# Problems of Structural Strength and Anti-Flutter Safety of High-Performance Gliders

*A short summary translation of the work by B. F. Ivanov, a research worker of the Kazan Aircraft Engineering Institute*

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*Introduction*

Flight performance of gliders has during recent years been greatly improved due to stricter requirements for design and construction.

Flight performance of gliders is characterized by two very important values—$L/D_{max}$ and $V_{sink\ min}$. The progress achieved during recent years as far as $V_{sink\ min}$ and $L/D_{max}$ are concerned can be clearly illustrated by the following comparison: best standard class gliders have $L/D_{max} = 40$, $V_{sink\ min} = 0.6$ m/sec, and open class gliders have $L/D_{max} = 45$–$46$ and $V_{sink\ min} = 0.5$ m/sec, while the best high performance glider A-9 designed by O. K. Antonov that was in production in the USSR before World War 2 had $L/D_{max} = 30$ and $V_{sink\ min} = 0.8$ m/sec.

Higher flight performances are attained not only through using special profiles and observing certain requirements such as providing smaller fuselage cross section (with the pilot in supine position), careful surface smoothing (polishing) and higher aspect ratios, but by selecting rational parameters and improving methods of calculations. More precise calculations result in creating structures that are better as to their weight and strength characteristics.

All these are significant in improving flight performance.

Employment of laminar wing structures and higher aspect ratios has a direct bearing on the problem of wing structural strength, which in turn essentially influences design methods.

To compare: KAI-19 has $b^2/S = 28.6$ kg/m² and A-9 has $b^2/S = 19.6$.

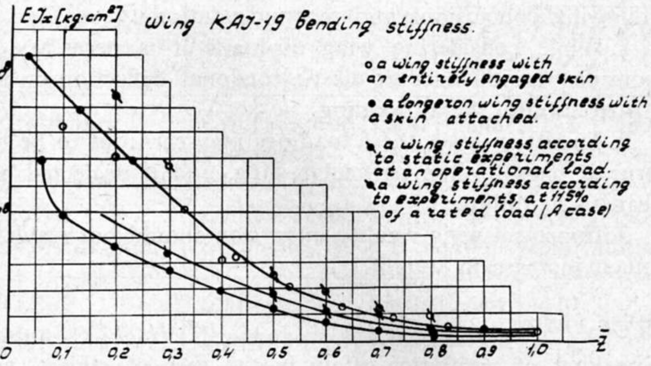


Fig. 1 – Bending stiffness of KAI-19 wing

At present gliding experts are engaged in heated dicussion as to what a high performance glider must be and what can be accepted as criteria for its performance. It transpires in the course of this discussion that:

1. $L/D_{max}$ and $V_{sink\ min}$ alone are by no means sufficient to characterize glider's flight performance.

2. A new criterion is being introduced for practical evaluation of flying performances—$V_{sink}$ at 150 km/per hour or at some higher cruising speed. Without discussing this criterion in detail let us point out its important features that have a direct bearing on the problem under consideration.

This criterion shows that operational cruising speeds have become considerably higher, and soaring flights at 150–200 km/per hour have become daily routine. Higher operational speeds directly affect certain aspects of aeroelasticity and flutter. This article touches upon three problems: static structural strength, aeroelasticity and flutter.

*Structure and Aeroelasticity of a high Performance Glider Wing*

All-metal wings of modern high-performance gliders are typically made on the basis of the following common structural and aeroelastic scheme: the main supporting element—a longitudinal beam called a spar—takes the major part of the bending moment affecting the root joint; a longitudinal rear web member with cut-outs for flaps, spoilers and ailerons ending with a rear wing-root joint; polished metal skin has no stringers, its transverse skeleton consisting of a set of pressed duraluminium ribs.

*Problems of Static Structural Strength*

A few words as to the calculation required for such a wing: we are of the opinion that the bending moment is resisted by the spar boom and by a section of skin 30 thicknesses wide, while the torque and shear force are taken by two rigid sheets. Thus we determine direct stresses in spar booms and tangential stresses in the skins.

During static tests of experimental models our attention was drawn to the following facts:

1. Stresses registered during the tests differed considerably from those calculated theoretically.

2. There were registered neither destruction at the weakest spot nor any loss of stability in the upper part of the spar.

3. Theoretically calculated stiffness values differed from those based on deformation measurements taken during the tests, with due regard to $I_{skin\ deprm}$.

4. Last by, the most important discovery was that the strength of the wing was 20–30 % higher and that of the tail 100–130 % higher than estimated.

To illustrate how essential these reserves are we can cite the following: with no reinforcement and having the same level of structural strength the KAI-19 wing can be used on the two-seater SA-7R, i. e. it can lift a second pilot. It should be noted that the estimated stresses in the upper part of the KAI-19 wing were relatively high. By using additional spanwise stiffeness we tried to make the overall and local loss of stability in different parts of the spar the same. Thus, the design compressive stress in the upper part of the spar was given the relatively high value of 3500–3700 kg/cm².

To study the problem in detail additional tests of KAI-19 wing were conducted. The wing was fixed to a supporting column with strain gauges glued to cross sections along the fifth, tenth and fifteenth ribs. Stresses in skins, spar boom and spar web as well as torsional and bending deformation were recorded during the tests. The wing was tested by applying torsional and bending loads and was broken under Case A loading. It failed along two cross sections simultaneously at 136% of the design KAI-19 loading.

The tests allowed certain preliminary conclusions to be drawn:

1. Increased strenght of wing and tail might well be explained by the fact that larger widths of skin develop lower stress than assumed. What arguments can be cited to support this view?

a. Our structures are characterized by very thin skins of 0.5, 0.6, 0.8 and more rarely of 1.0, and 1.2 mm, thickness. 1.5 mm-thick skins are used very seldom. The upper thickness limit of our skins is almost equal to the lower skin-thickness limit of aeroplane structures.

For aeroplane skins the limiting thickness is twice the critical thickness while in the case of glider structures it is appreciably higher at 5 to 10 times the critical thickness.

b. The wing having been tested to destruction, we conducted a longitudinal bending test of the spar boom. The recorded breaking stresses were in accord with those estimated, which leads one to think that the stresses in a real structure differ from the estimated ones.

2. The whole skin should be included when determining operational deformations.

For monospar wings the accepted modulus of torsional shear is $G = 2 \times 10^5$ kg/cm². Our tests, static as well as dynamic, showed that the modulus of torsional shear for our structures averaged to $G = 2.35 \times 10^5$ kg/cm².

These conclusions have a direct bearing on design.

*Problems of Aeroelasticity*

Problems of aeroelasticity are relatively new but none the less important when dealing with high aspect ratio wings. First of all, they bring about elucidation of elastic deformation influence on aerodynamics, structural strength and air loads. In our practice the problem first came up during flight tests of KAI-19 high-performance glider in the summer of 1963 when we discovered appreciable wing-twisting near maximum speed.

Leaving aside the influence of elastic wing-twisting on stability, let us dwell on problems of structural strength. Wing-twisting essentially affects the distribution of air loads. Fig. 2 presents curves for elastic and rigid wings. Due to the large angle of torsion at the wing-tip, the outer sections start operating at negative $C_L$. To maintain the overall aerodynamic lift the wing root sections have to operate at increased $C_L$.

Such redistribution of air loads due to wing-twisting basically changes the picture of wing-loading determined under the assumption that there is only negligible de-

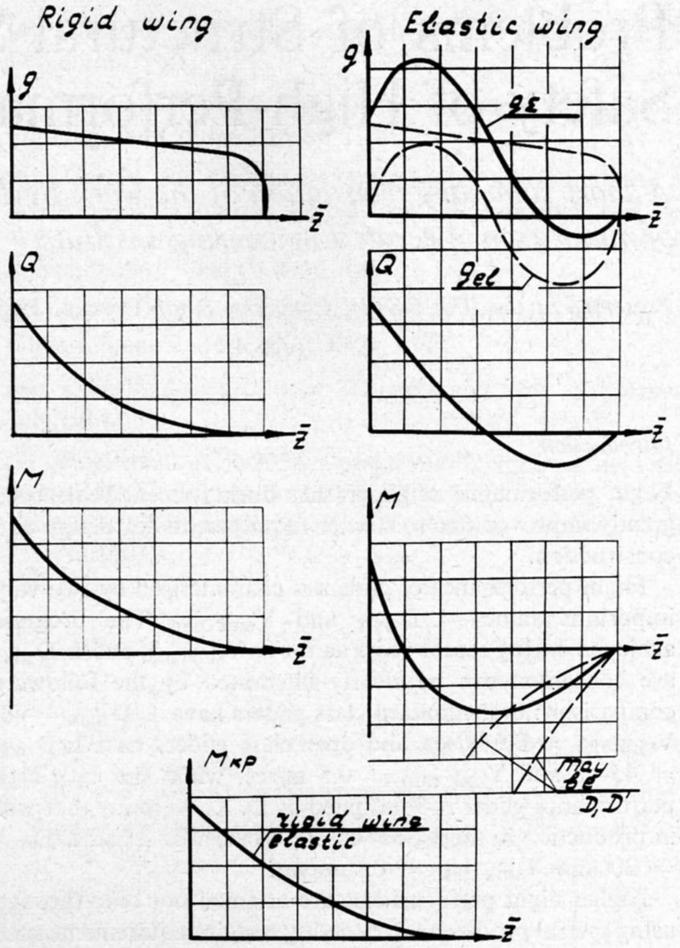


Fig. 2 – Spanwise load distribution.
$\bar{Z}$ = spanwise stat., g = load per m², Q = shear force, M = bending moment

formation. In the example of Fig. 2 change in the sign of the air-load at the wingtip results in shifting peak bending moment from the root to the middle of the wing and changing the sign of the moment. The value of the bending moment with the opposite sign may turn out to be comparable with those for cases D and D[1] and can be critical for some cross sections. The torques of the elastic and rigid wings are practically equal.

Fig. 3 presents the results of calculations for air-load affecting a KAI-19 wing with due regard to torsional deflection at $V_{max}$. These data permit one to come to the following conclusions and recommendations:

1. While considering wing air-loads it is necessary to consider the influence of elastic torsional deflection on the distribution of the air-loading.

2. In certain cases these loadings may turn out to be the critical ones for the particular wing, and if neglected can lead to its failure.

3. Improved wing rigidity in torsion should not result in much increase in weight.

*Wing Flutter*

Speaking of antiflutter safety in the case of gliders, two points should be noted which have a direct bearing on the problem in question:

1. Operational flight speeds have become considerably higher. Flights at 150–200 km/per hour cruising speeds have become a daily routine.

2. As wing calculations have become much more precise and structures are based on high aspect ratios, bending and

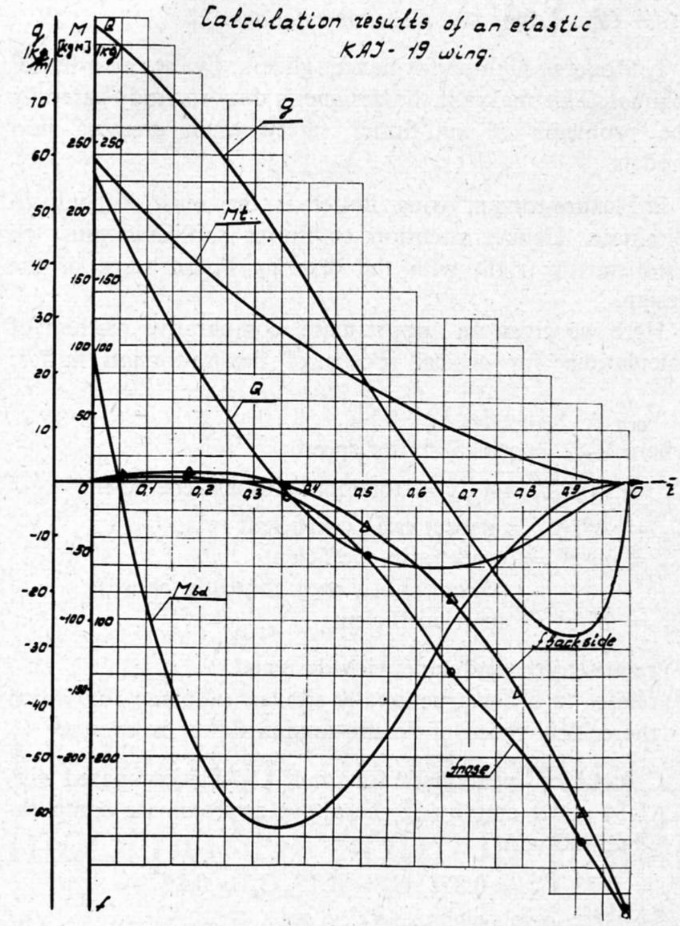


Fig. 3 – Load distribution on KAI-19 wing.
Mt = torsional moment, Mbd = bending moment

torsional rigidity of a wing have decreased. Thus we see that pre-war gliders had no flutter because their structures were over-strong and stiff and thus had greater speed reserves.

To illustrate the above we made flutter calculations for three gliders. The results of these calculations are presented in Table 1, which gives the critical speed of flexure-torsion wing flutter based on different calculating methods:

*Table 1*

| *Theory* | | *Glider* | | |
|---|---|---|---|---|
| | | *KAI-14* | *KAI-19* | *A-9* |
| Stationary | Critical speed km/h<br>Frequency c.p.m. | 248<br>2380 | 141<br>1648 | 320 |
| Soviet Non-stationary | Critical speed km/h<br>Frequency c.p.m. | 551<br>1440 | 354<br>1390 | No flutter |
| U.S. Non-stationary | Critical speed km/h<br>Frequency c.p.m. | 540<br>1160 | 440 | |
| Design maximum speed<br>Flight demonstrated speed | km/h<br>km/h | 250<br>310 | 250<br>250 | 200<br>200 |

Generally speaking, improvement of calculation methods of critical speeds is carried out in two ways:

1. Improvement of methods for calculating frequency and modes of natural vibration.

2. Determination of aerodynamic forces and moments affecting a vibrating wing.

Fig. 4 and 5 show the calculated frequencies and modes of natural wing vibration and those measured during the tests. The difference in values of calculated and measured critical speeds of flutter is negligible. It follows that improvement in the critical speeds of flutter is connected with more precise determination of the aerodynamics of a vibrating wing.

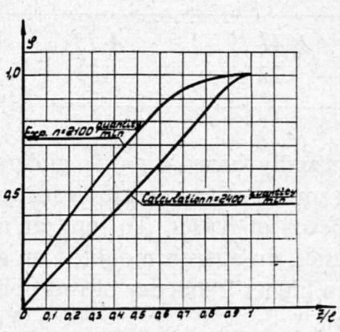


Fig. 5

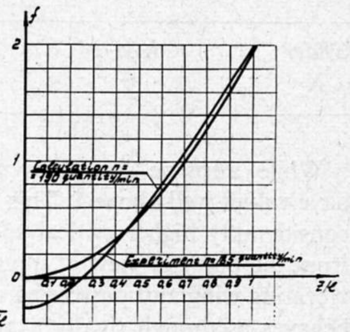


Fig. 4

Frequencies and modes of wing vibration

The accepted calculation methods are based on a stationary hypothesis which asserts that unsteady flow around a vibrating wing all the time interchanges with a steady one characterized by linear velocity $V_{linear}$ and angular velocity $\omega$. With this assumption aerodynamic forces and moments affecting a vibrating wing are relatively easy to calculate.

As shown by non-stationary theories, the stationary hypothesis leads to essential errors in determining a damping moment under torsional wing vibrations; the higher the wing aspect ratio, the greater the error becomes. Hence, critical speeds calculated on the basis of the stationary theory prove to be underestimated.

The table presents critical speed values calculated on the basis of two different non-stationary theories. According to the Soviet non-stationary theory KAI-14 must have $V_{crit.}$= 551 km/per hour and KAI-19 = 354 km/per hour, while the method suggested by Messrs. Bisplinghoff, Ashley and Halfman sets these values as KAI-14 = 540 km/per hour, KAI-19 = 440 km/per hour.

### *Rudder and Ailerons Flutter*

Practical safeguard from rudder and ailerons flutter lies in precise dynamic balancing of both rudder and ailerons.

We ran into great difficulties trying to instal a mass balance into the KAI-14 wing. The balance would not fit inside and could not be placed in the outside air-flow. A hydraulic vibration damper also proved to be difficult to fit inside and its weight was equal to that of a mass balance distributed spanwise over the aileron. In the end, we chose the mass balance, the weight of which was equal to the weight of the aileron.

Much calculation was done before we dared remove the mass balances from the ailerons. Theoretically determined frequencies and modes of flutter were used to calculate critical speeds of wing-aileron flutter corresponding to the first three modes of wing symmetric bending and the first two modes of antisymmetric bending. At the same time we calculated the flutter taking account also of wing torsion. All modes, except that for the fundamental symmetric bending, produced imaginary speed values, i. e. no flutter was possible.

Fig. 6 presents the results of calculations for wing-aileron flutter (taking account of bending only) corresponding to the fundamental mode for the KAI-14, KAI-19 and A-15 gliders. Table 2 gives values of X for these air-craft, where

$$X = \frac{\text{frequency of aileron symmetric rotation}}{\text{frequency of the fundamental symmetric bending vibrations}}$$

*Table 2*

| *Glider* | *KAI-14* | *KAI-19* | *A-15* |
|---|---|---|---|
| X | 6 | 23 | 13 |

While airplane structures usually have $X \doteq 1$, gliders have values well above 1. This spread of frequencies leads to considerably higher critical speeds of flutter. To look at it from the point of view of physics, an aileron mounted on a vibrating wing and possessing a higher frequency of rotation behaves as though rigidly fixed.

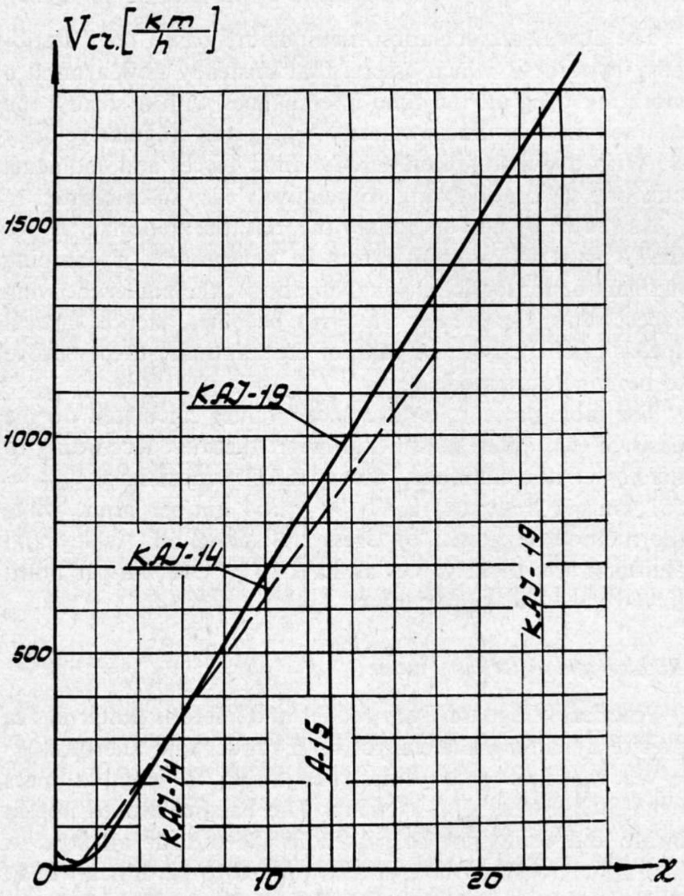


Fig. 6 – Critical speeds of wing-aileron flutter

The spread of frequencies widens with increase of control run inertia. The X value for the KAI-14 is much lower than those for the KAI-19 and A-15. This is one of the results of employment of cable control run on KAI-14 model.

We can refer to a test with an A-15 model carried out by O. K. Antonov. Its first experimental model had ailerons balanced with masses put outside in the airflow. Later the A-15 was equipped with hydraulic frequency dampers. Flight tests with the damper and without it and mass balances registered no flutter within the design speed limits.

*Main Conclusions and Recommendations*

1. Modern high-performance gliders fly at near-flutter regimes. This makes it the designer's duty to study carefully the problems of anti-flutter safety when creating new models.

2. Flexure-torsion wing flutter is the most difficult to eliminate. Hence, attention to flutter problems must be paid starting right with the drawing board stage of the design.

Here we given an approximate, comparative method of calculations for critical speeds of flexure-torsion flutter:

$$V^{1}_{crit} = V^{0}_{crit} \cdot C_1\, C_2\, C_3\, C_4$$

where $V_{crit}$ = critical flutter speed

$C_1 = \sqrt{GI^{1}_{crit} / GI^{0}_{crit}}$ = torsional stiffness coefficient

$C_2 = A^0/A^1$ = aspect ratio coefficient

$C_3 = \eta^1/\eta^0$ = taper ratio coefficient (taper ratio is root chord/tip chord)

$C_4 = b^0/b^1$ = span coefficient

(1) relates to the sailplane wing designed.

(2) relates to a constructionally similar sailplane for which the critical speed of flexure-torsion flutter is known.

Calculations were made for the KAI-19 as compared with KAI-14 glider employing the above approximate comparative method with

$C_1 = 0.73$, $C_2 = 0.875$, $C_3 = 1.15$, $C_4 = 0.89$

$V^{KAI\text{-}19}_{crit} = 0.73 \cdot 0.875 \cdot 1.15 \cdot 0.89$

$V^{KAI\text{-}19}_{crit} = 0.653 \cdot V^{KAI\text{-}14}_{crit} = 360$ km/per hour

More precise formulas give the critical speed of flexure-torsion flutter for the KAI-19 glider at 354 km/h. The good agreement between the two results can be explained by the succession of types having constructional similarity.

3. Calculations of critical speeds for bending and torsional flutter made on the basis of non-stationary theories produce results that are more precise, though the limit of precision has not as yet been evaluated.

To determine the true speed margin a flight test of the aircraft or wind-tunnel test of a dynamic scale model is essential.

4. Calculations and tests prove the necessity of rudder balancing. Much calculation and a test are required before eliminating rudder mass balances.

5. Practical and theoretical experience lead to the conclusion that ailerons can be left unbalanced. In order to take this decision as far as some specific model is concerned, its critical speeds must be calculated and the results compared with those registered on operational models.

6. Rigid aileron control runs are helpful in eliminating flexure-torsion flutter.

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