EVALUATION OF COUPLED VIBRATIONS IN AERO-ENGINE COMPRESSOR BLADED DISK

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ABSTRACT

Natural frequency determination in aero engine compressor blading is highly important in the design of turbo-machines. The difficulties faced by the designer during sizing of turbine blading are many. The major problem of design is a fair prediction of the natural frequencies of the compressor blading at the earlier stages. In general, a compressor blade is pre-twisted and tapered with an asymmetrical airfoil cross section and is mounted on the rotating turbine disk at a stagger angle. The differential equations of motion for the case of a single turbine blade are quite complex, and the solution of such equations is difficult to obtain. The present work deals with, establishing the best practice for coupled blade vibration analysis along with disk mode. The blade is considered to be mounted with the axis of symmetry in the plane of disk rotation. Simulation engineering is effectively utilized to analyze the blade and disk modes. Campbell diagrams are drawn at critical nodal diameters to arrive at separation margins in bladed disk assembly.

Keywords: *Campbell diagram, Finite element analysis, Modal analysis, Nodal diameters, Turbofan.*

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1. INTRODUCTION

Turbofan engines are found on commercial airliners around the world and have revolutionized the way we travel. The turbofan engine functions by way of a thermodynamic cycle where air is ingested into the engine, compressed, combusted, expanded, and exhausted from the engine creating thrust to propel the vehicle. These five steps are carried out by five major engine components: the fan, compressor (low and high pressure), combustor (or combustion chamber), turbine (high and low pressure), and exhaust nozzle [2].

The work carried out is analyzing the behavior of the turbofan in an aircraft engine using the analysis tool Ansys 14.5 Workbench. A single sector of a fan blade is modeled and analyzed with cyclic symmetry condition. Modal analysis is carried out to find different mode shapes and natural frequency at different nodal diameters. Campbell diagram is plotted to understand the resonance band.

2. PROBLEM DEFINITION

The major problem of design is a fair prediction of the natural frequencies of the compressor blading at the earlier stages. In general, a compressor blade is pre-twisted and tapered with an asymmetrical airfoil cross section and is mounted on the rotating turbine disk at a stagger angle. The differential equations of motion for the case of a single turbine blade are quite complex, and the solution of such equations is difficult to obtain. Also, the natural frequencies determined are affected by shear deflections, rotary inertia, fiber bending in torsion, warping of cross section, root fixing, and coriolis accelerations. Apart from all these the slender disk also participates in vibrations of bladed disk assembly, which is most critical.

2.1 RESEARCH OBJECTIVES

The Research objectives of the present work are

(1) Estimation of diametric modes shape considering the effect of pre twist, stress stiffening and spin softening.

(2) Campbell diagrams are to be drawn at critical nodal diameters to arrive at separation margins in bladed disk assembly.

2.3 Turbofan Terminology:

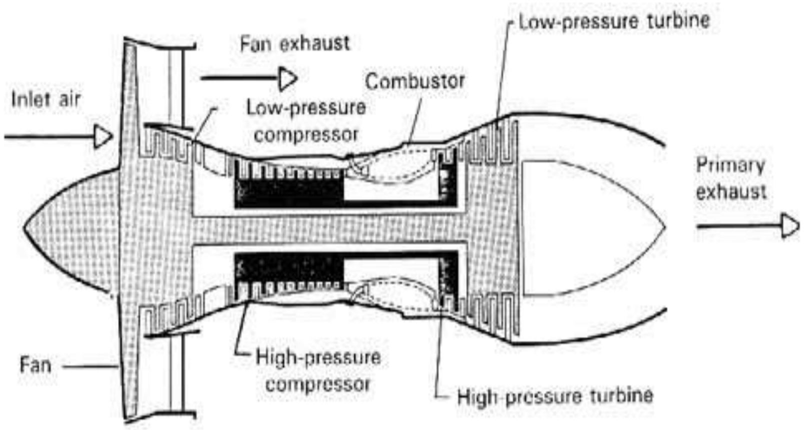


Figure 1: The figure shows the parts of turbofan engine used to propel the engine [source: history.nasa.gov]

Methodology:

Finite element analysis method is used to carry out the analyses by generating the single sector of turbofan model using the design modeler of Ansys 14.5 workbench. And analysis is done using mechanical of ansys 14.5; the material used for the analysis is Titanium Ti-6Al-4V which is most commonly used in the aircraft industry because, it has a good balance of characteristics including:

strength, ductility, fracture toughness, high temperature strength, creep characteristics, weldability, workability, and thermal process ability (higher strength is easily obtained by heat treatment)

Table 1: Fan Blade Configurations [1]

Component	Feature (mm)
Blade-tip radius	508
Blade-root radius	152.4
Blade-root stagger angle	17^o
Blade-tip stagger angle	40^o
Blade chord at tip	132.08
Blade chord at root	114.3
Number of rotor blades	20

Table2: Material Properties

Description	Value
Material	Titanium Ti-6Al-4V
Chemical Composition	6%Al+Max 0.25% Fe+ Max 0.2% O+90%T+4% V
Density	4430 kg/m3
Modulus of Elasticity	113.8 GPa
Poisson's Ratio	0.342
Tensile Strength, Ultimate	950 MPa
Tensile Strength, Yield	880 MPa
Compressive Yield Strength	970 MPa

Structural analysis is done using Titanium Ti-6Al-4V a turbofan material.

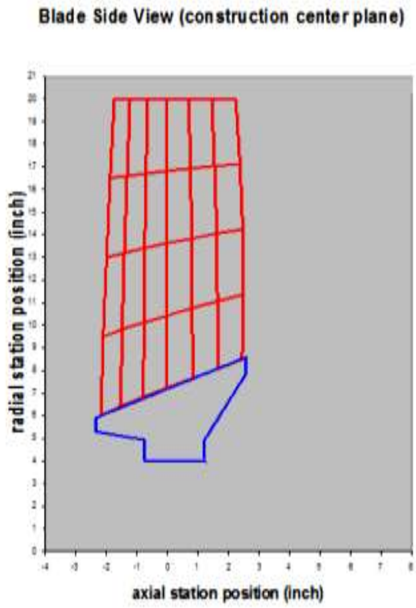


Figure 2: Shows the fan blade profile used

Figure 3: The computer-aided model (CAD) of a single sector turbofan

The mass and volume of single sector turbofan is m=2.9145 kg; V=6.579e+005 mm³.The cyclic symmetry option is used to reduce the solution time.

2.4 Mesh statistics and Boundary Conditions:

The FE model of the component has 29870 elements and 52252 Nodes. The higher order SOLID187 element is used for the mesh generation, because the element is defined by 10 nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element quality for the meshed is model is checked and found that the aspect ratio value is 2.4163 which is less well below the acceptable value of 5.

Boundary conditions are applied on to the finite element model; a separate cylindrical co-ordinate system is generated. The Displacement is constrained in Z-axis while X and Y axes are left free.

Theinertial rotational velocity of 7830rpm is applied in clockwise direction over Z-axis. Additional to the support and inertial loading thermal condition of 80^{o}C is also applied to the entire body.

Mesh convergence is done to the finite element model using the h-type convergence method, The analysis is run for two different mesh densities and the result is extracted for equivalent stress and plotted on a graph which is shown below,

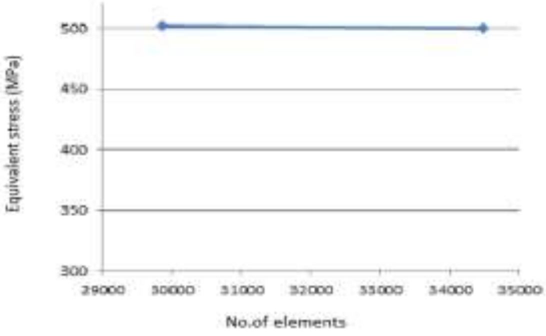


Figure 4: mesh check for applied boundary conditions

3.RESULTS AND DISCUSSIONS

Non-linear structural analysis is carried out under static conditions and the results are extracted.

Static stress:

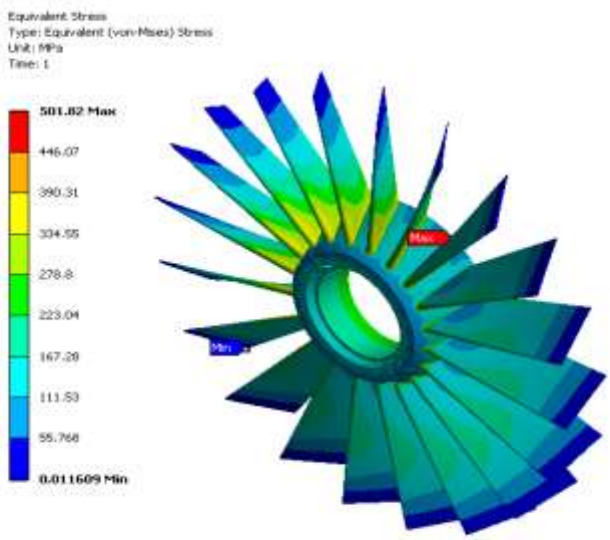


Figure 5: shows the equivalent stresses of full fan model

Figure 6: a single sector model showing the equivalent stresses

It is observed that maximum equivalent stress of 501.82MPa is at the fillet region of the trailing edge which is spurious in nature. But if we observe at the fillet region of the fan model the stress come under a range of 300 to 450MPa which is well within the design limit of 880MPa.

Gross yielding:

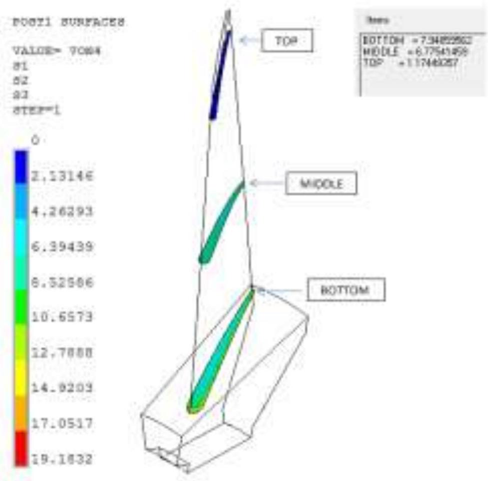


Figure 7: gross yielding of fan blade

Top = 1.1744	}	Obtained values
Middle = 6.7754		
Bottom = 7.9485		

3.1 Directional Deformation Radially:

The directional deformation obtained is 0.92685mm which is well within the limits of the casing clearance. The deformation occurred in the x-direction of local co-ordinate system as it can be inferred from the figure 7.

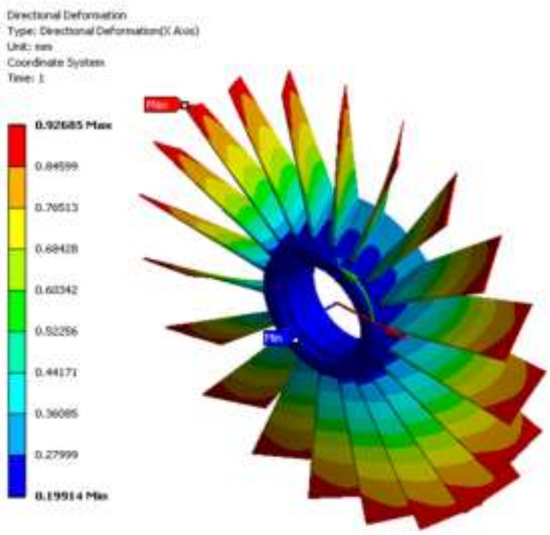
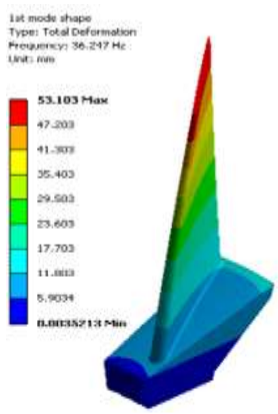


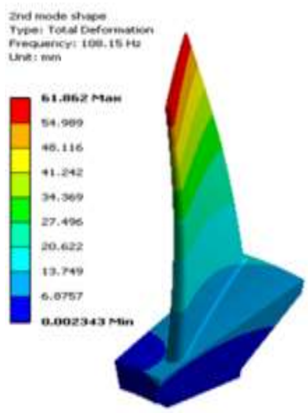
Figure 8: directional deformation of the cyclic fan model

3.2 Modal Analysis and Mode Shapes:

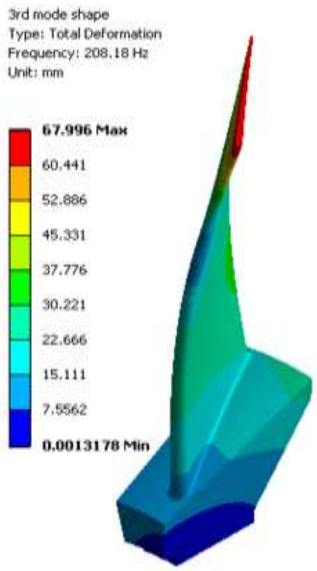
A modal analysis determines the vibration characteristics (natural frequencies and corresponding mode shapes) of a structure or a machine component. It can serve as a starting point for other types of analyses. Modal analysis is carried out in this study [3] and the first six mode shapes of cyclic turbofans are studied, which are shown below.



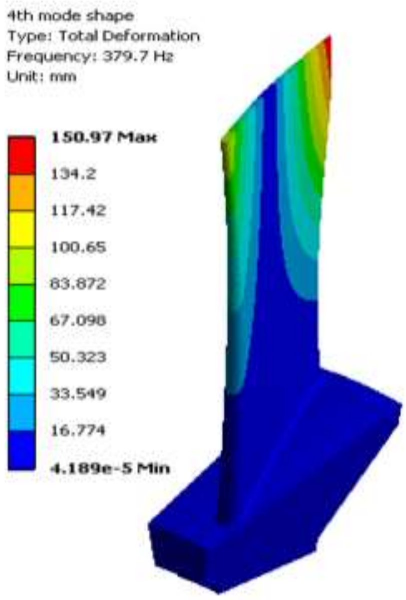
(a) First mode shape (Bending)



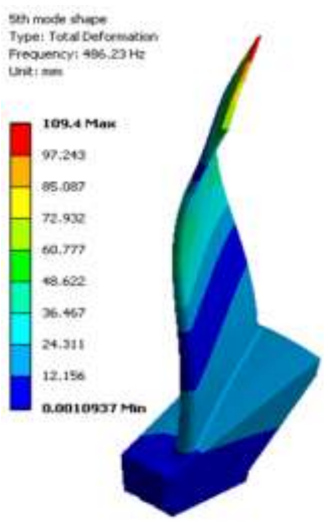
(b) 2nd mode shape (Second bending)



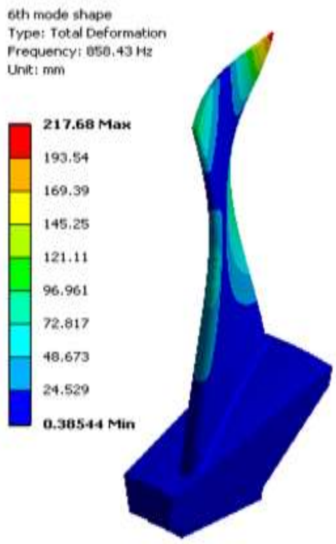
(c) 3rd mode shape
(First flip)



(d) 4th mode shape
(First torsion)



(e) 5th mode shape
(Second flip)



(f) 6th mode shape
(Second torsion)

3.3 Campbell Diagram:

The Campbell diagram for the turbofan model is plotted using the mode shapes, rotational velocity, natural frequency and having the over speed and operational speed and below the operational speed . The operational aped for the model is 7830 rpm which is considered to be 100% and the over speed is 121% of the operational speed which is 10000 rpm. The Campbell diagram for the fan model is drawn and shown below.

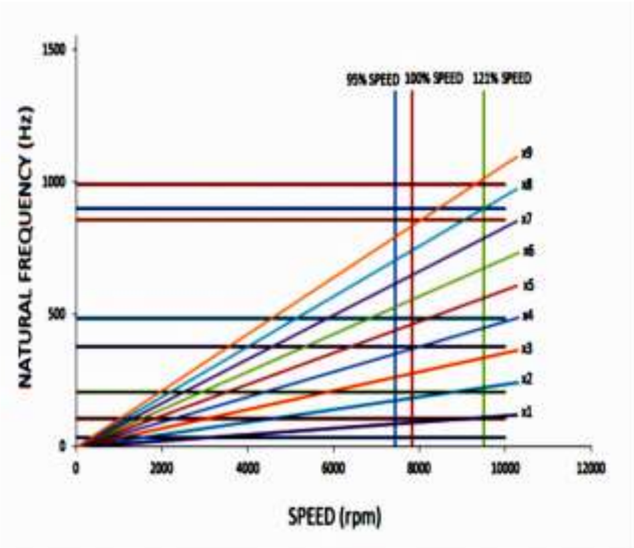


Figure 10: shows the Campbell diagram drawn for the cyclic fan model

4. CONCLUSION

Structural analysis of single sector fan blade is successfully carried out exploiting cyclic symmetry

Peak stresses and gross yielding are well within the design limits from strength point of view.

Modal analysis for free standing blade is successfully carried out to draw the separation margins of the free standing blade.

Campbell diagram is plotted and found that the resonance frequencies are away from operating bands.

Separation margin is found to be well within the threshold value for first blade mode.

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