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INVESTIGATION OF THE AUTOROTATION STABILITY OF A TURBOFAN ENGINE WITH A DETACHED FAN BLADE

One of the requirements for the aircraft being designed is the ability to continue flying and landing if one engine fails. One of the calculated cases of engine failure is the separation of the fan blade. This phenomenon causes large vibrations in both the engine itself and the aircraft structure. A calculation model and method for studying engine oscillations with damage in the form of blade separation have been developed. Numerical studies of the oscillations of the engine suspended on a pylon were conducted. The operation of an engine with an unbalance of the fan after switching off during the transition to autorotation is considered. Numerical simulation was performed using the ANSYS Workbench package. The front supports of the rotors are ball bearings installed in the elastic elements of the "squirrel cage". Ball bearings are modeled as a rigid hinge. There are two thin-walled shells, which are intermediate power elements outside the elastic element. With an increase in the imbalance of the fan rotor, the gap in the oil damper closes, the damper housing sits on the shells, switching on their rigidity to work. Thus the support stiffness characteristic is bilinear. The stiffness coefficients of the elastic element "squirrel cage" and the shells of the front support are determined by numerical simulation. The fan rotor is modeled as a rigid body on bearings. The motor stator is modeled by a rigid body on an elastic suspension. The pylon and elements of the elastic suspension of the engine are modeled by beams of variable section, working simultaneously in tension, torsion, and bending. Numerical analysis of the transient oscillations of the D-436-148FM engine mounted on the pylon of the AN-178 aircraft was performed. The amplitude-frequency response of oscillations is obtained in the frequency range below the fan speed in the cruising mode. The stability of engine oscillations at a resonant frequency close to the autorotation frequency has been studied. The results of the numerical simulation are presented in the form of diagrams. Orbits of the centers of gravity of the fan rotor and the motor casing in the resonant mode are constructed. Poincaré mappings of oscillations of the same points of the structure are also constructed.

Keywords: *engine; rotor damage; unbalance; vibration; numerical simulation; autorotation.*

Introduction

One of the conditions for aircraft certification under European Regulations section SC 25.362 (AMC 25.362) is the ability to continue flight and land if one of the engines fails. One of the calculated cases of engine failure is the separation of the fan blade [1]. This phenomenon causes large vibrations of both the engine itself and the aircraft structure.

A common cause of fan blade failure is bird ingestion. In [2 – 5], the influence of a bird strike on engine vibrations was studied. In these works, engine vibrations over the entire range of rotational speeds and the transfer of load to the pylon and wing of the aircraft were not studied.

The flutter of a wing section with flaps and an engine mounted on an elastic suspension is studied numerically and experimentally in [6]. In [7], the pylon attachment to the wing was designed using the FEM model. In [8], a nonlinear aeroelastic analysis of aircraft wings with a rotating unbalanced propeller mass was performed. These works did not investigate the forces acting on the pylon and the wing during transient vibrations caused by blade separation.

In [9] a finite element model was proposed to evaluate the connection strategies between the components of the power plant. It has been verified whether such mechanisms can effectively increase engine performance by reducing detrimental structural deformations of the engine, but no studies have been carried out on the transfer of loads to the aircraft wing.

The D-436-148FM engine under study contains three coaxial rotors – a fan, a low-pressure compressor (LPC) and a high-pressure compressor (HPC). The rotors are driven by their turbines and have different optimal rotational speeds for them and are interconnected only by gas-dynamic coupling.

The mass of the fan blade is 3.625 kg, and the radius of the center of mass from the axis of rotation is 0.365 m. The rotor blades of the LPC and HPC are small compared to the fan blades (the mass of the compressor blades is from 5 to 65 grams, the mass of the turbine blades is up to 80 grams). Therefore, the influence of the imbalance of these rotors on the engine mount is not taken into account.

All three rotors are mounted on non-linear elastic supports, which are fixed in the engine stator. The purpose of elastic-damper supports is to reduce the overall level of vibrations of the rotors and the entire engine as a whole and to eliminate dangerous resonant vibrations from the operating range or shift them to safe modes.

The aim of the work is to study the oscillations of an engine on an elastic suspension during the transition from cruising to autorotation after the loss of a fan blade.

The objectives of the study are: development of a calculation model and a method for studying engine oscillations with damage in the form of blade separation; determination of the resonant frequencies of the engine mounted on an elastic pylon; checking the amplitude and stability of oscillations at resonant frequencies.

1. Development of models of bearings and bearing supports

The front supports of all three rotors of the D-436-148FM engine are ball bearings installed in the "squirrel cage" elastic elements. A ball bearing is modeled as a rigid hinge. This model is justified by the fact that, firstly, the deformation of the ball bearing itself compared to the deformation of the elastic support can be neglected, and secondly, the frequency of free oscillations of the rotor on ball bearings without elastic supports differs from the oscillation frequency of the rotor of the existing design by several times [10].

The rear supports of all three rotors are roller bearings with a hydrodynamic oil film without elastic elements. The oil layer is fully load-bearing and damping.

The coefficient of rigidity of the elastic element "squirrel cage" of the front support was determined by numerical simulation, verified experimentally and is equal to $0.1\bullet10^8$ N/m. At a normal level of rotor unbalance, the elastic element provides a decrease in the rigidity of the mechanical connection of the rotor with the stator and allows rotor to pass the critical revolutions with low vibration to the idle mode.

Outside the elastic element, there are two thin-walled shells, which are the power elements for fastening the elastic element in the housing. With an increase in the unbalance of the fan rotor in the oil damper, a gap of 0.2 mm is closed and the damper body sits on the shells. After that, the elastic member and the shells are deformed together. To determine the stiffness coefficient of the shells of the support body, using the Solid Works finite element package, a model of the assembly of the shells was built and studied. The total stiffness coefficient of both shells is $2.89\cdot10^8$ N/m.

Thus, the support stiffness characteristic is bilinear.

Vibration damping devices in both supports are modeled by viscous dampers. The coefficient of viscous damping of the front support damper is $9.36\bullet10^5$ N•s/m^2, and that of the rear support is $4.65\bullet10^5$ N•s/m^2.

2. Development of models of engine rotors

The fan rotor is modeled as a solid body on bearing supports, since the deformations of the rotor parts are small compared to the deformations of the bearing supports and the lower natural frequency of the rotor oscillations as an elastic body is an order of magnitude higher than the frequency of oscillations of the rotor on bearing supports [11, 12].

Models of blades are accepted without shrouds and locks. The mass of locks and shrouds is added to the mass of the disk. Turbine blades (112 pieces on each disk) are not modeled, their masses are attached to the disk masses in the form of rims.

The assembled rotor is shown in Fig. 1. Its inertial characteristics are as follows: mass m = 345.15 kg; coordinate of the center of mass from the rear plane of the engine mount X = -1.31 m; central moments of inertia I_{xx} = 22.80, I_{yy} = I_{zz} = 265.51 kg·m^2.

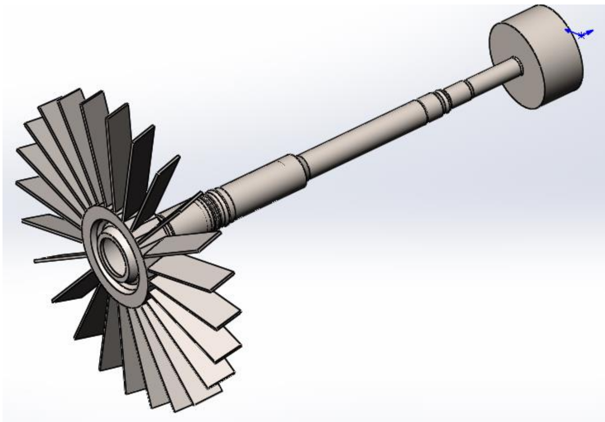

Fig. 1. Fan rotor model

LPC and HPC are modeled by solid symmetrical bodies on elastic supports with rolling bearings. The blades of these rotors are small compared to the fan rotor blades, so the effect of the imbalance of these rotors on the engine mount is not taken into account.

3. Development of an engine stator model

The stator of the engine will be called the assembly of its cases with all the equipment fixed on it and the engine nacelle. The engine case is modeled by a rigid body on an elastic suspension (Fig. 2).

Such a model allows one to pass to the finite element representation of the stator in the form of an abso-

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lutely solid weightless frame, the mass-inertial characteristics of which are set by one finite element "Structural Mass".

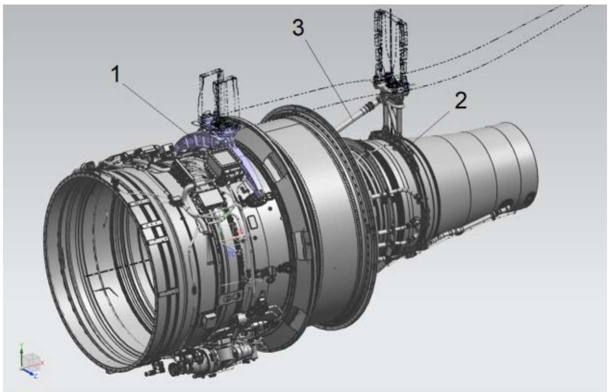

Fig. 2. Suspended engine case model

The frame is attached to the elastic elements of the suspension – the front traverse 1 and the rear traverse 2 and the pull rod 3. Inside, the rotor is connected to the frame by means of non-linearly elastic finite elements simulating bearing supports.

Traverses are modeled by elastic beams of variable cross section, working in bending. We model the pull rod with an elastic rod working in tension.

4. Development of calculation models of the pylon and engine mounts

The load-carrying element of the pylon is a torsion box. An engine with a nacelle, a pylon nose, fairings, a pylon aft, and a pylon fairing are attached to the torsion box.

The torsion box is modeled by a beam of variable cross-section working simultaneously in tension, torsion and bending. The finite element model of the torsion box is shown in Fig. 3. The finite elements of the torsion box are the sections between its ribs.

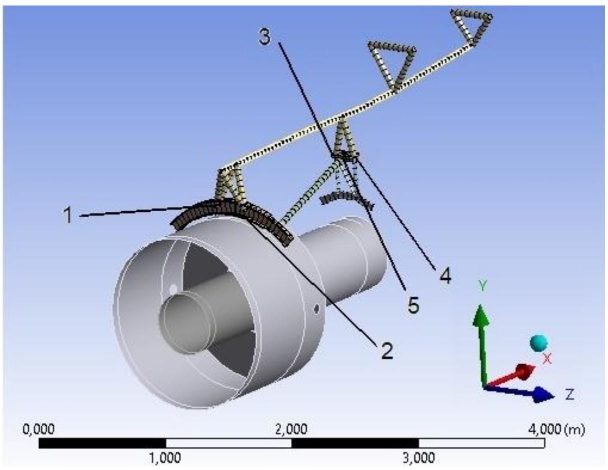

Fig. 3. Finite elements of the torsion box and engine

The front traverse is attached to the front suspension bracket with two bolts, which are modeled by hinges with axes parallel to the engine axis (nodes 1 and 2). The hinges transmit forces in a plane perpendicular to the axis of the engine.

The N-shaped truss of the rear attachment belt is also attached to the rear suspension bracket with two bolts, which are modeled by hinges with axes parallel to the engine axis (nodes 3 and 4). A pull rod is attached to the same bracket by a hinge with an axis perpendicular to the vertical plane (node 5).

5. Numerical analysis of the vibration of a rotor with a detached blade during the transition to autorotation

After the fan blade breaks off, large-scale vibrations begin in the entire structure. The pilot turns off the engine and its speed is reduced to the autorotation speed. The fan speed in cruising mode is f_c = 96.67 Hz. Frequencies and modes of free oscillations of the engine on the pylon are determined in the range from zero to f_c. To do this, a modal analysis of the model built in ANSYS was performed. The following series of frequencies f_1 – f_{14} was received: 3.00; 6.60; 10.35; 11.96; 25.19; 26.96; 29.35; 52.91; 62.12; 74.87; 79.42; 80.63; 87.16 and 89.18 Hz.

The fan rotating frequency during autorotation is f_a = 23.58 Hz. It can be seen that during the transition to autorotation, the engine speed passes through ten resonant frequencies f_{14} – f_5. The frequency f_5 = 25.19 Hz is close to the autorotation frequency. The oscillation mode at this frequency represents the translational movement and rotation of the engine on the pylon in a vertical plane. It is necessary to check the strength of the engine mount at this frequency.

To analyze the amplitude of oscillations, an amplitude-frequency response was considered near the autorotation frequency using Harmonic Response Analysis in the ANSYS package. (Fig. 4).

Peaks with a limited range are observed at all resonant frequencies. In the ANSYS package, the amplitude-frequency response is built without taking into account the nonlinearity of elastic elements, even if this nonlinearity is specified in the properties of the elements. Therefore, the amplitudes of oscillations at resonant frequencies were calculated by numerical integration of the nonlinear model over a time interval of 100 periods. At a resonant frequency of 25.19 Hz, the maximum forces in the fastening hinges of the engine traverses to the pylon are equal: in the front right – 14661 N, in the front left – 9408 N, in the rear right – 34383 N, in the rear left – 14083 N; the maximum forces in the fastening hinges of the pylon to the wing are equal: in the front right – 25881 N, in the front left – 45462 N, in the rear right – 28430 N, in the rear left – 40494 N.

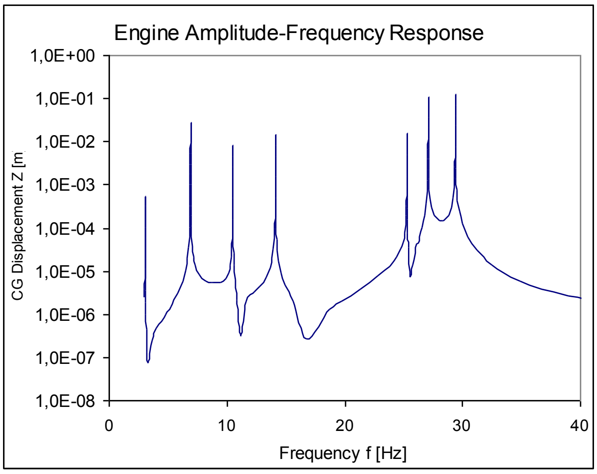

Fig. 4. Amplitude-frequency response

Since the rotor supports are non-linear, it is necessary to check the oscillation stability at the resonant frequency, which is close to the autorotation frequency. The orbits of the centers of mass of the fan rotor and the motor housing were plotted over a time interval of 100 periods (Fig. 5, 6). After the transition time, the orbits converge to ellipses, which is typical for stable oscillations. The slight blurring of the elliptic lines can be due both to the error of the ANSYS numerical integration and to the imposition of some chaoticity on the stable oscillations.

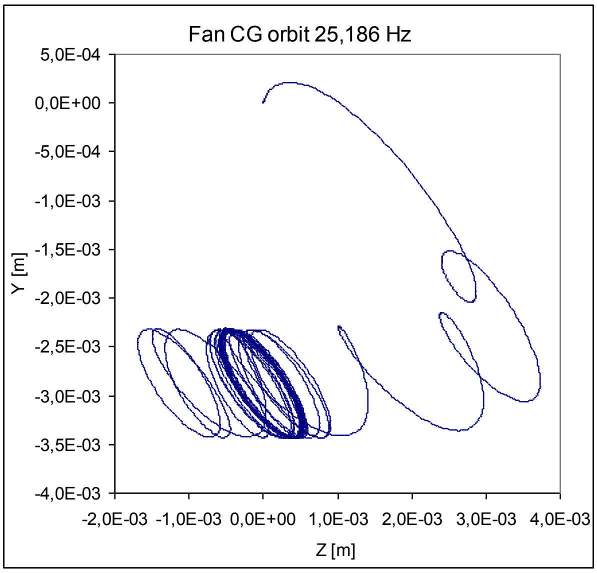

Fig. 5. Orbit of the fan center of mass

To refine the stability of the oscillations, the Poincaré maps of the same points over 1000 periods were constructed (Fig. 7, 8). After the transition process, the map of the center of mass of the fan rotor converges to a point (Fig. 7), and the map of the center of mass of the engine casing converges to a blurred point. Such mappings confirm the stability of nonlinear oscillations.

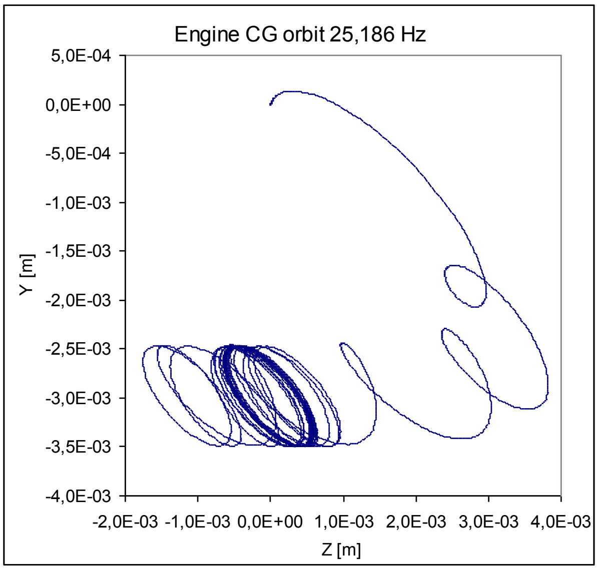

Fig. 6. Orbit of the engine center of mass

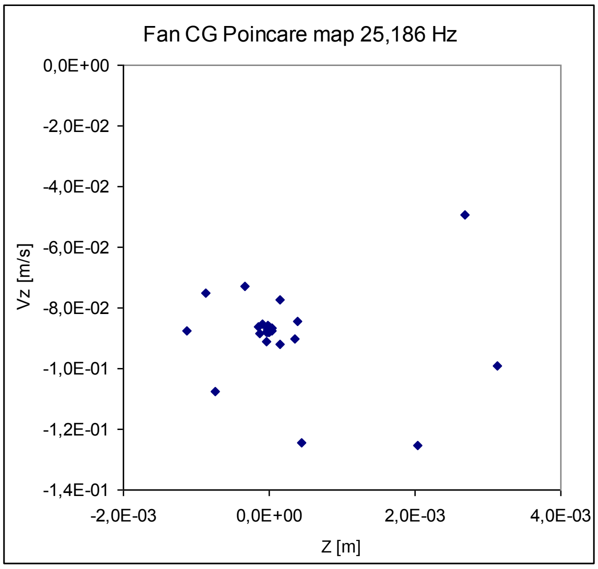

Fig. 7. Poincaré map of the fan center of mass

Conclusions

A method and a computer program have been developed for analyzing oscillations of a turbofan engine caused by a fan blade separation.

Bearing supports are modeled by elastic elements with viscous damping, while the front support has a bilinear characteristic due to the fact that during large fluctuations, the elastic element "squirrel cage" is first deformed, and then the support shells are deformed together with it.

A numerical analysis of the transient vibrations of the engine D-436-148FM on the pylon of the AN-178 aircraft was performed. In particular, the stability of the oscillations of the fan rotor during the transition to autorotation is considered.

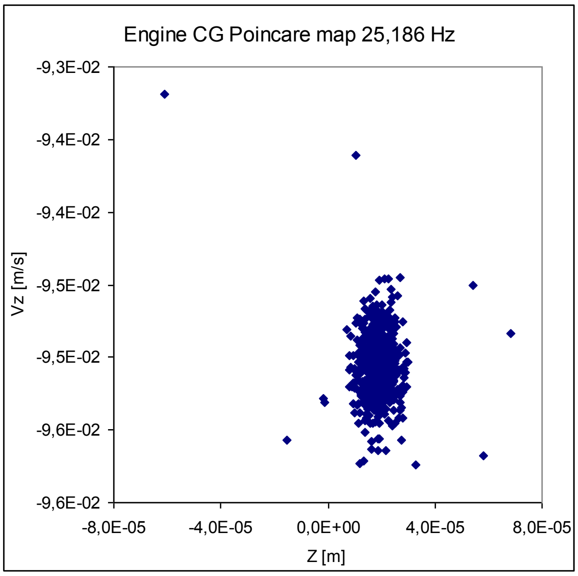

Fig. 8. Poincaré map of the engine center of mass

The results of the calculations are presented in the form of time-dependence graphs of the forces in the bearings and in the engine mounting joints.

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ДОСЛІДЖЕННЯ СТІЙКОСТІ АВТОРОТАЦІЇ ТУРБОВЕНТИЛЯТОРНОГО ДВИГУНА З ВІДІРВАНОЮ ЛОПАТКОЮ ВЕНТИЛЯТОРА

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Однією з вимог до літака що проектується є здатність продовжити політ і здійснити посадку при пошкодженні одного з двигунів. Одним з розрахункових випадків пошкодження двигуна є відрив лопатки вентилятора. Це викликає великі вібрації, як самого двигуна, так і конструкції літака. Розроблено розрахункову модель і метод дослідження коливань двигуна з пошкодженням у вигляді відриву лопатки. Проведено чисельні дослідження коливань двигуна, що підвішений на пілоні. Розглянуто роботу двигуна з дисбалансом вентилятора після відключення при переході до авторотації. Чисельне моделювання виконано за допомогою пакету ANSYS Workbench. Передні опори роторів – кулькові підшипники, які встановлено в пружних елементах «біляче колесо». Кульковий підшипник моделюється жорстким шарніром. Зовні пружного елемента розташовані дві тонкостінні обичайки, що є проміжними силовими елементами. При збільшенні дисбалансу ротора вентилятора закривається зазор в масляному демпфері, корпус демпфера сідає на обичайки, включаючи в роботу їх жорсткість. Таким чином, характеристика жорсткості опори є білінійною. Коефіцієнти жорсткості пружного елемента «біляче колесо» та обичайок передньої опори визначені методом чисельного моделювання. Ротор вентилятора моделюється твердим тілом на підшипникових опорах. Статор двигуна моделюється твердим тілом на пружній підвісці. Пілон і елементи пружної підвіски двигуна моделюються балками змінного перерізу, що працюють одночасно на розтяг, кручення та вигин. Виконано чисельний аналіз перехідних процесів коливань двигуна Д-436-148ФМ підвішеного на пілоні літака АН-178. Отримано амплітудно-частотну характеристику коливань в діапазоні частот нижче частоти обертання вентилятора на крейсерському режимі. Досліджено стійкість коливань двигуна на резонансній частоті, що близька до частоти авторотації. Результати чисельного моделювання представлені у вигляді діаграм. Побудовано траєкторії руху центрів мас ротора вентилятора та корпусу двигуна на резонансному режимі. Побудовано також відображення Пуанкаре коливань тих самих точок конструкції.

Ключові слова: двигун; ротор; пошкодження; дисбаланс; вібрація; чисельне моделювання; авторотація

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