INFLUENCE OF MASS CHANGES OF FLYING OBJECTS ON THEIR DYNAMIC FEATURES

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Abstract

The aim of this work is the experimental study of the weight loss impact on the properties of flying objects. Work is based on the results of resonance tests of the helicopter, gliders and military aircraft. In the presented flying objects group the possible occurrence of weight losses during the flight are up to 50%. The paper posed the following questions: How big can be, in practice, the weight loss during the flight? To which resonance the mass loss has the greatest impact? How and by what rules the map of resonances changes? Does in the process of weight loss there are other, worth-knowing events? Gliders, airplanes and a helicopter were investigated in the Resonance Test Laboratory of Institute of Aviation. The author has organized and for over 20 years led the Resonance Test Laboratory at the Institute of Aviation, in which he made or directed the investigations of dozens of aircraft, gliders, helicopters and their elements and components. Effect of weight loss on the flying objects properties is one of several „unusual" research topics phenomena, which the author observed during a standard resonance tests. The resonance of the mode shape of Jantar 15 glider, comparison of the relative increase in the frequencies of the resonances with mode shape for SZD-50 Jantar 15-2 and IS-2 Revelation gliders, results of investigations of the underwing stores loss of mass impact on the „Pattern" aircraft resonances frequencies, the resonance frequency of the I-22 Iryda aircraft are presented in the paper. The resonance of the mode shape of Jantar 15 glider, comparison of the relative increase in the frequencies of the resonances with mode shape for SZD-50 Jantar 15-2 and IS-2 Revelation gliders, results of investigations of the underwing stores loss of mass impact on the „Pattern" aircraft resonances frequencies, the resonance frequency of the I-22 Iryda aircraft are presented in the paper.

Keywords*: transport, air transport, dynamics features, resonance researches, mass loss*

1. Scope of the work

The aim of the study is to examine the impact of weight loss on the behaviour of flying objects.

The paper posed the following questions:

How big can be, in practice, the weight loss during the flight?

To which resonance the mass loss has the greatest impact?

How and by what rules the map of resonances changes?

Does in the process of weight loss there are other, worth-knowing events?

Dynamic properties of aircraft structures are examined, modelled and analyzed in order to anticipate and avoid behaviour that could endanger the lives and safety of people and equipment.

The model of flying object dynamics is represented by a system of equations:

$$m_i\ddot{q}_i + c_i\dot{q}_i + k_i q_i = f_i$$
$$\ddot{q}_i + b_i\dot{q}_i + \omega_i q_i = \hat{f}_i \quad ,$$

where i = 1.

The experimental way to obtain the m_i, c_i, k_i coefficients are the resonant tests.

Implementation of resonance tests proceeded in accordance with developed procedures.

These procedures and adapted laboratory equipment are the tools needed to assess knowledge and understanding of the object properties.

The author has organized and for over 20 years led the Resonance Test Laboratory at the Institute of Aviation, in which he made or directed the investigations of dozens of aircraft, gliders, helicopters and their elements and components.

2. Test procedures

In order to imitate the free flight conditions the object was suspended by elastic cords so that own frequency of its movement on the suspension was significantly lower than the resonant vibration frequencies of its structure.

In the case of studies of on the ground resonances the tested object stand on its own undercarriage. The electro-dynamic actuators were used to induce vibrations, the piezoelectric vibration sensor transducers were used for the vibrations measurements.

The size and phase of constraint forces and their points of application were selected individually for each resonance, so as to obtain the best isolation of it [4].

The first stage of the investigations consisted of recording of the frequency-amplitude characteristics.

The second stage of the study was the identification of individual frequencies and mode shapes for each of the resonances, which was implemented by choosing the size and the proportion of mutual phase shifts between the constraint forces.

Used in the selection criteria were based on minimizing the vibrations phase difference measured at several points of the structure.

The final stage of the investigations was to register the frequency and mode shapes of the tested generalized masses resonance and the resonance damping coefficients [4].

As a result of resonance test, the several resonances register (the resonance map) was obtained, essential from the flying object safety and comfort standpoint.

Tab. 1. Possible in-flight loss of weight for the selected gliders, helicopters and airplanes

Item	Flying object airplane	Own mass [kg]	Fuel mass [kg]	Cargo mass [kg]	Take-off mass m_{TO} [kg]	Possible in-flight weight loss Δm	$\frac{\Delta m}{m_{TO}}$
1	Airbus 380 airplane	_	100000	70000	600000	100000	0.17
2	SZD-52-2 Jantar 15	355	_	240	495	140	0.28
3	Glider IS-1 Revelation	400	_	200	600	200	0.33
4	Helicopter PZL Sokół	4066	1330	11004	6400	2334	0.36
5	H-18 Dromader airplane	2815	285	2200	5300	2485	0.47
6	Glider Wrona 2	260	_	240	500	240	0.48
7	Skytruck airplane	4360	1766	2300	7000	4066	0.58
8	Cessna 378 airplane	2815	2300	1230	6350	3530	0.59
9	I-22 Iryda airplane	4600	_	_	6900	2300	0.33

3. The in-flight object loss of mass

During the flight, from the take-off to landing the mass of flying objects changes due to fuel consumption, dropped armament, ballast water discharge, paratroopers, plant protection products, fire extinguishing, etc.

As an example, in the Tab. 1 are presented the mass data, including variable cargo load mass of selected flying objects.

In the presented cases, the mass of spent fuel and dropped loads are within the range from 0.19 to 0.59 of the take-off weight.

Gliders, airplanes and a helicopter (with the exception of item no. 1 and no. 3) the data of which are presented in the table were investigated in the Resonance Test Laboratory of the Institute of Aviation.

The tested gliders water ballast is located in the near fuselage wing tanks.

In the helicopters and agricultural airplanes the fuel and dropped agricultural load is distributed within the fuselage.

The combat aircraft fuel and weaponry is located both in the fuselage and on the under wing pylons/pods.

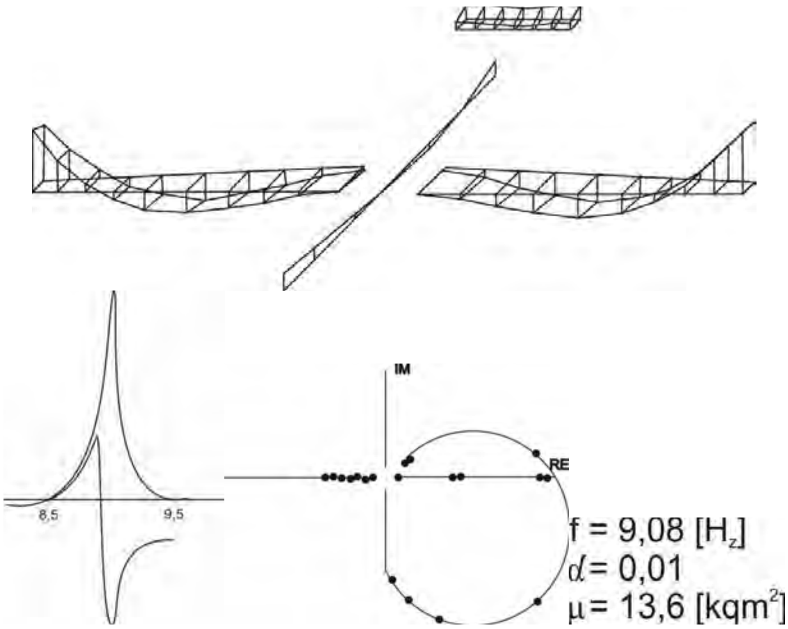

Fig. 1. The resonance of the mode shape „4-nodal vertical wings bending” of Jantar 15 glider

4. The resonances map

Results of the resonance tests form a map which illustrates the dynamic properties of the structure. This map is a list of resonance frequencies (generalized masses and damping coefficients) and the figures and tables of vibration modes coordinates.

Fig. 1 shows an example of one of the elements of the map: the results of resonance test with the mode shape „4-nodal vertical wing bending” of Jantar 15 glider.

From the impact perspective of the weight loss during flight, resonances of the following groups were selected for the analysis:

a. a group of six resonances of an object standing on ground on its own undercarriage,

b. a group of resonances with the mode shapes „vertical wing bending and twisting”,

c. airplanes with underwing tanks and munitions fundamental resonances group.

Selected three groups of resonances include and represent typical cases where the influence of weight loss occurred to the greatest extent.

5. A group of six resonances of an object standing on ground on its own undercarriage

The study of resonances of flying object standing on its own undercarriage, from the cognitive and utilitarian point of view concerns mostly helicopters.

Tab. 2 presents the results of the 6 main resonances of helicopter standing on its own undercarriage.

Tab. 2. The results of the 6 main resonances of helicopter standing on its own undercarriage

Item	Resonance mode shape	f1 [Hz] m=3190 [kg]	f2[Hz] m = 5410 [kg]	$\frac{f_2}{f_1}$
1.	Roll	1.42	1.37	1.04
2	Pitch	1.55	1.55	1.00
3	Yaw	2.11	1.06	1.02
4	Vertical oscillations	3.35	2.60	1.29
5	Longitudal oscillations	4.30	3.51	1.23
6	Lateral oscillations	6.21	5.50	1.13

Changes of the helicopter mass minimally affected the value of the frequencies of these resonances, which mode shapes are related to the rotations: rolling, pitching and yawing.

Changing of the helicopter mass clearly affected the values of the resonances, which mode shapes are related to the oscillations along the x-, y-, z-axis.

6. Group of resonances with mode shapes of vertical bending and twisting of glider wings

Changes in properties of resonances with mode shapes 2-, 3-, 4-, 5-, 6- and 7-nodal vertical wing bending and wings twisting arise from placement of water ballast tanks in near-fuselage part of the gliders wings.

The nature of the resonances changes is presented on examples of Polish glider SZD-52-2 Jantar - 15 [6] and South African glider IS-1 Revelation [7] investigations.

Tab. 3 presents the results of the resonance tests with mode shapes „vertical wings bending" and „the twisting of the wings" of SZD-50 Jantar 15-2 glider with empty and full ballast tank.f1 [H2] - resonance frequency of the glider without ballast; f2 [H2] - resonance frequency of the glider with 140 kg ballast.

Tab. 4 presents the results of the resonance tests with mode shapes „vertical wings bending" of IS-1 Revelation glider with empty and full ballast tank, f1 [H2] - resonance frequency of the glider without ballast; f2 [H2] - resonance frequency of the glider with ballast.

7. Group of resonances of aircraft with underwing tanks and munitions

A major influence on changes in the wings resonance is the hanging on their ends and on the underwing pylons/pods the fuel tanks and munitions.

The problem is illustrated in the examples made by the author - a study of two airplanes: pattern aircraft, and the I-22 Iryda aircraft.

The pattern aircraft was tested in three versions: with no underwing stores, in the version with full tanks at the wings ends and in the version with full tanks at the ends of the wings and underwing pods.

Fig. 3 presents results of investigations of the underwing stores loss of mass impact on the „Pattern" aircraft resonances frequencies.
Most susceptible to weight loss are resonances with mode shapes „twisting of the wings".

Emptying the tanks at the ends of the wings increases the frequency of these resonances about 2.6 times.

Fig. 4 presents the results of studies of the underwing stores impact on resonances for I-22 Iryda aircraft.

The plane has been studied in an „empty" version and in a version with underwing stores.

Ratio of resonance frequency f_1/f_2 of a wing with twisting mode shape for „empty" version and the version with loaded underwing stores is equal to 3.3 times.

Tab. 3. The results of the resonance tests with mode shapes „vertical wings bending" and „the twisting of the wings" of SZD-50 Jantar 15-2 glider with empty and full ballast tank.f1 [H2] - resonance frequency of the glider without ballast; f2 [H2] - resonance frequency of the glider with 140 kg ballast

Item	Resonance mode shape	f_1 [H2] empty	f_2 [H2] full	$\frac{f_2}{f_1}$
1	2-node wing bending	2.82	2.73	1.03
2	3-node wing bending	6.55	5.40	1.21
3	4-node wing bending	9.08	7.89	1.15
4	4-node wing bending 2-node fuselage bending.	11.5	10.6	1.08
5	5-node wing bending	16.3	14.1	1.16
6	6-node wing bending	20.7	17.2	1.20
7	7-node wing bending	34.5	25.1	1.37
1	1-node wing bending	25.4	24.3	1.05
2	2-node wing bending	25.8	23.2	1.11

Tab. 4. The results of the resonance tests with mode shapes „vertical wings bending" of IS-1 Revelation glider with empty and full ballast tank, f1 [H2] - resonance frequency of the glider without ballast; f2 [H2] - resonance frequency of the glider with ballast

Item	Resonance mode shape	f_1 [H2] empty	f_2 [H2] full	$\frac{f_2}{f_1}$
1	2-node wing bending	2.403	2.045	1.17
2	3-node wing bending	5.201	3.970	1.31
3	4-node wing bending	7.336	5.952	1.23
4	5-node wing bending	12.082	9.409	1.28
5	6-node wing bending	25.327	12.397	2.04
6	7-node wing bending	29.838	16.668	1.79

8. The resonances map decomposition

The flying object mass loss increases its resonance frequency.
Gradients of the individual resonances increases may be different.

For this reason, in some cases, two different resonance frequencies can approach to each other and become equal.

Phases of the frequencies approach are shown in Fig. 5, where frequency-amplitude **characteristics are drawn.**

Diminishment of fuel and cargo mass decomposes flying object resonances map.
Decomposition involves changes in resonances frequencies arrangement and changes in their mode shapes.

Fig. 2 presents comparison of the relative increase in the frequencies of the resonances with mode shape „vertical bending wings without and with water ballast" for SZD-50 Jantar 15-2 and IS-2 Revelation gliders.

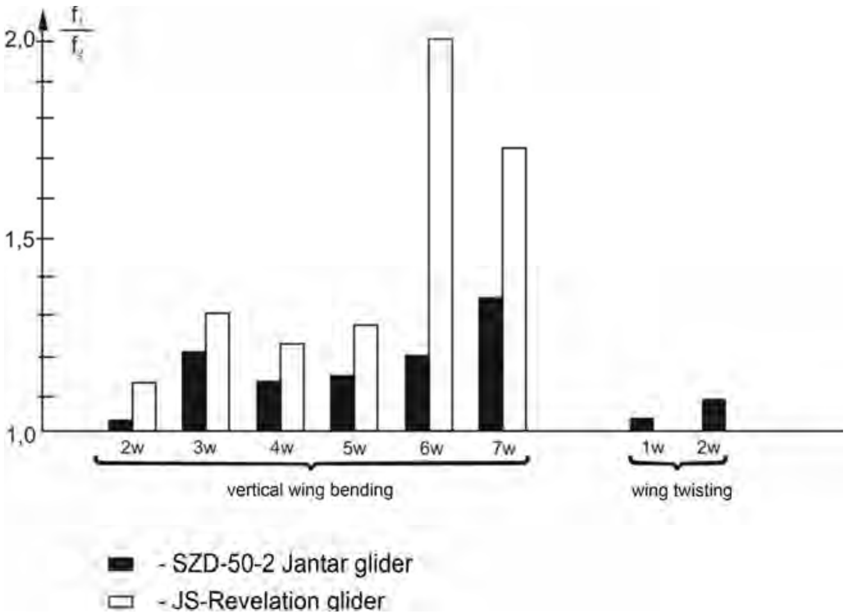

Fig. 2. Comparison of the relative increase in the frequencies of the resonances with mode shape „vertical wings bending without and with water ballast" for SZD-50 Jantar 15-2 and IS-2 Revelation gliders

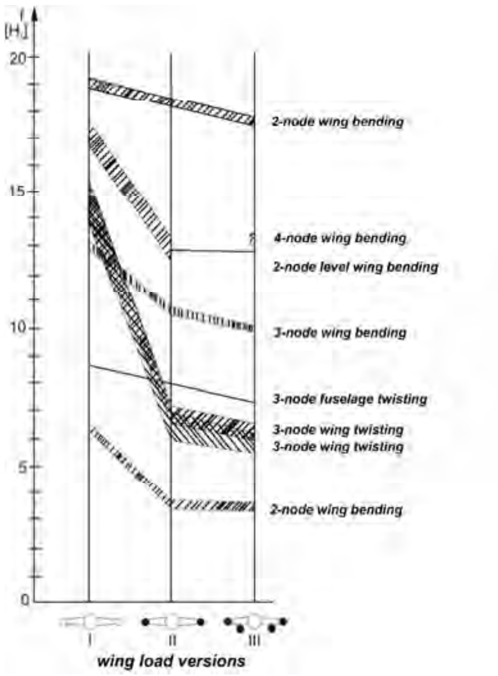

Fig. 3. Results of investigations of the underwing stores loss of mass impact on the „Pattern" aircraft resonances frequencies

9. Summary and conclusions

The aim of this work is the experimental study of the weight loss impact on the properties of flying objects.

Work is based on the results of resonance tests of the helicopter, gliders and military aircraft.

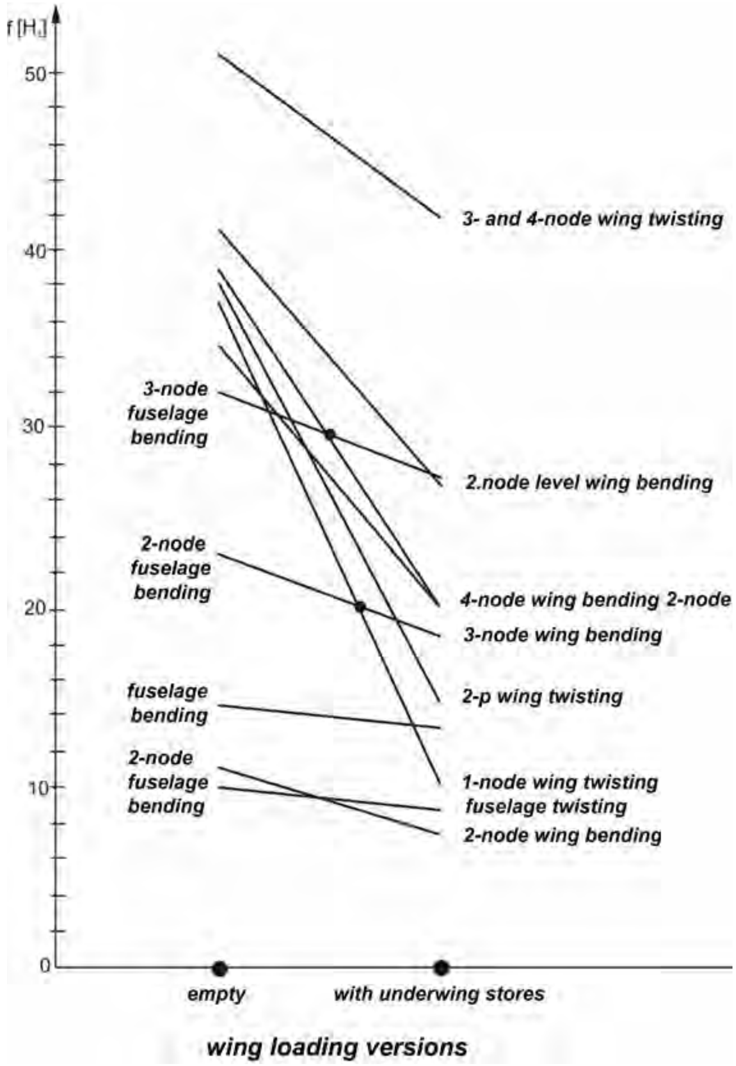

Fig. 4. The results of the underwing stores impact on the resonance frequency of the I-22 Iryda aircraft

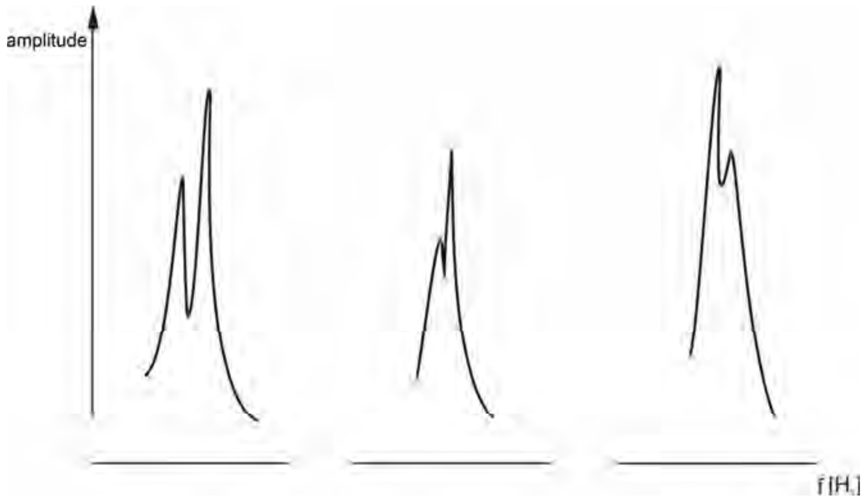

Fig. 5. Frequency-amplitude characteristics, phases of the two resonance frequencies approach

In the presented flying objects group the possible occurrence of weight losses during the flight are up to 50%.

The biggest impact of weight loss was found in the resonance frequencies with mode shapes „wings twisting” for the combat aircraft with underwing fuel tanks and munitions.

The weight loss also had significant impact on the resonance frequencies with mode shapes „vertical bending of the wings” for gliders with water ballast tanks and airplanes with wing fuel tanks and the underwing stores and on the resonance frequencies with mode shapes „rocking along the x-, y-axis”, with helicopters and airplanes with cargo in the fuselage, standing on their own undercarriage.

The gradients of the frequency resonances increases are different, depending on whether the weight losses are close to the crests, or close to the nodes of vibrations.

One should pay particular attention to the phenomenon of individual differences of resonances frequency, the „decanting” and the resulting changes in the resonance mode shapes.

Resonances approaching and „blending in” decomposes flying object resonances map.

Effect of weight loss on the flying objects properties is one of several „unusual” research topics phenomena, which the author observed during standard resonance tests [10].

The list of these investigations include, inter alia:

- phenomenon of near or equal frequencies resonances,
- effect of backlash on the properties of resonances, including the development of resonance method for assessing the backlash,
- generalized backlash definition,
- development of method for strain gauges resonance scaling,
- development of the resonance test method for resistance to vibration of thin-walled structures,
- developing principles of resonances classification based on the idea of groups related to vibration mode shapes.

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