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Numerical Analysis and Design Modifications to Investigate the Dynamic Response of a Turbine Blade

Engr. Stephen Tambari[1], Engr(Mrs) Gloria I.F Dan-Orawari[2], Engr. Ayodele Akinola Samuel[3],
[1,2,3]*Department of Mechanical Engineering Ken Saro Wiwa Polytechnics, Bori Rivers State, Nigeria*
Corresponding Author: Engr. Stephen Tambari

Abstract: *The project presents the investigation performed to find out the dynamic response of the turbine blade, which is in the 1st stage of manufacturing. According to engineering analysis, the blade has recorded some structural instability when approaching an operating speed of 5400 RPM. Failure in turbine fan blades is one of the most critical issues affecting the turbo machinery sector. Therefore, the resonant vibration of turbine blades plays a very crucial role in today's research works. This paper then investigates a modal analysis performed on the turbine fan blade and the natural frequencies are analysed. This report also discusses the measures and design modifications done in terms of material change, blade design change, which can be done in order to alleviate this instability occurring near maximum operating frequency of 90Hz. This numerical analysis is performed by a finite element method using ANSYS and the design modifications are carried out in Solid Works.*

Keywords: *Turbine, design, blade, dynamic response, modifications*

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I. Introduction

The successful operation of the engine depends on the structural stability of its operating parts, which in turn helps us to determine the dynamic behaviour. Engine vibration tests form a very critical part of research and development of newly developed power plants. Many cases have been recorded of system failure, due to fatigue, resonance and excessive vibration of one component or the other. It is much easier to modify and analyse structures, during the 1st and 2nd design stages. The frequency and amplitude of vibrations occurring in the structure can be controlled on the basis of two factors, namely the excitation applied and the structural response to that excitation. The latter factor depends mostly upon the method of application, location of the force and the dynamic characteristics of the structure, namely natural frequency and damping level. By reducing the amount of excitation applied, we can curb the level of vibration occurring in the structure. The structural response can be altered by changing the mass, stiffness or altering the damping within the structure. [1]Fan blade in turbine and compressor stages are subjected to forced vibration response that may occur at blades natural frequency. Mass imbalance in the rotating structure normally causes most of the problems relating to synchronous forces which result in reduced life span of components. [2] Dynamic analysis uses mass matrix, stiffness matrix and a damping matrix. Dynamic Response is a time dependent motion of a structure for a given load input.

In this particular report, we shall firstly create a finite element model of the given turbine blade and discuss about the dynamic response of the blade. On the basis of the results, we shall then perform a modal analysis to investigate the source of the instability occurring in the blade at 5400 RPM. When the source of the instability is known, then design modifications and material change for the blades will be investigated and a suitable solution will be obtained.

II. Theory

Modal analysis is the process of determining the dynamic properties in the forms of mode shapes, natural frequency, damping factors, etc. These factors are used to formulate a mathematical model for its dynamic behaviour. Modal analysis can be expressed as the linear combination of simple harmonic motions known as natural modes of vibration. [3]

1.1 Dynamic Response Analysis

In order to predict the natural frequency and the excitation response, it is vital that the theory of structural vibration is understood. In some structures, vibration can be analysed by considering them as single degree of freedom since one co-ordinate is needed to describe the motion of the system. In most of the cases, a few co-ordinates are used to describe the motion, because displacements of other co-ordinates are so small that they are neglected. However the analysis of a single degree of freedom is much easier to carry out than a multiple system. It is vital to find out the natural frequency of the structure, because if it is excited at one of these frequencies, resonance occurs. Therefore during design stages, resonance should be removed from the structure, so that it is not encountered during normal conditions. The form of the equation for a single degree of freedom is:

− = + + [4]

With a finite element structure with more than one degree of freedom, then the u is substituted by letter D, which comes under the nodal degree freedom and − is substituted by letter F, which represents the load vector, containing moments and forces. The letters k, c and m are substituted by mass matrix M, damping matrix C and stiffness matrix K. The equation for the physical model of a dynamic system for multiple degrees of freedom is

= + + **[4]……………..1**

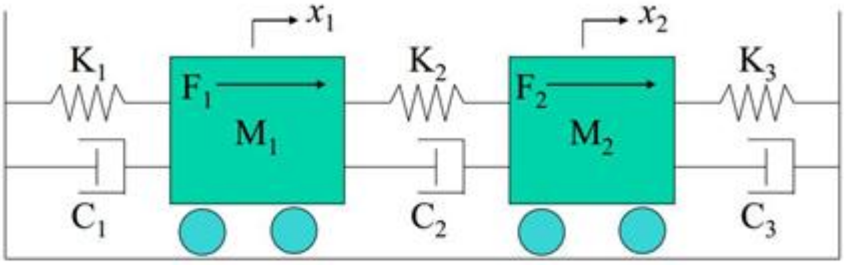


Figure 1: Multiple Degrees Of Freedom [5]

The above equation is the governing equation for structural dynamics. It states that, the sum of the three forces namely inertia forces MD, stiffness forces KD and damping forces CD are resisted by externally applied forces denoted by the letter F. all the forces are time dependent , when solving a dynamics related problems. But in a linear problem, K, C and M are constants and are not a function of time or displacement.

From equation 1, if we consider the system without damping, i.e. C=0, then the load F is either zero or any constant. Natural frequencies affect the massless loads, which thereby modifies stiffness. Actual loads are associated with mass, but in vibration analysis, the natural frequency and modes are taken into consideration. The equation for vibration motion is calculated in the form of,

= + … … ..**Equation 2**

Where is the nodal displacement amplitude and is the natural frequency. From the above equation, we get

−=0…………**Equation 3**

This equation is mathematically known as an Eigenvalue problem. The simplest result would be = 0. The natural frequency may also be known as resonant frequency and ^{2}, is known as an eigenvalue.

1.2 Mass Matrices

The simplest way of representing mass is by mass particles and its process is called mass lumping and it produces results in a lumped mass matrix. The matrix form of this method is shown below.

= / [4]

/

If we consider lateral displacements, with area A, length L and density , the element mass becomes .Mass lumping suggests that a displacement field of the two halves of the element translate separately. It is much appropriate to consider linear variation for lateral displacement, which results in linear distribution of the inertia force. [4]

1.3 Finite Element Method

The finite element method (FEM) can be used to model complicated structures. The main advantage of using FEM is that it can be used to calculate the different mode shapes and frequencies of an elastic linear system. When we solve beam systems using FEM, this system is considered to be a set of mass elements connected to each other with the help of finite springs. Therefore multi degrees of freedom are needed to solve this system which can thereby be reduced to a set of finite degrees of freedom which can be evaluated individually. When solving by the finite element method, the stresses and strains are defined in terms of displacement and forces and the mass of all elements is lumped at the nodes. [1]

III. Methodology

The 1st section deals with material selection. In order to construct the geometry, suitable material properties needs to be imported in the ANSYS engineering data. The 1st analysis was conducted by using tungsten as the material of the blade. After the material was selected, a 3D finite element model was created in ANSYS, by importing the geometry form the given file and a modal analysis was carried out. The material properties are given below.

Table 1: Material Properties for Tungsten

Material	Elastic Modulus(GPA)	Density (g/cm^3)	Poisson's Ratio
Tungsten	400	19	0.28

In order to further discuss the aims of the project, Tungsten was replaced by other nickel super alloys, whose designations are Inconel and MAR – M – 432. The material properties were obtained from the CES Edu pack software installed on University computers. The property table for the other two materials are given below.

Table 2: Property Table for Inconel 100

Material	Elastic Modulus(GPA)	Density (g/cm^3)	Poisson's Ratio
Inconel 100	210	7.65	0.3

Table 3: Property Table for MAR- M - 432

Material	Elastic Modulus(GPA)	Density (g/cm^3)	Poisson's Ratio
MAR – M – 432	195	8.05	0.27

The above mentioned materials are used in the manufacture of Jet engine turbine fan blades, and other essential aircraft components. They are non-ferrous metals and their base material is nickel. Both materials are a part of nickel - cobalt - chromium alloys.

Changing different types of materials, affect the density and invariably affect the mass.This report also discusses about the different structural modifications done in order to check the 1st mode of natural frequency of the blade. Different design changes were implemented. The design changes are shown in the figures given below.

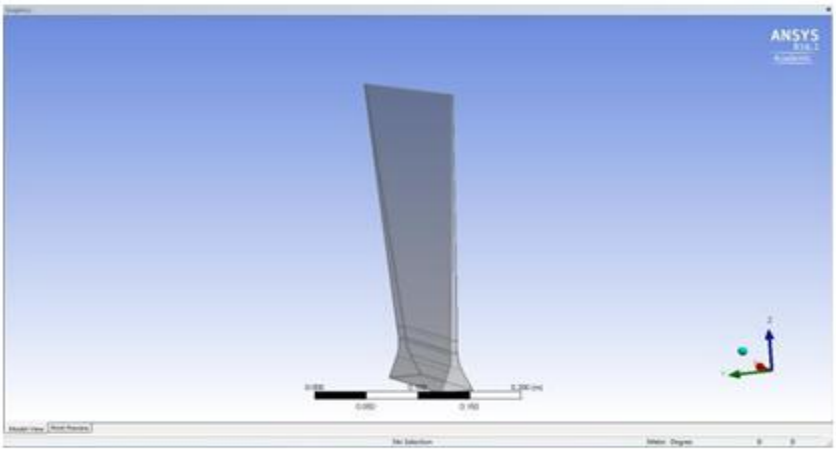


Figure 2: Full Model of the Turbine

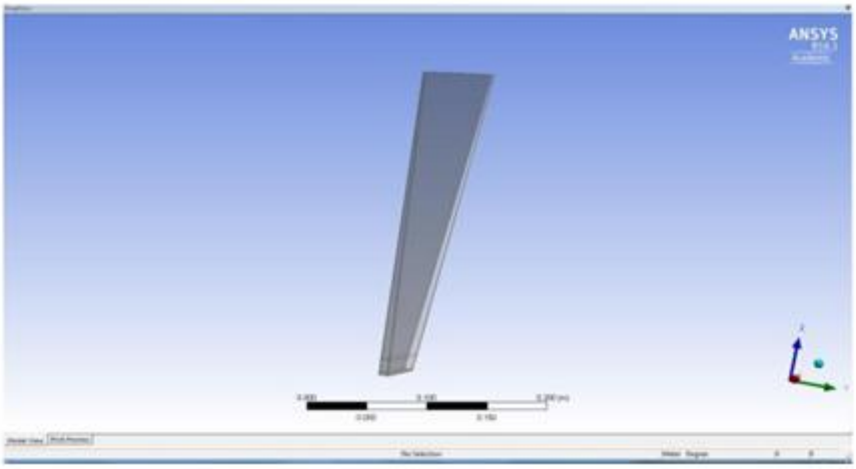


Figure 3: Model without the Base

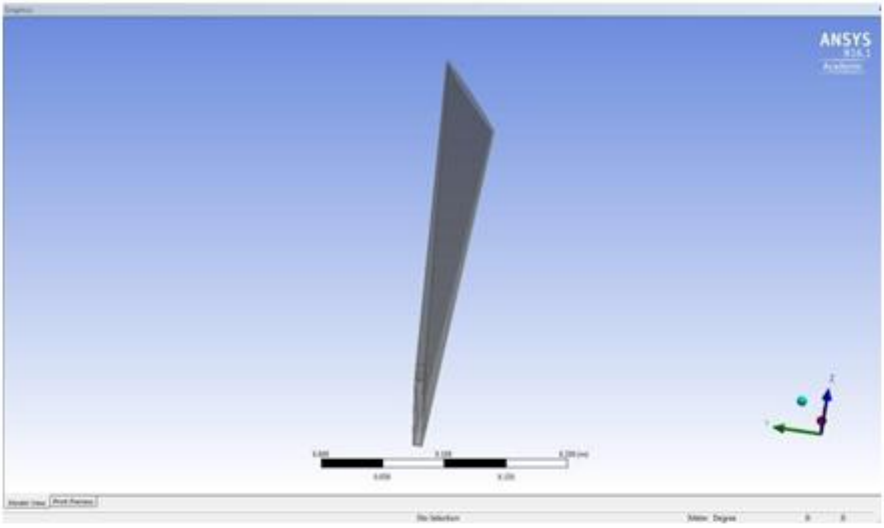


Figure 4: Shelled Model without the Base

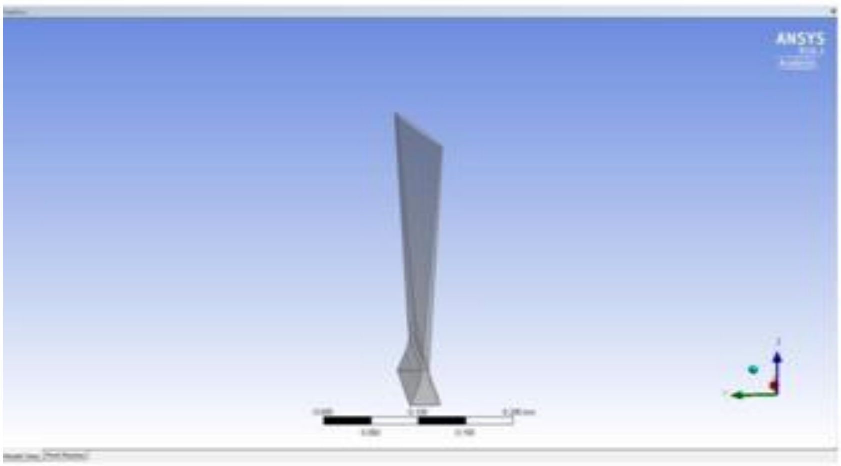


Figure 5: Model reduced by 20 mm Length

In order to carry out the design changes in the model, the full scale blade model was exported to SOLIDWORKS, where the above mentioned design changes were made.

1.4 Meshing

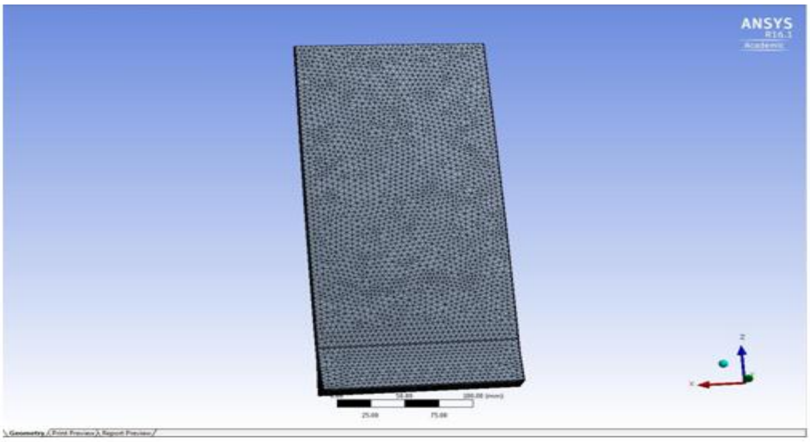
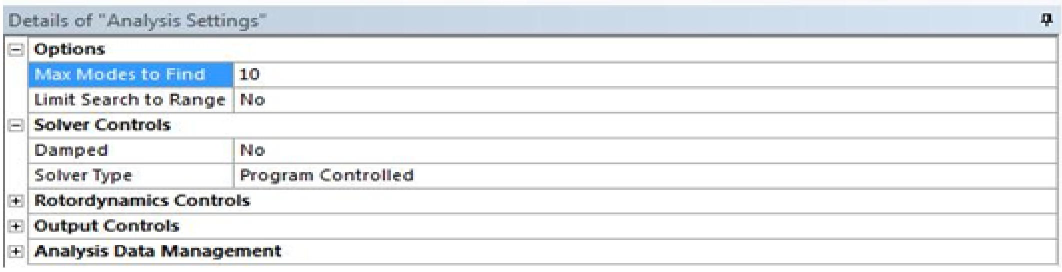


Figure 6: Meshing the Model

Mesh size and quality are very important considerations when solving a structural analysis problem. In order to achieve this mesh, a body sizing was used. The sizing was applied in the range of 10mm to 3.1 mm for different models that were analysed. In order to judge the independence of the mesh, a mesh convergence study was done which will be further on discussed in the results section.

1.5 Modal Analysis Procedure



Details of "Analysis Settings"	
Options	
Max Modes to Find	10
Limit Search to Range	No
Solver Controls	
Damped	No
Solver Type	Program Controlled
Rotordynamics Controls	
Output Controls	
Analysis Data Management	

Figure 7: Modal Analysis Settings

We specify the number of natural frequencies to solve in modal analysis, which in this case are 10 natural frequencies were chosen but since the frequencies above three or four modes do not actually exist in reality for the structure, we only take into consideration the beginning mode and its corresponding natural frequency.

1.6 Boundary Conditions

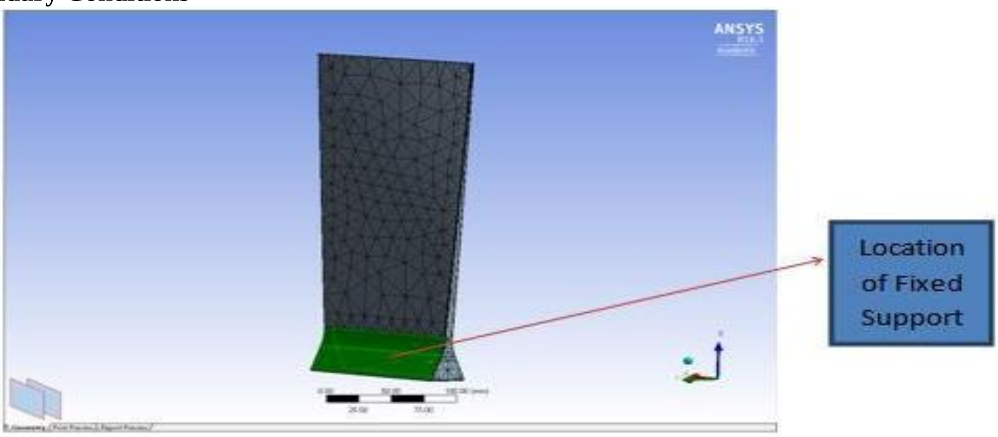


Figure 8: Location of Fixed Supports for Model with Base

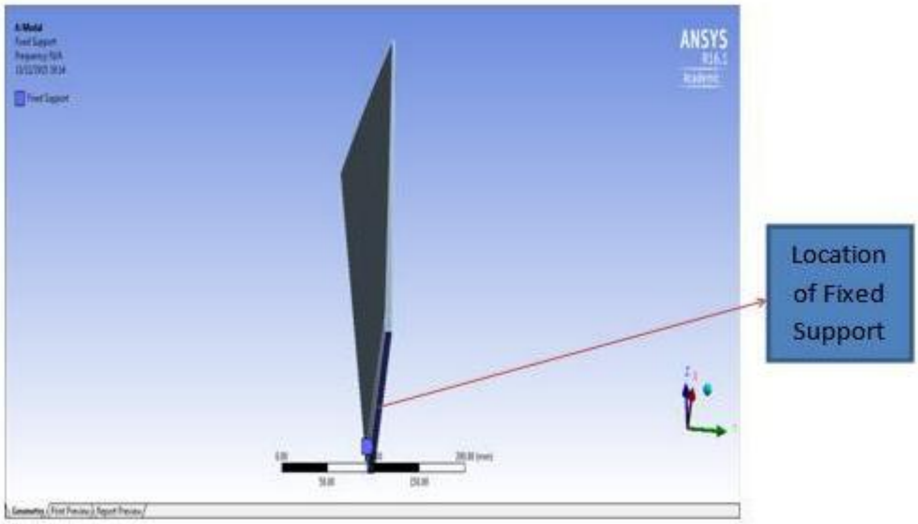
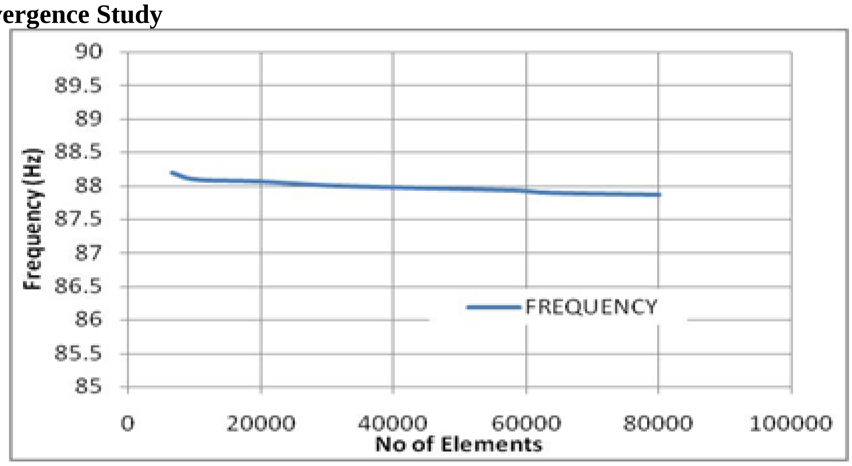


Figure 9: Location of fixed support for model without base

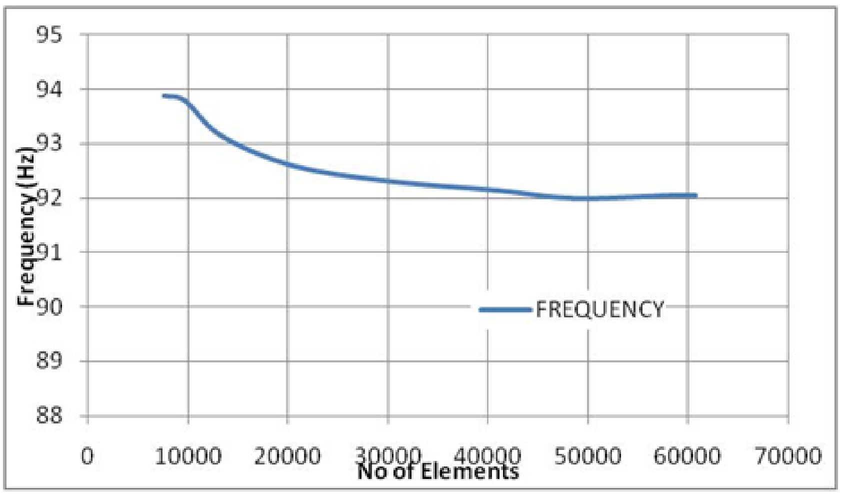
IV. Results and Discussion

Under service conditions, in order to examine the dynamic behaviour of the blade, a modal analysis was performed on the turbine blade.

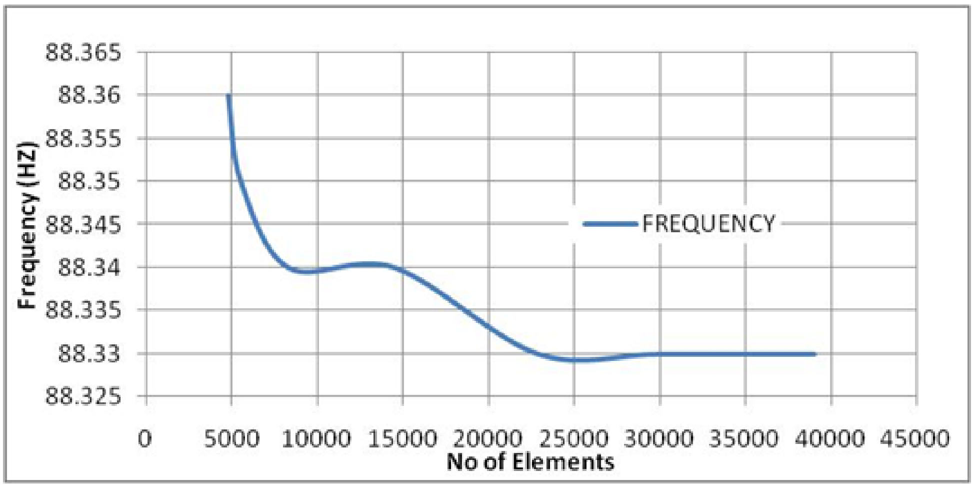
1.7 Mesh Convergence Study



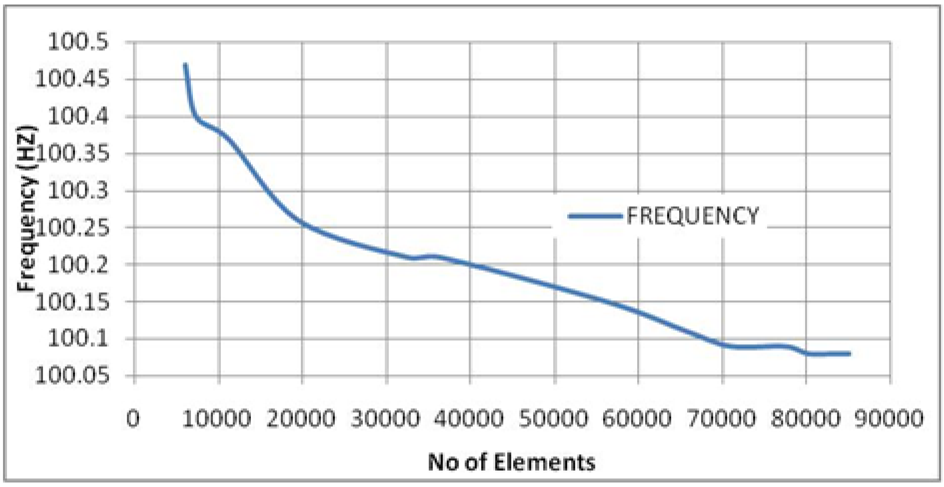
Graph 1: Mesh convergence for full model



Graph 2: Mesh convergence for shelled model without base



Graph 3: Mesh convergence of model without base



Graph 4: Mesh convergence of model with reduced blade length

Mesh convergence studies were undertaken for all the 4 different model designs. The body sizing for these designs were in the range of 10mm to 3 mm. if we look at the graphs, we know that the mesh becomes independent at around 60,000 elements. Mesh convergence does take place fairly quickly, which thereby goes on to explain that meshing the model doesn't however play a key role in obtaining the natural frequencies of the structure. In modal analysis, we are just finding out the natural frequency of the structure and neither the stresses or strains. Hence the variation in vibration frequency would not change with a variation in mesh density.

1.8 Design Modification

Structural modification forms an important application of modal analysis and it is used to study the changes observed on the dynamic characteristics of the structure, when the geometry and construction the structure is changed. The dynamic properties of the structure are in the form of natural frequency and modal shapes. The theory of structural modification is related to mass and stiffness matrix, therefore any geometrical parameter change will result in the change in the mass and stiffness properties of the model. In the case of a cantilever beam, in which one face of the structure if fixed, while the other is free. For such a continuous system, the parameter change can be in the form of thickness or length beam change for a particular section of the beam. But the changes in length and thickness, invariably affect the mass and stiffness behaviour of the structure. The main aim of structural modification is to enhance the dynamic characteristics of the structure and the main objective to achieve this aim is to change the natural frequency. A natural frequency near the operating vibration frequency is the main cause of excessive vibration that may invariably lead to failure. So the best solution of this problem is to move the natural frequency of the structure away from the normal operating frequency, using structural modification.

As per theory, we know the formula for stiffness for a cantilever beam.

= **…………….Equation 4**

Where K= Stiffness factor, E= young's Modulus, I= second moment of inertia and L= length of the beam. As per this formula as the length decreases, then the stiffness factor increases. We also know that

= … … … . …**Equation 5**

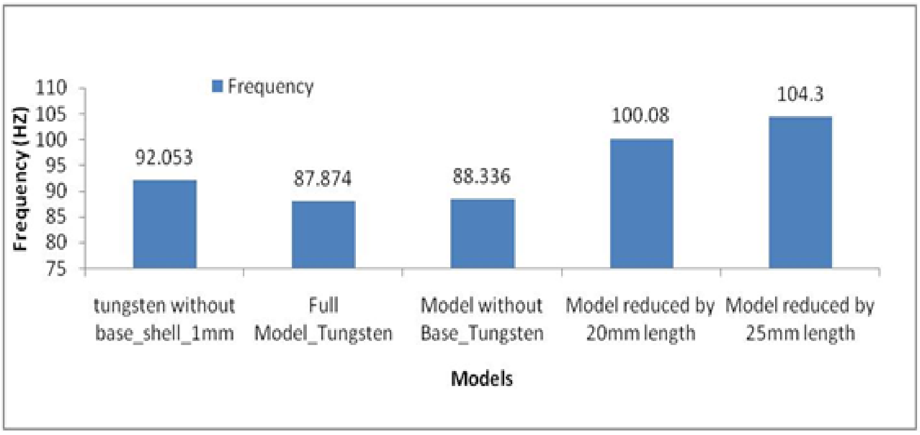
Where is the radian frequency, K is the stiffness factor and M is the mass of the body. But in order to express it in terms of natural frequency:

= … … … … ….**Equation 6**

Where is the natural frequency in hertz

On the basis of the formulas given above, we can say that the frequency increases with increased stiffness and reduced mass. Taking this idea into consideration, we have modelled the following blades with variation in the mass and have analysed the results.

Given below are the results for the analysis carried out on the different structural modifications carried out with the tungsten material.

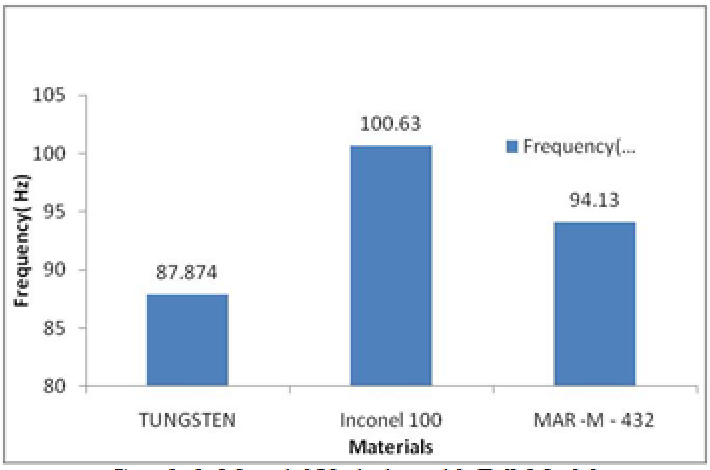


Graph 5: Change in Geometry v/s Frequency

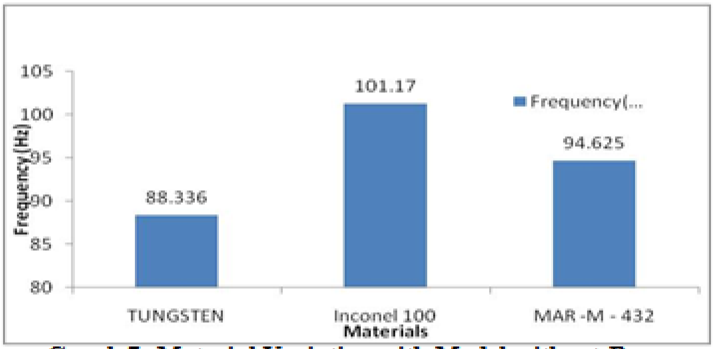
From the above graph, it is clearly evident that the structure with reduced blade length of 25 mm performs best with natural frequency results showing 104.3 Hz. But however reducing the length by 25 mm would cause some instability in the structure due to reduced blade length either altering the aerodynamic loads or the centrifugal loads. Therefore the model with reduced length of 20 mm is the best pick out of this list, because of the blades' reduced mass, the natural frequency improves.

1.9 Material Change

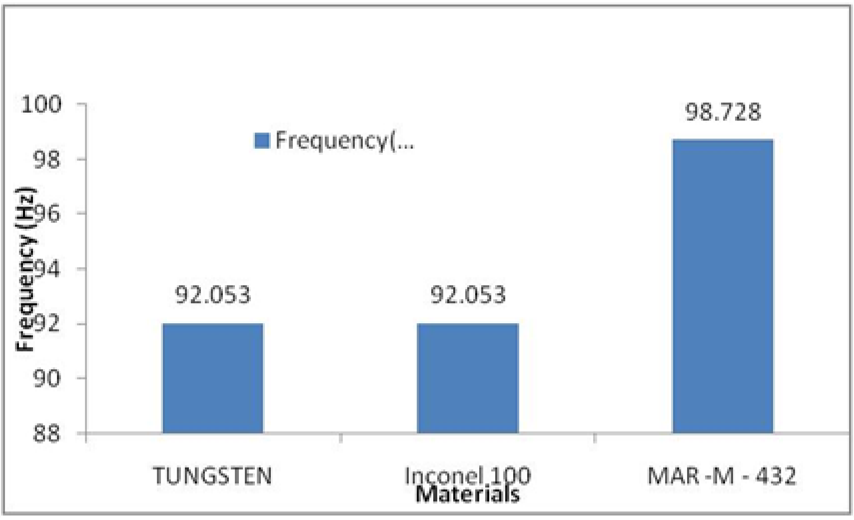
In this report we have analysed two nickel alloys and the original tungsten alloy. Below are given the results of analysing the different materials with the above mentioned models.



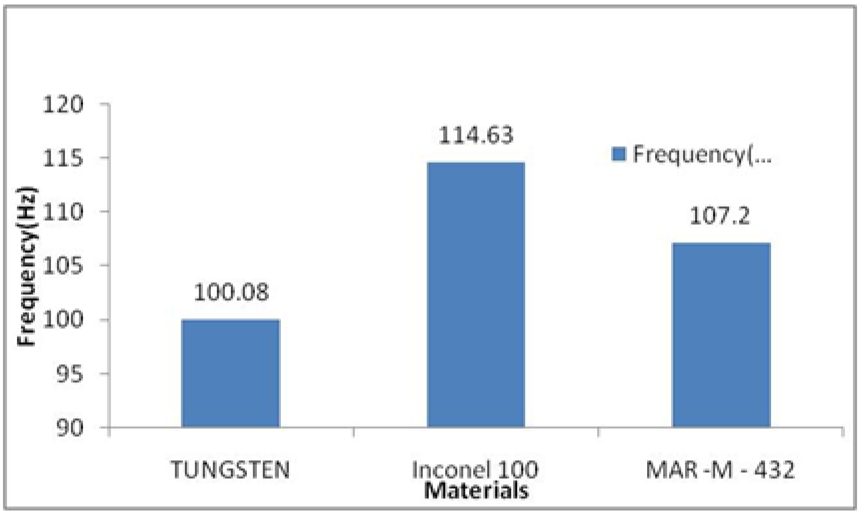
Graph 6: Material Variation with Full Model



Graph 7: Material Variation with Model without Base



Graph 8: Material Variation with model without base and shelled 1mm



Graph 9: Material Variation with reduced length of 20mm

The following materials were chosen since nickel alloys are mostly used to manufacture turbine fan blades. As per the graphs above, Inconel 100 scores the best in terms of results produced for maximum natural frequency. In particular if we look at graph 5, the reduced blade length has really benefitted the results with reference to equation 4 and 6, as the length decreases, the stiffness increases which thereby increases the natural frequency. I f we discuss in terms of material selection, the density parameter is of vital importance in increasing the natural frequency. By decreasing the density of the material from Tungsten to Nickel alloys, the mass decreases, thereby increasing the natural frequency.

V. Conclusion

Modal analysis is the process of determining the dynamic properties of the structure in the forms of mode shapes, natural frequency, damping factors, etc. In this project, a turbine fan blade was analysed which was experiencing structural instabilities at 90 Hz operating frequency. Hence a modal analysis was conducted in order to find a solution to this problem. After analysing the dynamic response of the blade it was found that the natural frequency of the blade was low as compared to the operating frequency. Hence a possible solution was devised in order to overcome this difficulty and alleviate this problem. In order to increase the natural frequency so as to get a factor of safety of at least 1.2- 1.3 [6] , structural design changes and material changes were analysed and investigated and satisfactory results were obtained. According to this analysis, reduced blade length of 20mm with nickel alloy, Inconel 100 proved to be the best pick which produced a natural frequency of 114.63Hz.

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