EVOLUTION OF ENGINES NEW GENERATION AIRPLANES: PROBLEMS AND SOLUTIONS

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Abstract

External noise reduction and significant increasing of full efficiency new generation airplanes are provided of engines of high by-pass ratio.

Low-frequency components will define spectrum dynamic effect transferred via engine mounting attachment to airframe.

Selecting power plant for airplanes of new generation should include developing a high-performance system of protection for the maintenance of comfortable conditions and flight safety.

1 Introduction

High by-pass ratio engines were installed at the aircraft 33 years ago.

External noise reduction and significant increasing of full efficiency new generation airplanes are provided of engines of super high by-pass ratio (8…12).

There is a tendency of switching from 4-engine power plants to 2-engine power plants of equivalent thrust for reduction maintenance costs.

Every way there is a tendency of fan diameters to increase while shockwaves tend to be generated at supersonic speed of blade tips.

One of necessary measures of shockwave control – is reduction of fan shaft speed. In this case to maintain gas generator efficiency a low speed low-pressure turbine should be provided with increased number of stages and blades which increases of engine weight and price.

In a Geared Turbofan engine, a reduction gear system allows the fan to operate independent of the low-pressure compressor and turbine. The fan can operate at a slower speed for less noise, and its diameter can be larger to achieve a higher bypass ratio for greater efficiency and fuel economy.

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 (Fig.1).

Thus some components of an air-gas path, for example, frequency of a rotary vortex ($f = (0,35\text{-}0,42)\, f_{\text{fan rotor}}$) were observed and earlier.

These components were already in the area of interaction with own frequencies of airframe (control system elements, for example).

Interaction of this component with airframe caused formation of a low-frequency component of high level.

Transition to engines super high by-pass ratio with the fan of the big diameter demands essential decrease in speed of fan`s shaft, that is confirmed by the newest engines GE 90-115B (m=9, 0) and TREND1000 (m=11), which have as the least speed of rotation of the fan (f=32-35Hz) nowadays.

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.

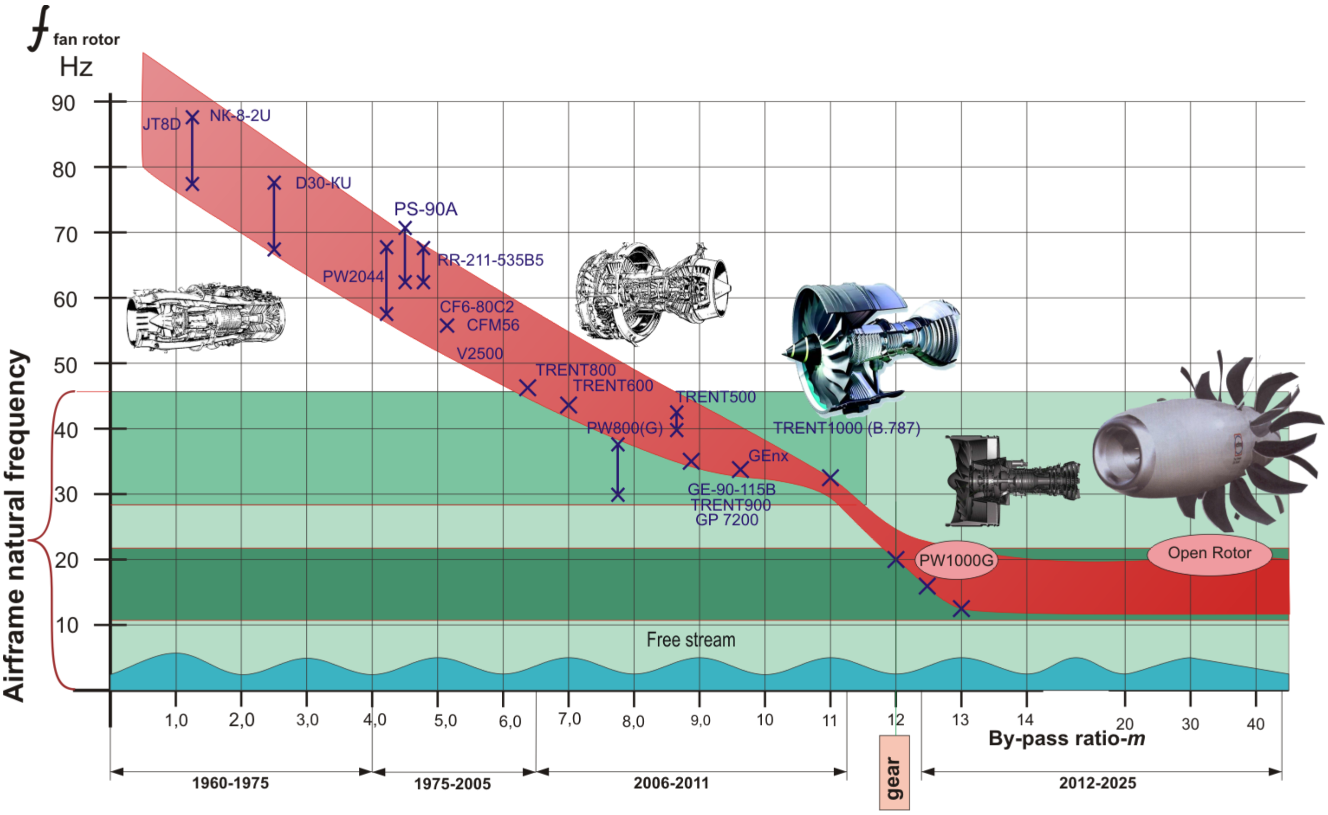

Fig. 1 .Change of frequency of rotation of fan shaft at degree increase by-pass ratio of engines.

2 Role of structural noise

Level of low-frequency components of the spectrum for Super-high by-pass ratio engines is mainly defined by conditions at the fan inlet (possibility of aerodynamic unbalance). These components will define spectrum of power plant dynamic effect transferred via engine mounting attachment to airframe. This spectrum is re – radiated in to the cabin in the form of structural noise.

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. 2).

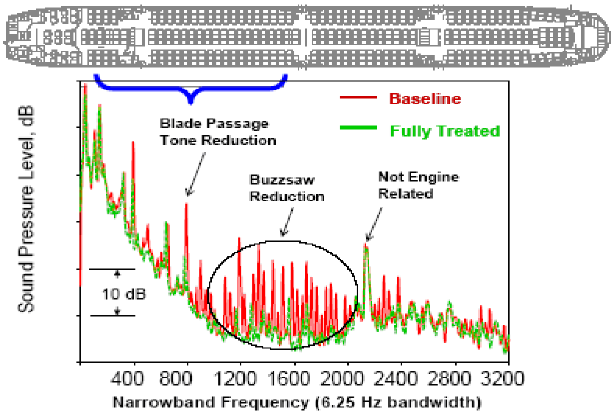

Fig. 2. Forward cabin interior noise reduction as result of acoustic smooth inlet [1]

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, for human health [2].

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.

Decreasing structure-borne noise will be an essential problem for providing comfortable conditions in the pressurized cabin, as its role increases with the introduction of high by-pass ratio engines.

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

3 The solution

A new decision concerning mounting of isolated engine is required in a wide range of frequencies, including an infrasound aspect.

Facilities for reduction engine vibration intensity and vibration transfer along structure come first by selecting of vibration protection for pressurized cabin and integration vibration protection units into engine mounting attachments seems to us the most effective.

But whatever vibration protection means (active or passive) are used to select parameters of vibration isolation units, calculated model is required which is based on real dynamic characteristics of engines and airframe in mounting points.

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.

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. 3). At figure 3 curve 1 corresponds to bypass ratio m=1, curve 2 – to m = 2,5 and curve 3 – to m = 4,5.

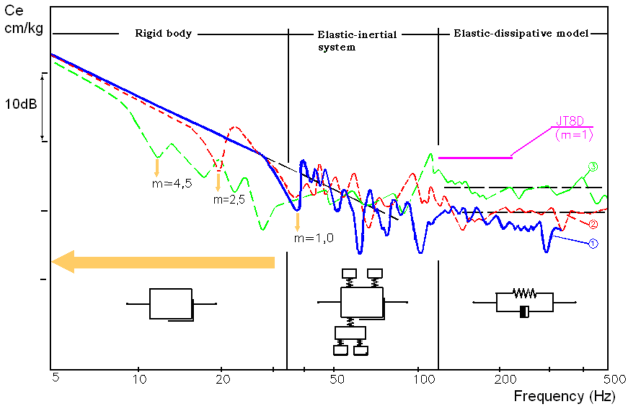

Fig.3. Dynamic compliances of engine body at attachment points.

The generalization of the performed invest behavior of an advanced gas turbine engine body corresponds to the rigid body model for frequencies below 20…40 Hz depending on by-pass ratio [5].

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.

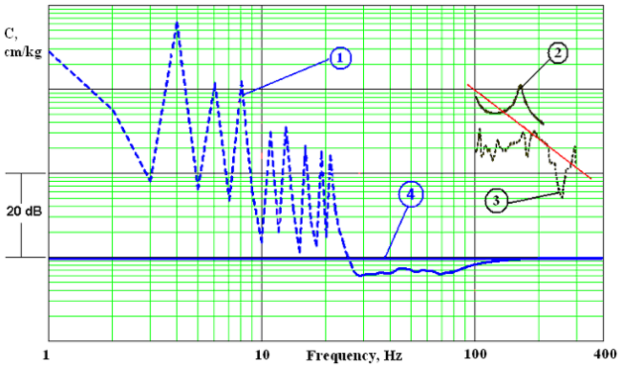

Fig. 4. The module dynamic compliance of the airframe.

As evident from presented data, the dynamic behavior of the airframe (at engine brackets attachment points) depends on the frequency range. Elastic airframe's behavior 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.4). At figure 4 curve 1 corresponds to proposed numerical model for the airframe into account of experimental results, curve 2 – to real dynamic compliance of mount bracket for JT8D on DC-9, curve 3 – to real dynamic compliance of mount bracket for D30-KU on TU-154M, and curve 4 – to model of airframe as elasticity.

The necessity of new isolation 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].

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 [4].

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 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:

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

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.

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:

$$p^n(f) = \sum_{i=1}^{m} H_A^{in}(f) \cdot R_E^i(f), \quad (2)$$

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; $R_E^i(f)$ - 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:

$$L^{ni}(f) = L_{H_A}^{in}(f) + 20 \cdot \lg(C_{ES}^i(f) + C_{AS}^i(f))^{-1} \cdot \frac{V_E^i(f)}{2\pi f \cdot F_{sh}^i(f)}, \quad (3)$$

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.

Reduction of the level of engine dynamic effect on the aircraft can be provided, for example, by building-in isolation units into the engine attachments, and then effectiveness (ΔL^i) of application of such units in case of dynamic independence of separate vibration vectors is defined for the i-attachment from the following expression:

$$\Delta L^i(f) = 20lg\frac{1}{\eta_i} = 20lg\left|\frac{C_e^i(f)+C_a^i(f)+C_{is}^i}{C_e^i(f)+C_a^i(f)}\right| \quad (4)$$

where: $\eta_i = \dfrac{R^i(f) \ \text{in case of vibroisolating mount}}{R^i(f) \ \text{in case of rigid attachment}}$.

From the latter of the expressions we can define isolator compliance to ensure the required level of reduction (η_0) of the forces transmitted to the aircraft.

$$C_{is}^i \geq \frac{1}{\eta_o}\sqrt{(\mathrm{Re}\,C_e^i+\mathrm{Re}\,C_a^i)^2+(JmC_e^i+JmC_a^i)^2(1-\eta_o^2)} \quad (5)$$
$$-(\mathrm{Re}\,C_e^i+\mathrm{Re}\,C_a^i)$$

where: $\mathrm{Re}\,C_e^i, \mathrm{Re}\,C_a^i$, JmC_e^i, JmC_a^i - the real and imaginary components of dynamic compliances for the engine and aircraft respectively in the locations of the i - attachment.

Different nature of structural dynamic behavior (the inertial one and the elastic one) convinces us in necessity to know real dynamic characteristics of an engine and aircraft at mounting points so that to develop effective isolating mountings of the engine.

Calculated model taking into account engine body and airframe real dynamical characteristics based on multi-coupled oscillation system “engine-mounting-airframe” proposed a computational algorithm for new generation engine’s dynamical impact on airframe, expected structural cabin noise and for low-frequency protection parameters selection.

The necessary level of vibration protection may be provided by using the isolation unit, having the nonlinear characteristic with section of quasi-zero stiffness by design load, for example, a cruise mode of flight (Fig. 5).

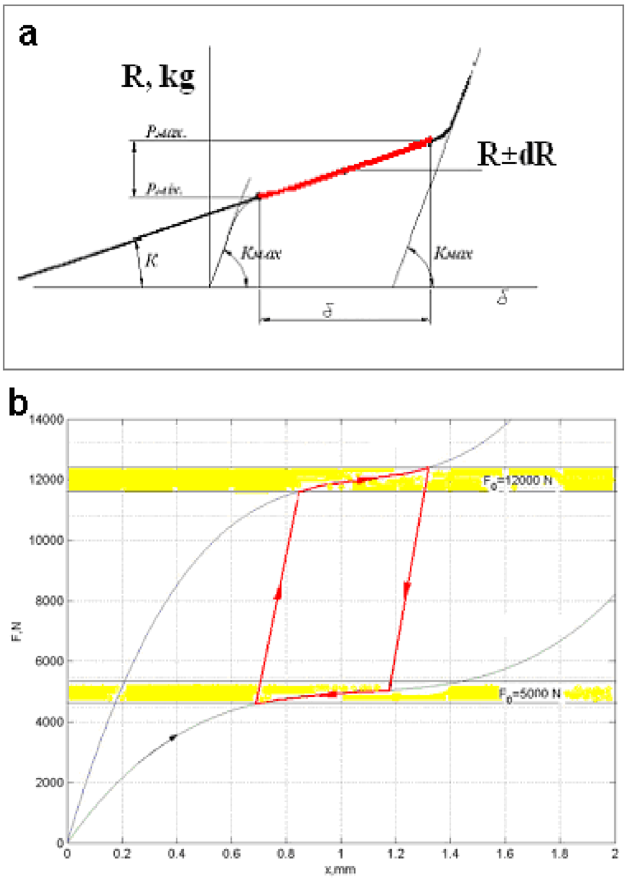

Fig. 5. Elastic characteristic of element mount (a), adapted mount on different static loads (b).

In the paper results of research offered low-frequency isolation mounting on the engine test bed with full-scale gas turbine engine are considered (Fig.6, 7).

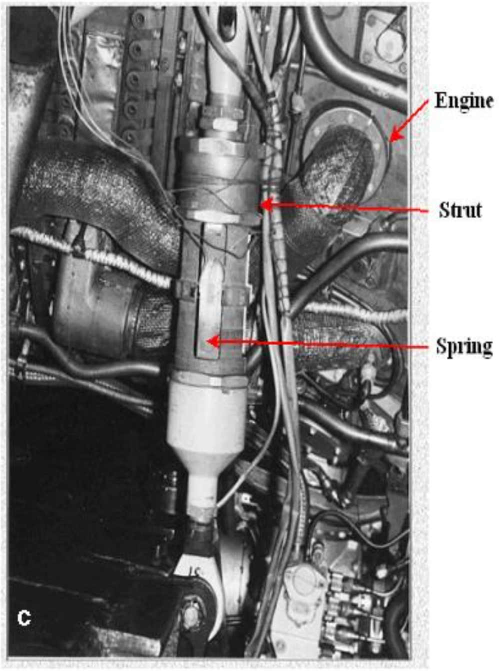

Fig. 6. Example of the mount strut.

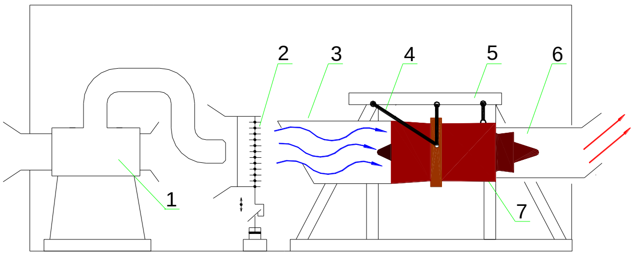

Fig.7. Test engine bench: 1.Air injection system, 2. Vibrating system, 3.Air inlet unit, 4.Mounting struts, 5.Engine base frame, 6.Exhaust unit, 7.Engine.

Proposed mounting have been investigated on special rig (Fig. 7) including gas turbine 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. 8).

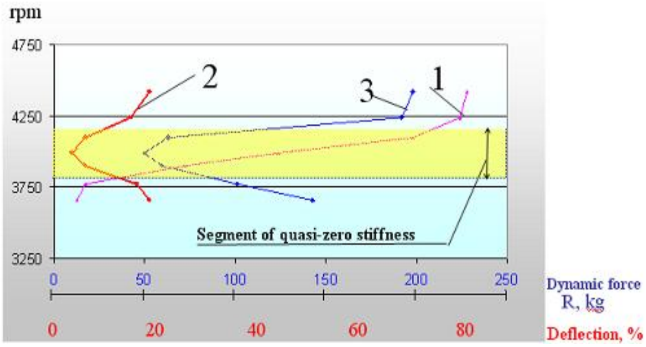

Fig.8. Experimental testing of new isolation device. 1 – elastic characteristic, 2 – rotor component, 3 – low-frequency component.

4 Conclusions

The vibrating spectrum of turbofan engines, especially extra high bypass ratio, essentially extends with shift in a low-frequency part of a spectrum, and will define a low-frequency part of a spectrum of noise in cabin.

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

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References

[1] Nesbitt E. and Yu Jia. Quiet Technology Demonstrator 2 Intake Liner Design and Validation. *12th AIAA/CEAS Aeroacoustics Conference*, Cambridge Massachusetts *AIAA Paper* 2006-2458, 2006.

[2] Alves-Pereira M., *Proc. of 11th International Congress on Sound and Vibration,* St. Petersburg, Russia, 5-8 July 2004.

[3] Agafonov V. K., Baklanov V. S., Vul V. M., Popkov V. I., Popov A. V. The Investigation of Dynamic and Vibroacoustic characteristics of Aircraft and an Engine by calibration Test Methods, //*Proc. of VII Aero-acoustic Conf., TsAGI*, Moscow, 1990, pp. 141-144.

[4] Baklanov V.S., Vul V.M. Vibration Isolation of Aviation Power Plants taking into account Real Dynamic Characteristics of Engine and Aircraft. Proceedings, *Second International Congress on Recent Developments in Air- and Structure-Borne Sound and Vibration*, , Auburn University, USA 1992.

[5] Baklanov V.S., Dynamic model of Engine-Mount-Airframe System of Trunk-Aircraft Basing on Results of Impedance Data Tests at Attachment Points, *Ninth Int. Congress on Sound and Vibration*, Orlando, Florida, USA 2002.

[6] Baklanov V.S. Low-frequency vibroisolation mounting of power plants for new generation airplanes with engines of extra-high bypass ratio. *J. of Sound and Vibration*, 308(3-5), pp. 709-720, 2007.

[7] Baklanov V.S., Golov I.V., Postnov S.S. Vibroisolation of power plants for new generation airplanes with engines of high by-pass ratio. // *Proc. of 10th AIAA/CEAS Aeroacoustics Conference*, Manchester, UK, 10-12 May 2004.

[8] Baklanov V., Zayakin A., Orlenko E., Postnov S. The calculation of structural noise in cabin for aircraft with high-by-pass ratio engines *11th AIAA/CEAS Aeroacoustics Conference*, Monterey, California, *AIAA Paper* 2005-3034, pp. 1-9, 2005.

[9] Baklanov V., Postnov S., Zayakin A.. The Computational Investigation of Low-Frequency Vibroisolation Mounting Dynamic Model. *// Proc. of 12th AIAA/CEAS Aeroacoustics Conference (27th AIAA Aeroacoustics Conference)*, Cambridge, Massachusetts, May 8-10, 2006, AIAA-2006-2658, pp. 1-5.

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