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Design Optimization of Radiator Fan Blade Using Fiber-Reinforced Plastic Material

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Abstract: The Aim of this paper is to study failures in radiator fan blades due to Resonance and optimization in design, which will withstand the failure conditions. The Modal Analysis is carried out in ANSYS and it is validated through Experimental Techniques. The correlation between modal analysis and experimental analysis is determined. Suitable material which withstands the resonance is determined and validated in ANSYS and FFT Analyzer. In absence of design data, the reverse engineering process is considered as a major tool for modeling. Using the data the solid model of the radiator blade is created in CAD. We have used modal analysis to calculate the natural frequencies and mode shapes of a Radiator fan. The natural frequencies and mode shapes are critical components in the design of any structure. Experimental Analysis is accomplished using FFT Analyzer with DEWESOFT software. The final results of CAE model and Experimental tested model are correlated.
Keywords: Natural Frequency, Mode Shapes, FFT, FEA.

I. INTRODUCTION

The increasing demands for higher speed transportation, coupled with the desire for better fuel economy, design engineers to use the obvious solution to reduce the mass of the structure. A result of this is that structures become weak, i.e. the resonance frequencies reduce in the frequency range to where the excitation frequencies are present. Due to this, structures fails under dynamic loading if the resonances energized during function are not adequately damped. These troubles still, can be reduced if the structure is so designed that the excitation frequencies are in the immediate area of the resonances. Today structures fail rarely due to static loads as this field has been studied for over a century and reached a adequate level of sophistication. Modal analysis is useful in understanding how structures behave under dynamic loads and Simulation or prediction when external forces are existent. Mathematical models describe generally the dynamic behavior, not the structure itself. They are often constrained by assumptions and boundary conditions. The modal parameters that completely describe the dynamics of a system are:

1) Modal frequency
2) Modal damping
3) Mode shape

The Tacoma Narrows bridge disaster example of this. This bridge was collapsed due to wind-induced vibration (i.e. flutter). These vibrations are generated at system's resonance frequency, then oscillation create excitation at an atomic level, where more and more energy is stored. This phenomenon is known as resonance, also as an aero elastic flutter – in which the structures are subjected to difficult, unstable oscillations that are caused by passing winds. Wings of airplanes can be subjected to similar phenomenon. Before an airplane is on the rampage, flight flutter tests have to be performed. Major part of the structures can be subjected to resonate, i.e. to vibrate with extreme oscillatory movement. Resonant vibration is mostly caused by a contact between the inertial and elastic properties of the materials. Resonance is often the reason of the vibration and noise connected troubles that happen in structures. To have better understanding of any structural vibration problem, the resonant frequencies of a structure need to be recognized. Modal analysis is an important way of analyzing the modes of vibration of a machine. In growth of a new or better mechanical invention, structural dynamics testing on product prototypes is used to assess its real dynamic behavior.

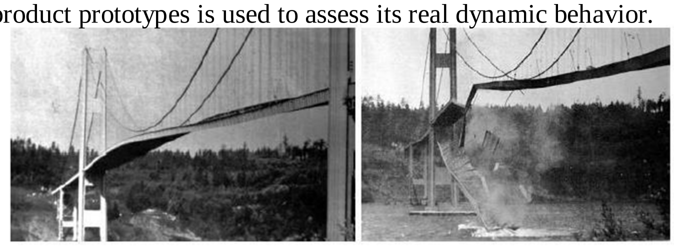

Figure 1: Tacoma Narrows Bridge Disaster.

II. LITERATURE REVIEW

1) Sarfraz Ali N. Quadri, Dhananjay R. Dolas[2015] carried out the Comparative Modal analysis of conventional spur gear with modified involute spur gear. In this research paper the modal analysis of involute spur gear pair is carried out using finite element analysis tool ANSYS.
2) Avinash Gudimetla, C V Gopinath, K L Narasimha Murty [2022] explained the Failure Analysis of Radiator Fan Blade of Diesel Locomotive Engine with Reverse Engineering. This research paper has covered the optimum material evaluation of the blade, to explore the causes of failure at junction of blade and flange and to suggest a suitable alternative material for the blade.
3) S. P. Chaphalkar, Subhash. N. Khetre, Arun M. Meshram [2015] carried out the Modal analysis of cantilever beam using Finite Element analysis associated with Experimental Analysis. In this research papers some generic concepts for modal analysis of vibration for fixed free beam are shown. An experimental setup and the associated theory which is used calculate the natural frequencies and vibration modes of a cantilever beam.
4) Cheng et al. (2009) carried out the analysis of the performance curve of the fan by employing the concept of reverse engineering. Chebyshev Polynomial has been used to simplify the performance curve of the fan in order to check the impedance curve of system and the obtained corresponding diagram was used to analyze the operating point of performance curve of the fan.
5) Brian J. Schwarz & Mark H. Richardson [1999] explained the Experimental Modal Analysis. In this research paper, they have explained the types of vibrations formed in the system. Also, they have explained the types of modes that can be formed during bending and torsion.

III. OBJECTIVE

The Objectives of this research work is as follows.

A. Develop 3D model of the radiator fan blade using Reverse Engineering concept.
B. Apply boundary condition through the entire length of the developed 3D solid model radiator fan and carry out the Material Analysis using ANSYS.
C. Experimental Analysis using FFT Analyzer with DEWESOFT software.
D. The analysis led to the identification of suitable material to withstand all the loads.

IV. METHODOLOGY

Each object when excited vibrates at its natural frequency, depending on its mass and stiffness. But, there are other side effects of this vibrations that lead to the failure of structures. This is applicable to small machine parts alike. Towers, skyscrapers and Bridges, but also bearings, blades, fasteners and piping are failed

due to resonance. When the Engine runs at higher operating speed, it vibrates and working Frequency matches with the natural Frequency of the Fan. Due to this Resonance is created and cracks in the Fan blade Occur for which leads to failure of Fan. The complete procedure is known as a Modal Analysis or Experimental Modal Analysis. There are various method available to do modal testing but impact hammer testing and shaker (vibration tester) testing are mainly used. In both cases energy is supplied to the system with known frequency content. There will be an amplification of the response, where structural resonances occur clearly seen in the response spectra. The identified important possible causes of failures in radiator fan blades are flow imbalances of the material in radiator fan blade, pressure imbalances along the length of the blade and other sundry causes.

The radiator fan blades are made up of various materials nowadays and here static analysis of the radiator fan is executed to different types of materials to check and evaluate the material and process conditions which can withstand the dynamic and structural loads.

The Methodology of this research work is as follows.

A. Carry out the Material Analysis using ANSYS for PVC Material and determine the Natural Frequency at which it fails.
B. Change the Material to FRP to the same boundary conditions and check if the material is safe.
C. Experimental Analysis using FFT Analyzer with DEWESOFT software for both the PVC and FRP Material.
D. Analysis of the results obtained from both ANSYS and Experimental Method for FRP and PVC Materials.

V. ANALITICAL CALCULATIONS

A. *Selection Of Method*

1) *Mode-Extraction Methods*

The most basic equation solved in a typical undamped modal analysis is given as the classical Eigen value problem:

$$[K]\ \{F\ i\} = \omega 2\ [M]\ \{Fi\} \quad \ldots\ldots\ldots\ldots (E\text{-}1)$$

Where,
[K] = stiffness matrix
{F i} = mode shape vector (eigenvector) of mode i
ω2i = natural circular frequency of mode i (ω2 is the Eigen value) [M] = mass matrix
Most of numerical methods are available to use the above equation. ANSYS offers these methods:

- Block Lanczos method (default)
- Subspace method
- Power Dynamics method
- Reduced (Householder) method
- Unsymmetric method
- Damped method
- QR damped method

The first four methods (Block Lanczos, subspace, Power Dynamics, and reduced) are the most commonly used. Following the table is a brief description of each mode-extraction method .

2) *Block Lanczos Method:* The Block Lanczoseigen value solver is the default. It uses the Lanczos algorithm wherever the Lanczos recursion is perform with a mass of vectors. This method is as precise as the subspace method, but quicker. The Block Lanczos method is particularly useful when searching for Eigen frequencies in a known element of the Eigen values scale of a given structure The meeting rate of the Eigen Frequencies will be similar when extract mode in the upper end of the range beyond the starting value of FREQB, the algorithm extract the n modes beyond FREQB at about the same speed as it extracts the lower n modes.

Table 1**:** Mode shape frequency for PVC Material

Mode	Analytical frequency in Hz
1	102.47
2	105.68
3	107.55
4	108.44

Table 2: Mode shape frequency for FRP Material.

Mode	Analytical frequency in Hz
1	117.20
2	120.56
3	126.55
4	129.66

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VI. FEA DESIGN

The conventional Radiator fan is taken for study its natural frequency with four basic modes. The Fan model with boundary conditions and meshed model is shown in below figure 2 and 3.

A. Modal Analysis of Radiator Fan

1) Material Specifications for PVC

- Young's Modulus -620.53 Mpa
- Poisson's ratio – 0.33
- Density – 1300 kg/m3

The three important steps in ANSYS programming are:

a) Pre-processing: This phase consists of making available the input data such as geometry, material properties, meshing of the model, boundary conditions and has the following steps:

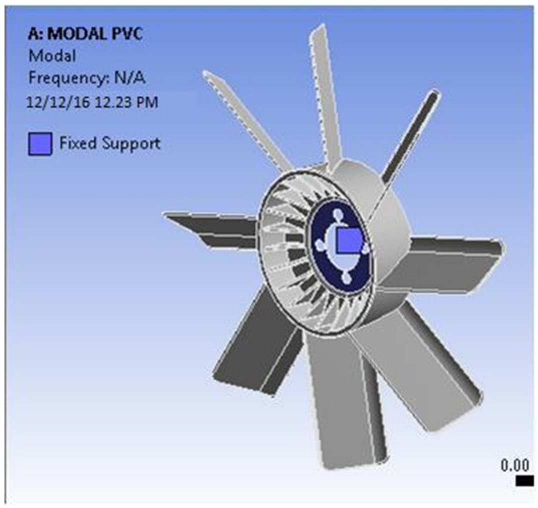

Figure 2: Set up in ANSYS

i) Create FE Model: In this step we divide the total volume into small simple regular volumes, which can be easily meshed. Then we define the mesh size for each small volume by virtually dividing all the edges of the small volume into same divisions.

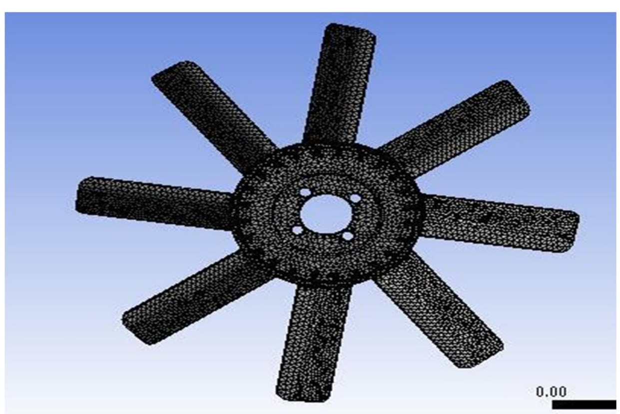

Figure 3: Meshing for fan blade

ii) Loading: In this step the boundary conditions are imposed, i.e. forces and constraints, on the model are defined.

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b) *Solution:* In this phase a solver is used to solve the basic equation for the analysis type and to compute the results. This phase is taken care by the software program. In the solution process, the solver is used to compute the solution for a steady state analysis.

c) *Post-processing:* This is the phase where the results are reviewed for the analysis done, by obtaining graphic displays, vector-plots and tabular reports of stress and displacement, etc.

Table 3: Range for Frequency

Max Modes to find	10
Limit search to range	Yes.
Range Minimum	50Hz
Range Maximum	110 Hz

2) Different Modes

Frequency Range: 50 – 110 Hz

Mode 1: Twisting

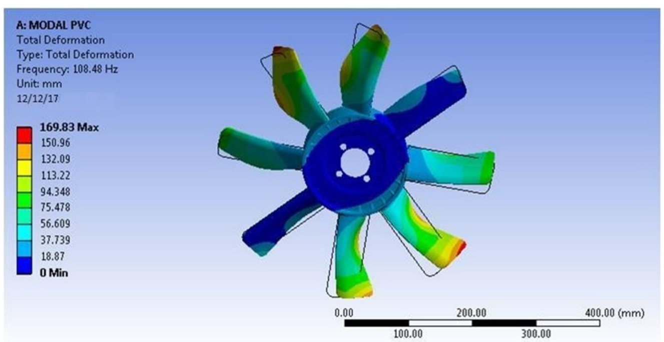

Figure 4 Mode 1: Twisting

Mode 2: Bending

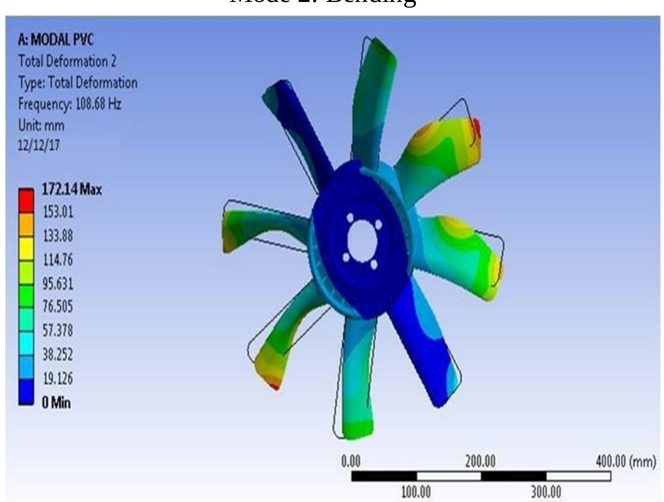

Figure 5 Mode 2: Bending

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Table 4: Result Table for ANSYS

	Mode	Frequency [Hz]
1	1.	66.418
2	2.	66.455
3	3.	66.667
4	4.	66.718
5	5.	67.251
6	6.	67.267
7	7.	67.319
8	8.	67.649
9	9.	108.48
10	10.	108.68

As we can see, for mode 9 and 10 the frequency is close to the Natural frequency. The Failure occurs in this region.
Material Specifications for FRP:

- Young's Modulus –13425 N/mm2
- Poisson's ratio – 0.265
- Density – 1.76*10(-6)

3) Different Modes Frequency Range: 50 – 110 Hz

Mode 1: Twisting

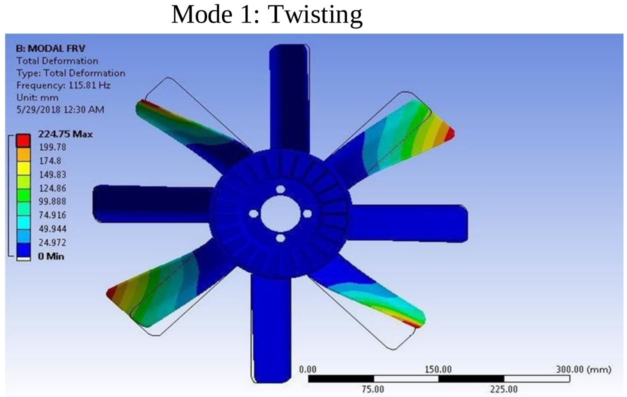

Figure 6 Mode 1: Twisting

Mode 2: Bending

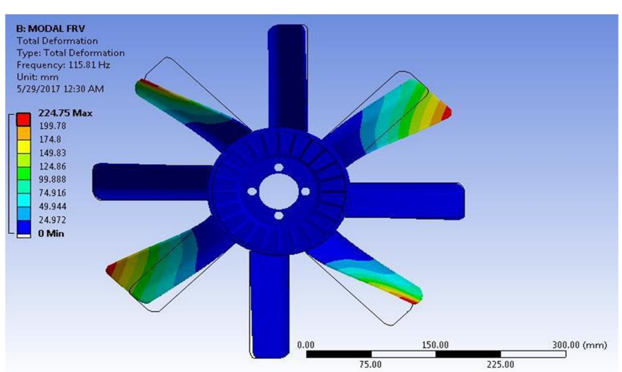

Figure 7 Mode 2: Bending

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Table 5**:** Result Table for ANSYS:

	Mode	Frequency [Hz]
1	1.	115.81
2	2.	115.83
3	3.	116.95
4	4.	116.98
5	5.	117.17
6	6.	117.19
7	7.	117.27
8	8.	118.15
9	9.	268.2
10	10.	268.36

As we can see frequency obtained for new material are greater than the Natural frequency.

VII. EXPERIMENTAL ANALYSIS

A. The Four Steps Of Modal Testing Are

1) *Modeling:* An important step in modal testing is to make the optimal test model. The first step is to create a geometrical model in the computer. The second is to define DOFs for the measurements. A DOF (degree of freedom) is a point with associated directions. One point can consist of up to 6 DOF's (three directions and three rotations).
2) *Measurements:* The FRFs must be measured for the Modal Post processing. Often other functions such as Auto spectra and coherence are measured for the validation of data.
3) Curve Fitting: It is the process which extracts the modal parameters from the measured set of FRFs.
4) *Validation:* It is important to do before the data are used for Simulation or comparison with FEM data. Validation takes place both after the measurements e.g. by evaluating the coherence function, Once the design of a structure has been accepted, a prototype is produced to carry out modal tests to verify the dynamic parameters – natural frequencies, modal damping and residues which are the components of the mode shapes –predicted for the design.

B. Measurements

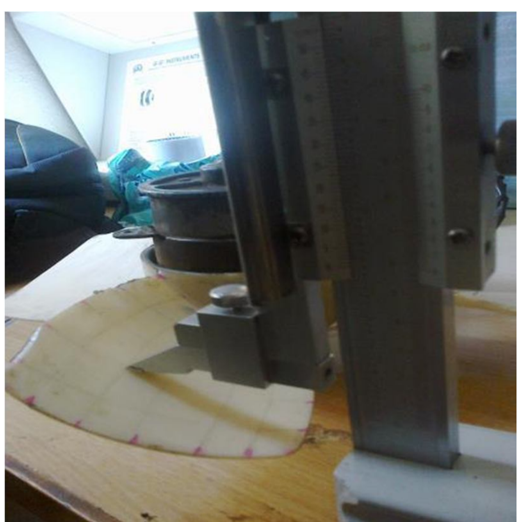

Figure 8: Measurement of Dimension

1) Meshing is done on fan blade and total 42 nodes are obtained.
2) X, Y, Z coordinates are found out with the help of Vernier and height gauge.
3) Geometry is made in DEWESOFT SOFTWARE.

C. Geometry Of Blade In Dewesoft

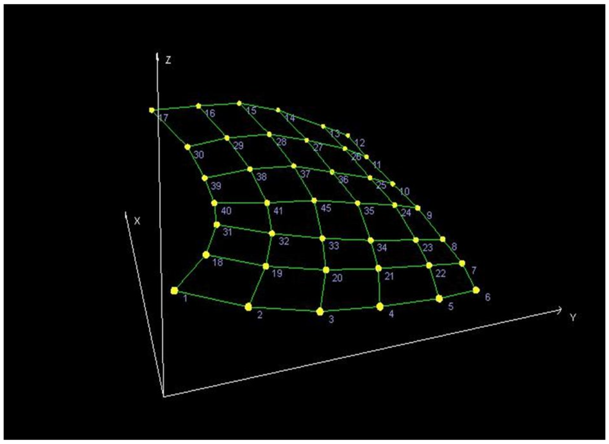

Figure 9: Geometry of blade in DEWESOFT

1) X, Y, Z co-ordinates are entered and 42 points are joined by links. Above figure shows the geometry obtained.

D. Experimental Set Up

We have used DEWESOFT 8 channel FFT analyzer. FFT is attached to computer. IN 1st slot Hammer connection is given. In 2nd slot sensor wire is placed while sensor head is attached to fan blade from back side. Excitation is given through hammer which is input. In this different nodes are hammered. Hammer contains transducer which measure Impulse imparted and sends this data to computer, output which is vibration is measured through sensor attached (stuck) to blade from back side.

Specifications of FFT Analyzer

1) Measurement range = 476µHz to 100 kHz.
2) Span = 191 MHz to 100 kHz in binary sequence.
3) Center frequency = anywhere within the 0-100kHz.
4) Accuracy = 25ppm from 20 ºc to 40 ºc.
5) Resolution = span/400.
6) Real time bandwidth = 100 kHz.

E. All Modes Graph

Following graphs are obtained as a result. Graphs are plotted with y-axis as amplitude while x axis as a frequency. In result we can see peaks at different nodes. These peaks indicate natural frequencies at their respective modes. Graph (Amplitude vs. Frequency) showing all modal frequencies peaks.

F. For Material PVC

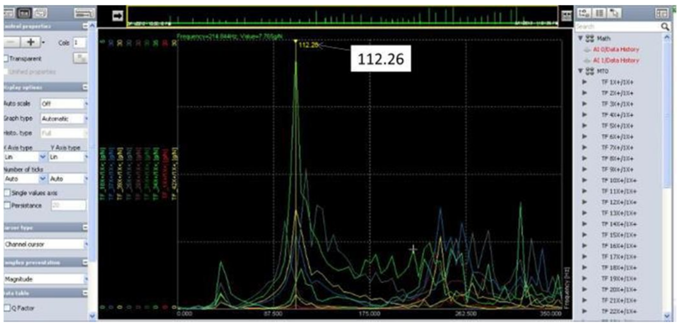

Figure 10: Mode 1 for PVC

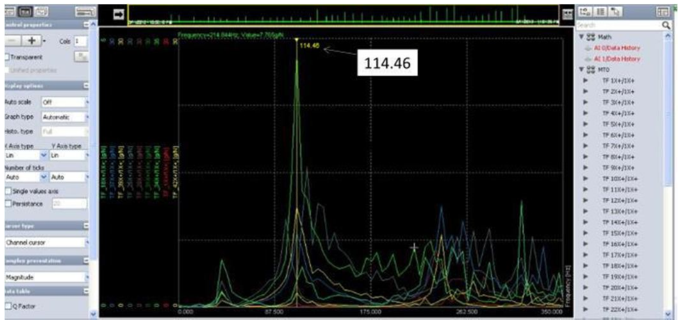

Figure 11: Mode 2 for PVC

The 4 modes show the frequency of the Fan in the range of 108.44 Hz to 114.64Hz, which is close to the natural frequency. The results are shown in table no. 6 below,

Table 6: Mode shape frequency by Experimental Method

Mode	Experimental frequency in Hz
1	108.44
2	109.65
3	112.26
4	114.64

G. For Material FRP

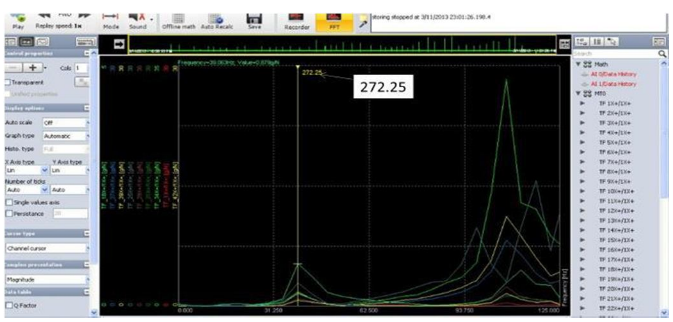

Figure 12: Mode 1 for FRP

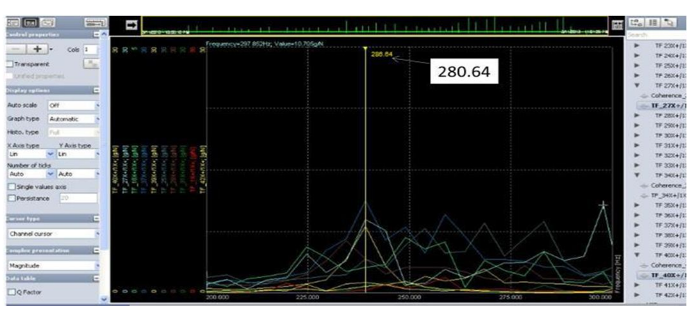

Figure 13**:** Mode 2 for FRP

The 4 modes show the frequency of the Fan in the range of 272.25 Hz to 285.66Hz, which is safe as it is greater than the natural frequency. The results are shown in table no. 7 below,

Table 7: Mode shape frequency by Experimental Method

Mode	Experimental frequency in Hz
1	272.25
2	280.64
3	281.47
4	285.66

VIII. SUMMARY OF RESULT

The numerically (FEA) calculated natural frequency and the experimentally calculated frequency at which the failure of fan is occurred are correlated for PVC Material. When the material is changed to FRP, the model analysis shows that the fan does not fail at the natural frequency. In addition, it also withstands at higher frequencies. The experimental analysis for the FRP shows that it is safe at the natural frequency. The summary of analysis
for PVA and FRP material are summarized as show in table 8 and 9.

Table 8: Summary of analysis for PVC

SET	ANSYS RESULT	EXPERIMENTAL RESULT
1	67.319	108.44
2	67.649	109.65
3	108.48	112.26
4	108.68	114.64

Table 9: Summary of analysis for FRP

SET	ANSYS RESULT	EXPERIMENTAL RESULT
1	117.27	272.25
2	118.15	280.64
3	268.2	281.47
4	268.36	285.66

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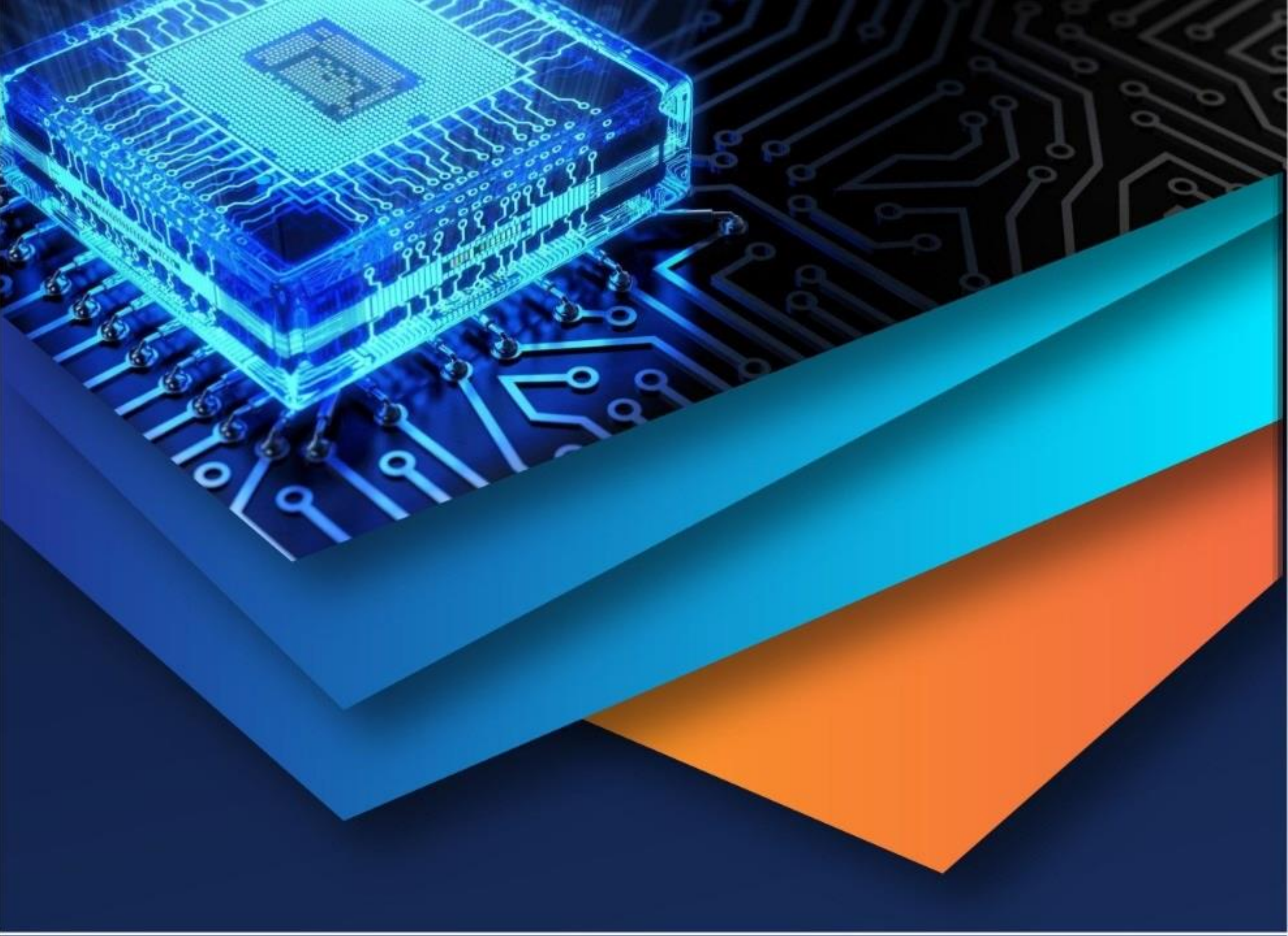

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