Ground Resonance Testing of Sailplanes

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1. Introduction

Resonance testing performed on many types of aircraft proved to be very helpful for forecasting of flutter and its prevention. The results of prototype resonance tests permitted the forecasting of flutter by taking advantage of the large experience before flight testing. They also suggested the direction of future design modifications.

As long as the speeds of sailplanes remained relatively low, sailplane designers showed little interest in problems of aeroelasticity and flutter prevention. The continuous development of sailplanes posed new increased requirements concerning load factors and diving speeds. This concerns first of all performance and aerobatic sailplanes; the required diving speed is nowadays for the former about 200–250 km/h. and for the latter to above 300 km/h., in particular cases even to 500 km/h. As a consequence of simultaneous endeavours towards lighter and stronger structures the question of flutter became urgent. Within the last decade a number of sailplane accidents clearly indicated that failure was due to flutter.

As a result, the question of efficient flutter forecasting and critical speed calculations became important. Resonance testing can be very helpful in this respect as a good knowledge of natural frequencies and modes of vibration of the sailplane structure, simplifies and increases the precision of the flutter calculations.

No results of systematic normal mode measurement of sailplanes are available.

A team in the Flight Mechanics Departement of the Aeronautics Faculty, Warsaw, performed resonance tests on eight performance and training sailplanes, i.e. IS-1 Sep (Vulture), IS-2 Mucha-bis (Fly-bis), and SZD-12 Mucha 100 (Fly-100) of Polish design, Kranich, Gövier, Weihe, and Minimoa of German design and Z-129 of Czechoslovakian design. All were wooden structures with orthodox layout, with monospar wings with an auxiliary small oblique spar and plywood-covered nose box, with fittings at the main and oblique spar. The Weihe only had main spar and leading edge fittings.

The monocoque fuselages with almost elliptical cross section were plywood covered as well as the stabilizer surfaces. The controls were fabric covered. The wing spans were between 14.8 m. and 18 m. and the aspect ratio of the wings between 11.5 and 17.8. Kranich and Gövier were two-seaters, the remaining sailplanes were single-seaters.

The purpose of the tests was to collect sufficient data for calculation of critical flutter speed using the Lagrange method. Endeavours were made to generalize the obtained results, which would permit the estimation of the approximate frequencies and modes of vibration on the basis of rigidity, mass and geometric dimensions of the structure.

Moreover, the analysis of the results was expected to give some indication whether the results of resonance tests only, without flutter calculations, may give information on the danger of flutter. One of the sailplanes on which several cases of flutter occured was subjected to a special investigation. Tests were performed on that sailplane with three different amounts of aileron balance in order to find out the influence of aileron mass balance on the normal mode of vibration and on the critical flutter speed. In addition the substantiation of the usual supposition of the rigidity of the aileron was also investigated.

2. Program and method of measurement

For resonance tests the sailplane was suspended in a special rig under conditions as near to those in flight as possible (fig. 1). The vibrations were excited by a force pulsating sinusoidally at variable frequency, acting on the forward part of the body. The direction of the force was selected—depending on the mode of vibrations to be excited—either symmetric or antisymmetric.

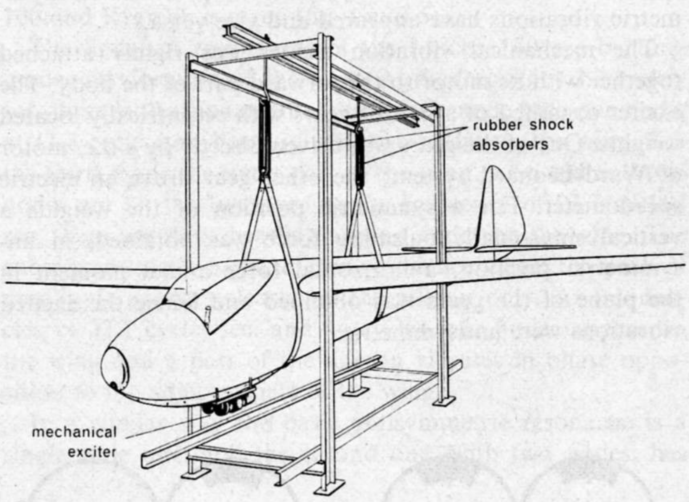


Fig. 1 Elastic suspension of sailplane for resonance testing

In order to define the resonance frequencies, measurements of the amplitudes of several characteristic points of the aircraft (for example of the wing tip, horizontal stablizer tip, nose, etc.) were performed at a variable frequency at every 0.8 cycle/sec. The investigation covered the frequency range of 0–50 cycles/sec. The results were plotted on the frequency amplitude diagram. In the vicinity of the frequency showing the maximum, more accurate measurements were carried out.

At each resonance frequency, i.e. a frequency at which the amplitude reached a maximum value, measurements of the displacement of the structure were carried out and plotted in the form of amplitude diagrams and nodal line graphs for individual parts of the sailplane.

2. 1. *Preparation of the sailplane for measurement*

Preparation of a sailplane for measurement consisted first of all in creation of conditions imitating a free flight with regard to mass distribution, position, and rigidity of suspension.

Sacks with sand were located in the cabin. Their weight together with that of the vibration exciter corresponded to the average weight of the pilot—75 kg. The plane was supported by two hemp belts on two frames, located before and behind the centre of gravity, and suspended on rubber shock absorbers. The longitudinal axis of the plane was inclined by approximately 5° to the horizon.

The natural frequency of suspension was approximately one cycle, i.e. approximately one third of the lowest sailplane resonance frequency. In this way conditions corresponding to vibrations of a freely suspended sailplane have been created.

The control stick was maintained in the neutral position by means of a soft rubber shock absorber fixed to the cabin.

2. 2. *Vibration excitation*

A sailplane as a system having a plane of symmetry has as a rule two types of normal modes of vibration—symmetric and antisymmetric. To excite symmetric vibration a vertical sinusoidal force was used, applied in the plane of symmetry. Antisymmetric vibrations were excited by means of a horizontal force perpendicular to the plane of symmetry, and a moment parallel to the longitudinal axis. While exciting with a vertical force not only symmetric but also antisymmetric vibrations have appeared and vice versa.

The mechanical vibration exciter was rigidly attached together with its motor to the forward part of the body. The exciter consisted of a pair of gears with eccentrically located weights. One of the gears was driven directly by a d.c. motor of Ward-Leonard system; the other gear drove an electric speedometer. For a symmetric position of the weights a vertical sinusoidally pulsating force was obtained, in unsymmetric position, a horizontal force and a moment in the plane of the gears was obtained and hence the excited vibrations were antisymmetric.

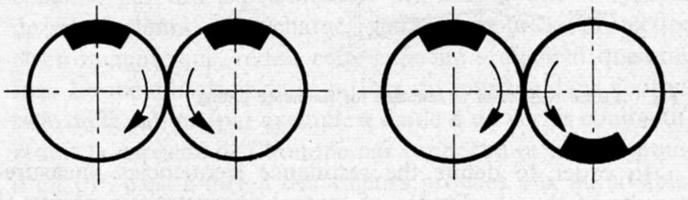


Fig. 1a, 1b Mechanical exciter

The excitation weights were selected in accordance with the number of revolutions, so as to provide a maximum vibration amplitude not exceeding 1 mm. Generally speaking the maximum amplitudes were even smaller and amounted to approximately 0.3–0.4 mm. In consequence, resonance testing neither destroyed the structure of the plane nor affected its strength and rigidity.

The weights were between 70 and 440 grammes on an arm of 33.5 mm.

2. 3. *Selected measuring points*

While dealing with symmetric modes of vibrations, vertical vibrations only were measured: on the wing at more than ten sections (on every other rib), in five points along the chord, at the end of the stabilizer spar and the horizontal control surface, and on at least seven frames of the fuselage. For determination of antisymmetric vibration modes, in addition to the above, horizontal vibrations were also measured: on the wing leading edge at every fourth rib, on several fuselage frames, on the stabilizer spar, and on the elevator. The torsion of the fuselage was determined by measuring the amplitudes of vertical vibrations on small blocks glued on both sides of the body.

2. 4. *Vibration measuring*

Measuring was performed by means of two electrodynamic vibration pick-ups combined with cathode-ray oscillographs. Impulses after amplification were transferred from each pick-up to the two oscillographs on which the amplitude was measured, and then, through an electron switch, to the third, acting as a double beam oscillograph, on which the phase was read. One of pick-ups, the so-called reference gauge, was permanently fixed to a chosen point of the sailplane, usually to the main spar. The other pick-up was transferred by the operator (held by hand) in turn to the selected measuring points. The phase displacement of the vibration was determined as either in phase or out of phase. The amplitudes of the pick-up were read on the oscillograph screen at constant amplification during one resonance frequency. As a rule, the absolute value of the amplitudes was not measured. Amplitudes obtained at various resonances and read at various amplifications cannot be compared with each other.

3. Results

3. 1. *Definitions*

As stated above, the results were given in form of diagrams of amplitudes and nodal lines. It is known that the nodal line of a system vibrating with a resonance frequency in the presence of slight damping is a zero-amplitude line which separates areas vibrating in opposite phases. Resonances with frequencies up to 20 cycles/sec. generally conform with that rule.

On the other hand, at higher resonance frequencies, rather considerable phase deviations often occured, probably owing to nonlinearity, alteration of the character of the damping and some other phenomena.

Instead of a nodal line a large band appeared where phases gradually passed from in phase to out of phase. In such cases the node was marked in points where the amplitude reached its minimum and the phase displacement amounted to 90°.

The excitation method applied did not provide the possibility of selecting a single required mode of vibration. Therefore it happened that near the investigated resonance frequency another one appeared; the measured mode was a sum of kinematic deviations corresponding to two excited modes of vibration. It resulted in addition a phase displacement of certain points, even of those located far from the nodes. A special case of that phenomenon was the simultaneous excitation of symmetric and antisymmetric modes, giving as a result an unsymmetric image of the vibrations.

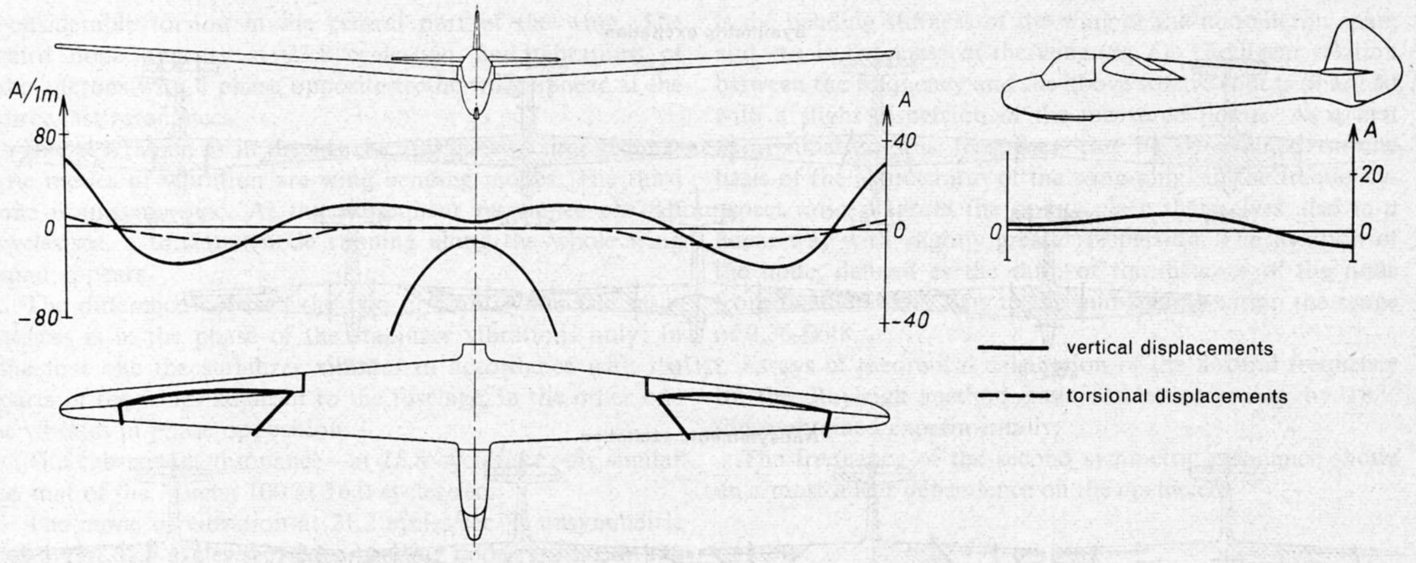


Fig. 2 Symmetric normal mode of Z-125 Sohaj sailplane–Frequency 17.5 cycles/sec.

Slight phase displacements were neglected. In case of large deviations, endeavours were made to check the suspected points by means of two pick-ups located near each other. However, in a few cases reliable and repeatable results were not obtained.

3. 2. Examples of the presentation of results

The figures 2 and 3 show a case of the symmetric mode of the sailplane Sohaj of 17.5 cycles/sec. and of the antisymmetric mode of the sailplane Mucha 100 at 16 cycles/sec. In the first case we have only a diagram of vertical vibration amplitudes along the spar, the fuselage, and the stabilizer, and of the torsional vibration amplitudes along the wing span. The scale of torsional vibrations is chosen as the difference of amplitudes in two points of the chord 1 m. apart. In the given example the torsion is very small, as it is a bending mode of the wing.

The tracing of nodal lines on the wing and the amplitude distribution along the chord are shown in the subsequent figure.

The diagrams were drawn with the centre of coordinate axes located in the centre of gravity of the glider. Positive directions of the axes X, Y, Z are directed forwards, to the right, downwards, and the positive rotations are clockwise.

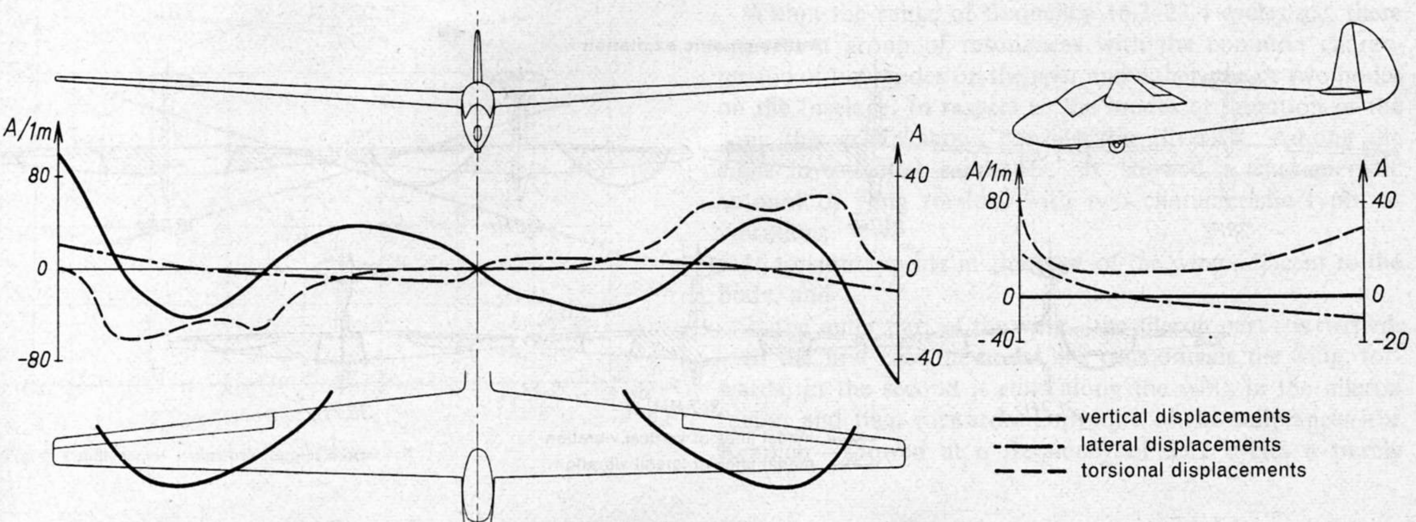
For antisymmetric modes, in addition to the vertical vibrations the distribution of amplitudes of lateral vibrations along the wing and the fuselage were also given, as well as the torsion of the fuselage.

For a better comparison of the individual resonances of each sailplane and of different sailplanes, diagrams were drawn where on the outline of the plane only nodes of vertical and horizontal vibrations were marked. As an example a comparison of modes of vibrations of the sailplanes Mucha 100 and Kranich is given (fig. 4 and 5).

The first two resonances of the Mucha 100 are bending modes of vibration of the wing. At the frequency 3.2 cycles/sec. there is the fundamental resonance mode with one node, at 11.3 cycles/sec. bending with two nodes on the wing. For the third mode the outer part of the wing is twisted and two nodes are on the fuselage. At the frequency of 23.7 cycles/sec. there are three bending torsion nodes on the wing. The subsequent mode is the aileron resonance where the peak of amplitude appears clearly on the aileron only. At frequencies of 37.1 cycles/sec. and 44 cycles four nodes appear on the wing and a part of the aileron vibrates in phase opposition to the adjacent part of the wing.

In a similar way the basic antisymmetric resonance is a single-node one, and the second one, with two nodes, has

Fig. 3 Antisymmetric normal mode of Mucha-100 sailplane–Frequency 16 cycles/sec.



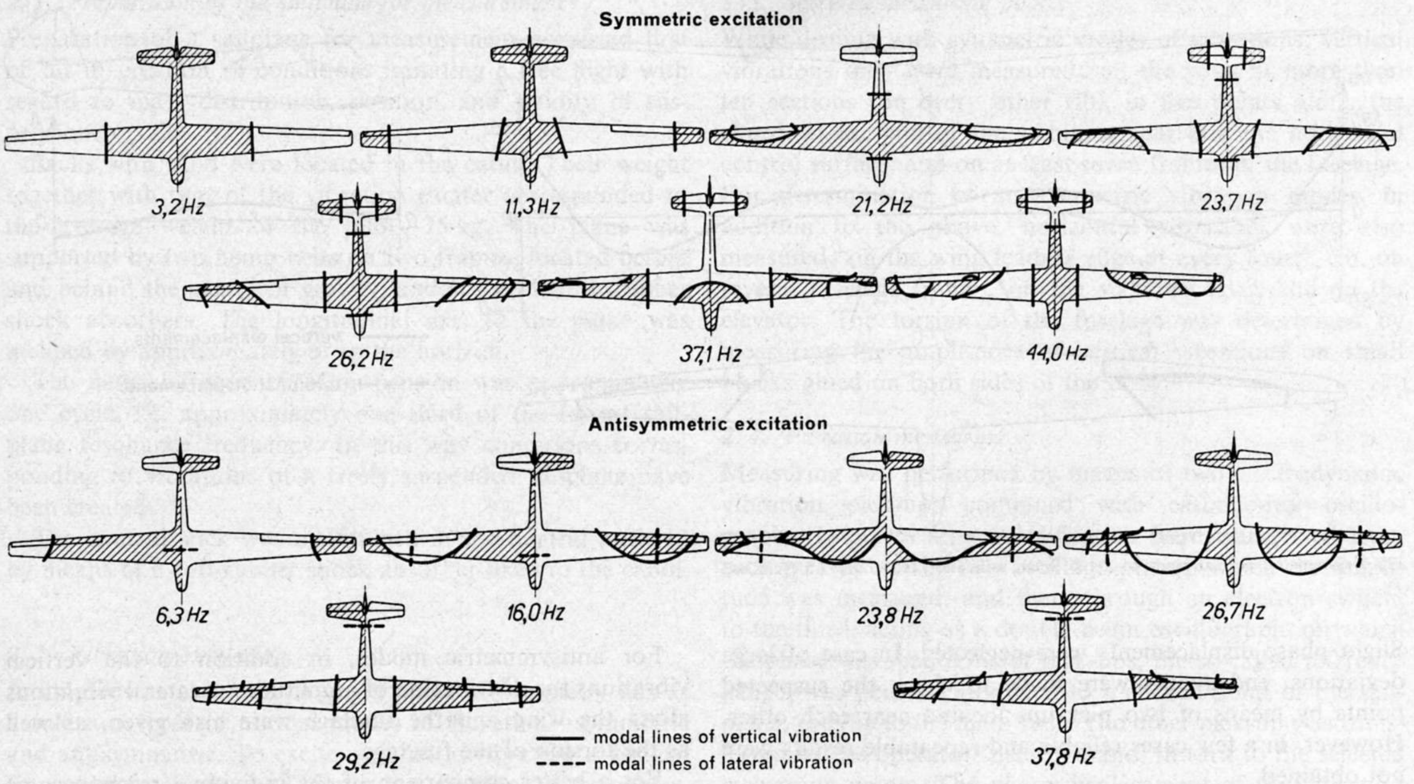
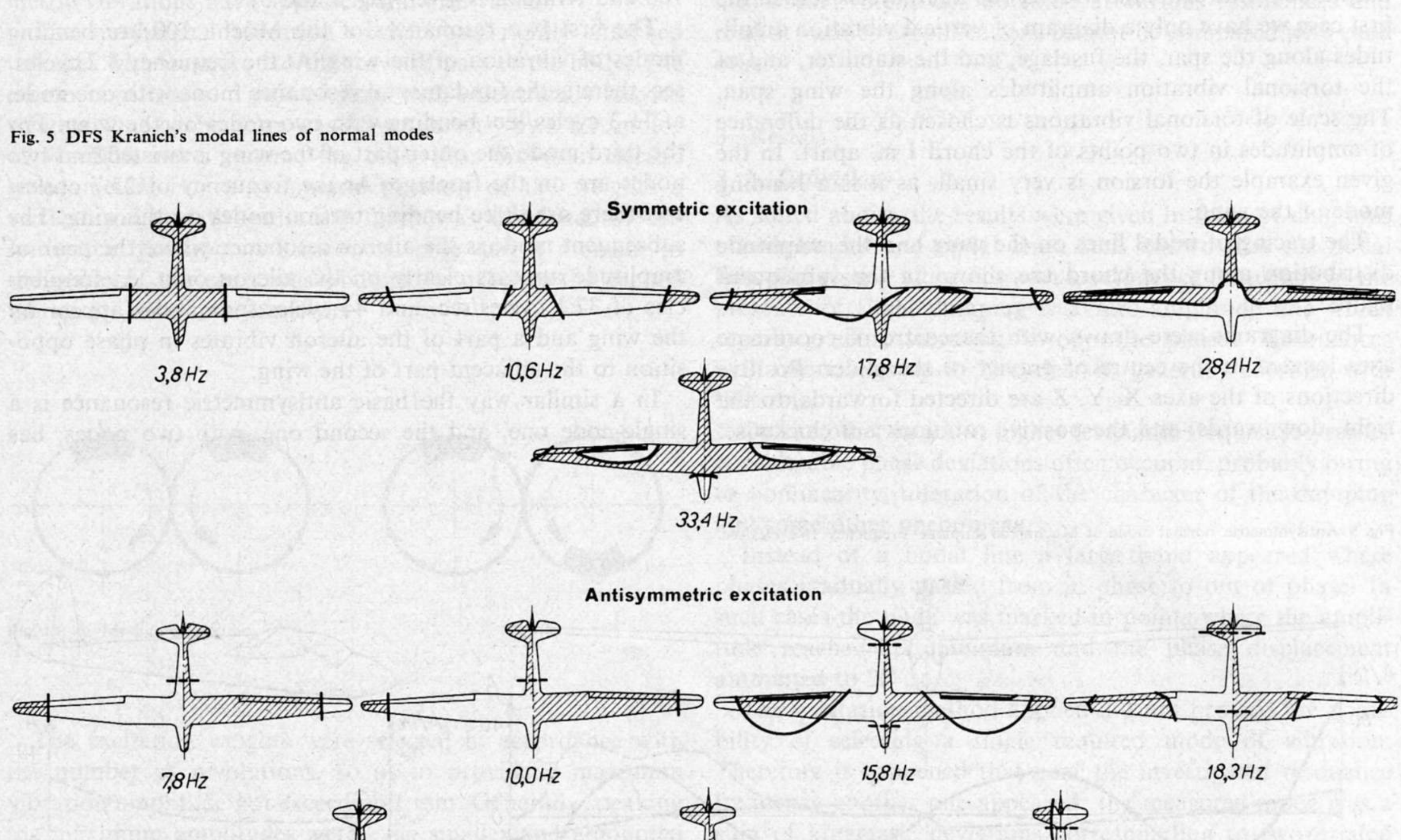


Fig. 4 Mucha-100's modal lines of normal modes

Fig. 5 DFS Kranich's modal lines of normal modes



considerable torsion in the central part of the wing. The third node appears at 23.8 cycles/sec. and vibrations of the ailerons with a phase opposite to the wing appear at the three last resonances.

In the Kranich as in the Mucha 100 the two first symmetric modes of vibration are wing bending modes. The third one is unsymmetric. At the subsequent resonance of 28.4 cycles/sec. a torsional node running along the whole wing span appears.

The difference between the two first antisymmetric resonances is in the phase of the stabilizer vibrations only: in the first one the stabilizer vibrates in accordance with the parts of the wings adjacent to the fuselage, in the other one it vibrates in phase opposition.

The subsequent resonance—at 15.8 cycles/sec.—is similar to that of the Mucha 100 at 16.0 cycles/sec.

The mode of vibration at 21.2 cycles/sec. is unsymmetric again. At 31.7 cycles/sec. three bending nodes appear on the wing.

3. 3. Attempts at generalization and analysis of the obtained results

The investigation of normal modes of vibration of eight sailplanes of various types provided the possibility of some generalization. Especially within the range of low frequencies on all the sailplanes analogous modes of vibration were obtained. Stiffness of sailplane measurements proved helpful in determining in conjunction with the known weights of the main components useful resonance frequency formulae.

At higher resonances it proved impossible to establish a direct connection between the frequency, the stiffness, and the mass of the system, the more so, that the modes of vibration of individual sailplanes differed very much between them.

The two first symmetric modes are most characteristic: the fundamental resonance with a single bending node on the wing; the frequency is within the range of 2.8–4.7 cycles/sec. The other one has two bending nodes on the wing and appears at frequencies of 8.3 up to 14.2 cycles/sec. At both modes the fuselage undergoes but small deformations and shows no nodes.

The frequency of the fundamental resonance is plotted in function of the coefficient

$$\sqrt{\frac{P_{fo,\,sbe}}{m_{sk}}} \quad \text{where } P_{fo,\,sbe}$$

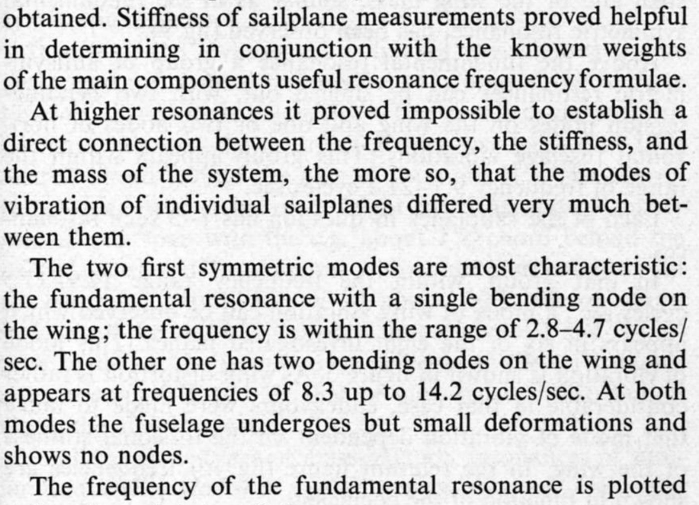


Fig. 6 Fundamental symmetric normal mode

is the bending stiffness of the wing at the mid-aileron span, and m_{sk} is the mass of the wing (fig. 6). The linear relation between the frequency and the above square root is obtained with a slight dispersion of the measured points. As a first approximation this frequency can be determined on the basis of the aspect ratio of the wing only. In the frequency-aspect ratio diagram the points place themselves also in a linear way with slightly greater dispersion. The location of the node, defined as the ratio of the distance of the node from the symmetry axis to the mid-span is within the range of 0.36–0.48.

Essays of theoretical calculation of the flexural frequency by the Rayleigh method gave results exceeding by 18% those obtained experimentally.

The frequency of the second symmetric resonance shows an almost linear dependence on the coefficient

$$\sqrt{\frac{Pf_{0.9}}{m_{sk}}}, \text{ where } Pf_{0.9}$$

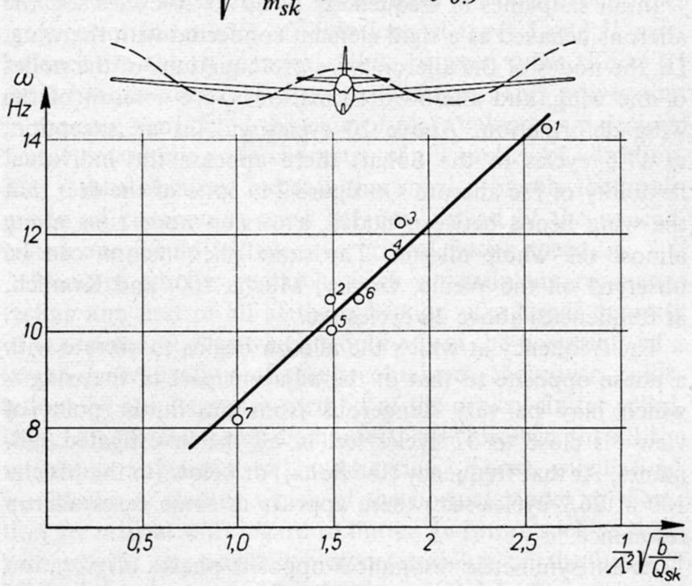


Fig. 7 Second symmetric bending normal mode

is the bending stiffness of the wing in section 0.9 $b/2$ (fig. 7).

We obtained the frequencies of the second resonance mode with similar accuracy in function of the coefficient

$$\frac{1}{\Omega 2}\sqrt{\frac{b}{Q_{sk}}} \quad \text{where } \Omega =$$

the aspect ratio of the wings, b = the span and Q_{sk} = the weight of the wings.

Within the range of frequency 16.3–23.4 cycles/sec. there appears a group of resonances with the common characteristic of two nodes on the spar and either one or two nodes on the fuselage. In respect to the modes of vibration of the wing this group shows considerable diversity. Among the eight investigated sailplanes, six showed a characteristic amount of wing torsion, with two characteristic types of vibration:

1. torsion appears in the part of the wing adjacent to the body, and
2. the outer part of the wing—the aileron part—is twisted.

In the first case the nodal line runs outside the wing, forwards, in the second it runs along the wing in the aileron region and then forwards. Only one of the sailplanes—the Kranich—showed at a frequency of 28.2 cycles a purely torsional mode of vibration, with a node running along the whole wing near the main spar.

Above the previously considered frequency of 23.4 cycles/sec. sailplanes with aspect ratio Ω equal to or greater than 15 have more than two torsion-bending nodes on the wing. The modes of vibration are either almost flexural (in the Minimoa, Mucha 100, Sohaj), or they show torsion as well as bending. Usually together with a change of the bending phase a change of torsion phase is also observed.

The sailplane Gövier with aspect ratio 11.5 even at a frequency of 32.3 cycles/sec. has on the spar only two nodes which give rather a considerable torsion.

Generally speaking, on sailplanes with aspect ratio less than 15 (Kranich and Gövier) torsion is strongly marked at several resonances.

The character of the torsion modes of vibration in sailplanes largely differs from those of aeroplanes. This matter needs further investigation.

In all sailplanes at frequencies of up to 20 cycles/sec. the ailerons behaved as a rigid element connected with the wing, i.e. the nodes of the aileron were prolongations of the nodes of the wing, and aileron deformations were a result of the wing deformation. Above 20 cycles/sec. (as an exception, at 17.5 cycles in the Sohaj) there appears the individual flexibility of the aileron. On figure 2 in spite of the fact that the wing bends between nodes, a torsion node runs along almost the whole aileron. The same phenomenon can be observed on the Weihe, Gövier, Mucha 100, and Kranich, at frequencies above 20 cycles/sec.

The frequency at which the aileron begins to vibrate with a phase opposite to that of the adjacent part of the wing—which may be very dangerous from the flutter point of view—is close to 37 cycles/sec. in all the investigated sailplanes. At that frequency (the Sohaj) or below (in the Mucha 100 at 26.2 cycles/sec.) there appears in some cases aileron resonance.

At antisymmetric resonances opposite phases of vibration of the aileron and of the wing either do not appear, or are

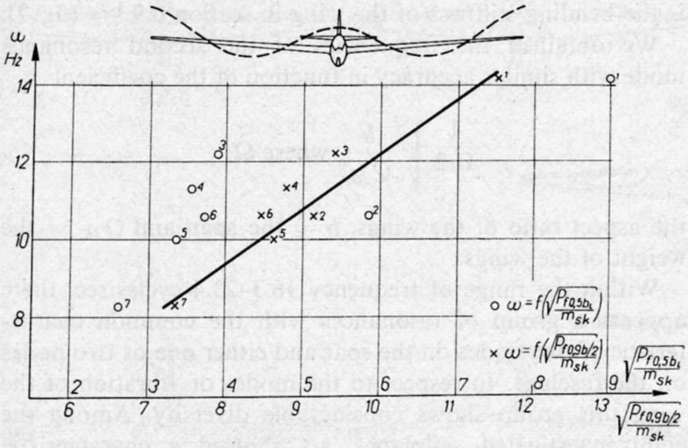


Fig. 8 Second symmetric bending normal mode

very slight. Only in the Mucha 100 that phenomenon was quite conspicuous at three resonances—26.7 cycles, 29.2 cycles, 37.8 cycles/sec.

The fundamental antisymmetric resonance with a single bending node on the wing and a single node of horizontal vibrations on the fuselage appears in the range of frequency 5–11.7 cycles/sec. Two types of that mode were excited: either the stabilizer vibrated in accordance with the part of the wing adjacent to the fuselage, or vice versa. Both types appeared in the Kranich only. The node of the fuselage appeared either in its fore and middle part, or in its rear part, and a direct connection between the bending stiffness of the fuselage and the frequency of the said mode of vibration could not be established. However, a certain relation

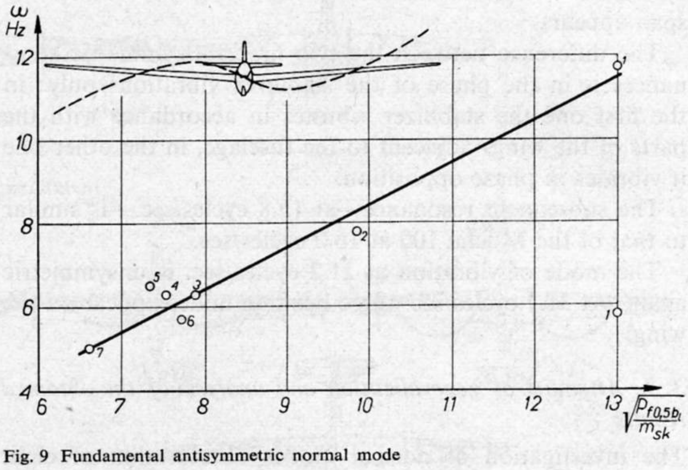


Fig. 9 Fundamental antisymmetric normal mode

of the frequency and of the bending stiffness at mid-aileron span and of the wing mass, similar as in the fundamental symmetric resonance, has been observed (fig. 9).

Above the fundamental resonance a group of antisymmetric resonances can be singled out, with two bending-torsion nodes on the wing and one or two nodes of horizontal fuselage vibrations. This group appears within the range of frequency 9.7–21.2 cycles/sec.

Each of the sailplanes in question has 1–3 such resonances.

In that group, within the frequency range 12.9–17.5 cycles/sec., a mode of wing vibration can be observed which appears in six of the eight investigated planes. This mode of vibration is shown in figure 3. As wing distortion is rather considerable in that case, endeavours were made to make that mode of vibration dependent on the torsional stiffness of the wing. In the relevant figure (fig. 10) frequencies are shown in function of the coefficient

$$\sqrt{\frac{m_{\varphi\, 0,9}}{m_{sk} \cdot \hat{C}^2}}$$

for various values of the coefficient

$$\sqrt{\frac{P_{f\, 0,9}}{m_{sk}}}$$

where m_{φ} 0.9 is the torsional stiffness of the wing in a section 0.9 semispan and $\hat{C}$ is the mean geometrical wing chord.

Generally speaking it should be observed that for antisymmetric modes of vibration the wing torsion is much stronger, it happens more often and it appears at lower frequencies than for symmetric ones. Also the flexibility of the aileron shown by modes with a nodal line along the aileron independently of the wing appeared at lower frequencies (Sohaj—16.7 cycles/sec., Weihe—17.5 cycles/sec.).

Considering the results of the ground resonance tests it should be underlined that as far as flutter calculations are

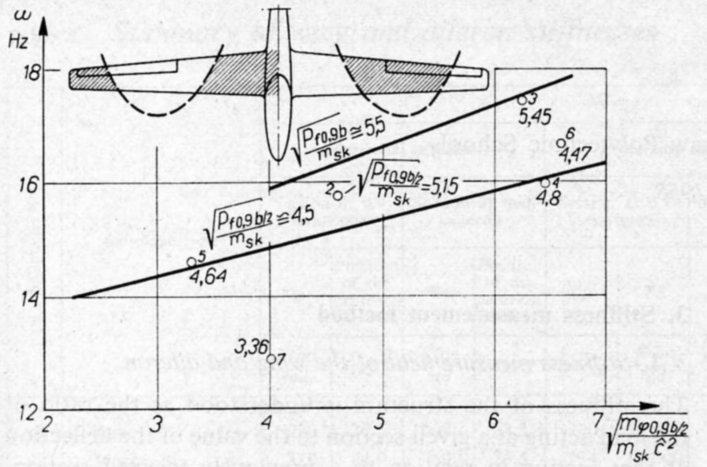


Fig. 10 Higher antisymmetric normal mode

concerned, the aileron cannot always be considered as a rigid element.

Above the value of 21.2 cycles/sec. all the investigated sailplanes had more than two torsion-bending nodes on the wing. Predominately torsional modes of vibration were also noted in that range (for example in the Weihe, the Minimoa). Horizontal vibrations of fuselage and wings were very diverse and no generalization could be established.

An interesting case is the sailplane Minimoa where strong fore–and–aft vibrations of the wing appeared at a single symmetric resonance.

In one of the investigated sailplanes measurements were performed of symmetric modes of vibration with three types of aileron mass balance. I.—The so-called ailerons with no mass balance—the centre of gravity was located at 10% aileron chord behind the axis of rotation. II.—The aileron is provided with a balance weight fitted at approximately mid-aileron span with the c.g. about 1% chord behind the axis of rotation. III.—Ailerons with continuous balance with the centre of gravity located at about 1.0% aileron chord in front of the axis of rotation. Comparison of I and II permits to define the influence of percentage aileron balance, comparison of II and III that of mass-balance distribution along the aileron span.

In all the three types of mass-balance, resonances of similar frequencies modes of vibration were obtained. Generally speaking it should be stated that differences between mass balance I and II were very slight, while those between II and III were rather considerable.

The two first bending resonance modes did not differ; small differences appeared only between the frequencies. The most essential differences were noted in the group of resonances within the frequency range 20–26.2 cycles/sec. Presumably that range of frequency plays an important part in wing-aileron flutter. For type I mass balance within the range of frequency 22.5–25.5 cycles/sec. three resonances were obtained. The last one, obtained at 25.5 cycles/sec., was an aileron resonance. Type II mass balance gave also three resonances, however, with a wider spacing between the resonance frequencies—21.2–26.2 cycles/sec. The last of those resonances was also an aileron resonance and the second one was slightly marked on the wing. Altogether with the continuous mass balance the aileron resonance disappears and only two resonances remain, even more distant from each other. Also within the range of higher frequencies the modes of vibrations of types I and II mass balance are almost identical, while between types II and III mass balance there are certain differences. This proves that in the case considered the kind of mass balance is a decisive factor determining the character of the modes of vibration. The results obtained indicate that most probably the application of continuous mass balance instead of the concentrated one would increase the critical flutter speed.

Plans of further research work on sailplane resonance testing aim first of all at the collection of a larger quantity of experimental data which would afford the possibility of a larger generalization of results obtained. Moreover, calculations by the Lagrange method of the critical flutter speed, using digital electronic computers, are foreseen for all the sailplanes subjected to investigation. Those calculations would aim at finding which of the normal modes of vibration are critical with regard to flutter. In future such analysis will provide the possibility of determining on the basis of resonance tests the danger of flutter and of dealing efficiently with it. More abundant experimental data as well as results of more calculations would provide a sounder basis for determining some stiffness criteria, or other means of flutter prediction, useful for sailplane designers.

List of sailplanes used for research work

Sailplane No.	Sailplane type	The wing span b (m)	Aspect ratio of the wing	Weight [1] Q (kg)
1	Gövier	14,8	11,5	400
2	DFS Kranich	18,0	14,3	460
3	IS-2 Mucha-bis	15,0	15,0	240
4	SZD-12 Mucha-100	15,0	15,0	256
5	Gö-3 Minimoa	17,0	15,2	300
6	Z-125 Sohaj	15,0	16,0	230
7	IS-1 Sep	17,5	17,8	350
8	DFS Weihe	18,0	17,8	300

[1] Weight of the investigated sailplane with ballast