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Effect of Particle Material, Size and Filling Percentage on Particle Damping Phenomenon for Gear Transmission System

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Abstract: Particle damping is a passive vibration control technology. At the present stage, particle damping technology is developing especially in machinery and aerospace fields. For studying the particle damping effect different parameters such as particle material, size and filling percentage is used. One of the applications for particle damping phenomenon is gear transmission system. For simulation of particle damping discrete element method (DEM) software is used. The simulation results have been validated by comparing with experimental results of a physical system. Find damping effect due to particle damping from simulation and experimentation.
Keywords: Particle damping, Gear transmission, DEM (Discrete Element Method)

I.INTRODUCTION

In most of the machinery, vibrations are many times can not be avoided or eliminated. The effect of vibrations can be reduced by two methods: Vibration damping and vibration isolation. Vibration isolation prevents energy from entering machinery. Vibration damping is the process of absorbing or changing vibration energy to reduce the amount of energy transmitted to the equipment or machinery. Three methods of vibration damping are: active, passive and semi- active methods. Depending upon the use active and passive methods can differentiate. Active vibration damping relies on a closed loop system with feedback whereas passive system uses simple mechanical devices, elastomeric materials or fluids. Viscous damping, friction damping, impact damping and particle damping are passive damping techniques. Viscoelastic materials tend to lose efficacy because they are sensitive and degrade in extremely low or high temperature. In high temperature environments friction dampers can be used, for example, in turbine blades. Friction damper is degrading due to continuous wear that is the problem with friction damper. The vibration of primary system by using the impact between the free mass (impactor) and the primary system during vibration process is controlled in impact damper. In impact damper, the level of noise generated will be high and strong contact force may cause local damage to the structure because, only single mass is used.

A. Advantages of Particle Damping

1) Moderate cost
2) Conceptual Simplicity
3) Good durability
4) Particle damper are also suitable in long term harsh environments, such as oil contaminations, severe cold, where other types of damping devices are no longer efficient or suitable.
5) Low maintenance damping methodology.
6) Ability to sustain wide range of working temperatures, tungsten powder can endure temperatures as high as 2000 °C.

II.THEORETICAL ANALYSIS OF PARTICLE DAMPING

A. Gear System Model in Centrifugal Field

Fig.1 shows the gear with particle damper in hole on it in which particles are placed.

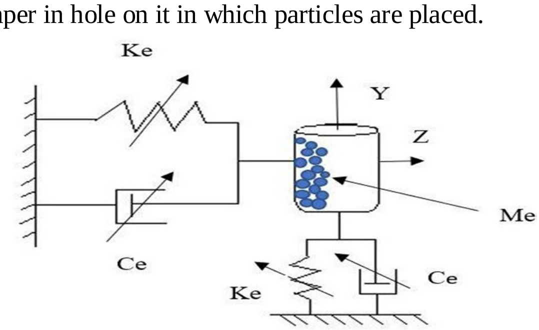

Fig. 1- Equivalent model of gear with particle damper

The equation of motion for primary system is given by [7],

$$M_e X'' + C_e X' + K_e X = \sum F + M_e g_x \qquad (1)$$

Where,
X", X' and X are the acceleration, velocity and displacement of equivalent system.
"K_e , C_e and M_e are the equivalent coefficient of stiffness, coefficient of damping and mass, respectively for the gear system, g_x is the acceleration of gravity, and □F is contact force "[7]. Contact force is the force acting on the gear by the particle units and provide link between particles and primary system.
In case of spring-mass-damper system having single degree of freedom system, the equivalent mass M_e, the equivalent stiffness K_e and the equivalent damping factor C_e implies to quality, the elasticity coefficient and the damping coefficient of gear under centrifugal load respectively. The natural frequency is given by,

$$\omega_n = \sqrt{\frac{K_e}{M_e}} \qquad (2)$$

From above equation the relationship between K_e and M_e for gear model is [7],

$$K_e = \omega_{ni}^2 (M_e + M_i)$$

Where, $$\omega_{ni}^2 = 4\pi^2 f_{ni}^2$$

$$K_e = 4\pi^2 f_{ni}^2 (M_e + M_i) \qquad (3)$$

M_i is mass of particles
If i = a and i = b for two different mass then

$$K_e = 4\pi^2 f_{na}^2 (M_e + M_a) \qquad (4)$$

$$K_e = 4\pi^2 f_{nb}^2 (M_e + M_b) \qquad (5)$$

Divide equation (3.4.4) by (3.4.5) and rearranging the term,

$$M_e = \frac{f_{nb}^2 M_b - f_{na}^2 M_a}{f_{na}^2 - f_{nb}^2} \qquad (6)$$

The equivalent damping factor C_e in terms of rotational speed ω given by,

$$C_e = 4\pi\xi f_{nj}[M_e(\omega_j) + M_i] \qquad (7)$$

III.EXPERIMENTAL SETUP

A. Gear pair

Single stage spur gear system is chosen for experimentation. The speed ratio is taken as 1:1. The detail gear specifications are as given in table 1.

Table 1- Parameters of gear

Parameters	Driving Gear	Driven Gear
Material	EN8	EN8
Module	4 mm	4 mm
Number of teeth	30	30
Pressure angle	20^o	20^o
Tooth width	40 mm	40 mm

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One set of spur gear is to be analyzed for particle damping method. The set of spur gear have six holes on each gear. Fig. 2 shows CAD model of gear with six holes.

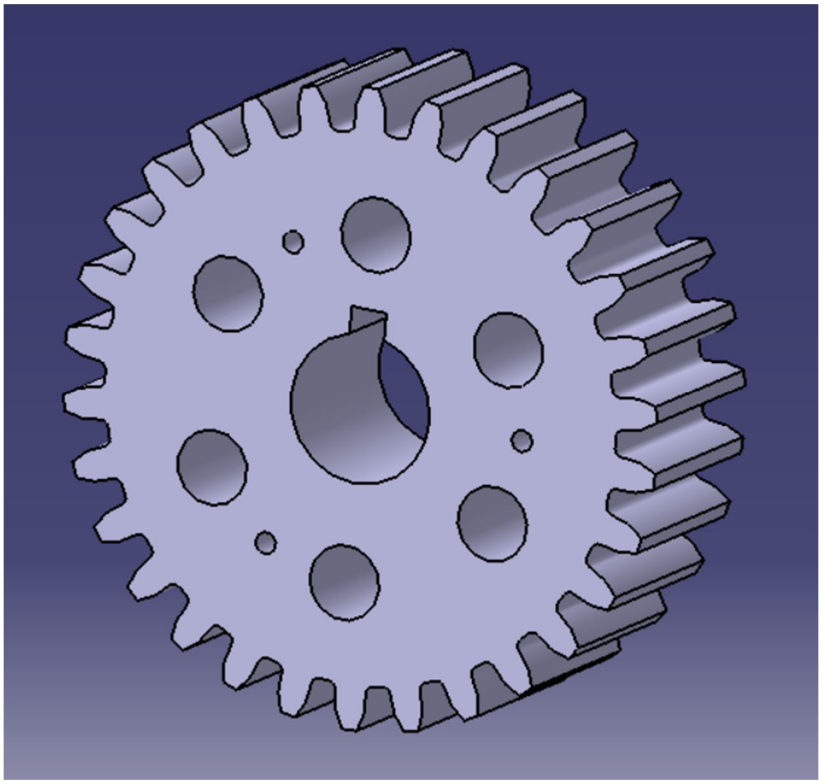

Fig. 2- Gear with six holes

The detail dimensions of six-hole gear are as shown in fig. 3.

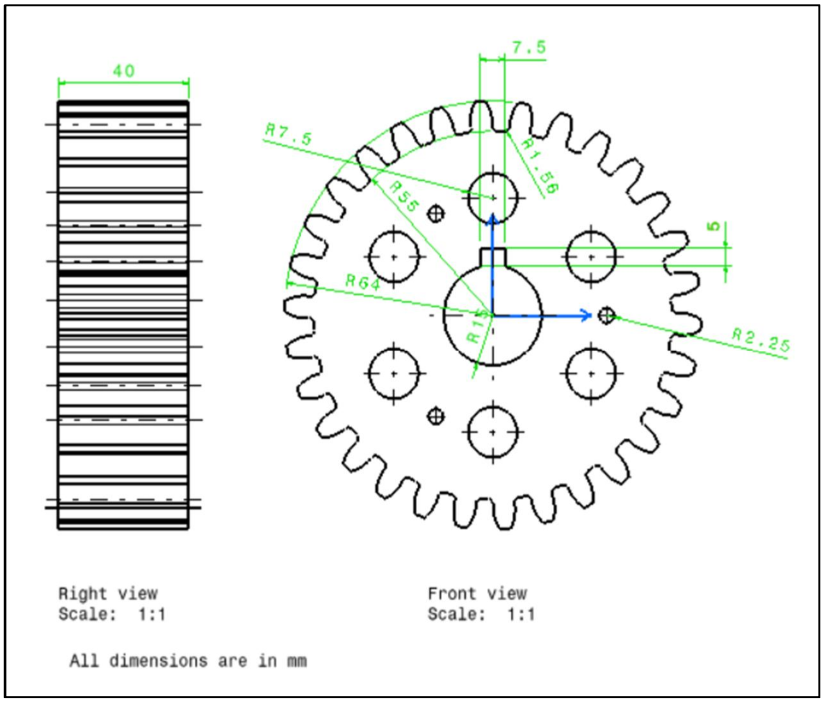

Fig. 3- Gear with dimensions

The assembly of spur gears in CATIA is shown in fig. 4.

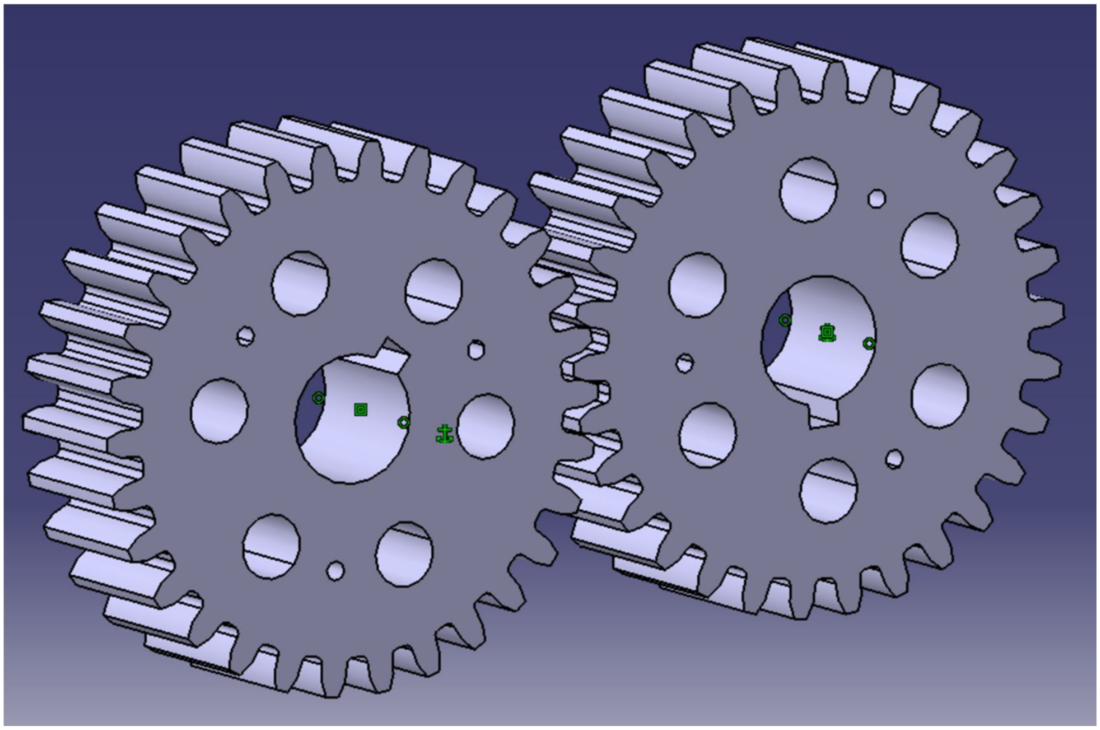

Fig. 4- Assembly of spur gears

Two shafts of 30 mm diameter are required for gear transmission system. For pedestal bearing of 30 mm inner diameter are required to support the two shafts at both ends. Electric motor of 1 HP is used as prime mover to drive the spur gear system. Electric motor is rotating at maximum 1500 rpm. Spherical particles of radius 1 mm, 2 mm and 3 mm can be used for vibration damping. These particles are filled in holes on gears. In this case it is possible to check damping effect under different particle material, radius of particles, particle filling percentage and speed of gear.
The layout of system is shown in fig. 5.

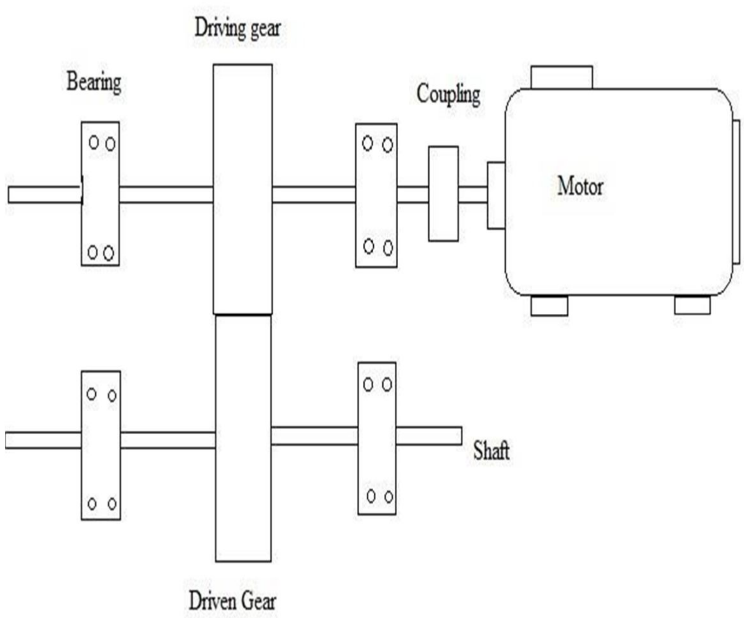

Fig. 5- Layout of experimental setup

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IV.DESIGN OF EXPERIMENTS (TEST RUNS)

Considering the particle material, radius of particles and particle filling percentage as three parameters, which are vary at three different levels. The following table shows the parameters and their levels.

Table 2- Parameters and their levels

Parameters	Level 1	Level 2	Level 3
Particle material	Steel	Copper	Cast Iron
Radius of particles (mm)	1	2	3
Particle filling Percentage (%)	25 %	50 %	75 %

For above three parameters and three levels, twenty seven tests need to be carried out. Speed of gear kept constant for all 27 tests i.e. 300 rpm.

Table 3- Experiment sequence

Experiment Number	Parameters		
	Particle material	Radius of particle (mm)	Particle filling Percentage (%)
1	Steel	1	25 %
2	Steel	1	50 %
3	Steel	1	75 %
4	Steel	2	25 %
5	Steel	2	50 %
6	Steel	2	75 %
7	Steel	3	25 %
8	Steel	3	50 %
9	Steel	3	75 %
10	Copper	1	25 %
11	Copper	1	50 %
12	Copper	1	75 %
13	Copper	2	25 %
14	Copper	2	50 %
15	Copper	2	75 %
16	Copper	3	25 %
17	Copper	3	50 %
18	Copper	3	75 %
19	Cast Iron	1	25 %
20	Cast Iron	1	50 %
21	Cast Iron	1	75 %
22	Cast Iron	2	25 %
23	Cast Iron	2	50 %
24	Cast Iron	2	75 %
25	Cast Iron	3	25 %
26	Cast Iron	3	50 %
27	Cast Iron	3	75 %

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V.DEM SIMULATIONS

After performing simulations for all test runs, following particle velocity results are obtained.

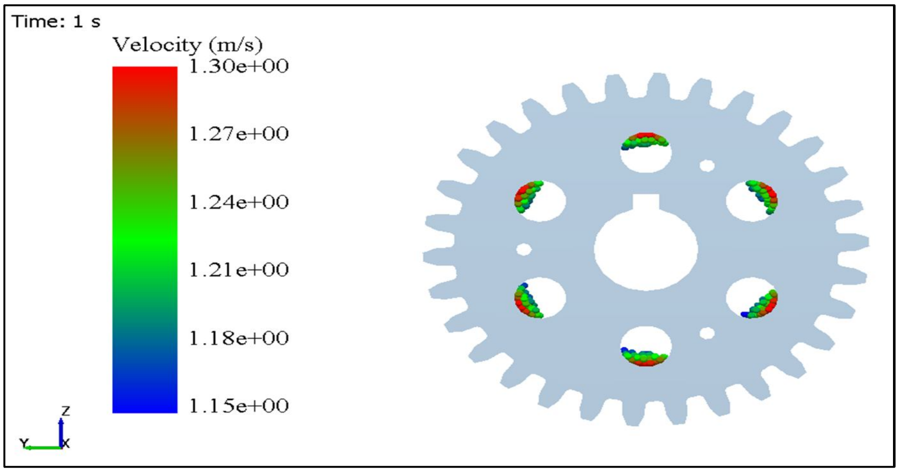

Fig. 6- Velocity of particles for test run 1

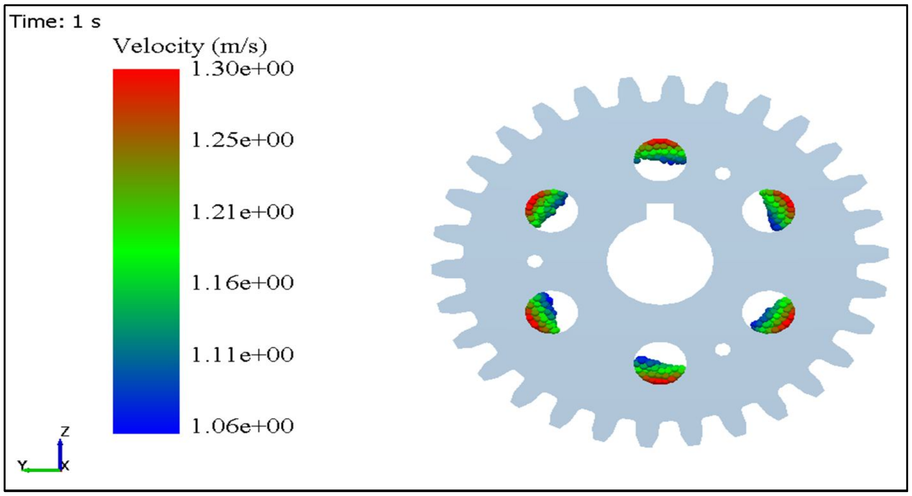

Fig. 7- Velocity of particles for test run 2

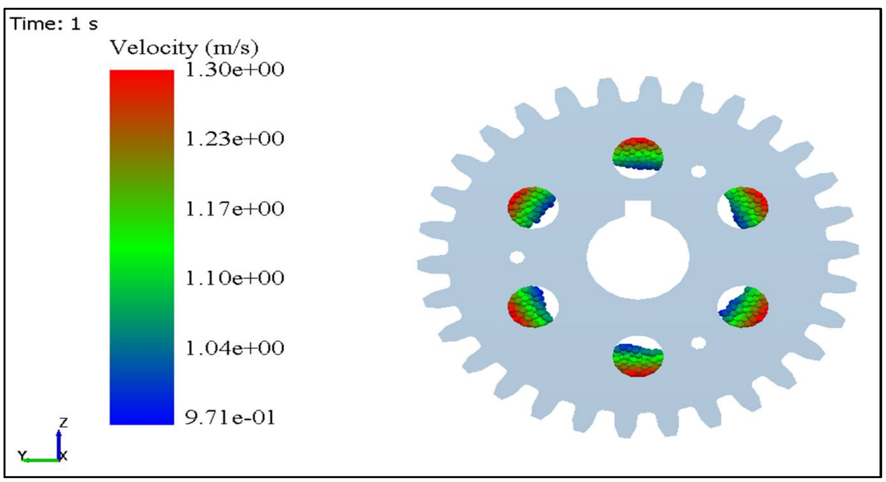

Fig. 8- Velocity of particles for test run 3

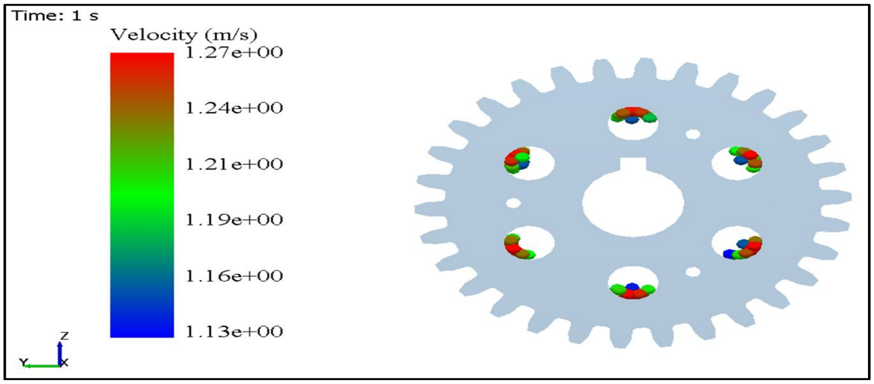

Fig. 9- Velocity of particles for test run 4

A. Evaluation of particle damping index (ζ)

From velocity of particle, particle damping index (ζ) can be calculated as

$$\zeta = \frac{\upsilon E \rho}{\sigma_s^2} (v_n + \mu_s v_t^2) \quad (8)$$

Where,

υ = Maximum velocity of particles from graph (m/s)

E = Elastic modulus of material (Pa)

ρ = Density of material (kg/m^3)

σ_s = Yield strength of material (Pa)

μ_s = Dynamic friction coefficient

v_n = Normal velocity (m/s)

v_t = Tangential velocity (m/s)

The normal and tangential velocity used in the formula 8 is set as a fixed value of 1 m/s and 0.1 m/s, respectively. Table 4 represents Particle velocity and Damping index.

Table 4- Particle damping index (ζ)

Test run	Velocity of particle (m/s)	Particle damping index (ζ)
1	1.30	0.0483
2	1.30	0.0483
3	1.30	0.0483
4	1.27	0.0472
5	1.27	0.0472
6	1.27	0.0472
7	1.24	0.0461
8	1.24	0.0461
9	1.24	0.0461
10	1.31	0.1338

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11	1.32	0.1348
12	1.30	0.1327
13	1.29	0.1317
14	1.27	0.1297
15	1.27	0.1297
16	1.29	0.1317
17	1.24	0.1266
18	1.24	0.1266
19	1.30	0.0240
20	1.33	0.0245
21	1.34	0.0247
22	1.27	0.0234
23	1.27	0.0234
24	1.27	0.0234
25	1.30	0.0240
26	1.24	0.0229
27	1.24	0.0229

VI.EXPERIMENTATION

The experimental setup used for experimentation is shown in fig. 10. Experimental setup includes FFT analyzer, spur gear assembly and variable frequency drive (VFD).

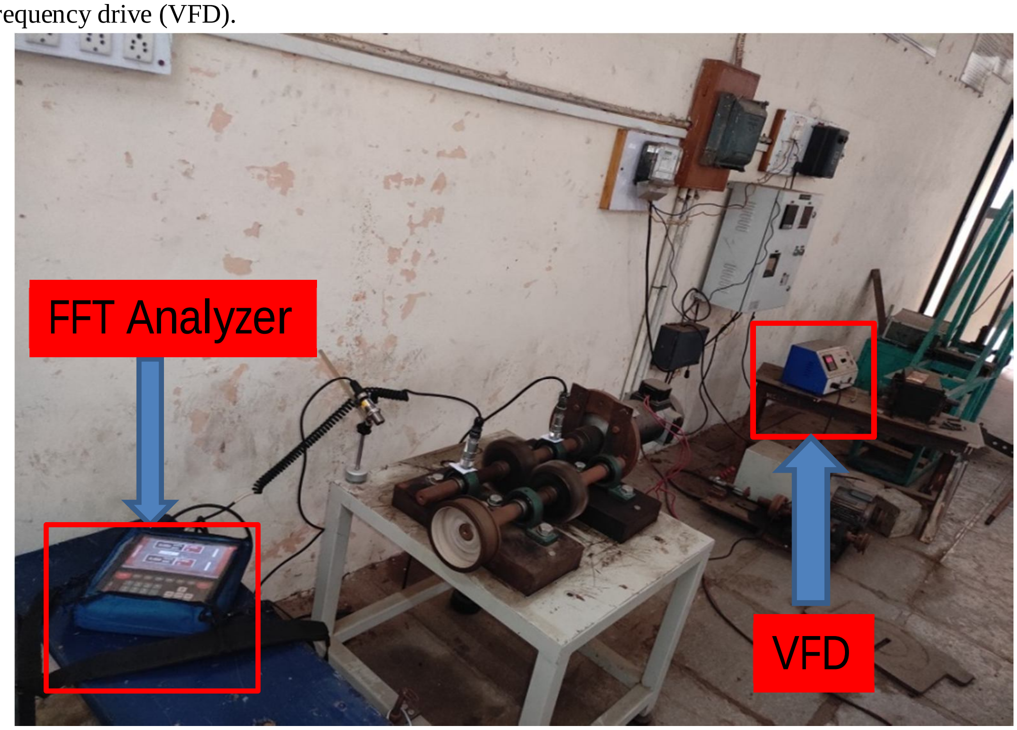

Fig. 10- Experimentation Setup

The readings are taken for first 18 experiments sequentially for steel and copper particles.
Readings are taken from experimentation for driving and non-driving end in vertical and horizontal positions.
Speed of gear kept constant for all experiment i. e. 300 rpm. Each test is repeated three times, with the average of the three results used.

Table 5- Vibration velocities at bearing without particle

Velocity at Vertical Position (mm/s)		Velocity at Horizontal Position (mm/s)	
D.E.	N.D.E.	D.E.	N.D.E.
2.27	1.14	1.37	0.75

Table 6– Vibration velocities at bearing with particle

Experiment Number	Velocity at Vertical Position (mm/s)		Velocity at Horizontal Position (mm/s)	
	D.E.	N.D.E.	D.E.	N.D.E.
1	2.12	1.08	1.29	0.69
2	1.94	0.95	1.13	0.64
3	2.05	1.01	1.23	0.66
4	1.99	0.98	1.20	0.64
5	1.87	0.85	1.09	0.57
6	1.93	0.92	1.12	0.61
7	1.90	0.97	1.09	0.59
8	1.78	0.82	1.07	0.62
9	1.84	0.87	1.10	0.61
10	1.52	0.82	0.92	0.49
11	1.37	0.75	0.79	0.45
12	1.44	0.79	0.85	0.47
13	1.32	0.73	0.85	0.46
14	1.21	0.61	0.75	0.39
15	1.28	0.66	0.69	0.36
16	1.23	0.62	0.72	0.37
17	1.15	0.53	0.64	0.38
18	1.19	0.55	0.69	0.40

A. Calculations of damping effect

The vibration velocity in two directions i. e. horizontal and vertical was measured in the experiment.
The damping effect is,

$$D = \left|\frac{E_i - E_0}{E_0}\right| \quad (9)$$

Where, E_0 = Original structure's total kinetic energy.
E_i = Total kinetic energy of system with particles

Particularly, $E_0 = \frac{1}{2} M_t \, v_{t0}^2$

$E_i = \frac{1}{2} M_t \, v_{ti}^2$

With M_t being the mass of test system, and thus the damping effect is rewritten as, [7]

$$D = \left|\frac{v_{ti}^2 - v_{t0}^2}{v_{t0}^2}\right| \quad (10)$$

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Table 7- Damping Effect

Experiment Number	Vertical		Horizontal	
	D.E.	N.D.E.	D.E.	N.D.E.
1	0.1278	0.1025	0.1134	0.1536
2	0.2696	0.3056	0.3197	0.2718
3	0.1844	0.2151	0.1939	0.2256
4	0.2315	0.2610	0.2328	0.2718
5	0.3214	0.4441	0.3670	0.4224
6	0.2771	0.3487	0.3317	0.3385
7	0.2994	0.2760	0.3670	0.3812
8	0.3214	0.4826	0.3900	0.3166
9	0.2771	0.4176	0.3553	0.3341
10	0.5516	0.4826	0.5490	0.5732
11	0.6358	0.5672	0.6675	0.6400
12	0.5975	0.5198	0.6151	0.6073
13	0.6619	0.5900	0.6330	0.6238
14	0.7158	0.7137	0.7003	0.7296
15	0.6820	0.6648	0.7463	0.7696
16	0.7064	0.7042	0.7238	0.7566
17	0.7433	0.7838	0.7818	0.7433
18	0.7251	0.7672	0.7463	0.7156

VII.INTERPRETATION OF SIMULATION AND EXPERIMENTATION RESULTS

A. Interpretation of Simulation Results

From Simulation results, Graph of Particle Damping Index (ζ) Vs Particle Filling Percentage (%) for 1 mm, 2 mm and 3mm particle Radius are drawn which is shown in fig. 11, fig. 12 and fig. 13.

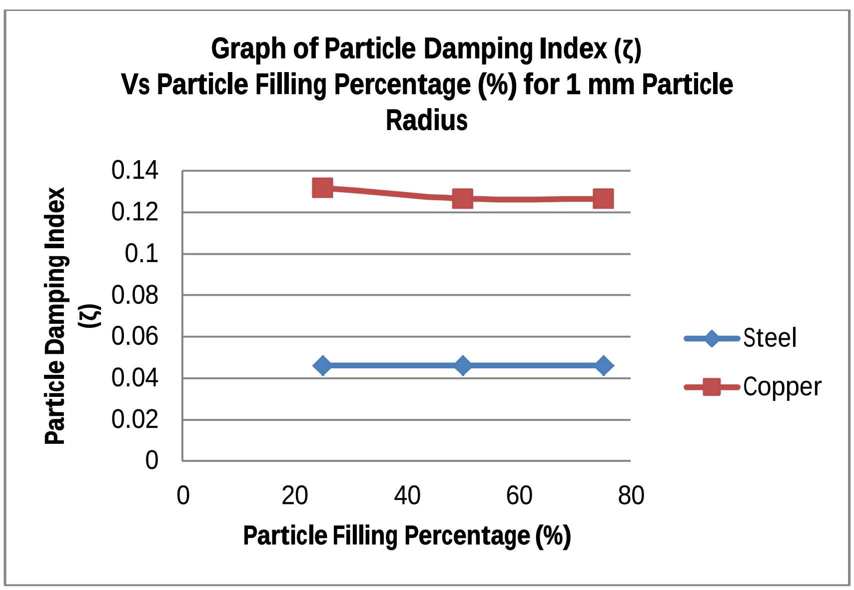

Fig. 11- Graph of Particle Damping Index (ζ) Vs Particle Filling Percentage (%) for 1 mm Particle Radius

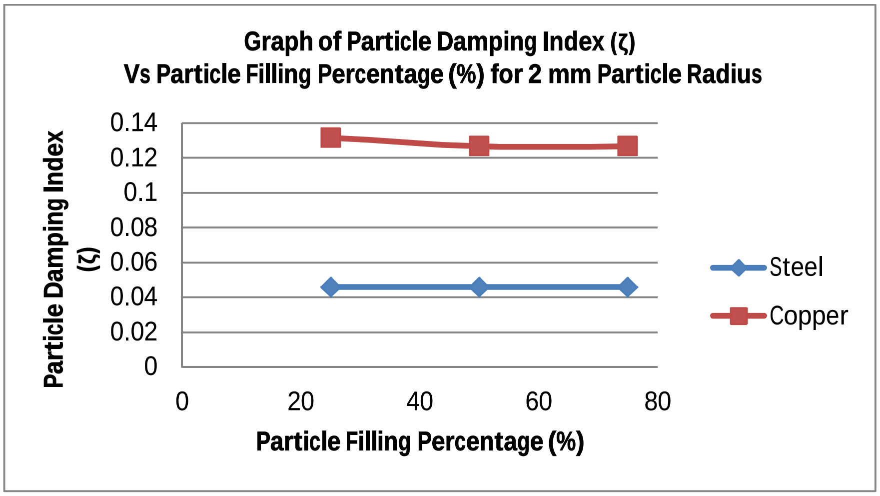

Fig. 12 - Graph of Particle Damping Index (ζ) Vs Particle Filling Percentage (%) for 2 mm Particle Radius

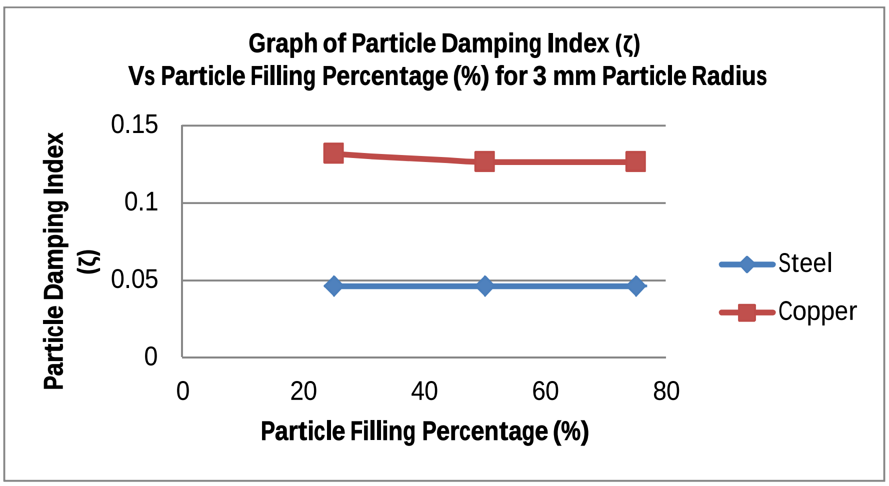

Fig. 13- Graph of Particle Damping Index (ζ) Vs Particle Filling Percentage (%) for 3 mm Particle Radius

B. Interpretation of Experimentation Results

From experimentation results, graph of Graph of Damping Effect Vs Particle Filling Percentage (%) for 1 mm, 2 mm and 3mm particle Radius are drawn which is shown in fig. 14, fig. 15 and fig. 16.

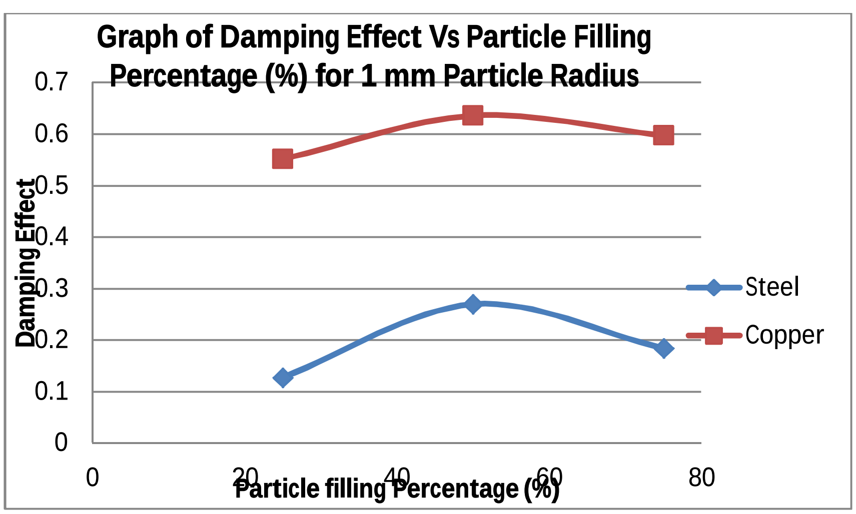

Fig. 14- Graph of Damping Effect Vs Particle Filling Percentage (%) for 1 mm Particle Radius

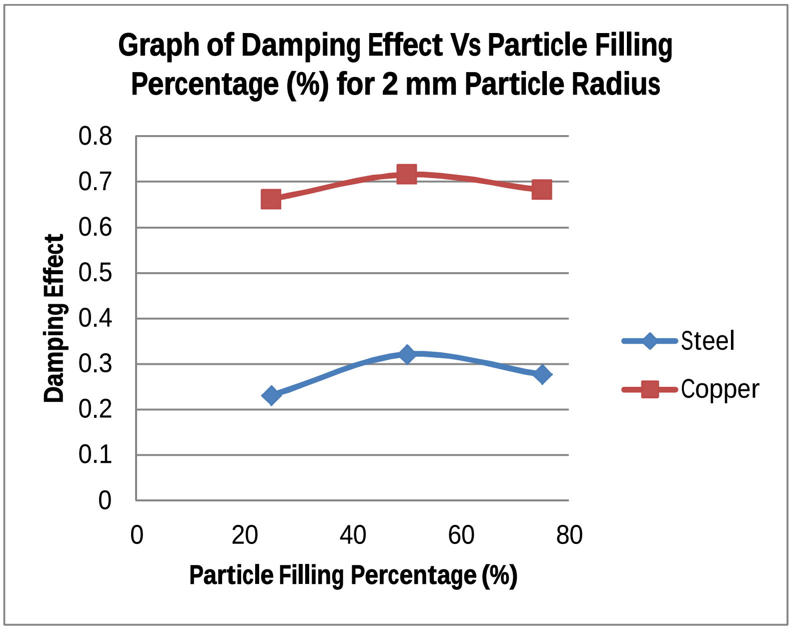

Fig. 15- Graph of Damping Effect Vs Particle Filling Percentage (%) for 2 mm Particle Radius

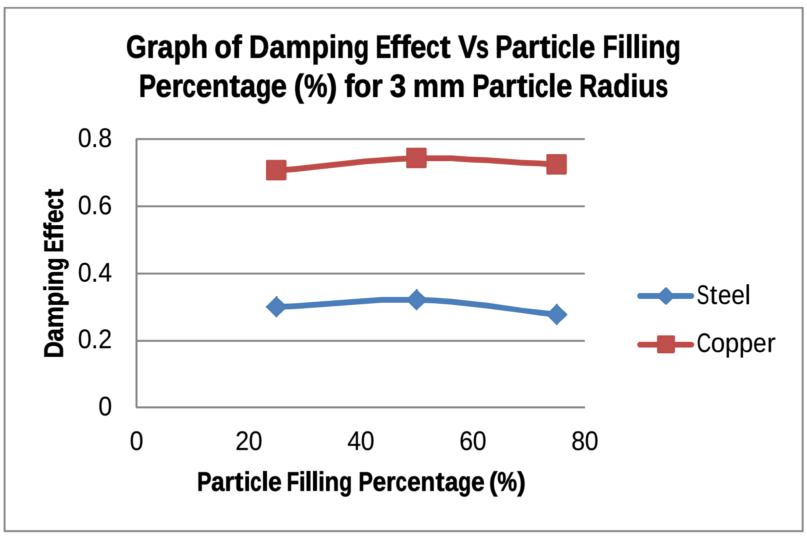

Fig. 16 - Graph of Damping Effect Vs Particle Filling Percentage (%) for 3 mm Particle Radius

VIII.OPTIMIZATION BY USING TAGUCHI METHOD (MINITAB SOFTWARE)

A. Optimization for simulation results

Table 8- Parameters and their levels

Parameters	Level 1	Level 2	Level 3
Particle material	Steel	Copper	Cast Iron
Radius of particles (mm)	1	2	3
Particle filling Percentage (%)	25 %	50 %	75 %

Response data : Particle damping index, Total energy (J)

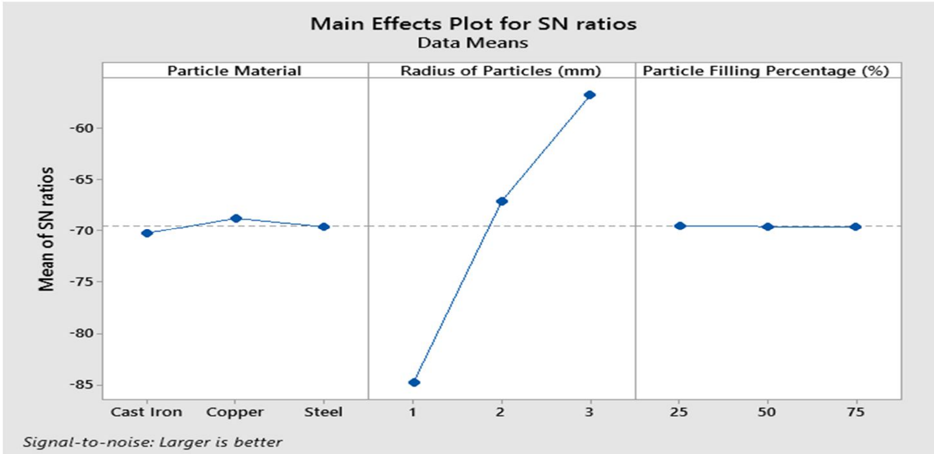

Fig. 17-Main effects plot for SN ratios

From fig. 17, it is clear that signal to noise ratio larger is better for following parameters.

Table 9- Parameters and SN ratio (Larger is better)

Parameters	SN ratio (Larger is better)
Particle Material	Copper
Radius of Particle	3 mm
Particle filling percentage	50 %

B. Optimization for Experimentation Results

Table 10- Parameters and their levels

Parameters	Level 1	Level 2	Level 3
Particle material	Steel	Copper	-
Radius of particles (mm)	1	2	3
Particle filling Percentage (%)	25 %	50 %	75 %

Response data : Damping effect

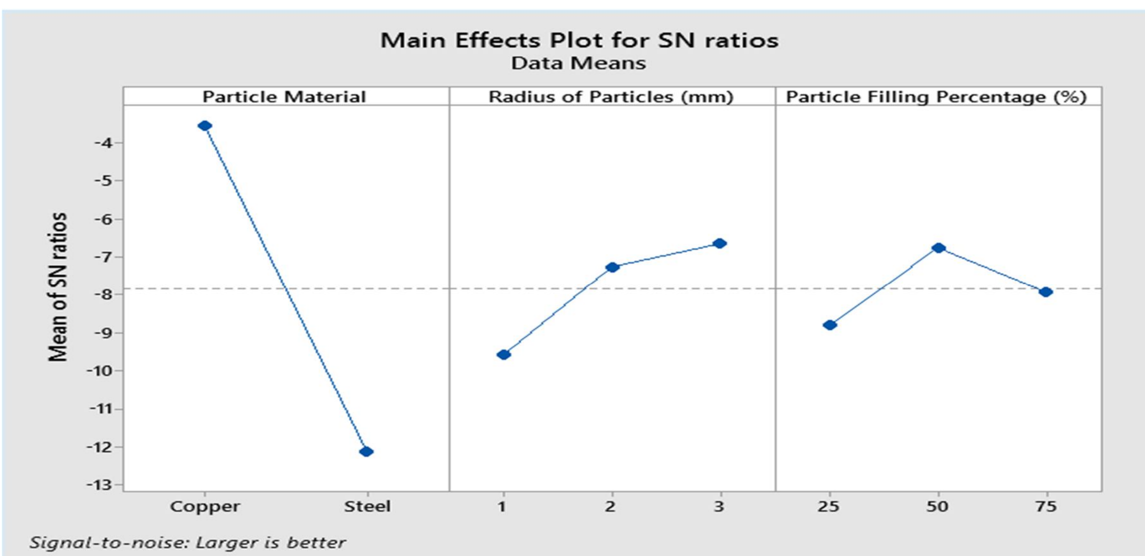

Fig. 18-Main effects plot for SN ratios

From fig. 18, it is clear that signal to noise ratio larger is better for following parameters.

Table 11- Parameters and SN ratio (Larger is better)

Parameters	SN ratio (Larger is better)
Particle Material	Copper
Radius of Particle	3 mm
Particle filling percentage	50 %

IX.CONCLUSION

Particle damping phenomenon studied with three important parameters such as particle material, particle size and particle filling percentage. Following conclusions can be drawn from simulation and experimentation results.

1) Discrete element method is effective to simulate the particle damping under centrifugal load.
2) Conclusions from simulation results,
a) Copper has higher particle damping index then steel and last cast iron. Hence copper has a better performance in energy dissipation among steel, copper and cast iron.
b) As radius of particles increases total energy associated with particles increases.
c) If material and radius of particles kept constant, particle filling percentage is increased as 25%, 50% and 75%, then the total energy associated with particles increases.

3) Conclusions from experimentation results,
a) Copper has better damping effect than steel.
b) As radius of particles increases damping effect increases.
c) If material and radius of particles kept constant, particle filling percentage is increased as 25%, 50% and 75%, then the damping effect increases upto 50 % then slightly decreases.

4) Optimization results for simulation and experimentation by using Taguchi method are same i. e. for better damping effect particle material is Copper, radius of particle is 3 mm and particle filling percentage is 50 %.

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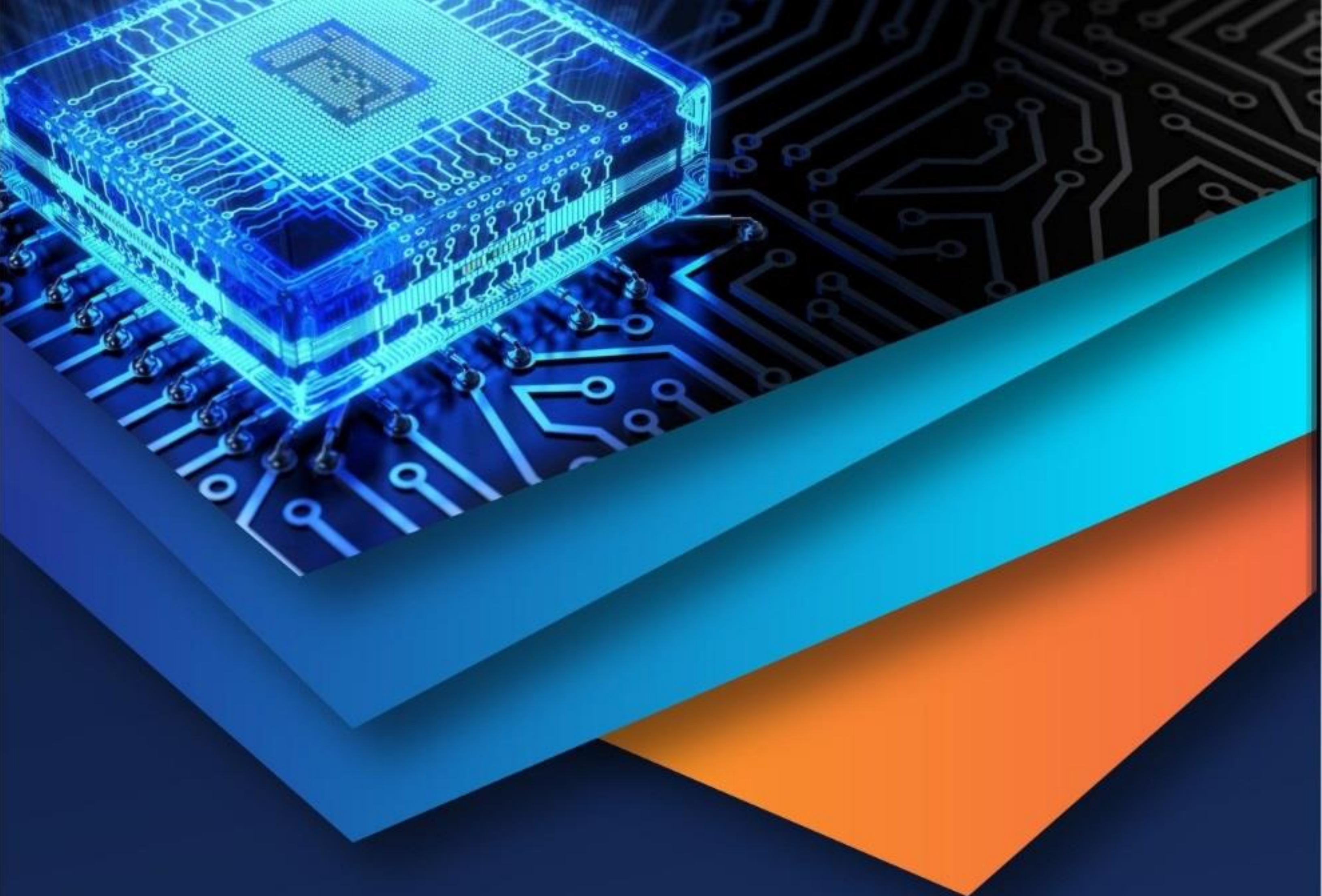

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