EXPERIENCE OF FLUTTER CLEARANCE OF THE SUCHOI SSJ 100 REGIONAL JET

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Abstract: Ensuring the safety of aircraft from adverse aeroelasticity phenomena and, in particular, flutter plays an important role in creating a new aircraft. The problem is especially relevant nowadays, because intense competition in the global market requires the creation of a modern aircraft with high weight perfection. This results in minimizing the structural weight of an airframe, and, therefore, in reducing its stiffness thus decreasing flutter speed.

This paper shows the methods of research into SSJ100 aircraft flutter and steps based on the analysis of research results, which have been taken to increase the critical speed of the determining flutter mode to ensure the required flutter speed margins.

1 INTRODUCTION

The Central Aerohydrodynamic Institute (TsAGI) and the Suchoi Civil Aircraft Corporation (SCAC) started working on safety from flutter of the Suchoi SSJ-100 in 2004, alongside with all the other design activities. Appropriate mathematical model of the airplane was created on the base of beam approximation (stick model), and preliminary flutter analysis of the full-scale aircraft was carried out using dedicated in-house RIF software package.

Meanwhile similar researches were being performed by SCAC using another software code, named KS. This approach is considered to be the most efficient since RIF code provides well enough analysis of flutter involving main lifting surfaces (wing and empennage), while KS is effective in analysis of control surface flutter.

However flutter safety of such an aircraft type also have to be proved experimentally. So far the so-called pod-and-spar dynamically scaled models have been successfully used for this purpose.

The Analysis included determination of flutter boundaries for the whole aircraft and control surface flutter taking into account possible deterioration of aircraft structural properties (e.g. stiffness variation).

Experiments to ensure flutter safety included:

1. Creation of a dynamically scaled model.

2. Ground vibration tests (GVT) and wind tunnel flutter tests of the dynamically scaled model in TsAGI T-104 wind tunnel (Fig.1).

Figure 1

3. Full-scale aircraft GVT

4. Stiffness measurements and GVT of the full-scale "SaM146 engine – Pylon" isolated system installed on a rigid pillar. (Fig.2).

Figure 2

5. Determination of inertial characteristics of full-scale control surfaces.

6. Flutter flight tests of the SSJ-100 (Fig. 3).

Figure 3

2 ANALITYCAL AND EXPERIMENTAL STUDIES OF SSJ 100 AIRCRAFT FLUTTER

2.1 Analytical researches

Analysis was carried out with the aid of TsAGI in-house RIF software code. The results are shown below in the figures, where the mass of the flutter-preventive weight in horizontal axis corresponds to 2% of wing weight in one half of the wing.

Dependence of flutter speed on the mass of flutter-preventive weight installed at the wing tip is shown in figs. 4-9 for different fuel weight and 100% of payload. The lowest flutter mode is the bending-torsion wing flutter which is in phase with pitching oscillations of the engine. The next flutter mode is due to the wing 2nd bending/torsion coupling. This mode has sufficient flutter margin for the considered structural parameters.

The most interesting research results are demonstrated further.

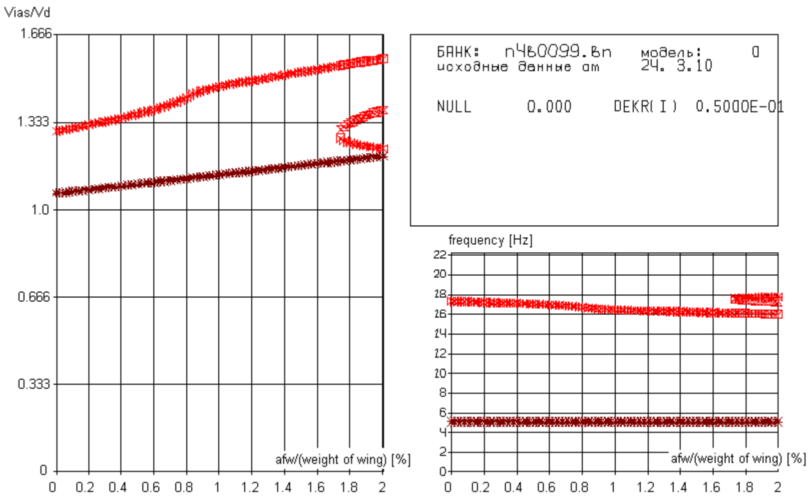

Figure 4: Flutter critical speed vs. the mass of anti-flutter weight.
0% of fuel and 100% of payload

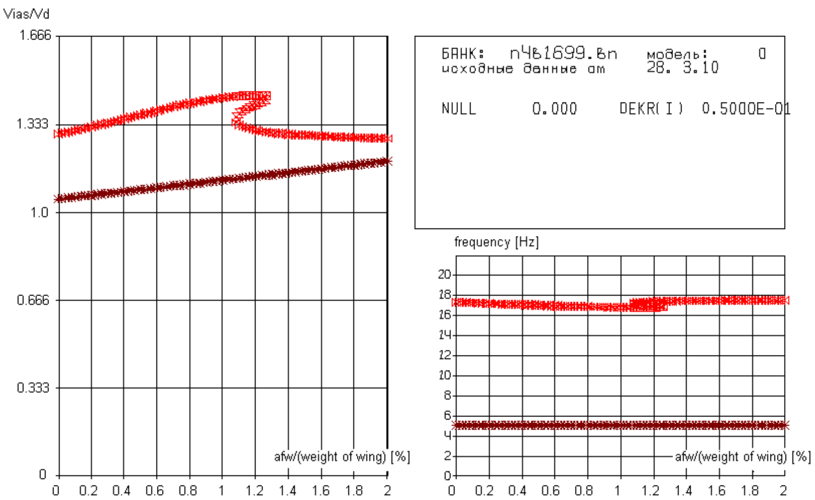

Figure 5: Flutter speed vs. the mass of anti-flutter weight.
16% of fuel and 100% of payload

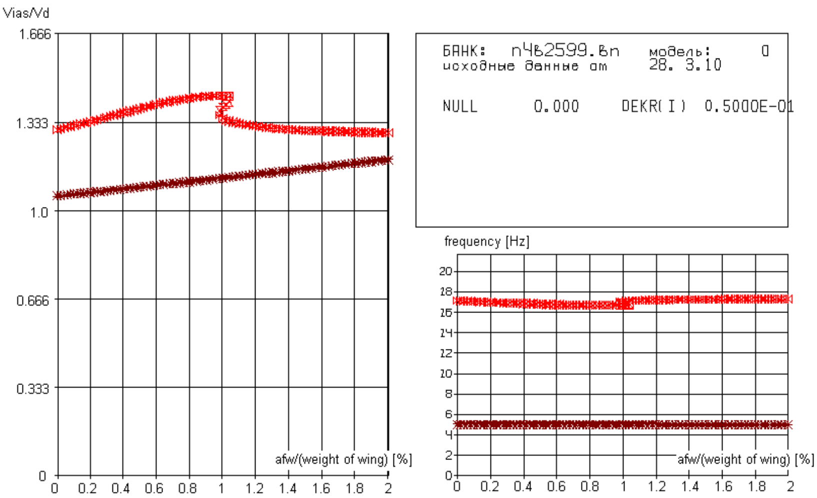

Figure 6: Flutter speed vs. the mass of anti-flutter weight.
25% of fuel and 100% of payload

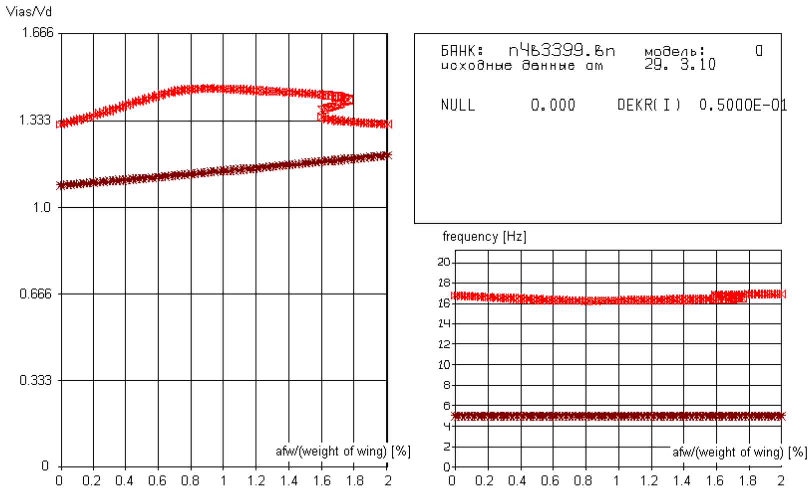

Figure 7: Flutter speed vs. the mass of anti-flutter weight.
33% of fuel and 100% of payload

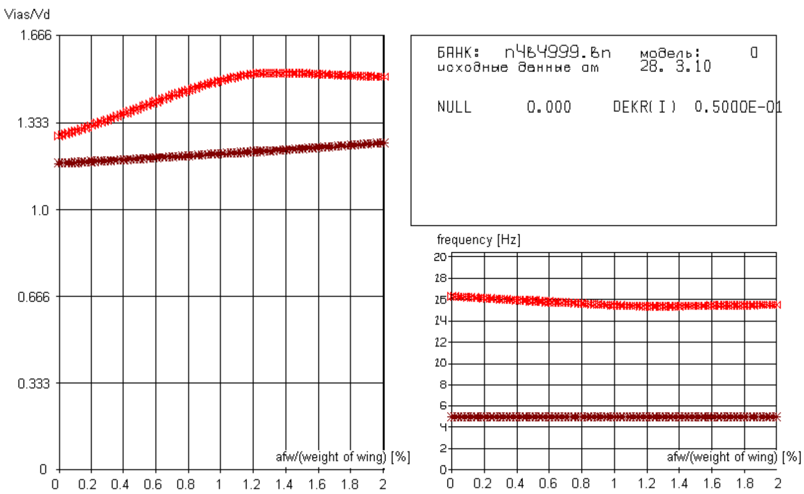

Figure 8: Flutter speed vs. the mass of anti-flutter weight.
49% of fuel and 100% of payload

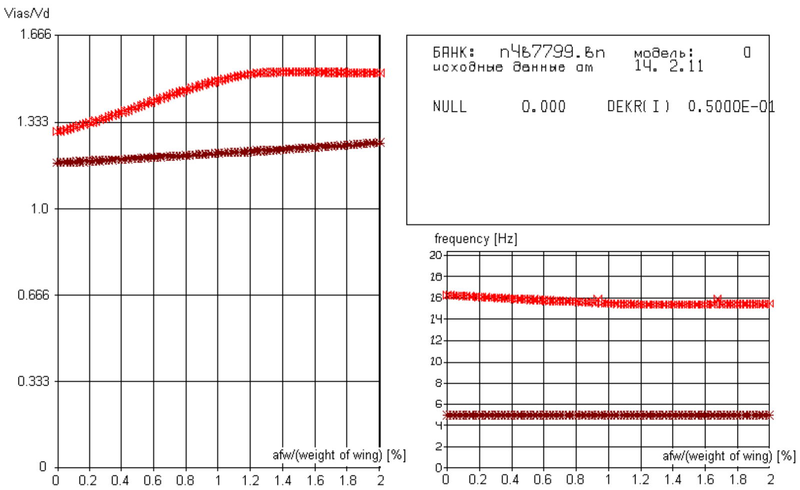

Figure 9: Flutter speed vs. the mass of anti-flutter weight.
77% of fuel and 100% of payload

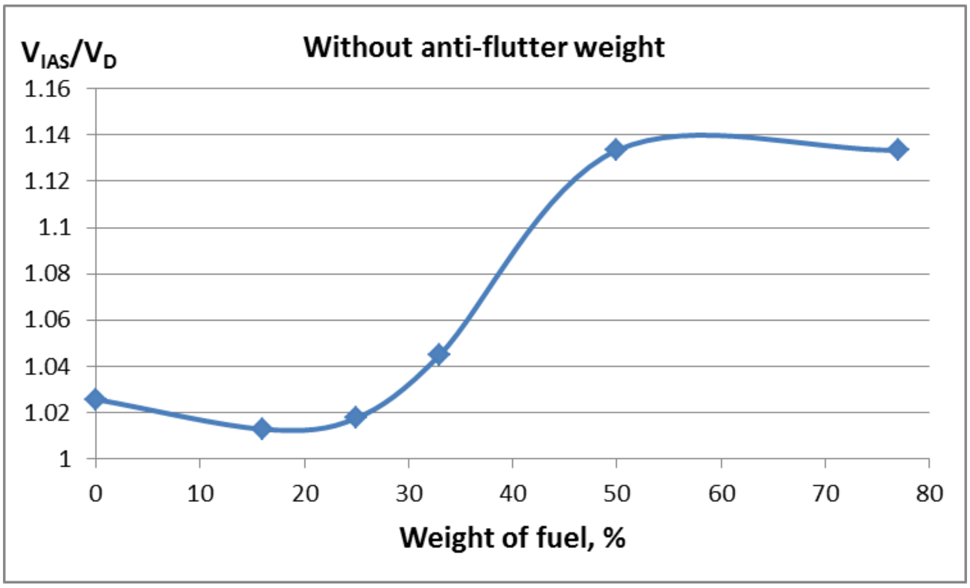

Figure 10: Flutter critical speed vs. fuel mass. 100% of payload

Similar calculations were also carried out for 0% of payload. These results are not presented here as flutter margin is sufficiently high in this case.

2.2 Experimental studies

A dynamically scaled model of the whole aircraft was designed and manufactured for flutter and static aeroelasticity studies in low speed wind tunnel to provide the safety of the SSJ-100 aircraft.

The model underwent a series of tests with large volume of parametric studies to reveal all possible flutter modes. The tests have shown that the so-called "engine" flutter mode with insufficient flutter margins is critical for the aircraft.

The work done revealed the need for certain improvements of the model. The improvements were dictated by the data obtained from the following:

1) more precise determination of bending and torsional stiffness along the elasticity axis of the wing;

2) determination of inertial characteristics of full-scale control surfaces (aileron, elevator, rudder);

3) ground vibration tests of full SSJ 100 aircraft;

4) ground vibration tests and stiffness measurements of the "pylon-engine" system installed on a rigid pillar;

5) stiffness tests of the airframe of the SSJ-100 aircraft.

All the test results are demonstrated hereafter for the finally approved scaled model.

The model and full-scale frequencies for the first symmetric and antisymmetric vibration modes are compared in Tables 1 and 2.

Title of mode	K*, %
Oscillation around the Z axis	196
1-st wing bending	105
engine movement on Z	109
engine movement on Y	88
1-st fuselage vertical bending	103
1-st horizontal wing bending	73
1-st stabilizer bending	98
2-d wing bending	114
1-st wing torsion	91

Table 1: Comparison of the model and full-scale frequencies for symmetric modes

* $K = f_{\text{of model recalculated for full scale aircraft}} / f_{\text{of full-scale aircraft}}$

Title of mode	K*, %
1-st wing bending	100
engine movement on Z	93
engine movement on Y	107

1-st horizontal wing bending	101
1-st stabilizer bending	99
1-st vertical tail bending	96
1-st horizontal fuselage bending	94.5
2-d wing bending	100
1-st wing torsion	92

Table 2: Comparison of the model and full-scale frequencies for antisymmetric modes

* K = f of model recalculated for full scale aircraft / f of full-scale aircraft

3 WIND TUNNEL FLUTTER TEST RESULT

The tests were carried out in the test section of a low speed (subsonic) wind tunnel. The model was hung on a dedicated "floating" suspension system. A significant volume of the whole tunnel program was devoted to studies of the critical "engine pitch" flutter mode. Numerous variations of engines pitching frequency for different fuel weight in tanks and payload in the fuselage were made. The lowest critical flutter speed about 1.01 V_D was obtained for 20% of fuel and 100% of payload. Pitching oscillation frequency varied within 0.93-1.06 range of the initial frequency (f_i) (Figs.11, 12). Since the low value of the critical speed for this mode was unacceptable, it was necessary to find out the ways to increase it.

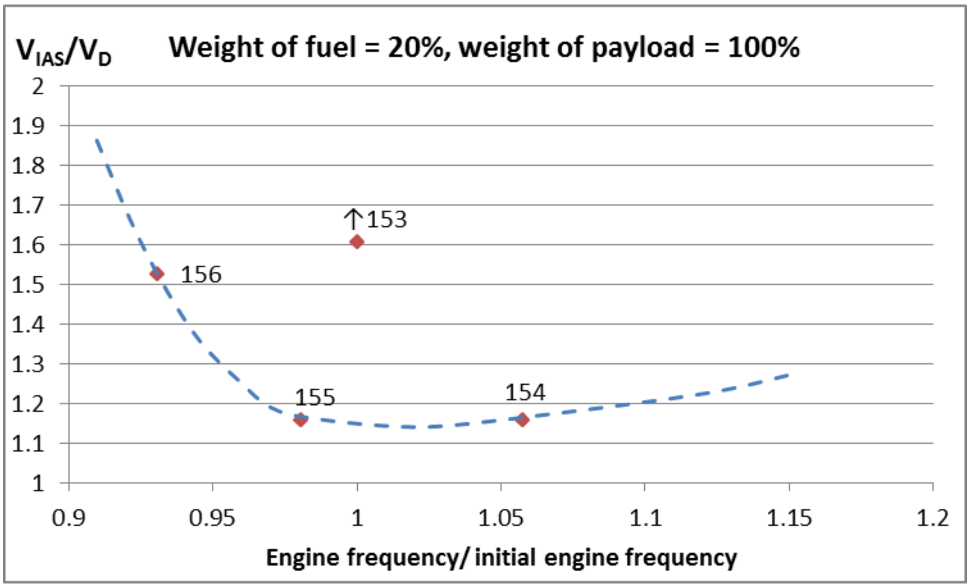

Figure 11

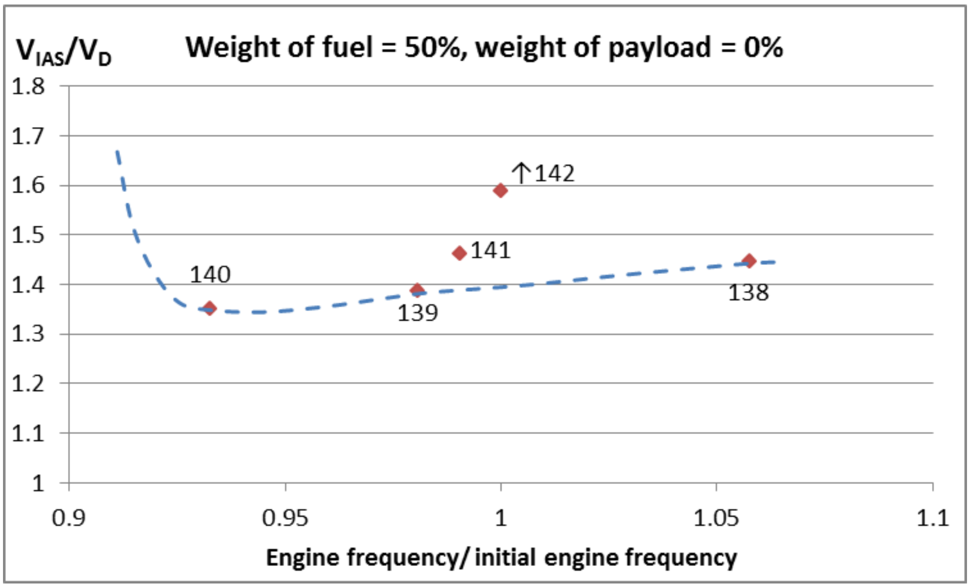

Figure 12

One of the traditional ways to increase flutter speed is the installation of a flutter-preventive weight at the end of the wing. This weight decreases wing bending frequency, thus torsional/bending frequencies ratio increases.

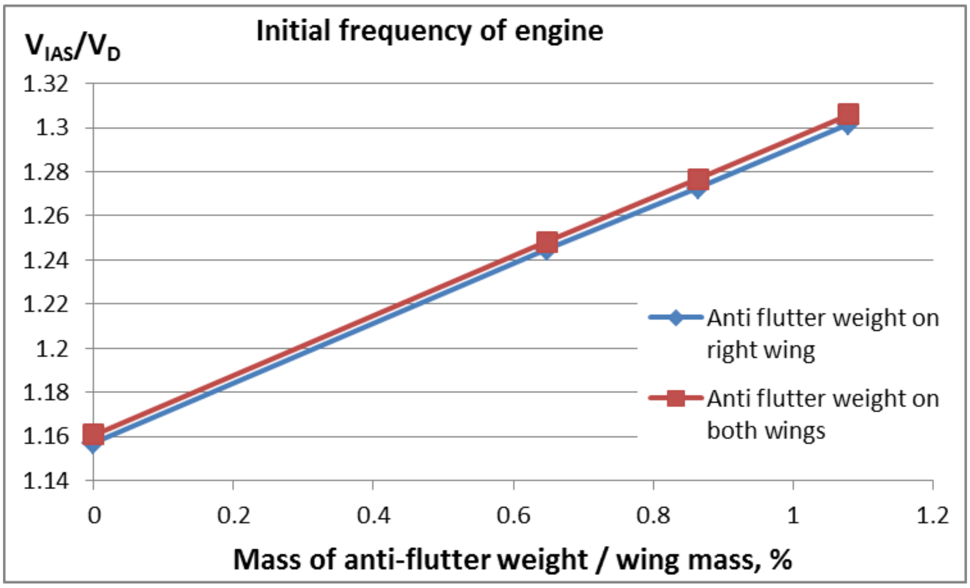

Figure 13

Figure 13 shows the curves corresponding to the installation of one or two flutter-preventive weights on the aircraft. Experiments show real opportunity to increase critical flutter speed with the aid of a flutter-preventive weight in one half of the wing which gives beneficial changes of the symmetrical flutter mode.

Also of interest is the flutter speed increase by means of asymmetrical pylon stiffness. For example, providing the left and right pylons pitch frequency is 1.06 f_i and 0.93 f_i accordingly, the flutter speed will exceed 1.45 V_D (Fig. 12).

It should be noted that any design asymmetry requires upgrade of the aircraft structure and appropriate researches on static and fatigue strength. For the considered aircraft type, two anti-flutter weights were installed on the right and left wing tips; 0.84% of wing weight of each mass was chosen on the basis of the test and analysis results.

4 FLUTTER TESTS OF TAIL CONTROLS

Flutter tests of the tail control surfaces were carried out using the same dynamically scaled model.

For stabilizer, the stabilizer bending/elevator rotation flutter features high parameter margin (for elevator rotation frequency), and tail torsion/elevator rotation flutter has sufficient speed margin.

Fin/rudder flutter performance is similar to the stabilizer.

During tail flutter tests, the springs simulating right and left engine pylons at the model had different stiffness, so pitching frequency for one engine was 1.06 f_i, and 0.93 f_i for the other. This was done deliberately to increase critical speed of engine pitch flutter mode that interfere and impeded proper detection of the tail flutter modes. The results are presented in Figs.14, 15.

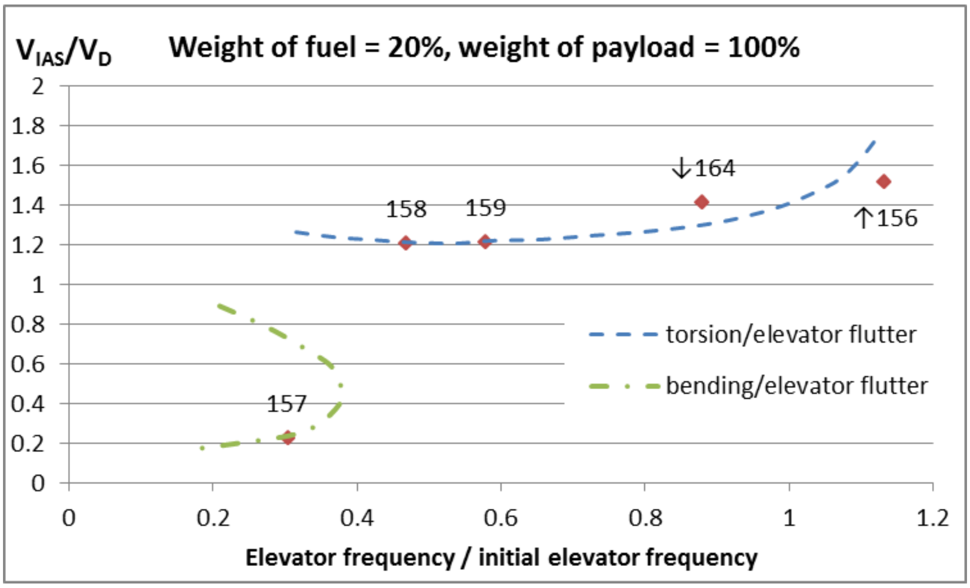

Figure 14

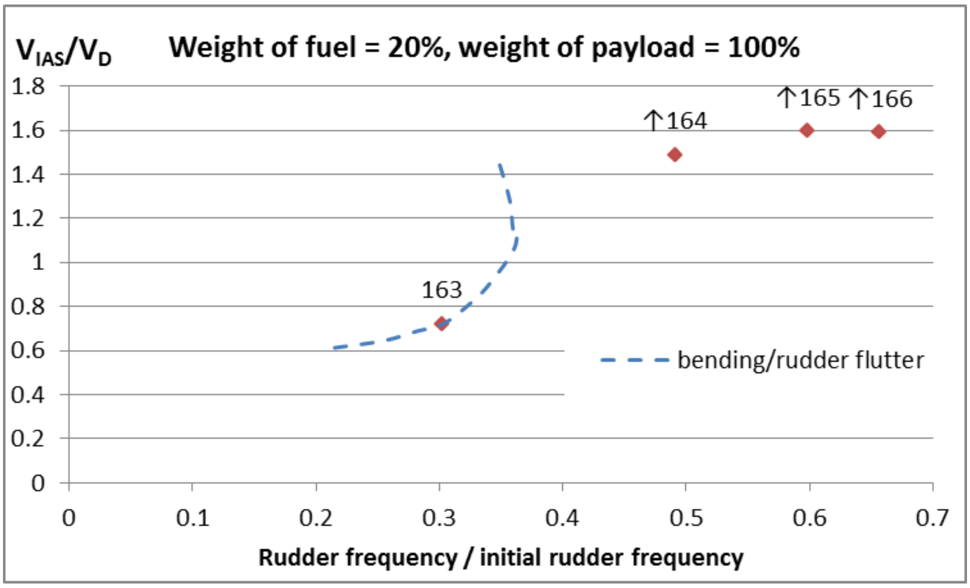

Figure 15

5 FULL SCALE FLIGHT FLUTTER TESTS

The flight flutter tests included two stages.

In the first stage the flight velocity and Mach number varied within the range:

$V_{IAS} = 0.64 \div 1.06\ V_D$;

$M = 0.62 \div 0.88$.

In the second stage the velocity range was: $V_{IAS} = 1.06 \div 1.125\ V_D$.

The tests were carried out with minimum fuel weight.

Frequencies and damping of the main vibration modes were determined on the basis of structural response to the applied excitation.

Frequency-based method (FRF measurements) and decay sine oscillations method (after sudden drop of tuned sine excitation) were used.

Figures 16-20 show recorded acceleration time histories in the nose part of the left and right engines at aircraft speed 1.117, 1.122 and 1.125 of V_D.

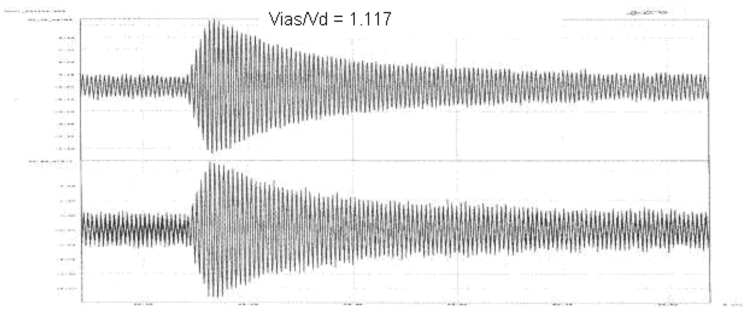

Figure 16

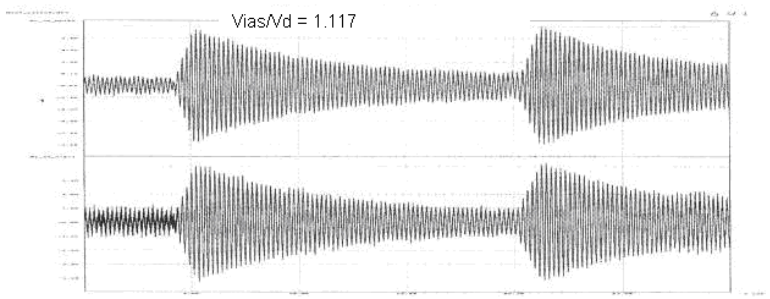

Figure 17

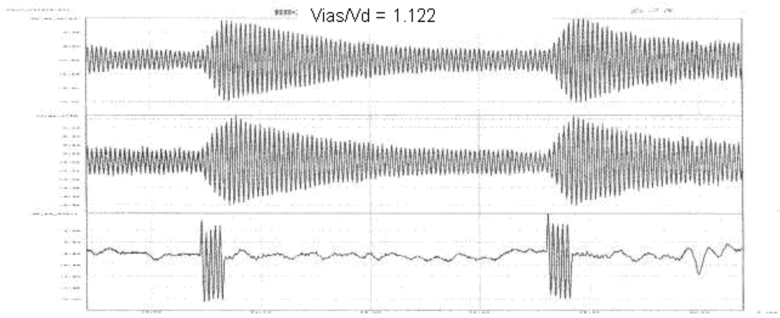

Figure 18

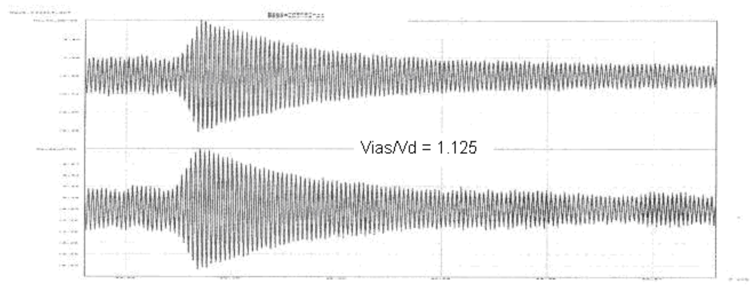

Figure 19

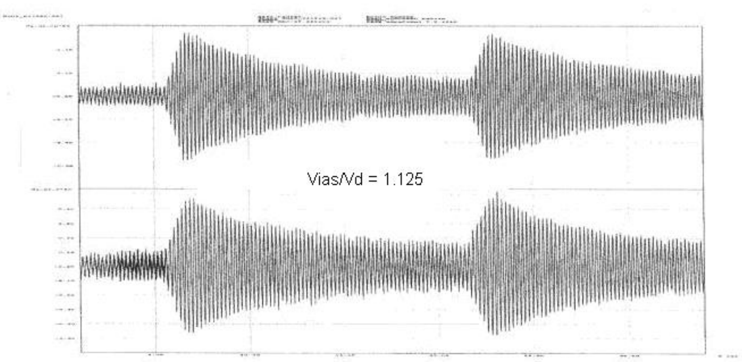

Figure 20

The major results of the flight tests are as follows:

- The critical flutter mode involves engine pitch motion with wing bending.

- For minimum aircraft weight G_{min}, flutter mode damping in terms of g varies from 0.025 at V_{IAS}=0.96 V_D to 0.02 on the average when V_{IAS} is in the range between 1.0 V_D and 1.06 V_D, and g falls down to 0.01 at V_{IAS}=1.125 V_D.
- For maximum aircraft weight G_{max}, no damping decrease was detected up to 1.125 V_D;
- Bending vibration modes of the horizontal tail and the fin features sufficiently high damping within the examined flight envelope.

6 SURVEY OF THE OBTAINED RESULT

The following conclusions based on the analytical and test researches can be drawn:

1. The aircraft with 20% fuel weight and 100% payload weight features the lowest flutter speed.
2. The critical flutter speed can be increased by flutter-preventive weights in wing tips.
3. 1 kg mass of flutter-preventive weight increases the flutter speed in average by 0.64% of V_D.
4. To ensure sufficient flutter speed margin the mass of flutter-preventive weights which installed in each wing tip should be equal to 0.84% of wing mass.

The summary diagram is shown in Fig. 21.

The payload weight is 100%.

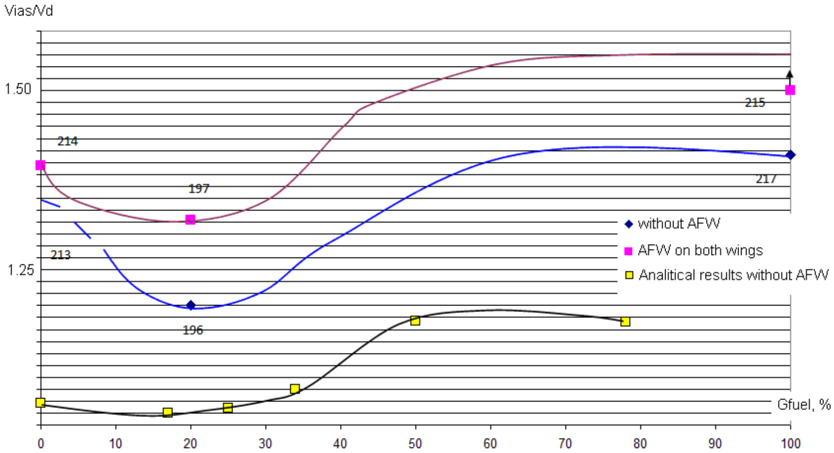

Figure 21: Influence of the wing fuel weight on flutter speed

The following three curves illustrate the dependence of “engine” flutter speed on fuel weight.

The top one is drawn through the test points for the dynamically scaled model simulating 100% payload weight and weight of flutter-preventive weights equaled to 0.84% weight of wing. Fuel weight varies from 0 to 100%. There is the dip for fuel weight in 15–25% range. Minimum flutter speed is about 1.27 V_D.

The middle curve almost repeats the top one but for the model without flutter-preventive weights. In this case minimum flutter speed is 1.157 V_D.

The bottom curve show analysis results for 100% payload and without flutter-preventive weights. It shifted down but generally is similar to the two experimental curves.

We should take into account that the analysis employed a steady aerodynamic theory, which results in about 20% decrease of flutter speed.

The results of flutter tests of the dynamically scaled model are in good agreement with the analysis and flight tests results.

7 COPYRIGHT STATEMENT