431. Multi-connecting system "engine-attachment-airframe"

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Abstract. The paper reports the research of the “engine-attachment-airframe” multi-connecting dynamic model by separation it into independent sub-systems according to the engine support (engine mounting points). New generation aircraft are switching to engines of high bypass ratio, which require dynamic characteristics of new structures to be refined. The studies we have performed allowed us to refine significantly dynamic models of aviation gas turbine engine and airframe within rotor frequencies range and to reveal tendency of changes of dynamic characteristics particularly those of engine bodies with increased bypass ratio.

Keywords: engine body, airframe, dynamic compliance, attachment

Introduction

Compliance of aircraft to new noise standards defines the tendency to switch to extra-high bypass ratio engines (from 4…6 to 8…11).

The introduction of high by-pass ratio engines has caused broadening of the spectrum of power plant vibration impact and increase of structure-borne noise contribution to the acoustic field of the pressurized cabin.

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

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

The long-term investigations directed to definition of dynamical characteristics 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 rotor frequency range.

Calculation model

A multi-coupled model “engine-attachment-airframe” that uses dynamical characteristics (dynamical compliance or elasticity, mechanical impedance or admittance etc.) in attachment points is considered in this work [1].

Examples of successful application of such characteristics are known. One of the first times when such research was performed in current aviation (1967) was an investigation of DC-9 aircraft in the course of activities on eliminating reasons for increase of noise level in the cabin of the aircraft. But this analysis was confined to airframe and engine body impedance determination in one attachment point [2].

A broad investigation of the set of dynamic compliances at the tail-end of airframe (the place of central engine location) and at the pods (the place of side engines location) as well as dynamical compliances of engine body at the attachment points was carried out for the first time in 1973 on the first samples of the TU-154 aircraft with NK-8-2U engines.

A new procedure of estimation of engine dynamic impact on the airframe and of structural noise, created by engine vibration was suggested on the base of studying airframe and engine body dynamic characteristics and dynamic loading of engine struts.

This procedure was realized during the program by investigating dynamic compliances of TU-154M airframe and engine D-30KU body, and also by testing transfer function of vibroacoustics conductivities of airframe design between impact points (engine mounting units) and the noise and vibration level check points (crew and passenger cabins).

An analogy for this procedure was used in the USA for a light airplane (Cessna 172) transmission model that includes engine mount dynamic characteristics at the attachment points and the acoustic response of selected cabin interior points and determined by impedance testing, but the engine in this case was represented as a rigid body [3].

A multi-connected dynamic model of the system «Engine-mount-airframe» (Fig. 1) 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.

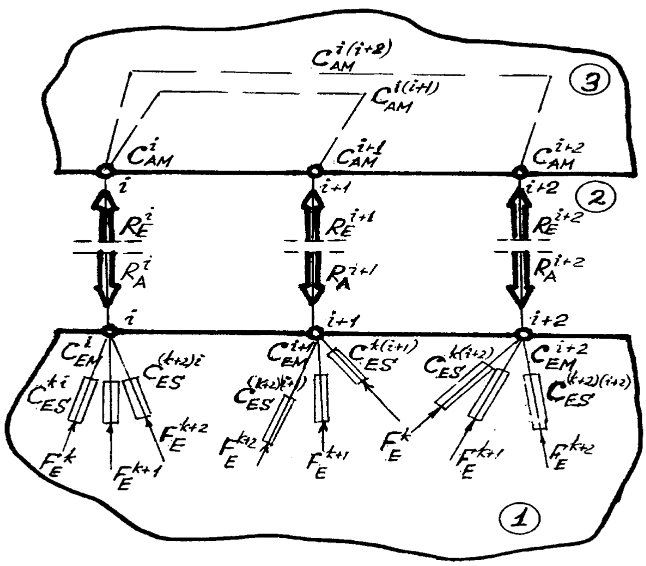

Fig. 1. Separation scheme of full system “Engine-Mounting-Airframe” on subsystems. 1 – Engine; 2 – Mounting; 3 – Airframe

Writing equations for displacements in separation points for each system the following will be obtained:

$$\{X_E\} = [C_{ES}] \cdot \{F_E\} + [C_E] \cdot \{R_E\}, \qquad (1)$$
$$\{X_A\} = [C_A] \cdot \{R_A\}.$$

where $[C_E],[C_A]$ - matrices of dynamic compliances of engine and airframe in attachment points correspondingly; $[C_{ES}]$ - matrix of transition compliances of engine construction from perturbation force in engine elements to attachment points; $\{F_E\}$ - matrix-vector of perturbation force in engine elements; $\{R_E\}$, $\{R_A\}$ - matrices-vectors of response forces in attachment points, which describe engine and airframe dynamical behavior correspondingly.

Engine as a rigid body that has six degrees of freedom (*N=6*). Six struts are used for engine mounting. These struts are combined into front and after engine mounting.

Matrices $[C_E],[C_A]$ have $N \times N$ dimension, where *N* – number of degrees of freedom. $\{R_E\}$ and $\{R_A\}$ is a matrices-vectors with *N* lines. $[C_{ES}]$ matrix depends on engine construction and have *K* degrees of freedom and in the general case this matrix have *N* lines and *K* columns. $\{F_E\}$ matrix also has *K* lines.

In view that $\{X_E\} = \{X_A\}$ and reactions in these separation points are $\{R_E\} = -\{R_A\}$ the expression for estimation of level engine dynamical impact on airframe can be obtained:

$$\left([C_E] + [C_A]\right) \cdot \{R_E\} = [C_{ES}] \cdot \{F\}, \qquad (2)$$

In this convention expression for estimation of level engine dynamical impact on airframe becomes:

$$\{R_E\} = \left([C_E] + [C_A]\right)^{-1} \cdot [C_{ES}] \cdot \{F_E\}, \qquad (3)$$

Using the set of real dynamic compliances of the engines and airframes, determined from experiments, 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) were investigated as well.

The analysis of the obtained characteristics indicates that that ratio of dynamic compliances (input and transient) differs considerably in the frequency range of disturbing effect.

Taking into account this ratio, it is proposed to evaluate possibility of ignoring the transient compliances on the basis of comparison of the following matrix rates:

$$L = \sqrt{\sum_{i,j=1}^{m} \left|C^{ij}\right|^2} \,;\; L^* = \sqrt{\sum_{i=1}^{m} \left|C^{ii}\right|^2} \qquad (4)$$

where *L* and L^* are the Euclidean rates of the total and diagonal structural matrices.

Then the value of $\alpha = \left(L - L^*\right)/L^*$ can be identified as a system coupling coefficient.

Performed calculations convinced us that at its sufficiently small values (less the 0,5 %) the “Engine-Mounting-Airframe” complete system disintegrates to *m* – disconnected systems, which analysis is substantially simplified [4].

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:

$$R_e^i(f) = \left[C_e^i(f) + C_a^i(f)\right]^{-1} \cdot \sum_{k=1}^{m} C_{es}^{ki}(f) \cdot F_e^k(f) \qquad (5)$$

where the expression $\sum_{k=1}^{m} C_{es}^{ki}(f) \cdot F_e^k(f)$ characterizes 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 body 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.

The equation for the dynamic displacements x_E^i of engine case in each *i*-th mount point can be transformed as follows:

$$x_E^i(f) = \left[1 - \frac{C_E^i(f)}{C_E^i(f) + C_a^i(f)}\right] \sum_{k=1}^{m} C_{ES}^{ki}(f) F_E^k(f) \qquad (6)$$

Obtained expression enables estimation of expected dynamic impact level from basic sources (residual disbalance of engine rotors) and other vibroactive elements installed on engine (hydropumps, gearbox, perturbations in engine gas-air flow duct).

Experimental data

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 degrees of freedom, the engine is still considered to be a rigid body, its mass and moments of inertia taken into account only [5-8].

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 develop the dynamic model for an aviation gas-turbine engine more precisely, particularly in the rotor frequency range [9].

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 electrodynamic shaker while the harmonic input force amplitude was constant and its frequency was varying automatically within the studied range (Figs. 2-3).

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.

Engine and airframe was subjected to harmonic force being maintained constant within the entire range investigated.

The tested system linearity was verified by changing the effective force several times. Reciprocity principle was controlled by changing the locations of force application and response measurement. The information was processed with the use of a magnetic recorder unit, a 2-channel analyzer and a XY-recorder.

The information was transmitted from the digital output of the analyzer to digital cassette recorder in order to create a databank. Then it was loaded in a computer to perform necessary calculations, for example, to estimate the expected noise level due to engine vibration action.

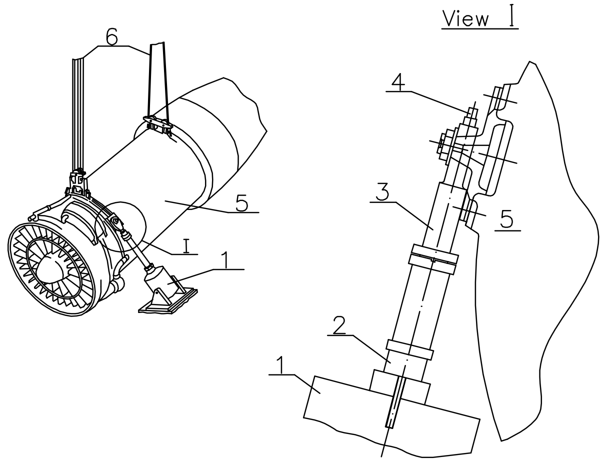

Fig. 2. Testing of engine dynamic characteristics
1 – electrodynamic shaker, 2 – sensor of force, 3 – testing strut, 4 – pickup, 5 – engine, 6 – cords

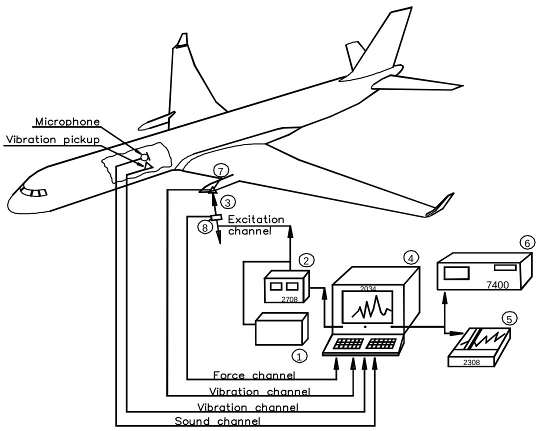

Fig. 3. Testing of airframe dynamic characteristics: 1 – power amplifier, 2 – sonic generator, 3 – shaker, 4 – two-channel analyzer, 5 – XY-recorder, 6 – digital cassette recorder, 7 – vibration pickup, 8 – sensor of force

In Fig. 4 modifications of airframe frequency characteristics are presented. Below 50 Hz the fuselage is characterized by the row of resonances, being typical of beam-type airframe structure. In the range between 50 Hz and 300 Hz the fuselage behaves as a hard elastic spring, if the force is applied in the longitudinal direction (X).

When the force acts in other directions (Y, Z), the frequency range of fuselage elastic behavior shrinks down to 50-100 Hz at the same time the stiffness is decreased 5…10 times.

The row of resonances, typical for separate elements of constructions (beams, frames, brackets…), is observed above 100 Hz (curves 1, 2, 3, 4).

As it is evident from the presented data, the dynamic behavior of the airframe (at engine brackets attachment points) depends on the frequency range. Elastic airframe 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 multi-shaft engine.

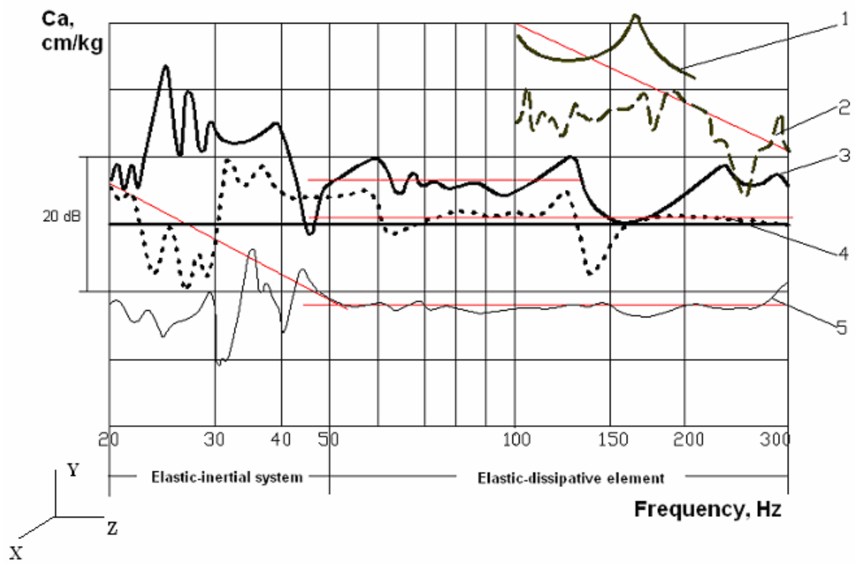

Fig. 4. Dynamic compliance of airframe at the attachment points.
1- DC-9; 2- TU-154M; 3- compliance of airframe in the z-direction;
4- compliance of airframe in the y-direction; 5- compliance of airframe in the x-direction (longitudinal)

Modifications of frequency characteristics of engine dynamic compliances are presented in Fig. 5.

The straight line in double-log scale (x-axis – frequency, y-axis – compliance) with slope factor 12 dB per octave corresponds to the function $C(f) = 1/m(2\pi f)^2$, ($C(f)$ - dynamic compliance), which is a feature of a rigid body.

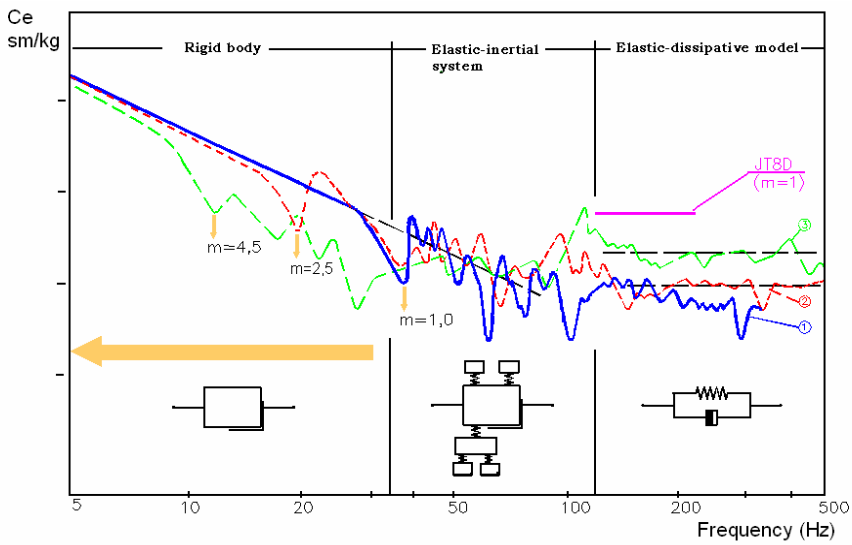

Fig. 5. Dynamic compliances of engine body at attachment points,
1 – m = 1; 2 – m = 2,5; 3 – m = 4,5

The straight line parallel to x-axis is a feature of an elastic element, whereas the one with the slope of 6 dB per octave belongs to an elastic-dissipative element.

Analysis of obtained data enables division of 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 – sufficiently simple and clear (Fig. 5).

Dynamic compliances of engine body at the attachment points has revealed that the body of engines with by-pass ratio (*m*) of 0.5…1.1 corresponds to the rigid body model for frequencies below 40 Hz, while for engines with by-pass ratio of 2.5…4.5 the upper boundary of the rigid body model behavior is shifted to 20 Hz.

It has been found out that at frequencies between 20…40 Hz and 120 Hz the engine body behaves as an elastic-inertial system with a large number of resonances of various damping degrees.

Within the frequency range of 120…500 Hz the engine body corresponds to the model of elastic – dissipative element. The case of engine JT8D also corresponds to this model at the indicated frequency range [2].

The generalization of the performed investigations has revealed that the dynamic 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.

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 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.

The analysis of the features of dynamical compliances (input and transition compliances between the considered attachment points, Fig. 6) has shown the transition compliance to be 20 dB lower then the input compliances (at frequencies above 30 Hz), within a broad frequency range corresponding to the rotor frequencies. These attachments points can be considered therefore as independent vibroconductors.

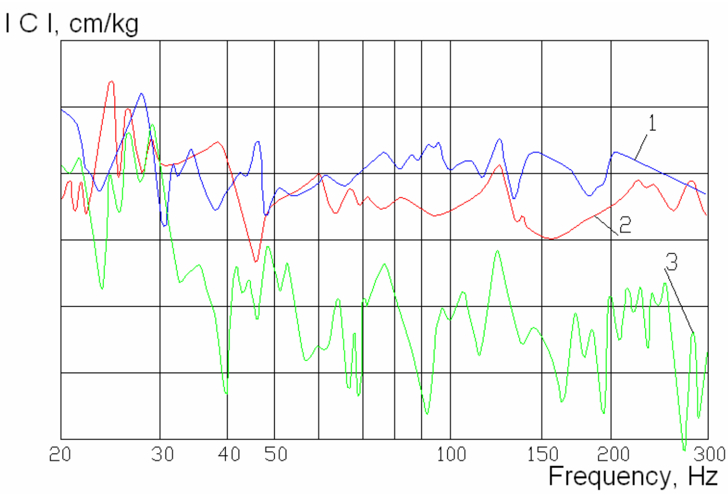

Fig. 6. Comparison of input- and transfer compliance for the front and the rear engine mount.
1,2 – input-compliance for the rear and the front engine mount correspondingly.
3 – transfer compliance between the mounts

Conclusions

Knowledge of the set of real transfer functions by test impact at the attachment points enables estimation of the expected structure-borne noise due to vibration impact of power plant.

Serious doubts regarding reliability of the results arise if the calculation models of some structure elements are combined artificially by using some arbitrary coefficients, which do not reveal the true dynamic behavior of the structure, instead of taking into account real dynamical characteristics (boundary conditions).

We believe it is necessary to extend common frequency tests for the determination of oscillation modes by including the investigation of dynamic characteristics of engine and airframe into the technological process of engine and airframe design. These characteristics should include dynamic compliance or mechanical impedance at the attachments points as well as frequency transfer characteristics between attachment points and various noise and vibration control locations (both in the pressurized cabin and in the engine – on accessory box, input device, reversing gear).

Due to the high self-descriptiveness and stability of dynamic characteristics (e.g. dynamic compliance of engine body and airframe) it is necessary to include their determination into the technological process of engine and plane design.

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