PROBLEMS OF VIBROACOUSTICS FOR NEW AIRPLAN GENERATION

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Abstract

Substantial noise redistribution has occurred in the aircraft of new generation. While jet noise has been reduced dramatically, the engine still remains the basic source of noise, which is a fan noise. In the forward hemisphere, beside the discrete components at fan blade frequency, long row of discrete components has been observed around the principal blade frequencies as result of shockwave influence. This phenomenon is called "buzz-saw noise". Fan shaft frequency reduction is one of the necessary measures for shockwaves control. Due to the decrease of frequency vibration spectrum shifts towards the low-frequency range. Such components will determine dynamical impact spectrum of power plant, transmitted through mounting to airframe construction. An airframe typically possesses dozens of oscillation modes in the low-frequency spectrum part. Interaction of some of them with the influence of power plant may generation of discrete low-frequency high-level noise components in cabin. Selecting power plant for airplanes of new generation, beside solving the problems of community noise, should include developing a high-performance system of vibroprotection of crew and passengers for the maintenance of comfortable conditions and flight safety.

1 Introduction

There is an event which and today defines development of planes of new generation in a centenary history of aviation.

High by-pass ratio engines were installed at the aircraft 35 years ago.

An appearing of high-by-pass ratio turbofan engines provide a significant increasing of fuel efficiency and noise reduction of new generation aircraft in recent 20 years on 20 dB.

However, efficiency of noise suppression is necessary to increase, because new toughening standards are already discussed.

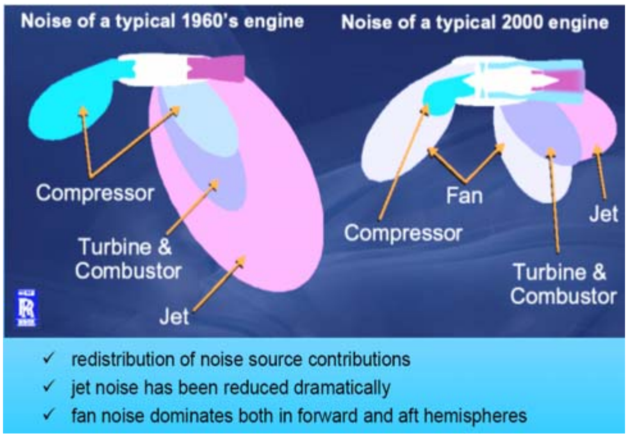

Fig.1. Engine noise sources – Old versus new [1].

Today, several Research Programs on noise decreasing in have been accepted. One of the basic directions is transition from high bypass-ratio engines (4,5 …. 6,0) to super high bypass-ratio engines (8 … 12).

Field experience showed that significant noise redistribution occurred for new generation aircraft. Despite giant jet noise reduction engine remains a general noise source. But now it's fan noise in both of forward and backward hemispheres (Fig.1) [1].

2 Spectrums, sources and paths propagation

The investigations carried out within Quiet Technology Demonstrator have yielded the presence of so-called buzz-saw noise, discovered in the front cabin of B-777-200 ER equipped by Trent 800 [2].

These components are 10-25 dB more intensive then cabin background noise.

Fan diameter increasing in high bypass ratio engines, fan blades start rotating at ultrasonic speed, thus generating shockwaves [3].

Buzz-saw noise in cabin is a special feature of extra-high bypass ratio engine fan emission. It manifests itself in the rise of a long row of discrete spectral components around the principal blade frequencies (1^{st} and 2^{nd} harmonics) in the forward hemisphere (Fig.2).

Such properties of fan emission at an enhanced operation level are explained by the interaction of shockwaves with fan wheel, which results in generating of a polyharmonic series of discrete components within 800..3200 Hz, spaced by fan rotation frequency.

More than 50 high-frequency harmonics are observed in the cabin within the range 750-3200 Hz. This is a result of underestimating of the fan acoustic emission power of an extra-high bypass ratio engine when choosing noise isolation of the aircraft side within the front hemisphere of engine inlet.

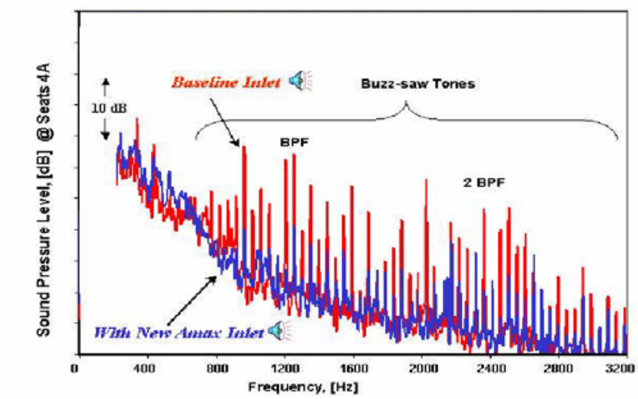

Fig. 2. Buzz-saw noise decrease in B-777 cabin (new A_{max} - inlet) [2].

Buzz-saw noise is one part (high-frequency region) of the spectrum of noise expected in the pressurized cabin of new generation engines with extra high bypass ratio. The other part of the spectrum is the low-frequency region, which includes rotor frequencies of the three shafts and duct low frequency components has not been shown in Fig.1.

Shockwaves interacting with fan wheel generate a wide spectrum of vibrations transferred to engine body via mounting points; the low-frequency part of spectrum (below 500 Hz) spreads over the construction as structure-borne noise.

Vibration contribution to the acoustic properties of the pressurized cabin has been determined during the investigations of the vibroisolating engine mount, which was designed taking into account the real dynamic characteristics (engine case and airframe dynamic compliance) [4].

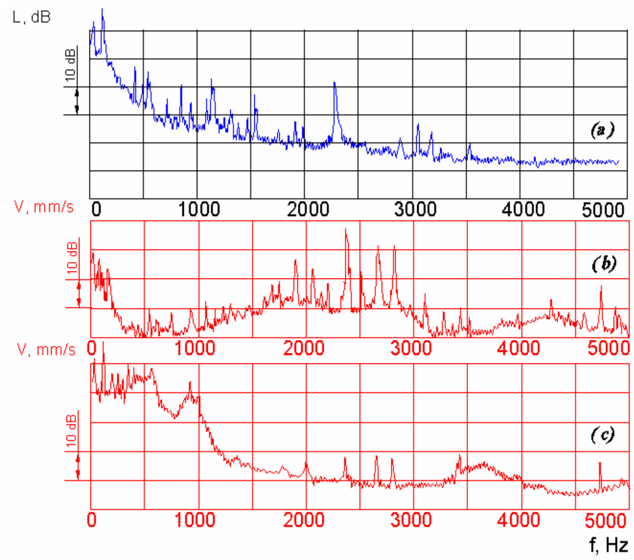

Fig. 3. Noise and vibration spectrums (various location of the sensor). (a) – noise spectrum in pressurized cabin (engine mount zone), (b) – vibrations spectrum of engine case (front mount), (c) – vibrations spectrum of engine case (aft mount).

Vibration spectra of engine case for front (Fig. 3b, Fig. 3c) and aft mount location of sensors are presented in fig. 3. A series of polyharmonic discrete components has been observed in the spectrum of engine case vibrations especially for the front mount location. These components are grouped around the main blade frequencies (the 1^{st} and the 2^{nd} harmonics), the distance between the components and blade frequency being equal to shaft rotation frequency.

All these components of the vibration spectrum, as well as the discrete components of vibroactive devices, installed in the engine (e.g. plunger pump), or the spectral components of new devices (e.g. chevron nozzles, introduced into the stream and supplementing the vibration spectrum of engine case) will be a source of structure-borne noise, transferred via mounting points onto the airframe and re-emitted into the pressurized cabin.

A sparser series of high-frequency noise components, in comparison with fig.1, is observed in the pressurized cabin noise (fig. 3a), but an impressive series of low-frequency components is also reported in the spectrum (corresponding to fan shaft harmonics and the plunger pump harmonic).

The acoustic field of the pressurized cabin has become a subject to essential changes since high by-pass engines were introduced [5].

Fan shaft frequency reduction is one of the necessary measures for shockwaves control. Due to the decrease of frequency vibration spectrum shifts towards the low-frequency range. Such components will determine dynamical impact spectrum of power plant, transmitted through mounting to airframe construction. An airframe typically possesses dozens of oscillation modes in the low-frequency spectrum part. Interaction of some of them with the influence of power plant may cause low-frequency high-level noise in the cabin.

Investigations of the Portuguese Medical Centre point out the increased level of infrasound components in crew cabin with regard to passenger cabin in modern airplanes (Fig.4) [6].

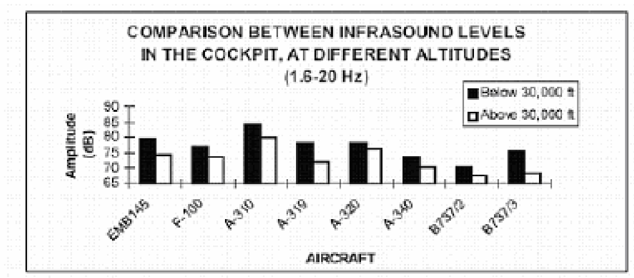

Fig. 4. Level of infrasound components in crew cabin.

These components arise both due to the exciting impact of oncoming flow and to the effect of power plant – airframe interaction mentioned above. These data cause anxiety due to possible increase of these components when switching to high by-pass ratio engines.

3. Role of structure noise

Noted progress of internal noise decreasing in the cabin are connected with actions on noise decreasing in the source (blades, chevrons) and with propagation paths (increase of sound absorbing panels area at entry of inlet and increase its efficiency). This progress is cased of external acoustical impact decreasing on fuselage facing in the front part as well as tail-end of the cabin.

Unfortunately, the problems of the properties of structure-borne noise inside the pressurized cabin being changed by introducing high by-pass ratio engines are still beyond the scope of the general discussion (Fig.5).

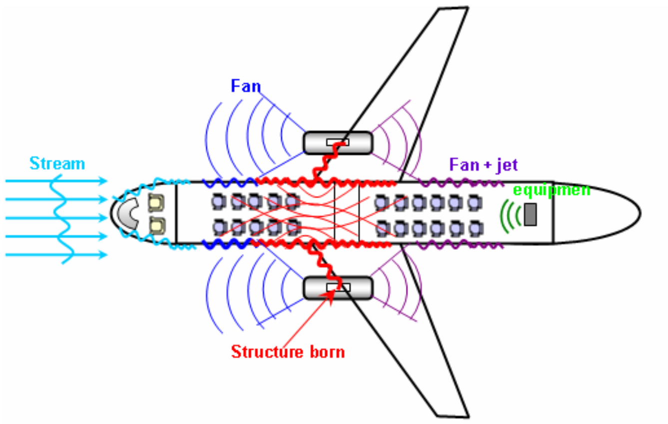

Figure 5. Main noise sources in cabin.

The vibration spectrum of turbofan engines, especially of those with high bypass ratio, substantially extends due to the possible use of low speed of the fan rotor, 2-3-shaft schemes and low-frequency terms of perturbation action of the engine gas-air flow duct. This spectrum determines the type of vibrating process of the engine body.

Hygienic, clinical-physiological and experimental researches make it reasonable to claim the low-frequency noise (including 31 Hz octave band and especially infrasonic range within 8 and 16 Hz octave bands) to be professionally harmful factor, influencing human health [7,8].

There are no obligatory international standards limiting internal noise in cabins of airplanes today. Execution of those or other conditions on noise (according to national standards) is a parameter of competitiveness of manufacturers or aircraft. The noise level in a cabin of pilots is fixed by the manufacturer in view of opinion of large airlines that covenant with trade union of pilots.

Therefore, the allowed infrasound levels at the places of operators, who perform tasks of different mental and emotional tension, are proposed to be lowered.

We believe finding a complex solution to the problem of both communities noise and cabin noise to be the most important challenge.

Selecting power plant for airplanes of new generation, besides solving the problems of external noise, should include developing a high-performance system of vibroprotection of crew and passengers for the maintenance of comfortable conditions and flight safety [9].

4 Calculation model

The long-term investigations directed to dynamical characteristics definition for bodies of several engines (with different by-pass ratio) and airframe constructions of main-line aircraft allow to significantly specify calculation models of modern aircraft constructions in engine's rotor frequency range. And it allows to define tendency of engine's dynamical characteristics variation with by-pass ratio increasing [10-12].

In the paper discussion the calculated model which is taking into account real dynamic characteristics of modern designs which are characterized by a matrix of dynamic compliance of the engine' body at the attachment points and the answer attachment points on an airframe and also by tensor of transfer functions from attachment points with various cabin elements [13].

The multi-connected dynamic model of the system «Engine-mount-airframe» can be studied by dividing it into independent subsystems, reaction forces being applied in the separation points. Then the differential equations for the displacements of separation points are written down, where the generalized dynamic characteristics (for example, dynamic compliance) are used as factors of proportionality between dynamic displacement and forces.

Using the set of the real dynamic compliances of the engines and airframes, defined by experimental way, the limits of coupled vibrations of the "engine-attachment-airframe" system and possibility of presentation of the system in the form of independent one-dimensional vectors (vibroconduits) as well were investigated.

If the engine mounting attachments are dynamically independent, the equation for dynamic forces, acting from the engine upon *i*-th coupling point, can be reduced to the following form:

$$R_e^i(f)=\left[C_e^i(f)+C_a^i(f)\right]^{-1}\cdot\sum_{k=1}^{m}C_{es}^{ki}(f)\cdot F_e^k(f) \qquad (2)$$

where the expression $\sum_{k=1}^{m}C_{es}^{ki}(f)\cdot F_e^k(f)$ characterises engine vibration activity. Actually, this is engine displacement at the attachment points (where the standard vibration pickups are usually installed), C_{EM}, C_{AM} – engine and airframe casing structure dynamic compliances respectively at the attachment points; C_{ES} - transition compliances of engine structure between the points of force application and the attachment points; F_E - excitation forces within the engine components; R_E - reaction forces at the attachment points, which characterize the dynamic influence of the engine upon the airframe.

Obtained expression allow to estimate an expecting dynamical impact level from basic sources (residual disbalance of engine's rotors) and other vibroactive elements installed on engine (hydropumps, gearbox, perturbations in engine's gas-air flow duct).

Considering each *i*-th coupling of *m* engine support couplings with the airframe structure to be a separate source of excitation, we can determine sound pressure level p^n that is generated at some point *n* of the pressurised cabin as a sum of sound pressure values excited by each said source:

$$p^n(f) = \sum_{i=1}^{m} H_A^{in}(f) \cdot R_E^i(f), \qquad (3)$$

Where: $H_A^{in}(f)$ is transfer function characterising acoustic conductance of the airframe structure from the engine vibration exciting points (attachment points) to noise measurement locations; $H_A^{in}(f)\ R_E^i(f)$ - the level of the engine dynamic effect upon the airframe structure at the *i*-th point of coupling [5].

After dB-noise evaluation can be written as:

$$L^{ni}(f) = L_{H_A}^{in}(f) + 20 \cdot \lg(C_{ES}^i(f) + C_{AS}^i(f))^{-1} \cdot \frac{V_E^i(f)}{2\pi f \cdot F_{sh}^i(f)}, \qquad (4)$$

Where: $L_{H_A}^{in}(f)$ is the function of airframe structure acoustic conductance towards point *n*, if the impact is at the *i*-th attachment point, dB; $V_E^i(f)$ is engine casing vibration level near the *i*-th point of coupling, cm/s; $C_{ES}^i(f), C_{AS}^i(f)$ – engine casing and airframe dynamic compliances at the *i*-th point of coupling, cm/kg; *f* – frequency, Hz; $F_{sh}^i(f)$ - force acting upon the airframe in the *i*-th attachment point, kg.

Combining the separate sources of all engines, we obtain the total noise level of power plant vibration.

5 Experimental data analysis

Several analytical models are considered together nowadays to predict the acoustic properties of the cabin. Although design models of the airframe, the pylon and the cabin take into account some thousands of freedom degrees, the engine is still considered to be a rigid body, its mass and moments of inertia taken into account only.

This is the due to an old tradition of successful flutter calculations, as the rigid-body engine model is still true in that range (low frequency range, below 15 Hz).

The dynamic characteristics enabled us to make the dynamic model for an aviation gas-turbine engine more precise, especially in the rotor frequency range.

Such characteristics were determined for a number of by-pass turbofan engines distinguished substantially both in thrust and by-pass ratio m (from 0,5...1,1 to 2,5...5,0), and for airframes of trunk-route aircraft.

A well-known impedance testing technique was used: for the determination of these characteristics the structures were excited by an electrodynamics shaker while the harmonic input force amplitude was constant and its frequency was varying automatically within the studied range.

Compliance values of such sub-systems as the engine and the airframe were determined by method of test effect within 10…500 Hz frequency range.

Analysis of obtained data makes it possible to divide the frequency range of investigation into three sub-ranges characterized by certain dynamic behavior of the engine and consequently each of said ranges can be provided with its special mathematical model – simple and clear enough (Fig. 6).

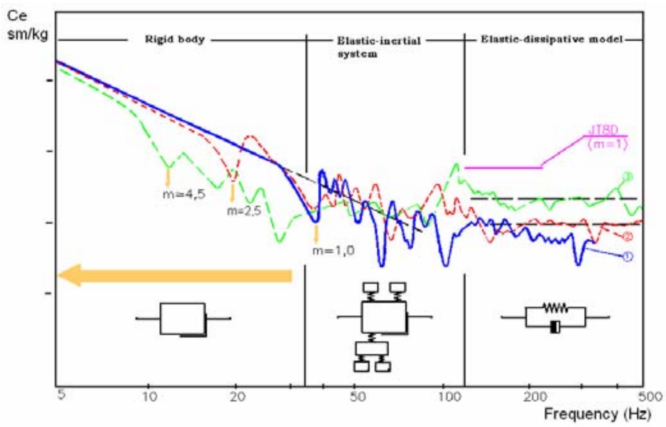

Fig. 6. Dynamic compliances of engine body at attachment points;
1 – m = 1; 2 – m = 2,5; 3 – m = 4,5.

The generalization of the performed investigations has revealed that the dynamic behaviour of an advanced gas turbine engine body corresponds to the rigid body model for frequencies below 20…40 Hz depending on by-pass ratio.

If by-pass ratio is increased up to estimated 8…12 we should expect that the upper boundary of rigid-body-like dynamic behavior of the engine does not exceed 10 Hz.

Within a wide range of rotor frequencies the dynamic behavior of engine body corresponds to the model of elastic-inertial system or to an elastic-dissipative element. It differs substantially from the idealized rigid-body model of aircraft gas turbine engine both by the value of dynamic compliance module and by the type of dynamic behavior.

As evident from presented data, the dynamic behaviour of the airframe (at engine brackets attachment points) depends on the frequency range. Elastic airframe's behaviour accepted in many calculation models is limited by a rather narrow frequency range (50…100 Hz), which doesn't embrace the rotor frequency range of many-shaft engine (Fig.7).

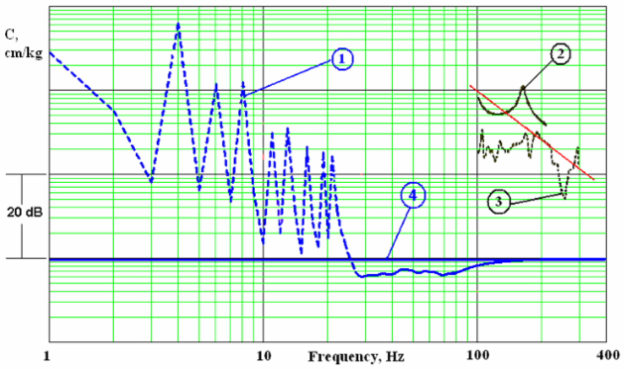

Fig. 7. The module compliance of the airframe. 1 – proposed numerical model for the airframe into account of experimental results, 2 – real dynamic compliance of mount bracket for JT8D on DC-9, 3 – real dynamic compliance of mount bracket for D30-KU on TU-154M, 4 - model of airframe as elasticity.

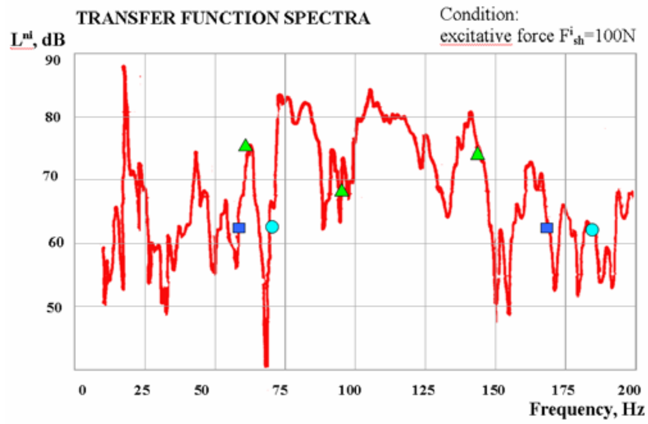

Fig. 8. Vibro-acoustic conductivity (marked points-cruise modes for different engines).

An example of vibroacoustical compliance transfer function between a point of impact (place of bracket attachment of engine) and a point in the cabin (place of noise monitoring) is presented in Fig. 8.

Transfer function characterizes the acoustic response of the cabin to the vibration impact of engine.

About 20 resonances have been observed in the frequency range between 20 Hz and 200 Hz, sound pressure difference reaching 30 dB.

The points on the curve denote cruising rotation regimes for three engine types planned to be installed on the aircraft.

It should be noted that at the same acoustic impact level the difference of the response of the cabin reaches 15 dB for different engines at cruising regimes.

The obtained characteristics and algorithms described above have allowed us to calculate the expected noise due to vibration impact of engine.

Thus high-level frequency components of noise generated by vibration impact from power plant can be observed in the cockpit. The calculation data have been confirmed by the results of experimental measurement (Fig. 9).

The comparison of the expected noise and the experimental data yields both a good convergence of fan rotor harmonic level and a possibility of high-intensity low-frequency components generation at the operation level of engine vibration.

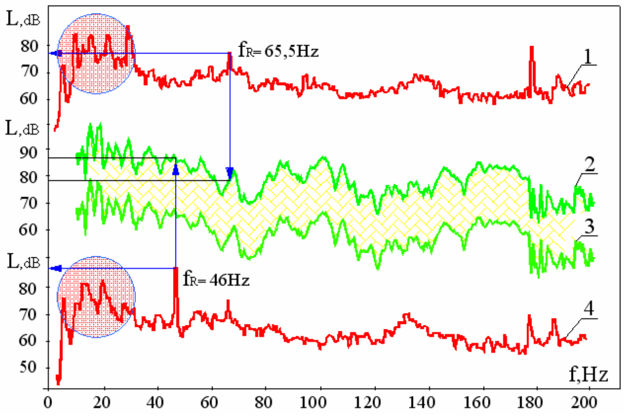

Fig. 9. Structure-borne sound in cabin. 1,4 – experimental data, $V_E = 10mm/s$; 2,3 – prediction data, $V_E = 10mm/s$ and $V_E = 1mm/s$ correspondingly.

On decreasing of fan noise the low-frequency discrete components will be determine the acoustical climate in the cabin. It was confirmed by new investigations on aircraft-demonstrator QTD-2 (Boeing-777 with engine GE-90-115B with bypass-ratio - 8), where low-frequency components rise over 30-40 dB (Fig.10).

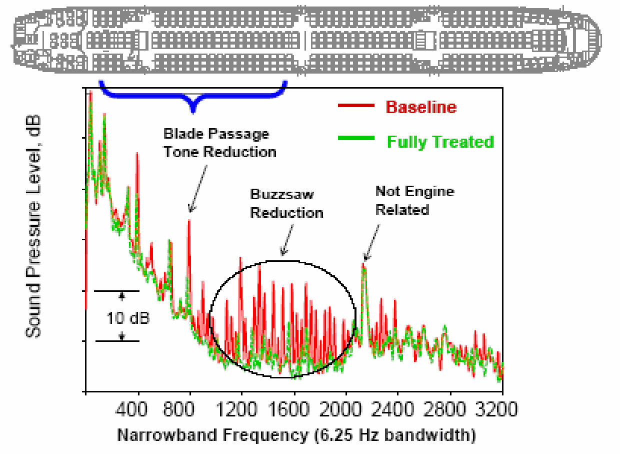

Fig. 10. Forward cabin interior noise reduction as result of acoustic smooth inlet [14].

The necessity of new vibroisolation mounting relates with: 1) extension of vibration spectrum of modern engines and its tendency to shift towards the low-frequency region; 2) insufficient efficiency of existing vibration protection, developed on basis of out-of-date computation models, especially in the low-frequency region; 3) change of dynamic characteristics of airframe and engine bodies at attachment points with the increase of engines by-pass ratio.

6 Vibroisolation model and investigations

Necessary vibroprotection level can be supplied by vibroisolation block with nonlinear elastic characteristics with quasi-zero stiffness work field for calculated force (for example, at cruise) [12, 15].

Such device provides a large static elasticity of vibroisolation mounting and can function in wide range of dynamical forces and narrow displacement range.

All of these requirements satisfied using a vibroisolation mounting based on initially deformed elements with quasi-zero stiffness zone. It contains quasi-unstable elements of different configurations with special non-idealities of shape and boundary conditions which determine an elastic characteristic: soft nonlinear with quasi-zero work field at calculated force.

The mounting functioning principle based on using of small elasticity of such elements near their field of stability loss from static forces in attachment knots at calculated regimes. On Fig. 11 the elastic characteristic of element mount (a), oriented mount on different static loads (b) and example mount strut (Fig.12) are presented.

The computational investigations of low-frequency vibroisolation mounting dynamic model were carried out. Numerical investigations allowed to obtain a significant decreasing of oscillation amplitude in case of nonlinear elastic characteristics using for all of external dynamical force types [16]. Numerical data are in qualitative and quantitative accordance with experimental data.

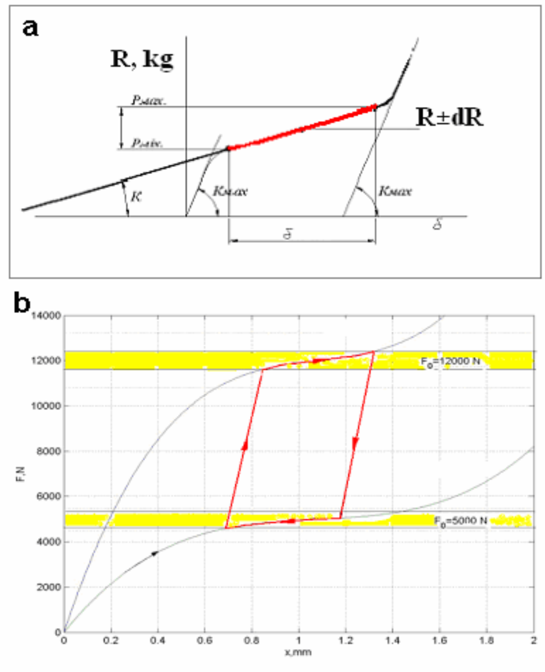

Fig. 11. Elastic characteristic of element mount (a), oriented mount on different static loads (b).

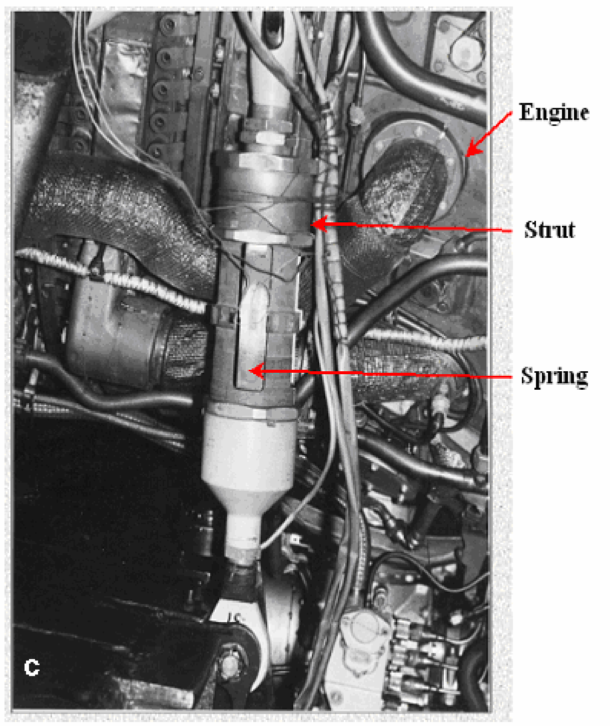

Fig. 12. Example of the mount strut.

Proposed mounting have been investigated on special rig (Fig. 13) including gasturbine engine and unit, creating low-frequency forces from engine. Results of suspension tests showed that engine with such suspension oscillation's own frequencies exceed 3.5 Hz at static displacement of 2.5 mm. Dynamic force passed via suspension from the engine decreased by 12-14 dB at frequencies 8-60 Hz (Fig. 14).

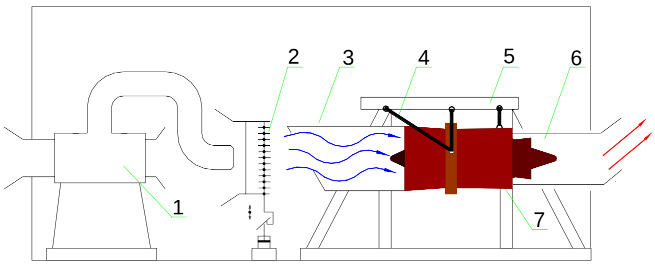

Fig. 13. Test engine bench: 1.Air injection system, 2. Vibrating system, 3.Air inlet unit, 4.Mounting struts, 5.Engine base frame, 6.Exhaust unit, 7-Engine.

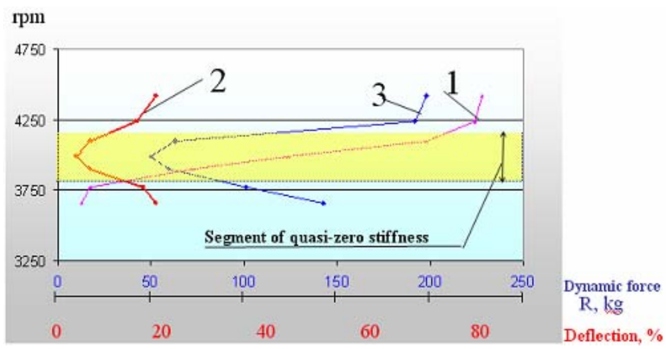

Fig. 14. Experimental testing of new vibroisolation device. 1 – elastic characteristic, 2 – rotor component, 3 – low-frequency component.

7 Conclusions

We have suggested a method of structural noise calculation, which takes into account real dynamic characteristics, such as dynamic compliance of engine's body and airframe and allows us estimate changes of the acoustic field in the pressurized cabin for new aircraft generation.

Selecting power plant for airplanes of new generation, beside solving the problems of community noise, should include developing a high-performance system of vibroprotection of crew and passengers for the maintenance of comfortable conditions and flight safety.

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