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Vibration Analysis of Cantilever Beam with Damped Dynamic Vibration Absorber with Adjustable Stiffness with Nonlinear Parameters

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ABSTRACT

The vibration absorbers are frequently used to control and to minimize excess vibration in structural systems. To reduce the vibration of the main system or machine, the frequency of absorber should be equal to excitation frequency. Vibration absorption is a method of adding a tuned absorber mass to a system to create anti-resonance at a resonance of the original system. In vibration analysis, a dynamic vibration absorber is a tuned spring-mass system which reduces or eliminates the vibration of harmonically excited system.A beam is an elongated member, usually slender, intended to resist lateral loads by bending [1]. Structures such as antennas, helicopter rotor blades, aircraft wings, towers and high rise buildings are examples of beams. These beam-like structures are typically subjected to dynamic loads. Therefore, the vibration of beams is of particular interest to the engineer.The stiffness of beam can be varied to adapt the changes in excitation frequencies. If forced frequencies vary from the anti-resonance frequency, their vibration amplitudes increase significantly. Then the absorber without damping cannot be applied to the structure subjected to variable frequency loads or the loads having high-frequency components. For this purpose the absorber should be tuned to excitation frequency by varying the stiffness of absorber with the help of variable stiffness mechanism.In this research work variable stiffness tuned vibration absorber will be designed to control the vibrations of cantilever beam. As linear theory fails to evaluate the real life results various nonlinear parameters are considered for vibration analysis of cantilever beam with dynamic vibration absorber.

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I.INTRODUCTION

A beam is an elongated member, usually slender, intended to resist lateral loads by bending [1]. Structures such as antennas, helicopter rotor blades, aircraft wings, towers and high rise buildings are examples of beams. These beam-like structures are typically subjected to dynamic loads. Therefore, the vibration of beams is of particular interest to the engineer.

For beams undergoing small displacements, linear beam theory can be used to calculate the natural frequencies, mode shapes, and the response for a given excitation. However, when the displacements are large, linear beam theory fails to accurately describe the dynamic characteristics of the system. Highly flexible beams, typically found in aerospace applications, may experience large displacements. These large displacements cause geometric and other nonlinearities to be significant. The nonlinearities couple the (linearly uncoupled) modes of vibration and can lead to modal interactions where energy is transferred between modes [2].

Vibration absorption is a method of adding a tuned absorber mass to a system to create anti-resonance at a resonance of the original system.In vibration analysis, a dynamic vibration absorber is a tuned spring-mass system which reduces or eliminates the vibration of harmonically excited system.

The stiffness of beam can be varied to adapt the changes in excitation frequencies.If forced frequencies vary from the anti-resonance frequency, their vibration amplitudes increase significantly. Then the absorber without damping cannot be applied to the structure subjected to variable frequency loads or the loads having high-frequency components.For this purpose the absorber should be tuned to excitation frequency by varying the stiffness of absorber with the help of variable stiffness mechanism.

II.PROBLEM DEFINITION

A)Problem Statement

To perform the Vibration Analysis of Cantilever Beam with Damped Dynamic Vibration Absorber with Adjustable Stiffness with Nonlinear Parameters.In order to find out effect of various inherent nonlinearities on vibrational behaviors of the beams.

Also development of experimental setup for validation of the Theoretical and Numerical Analysis.

B)Objective

Comparison of Theoretical, Numerical and Experimental Vibrational analysis of Cantilever Beam with Damped dynamic vibration absorber with adjustable stiffness with nonlinear parameters.To find out effect of various inherent nonlinearities on vibrational behaviors of the beams.

C)Scope

a) Well definition of the problem.
b) Learning and use of MATLAB and ANSYS Software.
c) Theoretical study of vibrations of continues systems like Beams.
d) Numerical analysis of a cantilever beam subjected to free Vibrations with nonlinear parameters with variable stiffness & damping.
e) Development of experimental setup to carryout vibrational analysis of cantilever beam with variable stiffness and variable damping.

D)Motivation

Vibration absorbers have been used on a wide variety of structures to reduce vibration in an attempt to reduce the radiated noise.It is an interdisciplinary field where physicist, mathematician and engineer interact in a closed loop.The engineers emerged on the scene with vibration problems which began to design and construct the machines and structures. The engineers grappled with vibration and noise problems faced by the industry. With the developments in the digital and hybrid computers, integrated circuits, microprocessor devices like spectrum analyzers, shakers, piezoelectric accelerometers and also with the developments in software and hardware, it is possible to tackle vibration problems in such diverse areas.

The structures like helicopter rotor blades, spacecraft antennae, flexibleairplane wings, gun barrels, robot arms, high-rise buildings, long-span bridges, and subsystems of more complex structures can be modeled as a beam-like slender member. Therefore, studying the static and dynamic response, both theoretically and experimentally, of these simple structural components under various loading conditions would help in understanding and explaining the behavior of morecomplex, real structures under similar loading.Rotating machines such as engines, motors, and pumps often incite vibration due to rotational imbalances. A dynamic absorber can be affixed to the rotating machine and tuned to oscillate in such a way that exactly counteracts the force from the rotating imbalance. This reduces the possibility that a resonance condition will occur, which can cause rapid catastrophic failure. Properly implemented, a dynamic absorber will neutralize the undesirable vibration, which would otherwise reduce service life or cause mechanical damage.

In reality, no physical system is strictly linear and hence linear models of physical systems have limitations of their own. Normally nonlinear properties likematerial, geometric effects, structural joints and nonlinear boundary conditions are neglected bylinearization in the intended working range. However, it becomes increasingly more important to take the nonlinear effects into account[3, 4].Thus, to accurately identify and understand the dynamic behavior of a structural system under general loading conditions, it is essential that the nonlinearities present in the system willalsobe modeled and studied.

External interface requirement:

a) CAD/CAE lab equipped with MATLAB and ANSYS Software.
b) PG Research Lab equipped with FFT Analyzer.

E)Plan of execution

It is proposed to carryout Design and Vibration Analysis of Damped Dynamic Vibration Absorber System Subjected toFree VibrationwithNonlinear Parameters. For this dissertation work it is proposed to carry out the work in the following phases.

*Phase I:*Theoretical study of vibrations of continues systems like Beams. Study of various literatures related to proposed work.

*Phase II:*Study ofsoftware’s like MATLAB/ANSYS. Numerical verification of natural frequency and mode shapes of cantilever beam considering linear system.

Phase III:Study of various techniques to obtain variable stiffness and variable damping of Dynamic Vibration Absorber.For this purpose eddy current effect on damping will be studied by varying magnetic flux.

*Phase IV:*Determination of various nonlinear parameters affecting the performance of Dynamic Vibration Absorber. Nonlinearity in Stiffness and Damping parameters will be considered for this work. Load deflection characteristics will be studied to evaluate effect of nonlinearities.

*Phase V:*Numericalevaluation of effect of various nonlinear parameters on the performance of Dynamic Vibration Absorber.

*PhaseVI:*Experimental setup and methodology will be developed for experimental validation of results obtained by theoretical and numerical method. The FFT Analyzer will be used to carryout vibrational analysis of cantileverbeam having variable stiffness and variable damping of Dynamic Vibration Absorber with nonlinear parameters.

*Phase VII:*Comparison of Theoretical, Numerical and Experimental results for the validation.

III. RESEARCH METHODOLOGY

Theoretical study of vibrations of continues systems like Beams. Study of various literatures related to proposed work. Vibration analysis of cantilever beam will be studied considering linear system for evaluation of natural frequency and mode shapesfor both Free and Forced vibration.Study of Numerical software's like MATLAB/ANSYS. Numerical Verification of natural frequency and mode shapes of cantilever beam considering linear system. Theoretical study of stiffness effect and damping properties of absorber system on natural frequency and modes shapes of vibrating beam.Study of various techniques to obtain variable stiffness and variable damping of Dynamic Vibration Absorber.For this purpose eddy current effect on damping will be studied by varying magnetic flux. Determination of various nonlinear parameters affecting on the performance of the Dynamic Vibration Absorber. Nonlinearity in Stiffness and Damping parameters will be considered for this work.

Numericalevaluation of effect of various nonlinear parameters on the performance of Dynamic Vibration Absorber.Experimental setup and methodology will be developed for experimental validation of results obtained by theoretical and numerical method. The FFT Analyzer will be used to carryout vibrational analysis of cantilever beamhaving variable stiffness and variable damping of Dynamic Vibration Absorber with nonlinear parameters.Comparison of Theoretical, Numerical and Experimental results for the validation.

A)*Simulation and Software Details*

For numerical analysis ANSYS/MATLAB software will be used.

In order to carryout modal analysis to find out the natural frequency and mode shapes Ansys software will be used. Result obtained by Ansys will be validated y theoretical and Experimental analysis.

B)Parameter selection

Various types of cantilever beam sections will be studied and one section will be opted for the research work.

a) Length of Cantilever Beam
b) Cross section of Cantilever Beam
c) Absorber Mass and Beam
d) Variable stiffness mechanism

C)Details of analysis

First linear system will be considered. Theoretical analysis of cantilever beam will be carried out to find the natural frequency and mode shapes. Theoretical results will be validated by using Ansys software.

Load deflection characteristics will be evaluated to find out the effect of nonlinearities in beam on stiffness and Young's modulus.

By using young's modulus evaluated by considering nonlinearities will be now considered to find out the natural frequency and mode shapes of cantilever beam. For that natural frequency vibration absorber will be designed.

Experimental analysis will be carried out to validate the theoretical, numerical results of vibration analysis.

a)Theoretical Calculations

Modal analysis is a worldwide used methodology that allows fast and reliable identification of system dynamics in complex structures. In the last decades several methods have been developed in quest to improve accuracy of modal models extracted from test data and to enlarge the applicability of modal analysis in industrial context. Structures vibrate in special shapes called mode shapes when excited at their resonant frequencies. A mode shape is the characteristics deformation shape defined by relative amplitudes of the extreme positions of vibration of a system at a single natural frequency. The modal parameters are the natural frequencies, damping ratios and modal masses associated with each of the mode shapes. Under normal operating conditions, the structure will vibrate in a complex combination of all the mode shapes. Modal analysis refers to measuring and predicting the mode shapes and frequencies of a structure.

Vibration analysis is very important in designing of structural and mechanical system .This information helps us to predict the behavior of structure under different load distribution and helps to design system to control the excessive amplitude of the vibration [1]. In order to analyze the vibrations in structures, members of structures are modeled as cantilever beam. Therefore the process of analyzing is simplified. Using cantilever beam is just one the numerous methods for analyzing the vibration of unknown systems. A beam is an elongated member, usually slender, intended to resist lateral loads by bending. These beam-like structures are typically subjected to dynamic loads. Therefore, the vibration analysis is one the vital tasks in designing of structural and mechanical system .In this paper the theoretical analysis of cantilever beam is carried out by using vibration measuring system like accelerometer.

b) Theoretical Analysis

i) Beam

A beam is a horizontal or vertical structural element that is capable of withstanding load primarily by resisting bending. The bending force induced into the material of the beam as a result of the external loads, own weight, span and external reactions to these loads is called a bending moment. Beams are traditionally descriptions of building or civil engineering structural elements, but smaller structures such as truck or automobile frames, machine frames, and other mechanical or structural systems contain beam structures that are designed and analyzed in a similar fashion.

ii) Types of Beams

Beams are characterized by their profile (the shape of their cross-section), their length, and their material. In contemporary constructions, beams are typically made of steel, reinforced concrete or wood. One of the most common types of steel beam is the I-beam or wide - flange beam (also known as a "universal beam" or, for stouter sections, a "universal column"). This is commonly used in steel-frame buildings and bridges. Other common beam profiles are the C- channels, the hollow structural section beam, the pipe, and the angle. Beams are also described by how they are supported. Supports restrict lateral or rotational movements so as to satisfy stability conditions as well as to limit the deformations to a certain allowance. A simple beam is supported by a pin support at one end and a roller support at the other end. A beam with a laterally and rotationally fixed support at one end with no support at the other end is called a cantilever beam. A beam simply supported at two points and having one end or both ends extended beyond the supports is called an overhanging beam.

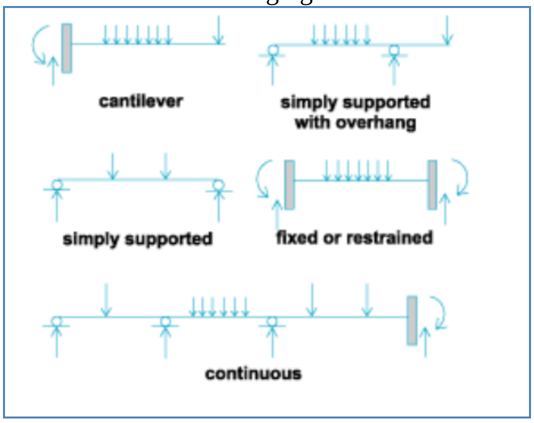


Fig. 1 Various Types of Beams

A cantilever beam is an elongated member, usually slender, which is fixed at one end and free at the other end. By subjecting a point load P, assuming that the beam undergoes small deflection and it is in the linear elastic region and has a uniformcross-section, the beam will deflect into a curve. The equation shown in below is related to the curvature of the beam to the bending moment at each section of the beam

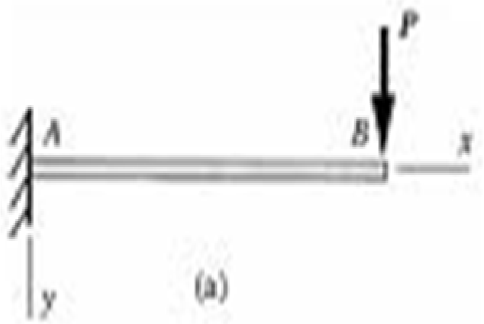
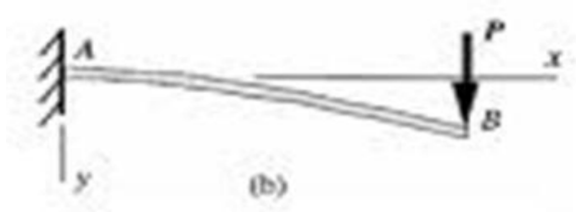


Fig. 2 (a) Cantilever beam subjecting a point load



P

Fig. 2 (b) Cantilever beam with small deflection

$$\mathbf{M} = \mathbf{EI}\frac{\partial^2 y}{\partial x^2} \quad (1)$$

Where E is Young's Modulus and I is moment of inertia of the beam.The Equation (1) is based on the assumptions that the material is homogeneous, isotropic, obeys Hooke's law and the beam is straight and of uniform cross section. This equation is valid only for small deflection and for beams that are long compared to cross sectional dimensions since the effects of shear deflection are neglected.

Consider a cantilever beam; it is subjected to a point load P therefore the beam will deflect into a curve. When the force, P, is removed from a displaced beam, it will return to its original shape. However inertia of the beam will make the beam to vibrate about its initial location. The equation of beam is

$$\frac{EI}{\rho A}\frac{\partial^4 y}{\partial x^4} + \frac{\partial^2 w}{\partial t^2} = 0 \qquad (2)$$

Where, ρ is the mass density and A is cross sectional area of beam.

$$C^2\frac{\partial^4 y}{\partial x^4} + \frac{\partial^2 y}{\partial t^2} \qquad (3)$$

Where,

$$C = \sqrt{\frac{EI}{\rho A}}$$

The solution of Eq. (2) is to separate the variables one depends on position and another on time.

$$y = W(x)\,T(t) \quad (4)$$

By substituting Eq. (4) to Eq. (3), and simplifying, the Equation is:

$$\frac{C^2}{w(x)}\frac{\partial^4 y}{\partial x^4} = -\frac{1}{T(t)}\frac{\partial^2 T(t)}{\partial t^2} \quad (5)$$

The Eq. (5) can be written as two separate differential equation.

$$\frac{\partial^4 w}{\partial x^4} - \beta^2\, W(x) = 0 \qquad (5a)$$

$$\frac{\partial^2 T}{\partial t^2} + \omega^2\, T(t) = 0 \qquad (5b)$$

Where,

$$\beta^4 = \frac{\omega^2}{c^2} = \frac{\rho A \omega^2}{EI} \quad (6)$$

To find out the solution of Eq. (5a) ,Consider the equation

$$W(x) = C_1 \cosh\beta x + C_2 \sinh\beta x + C_3 \cos h\beta x\, h + C_4 \sin h\beta x \qquad (7)$$

In order to solve Eq. (7) the following boundary conditions for cantilever beam are needed:

1. At x=0 → W=0
2. At x=0 → W|=0
3. At x=L→ W||=0
4. At x=L→ W|||=0

By substituting boundary conditions intoW|, W||, W|||.

We obtain the following values of C1, C2, C3, and C4:

$$[\cos h\beta l + \cos \beta l]C_3 + [\sin h\beta l + \sin \beta l]C_4 = 0$$

$$[\sin h\beta l - \sin \beta l]C_3 + [\cos h\beta l + \cos \beta l]C_4 = 0 \qquad (8)$$

We can write Eq. (8) in matrix form as

$$\begin{bmatrix} \cos h\beta l + & \cos \beta l + & \sin h\beta l + \sin \beta l \\ \sin h\beta l - & \sin \beta l - & \cos h\beta l + \cos \beta l \end{bmatrix} \begin{bmatrix} C_3 \\ C_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} (9)$$

For solving matrix of Eq. (9), we get determinant

$$(\cos h\beta l + \cos \beta l)^2 - (\sin h\beta l + \sin \beta l)(\sin h\beta l - \sin \beta l) = 0$$
$$\cos h^2 \beta l + 2 \cos h\beta l + \cos^2 \beta l - \sin h^2 \beta l + \sin^2 \beta l = 0$$

But it is well known that

$$\cos h^2 \beta l - \sin h^2 \beta l = 1$$

Hence we get,

$$\cos \beta l \ \cos h\beta l = -1 \qquad (10)$$

This transcendental equation has an infinite number of solutions $\beta i = 1,2,3 \dots n.$

Corresponding giving an infinite number of natural frequencies,

$$\omega_1 = (\beta_1 l)^2 \sqrt{\frac{EI}{\rho A l^4}} (11)$$

The first five roots of Eq. (10) are shown in Table I [1, 2]. [Ref S. S. Rao Page 643]

Table I
Value of Roots

Root	ß1l
1	1.86
2	4.69
3	7.85
4	11
5	14.13

The dimensions and the material constant for a cantilever beam studied in this paper are shown in Table II.

Table II
Experimental Parameters

Parameter	Symbol	Value
Material of beam	MS	-
Total length	L	0.75 m
Width	B	0.050m
Thickness	T	0.010 m
Moment of inertia	I	4.16667E-9m4
Young's Modulus	E	2 x 1011N/m2
Mass density	ρ	7830 kg/m3

Putting all required data in Eq. (11) we get the five modes as shown in Table III.

Table III
Mode Shape Frequency

Mode	Frequency in Hz
1	14.2812
2	90.7997
3	254.377
4	499.4867
5	824.1815

iii) Numerical Analysis

ANSYS is a finite element modeling and analysis tool. It can be used to analyze complex problems in mechanical structures, thermal processes, computational fluid dynamics, and magnetic, electrical fields, just to mention some of its applications. ANSYS provides a rich graphics capability that can be used to display results of analysis on a high-resolution graphics workstation.

The numerical analysis of the system using the ANSYS program, a comprehensive finite element package, which enables students to solve the nonlinear differential equation and to perform modal analysis to find out natural frequency and mode shapes.

Description of the Finite Element Method

The finite element method (FEM), is sometimes referred to as finite element analysis (FEA), is a computational technique used to obtain approximate solutions of boundary value problems in engineering. Due to the complexity of the structures stresses are usually calculated by numerical methods such as the finite element method. The finite element analysis (FEA) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations . The solution approach is based either on eliminating the differential equation completely, or rendering the PDE into an approximating system of ordinary differential equations, which are then numerically integrated. A finite element analysis is able to determine stress and strain distributions throughout a bonded structure resulting from an applied force or displacement. It is possible to calculate the stiffness of the joint and to locate regions of stress and strain concentration where failure is expected to initiate. Using a suitably fine mesh the influence of geometrical features, such as the size and shape of fillets at the ends of the adhesive layer, on stress and strain distributions can be evaluated. Certain steps in formulating finite element analysis of a problem are common to all such analyses whether structural, heat transfer, fluid flow or some other problem. These steps are embodied in commercial finite element software packages [3]. Figurer shows general procedure for finite element method. These steps are described below,

Steps for finite element analysis: FEA is mainly divided into three following stages:

i. Preprocessing
ii. Creating the model. Defining the element type
iii. Defining Material Properties
iv. Meshing
v. Applying loads
vi. Applying boundary conditions
vii. Solution: Assembly of equations and obtaining solution.
viii. Post processing: Review of results such as deformation plot, stress plot, etc.

IV.PROJECT DESIGN

A)Facilities Available and Requirements

a) Central and Departmental Library.
b) Computer Lab and Internet lab equipped with High speed Broadband and Lease Line.
c) Central Workshop.
d) CAD/CAE lab equipped with MATLAB and ANSYS Software.
e) PG Research Lab equipped with FFT Analyzer.

B)Feasibility Study

The feasibility of the project is analyzed in this phase and business proposal is put forth with a very general plan for the project and some cost estimates. During system analysis the feasibility study of the proposed system is to be carried out. This is to ensure that the proposed system is not a burden to the company. For feasibility analysis, some understanding of the major requirements for the system is essential.

Three key considerations involved in the feasibility analysis are

a) Economic Feasibility
b) Technical Feasibility
c) Operational Feasibility

a) Economical Feasibility

This study is carried out to check the economic impact that the system will have on the organization. The amount of fund that the company can pour into the research and development of the system is limited. The expenditures must be justified. Thus the developed system as well within the budget and this was achieved because most of the technologies used are freely available. Only the customized products had to be purchased

b) Technical Feasibility

This study is carried out to check the technical feasibility, that is, the technical requirements of the system. Any system developed must not have a high demand on the available technical resources. This will lead to high demands on the available technical resources. This will lead to high demands being placed on the client. The developed system must have a modest requirement, as only minimal or null changes are required for implementing this system.

c) Operational Feasibility

Operational feasibility is a measure of how well a proposed system solves the problems, and takes advantages of the opportunities identified during scope definition and how it satisfies the requirements identified in the requirements analysis phase of the system development.

V. Observation

A)Numerical Results

The numerical results were obtained by using ANSYS are as shown in Table IV.

Table IV

Mode Shape Frequency using ANSYS

Mode	Frequency in Hz
1	14.568
2	91.22
3	255.15
4	499.32
5	824.02

The mode shapes of free vibration of Cantilever Beam are shown in Figure

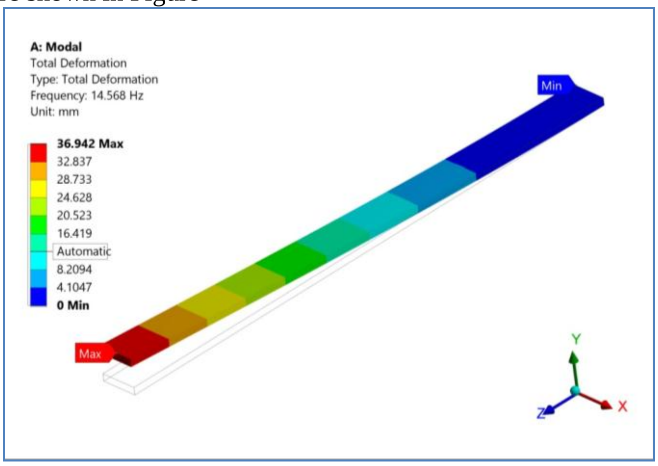


Fig. 3 1st Mode shapes of free vibration of Cantilever Beam

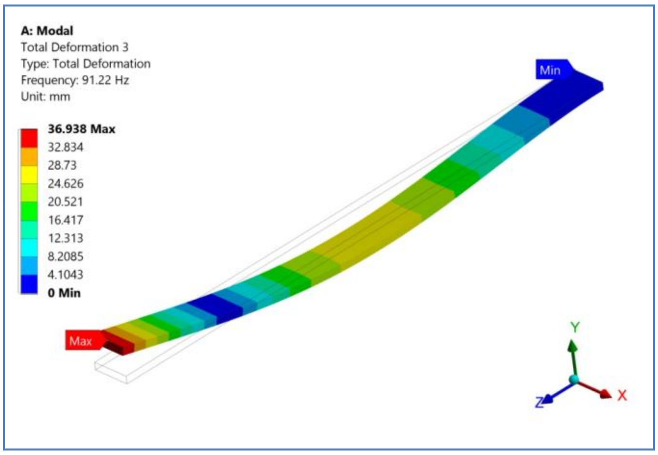


Fig.4 2nd Mode shapes of free vibration of Cantilever Beam

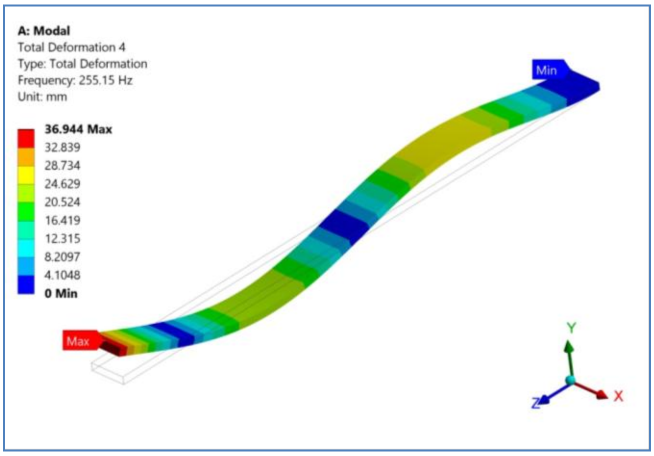


Fig.5 3rd Mode shapes of free vibration of Cantilever Beam

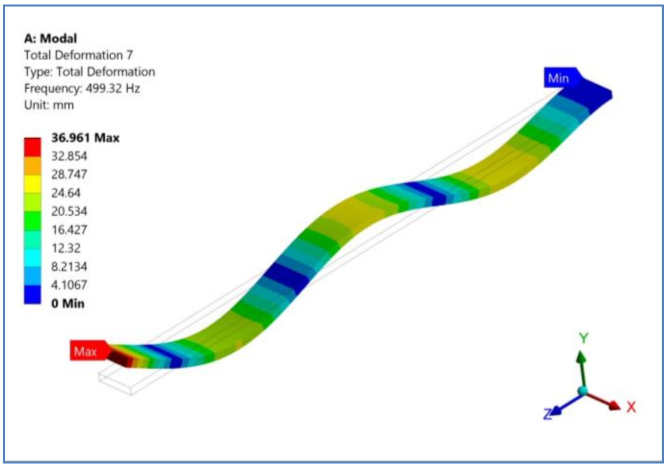


Fig.6 4th Mode shapes of free vibration of Cantilever Beam

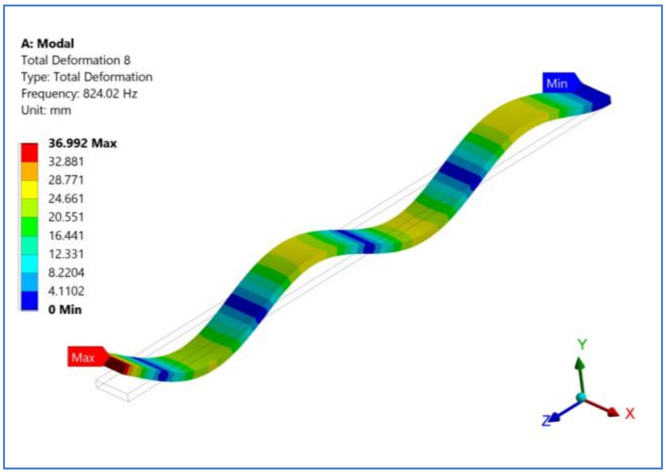


Fig. 7 5th Mode shapes of free vibration of Cantilever Beam

VI. RESULT AND DISCUSSION

From the theoretical approach and the numerical approach of the free vibration of cantilever beam, it has been found that the relative error between these two approaches is very minute. The percentage error between the numerical and theoretical methods is shown in Table V.

Table V
Percentage Error

Mode	Theoretical Frequency	Numerical Frequency from ANSYS	Percentage Error
	inHz	in Hz	%
1	14.2812	14.568	1.9686
2	90.7997	91.22	0.46075
3	254.377	255.15	0.3029
4	499.4867	499.32	0.03203
5	824.1815	824.02	0.0194

VII.FUTURE WORK

During the theoretical and numerical analysis certain assumptions are made but the nonlinearities present in the system are not considered. Due to this the results obtained from theoretical and numerical analysis is not real.

In experimental analysis nonlinearities will be considered so that the results obtained during experimental analysis are real. Hence for exact analysis of cantilever beam, experimental analysis is to be carried out.

VIII. PROPOSED EXPERIMENTAL SETUP

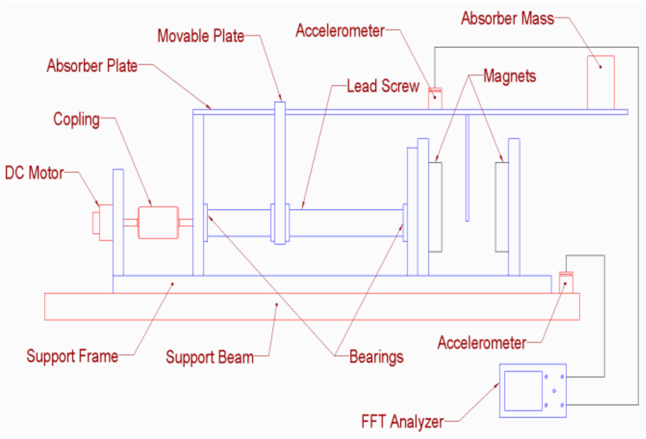


Fig. 8 Proposed Experimental Setup

IX. CONCLUSION

At this stage literature has been reviewed and theoretical study related to vibration analysis of damped dynamic vibration absorber has been carried out. The Numerical study using ANSYS allows investigating the free vibration of Cantilever beam to find out mode shape and their frequencies with high accuracy. Therefore it can be concluded that the theoretical data is in good agreement with the numerical results with negligible error, and which may be due to truncation. This theoretical study will be main base for further research work.

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