Abstract: Most of the damping mechanisms add damping to the structure by coming in physical contact with the structure thereby adding mass and altering the stiffness properties of the structure as a result of which the dynamics of structural elements are altered. Also they can cause localized defects/imperfections to structural elements. To overcome these drawbacks researchers are looking for potential methods which can add significant damping to the structure without coming in direct contact with the structure. One such method of adding damping is Eddy Current Damper (ECD). Eddy Current Damper (ECD) works on the principle of Electromagnetic Induction. According to the theory of electromagnetic induction, a current flows in a conductor whenever a change in magnetic flux is linked with it. Change in magnetic flux takes place when a conductor moves in a stationary or transient magnetic field. And according to Lenz’s law, the resulting magnetic field opposes the cause of changing magnetic flux. The cause in present study is the motion of the conductor. Hence the resulting magnetic field opposes the motion of conductor. In dynamics of structural elements, the kinetic energy resulting from the motion of the structure is converted into potential energy and vice versa. Hence we need to find a system which dissipates this energy through a specific dissipation function. The motivation of the research lies in the formulation of this dissipation function. A theoretical model of the system is derived using electromagnetic induction theory enabling us to estimate the damping force induced in the structure. Experiments were conducted on basis of theoretical models proposed in recent literatures on the cantilever beam. It was found that the eddy current damping mechanism adds significant amount of damping to the beam.

I. INTRODUCTION

A structure is a combination of parts fastened together to create a supporting framework, which may be part of a building, ship, machine, space vehicle, engine or some other system. One of the major causes of failure of structures is vibration or dynamic loads (time varying loads) which produces the dynamic stresses in the structural elements. The analysis of structural vibration is necessary in order to calculate the natural frequencies of a structure, and the response to the expected excitation. In this way it can be determined whether a particular structure will fulfill its intended function and, in addition, the results of the dynamic loadings acting on a structure can be predicted, such as the dynamic stresses, fatigue life and noise levels. Hence the integrity and usefulness of a structure can be maximized and maintained. From the analysis it can be seen which structural parameters most affect the dynamic response so that if an improvement or change in the response is required, the structure can be modified in the most economic and appropriate way. Very often the dynamic response can only be effectively controlled by changing the damping in the structure. There are many sources of damping in structures to consider and the ways of changing the damping using both active and passive methods require an understanding of their mechanism and control.

a. EFFECTS OF DAMPING ON VIBRATION RESPONSE OF STRUCTURES

It is desirable for all structures to possess sufficient damping so that their response to the expected excitation is acceptable. Increasing the damping in a structure will reduce its response to a given excitation. Thus if the damping in a structure is increased there will be a reduction in vibration and noise, and the dynamic stresses in the structure will be reduced with a resulting benefit to the fatigue life.

b. CONVENTIONAL DAMPING SYSTEMS AND THEIR DISADVANTAGES

There are many types of conventional damping systems like Inherent damping (Hysteretic or material damping) viscous damping etc but none of them add damping to the structure without coming in contact with the structure. There are thin shells like structure (spacecrafts, solar sail arrays) in which conventional damping systems cannot be employed. Conventional damping mechanisms can not be employed to these flexible structures as they can cause localized damage to the structure due to mechanical contact between the damper and flexible structure. Also when these damping mechanisms are used, they add mass and stiffness to the structure which is undesirable in most of industrial applications. Either we have to make such kinds of materials for these structures which possess enough inherent damping to avoid excess of dynamic stresses and ultimately failure or we have to look for such kind of damping mechanisms which can be employed without coming in contact with structures. One such mechanism is eddy current damping which is explained in the following section.

c. INTRODUCTION TO EDDY CURRENT DAMPING

When a conductor moves in a magnetic field (stationary or transient), a changing magnetic flux is linked with the conductor and an emf (electromotive force) is induced in the conductor. The induced emf in the conductor is proportional to the rate of change of magnetic flux (or velocity of conductor).
This induced emf causes currents to flow. The nature of these currents is such that they induce their own magnetic field which always opposes the change in magnetic flux that induces the current i.e. the induced magnetic field opposes the motion of conductor by causing the resistance to the motion. In a solid conductor, induced currents flow simultaneously along many different paths. Since they flow in a resistive medium, the eddy currents dissipate energy.

Undesirable vibrations of structures and mechanical systems can be reduced to desirable amount by adding damping systems. Eddy current dampers (ECD) can add significant amount damping to plate/thin beam like structures without coming in contact with the structural elements. These dampers can be installed as active dampers (using electromagnets) or passive dampers (using permanent magnets). The advantage of using electromagnets over permanent is that in electromagnets relays can be employed to the circuit which switches on the current when the vibration level reaches a threshold value. The phenomenon of eddy currents is successfully employed as magnetic braking in commercially installed turbine rotors and roller coasters.

II. LITERATURE REVIEW

The most of the literature review presented here is taken from reference [sodano 2005a] [1] which is a wonderful compilation of the literature of eddy current and its applicable fields. The applicable field of eddy current and related phenomenon is very vast ranging from braking to damping and much more. A brief introduction is presented here in field of braking and damping. The literature survey will flow in the order of occurrence.

Nagaya et al. (1984) [2] investigated the eddy current damping force induced on a conducting plate of arbitrary finite size moving with a velocity parallel to the face of a cylindrical magnet. To account for the boundary conditions of the conducting plate, the Fourier expansion collocation method was used, which provides no restrictions on the conductor shape. They state that due to this assumption, the model is only accurate for conductors of which the area is about ten times the cross sectional area of the magnet. Furthermore, the authors assume that the eddy currents generated through the thickness of the conductor are zero because of the conductor’s small thickness. However, through experiments it was found that this assumption is only valid for conductors with a thickness under of 5 mm.

Wiederick et al. (1987) [3] proposed a simple theory for the magnetic braking force induced by eddy currents in a thin rotating conductive disk passing through the poles of an electromagnet. Their model found the damping force to be linearly related to the velocity, conductivity and air gap, but quadratically dependent on the magnetic flux. The proposed model does not consider the effects of the edges of the conducting plate and while the paper provides an experimental study, it does not validate the accuracy of the model well. Heald (1988) [4] took the model proposed by Wiederick et al. (1987) [3] and formulated expressions that alleviated the need to assume a constant eddy current density in the “footprint” of the electromagnet and zero elsewhere. The results of the improved model were compared to those found by Wiederick et al. (1987) [3] and were shown to increase the accuracy from 96.3% to 99.4%.

Karnopp (1989) [4] introduced the idea that a linear electrodynamic motor consisting of coils of copper wire and permanent magnets could be used as an electromechanical damper for vehicle suspension systems. The study presented the ability to use a moving coil and a moving magnet actuator as the damping mechanism and employed some rough calculations to identify the system performance. The author showed that his actuator could be much smaller and lighter than conventional actuators while still providing effective damping in the frequency range typically encountered by road vehicle suspension systems.

Kienholz et al. (1994) [5] developed a tuned mass damper vibration absorber to suppress the vibration of a solar sail array. The frequency range of interest was from 0.1-1.0 Hz, thus the spring element of the system was required to have a very low stiffness and large stroke. Because the stroke of the absorber was very large (8 in) and most dampers would add stiffness to the structure, the choice of damping mechanism was difficult. After dynamic testing of the solar array it was found that in the two targeted modes (1st torsion at 0.153Hz and 1st out of plane bending of 0.222Hz) the damping was increased by 30 dB and 28 dB respectively, while the higher frequency untargeted modes in the range of 0.4-0.8 Hz were damped between 11-16 dB. These results indicate the high damping forces that can be achieved using magnetic damping techniques.

Frederick and Darlow (1994) [6] looked at using an eddy current damper to replace the coulomb or squeeze film dampers typically used in rotating machinery, whose damping properties typically change with temperature and cause additional torque loading and wear. The study was purely experimental and showed that the peak to peak response was reduced in the X-direction by 15.6% and in the Y-direction by 27.5%.

McCarthy (1995) [7] analyzed the basic physics of a mechanical, damped, forced, harmonic oscillator system with the help computer data acquisition technique. His aim was to make accurate comparisons of experimental data with the standard textbook analyses, especially with regard to the phase difference between the displacement response and the driving force, and to the functional form of the displacement response versus frequency curve. When he used the electromagnetic damping, he considered the effective restoring forces which included the electromagnetic forces resulting from the interaction of the “eddy” currents with the damping magnetic field, as increase in the effective spring constant. When viscous damping was used, fluid adhering to the damping system changed the effective oscillating mass. Both of these effects changed the resonant frequency. He concluded that with electromagnetic damping the resonant frequency was increased because the effective restoring force was increased by the electromagnetic force.

Cadwell (1995) [8] investigated the breaking force exerted on an aluminum plate as it passes between the poles of a horseshoe electromagnet. A simple model of the system was developed that leaves the length of the eddy currents path as an unknown parameter, which is fit using the experimentally obtained results. By adjusting the length of the eddy current,
the damping force induced on the aluminum plate can be varied. Experiments were performed by sliding a cart with a vertical aluminum plate attached down an air track. After performing the experiments the authors found the length of the eddy current path to be slightly less than the vertical height of the effective magnetic field.

Kligerman et al. (1998a, 1998b) [9] and Kligerman and Gottlieb (1998) [10] published a series of papers investigating the instability in rotor dynamics caused by the use of electromagnetic eddy current dampers. The first study of the series (Kligerman et al. (1998a) [9][10][11] theoretically and experimentally showed that eddy current dampers are not effective for use in rotating systems that are operating in the supercritical range because the dampers can induce unstable operation. The test results showed that indeed the rotation of the conductor between the magnets was responsible for the destabilizing effect and that the damper’s effectiveness improved with an increase in current applied to the electromagnet. The stability of the shaft with a freely rotating conductor was evident through the supercritical range.

Plassi et al. (2004) [12] discussed theoretical and experimental investigations of the use of eddy current damping for multi-stage pendulum suspensions such as those intended for use in Advanced LIGO, the proposed upgrade to LIGO (the US laser interferometric gravitational-wave observatory). The design of these suspensions is based on the triple pendulum suspension design developed for GEO 600, the German/UK interferometric gravitational wave detector, currently being commissioned. In that detector all the low frequency resonant modes of the triple pendulums are damped by control systems using collocated sensing and feedback at the highest mass of each pendulum, so that significant attenuation of noise associated with this so-called local control is achieved at the test masses. They also showed that eddy current damping is indeed a practical alternative to the development of very low noise sensors for active damping of triple pendulums, and may also have application to the heavier quadruple pendulums at a reduced level of damping.

III. THEORETICAL ANALYSIS OF FREE VIBRATION OF CANTILEVER BEAM

a. FREE VIBRATION ANALYSIS OF CANTILEVER BEAM WITHOUT DAMPING

The governing equations of an elastic beam undergoing small transverse vibrations for arbitrary loading is given by

\[ \rho A \frac{\partial^2 u}{\partial t^2} + EI \frac{\partial^4 u}{\partial x^4} = f(x, t) \]  

or free vibrating condition equation (4.1) reduces to

\[ \rho A \frac{\partial^2 u}{\partial t^2} + EI \frac{\partial^4 u}{\partial x^4} = 0 \]  

The boundary conditions are

At \( x = 0 \)
\[ u = 0, \quad \frac{du}{dx} = 0 \]

At \( x = L \)
\[ EI \frac{\partial^3 u}{\partial x^3} = 0, \quad EI \frac{\partial^3 u}{\partial x^3} = 0 \]

The initial conditions are

At \( t = 0 \)
\[ u = u_0, \quad \frac{du}{dt} = u' \]

The general solution of equation (4.2) is

\[ u(x, t) = \{C_1 \cos(\lambda x) + C_2 \sin(\lambda x) + C_4 \cos(\lambda x) + C_4 \sin(\lambda x)\} \{\cos(\sqrt{\lambda} t) + B \sin (\sqrt{\lambda} t)\} \]

or

\[ u(x, t) = X(x)T(t) \]

Where, \( \lambda \) is a constant. For a cantilever beam the characteristic equation in terms of \( \lambda \) is

\[ \Cosh(\lambda^{1/4}) \cos(\lambda^{1/4}) = -1 \]

To find the roots of this equation codes were written on MATHEMATICA®. The code is listed in appendix. Applying boundary conditions and solving for constants the equation (3) reduces to

\[ u_i(x, t) = C_i(\cos(\lambda x) - \cos(\lambda x) + a_i(\sinh(\lambda x) - \sin(\lambda x)))\{\cos(\sqrt{\lambda} t) + B \sin (\sqrt{\lambda} t)\} \]

Where

\[ a_i = \frac{\sqrt{\lambda_i}(\cosh(\lambda_i^{1/4}) - \sinh(\lambda_i^{1/4}))}{\sinh(\lambda_i^{1/4}) + \sin(\lambda_i^{1/4})} \]

The normalization of the mode shapes with respect to the kinetic energy scalar product yields the value of \( C_i \). The values of constant A and B can be found out by applying the initial conditions.

<table>
<thead>
<tr>
<th>Table.1 Properties for theoretical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_0 )</td>
</tr>
<tr>
<td>( u_0' )</td>
</tr>
<tr>
<td>Young’s modulus of cantilever beam</td>
</tr>
<tr>
<td>Density of cantilever beam</td>
</tr>
<tr>
<td>Loss factor</td>
</tr>
<tr>
<td>Thickness of beam</td>
</tr>
<tr>
<td>Length of beam</td>
</tr>
<tr>
<td>Width of beam</td>
</tr>
<tr>
<td>Depth of beam</td>
</tr>
</tbody>
</table>

Taking the general values provided in table 1 and solving the equation stated above we get the following results for first four modes of vibration. The values of constant \( A_i \) are listed in table 2

<table>
<thead>
<tr>
<th>Table.2 values of constant ( A_i ) for first four modes of vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
</tr>
<tr>
<td>( A_2 )</td>
</tr>
<tr>
<td>( A_3 )</td>
</tr>
<tr>
<td>( A_4 )</td>
</tr>
</tbody>
</table>

It is seen that \( A_1 \) is by far the largest coefficient, and so the response of the first mode strongly dominates the ensuing motion. This is as expected, because the parabolic initial shape approximates the first vibration mode shape reasonably well.

If the beam were initially displaced in exactly the first mode shape, it would vibrate subsequently in that single mode - no other modes would be involved at all.
IV. EXPERIMENTAL ANALYSIS OF EDDY-CURRENT DAMPER
a. EXPERIMENTAL SET UP DETAIL

The goal of the experiment performed in this study is to identify the damping ratio. The experiment was performed on a cantilever beam made up of aluminum. Two thin copper plates were used in order to increase the eddy current density. The detailed dimensions and physical properties of the beam are listed in table 1. Instead of permanent magnets electromagnets were used in experimental study in order to incorporate the issue of change in magnetic flux by changing the current. Set up consists of following parts:

- Cantilever beam (Al)
- Electromagnets
- Sensing unit

![Fig.4 the detailed set up is shown](image)

b. CANTILEVER BEAM

The cantilever beam which was used in study is shown in fig 4

![Fig.5 Cantilever beam](image)

### Table 3 Physical and geometrical properties of the beam

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus of cantilever beam</td>
<td>75 GPa</td>
</tr>
<tr>
<td>Density of cantilever beam</td>
<td>2700 Kg/m3</td>
</tr>
<tr>
<td>Conductivity of beam</td>
<td>3.82 x 10^7 mho/m</td>
</tr>
<tr>
<td>Thickness of beam</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Thickness of copper conductor</td>
<td>* mm</td>
</tr>
<tr>
<td>Conductivity of copper conductor</td>
<td>5.80 x 10^7 mho/m</td>
</tr>
<tr>
<td>Length of beam</td>
<td>500 mm</td>
</tr>
<tr>
<td>Width of beam</td>
<td>5 mm</td>
</tr>
<tr>
<td>Depth of beam</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

c. ELECTROMAGNETS

Two electromagnets were used in experiment. Each consists of copper coil wound on a soft iron core. The detail construction of electromagnets are listed in table 4
The electromagnets were simulated through computer software ‘COMSOL’. The steps are listed in appendix.

d. SENSING UNIT

The response of beam was checked with the help of a multi-meter. The input to the multi-meter was provided through a sensing unit. The sensing unit consists of following parts

- Sensor
- Amplifier circuit
- Receiver

V. RESULTS AND CONCLUSIONS

This report has analyzed the damping produced by the eddy current damper as applied to a cantilever beam. Two electromagnets were used in the experimental work with same poles facing each other. The performance of the system was analyzed and it was found that the damping ratio comes out to be 58.1% more than that with the consideration of structure damping only. The damping ratio was computed from the logarithmic decrement for the two cases.

- With structural damping only
- With combined effect of structural damping and eddy current damping.

The value for both the cases are listed in Table 5

Table.5 Values of damping ratio

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>With structural damping only.</td>
<td>0.0003768</td>
<td>0.006039</td>
</tr>
<tr>
<td>With combined effect of structural damping and eddy current damping.</td>
<td>0.0122487</td>
<td>0.01038</td>
</tr>
</tbody>
</table>

Table.6 Values of logarithmic decrement

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>With structural damping only.</td>
<td>0.002367</td>
<td>0.037949</td>
</tr>
<tr>
<td>With combined effect of structural damping and eddy current damping.</td>
<td>0.0769668</td>
<td>0.065325</td>
</tr>
</tbody>
</table>

For the optimal performance of a machine element or a structure, it required that vibration of system must be suppressed quickly. Eddy currents provides an efficient way of adding damping to the structure without coming in contact with the structure thereby eliminating the possibilities of the localized damage, altered dynamics of structure and problems like deterioration of seals, leaking liquids etc. The assumption of infinite conductor can produce slight errors for which some methods like method of images could be employed to improve the eddy current model.

VI. REFERENCES


