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Analysis of a Fuzzy Logic based Non Contact Vibration Damper Made up of an Electromagnet

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Abstract—*The present work deals with performance analysis of a non-contact vibration damper made up of an electromagnet. The damper is used to minimize the vibration of a cantilever beam. A fuzzy logic based control technique is applied here to minimize the vibration of the beam. An electromagnet is placed at the free end of the beam. A non contact displacement sensor is used to measure the displacement of the beam. Depending on the displacement and velocity at the free end of the beam, the fuzzy logic control technique is used to control the current through the coils of the electromagnet. During the upward displacement of the beam above the static equilibrium position the electromagnet is switched on and electromagnet will give a magnetic force in the opposite direction of motion of the beam. During the downward movement of the beam and during the upward movement below the static equilibrium position, the electromagnet is switched off. In this paper it is shown that the proposed damper successfully minimizes the amplitude of vibration of the beam under the action of step excitation and swept sine excitation.*

1. INTRODUCTION

Magnetic actuators have been extensively used to excite and control the vibration of beams It has the advantage of applying non contact actuating force to control and excite structures. The magnetic force turns out to be different from a simple force because of the fact that it also changes the stiffness of the system.

Schweitzer et al. (2003), Genta (2004), Chiba et al.(2005) systematically documented the extensive research output in the field of active magnetic bearings in their well-known texts on the subject. Fung et al. (2005) developed an electromagnetic actuator for the vibration control of a cantilever beam with a tip mass. The proposed actuator system consisted of an electromagnet and a permanent magnet attached at its top, whereas another permanent magnet was installed at the tip of the cantilever beam. They applied the PID control, quadratic feedback control and optimal feedback control laws to control the coil current of the electromagnet to suppress the vibration of the beam. Nandi et al. (2009) proposed a one sided electromagnetic actuator to control the vibration of a structure or rotor. A simple proportional derivative (PD) control technique was suggested to control the vibration. Depending upon the displacement, the current through the coil of the electromagnet was varied to achieve the required control force. Nandi and Neogy (2010) presented a non-contact hybrid exciter for harmonic excitation of lightly damped structures or rotors. In their proposed exciter an electromagnet was placed on a piezoelectric stack and the extension of the piezoelectric stack was made almost equal to the displacement of the structure. A sinusoidal current passed through the coil of the electromagnet to produce electromagnetic force to excite the beam.

Fuzzy logic technique includes intelligent characteristics in the system. Based on the virtues of fuzzy logic control, Park et al. (2000) established the approximate model of the driver, the sensor, and fuzzy logic controller to solve the problems of vibration for flexible structures. Mahfoud and Hagopian (2011) numerically and experimentally controlled the vibration of a flexible beam by using an electromagnetic actuator. Fuzzy control strategy was used with displacement and velocity as the input.

In this paper a single electromagnetic actuator is used to control the vibration of a cantilever beam. The electromagnetic actuator is placed below the free end of the beam. Fuzzy control technique is used to control the current through the coil of the electromagnet. Due to the current in the coil of the electromagnet, the magnetic force is acted on the beam which is responsible to minimize the amplitude of the vibration of the beam.

2. ANALYSIS

Fig. 1 shows the working principle of the single electromagnetic actuator to control the vibration of the beam. It is well known that the force exerted on a structure by a one-sided actuator is directly proportional to the square of the current in the electromagnet and inversely to the square of gap between the actuator and the structure/rotor. If the force exerted on the structure is denoted by F, then

$F = k' \frac{i^2}{(x_0 - x)^2}$. Where 'i' is the current through the coil of the electromagnet, x_0 is the initial gap between the free end of the beam and the actuator, and x is the displacement of the free end of the beam. The constant $k' = \frac{\mu_0 n^2 A_m}{4}$ where μ_0 is permeability of free space $= 4\pi * 10^{-7}$ N/A^2, n is the number of turns in the coil of the magnet and A_m cross-sectional area of the magnet.

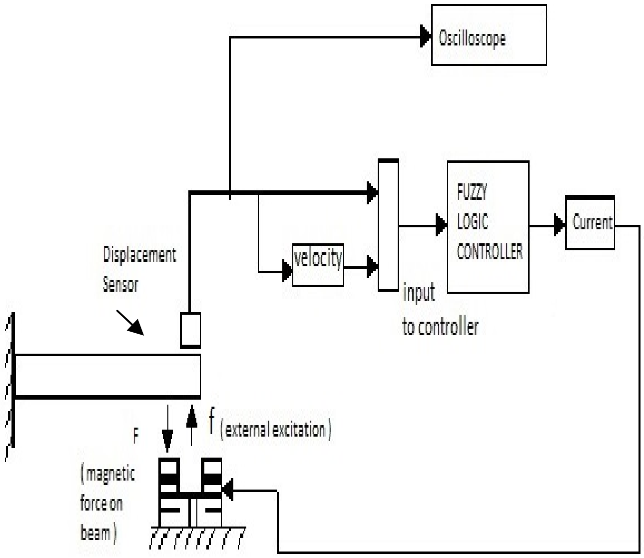


Fig. 1: Schematic diagram showing the arrangement of the beam along with actuator and controller

2.1 MDOF model

In a multi-degree of freedom (MDOF) model of the beam let the $n \times 1$ vector $\{X\}$ contains the displacements of the beam at its degrees of freedom. Let the actuator force be applied at the jth degree of freedom. If the mass, stiffness and damping matrices of sizes $n \times n$ are represented by the symbols $[M]$, $[K]$ and $[C]$ respectively, the governing equation of motion for the system can be written as follows:-

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{T_e\} f + \{T_c\}(-F) \quad (1)$$

The $n \times 1$ vector $\{T_c\}$ has all zero entries except for the jth row. This row has a unity entry. Similarly, $\{T_e\}$ has a unity entry only at that degree of freedom where the external excitation is applied.

In state space notations,

$$\begin{Bmatrix} \{\ddot{X}\} \\ \{\dot{X}\} \end{Bmatrix} = -\begin{bmatrix} [M]^{-1}[C] & [M]^{-1}[K] \\ -[I] & [0] \end{bmatrix} \begin{Bmatrix} \{\dot{X}\} \\ \{X\} \end{Bmatrix} + \begin{bmatrix} [M]^{-1}\{T_e\} & [M]^{-1}\{T_c\} \\ [0] & [0] \end{bmatrix} \begin{Bmatrix} f \\ (-F) \end{Bmatrix} \quad (2a)$$

$$\text{Or, } \{\dot{Z}\} = [A]\{Z\} + [B] \begin{Bmatrix} f \\ (-F) \end{Bmatrix} \quad (2b)$$

The displacement of the beam at the location of the actuator can be obtained as

$$x = [C_1]\{Z\} \quad (3)$$

2.2 Fuzzy logic controller

A. Modeling of fuzzy controller

Fuzzy logic idea is similar to the human being's feeling and inference process. The basic idea behind fuzzy logic control is to incorporate the "expert experience" of a human operator in the design of a controller in controlling a process whose input-output relationship is described by a collection of fuzzy control rules (e.g. IF-THEN rules) involving linguistic variables.

Fuzzy controller block diagram is shown in Fig.2

Fuzzy logic controller has four parts:

1) Fuzzification: It transforms input into suitable linguistic value so that can be compared to the rule in rule base system of fuzzy logic. It involves the conversion of the input/output signals into a number of fuzzy represented values (fuzzy sets).
2) Rule Base: It contains the knowledge in form of a set of rules to control the artificial system. It is the collection of rules. The basic function of rule base is to provide the necessary information to fuzzification module, the rule base and the defuzzification module. 'If' part is called antecedent and 'then' part is called consequent.
3) Inference Engine: If control rules are relevant then it decides the input to the plant. The Inference Mechanism provides the mechanism for invoking or referring to the rule base such that the appropriate rules are fired on the situation.
4) Defuzzification: It converts fuzzy output to crisp output. In this paper centroid method is used for defuzzification. Defuzzification interprets membership degree in the fuzzy sets into a specific action or real-value

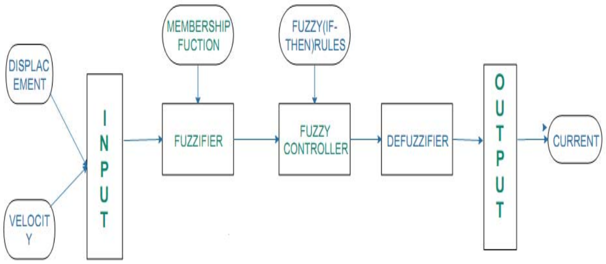


Fig. 2: Fuzzy controller block diagram

In this paper ,fuzzy controller is designed as double input, single output(DISO) system. Displacement and velocity are the input to the system and current is the output from the system. Triangular membership is used in this controller. Centroid method is used for fuzzification.

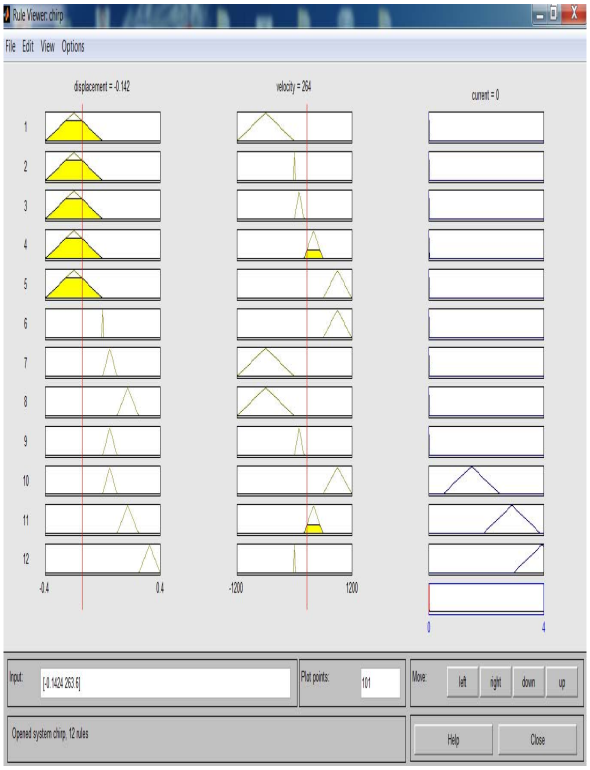
B. Rules of fuzzy controller

Fuzzy rule interacts between input and output. It makes relationship between input and output. Displacement and velocity are as input and current is output. Fuzzy controller executes the rule and according to rule base gives output. The function of fuzzy controller is to provide the current to electromagnet to reduce the amplitude of vibration.

There are several rules obtained as fellow:

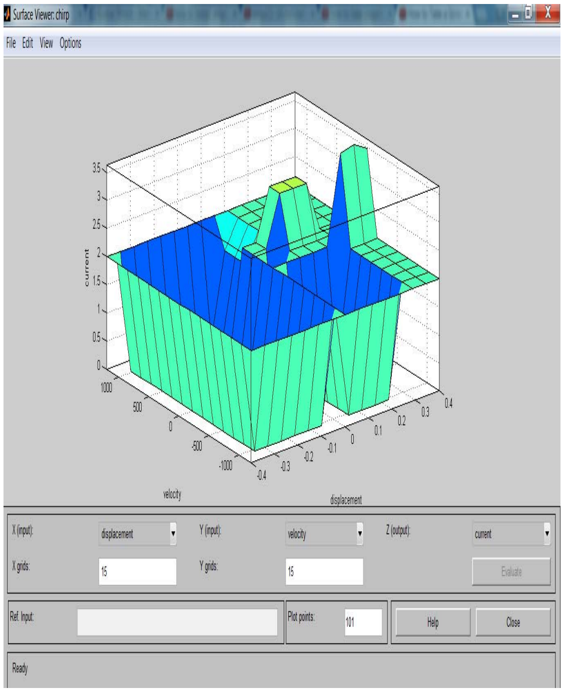
1) If Displacement is PS and Velocity is PB ,the beam is up from of equilibrium position .so it needs to supply the PS Current to electromagnet and makes the beam close to reference values.
2) If Displacement is PM and Velocity is PM, the beam is up from of equilibrium position .so it needs to supply the PM Current to electromagnet and makes the beam close to reference values.
3) If Displacement is PB and Velocity is ZE(zero),the beam is up from of equilibrium position. so it needs to supply PB Current to electromagnet and makes the beam close to reference values.
4) If Displacement is PM and Velocity is NM, then supply the Current ZE to electromagnet and makes the beam close to reference values.
5) If Displacement is PS and Velocity is NB ,then supply current ZE to electromagnet and makes the beam close to reference values.
6) If Displacement is ZE and Velocity is any one ,then supply current ZE to electromagnet and makes beam close to reference.
7) If Displacement is Negative and Velocity is anyone ,then supply current ZE to electromagnet and makes the beam close to reference.
8) If Displacement is PS and Velocity is PS, then supply current ZE to electromagnet and makes the beam close to reference.

Fuzzy IF-THEN rule base is obtained by analysis, with many trail and error. The fuzzy rule is not invariable, it could be modified according to the situation .



Input: [-0.1424 263.6]
Plot points: 101
Opened system chirp, 12 rules

Fig. 3: Rule viewer of fuzzy controller



X (input): displacement
Y (input): velocity
Z (output): current
X grids: 15
Y grids: 15
Ref. Input:
Plot points: 101
Ready

Fig. 4: Surface viewer of fuzzy controller

3. MATLAB SIMULINK MODEL

The performance analysis of the single electromagnetic actuator is done using matlab simulation. The following Fig. shows the block diagram for the simulink model.

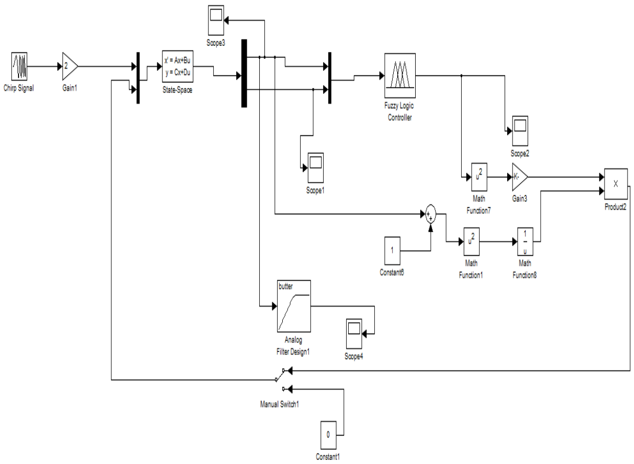


Fig. 5: Matlab simulink model of the proposed actuator

4. NUMERICAL STUDY

A ten-element finite element discretization of a steel cantilever beam is considered here. The rotation degrees of freedom are removed using Guyan reduction technique. A small damping of the beam is considered in the form of Rayleigh damping. In SIMULINK, a state space block is used to represent the beam model in state space form. The beam is $200mm$ in length and $18mm \times 10mm$ in cross-section. The actuator is placed below the free end of the beam. The Electromagnetic actuator contains a coil wrapped around the core in which the current flows and an electromagnetic force is produced. The electromagnet considered here has the following specification Number of turns of wire on the electromagnet, n=100,cross-sectional area of the core, A_m=200mm^2,permeability of air=4π*10^{-7}N/amp^2.

The beam is first subjected to a step excitation applied at a time $t = 0$ .Depending upon the velocity and displacement at the free end of the beam, the current in the actuator is controlled by the fuzzy logic controller and the actuating force is acted on the beam. The response to the excitation is shown in Fig. 7 for the uncontrolled system and the controlled system. The amplitude of vibration of the uncontrolled system slowly reduces with time as there is a small damping present in the material of the beam. The controlled system quickly reaches its static equilibrium position as the vibration quickly dies down.

The beam is then subjected to a swept sine signal. The amplitude of the signal is kept constant at a value of $2N$. For the signal the frequency centers around the first natural frequency of the beam and varies from $530Hz$ to $560Hz$ in a time span of $1s$. During this excitation the beam passes through its first natural frequency. The response of the uncontrolled beam and the controlled one is presented in Fig. 6

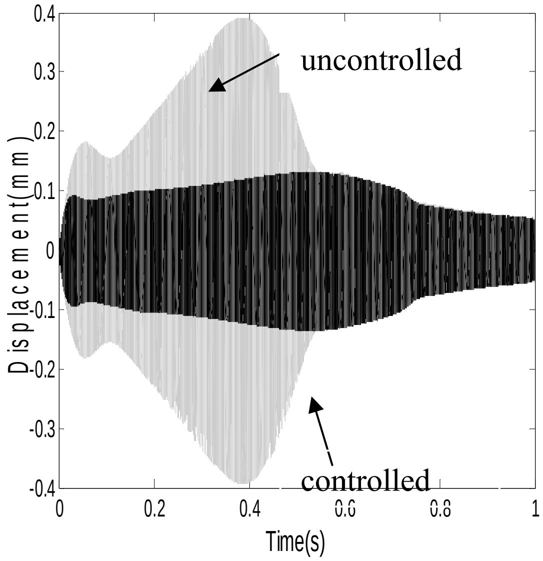


Fig. 6: Uncontrolled and controlled response of the free end of the cantilever beam under the action of swept sine excitation

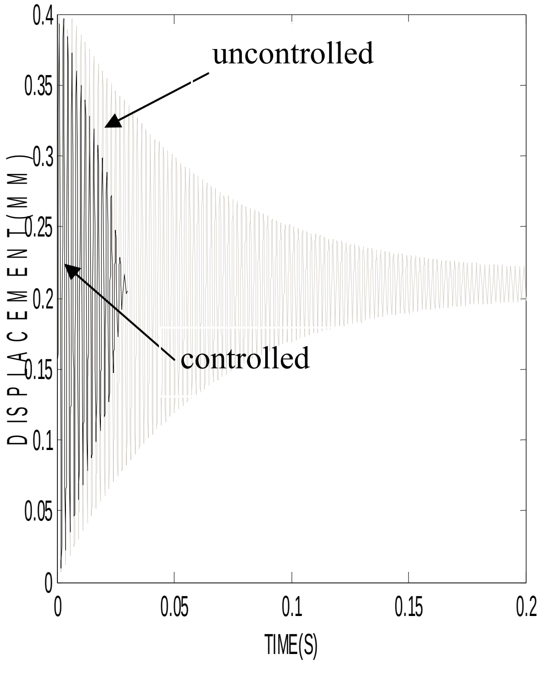


Fig. 7: Uncontrolled and controlled response of the free end of the cantilever beam under the action of step excitation

5. CONCLUSION

The proposed electromagnetic actuator successfully minimized the amplitude of vibration of a cantilever beam for step and swept sine signal input. Fuzzy logic controller provides an effective means to control the current through the coil of the electromagnet. In future, the same arrangement, with little modification, can be easily extended to a similar attempt to control vibration of a light rotor, where the conducting disc is prevented from rotating with the shaft.

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