Modal Analysis of a cantilever beam using Finite Element Method and its Experimental Validation

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Abstract - Modal analysis is a type of dynamic analysis that focuses on studying the response of a mechanical structure to dynamic loads at its natural frequencies. Modal analysis is conducted to determine the natural frequencies and mode shapes of the structure. In this paper, modal analysis of a cantilever beam to obtain natural frequencies and mode shapes is carried out using two FEA software, ANSYS and ABAQUS. The pattern of motion exhibited by a vibrating beam structure to the corresponding natural frequencies to the excitation force is simulated in the form of mode shape using FEA software ANSYS and ABAQUS. The cantilever beams are important structural members in varieties of engineering applications. Model developed in FEA software is validated by comparing the results of the simulation to experimental data to ensure that the model accurately represents the behaviour of the real system. The natural frequencies obtained through finite element analysis software are compared with the natural frequencies obtained experimentally and are found in good agreement. The Frequency Response Function (FRF) is measured experimentally that signifies the magnitude of the structure's response at different frequencies over a predetermined range of frequencies. Modal analysis helps engineers and designers to understand the dynamic behaviour of structures, to predict and mitigate potential resonance related issues, ensuring the safety, reliability, and performance of structures under dynamic loads.

Key Words: Modal Analysis, Natural Frequency, Resonance, Mode Shapes, FEA.

1.INTRODUCTION

Modal analysis is a process used to study the dynamic behaviour of structures subjected to external forces or excitations. [1] The first step in this work of modal analysis is to create a model of the structure under consideration using finite element analysis (FEA) techniques. The model should include the geometry, material properties, and boundary conditions of the structure. The structure considered in this work is a uniform rectangular beam of mild steel in free - fixed condition. Determining natural frequencies is the next step. The next step is to determine the excitation sources that the structure may be subjected to. Once the natural frequencies and excitation sources are known, the resonance conditions can be evaluated. Finally, the finite element analysis results are validated through experimental testing. [2, 5]

When natural frequency of body matches with external excitation frequency, resonance occurs i.e. body vibrates with maximum amplitude and certain damages may happen. The effects of resonance can include excessive vibrations, stress concentrations, or even failure of the structure. By analysing resonance effects, engineers can identify critical frequencies and modes that may cause undesirable dynamic responses. If resonance conditions are identified, various strategies can be employed to mitigate the effects. These may include modifying the structure's design, changing material properties or adding damping elements. [3-4]

Modal analysis provides insights into the behaviour of structures under specific loading conditions. By understanding the natural frequencies, mode shapes, and response amplitudes, engineers can optimize the design and operational parameters to enhance the performance of the structure, such as minimizing vibrations, improving energy dissipation, or reducing noise levels, reducing potential damage and increasing the service life of the structure. Overall, the significance of modal analysis lies in its ability to predict and mitigate potential resonance-related issues, ensuring the safety, reliability, and performance of structures under dynamic loads. By understanding and controlling resonance effects, engineers can design structures that are more efficient, durable, and capable of withstanding external forces, thereby reducing maintenance costs and enhancing overall structural performance. [2-3]

Cantilever beams play a crucial role in a wide range of structural applications. Modal analysis is the process to determine the modal parameters in the form of natural frequency and mode shape. Modal characteristics of a system can be ascertained through a variety of approaches, including numerical analysis, finite element analysis, and experimental analysis. These diverse methodologies offer multiple avenues to gain insights into the dynamic behaviour of a system. In this paper the method of finite element analysis and experimental analysis is used. This paper illustrates comparative study of the finite element analysis and experimental analysis methods of modal analysis. In this work we compared the natural frequency obtained using FEA software with that acquired through experimental means. Mode shapes are studied in two FEA Software ANSYS and ABAQUS.

From Finite Element modal analysis, the natural frequencies, and mode shapes are obtained. In addition to modal analysis, the harmonic analysis is also carried out to find the amplitude at different frequencies. The numerical modal analysis of beam is performed using the finite element analysis (FEA) software, ANSYS workbench & ABAQUS. The experimental investigation is also done using a vibration test rig employing impact hammer testing. This paper presents a numerical and experimental modal analysis of single regular rectangular beam in free-fixed boundary condition.

The theoretical and experimental modal analysis of the two cantilever beams of same length and cross section of Mild Steel and Aluminium has carried out by Walunj Prashant S.et al. [6] M. A. Anuar et al. investigated the dynamic characteristics of CEM-1 Single-layer PCB using Experimental Modal Analysis (EMA) method for free-free end condition. [7] S. Sivaraj et al. carried out Experimental modal analysis on wheel in free and loaded condition. [8] P. Mohanty and D.J. Rixen proposed the method to identify modal parameters in the presence of harmonic excitation with a frequency close to an eigen frequency. [9] V. Ondra and B. Titurus derived the theoretical model of the free vibration on a beam-tendon system and thoroughly experimentally validated. The study of beams and tendons as a coupled system that consists of a cantilever beam of a box cross-section that is axially loaded by a tendon that passes through the body of the beam is carried out. [10]

Abbas Ali Diwan et al. experimentally and theoretically investigated the maximum static deflection and the natural frequency of aluminium cantilever stepped beam (two steps). [11] J.W. Jaworski and E.H. Dowell theoretically and experimentally investigated the flexural-free vibration of a cantilevered beam with multiple cross-section steps. [12]

Guy Banwell et al. carried out the modal analysis of tennis racket using FE model by comparing with experimental modal analysis (EMA) data measured from a manufactured racket. [13] N.M. Bhaskar et al carried out numerical and experimental modal analysis of car roof for free – free conditions incorporating viscoelastic damper. [14] Chandru B T and Suresh P M carried out the experimental modal analysis with and without dampers for the car roof and the results validation was carried out. [15] Ayoub Mbarek et al. presented a comparison between an Experimental Modal Analysis (EMA) test, and an Operational Modal Analysis (OMA) test applied on a recirculating energy planetary gear. [16] Esben Orlowitz and Anders Brandt presented a comparison of an Experimental Modal Analysis (EMA) test and an Operational Modal Analysis (OMA) test on a Plexiglas plate. [17]

C. Doukas et al. investigated the structural behaviour of industrial robots. [18] Minh-Nha Pham et al. carried out Parameterized finite element modeling and experimental modal testing for vibration analysis of an industrial hexapod for machining. [19] Mark A. Kamel et al. compared the effects of different vibration controllers on system performance by developing a dynamic model using the finite element analysis. [20]

A vibration analysis of the robot having crack and without having crack carried out by Supriya Sahu et al. through the different modes of frequencies based on the finite element method (FEM). [21] Akash Shukla and S.P. Harsha studied the variation in natural frequency and mode shapes for cracked and un-cracked Steam Turbine blade. [22] The effects of crack depth on natural frequency and mode shape of cantilever and fixed fixed beam are analysed by Irshad A Khan and Dayal R Parhi. [23] Siva Sankara Babu Chinka et al. used mode shape curvatures and natural frequencies to evaluate crack location and crack depth on cantilever beam. [24]

Poi Voon Er and Kok Kiong Tan carried out frequency response functions (FRF) based machine vibration analysis using Experimental Modal Analysis (EMA). [25] Ishan Nadkarni et al. identified the dynamic characteristics of a structure, by Experimental Modal Analysis (EMA). [26] Chang-Ju Kim et al. developed a model for vibration transmission in precision machines. [27]

M. A. Castillo et al. numerically and experimentally identified modal parameters of an Electrical Submersible Pump (ESP). [28] A methodology for obtaining the FRF under real cutting conditions using the milling force itself as input excitation (sweep milling force excitation method) has been developed by Jokin Munoa and Joaquim Ciurana. [29] Taylan Karaagaçlı and H. Nevzat Özgüven proposed an approach for experimental modal analysis of nonlinear systems. [30] A. Jannifar et al. performed Experimental Modal Analysis (EMA) in running harmonics. [31] Shin Yee Khoo et al. investigated the performance of the oblique impact testing. [32]

The study of vibration plays a significant role in many engineering problem. Free vibration analysis of a continuous beam with free-fixed boundary condition is carried out in this work. FEM model of the beam has been created and simulation work is carried out on ANSYS and ABAQUS software. Moreover, experimental data acquisition and analysis is also performed through DEWESOFT software. The Dewesoft software platform provides a user-friendly interface for setting up measurements, acquiring data, and performing real-time analysis. Results obtained computationally through FE model are further compared with experimental model, which provide a considerable agreement with each other.

The main objective of this paper is to determine the natural frequency and mode shape of a single rectangular cantilever beam and to compare the results obtained by finite element analysis with experimental results. The cantilever beam of rectangular shape is designed and analysed in two FEA Software ANSYS and ABAQUS. A good correlation between the FEA and experimental result is observed. Mild Steel single rectangular cantilever beam is studied in this work.

2. MATERIAL SPECIFICATIONS AND BEAM DIMENSIONS

Material selected for modal analysis of rectangular cantilever beam is Mild Steel. The material properties of the mild steel are as shown in Table 1. [33]

Table -1: Material properties of Mild Steel

Young's modulus of Mild Steel	$E = 210 \times 10^9$ (N/mm^2)
Poission's ratio of Mild Steel	$v = 0.24$
Density of Mild Steel	$\rho = 7870$ (Kg/m^3)

Dimensions of the beam are taken as shown in Table 2.

Table -2: Dimensions of cantilever beam

Length of beam	L = 288 mm
Width of beam	b = 29.07 mm
Thickness of beam	h = 2.86 mm

3. FEA USING ANSYS AND ABAQUS

Finite element analysis and simulation of mechanical system is used to analyse the static and dynamic behaviour of the structural elements directly on the computer. The free vibration modal analysis is carried out on mild steel cantilever beam to find the natural frequencies and their mode shapes, the harmonic analysis is done to find the response at different frequencies by using ANSYS and ABAQUS.

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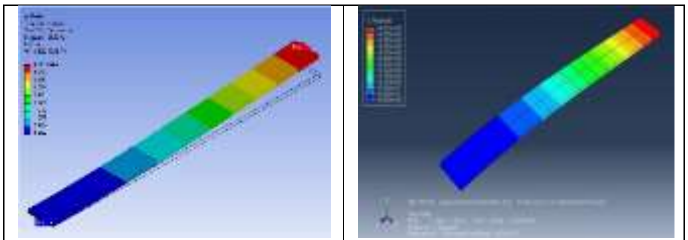
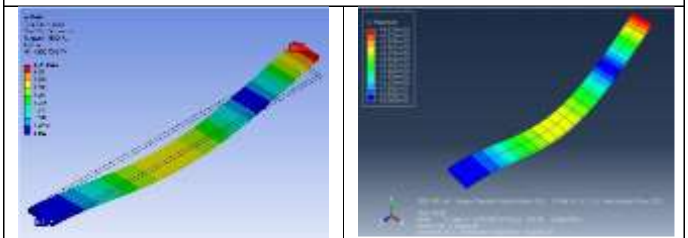
ANSYS workbench and ABAQUS is used to find out natural frequencies and mode shape of cantilever beam in free fixed condition. Model of single rectangular cantilever beam is constructed and material properties as mentioned in table 1 are assigned to the model. Boundary condition is applied by providing fixed support at one end of the beam in ANSYS, to calculate natural frequencies and mode shapes. Encastre constraint on all displacements and rotations is applied on one end of the beam to obtain eigen values and eigen vectors in ABAQUS. Quadratic meshing type is used in order to split the beam into numerous elements. The computational modal analysis is performed to generate natural frequencies and mode shapes in ANSYS. Eigen frequencies of the system are obtained in modal analysis step by linear perturbation procedure type using lanczos eigensolver in ABAQUS. Modal analysis is carried out and the mode shape with respect to the corresponding frequency is noted down. Figure 1 shows the different mode shape of single rectangular cross sectioned cantilever beam obtained by modal analysis in ANSYS and ABAQUS. Mode shape shows the shapes of deformations, minimum and maximum deflections at various resonant frequencies.

Harmonic response analysis is used to obtain the frequency response curves of a mechanical system which gives an idea of the peak response of the structure in frequency domain where the excitation is harmonic. The response of the structure is recorded at a given frequency range under a steady state sinusoidal (harmonic) loading. The maximum frequency considered for harmonic analysis in this work is 2505 Hz. Figure 2 shows the Directional acceleration of X axis orientation Bode display using ANSYS and Figure 3 shows the spatial acceleration of X axis orientation using ABAQUS.



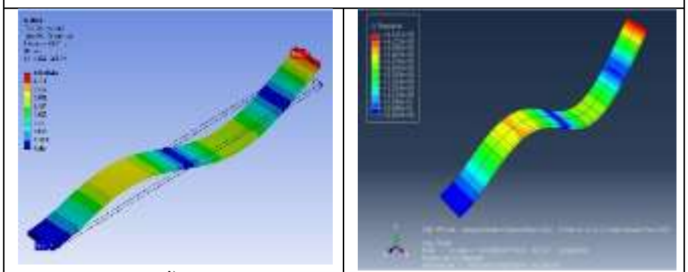
i) ii)

a) First Mode Shape i) by ANSYS ii) by ABAQUS



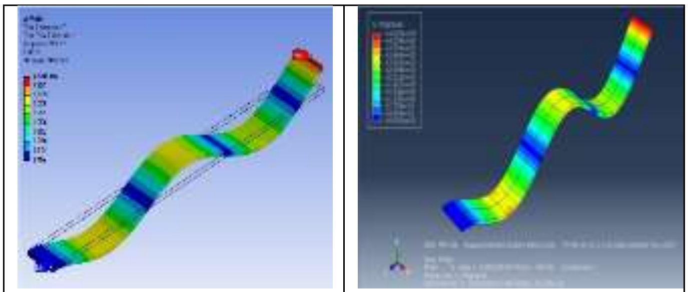
i) ii)

b) Second Mode Shape i) by ANSYS ii) by ABAQUS



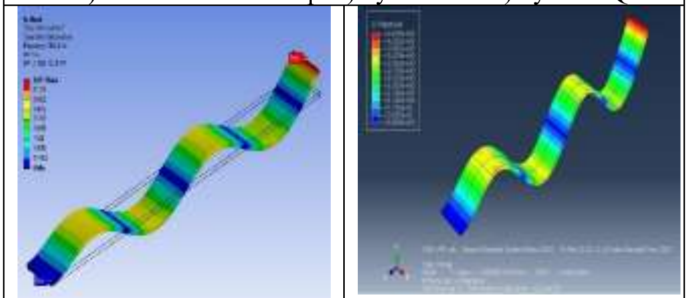
i) ii)

c) Third Mode Shape i) by ANSYS ii) by ABAQUS



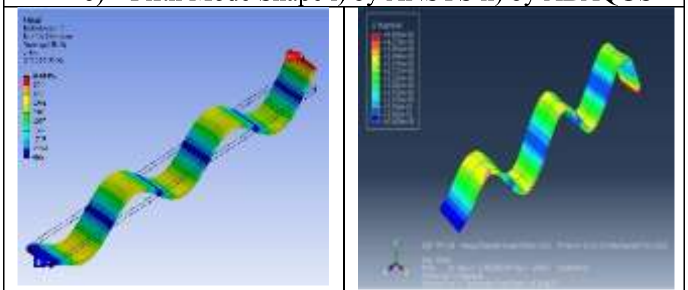
i) ii)

d) Fourth Mode Shape i) by ANSYS ii) by ABAQUS



i) ii)

e) Fifth Mode Shape i) by ANSYS ii) by ABAQUS



i) ii)

f) Sixth Mode Shape i) by ANSYS ii) by ABAQUS

Fig -1: Mode shapes of cantilever Beam obtained using ANSYS and ABAQUS.

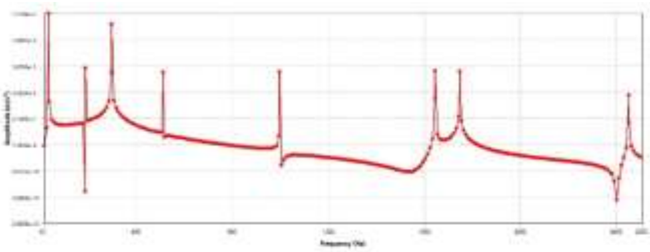


Fig -2: Directional acceleration of X axis orientation Bode display using ANSYS

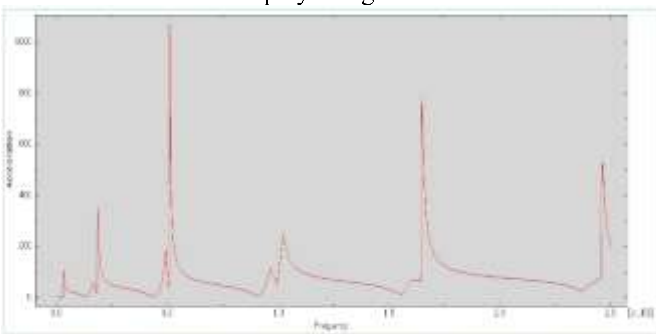


Fig -3: Spatial acceleration of X axis orientation using ABAQUS

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4. EXPERIMENTAL MODAL ANALYSIS

The approach of Experimental Modal Analysis involves the comprehensive study of dynamic behaviour of structure when subjected to external stimuli. In this work the beam is excited using impact hammer. Figure 4 shows the setup for the experiments. The test beam is a stiff rectangular beam made up of mild steel. An instrumented impact hammer type 8206 (Brüel & Kjær) with a head mass of 100 g, and a sensitivity of 22.7 mV/N is used as the source of excitation. Response of the beam is measured by a uni-axial accelerometer Type 4500-A (Brüel & Kjær) placed on the beam, and delivered to the 8-channel data acquisition system as the channel signal. DeweSoft software is used for data acquisition, generation of transfer function, and analysis. [34] In a test-based modal analysis the transfer function is calculated by dividing the response of a system by the excitation force (referred as the transfer function or frequency response function). Then, the modal parameters are derived from the transfer function. Frequency Response Functions and subsequent extraction of modal data is performed using DEWESoft software. The roving hammer/force approach, where the input excitation is applied to different excitation locations and a response is obtained at a fix location is implemented for the testing. In this test a single input single output (SISO) type measurements are considered.

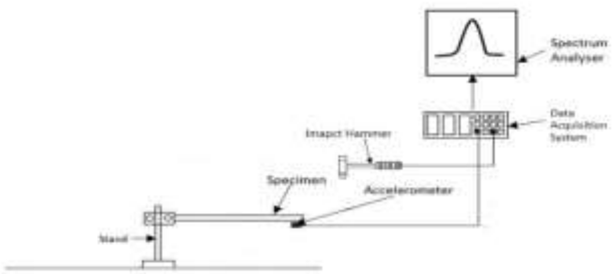

Fig -4: Schematic of setup for modal testing

5. FREQUENCY RESPONSE FUNCTION (FRF)

The FRF is typically defined as the ratio of the output response of a system to the input excitation at each frequency. It describes how the system responds to excitation inputs at different frequencies. The FRF is measured experimentally by applying a known input signal to the system through impact hammer to which load cell is connected and measuring the resulting output at different frequencies using accelerometer mounted on cantilever beam. It provides valuable information about the behaviour and characteristics of a system in the frequency domain. It is represented as a complex function, with a magnitude and phase component. The magnitude represents the amplitude ratio between the output and input, while the phase indicates the phase shift between them. The FRF is obtained by the experimental modal analysis is shown in figure 5.

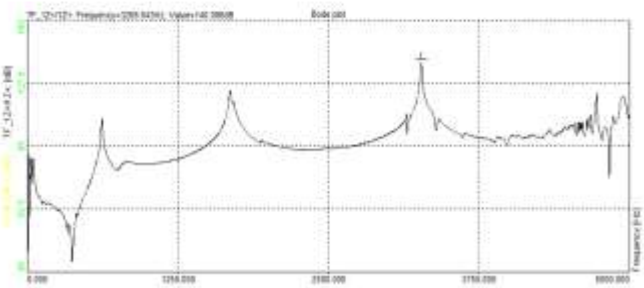

Fig -5: Frequency Response Function (FRF) obtained experimentally

6. RESULT AND DISCUSSION

In this work, modal analysis of single uniform rectangular cantilever beam has been carried out. Natural frequencies of single rectangular cantilever beam are obtained by FEA using ANSYS and ABAQUS software and experimentally. The natural frequencies obtained from FEA and experiment are presented in table 3. From this analysis it is observed that the natural frequencies obtained by FEA and experiment are in good agreement with each other. This work discusses one of the most frequently used technique for modal testing, which is based upon the excitation of structure with an impulsive force applied through an impact hammer and vibration response is recorded through accelerometer. These signals are then fed into analyser to compute frequency response functions (FRFs). There is good correlation between the finite element model and experimental results. As mentioned earlier, the modal testing is carried out under “free - fixed” condition.

Natural frequency obtained analytically with the help of FEA software ANSYS and ABAQUS whereas experimentally obtained with the help of DEWESoft data acquisition software. The difference in the values of natural frequency obtained is due to ideal material properties considered in material library of FEM Software such as elastic, isotropic, homogenous material. However in practice, there exists some degree of anisotropic, non-homogeneity in the material which is reason of difference of the two values.

Table -3: Natural frequencies computed by Finite Element Analysis Software (ANSYS and ABAQUS) and by Experimental Modal Analysis (EMA)

Mode	ANSYS	ABAQUS	EMA
1	28.89	28.96	28.35
2	180.94	181.40	180.79
3	506.51	507.82	509.46
4	992.4	995.09	998.38
5	1640.2	1645.1	1655.6
6	2449.3	2458.0	2470.74

It can be observed that as the mode order increases, there is greater variation or error between natural frequency obtained by software and natural frequency obtained experimentally. This may be due to the fact that as frequency is increased, number of partial differential equations on which software have to operate rises. As FEA Software works on approximate method that in turn increases the chances of error in the measured value over wide operating range.

7 CONCLUSIONS

The modal analysis is an effective and non-destructive test method for the determination of dynamic characteristics of beam. In this work the FEM model of the cantilever beam is constructed and validated by the experiment for modal analysis. The required modal frequencies and the mode shapes of the beam are obtained by the FEA. Finally, the resonant frequencies from the experimental testing are compared to the corresponding resonant frequencies from the FE-models and those have a good agreement to each other.

In this work, computational and experimental modal analysis of a uniform rectangular beam with a free-fixed boundary condition is studied and its characteristics parameter such natural frequency and mode shape are discussed. Following conclusion can be made:

1. Boundary condition of the beam plays a very significant role in the vibration response of the beam.
2. Simulation results are compared with and found in good agreement with experimental data which is obtained through DEWESoft data acquisition system.
3. Error observed between experimental value and ANSYS value is because a real beam material is not perfectly homogenous, elastic and isotropic as is considered by FEA Software.

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