ON SIMPLIFIED ANALYTICAL FLUTTER CLEARANCE PROCEDURES FOR LIGHT AIRCRAFT

by Prof. Fritz Kiessling, DLR Gottingen, Germany

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1. Introduction

One of many problems arising in the field of airplane design is that of aeroelastic stability; specifically that of flutter. Unpleasant experiences with regard to this problem are not only confined to large and high-speed aircraft of the major companies. The manufacturers of small airplanes are also faced with the difficult problem of flutter. However, they are in a much weaker position to recognize and solve the problems. They cannot afford to employ their own aeroelastic specialists, nor pay for the necessary testing and computing facilities.

Practicing designers of gliders and light aircraft seldom have the opportunity to spend a great deal of time studying the difficult mathematical background of flutter for they receive no immediate benefit for their current efforts. Therefore, among the small airplane manufacturers in Germany, it is common practice to leave ground vibration tests and subsequent flutter calculations to an institution authorized by the Federal Office of Civil Aeronautics. The flight flutter tests, however, are carried out by the manufacturing firms themselves. Both investigations should establish the aeroelastic stability of the airplane necessitating at best no, or only minor, modifications.

The prevention of significant modifications requires that the designer, from the outset, consider the flutter danger as important as he considers the importance of the structure's strength. For this reason, acceptable design criteria and test procedures based on past experience are most beneficial.

The role of the aeroelastic consultant entails not only detecting flutter hazards, but also suggesting methods of preventing them within the limits of constructional feasibility. In Germany, it is the meritorious work of W. Stender who bridged the gap between the designer's and the specialist's perceptions. His work was gathered through practical experience during flutter investigations on numerous gliders and light aircraft (1).

When attempting to fully utilize modern aeroelastic tools, such as sophisticated ground vibration tests and wind tunnel tests or three-dimensional computations of the structure, as well as of the unsteady airloads acting on it, the small manufacturers are overburdened by high costs. It must be recognized that the efforts in the field of flutter clearance are related to the function, the price and expected number of airplanes to be produced, the experience with similar designs, the maximum airspeed, and the justifiable residual risk, for example. Low costs are essential if small manufacturers are to concern themselves with aeroelastic matters before they attempt to demonstrate freedom of flutter by flight tests.

This report deals specifically with gliders, however much can be applied equally to light aircraft with manual controls. An example of the typical problems which have occurred in the past is illustrated in Figure 1, i. e. bending/control surface flutter. The sequence taken from the flutter film produced by the Akaflieg Braunschweig shows limit-cycle oscillations of the 22 m spanning SB-9 with a frequency of 5.8 Hz in the speed range between 39 and 44 m/s. In this case, the first and second antisymmetrical wing bending modes and the aileron rotation are involved. The 21 m version of the same type showed additional flutter with first antisymmetric wing bending and aileron rotation between 24 and 26 m/s (frequency 3.3 Hz). Adequate mass balancing of the ailerons eliminated these relatively mild oscillations.

Generally, the danger of violent classical bending/torsion wing flutter dwindled with the widespread use of the torsional

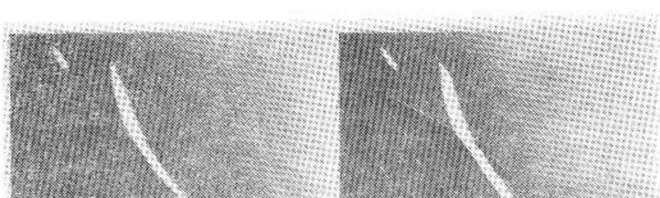

FIGURE 1. Flutter of SB-9

stiff monocoque construction. But with increasing maximum speeds and with large amounts of water ballast - even more than the wing structure's mass - new aeroelastic problems such as torsion/aileron flutter may appear.

2. Measures against flutter of small airplanes

The stages of work regarding flutter clearance in the development of small airplanes are shown in Figure 2. Many possibilities are open to the designer in preventing serious difficul-

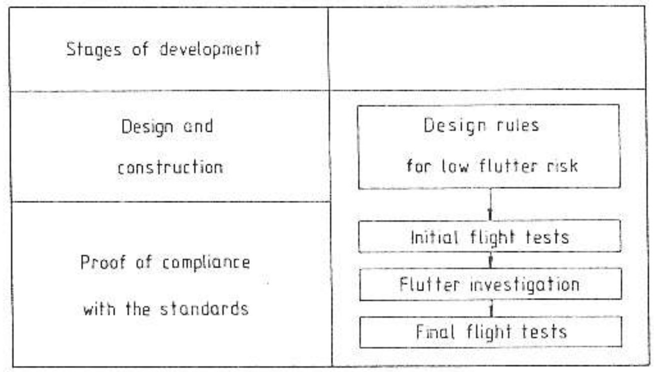

FIGURE 2. Measures for flutter prevention of small airplanes.

ties with the completed airplane. Many recommendations which will also result in higher quality of the construction are given in (1). They are centered around the following points:

- sufficient torsional stiffness of wing, stabilizer, and fin
- sufficient stiffness of the control surfaces against bending and torsion
- sufficient stiffness of the control system (long-stroke type)
- avoidance of local flexibilities near control system fittings
- lightweight construction of the rear parts of control surfaces and wing
- adequate dynamic mass balancing of the control surfaces or at least provision of space to install it later if necessary
- avoidance of adverse mass coupling resulting from lead-lag motions
- avoidance of adverse kinematic coupling between structural and control surface modes
- strict avoidance of reversible tabs

General estimates for eigenfrequencies are also given in the reference above.

In the early stages of small airplane development, eigenanalyses and flutter calculations through the input from drawings are generally not worth the invested effort, because they can only provide fragmentary solutions to the real problems. The accuracy depends largely on uncertain factors like junction stiffnesses, material data of composites, etc. Existing data of similarly constructed forerunners of the airplane under consideration is of greater value. A more detailed statement about the vibration behavior of small airplanes can not be given until the ground vibration test is finished.

Experience has shown that proper designed airplanes are not susceptible to violent flutter when flying in the lower speed range. Early flight tests in that range are highly recommended, for they offer the possibility of taking early corrective action regarding the flutter behavior based on the flight experience. The maximum speed for these tests is fixed between 1.5 V_s (stalling speed) and V_M (maneuvering speed). The increase in speed should be incremented in steps of approximately 3 m/s. In each speed step the controls are struck and shaken, and then freed in order to recognize tendencies of self-sustained vibrations.

The final flight testing must be scheduled after the flutter investigation. It should demonstrate freedom of flutter up to a maximum speed defined as V_{DF} which is at least 1.1 V_{NE} (never exceed speed) or V_D (design maximum speed). In the case of high-performance gliders red-line exceedings during contest flights must be expected and an adequately increased V_{DF} should be fixed. Between V_N and V_{DF} the speed increments should be halved. In the case of decreasing damping the frequency and mode should be estimated and communicated to the aeroelastic consultant. The continuation of night testing must be delayed until a satisfactory explanation and remedy have been found. It is strongly recommended that the test pilot attend the ground vibration test to classify his observations.

Generally, it is desirable to use some small and inexpensive flight instrumentation for quantitative measurements of damping. Unfortunately, it is not possible for small manufacturers to utilize such equipment. Therefore, they should be allowed to resort to manual excitation in flight flutter testing which of course is objectionable. It should be noted that flutter clearance cannot be established by night demonstration alone, because modifying the tested airplane would require new expensive testing. This can be handled by the flutter investigation more economically, so that combining both approaches is possibly the best method.

3. Flutter investigation

When considering low costs, the expense of a flutter investigation must be able to be differentiated. Therefore, Figure 3 outlines some different methods of approach.

The first criterion in pursuing the best method is through verification of the present construction with regard to airplanes

Type of airplane	conventional		unconventional
Frequency level	high	low	
Ground vibration test	simplified		detailed
Test evaluation	empirical estimation	flutter computation	flutter computation
based on	„standard" modes statistic data	„standard" modes measured modes	measured modes exclusively

FIGURE 3. Flutter investigation of small airplanes.

which are aeroelastically similar, in particular the forerunners. Conventional and unconventional airplanes can be distinguished accordingly. Sufficient experience with regard to the aeroelastic behavior of the unconventional airplanes is not present. Therefore, a comprehensive investigation is necessary. The investigation is based on an extensive ground vibration test, in which normal modes and their associated parameters are determined with a large number of pickups. The experimental results - possibly with more detailed data of the construction, for example, the control surfaces are used for application in the flutter calculation. Actually, this is the standard method for flutter investigation of an airplane, when disregarding a purely analytical treatment of the problem.

An additional distinction can be made in the field of conventional airplanes. It is dependent on the level of certain eigenfrequencies of the airplane under consideration. There are limiting frequencies depending on maximum speed and on the mean chords of the lifting surfaces, as will be shown later. All natural modes up to these frequencies must be considered. On this basis, the flutter investigation can be simplified when the wing torsional modes are no longer involved. In this case, the bending modes to be considered generally contain negligible torsional deflections. The decision as to the method for proceeding will in each case be made by means of a ground vibration test, which can be conducted at less expense.

If the wing torsional modes must still be considered, then only the normal modes including torsional deflections are more precisely measured in the test. Especially in the case of the low-frequency wing bending modes, one can he satisfied with a brief reexamination of whether these modes agree with the statistically obtained "standard" modes.

If the wing torsional frequencies are sufficiently high, an empirical estimation can also he employed, which, in a statistical way, relies on previous experience with flutter. Then, of course, larger safety margins and more severe prevention measures must he accepted. In other cases, flutter calculations must he carried out.

3.1 Empirical method

Experience shows that fluttering of an airplane does not occur for every ratio of the plane's speed and frequency. An essential parameter is the well-known reduced frequency

$k = \omega c / V$

in which the circular frequency, ω, the half mean chord of the lifting surface, c, and the plane's speed, V, are represented. From the beginning, statistics were compiled from this knowledge, which actually classified the cases of flutter in this way, see (2) and (3). With regard to gliders and light aircraft, this empirical data was completed in (1) with thirty provable and interpretive cases of flutter. It was thereby possible to order the cases according to the flutter of specific parts of the airplane. Figure 4 shows the fields of the statistically recorded cases of

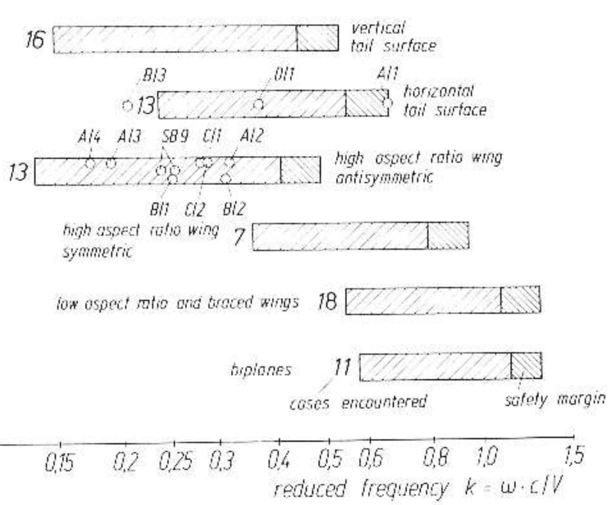

FIGURE 4. Statistical classification of flutter incidents.

flutter. Also shown is the number of cases encountered in these ranges. Distinctively labeled are the previously mentioned SB-9 flutter, as well as more extensively analyzed and encountered cases, which will be dealt with in more detail.

When one considers, as indicated, a safety margin added to the larger reduced frequencies, then for a given maximum flight speed, the flutter of a component part with a significant contribution of a normal mode is improbable, which has an eigenfrequency above the thus established "design frequency". Therefore, the first objective is to raise the eigenfrequencies above the "design frequencies". With gliders this is becoming increasingly difficult to realize due to the constantly rising maximum speeds and due to the increase of aspect ratios and corresponding decrease of chord lengths. Therefore, in most cases, the control surfaces must he mass balanced as an additional measure. This occurs by the empirical method such that all normal modes to be considered, which can couple with rigid or elastic control surface degrees of freedom, are dynamically mass balanced.

A method for determining the position and size of the mass balance is described in (1). With regard to elastic degrees of freedom of the control surfaces as well as the control system, the distance of the eigenfrequencies can be taken into account. A reduction of the mass balance is possibly permissible considering low aspect ratio wings or empennages according to (1) and (4). Although structural damping and especially friction in the controls have a strong and beneficial influence on flutter behavior, in view of their insufficiently precisely definable quantity, it appears problematical to take them into consideration as flutter-preventing devices.

3.2 Analytical method

When the requirements for application of the empirical method are no longer taken for granted, or when the resulting measures are so strict that a more exact examination is worthwhile, flutter calculations must be carried out. When regarding the present day gliders, one must deal with approximately 10 to 16 degrees of freedom in the antisymmetrical case, and 9 to 15 degrees of freedom in the symmetrical one. The lower number applies to airplanes of the so-called standard class; the higher number is representative for open class and I5-m racing class gliders and is caused by the additional flaps. Basically, computations with all degrees of freedom are performed, but for the investigation of individual flutter cases their number is reduced to the essential ones.

Although the amount of CPU time spent is somewhat greater than when using the conventional V,g-method of flutter calculation, the p,k-iteration of (5) has withstood the test. This method also supplies approximate solutions apart from the critical speeds and thereby provides an estimate for the suddenness of flutter onset. Only solutions in the speed range of interest are determined. In general, it is no problem to trace the solutions. In consideration of the uncertainties of the calculation, beginning with the impreciseness of the input data, to the simplifications in the determination of unsteady airloads according to strip theory, to the supposition of linearity, the speed range should be adequately extended in the calculation. The computer results of the following examples were obtained with help of the p,k-method which was continuously improved concerning the aerodynamic modeling and the numerical accuracy and efficiency in past years.

4. Examples

The selected examples should serve two purposes: firstly, to compare the empirical and analytical investigation in a case where the conditions for the empirical approach are met; secondly, to correlate more recently encountered flutter incidents with corresponding flutter computations. These incidents, however, happened to airplanes which, strictly speaking, cannot be investigated by the empirical method. The flutter investigation of an unconventional glider in the early design stage is included as well.

4.1 Comparison of methods with a representative glider

The following comparison is based on a conventional hypothetical glider with a T-tail and without flaps, as shown in Figure 5. The most important data is summarized in Table 1 and Table 2. This data can be considered realistic. The wing torsional eigenfrequency is placed so high, that for the considered maximum free-of-flutter speed $V_D = 60\text{m/s}$, the conditions for the empirical method are fulfilled. First, the considerations and conclusions with the empirical procedure are described.

Bending/torsion flutter of the wing and the horizontal tail surface can be excluded in this case. It should be noted that it is supposed that the node line of the wing torsional mode is located at 45% of the chord and that the bending modes contain no torsional contributions.

The investigation of the ailerons proceeds from the assumption that the symmetrical aileron rotation due to flexibility of the controls can possibly couple with the first three symmetrical wing bending modes. Therefore, the ailerons have to be dynamically mass balanced with respect to these modes. The frequency distance can be taken into account.

In the antisymmetrical case the aileron rotation can couple

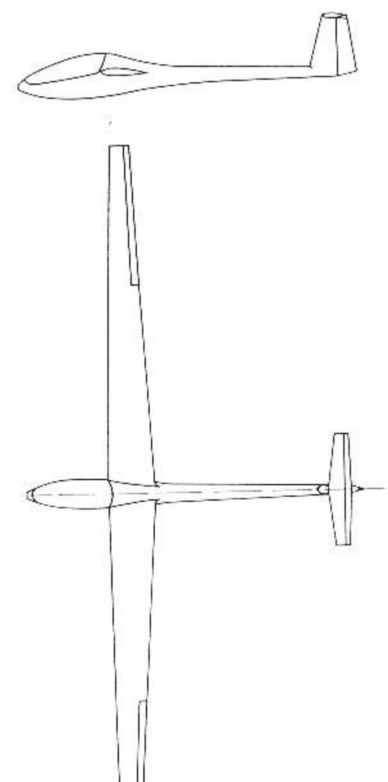

FIGURE 5. Representative glider.

Maximum free-of-flutter speed :		V_D	60.0 m/s
a) wing			
span	15.0 m	total mass	120.0 kg
root chord	1.0 m		
tip chord	0.4 m		
b) horizontal tail plane			
span	2.4 m	total mass	6.0 kg
root chord	0.5 m		
tip chord	0.3 m		
c) vertical tail plane			
height	1.2 m	total mass	6.0 kg
bottom chord	1.0 m		
top chord	0.5 m		
d) fuselage			
length	6.5 m	total mass	88.0 kg
width	0.6 m		
e) aileron			
span	3.0 m	mass	3.0 kg
between	4.5 m and 7.5 m	static mass moment	15.0 kgcm
chord ratio	25.0 %	mass moment of inertia	200.0 kgcm2
f) elevator			
chord ratio	30.0 %	mass	2.0 kg
		static mass moment	4.0 kgcm
		mass moment of inertia	50.0 kgcm2
g) rudder			
chord ratio	40.0 %	mass	2.0 kg
		static mass moment	20.0 kgcm
		mass moment of inertia	500.0 kgcm2

TABLE 1. General data of the representative glider.

Symmetric modes	Hz	Antisymmetric modes	Hz
1. wing bending	3.	1. wing bending	6.
2. wing bending	9.	2. wing bending	17.
3. wing bending	22.	3. wing bending	31.
1. wing torsion	35.	1. wing torsion	35.
fuselage bending	14.	wing/fuselage lead-lag	5.
stabilizer bending	28.	1. stabilizer rolling	8.
aileron/control	20.	2. stabilizer rolling	14.
elevator/control	30.	fin torsion	15.
elevator rotation	---	fuselage bending/torsion	20.
		aileron rotation	---
		rudder rotation	---

TABLE 2. Eigenfrequencies of the representative glider.

with the first two antisymmetrical wing bending modes. Full dynamic mass balancing respect to these modes is necessary. Actually, this requirement dictates the ultimate aileron mass balance, namely 75% of the static value at 53% of the aileron span.

With the horizontal tail surface a coupling possibility exists in the symmetrical case, between elevator rotation and fuselage bending, or the elevator/control mode and horizontal tail surface bending. The empirical method requires mass balancing, which amounts to 100% of the static value and could be installed beyond 50% of the span. A reduction according to (1) and (4) cannot be allowed.

Bending/torsion flutter of the vertical tail surface can be excluded, because the fin torsional eigenfrequency is located above the corresponding "design frequency".

According to the statistical data, the rudder rotation can couple with the wing/fuselage lead-lag mode and the first antisymmetrical wing bending, both containing vertical tail plane motion. Without allowing a reduction, a full static mass balance must be provided. It can be installed above 41% of the height of the rudder.

With respect to these conclusions of the empirical method, computations have been performed. In Figure 6 and Figure 7 the results before execution of the necessary actions are shown.

In the symmetrical case there is weak flutter starting at 57.5 m/s. The elevator/control mode and horizontal surface bending are mainly involved. This case, which is labeled A/1 in Figure 6, is located at the boundary of the speed range and the reduced frequency range as well. In practice, due to the presence of damping, the critical flutter speed would be higher and the reduced frequency would be lower.

In the antisymmetrical case, two damping losses appear (A/2 at 30 m/s and A/3 at 55 m/s), which are due to coupling of the wing/fuselage lead-lag mode, the first antisymmetrical wing bending mode, aileron and rudder rotation. More severe flutter occurs at 42 m/s with contributions of the first antisymmetrical wing bending mode and aileron rotation (A/4).

Now, the requirements stated by the empirical method are introduced into the computation. The results are shown in Figure 8 and Figure 9. Flutter is completely absent and the susceptible modes are well damped. Of course, on the basis of further computations one would come to the conclusion that less mass balancing would suffice, but even with the more accurate analytical method a safety margin must be observed.

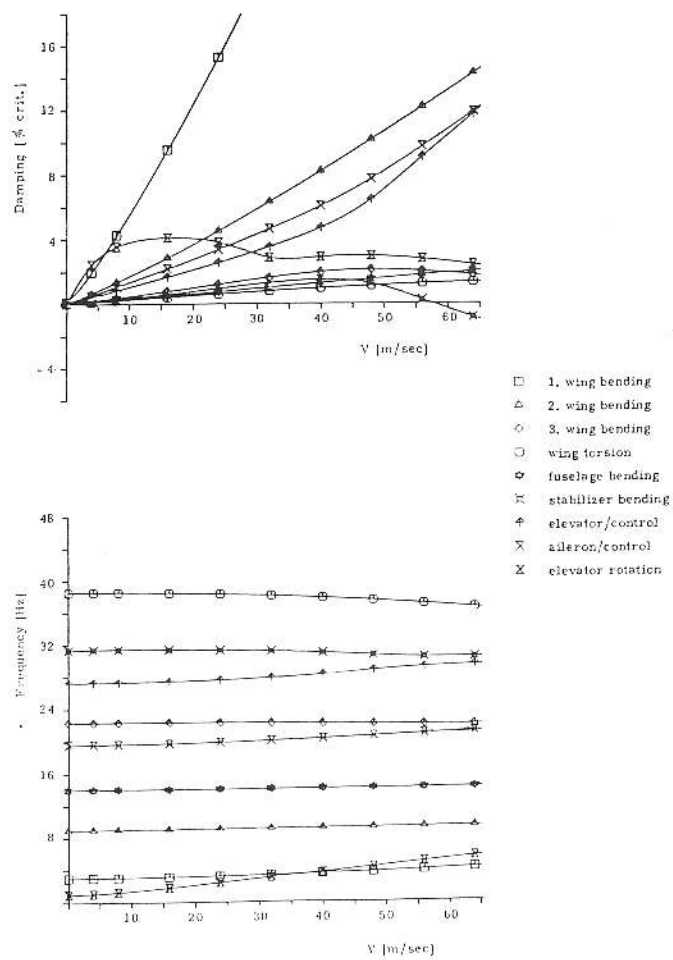

FIGURE 6. Symmetrical flutter calculation (original glider A).

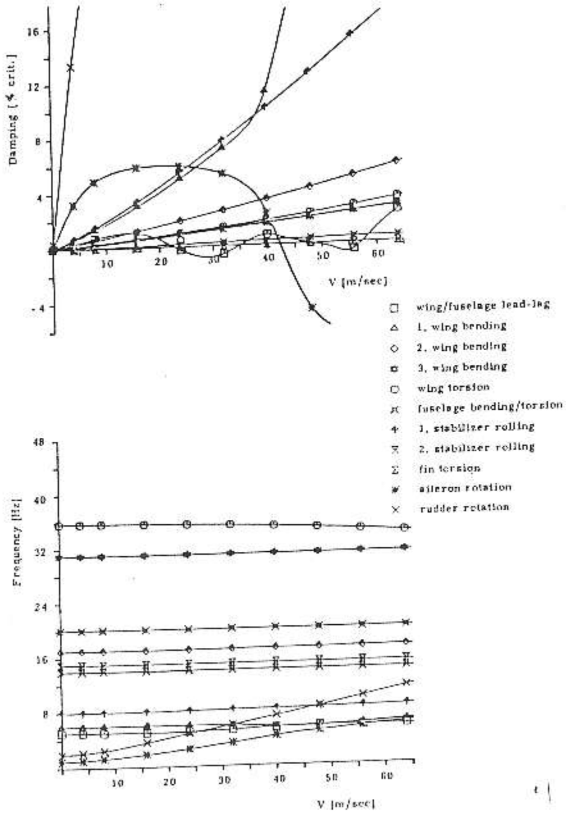

FIGURE 7. Antisymmetrical flutter calculation (original glider A).

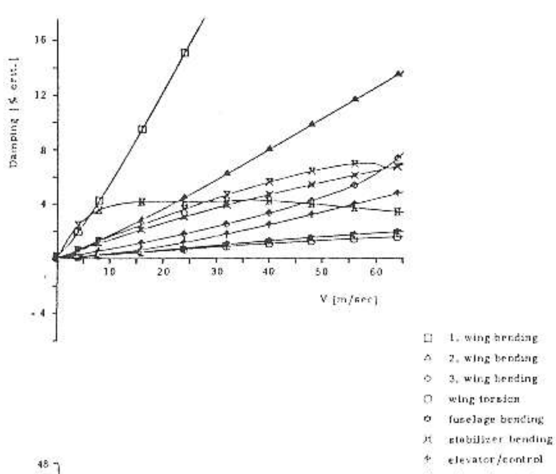

FIGURE 8. Symmetrical flutter calculation (corrected glider A).

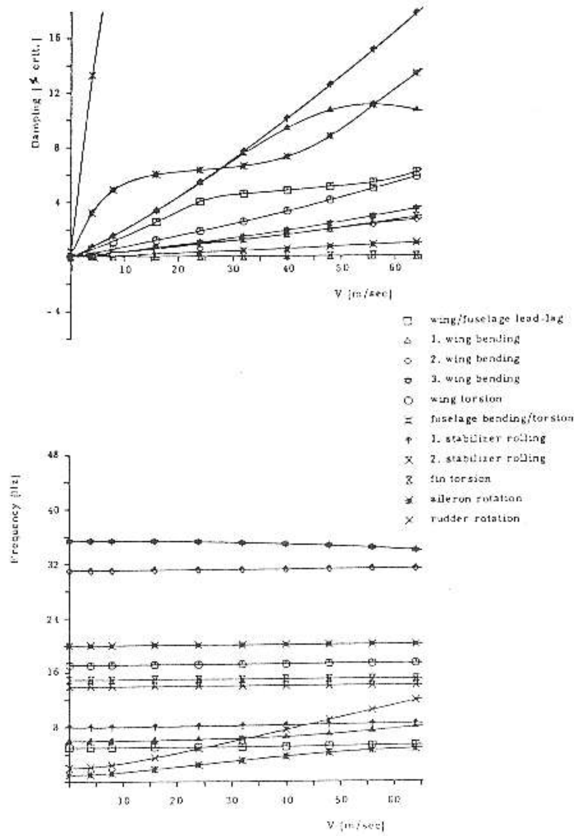

FIGURE 9. Antisymmetrical flutter calculation (corrected glider A).

4.2 Encountered flutter incidents

During flight tests of glider B, antisymmetrical flutter could be induced in a speed range between 50 and 60 m/s. On the aileron a concentrated mass balance had been installed in a near inboard position. The rudder was relatively heavy and not mass balanced. The results of the corresponding flutter computation are shown in Figure 10. Flutter starting at 40 m/s (B/1) was caused by the wrong location of the aileron mass balance inboard of the node line of the first antisymmetric bending mode, causing the mode to couple with aileron rotation. A corresponding correction and a reduction of the rudder mass result in freedom of flutter in the second case (B/2), also, in which the wing/fuselage lead-lag mode, aileron and rudder rotation are mainly involved.

In the symmetrical computation shown in Figure 11 an instability of the horizontal tail surface is evident (B/3), which is caused by coupling of the trim-spring restrained elevator rotation and fuselage bending. Horizontal tail surface bending is also involved. Flutter can be prevented by a concentrated mass balance near the elevator tip.

During flight tests of glider C, antisymmetrical flutter with a frequency of about 4 Hz were induced by trampling the lateral controls in a speed range between 39 m/s and 61 m/s. The damping curves of the flutter computations shown in Figure 12 are similar to those of glider B. C/1 represents loss of damping of the first antisymmetrical wing bending mode coupled with aileron rotation at 50 m/s. Again, the wing/fuselage lead-lag mode, aileron and rudder rotation are the ingredients of the encountered C/2 case, starting with 33 m/s. Flutter has been eliminated by adequate mass balancing of the ailerons and the rudder.

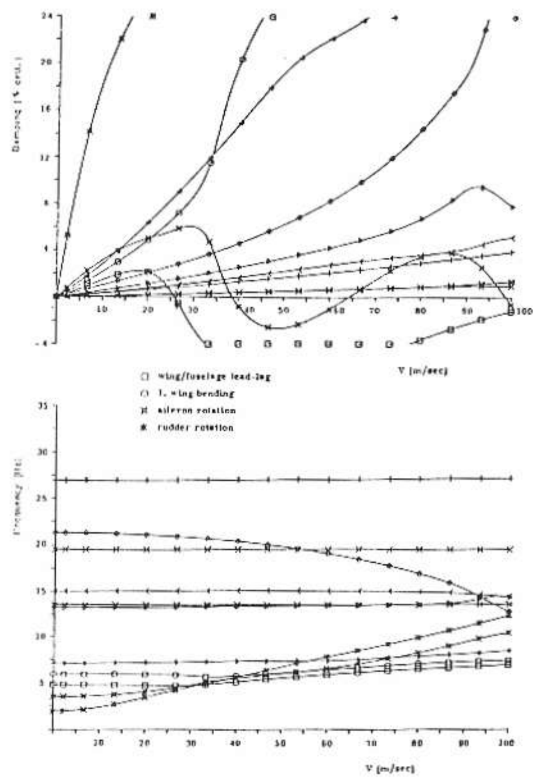

FIGURE 10. Antisymmetrical flutter calculation (glider B).

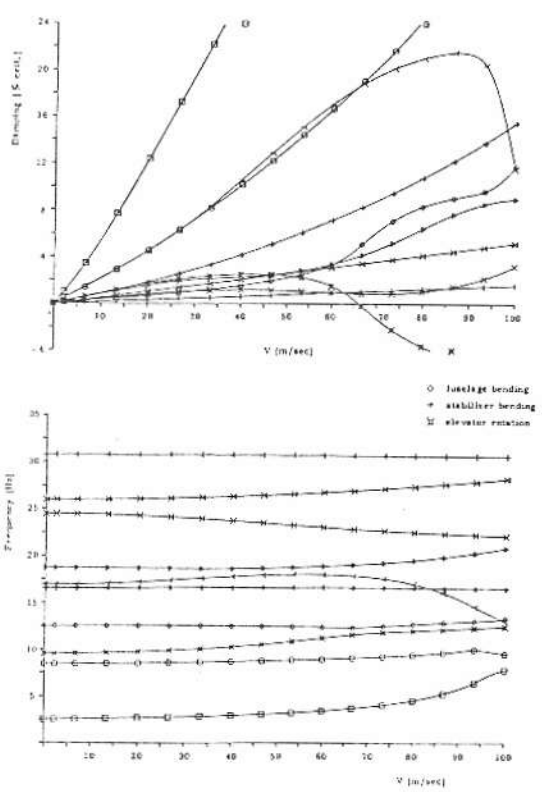

FIGURE 11. Symmetrical flutter calculation (glider B).

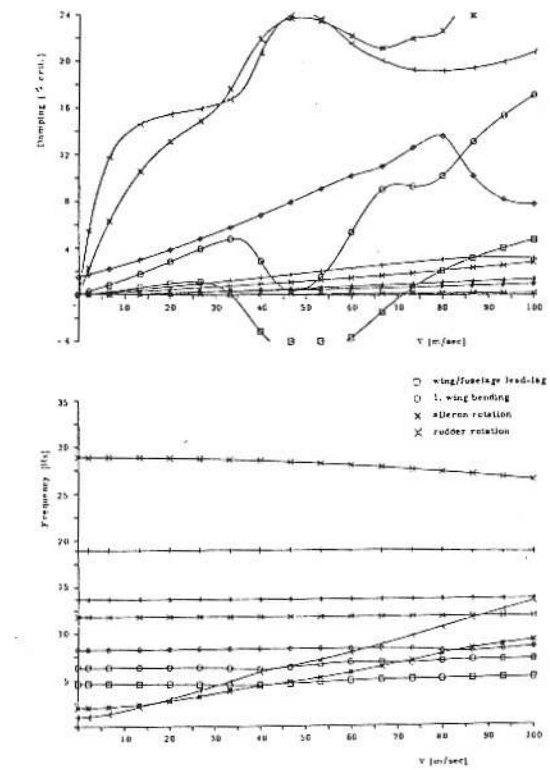

FIGURE 12. Antisymmetrical flutter calculation (glider C).

The flight tests of glider D revealed a sudden symmetrical flutter of the horizontal tail surface, the onset of which delayed apparently due to nonlinearities and occurred about 75 m/s. The computational results shown in Figure 13 confirm this case, labeled D/1. The main contributors are elevator rotation and symmetrical horizontal tail surface bending. This has been remedied by increasing the eigenfrequency of the latter mode and shifting the eigenfrequency of the elastic elevator/control mode above the "design frequency".

During flight tests of a 1/3 scaled remote-controlled model of the SB-13 tailless glider, onset of self-excited vibrations has been observed at 15 m/s with a frequency of 3 Hz. For investigation of the physical reasons of this instability a ground vibration test has been performed on the model to obtain the necessary input data for a flutter calculation. It turned out that the fundamental bending mode looks completely different than those of conventional designs, see Figure 14. A large amount of rigid pitch rotation can be observed. The flutter calculation showed an unstable motion due to coupling of the rigid-body pitching mode and the elastic mode mentioned above. The correlation with the flight observations was fairly good. The results of the flutter calculation on the preliminary design of the full-scale glider can be seen in Figure 15. Clearly the low critical speed of 34 m/s is not acceptable. H.J. Berns (6) investigated means to improve the flutter behavior including modern aeroelastic tailoring techniques. Figure 16 shows the final design with optimized sweep-back and a carbonfiber-reinforced spar. The corresponding flutter calculation in Figure 17 indicates a significant improvement in critical speed

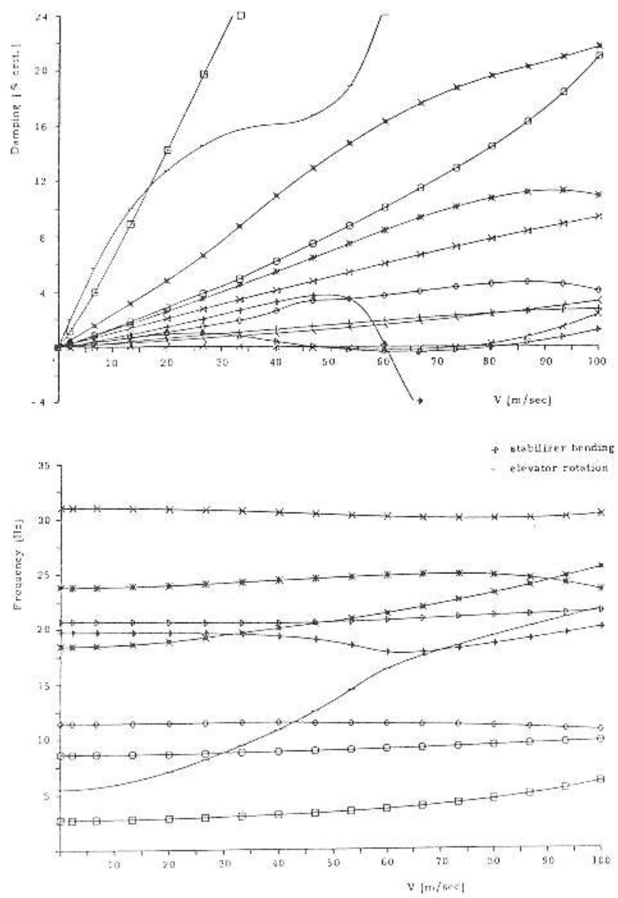

FIGURE 13. Symmetrical flutter calculation (glider D).

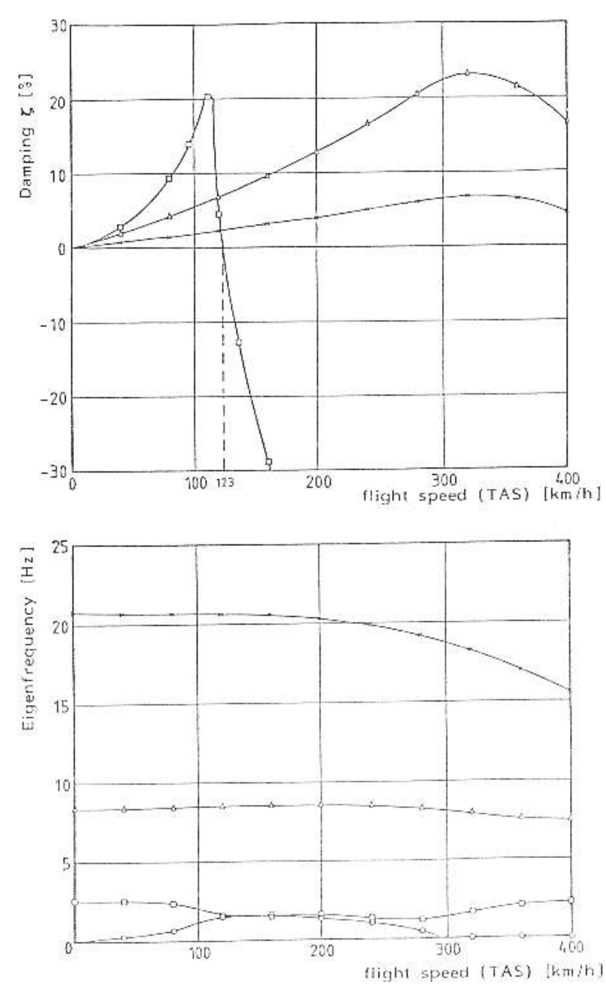

FIGURE 15. Flutter calculation of SB-13 preliminary design.

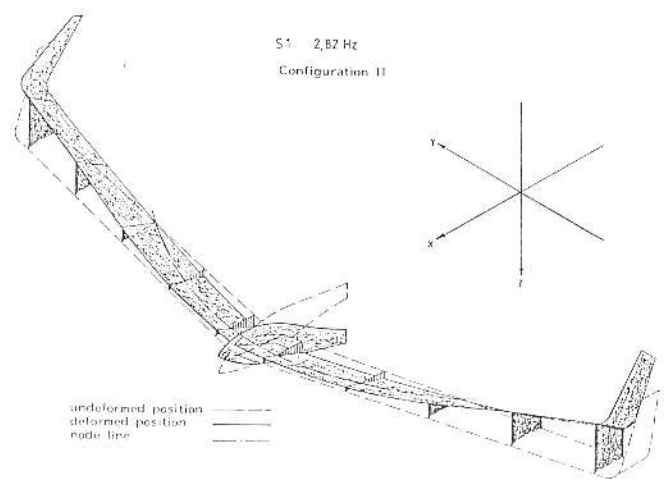

FIGURE 14. Fundamental bending mode of tailless SB-13 glider model.

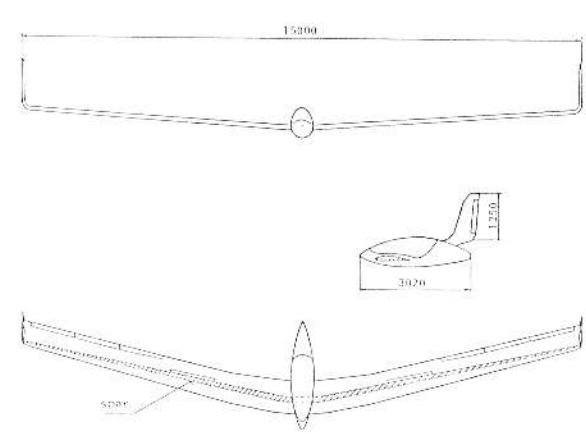

FIGURE 16. Tailless glider SB-13.

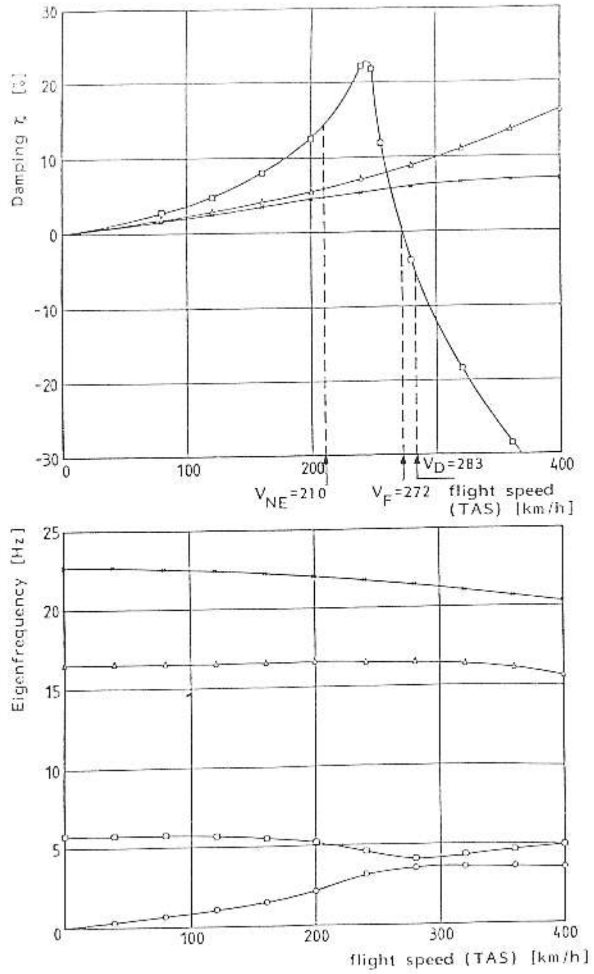

FIGURE 17. Flutter calculation of SB-13 final design.

mainly caused by the use of high-modulus fibers to increase the bending stiffness.

5. Conclusions

In the case of conventional gliders and light aircraft, flutter investigations can be simplified. From the results of a simplified ground vibration test, it can be determined whether an empirical estimation without flutter calculation is possible. In general, the measures to be taken according to this method consist of frequency shifting and mass balancing. The requirements are more severe than those obtained by flutter calculations. Therefore, it may be advantageous in certain cases to carry out an analytical investigation based on the test data. Nevertheless, if the conditions for the empirical approach are met, it can be considered an admissible procedure. It must be noted that even sophisticated flutter computations have their limitations of accuracy, for example due to the presence of nonlinearities.

The empirical estimation of flutter as well as design recommendations which emphasize aeroelastic effects, offer the designer markedly simple tools for flutter prevention. To broaden the scope of the empirical method, more flutter incidents and their remedies should be incorporated into the data collection. Corresponding flutter computations should be made to further check the validity of flutter investigation methods. Therefore, manufacturers and pilots of small airplanes should be encouraged to contribute observations of aeroelastic vibrations. Through attempting to thoroughly explain these observations, accuracy of flutter prediction will improve in the future.

6. Bibliography

(1) Stender, W. Praxisnahe Abschatzungs- und Vorbeugungsmoglichkeiten gegen die Flattergefahrdung von Segelflugzeugen und kleinen Motorflugzeugen DFVLR Interne Berichte (3 Vols.), Gottingen, 1974.

(2) Kussner, H. G. Augenblicklicher Entwicklungsstand der Frage des Flugelflatterns. Luftfahrtforschung, Vol. 12 (1935), pp 193-209.

(3) Schwarzmann, K. Flatterfalle und Flatterkonstruktionsvorschriften. Lilienthal-Gesellschaft fuer Luftfahrtforschung Report 135 (1941), pp. 3-11.

(4) Rosenbaum, R. Simplified Flutter Prevention Criteria for Personal Type Aircraft. Airframe and Equipment Engineering Report No. 45

(5) Hassig, H. J. An Approximate True Damping Solution of the Flutter Equation by Determinant Iteration . AIAA .1. Aircraft, Vol. 8, No. 11, November 1971, pp. 885-889

(6) Berns, H.J. Untersuchung des Flatterverhaltens eines ruckwarts gepfeilten NurflugelSegelflugzeugs unter Verwen(lung eines Strukturoptimierungsprogramms. DFVLR Interner Bericht, Gottingen, 1985.