# POSSIBILITIES OF HIGH ALTITUDE FLUTTER DURING WAVE FLIGHTS

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## 1. The Pilot's Problem

The question of what maximum speed to fly in order to prevent high altitude flutter has been a hot subject of discussion among experienced wave flyers for a long time. It is not trivial because a bailout at altitudes with outside temperatures of -70° C is a considerable hazard in itself. The question is: Does the red-line airspeed apply to indicated airspeed (IAS) or to true airspeed (TAS) as far as flutter at high altitude is concerned? Or is there an in-between limit?

It is no overstatement to say that presently there is widespread confusion on this issue, not only among pilots, but also in the soaring literature (see for example: B. Puchtler, *Soaring*, March 1990, p. 6; M. Morton, *Soaring*, July 1991, p. 4; J. Kuettner, *Soaring*, October 1991, p. 7; L. Hoffmann, *Soaring*, 1993, in press.). Expert pilots have made contradictory statements publicly, in books and journals. Puchtler quotes M. Palmer, C. Herold, and S. Smith, and that is only in the U.S.A.

The problem is specific for wave soaring. As the mountain wave is stationary over ground, wave soaring always involves flying against strong winds. Almost every high altitude night at some time needs to penetrate against such winds. Typical examples for such needs are:

- to locate a lift maximum,
- to reach wave lift of a moutain range farther upwind,
- to reach the primary wave,
- to leave a severe wave downdraft,
- to descend quickly due to equipment failure,
- to return quickly to base because of darkness,
- to avoid landing in rough terrain.

In many of these cases the temptation is large to fly near the red-line IAS limit (In the usually smooth wave, this could even be the "smooth-air" red-line.). However, at 40,000 feet, the TAS is almost precisely double the IAS. If the never-exceed airspeed, $V_{NE}$, is - typically - 270 km/h, a pilot may interpret this as allowance to fly a TAS of 540 km/h (300 knots). In turn, if $V_{NE}$ applies to the TAS, the wave pilot at 40,000 ft should not exceed an IAS of 75 knots, often not sufficient to make noticeable progress against the upper air winds.

We illustrate this situation with an actual example experienced by one of the authors (Kuettner). This describes an emergency situation with the sailplane caught in widespread lift at very high altitude with the spoilers frozen, and occurred on a flight during the "Sierra Wave Project" when numerous sailplane research flights were made safely between 40,000 and 45,000 feet. The following experience refers to one of these flights:

At 41,000 feet with the jet stream velocity exceeding 200 km/h and the outside temperature at -70° C (-95° F), the oxygen valve began to fail intermittently. Rapid descent was required, but the spoilers could not be deployed because they were frozen in the closed position. The conventional problem of the glider pilot to find updrafts reverted to one of finding downdrafts since normal descent with high speed would take much too long and could lead to flutter. The aircraft was a Schweizer 2-25, forerunner of the 2-32 two-place, but was flown single-seated because of heavy research instrumentation.

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During the long, tail-wind flight, the sailplane rose another 500 feet and airspeed and the turn-and-bank indicator fell asleep after one hour at this low temperature. Flight through thick cirrus was necessary, causing problems. Downdrafts were finally reached in a restricted nuclear test area, and the descent, at presumably flutter-safe speeds against the wind, allowed little penetration, resulting in a difficult return to base at low levels through hills and passes.

It was the uncertainty about flutter limits - especially after the first described experience - that caused some of the problems, but this caution may have saved my life.

This uncertainty needs to be removed, because wave pilots - especially those flying to record heights - must be able to inform themselves soundly about the conditions under which flutter can occur, about its consequences and the chances of recovery, and they should try to understand the mechanism of the flutter phenomenon. This paper makes an attempt to provide such badly needed information.

## 2. The Mechanism of Flutter

For the certification of modern sailplanes a complex investigation procedure is required. First, the dynamic characteristics of the soft suspended plane are measured in a ground vibration test. Then, feeding the results into a computer, flutter calculations are performed for selected cases, and a number of **critical speeds** are obtained. At each of these speeds a specific flutter is predicted to set in. The lowest critical speed represents the **flutter speed.**

Obviously, an adequate margin of safety is required between the flutter speed and the "never-exceed" speed limit $V_{NE}$. If the margin is too small, remedies are necessary, which must be checked by the flutter specialist. Sometimes parts of the previous procedure must be repeated.

It is usual practice and covered by the requirements to limit the procedure to the altitude range for normal soaring, i.e. up to 3 or 5 km above sea level. For high tropospheric or even stratospheric flight, air densities are a small fraction of the approved values, and a flutter prediction may not exist. The following gives an overview of the physical situation.

### 2.1 Damping

At low flight speed, oscillations of the sailplane arising from a single gust or control input are well damped and soon come to rest. This **damping** is caused by internal friction within the material, by aerodynamic forces, and by mechanical friction of the movable control systems. The doubtful role of the last contribution will be discussed later.

The structural damping, in an abbreviated flutter analysis can be neglected, but its influence can be important if weak damping is present throughout the speed range.

Most of the damping is supplied by the aerodynamic forces. For example, a wing oscillating perpendicularly to the flight path generates aerodynamic forces resisting the vibration. Generally, these forces increase approximately linearly with the flight speed and the air density. They are proportional to the **amplitude** (maximum deflection during a cycle) and the **frequency** of oscillation, i.e. the number of cycles per second.

### 2.2 Excitation

With increasing flight speed, the oscillating wing can generate aerodynamic forces driving the vibration. This **excitation** counteracts the damping forces. If, at a specific flight speed, the work of the driving forces balances the work of the damping forces during a cycle, the critical speed is reached. Flutter with growing amplitudes occurs if the damping can no longer compensate the excitation. This depends on flight speed, air density, and the motion of the oscillating components itself. This is a complex process that must be explained in more detail.

We will consider a wing, which is flexible **both in bending,** a motion of the tips up and down only, and in **torsion,** a pure rotation of the tips about a lateral axis. Each wing section contains three significant points which plot corresponding axes, if the whole wing span is considered:

- The **aerodynamic axis AA,** where those lift forces act that result from variations of the angle of incidence. This axis is generally located near 25% of the chord.
- The **elastic axis EA,** which is located within the range of 30 to 35% of the chord on modern sailplane wings. Its definition can be simply given as follows: Let a load travel along the chord. If loading the leading edge, the flexible wing would pitch nose down. If loading the trailing edge, it would pitch nose up. In between, just on the elastic axis, the wing would remain undeflected in torsion.
- The **mass axis MA,** a spanwise connection of the centers of gravity of the individual wing sections. Of course, the result is certainly not a straight line, but on the average its location can be assumed to be between 40 and 45% of the chord on a sailplane wing without ballast.

These three axes are shown in Figure 1 for a representative wing section somewhere near the wing tip.

The motion during a cycle is illustrated at four sequential instants of time (clockwise direction) in Figure 2. Each cycle consists of an up and a down motion, with two reversal phases in between (for and aft motion is not implied). During the up and down motions a vertical speed dominates, during the reversal phases an acceleration. Aerodynamic forces (note that the lift forces for steady flight are neglected in flutter mechanics) result both from an upand-down moving willg with zero incidence, the previously mentioned damping effect, and from an angle of incidence generated by periodic pitching of the wing. The acceleration, a consequence of the reversed motion, generates an inertia force at MA,

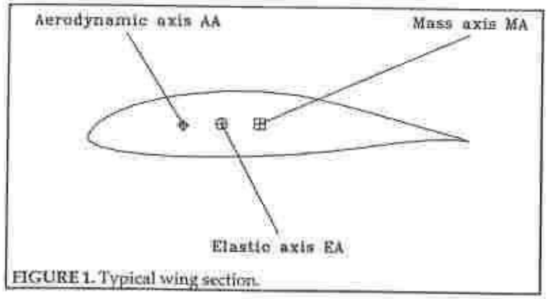

FIGURE 1. Typical wing section.

which tends to drive the section center of gravity more away from the base line. This mass force M acting aft of the elastic axis EA rotates the section and generates an angle of incidence. Thus, a corresponding downward directed lift force develops during the down motion. Similar reasoning applies to the upward motion.

A general feature of the flexible wing is that it, thanks to the elastic force E, tends to restore its undeflected position. The aerodynamic force A, however, drives the up-and-down motion and, therefore, has an exciting effect. This force is responsible for the flutter.

Unfortunately, the consideration of moments is more involved, and a discussion of the exciting effect on the pitching motion must be omitted here. Only one fact is obvious: In all existing wing designs AA is in front of EA, and MA is behind of EA. Both of these locations increase the excitation, and from most flutter analyses it is known that the mass effects dominate in producing the pitching moment. If it would be possible to reduce the distance between MA and EA to zero, most of the exciting moment would disappear. This ideal case **of mass balance** of the wing is unattainable in current designs.

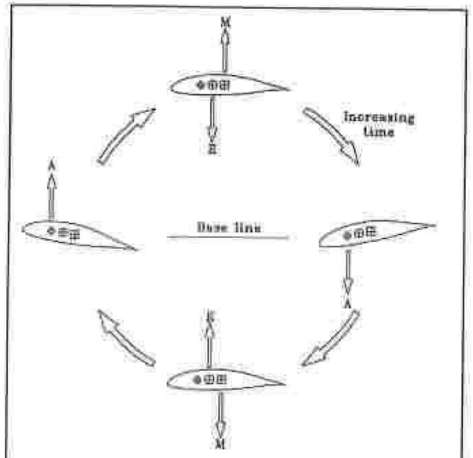

FIGURE 2. Flutter motion (wing bending/torsion).

**2.3 Excitation with Control Surfaces**

Similar in principle, but different in detail, control surfaces can generate an excitation. In Figure 3 and Figure 4 we consider a wing section as before, equipped with an aileron. For simplification we assume that the wing is rigid in torsion and its sections always remain parallel to the base line. Only the aileron can deflect, and it is known that this deflection produces a lift force similar to an angle of incidence but acting at a different aerodynamic axis AC, which is more aft than AA. For simplification, in this example it is assumed that the aileron can rotate without significant elastic or aerodynamic restraint and is submitted to inertia forces only.

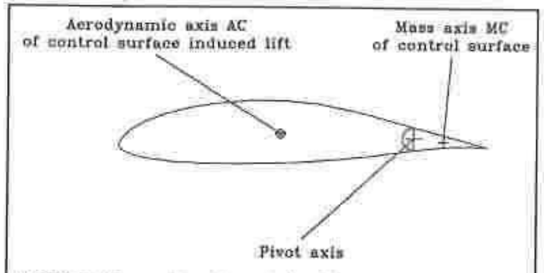

FIGURE 3. Wing section with control surface.

The center of gravity MC of an unbalanced aileron is located at about 30 or 40% of its chord. During the return phase of the deflected wing the aileron tends to continue the outward motion, thus generating an angle of deflection and a corresponding lift on the main wing section. This leads to the same driving effect as in the bending/torsion case shown in Figure 2. Now, however, with complete mass balancing of this aileron section it is really possible to set the distance between the aileron center of gravity and the hinge to zero and to eliminate the exciting effect. The aerodynamic moments acting on the control surface are also important, and the flutter analyst takes account of them.

**2.4 Ground Vibration Test**

Elastic structures, if suitably thrown into vibration by a shock or harmonic forces, tend to respond with a specific frequency and deflection pattern, which is called **a mode.** Sailplane wings, tailplanes, and sometimes the fuselage, too, are very flexible, and about two dozen modes must be considered. With a vibration test on an elastically suspended sailplane, these different modes, both symmetrical and antisymmetrical, are determined together with their **natural frequencies** and mode shapes including the nodal lines.

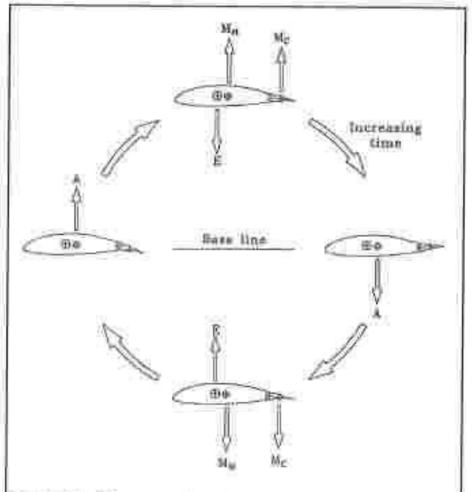

FIGURE 4. Flutter motion (wing bending/control surface rotation).

As most modern sailplanes are quite similar in configuration and proportions, similar modes are also revealed. Typical examples are the wing bending and torsion modes, shown in Figure 5. Only half of the wing is drawn for each mode; bending modes are indicated by solid lines and torsion modes by dashed lines. On the left-hand side, the base lines of the symmetric wing modes are staggered corresponding to their frequencies (cycles per second) indicated at the center line. On the right-hand side, the antisymmetric wing modes are presented accordingly. Normally, the fundamental symmetrical bending, called Sl, has a frequency at about 3 Hz. The antisymmetric and all higher modes follow with the approximate frequencies in the figure. The sequence of modes relevant for flutter must include at least the primary wing torsion at about 25 Hz.

The tailplanes, less slender than the wings, reveal higher frequencies, and normally only the primary bending modes are important, some of them in connection with fuselage bending or fuselage torsion. In separate tests, the frequencies of the control surfaces are determined with fixed and free controls, respectively. The determination of the symmetric aileron vibration and sometimes of the flap vibrations is most important. Possibly, the antisymmetric vibration of the two halves of the elevator must be considered.

**2.5 Coupling of Modes for Flutter**

Classical flutter is possible only if two or more individual modes can couple and approach a common frequency. Then they act together in a manner as shown in Figures 2 and 4. It is necessary that at least one of these modes includes wing torsion, i.e. an angle of incidence vauiation, or a control surface deflection. The question is how and when coupling can alter frequencies of the modes until they are sufficiently close to enable a continuous vibration. This is where airspeed comes in, because the coupling can and will happen at a sufficient airspeed. The collapse then may be sudden.

Normally, a wing bending mode would couple with a wing torsion mode or an aileron deflection, respectively. In the resulting coupled modes a time lag occurs between both elementary motions, called **phase.** In Figure 2 and Figure 4 a lag of a quarter cycle is illustrated for simplicity. The angle of incidence alters its sign after the bending motion passes the base line, which is a necessary requirement for generation of driving forces at the right time.

As a result of the air flow around the oscillating surface, the frequencies of the natural vibrations will be different from those of the ground test. The rotational vibration will decrease and include some bending, and the bending vibration will slowly increase and include some rotation until at the critical speed their frequencies will be close to coincidence and flutter occurs in one of the two coupled motions. The mentioned phase, required for excitation, results automatically.

**2.6 The Damping Diagram**

The most valuable information about the character of a flutter case is given by a diagram of damping versus

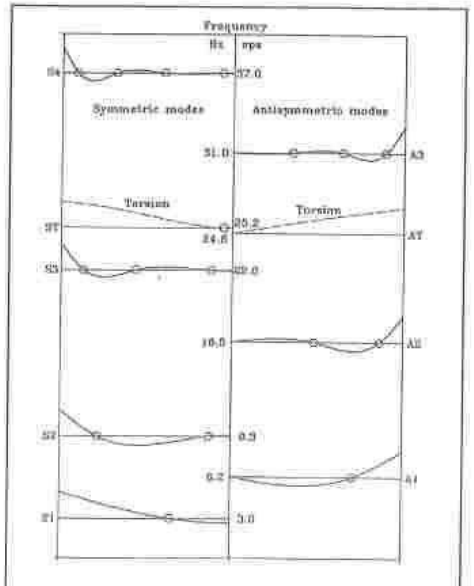

FIGURE 5. Natural wing vibration modes.

speed. Thus, the total of damping and excitation during a cycle is indicated. It is normal practice to calculate these curves and to judge their crossings with the zero damping line, i.e. the critical speeds. Some typical curves are shown in Figure 6 (Damping is usually given as a percentage of **critical damping** defined by the transition to non-oscillatory motion).

A This curve shows positive damping throughout, which is mainly due to aerodynamic effects.

B The initial damping has a similar trend as in A. Suddenly, at a higher speed an abrupt reversal of the positive trend indicates the appearance of a strong excitation. The forementioned neighborhood of frequencies of the involved modes plays a prominent role. At a critical speed the curve crosses the line of zero damping in a steep slope, causing violent flutter to occur beyond this point.

C The initial damping is poor, and soon moderate excitation causes a slight decline of the curve, which may cross over for a limited speed range. The excitation may appear again at a higher speed and lead to a substantial, yet not very violent, flutter.

Curve A, the safest case, is not natural for modern high-speed sailplanes with their slender wings. A coupling of wing torsion with bending modes cannot be excluded and would lead to flutter with a behavior as in Curve B. The same violent characteristics are possible with coupling of symmetrical aileron vibration and wing bending modes.

Curve C is typical for low frequency or stick-free control surface modes coupled with wing bending. Sometimes a coupling of rudder deflection and fuselage torsion or another low frequency fuselage deflection shows similar behavior. In such cases it is possible to provoke a pronounced vibration by shaking the corresponding controls. The response is more or less damped, or even slightly excited. Such behaviour should be a warning that at a higher speed a serious flutter will occur.

### 3. How Does High Altitude Affect Flutter?

Damping curves are often determined only for two representative altitudes like sea level and 5000 m, for example. If more such curves are available for a wide range of altitudes, a diagram as shown in Figure 7 can be drawn. This example was calculated at the DLR Institute of Aeroelasticity in Gottingen, Germany. It ranges up to stratospheric flight conditions. On this diagram of altitude versus equivalent air speed EAS (a definition used in calculations and which is very close to indicated air speed IAS), limits of the stalling speed and the never exceed speed $V_{NE}$ are shown. The $V_{NE}$ limits corresponding to constant true air speed TAS and constant equivalent air speed EAS above the approved altitude are also indicated. Obviously, the margin between the TAS limit and the stalling speed can become too small for operation. On the other hand, safety margins between the EAS limit and the flutter speed decrease with increasing altitude.

Figure 7 shows three unstable regions. Region (a) was not relevant for the original certification covering altitudes of normal operation. The unstable region develops at higher altitudes and becomes wider and certainly more pronounced in the stratosphere. A simple extrapolation of the results from low altitudes may not reveal the appearance of instability amidst the operational range. Fortunately, in this case the flutter is caused by the low frequency antisymmetric wing bending A1 (see Figure 7) coupled with stick-free aileron rotation. Chances may be good to stop this flutter by fixing the stick. It should be mentioned that an improved mass balance of the ailerons would completely eliminate this kind of flutter.

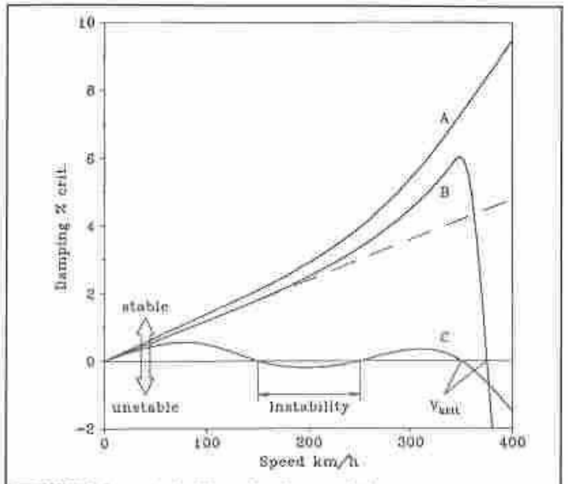

FIGURE 6. Some typical damping characteristics.

The more serious problems are with Region (b). This flutter also results from a wing/aileron coupling, but with the mode A2 (see Figure 7). This case is more violent due to the higher frequency and fixing the stick will probably not stop the flutter. However, the chance of recovery is good with comparatively little trouble. As in the former case, a suitably arranged mass balance would eliminate this flutter, too.

The flutter region (c) results from coupling of wing bending and torsion and is of the most detrimental type, as indicated by Curve B in Figure 6. A remedy is possible with simple modifications, and a margin of safety with respect to the $V_{NE}$ limit is indispensable. In the example of Figure 7 the margin remains acceptable in high altitudes, even if the constant EAS line is regarded as the operational limit. However, with a higher $V_{NE}$ or a lower critical speed of (c), the safety margin can become too small. The boundary of (b) and (c) is probably of the same character in other cases, namely tending to lower critical speeds at higher altitudes. If this is generally true and regions such as (a) are eliminated by adequate mass balancing, it becomes obvious that a mean value between the TAS and EAS limit will satisfy all safety needs with regard to both flutter and stall. As long as other information is lacking, it is recommended as a preliminary solution.

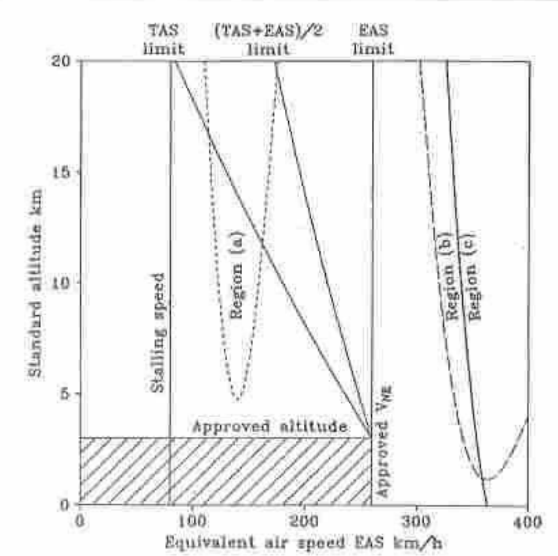

FIGURE 7. Example of unstable regions and speed limits:

(a) Envelope of critical speed for wing bending A1, coupled with aileron deflection. This mild flutter tendency can be eliminated by mass balancing.

(b) Wing bending A2 with aileron deflection. Mass balance would eliminate this unstable region, too.

(c) Critical speed of symmetrical wing torsion coupled with wing bending S1. Improvement of this limit would require an expensive redesign of the wing structure.

Note the small margin between the stalling speed and the TAS limit, and the decreasing safety margins between the EAS limit and the flutter boundaries of (b) and (c) with increasing altitudes.

### 4. Design Reflections

Bending/torsion flutter occurs inevitably somewhere in the high speed range. Consequently, the limit (c) in Figure 7 is a general fact. Normally the critical equivalent or indicated air speed decreases with increasing altitude. Thus, the margin of safety with respect to constant $V_{NE}$ considered either EAS or IAS is reduced.

The unstable regions (a) and (b) in Figure 7 are specific to the presented example. Other locations, if any, are possible with other types of control surface flutter. These regions develop from stable damping minima at low altitudes. Instability appears at some altitude and broadens with increasing altitudes. This characteristic may be similar even for different types of flutter. Fortunately, a correctly located and dimensioned partial mass balance of the control surfaces would absolutely eliminate the threat of these flutter cases, which certainly is a considerable advantage. A skilled designer with the respective know-how can act in this way. Another method of mass balance, applicable with less knowledge of flutter conditions, is a total mass balance on the whole length of the control surface. At first glance, this method looks less attractive, but a proper design without substantial weight and drag penalties is feasible indeed.

### 5. Pilot Concerns

The presently available sailplanes have not necessarily been investigated and approved for flight conditions at very high altitudes. On request, the manufacturer would certainly provide information about the results of the flutter analysis. Possibly, some conclusions can be drawn from the known flutter characteristics, but even then caution is needed, and as speed limit $V_{NE}$ the mean value between constant TAS and IAS above the approved altitude remains the best solution at hand. A well readable chart with the IAS values of this limit in various altitudes should be installed in front of the pilot.

The sailplane for high altitude flights should be a modern type, well proven in normal service, and in perfect condition. It must not be overloaded, and additional equipment must not be located in the rear fuselage or on the outer wing aft of the 30% chord line.

The control systems should be free of play and with the least possible mechanical friction. Cable tension should be properly adjusted. Long control cables running in metal structures slacken at low temperatures of high altitudes. A too flexible control system is frequently a source of flutter trouble. The flexibility of the system can be checked by fixing the control surfaces and applying a usual force to the stick or pedals. The deflection should be a small fraction of the available travel. Lift flaps, if set to a positive stop in high-speed flight, are not essential for flutter.