MODAL & FATIGUE ANALYSIS OF DIFFERENT BLADE PROFILES OF AXIAL FLOW TURBINE

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CERTIFICATE OF RESEARCH

This thesis titled "MODAL & FATIGUE ANALYSIS OF DIFFERENT BLADE PROFILES OF AXIAL FLOW TURBINE" submitted by SHIHABUS SAKIB RAD (170011040) and MD. SALEH AKRAM (170011050) has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Mechanical Engineering.

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DECLARATION

We hereby declare that this thesis entitled "***MODAL & FATIGUE ANALYSIS OF DIFFERENT BLADE PROFILES OF AXIAL FLOW TURBINE***" is an authentic report of our study carried out as requirement for the award of degree B.Sc. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of ***Dr. Md. Zahid Hossain,*** Professor, MPE, IUT in the year 2022

The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.

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Although we tried out best to complete this research flawlessly, we seek apology if there is any error found in this report.

ABSTRACT

The profile shapes of axial turbine blades need to fulfil the requirements of not only aerodynamics but also mechanical criteria. A design requires aerodynamically favorable velocity distribution as well as mechanically favorable geometry that can withstand the dynamic forces. So, several constraints from Aerodynamic, mechanical perspective are generally imposed while optimizing blade profile that fulfills all engineering restriction. But in this work, only mechanical aspect of design is investigated ignoring aerodynamics, to provide a better insight on effect of different blade profiles on Modal & fatigue behavior of the blade. As Previous works includes fatigue analysis on case-by-case basis. No one worked on comparative analysis on fatigue and modes with blade profile with varying angle of twists. First several NACA-4 series profiles were selected and the coordinates of selected profiles were generated with python programming language. The equations for NACA four series profile were used to calculate the coordinates of profile. Using the generated coordinate files, The CAD models were generated using Visual Basic programming language in Visual Studio 2015 with the help of SolidWorks 2021 API. The CAD models were created from the combinations of selected NACA profiles and selected twist angles. The CAD models were imported into ANSYS Workbench using scripting language to perform Modal and Fatigue analysis using Finite Element Method (FEM). The mesh settings were chosen such that the results converge to a satisfactory degree. The results were then exported to Excel file to comparative analysis and graph generation. The simulation results showed interesting trend with blade profiles. The change of natural frequencies with respect to increasing degree of twist is observed to have a downward trend for 1st and 2nd modes. But an opposite trend is found for 4th, 5th and 6th modes. A correlation between Fatigue life cycle with respect to degree of twist is also discovered. The fatigue life is found to be increased with increasing angle of twist. A similarity is found in the results for different NACA profiles.

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NOMENCLATURE

ANSYS	An engineering simulation software for analyzing various types of things. Modal, mechanical, thermal, harmonic, computational fluid dynamics and many other types of simulation can be done by this
SOLIDWORKS	Software for generating computer aided design
Visual Studio	An Integrated Development Environment for programming.
Python	An interpreted high-level programming language
Visual Basic	A compiled programming language developed by Microsoft
NACA	National Advisory Committee for Aeronautics
Modal Analysis	Modal analysis is the study of the dynamic properties of systems in the frequency domain.
Fatigue analysis	Fatigue Analysis is the structural analysis of a system's failure tendency under cyclical loads.
Ti6Al4V	A titanium alloy
Meshing	Meshing is the process of turning irregular shapes into more recognizable volumes called “elements.”
API	Application Programming Interface
CAD	Computer aided design
Airfoil	A kind of curved surface which helps us to find optimal design of aircraft wings, turbine, compressor blades etc.
SLDPRT	SOLIDWORKS file extension
Axial Flow Turbine	Turbine in which the flow of fluid is parallel to the axis or shaft of the turbine

Chapter 1

1.1 INTRODUCTION

Axial flow turbines are most commonly used turbine. Gas turbine & Steam turbine are example of it. In these types of turbines, the flow of fluid is parallel to the axis or shaft of the turbine. These turbines generate power by extracting the energy of high temperature and pressure fluid that expands through the several stage of fixed and moving blades. The fixed ones are called stator and the moving one are called rotor. The rotors are the one that extract the fluid energy to mechanical energy.

This rotating blade works more or less the same way as an airplane wing generates lift. These blades deflect the high velocity fluid, transferring momentum from fluid to the blade.

There are various parameters that affects the shape of an airfoil section. But the National Advisory Committee for Aeronautic known as NACA, tested a series of airfoils and each airfoil was designated with a 4-digit number that represented the airfoil section's geometric properties. In percentage of chord length, the first digit denotes the maximum camber, the second digit times ten will indicates the maximum camber position and last two-digit provides the maximum thickness of the airfoil.

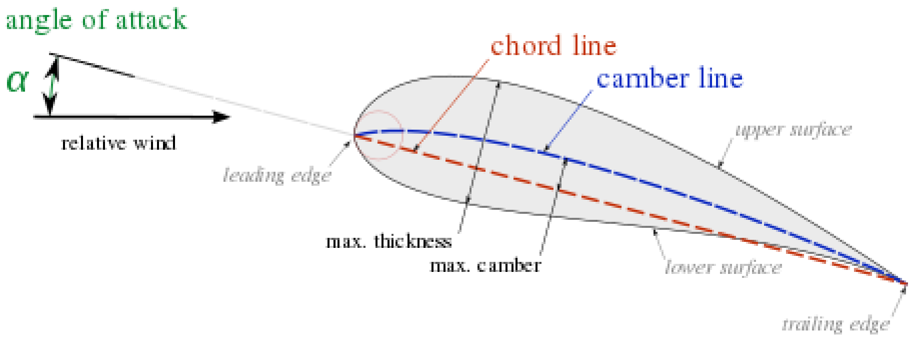

Figure 1.1 Geometric Terms for Airfoil Section[1]

To illustrate, NACA-8416 has maximum camber of 8% of chord and the location of maximum camber is at 40% from the left. And 16% of chord is the maximum thickness.

The X axis denotes normalized chord length and Y axis denotes thickness distribution.

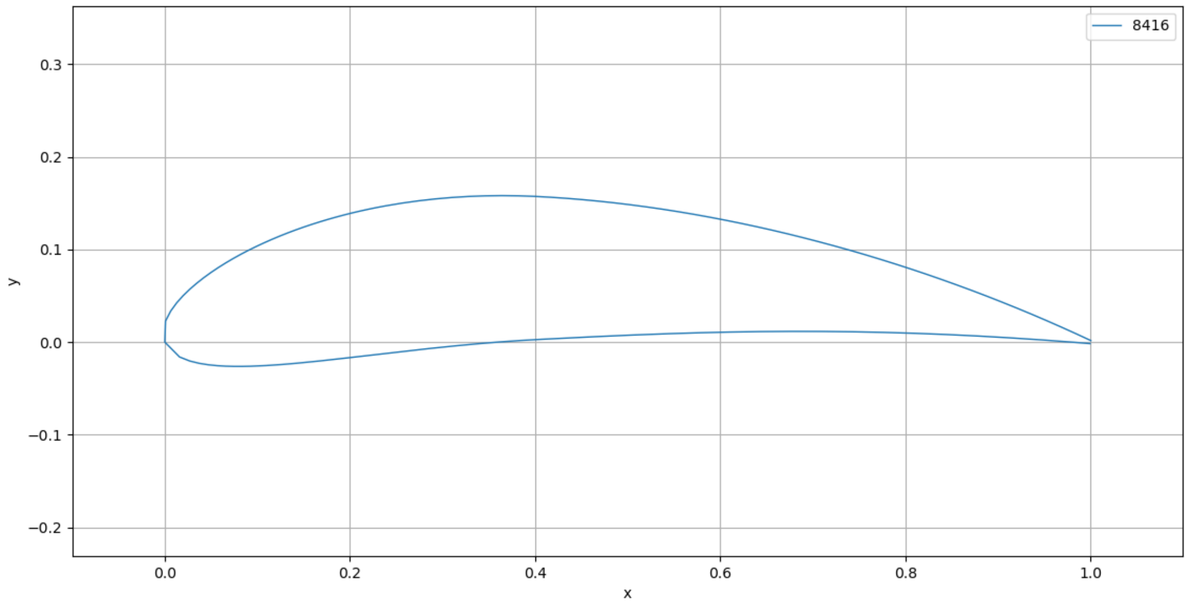

Figure 1.2 NACA 8416 profile

When A rotor blade moves past a stator blade, the force experienced by the blade varies. Although The stress is well below the yield stress of the material, the blade might fail due to fatigue. This is not surprising as Around 90% of mechanical failures is due to fatigue. Fatigue analysis tries to predict the life cycle of a component under cyclic loading.

While designing thermodynamics aspects of the turbine, it is assumed that fluid flows through the turbine in steady condition. But A structural designer needs to account the unsteadiness of the flow. Turbulence, Pressure disturbances, flow distortions, shock-wave and secondary flows produce time varying pressure forces on a rotor as well as on a stator as seen in the graph.

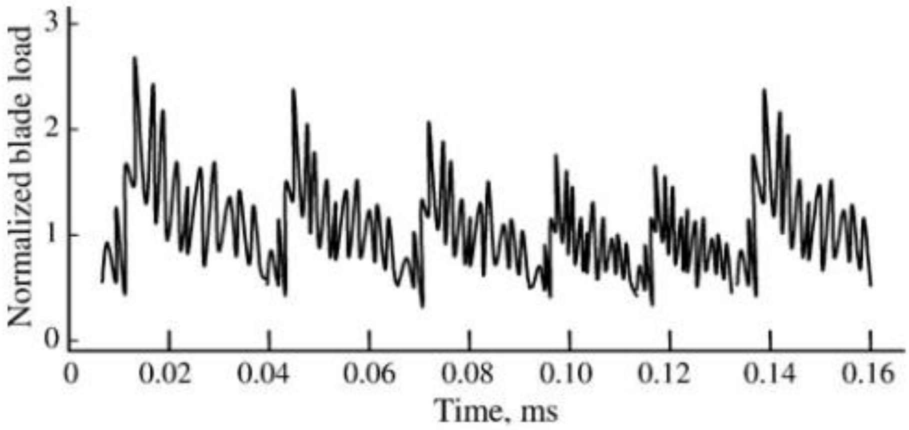

Figure 1.3 Blade load varying over time[2]

Failure of mechanical components by fatigue is due to varied or repeated force which is much below than the static yield load. In service many turbine components including rotor blades are subject to time varying loads. Nearly all failures in turbines employed in power plants & industrial plants are due to fatigue failure. Their operational life is limited by this factor. The most dangerous feature of fatigue failure is that it is sudden with no prior sign of failure as it is very difficult and nearly impossible to detect microscopic fatigue cracks.

There is another aspect of turbine design. the rotating speed of turbine can only be determined after all the vulnerable natural frequencies are known to a certain degree of confidence. Modal analysis is used to determine the mode shapes along with the natural frequencies which is the inherent dynamic characteristics of the blade.

A certain system like turbine blades has more than one natural frequency. If any of the natural frequencies of the system is matched with frequency of externally applied force, the amplitude of oscillation will be dangerously large. That is why all the vulnerable natural frequencies of any system must be known to a certain degree of confidence before completing the rest of design.

Failure may occur due to resonance at the first torsion and bending modes during startup and shutdown of turbine.

As the blades rotate with a certain RPM, the peripheral velocity of the tip of blade can be much greater than the root of the blade depending on the length and mean radius of the blade. For this reason, the relative velocity between the fluid and the blade changes from root to tip. To maintain a favorable angle of attack, the blade needs to be twisted with an angle.

There are some paper published over the years that did fatigue analysis of failed blades during service time. Previous works includes fatigue analysis on case by case basis. No one worked on comparative analysis on fatigue and modes with blade profile with varying angle of twists.

Our objective of the research was to find the effect of angle of twist and blade profiles on the results of Modal & fatigue analysis, that is the natural frequencies & life cycle.

Figure 1.4 Twisted blade airfoil shape[3]

1.2 LITERATURE REVIEW

To claim our objectives and to find out new scopes for any new method of design or to do some modifications a literature survey is done over the researchers concerned with the detailed study on turbine blade.

Ravi Ranjan Kumar et al. have done static analysis. In their paper they used existing NACA6409 profile with different speed 20000, 40000, 600000 rpm. They used super alloy X, Inconel 625 and Nimonic 80A as materials. They have done only stress analysis. Their maximum stress was around 25000 to 32000 MPa. The deflection was 3-4mm.[4]

Kamal A. R. Ismail et al. worked on energy analysis. Here they varied the twist angle from -5 to 35 degree and studied chord and twist angle distribution with blade length. They have given solution on how to increase efficiency using different profile in same blade.[5]

Ahmed Tahir et al. have varied the twist angle from -20 to 50 degree and studied twist angle and chord length distribution with radius. They have shown chord length and twist angle decreases with radius.[6]

Win Lai Htwe et al. worked with thermal and static analysis. But they have done it for various hole configuration. Also, they only used structural steel as material. They also used ANSYS for simulation. They have compared thermal and static condition varying number of holes in turbine blade.[7]

Samuel O. Afolabia et al. also worked on static analysis. They have done fatigue analysis but only for turbine shaft of 30mm diameter and 20mm diameter. They have shown the factor of safety variation. They did not done analysis for blade. Their bending moment was 1111N.[8]

T Puja Priyanka et al. have taken blade for a small turbine and done static analysis on it. Load and pressure were given. After that they only calculated Von Mises stress. So, they did not do fatigue analysis. Their von Miss stress was 2.5 GPa.[9]

Haresh Pal Singh et al. have done modal and stress analysis varying blade materials only. They have taken only 1 blade geometry. So, they did not vary the blade profile. They did not do any fatigue analysis. Here the stress was 7-8 GPa. As their design is slightly similar to ours; some of the mode shapes was similar with ours. The first, second and fourth mode shape is similar.[10]

P.Brandão et al. have studied thermal and static analysis. They studied high pressure turbine where they have used finite element method (FEM). They have done reverse engineering and they worked with creep. Their displacement result was around -5 to 5 mm.[11]

Gopinath Chintala et al. have done static analysis. They have given the forces and rotational velocity on a blade. They have selected the rotational speed from the criteria 3000-8000RPM. They have also done reverse engineering and ultimately have the result of Von Mis stress and deflection in each axis. In this paper we have seen the maximum stress appears in the thicker side of the blade where fixed support is situated. Our result was also similar.[12]

G. Urquiza et al. worked on failure analysis of turbine shaft. They have generated the simulation result of Von Mis stress and done metallurgical study with the actual shaft. Comparison of actual data and simulation result were checked. People only done static and modal analysis. But they did not do fatigue analysis on blade. Moreover, blade profile comparison was not also done**.** [13]

R. S. Mohan et al. have done modal analysis and harmonic analysis on turbine blade for both stationary blades and rotating blades. Four types of modes were found by them for stationary blades. Two flexural mode, one torsional mode, one edge bending mode. Six mode results were given in the paper for rotational blade. Three flexural mode, two torsional mode and one edge bending mode. They also given result for Von Miss stress.[14]

L. Moroz et al. have also done modal analysis on the full turbine blade setup. Two types of blade patterns were taken. There were variations with heavier and lighter blades. And they have shown that the change in stage variation have very less effect in the change in natural frequency.[15]

B. Deepanraj et al. have done thermal structural analysis on one turbine blade. One real model of the blade was taken. Then for different numbers of cooling passages stress analysis were done. The actual blade having 12 holes had too much bending stress. The results they got were with increase of number of holes; there were increase in bending stress. But the temperature drops with increase of cooling tunnel.[16]

Aniekan E. Ikpe et al. have done modal analysis of one blade model where two types of material were taken: In738 and U500. They have taken the airfoil NACA6409 and made the blade model. Their mode shape results were very similar to ours.[17]

Chunli Liu et al. have done modal analysis and structural analysis on fillet section of blades. Different types of fillets were taken. After that comparison among those were done from the results of modal and stress analysis.[18]

1.3 SIGNIFICANCE

As evident from literature review, previous researches primarily focused on working on a single blade only for a specific scenario. Some researchers worked on a single blade varying the materials of the blade that resulted in comparative analysis of materials in terms of stress concentration and natural frequencies. Some researches were found where the author varied the number of cooling tunnel and corresponding effect on stress concentration was analyzed. There were also some studies that deals deflection of blade under various load.

Fatigue and creep analysis were also done by some authors but for either single blade or turbine shaft. No previous works were found that deals with general comparative analysis of fatigue life and natural frequencies with various blade profiles and angle of twists. This was identified as research gap.

This study focuses on comparative study of natural frequency and life cycles of turbine blades varying the blade profile and twist angle.

1.4 METHODOLOGY

Some NACA-4 series profiles were selected for analysis. (See Appendix 1). Then, the coordinates of the profiles were generated through python code using the formulas provided by NACA. The coordinates were saved as txt file for each profile.

A program was written in Visual Basic language to generate CAD file of blade geometry using the SolidWorks API. (See Appendix 3) The code was written in visual studio 2015 and SolidWorks version was 2021. Different CAD files were generated for different angle of twist for each NACA profile. The CAD files were saves as SLDPRT file.

Using SolidWorks interface for ANSYS, these files were directly imported to ANSYS 2020 R1. ANSYS workbench journal script was used to automate the process (See Appendix 2). The modal and fatigue analysis were performed for each CAD file.

The results were exported to Excel files and appropriate graphs were generated to compare the results.

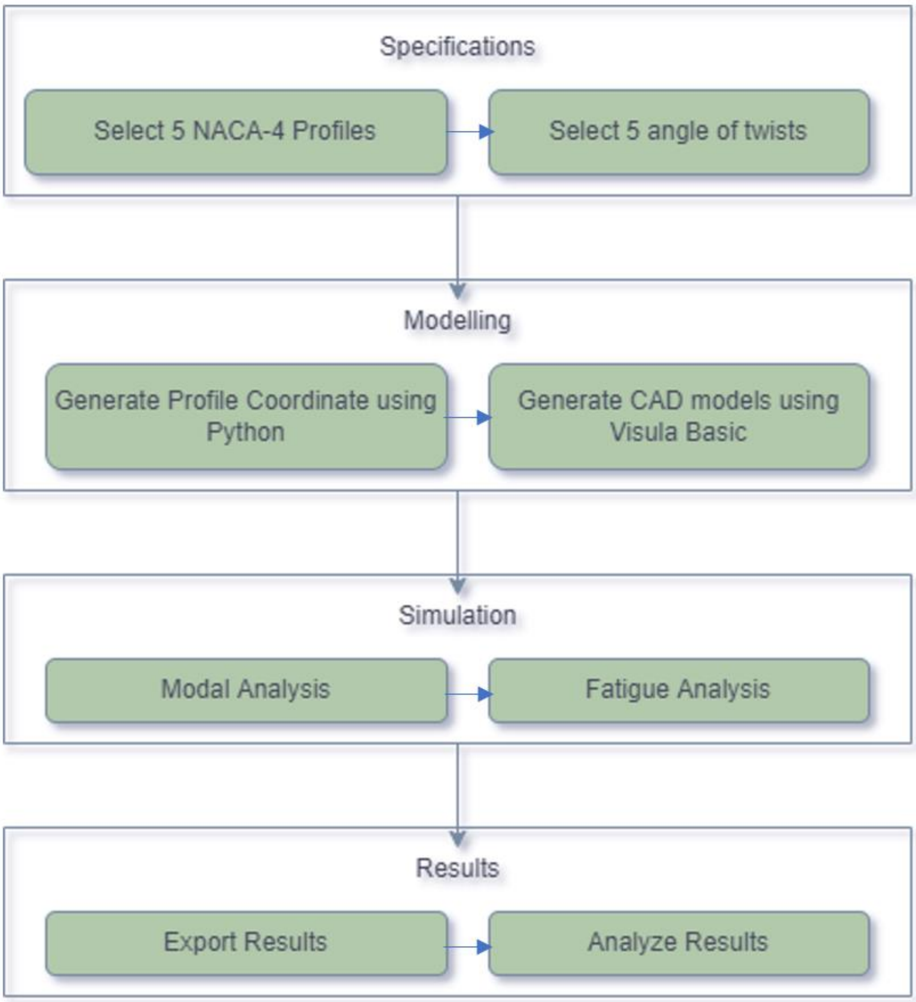

Figure 1.5 Flowchart for methodology

Chapter 2

2.1 MODELLING & SPECIFICATIONS

In order to run simulation, some CAD models needed to be created. SolidWorks 2021 was used for creating CAD files. Using Visual Studio 2015, The CAD modelling process was automated in Visual Basic programming language with the help of SolidWorks API.

The last Coefficient of NACA-4 equation was modified to be -0.08 to have machinable trailing edge thickness.

The specifications for the CAD model are given below

Table 2.1 CAD model Specifications

NACA	6412, 9412, 4412, 7315, 8410,
Twist	30°, 35°, 40°, 45°, 50°
Width	40 mm
Length	80 mm

The profiles selected are plotted below. The *x* axis denotes normalized chord length and *y* axis denotes thickness distribution.

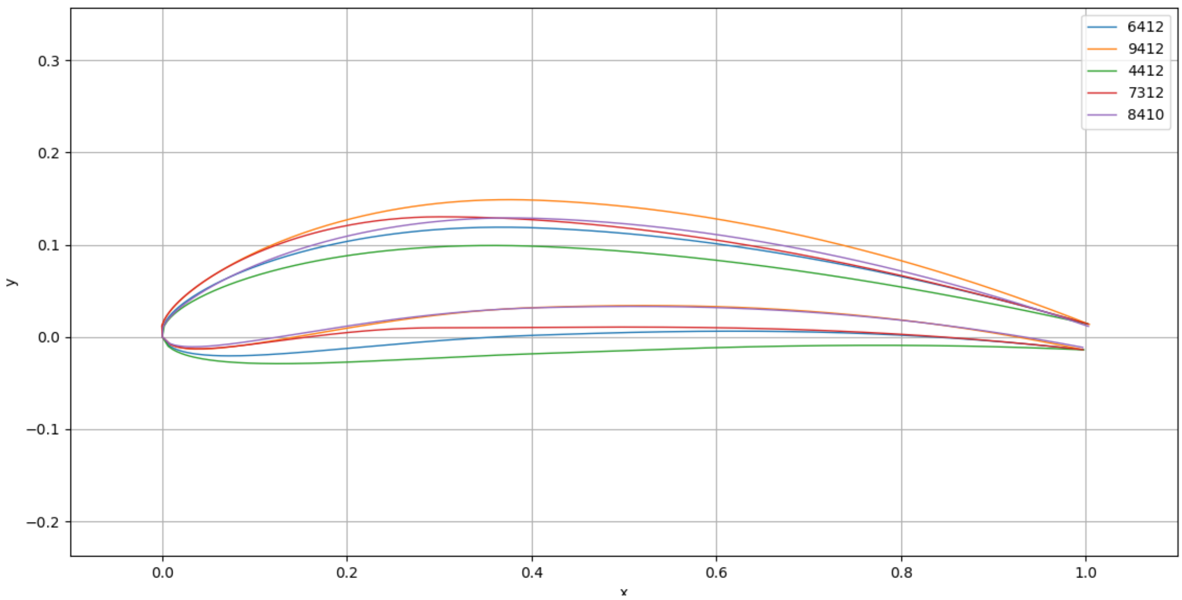

Figure 2.1 Profile Plot for selected NACA profiles

The Cad models for 30-degree twist for five profiles are given below.

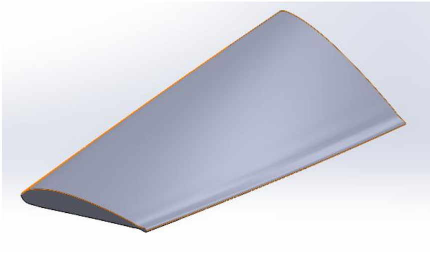

Figure 2.2 NACA 4412 - 30 deg

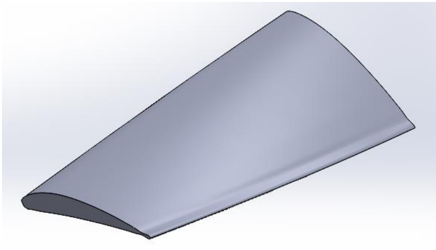

Figure 2.3 NACA 6412 - 30 deg

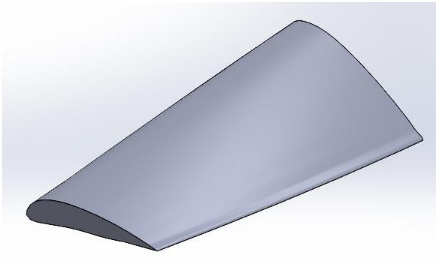

Figure 2.4 NACA 7315 - 30 deg

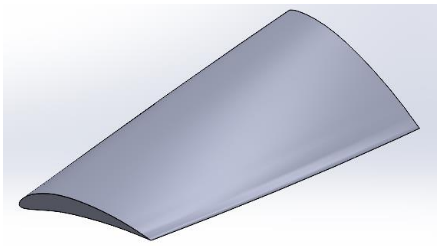

Figure 2.5 NACA 8410 - 30 deg

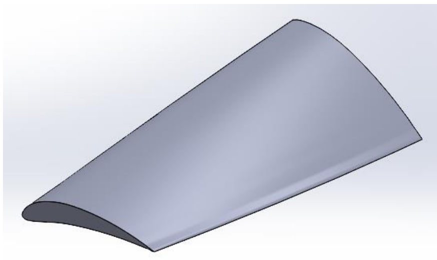

Figure 2.6 NACA 9410 - 30 deg

The CAD models for NACA 4412 for varying degree of twists

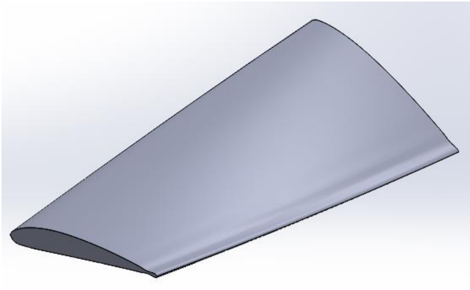

Figure 2.7 NACA 4412 - 30 deg

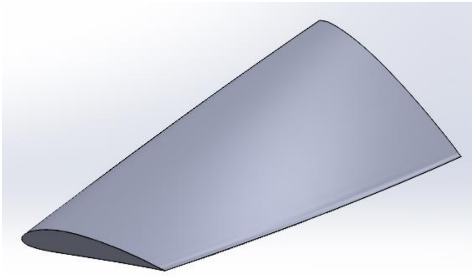

Figure 2.8 NACA 4412 - 35 deg

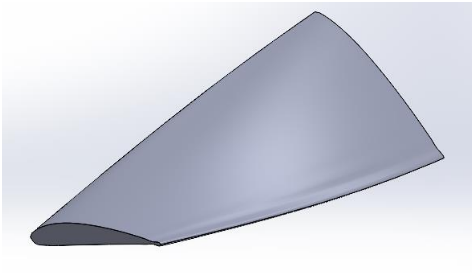

Figure 2.9 NACA 4412 - 40 deg

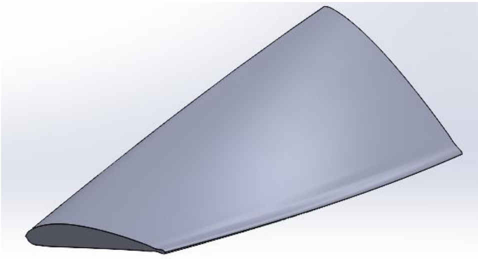

Figure 2.10 NACA 4412 - 45 deg

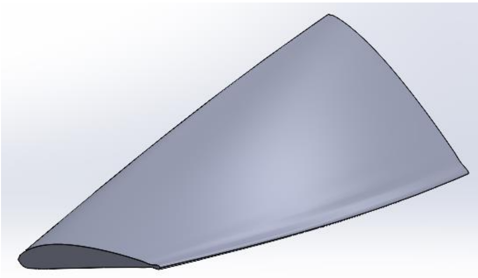

Figure 2.11 NACA 4412 – 50 deg

2.2 SIMULATION

ANSYS 2020 was used to perform modal and fatigue analysis using Finite Element Method (FEM). ANSYS workbench journaling feature was utilized to automatically importing CAD files and preparing the simulations.

Finite element analysis is useful when the shape of the mechanical component is complex.

To perfume simulation following mesh setting were employed. The curvature and proximity capture were turned on for finer mesh in curvy & narrow region. Mesh defeaturing was turned on to avoid meshing very small features. The results were confirmed to converge to reasonable degree using the following mesh.

Table 2.2 Mesh Settings

Mesh Size	1.5 mm
Mesh Type	Tetrahedron
Defeaturing	0.1 mm
Curvature (min)	0.5 mm
Proximity (min)	0.5 mm
Total Elements	~ 0.5 million
Total Nodes	~ 2 million

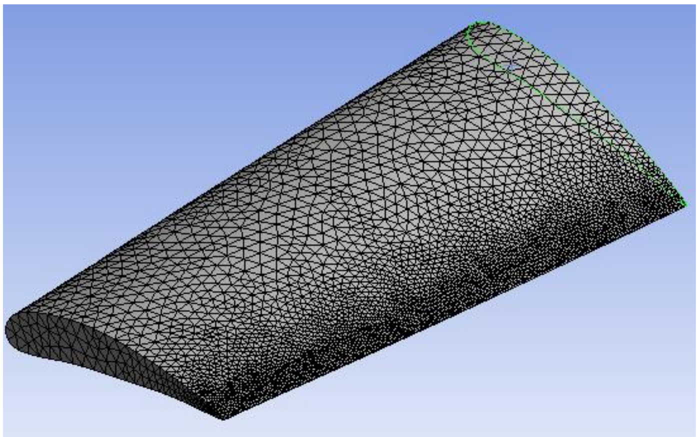

Figure 2.12 Meshing (NACA 4412 30° twist angle)

The root of the blade was given fixed support. Around 10000 rpm at 15 cm radius was applied to account for the centrifugal force and around 1 KN force was applied in the tangential direction. The temperature was set 500 C.

For Modal Analysis, the analysis settings were set to find the 6 natural frequencies and their corresponding mode shapes.

A titanium alloy, Ti6AL4V, was chosen for simulation which is known for having high endurance for fatigue. The properties and SN table are given below.

Properties: -

Table 2.3 Material Properties used in ANSYS

Temperature (°C)	Young's Modulus (GPa)	Poisson's Ratio	Bulk Modulus (GPa)	Shear Modulus (GPa)
100	103	0.328	100	38
200	99	0.334	99	37
300	93	0.339	97	34
400	85	0.345	92	31
500	74	0.351	83	27
600	61	0.357	72	22
700	48	0.369	58	17

SN Data:

Table 2.4 SN Data used for fatigue analysis

Cycles	Alternating Stress (MPa)
10^4	720
10^5	582
10^6	530
10^7	500
10^8	475
10^9	460
10^{10}	450

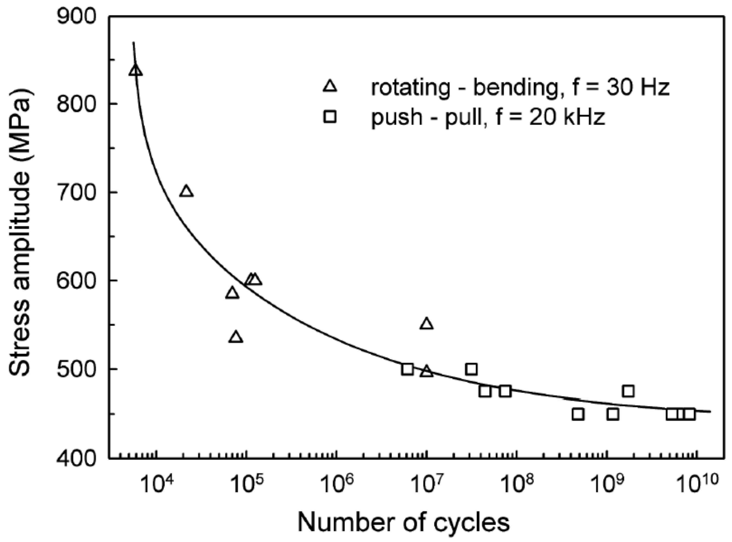

Figure 2.13 S-N curve of Ti6Al4V alloy [19]

Chapter 3

3.1 MODAL ANALYSIS

ANSYS Modal analysis module was used for finding the natural frequencies and mode shapes of turbine blades. Fixed support was given at one end of the blade (root of the blade). Six mode shape and natural frequency results were extracted from ANSYS and the results were exported in Excel for further analysis. The Mode Shapes for NACA 7315 and 30 degrees of twist are shown and explained below.

In the 1st mode shown in figure 3.1, the blade acts like a cantilever beam. Only bending is present there. The free end of the blade will bend along y axis. The corresponding measure of frequency was 632.14 Hz.

In the 2nd mode shown in figure 3.2 it is shown that the blade is twisting. The 2 sides of the free end will twist along y axis. In this case, the frequency was found to be 2553.1 Hz.

In the 3rd mode, shown in figure 3.3, it is observed that there is twisting but the thicker part of the blade is moving very less, nearly stationary but thinner part is twisting. So, it can be said that in the thinner side of the blade the twisting is more with natural frequency of 3193.9 Hz.

In 4th mode shown in figure 3.4, it is bending but a node in the middle of it is present. It is called 2nd mode of bending. Here the critical point is at the node where maximum frequency will appear. The area where maximum stress concentration due to bending is presented by red color in the figure 3.4 where the nature frequency was found to be of 4433.3 Hz

In the 5th mode, shown in figure 3.5, it twists near 4 corners of the blade. Some bending is also present here. The characteristics of this mode is quite similar to 3rd mode. Here twist happens at the four areas along y axis. The bending happening at one of the critical points near fixed support along y axis.

In the 6th mode, shown in figure 3.6, it is also twisting with a frequency of 9738.5 Hz. But twist occurs on more areas than the 5th mode. Adding, the twist magnitude is less compared to the 5th mode.

In other word we can say, the 1st mode is showing V mode and the 4th mode is showing S mode. These 2 modes are bending mode. The others mentioned above are twisting.

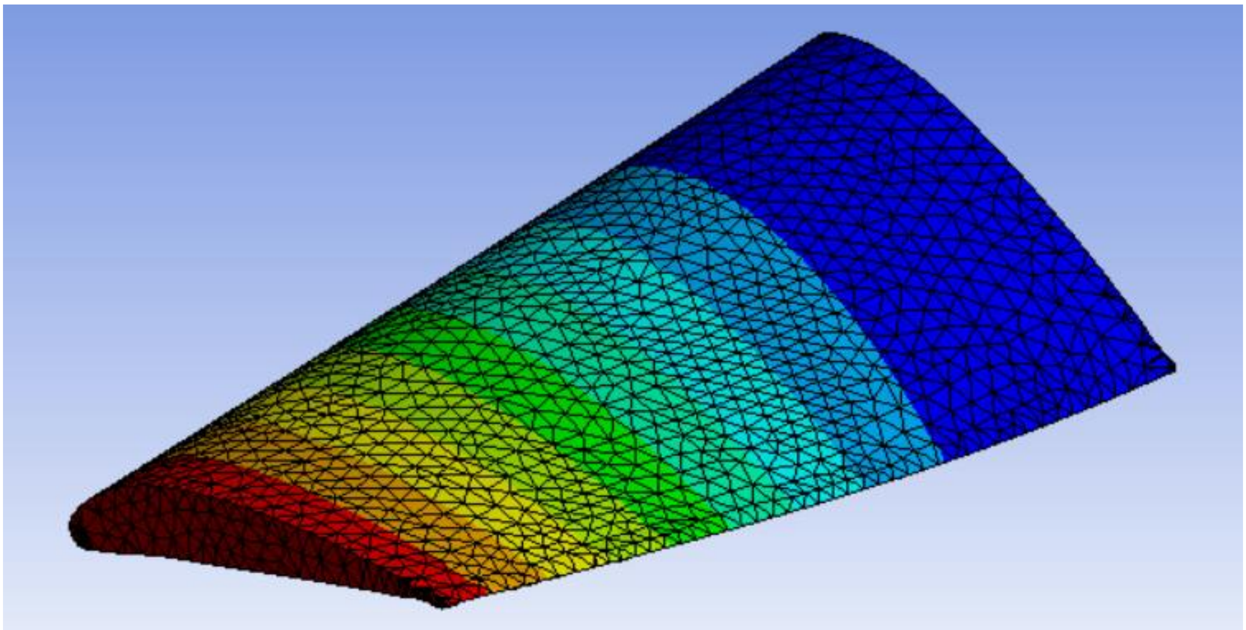

Figure 3.1 1st mode at Natural frequency of 632.14 Hz for NACA 7315 – 30 deg

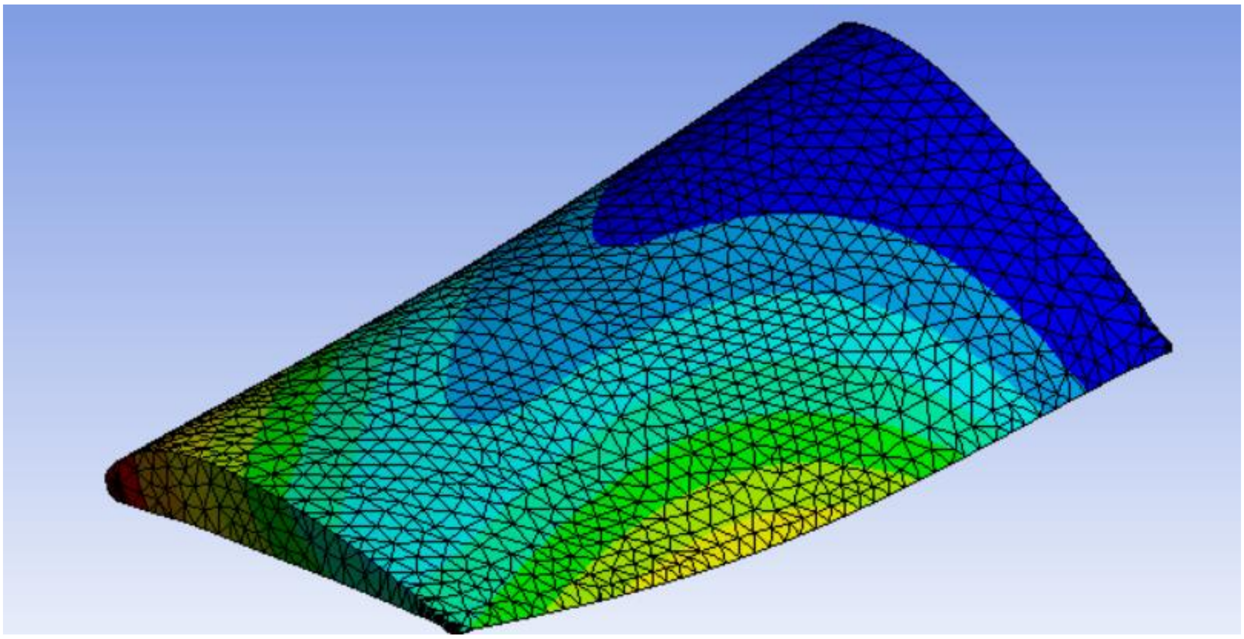

Figure 3.2 2nd mode at Natural frequency of 2553.1 Hz for NACA 7315 – 30 deg

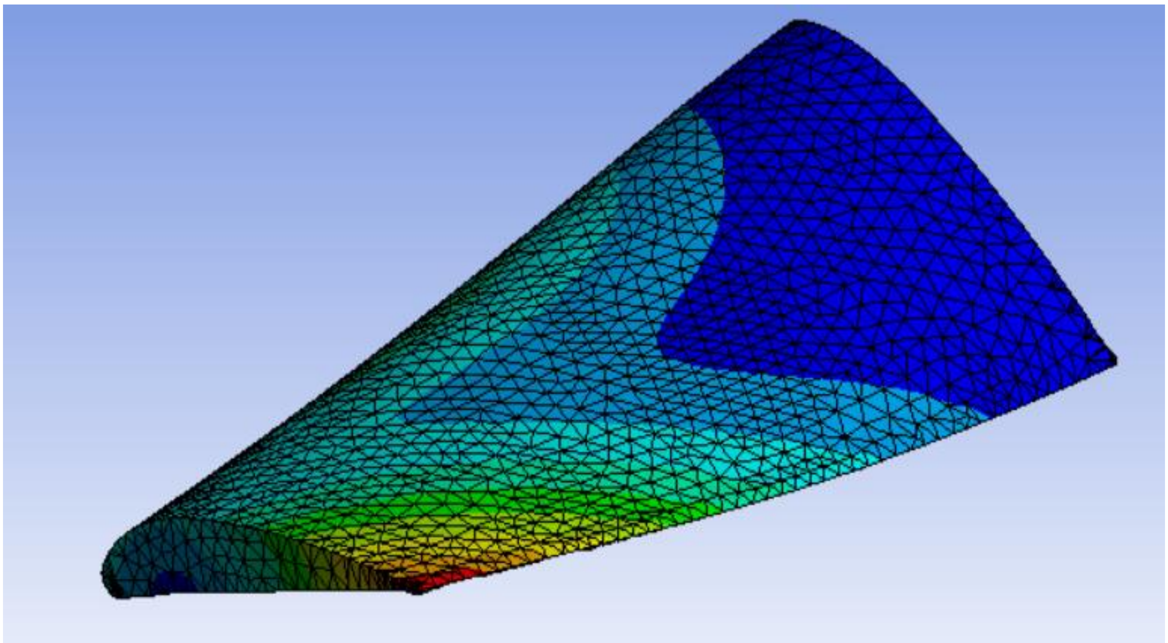

Figure 3.3 3rd mode at Natural frequency of 3193.9 Hz for NACA 7315 – 30 deg

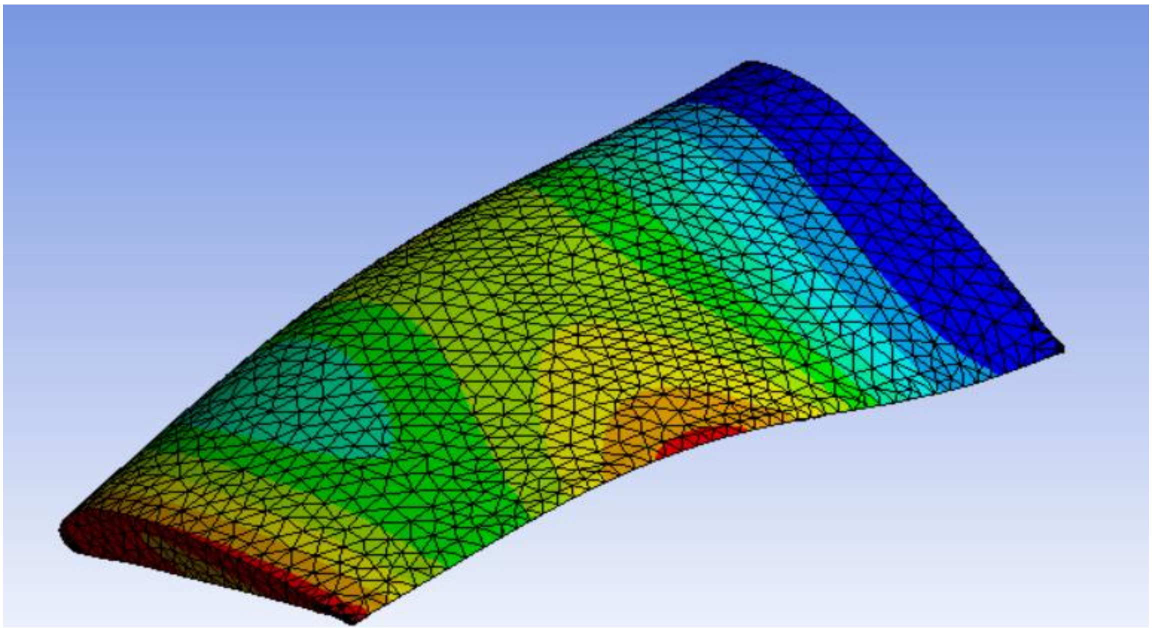

Figure 3.4 4th mode at Natural frequency of 4433.3 Hz for NACA 7315 – 30 deg

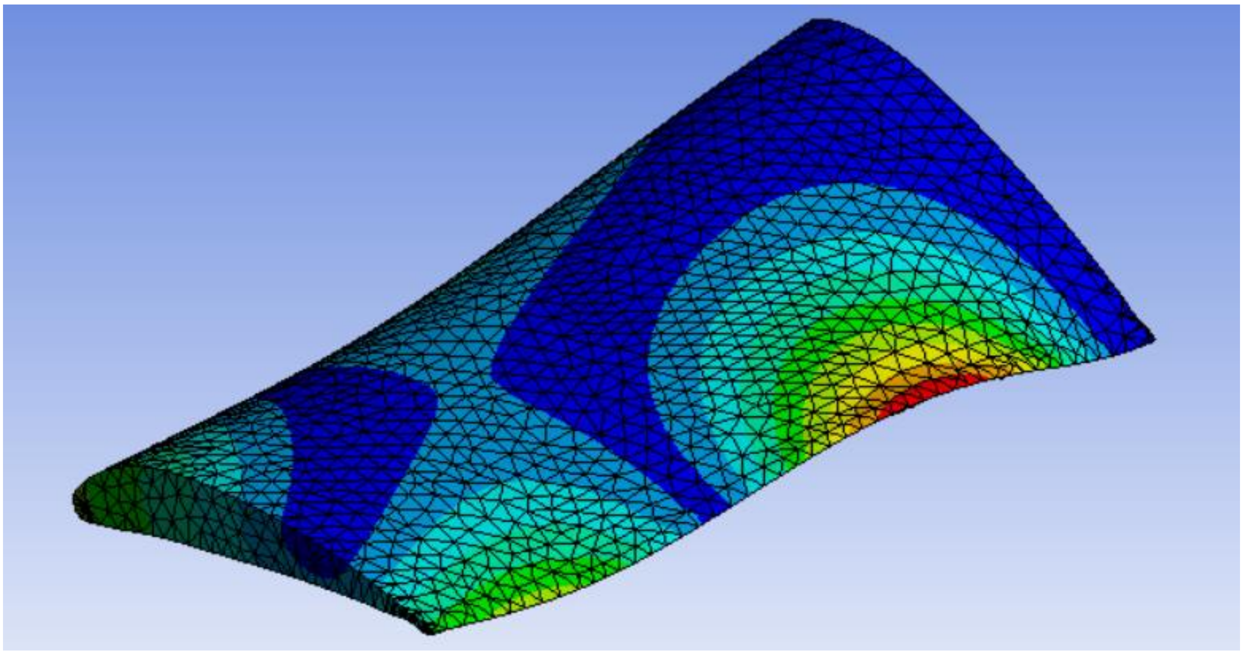

Figure 3.5 5th mode at Natural frequency of 7995.8 Hz for NACA 7315 – 30 deg

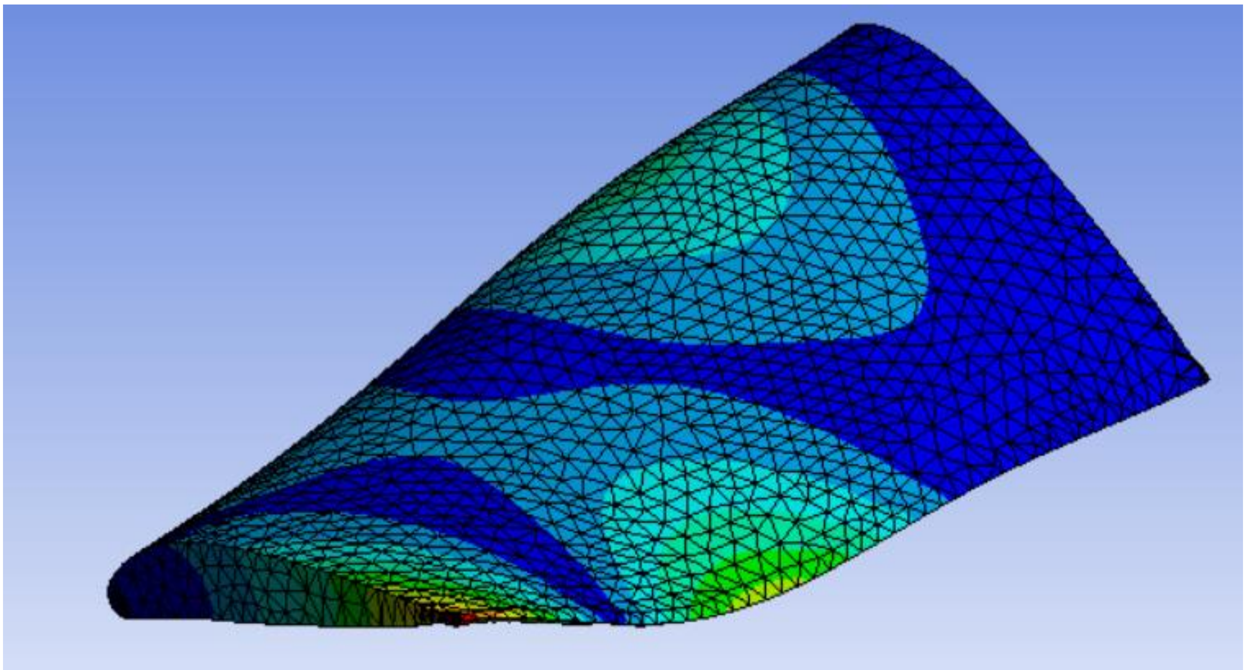

Figure 3.6 6th mode at Natural frequency of 9738.5 Hz for NACA 7315 – 30 deg

The natural frequencies of different blade profile with variation with twist angle are tabulated below.

Table 3.1 Modal Analysis Results for NACA 4412

NACA 4412	Degree of Twist				
	30	35	40	45	50
1st Mode	491.08	490.34	489.21	487.88	486.8
2nd Mode	2181.7	2148.9	2100.3	2042	1979.4
3rd Mode	2662.7	2658.8	2678	2715.1	2766.7
4th Mode	4059.7	4200.2	4338.1	4472.3	4601.7
5th Mode	6584.2	6623.6	6657.2	6682.1	6696.9
6th Mode	8057.9	8057.9	8057.9	8057.9	8057.9

Table 3.2 Modal Analysis Results for NACA 6412

NACA 6412	Degree of Twist				
	30	35	40	45	50
1st Mode	515.86	512.98	511	509.08	507.02
2nd Mode	2200.2	2144.2	2102.2	2049.8	1992.9
3rd Mode	2761.6	2744.8	2753.3	2781.7	2822.8
4th Mode	4079.9	4232.7	4370	4501	4631.2
5th Mode	6824.6	6636.9	6663.5	6685.7	6704.4
6th Mode	8231.4	8158.3	8196.1	8243.5	8300.9

Table 3.3 Modal Analysis Results for NACA 7315

NACA 7315	Degree of Twist				
	30	35	40	45	50
1st Mode	632.14	631.15	629.93	628.14	626.4
2nd Mode	2553.1	2502.3	2445.5	2381.2	2311.7
3rd Mode	3193.9	3189.1	3201.3	3224.8	3260.2
4th Mode	4433.3	4574.2	4713.7	4850.6	4989.9
5th Mode	7995.8	7998.5	8015.2	8023.6	8034.8
6th Mode	9738.5	9744.2	9747.9	9752	9755.7

Table 3.4 Modal Analysis Results for NACA 9412

NACA 9412	Degree of Twist				
	30	35	40	45	50
1st Mode	566.39	561.83	557.4	553	548.77
2nd Mode	2147.3	2127.1	2097	2058.6	2012.1
3rd Mode	2938.8	2907.8	2898.6	2908.1	2936.9
4th Mode	4218.6	4349.8	4477.1	4603.9	4721.1
5th Mode	6535.8	6565.8	6602.9	6641	6676.6
6th Mode	7857.7	7888.5	7927.9	7981.8	8057.9

Table 3.5 Modal Analysis Results for NACA 8410

NACA 8410	Degree of Twist				
	30	35	40	45	50
1st Mode	479.39	475.4	470.44	465.3	460.48
2nd Mode	1869.5	1854.9	1837.8	1807.4	1766.8
3rd Mode	2599.5	2579.1	2575.3	2592.5	2629.4
4th Mode	4015.1	4146.8	4260.5	4365.4	4459.9
5th Mode	5605.5	5605.6	5674.5	5786.5	5817.1
6th Mode	7409	7421.1	7475	7534.1	7605.3

Graphs using the above data have been generated. The trend is similar for all blade design.

Here the horizontal axis represents the twist angle (degree) and vertical axis represents the natural frequency (Hz)

Here, in the first and second mode shown in figure 3.7 and 3.8, natural frequency decrease with the increase of twist angle. In third mode first it decreased then increased (figure 3.9). In fourth, fifth and sixth mode the natural frequency increases with increase of twist angle (figure 3.10,11,12).

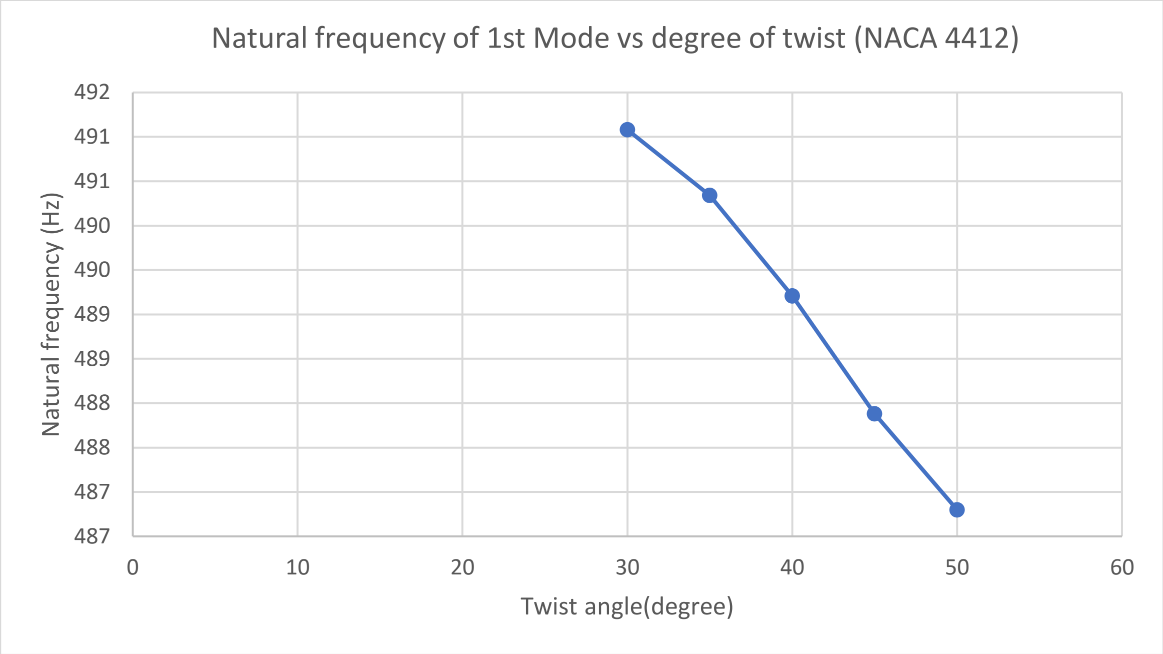

Figure 3.7 Natural frequency of 1st Mode vs degree of twist (NACA 4412)

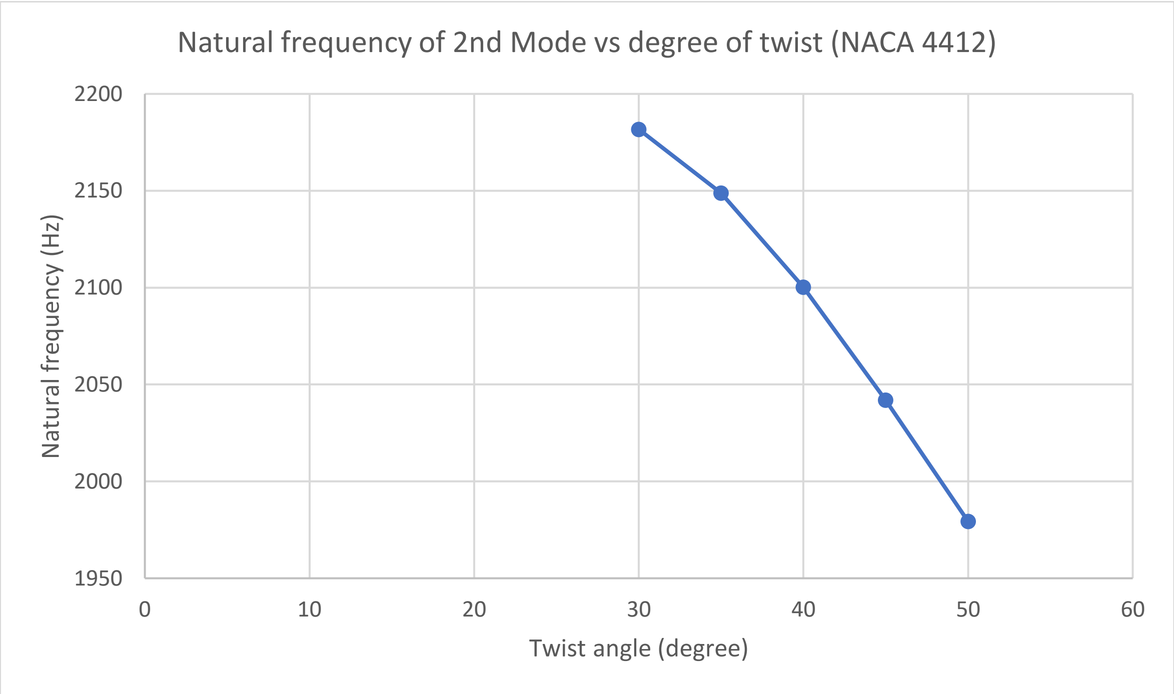

Figure 3.8 Natural frequency of 2nd Mode vs degree of twist (NACA 4412)

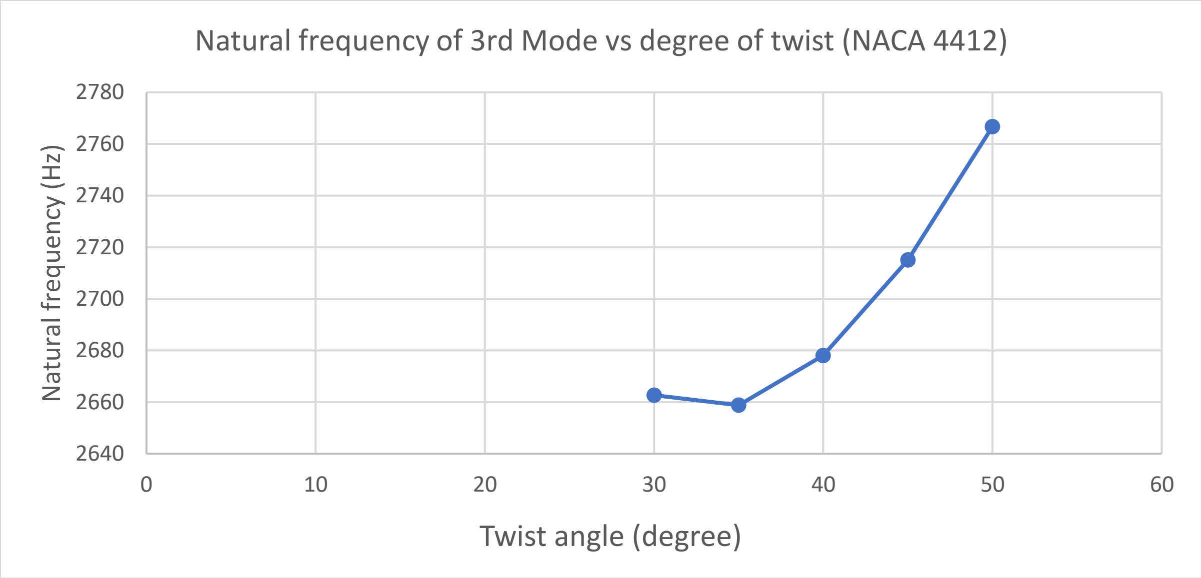

Figure 3.9 Natural frequency of 3rd Mode vs degree of twist (NACA 4412)

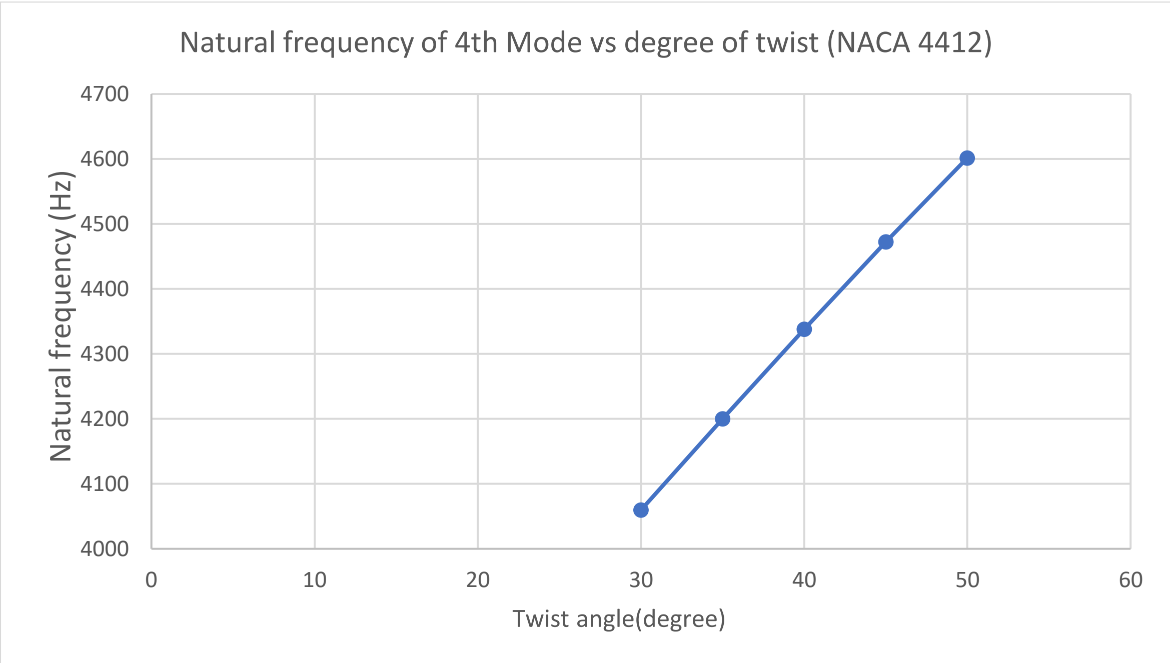

Figure 3.10 Natural frequency of 4th Mode vs degree of twist (NACA 4412)

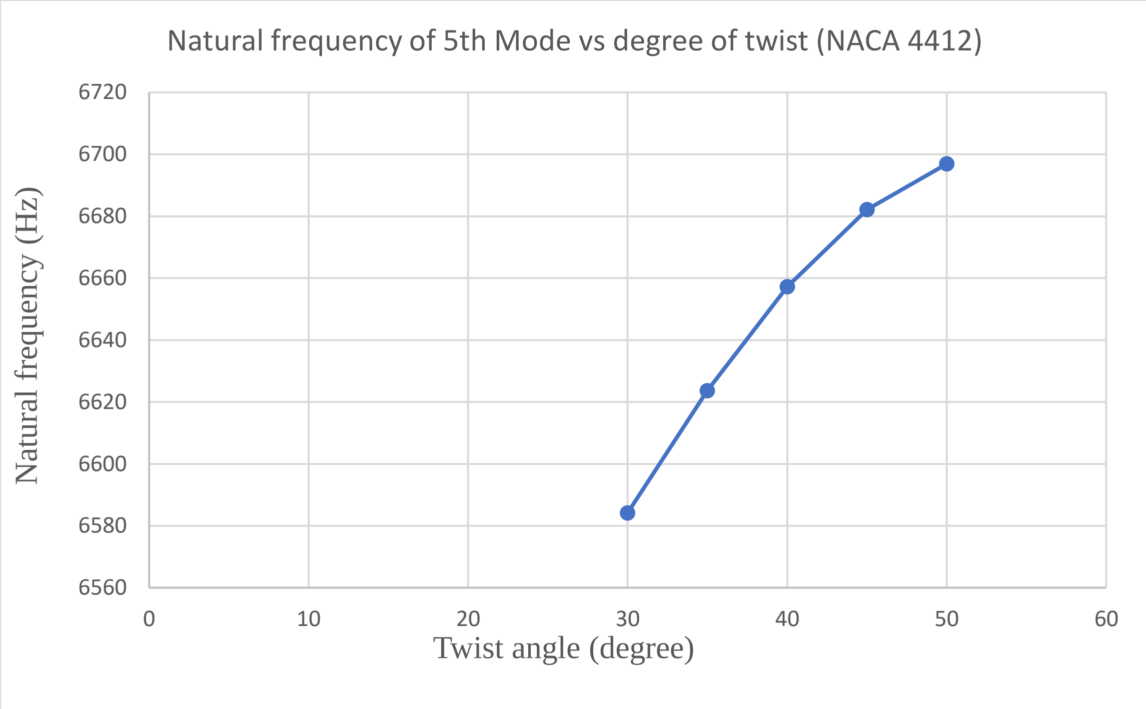

Figure 3.11 Natural frequency of 5th Mode vs degree of twist (NACA 4412)

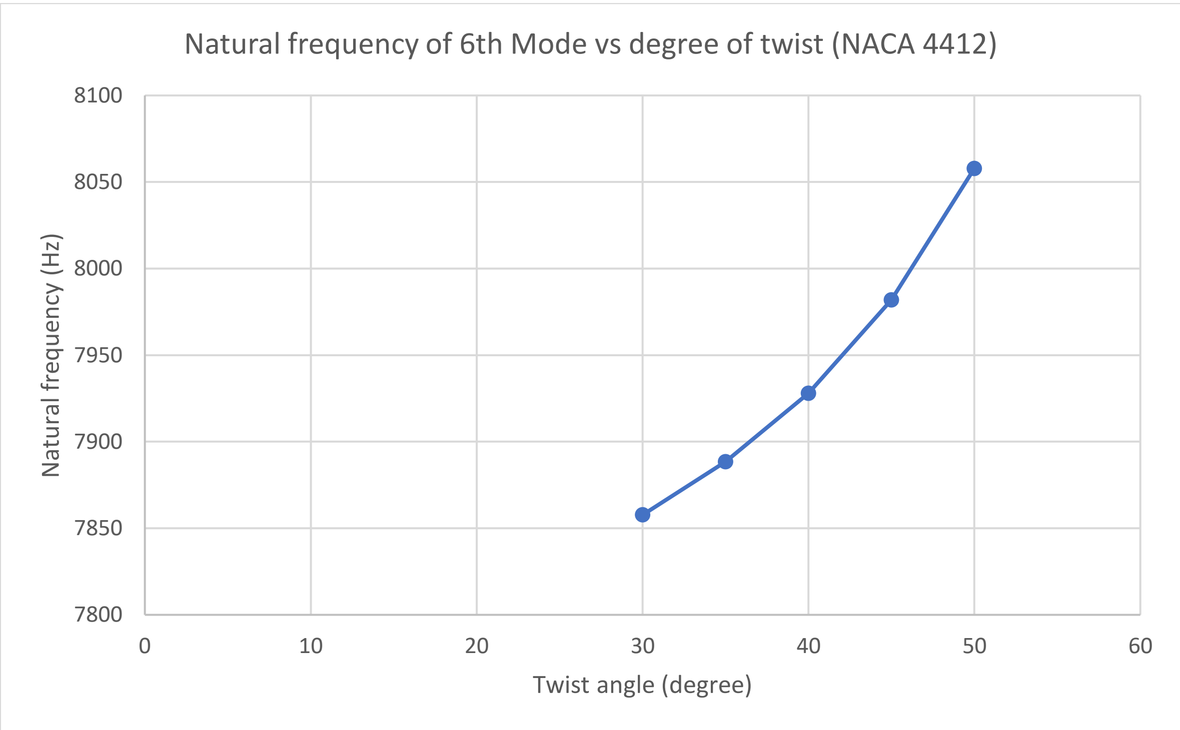

Figure 3.12 Natural frequency of 6th Mode vs degree of twist (NACA 4412)

More graphs are shown in Appendix 4

3.2 FATIGUE ANALYSIS

ANSYS Static structural module was used for calculating fatigue life with the help of Fatigue tool. The data of S-N curve was taken from a literature and imported into ANSYS.

The results from Fatigue Analysis are given below. (Table 3.6,7,8,9,10)

Here in the NACA 4412 profile we can see the from the graph (figure 3.15) the life cycle increases with the twist angle. For the other NACA profiles; NACA 7315, NACA 6412, NACA 8410, NACA 9412 we can see from the graph from figure 3.16 ,3.17, 3.18, 3.19 respectively we can see the increase in life cycle with twist angle. From all the graphs mentioned in the last paragraph, it can be seen that the life cycle increases drastically from 45^0 to 50^0.

Here it is observed in the figure 3.13 life cycle of NACA 4412 and twist angle of 50^0 for Titanium alloy (Ti6Al4V) material. The maximum life cycle is denoted by the blue color, whereas the red color indicates minimum life cycle. The figure indicates that failure will happen near the fixed support end and it will be on the thicker side of the blade.

From the figure 3.14 the life cycle of NACA 4412 and twist angle of 45^0 is observed. Here the material is structural steel. The red area indicates the minimum life cycle. It is observed that the red area is more here than of Titanium alloy shown in figure 3.13. This happened as that material's mechanical characteristics are much lower than the Titanium alloy we used. A bigger load was given when doing simulation so that a finite life can be gotten. This load was given to all the blade profiles worked by us under 5 twist angles (30^0, 35^0, 40^0, 45^0, 50^0).

The trend of the life cycle vs twist angle graph shown in figure 3-20 shows us the results for structural steel. It can be seen that there the life cycle is decreasing with twist angle, which is opposite of the blade of Titanium alloy Ti6Al4V.

NACA 4412

Table 3.6 Degree of twist vs Life Cycle for NACA 4412

Degree of twist	Life cycle
30	1329600
35	2284900
40	2430400
45	2797900
50	5128000

NACA 7315

Table 3.7 Degree of twist vs Life Cycle for NACA 7315

Degree of twist	Life cycle
30	1778000
35	2006400
40	2331900
45	2665900
50	3735000

NACA 6412

Table 3.8 Degree of twist vs Life Cycle for NACA 6412

Degree of twist	Life cycle
30	1998600
35	2267000
40	2784500
45	3482000
50	4195000

NACA 8410

Table 3.9 Degree of twist vs Life Cycle for NACA 8410

Degree of twist	Life cycle
30	1547000
35	1778900
40	2268000
45	3624000
50	3974300

NACA 9412

Table 3.10 Degree of twist vs Life Cycle for NACA 9412

Degree of twist	Life cycle
30	1295000
35	1528000
40	1994600
45	2467000
50	4360000

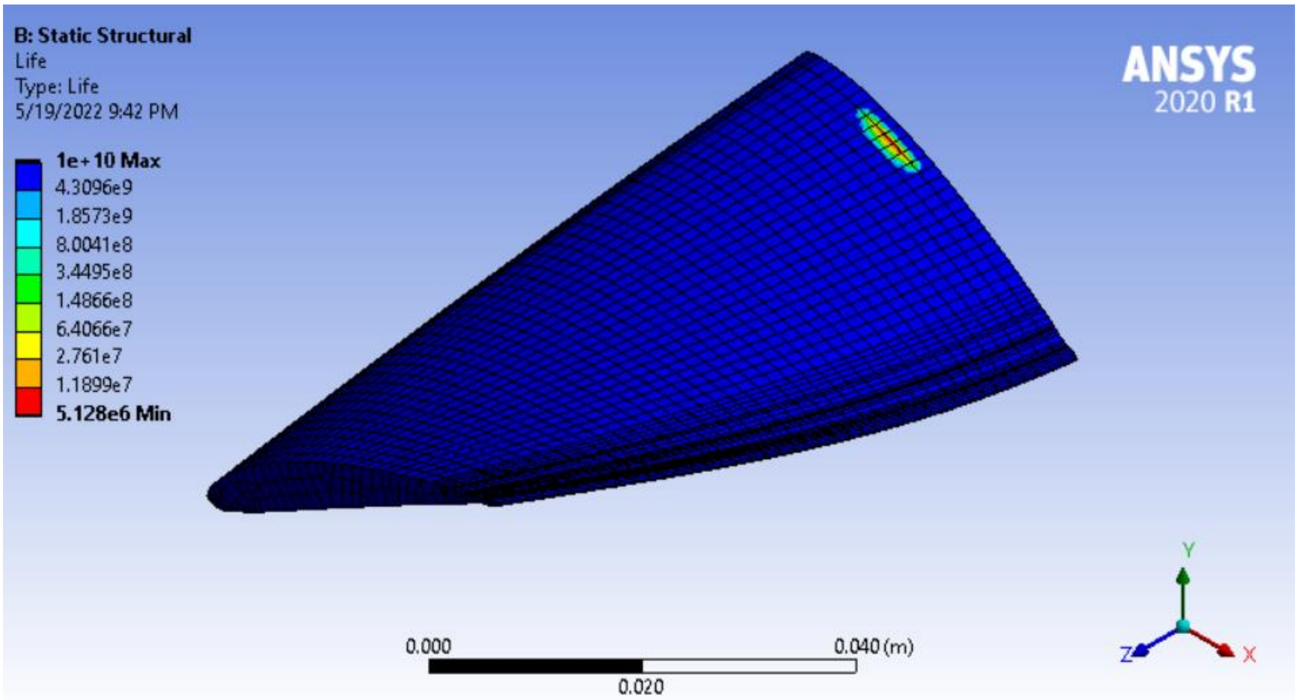

Figure 3.13 Critical Stress Point NACA 4412 50^0 twist angle for Titanium alloy (Ti6Al4V)

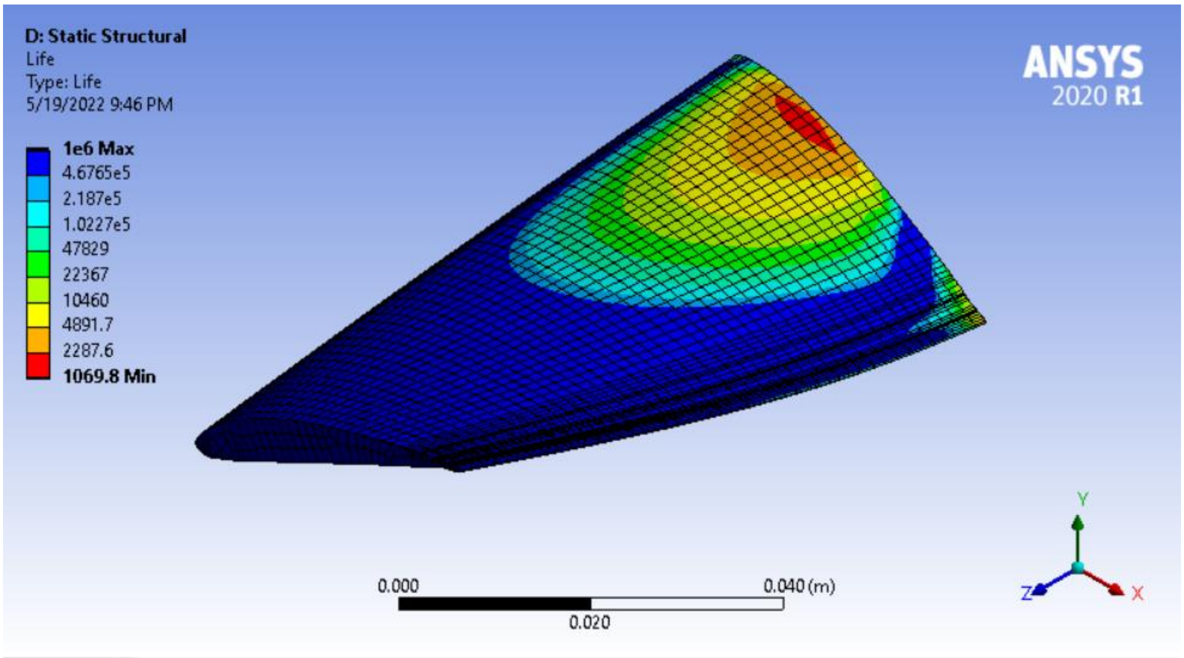

Figure 3.14 Critical Stress Point NACA 4412 45^0 twist angle for Structural Steel

Some graphs are presented from the tables above (table 3.6-10) where the horizontal axis represents the degree of twist and the vertical axis represent the life cycle.

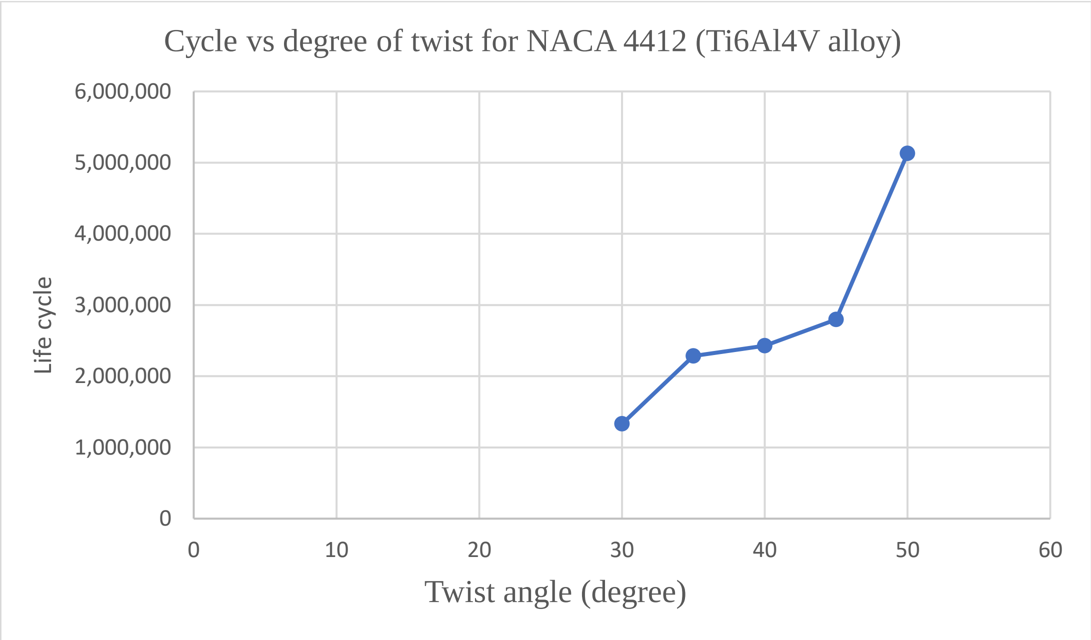

Figure 3.15 cycle vs degree of twist for NACA 4412 (Ti6Al4V alloy)

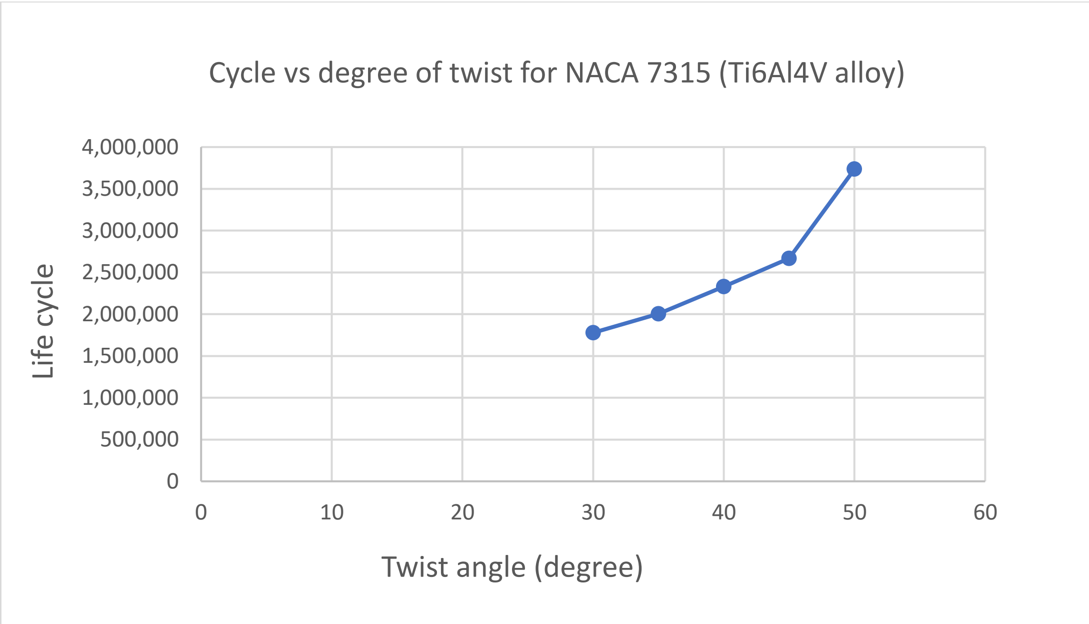

Figure 3.16 cycle vs degree of twist for NACA 7315 (Ti6Al4V alloy)

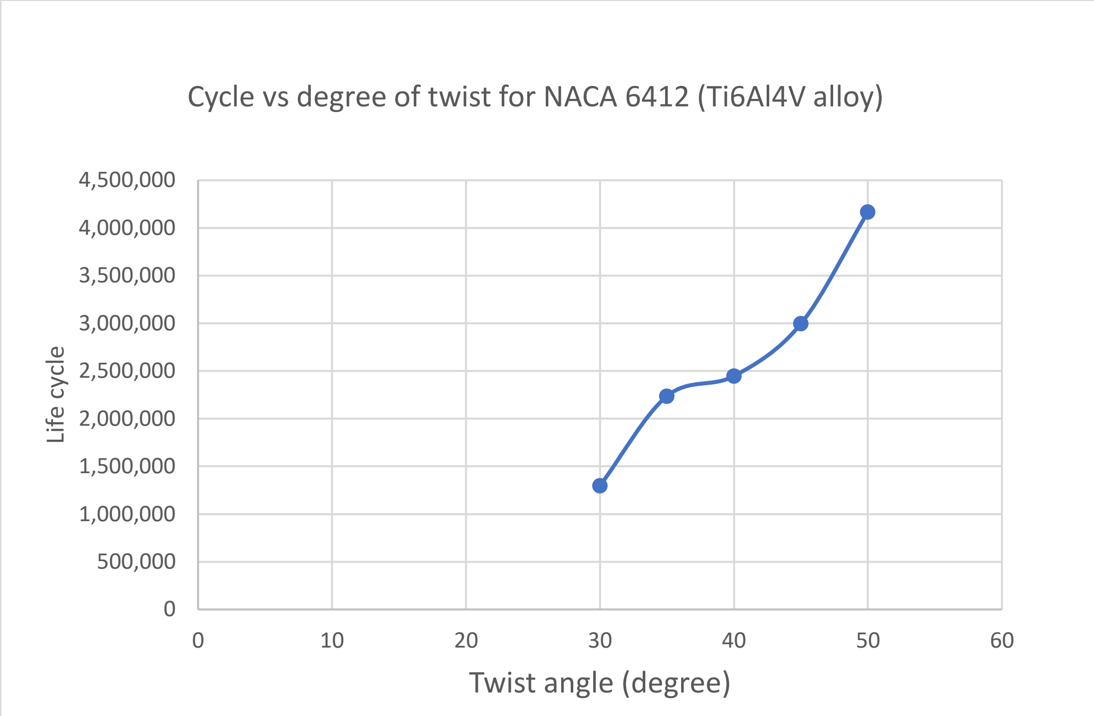

Figure 3.17 cycle vs degree of twist for NACA 6412 (Ti6Al4V alloy)

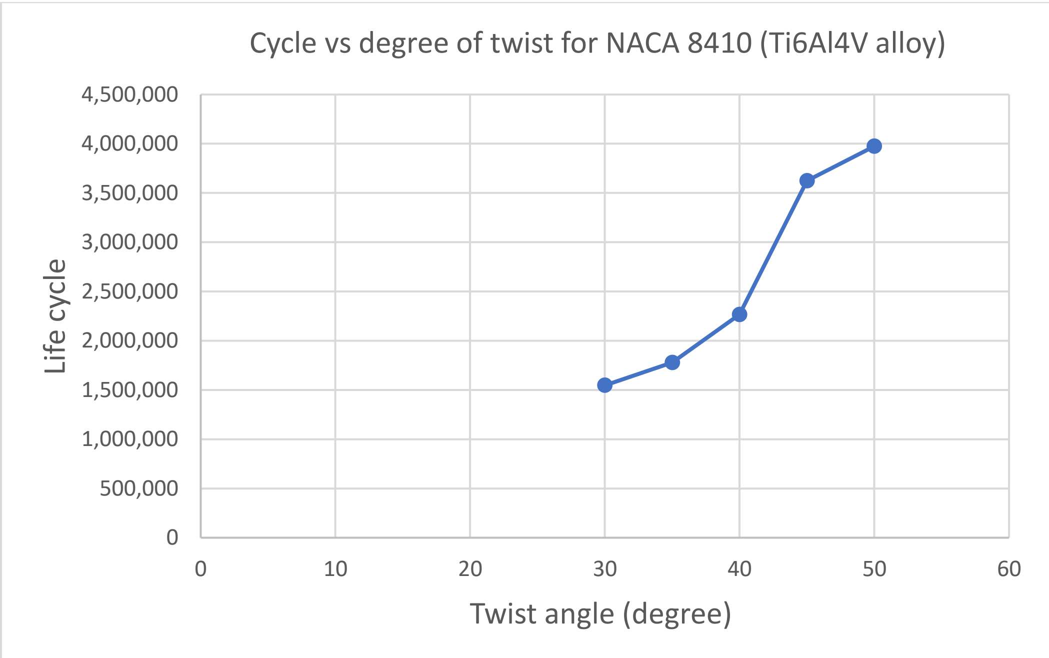

Figure 3.18 cycle vs degree of twist for NACA 8410 (Ti6Al4V alloy)

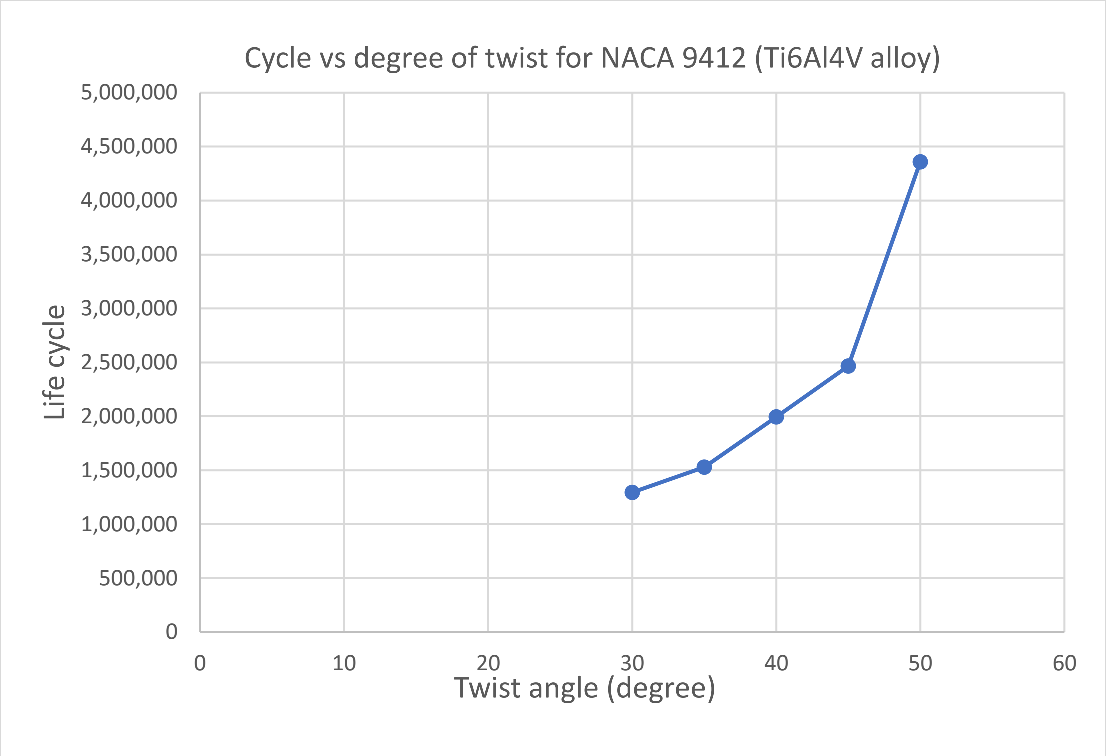

Figure 3.19 cycle vs degree of twist for NACA 8410 (Ti6Al4V alloy)

But as Ti6Al4V is very hard to manage and it could not be found. Therefore, the simulation was done for structural steel also. The validation will be done using structural steel.

Table 3.11 Degree of twist vs Life Cycle for NACA 4412 (Structural Steel)

Degree of twist	Life cycle
30	1153
35	1098
40	1071
45	1069
50	1006.8

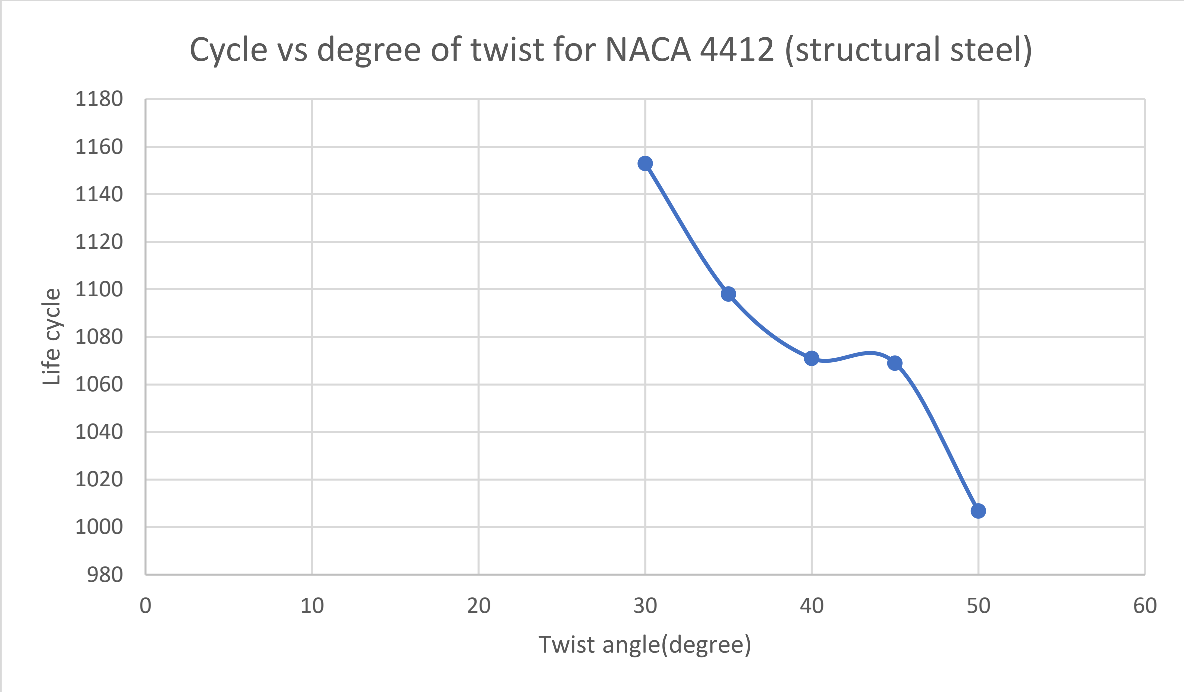

Figure 3.20 cycle vs degree of twist for NACA 4412 (structural steel)

The graph above (figure 3.20) is seemed to be trending downward which means if the twist angle is increased, the life cycle decreases. Therefore, the life cycle vs twist angle graph is showing completely different behavior than the graph shown in figure 3.15-19. The parameter which was changed is blade material. The material was changed to structural steel from titanium alloy. The change which is observed in the graph of 3.20 from the graphs of 3.15-19 are because of different S-N curve data and different properties of structural steel. So, it can be said that fatigue life depends on material characteristics also.

Chapter 4

4.1 DISCUSSION

It can be said that the natural frequency depends on the geometry and body shape of an object. The first and second mode's natural frequency decreases with the increasing twist angle. The third mode natural frequency gives an interesting result. From 30° to 35°, the natural frequency decreases but after that it increases. So, we can say varying the degree of twist can give different mode shape and different trend in natural frequency. In the fourth, fifth and sixth mode natural frequency increases with twist angle from 30° to 35°.

So, mode shapes and natural frequency varies with blade profiles, twist angle and materials also.

In fatigue analysis, for the structural steel the fatigue life decreases with twist angle. But for Ti6Al4V alloy it increases. So, it can be said that the fatigue life is deeply connected with materials we choose. It was seen that, for structural steel the trend of the graph was downward; which means with the increase of twist angle from 30° to 50° the fatigue life is decreased. But for Ti6Al4V it was the opposite.

For Ti6Al4V the area where failure is most likely to appear is near the fixed support end of the blade and at a place where blade thickness is comparatively more.

In the case of structural steel, the area where failure can occur is more. As fatigue endurance of structural steel are much lower than the Ti6Al4V alloy. The area where failure will happen first is both near the fixed end and thicker side of the blade; also, at the edge of the thinner side of the blade.

4.2 CONCLUSIONS

- The natural frequency of first and second mode decreases with the increase of degree of twist.
- Third mode's natural frequency decreases at first then it increases.
- Natural frequency of fourth, fifth and sixth mode increases with increase of twist angle.
- The failure most likely to happen near the fixed support and thicker side of the blade.
- Failure or fatigue is deeply connected to the materials used. The trend of life cycle vs twist angle graph is totally different for structural steel and Ti6Al4V. We can see, two different materials give totally different types of result.
- With different twist angle the fatigue life is changed. For Ti6Al4V alloy the life cycle increases and for structural steel is decreases.
- Life cycle increase is very high when the twist angle is changed from 45^0 to 50^0
- For same material, similar trend was obtained for all the selected NACA profile we worked with. So, the fatigue life is dominated more by twist angle than blade profile.

4.3 FUTURE SCOPE

Ti6Al4V is pretty new titanium alloy which has very high mechanical properties which makes it a very expensive material. Thus, managing this material and doing experimental work with this alloy was not possible. Therefore, validation of this thesis work need to be carried out with a blade made with structural steel or Aluminum alloy which are comparatively cheap and available. CNC machining could be utilized for making the blade. The experiment can be carried out in the lab for validation.

The number of parameters in NACA 4 series parameter is three: namely Camber, Camber thickness and thickness. Since three variable defines the profile, the effect of profile on natural frequencies and life cycle of blade can be found out by varying one parameter of profile and holding other two parameters constant. For this, simulation need to be carried out using at least $5 \times 5 \times 5 = 125$ profiles. Moreover, 125 profiles coupled with five angle of twist parameter will result in total $125 \times 5 = 625$ simulations. The codes for automating the simulations are written and listed in Appendix. But due to the lack of computing power, the simulations couldn't be completed. So, analysis was done mainly focusing the angle of twist. The work can be completed with the help of a high configuration PC.

4.4 REFERENCES

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4.5 APPENDIX

4.5.1 Python code for generating ANSYS Workbench automation script.

```python
"""
Created on Fri June  11 23:19:28 2021

@author: Shihabus Sakib Rad

This is code for generating ANSYS Workbench Automation script
"""
def main():
    thicknesses = ["12", "14", "16", "18", "20"]
    cambers = ['24', '44', '64', '84']
    angles = ['5', '10', '15', '20', '25']

    names: list[str] = []

    for camber in cambers:
        for thickness in thicknesses:
            for angle in angles:
                name: str = camber+thickness + "_" + angle
                names.append(name)

    last: str = '8414_15'
    last_index = names.index(last)
    remaining_names: list[str] = names[last_index + 1:]
    i: int = last_index - 1

    for name in remaining_names:
        txt = f"""
system1 = GetSystem(Name="Static Structural (ANSYS) {i}")
system2 = GetSystem(Name="Modal (ANSYS) {i}")
CopySystems(
Systems=[system1, system2],
KeepConnections=True)
system3 = GetSystem(Name="Modal (ANSYS) {i+1}")
system4 = GetSystem(Name="Static Structural (ANSYS) {i+1}")
system3.DisplayText = "{name}"
system4.DisplayText = "{name}"
geometry1 = system3.GetContainer(ComponentName="Geometry")
geometry1.SetFile(FilePath="G:/Thesis/cad3/{name}.SLDPRT")
modelComponent1 = system3.GetComponent(Name="Model")
modelComponent1.Update(AllDependencies=True)"""
        print(txt)
        i = i + 1


if __name__ == '__main__':
    main()
```

4.5.2 Python code for generating NACA Profiles

```
"""
Created on Fri June  11 23:19:28 2021

@author: Shihabus Sakib Rad

This is code for generating NACA profiles and saving coordinated on txt
file
"""


import numpy as np
from math import cos, sin, pi, sqrt, atan

def linspace(start, stop, np):
    return [start + (stop - start) * i / (np - 1) for i in range(np)]


def NACA4(number, n, finite_TE=True, half_cosine_spacing=False, a4=-0.08):

    m = float(number[0]) / 100.0
    p = float(number[1]) / 10.0
    t = float(number[2:]) / 100.0

    a0 = +0.2969
    a1 = -0.1260
    a2 = -0.3516
    a3 = +0.2843

    if half_cosine_spacing:
        beta = linspace(0.0, pi, n + 1)
        x = [(0.5 * (1.0 - cos(xx))) for xx in beta]
    else:
        x = linspace(0.0, 1.0, n + 1)

    yt = [5 * t * (a0 * sqrt(xx) + a1 * xx + a2 * pow(xx, 2) + a3 * pow(xx,
3) + a4 * pow(xx, 4)) for xx in x]

    xc1 = [xx for xx in x if xx <= p]
    xc2 = [xx for xx in x if xx > p]

    if p == 0:
        xu = x
        yu = yt

        xl = x
        yl = [-xx for xx in yt]

        xc = xc1 + xc2
        zc = [0] * len(xc)
    else:
        yc1 = [m / pow(p, 2) * xx * (2 * p - xx) for xx in xc1]
        yc2 = [m / pow(1 - p, 2) * (1 - 2 * p + xx) * (1 - xx) for xx in
xc2]
        zc = yc1 + yc2

        dyc1_dx = [m / pow(p, 2) * (2 * p - 2 * xx) for xx in xc1]
        dyc2_dx = [m / pow(1 - p, 2) * (2 * p - 2 * xx) for xx in xc2]
        dyc_dx = dyc1_dx + dyc2_dx

        theta = [atan(xx) for xx in dyc_dx]
```

```python
        xu = [xx - yy * sin(zz) for xx, yy, zz in zip(x, yt, theta)]
        yu = [xx + yy * cos(zz) for xx, yy, zz in zip(zc, yt, theta)]

        xl = [xx + yy * sin(zz) for xx, yy, zz in zip(x, yt, theta)]
        yl = [xx - yy * cos(zz) for xx, yy, zz in zip(zc, yt, theta)]

    X = xu[::-1] + xl[1:]
    Z = yu[::-1] + yl[1:]

    return X, Z


def scaled(ls: list, scale=40):
    ls_new = [i * scale for i in ls]
    return ls_new


def main():
    thicknesses = ["12", "14", "16", "18", "20"]
    cambers = ['24', '44', '64', '84']

    for camber in cambers:
        for thickness in thicknesses:
            profile: str = camber + thickness
            filename: str = "profiles3/" + profile + '.txt'
            print(filename)
            X, Y = NACA4(profile, 300, True, False)
            Z = [0] * len(X)
            X = scaled(X)
            Y = scaled(Y)

            np.savetxt(filename, np.column_stack((X, Y, Z)), fmt="%.2f")


if __name__ == '__main__':
    main()
```

4.5.3 Visual Basic Code for Generating CAD Models

```
' Created on Fri June  17 20:02:25 2021
' This is code for generating SolidWorks model with the help of SolidWorks API

Imports SolidWorks.Interop.sldworks
Imports SolidWorks.Interop.swconst
Imports System.Runtime.InteropServices
Imports System


Partial Class SolidWorksMacro
    Public Sub main()

        Dim FSO As Object = CreateObject("Scripting.FileSystemObject")
        Dim oFile As Object
        Dim oFolder As Object = FSO.GetFolder("G:\Thesis\profiles3")

        For Each oFile In oFolder.Files
            Dim nameParts(2) As String
            nameParts = Split(oFile.Name, ".")
            Dim strNACA As String = nameParts(0)

            Dim lines(3) As String
            Dim strLine As String

            Dim listX As New List(Of Double)
            Dim listY As New List(Of Double)

            Const ForReading = 1
            Dim txtStream = FSO.OpenTextFile(oFile, ForReading, False)

            Do While Not txtStream.AtEndOfStream
                strLine = txtStream.ReadLine
                lines = Split(strLine, " ")

                listX.Add(CDbl(lines(0)) / 1000)
                listY.Add(CDbl(lines(1)) / 1000)
            Loop
            txtStream.Close

            Dim angles() As Integer = {5, 10, 15, 20, 25} '20, 25, 30, 35, 40

            For Each angle In angles
                Dim angle_rad As Double = angle * (3.1416 / 180)
                Dim angles_str As String = CStr(angle)
                Dim strPart As String = strNACA & "_" & angles_str

                'New
                Dim swDoc As ModelDoc2 = Nothing
                Dim swPart As PartDoc = Nothing
                Dim swDrawing As DrawingDoc = Nothing
                Dim swAssembly As AssemblyDoc = Nothing
                Dim boolstatus As Boolean = False
                Dim longstatus As Integer = 0
                Dim longwarnings As Integer = 0
                '
                'New Document
                Dim swSheetWidth As Double
                swSheetWidth = 0
                Dim swSheetHeight As Double
                swSheetHeight = 0
```

```
                swDoc = CType(swApp.NewDocument("C:\ProgramData\SolidWorks\SOLIDWORKS
2021\templates\Part.prtdot", 0, swSheetWidth, swSheetHeight), ModelDoc2)
                swPart = swDoc

                swApp.ActivateDoc2(strPart, False, longstatus)
                swDoc = CType(swApp.ActiveDoc, ModelDoc2)

                Dim myModelView As ModelView = Nothing
                myModelView = CType(swDoc.ActiveView, ModelView)
                myModelView.FrameState = CType(swWindowState_e.swWindowMaximized,
Integer)

                swDoc.InsertCurveFileBegin()
                Dim i As Integer = 0
                Do Until i = listX.Count
                    boolstatus = swDoc.InsertCurveFilePoint(listX(i), listY(i), 0)
                    i = i + 1
                Loop
                boolstatus = swDoc.InsertCurveFileEnd()

                boolstatus = swDoc.Extension.SelectByID2("Front Plane", "PLANE", 0, 0,
0, False, 0, Nothing, 0)

                swDoc.SketchManager.InsertSketch(True)
                boolstatus = swDoc.Extension.SelectByID2("Curve1", "REFERENCECURVES",
0, 0, 0, False, 0, Nothing, 0)

                boolstatus = swDoc.SketchManager.SketchUseEdge3(False, False)
                swDoc.ClearSelection2(True)
                boolstatus = swDoc.Extension.SelectByID2("Curve1", "REFERENCECURVES",
0, 0, 0, False, 0, Nothing, 0)
                swDoc.BlankRefGeom()

                Dim skSegment As SketchSegment = Nothing
                skSegment = CType(swDoc.SketchManager.CreateLine(listX(0), listY(0),
0R, listX(listX.Count - 1), listY(listY.Count - 1), 0R), SketchSegment)

                swDoc.ClearSelection2(True)
                swDoc.SketchManager.InsertSketch(True)
                boolstatus = swDoc.Extension.SelectByID2("Sketch1", "SKETCH", 0, 0, 0,
False, 0, Nothing, 0)
                swDoc.EditCopy()
                boolstatus = swDoc.Extension.SelectByID2("Front Plane", "PLANE", 0, 0,
0, True, 0, Nothing, 0)

                Dim myRefPlane As RefPlane = Nothing
                myRefPlane = CType(swDoc.FeatureManager.InsertRefPlane(8, 0.08R, 0, 0,
0, 0), RefPlane)

                swDoc.ClearSelection2(True)
                boolstatus = swDoc.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0,
False, 0, Nothing, 0)
                swDoc.Paste()
                swDoc.ClearSelection2(True)

                boolstatus = swDoc.Extension.SelectByID2("Sketch2", "SKETCH", 0, 0, 0,
False, 0, Nothing, 0)

                swDoc.EditSketch()
                swDoc.ClearSelection2(True)
                boolstatus = swDoc.Extension.SelectByID2("Spline2", "SKETCHSEGMENT",
0.0045651717400194448R, -0.0026023751976361961R, 0, True, 0, Nothing, 0)
```

```
                boolstatus = swDoc.Extension.SelectByID2("Line1", "SKETCHSEGMENT", 
0.040019753576464728R, 0.000066985210899258435R, 0, True, 0, Nothing, 0)
                swDoc.Extension.RotateOrCopy(False, 1, False, 0, 0, 0, 0, 0, 1, 
angle_rad)
                swDoc.Extension.RotateOrCopy(False, 1, False, 0, 0, 0, 0, 0, 1, 
angle_rad)
                swDoc.ClearSelection2(True)

                swDoc.SketchManager.InsertSketch(True)
                boolstatus = swDoc.Extension.SelectByID2("Sketch1", "SKETCH", 0, 0, 0, 
True, 0, Nothing, 0)
                boolstatus = swDoc.Extension.SelectByID2("Sketch2", "SKETCH", 0, 0, 0, 
True, 0, Nothing, 0)

                swDoc.ClearSelection2(True)

                boolstatus = swDoc.Extension.SelectByID2("Sketch1", "SKETCH", 
0.039880000000000006R, -0.00093999999999999932R, 0, False, 1, Nothing, 0)
                boolstatus = swDoc.Extension.SelectByID2("Sketch2", "SKETCH", 
0.037796440651668144R, 0.012756452252288945R, 0.08R, True, 1, Nothing, 0)
                swDoc.FeatureManager.InsertProtrusionBlend(False, True, False, 1, 0, 
0, 1, 1, True, True, False, 0, 0, 0, True, True, True)
                boolstatus = swDoc.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 
0, False, 0, Nothing, 0)
                swDoc.SketchManager.InsertSketch(True)
                '

                'Named View
                swDoc.ShowNamedView2("*Bottom", 6)
                swDoc.ViewZoomtofit2()
                swDoc.ClearSelection2(True)
                skSegment = CType(swDoc.SketchManager.CreateCenterLine(0.046687R, 0R, 
0R, -0.046687R, 0R, 0R), SketchSegment)
                swDoc.SetPickMode()
                swDoc.ClearSelection2(True)
                skSegment = CType(swDoc.SketchManager.CreateLine(0.002R, 0R, 0R, 
0.002R, -0.08R, 0R), SketchSegment)
                swDoc.SetPickMode()
                swDoc.ClearSelection2(True)

                boolstatus = swDoc.Extension.SelectByID2("Sketch3", "SKETCH", 0, 0, 0, 
False, 4, Nothing, 0)
                boolstatus = swDoc.Extension.SelectByRay(0.019421911238934275R, 
0.0015045585109305648R, 0.041486667071243169R, 0, 1, 0, 0.00060099374580722R, 2, True, 
1, 0)

                swDoc.InsertSplitLineProject(False, False)
                boolstatus = swDoc.Extension.SelectByRay(0.017123993975553725R, 
0.00085224211954937346R, 0.040602852739173731R, 0, 1, 0, 0.00060099374580722R, 2, 
False, 0, 0)

                boolstatus = swDoc.Extension.SelectByRay(0.017123993975553725R, 
0.00085224211954937346R, 0.040602852739173731R, 0, 1, 0, 0.00060099374580722R, 2, 
False, 0, 0)

                boolstatus = swDoc.SelectedFaceProperties(0, 0, 0, 0, 0, 0, 0, True, 
"NS_force")

                '
                'Named View
                swDoc.ShowNamedView2("*Back", 2)
                swDoc.ViewZoomtofit2()
```

```
                boolstatus = swDoc.Extension.SelectByRay(0.0050449280244487813R,
0.0011040455159305753R, 0, 0, 0, 1, 0.00025786729005488251R, 2, False, 0, 0)
                boolstatus = swDoc.Extension.SelectByRay(0.0050449280244487813R,
0.0011040455159305753R, 0, 0, 0, 1, 0.00025786729005488251R, 2, False, 0, 0)
                boolstatus = swDoc.SelectedFaceProperties(0, 0, 0, 0, 0, 0, 0, True,
"NS_fix")
                '
                'Save As
                longstatus = swDoc.SaveAs3("G:\Thesis\cad3\" & strPart & ".SLDPRT", 0,
0)
                swDoc.ClearSelection2(True)
                '
                'Close Document
                swPart = Nothing
                swDoc = Nothing
                swApp.CloseDoc(strPart & ".SLDPRT")
            Next angle
        Next oFile


    End Sub

    Public swApp As SldWorks
End Class
```

4.5.4 Graphs of results of Modal Analysis for NACA 6412

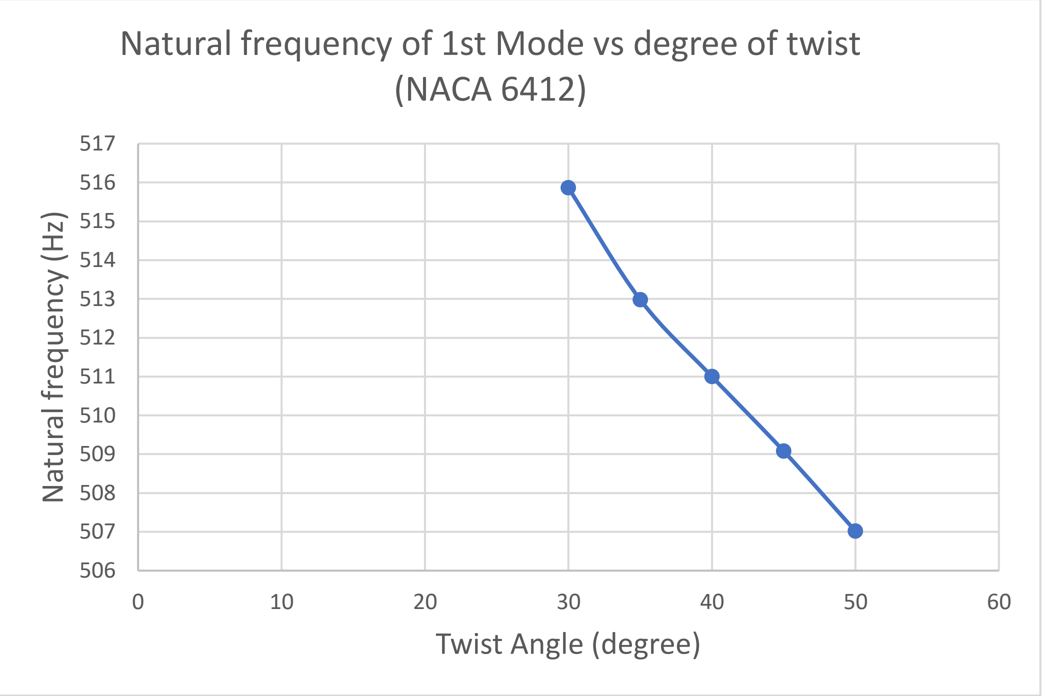

Figure 4.1 Natural frequency of 1st Mode vs degree of twist (NACA 6412)

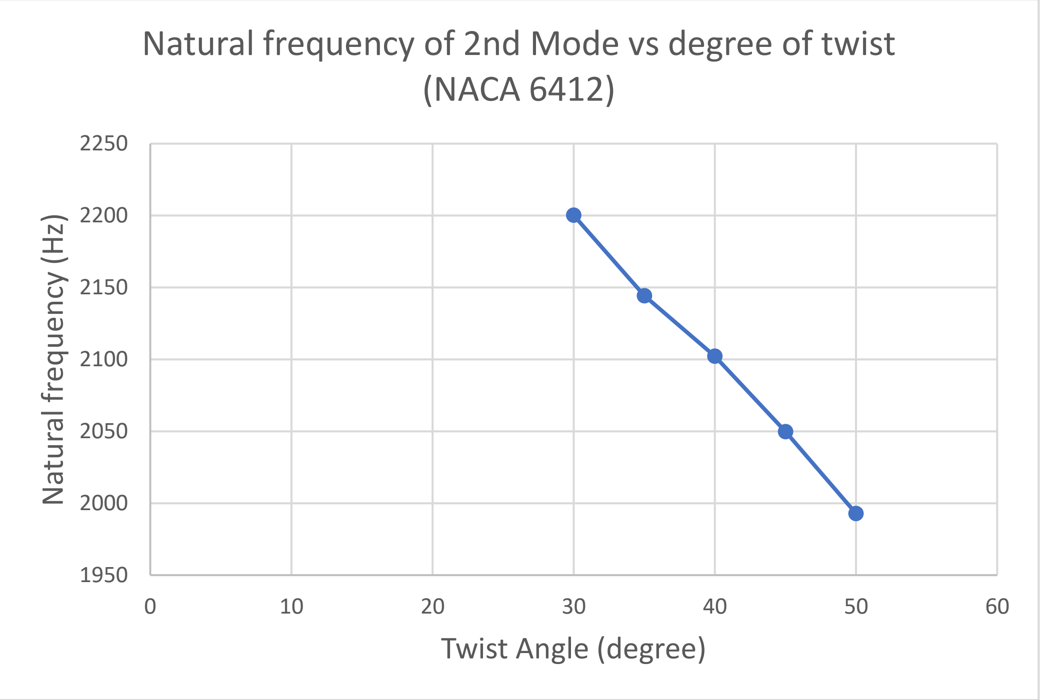

Figure 4.2 Natural frequency of 2nd Mode vs degree of twist (NACA 6412)

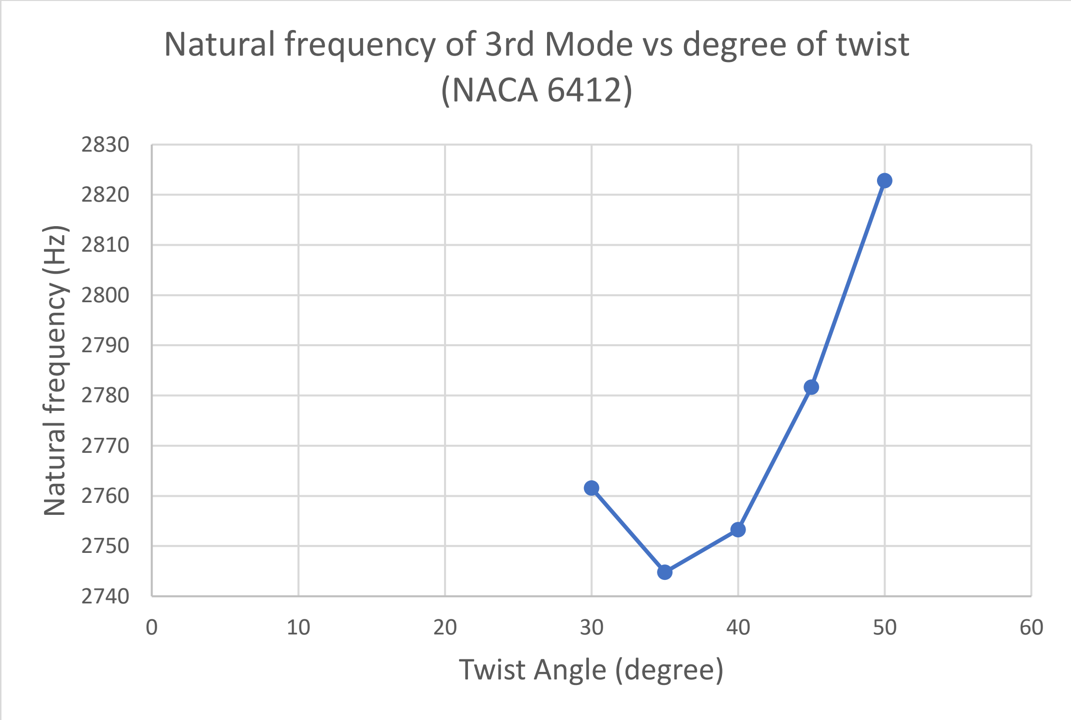

Figure 4.3 Natural frequency of 3rd Mode vs degree of twist (NACA 6412)

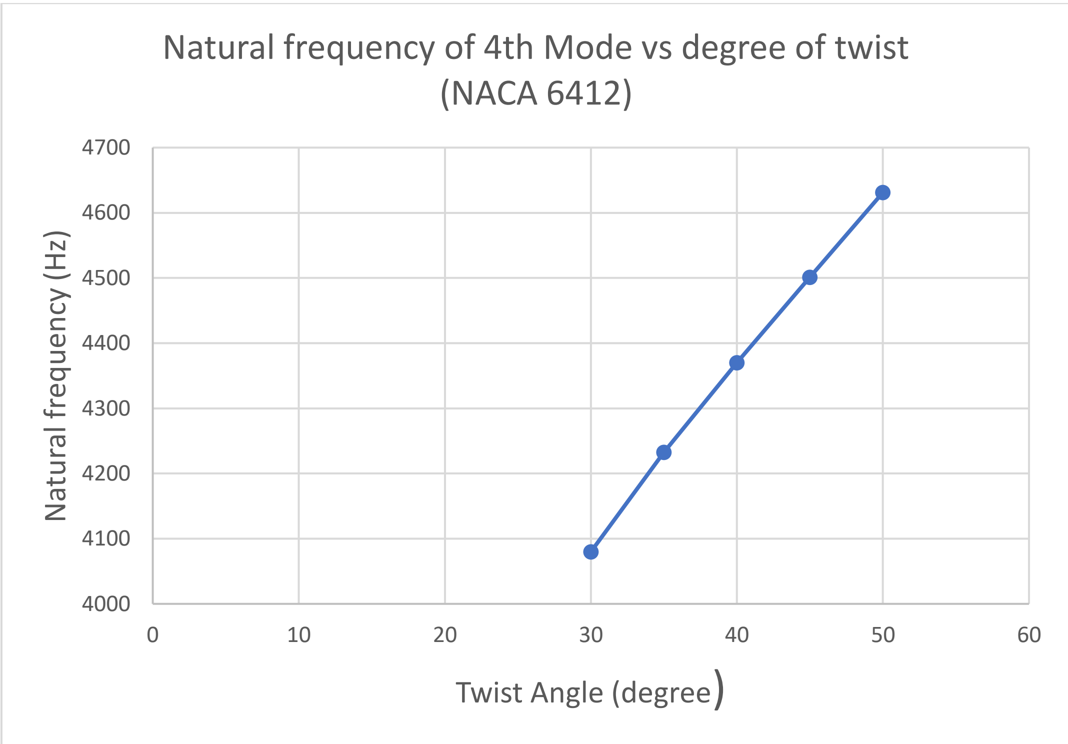

Figure 4.4 Natural frequency of 4th Mode vs degree of twist (NACA 6412)

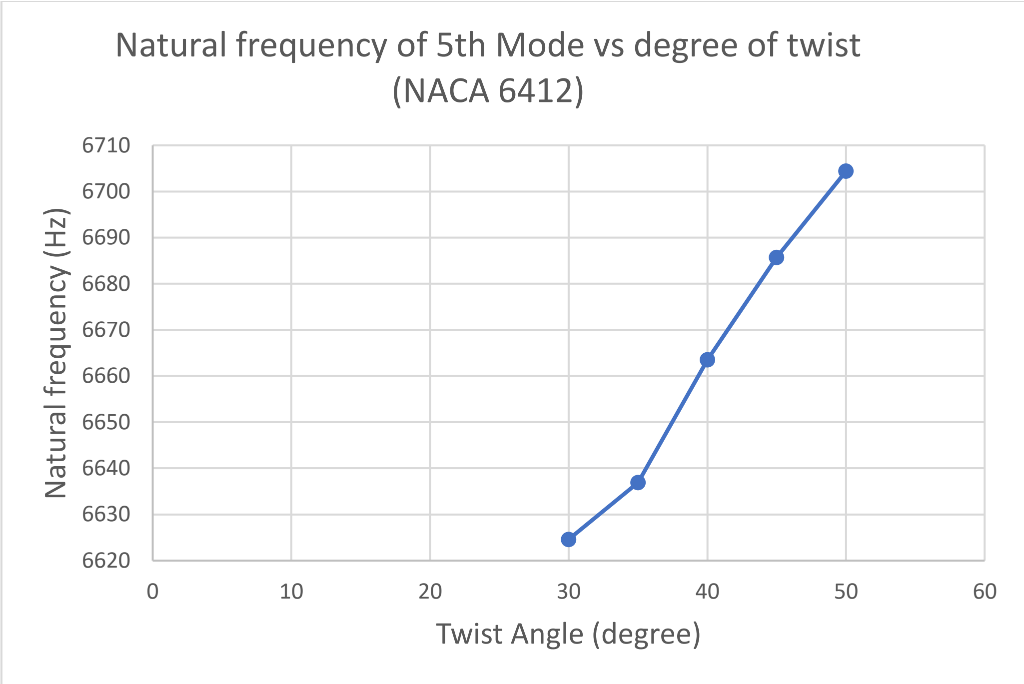

Figure 4.5 Natural frequency of 5th Mode vs degree of twist (NACA 6412)

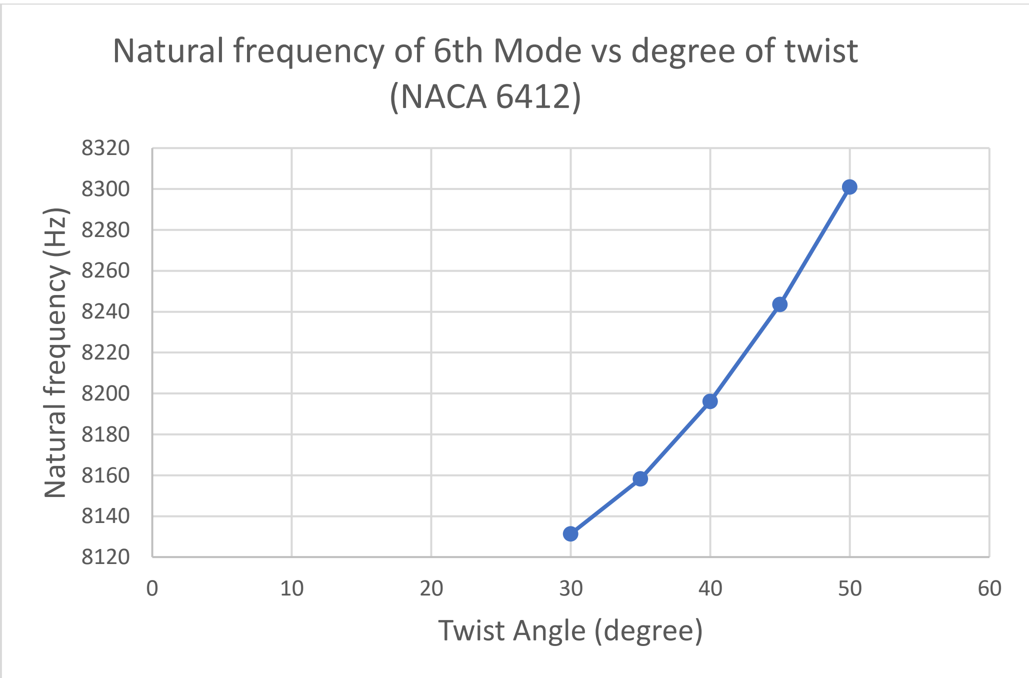

Figure 4.6 Natural frequency of 6th Mode vs degree of twist (NACA 6412)