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Finite Element Modelling For Coupled Field Analysis Of A Magnetostrictive Material

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Abstract-**The key motivation for this paper is the advancement in the field of smart materials. The present work is aimed at active vibration control of an isotropic beam using a magnetostrictive layer as sensor and actuator. It includes cantilever beam surrounded with varying strength of magnetic fields. The paper describes the development and validation of finite element model for coupled field analysis of magnetostrictive fields.**

The paper is restricted to simulation using commercial FEA software. The case study has been modeled and studied. The finite element model is developed using ANSYS. The transient analysis for the beam is performed to show the time history response of the system. In the present study, the results showed that the deflection of beam decreases as we increase the current density. This shows that the active vibration control is successfully achieved in the analysis.

***Keywords*- Vibration control, Magnetostriction, FE Simulation**

I-INTRODUCTION

The major problem which all mechanical systems are facing today is the vibration. Research is always going on to control the vibration of a system using different damping methods. After the emergence of smart materials, researchers found smarter way of reducing the vibrations that is called as active vibration control using magnetostrictive materials. Magnetostrictive materials are preferred because of its unique coupling nature. In addition, magnetostrictive materials have several attractive advantages including can be easily shaped and bonded to surfaces, and embedded into structures. These materials had the unusual capability of converting mechanical strain energy into magnetic energy and vice versa. Magnetostrictive materials are able to exhibit a strong coupling between the mechanical degrees of freedom and the magnetic degrees of freedom.

Helicopters are susceptible to high vibratory loads, excessive noise levels, due to aeromechanical instabilities, poor flight stability, characteristics and high dynamic stress. Compared to fixed wing aircraft, helicopters suffer from high operating cost, poor ride quality, low fatigue life of structural components, inferior handling qualities. To reduce these problems to an acceptable level, passive and active devices, and many design fixes are restored to with resultant weight penalties and reduced pay loads one innovative idea that appears to show potential for a significant gain in performance improvement at a small penalty is to apply the technology of smart structures to rotor craft . For such an application, numerous light weight sensors and actuators are embedded at different stations on rotor blades.

The term active vibration control generally refers to the attenuation of vibration or to the shifting of vibration to a different frequency band. However, in some applications an amplification of vibration may be reduced. Active vibration control of structures is usually divided into active or semi active control. In active vibration control, a dynamic force is applied against the vibration to be attenuated for example; a force–producing member in a structure may compensate vibrations by inducing forces in the structures. In semi active vibration control, the characteristics of a structure are adjusted in such a way that the vibration response is optimized, for example, a component with controllable stiffness or damping may be used.

Smart materials produce response to signals such as temperature, voltage, pressure, magnetic fields and so on. These materials have the ability to transform one type of energy into another and therefore use of these materials improves the overall performance of a device/structure. Smart structure is a device that involves integration of actuators, sensors and processor. Smart materials can be grouped under the following categories. A passively smart material has the ability to respond to environmental conditions in a useful manner showing a distinction from an actively smart material in that there are no external fields, forces or feedback systems used to enhance its behaviour.

- Magneto Rheological Fluids
- Shape Memory Alloys
- Electrostrictive Materials
- Piezoelectric Materials
- Magnetostrictive Materials

A Giant Magnetostrictive Materials

Generally, magnetostriction is the change in shape of materials under the influence of an external magnetic field. The magnetostrictive effect was first described in the 19th century (1842) by an English physicist James Joule.He observed that a sample of ferromagnetic material, i.e. iron, changes its length in the presence of a magnetic field. Joule actually observed a material with negative magnetostriction, but since that time materials with positive magnetostriction have been discovered. The causes of magnetostriction are similar for both types of material. This change in length is the result of the rotation of small magnetic domains. This rotation and re-orientation causes internal strains in the material structure.

The strains in the structure lead to the stretching, in the case of positive magnetostriction, of the material in the direction of the magnetic field. During this stretching process the cross-section is reduced in a way that the volume is kept nearly constant. The size of the volume change is so small that it can be neglected under normal operating conditions. Applying a stronger field leads to stronger and more definite re-orientation of more and more domains in the direction of magnetic field. When all the magnetic domains have become aligned with the magnetic field the saturation point has been achieved.

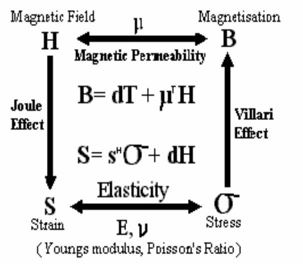

Fig. 1 Magnetostrictive effects

Tb0.3D0.7Fe1.9 Terfenol-D was discovered by a research group led by A.E. Clark in the 1970's at the Naval Ordnance Laboratory. Terfenol-D produces comparatively larger magnetostriction resulting in the maximum strain of the order of 4000ppm at resonance frequency. It consists of iron, rare earth elements terbium and dysprosium and is usually available in the form of rods having different diameters with residual magnetic fields nearly perpendicular to the rod axis. This is due to the fact that domains in the material with magnetic fields already aligned with the rod axis do not change in direction when an external magnetic field is applied along the rod axis. Therefore, these domains do not contribute to the magnetostriction. The magnetic field is produced either by a magnetic coil surrounding the rod or by a permanent magnet. Usually a configuration is selected where a permanent magnet is used to generate a steady bias field, and an ac current is applied to control the transient magnetic field or strain respectively. Advantages of TERFENOL-D are

- High strain
- High force
- Wide bandwidth
- High reliability/unlimited cycle life
- Wide temperature range
- Microsecond response time
- Attractive controllability with high power density
- High-precision motion
- High efficiencies
- High power levels
- High magnetomechanical coupling
- High load bearing capability
- High compressional strength
- Durability under static and dynamic loading
- Low voltage operation
- Simple fabrication process

The magnetic properties of these materials originate from magnetic moments which results from the spins of electrons in incomplete occupied inner orbitals of the atom. Due to spin orbit coupling, which is a purely quantum mechanical interaction, the magnetic moments are closely connected with the shape of the electron hull. The electrical negative electron hull affects Coulomb forces to the neighboring atoms in the lattice. Regarding the complex shape of electron hull these forces are not isotropic, this is important for magnetostrictive coupling. Applying an external magnetic field the magnetic moments switch in the direction of H. This process is associated with the rotation of the electron hulls. Along with the rotation of electron hull the Coulomb forces between the atoms change and the gaps in the lattice shift. Consequently, a deformation of the specimen is observed. Typical strain amounts from Terfenol-D rods are 0.001 per inch of exposed length in 500 Oe magnetic field.

B Applications of TERFENOL-D

Magnetostrictive technology has been successfully employed in low and high volume products. The two main areas of Terfenol-D applications are actuators and sensors. One of the first studied applications of highly magnetostrictive materials was as a generator of force and motion for underwater sound sources. Magnetostrictive transducers are used in high-class industrial devices, motorization, biomedical applications and arm industry, among which following can be ranked:

1 Active control of vibration
2 Micro-positioning
3 Devices used to degas while vulcanization of rubber
4 Intelligent plane wings able to change shape depending on flight speed and saving fuel thanks to that
5 Generating ultrasound in applications for surgical tools or acoustic devices
6 Electromechanical converters

II-OBJECTIVES

The paper describes the development and validation of finite element model for coupled field analysis of magnetostrictive material. The aim of the paper is to analyze isotropic beam along with magnetostrictive layers to control the vibration. The paper is restricted to simulation using commercial FEA software ANSYS. In this paper focus is put on the active vibration control of isotropic beam.

III-METHODOLOGY

ANSYS, a commercial Finite Element Analysis tool, shows it has all the options to perform coupled-field analysis. The ANSYS program performs coupled analysis sequentially using the concept of physics environment. ANSYS has elements which can specifically suit characteristics of magnetosrictive materials. When the input of one field analysis depends on results from another analysis, the analyses is coupled. Some analyses can have one-way coupling. For example, in thermal stress problem, temperature field introduces thermal strains in structural field, but structural strains generally do not affect temperature distribution. Thus, there is no need to iterate between the two field solutions. More complicated cases involve two-way coupling. A magneto structural analysis, for example, handles the interaction between the structural and magnetic fields.2 types of coupled field analysis are,

a) Sequential Method

The sequential method involves two or more sequential analyses, each belonging to a different field. There are different types of sequential analysis.

b) Direct Method

The direct method usually involves just one analysis that uses a coupled-field element type containing all necessary degrees of freedom. Coupling is handled by calculating element matrices or element load vectors that contain all necessary terms. An example of this is a piezoelectric analysis using the PLANE223, SOLID226, or SOLID227 elements.

The coupling between the fields can be accomplished by either direct coupling (matrix coupling) or sequential coupling (load vector coupling). Load transfer can take place across surfaces or volumes. Coupling across fields can be complicated because different fields may be solving for different types of analyses during a simulation. For example, in an induction heating problem, a harmonic electromagnetic analysis calculates Joule heating, which is used in a transient thermal analysis to predict a time-dependent temperature solution. The induction heating problem is complicated further by the fact that the material properties in both physics simulations depend highly on temperature.

PLANE13 Element Description

PLANE13 has a 2D magnetic, thermal, electrical, piezoelectric and structural field capability with limited coupling between the fields. PLANE13 is defined by four nodes with up to four degrees of freedom per node UX, UY TEMP and Magnetic Vector potential AZ. The element has nonlinear magnetic capability for modelling B-H curves or permanent magnet demagnetization curves. PLANE13 has large deflection and stress stiffening capabilities. When used in purely structural analyses, PLANE13 also has large strain capabilities.

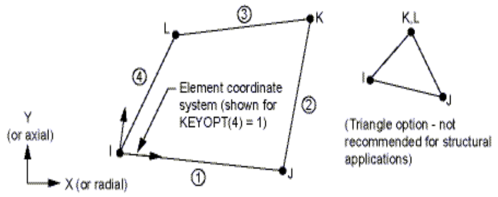

Fig. 2 Geometry of PLANE13 element in ANSYS

IV-VALIDATION OF FINITE ELEMENT MODEL

Magnetostrictive are widely used for actuation and sensing. In the actuation mode, on the application of a magnetic field along the beam, results in the bending of the entire structure and tip deflection. A beam as shown in Fig 3 is considered. The problem involves 2D analysis of a beam mounted as a cantilever beam. A current density of 240amps/m^2 is applied to beam.

Material Properties:

Young's modulus	$E = 25 \times 10^9$ N/m^2
Poisson's ratio	$\nu = 0.3$
Density	ρ= 9250 kg/m^3
Coefficient of thermal expansion	α= 12 ppm/°C
Specific heat coefficient	C= 0.35 kJ/kgK @25°C
Thermal conductivity	K=13.5 W/mK @25°C
Relative permeability	μ=10

Geometric Properties:

Length of the beam	L = 100 mm
Height	H =5 mm

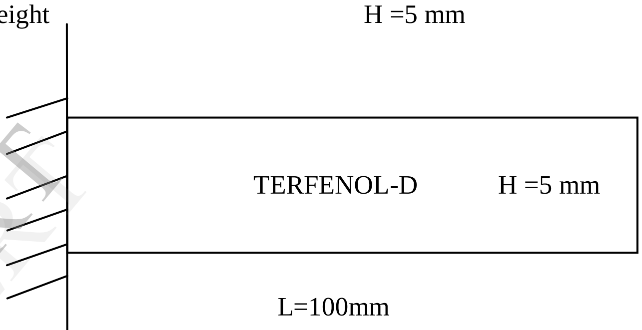

Fig. 3 Geometry of 2D Beam

A Finite Element Modelling of 2D Beam

PLANE13 (8-Noded coupled-field quadrilateral) element type is used to model the beam. This element is having 4 degrees of freedom, namely displacements along x and y direction, Temperature and Magnetic vector potential (AZ) as a degree of freedom. Finite element model generated using ANSYS is shown in Fig. 4

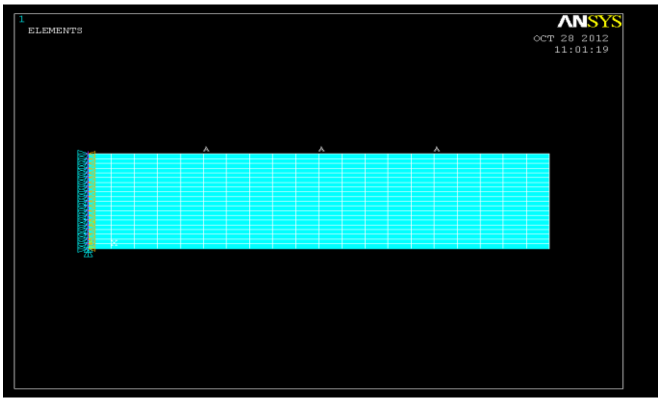

Fig. 4 Finite Element Model of 2D Beam

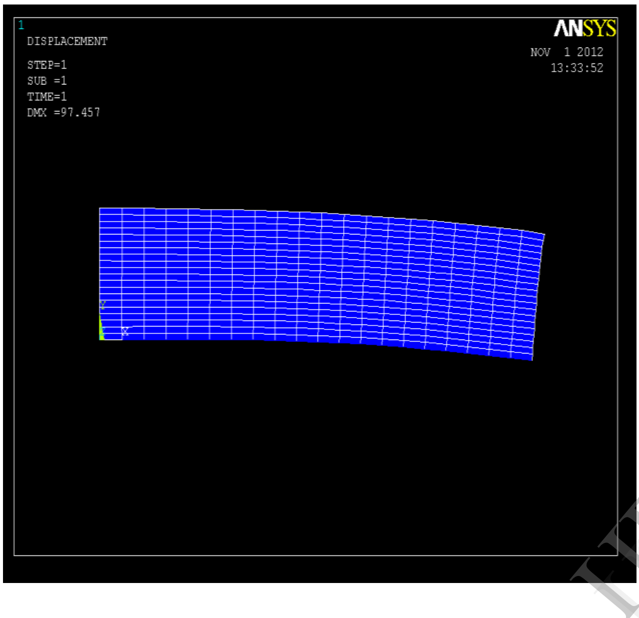

Fig. 5 Deformed Shape of 2D Beam

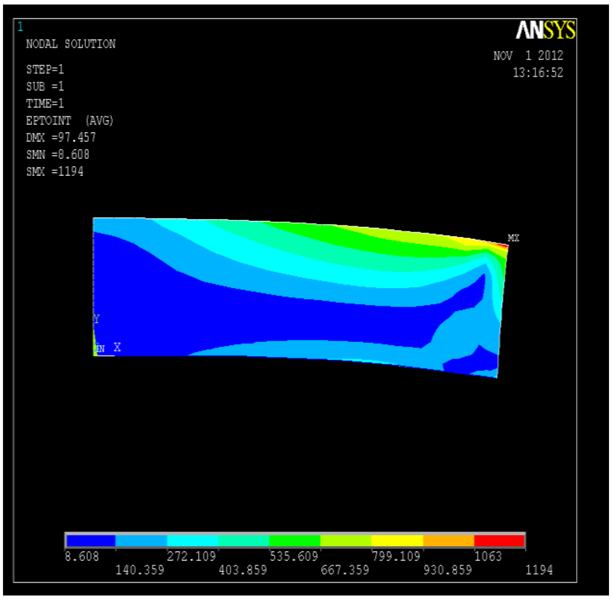

Fig. 6 Strain of 2D Beam along its length

All parameters, material properties and loading are input through suitable pre-processing commands. Mesh control option is used for meshing purpose and the size is 20 × 20 for beam. The behavior of beam is observed for deflection.

B Results and Discussion

Fig. 5 and Fig 6 show the deformed shape and strain of the 2D beam respectively. A strain of 1194 ppm is observed. Below equation gives an analytical solution for strain of a magnetostrictive beam.

$$H = NI/L \qquad (6.1)$$

$$= 600*2/0.1$$

$$= 12000$$

$$S = C\sigma + dH \qquad (6.2)$$

$$= (1/25E9)*30E12 + 1.67E\text{-}8*12000$$

$$= 1200 + 2E\text{-}4$$

$$= 1200 \text{ ppm}$$

It is evident that the strain obtained by numerical solution is in comparison with that of analytical solution. Deflection obtained is also within the limits of range of deflection that is 100microns.

V-CASE STUDY

We consider a cantilever beam having rectangular cross section on which magnetostrictive layer is mounted. The magnetostrictive layer acts as actuator. Here, steel material properties are used for isotropic beam and TERFENOL-D material properties for the actuator. The two layers have been glued rigidly.

Dimensional Parameters

Length of Beam	$L = 100$ mm
Width of Beam	$b = 10$ mm
Thickness of Beam	$t_1 = 10$ mm
Length of Actuator	$B = 50$ mm
Width of Actuator	$b = 1$ mm
Height of Actuator	$t_2 = 2.5$ mm
Actuator distance	$d_a = 50$ mm

Material properties

a) Steel Beam

Young's Modulus	$E = 20\times10^9$ Nm^{-2}
Poisson's ratio	$\nu = 0.3$
Density of beam	$\rho = 7800$ Kgm^{-3}

A Finite Element Modelling of Cantilever Smart Beam

The finite element model of the beam is shown in Fig.7 PLANE13 (coupled-field quadrilateral solid) and BEAM3 (2-

D Elastic Beam) element types are used to model the actuator and the beam respectively. For magnetostructural analysis, the degrees of freedom of PLANE13 and BEAM3 are 4 and 3 respectively. The material properties are input using TBDATA command in ANSYS. Pre-processor involves material properties, model generation and meshing. The connectivity between beam and actuator is given by using GLUE command in ANSYS. The beam is discretized into 40 × 1 mesh and the actuator is discretized into 20 × 10 × 1 mesh.

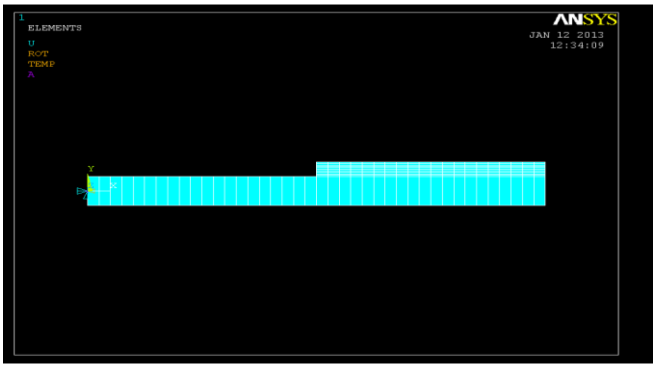

Fig. 7 Finite element model of cantilever Smart Beam

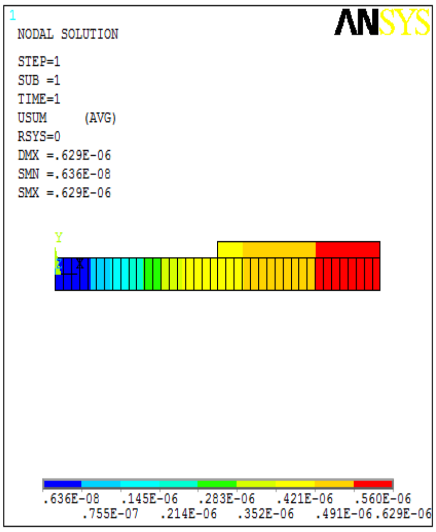

Fig. 8 Displacement without Current Density

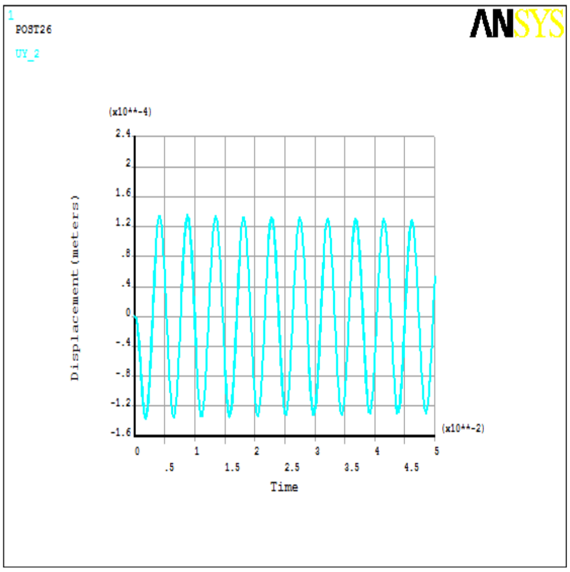

Fig. 9 Undamped Response of Beam

From fig 8 we can obtain the diflection when there is no magnetic field is acting on the beam, from fig 9 we can observe that how deflection varies with the time. Here, the deflection remains constant almost with the time, i.e., no reduction in vibration which is a character of un-damped vibrations. On validation of the Finite Element model, specific case study have been considered, by varying the current density(J) which varies the damping property of the smart beam that is to be controlled for vibration using magnetostrictive actuators. The transient dynamic analysis is performed to plot the time history of displacement.

B By applying a current density of 25amps/m^2 to the beam

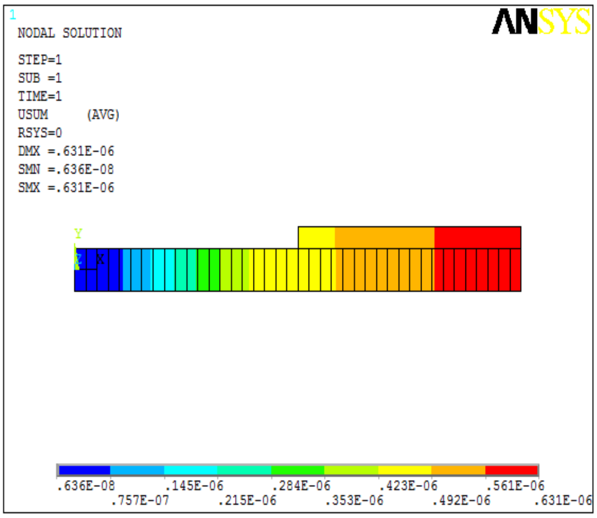

Fig.10 Displacement with J= 25amps/m^2

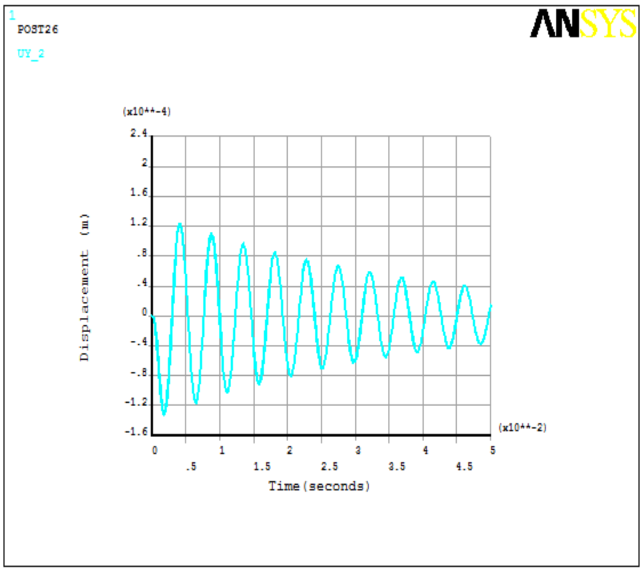

Fig.11 Damped Response (J=25 amps/m^2)

C By applying current density of 100amps/m^2 to the beam

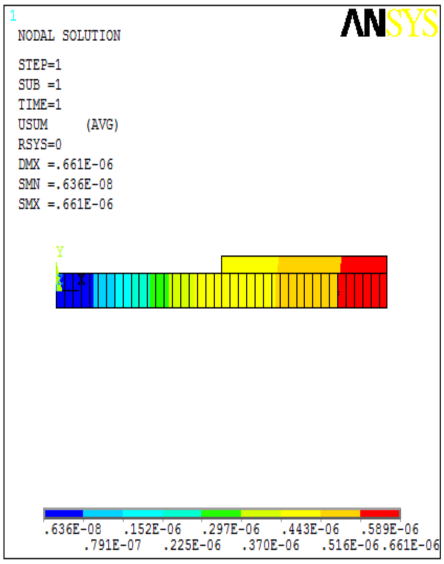

Fig. 5.12 Displacement with J= 100 amps/m^2

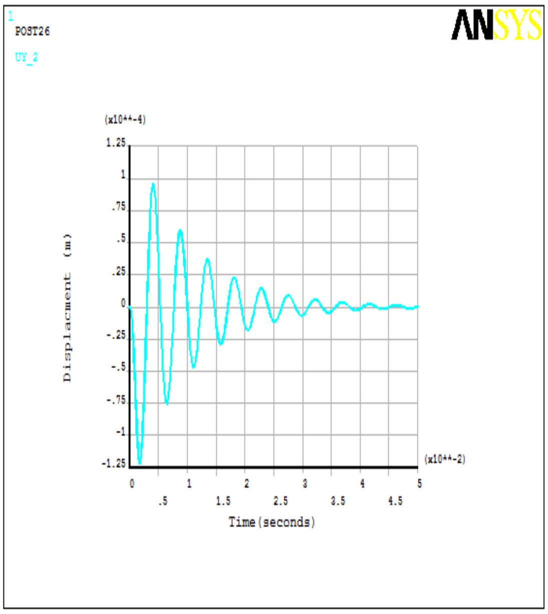

Fig. 5.13 Damped Response (J= 100 amps/m^2)

Fig10, 12, show the tip deflections obtained for different values of J. It is observed from the Fig 11, 13 that the tip deflection reduces as the J (current density) value increase. So we can say that vibration of a system is almost reduced and the amplitude decays to zero at J=100 amps/m^2. Here, we have also calculated the percentage reduction in the displacement value or tip deflection for 10 numbers of cycles.

Table 1 Current Density vs. Damping Ratio

Current Density	Displacement (microns)	frequency (f_d)	Damping Ratio
25	0.631	3943	0.0563
50	0.637	3924	0.1121
75	0.647	3894	0.1668
100	0.661	3852	0.228

Table 2 Damping ratio vs. % Reduction in Displacement

Damping Ratio	**Amplitude of Vibration (microns)**	**%reduction (in10 cycles)**
0	52.85	-
0.0563	14.36	72.8
0.1121	3.723	92.95
0.1668	0.912	98.27
0.228	0.203	99.61

VI-SUMMARY

A CONCLUSION

In the present study the results shows that the deflection of beam decreases as we increase the current density parameter. The analysis carried out by using simulation software ANSYS shows that the active vibration control is successfully achieved using magnetostrictive actuators. Magnetostrictive materials have a major role in active vibration control. And also we can conclude that ANSYS program is approximately good answer for coupled-field analysis.

B FUTURE WORK

Every Finite Element Analysis will come to reality, after being executed on a computer, only when it is implemented practically for a particular structure. So far what we have done is an analysis using ANSYS. Research and implementation is going on to show smart materials have a vital role in active vibration control. Looking at the literature review, we can notice that the simulations and experiments using Magnetostrictive actuators (or sensors) are restricted only to the simple structures. In future we have to focus on simulation for active vibration control of complicated structures and composites.

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