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# Research of elastic suspension systems influence on the accuracy of aircraft modal parameters estimation

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## Abstract

Some variants of elastic support systems, their features and practical examples of application are presented. The results of computational and experimental research of elastic support system influence on aircraft modal parameters are shown. Data on various elastic support systems are presented and the influence of “aircraft-elastic support system” rigid body modes on elastic modes of aircraft is shown. The minimum ratio between the highest frequency of the aircrafts rigid body modes and the first elastic mode is determined. In this case, elastic support system provides minimum impact on frequencies, damping and mode shapes of lower elastic modes of aircraft.

## 1. Introduction

When ensuring the safety of aircraft against aeroelasticity phenomena, one of the important steps of research is ground vibration testing (GVT). The inability to evaluate all features of a real structure using only numerical methods necessitates to obtain experimental modal characteristics of test objects and then to correct dynamic mathematical models. Aircraft ground vibration testing is the most reliable method to determine such characteristics as eigen frequencies, mode shapes and damping. In order to conduct such tests a structure must be fixed in such a way that boundary conditions can be adequately described in a numerical model and reproduced in other tests of a similar structure with a high degree of accuracy. “Free-free” boundary condition turns out to be the most applicable for analysis; for this purpose an aircraft is installed on elastic support system (ESS) during GVT [1, 2]. At the same time, oscillations of an aircraft as a rigid body on ESS should not affect frequencies, mode shapes and damping of elastic modes. Practical recommendations suggest that the frequency of the highest rigid body mode of the test object on ESS should be several times lower than the frequency of the first elastic mode. Usually, the ratio of these frequencies is determined by the specific conditions and the test object.

## 2. Elastic support systems

High requirements are imposed on the parameters of an aircraft ESS. It should take the weight load of an aircraft, providing its movement in six degrees of freedom and conditions corresponding to a free flight, while exerting minimal influence on the aircraft modal characteristics. The suspension system should be characterized by a low eigen frequency, low internal friction and small additional masses of moving elements. Before being used in industrial tests, ESS undergoes preliminary tests on a weight model of an aircraft. Moreover, the lower elastic modes frequencies of an aircraft are, the more time-consuming becomes the process of designing the ESS.

During aircraft installation on ESS the points of suspension should be located as close as possible to the nodal lines of the most important lower elastic modes or at points where amplitudes of oscillations are small. The position of ESS can be adjusted after measuring the characteristic elastic mode shapes of an aircraft. Support location is also determined by the structural scheme of the aircraft. Usually, the type of ESS used is determined by the specific test conditions. Different types of ESS most commonly used in practice of GVT are presented below.

### 2.1 ESS on the base of pneumatic supports

There are a number of pneumatic supports of various load capacities, allowing suspending objects with weight from one ton to hundreds of tons. At the same time, sufficiently low frequencies of structure oscillations as a rigid body are achieved and an automatic control of the pneumatic supports ensures the stability of a structure in the suspended state. Pneumatic supports as the part of ESS are installed under the aircraft and provide its lateral stability during

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GVT. Rigging points or gear attachment points are used as supporting points on the aircraft, which transfer the load to the pneumatic supports through the transitional devices. For typical pneumatic support maximum amplitude of moving part displacement in any direction is about ± 10 mm. Figure 1 shows installation scheme of the pneumatic support with its main parts.

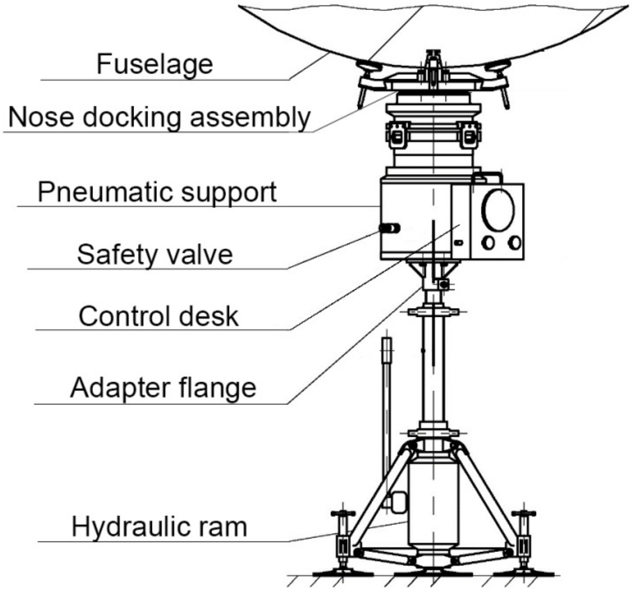

Figure 1: Pneumatic support installation scheme

To ensure safety, pneumatic supports are durability and leak-tested. Also, to confirm claimed modal characteristics, GVT of pneumatic supports are carried out on a weight model (Figure 2).

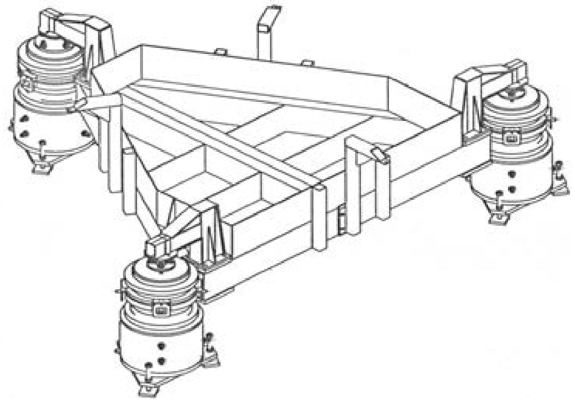

Figure 2: Weight model for testing pneumatic support based ESS

After passing all the tests pneumatic supports are used in industrial GVT of aircraft. As an example, Figure 3 shows a three-point ESS based on pneumatic support.

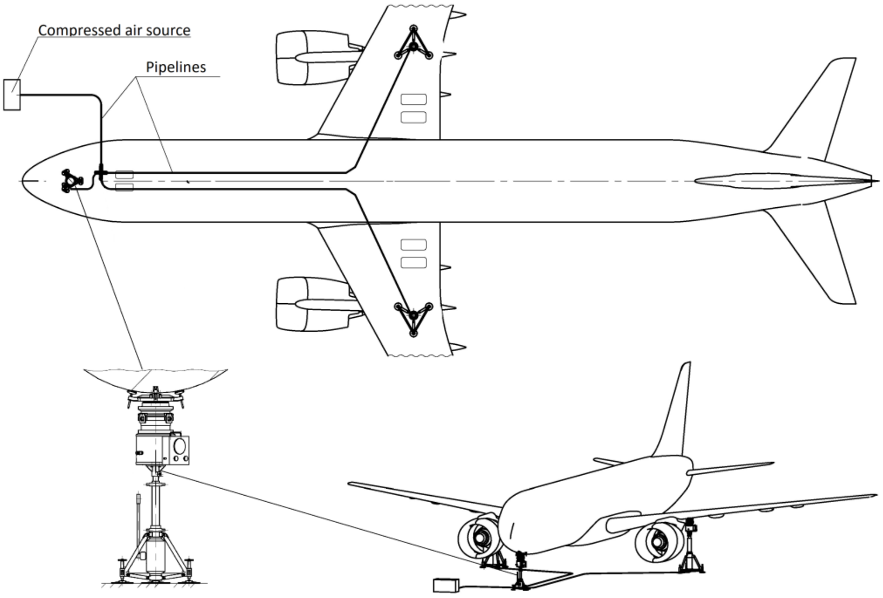

Figure 3: Three-point scheme of aircraft suspending on pneumatic support

Table 1 shows a comparison between frequencies and damping of oscillations of the weight model (Figure 2) and the aircraft (Figure 3) installed on the same pneumatic support.

Table 1 – Results of pneumatic support testing on weight model and aircraft

| | Weight model | | Aircraft | |
|---|---|---|---|---|
| Mode shape | *f*, Hz | δ | *f*, Hz | δ |
| Vertical translation | 0.93 | 0.19 | 0.85 | 0.20 |
| First vertical wing bending | - | - | 3.26 | 0.03 |
| Frequencies ratio | - | - | 3.84 | - |

From Table 1 it can be seen that the ratio of frequencies between the highest mode of an aircraft as a rigid body on ESS and the lower elastic mode provides the minimum effect of the ESS on modal characteristics.

## 2.2 Bungee cord ESS

Structures are usually suspended on bungee cords at two or three points (Figure 4). By varying the length and number of wraps it is possible to adjust frequencies of a structure as a rigid body within certain limits. To determine the number of wraps of the bungee cord, it is necessary to know the load from the weight of the aircraft located in a specific section. Usually, to obtain minimum oscillation frequency of an aircraft on ESS, the stretching of cords under the weight of an aircraft should be 135-140% of the original length. The required stretching is determined by the stress-strain diagram and depends on the type of cord. With such method an aircraft is usually suspended on the attachment points of the wings to the fuselage or on the fuselage frames. It is also necessary to pay attention to the stability of the object in a suspended state while using these methods of suspension. The specific example of the use of this ESS type will be given in Part 3 of this paper.

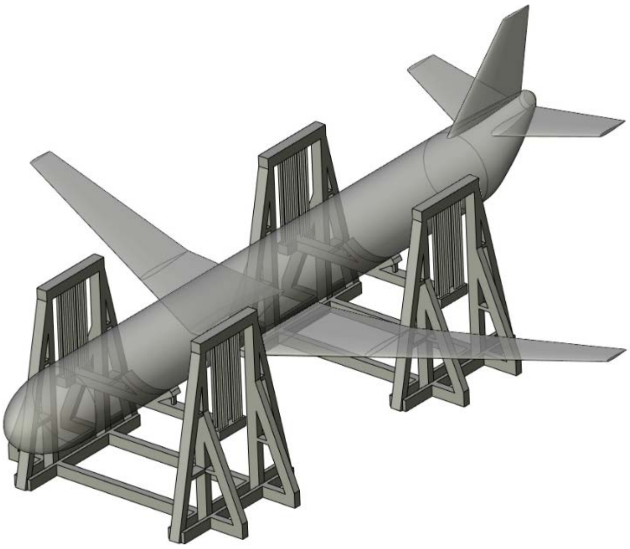

Figure 4: Suspending on bungee cords

## 2.3 Combined ESS

It’s also possible to use the combined suspension. For example, two pneumatic supports are installed under the wing of an aircraft, and a fuselage is suspended on bungee cords in the nose section (Figure 5).

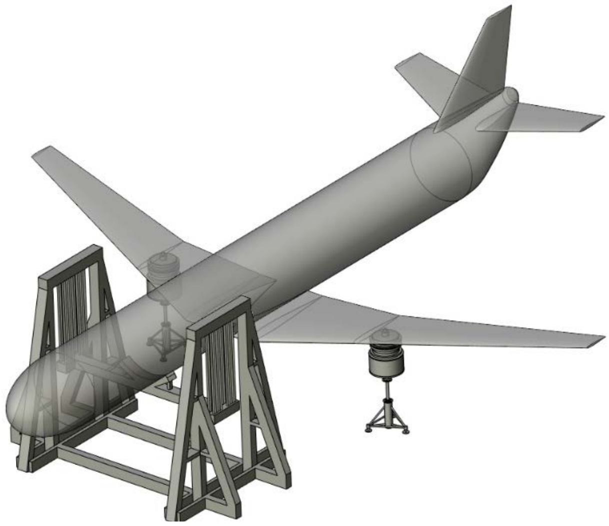

Figure 5: Aircraft suspending on combined ESS

Another variant of the combined suspension is also used: the aircraft is installed on the main landing gear and the nose of the fuselage is suspended on bungee cords. In this case, the nose landing gear is retracted and main landing gear tires are deflated, some struts of main landing gear can be retracted (in the case of a dual-tandem gear). If it is necessary, some of tires from the main landing gear can be removed.

## 2.4 Testing on landing gear

Sometimes it is acceptable to conduct aircraft GVT on landing gear. In this case, the pressure in landing gear tires should be reduced by 30-50% of the nominal value. With deflated tires there shouldn’t be loss of stability. This method is used when the conditions of test conducting do not allow the use of ESS or aircraft parts are investigated.
Some GVT results for two different classes of modern aircraft tested on ESS and on landing gear are shown below. Tables 2-3 show frequencies and damping for the highest rigid body mode and the lower elastic mode as well as frequencies ratio.

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Table 2: GVT results of regional jet

| Mode shape | On ESS | | On landing gear | |
|---|---|---|---|---|
| | *f*, Hz | δ | *f*, Hz | δ |
| Vertical translation of an aircraft | 0.87 | 0.085 | 2.63 | 0.143 |
| First vertical wing bending | 3.13 | 0.017 | 3.18 | 0.022 |
| Frequencies ratio | 3.6 | | 1.21 | |

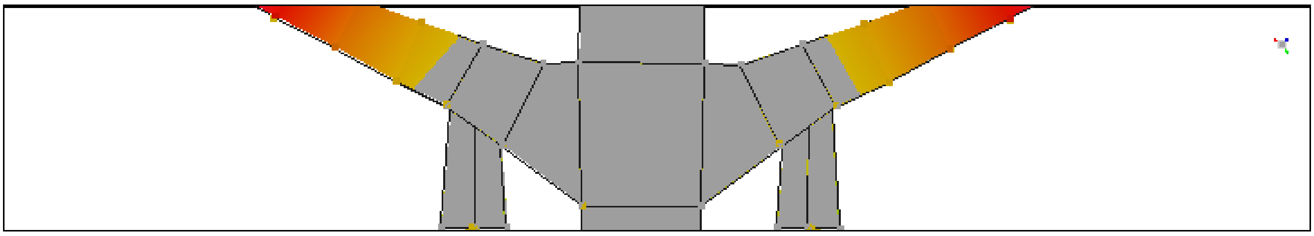
Table 3: GVT results of heavy cargo aircraft

| Mode shape | On ESS | | On combined ESS | | On landing gear | |
|---|---|---|---|---|---|---|
| | *f*, Hz | δ | *f*, Hz | δ | *f*, Hz | δ |
| Vertical translation of an aircraft | 0.76 | 0.17 | 1.16 | 0.276 | 1.57 | - |
| First vertical wing bending | 1.81 | 0.03 | 1.76 | 0.069 | 2.08 | 0.14 |
| Frequencies ratio | 2.38 | | 1.52 | | 1.32 | |

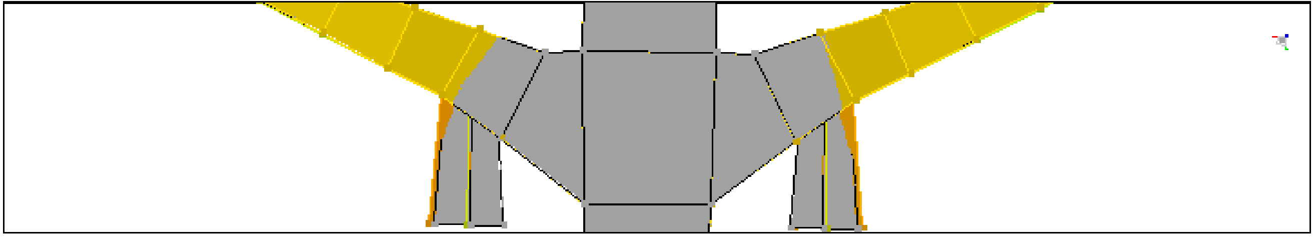
From Tables 2-3 it is observed that “aircraft-ESS” system with sufficiently low frequencies and damping has a minimal effect on the lower elastic mode of an aircraft. In case of an aircraft on landing gear, the increase in frequency of the lower elastic mode is up to 2% for a regional jet and up to 15% for a heavy cargo aircraft, and frequencies ratio is about 1.3. Landing gear has a more significant effect on damping (δ): up to 30% for a regional jet and up to 300% for a heavy cargo aircraft. Installation of an aircraft on a combined suspension (table 3) is more acceptable than on landing gear, but an elastic mode damping is higher by 130%, the ratio of frequencies is about 1.5. ESS on the basis of a pneumatic support provides frequencies ratio of rigid body and elastic modes up to 3.6 for regional jet and about 2.4 for heavy cargo aircraft.

The applicability of an aircraft testing on landing gear must be proved by a special numerical analysis in each case. Numerical modeling of an aircraft on landing gear is quite a challenge. It is necessary to take into account static indeterminacy, dampers characteristics, non-linearity and correctly selected parameters of springs modeling landing gear stiffness. In [3] a method for recalculating frequencies and mode shapes of an aircraft mounted on landing gear into eigen modes of a “free-free” condition aircraft is proposed.

In addition, it is necessary to take into account that nodal lines position on mode shapes will be different in the case of an aircraft on landing gear and on ESS as shown in Figure 6. At the same time, the nodal lines position of an aircraft on ESS is close to the nodal lines position of an aircraft in “free-free” condition.



a) on landing gear



b) on ESS

Figure 6: Nodal lines position of the first vertical wing bending mode shape of regional jet.

Thus, the test results show that in case of rigid body and elastic modes proximity, suspension system can have the most significant influence on damping. At the same time, test results of an aircraft installed on deflated tires show the greatest changes in mode shapes, frequencies and damping of lower elastic modes.

## 3. Computational and experimental research of an ESS influence on modal characteristics

Below are the GVT results of a light turboprop aircraft hanged out on fuselage frames using 20 mm diameter bungee cords in the positions of nodal lines of the first vertical bending of the fuselage mode shape. Initially, there were 11 wraps installed in the front and 7 wraps in aft of the fuselage. According to the test results, the suspension was found to be too rigid and the highest suspension mode was close to the first symmetrical wing bending (SWB- I mode).
Further, a number of wraps was reduced in two stages, until the influence of the suspension became minimal. The minimum stiffness of the suspension was also limited by the technical test conditions. For the control several criteria were used: a change in the frequencies and damping, nodal lines shift of the SWB-I mode.
Table 4 shows a comparison between frequencies of three highest suspension modes and a lower elastic mode while changing suspension stiffness. As it can be seen from Table 4, with a decrease of ESS stiffness frequencies of all three rigid body modes also decrease.

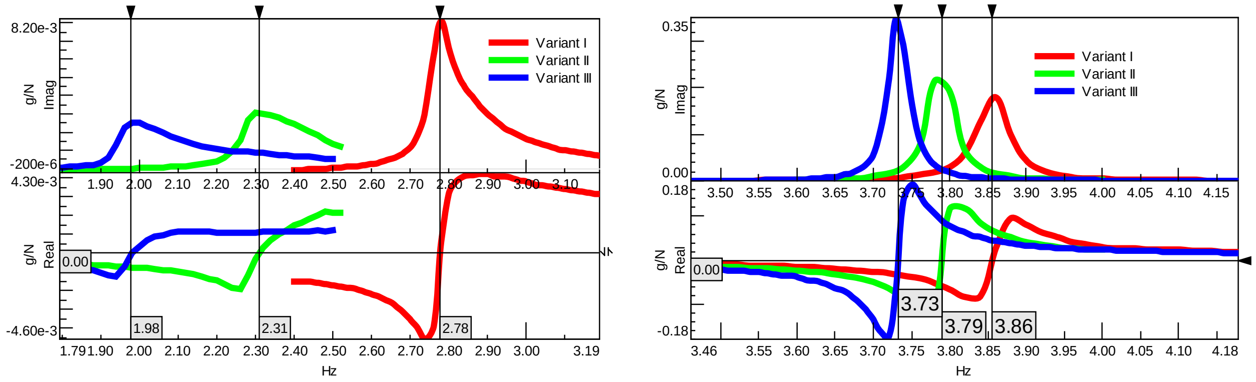
Table 4: Comparison of lower mode frequencies of light turboprop aircraft

| | Eigen frequencies changes depending on ESS stiffness, Hz | | |
|---|---|---|---|
| Mode shape | I | II | III |
| | 11 wraps in front, 7 wraps in aft | 10 wraps in front, 6 wraps in aft | 10 wraps in front, 5.5 wraps in aft |
| Rolling | 1.48 | 1.17 | 0.76 |
| Pitching | 2.07 | 1.39 | 1.32 |
| Vertical translation | 2.78 | 2.32 | 1.98 |
| SWB-I | 3.85 | 3.79 | 3.73 |

Since the frequency of an aircraft translation along the vertical axis is the highest and has the greatest effect on the SWB-I mode, this suspension mode has been studied in more detail. As it can be seen from the results presented in Table 5 and in Figure 7, due to a decrease in the suspension stiffness, the highest suspension mode frequency became lower than an elastic mode frequency by 47.5%, while the SWB-I mode frequency decreased by 3.1%. The greatest effect of ESS was on damping of the SWB-I mode, which decreased by 40% from 0.045 to 0.027. The obtained results allowed to achieve the lack of the suspension influence.

Table 5: GVT results of light turboprop aircraft

| | Eigen modes changes depending on ESS stiffness | | | | | |
|---|---|---|---|---|---|---|
| Mode | I | | II | | III | |
| | 11 wraps in front, 7 wraps in aft | | 10 wraps in front, 6 wraps in aft | | 10 wraps in front, 5.5 wraps in aft | |
| | *f*, Hz | δ | *f*, Hz | δ | *f*, Hz | δ |
| Vertical translation of an aircraft | 2.78 | 0.182 | 2.32 | 0.322 | 1.96 | 0.309 |
| SWB-I | 3.85 | 0.045 | 3.79 | 0.042 | 3.73 | 0.027 |
| Frequency ratio | 1.38 | | 1.63 | | 1.9 | |



a)

b)

Figure 7: Changes in mode frequency depending on ESS stiffness: a) vertical translation, b) SWB-I

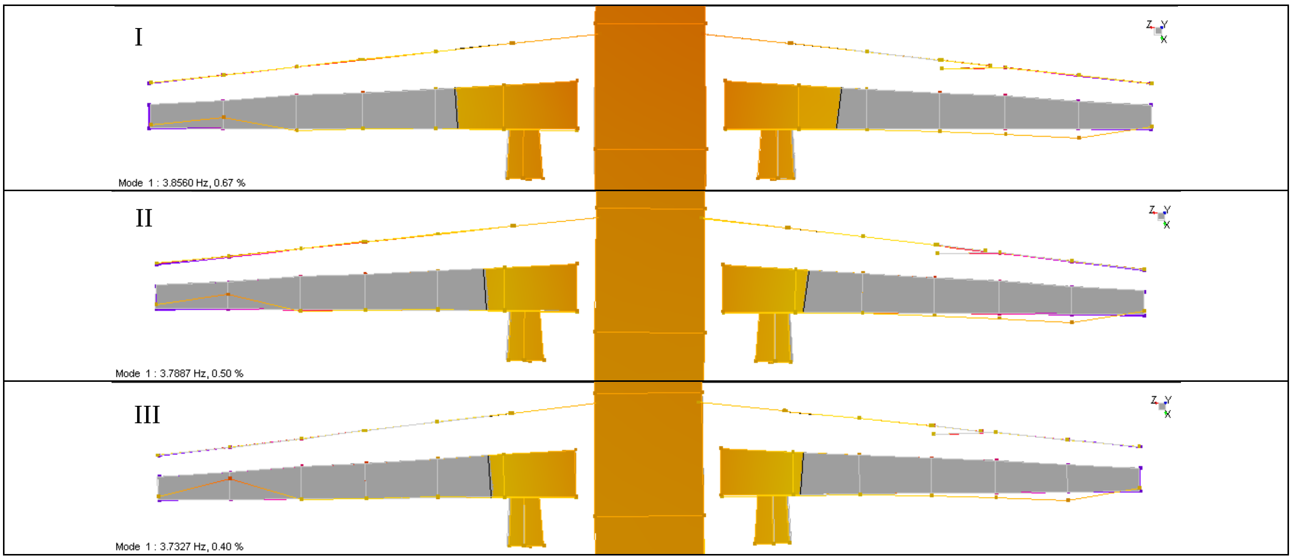
Calculations also showed an aircraft eigen modes frequencies overestimation due to the influence of the ESS, as well as the displacement of the SWB-I mode nodal lines position from the sidewalls of the fuselage.

Numerical model for eigen modes calculations is constructed using beam schematization and polynomial method. The suspension system was modeled with point springs. The stiffness matrices of springs were adjusted in front and aft of the structure depending on the number of wraps to match the frequencies and shapes of the suspension modes obtained in GVT. After obtaining the results on suspension with minimum stiffness a calculation of “free-free” aircraft modes was made. A comparison of the results obtained in the calculation and the experiment was made, which confirmed the influence of the ESS on the SWB-I mode frequency (Table 6).

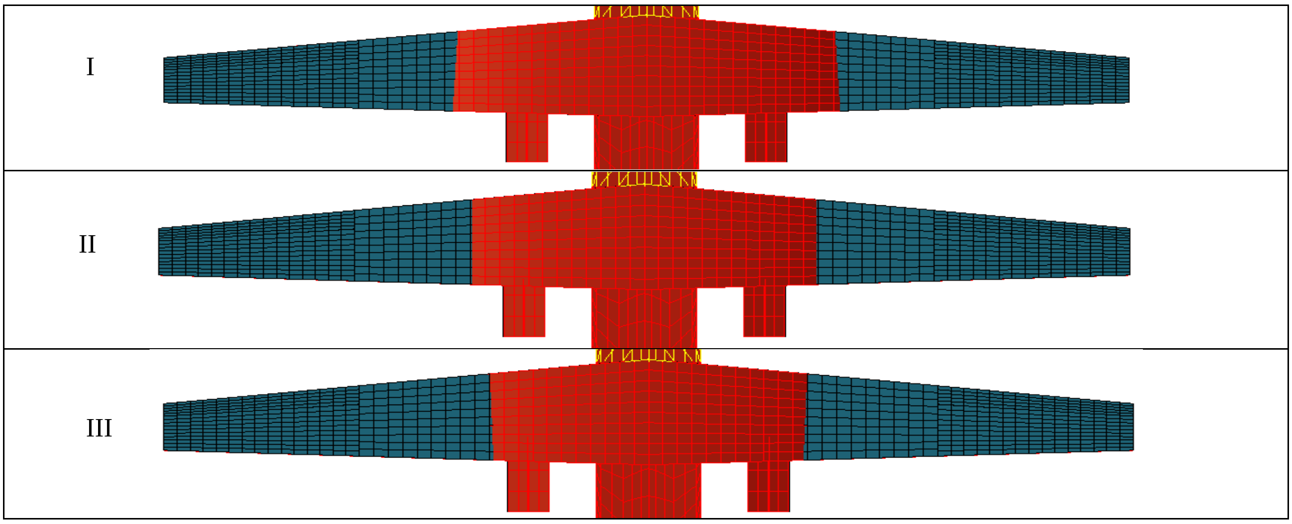
Table 6: Calculation and experimental frequencies for three suspension stiffness variants

| Suspension variant | I | II | III | Free boundary condition |
|---|---|---|---|---|
| *f*, Hz (calculation) | | | | |
| Vertical aircraft translation | 2.73 | 2.30 | 1.95 | - |
| SWB-I | 3.89 | 3.79 | 3.73 | 3.73 |
| *f*, Hz (experiment) | | | | |
| Vertical aircraft translation. | 2.78 | 2.32 | 1.98 | - |
| SWB-I | 3.85 | 3.79 | 3.73 | - |

In addition to changes in frequencies and damping with a decrease of the suspension stiffness, nodal lines of the SWB-I mode (Figure 7) shifted closer to the sidewalls of the fuselage, both in the numerical model and in the experiment.



a) experiment



b) calculation

Figure 8: Nodal lines shift due to changes in suspension stiffness

The example above clearly shows the effect of the ESS stiffness on the frequencies, damping and mode shapes of an aircraft elastic modes. Analysis of changes in frequencies and damping, the shift of the nodal lines on the SWB-I mode with variations of the suspension shows that as the ratio of the highest mode of an aircraft as a rigid body and the first elastic mode (SWB-I) frequencies approaches to ~0.5, influence of suspension modes on elastic modes disappears. In addition, parametric studies on a simplified analytical model also give similar results [4].

## Conclusions

Research results show that for a specific aircraft type ESS should be selected individually. For medium and heavy classes of aircraft ESS on the basis of pneumatic support can be considered the most appropriate choice for the GVT. At this moment it provides the best ratio of elastic and suspension modes frequencies, and has rather low damping.

The use of pneumatic supports not always can be justified in case of small and light aircraft, since in this case the cost and influence of the suspension system can be significant. In this case, it becomes relevant to create ESS on the basis of bungee cords, or a combined ESS.

Tests on landing gear may be conducted only in individual cases, but this requires justification by special numerical analysis. Landing gear affect all modal parameters of the lower elastic mode and can significantly distort the result. It is necessary to take into account static indeterminacy, dampers characteristics, non-linearity and correctly selected parameters of springs modeling landing gear stiffness.

The results of the conducted studies show that the minimum ratio between first elastic mode of an aircraft and the highest mode of an aircraft as a rigid body should be at least 2. In this case, the ESS will have a slight effect on the frequencies, damping and mode shapes of the elastic modes of the aircraft.

## Acknowledgments

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