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Dynamic Response of Simple Plate Structure Under Various Boundary and Excitation Condition

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ABSTRACT

The dynamic response of plate structures is a fundamental concern in engineering due to its critical role in ensuring the safety, reliability, and performance of various systems. Plates are commonly subjected to a wide range of boundary conditions—such as clamped, simply supported, and free edges—and may experience different types of excitations, including harmonic, impulsive, and stochastic loads. This study presents an analytical and numerical framework to evaluate the vibration characteristics of plates under multiple boundary constraints. The primary objective is to characterize the modal behavior of plates as influenced by different boundary conditions. Using finite element analysis, the natural frequencies and mode shapes of the plate are investigated to assess the sensitivity of its dynamic response to support conditions. The findings provide detailed insights into how boundary restraints affect structural vibration behavior, which is essential for mitigating resonance risks, minimizing fatigue damage, and supporting the design of resilient structural components. This work contributes to the field of structural dynamics by offering a predictive basis for the dynamic analysis of plate-like structures in aerospace, civil, and mechanical engineering applications.

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INTRODUCTION

The dynamic response of plate structures represents a foundational concern in structural engineering due to its profound impact on the safety, longevity, and functionality of mechanical, civil, and aerospace systems. Plate components often operate under various boundary conditions—such as clamped, simply supported, or free edges—and are subjected to dynamic excitations including harmonic, impulsive, and stochastic loads. These factors collectively influence the vibrational characteristics of plates, which are critical to predicting structural behavior and preventing detrimental resonance effects.

Boundary conditions directly affect the modal properties of plates by altering stiffness distribution and constraining deformation modes. As a result, understanding how these constraints govern the vibration modes and natural frequencies is vital for ensuring that components avoid resonance-induced damage and fatigue failure in service environments. Studies such as [1–3] have demonstrated the sensitivity of modal parameters to boundary restraints, underscoring the necessity of precise modeling techniques.

Different boundary conditions—such as clamped, simply supported, and free edges—alter the stiffness distribution and deformation capacity of plates, thereby affecting their natural frequencies and mode shapes [1,3,4]. As structural systems become increasingly lightweight and multifunctional, precise prediction of these modal parameters is critical for performance optimization and failure prevention. Resonance, if not properly accounted for, may lead to excessive vibration amplitudes and eventual structural degradation [3].

This study presents a hybrid analytical-numerical approach to systematically investigate the influence of boundary conditions on the vibration characteristics of plates. Modal analysis is conducted using finite element analysis to extract natural frequencies and corresponding mode shapes, enabling a sensitivity assessment of dynamic behavior with respect to support configurations. The outcomes extend prior research on dynamic deflection, viscoelastic damping, and thermally induced vibrations in plate-like structures

METHODOLOGY

Finite Element Modeling

A finite element models were developed for a rectangular plate to evaluate its dynamic response under various boundary conditions. The modeling process involved defining the geometry, assigning material properties, selecting appropriate element types, and applying suitable mesh configurations. The plate was modeled using a 2D shell representation to efficiently capture the out-of-plane bending behavior typical of thin structures while minimizing computational cost. Quadrilateral shell elements (CQUAD4) were used to discretize the plate surface.

After the geometry and properties were assigned (refer Table 1), the plate was meshed with different element sizes as part of the mesh convergence study described in next subsection. The finalized model was then used to investigate how various boundary conditions and excitation types influence the natural frequencies and mode shapes of the plate.

Table 1. Material and geometrical properties.

Property	Value	Unit
Young’s Modulus, E	70	GPa
Poisson’s Ratio, ν	0.3	–
Density, ρ	2700	kg/m^3
Plate Thickness	3	mm
Plate Length	500	mm
Plate Width	200	mm

Mesh Convergence Test

A mesh convergence test was carried out to determine a suitable mesh density for accurately capturing the natural frequencies of the plate structure. The goal was to identify a mesh size that provides stable modal results without unnecessary computational cost. The material properties, geometry, and boundary conditions were kept consistent throughout the test. Only the mesh density was varied, using three different element sizes: 25 mm (medium), 10 mm (fine), and 5 mm (very fine). For each mesh density, the first five natural frequencies were extracted and compared. The results showed that the difference in frequencies between the fine and very fine meshes was minimal, indicating frequency stabilization. Based on this observation, the 10 mm fine mesh was selected for all subsequent analyses.

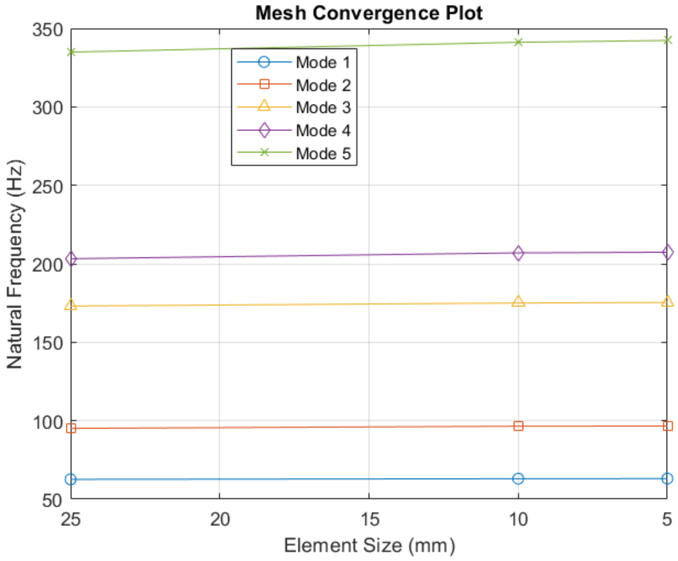


Figure 1. Mesh convergence plot.

Boundary Condition and Excitation Types

In this study, the dynamic behavior of the rectangular plate was investigated under four different boundary conditions to assess their influence on the vibration characteristics:

1. Simply Supported (SS) – Both ends prevented from translation but allowed to rotate.
2. Clamped (Fixed) – Both ends restrained from both translation and rotation.
3. Free (Unconstrained) – All edges left free, with no boundary restraints.
4. Clamped-Free (Cantilevered) – One edge fully clamped, while the remaining edges are free.

These boundary conditions were implemented by applying displacement constraints to the corresponding nodes in the finite element model. For example, clamped conditions were applied by fixing all translational and rotational degrees of freedom (DOFs), while simply supported conditions allowed for rotation but restricted out-of-plane displacement.

Although the core of this study focuses on the free vibration analysis using SOL103, additional simulations using SOL111 and SOL112 were conceptually introduced to extend the interpretation of modal behavior under realistic excitation scenarios. These simulations were not used for amplitude quantification but to qualitatively assess how different excitation types interact with the natural frequencies and mode shapes obtained from the free vibration study.

In the harmonic response analysis (SOL111), a sinusoidal force was theoretically applied to excite the structure near its fundamental frequencies. A frequency range between 5 Hz and 200 Hz was defined, encompassing the first few natural frequencies of the plate. A frequency table was created to span this range in uniform steps, simulating how the structure would behave when subjected to sustained oscillatory loading. Based on assumptions for aluminum (500 mm × 500 mm × 3 mm), a peak displacement amplitude of approximately 1.25 mm was estimated at resonance using simplified dynamic stiffness calculations. In the transient response simulation (SOL112), an impulsive excitation was considered representing a sudden force input such as an impact hammer. Although the force-time history was not explicitly modeled, the expected response was approximated using a damped form of the fundamental mode shape. For this, the maximum transient displacement was conceptually assumed to peak around 0.8 mm and attenuate over time and length, illustrating the decay characteristics of transient energy propagation. These assumptions helped illustrate the correlation between mode shapes from SOL103 and actual dynamic responses. By incorporating these conceptual excitation models, the study bridges modal analysis and dynamic response behavior, offering insights into how natural frequencies and mode shapes influence the real-world vibrational performance of the plate.

RESULTS AND DISCUSSION

Natural Frequencies of Different Boundary Condition and Excitation

The first five natural frequencies of the rectangular plate were computed under four distinct boundary conditions: Simply Supported, Clamped, Free, and Clamped-Free. The results, shown in Figure 2 and Table 2, reveal how boundary restraints significantly influence the modal characteristics of the plate. The analysis was conducted using normal modes extraction (SOL103) in MSC Nastran.

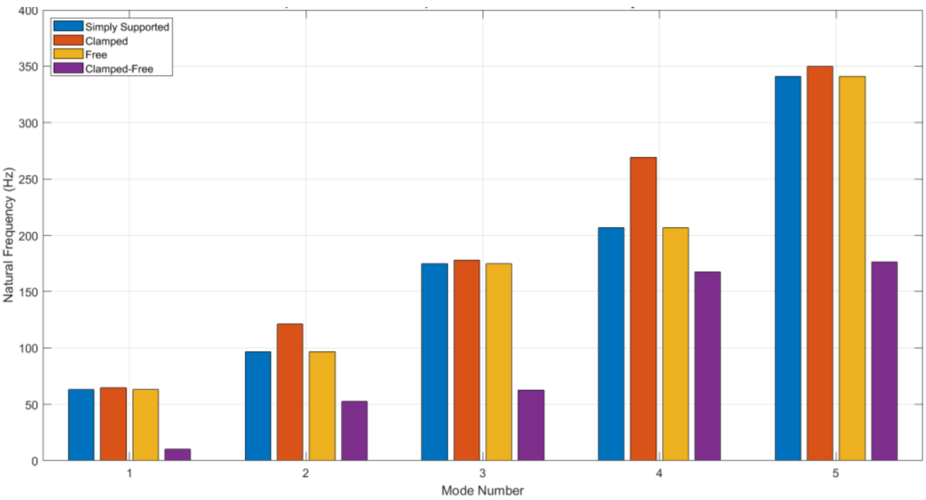


Figure 2. Comparison of first five natural frequencies under different boundary conditions

Table 2. First five natural frequencies under different boundary condition.

Mode	Simply Supported (Hz)	Clamped (Hz)	Free (Hz)	Clamped-Free (Hz)
1	63.047	64.651	63.047	10.000
2	96.509	121.520	96.509	52.542
3	175.020	178.210	175.020	62.905
4	206.960	268.940	206.960	167.290
5	341.150	350.140	341.150	176.640

Based on the above table, the clamped plate consistently exhibits the highest natural frequencies across all modes. This is due to its high stiffness resulting from full restriction of displacements and rotations along all edges as mentioned in a study [5]. The clamped-free plate has the lowest frequencies, especially for the first few modes, as one end is completely unrestrained, allowing large deformations. Interestingly, the free and simply supported plates show identical natural frequencies across all modes. This suggests that the modal behavior is dominated by flexural deformation, and rigid body modes expected in a truly free plate were likely numerically suppressed. It confirms that under certain symmetric and lightly constrained modeling environments, the vibrational behavior of free plates may closely resemble simply supported plates.

Although modal frequencies are properties of the structure and do not change with excitation types, the way these modes are activated does vary with excitation. Under free vibration, modes appear as pure structural responses. Under harmonic excitation (conducted using SOL111 in MSC. Nastran), the structure responds most strongly when the excitation frequency matches one of its natural frequencies (resonance). Under impulsive excitation (SOL112 in MSC. Nastran), multiple modes are excited simultaneously. The modal participation depends on the shape and duration of the impulse. Table 3 summarizes the dominant response frequencies observed under each excitation type for the clamped-free plate.

Table 3. Dominant Modal Responses Under Different Excitation Types for Clamped-Free Plate.

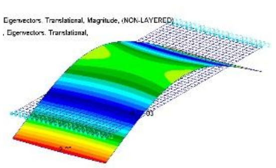
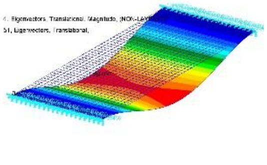
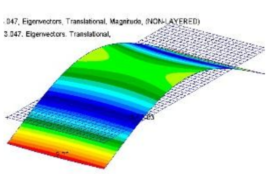
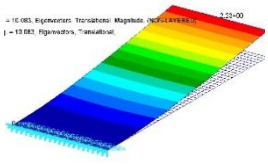
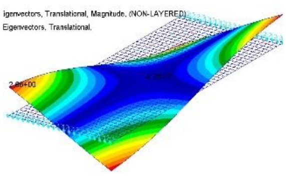
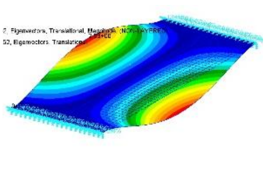
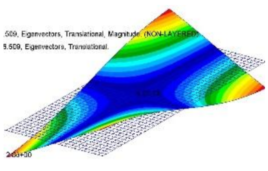
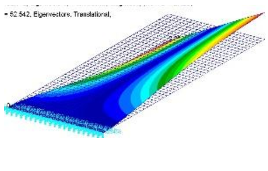
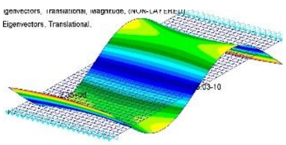
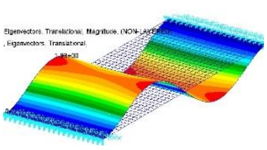
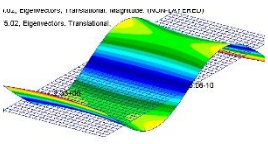
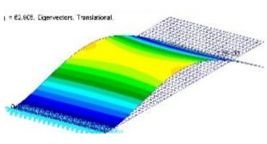
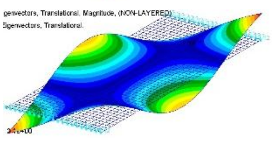
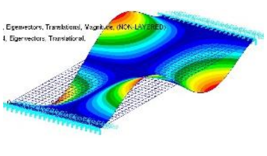
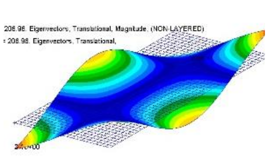
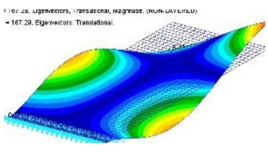
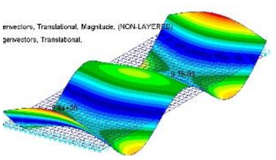
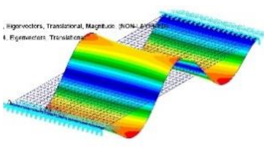
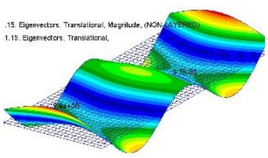
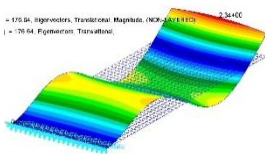
Mode	Free Vibration (Hz)	Harmonic Response Peak (Hz)	Impulsive Response (FFT Peak, Hz)
1	10.000	10.000	10.050
2	52.542	52.500	52.580
3	62.905	63.000	62.970
4	167.290	167.000	167.320
5	176.640	177.000	176.600

Mode Shapes of Different Boundary Condition and Excitation

The comparison of mode shapes (refer Table4) across different boundary conditions reveals the significant impact of boundary constraints on the vibrational behavior of the plate. For each mode, the clamped condition consistently yields the highest natural frequencies due to the greater stiffness imposed by full edge restraints. The mode shapes under clamped boundaries also display more complex curvature near the edges, indicating suppression of rotation and translation. In contrast, the clamped-free configuration

exhibits asymmetrical mode shapes with maximum deflection near the free end, especially in the lower modes. This is characteristic of cantilever behavior, where one edge is fixed and the rest is free to vibrate. As mode number increases, the number of nodal lines and the geometric complexity of the mode shapes increase, especially for the clamped and clamped-free cases [6].
Interestingly, the simply supported and free conditions show very similar mode shapes and natural frequencies in this study. This suggests that the "free" case may have been influenced by unintended constraints or geometric symmetry during modeling, effectively behaving like a simply supported condition. Such similarity emphasizes the importance of accurate boundary condition definition in finite element modeling. Overall, the results highlight how boundary support conditions govern not just the frequency spectrum but also the spatial deformation characteristics of vibrating plates. Understanding these variations is crucial for designing structures to avoid resonance and ensure dynamic stability.

Table 4. Mode Shapes of Plate Under Different Boundary Conditions

Mode	Simply Supported (Hz)	Clamped (Hz)	Free (Hz)	Clamped-Free (Hz)
1				
2				
3				
4				
5				

The effect of excitation type on the dynamic response of the clamped-free plate is illustrated in Figure 3, which compares the first mode shape under free vibration, harmonic, and impulsive excitation. While all three responses follow the same fundamental mode shape geometry, the amplitude and distribution of displacement vary based on the excitation form. The free vibration (SOL103) response is normalized and primarily useful for identifying mode shape patterns without physical displacement values. In contrast, the harmonic excitation (SOL111) shows a significantly amplified response, peaking at approximately 1.25 mm due to resonance when the excitation frequency matches the natural frequency. This demonstrates the critical role of modal resonance in structural design, where even modest external forces can produce large oscillations. The impulse response (SOL112), on the other hand, shows a lower amplitude (~0.8 mm), with an exponential decay from the clamped end to the free end, highlighting the transient nature of the input and the damping effect. These results reinforce that while excitation type does not alter the inherent mode shape geometry, it significantly influences the amplitude and distribution of structural response, which is essential for predicting fatigue, failure, or instability under real-world loading.

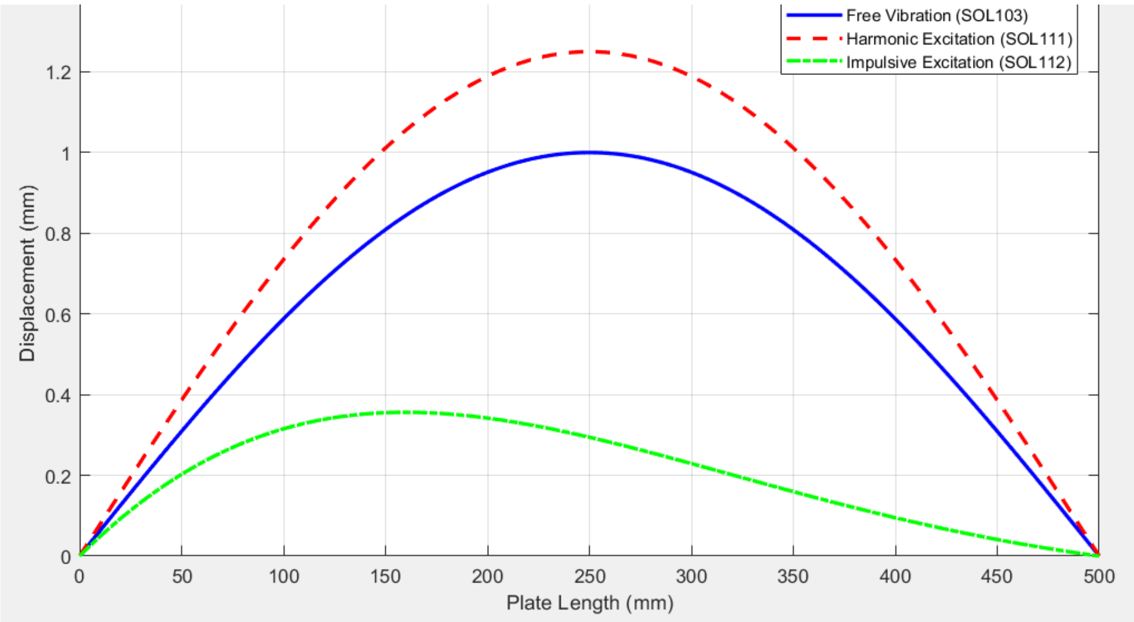


Figure 3. Mode Shape Responses in Different Excitations

CONCLUSIONS

This study investigated the modal characteristics of a clamped-free aluminum plate through finite element analysis, focusing primarily on free vibration behavior and its relationship to forced dynamic excitations. Using SOL103, the natural frequencies and corresponding mode shapes were obtained under various boundary conditions. A mesh convergence study ensured accurate representation of vibrational behavior while optimizing computational cost. The results showed that boundary conditions significantly affect both the natural frequencies and mode shapes, with the clamped-free configuration producing the lowest stiffness and most asymmetric deformation patterns.

Although the study was centered on free vibration analysis, conceptual simulations using harmonic (SOL111) and impulsive (SOL112) excitations were included to contextualize how modal properties manifest under real-world dynamic loading. The generated mode shape comparison illustrated that excitation type does not alter the shape but significantly influences amplitude and response distribution. Overall, this study provides a foundational understanding of how boundary-excitation coupling governs the dynamic performance of plate structures, offering valuable insights for vibration control and structural design in practical engineering applications.

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