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Finite Element Analysis and Experimental Validation of Carbon Fiber-Reinforced Nitrile Rubber Composite Mount Baffles for Vibration Isolation Applications

Shajahan K[1], Arun Sundar RS[2], Ramesh Kumar AV[3], Reji John[4]
[1, 2, 3]Naval Physical &Oceanographic Laboratory, Thrikkakara, Cochin, Kerala, India
[4]Cochin University of Science and Technology, Cochin, Kerala, India

Abstract: On-board machinery in marine vessels such as ships and submarines generates vibrations that can degrade equipment longevity, interfere with communication systems, and compromise stealth capabilities. Among various mitigation techniques, passive anti-vibration mount baffles are widely employed for their effectiveness in isolating vibrations above specified frequencies. This study presents a comprehensive finite element (FE) analysis and experimental validation of nitrile rubber (NBR)-based composite mount baffles reinforced with varying percentages of carbon fiber (5–25%). The composite design was modelled using CAD tools and analysed using advanced finite element methods to assess static deformation and dynamic performance. Material properties were experimentally characterized and used for accurate FE modelling. The mount baffle with 5% carbon fiber exhibited the highest deflection (1.24 mm) and the lowest resonance frequency (16 Hz), indicating superior low-frequency isolation characteristics. A comparative study highlights the correlation between fiber loading, stiffness, and vibration isolation performance.
Keywords: Vibration isolation, Composite anti-vibration mount baffle, transmissibility, nitrile rubber, low frequency

I. INTRODUCTION

On-board machinery vibrations inside the ship and submarines can cause many adverse effects like reducing the life of different equipment, interference with the ship communication systems, affecting the stealth nature of the vessel etc. Antivibration Mount Baffles are an effective way of reducing the adverse effect of vibration produced by different machinery. The development of Mount Baffles using different design and material considerations is a wide field of study. Design and material considerations are based on a wide variety of aspects such as the loading rating, the type of loading, the isolation frequency required, the working environment etc. The composite anti-vibration mount baffle developed has a load rating of 1200 Kg. Designing of the mount baffle is done on Modelling software considering the load rating, the dimensional constraints, the permissible static deflection and the isolation frequency required. Material and fibre are chosen based on the damping requirement, hardness and environment of the mount baffle to be operated [1]. A rubber matrix is used along with carbon short fibre having 3mm length at different loading percentages as 5%, 10%, 15%, 20% and 25% of the fibre. Mechanical and damping properties of nitrile rubber composite with neat and short carbon fibre loading up to 4% was studied and documented elsewhere [2]. Material testing is done to find out different mechanical and damping characteristics and also these properties are used for the material modelling in finite element analysis [3]. The designed mount baffle is analyzed using finite element software to study its static characteristics, transmissibility and isolation characteristics and also its energy loss or hysteresis characteristics.

II. DESIGN OF MOUNT BAFFLE

Mount baffle designing is done based on factors like geometric constraints, load rate, static deflection required, resonance and isolation frequency, damping required, environmental conditions etc. [4]. The geometric constraints for the mount baffle involve the hole positions required, the height consideration etc. based on the equipment mounted on top of the mount baffle. The load rating here is 1200 kg. The mount baffle is supposed to be used inside the ship and submarines so the design should be leak-proof. The mount baffle is designed in SOLIDWORKS software.

The parts involved are float, loading plate, middle plate, bottom plate, elastomeric stack, and encapsulation. The float, loading late, middle plate and bottom plate are made of SS. The Nitrile rubber-based stack and encapsulation is made of rubber composite with varying fibre load.

III. MATERIALS AND METHODOLOGY

The float, loading late, middle plate and bottom plate are made of SS. The elastomeric stack and encapsulation are made of rubber composite with varying fibre load [5]. The rubber samples with specific compositions are moulded into sheets and button samples. The samples are cured at a certain temperature for a specific period of time before using for different testing purposes.

IV. MATERIAL TESTING

Properties like density, hardness, modulus of elasticity; UTS, tear strength, compression set etc. are taken to characterize the materials [6]. The density of the material is measured by using sophisticated equipment. The Hardness is measured by using a Bareiss shore A durometer. Material testing is done for different compositions by using tensile and button samples of the specific compositions. The tensile specimen and tear specimen are cut out from the sheet as per the ASTM standard using a die and the testing is done using a universal testing machine. The data obtained from the testing is used for identifying different mechanical properties like the ultimate tensile strength, percentage elongation, modulus of elasticity at various elongations of the material and tear strength are given in Table I. Characterization techniques like dynamic mechanical analysis (DMA), scanning electron microscopy and thermal analysis like TGA and DSC are also carried out. Materials resistance to liquids is analysed by doing water absorption and diesel absorption tests. Furthermore, these data are utilized for the purpose of material modelling in Finite element analysis software. The button sample is used for the purpose of compression test, stress relaxation test, permanent set test so that properties like compressive modulus, stress relaxation data, and compression set etc. can be obtained [7]. The stress relaxation data can be utilized for modelling the viscoelastic property of the material using FEA software. The tear strength of the material is calculated by testing the sample in UTM. The samples are cut out from the sheet as per ASTM standards.

TABLE I MATERIAL PROPERTIES OF SAMPLES

Properties	Unit	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Carbon fibre	%	5	10	15	20	25
Hardness	Shore A	76.63	80.97	87.26	89.5	48.4 (Shore D)
Density	g/cc	1.271	1.281	1.289	1.295	1.29
Tensile strength	MPa	11.81	12.53	12.88	12.99	13.21
M100	MPa	5.08	6.38	7.08	7.39	-
M200	MPa	8.78	9.33	9.65	10.4	-
M300	MPa	11.82	12.82	-	-	-
EB%	%	306	304	263	226	23
Tear strength	N/mm	40.91	41.4	43.07	47.09	51.5
Compression set	%	15.16	16.1	13.37	11.86	7.59

V. MATERIAL ANALYSIS AND MODELING USING FEA

For analysing a prototype made up of non-linear materials it is important to properly define the material properties to the software. Such kind of non-linear materials cannot be pre-defined in the material libraries. Here we are using polymer composites which are hyperelastic viscoelastic in nature. The hyperelastic properties are defined using strain energy density functions and the viscoelastic properties are defined using Prony series. For hyperelastic material modelling the experimental uni axial data is required, here we are making use of uniaxial tensile test data for hyperelastic curve fitting in ANSYS workbench. The uniaxial data are imported into the hyperelastic modelling module of ANSYS and different hyperelastic models are curve fitted to the experimental data shown in Fig.1. The model with the least error is chosen and the curve fit solution is done to obtain the hyperelastic material constants as given in Table II.

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The hyperelastic curve fitted data for different samples and the corresponding strain energy functions are found as an input to the static structural and harmonic analysis of Mount Baffles. Here we are using Mooney Rivlin two two-parameter model for defining the hyperelastic property of the elastomeric samples as given in Table II.

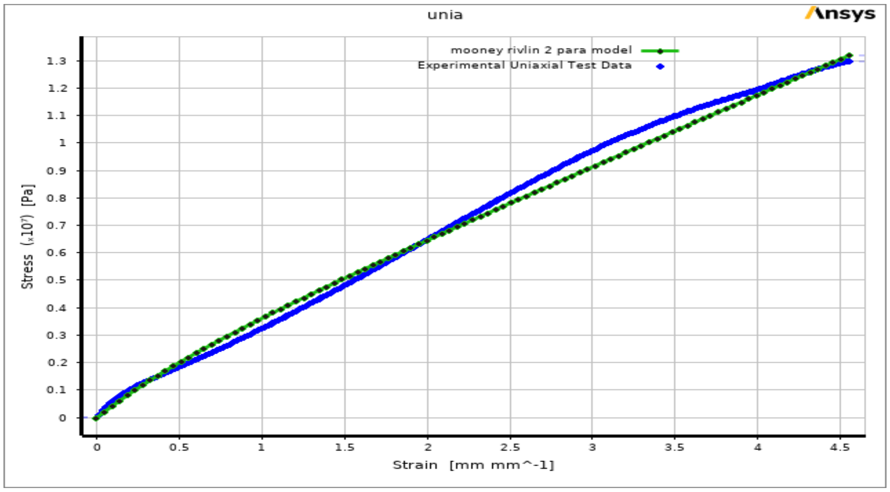

Fig.1 Curve fitting of tensile data using Mooney Rivlin 2 parameter model

TABLE II MOONEY RIVLIN TWO PARAMETER CONSTANTS FOR DIFFERENT MATERIAL SAMPLES.

Sl. No.	MaterialProperty (MPa)
Mount Baffle 1	C10=1.553741
	C01=-0.0988279
Mount Baffle2	C10=1.0652049
	C01=1.578555
Mount Baffle3	C10=0.95103
	C01=2.46691
Mount Baffle4	C10=-0.2949227
	C01=5.461627
Mount Baffle5	C10=32.9476
	C01=-17.2791

VI. MOUNT BAFFLE ANALYSIS USING FEA

Material modelling is done as a prerequisite for analysing the mount baffle prototype by using FEA tools. The final mount baffle geometry created is imported to the FEA software and the material properties are assigned to the different parts of the mount baffle. Static structural analysis, Eigen frequency or model analysis, Transmissibility analysis using frequency domain study are done using the FEA tool. Proper boundary condition like the fixed constrains, force constrains and directions should be given. Meshing should be done such that a uniform mesh having a high quality, low skewness is obtained (Fig.2). Initially the static structural analysis is done on the Mount Baffles using the stationary module of COMSOL multi physics software as shown in Fig.3. The mount baffle geometry is imported into the software, the material properties are assigned to the different parts of the mount baffle. For material assignment of elastomer the hyperelastic materiel model is chosen and the material property obtained from ANSYS workbench is fed to the model [8]. Next the boundary loading and fixed boundary conditions are given to the geometry. The analysis gives us the maximum deflection of the mount baffle at the given loading condition as shown in Table III. It can be concluded from the analysis that as the fibre loading is increasing the deflection is decreasing showing that the mount baffle is becoming stiffer by the fibre addition.

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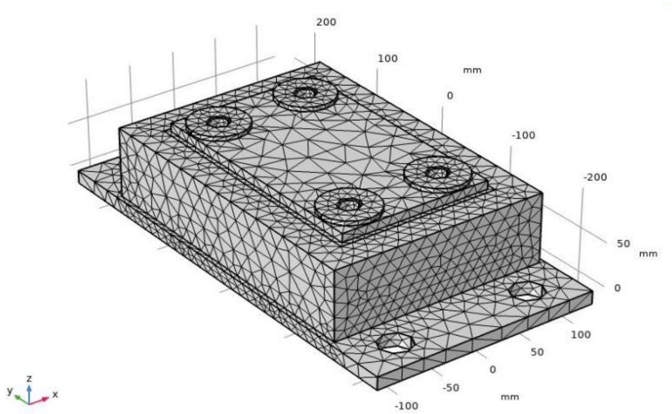

Fig.2 Mount Baffle after meshing for static analysis

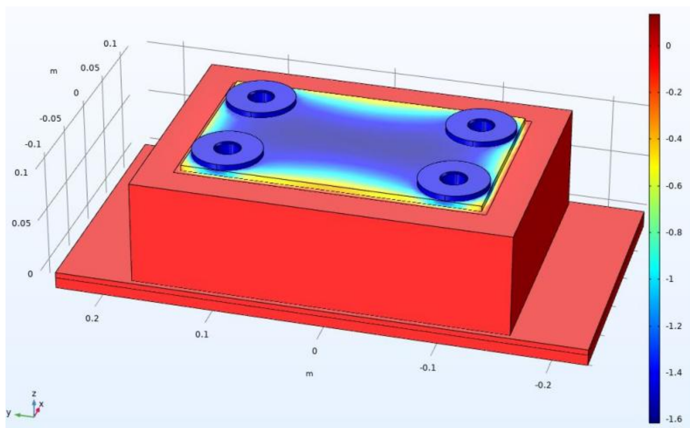

Fig-3. Surface displacement field, Z component (mm)

TABLE III DEFLECTION OF MOUNT BAFFLES OBTAINED FROM COMSOL

Sl. No	Static Deflection in COMSOL(mm)
Mount Baffle 1	1.236
Mount Baffle 2	0.71306
Mount Baffle 3	0.56514
Mount Baffle 4	0.3162
Mount Baffle 5	0.1576

Next, the harmonic analysis of Mount Baffles is carried out using the frequency domain module of COMSOL Multiphysics [9]. The mount baffle geometry is imported into the software, the material properties are assigned to the different parts of the mount baffle. Next, give the proper boundary conditions to the mount baffle. The bottom base plate is fixed and a predefined acceleration of 1g (9.81 m/s^2) is applied in the vertically upward direction. Two accelerometer probes are attached to the top of the weight and bottom base plate to measure the acceleration transmissibility of the Mount Baffles. The schematic of such an arrangement is given in Fig. 4. A frequency sweep from 1 to 500 Hz is given to the system. The graph obtained will be the frequency vs transmissibility curve is shown in Fig.5. Table IV shows the results obtained from frequency analysis of mount baffles in COMSOL.

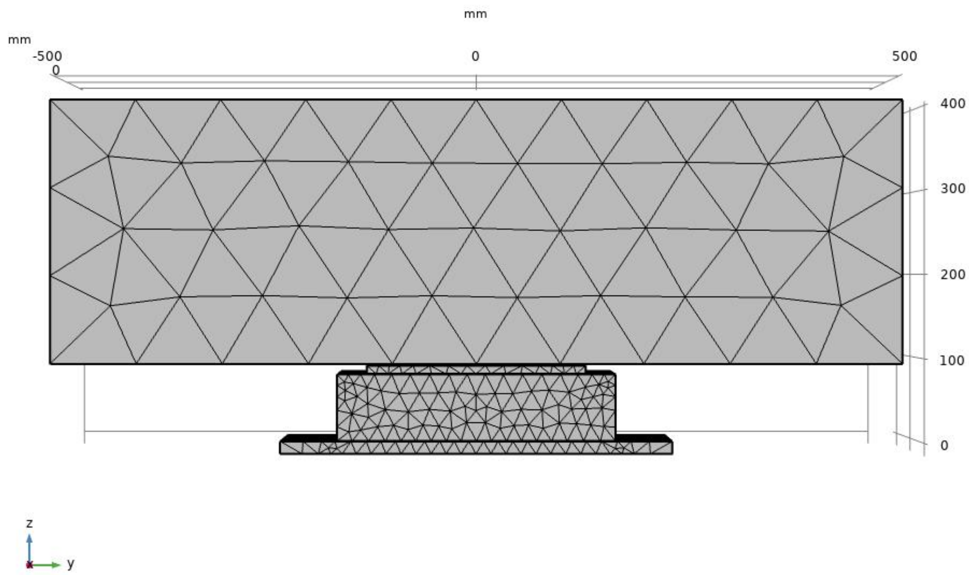

Fig.4 Mount baffle with 1200 kg weight after meshing for harmonic analysis

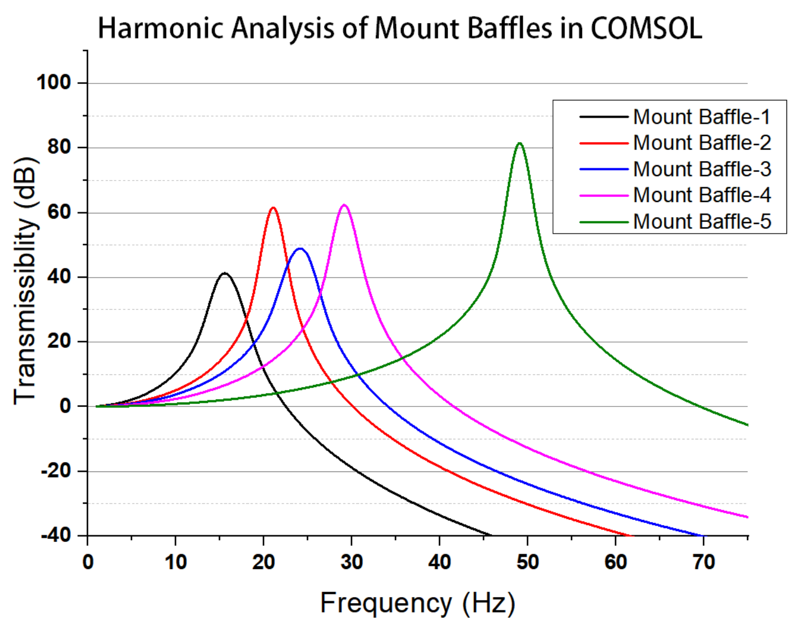

Fig.5 Frequency analysis results of mount baffle from COMSOL

TABLE IV FREQUENCY ANALYSIS OF MOUNT BAFFLES IN COMSOL

Sl. No.	Resonance Frequency at 1200 kg in COMSOL(Hz)
Mount baffle 1	15
Mount baffle 2	21
Mount baffle 3	25
Mount baffle 4	29
Mount baffle 5	49

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VII.COMPARATIVE STUDY

The Table V shows the comparative study between the Mount Baffles which are obtained from mount baffle analysis done on COMSOL and experimental data. The static deflection values and the resonance values corresponding to each Mount Baffles are observed and it can be seen that as the deflection of the mount baffle is decreasing when the resonance frequency is shifting to the higher end. Fig. 6 shows the comparison of static deflection at 1200kg load in Z direction obtained in FEM and experiment. Resonance frequency comparison between different Mount Baffles in COMSOL and experiment is illustrated in Fig. 6.

TABLE V COMPARATIVE STUDY BETWEEN THE COMSOL ANALYSIS AND EXPERIMENTAL VALUES FOR DIFFERENT MOUNT BAFFLES

Sl. No.	Fiber Loading	Static Deflection (mm)		Resonance Frequency at 1200 kg (Hz)	
		FEM	EXPT	FEM	EXPT
Mount baffle 1	5%	1.236	1.24	15	16
Mount baffle 2	10%	0.71306	0.73	21	22
Mount baffle 3	15%	0.56514	0.58	25	27
Mount baffle 4	20%	0.3162	0.33	29	33
Mount baffle 5	25%	0.1576	0.18	49	52

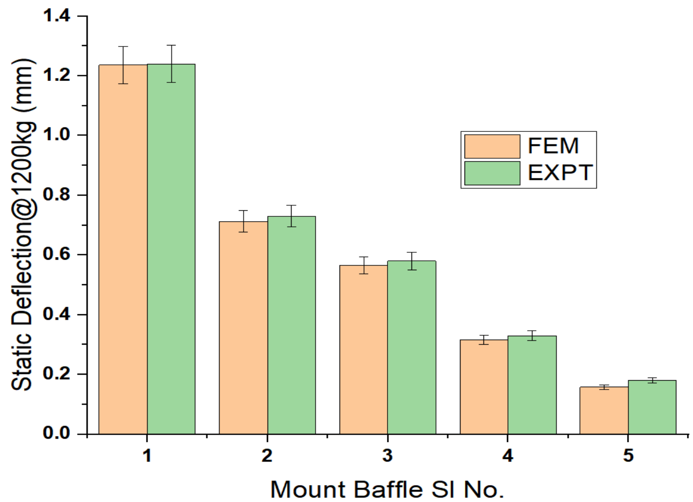

Fig.6 Comparison between static deflections in COMSOL and Experimental

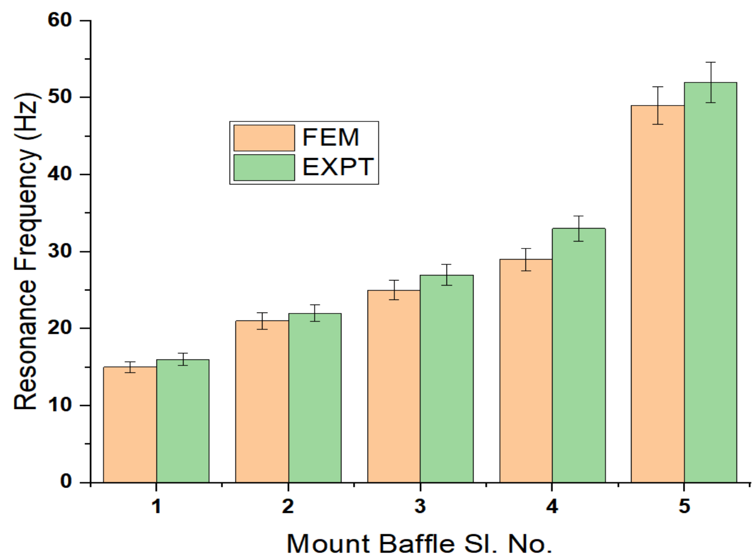

Fig.7 Resonance frequency comparison between different Mount Baffles in COMSOL and experiment

VIII. RESULTS AND DISCUSSION

From the material testing, we can observe that as the fibre percentage increased from 5 to 25% the shore A hardness of the material increased linearly from 76.63 to 89.5 Shore A and the fifth sample exhibited a shore D hardness value of 48.4. This trend was well reported in the literature due to the increase in modulus with the addition of carbon fibre[2]. Similarly the tensile strength also linearly is also well documented. The percentage elongation at break also linearly decreased with increasing the fibre loading. The lowest was shown by 25% fibre loading and the highest was shown by 5% fibre loading is also reported in the literature. The modulus at 100% elongation, 200% elongation and 300% elongation increased linearly due to the presence of a higher volume of fibre in the matrix. The tear strength values increased from 40.91 to 51.5 N/mm due to the increased fibre matrix interaction. Compression set values were lowest at 7.59% for the 25% fibre-loaded imposition and highest at 15.16 for the 5% fibre-loaded compound.

The objective of the study was to find out the vibration properties of Mount Baffles moulded with these compositions. The resonance frequency and the isolation frequency of the 5% fibre-loaded mount baffle is the lowest among the 5 Mount Baffles. A deflection of 1.24mm was the highest among the series and was observed on mount baffle 1. The maximum value of resonance is exhibited by the mount baffle having 25% fibre loading which also exhibited the lowest deflection at the rated load of 1200 kg. The mount baffle1 with 1.24mm deflection and a resonance frequency of 16 Hz meets the requirement of low-frequency application.

Material characterization confirmed the expected trends: increasing fiber content enhanced tensile strength, hardness, and tear strength, but reduced elongation was reported in literature [10]. Mount Baffle 1 (5% fiber) showed the best low-frequency isolation performance, while Mount Baffle 5 (25% fiber) exhibited the highest stiffness but also the highest resonance frequency, making it unsuitable for low-frequency applications

IX. CONCLUSION

A carbon fiber-reinforced NBR composite mount baffle was developed and validated for vibration isolation in marine applications. The mount baffle with 5% carbon fiber demonstrated optimal performance, combining adequate stiffness with the lowest resonance frequency. FE simulation results aligned well with experimental data, validating the modelling approach. Higher fiber contents were found to compromise low-frequency isolation, making Mount Baffle 1 the most suitable candidate for such applications.

X. ACKNOWLEDGMENT

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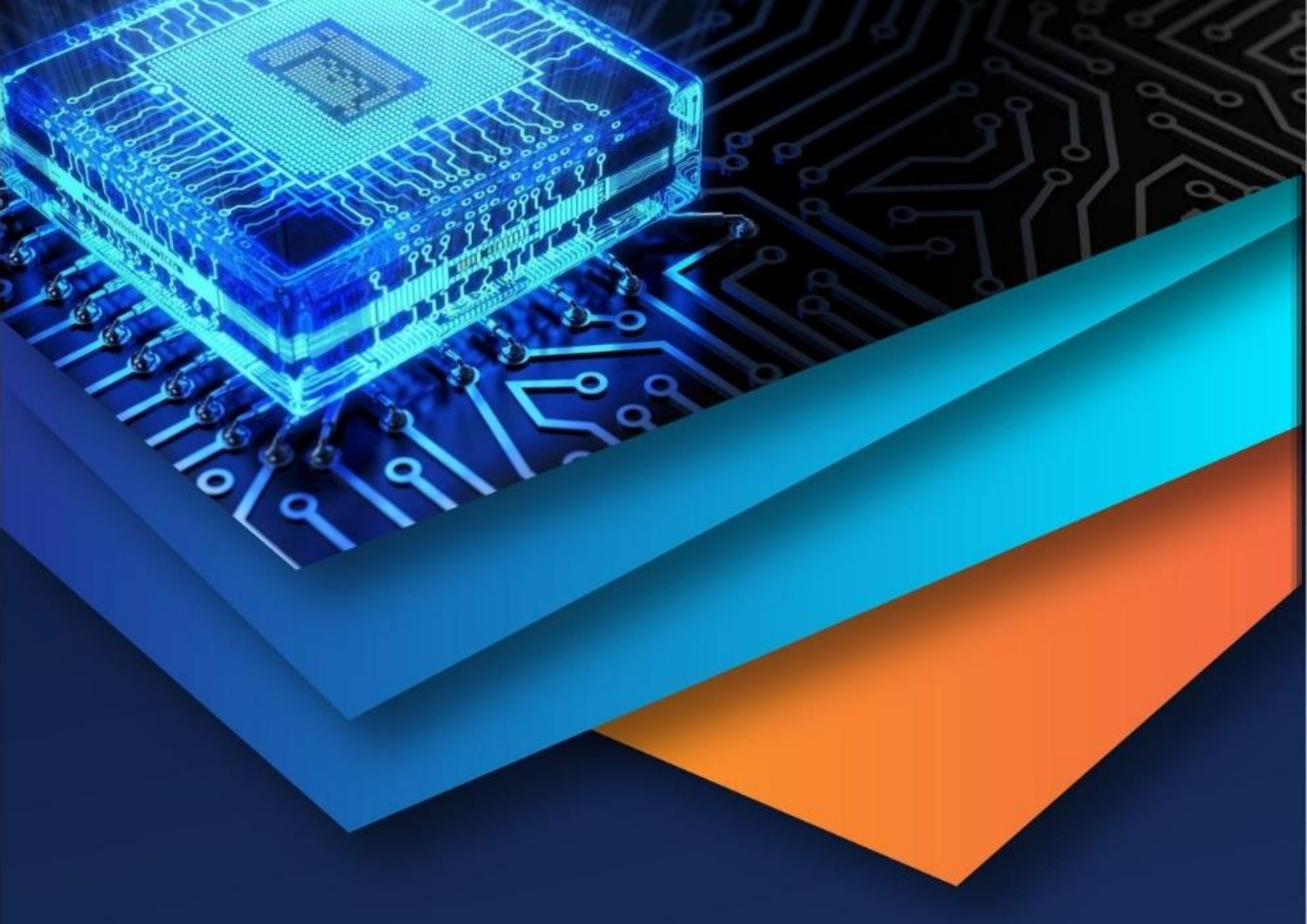

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