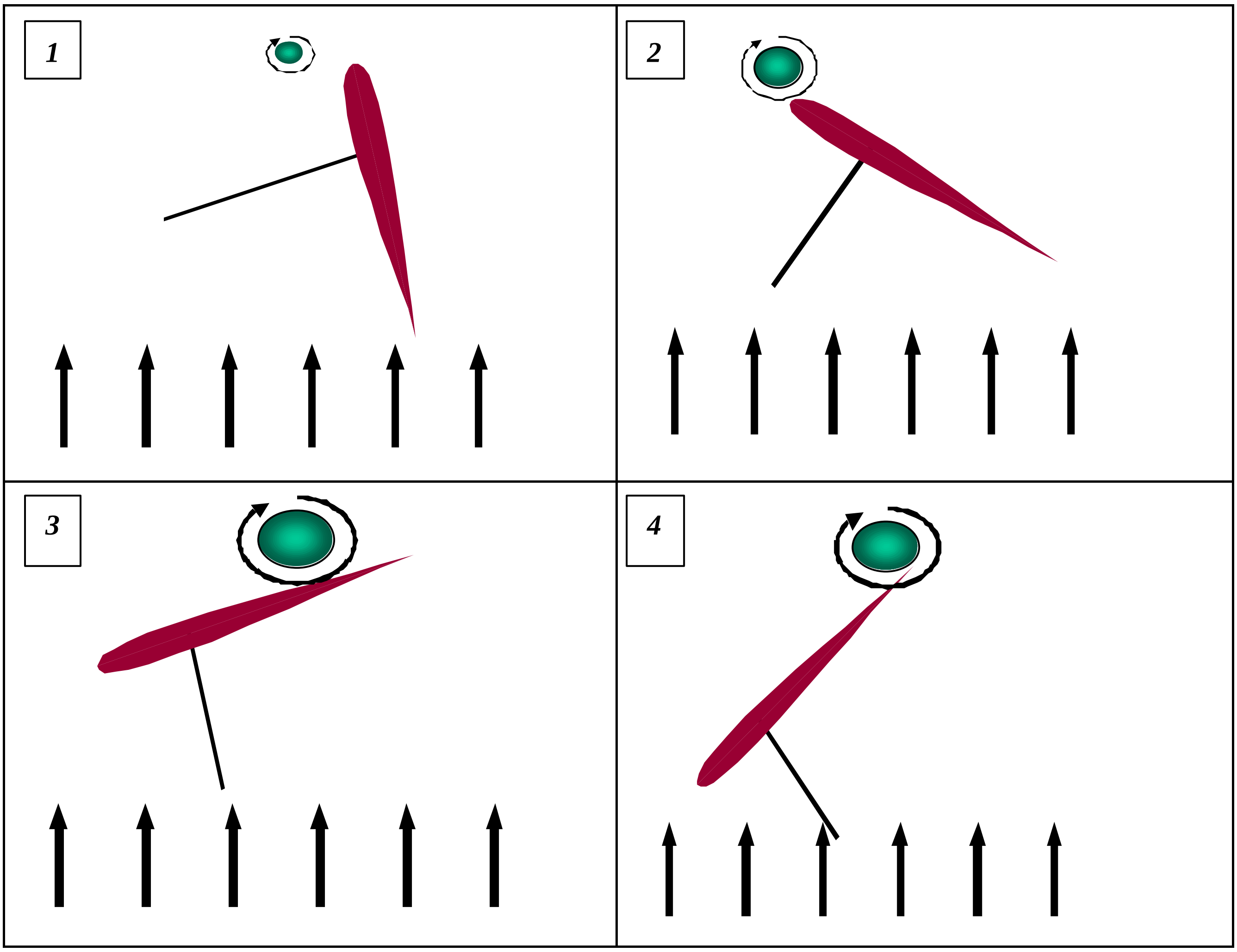
The fatal accident to G-MVDO **[17]** in 1992 was almost certainly a tumble and in-flight break-up following a pilot flying what were observed from the ground to have been extremely tight turns of 360° or more.

Further evidence – wind tunnel testing of a whole aircraft model

Some further recent work has been carried out at the University of Southampton and is reported in reference **[18]**. This work has involved testing in a wind tunnel a representative model of the whole aircraft, inducing a tumble motion within the wind tunnel. Flow measurement has shown that as the wing moves upward from the vertical a vortical flow develops – not unlike a starting vortex. As the wing passes through (what would be) the level flight attitude, this vortical flow intensifies and a concentrated vortex is produced over the leading edge. The strength increases as this vortex passes across the wing chord and produces a low pressure region towards the trailing edge of the wing. This will impart a nose-down pitching moment tending to promote the tumble motion. This effect disappears as the wing passes downwards and will reappear as the same part of the following cycle. This vortex development has large similarities with the flow caused by the dynamic stalling of an aerofoil which further supports the generation of the additional nose-down pitching moment. It also gives a partial explanation for the apparently non-constant pitch rate of the motion shown in **Figure 2**.

This is illustrated below in **Figure 10**; it should be emphasised that this is at this stage very early research. It is uncertain at present whether this work will make any meaningful contribution towards the development of tumble resistant aircraft.

Figure 10, Vortex generation and passage during tumble motion (from wind tunnel results)



Piloting advice

The main output of this programme so far has been advice to pilots (and in particular to microlight instructors) concerning tumble avoidance. Conclusions and advice based upon this conclusions of this ongoing programme have been promulgated via publications directed at microlight pilots and flying instructors since mid 2002. The main points of this advice have been:-

(1) That whipstalling is an unnecessary and entirely avoidable manoeuvre, related to the importance of remaining within published maximum pitch attitude and minimum climb speed limits in weightshift aircraft.

(2) The importance of maintaining a visual horizon and, should IMC be inadvertently entered, the preferred exit route being a flight idle descent (ensuring the best possible spiral stability) and not to climb through it.

(3) That turns beyond 270° (and preferably beyond 180°) in weightshift aircraft should include a component of climb or descent, so as to avoid an aircraft entering it's own wake vortex.

(4) The importance of realising that a major reason why no weightshift aircraft is approved for aerobatic use is the strong risk of an unrecoverable departure from controlled flight.

These lessons have been readily accepted by the microlight operating community so far, since they offer a painless and cost-free way to eliminate what has historically been a major cause of fatal accidents. Since the first publication of such advice to pilots, the UK has not suffered any new tumble accidents; this is encouraging, however it is only two years since this was done and as yet there is no cause for complacency.

Towards the tumble resistant aircraft

Almost certainly pilot training and continuous safety education is the best approach to tumble avoidance. However, the whip-stall, which appears historically to have been the most common cause of tumble entry is also potentially the most avoidable by design solution.

Work is ongoing to develop analytical methods which may be used to determine at what combination of weight and trike pitch attitude an aircraft may become tumble prone. This may then be used to determine what safety margin exists between the achievable operating envelope and the point of departure into a tumble. It is hoped that once this tool has been developed – which is becoming imminent, this may be used to ensure that aircraft designs are not subject to any significant risk of a tumble when flown within approved limits (or if necessary setting operating limits –in particular minimum flight weight and minimum climb speed to ensure this).

Once this tool has been developed, it is our intention to place it into the public domain and the authors would also like to recommend that it is incorporated into design codes such as BCAR Section S so as to ensure that tumble resistance become a basic certification requirement for weightshift aeroplanes. The initial understanding of the phenomenon allows the following assessment method to be suggested.

- Determine through flight testing the relationship between trike pitch attitude and climb speed at full power climb.
- Based upon the above information and experimental or analytical determination of the trike CG position, calculate the relationship between climb speed / attitude and nose-down pitching motion about the hangpoint.
- Calculate, assuming that there is no significant drag or thrust component acting, the nose-down pitching acceleration of the trike.
- Determine (probably through test at low trike attitudes with an element of extrapolation) the nose-down pitch-rate of the wing at a worst-case

The range of conditions where the nose-down pitch rate due to an out of balance trike will exceed the nose-down pitch rate due to an immediately post-stall wing may therefore be identified. These can then be used to determine safe pitch and climb-speed or power operating limitations that should avoid the risk of tumble entry following a whip-stall.

Conclusion

The programme to investigate the tumble mode has been an unusual one, since whilst a classic flight test problem, it could never for safety reasons be directly investigated. Nonetheless, by a complex combination of flight testing, ground testing, analysis of accident reports and mathematical modelling an explanation of the tumble has been produced, along with (more importantly) clear guidance on how to avoid this unrecoverable departure from controlled flight.

The most important product of this programme has been the advice that is now being promulgated to pilots concerning tumble avoidance. This seems to be working, and will continue to be pushed through the microlight training system.

In addition however the development of a tool to determine that an aircraft has an acceptable margin of tumble resistance is important since any aircraft is at risk of mishandling; work will continue to try and incorporate this work into design codes. It is unlikely however that a weightshift controlled aircraft can ever be made totally tumble resistant, and education of pilots will remain essential.

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