PECULIARITIES OF AIRCRAFT VARIABLE LOADING AND VIBRATION SUPPRESSION ABILITIES

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Abstract: The contribution of the stages of flight with appreciable separated flows (a flaps extension and a slowdown by spoilers) in a cumulative fatigue damage of an airframe is demonstrated. Possibilities of the vibrations suppression caused by separated flows are shown. The results of analytical and experimental researches to increase the fatigue characteristics of an aircraft by means of loads alleviation system are described. Capabilities of loads exceedances reduction during ground operations by optimization of shock absorption characteristics are shown.

1 INFLUENCE OF FLIGHT STAGES WITH APPRECIABLE STALLED FLOWS ON FATIGUE DAMAGES

It is considered traditionally that variable loads which act on a plane and define it’s fatigue characteristics, are mainly 1-g loads which are changed during different stages of flight, maneuver loads, loads due to atmospheric turbulence and roughness of taxiways and runways.

The researches of in-flight strain gauge measurements show that separated flows caused by deflection of spoilers, flaps and slats in air and on the ground (when air-brake flaps and thrust reverse are used during landing run) give a growth of construction vibrations and essential contribution to fatigue damages accumulation. The analytical methods of researching of variable loads caused by stalled flows haven’t been sufficiently developed. The aim of this work is to detect the regularities of such loading on the basis of experimental materials and show the possibilities of alleviation of these vibrations.

The main part of construction which determines the fatigue service life of an aircraft according to conditions of fatigue strength is, as a rule, the lower panels of a wing, the main load is a bending moment. As a rule, decrease of variable loads on a wing (vibration suppression) leads to decreasing of loads on other parts of a structure, e.g. load factors on a fuselage are being reduced (the comfort is being improved). It is important to know the contributions of various stages of flight into fatigue damage when active systems of variable loads suppression are under design. It is necessary to choose type of a control signal (for example, vertical load factor), a place where the sensor should be installed, correlation of this signal with a load which is minimized, frequency range of an automatic control system (ACS) activity. It is necessary to know amplitude-frequency responses of the load and the sensor signal to an angle of a deviation of a control surface (e.g. an aileron, an elevation rudder). The optimum control law of an active ACS should reduce loads as much as possible, and its amplitude-frequency response of the angle of a deviation of a control surface caused by the sensor signal should be within the aeroelastic stability.

The example of time history of a bending moment during different stages of flight in a root wing section is shown in Fig.1. The contribution of flight stages into cumulative fatigue damage of the upper and lower panels of a wing caused by bending moment in this section is given in a Fig.2 (average cumulative damages were obtained through the processing of several flights). Correlation between a bending moment in root wing section and vertical load factor in the aircraft center of gravity for a slowdown by spoilers with retracted slats and flaps is analyzed. The spectral densities of these loads are given in a Fig.3. It shows that low frequencies (less than 3 Hz) give essential contribution to loads and therefore to fatigue damage accumulation. Coherence function in Fig.4 shows that the bending moment is considerably linearly correlated with the load factor up to 3 Hz frequency. The amplitude of a frequency response of the bending moment to the load factor and the phase difference between these loads are shown in Fig.5. The similar behavior of a loading has been detected and for a number of other stages determining fatigue damage of a wing (Figs. 6–8 are obtained for a flight in atmospheric turbulence, Figs. 9–11 – for flaps down departure).

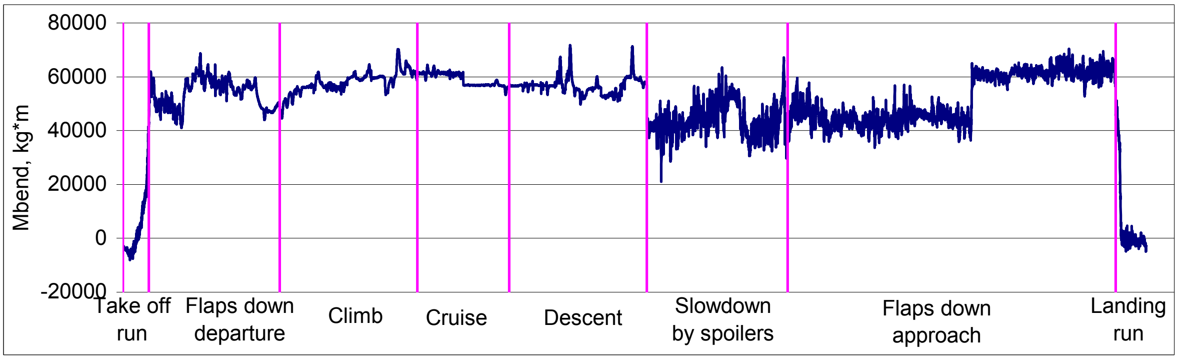

Figure 1: Changing of the wing bending moment in a root section during flight stages

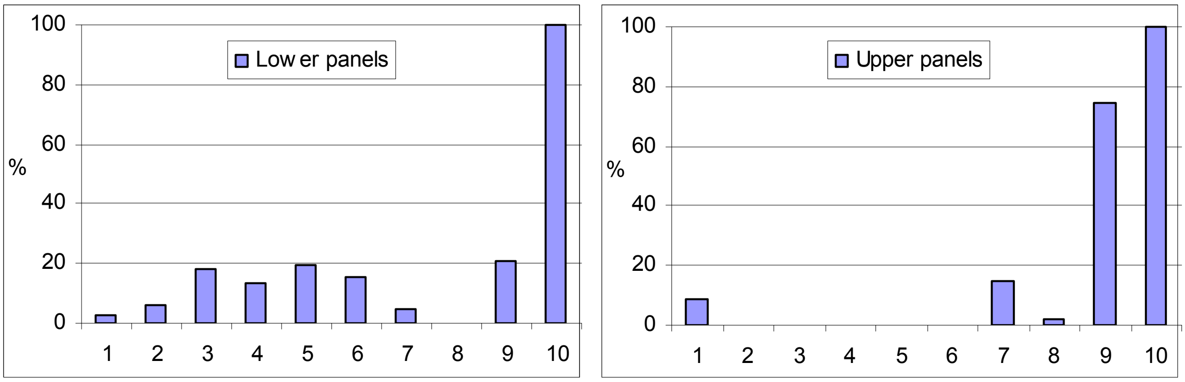

Figure 2: The contribution (%) of flight stages in cumulative fatigue damages of lower and upper wing panels (1 – takeoff; 2 – flaps down departure; 3 – flight with retracted flaps and spoilers (turbulence, analytical researches); 4 – slowdown by spoilers with retracted flaps; 5 – slowdown by spoilers with flaps deflection; 6 – Flaps down approach; 7 – landing run with thrust reverse; 8 – taxi; 9 – Ground-Air-Ground cycle; 10 – total flight)

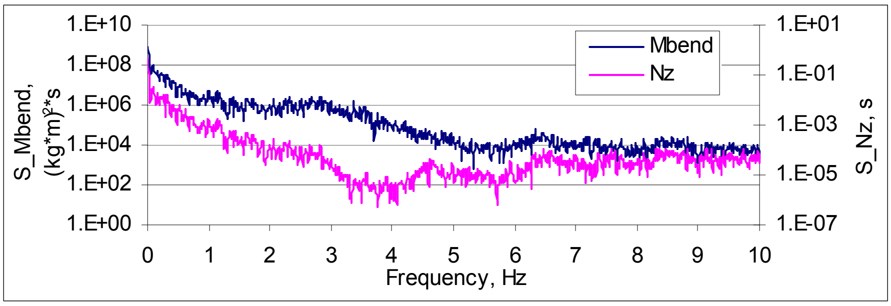

Figure 3: The spectral densities of wing bending moment and vertical load factor in aircraft center of gravity. The slowdown by spoilers stage

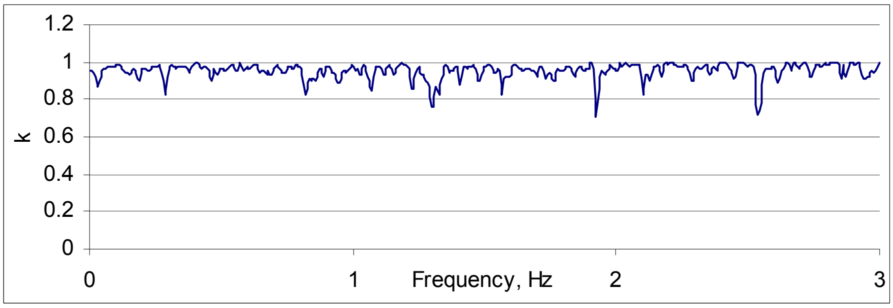

Figure 4: The coherence function between the wing bending moment and the vertical load factor. The slowdown by spoilers stage

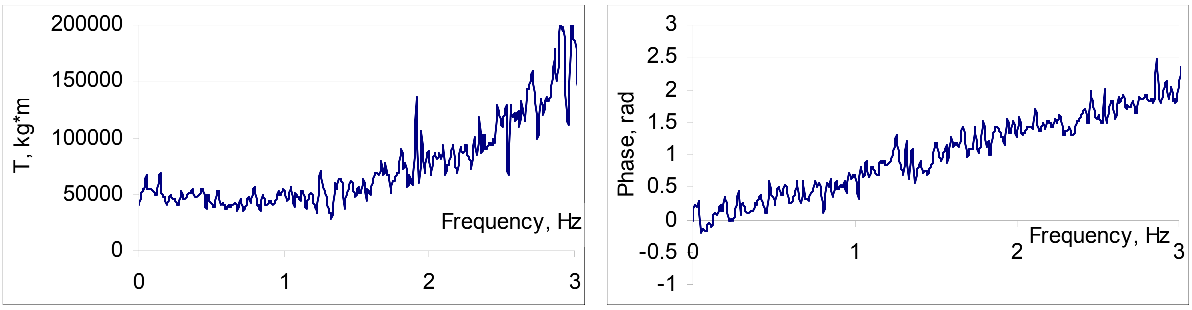

Figure 5: Amplitude-phase frequency response of the wing bending moment to the vertical load factor. The slowdown by spoilers stage

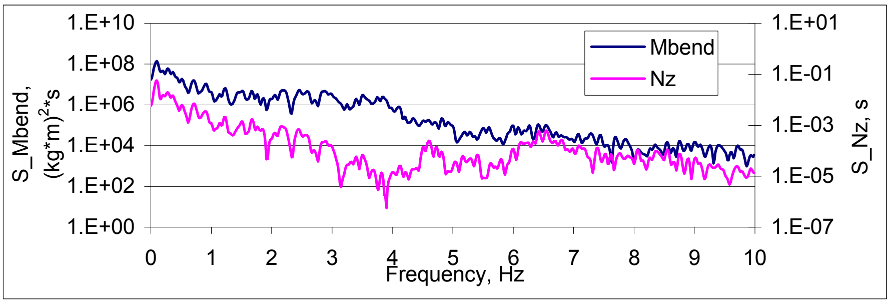

Figure 6: The spectral densities of wing bending moment and a vertical load factor in the aircraft center of gravity. Flight in turbulence. Flaps and spoilers are retracted

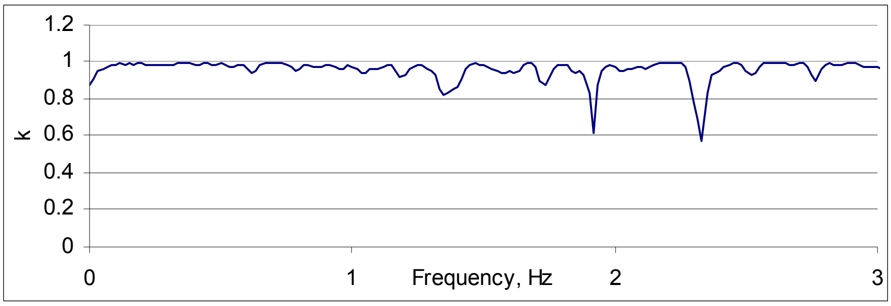

Figure 7: The coherence function between the wing bending moment and the vertical load factor. Flight in turbulence. Flaps and spoilers are retracted

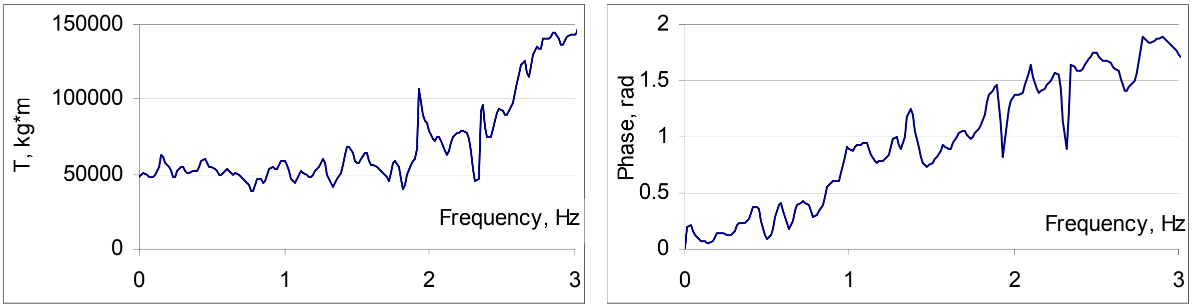

Figure 8: Amplitude-phase frequency response of the wing bending moment to the vertical load factor. Flight in turbulence. Flaps and spoilers are retracted

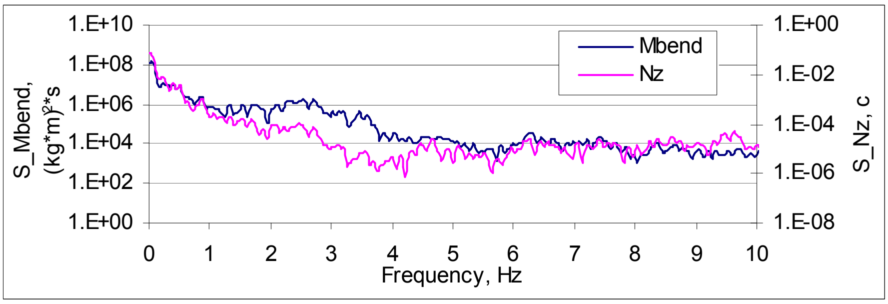

Figure 9: The spectral densities of a wing bending moment and a vertical load factor in the aircraft center of gravity. Flaps down departure

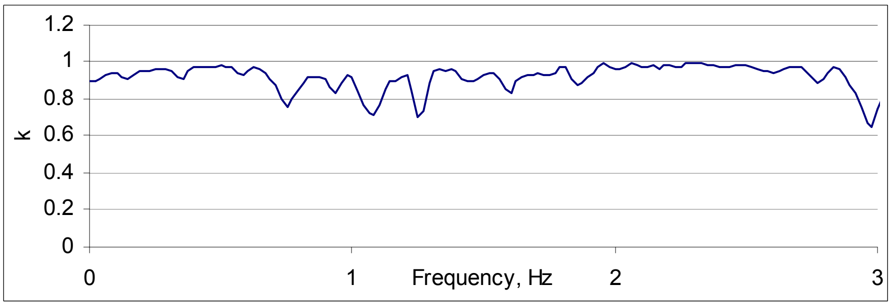

Figure 10: The coherence function between the wing bending moment and the vertical load factor. Flaps down departure

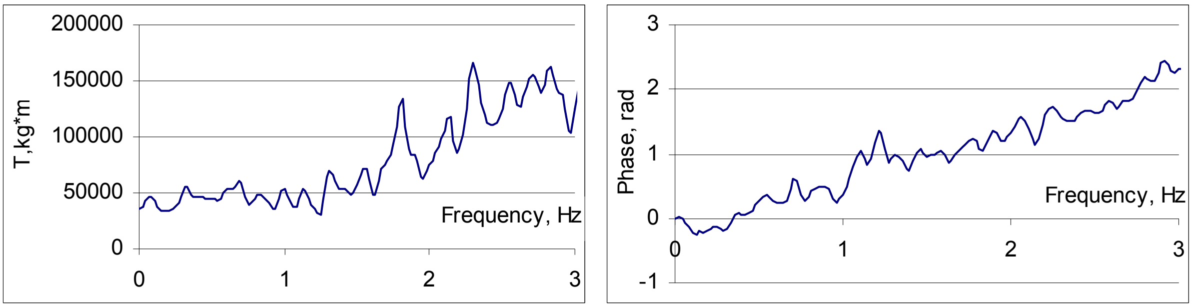

Figure 11: Amplitude-phase frequency response of the wing bending moment to the vertical load factor. Flaps down departure

Correlation between bending moment in some sections of a vertical tail and a lateral load factor in an aircraft center of gravity is analyzed. The time history of a bending moment in a root section of a vertical tail which was recorded during one flight (Figure 12) shows that as in the case with a wing the greatest contribution in fatigue damage give air stages with deflected spoilers and extended slats and flaps and also the landing run stage. The average fatigue damages in percent for different stages of flight are shown in the Figure 13. The correlation between bending moment and lateral load factor for a slowdown by spoilers stage is shown in Figures 14-16. The correlations for other stages of flight are similar.

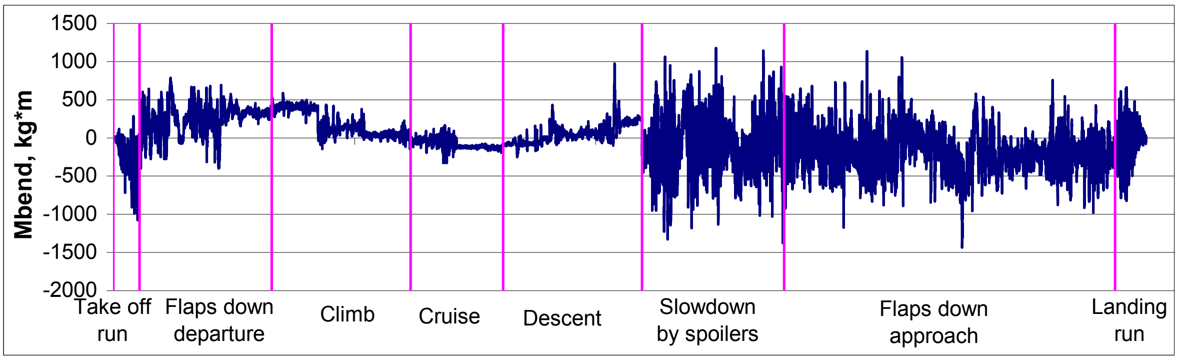

Figure 12: Changing of the bending moment in a root section of a vertical tail during flight stages

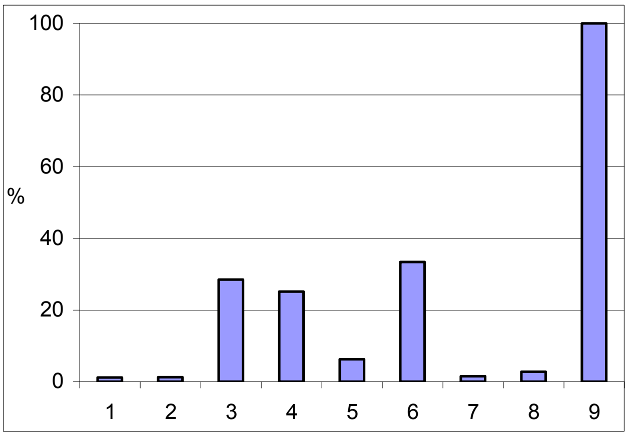

Figure 13: The contribution (%) of flight stages in cumulative fatigue damages of panels in a root section of vertical tail (1 – takeoff; 2 – flaps down departure; 3 – flight with retracted flaps and spoilers (turbulence, analytical researches); 4 – slowdown by spoilers with retracted flaps; 5 – Flaps down approach; 6 – landing run with thrust reverse; 7 – taxi; 8 – Ground-Air-Ground cycle; 9 – total flight)

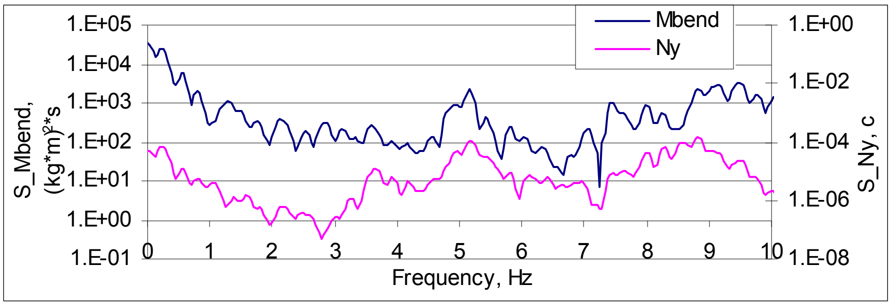

Figure 14: The spectral densities of a vertical tail bending moment and a lateral load factor in an center of gravity. The slowdown by spoilers stage

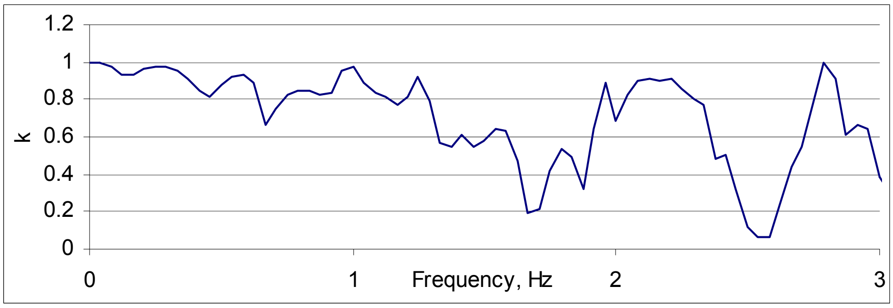

Figure 15: The coherence function between the vertical tail bending moment and the lateral load factor. The slowdown by spoilers stage

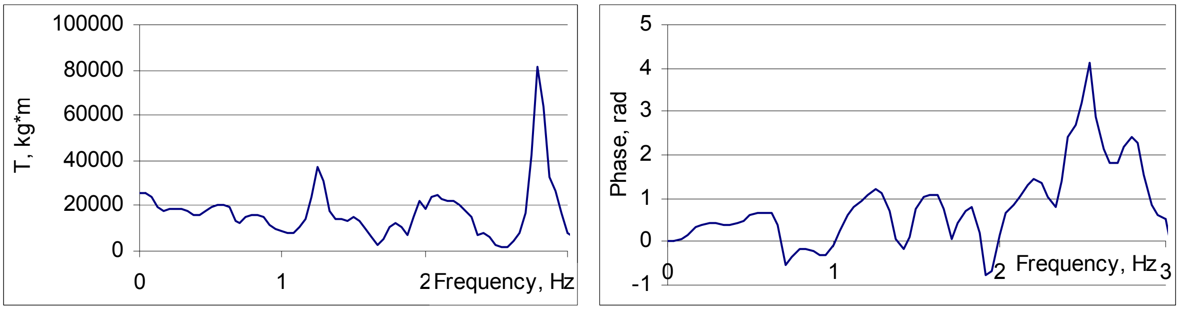

Figure 16: Amplitude-phase frequency response of the vertical tail bending moment to the lateral load factor. The slowdown by spoilers stage

The following conclusions were made after analysis of these materials:

1. The main contribution into cumulative fatigue damage is given by variable loads with frequencies less than 1.5-3.0 Hz.

2. Separated flows cause asymmetrical loading.

3. The loads in this frequency range are correlated with vertical and lateral load factors in an aircraft center of mass;

4. It is possible to choose laws of active channels of automatic control system being designed to decrease loads caused by atmospheric turbulence which also will be effective in cases of separated flows of the wing (during air stages of deflection of spoilers and flaps). Frequency range of the symmetric channel is 0-3 Hz, a control signal is vertical load factor, damping is fulfilled by a symmetric deflection of ailerons (and elevator for balancing). Frequency range of the antisymmetric channel is 0-1 Hz,

a control signal is a lateral load factor, and the damping is fulfilled by a deflection of a rudder and antisymmetric deflection of ailerons.

5. Preliminary estimations of ACS's active channels efficiency show a possibility to decrease fatigue damage of the lower panel of a wing by 4 times for flight in whole for metal parts of a construction (while angles of a deflection of control surfaces are several degrees and velocities of actuators are existing; fail - safe demands are minimum). The efficiency of such system to reduce the fatigue damage of composite elements will be by dozens higher.

2 THE POSSIBILITIES OF ACTIVE LOAD ALLEVIATION SYSTEMS

The spectral densities of bending moment in a wing section of an Il-86 aircraft during flight in turbulent atmosphere with turned on and turned off load alleviation system are given in Fig.17. This figure shows that this system gives essential decrease of oscillation at frequencies of rigid body and at first elastic modes. The same results were obtained through analytical researches.

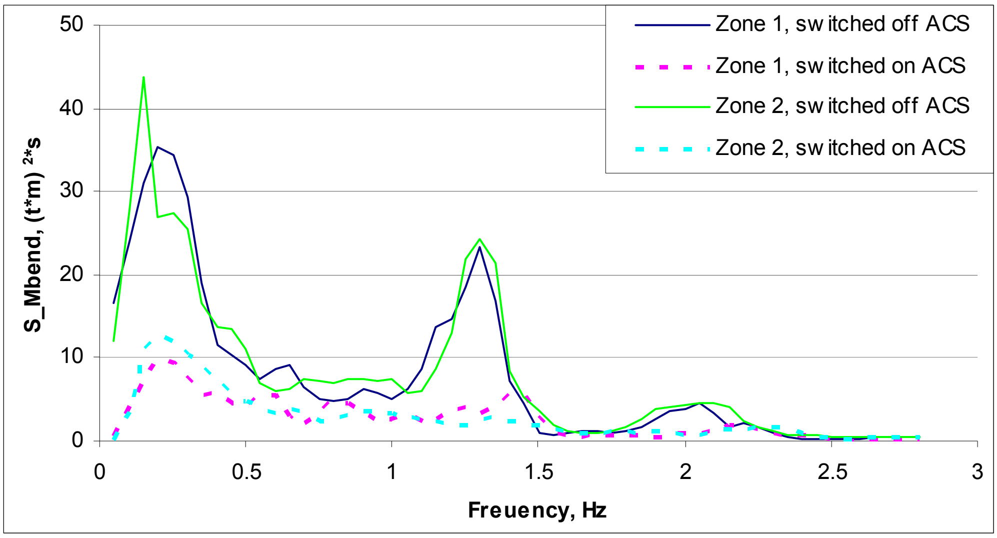

Figure 17: Il-86. Flight test. Effects of turbulence. Spectral densities of bending moment in a wing section

The rational structure and control laws of active loads alleviation system were determined for a passenger mid-range aircraft. The efficiency of such system to decrease the frequency of bending moment in wing sections (and appropriate fatigue damage of lower panels of wing) is demonstrated by Fig.18. This figure shows the relation of fatigue damages along wing span to the damages when system is turned off. Fatigue damages were calculated for air stages of flight taking into account effects of multidimensional atmospheric turbulence and for all flight including ground stages. We can see, for example, that this system reduce fatigue damage caused by atmospheric turbulence in wing root sections by three times and by two times for flight in whole (the effects of separated flows weren't taken into account in these researches).

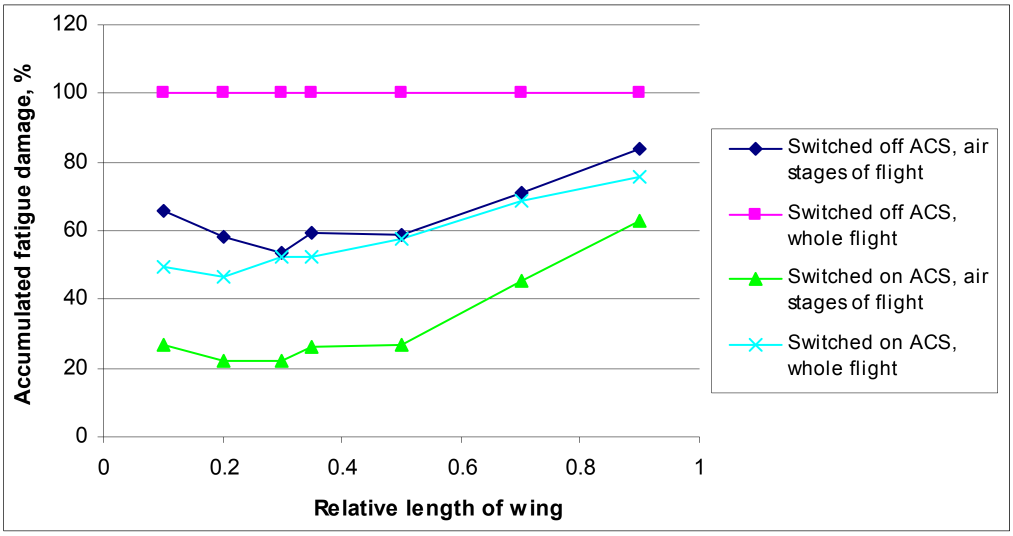

Figure 18: The relation of fatigue damages along wingspan caused by bending moment to damages in flight when loads alleviation system (LAS) is switched off

The described above influence of loads alleviation and controllability and stability augmentation channels of an ACS on fatigue damage was researched for metal components of construction when the power of *S-N* curve is about 4. The analysis of efficiency of active systems shows that calculated (from the point of view of the static strength) values of bending moments on a wing for cases of maneuvers, effects of a discrete gust and continuous turbulence decrease by 10%–20%. And demands to residual strength of the damaged construction are reduced by 10%–20%.

More detailed comparison of cumulative fatigue damages in wing section of a passenger mid-range airplane caused by atmospheric turbulence during a descent stage of the typical flight is given below. The influence of ACS on composite materials of the aircraft was estimated taking into account today's understanding of fatigue damage accumulation physics, properties of composites and their ultimate strength. Critical places for fatigue strength of composites aren’t the lower panels of a wing (as for metal) but the upper panels. The frequency of the normal stresses increments along elastic axis of a wing in the upper panel of a root section of a wing is shown in Fig.19 for switched off and switched on channels of ACS. The comparison of the contribution into cumulative fatigue damage of stresses increments at average compression stress -6.47 kg/mm^2 is shown in Figure 20. Damages were calculated using the data presented in a Figure 19 and “peaks" method. It follows from Figure 20 that a fatigue damage is determined by seldom large loads which occur in a range from once for 100 flights (stages) to once for lifetime. In this example the active ACS reduces fatigue damage of composite structure caused by many-dimensional atmospheric turbulence by hundreds of times.

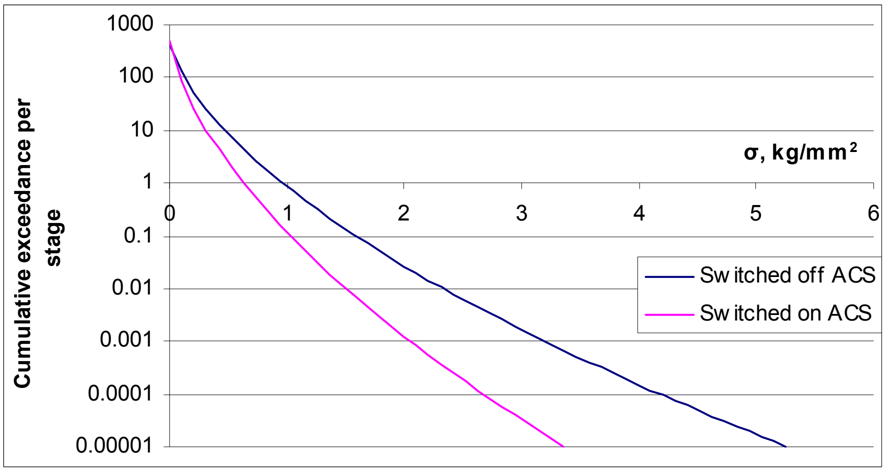

Figure19: Spectra of normal stresses in upper panel of root wing section per descent stage of typical flight

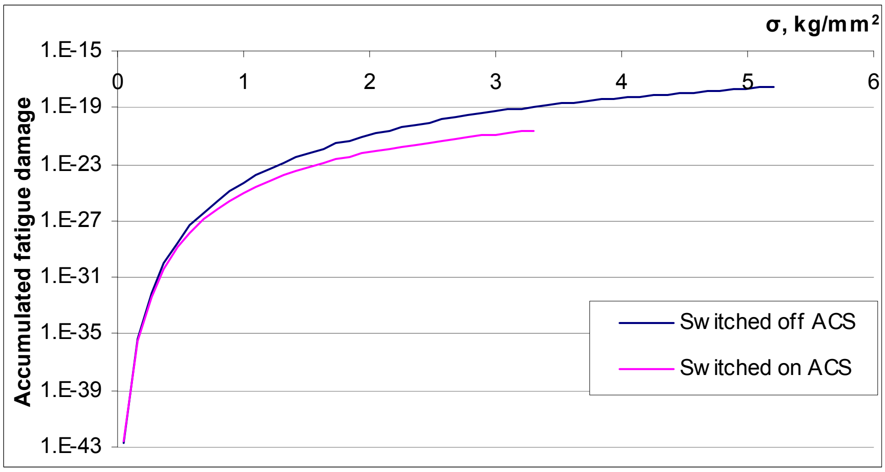

Figure 20: Contribution of stress amplitudes into fatigue damage

3 THE POSSIBILITIES OF LOADS EXCEEDANCES DECREASING FOR GROUND STAGES OF FLIGHT

There are restricted capabilities of aerodynamic damping of vibration during take-off and landing because control surfaces are effective at higher speeds. So it is necessary to give the main attention to optimization of shock absorbers of landing gears to decrease the repeatability of loads during ground stages of flight.

The loads on an airframe and the landing gear of a passenger mid-range aircraft which were measured during ground operations (especially during taxi) showed the necessity the landing gear parameters optimization (for example, decrease of hydraulic forces at standing compression of landing gears). It will give the minimization of repeatability of variable loads and increase of lifetime of an airframe and the landing gears. This is confirmed by Figures 21–24. Variable landing gear compressions are minimal while vertical aircraft accelerations are considerable.

The hydraulic force $P_h = k \cdot \dot{S} \cdot |\dot{S}|$ is proportional to square of the shock strut piston velocity, and the factor *k* for compression (forward) and extension (backward) motions will higher if static compression is higher (relations are given by the designers of the landing gear). The standing compression is 320 mm (80% of total stroke which is 400 mm) and it gives maximal hydraulic forces.

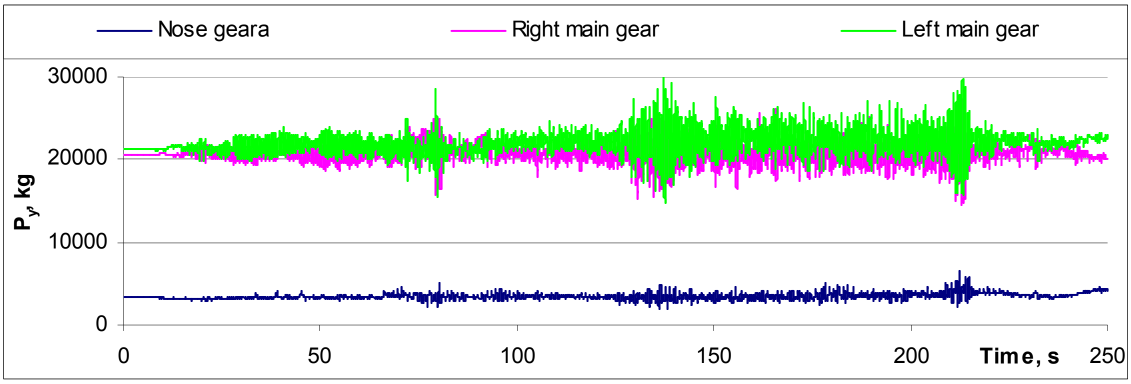

Figure 21: Taxi out. Vertical forces on landing gears

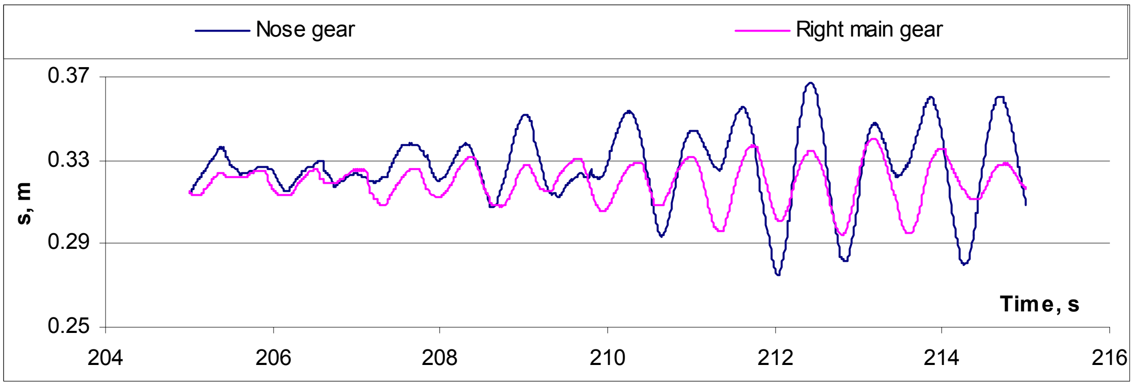

Figure 22: Taxi out. Strokes of landing gears

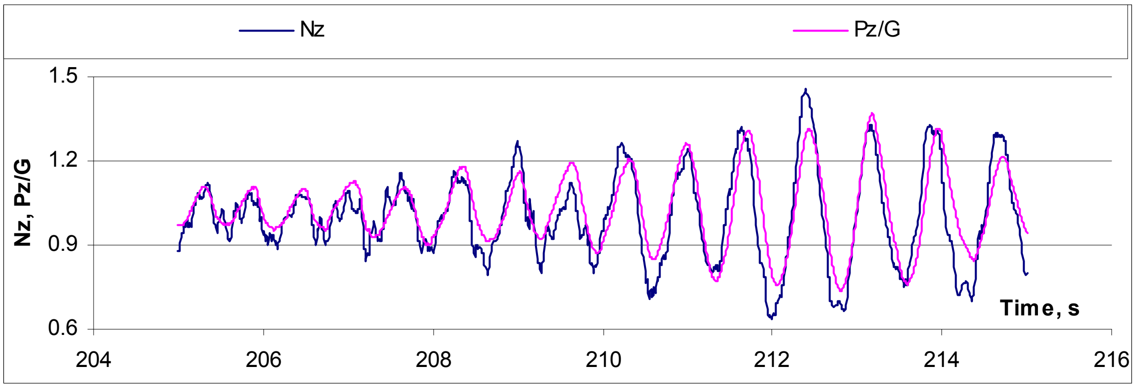

Figure 23: Taxi out. Vertical load factor and sum of vertical forces on landing gears divided by aircraft weight (Pz/G)

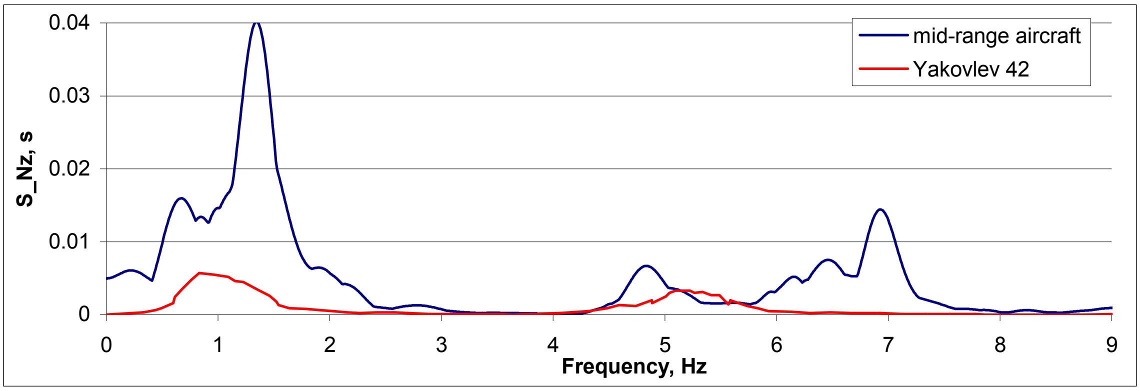

Figure 24: Envelope curve of spectral densities of vertical load factor in aircraft gravity center for ground stages of flight

Fatigue damages caused by variable loads on various parts of the airframe of the considered aircraft (shear forces, bending moments, load factors, loads on landing gears) were calculated for taxiing with various velocities along fragments of runways of several airports (Ramenskoe, Penza, San Francisco), the measured data of irregularities were used. Two cases of take-off and landing configuration with average mass and centre-of-gravity position were chosen. The purpose of examinations was to estimate the decrease of a variable loading if hydraulic forces at standing compressions have been reduced. Having ready-made landing gear this purpose can be achieved by increasing the pressure in the gas chamber (the compression of the gear is reduced and value of k is also decreased). It is possible to implement this procedure in flight tests also ("serious" optimization might cause a modification of needles profiles, etc.).

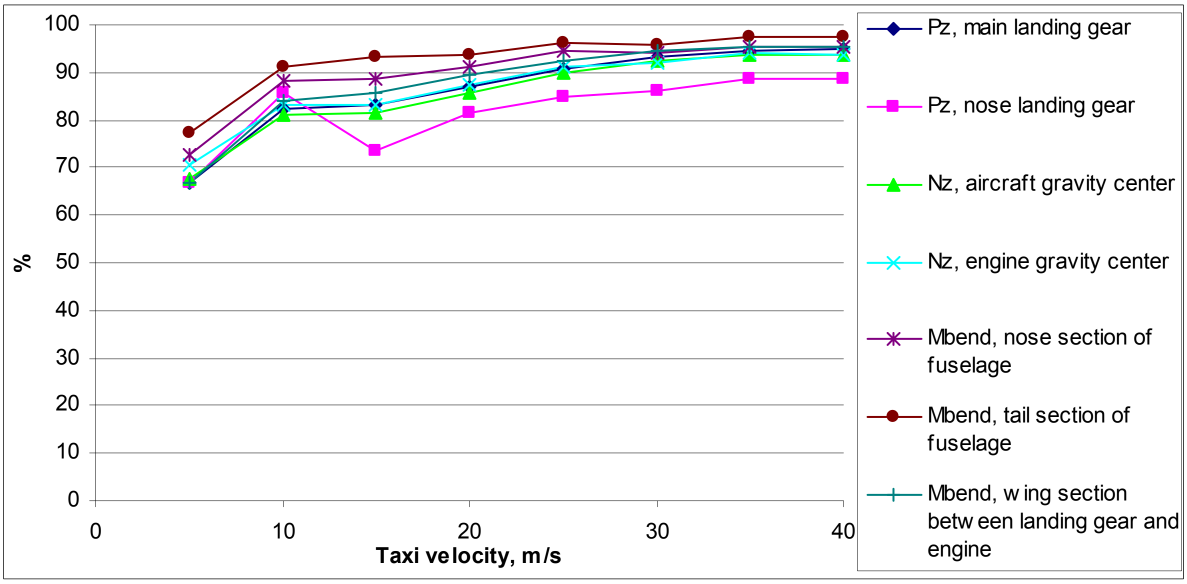

Figure 25: The ratio of fatigue damages at increased pressure in the gas chamber to damages at initial pressure (the extension of gears is 9 mm)

The fatigue damages for increased by 80% pressure in a gas chamber divided by damages at initial pressure are shown in Figure 25. Cumulative fatigue damages caused by vertical force P_z on landing gears, by vertical load factors n_z in an airplane and engine centre of gravity, by vertical bending moments M_{bend} in fuselage and wing sections were considered. If the pressure is increased the main landing gear extends by 9 mm and factor k of hydraulic force for forward motion is decreased by 10% in comparison with initial pressure while this factor can vary for different standing compressions by 40 times.

The same ratio in the case when increased pressure gives a half of initial factor k for forward motion are shown in Figure 26 (landing gears were extended approximately by 100 mm). Spectral densities of some loads at taxiing with velocity of 10 m/s on one of the taxiways for increased pressure and for initial pressure are shown in Figures 27–30.

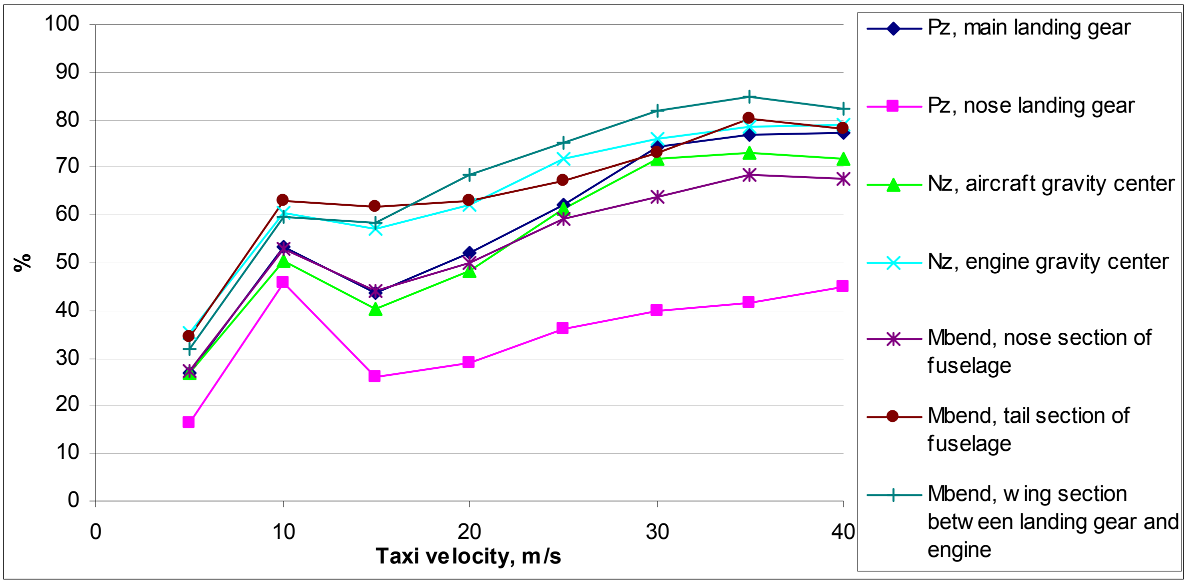

Figure 26: The ratio of cumulative fatigue damages at increased pressure in the gas chamber to damages at initial pressure (the extension of gears is 100 mm)

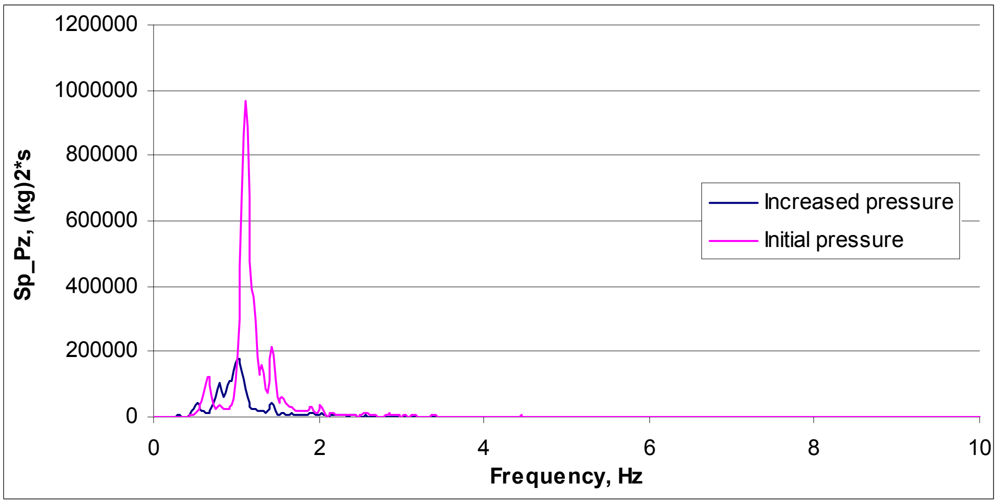

Figure 27: The spectral density of vertical load on a main landing gear

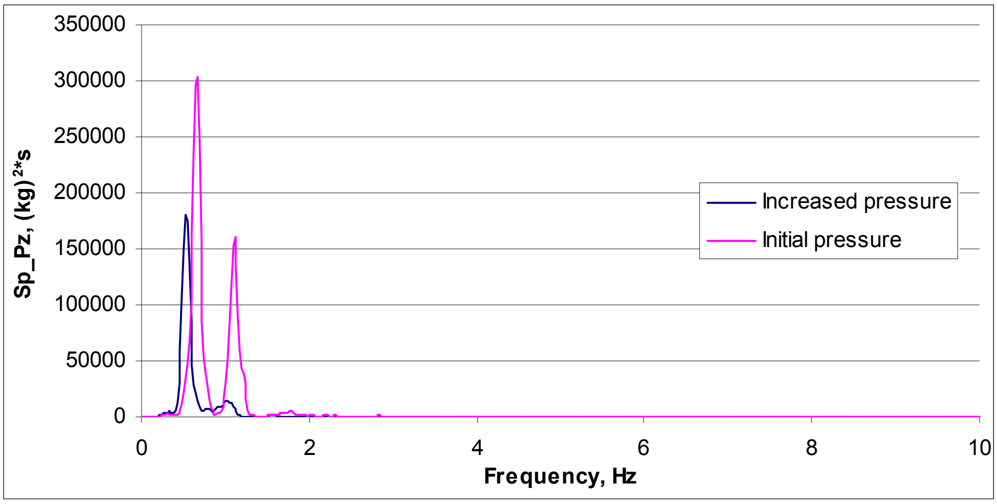

Figure 28: The spectral density of vertical load on a nose landing gear

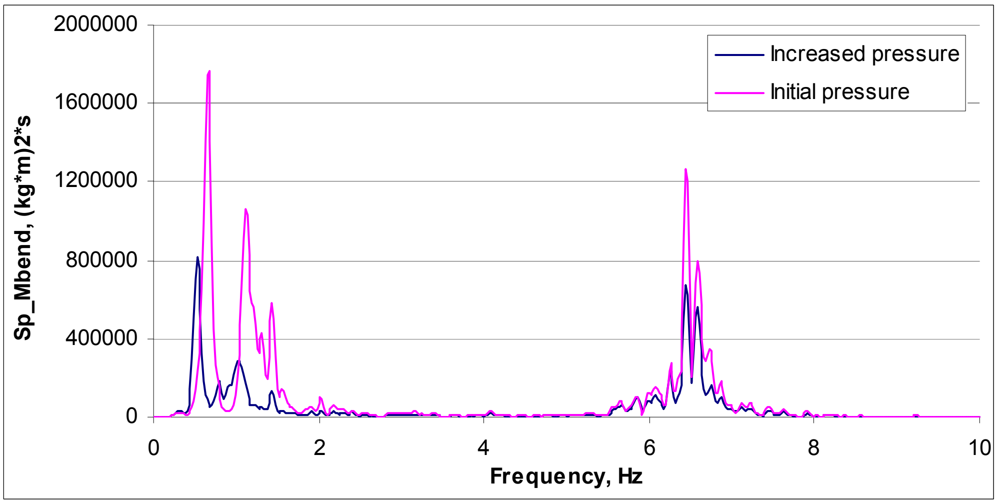

Figure 29: The spectral density of vertical bending moment in tail part of a fuselage

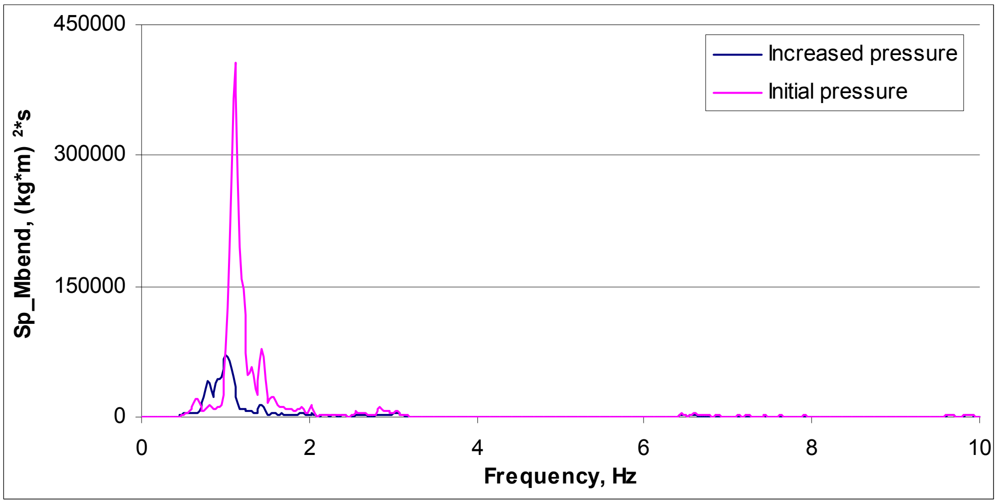

Figure 30: The spectral density of vertical bending moment in a wing section

These researches prove the validity of such approach and the necessity of a separate variation of parameters of the main and nose gears. The results of calculations of landing gears impact tests (the analysis of maximal forces and energy absorption) allow concluding that operation of landing gears is possible with increased pressure in the gas chamber.

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