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Experimental and Numerical Study of Free Vibration Characteristics of Plates

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Abstract: The present experimental work deals with the study of free vibration characteristics of flexible rectangular stainless steel plates. Initially plates were fabricated in sets of two with aspect ratio 1. The investigation is carried out to assess the effect of boundary condition and variation of thickness on the Natural frequencies of plates. The results are presented in the form of fundamental natural frequencies for various modes. Experimental natural frequency obtained for different modes are compared with those from the Numerical study obtained by ANSYS Workbench.
Keywords: Stainless Steel, Aspect ratio, Ansys Workbench, Boundary conditions, Natural frequency

I. INTRODUCTION

In many engineering applications, the natural frequencies at which a body vibrates is of utmost importance. Estimating the natural frequencies of a vibrating body is a common aspect of dynamic analysis and can be referred to as Eigen value analyses. The un-damped free vibration response of a structure called mode shapes is also an important inherent property of a structure.

The free vibration response is caused by initial disturbance from the static equilibrium position. This disturbance causes amplitude which creates oscillations or motions which repeat at regular intervals of time, the cycles completed in one second gives its Natural Frequency. As we know the system will have maximum amplitude of vibration which causes failure of the system occurs when the excitation frequency is same as that of its Natural frequency. Therefore, it is necessary to determine system's Natural frequency so that it would be easier to avoid its Structural failure. This failure is applicable to large structures and small machine parts also. Not only bridges, towers and skyscrapers, but also blades, bearings, piping and fasteners can fail due to resonance. Air and gas vapour columns can also resonate at their natural frequencies and can lead to failures. Every system depending on its mass and stiffness when excited vibrates at its natural frequency, to change its Natural frequency either its mass or stiffness need to be changed. Damping is one of the methods which affect the Natural frequency of the system. Architects consider this while designing large and tall buildings. The Taipei 101, one the tallest building in the world, has a 660 Ton pendulum acting as mass damper to cancel any resonance. Hence there is a necessity to determine on how the Mass and Stiffness affects the Natural frequency of the system. Many of the previous studies have implemented various Experimental and Numerical methods to determine Natural frequency of the system.

In this study, a range of plates from thin plates to moderately thin plates based on Classic Plate Theory (CPT) whose aspect ratio kept as 1 are subjected to different boundary conditions and are excited by using Impact Hammer. The results obtained from Experiment are compared with the Numerical results obtained from ANSYS Workbench.

II. EXPERIMENTAL SET-UP

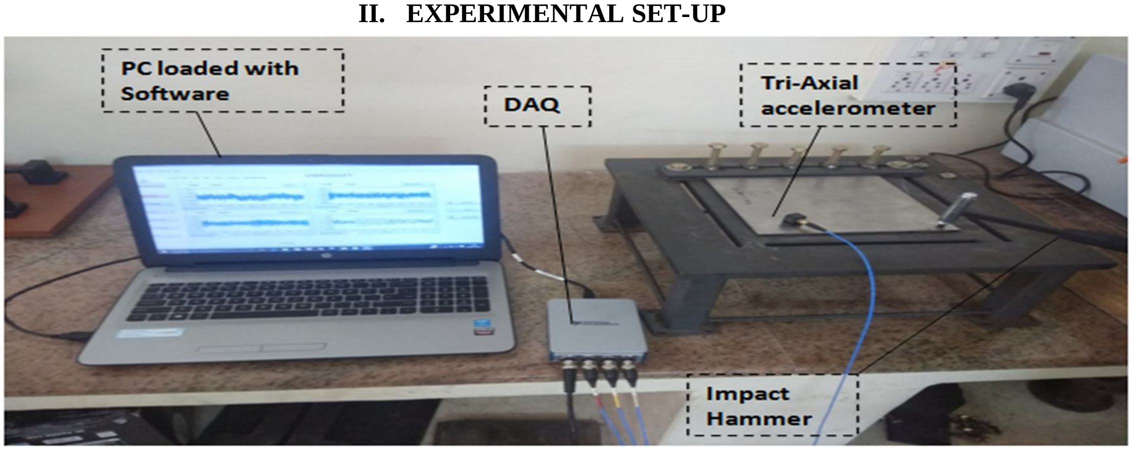

Fig.1 Experimental set-up

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Fig 1 shows the experimental set-up used in present study. The test specimens were made of stainless steel 304 with a cross-section of 200*200mm. Different thicknesses of plates is mounted on to the fixture. The Plate is attached to the fixtures and the experiment is conducted based on the different boundary conditions. Tri-axial accelerometer is then attached away from the Clamping boundary by the aid of paraffin wax. Vibrosoft software is used for Vibration measurements. The connections of DAQ, accelerometer, Impact Hammer, are as shown in fig1. Pre-trigger samples are taken by Impact Hammer and are recorded. The reading is plotted in the FRF graph. The peak obtained in the FRF graph is considered as excitation frequency. The natural frequencies are obtained by Numerical results and excitation frequencies which are closer to natural frequency are considered as resonance conditions. The damping factor is determined using the Half Power Band Width Method from FRF plots.Then compare the results of all boundary conditions with different thicknesses along with Numerical results.

Table 1
Material Specifications of Plate

Material	Stainless Steel 304L
Density, ρ	7880 kg/m^3
Young's Modulus, E	200GPa
Tensile yield Strength	215MPa
Tensile Ultimate Strength	505MPa
Poisson's ratio, μ	0.29

A. Experimental Cases

The experiment was conducted for free vibration of flexible square plates of stainless steel for different thicknesses for different boundary conditions were investigated experimentally by considering 20 cases shown in Table 3 to Table 7

Cases	Material	Thickness	Boundary Conditions
1	Stainless Steel 304	200*200*2	Clamped-Free-Free-Free (CFFF)
2	Stainless Steel 304	200*200*2	Clamped-Clamped-Free-Free (CCFF)
3	Stainless Steel 304	200*200*2	Clamped-Free-Clamped-Free CFCF
4	Stainless Steel 304	200*200*2	Clamped-Clamped-Clamped-Free CCCF

Table 3 Plate_2mm thickness

Cases	Material	Thickness	Boundary Conditions
1	Stainless Steel 304	200*200*4	Clamped-Free-Free-Free (CFFF)
2	Stainless Steel 304	200*200*4	Clamped-Clamped-Free-Free (CCFF)
3	Stainless Steel 304	200*200*4	Clamped-Free-Clamped-Free CFCF
4	Stainless Steel 304	200*200*4	Clamped-Clamped-Clamped-Free CCCF

Table 4 Plate_4mm thickness

Cases	Material	Thickness	Boundary Conditions
1	Stainless Steel 304	200*200*6	Clamped-Free-Free-Free (CFFF)
2	Stainless Steel 304	200*200*6	Clamped-Clamped-Free-Free (CCFF)
3	Stainless Steel 304	200*200*6	Clamped-Free-Clamped-Free CFCF
4	Stainless Steel 304	200*200*6	Clamped-Clamped-Clamped-Free CCCF

Table 5 Plate_6mm thickness

Cases	Material	Thickness	Boundary Conditions
1	Stainless Steel 304	200*200*8	Clamped-Free-Free-Free (CFFF)
2	Stainless Steel 304	200*200*8	Clamped-Clamped-Free-Free (CCFF)
3	Stainless Steel 304	200*200*8	Clamped-Free-Clamped-Free CFCF
4	Stainless Steel 304	200*200*8	Clamped-Clamped-Clamped-Free CCCF

Table 6 Plate_8mm thickness

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Cases	Material	Thickness	Boundary Conditions
1	Stainless Steel 304	200*200*10	Clamped-Free-Free-Free (CFFF)
2	Stainless Steel 304	200*200*10	Clamped-Clamped-Free-Free (CCFF)
3	Stainless Steel 304	200*200*10	Clamped-Free-Clamped-Free CFCF
4	Stainless Steel 304	200*200*10	Clamped-Clamped-Clamped-Free CCCF

Table 7 Plate_10mm thickness

III. RESULTS AND DISCUSSION

In the current study the Numerical study is carried by using Ansys Workbench 15.0. It is seen that Numerical values are in agree with the experimental values and percentage of error are calculated by using the following formula

$$\text{Percentage Of Error}(\%) = \left|\frac{\text{Numerical Frequency} - \text{Experimental Frequency}}{\text{Numerical Frequency}}\right| \times 100$$

The Error percentages of Natural frequencies are calculated for all plates of Different boundary conditions and for all modes are tabulated below. The Table 8 shows error percentages of Natural frequencies (Hz) for different boundary conditions for the plates of different thickness

Plate dimensions	Boundary conditions	Mode 1			Mode 2			Mode 3			Mode 4			Mode 5		
		Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
200*200*2	CFFF	33	41.87	21.19	97	101.85	4.76	295	256.12	15.18	339	326.99	3.67	383	371.09	3.21
200*200*2	CCFF	86	83.15	3.42	309	286.94	7.69	422	320.32	31.74	569	571.84	0.50	772	754.21	2.36
200*200*2	CFCF	249	267.71	3.25	306	317.85	3.73	528	523.75	0.81	737	738.23	0.17	805	808.97	0.49
200*200*2	CCCF	292	288.59	1.18	480	481.79	0.37	762	762.60	0.08	899	923.94	2.70	976	970.64	0.55
Plate dimensions	Boundary conditions	Mode 1			Mode 2			Mode 3			Mode 4			Mode 5		
		Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
200*200*4	CFFF	102	83.71	21.86	190	203.03	3.46	521	511.27	1.90	642	652.13	1.55	747	738.95	1.09
200*200*4	CCFF	168	165.99	1.21	557	572.09	2.64	677	639.01	5.95	1149	1137.60	1.00	1504	1501.50	0.17
200*200*4	CFCF	534	534.35	0.07	627	633.50	1.03	1054	1042.10	1.14	1473	1469.90	0.21	1614	1609.00	0.31
200*200*4	CCCF	589	575.77	2.30	944	959.61	1.65	1503	1518.00	0.98	1845	1837.40	0.41	1924	1929.10	0.26
Plate dimensions	Boundary conditions	Mode 1			Mode 2			Mode 3			Mode 4			Mode 5		
		Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
200*200*6	CFFF	124	125.47	1.17	308	303.06	1.63	743	764.34	2.79	956	974.06	1.85	1104	1100.80	0.29
200*200*6	CCFF	256	248.21	3.14	889	853.47	4.16	926	954.63	3.00	1691	1691.50	0.03	2227	2235.40	0.38
200*200*6	CFCF	800	798.46	0.19	943	944.05	0.11	1541	1549.70	0.56	2192	2187.00	0.23	2383	2388.70	0.24
200*200*6	CCCF	803	859.61	1.35	1403	1429.40	1.85	2258	2257.30	0.03	2732	2730.90	0.04	2864	2862.60	0.05
Plate dimensions	Boundary conditions	Mode 1			Mode 2			Mode 3			Mode 4			Mode 5		
		Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
200*200*8	CFFF	166	166.13	0.08	401	400.97	0.01	1006	1009.60	0.36	1291	1290.10	0.07	1451	1451.50	0.03
200*200*8	CCFF	328	328.18	0.05	1124	1125.80	0.16	1248	1258.60	0.84	2230	2221.20	0.40	2936	2933.10	0.10
200*200*8	CFCF	1040	1047.30	0.70	1230	1239.10	0.73	2025	2036.10	0.55	2845	2851.80	0.24	3114	3116.40	0.08
200*200*8	CCCF	1019	1127.70	9.64	2211	1873.30	18.03	2930	2943.40	0.46	3611	3568.70	1.19	3784	3725.60	1.57
Plate dimensions	Boundary conditions	Mode 1			Mode 2			Mode 3			Mode 4			Mode 5		
		Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)	Exp	Num	Error (%)
200*200*10	CFFF	196	207.01	5.32	501	498.14	0.57	1248	1253.50	0.44	1590	1602.40	0.77	1796	1796.70	0.04
200*200*10	CCFF	486	408.09	19.09	1386	1395.20	0.66	1567	1560.20	0.44	2738	2739.40	0.05	3618	3615.50	0.07
200*200*10	CFCF	1296	1296.30	0.02	1535	1531.60	0.22	2503	2512.10	0.36	3508	3505.50	0.07	3828	3826.30	0.04
200*200*10	CCCF	1404	1395.10	0.64	2305	2311.20	0.27	3614	3616.70	0.07	4386	4384.60	0.03	4567	4564.90	0.05

Table 8 Comparison of Experimental and Numerical study

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From the Table 8,

1) For 2mm thickness plate, the error percentage is 21.19% for Mode 1 of CFFF boundary condition and 15.18% for Mode 3 of CFFF boundary condition which are higher compared to remaining modes; this is because for a 2mm plate in CFFF boundary condition the degree of freedom is high which results in more vibrations with frequent phase changes. At this condition it is difficult to identify maximum displacement peaks corresponding to its Natural frequency. The error percentage is more (31.74%) in Mode 3 of CCFF boundary condition. This is because the difference between Mode 2 and Mode 3 frequencies of CCFF condition is less, therefore it is difficult to extract displacement peak for each consecutive mode from FRF plot resulting in maximum error.

2) For 4mm thickness plate, the error percentage is 21.86% for Mode 1 of CFFF boundary condition is observed. Similar to 2mm thickness plate, in 4mm thickness plate also it is difficult to extract displacement peak for lower modes especially in CFFF boundary condition where the degree of freedom will be higher.

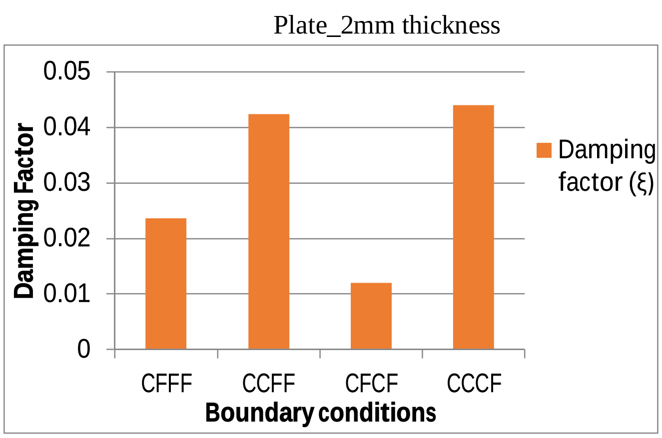
3) For 6mm thickness plate, the maximum error percentage is 4.13% and 2.99% for Mode 2 and Mode 3 of CCFF boundary condition respectively; this is due to the less difference in Mode 2 and Mode 3 Natural frequencies.

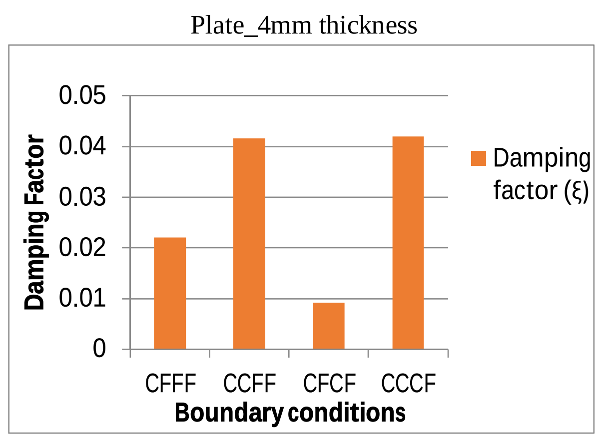
4) For 8mm thickness plate, the maximum error percentage is 18.027% and 9.639% for Mode 2 and Mode 1 of CCCF boundary condition respectively; this is due to the high frequency range especially for CCCF condition and it is difficult to extract displacement peaks for the lower modes where the first Natural frequency starts.

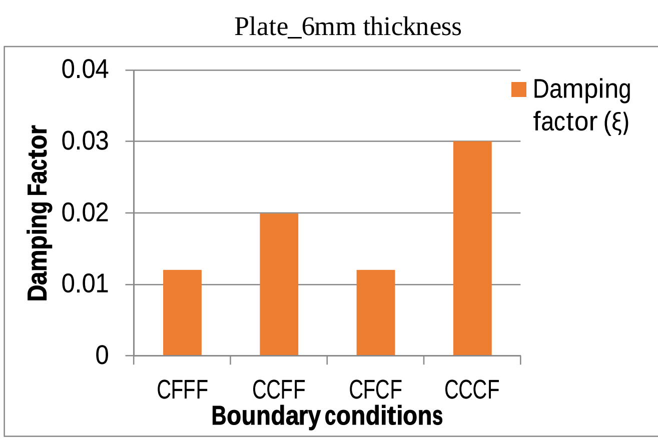
5) For 10mm thickness plate, the maximum error percentage is 19.09% and 5.318% for Mode 1 of CFFF and Mode 1 of CCFF boundary condition respectively; the Mode 1 and Mode 2 frequencies of CFFF and CCFF are the lowest frequencies compared to the other frequencies of different boundary conditions. Therefore a small deviation from Experimental frequencies will result in high error percentage.

A. Effect of Boundary conditions on Damping Factor

The effect of Boundary conditions on damping factor for various boundary conditions and for plates of all thicknesses has been plotted below.







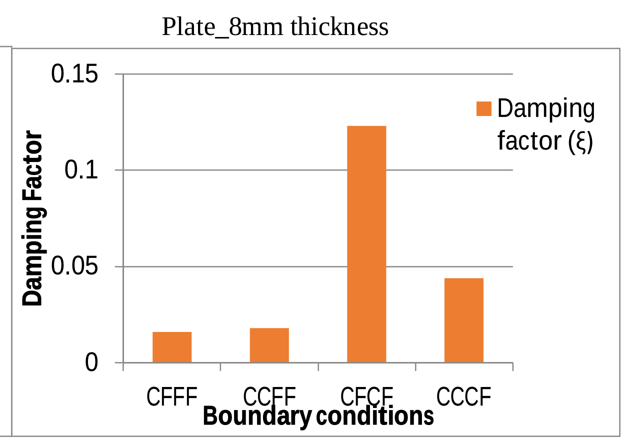


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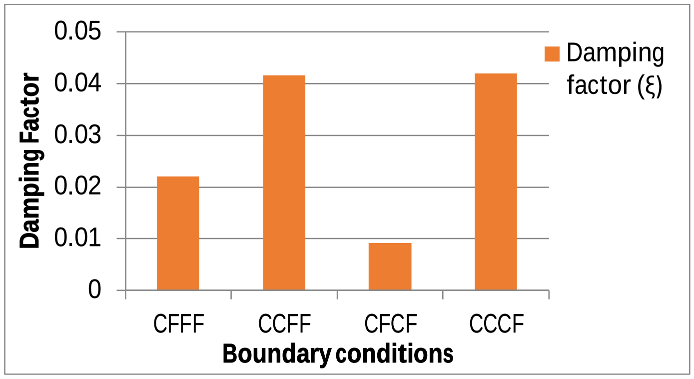
Plate_10mm thickness



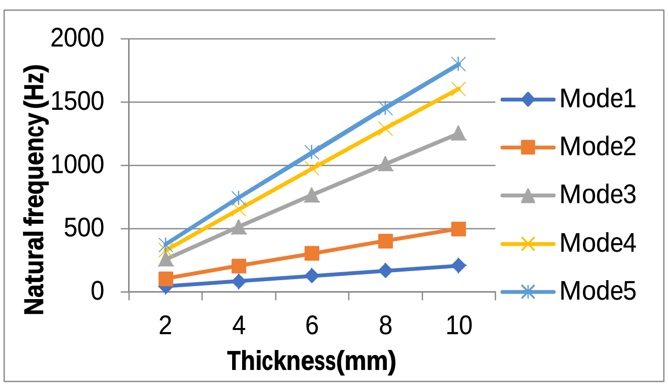
From the above graphs it can be concluded that:-

1) For the Plates of 2mm, 4mm and 10mm thickness, the Damping Factor is high for CCCF and CCFF boundary conditions where as it is low for CFFF and CFCF boundary conditions. Also, Damping factor is nearly same for CCCF and CCFF boundary conditions.
2) For Plates of 6mm and 8mm thickness the Damping factor is maximum at CFCF boundary condition and CCCF boundary condition respectively.
3) Based on above two observations, thick plates such as 8mm and 10mm thickness damped more due to higher mass, hence the displacement is minimum and the damping factor is nearly same for different boundary conditions.

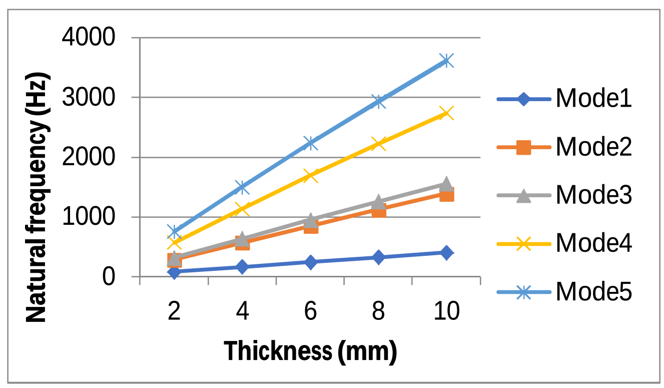
B. *Effect of Thickness on Natural Frequency*

The effect of thickness of plate on Natural frequency for various boundary conditions has been plotted below.

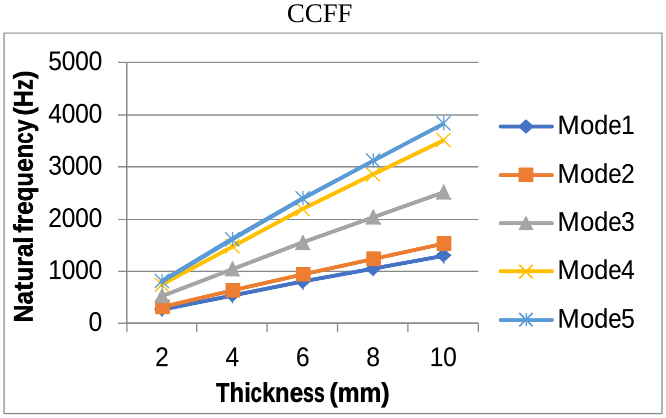
CFFF



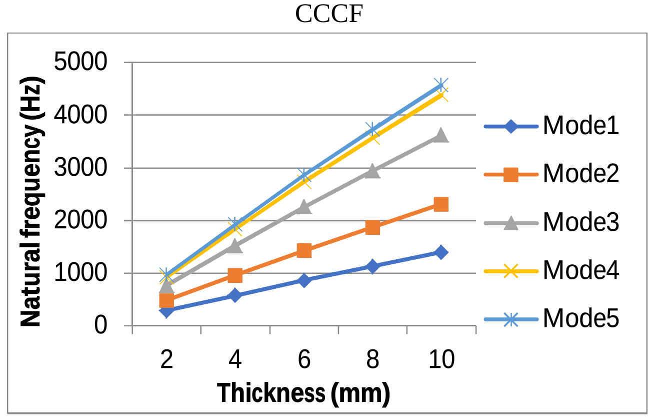
CFCF



CCFF



CCCF



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From the above graphs it can be concluded that:-

1) Natural frequency increases with the increase in the thickness of the Plate. It can be clearly evidenced from the graph, as the thickness changes the Natural frequencies are also increasing for all the Boundary conditions. Therefore it can be said that the Natural frequency increases linearly with the increase in the Thickness irrespective of the Boundary conditions.

C. Effect of Boundary Conditions on Natural Frequency

The effect of thickness of plate on Natural frequency for various boundary conditions has been plotted below.

Plate_2mm thickness

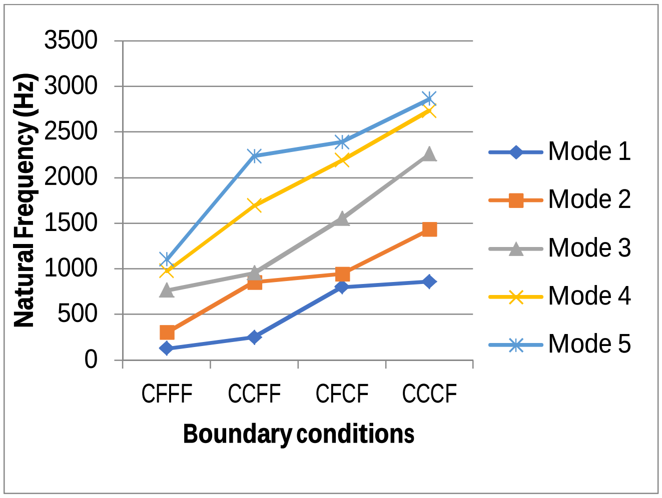


Plate_4mm thickness

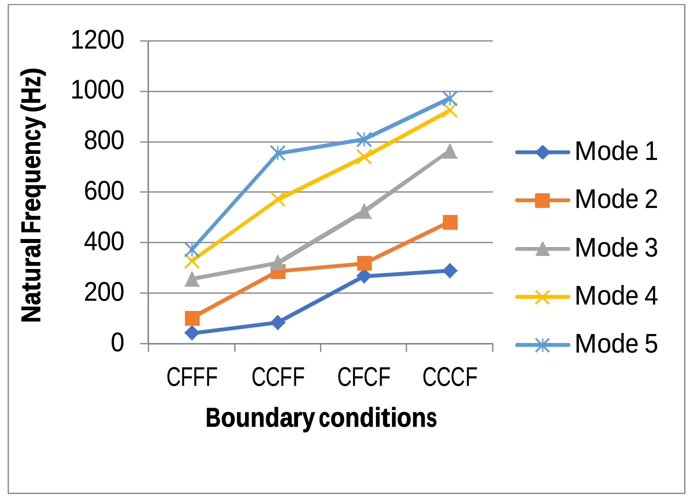


Plate_6mm thickness

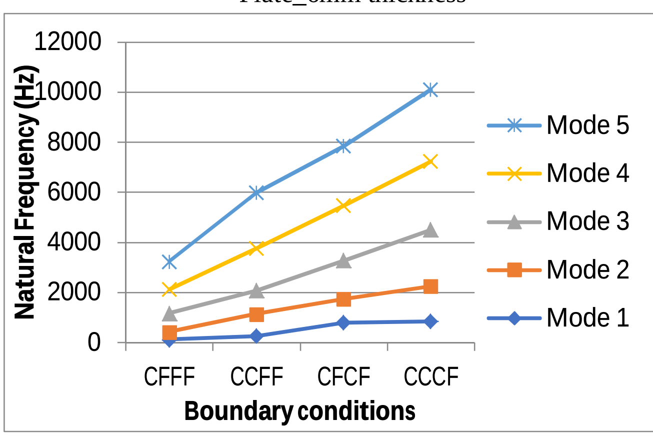


Plate_8mm thickness

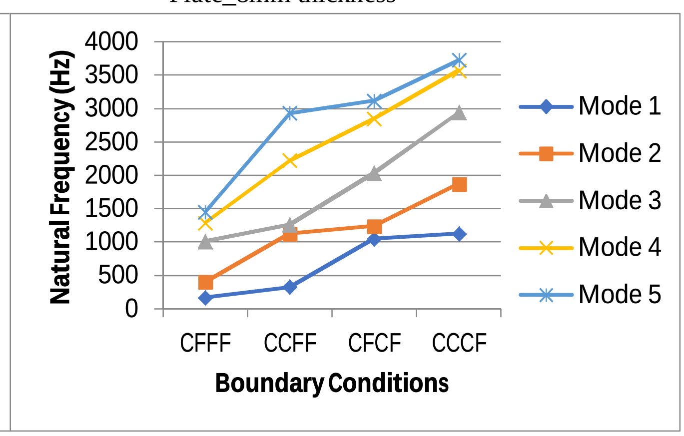
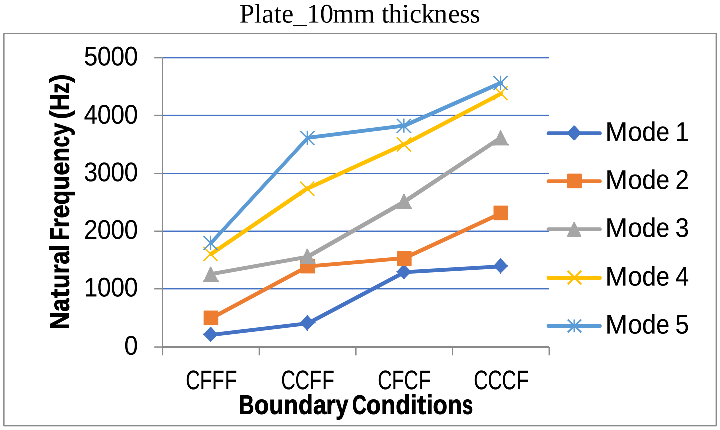


Plate_10mm thickness



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From the above graphs it can be concluded that:-

1) Natural frequencies increase as the DOF of the system decreases giving less amplitude of displacement resulting in more cycles per second i.e., frequency.
2) This can be further extended for Point supports, simply support structures and corner clamped structures to obtain the relationship between DOF of the system to its Natural frequency.

IV. CONCLUSIONS

In this study, the Experimental Modal Analysis is compared with the Numerical study and the following Conclusions were made:

A. Based on observation, the difference in the Natural frequencies of Mode 2 and Mode 3 for CCFF boundary conditions is very less compared to other modes of different boundary conditions.
B. The Percentage error was maximum for lower modes of Natural frequencies in CFFF and CFCF boundary conditions irrespective of thickness.
C. The Percentage error was maximum for high range of Natural frequencies in CCCF boundary condition.
D. The Damping Factor is maximum for CCCF (three edges fixed) and CCFF (two adjacent edges fixed) boundary conditions.
E. As the thickness of the Plate increases the plate is damped due to mass of the plate rather than the boundary conditions and the difference in Damping Factor for different boundary conditions is very less.
F. The Natural frequency of the Plate increases linearly with the thickness of the plate.
G. The Natural frequency of the Plate increases with the increase in the constraints to the boundary conditions in the order of CFFF (one edge fixed), CCFF (two adjacent edges fixed), CFCF (two opposite edges fixed) and CCCF (three edges fixed).

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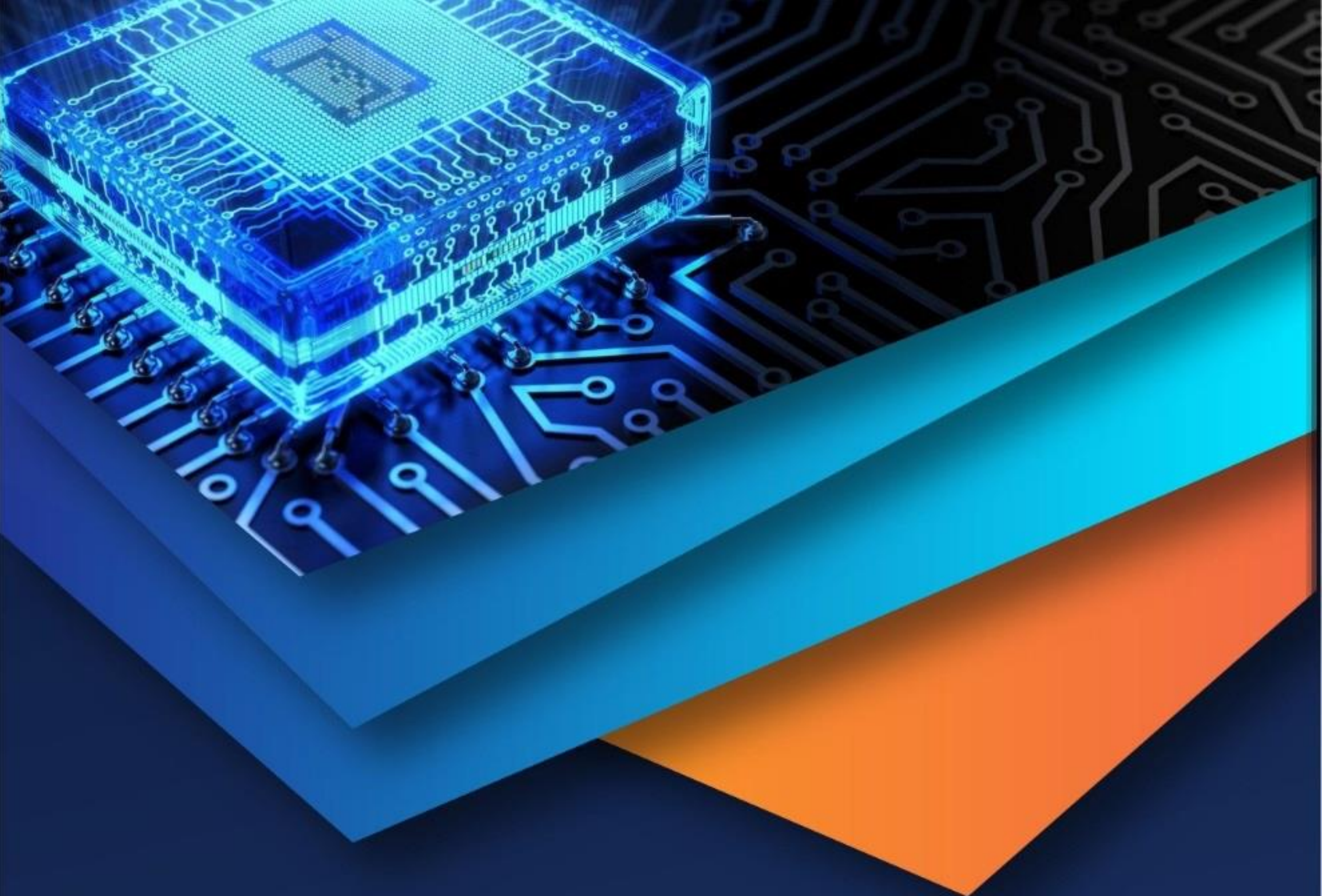

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