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Comparison of Modal Parameters of a Square Steel Plate Using Finite Element Method and Operational Modal Analysis

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Abstract: In engineering domains, modal analysis is a field that is studied extensively with the goal of better characterizing components or structures. The modal analysis produces modal parameters, which are essential properties of a system that can be employed for damage identification, vibration analysis, and structural health monitoring. Plated element's relevance in various applications makes it an intriguing vibration study subject. In this research, modal analysis was performed on a square steel plate in free ends condition. This work aimed to provide a complete anatomical description of this complex boundary condition and its implications on modal parameters. Before comparing modal parameters with experimental data, a primary modal analysis was performed using finite element (FE) method. Then experimental analysis was conducted under the operational modal analysis setup (OMA). As the results, six natural frequencies are retrieved and compared amongst the two methods, recording the maximum of 6% percentage difference from the readings. This implied a close values estimated between the methods used. For mode shapes, nine modes are identified from FE method and discussed according to established free plate vibration studies, while three similarly identified modes successfully recognized by using OMA.

Keywords: Dynamic properties, operational modal analysis, steel plate, natural frequencies, mode shapes

1. Introduction

Vibration issues are frequently encountered in various engineering and have been associated with a vast scope of machine and structure components. The modal qualities of a structure are its distinguishing features in terms of how it reacts to vibrations-different types of structures experience vibrations in distinct frequency ranges. Extremely high vibrations can occur in a design if the excitation frequency is either higher than or equal to the system's natural frequency [1]. Therefore, it is essential to conduct an analysis for checking natural frequencies at which structures operate when subjected to loading. Modal analysis is a method for characterising the geometry's (the structure's) innate attributes, such as damping, mass, mode shapes (dynamic properties), and natural frequency [2].

Additionally, it was proposed that exploiting the change in natural frequencies can detect structural degradation [3]. Since then, researchers have examined the effectiveness of frequency shifts as a diagnostic tool for structural degradation [4]-[8]. Resonant vibrations are defined technically by a straightforward and efficient usage of modes. Modes are also known as inherent features of a structure. The interaction of a structure's elastic characteristics and the inertial mass

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generates this parameter. Modal analysis is beneficial for structural analysis since it highlights problematic areas of design that need improvements [9].

Numerous element types and materials have been tested under modal analysis to study the effects of modification on modal characteristics. As plated structures are an integral aspect of good load carrying and a significant building component in the construction industry, modal analysis on plated parts also has interested research communities. The modal parameters of a thin aluminium isotropic plate were determined by conducting a modal analysis and assessing the generated ten natural frequencies as well as the mode shapes [10]. Besides, the hexagonal plates used in the structural design of satellites were subjected to modal analysis and testing [11]. An extensive experimental method was used to verify the results from finite element analysis (FEA), which studied the vibration properties of woven fibreglass/epoxy composite plates [12]. It was also discovered that shell element (S4R) given by commercialised FEA codes could perform modal analysis on a supported rectangular plate with 20 natural frequencies and mode shapes [13]. Modal analysis on plated structures with fixed, cantilever, and supported ends has established a solid research database for modal parameters along these boundary conditions [6], [14]-[16].

Nevertheless, there is a considerable gap in research concerning free vibration analysis integrating steel plate components. Although the superposition method has been used to tackle free vibration issues with rectangular plates, it has so far only been used as a reference point for the verification of other theoretical and numerical approaches [17]-[19]. The free vibration concepts are still the most challenging and inadequately performed representations to acquire an analytical solution under a diverse range of final conditions. The issue arises due to (i) the square plate having free edges and corners, (ii) it having more symmetry, and (iii) it being extra challenging to distinguish between several possible modes [20]. Thus, given to stainless materials and tested structure size, the current work aims to extract the natural frequency for free plates condition to develop a reasonable quarry for such modal problems.

Modal analysis predicated using numerical models is also being conducted to assess structure dynamics. This necessitates conducting experiments on the problems to validate or improve the numerical models. Thus, researchers have actively used numerical dynamic models and experimental settings to verify their findings. Natural frequencies of a single rectangular plate were compared through a combination of mathematical, FEA, and practical methods [14]. The results showed a remarkable consistency between FEA and experimental data and between the experimental and natural frequencies calculated using the equation. Moreover, another study raises concerns regarding the precision of modal analysis by outlining the different factors that can influence the output of finite element analysis solvers [21]. Modal analysis results from HYPERMESH, ANSYS 6 degree of freedom (dof) , and ANSYS 5 degree of freedom are compared to those from an experimental examination of a flat plate mounted on a shaker. These findings demonstrated the versatility of all approaches to assessing a body's modal frequencies. However, it is critical to bear in mind each approach's caveats when conveying real-life scenarios. The computation of modal parameters comprises the consideration of boundary conditions.

The increasing diversity of test subjects demands an improved methodology appropriate for the study. Operational modal analysis (OMA) is favoured over experimental modal analysis (EMA) because it is better suited to testing rigid structures [22]. Validation of numerical models can benefit from OMA since it stretches the structure under its actual boundary conditions. Theoretically, an OMA and EMA test should yield the exact estimates for the natural frequencies and damping ratios. Despite this, it is still commonly believed that EMA testing yield better accurate results. OMA and EMA studies have been performed on a Plexiglas plate for comparison [9]. The results of both tests indicate that the cross-MAC values between the mode shapes are greater than 0.99, the natural frequencies differ by less than 0.3%, and the damping ratios by less than 7%. This suggests that the derived parameter for the mode shapes is somewhat similar. OMA was also implemented to examine the vibration of a free-free end beam state, often utilising several different OMA algorithms [23]. In this study, various algorithms in OMA, such as Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD), and Stochastic Subspace Identification (SSI), were utilised as the measure to compare and validate each of the approaches used. The findings showed that these strategies displayed a rather significant correlation. However, the absence of the FEA test in this study was further encouraged to compare with the practised technique.

This work implements a method for extracting a steel plate's natural frequencies to catalogue the numerous case studies of steel plate vibration with a free-free boundary condition. Modal analysis is performed on a free-laying square steel plate element, in which several algorithms are analysed and compared. The natural frequencies and mode forms of a structure are calculated using the finite element (FE) approach, which is the first method employed. The natural frequencies of the plate are extracted using some OMA methods, and then the results of these techniques and the FE method are compared on a percentage difference. In addition, the mode forms identified by the OMA test were also inspected and compared to the mode shapes identified by the FE approach.

2. Methodology

The experimental test for Operational Modal Analysis (OMA) used a stainless steel plate with dimensions of 350mm × 350mm × 5mm grade 304 (AISI). The plate was modelled in FEA software using the FE method for modal analysis. Since the analysis based on the FE model served as the guide to help identify the modes in the OMA test, the first stage was to conduct a FEM analysis. The methodology for each analysis was described in the following section.

2.1 Finite Element Method (FEM)

The Finite Element Method is widely used for numerically solving modal analysis. The fundamental idea behind the FEM is that any continuous object can be represented by a collection of discrete elements with a clearly defined force, displacement, and material connections [13]. In this research, Abaqus FEA was employed to determine the natural frequencies exhibited by the plate. Fig. 1 depicts the outcome of applying the plate's dimensions. Table 1 summarises the mechanical properties of AISI 304 stainless steel, which were used to ascertain the required input value for the material [24].

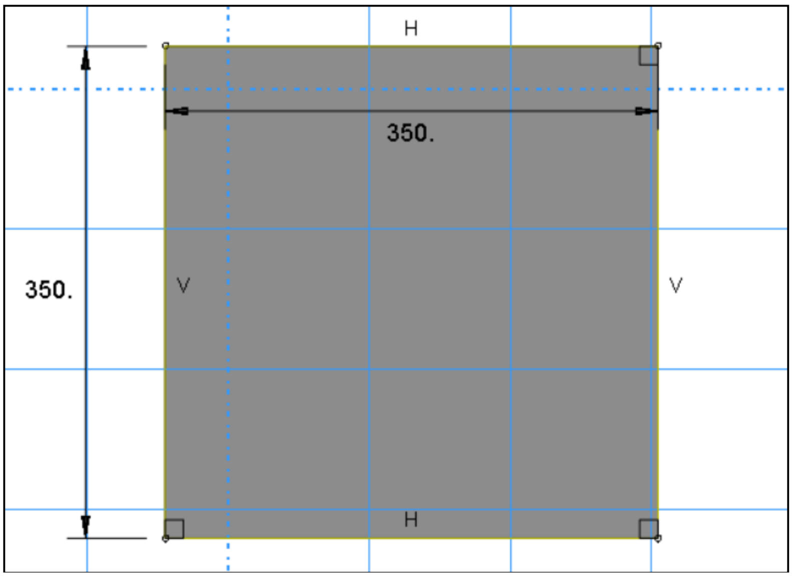


Fig. 1 - The dimension of the steel plate

Table 1 - Material properties for stainless steel grade 304

Characteristic	Unit	Value
Young's modulus	GPa	193
Poisson ratio	-	0.25
Density	kg/m^3	7896
Thickness of plate	mm	5

Free plate problems were analysed without specifying any boundary conditions. The extrusion mode was used to model the component, representing the size in millimetres. The meshing module's approximate global size is 10, producing 1,225 elements (Fig. 2). The initial six observed natural frequencies are then tabulated for further discussion.

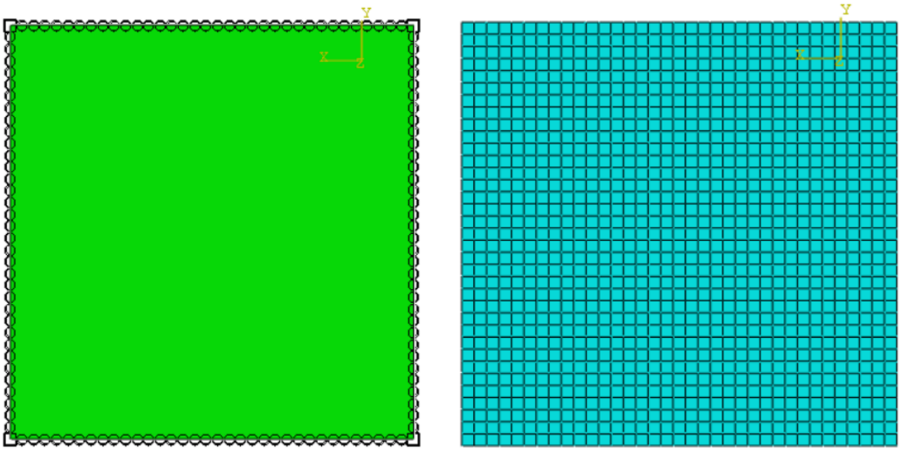


Fig. 2 - The seeds display and mesh element of steel plate

2.2 Operational Modal Analysis (OMA)

A dense sponge was selected to mimic the free-free-ends phenomenon at each edge of the stainless steel plate (Fig. 3). The following measurement and processing setup were used to identify the dynamic properties. As detailed in Table 2, the nine (9) PCB Piezotronics Model 393B04 accelerometers are attached to a Dewesoft DAQ analyser, with a resolution of 1000 mV/g. A hexagonal adaptor was used to attach the sensor to the steel plate at 135 mm spacing in both directions.

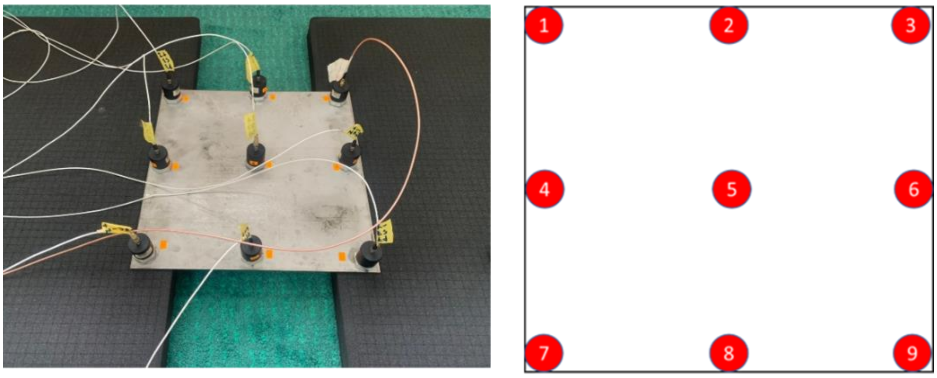


Fig. 3 - The sensors setup on steel plate

Table 2 - Sensor setup for Operational Modal Analysis (OMA) test

Location	Sensor ID	Channel ID
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9

This experiment assigned 9 degrees of freedom to the analyser setup, allowing for measuring acceleration in a single direction. In this configuration, the analyser is linked to nine white cables connecting an accelerometer. The results of the FE analysis were used to help set up the test, including the sampling rate and the estimated minimum duration of the measurements, by providing values for the natural frequencies involved. Data is sampled at a certain rate, expressed as several samples per second (sps). Eq. (1) provides a suggested sampling rate [25]:

$$f_s > 2.4 f_{\max} \tag{1}$$

where f_s is the sampling frequency, f_{max} is the highest frequency of interest. As our frequency of interest is 5000Hz, thus the decided sampling frequency is 10000Hz. Then, the expression stated in Brincker and Ventura where the minimum recommended time required for operational modal analysis is suggested as (Eq. 2) [25]:

$$T_{recommended} = \frac{10}{\zeta f_{\min}} \tag{2}$$

The expression assumed that the longest correlation time is defined by the lowest natural frequency of the system which is f_{min}. To determine our f_{min}, the frequency of 20Hz is used which is predicted by using FEM. Therefore, assuming a damping ratio (ζ) of 1.0, the $T_{recommended}$ yield the usage time of 60 seconds or 1 minute. Nonetheless, an extra 2 minutes were added to the data collection process to establish more measurements, bringing the total time for data collection to 180 seconds. It was opted to adopt a relatively long measurement time to minimise the impact of time constraints on the modal parameters [26]. The stimulation was accomplished by randomly tapping the plate surface with the pencil point. Since the scratching method of excitation could significantly affect the dynamics of a structure in terms of natural frequencies and damping ratios, tapping was chosen to lessen the interaction with the plate [9]. The operating deflection shapes (ODS) testing procedure was carried out in the Hanning FFT window, and the raw modal data was then processed further in Artemis Modal Pro.

3. Results and Discussion

This section elaborated further on outcomes from the technique-derived modal parameter. The first category is Hz-recorded natural frequencies. A system's natural frequency is the frequency at which it tends to vibrate or oscillate when no external force is applied. Instead of depending on the load function, the natural frequency is affected by the masses and structural stiffness involved. For flexural members, the natural frequency is found to be directly proportional to stiffness using an equation calculated theoretically [29]. Fundamentally, the natural frequency shift implied the structural stiffness shift, which allowed for damage prediction. A crucial component of structural analysis is monitoring whether or not the frequency of the applied loading will significantly conflict with the structure system's natural frequency. Keeping the structure's natural frequency outside the excitation frequency range is a primary design goal for engineers. The resonance between the two can lead to costly repairs if the structure is not properly isolated. Nevertheless, mode shapes serve to visualise the deformation of a structure at a single natural frequency. Mode shapes can also be used to visualise where in the system stresses are concentrated. These locations are beneficial in assisting researchers in obtaining a better localised natural frequency via the prediction of high-stress spots based on mode shapes, which allows for the sensor installation for experimental data reading.

3.1 Natural Frequencies

The natural frequencies of stainless steel plates greatly impacted the dynamic properties of a plated element. It is essential to have a solid understanding of the values of the element's initial few modes because these modes contain a more significant proportion of the total vibrational energy of the system contrasted to the modes that follow [6]. Once a change has been detected, it is possible to review the global vibration relevant data of the structure by looking at the lower order modes in the region of these first few modes using natural frequency as an extension of damage assessment. Therefore, using Operational Modal Analysis (OMA), the first six natural frequencies were recorded using the FE Method and compared to the natural frequencies results from the experimental test. Operational Modal Analysis (OMA) was utilised in this investigation to determine the modal parameters and assess the reliability and validity of a small set of algorithms. Among the OMA computations available in Artemis Modal Pro are Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD), and Stochastic Subspace Identification (SSI). There are advantages and disadvantages to using each of these algorithms, depending on the particulars of the technical computations needed to produce the desired result [27]. Previous work has shown that a good decimation value can affect the efficiency with which SSI algorithms estimate modal parameters, so decimation up to 1000Hz was applied to the data settings. The signal processing in this investigation was configured to have a resolution of 2048, with a frequency line width of 0.488 units. All SSI estimation was turned on, activating nine projection channels. Artemis Modal Pro data is converted into SVD lines for further examination.

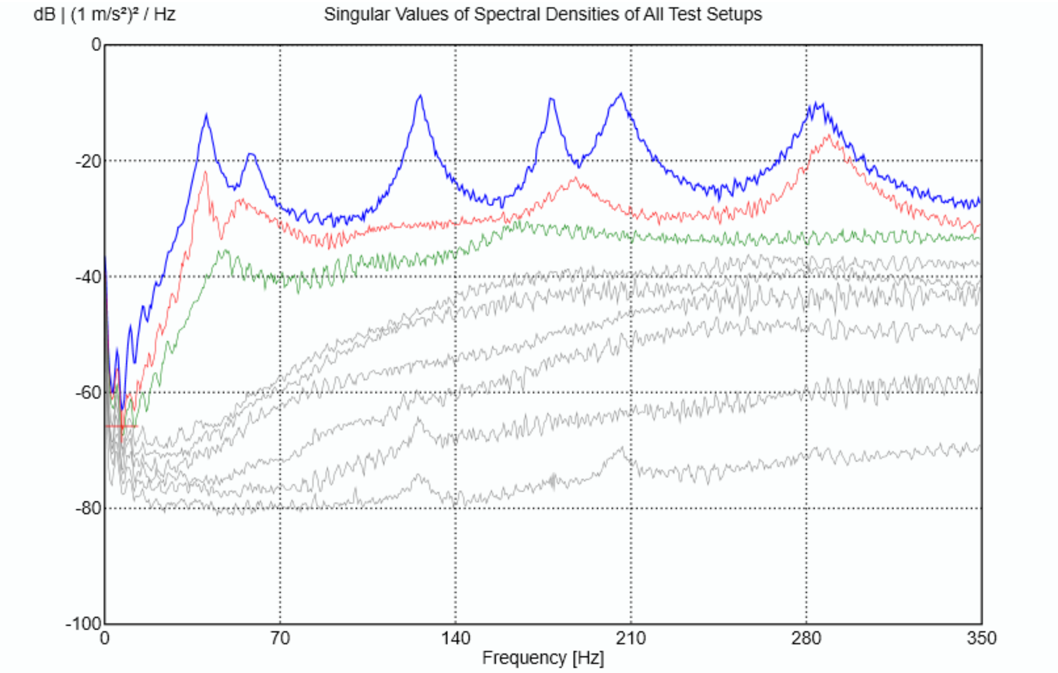


Fig. 4 - The SVD lines generated from the steel plate OMA test

The singular value decomposition (SVD) analysis begins with data quality evaluation. This allows for visualisation of visibly good peaks. The signal-to-noise ratio (S/N) is a crucial metric for evaluating modal data quality because it compares the presence or absence of the desired signal and any residual noise present. The desired signal offers more valuable insights about the modal data than the unwanted signal. Fig. 4 shows the SVD plot used to calculate the S/N for this study; the value of 70 dB indicates a good S/N [25]. Afterwards, data from each algorithm were analysed, compiled, and tabulated (Table 3).

Table 3 - Six natural frequencies results from FEM and OMA

Modes	**f_{fem} (Hz)**	**f_{oma} (Hz)**					
		FDD	**EFDD**	**CFDD**	**SSI-UPC**	**SSI-PC**	**SSI-UPCX**
1	42.820	40.527	40.529	40.432	-	40.045	-
2	60.486	57.617	58.407	58.287	58.003	57.864	58.002
3	118.35	125.977	125.589	125.785	125.591	125.458	125.601
4	172.01	177.734	178.725	178.480	178.498	1784.000	178.510
5	210.14	206.055	204.998	205.275	205.468	205.189	20.407
6	290.81	283.691	284.463	284.325	284.314	284.401	284.289

The natural frequency was calculated using the peak-picking method applied to the OMA outputs. Since FEM only estimates normal modes, the first noticeable peak appeared at 40.527 Hz with low complexity, allowing for comparison with FEM natural frequencies. Then, there were subsequent distinct peaks at 57.617 Hz, 125.977 Hz, 177.734 Hz, 206.055 Hz, and 283.691 Hz. These modes have less than 7% complexity values, further confirming the accuracy. Furthermore, six natural frequencies were calculated across all algorithms, demonstrating that SSI-UPC and SSI-UPCX cannot predict the frequencies of the first modes without those two missing pieces of data. Statistical analysis determined the percentage difference between f_{fem} (Hz) and f_{oma} (Hz) - FDD. Since FDD's modal extraction via the peak-picking method on its SVD is straightforward, it was selected as the benchmark. The modes can be inferred with a high degree of certainty from such a bare-bones selection. Table 4 exhibits that the greatest percentage difference occurred in the third mode (up to 6 %), while the lowest occurred in the fifth mode (only 1 %).

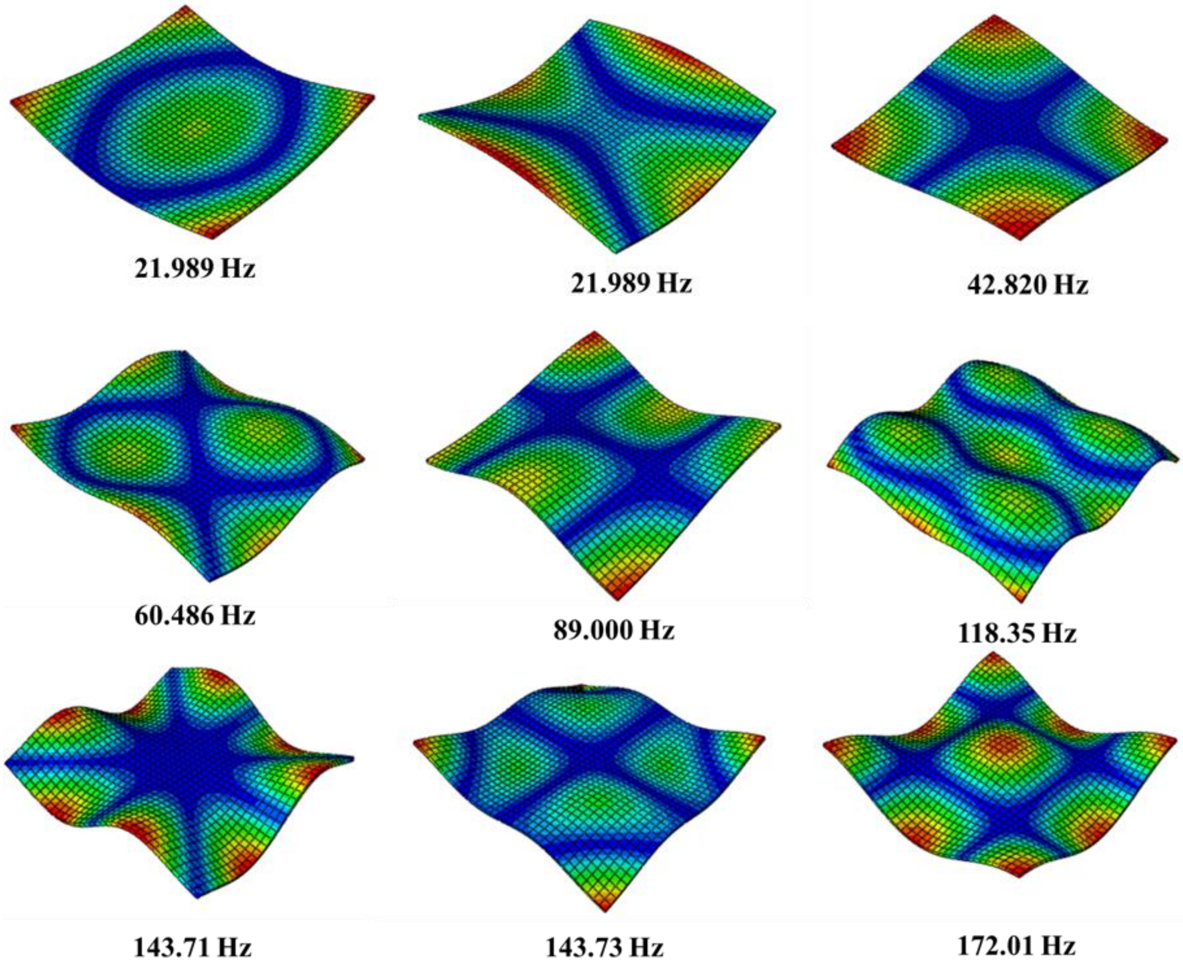
Table 4 - Percentage difference calculation of natural frequencies between FEM and OMA

Modes	**f_{fem} (Hz)**	**f_{oma} (Hz)**	**Percentage Difference (%)**
1	42.820	40.527	5.658
2	60.486	57.617	4.979
3	118.350	125.977	6.054
4	172.010	177.734	3.221
5	210.140	206.055	1.982
6	290.810	283.691	2.509

Natural frequency results demonstrated a good agreement between OMA and FE method natural frequencies for the scenario of free vibration of stainless-steel plates, with differences below 10%. In comparison to other plate problems that have been solved in previous studies, the obtained first mode for this plate is relatively low [16], [17], [28]. Therefore, theoretical validation is recommended in this scenario to verify the achieved findings.

3.2 Mode Shapes

The mode shape is regarded as a crucial modal parameter in determining the dynamic property of an element alongside the natural frequency. Although examples of free vibrations of steel plate structures have been presented, defining a plate's mode shapes is complicated. Shapes of modes in plate structures have been described using a matrix of m and n numbers to classify the modes, with a threshold to fixed ends and simply supported boundary conditions [10], [13]. Thus, the current results were compared to the newly discovered free vibrations mode shapes [17]. Prior to analysing mode shape data, it is critical to recognise mode shapes and give a reasonable justification for identification. This is because a definition of mode shapes is necessary for targeting and reporting on the subject parameters by all methods used in the computation of modal parameters. After reviewing previous literature, this study's FE Analysis yielded the extraction of 9 different modes. The positions of the same modes were found in the OMA data. The identification procedure has not produced many distinct modes because of the insufficient number of accelerometers used. Accordingly, the operational modal analysis (OMA) method can only report up to three mode shapes, while the modal analysis based on FEM can report up to nine. Fig. 5 shows the nine extracted mode shapes and the natural frequencies from this plate study.



21.989 Hz
21.989 Hz
42.820 Hz
60.486 Hz
89.000 Hz
118.35 Hz
143.71 Hz
143.73 Hz
172.01 Hz

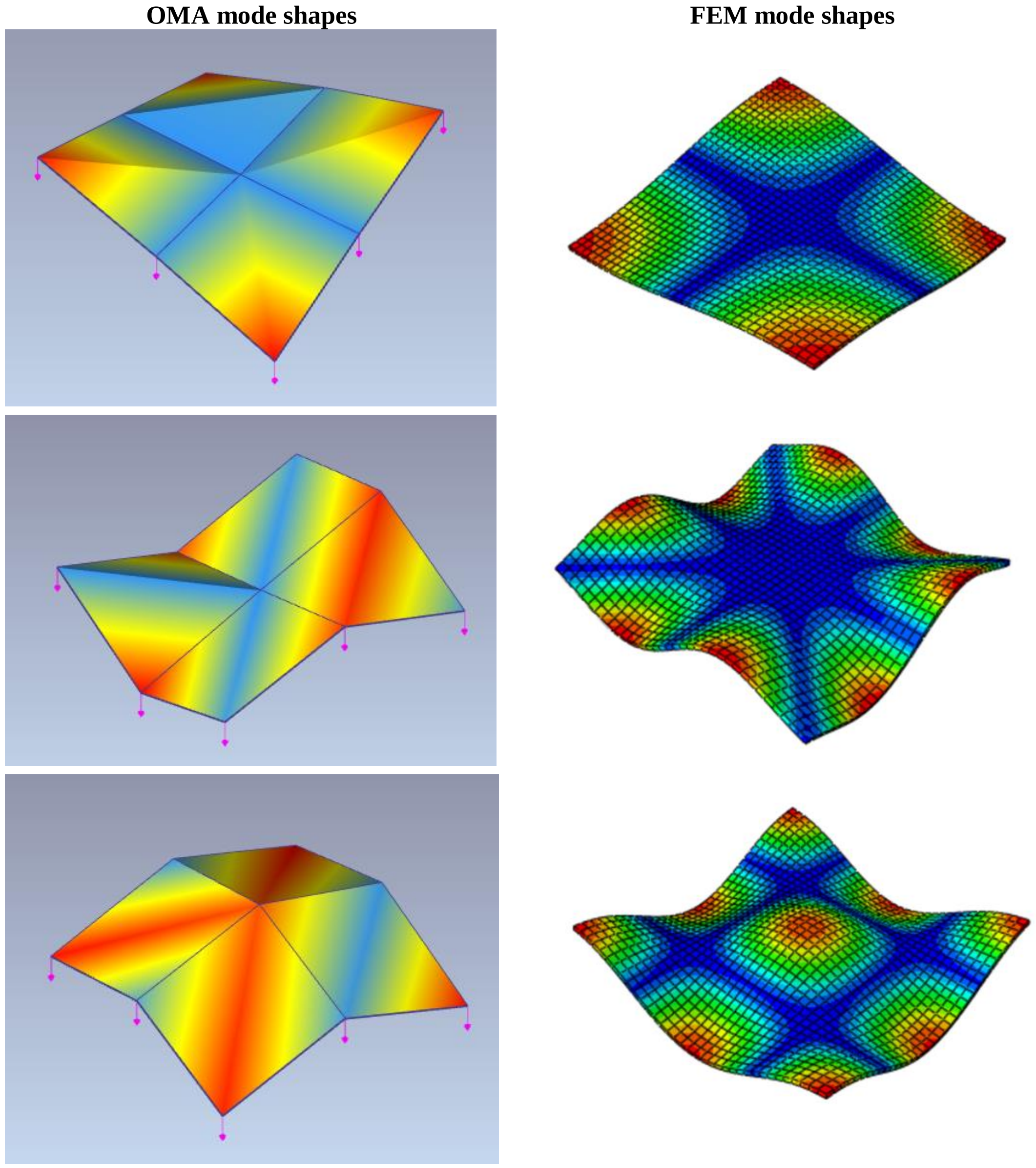
Fig. 5 - The nine (9) mode shapes extracted from the FE method

From the identified mode shapes, it is clear that all modes have revolving edges at both ends due to the arbitrary boundary conditions. Furthermore, there is a clear correlation between the frequency and the appearance of normal (blue) lines in the nine mode shapes. The mode shapes of plates can warp differently due to the free ends. The random appearance of a few magnitude extremes, denoted by the red region, further complicated the analytical methodology towards this sort of terminal condition. Nevertheless, the reported modes have the potential to serve as the basis for the substantiation of the findings, thereby expanding on the results of other previous studies.

By comparing the normalised amplitudes of the target modes with those of the baseline modes in FEM, the OMA test can identify a subset of the target modes that are similar to the baseline modes (blue lines). Fig. 6 displays the similarities between the three mode shapes retrieved and those extracted using finite element modelling. Nonetheless, to convey the modes in an easily understandable manner, the precision magnitude of these modes needs to be further validated using a greater number of sensors. While experimental works highly depend on the data available at a given location, FEM modes demonstrated precise magnitudes of elements computed by the software. Accurately determining the actual behaviour of mode shapes from experiments is notoriously tricky due to the interplay between sensitivity, sensor attachment, and excitation quality. Vibration data from a larger plate area is required to test the improved hypothesis. Future research may also consider MAC parameters a good measurement tool for modes similarity [23], [30].

4. Conclusion

A square plate of stainless steel was subjected to several modal analysis studies. The plate's six natural frequencies were measured and compared to the results of the FE method and a few number of experimental computation techniques derived from the operational modal analysis (OMA) approach. The algorithms can successfully extract all of the natural frequencies calculated using the FE method. For the scenario of free vibrations of a steel plate, nine (9) different mode shapes were extracted for comparison. Moreover, three (3) modes found in the OMA mode shapes result were found to be visually identical to those retrieved using the FE method. Throughout this research, nine sensors for the modal analysis were employed, which is the current upper bound on the number of mode shapes detected. For a more precise mode shape extraction from the experimental setup, it is necessary to conduct additional verification on the mode shapes, using more accelerometers. However, while a good correlation is observed between the measured and predicted natural frequencies, it is also recommended that a theoretical modal analysis be performed to corroborate the obtained natural frequencies.


OMA mode shapes

FEM mode shapes

Fig. 6 - The nine mode shapes extracted from the FE method

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