# Aeroelasticity in Sailplane Design

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## Introduction

One of many problems in the field of sailplane design is that of aeroelastic stability. Practicing designers of gliders and light aircraft seldom have the opportunity to spend a great deal of time studying the difficult background of flutter. Therefore, the flutter engineers at the Institute of Aeroelasticity are traditionally consulted to test and to certify light aircrafts and gliders for flutter stability.

In the following the basics for the mechanism of flutter are presented and the certification process is explained for a representative modern sailplane of the 18m-class starting with the requirements of the Joint Aviation Authorities (JAA). The objectives and methods of the ground vibration test are introduced to measure the vibration properties of the aircraft structure. These data are used to perform the flutter analysis in order to find possible flutter instabilities in the flight envelope. As the maximum flight speed of modern high performance sailplanes is further increased, costly modifications of the prototype are often necessary to satisfy a safe design. Therefore, a method is presented to estimate the flutter behavior during the design process.

## Aeroelastic problems

Aeroelasticity is a multidisciplinary problem which includes the disciplines aerodynamics, elasticity and inertial forces. The problems can be subdivided into steady aeroelastic problems which depend on geometry and stiffness distribution of lifting surfaces and are described by

- twist deformation, which influences the lift distribution,
- divergence,
- control efficiency and reversal.

Unsteady aeroelastic problems deal with the dynamics of lifting surfaces, which depends on stiffness and mass distribution in the aircraft structure and control system. Here

- flutter and
- gust response must be mentioned.

Sailplane wings show large aspect ratios with high flexibility. Therefore, flutter is the main aeroelastic problem.

## Flutter

For the special version of the DG300 with 17m span, which is used as IDAFLIEG calibration glider for flight performance tests, the flutter analysis performed by the flutter engineers of the Institute of Aeroelasticity showed instabilities in lower speed range, if the water ballast is overloaded. The first antisymmetrical bending mode A1 couples with the aileron deflection in the range between 140-150km/h. The nodal line of bending mode is shifted to the wing root with water ballast and the effect of unsteady forces caused by aileron deflection becomes more effective. The flutter instability can be induced by oscillating the control stick, the amplitude is limited by maximum aileron deflection angle. To verify the theoretical results flight tests were performed by the DLR Flight Facility in Braunschweig and the occurring oscillation was filmed in flight.

Each wing can be simplified to an arrangement of several neighbored wing sections. The motion of every strip can be composed by superposition of heave, pitch and control surface deflection (three degrees of freedoms, dof). Each dof oscillates with a certain frequency depending on spring stiffness and section mass, which depend on the stiffness and mass distribution of the wing. For the self excited flutter motion at least two dof are involved, where one must have a rotational part to induce additional unsteady lift. Flutter is unlikely to occur in higher frequency range above a reduced wave length of 7.7 in maximum for gliders and is dependant on vibration frequency, flight velocity and a reference chord. This corresponds with a maximum frequency of about 50Hz, which must be recognized in the flutter analysis. If a critical flutter speed is exceeded the exciting unsteady aerodynamic forces will overcome the damping forces of the structure. Energy passes from the flow to the structure and can destroy the aircraft in a very few seconds.

The resulting frequencies and dampings of all dof are calculated including the influence of the induced unsteady aerodynamic forces and are plotted against flight velocity in the flutter diagram. The behavior of the three dof with increasing flight velocity is as follows. The frequency of heave motion is constant, pitch frequency is decreasing and frequency of control surface rotation is increasing. At a certain critical velocity frequencies of two neighbored modes approximate each other and unstable coupling becomes possible. The damping behaviors can be classified into three types: The stable mode does not reach zero damping. The damping of the unstable mode decreases very rapidly. The hump mode becomes unstable at certain speed and returns back to the stable region at a higher speed. This type of instability can usually appear if a control deflection is involved.

## Certification process

For the new construction of the Akaflieg Braunschweig, the SB14, the certification process for flutter prevention is presented exemplarily in the following. The SB14 is a high performance single-seater for the 18m class in full carbon-construction. The fuselage is minimized in order to reduce drag, so that the empannage is connected to the cockpit by a very thin carbon tube. The flaperons are made from high module carbon and are extremely light. The first flight took place on the 17 January 2003. The design diving speed is $V_D$ =320km/h (EAS).

In the Joint Airworthiness Requirements JAR the following paragraph JAR 22.629 can be found which determines the rules for the flutter analysis:

(a) The sailplane must be free from flutter, aerofoil divergence, and control reversal in each configuration and at each appropriate speed up to at least $V_D$. Sufficient damping must be available at any appropriate speed so that aeroelastic vibration dies away rapidly.

(b) Compliance with sub-paragraph (a) must be shown by:
- (1) a ground vibration test which includes an analysis and an evaluation of the established vibration modes and frequencies for the purpose of recognising combinations critical for flutter, either by:
  - (i) an analytical method, which will determine any critical speed in the range up to 1.2 VD, or
  - (ii) any other approved method.
- (2) systematic flight tests to induce flutter at speeds up to $V_{DF}$. These tests must show that a suitable margin of damping is available and that there is no rapid reduction of damping as $V_{DF}$ is approached.
- (3) flight tests to show that when approaching $V_{DF}$:
  - (i) control effectiveness around all three axes is not decreasing in an unusually rapid manner, and
  - (ii) no signs of approaching aerofoil divergence of wings, tailplane and fuselage result from the trend of the static stabilities and trim conditions.

At the Institute of Aeroelasticity in Gottingen the certification process starts with the ground vibration test (GVT) in order to measure eigenmodes with eigenfrequencies, generalized mass and damping. So the prototype of the new glider must be available. Alternatively, if an analytical model can be delivered, which is usually a finite-element model, the modal data can be calculated by modal analysis. For certification it is required that the analytical model represents the reality in the interesting frequency range. For the flutter analysis an unsteady aerodynamic model must be composed, which is based on the strip theory or on the more advanced doublet-lattice-method DLM and provides unsteady aerodynamic forces for harmonic oscillations. The amplitudes of the measured or calculated eigenmodes are interpolated to the aerodynamic grid and the so-called generalized airloads are composed. The stability analysis is feed with the modal data and provides frequencies and dampings for every modes with increasing flight velocity. For this task the DLR flutter software uses a modified p-k-method.

For the GVT the suspension of the aircraft must be very soft to simulate the free flying condition. As a rule of thumb the frequency of suspension must be lower than 1/3 of first flexible mode. In the laboratory of the Institute the glider hangs at four bungee ropes under a crane bridge. The glider is equipped with 50-80 acceleration sensors depending on the span. As the sensors can only measure translational accelerations the twist of the lifting surfaces must be calculated from amplitude differences at leading edge, trailing edge and hinge line, respectively. The structure is excited by electromagnetic shakers, which produce harmonic oscillating forces controlled by a frequency generator. At the beginning frequency sweeps search for the eigenfrequencies. If an exciting frequency is equal to an eigenfrequency of the structure the amplitude increases (resonance), which can be identified from the frequency response. After the interesting frequency range is scanned all identified modes are tuned with the phase resonance criterion, which requires that all sensors must oscillate harmonically in phase. The sensor signals are recorded for this tuned state. As the acceleration is the second derivative of the deflection for the harmonic motion the absolute values of both are equal, if the signals are normalized to the maximum amplitude. The damping and the generalized mass is calculated by the applied shaker power.

For every glider a list of eigenmodes can be identified in the vibration test, which can be subdivided in symmetrical and antisymmetrical modes. Because the fuselage is acting as an interface between the wing and the tailplane, a wing vibration mode can cause reactions to the tailplane. The opposite can occur as well. The frequency values are specific for different constructions but the sequence of frequencies is almost fixed.

Symmetrical modes:

S1 fundamental wing bending mode, 1 node per side,
SZ1 first inplane wing bending mode, 1 node per side,
S2 second wing bending, 2 nodes per side,
SR2 2 node fuselage bending mode, vertical,
S3 third wing bending, 3 nodes per side,
SH fundamental bending tailplane mode,
SZ2 second inplane wing bending mode, 2 nodes per side,
SR3 3 node fuselage bending mode, vertical,
ST first wing torsion mode,

Antisymmetrical modes:

AZ fuselage yaws antiphase to the wings around the z-axis, middle section acting as a spring, wings bend inplane,
A1 first wing bending mode, 1 node per side, 1 node in the middle,
AH1 horizontal tailplane rolls, fittings and fuselage torsional flexibility are acting as a spring,
AZ1 first inplane wing bending mode, 2 nodes per side , 1 node in the middle,
AST vertical tailplane torsion,
A2 second wing bending mode, 2 nodes per side, 1 node in the middle,
AR2 fuselage side bending mode,
A3 third wing bending mode, 3 nodes per side, 1 node in the middle,
AT first wing torsion mode.

The symmetrical flutter analysis showed an instability at 341.7km/h with a frequency of 9Hz, which is below the required 1.2 $V_D$. In an altitude of 5000m the critical flutter speed reduces to 313.9km/h. The second wing bending and the fuselage bending are involved, which are very similar in type and frequency. The fuselage bending includes more wing twist, which induces the exciting air forces. As no participation of control modes like elevator could be found, there was no possibility to heal the instability with additional mass balance. It was decided to reinforce the fuselage tube with bending stiffness to increase the frequency of fuselage bending. Unidirectional carbon layers were laminated on the upper and lower side of the tube.

This modification results in an increase of bending stiffness by 235% to satisfy all flutter requirements. The resulting crack for the tube is 7.3. The frequency distance for the two participating modes increases from 1.89Hz to 4.62Hz, so that the critical flutter speed arises to 385km/h. For the SB14 the fuselage structure is driven by stiffness constraints and not by security against fracture.

## Numerical modeling

As dynamic problems with the minimal fuselage were assumed in the design phase an analytical model of the structure was composed to predict the dynamic properties before the GVT. The objective is to analyze the flutter behavior during the glider design process based on calculated eigenmodes. The glider structure is numerically composed as idealized beam model with point masses inside a commercial Finite-Element-Software which allows modal analysis in order to predict the frequencies and eigenmodes by modal analysis, to search for structural sensitivities with respect to flutter instabilities and to quantify the amount of additional stiffness in critical areas. As a requirement only construction data from strength analysis are used which are usually available as spreadsheet from the sailplane designer. The beam model is based on the stiffness and mass distributions calculated from geometry and material data accumulated during design process.

The flutter result based on the analytical beam model shows the same flutter mechanism as the analysis based on measured vibration modes. The critical flutter speed is predicted to low, but the damping descent of the unstable fuselage mode is flat. The model can be used to find sensible structure components to increase flutter speed and to quantify the amount of additional stiffness. So after the FE-model was manually updated in order to reproduce the measured modal data the final flutter analysis was performed with the model including the necessary stiffness reinforcement.

For the antisymmetrical flutter analysis no instability was found in the required speed range. But at about 400km/h the torsion mode, whose frequency falls to 21Hz, starts to couple with the flaperon deflection, whose frequency increases to 12Hz. This behavior can be found for all modern sailplane constructions in the speed range between 350km/h and 400km/h, where $1.2V_D$ is usually located. The design diving speed $V_D$ is increased by high wing loading G/S and low drag coefficient $Cw_{min}$. For modern high performance sailplane both parameters become more extreme. The flutter certification requirement reaches $1.2V_D$ = 400km/h (EAS) in an altitude from 0m to 5000m.

## Conclusions

In this high speed range the instabilities including the torsion and control modes cannot be avoided with mass balance. So it seems that 400km/h limit is an “aeroelastic show stopper” if the sailplane structures are only constructed for strength requirements. Aeroelasticity and especially flutter must be incorporated in the design process of future more efficient sailplane constructions. The structure can be modeled as FE-beams based on construction including masses and moments of inertia along the span or the fuselage and calculated bending and torsion stiffness. The eigenfrequencies, eigenmodes are calculated by modal analysis. The control system can be integrated as cinematic chain from stick to control surface with elastic and mass properties. A further aspect is to analyze nonlinearities in the control system, which can be caused by friction, freeplay or geometrical aspects. The resulting model must be updated with the ground vibration test to reproduce the dynamic behavior of the structure. As a benefit such model can be used for the certification process of subsequent modification of the new sailplane like additional span, new winglets, change of mass distribution and so on. There is no need for a new ground vibration test, which will reduce effort and costs for improvements in the life of a sailplane development.

## References

(1) JAR 22.629, Flutter paragraph, www.jaa.nl.
(2) FAA Advisory Circular: Means of Compliance With Section 23.629, Flutter, AC23-629-1a, www.airweb.faa.gov.
(3) W. Stender, F. Kieáling: Aeroelastic Flutter Prevention in Gliders and Small Aircraft, DLR IB 232 - 90 J 10, DLR 1990.
(4) F. Kieáling: On Simplified Analytical Flutter Clearance Procedures for Light Aircraft, DFVLR IB 232 - 87 J 13, DLR 1987.
(5) F. PAtzold: Standschwingungsversuch und Flatterrechung des Segelflugzeugs SB14, DFR IB 232 - 03 J 06, DLR 2003.
(6) M. Hollmann: Modern Aerodynamic Flutter Analysis, Aircraft Designs, Inc., Monterey, California 1991, http://www.aircraftdesigns.com/flutter_analysis.html.