DYNAMICS OF BLADE LOSS OF HIGH BYPASS RATIO ENGINE

Leontiev M.K.[1], Davydov A.V. [1], Degtyarev S.A.[2], Gladkiy I.L.[3],

[1]Moscow aviation institute
[2] Alfa-Tranzit Co Ltd.
[3] Aviadvigatel OJSC

Annotation

The article gives results of modeling of dynamics characteristics of the turbofan engine during and after a fan blade loss. To solve the task, the nonlinear non-stationary model was created. It includes the LP rotor, the HP rotor, the cases, the nacelle with the thrust reverser, the engine mount to the pylon, the pylon, the aircraft hanger to the wing. The rotor system model also embraces the rolling bearings, whose stiffness was calculated for the engine work at different regimes, the nonlinear hydrodynamic dampers and the elastic elements ("squirrel cages").

Key words: *rotordynamics, blade loss, rotor rundown, autorotation, nonlinear model, non-stationary analysis, Dynamics R4*

Introduction

Let us note some peculiarities of the problem considered in this article taking into account Russian airworthiness requirements AP-33 [1], and also recommendations given in the memorandum [2] and the circular [3] of Federal Aviation Administration (FAA) in the USA. General requirements of these documents set that neither defects nor failures in the aircraft power plant nor their combinations should disturb its safe flight. There are also regulations which require stopping the engine rotation in case of dangerous defects and which may lead to failures of the aircraft.

Besides, it should be noted that for the high bypass ratio engines it is virtually impossible to stop the engines rotation during flight, so there is constant rotor's autorotation provoked by approach air flow. Autorotation regime should be safe enough considering loads and the shafts displacements in order to provide the safe flight to the landing place.

One of the most dangerous defects of the high bypass ratio engines is the fan blade loss leading to different kinds of structural destructions of its units and the nacelle with the most important aggregates on it. Significant unbalance forces appeared after the blade loss and acting from the side of the fan rotor to the engine case may provoke great vibrations transferring through the mount and the engine pylon to the aircraft's wing and the fuselage.

In the analysis of the blade loss dynamics it is possible to highlight three phases of the process when under unbalanced force appearing in the rotor, significant displacements of the rotors, deformations of the case elements of the engine design , contact between the rotor and the stator may take place:

-the moment of the blade loss when some case elements are destroyed, contact between the fan blades and boosters with the case takes place;

-the rotors' rundown after switching off fuel feeding into the combustion chamber up to the autorotation regime;

- autorotation regime.

This problem became topical when high bypass ratio engines appeared. For big commercial aviation engines centrifugal load at one fan blade may exceed the engine thrust in 2-3 times. So, for the engine GE90-115B thrust is 450000…512000 N. For the engines GEnx – 240000…334000 N. It is possible to estimate consequences of the blade loss using these numbers [4].

Normative documents mentioned above require carrying out the necessary modeling and analysis of the blade loss dynamics using certain software with the following adjustment of the mathematical model of both base engine and derived one using different methods (calculated, experimental, empirical). It is important to carry out the experiment with blade loss on special rig including the fan rotor and the case or on the actual engine. Experiments with the blade loss and also numerical analysis were conducted on engines GE90-115B [4], SaM 146 [5] and the others.

The engine model for analysis should include all the functional engine units – the rotors, the cases, the mount, the nacelle with the aggregates, the pylon, dampers, and the rolling bearings. Calculation may be done both at linear and nonlinear statement insofar as there is understanding of nonlinear effects. Any change in design of the base engine should be analyzed and compared with the results of modeling of the derived engine [1], [2], [3].

There are only a few published works on the theme of mathematical modeling of the blade loss of high bypass ratio engines in spite of the fact that almost all leading engine world companies develop the models and algorithms, conduct numerical analysis and experimental tests with blade loss using them. The models for investigation are built using standard finite-element programs such as LS-DYNA and MSC NASTRAN. Investigations take place using both simple models including only the fan rotor and its stator [6] and more complex ones including the rotors, the cases, the mount and the pylon [7]. The obtained results are used to verify the models and to prepare experiments with the blade loss. Besides, there some general limitations and assumptions in the above mentioned works: investigations take place at linear statement; transient processes last only three-four seconds after the blade loss.

The present article gives the results of modeling of dynamic characteristics of high bypass ratio engines during and after the fan blade loss in the software system Dynamics R4 [8]. The software system gives an opportunity to create the finite-element engine models with consideration of almost all the above-mentioned requirements and to carry out the analysis both at linear and nonlinear unsteady statement using the ordinary computers without involving computing clusters.

The work was carried out taking into account airworthiness requirements AP-33 and FAA Memorandum. The model takes into consideration nonlinear characteristics of the rotors supports, stiffness and damping change at significant displacements in supports. The model was adjusted to estimate all three phases of the process: sudden unbalance appearance in the fan unit at maximum allowed rotating speed (unsteady process); decrease in rotating speed from maximum allowed speed up to the autorotation speed (unsteady process) at the existing fan unbalance and work at autorotation regime.

Transient processes were analyzed from the moment of the fan blade loss up to the going to autorotation regime. As a result of calculations, loads on the elements of the engine loading pattern at the fan blade loss at maximum rotating speed, at the rotor's rundown and at autorotation regime.

General theory

Dynamic motion equation in matrix form for the rotor system is the following in the general case:

$$[M]\{\ddot{q}(t)\} + [C]\{\dot{q}(t)\} + [K]\{q(t)\} = \{F_{UN}\} + \{R_{SFD}\} + \{R_{BEAR}\} + \{R_{CLR}\},$$

where $[M]$, $[C]$, $[K]$ – matrixes of inertia, damping, gyroscopes and stiffness correspondingly, obtained by discretization of the finite-element engine model; $\{\ddot{q}(t)\}$, $\{\dot{q}(t)\}$, $\{q(t)\}$ – vectors of acceleration, velocity and displacement correspondingly; $\{F_{UN}\}$, $\{R_{SFD}\}$, $\{R_{BEAR}\}$, $\{R_{CLR}\}$ – forces vectors from unbalance, reactions from hydrodynamic dampers, reactions from bearings and reactions in contact between the rotor and the stator. The equation is nonlinear, because reactions of the bearings, dampers and contacts depend on displacements and velocities in the dynamic system.

The most general method of dynamic analysis of the complex nonlinear unsteady rotor systems is integration of the joint motion equations. Dynamic behavior of the system is calculated for some consecutive time ranges with dynamic characteristics defined at the beginning of the considered range. New dynamic characteristics are obtained using the models of nonlinear elements. Input parameters of these models are displacements and velocities from the previous integration step. Nonlinear elements are connected with the rest of the dynamic system through them. Output parameters are dynamic reactions. External system loading may also change.

Dimension of the corresponding matrixes of inertia, stiffness, damping in the motion equation is equal to the number of freedom degrees of the built model. In this case there are about 6000. Direct integration of such equations system is time-consuming and takes a lot of machine time with consideration of necessity to calculate reactions of nonlinear elements at every step. That is why the system of motion equations is written in the modal form and is reduced in the way that calculation error is minimum with consideration of acceptable integration time [9].

Engine model

To solve the task, the spatial rod model of the engine including all the main engine components – the low pressure rotor, the high pressure rotor, the cases, the nacelle with reverse, the engine mount to the pylon, the pylon and the aircraft hanger to the wing – was created, Figure 1.

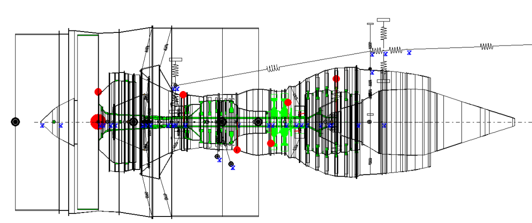
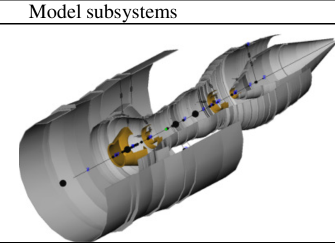
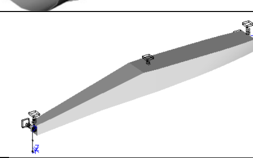
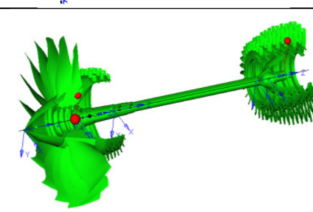
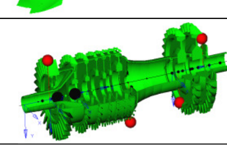
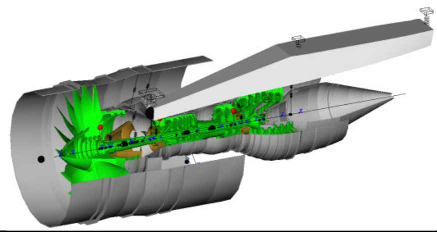


Figure 1 Finite-element model of investigated engine

The rotor system model includes also the bearings whose stiffness depends on the engine operating mode, nonlinear hydrodynamic dampers, elastic elements. Table 1 shows the main model components (hereinafter referred to as subsystems).

Table1

Model subsystems	
Engine case and nacelle with reverse	
Pylon	
Low pressure rotor	
High pressure rotor	

Assembled engine model	

All the subsystems are connected by elastic links simulating bearings, elastic elements, hydrodynamic dampers, flanges, etc.

In case of the fan blade loss, the engine is switched off, and rotors start autorotation. Figure 2 shows the diagram of change in low pressure rotor speed at autorotation start.

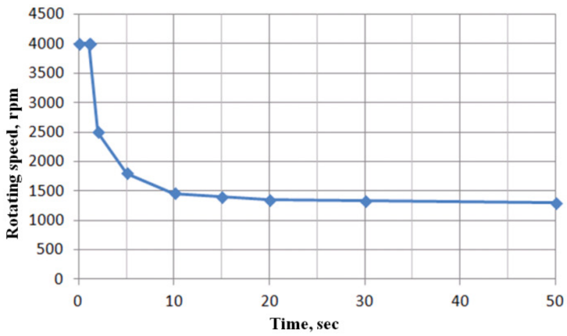


Figure 2 Change in rotating speed of low pressure rotor during rundown

To simulate elastic-inertia characteristics of the main engine components, the rod finite elements included into the library of the Dynamics R4 software system were used. There are conical beams and shells, inertia elements, springs, hinges, etc. among them. Elastic coefficients for all elements are calculated using the corresponding algorithms of the program system. For complex structural components elastic characteristics are obtained by creation of 3D models and obtainment of their full flexibility matrixes.

Modeling of squirrel cages

Coefficients of stiffness matrix of elastic elements of "squirrel cages" are determined in the finite-element program. One of the aims is to centre the rotor in clearance of hydrodynamic damper. The first condition to be met at designing of the elastic element is that the rotor shaft displacement under weight force does not exceed at least half of hydrodynamic damper clearance. At the following optimization of the engine dynamic system at the expense of elastic elements, decrease in their stiffness is undesirable. When obtaining the stiffness coefficients of squirrel cages the axial load transferring through it should be also taken into consideration [10].

Simulation of rolling bearings

There are two approaches when creating models of the rotor systems with rolling bearings: the first one is addition of nonlinear elements simulating rolling bearings into the model and analysis of the model at nonlinear statement; the other one is preliminary linearization of elastic characteristics of rolling bearings at regimes and their following use in the model. In the first case at current integration step of motion equations, the bearings reactions are calculated. They are defined by static forces acting on them and by rotors' unbalances. The obtained reactions are used in motion equations at the following integration step. In the second case the model complexity decreases, and integration takes much less lime [11].

Model of hydrodynamic damper

Hydrodynamic dampers were simulated on the basis of the known analytical solutions obtained for Reynolds equations [12]. The type of the dampers' models is chosen considering peculiarities of the damper oil feed. For all dampers oil is supplied through the holes without distributing groove. This gives an opportunity to apply the model of "long' damper for all dampers. The whole coverage by 2π oil film of damper of vibration machine is chosen considering that the damper load-carrying ability is preferable to make close to minimum one with maximum value of damping part of hydrodynamic force. This makes it possible to lower the dampers influence on radial stiffness of support unit. Analytical solutions used in the nonlinear rotor model were obtained applying different assumptions and work with practical accuracy in the range of relative eccentricities up to 0.5…0.6. At the blade loss, loads acting during transient process lead to eccentricity increase up to oil film rupture. With consideration of this, it may be assumed that the damper stops performing its functions at increased eccentricities, and it becomes necessary to exclude it from the support unit model at these eccentricities. Meanwhile, change in stiffness and damping characteristics of dampers by constants at the rotors rundown after the blade loss is not correct.

Fan unbalance

The fan rotor unbalance after the blade loss is obtained considering that loss of one blade is also accompanied by destruction of the half of the second blade.

Setting of engine model

The model was adjusted to investigate all the phases of unsteady process after the blade loss: sudden unbalance appearance in the fan unit at operating rotating speed; decrease in rotating speed to the autorotation rotating speed under the existing fan unbalance; the engine operation at autorotation regime. Integration time of motion equations corresponds to 50 seconds of the actual time of the rotors rundown. The used basis of frequencies and natural mode shapes was calculated in the range up to 30000 rpm and includes 61 mode shapes of bending, torsional and longitudinal joint oscillations. Contact of the rotor blades with the case was not taken into account.

Figures 3, 4 show bearings and flanges location to output the analysis results. Loads and deformations were investigated in the bearings of the rotors' supports; loads on flange joints of the fan cases F_x, F_y, F_z, M_x, M_y, M_z were obtained; loads on the mount elements F_x, F_y, F_z, M_x, M_y, M_z were obtained.

Critical speeds and mode shapes

Figure 5 shows the mode shape of the engine dynamic system, which defines the engine behavior after the blade loss during the rotors rundown at autorotation regime. All the other mode shapes do not virtually influence loss and rundown dynamics.

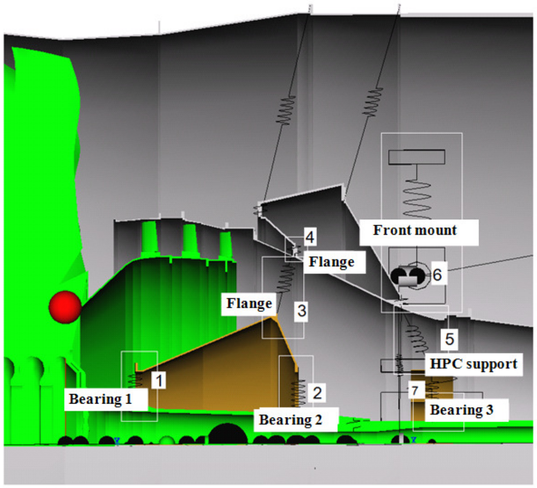


Figure 3 Places of results output at fan

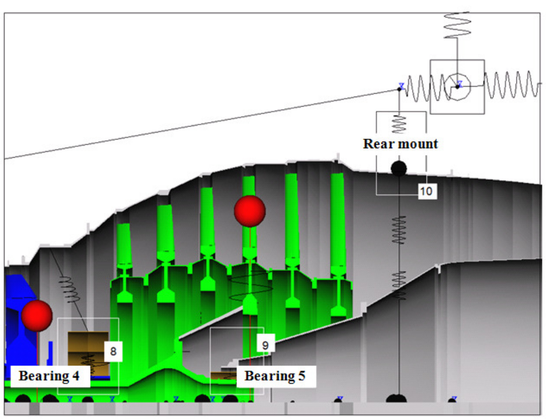


Figure 4 Places of results output at turbine

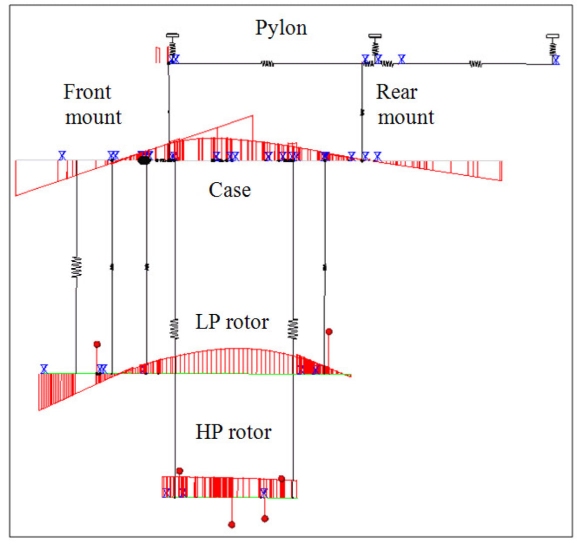


Figure 5 Natural mode shape at 1538 rpm

Resonance may be expected in the system during rundown and at significant fan unbalance at 8-9 second.

Dynamics of blade loss

Analysis results are output as amplitude-time characteristics for the whole transient process, starting from the blade loss and up to the autorotation regime. General calculation time accounted ~ 1 hour 30 minutes for the used computer. The general volume of the created file is ~530000 Kbyte. The file includes information on all the freedom degrees of the engine model and at all possible parameters- displacement, velocity, deformation, forces, reactions, etc. Figures 6…8 show amplitude-time characteristics of the acting reactions in the engines mounts starting from the blade loss moment at the 1-st second, switching off the engine at1.1-st second and up to 50-th second of the rotor rundown.

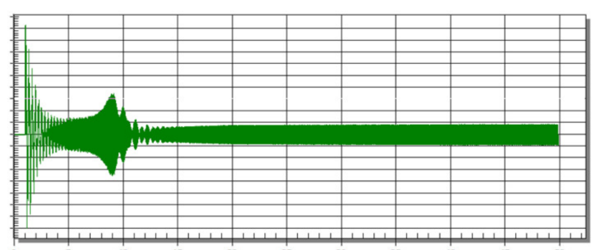


Figure 6 Reaction in engine front mount(Y direction)

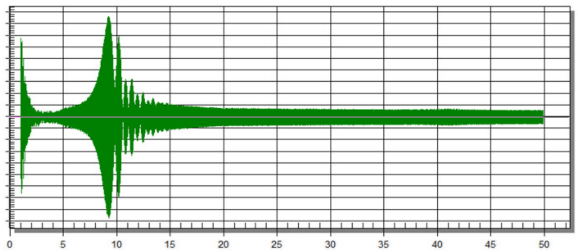


Figure 7 Reaction in rear mount
(Y direction)

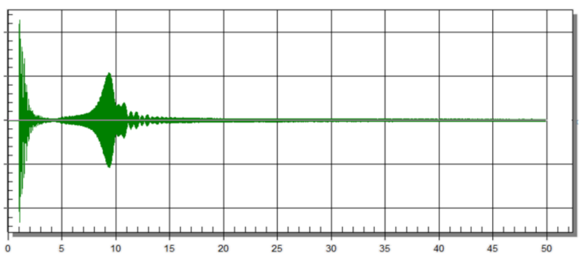


Figure 8 Reaction in rear mount
(Z direction)

Similar results were obtained for the other engine places. Analysis shows that significant loads on the elements appear not only at the moment of blade loss but also during the rotor rundown at resonance frequency.

Conclusions

The methodology of dynamics investigation of the blade loss in high bypass ratio engines in the software system Dynamics R4 is presented. Dynamic characteristics of the turbofan model at unsteady statement including all the main components of flow chart of the engine – the rotors, the cases, the pylon, the mount – were analyzed. For the first time the task of the blade loss was solved for the model including nonlinear design elements – rolling bearings and hydrodynamic dampers, which gave opportunity to make the obtained results close to the actual physical processes. The developed model of the blade loss and the obtained results may be used to prepare actual experiment on the blade loss and to its following validation in correspondence with Aviation rules of flight safety protection.

Literature

1. Авиационные правила, Часть 33 "Нормы летной годности двигателей воздушных судов" (АП-33).

2. Policy for Propeller Safety Analysis. Memorandum, US Department of Transportation/Federal Aviation Administration. ANE-2002-35.15-R0, October 30, 2003

3. Advisory Circular. US Department of Transportation/Federal Aviation Administration. 8/2/2000. AC No.:25-24.

4. Use of LS-Dyna Tool for Predicting Fan Blade Out (FBO) Response. General Electric. Users Conference Innovation Through Simulation/August 3-5, 2006, Bangalore.

5. A. Ryabov, V. Rechkin, S. Kukanov, Y. Shmotin, D. Gabov. Numerical Analysis of Aircraft Engine Fan Blade-Out Dynamics//Proceedings of 42ndAIAA/ASME/SAE/ASEE Joint Propulsion Conference «The impulse to Explore – Ignitinga Passion for Space», - Sacramento CA, USA, 2006.

6. Charles Lawrence and Kelly Carney. Simulation of Aircraft Engine Blade-Out Structural Dynamics. NASA/TM-2001-210957, June 2001, 24 pp.

7. Mohammad A. Heidari, David L.Carlson, Ted Yantis. Rotor-dynamics Analysis Process, Post Conference Web Page, Worldwide Aerospace Conference & Technology Showcase, April 8 - 10, 2002 in Toulouse.

8. Леонтьев М.К., Дегтярев С.А., Иванов А.В. Программная система расчета динамики роторов Dynamics R4. Свидетельство об отраслевой разработке №6691. Отраслевой фонд алгоритмов и программ. Государственный информационный центр информационных технологий. Министерство образования Российской Федерации. 2006 г.

9. Леонтьев М.К., Иванов А.В. Модальный анализ динамических систем роторов. “Известия высших учебных заведений. Авиационная техника”. 2005, №3.

10. Леонтьев М.К., Терешко А.Г., Исследование влияния характеристик упругих элементов опор роторов на динамику ГТД. Международный научно-технический форум, посвященный 100-летию ОАО «Кузнецов» и 70-летию СГАУ, Самара, 5-7 сентября 2012 года. Сборник трудов в 3-х томах Самара, 2012.

11. Леонтьев М.К, Снеткова Е.И. Нелинейные модели подшипников качения в роторной динамике. «Вестник Московского авиационного института» № 2, 2012 г., т. 19.

12. John M.Vance. Rotordynamics of Turbomachinery. Willey-Interscience Publication/ John Willey & Sons Inc., 1987, 388 p.

Information about authors

Leontiev Mikhail K., professor of Moscow Aviation Institute (National Research University), Doctor of Technical Science, MAI, Volokolamskoe road., 4, Moscow, A-80, GSP-3, 125993; tel.: +7-985-768-71-29; e-mail: lemk@alfatran.com. Stability and dynamics of constructions, rotordynamics of turbomachines, vibration diagnostic.

Davydov Arkadiy V., post-graduate student of Moscow Aviation Institute (National Research University) MAI, Volokolamskoe road., 4, Moscow, A-80, GSP-3, 125993; tel.: +7-985-768-71-29; e-mail:

davidovarc@gmail.com . Stability and dynamics of constructions.

Degtyarev Sergey A. , development team leader of the Scientific and technical centre of rotordynamics Alfa-Tranzit Ltd., Russia, Moscow region, 141400, Khimky,
Leningradskaya street, 1; tel: +7 -916- 516-75-27, e-mail: degs@alfatran.com. Rotordynamics of turbomachines, vibration diagnostic.

Gladkij I.L., head of department, candidate of technical science, Aviadvigatel OJSC, 93 Komsomolski prospect, Perm, GSP, Russia, 614990. Tel. 8-922-649-51-49. Stability and dynamics of constructions.