Sailplane Loads in Aero-Tow under Turbulent Conditions

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1. Introduction

The present theory and practice of calculating loads acting on a sailplane being towed in turbulent air, is based on the arbitrary assumption that the maximum loads in aero-tow differ from the respective values for the free flight only in the initial static load resulting from the tow rope.

The subject of the paper is an analysis of the influence of sailplane and aero-tow parameters (including the parameters of aircraft and tow rope) on both the time history and maximum values of sailplane loads in aero-tow under turbulent conditions. Special attention has been paid to the possibility of the occurrence of loads exceeding those appearing in free flight. A comprehensive discussion of the problem including mathematical models was presented in Prace Instytutu Lotnictwa (ref. 1).

2. Method of analysis

The loads acting on a sailplane are determined on the base of the discrete-gust approach. Considering the gusts of maximum intensity encountered in actual sailplane flight the analysis is concentrated in principle on lee-wave gusts. The assumed intensity is no less than 10 m/s the air velocity distribution obeying the following formula:

$$w_g = w_o \cdot \sin \omega t$$

The lowest value of gust wavelength has been determined as 60 m on the basis of existing measurement results (ref. 2).

The upper limit of gust wavelength has been found following the assumption that the pilot does not intervene so as to modify the time history of the load increase; then the increase to the load maximum should not take more than 2.0 seconds.

The gust wavelength is inherently connected with the problem of unsteady flow. The Strouhal number for the assumed range of gust wavelength is less than 0,8, so the calculation of the sailplane aerodynamic coefficients can be based on the assumption of a quasi-steady flow.

As to the aero-tow parameters the basic assumptions are:

- constant horizontal airspeed of both the towing aircraft and sailplane
- no influence of the sailplane on the towing aircraft flight path (trajectory), the latter being disturbed by gusts only.

The towing aircraft parameters were not subjected to any initial limitations; a Wilga 2 C was taken as an example of a lightweight towing aircraft, whose response to vertical displacement caused by gust was controlled by changing the static margin.

Essential towing parameters are the tow rope features, in particular, its length and elasticity.

For many years 40 m tow ropes have been used by Polish pilots; however the experience gained in flights under lee-wave conditions is favourable for shorter ropes, even down to a length of 20 m.

In this connection the tow rope length is limited to 40 and 20 m in this paper. The remaining parameters of tow ropes, in particular their stretch factors, were measured in ropes currently in use.

Before proceeding to an analysis of loads in aero-tow some fundamental properties have been examined on a sample sailplane Zefir-2, pertaining to the time history and maximum values of normal acceleration z'' acting on the sailplane in free flight across a lee-wave gust, the mentioned properties being considered basic data for further comparisons and conclusions.

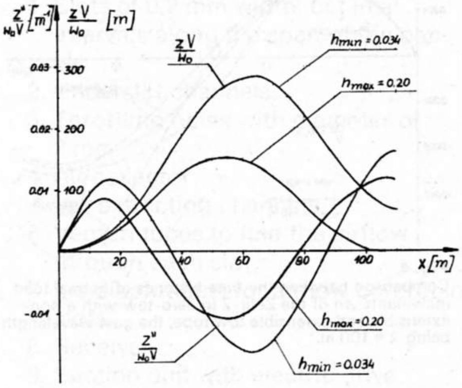

Fig. 1.
Time history of normal acceleration z'' and vertical displacement z of Zefir-2 in free flight; gust wavelength $\lambda = 100$ m.

In addition, the time history of the sailplane vertical displacement z with respect to the towing aircraft have been calculated. Some examples of calculation results are shown in Fig. 1.

Technical data of Zefir-2:
Flying weight $W = 375$ kgs
Moment of inertia $B = 75$ kgms^2
Wing area $S = 14$ sq.m
Mean aerodynamic chord $c = 0.87$ m
Reference length $l = 0.435$ m
Elevator unit area $S_t = 1.5$ sq.m
Tail arm (distance from C.G.) $l_t = 4.1$ m
Tow hook distance from C.G. $l_x = 2.05$ m
Static margins
max $h_{max} = 0.20$
min $h_{min} = 0.034$

$$\frac{dC_L}{d\alpha} = a = 5.53 \qquad \frac{dC_{Lt}}{d\alpha} = a_1 = 3.5$$

$$\mu = \frac{W}{g \cdot \varrho \cdot S \cdot l} = 50.2 \qquad i_B = \frac{B}{\varrho s l^3} = 520$$

The analysis of loads indicates that for a sailplane of conventional design, in case of a gust having the sinusoidal velocity distribution, the absolute value of the load factor second maximum is higher than the first maximum.

This fact seems very important for engineering practice, in addition, it is essential for this investigation. Based on the results of the preliminary analysis a hypothesis is framed here that the tow rope which cannot affect the first maximum of the sailplane load, since the sailplane displacement with respect to the towing aircraft is then very small, can, however, exert a substantial influence on the second maximum, when the sailplane displacement with respect to the towing aeroplane reaches a maximum value. If the tow hook is located in the fuselage front portion a pitching moment arises from the vertical component of the rope force. That moment changes incidence and increases the value of the second load maximum.

- The mathematical analysis was based on Euler equations of motion. After the terms describing the tow rope effect have been introduced a system of non-linear differential equations is obtained, the equations being of very complex form and analytically insoluble. Considering the convenience of analogue computation for the investigation of dynamic phenomena, some simplifications have been introduced into the equations referred to, to make it possible to model them in the analogue computer type SOLARTRON HS-7-2 (ref. 1).

Considering the fact that the difference between the time histories of sailplane load in aero-tow and in free flight is substantially influenced by the time history of the force appearing in the tow rope, the parameters affecting the time history of the force in a non-extensible tow rope have been examined while the said force has been considered the exciting force in the vibrating system "extensible tow rope + sailplane".

A theoretical analysis has made it possible to find an approximate relation between the gust angular frequency and that of the non-damped natural vibration of the system "tow rope + sailplane", while for the latter angular frequency the phase shift of the force in the extensible rope in respect to the exciting force causes a dangerous synchronization between the rope and gust effects.

A number of computations have been carried out in the SOLARTRON computer within the previously defined range of parameters of sailplane, aero-tow and gust wavelength in order to verify the analysis results and to determine the values of load increment appearing in aero-tow.

The computation results have confirmed that the non-extensible rope exerts an insignificant influence on both the load factor max. value (Fig. 2) and time history while the rope elasticity, causing a phase shift of the force-time history, can contribute to a considerable increase in the load factor second maximum (Fig. 3 and 4).

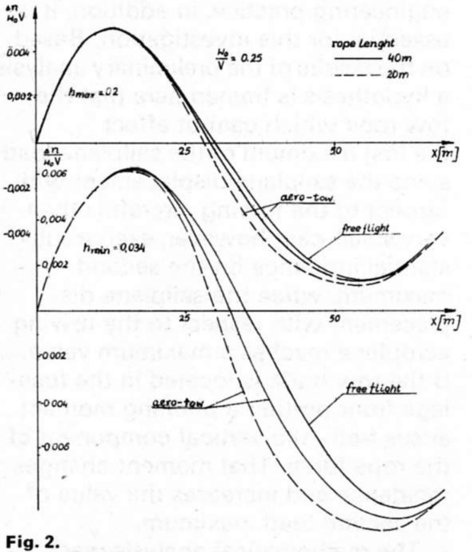

Fig. 2.
Comparison between the time histories of normal load increments Δn of the Zefir-2 in free flight and aero-tow with a non-extensible tow rope, gust wavelength being $\lambda = 100$ m.

These findings obtained for the lee-wave turbulence have been compared with the results of computations for the gust velocity distribution

$$w_g = \frac{W_o}{2}\,(1 - \cos 2\,\omega t),$$

used to calculate the aircraft loads.

It is evident that the velocity distribution for the lee-wave turbulence is the more dangerous of the tow. That distribution, besides causing higher basic loads i.e. the loads acting in free flight, results in a greater vertical displacement of the sailplane and a more unfavourable time history of the pitching moment arising from the tow rope.

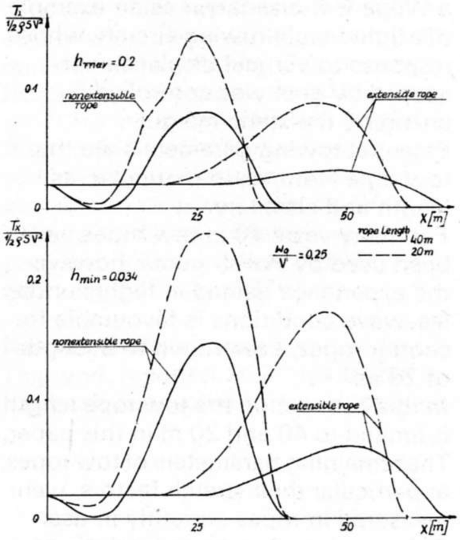

Fig. 3.
Comparison between the time histories of the horizontal component of the force T_x in both the non-extensible and extensible tow ropes; the gust wavelength being $\lambda = 100$ m.

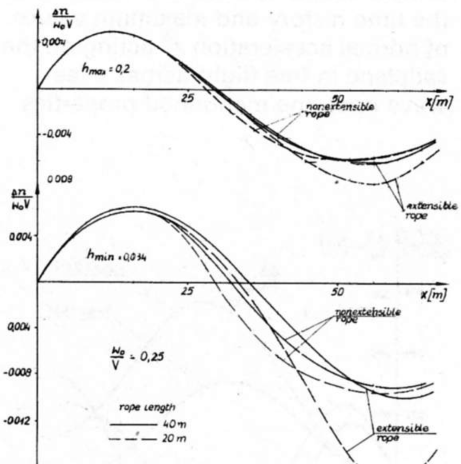

Fig. 4.
Comparison between the time histories of normal load increments Δn of the Zefir-2 in aero-tow with a non-extensible and extensible tow rope, the gust wavelength being $\lambda = 100$ m.

In addition, the investigation has covered the effect of wing elasticity on the difference between the maximum loads in free flight and aero-tow. The effect has proved negligible.

3. Concluding remarks

The main conclusion which can be drawn from this paper states the possibility of a considerable increase in the load factor second maximum in aero-tow as compared to the free flight case. The phenomenon can cause:

- loads exceeding the proof values when the airspeed in aero-tow is higher than the safe speed V_{safe}

$$V_{safe} = V_{min}\sqrt{n_{proof}\frac{C_{L\ max\ static}}{C_{L\ max\ dynamic}}}$$

- incidence higher than the angle of attack for maximum lift and sailplane stall when the airspeed in aero-tow is equal to or less than the safe speed.

A substantial influence on the relative increment in the load factor as defined to be: $\frac{\Delta n_{max\ tow} - \Delta n_{max\ free}}{\Delta n_{max\ free}}$ is exerted by the parameters of both the sailplane design and aero-tow.

Concerning the sailplane design parameters the most important influence is exerted by the tow hook horizontal distance from the sailplane centre of gravity – a tow hook situated in the vicinity of the sailplane centre of gravity prevents any significant increment of load. An interesting point to note here is that a decrease in the margin of static longitudinal stability involves an increase of both the relative load increment in aero-tow and the basic load (in free flight).

- The influence of aero-tow parameters on the relative increment of sailplane load manifests itself mainly by the influence of dynamic characteristics of the system "tow rope + sailplane" on the phase shift of the rope force with respect to the exciting force.

  It should be noted that the frequencies of natural vibration of the system "tow rope + sailplane", for the tow ropes now in use, can approach the critical frequencies, at which there occurs a dangerous synchronization of load caused by the gust with the pitching moment due to the tow rope.

4. Bibliography

1 J. Sandauer: Loading of a rigid sailplane in aero-tow under turbulent atmospheric conditions. Prace Instytutu Lotnictwa nr 43 (1970).
2 F. Donely: Summary of information relating to gusts on airplanes, NACA Rep. 997 (1950).