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Research Article

Effect Stress and Vibration Analysis at NACA Airfoil towards Axial Fan Blade Performance

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Abstract

Axial fans are widely applied in the industrial sector. Axial fans are used for ventilation systems and other cooling systems. The blade design of the axial fan requires an airfoil study. Unfortunately, there are not many articles that discuss in detail about airfoils, especially on noise and vibration that can have an impact on axial fan performance using computational fluid methods or software. This study performs axial fan analysis using computational methods with ANSYS Fluent, Static Structural, Modal and Harmonic Response software to obtain the values of stress, vibration and fluid flow. The experimental design used is using NACA 1412, 4142, and 6412 airfoils on the tip with variations in angles of 60, 74, and 80. While on the hub uses NACA 9312, 9412, and 9512 airfoils with angle variations of 20, 30, and 60 and simulated to find the value of vibration and stress analysis. The 3D axial fan design is imported into the ANSYS Fluent, Static Structural, Modal and Harmonic Response software. The simulation results using Ansys Fluent, shows the pressure contour with a maximum value of 198.424 Pa and Velocity streamline with a maximum value of 28.8669 m/s. the results of the Ansys Static Structural simulation show that the average total deformation is 9.9275e-008 m. The simulation results using Ansys Modal, show that there is a natural frequency of 287.8 Hz and the simulation results of Ansys Harmonic Response obtained an average total deformation of 5.0809e-012 m and the equivalent stress value with a maximum value of $\sigma_{y,\,max}$ *= 0.20186 Pa.*

Keywords : *airfoil, axial fan, NACA, Ansys Fluent, Static Structural, Harmonic Response.*

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INTRODUCTION

Axial fan is defined as a fluid engine with the function to increase pressure and volume of flow rate. Axial fans are widely applied in the industrial sector, for example, HVAC (Heating, Ventilating and Air Conditioning), computers, automobiles, machineries, and electronics applications. The types of axial fans are considered to the intended use and the space provided for installation. Due to the variety of different requirements, the design of the axial fan becomes very important to meet the intended use. There are several methods to determine the initial design or preliminary design aimed to get better efficiency, rpm, high volume flow rate, and low pressure. The focus of this research is to minimize of vibration before fabrication process, This reduction has affect for comfort, safety, and health workers [1]

This research is a continue the study of Hanif [2] about the effect of variations in angle of attack and the shape of the 4-digit NACA airfoil on the axial fan. From previous research, only observing the pattern of air flow velocity, velocity streamline, and pressure that affect vibration using ANSYS Fluent software. The noise and vibration generated by the blades are not noticed due to the turbulent flowrate that occured. Laminar flow rates are often formed due to the wrong airfoil design and angle of attack setting. One indicate of better efficiency and reduce noise is the axial fan use small amount of blade and larger blade area. However, if the blade design has a surface that is too wide, the fan rotation is decreasing because the load received by the shaft is greate. The methods that can be used for preliminary design are divided into two, namely traditional methods and modern methods. The traditional method used for preliminary design is no longer used. Generally designers have to try one by one design and size. The method has effect in time and cost effectiveness compared to using modern methods. The modern methods used for preliminary design are subdivided into other methods. Some of the modern methods used are, Multi-Objective Optimization, 3D Inverse Design Method.

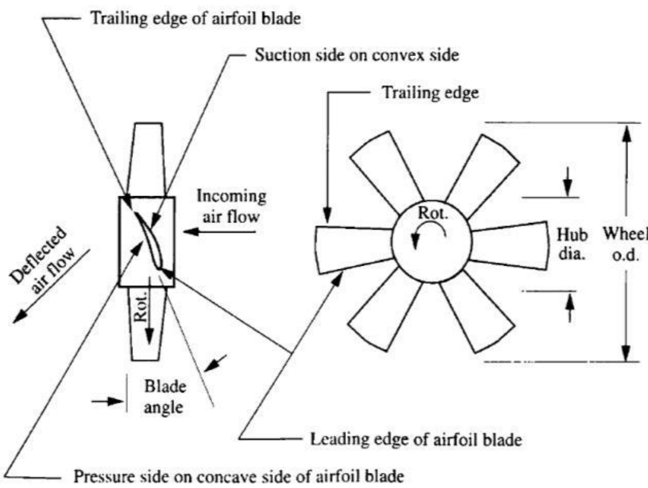


Figure 1 Axial fan dimension parameter [3]

There are three types of fans based on the direction of air flow used for ventilation systems used in industry, namely axial fans, centrifugal fans, and radial fans. The are many applications of axial fan such as, HVAC, computers, automobiles, machineries, and electronics applications. Axial fan is a tool that used to alter the amount of the volume and pressure of air in the ventilation system with one-way airflow. The selection of blade types and axial fan dimensions is adjusted to the conditions and purposes of use in the field. Centrifugal fans and axial fans have differences in terms of construction. The blade on the axial fan is directly connected to the hub as showed in figure 1.

Axial fans have limited use in certain work locations, because the blades on the axial fan can experience stall conditions. The stall condition is a condition where the flow is experiences the separation, this occurs when the boundary layer that is flowing over the top surface of the wing is released and becomes turbulent flow.

Because of the stall condition, the axial fan is classified as a fan with unstable working conditions. This can cause the axial fan to produce lower noise, flowrate, and efficiency. However, the stall can be overcome by the angle of attack on the blade and choosing the right type of airfoil. The angle of attack is defined as angle between the chord line and relative the incoming flow. When the fluid flowing through the airfoil, an aerodynamic force are generated i.e. lift force and drag force. The lift produced by an air foil is the total force produced perpendicular to the wind. The drag caused by an air foil is the net force produced parallel to the wind. The aerodynamic forces generation in the airfoil as shows in Figure 2.

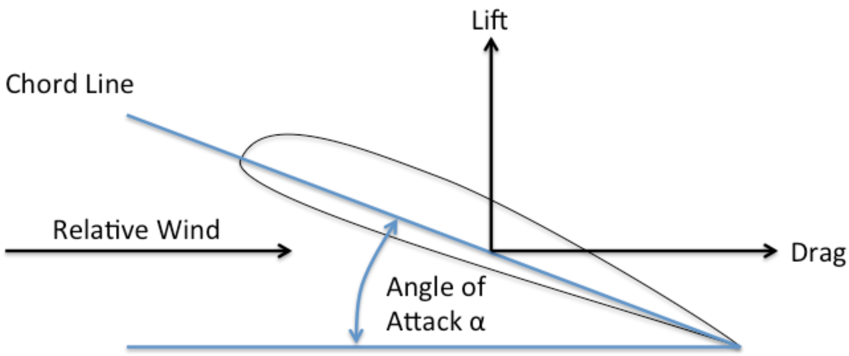


Figure 2 Angle of attack cause lift [4]

Axial fans have different characteristics as showed in figure 3, these differences are followed by differences in pressure, volume of air produced, noise, power required, and efficiency. The characteristics of the axial fan can be shown by the following characteristic curve:

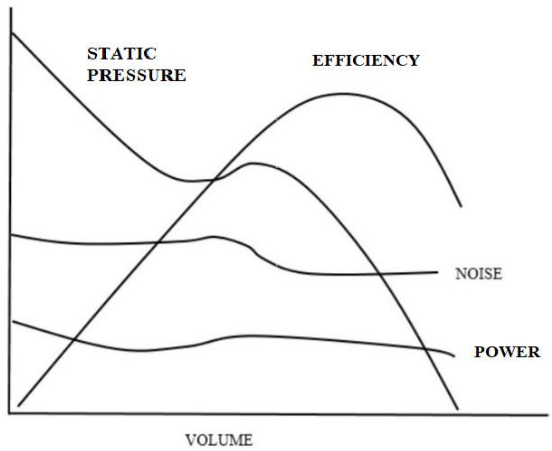


Figure 3 Characteristic curve axial fan (5)

The characteristic curve shows that the static pressure will decrease if the flowrate increases, the efficiency of the axial fan will reach its maximum point at a certain flowrate, the higher the flowrate, the higher the noise and power required to rotate the axial fan. Tanjung, A. S [5] claimed that higher angle of attack on the axial fan blade produced the lower efficiency. At angle of attack 30°, the efficiency is 25% - 30%, meanwhile at the angle of attack 60° the efficiency value drops to 6% - 10%. This due to the backflow appearances on the blade surface. This study did not pay attention to the effect of turbulent flow.
Bernoulli's law is a principle of fluid flow which explains the equation that the fluid in the same container will have the same energy value even though the container has a different area. Bernoulli's law is used to determine the magnitude of the velocity and pressure of a fluid flowing in different positions. The process that occurs in Bernoulli's law and the effect on the flow of air flowing in the axial fan will be explained in the following figure 4.

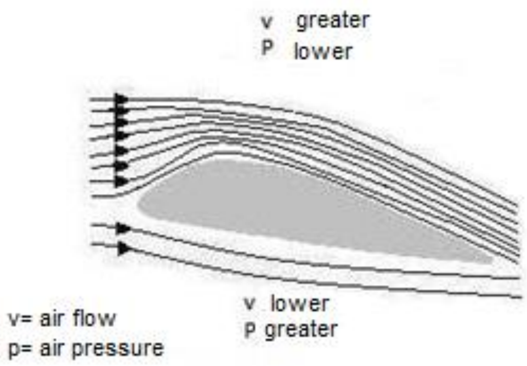


Figure 4 Bernoulli’s Law for air foils [6]

Vibration is movement back and forth in a certain time interval. Vibration is related to the oscillating motion of objects and the forces associated with that motion. Vibration that occurs in the turbine engine can be caused by fan unbalance, either in the form of static unbalance, mass moment unbalance, or aerodynamic unbalance. If the vibration problem is not addressed immediately, it can cause unwanted things, namely damage on the fan blade itself, which among other things allows the fan blade to break fatigue due to continuous vibration. In addition it can damage other components. Vibration can be classified according to the presence or absence of excitation that works continuously, according to the degree of freedom or the mass system. According to the first classification, vibrations are distinguished as free vibrations or forced vibrations. It is called a forced vibration if in the vibration system there is a periodic excitation force that acts continuously as a function of time. In a free vibration system, vibration occurs because of a momentary excitation such as an impulsive force or an initial deviation. According to the degrees of freedom, vibrations can be distinguished as vibrations of one, two, or n degrees according to the number of independent coordinates needed to define in the motion equation of the system [7]

Another research about axial fan was conducted by Kim et al., [8] Conducted a study. They concluded that optimizing fan performance requires eight most important factors, namely stagger angle, mid-span of the blade angle, air foils at tip agle, hub tip ratio, hub cap installation distance, and Hub cap ratio and stagger angle at the mid-span and tip. This study analyzes the impact of the installation of the hub cap and the installation distance on the blade. However, this study did not pay attention to the effect of turbulent flow which can cause noise and vibration on the trailing edge.

Izadi & Falahat, [9] analyzed the flow rate on the axial fan with a hub diameter ratio variation of 0.2 – 0.4, the number of blades 2 – 6, the blade angle setting 30° - 70°. The results of this study concluded that the axial fan design has a maximum flow rate at a setting angle of 40° - 50°.

Luo et al., [10] conducted research with increasing focus on energy conservation and noise reduction, both the academic and industrial communities have discussed studies for the development of concepts and technologies for efficient low noise fans. However, the aerodynamic performance and acoustic emission of the axial fan are greatly affected by the unavoidable tip distance. Due to the pressure gradient between the suction side and the blade pressure, tip leakage flow (TLF) and tip leakage vortex (TLV) occur, which can cause several adverse impacts on fan performance, including blockage of the main flow in the section, energy loss, and noise generation. A number of researchers have focused on this flow phenomenon. Researchers used three-dimensional laser Doppler velocimetry (LDV) measurements and numerical solutions to investigate TLF in a forward-swept axial fan and observed that leakage flow appeared in approximately 12% of the axial chord tip downstream of the leading edge (LE) of the blade, which is responsible for to block flow and loss of aerodynamics. Using the Large Eddy Simulation (LES)-based cut cell method, he investigated the TLV in an axial fan and observed that a reduction in tip-clearance size caused a change in the shape of the TLV and led to greater flow separation and counter-rotating vortices in the end gap. Conclusions from this study in axial fans, the first zone with high PSD (Power Spectral Density) can be found at the tip of the blade near the back of the chord, which coincides with the location of the vortex tip and can be attributed to the interaction of the vortex tip with the blade. Another zone of high PSD is in the LE near the top of the blade, which could be attributed to boundary layer separation in the LE due to the thin air foils and interaction of the LE with coherent flow structures in the tip region. In addition, a third zone of high-pressure fluctuation can be found in the TE, which can be attributed to the interaction of TE with TLV and boundary layer instability. In addition, the increased intensity of the blade tip vortex and thus the enhanced interaction with the blade surface are the main drivers of extra wideband noise for greater tip distance.

RESEARCH METHOD

This research was carried out in numerical analysis by using ANSYS software. The method in this research was related to the previous research inluding ANSYS analysis,numer of blades and vibration calculation. For the time of this research was carried out in the 3rd week of January ending in the last week of June.

Research variable

The research variables used are as follows :

a. The 4-digit NACA airfoil is a cross-sectional design of the aircraft wing or blade parallel to the direction of the incoming flow. sequentially 4 digits following the word NACA indicates the percentage of the maximum height of the chord. maximum location of the chamber on the chord, and the maximum percentage of airfoil thickness. 4-digit NACA airfoil variable used in the previous research, two airfoils above the specification and two airfoils below the previous specification.

b. The angle of attack from the blade is the dimension from condition of blade in a stall against the angle of the flow direction.

Experimental design

The experimental design that used in this study is NACA 1412, 4142, and 6412 airfoils on the tip with variations in angles variations of 60°, 74°, and 80°. While on the hub uses NACA 9312, 9412, and 9512 airfoils with angle variations of 20°, 30°, and 60°. This parameter will be simulated to analyze the vibration and stres on the airfoil.

Research object

The objective of this study is the variation of the angle of attack on the blade and replacement of airfoil type. For further information, Figure 5 shows the aranggement of this variation. The object of previous research is taken from research journals that have been done before.

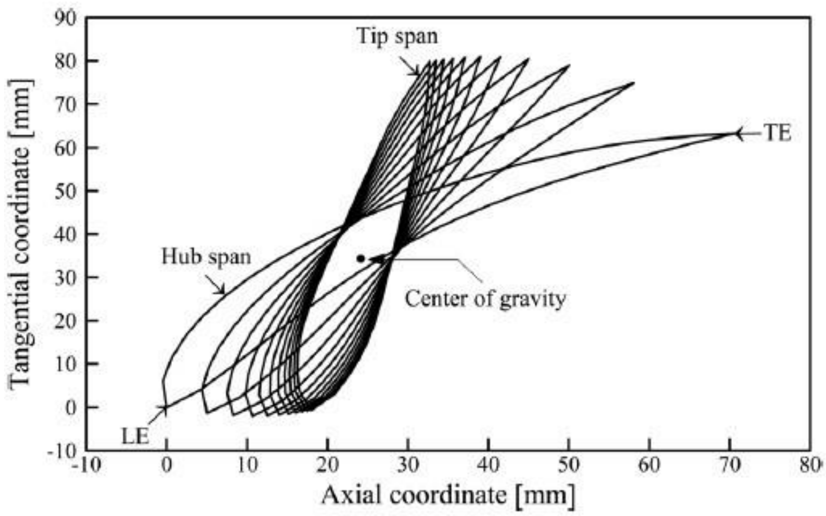


Figure 5 Shape of the airfoil based on altitude [8]

Table 1 Dimensions from NACA

Parameter	Unit
Diameter fan	510 mm
Diameter hub – hub ratio	149.94 mm
Motor RPM	1170 rpm
Shroud diameter	514 mm
Fan Clearance	2 mm
Number of blades	10 blades

The preeliminary aerodynamic blade design of the axial-flow fan (Figure 5), is conducted by using a through-flow modeling technique to successively determine the blade angle distribution, camber line, and airfoil thickness distribution, and finally stack the blade profiles in the spanwise direction. Before creating the preliminary design, however, the four design variables (e.g., tip diameter, hub- to-tip ratio, chord length, number of blades) are decied by setting the design requirements. In this research for the airfoil used on the hub using NACA 9412 and on the mid to tip using NACA 4412. The detail dimensions can be seen in Table 1.

Geometry Model

This research was started with identifying the problem and making a solution. in accordance with the topics raised in this research, namely by adding simulations of vibration values and stress analysis using NACA 1412, 412, and 6412 airfoils on the tip with variations in angles of 60°, 74°, and 80°. While in the hub section using NACA 9312 airfoils, 9412, 9512 with various angles of 20°, 30°, and 60°. This final project is planned through 6 main stages, namely the first stage of initial identification and data collection, the second stage of geometric design, the third stage of analysis on fluent ansys, the fourth stage of analysis on structural ansys, the fifth stage of analysis on the ansys model, and the last stage of analysis on the ansys harmonic.

The axial fan design was modeled by using ANSYS desain modeller software as shown in Figure 6. The modeling aims to get the data and see if the steps in the modeling have been carried out and produce the correct and appropriate data. The design validation modeling is only using airfoil NACA 1412 on the tip and 9312 on the hub while the angle of attack used is 20° on the hub and 80° on the tip.

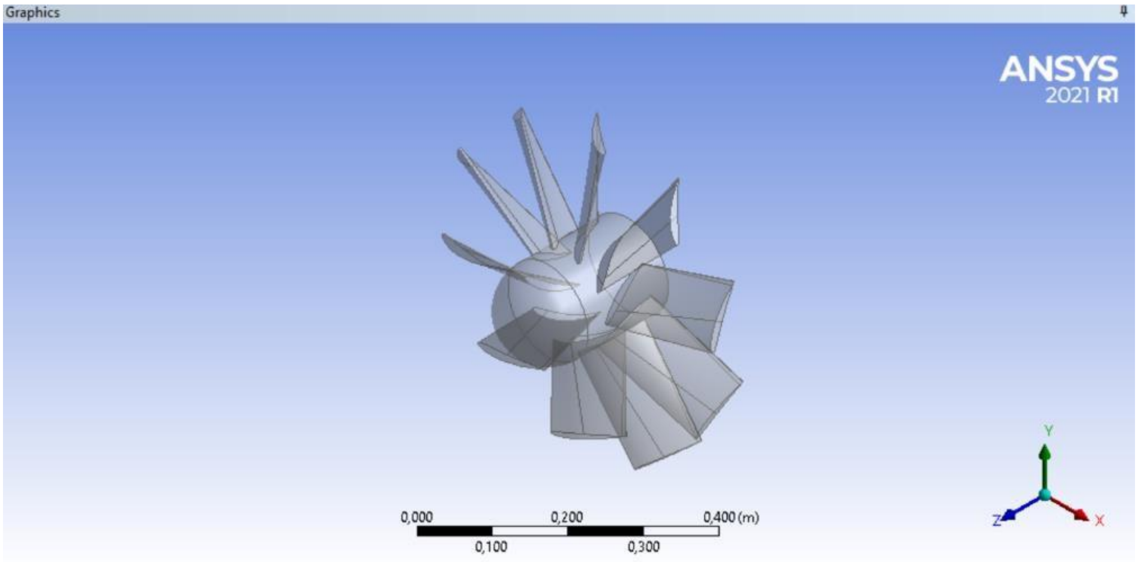


Figure 6 Fan Geometry

Analysis of models from using ANSYS CFX. In general, doing simulation method is divided in three steps. The first step is creating the model with correct scale from the real model. Then, the second step is meshing process which is the model will be devied into many parts the do the mesh processing. In this step, higher skewness of the mesh should be avoided to reach the precise results. The design analysis used is set by the boundary set in the ANSYS CFX setup section. The inlet flow velocity is 4.067 m/s with the output flow is 115 Pa.

Validation will be carried out after design and analyze process. This validation is a comparison of velocity contour from previous reserach that it has low deviation. After doing the modeling on the axial fan, the data from the modeling result is exported to ANSYS structural to analyze the stresses that occur in each blade and airfoil. In this simulation, the workpiece properties use the NACA 1412 airfoil on the tip and the NACA 9312 airfoil on the hub. This is a step that aims to determine the value of the vibration values for each blade variation by simulation using the ANSYS harmonic software.
Figure 7-9 is the axial fan design geometry used as design validation:

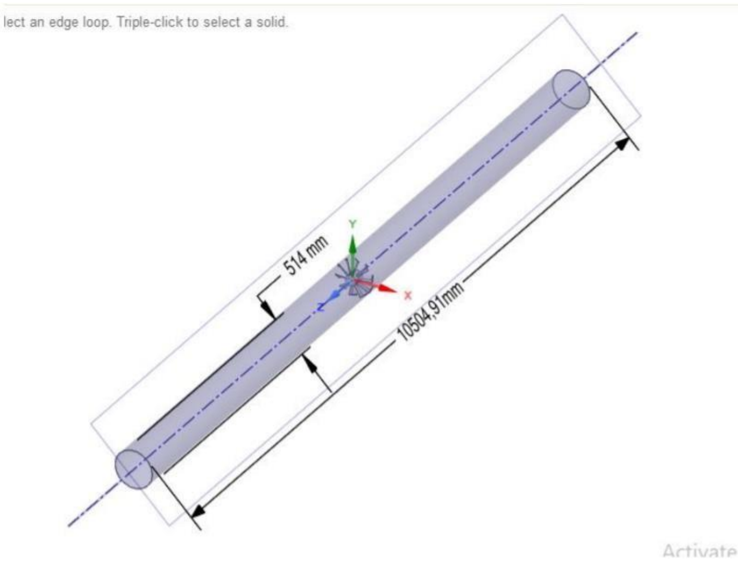


Figure 7 Shroud dimension

Figure 8 Airfoil type and blade angle of attack

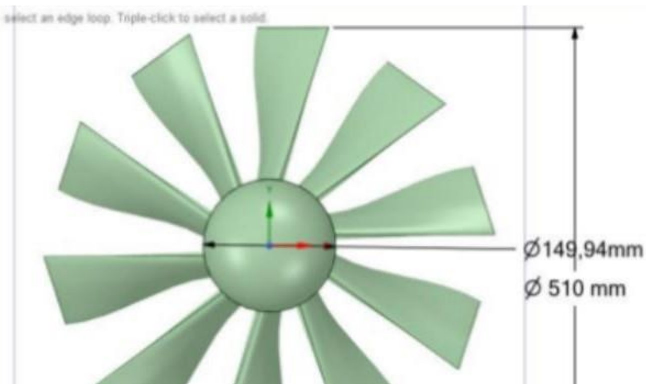


Figure 9 Fan dimensions

Meshing

The meshing generation is the second step after modeling the simulation object. The whole object will be diveded into element izes till 0.1265 m in this case. Changes in element size are required for the details of the meshing density and the details of the velocity contours later. At the next mesh stage using an inflation mesh. Inflation mesh used at the inlet and outlet boundaries. Inflation mesh is used for closer the mesh and the incoming air flow conditions become regular. The maximum layer change is required for the detailed mesh used. The maximum layer change is from 5 layers to 15 layers. The figure

10 is detail hexagonal mesh is the results of 116096 nodes and 62965 elements. Figure 11 is view static structural mesh detal from this research to get desription of detail visualisation post processing after running.

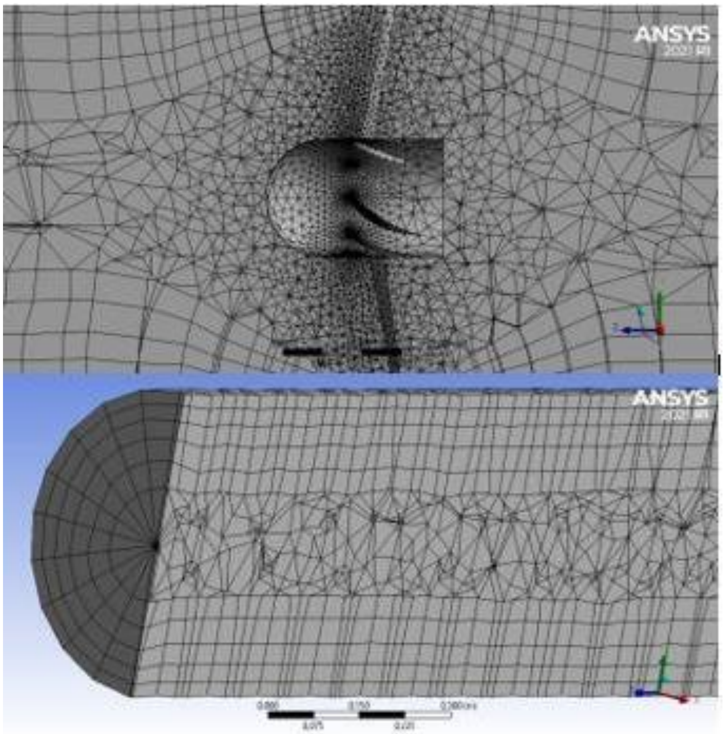


Figure 10 Detail Mesh in Geometry model

RESULTS AND DISCUSSION

The results section makes it easy to find or display any required solutions. In this section, it shows the contour and streamline. The analysis is carried out on the fan that receives pressure and velocity. The results of the simulation can be seen after the process of calculating the Ansys Fluent 2021 R1 software is complete, which is shown in the following figures.

After the geometry of the variation design is formed, the next step in CFD is the meshing stage. The meshing stage can help to visualize the contours of the CFD results. Meshing design variations in the element size and inflation column in the mesh tree only have a slight difference in the element size in the detail mesh column, which is 526.5 mm. for better mesh detail, a reduction in the element size is required and it is changed to less than one hundred and fifty millimeters. In addition to reducing the meshing element size, it also requires additional inflation for additional mesh details. Inflation setting by setting the boundary on the shroud and the maximum layer on the inlet outlet boundary to ten layers.

Velocity streamline as shows in Figure 12 in the design shows a blue color on the fluid inlet to outlet, then yellow and green on the axial fan. As well as changes in fluid flow to become turbulent when passing through the axial fan.

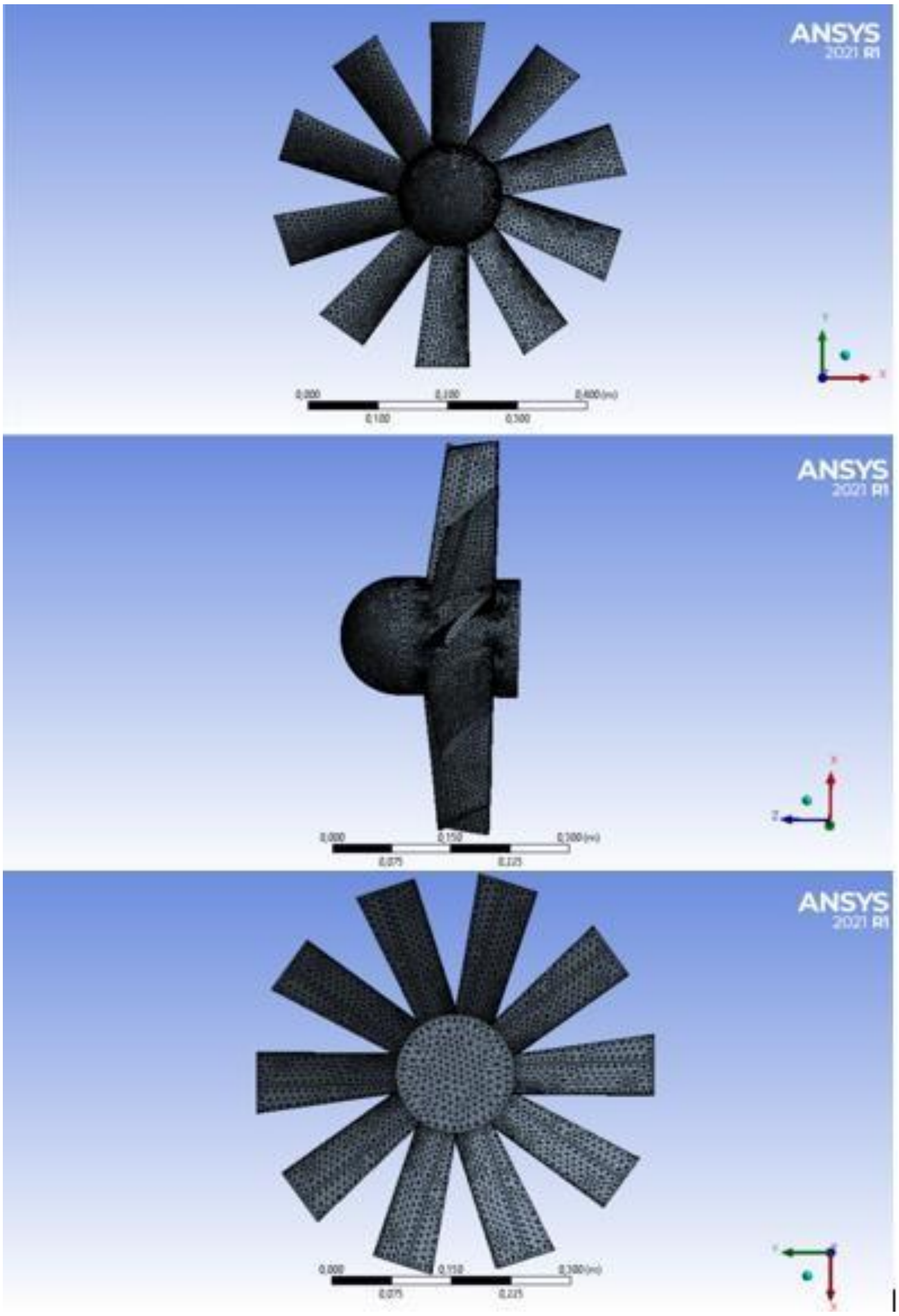


Figure 11 Static structural mesh details.

The analysis was carried out on all parts of the model that received the load and the input material using aluminum alloy. The results of the solution from the simulation can be seen after the Ansys 2021 R1 software solving process is complete, which is shown in Figure 13.(a). This is the first mode, it can be seen that there is a natural frequency of 86.13 Hz. Vibration mode that occurs vibration in the form of a deflection of the fluid tube. The vibrations that occur can cause impact loads to occur on the fans.

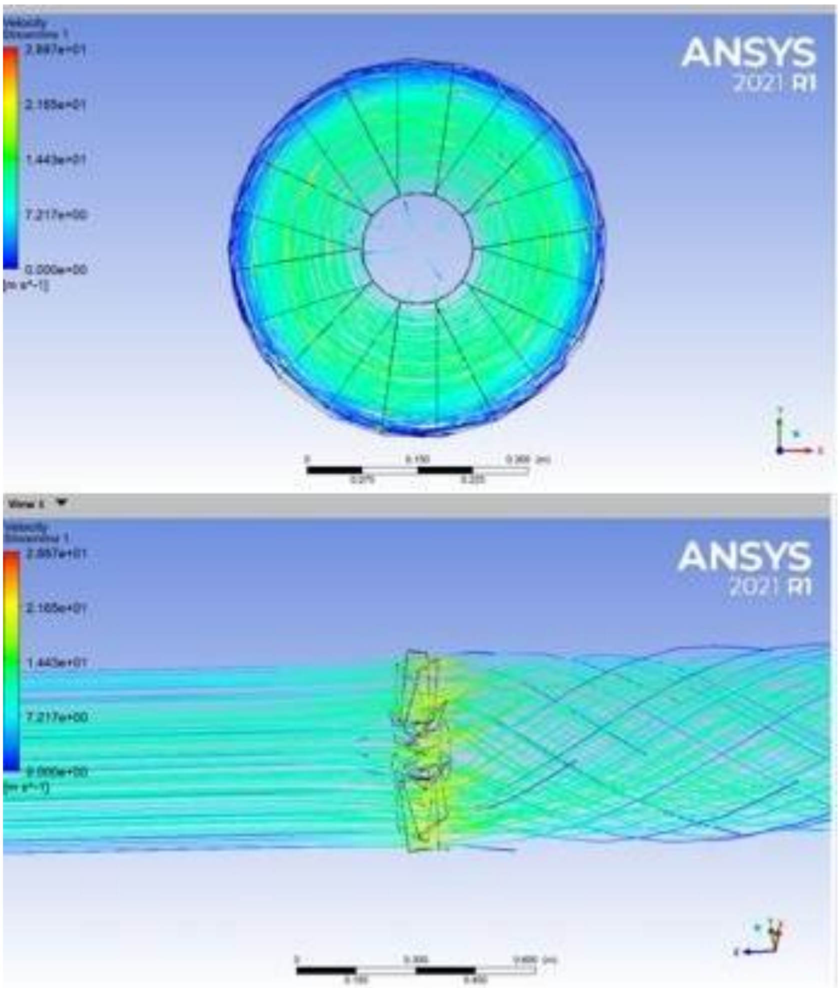
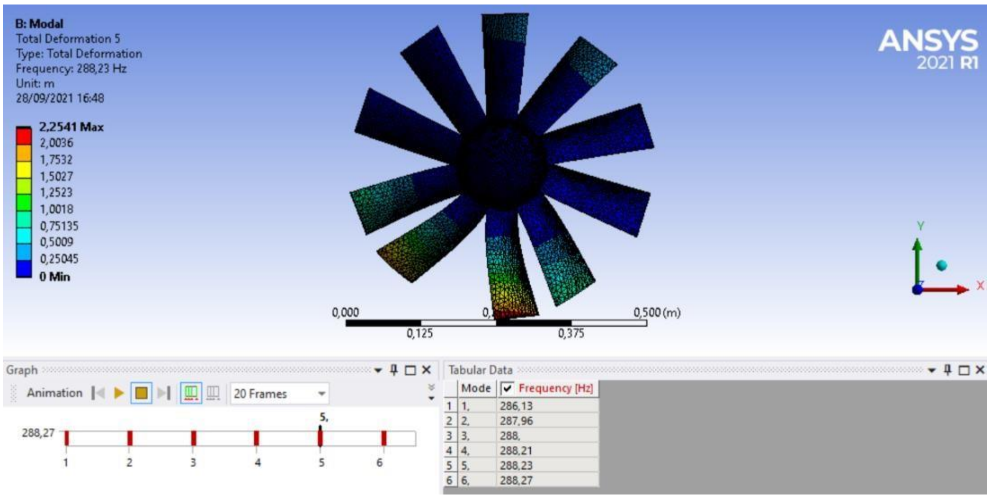


Figure 12 Streamline

Figure 13.(b) is the second mode, it can be seen that there is a natural frequency of 287.96 Hz. The vibration mode that occurs is in the form of an axial vibration of the deflection of the blade. The vibrations that occur can cause an **impact** load to occur on the fan. Then, figure 13.(c) is the third mode, there is a natural frequency of 288 Hz. Vibration mode that occurs vibration in the form of deflection on the three blades. Figure 13.(d) is the fourth mode, it can be seen that there is a natural frequency of 288.21 Hz. Vibration mode that occurs is an axial deflection of the blade. Then figure 13.(e) is the fifth mode, it can be seen that there is a natural frequency of 288.23 Hz. The vibration mode that occurs is axial deflection at the bottom of the blade. Vibration mode that occurs can cause **damage** to the fan components. Last but not least, figure 13.(f) is the sixth mode, it can be seen that there is a natural frequency of 288.27 Hz. The vibration mode that occurs is the **axial deflection** on the right and left blades of 5. The vibration mode that occurs can cause **damage** to the fan components.

Numerical results of the stress and deformations are computed for axial fan blade. The study has covered the effect of the speed of rotiation, skew angle, thickness and curvature effects on the performance od fan blade. It has been found thar the xx- stress is predominant among normal stress component and shear stresses in the xy plane compared to the other components of the stresses. It can be recognized that when the thickness increases the stresses and deformations decreases, this effect is due to the reduction in the strutural stiffness, and thus a large deflection and higher stresses are generated due to the reduction in the blade thickness.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Frequency: 288,23 Hz
Unit: m
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1,5027
1,2523
1,0018
0,75135
0,5009
0,25045
0 Min
ANSYS
2021 R1
0,000
0,500 (m)
0,125
0,375
Graph
Animation
20 Frames
288,27
Tabular Data
Mode
Frequency [Hz]
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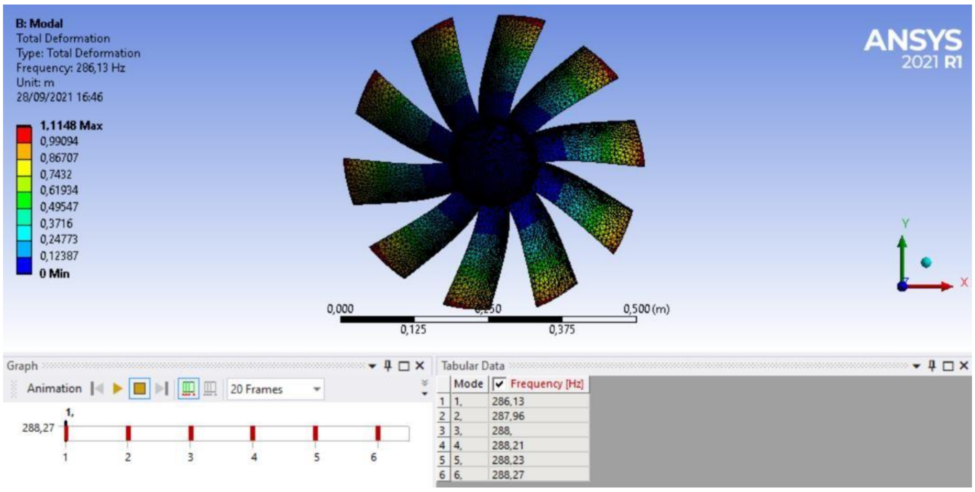
2, 287,96
3, 288,
4, 288,21
5, 288,23
6, 288,27

(a)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Total Deformation
Type: Total Deformation
Frequency: 286,13 Hz
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0,61934
0,49547
0,3716
0,24773
0,12387
0 Min
ANSYS
2021 R1
0,000
0,500 (m)
0,125
0,375
Graph
Animation
20 Frames
288,27
Tabular Data
Mode
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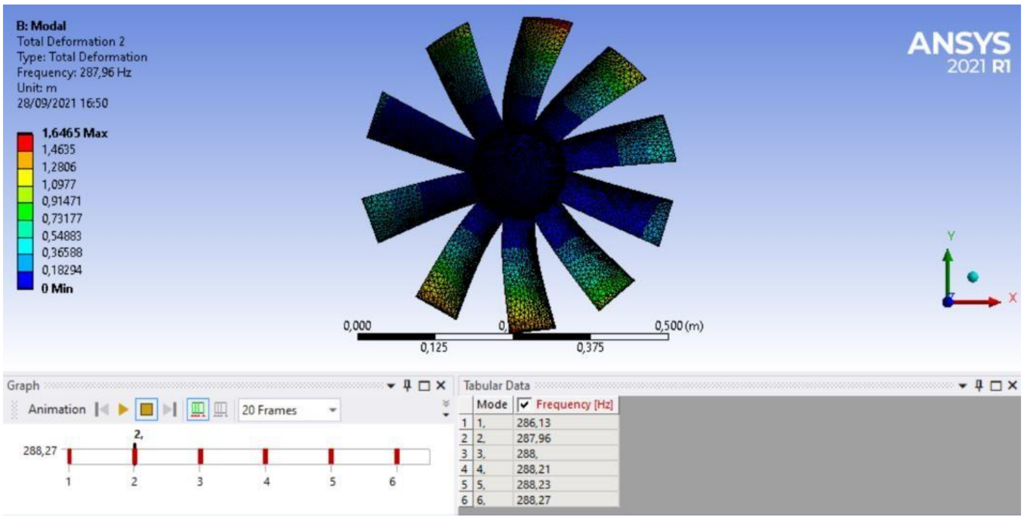
5, 288,23
6, 288,27

(b)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Total Deformation 2
Type: Total Deformation
Frequency: 287,96 Hz
Unit: m
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1,0977
0,91471
0,73177
0,54883
0,36588
0,18294
0 Min
ANSYS
2021 R1
0,000
0,500 (m)
0,125
0,375
Graph
Animation
20 Frames
288,27
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Frequency [Hz]
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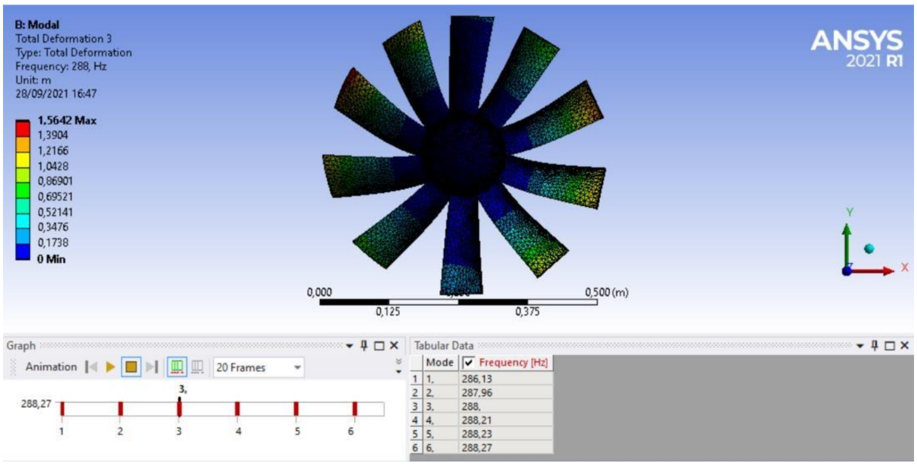
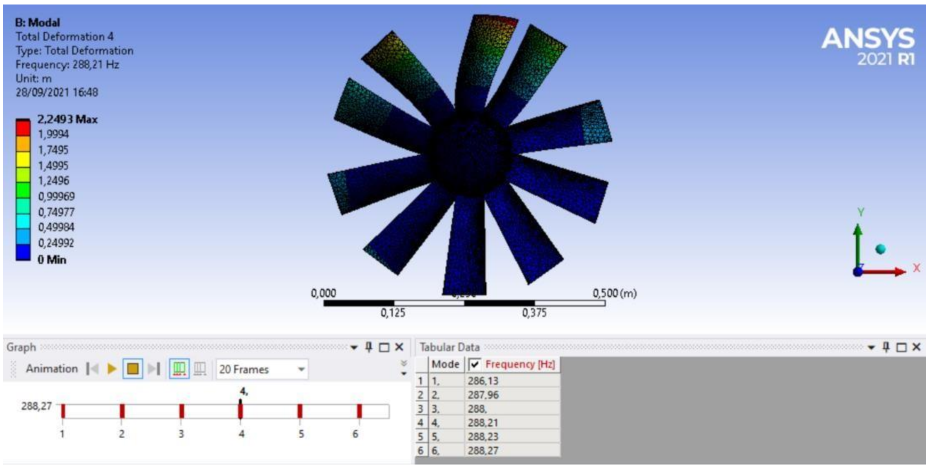
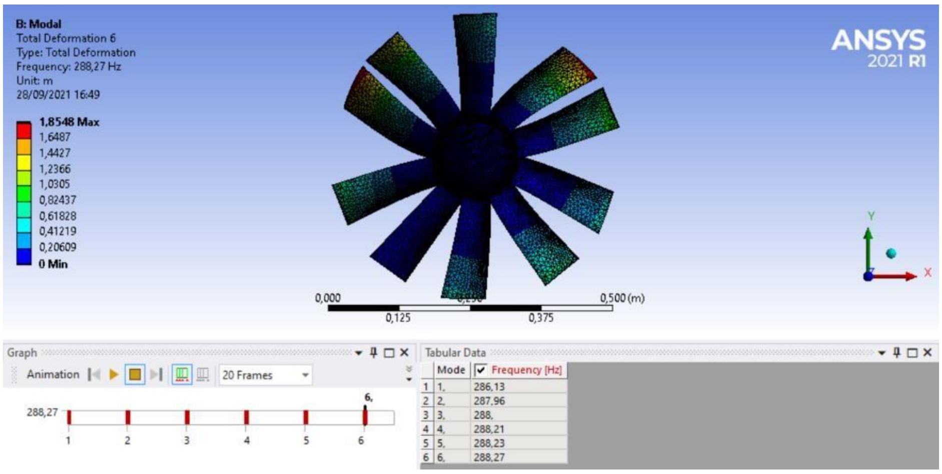
(c)



(d)



(e)



(f)

Figure 13 (a) Total deformation 1, (b) Total deformation 2, (c) Total Deformation 3, (d) Total deformation 4, (e) Total deformation 5, (f) Total deformation 6

Process for Reading Harmonic Response Results

The solution section is useful for finding or displaying any required solutions. This section displays the total deformation, equivalent stress, and frequency response.

The analysis was carried out on all parts of the fan that received the load and the input material using aluminum alloy. The results of the solution from the simulation can be seen after the completion of the Ansys 2021 R1 software solving process, which is shown in the Figure 14-16.

Figure 14 is a total deformation mode with a maximum value of δ_maks=3,1206e-11 Hz. Figure 15 is the equivalent voltage (equivalent Von-Mises Stress, $\sigma_{y\ \mathrm{maks}}$) with a maximum value of $\sigma_{y\ \mathrm{maks}}$ = 1,3503 Pa. This is a results of *frequency response* with *range maximum* 4000 Hz.

Figure 16 (a-b) shows the frequency response in the far field of the two tip-gap sizes. The broadband noise is mostly dominant, whereas the peaks at the blade passing frequency and its harmonics are not captured in the predicted spectra for the either tip-clearance size. As previously mentioned, the tonal noise at blade passing frequency and its harmonics of an isolated axial fan is mainly due to a large-scale inflow distortion and flow asymmetries, which are not considered in the computation. Regarding broadband noise, these noise components could be linked to the blade tip vortex and the interation of the boundary layer with the blade surface.

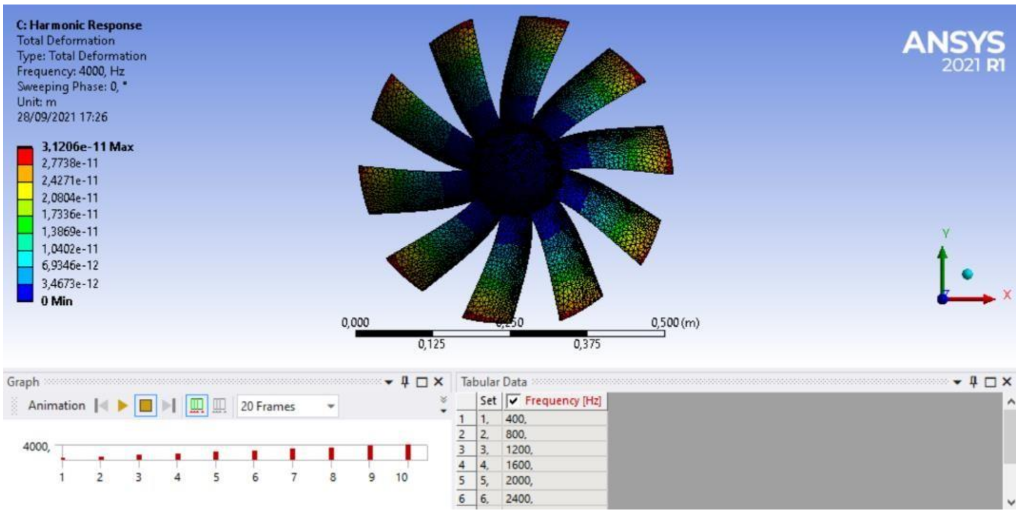


Figure 14 Total deformation Harmonic

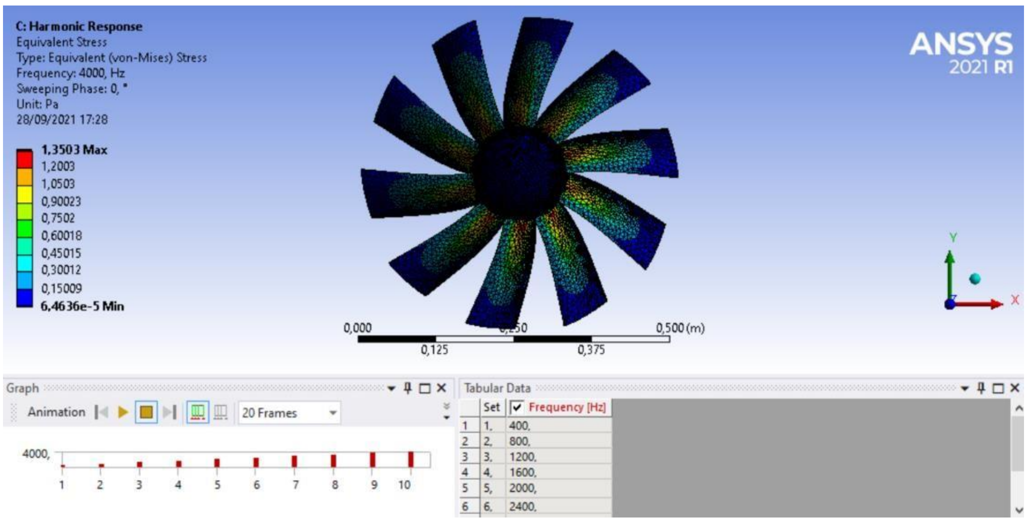
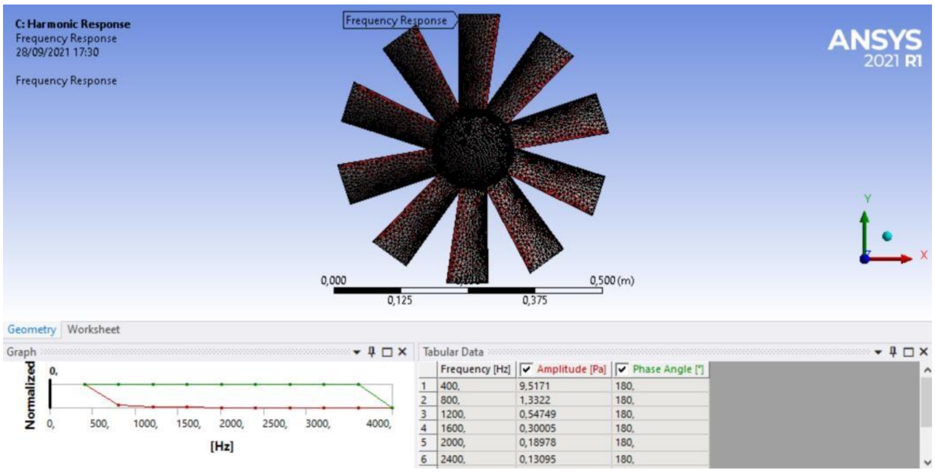
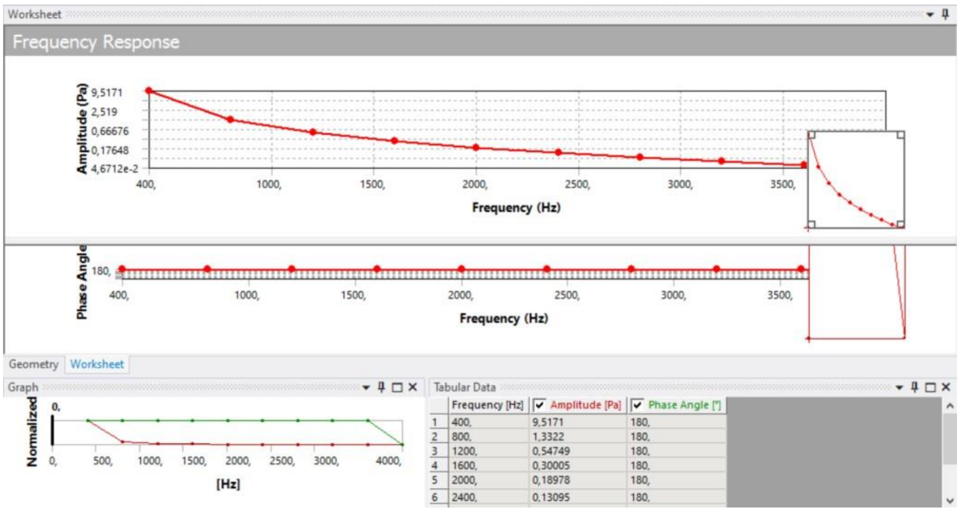


Figure 15 Equivalent (von-Mises) Stress



(a)



(b)

Figure 16 (a) Frequency response (b) Frequency graph

CONCLUSIONS

The Ansys Fluent simulation results obtained the maximum pressure contour value is 198.424 Pa. and the maximum value of velocity streamline is 28.8669 m/s. The results of the Ansys Static Structural simulation, the total average result is obtained deformation is 9.9275e-008 m, and the average stress value is 4303.1 Pa. From the Ansys Modal simulation results obtained the average total deformation 0.151767 m. and the average frequency is 287.8 Hz. From the simulation results of Ansys Harmonic Response, the total average is obtained deformation is 5.0809e-012 m, and the maximum value of equivalent von-mises stress of 1.3503 Pa.

From the results of this study, the average frequency value is 287.8 Hz and is still within below the threshold value, namely with a frequency of 20-2000 Hz and an intensity of sound up to 85 dB (decibels). And from the results of running simulations Ansys Harmonic shows the equivalent value of maximum von-mises stress of 1.3503 Pa and from running simulations Ansys Static structural shows the equivalent value of von-mises stress maximum as big as 45901 Pa. Whereas mark tensile yield strength from material aluminum alloy as big as 280 Mpa or 2.8e+08 Pa. Thing this show that the results of running simulations, the strength of the material is still below the limit maximum tensile yield strength of aluminum alloy material.

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DECLARATION OF CONFLICTING INTERESTS

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