TOWARDS THE TUMBLE RESISTANT MICROLIGHT

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ABSTRACT

The tumble mode is a pitching departure from controlled flight which leads to a pitch autorotation that is generally unrecoverable – resulting in vertical ground impact, usually preceded by in-flight breakup (the mechanism for which, surprisingly, can sometimes *prevent* loss of life). This was identified in work led by the British Microlight Aircraft Association beginning in 1997 as a response to a number of fatal accidents in Rogallo winged microlight aeroplanes, although the tumble is also known to occur to hang-gliders.

This paper explains how this class of aeroplane is controlled, and how it has been found that they can enter the tumble mode.

The mechanism by which the tumble can be entered is described. This has led to work showing how flight testing can be used to establish and demonstrate resistance to tumble entry – particularly important with increasing number of very high performance flexwings. These flight tests will be explained, together with the significance of the results.

Recent accident investigation work has also shown a new mechanism of tumble entry, through partial failure of the A-frame structure and the pitch-trimmer mechanism. Also described is a possible relevance to well known historical accidents to flying wing aeroplanes – specifically the YB-49 and dH-108, and discovered data on the characteristics of the BKB-1 flying wing glider; are also described.

INTRODUCTION

The tumble mode is a departure from controlled flight which was first studied rigorously by the British Microlight Aircraft Association (BMAA) following a fatal accident to fatal accident to Gemini Flash IIa aircraft G-MVEP[1]. Conclusions were reached concerning this mode [2],[3], which may be summarised by:

- The mode is a nose-down pitching departure from controlled flight, leading to a pitch autorotation at rates up to 400°/s.
- No pre-breakup 'escape route' from an established tumble mode has been identified.
- The tumble invariably leads to loss of the aircraft, and in a large proportion of cases [usually those where the monopole failed during in-flight breakup] loss of the crew also.

Four potential entry routes were identified, which were:
- The whip-stall;
- Spiral instability combined with loss of visual horizon;
- Failed loop (or other aerobatic) manoeuvre;
- Flight through (own) wake vortex.

That work also led to training material being published which has been used to actively advise microlight pilots regarding tumble avoidance [4], [5]. This advice has been repeated elsewhere for the education of both microlight and hang-glider pilots, e.g. [6, 7, 8, 9].

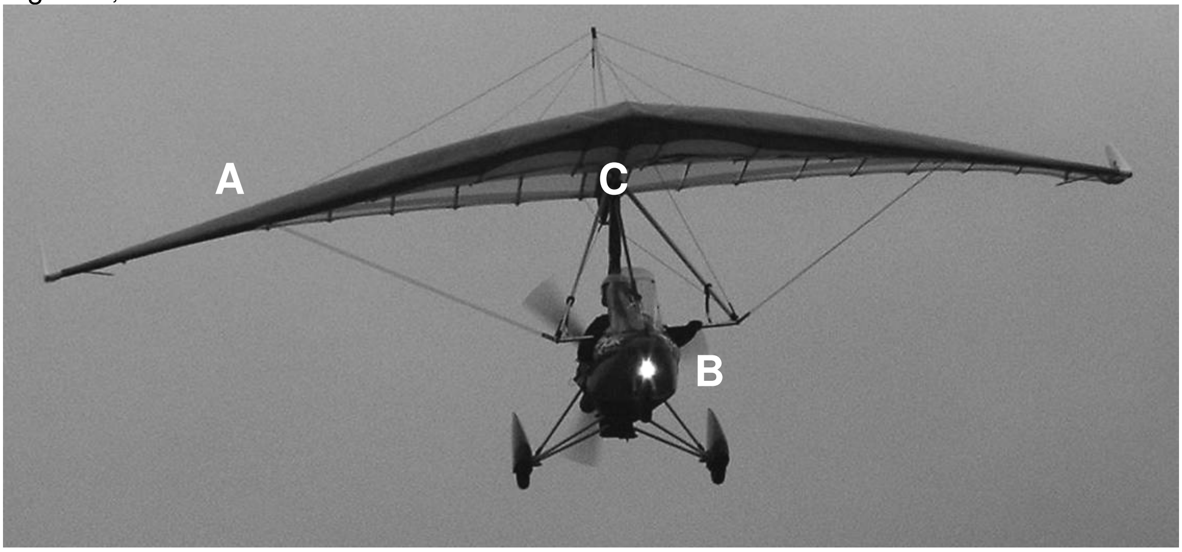
During the 4 years since that published advice, the UK has seen a single tumble microlight accident, with the loss of two lives [10]. It is highly unlikely that this particular accident would have been prevented by adherence to published avoidance advice, since the accident report concluded that the causal event was an in-flight structural failure (which nonetheless has interesting handling-qualities implications and will be discussed later). However despite this apparent success in accident reduction caused by publishing training and operational advice, work has continued aimed firstly at understanding the nature of the tumble mode itself, and secondly (and far more importantly) aiming to establish the flight test and certification requirements that will achieve an aeroplane which, even if operated significantly outside of the permitted envelope, will be as resistant as possible to tumble entry.

Finally, some historical investigations have been conducted which indicate that the tumble mode is not in-fact restricted to Rogallo winged aircraft (that is, flexwing microlights and hang-gliders) and may historically have occurred in several prototype rigid ‘flying wing’ aeroplanes: specifically the Northrop YB-49 and XP-79, the de-Havilland dH-108 and the BKB-1 tailless glider. This may increase the importance of this work, since interest in flying wings has never ceased (indeed the B-2 Stealth, a flying-wing is now the mainstay of the USAF long-range bombing fleet), and the tumble characteristics may yet repeat in future rigid flying-wings.

PRIMARY CONTROL OF ROGALLO WINGED AEROPLANES

Readers unfamiliar with the general design of weightshift (Rogallo winged) microlights are referred to reference [11]; however, it is useful to remind the reader of the method of control of a weighshift controlled aeroplanes. Considering Figure 1 below, weightshift microlight consists of two parts – the wing (including flying wires and control frame) A, and the trike B: these are linked by a hangpoint C which is a joint allowing free rotation of the wing and trike relative to each other in pitch and roll.

Figure 1, P&M Quik GT450 front view



In straight and level flight, the trike hangs below the wing, with forces upon the whole aircraft, and moments acting within each of the wing and trike, about the hangpoint, as well as total aircraft moments about the CG being in balance.

Thrust control is via the throttle in the conventional manner, although the aeroplane has two throttle controls – a normal hand-throttle (most commonly adjacent to the pilot’s left hand), and a sprung foot-throttle on the pilot’s right pedal similar in operation to the accelerator (gas) pedal in a car. In the cruise it is normal to set power using the hand-throttle, but the foot-throttle may always increase power above that which provides a minimum power setting.

Pitch control is via the control bar (the lower part of the triangular frame in front of the pilot). In order to pitch nose-down, the pilot must pull the bar towards him, applying a direct nose-down pitching moment to the wing. Conversely, to pitch nose-up, the pilot must push the bar forwards, applying a direct nose-up pitching moment to the wing. From the pilot's perspective, these are the opposite to those in a conventional aeroplane.

For roll control, in order to initiate a turn to the right, the control bar should be pushed to the left. Initially this applies a direct rolling moment to the wing; however, once a turn has been initiated, two factors then amplify this turn so that only relatively small pilot input forces are required. Firstly via a flexible surface amplified by lufflines running through the top of the kingpost (both are visible at the top of Figure 1) the trailing edge of the downgoing wing will tend to travel upwards and the trailing edge of the upgoing wing will tend to travel downwards – thus creating an aileron effect known as billow shift. Secondly, the vertical CG will have displaced to one side, of the lift vector, so that that lift force is now acting about (rather than through) the lateral CG position, creating a net rolling moment. The result is roll authority capable typically between 2.5 - 5.0 seconds from 30°-30° without exceptional piloting effort., although as with pitch control the pilot's perception is that the control operates in reverse to the primary controls of a conventional aeroplane.

DESCRIBING THE ENTRY MECHANISMS

The Whip Stall

The whip-stall is an aggressive entry to the aerodynamic stall (pushing the bar out aggressively to achieve a high deceleration rate, well in excess of the 1kn/s normally recommended), followed by an equally aggressive recovery initiation by the pilot (pulling in the control bar rapidly). This is a manoeuvre which may be used during flight testing (with great care) to demonstrate V_{NE} or V_{DF} [12], which are otherwise usually control limited. However, there is absolutely no need for a pilot, other than a test pilot in the course of their duties, to ever carry out this manoeuvre in normal flight; the whip-stall is specifically prohibited by all microlight manufacturers, and by the UK pilot training syllabus[13]. It is considered likely (and several eyewitness reports of fatal accidents bear this out - most recently the October 2000 fatality to a Pegasus Quantum [14]) that this mechanism can lead to the tumble.

The sequence of actions in the whip stall is detailed below.

- The pilot places the aircraft in a climbing attitude, and pushes the control bar out rapidly to achieve a high deceleration rate. At the steepest possible nose-up attitude, the throttle is closed.
- The airspeed decreases rapidly, with nose-up rotational inertia pitching the aircraft nose-up past the normal AoA than would normally be expected for the stall, associated loss of airspeed will also occur. As a consequence, the aircraft will reach a state where the AoA is greater and the airspeed lower than would normally be expected at the stall. This point, when the maximum nose-up attitude is reached is the stall as perceived by the pilot.
- At the point of stall, the wings aerodynamic pitching moment becomes strongly nose down. Due to the low airspeed, this is likely to be less than if the stalling angle of attack is reached in a less dynamic manoeuvre.
- The trike, which had been held in a steep nose-up attitude by thrust, pitches down and pushes against the wing (front strut against 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 can initiate the tumble, as previously discussed.

Spiral Instability

Weightshift microlight aircraft are normally 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 conditions where a defined horizon cannot be guaranteed (most commonly by entering cloud). If this happens, any pilot should attempt to remove the aircraft from this condition as quickly as possible; however, if the pilot is unable to extract themselves from this situation it is almost inevitable that some cause (most likely the turbulence commonly found inside or near to most clouds) will initiate an undemanded rolling manoeuvre. Unlike most conventional fixed wing aeroplanes, 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 then enter a divergent rolling manoeuvre, potentially through 90° of bank to a condition where the pendulum stability which keeps the trike below the wing will cease to act, and the wing angle of attack will reverse sense – inevitably causing some loss of control. Some tumble accidents, for example 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.

Failed Loop

Whilst weightshift microlight aircraft are neither approved, nor should be, for aerobatics, it is occasionally known for a pilot to attempt aerobatic manoeuvres. There are several reported instances of pilots attempting to conduct a loop in a weightshift microlight. If positive normal acceleration is maintained throughout this manoeuvre then it can be executed as safely as in any other aeroplane. However, as with any other aircraft, if the aircraft runs out of kinetic energy near to the top of the loop, then the pilot will find themselves inverted without sufficient airspeed to complete the manoeuvre. In this case, the inevitable consequence will be a negative angle of attack, potentially leading to a tumble. A time-frame analysis of such a failed loop leading to an unrecoverable tumble is shown in references [2, 3, 4].

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 [15, 16] 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 [17]. For this reason, pilots of weightshift aircraft are taught that level turns should never be continued beyond 270° and preferably not beyond 180° without climbing or descending during the turn.

Considering a typical turning manoeuvre at 45 kn CAS, 60° bank, 2000ft 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 in 1992 was considered by the AAIB investigation report [18] to have been 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.

THE FATAL ACCIDENT TO G-STYX: A NEW TUMBLE ENTRY MECHANISM

Reference [10] describes a fatal accident to a Pegasus Quik aircraft, which is the fastest of the latest generation of high performance flexwings – boasting a maximum cruise speed in excess of 90 knots (compared to around 65 knots for previous generation such as the

Pegasus Quantum or Mainair Blade), together with MAUW climb rates around 1200fpm [19]. At the time of the accident, the aeroplane was engaged in an instructional flight when it entered a tumble autorotation, leading to separation of wing and trike. A similar aircraft is shown in Figure 2 below.

Figure 2, Pegasus Quik

Description of the accident causes

The AAIB report into the accident to G-STYX concluded that the initiating event was a partial structural failure of the upper joint of the starboard control frame upright (indicated by A in Figure 2 above). A maintenance error cause the joint, which is normally loaded in compression, to buckle. In itself, this would be serious but unlikely to cause rapid loss of the aircraft; however, on this particular aircraft (in common with many flexwing microlights of the same or previous generation), the pitch trim mechanism consists of a tensioning device pulling upon the lufflines at B. This in turn is linked to a trim control on the starboard upright at C, via a cable which passes through the upright and its top joint. When the top joint failed, this suddenly shortened the pitch trimmer cable, tensioning the lufflines and creating (combined with what on-board data recording showed to be high speed / full power flight) a sudden nose-up control input. It is believed that once the aircraft had pitched steeply nose-up, the pilot rapidly closed the throttle, leading to a whipstall as described above.

The safety lessons to be learned from this are complex, concentrating primarily upon maintenance control. However, it has emphasised to the microlight flight test community the importance of considering the flight test and handling-qualities implications of systems failure – it is possible that different handling qualities could have resulted in an aircraft that did not suffer a whip-stall and resultant tumble, notwithstanding that the cause of the accident was an unforeseen (and largely unforeseeable) structural failure.

UNDERSTANDING THE AERODYNAMICS OF THE TUMBLE

Research has also been carried out to investigate the flow around a tumbling aircraft [20]. Since testing with a manned aeroplane would probably be non-survivable, this has made use of a rigid scaled model based upon the shape (and in particular the 3-dimensional wing shape) of the Gemini Flash 2 alpha aircraft [21] which was the type involved in the first investigated accident; this model is shown in Figure 3 below.

Figure 3, Scale model of Mainair Gemini Flash 2 alpha aircraft, used in wind tunnel tests

Photograph courtesy of Oliver Moncrieff

This model, which was 1:30 scaled down from the actual aircraft and set with geometry resembling an aircraft with the basebar against the front strut, was rotated in pitch within the University of Southampton's 7' x 5' (2.1m x 1.5m) low-speed wind tunnel which is fitted with Particle Image Velocimetry (PIV) equipment. No attempt was made to create a self-sustaining tumble, the subject of interest being the qualitative flow characteristics around the aircraft rather than quantitative effects. The airspeed and rotation rate were varied between 0.13-0.26m/s and 310-775°/s. Initial testing with smoke and a video camera showed the primary area of interest being 1 wing chord before and after the rotating aircraft in the direction of ambient airflow. Figure 4 below shows the flow at two spanwise stations:-

Figure 4, Illustration of flow near[1] the wing root during nose-down tumble rotation

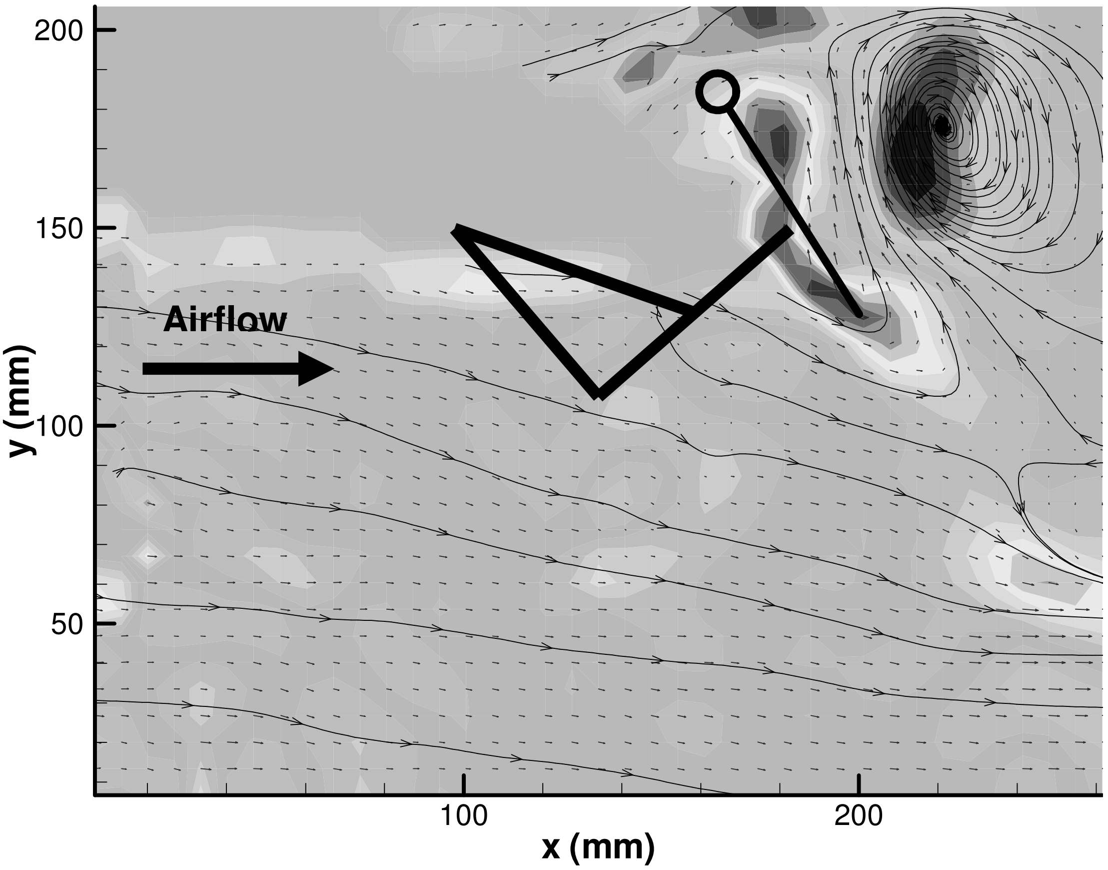
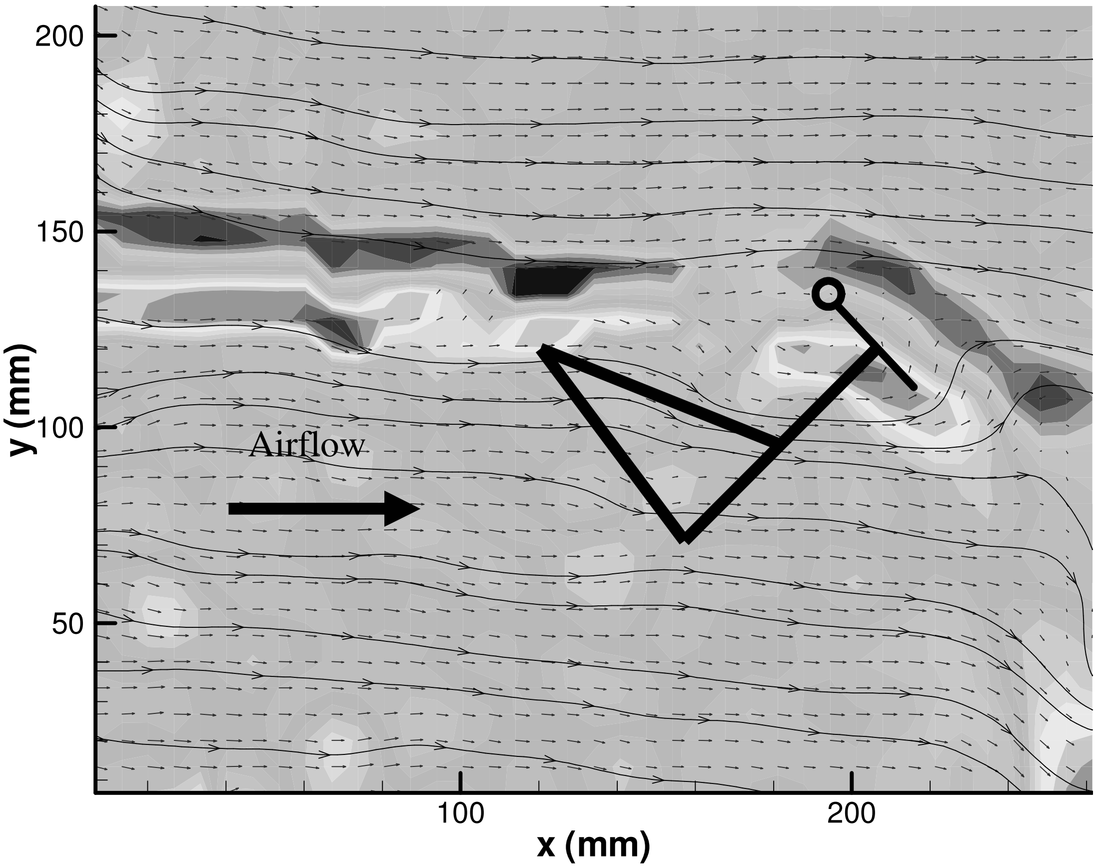


Figure 5, Illustration of flow near the wing tip[2] during nose-down tumble rotation



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[1] 10mm outboard of wing root of model

[2] 10mm inboard or wing tip on model.

It may be seen from these flow visualisations that there is evidence of a significant (nominally spanwise) vortex formation occurring near to the wing root, but very little significant effect near the tip. Further investigation showed that the most readily visible vortex formation occurred at about 1/3 semi-span outboard of the root – partly because of well developed vortex shapes, and partly because at stations more inboard, partial blanking of the laser occurred due to the trike. The series of diagrams in Figure 6 (from [20]) ; show the flow around this station during a single tumble rotation at 620°/s in a steady airflow of 0.26m/s; symbology and orientation are identical to Figure 4, except that the trike diagram and wind vector are omitted for clarity.

Figure 6, Series of illustrations of flow around aircraft during one tumble cycle.
(All illustrations in same orientation)

Common Data Block for Figure 6
Rotational velocity = 620 °/s (10.8 rad/s)
Free stream velocity = 0.26m/s
Nominally ISA sea-level conditions, ambient air.
Reynolds number ~1.8x10^{-3} (based upon centreline chord and free stream velocity)
All illustrations within this figure from Moncrieff [20]

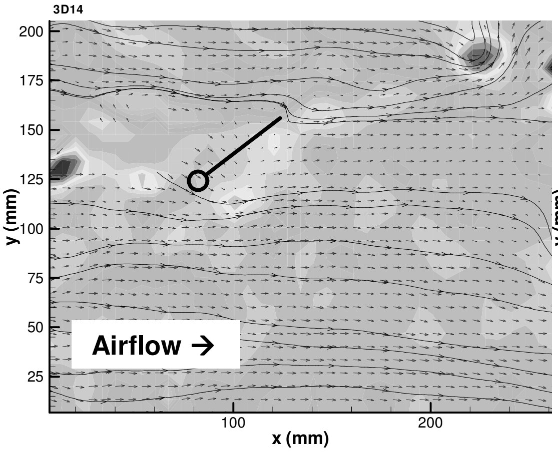


Figure 6(a)

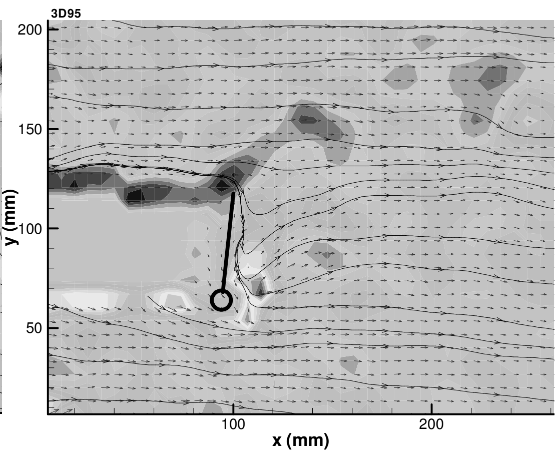


Figure 6(b)

The flow is steadiest when the wing is in the position shown in Figure 6 (a) which is approximately 135° nose-down compared to the level flight attitude, this provides a convenient starting point from which to analyse the tumble.

Figure 6(b) following shows the major impact the wing has on the freestream flow as it moves cross stream (inverted compared to the level flight attitude, the trike is to the right of the wing in the diagram), resulting vorticity is visible: clockwise at the trailing-edge and anti-clockwise to leeward of the leading-edge.

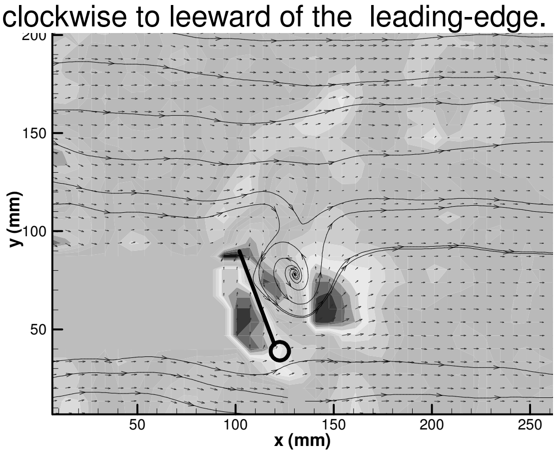


Figure 6 (c)

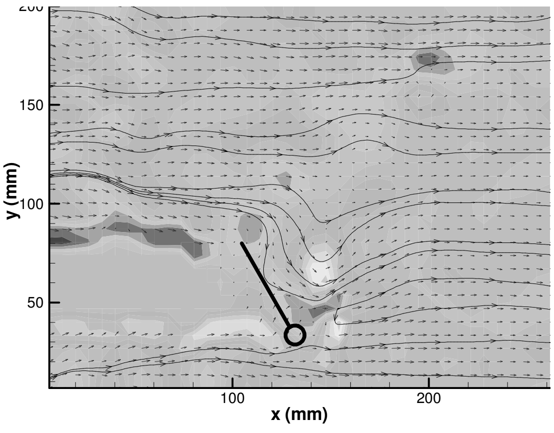


Figure 6 (d)

In Figure 6 (c) a vortex forms in the area between the hangpoint and trailing edge but rapidly dissipates – as may be seen in Figure 6 (d). Because of the short life of this vortex, it is assumed to have only small effect upon the wing – although it may create briefly an area of low pressure below the wing, generate, briefly, a force acting towards the aircraft CG.

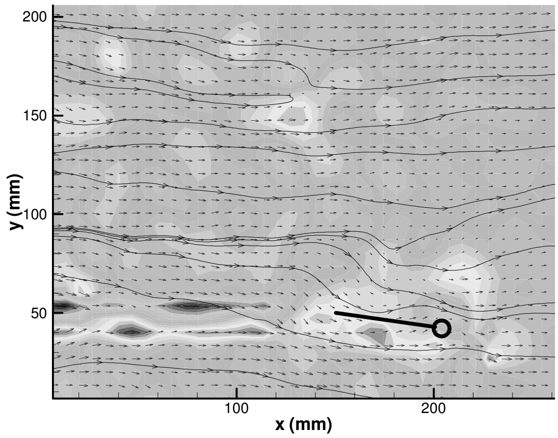


Figure 6 (e)

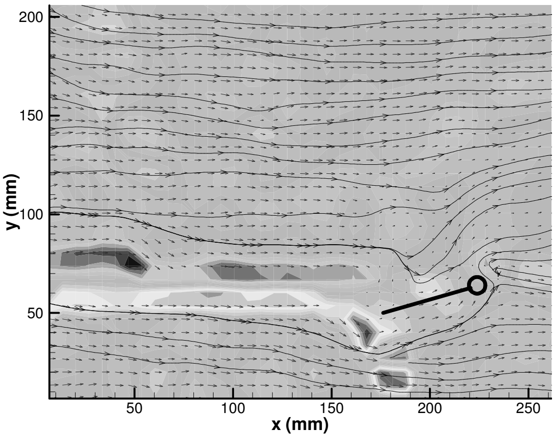


Figure 6 (f)

As the wing passes through the condition approximately 90° nose-up compared to the level flight condition, the flow smoothes out as the wing effectively moves downstream, travelling at approximately three times the freestream velocity. As the wing begins to pitch up into the flow, the flow initially remains attached to the wing (Figure 6(f)).

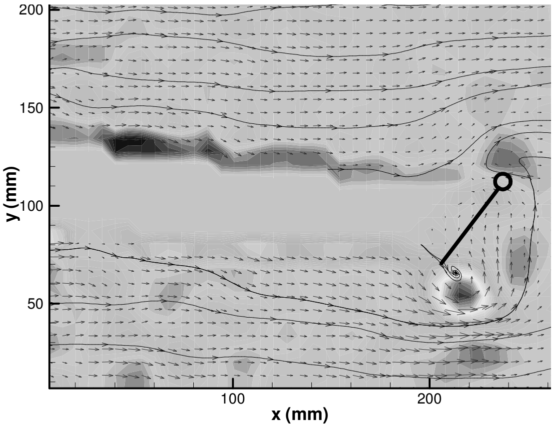


Figure 6 (g)

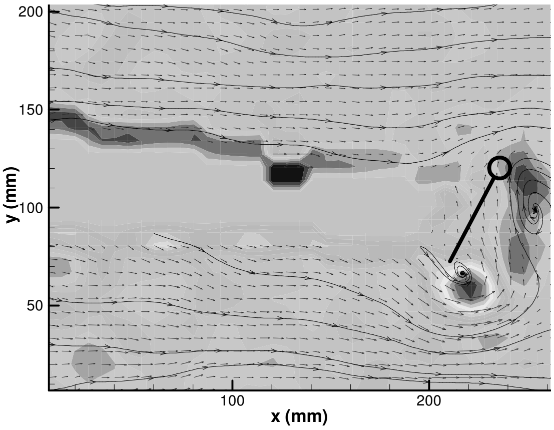
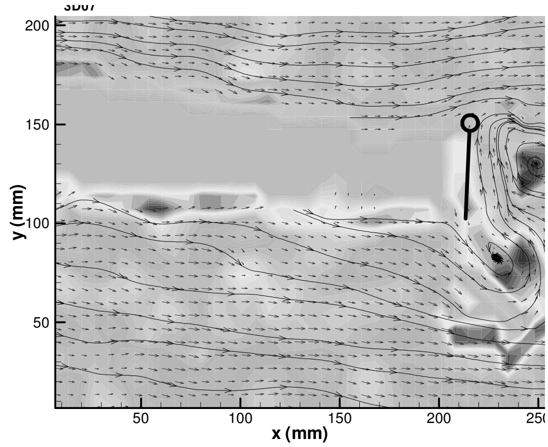


Figure 6(h)

Flow separation at the leading-edge takes place at the same time as the formation of a trailing-edge clockwise vortex as the aircraft approaches something equivalent to a steep climbing attitude. Simultaneously, a smaller vortex in the opposite sense forms above the trailing edge.



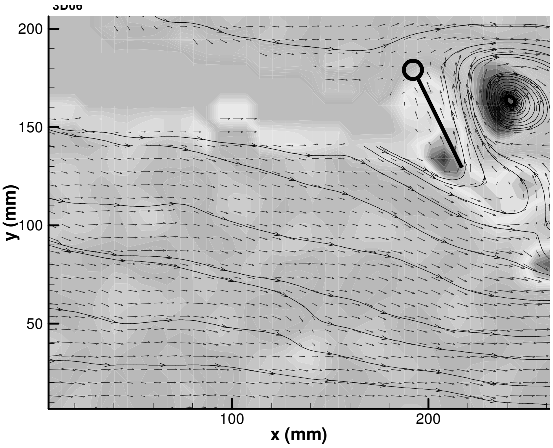


Figure 6 (i) Figure 6(j)

As the aircraft passes through the level flight attitude, the clockwise vortex has now detached itself from the trailing-edge; meanwhile, the anti-clockwise vortex created above the leading edge is growing rapidly and appears to move along the upper surface of the aerofoil towards the trailing edge as the wing continues its nose-down rotation.

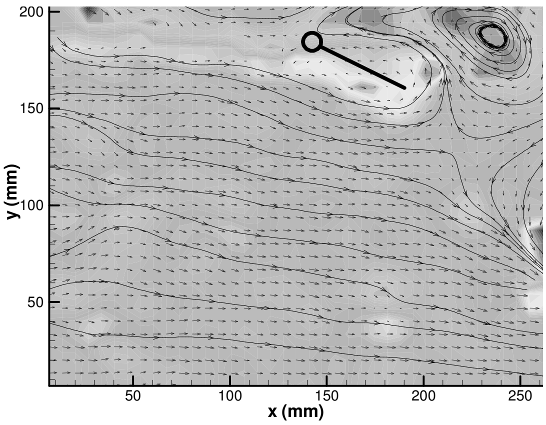


Figure 6 (k)

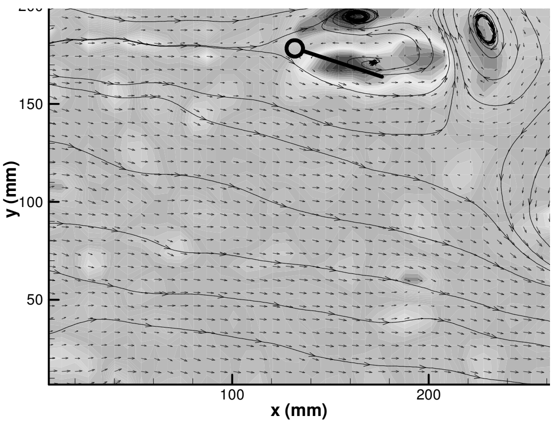


Figure 6(l)

As the aircraft approaches an attitude approximately 90° nose-down from the level flight attitude, the suction force at the trailing edge of the wing is still present as the aerofoil moves forward into the free-stream. Figure 6 (l) shows classical von Kármán vortex shedding [22], as the inflow sweeps the alternating clockwise and anti-clockwise vortices downstream.

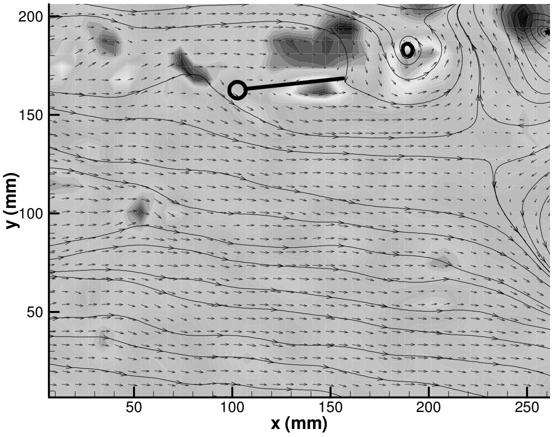


Figure 6 (m)

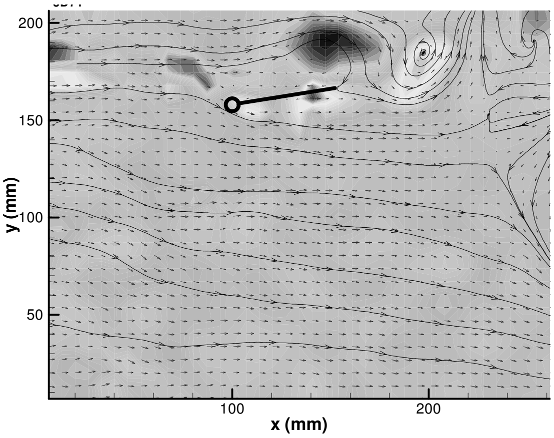


Figure 6 (n)

The remains of the vortex shedding are still visible in Figure 6 (m) as the flow becomes steadier via Figure 6 (n), returning to smoother flow of the initial image for the rotation, as shown in Figure 6 (a).

DEMONSTRATING A TUMBLE-RESISTANT AIRCRAFT

Of the four identified tumble entry mechanisms (counting the accident to G-STYX as another example of a whip-stall) two are considered to be primarily a pilot training issue and not an aircraft design and testing issue: those are the failed aerobatic, and flight through the aircraft's own wake vortex. Both are easily avoidable through pilot awareness, without any detriment to the role and operation of the aircraft.

The other two entries however: the spiral departure following loss of controlled horizon, and the whip-stall entry whilst again avoidable through pilot action, are related to aeroplane handling qualities.

The spiral departure

Discussions and comparison of various aircraft characteristics within the microlight industry have shown this issue to be a difficult one. Firstly not all aeroplanes in this class display spiral divergence (particularly at lower powers), and also many aircraft which are spirally divergent do not purely "roll-off", but tend to simultaneously pitch nose-down resulting in a spiral dive which stabilises at a steep bank angle and high speed, although generally below V_{NE}. This resultant manoeuvre is unpleasant and results in a high rate of descent but is unlikely to result in any immediate overstress, and also is easily and immediately recoverable once a visual horizon is available – probably with less than 100ft of height loss.

Additionally, the majority of aircraft are spirally convergent at idle power, allowing an aircraft which has lost its visual horizon to descend, without substantial risk of a rolling departure, until a visual horizon has been restored. This has been reflected in educational advice given to microlight pilots, and as with the advice offered concerning avoidance of the aerobatic and wake-vortex entries, the advice presents no operational restriction.

Therefore conclusions drawn have been that although there might be small safety advantages in an aircraft which is spirally convergent throughout the power envelope, this is not readily achievable, and is unlikely to outweigh the constraints that this will place upon the designer in his necessary desire to optimise all other aspects of stability and control.

However, it remains important that a pilot who does inadvertently enter cloud must always have the ability to descend at idle power until a visual horizon is restored. Therefore, it is the authors' opinion that during certification and developmental flight testing it must be demonstrated that any weightshift controlled aeroplane must display spiral convergence at idle power, at any weight or hangpoint position.

Resistance to the whip-stall

The remaining entry mode is the whip-stall. Whilst it is possible to enter this through aggressive mishandling of the aeroplane, it is also possible to whip-stall inadvertently. The accident to G-STYX showed this dramatically, but also it is known that in an aircraft with a combination of a high power : weight ratio being climbed at a very steep attitude (likely to be a speed just above the stall), if there is a sudden loss of power then there is a strong risk of a whipstall occurring, particularly if the pilot does not pitch nose-down immediately after power failure, so as to avoid the aircraft stalling.

The problem therefore has been to identify means to ensure that should a sudden engine failure occur in the climb, this will not result in a whip-stall. Previous work [2, 3] has shown that this is likely to occur at minimum flying weight, and that the steeper the nose-up pitch attitude, the greater the risk of a whip-stall leading to a tumble entry. The critical factor is considered to be the proximity of the control bar to the front strut; if the control bar leads the front strut during the stall event (even if it strikes the pilot) then there is considered to be no substantial risk of a following tumble. If however, the front strut leads the basebar – potentially leading to contact between the two, then the wing is at risk of rotating about the aircraft CG (instead of the hangpoint as normal) giving rise to a risk of tumble entry. Between the two, there is an intermediate state where from the pilot's perspective (the pilot's body being stationary relative to the front strut) the control bar appears to "float" – an apparence of neutral longitudinal static stability.

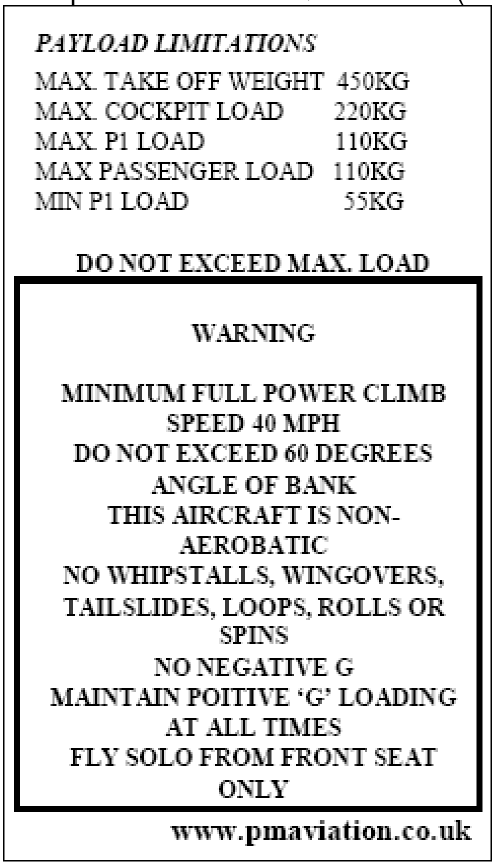
In flight testing various aircraft (most notably the P&M GT450 shown in Figure 7 below, and the Air Creation Tanarg), it has become apparent that whilst the critical parameter during the climb is pitch attitude, this is not readily measurable – whilst an attitude indicator could be fitted this wouldn't be normally fitted in a private aircraft, and even if it were it is unlikely that most pilots would monitor it during (for example) a take-off and initial climb. The nature of a weightshift aircraft is that visual references make identification of attitude visually extremely approximate; so, this does not offer any significant potential. However, at a constant weight, there is a direct and approximately linear relationship between pitch attitude and airspeed.

Therefore, it has been found during test programmes that the best way to identify the critical pitch attitude is to fly a series of simulated sudden engine failures at minimum achievable flight weight and maximum power, starting at V_H, then reducing speed steadily, each time making no nose-down corrective action. If, even down to closure of the throttle at a very small margin above the stall, there is no tendency for the control bar to float or for the front strut to lead the control bar, then the aircraft may be considered substantially resistant to whip-stalling.

If however a speed is reached where bar float is observed, then this is clearly the slowest speed at which a full power climb should be attempted in the aircraft – and it would be extremely wise for any full power climb to be performed no slower than this speed, irrespective of the aircraft's best climb speed determined by other means. Clearly reductions in power (through operation of the throttle, or ageing of the engine), or increases in weight will only serve to reduce the full-power pitch attitude, and thus further reduce the risk of a whip-stall. Whilst in theory one might prepare variable limits, the nature of the aircraft class is that a single "minimum climb speed limitation" is sufficient and conservative. This has been accepted for several programmes now and, for example, Figure 8 below is an excerpt from the GT450's limitations placards showing a minimum full-power climb speed of 40 mph IAS.

Figure 7, P&M Quik GT450 from 2 O'Clock

Figure 8, Part of flight limitations placard for P&M Quik GT450 (from [23].)



PAYLOAD LIMITATIONS

MAX. TAKE OFF WEIGHT	450KG
MAX. COCKPIT LOAD	220KG
MAX. P1 LOAD	110KG
MAX PASSENGER LOAD	110KG
MIN P1 LOAD	55KG

DO NOT EXCEED MAX. LOAD

WARNING

MINIMUM FULL POWER CLIMB SPEED 40 MPH
DO NOT EXCEED 60 DEGREES ANGLE OF BANK
THIS AIRCRAFT IS NON-AEROBATIC
NO WHIPSTALLS, WINGOVERS, TAILSLIDES, LOOPS, ROLLS OR SPINS
NO NEGATIVE G
MAINTAIN POITIVE 'G' LOADING AT ALL TIMES
FLY SOLO FROM FRONT SEAT ONLY

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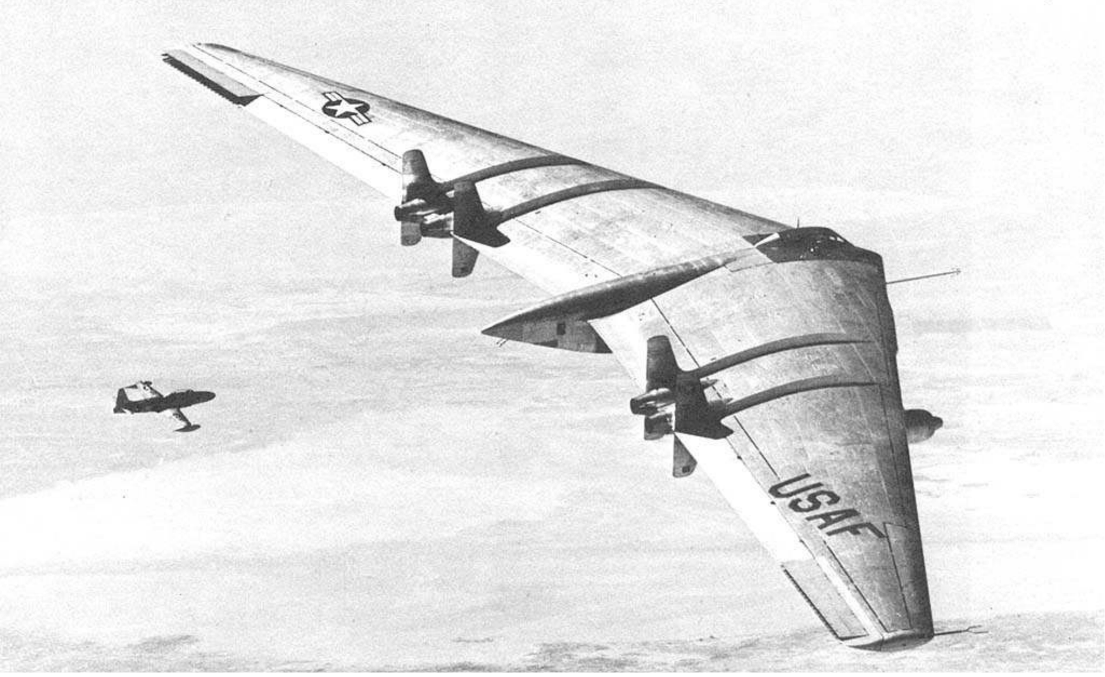
It is worthy of further note that this class of aircraft has another good reason for mandating a minimum full-power climb speed. In common with most other tailless delta-winged aeroplanes, at high angles of attack, these aircraft display very high lateral stability. There have been occasions of loss of control during initial climb-out after take-off where an aircraft has been climbed too slowly, several times with resultant ground impact and destruction of the aircraft. Therefore the concept and requirement of a minimum climb speed for weightshift controlled microlights is not new, and it may be that there will be occasions where the avoidance of a whipstall is not the determining factor in setting a minimum full power climb speed.

HISTORICAL NOTES – TUMBLE MODE IN RIGID FLYING WINGS

Historical note #1 – the Northrop YB-49 "Flying Wing Bomber"

During the 1940s and 1950s there was a great deal of interest in the development of flying wing aircraft, particularly in the USA for military purposes. One such aircraft was the Northrop YB-49 (See Figure 9 below) [**24**]. Although attributed at that time primarily to inertia coupling, there are a number of notable occasions where these aircraft suffered a pitching departure from controlled flight.

Figure 9, Northrop YB-49 experimental flying wing bomber.



Photograph courtesy of Northrop Grumman Corporation

The following account is by Brig.Gen. Robert Cardenas (MSETP) working in 1948 upon evaluation of the YB-49 aircraft [25], and describes a pitching loss of control in this aircraft. The use of the word "tumble" is that selected by the Gen.Cardenas at the time.

"23 February YB-49 #368 one landing local Muroc-------- 0:35 mins.
Recommended no intentional stalls due to the fact that during the final phase of the stall entry maneuver it lurched over backwards into a tumble. Had to use asymmetric power to recover. Submitted a full report and thankful that the throttles were hanging down from the ceiling rather than in a normal position since G forces had my arms locked upwards and my rear off the seat. Flight test engineers told me later that I had encountered inertial coupling"

"the results of my one Stall Test during which the aircraft had assumed a very high angle of attack without a stall warning and then pitched over backwards…. The rotation was severe and made it difficult to keep my hands and feet on the controls. The engineers called it a lateral roll but I was experiencing a tumble! I was lucky that the designers had put two throttles hanging down from the upper surfaces, each connected to four engines.I applied full power with the left throttle and resolved the "tumble" with asymmetric power and elevon control."

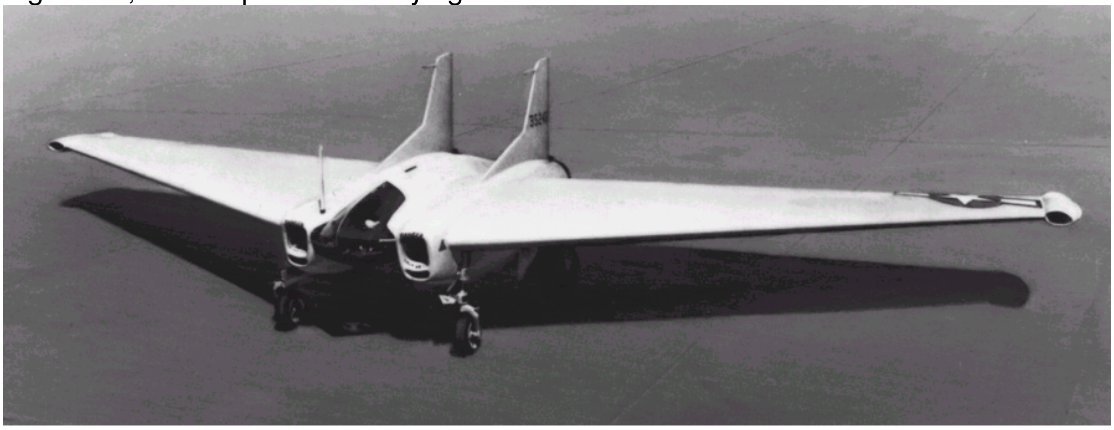
The aircraft was subsequently lost on 5 June 1948 whilst flying under the control of Capt. Glen Edwards from Muroc Field (later Edwards AFB killing all on board. Available reports indicate that the aircraft lost control in pitch at about 40,000ft[26], with the wingtips detaching from the airframe at a high altitude under loading which exceeded 4.8g[27]. The aircraft descended almost vertically, impacting inverted, whilst the wingtips were found several miles away. It is interesting to note that this is consistent with microlight tumble accidents, in that the departure from controlled flight was in pitch, descent was vertical from departure from controlled flight, and there was structural failure of the wingtips before impact with the ground. There are two obvious differences, which is that the aircraft had a CG which was within the airframe (rather than below), and that the rotation was nose-up (rather than nose-down). However, this only negates the mechanisms previously described for the microlight tumble and not the aerodynamics of the established tumble; therefore, whilst it is not reasonable to assume a similar entry mechanism to that shown for a weightshift controlled microlight, there is no obvious reason why the aerodynamic characteristics that sustain this pitch autorotation are not similar in each case.

It is therefore indicated that the tumble as discussed in this section, and the tumble as described in the Pilot's account when describing loss of control in the Northrop YB-49, may well be closely related.

Historical Note #2, the Northrop XP-79 "Flying Ram" experimental fighter

A later experimental aircraft, also developed by Northrop, was the XP-79 (Figure 10), which was a tailless experimental fighter produced for the USAF. This aircraft was lost on it's first flight on 12 September 1945. Very little information is available as to the reason why this aircraft was lost; however, it is known that the aircraft suffered a departure from controlled flight during which the pilot was subject to sufficient forces that he was unable to abandon the cockpit (where he was located in a "prone" position) before ground impact, causing loss of both the aircraft and pilot.

Figure 10, Northrop XP-79B "Flying Ram"



Photograph courtesy of Northrop Grumman Corporation

The specific nature of the departure from controlled flight that led to loss of the aircraft is not known, and it is highly unlikely now that any new information will become available. However, it is again interesting to note that this is a further departure from controlled flight of a tailless delta winged aircraft, where high forces are likely to have been a significant factor. This *may* have been a tumbling departure, similar to that apparently suffered by the YB-49.

Historical Note #3, The de Havilland DH108 "Swallow"

The de Havilland DH108 (Figure 11 below, also reference [28]) was a British research aircraft of which three examples were built, all in the late 1940s. The aircraft was a high performance tailless delta-winged aeroplane, designed specifically for research into the control of flying-wing aeroplanes, and into the transonic flight regime. All three of these aircraft were lost in fatal flight testing accidents.

Figure 11, de Havilland DH108 Swallow

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The first of these accidents [29, 30, 31], which was to aircraft TG306 occurred on 27 September 1946 is well known, having resulted in the death of Geoffrey de Havilland Jr., who was Chief Test Pilot of de Havilland at that time. The aircraft was investigating high speed controllability in a dive when the aircraft broke up "following violent divergent instability at Mach 0.9", which is believed to have been in pitch. Investigation of the wreckage of the aircraft which had impacted into soft mud and therefore were able to be inspected (although unfortunately the early accident data recorder fitted was destroyed by immersion in the same mud) showed that both wings had failed in download. Therefore there are certain common threads here with known tumble departures, specifically:-

- A loss of control in the pitch axis from which recovery could not be effected.
- Forces acting upon the aircraft which apparently were so great that the pilot was unable to successfully abandon the aircraft.
- A structural failure in the air, which included a download failure of the wings.

The second such accident [29] was on 15 February 1950 to aircraft VW120 and was during a sortie from the Royal Aircraft Establishment at Farnborough to evaluate longitudinal stability and aero-elastic distortion at high Mach numbers. However, the aircraft did not achieve its intended initial test altitude of 38,000ft instead departing from controlled flight at 27,000 ft following the onset of divergent longitudinal oscillations. The aircraft is then reported to have descended at a very high rate, before breaking up somewhere between the surface and 10,000ft. Whilst it cannot be certain that the tumble was a factor (and contemporary reports indicate that the pilot had most likely lost consciousness due to an oxygen system failure), this accident again shows several common factors to those identified as part of the tumble, specifically:-

- *A departure in pitch from controlled flight.*
- A very rapid, apparently near-vertical, descent.
- A structural failure in the air (note, compared to TG306 the structure of VW120 had been strengthened).

It seems likely, therefore, that VW120 had entered something similar to the tumble as previously described. The departure mechanism from controlled flight was certainly unrelated to those which affect weightshift microlight aeroplanes, but the aerodynamics sustaining the tumble, as described above may reasonably be considered to apply equally to this aircraft.

The third accident to the DH108 was on 1 May 1950 to aircraft TG283 also flying from RAE Farnborough; however, in this case the aircraft entered an inverted spin, which was identified and reported by the pilot. The aircraft spin recovery parachutes failed, as partially did the pilot's personal parachute – resulting in a fatal accident. However, this is appears unrelated to the tumble, and therefore not of interest in the context of this study.

Historical Note #4, the BKB-1

Figure 12 below was an experimental tailless swept-wing glider developed in Canada in the 1950s[32, 33], which was later developed in the USA into a powered microlight aircraft known as the Kasperwing. Both the BKB-1 and the Kasperwing were shown to be able to enter a manoeuvre which was referred to at the time as a tumble, this was displayed extensively in the USA during the 1960s. It has been reported that the sustained tumble in these aircraft was believed due to "a strong vortex occurring just above the wing" [34]. The unique characteristic of the tumble in these aircraft was that it could be entered deliberately, and subsequently recovered from.

It is reported [35] that the method used to enter the tumble in this aircraft was to pull the aircraft into a vertical climb (effectively the first part of the loop), pause the pitching motion by moving the stick forwards with the aircraft pointed vertically upwards, then to pull the stick fully backwards (pitching nose-up), and that this would initiate a nose-up pitch autorotation. The pitch rate was recorded at approximately 360°/s, with the pilot experience positive normal accelerations of about 2g. The pilot of the aircraft reported that it was possible to tumble forwards only by moving the CG significantly forwards in the aircraft, and that in this instance the pitch rate increased to about 720°/s whilst the acceleration forces upon his body became high and disorienting (as well as sufficient to damage the seat structure). In both cases centralisation of the pitch control was reported to recover the aircraft from the tumble with minimal height loss.

This appears to be further evidence that a rigid tailless aircraft is capable of entering a tumble, and also that this motion is rapid and can cause structural damage to the aircraft. Commonly with the evidence of the YB-49 it indicates a nose-up tumble as the most readily entered mode, and also shows that recovery is possible – in this case symmetrically using elevon control.

Figure 12, BKB-1 in flight

Reproduced courtesy of Mr D Webb

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations have been reached through this work so far. These are:

(1) That the tumble mode can occur both in Rogallo-winged and rigid-winged flying wing aircraft, although the entry mechanisms apparently vary between them.

(2) That in weightshift controlled microlight aeroplanes, there remain four identifiable entry mechanisms, although it has been shown that structural failure can also lead to tumble entry, via an introduction to the whip-stall.

(3) That the tumble is sustained through formation of a spanwise vortex that forms over the leading edge as the aircraft rotates nose-down through the level-flight attitude, becoming larger and moving to provide a large area of low pressure above the trailing edge.

(4) That pilot education must remain the primary means of avoiding the failed aerobatic and wake vortex entry mechanisms in weightshift controlled microlights.

(5) That microlight pilots should continue to be taught that, if they have inadvertently entered a regime with no visual horizon, the best exit route is to conduct an idle power wings-level descent until a horizon is regained.

(6) To ensure that (5) remains best advice, that all aircraft should demonstrate positive spiral stability at idle power, and any weight and hangpoint combination.

(7) That when any weightshift controlled microlight is capable of showing a floating control bar following a sudden engine failure in the climb, a minimum full power climb speed should be laid down, which is no slower than the speed at which this occurs, from a test at maximum power and minimum flying weight.

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