AIRPLANE GROUND TESTS WITH ROTATING FORCE SIMULATION

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Abstract: Airplane vibration analysis during an engine blade loss flight depends on the mathematical model reliability. All the information to adjust the math model can be derived from ground vibration tests (GVT) with an engine imbalance force simulation. Force actions to the damaged engine include the rotating inertial force generated during tests and the gyroscopic moment. Experimental evaluation of possibility to replace the rotating force with two separate (vertical or horizontal) projections of this force is conducted, with further superposition of responses in processing of experimental data. Windmilling steady-state vibrations were measured. Experimental data of amplitude frequency response functions for accelerations at airplane structural points are presented.

1 INTRODUCTION

This paper is continuing the publications [1-3], where the computational research data and the general imbalance modeling procedure in ground tests are given.

In-flight airplane vibration analysis during an engine blade loss, causing an engine imbalance, depends largely on the mathematical model reliability, with its features, such as nonlinear elastic and damping characteristics.

The purpose of ground experiments with an engine imbalance force simulation is to provide the initial data for adjust the math model and to perform analysis to determine the dynamic loads on the aircraft.

After a blade loss and in-flight engine turned off there are two main stages of the imbalance: the transition process (from cruising to stationary stopped engine speed) and the steady process – windmilling, with constant speed which depends on flight conditions, including Mach number [4].

Therefore, the force simulation problem at imbalance can be split into two. The first one is to simulate transient processes with continuous variation of frequency and amplitude of excitation forces in real time scale; the second one is to simulate steady oscillations for each value of Mach number.

In this paper we consider only steady oscillations simulation while windmilling.

Force actions to the damaged engine include the rotating inertial force and the gyroscopic moment. During the tests, it is recommended to simulate the inertial force only, and to leave the effect of the gyroscopic moment for analysis estimation.

Only inertial force is simulated during these ground experiments.

2 BASIC EQUATION

Airplane vibration equation in flight after engine blade loss can be represented as:

$$\mathbf{C}\ddot{\mathbf{q}} + \mathbf{H}\dot{\mathbf{q}} + \mathbf{G}\mathbf{q} + \left[v\mathbf{D}\dot{\mathbf{q}} + v^2\mathbf{B}\mathbf{q} \right] = \Psi^{\mathbf{T}}\mathbf{F}^{\mathbf{I}} \tag{1}$$

where $\mathbf{q}$ - generalized coordinates vector, v – flight velocity, $\mathbf{C}$, $\mathbf{H}$, $\mathbf{D}$, $\mathbf{G}$ и $\mathbf{B}$ - matrices of inertia, structural damping and aerodynamic damping, structural stiffness and aerodynamic stiffness, respectively. The right side of the equation – external forces - is represented by inertial force vector from engine imbalance $\mathbf{F}^{\mathbf{I}}$. $\Psi^{\mathbf{T}}$ - transposed transition matrices from the forces in the "physical" coordinates $\mathbf{y}$ to the generalized coordinates $\mathbf{q}$: $\mathbf{y} = \Psi\mathbf{q}$.

Airplane vibration equation during GVT with inertial force simulation due to engine blade loss can be received from (1) when $v = 0$.

Caused by blade loss the inertial force vector, rotating in the plane normal to the engine rotor axis, is written as

$$\mathbf{F}^{\mathbf{I}} = \left[0,..., f_n,...,0\right]^{\mathrm{T}}, \quad f_n = \Omega^2\left(rm\right) \tag{2}$$

where Ω - engine rotor rotational speed, constants at windwilling regime for selected Mach numbers, r – the radius from the rotor axis to the center of gravity of m, m - missing blade mass, f_n – the resultant force of all blades in damaged section of the engine.

3 ROTATING FORCE SIMULATION

The simplest version of modeling the inertial force (at imbalance) is associated with the use of two fixed-mounted electrodynamic exciters, controlled by sine generator signals with phase shifted by 90 degrees.

To generate the resultant rotating force it is enough to apply two of its projection - fixed - to the engine, in one of its sections near the 1st stage (ventilator), assuming that the rotor axis and the section are undeformable [3].

Projections of rotating vector of inertial force on the vertical axis *y* and the lateral axis *z*, are equal to

$$F_{\mathbf{y}}^{\mathbf{I}} = \Omega^2\left(rm\right)\cos\left(\Omega t\right), \quad F_{\mathbf{z}}^{\mathbf{I}} = \Omega^2\left(rm\right)\sin\left(\Omega t\right) \tag{3}$$

It should be noted, if structure characteristics are linear and retained in time, then the rotating force can be replaced by two projections of force on vertical *y* and lateral axes *z*, i.e. when vibrations are caused by each of these projections, applied at different times (considered the superposition of vibrations).

It was proposed verification of vibration's superposition results obtained during ground vibration tests of airplane. Such superposition has been successfully applied previously in vibration analysis with of airplane with linear characteristics [1, 2].

4 HISTORY OF ROTATING FORCE SIMULATION AT IMBALAMCE

In paper [5] data obtained with the simulation of rotating forces during GVT on A340-500 aircraft with two engines mounted on pylons was shown. That data were obtained for almost steady, forced oscillations (windmilling) with a continuous change of the excitation frequency ω (t) in the range of 9-50 Hz, and 1-12.5 Hz.

In paper [3] it was shown data examples obtained with the simulation of rotating forces during regular GVT on Russian transport airplanes - No.1 with two engines mounted on pylons (in 2011) and No.2 with four engines mounted on pylons (in 2012). That data were obtained for almost steady, forced oscillations (windmilling) with a continuous change of the excitation frequency ω (t) in the range of 1.5-5.0 Hz for airplane No.1, and in range of 3.0-20.0 Hz for airplane No.2.

It should be mentioned, in [5] a positive response to the question of the admissibility to replace the vibrations of the rotating force to superposition of vibrations is given. The author also has received positive test results with measurements of vibrations caused by only horizontal or by only vertical force, sequentially, that makes possible to correct the analysis data according to experiment data with the superposition of vibrations.

5 DATA EXAMPLES

Experimental data of amplitude frequency response functions (FRFs) for accelerations at structural points for airplane No.1 and No.2, obtained in simulation of the rotating inertial force and the superposition of oscillations, caused only by one vertical force or one lateral force, sequentially, are received.

On Figure 5.1, for example, amplitude frequency response functions for accelerations in pilot cabin are presented.

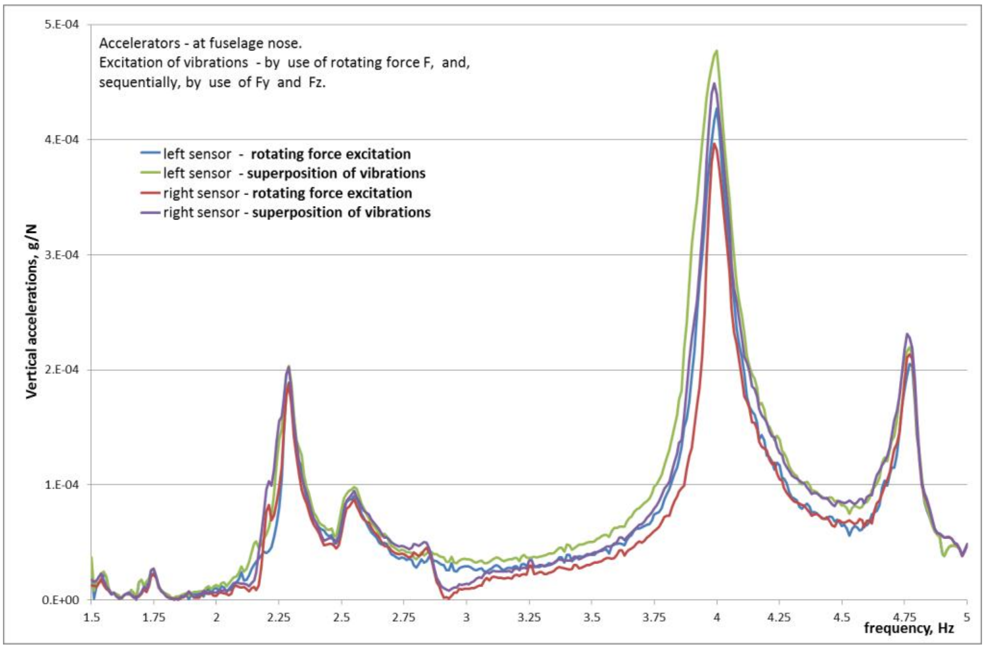

Figure 5.1: FRFs in pilot cabin

6 CONCLUSIONS

Rotating force simulation in the case of steady vibrations at imbalance is part of the common problem necessary to adjust the calculations of dynamic loads due to engine blade loss in flight.

The ground test method with the vibration simulation from the rotating force and with its replacement by a superposition of vibrations from the engine imbalance on full-scale airplanes was perfected.

Experiment with the imbalance could be run in the process of "regular" GVTs without any significant costs nor on the time, nor on the complexity.

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