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Effect of Geometrical Parameters on Mode Frequency of Turbomachine Blade: A Finite Element Approach

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ABSTRACT:

Fatigue failure of turbomachine blades is one of the most crucial subject areas in the design of turbomachines since the demand for greater capacity turbomachines have been increased. The one of the source of dynamic loads on blading being the operating principles on which the machine is designed. The blades are flexible structural members and hence a significant number of their fundamental frequencies may be in the region of probable nozzle excitation frequencies. It is possible in small machines to reduce possible resonance and thus avoiding fatigue failures. In bigger and high speed machines this is not always possible, since there may be several stages of blades of different characteristics. An attempt has been made to determine the effect of geometrical parameters such as aspect ratio and thickness on the natural frequencies of aerofoil section blades. This paper presents the use of finite element method and ANSYS to calculate the natural frequencies of aerofoil section blade. The results show that natural frequency attains maximum value for some particular value of thickness.

KEYWORDS: Aerofoil, Blade, Finite element method

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INTRODUCTION

Fatigue failure of turbomachine blades is one of the most crucial subject areas in the design of turbomachines since the demand for greater capacity turbomachines have been increased. The one of the source of dynamic loads on blading being the operating principles on which the machine is designed. Although a machine may be designed to avoid resonance at its constant operating speed, it is subjected to resonance many times during the starting and shutting down of the machine. The blades are flexible structural members and hence a significant number of their fundamental frequencies may be in the region of probable nozzle excitation frequencies. It is possible in small machines to reduce possible resonance and thus avoiding fatigue failures. In bigger and high speed machines this is not always possible, since there may be several stages of blades of different characteristics. Hence it is needed to determine blade excitation forces, coming out of stage flow interaction. Under the influences of these forces the blade experiences fluctuating stress which can be limited only by the damping present in the system[1]. A lot of research work has been done to understand the effect of different factors on the vibration characteristics of blades such as taper, asymmetry, centrifugal forces etc. Aflobi[2,3] showed that resonance of blade vibration frequency with nozzle excitation frequency is the main reason of blade failure. Cranch[4] used Rayleigh energy approach and calculated the frequency of three modes of vibration of rotating beam. Feiner[5] utilized Rayleigh-Ritz method to formulate the fundamental frequency of vibration. An expression for the work done due to centrifugal effects for small vibrations rotating cantilever beams has also been derived. Schill[6] deduced that the stiffening effect of centrifugal forces on the minimum bending frequency of a cantilever beam depends upon the ratio of hub radius to the blade length and also the angle between blade chord and the rotational velocity. If the blade is pretwisted, uncoupled bending modes in flapwise and chordwise deflection are impossible. Sisto[7] found Ritz principle useful to solve the equation of motion of a pretwisted cantilever blade. Rossard[8] used Galkerine finite element method to find first five frequencies of twisted cantilever beam and presented that the effect of twist is proportional to the width to thickness ratio. Carneige[9,10] gave the general equation of motion of a pretwisted cantilever blade of asymmetrical aerofoil cross section including effect of torsion. He derived torsional frequency equation taking into account the bending effect using Rayleigh method. Klein[11] made use of the combination of both finite element approach and Rayleigh-Ritz analysis to study the free vibration of beams with non-uniform characteristics. Lag[12] used Galkerin finite element technique to find natural frequency of non-uniform blades. Lee[13,14] presented vibration characteristics of a tapered beam and developed formula for fundamental frequency. It was concluded that with a reduction of cross sectional dimension in thickness keeping constant breadth increases the fundamental bending frequency and reduces higher modes of bending frequencies.

Downs[15] presented transverse vibration of cantilever beams of unequal breadth and taper using dynamic discretization method and deduced that by increasing mode order the vibration becomes concentrated at the tip. Dhar[16] used the nonlinear finite element approach to understand the effect of non- linearities in material properties and stiffness on natural frequencies of turbine blade. It was concluded that at transient stage there was a prominent change in blade frequency. Euler[17] studied the effect of mistuning on vibration characteristics and presented that due to mistuning the identical blades on a rotor are compelled to vibrate with unequal amplitudes under certain circumstances. Vakaitis[18] studied the effect of centrifugal forces and deduced that the centrifugal forces have influence on fundamental mode and relatively small influence on higher modes. He found that the blade becomes stiffened because of centrifugal forces and hence the bending natural frequencies increase with speed of rotation. Thomas[19] developed a techniques using finite element approach for Timoshenko beams and concluded that the disc radius has profound effect on flapwise mode of vibration. Also the natural frequency increases with increase in radius of disc. Murthy[20,21] studied the vibration characteristics with the effect of asymmetry of cross section using Integration Matrix approach and deduced that bending frequencies reduces with asymmetry and torsional frequencies increase with asymmetry. Beisheim[22] worked on the effect of mistuning and showed that if the primary resonance being excited the highest responding blades are those with extreme mistuning and such blades are instrumented during tests.

This paper presents the use of finite element method and ANSYS to calculate the natural frequencies of turbomachine blades. An attempt has been made to obtain the mode shapes for different aerofoil sections and to analyze vibration characteristics of turbomachine blades, having different chord length, length and thickness.

DISCRETIZING AND MODELLING

Discrete analysis techniques

The continuum approach for a free standing blade, requires much analytical work before a numerical methodology may be adopted to go for mode-frequency analysis. Discretizing the blade and using suitable element relations is easier than the analytical work with continuum methods and thus the discrete techniques are preferred by most of the research workers.

The can be broadly classified into the following methods:

1. Holzer method
2. Myklestad / Prohl method
3. Matrix method
4. Finite difference method and
5. Finite element method

Finite element method can be used to determine the combined bending and torsional vibration modes taking into account the effect of root flexibility. The Finite element approach looks for approximating the solution of partial differential equation integrated over a series of finite elements. This results in a system of simultaneous linear equations. Therefore their solutions is more expensive and time consuming. As compared to finite difference method the number of nodes required in finite element method is usually much less than the number of grid points required in finite difference method for comparable accuracy. Finite element method is more beneficial for complex problems[23,24].

Modelling technique

The discrete analysis of aerofoil section blade for mode and frequency using finite element method is performed with help of ANSYS software[25]. ANSYS finite element analysis software enables the transformation of an engineering system to a finite model. Model is a mathematical idealization of the real system described by nodes, elements and boundary conditions. To perform the various analysis functions ANSYS used the following processors:

1. Pre-processor (PREP-7) – It is used to build a graphical model of a given problem.
2. Solution processor (SOLUTION) – In this module, various properties, load and boundary conditions are defined and solution of a given problem is obtained.
3. General post processor (POST1) – Through this module, the results are reviewed and are presented in graphical form.

In addition to these, additional post processor, POST26, enables to evaluate solution results at specific point in the model. ANSYS program stores all input data (e.g. modal dimensions, material properties, load data etc.) and results data (frequencies, mode shapes etc.) in a large database in an organized fashion. The main advantage of the database is that we can list, display, modify or delete any specific data item quickly and easily. In the present study finite element method is used to discretize the blade and implementation of modelling is carried out in ANSYS software.

MODE-FREQUENCY ANALYSIS OF BLADE

Problem description

In the present work a blade of aerofoil section of a turbine is chosen for mode-frequency analysis. The configuration of blade is uniform along its length. The blade is solid and properties of material are constant and isotropic. In the present study the geometry of aerofoil section has been taken from the research conducted by National Advisory Committee for Aeronautics (NACA). The NACA has classified different aerofoil sections and designated by NACA code[26]. Though hundreds of different sections have been developed, in the present study only five different types of sections have been chosen to determine the natural frequencies of vibration.

The material properties and geometrical date which are used: Blade Material:Nickel alloy, Modulus of elasticity: 2.11×10^{11} N/m^2, Density:7850 Kg/m^3, Poission's ratio:0.3, Length of blade:0.3 m, Chord length:0.025 m, Aerofoil sections employed:(a) NACA-63-006, (b) NACA-63-0018, (c) NACA-64-010, (d) NACA-67-015

The blade is treated as cantilever beam, therefore boundary conditions are applied to all the nodes which are fixed at the base of the rotor. It is held fixed to one end and hangs freely at the other.

Modelling procedure

The finite element analysis problems in ANSYS can be performed by two ways:

i. Interactive method, using graphical user interface and
ii. Batch method

The three major steps required to carry out mode frequency analysis in the interactive method are as under:

a) Pre Processing
b) Solution
c) Post Processing

The details of these steps are discussed in following sections.

a. Preprocessing

Pre processing is a step in which geometric model of the given problem is constructed through various graphic command.

(i) Create aerofoil section

As a first step in preprocessing the geometry of aerofoil section is created in 2-dimensional coordinate. To define an aerofoil section, firstly the coordinates of the key points are defined in X-Y coordinate. The X-Y coordinates are derived from Abbott[42] for NACA aerofoil section. These key points are connected using lines and splines to construct aerofoil section as shown in Fig 5.1. ANSYS provides an option to define the orientation of an outward vector tangent at the first and last points on the splines.

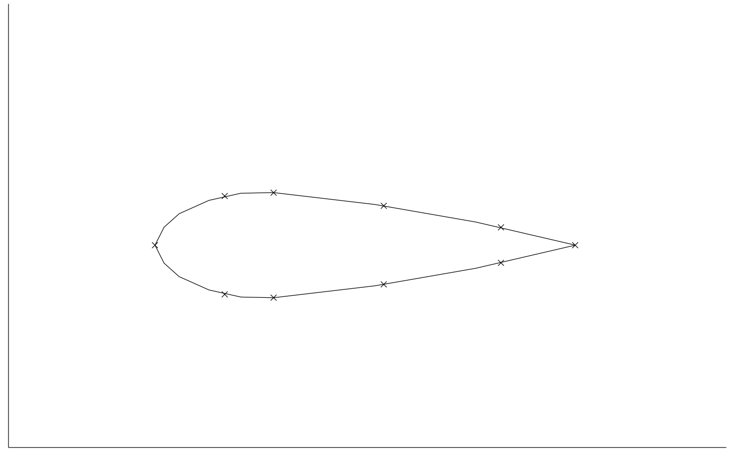

Fig. 1. Creating geometry of aerofoil section

(ii) Define element shape

In this step shape of the element is opted. In this study quadrilateral elements without mid side node are being used. Looking into the limitation of the software, PLANE 42 elements are used.

(iii) Create finite element mesh

The creation of a good finite element mesh is quite important in the analysis. The general philosophy of putting more elements in the regions where there is a higher solution gradient applies here. The mesh density should be sufficient to enable the program to capture the nature of the phenomenon. In the present study an automatic mesh gradient algorithm available in ANSYS is used to generate optimal mesh distribution.

(iv) Extrude the mesh

Since the turbine element is a 3-D element, the 2-D mesh generated using PLANE 42 element is extruded along z-axis to generate the 3-D meshed aerofoil section. This is done by changing element type to SOLID 45, which is defined as element type 2. This results in extruding the area into a volume. In the present formulation 140 SOLID45 elements are used to generate the 3-D mode of aerofoil section blade. All PLANE 42 elements used for 2-D area mesh are unselected, as they are not used in the analysis.

(v) Solution

The aerofoil section blade is treated as a cantilever beam, therefore constraints are applied to all the nodes which are fixed to the base of the rotor. The displacements at all the fixed nodes are put to zero. Further the number of frequencies to be extracted are defined. In this study first five modes of frequency are extracted.

After defining the boundary conditions and the number of frequencies to be extracted, the second step of analysis is performed by SOLVE command. In this sub-space vector iteration technique is used to extract the frequencies and mode shapes of the blade data. The maximum number of iterations was restricted to 100 and maximum number of equations is 420. The solution converges to 4 iterations only requiring approximate 167 seconds.

(vi) Post processing

Post processing is the interpretation of results i.e. reading the latest set of solution results and plotting the mode shape for interpretation. It also permits to animate the vibrating modes of the blade.

RESULTS AND DISCUSSIONS

In the present study the mode frequency analysis for first five modes of aerofoil section blade with properties listed in section 3.1 is performed by running interactive method using Graphical User Interface. The same problem may be solved using Batch file method. A Batch file is a standard ASCII file in which various commands and input data are listed.

Frequency analysis of aerofoil sections: variation in thickness

The solution methodology developed in previous section is applied to various types of aerofoil sections. The natural frequencies of these types of aerofoil sections are listed in Table 1. The variation of frequency with various modes of vibration is shown in Fig. 2. The close observation of the Fig. 2. shows that frequency increases in each mode in all the aerofoil section.

Table 1. Natural frequencies of various aerofoil sections

Aerofoil Section	Natural frequency (Hz) Modes				
	I	II	III	IV	V
NACA 0018	44.406	166.156	284.38	650.2	907.059
NACA 63-006	76.163	200.5	450.3	690.66	1090
NACA 63-0018	43.603	157.43	310.6	670.9	937.64
NACA 64-010	61.415	165.45	392.433	670.15	1041.33
NACA 67-015	43.22	164.123	278.244	620.6	826.62

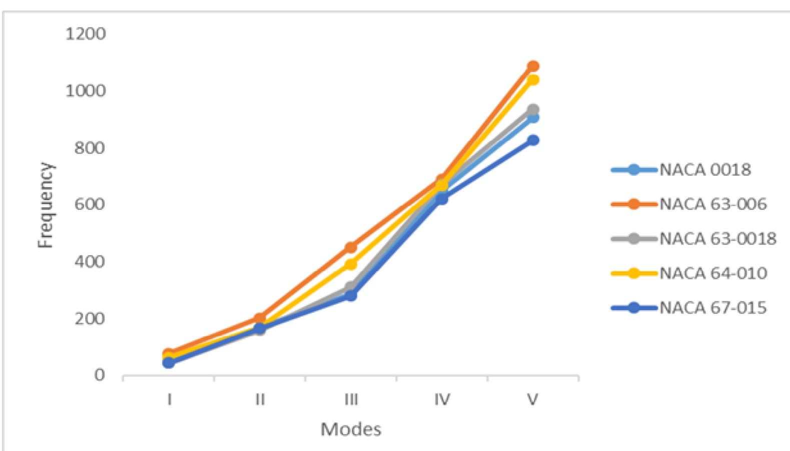

Fig. 2 Variation of frequency with modes

Frequency analysis of aerofoil sections: variation in aspect ratio

Aspect ratio is the ratio of chord length to the length of blade. In the present section the effect of aspect ratio on the natural frequency characteristics of various aerofoil sections has been studied. The variation of natural frequency in fundamental mode and second mode for the different aspect ratio is listed in Table 2 and Table 3 respectively. These frequencies are plotted as shown in Fig. 3 and Fig 4. The study is restricted to first two modes only as the turbine is expected to run in these frequency ranges.

Close look to the Fig. 3 and 4 reveal that the vibration frequency in fundamental and second mode is increased almost 4 times when aspect ratio is increased from 0.0625 to 0.25. This is due to the fact that as aspect ratio is increased, aerofoil section becomes stiffer; hence increase in frequency is observed. It is also observed that behavior of blades NACA 0018 and NACA 63-0018 are more or less similar as their geometrical configuration do not have much difference. The vibration frequencies of all types of blade sections are increased with increasing aspect ratio, which clearly shows that behavior of blade is like a plate instead of a beam. It can be safely concluded that the beam modeling approach of blade section is good approximation for determining frequency.

Table 2. Effect of aspect ratio on natural frequency of fundamental mode

Aerofoil Section	**Frequency (Hz) in Fundamental mode Aspect Ratio**			
	0.0625	**0.0835**	**0.125**	**0.25**
NACA 0018	29.22	44.406	83.231	286.32
NACA 63-006	56.53	76.163	115.533	245.12
NACA 63-0018	29.95	43.603	81.42	281.51
NACA 64-010	45.56	61.415	96.626	234.145
NACA 67-015	30.12	43.22	78.84	257.62

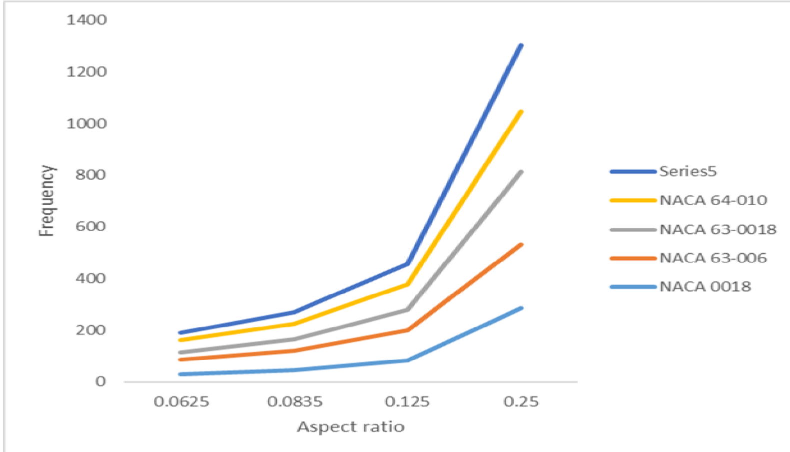

Fig. 3 Variation of vibration frequency in fundamental mode with aspect ratio.

Table 3. Effect of aspect ratio natural frequency of second mode

Aerofoil Section	Frequency (Hz) in second mode Aspect Ratio			
	0.0625	**0.0835**	**0.125**	**0.25**
NACA 0018	95.43	166.156	368.53	1434.26
NACA 63-006	104.733	173.193	367.133	1390.132
NACA 63-0018	90.12	157.43	348.514	1361.23
NACA 64-010	97.84	165.435	357.42	1372.23
NACA 67-015	94.43	164.123	363.366	1415

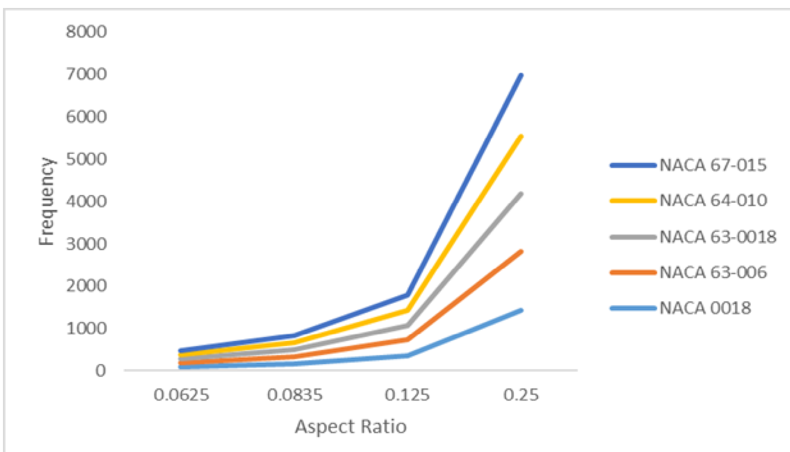

Fig. 4. Variation of vibration frequency in second mode with aspect ratio.

CONCLUSION

Based upon the studies conducted and reported in previous chapters, following major conclusions can be drawn:

1. The finite element software ANSYS can be effectively used for modeling and mode-frequency analysis of turbine blade.
2. The graph constructed for various types of blade sections can be used as design monograph for the selection of aerofoil section.

3. It is also observed as the aspect ratio increases, the natural frequency in all the modes is increased.
4. At higher values of aspect ratio blade starts behaving like a plate instead of a beam as the stiffness in cross coupled mode of vibration is found to be increased.

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