Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 02, February-2017

Design and Mathematical Modeling of Smart Fluid Damper for Vibration Control

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***Abstract*- In general vibration is highly unwanted in any of the application. To beware of vibration experienced during course of application various methods of vibration control exist. Among them damping gives sure shot solution against vibration. Damping of any vibrating system can be improved either by improving the material or with implementation of damping layer treatment, etc. In the present scenario there has been growing attention in the development of controllable dampers that utilize smart fluids. Design and mathematical modeling of such smart fluid dampers is taken up in this project. To start with in the first phase detailed mathematical modeling of smart fluid damper will be carried out and certain governing equations with regard to design parameters will be evolved. In the second phase mathematical model will be converted in form of a program using MATLAB software which will overlay the way for design. Accordingly in the next phase design of smart fluid damper meant for control of vibration will be carried out. In the final phase simulation will be carried out to optimize the design process. Intended outcome of this project would be design and mathematical model of smart fluid damper for vibration control.**

I. INTRODUCTION

Vibrations have bad effects on the performance of many structures and applications. Smart fluids are one example of smart materials, and are considered as the one of most superior means of controlling vibration, and lots of semi-active applications have been employed successfully. Smart fluids a fluid that changes its properties in response to an applied electric or magnetic field. It consists of micron sized particles suspended in an inert carrier liquid.Conventional Smart fluid dampers are designed with normal hydraulic Smart fluid dampers that use a cylinder, piston and valve housed in the cylinder is shown in Fig. 1.

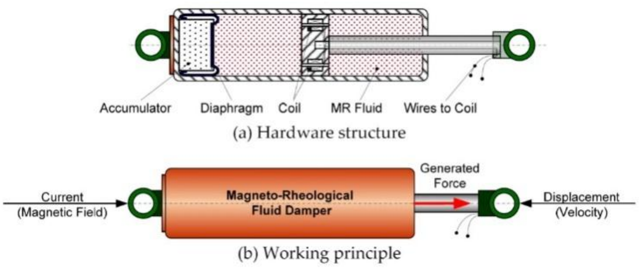

Fig. 1.Conventional damper

However, the majority of conventional Smart fluid dampers have been designed by using a hydraulic Smart fluid damper, which has a dry seal friction. This friction can have a negative effect on the vibration performance of the system. To overcome the friction associated issue with conventional damper, design of a Smart fluid damper is proposed in this project which will have a low value of static friction.

Analytical and experimental studies of a magneto-rheological fluid (MRF) damper for the back sideisoaltion of two wheeler is presented[1]. Estimation of design parameters using a method is discussed for MR fluid damper. An improved dynamical model is implemented and the outcome is obtained[2].Numerous merits associated with MRF damper in contrast with passive vibration control technique are brought out[3].Construction details of MRF damper along with its prime characteristics are discussed. Further simulations studies of the same device are also presented [4].Configuration aspects of MR fluid damper device for a washing machine are mentioned. Further same has been optimized with respect to its performace. Finite Element Analysis (FEA) [5]. In addition to theoretical design, a prototype model of MR fluid damper has been fabricated. With experimentation carried out on prototype model design calculations are thoroughly validated[6].Vibration performance of the damper has been studied against harmonic and random excitation. These studies have revealed that intended damper will also imparts stability in addition to primary function i.e. vibration control [7].Another variety of active vibration control MR fluid damper is designed. However mounting bracket is also considered for studies [8].

As it can be seen,

- No one dealt with simulation of MR fluid damper for the sake of optimization
- Most of the dampers mentioned are conventional piston cylinder types
- All most all the literature touches up on fully active control type of dampers
- Research work is yet to be done to bring out the optimal design philosophy.

Based on the limitations brought out as an outcome of literature review it is aimed to design a novel MR fluid damper in this work which will have a low value of static friction; so it is less affected by stick-slip phenomena.

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II. DESIGN PHILOSOPHY

Mathematical model consists of: a tube, valve and pressurized accumulator. This tube consists of a rubber tube surrounded by an expansible braided cover. It is sealed at one end, and it is able to carry load at this tip, while the tube is attached to an accumulator via a ball valve at another end. It is assumed to be fixed in a frame to simulate service mount condition. The frame is covered to protect electrical devices in case of tube explosion at high pressure. Pressurizing the tube could be achieved by using a pump through a valve located at the top of the accumulator. The pump is connected to a gage pressure to measure the pressure of the accumulator and inside the Smart fluid damper in case of an open valve. There is an additional digital gage pressure installed between the tube and ball valve to measure the pressure in case of a closed valve. The idea of this device is: applying force to the end of the test rig will change the volume of the tube, and consequently the pressure will be increased inside the tube. Then, the fluid is able to flow in and out of the tube, and energy will be eliminated through the viscous effect of the controlled valve. Similar to this, a damper was introduced.

III. DESIGN OF SMART FLUID DAMPER

Following assumptions are taken for design.

- Energy stored in an inner tube (rubber tube) is zero.
- Wall thickness of the inner tube is zero.
- The shape of the McKibben tube is cylindrical.

There are three variable parameters of this device:

- A force applied to the test rig
- Internal pressure of the tube
- Length of the tube

There are several techniques used for predicting the behaviour of this Smart fluid damper and to provide a relationship between variable parameters. The technique of energy analysis, where input work (Win) is equal to the output work (Wout), will be used in this work.

The input work is done on this Smart fluid damper by applying compressed air; this air moves the inner rubber surface, so the work is:

$dWin = P^1 dV$

Where

dV: Volume change

P^1: Gauge pressure.

The output work from this pressure is tension in the Smart fluid damper, which leads to a decrease in the length of the tube:

$dWout = - F\, dL$

Where

F: Axial force

dL: Axial displacement

From the principle of virtual work, we could reach to the next expression

$P^1 dV = - F\, dL$

Alternatively

$$F = - P^1 \frac{dV}{dL}$$

This equation is similar to the hydraulic cylinder equation ; the amount of force a hydraulic cylinder can generate is equal to the hydraulic pressure times the effective area of the cylinder. Therefore, the value of is the effective hydraulic area of the Smart fluid damper.

It is difficult to find for irregular shapes, therefore the shape of a tube is assumed as a cylindrical shape. The dimensions of this cylinder are

- Length
- Diameter
- Fibre angle is θ

These dimensions are changing during the applying load. The geometry has constant dimensions: is the length of uncoiled fibre and the number of turns for a single fibre. The relationship between L and D is as follows.

$L = b \cos \theta$

The volume of a cylinder is

From these equations, the axial force could be expressed

$$F = - p^1 \frac{dV}{dL} = - p^1 \frac{\frac{dV}{d\theta}}{\frac{dL}{d\theta}}$$

$$F = \frac{\pi D_{\theta=90}^2 p^1}{4} \left(3 \cos^2\theta - 1\right)$$

Where D_θ =90 is the diameter when $\theta = 90^0$,

$$D_0 = \frac{b}{\pi n}$$

Due to the difficulty of measuring of fibre angle ±θ, it is worth expressing the equation in terms of tube length, and uncoiled length of fibre ‘b’ and rearranging the above mentioned equations.

$$F = P^1 \left(\frac{3L^2 - b^2}{4\pi n^2} \right)$$

The equation illustrates that there are three variable parameters of this device: an applied force, internal pressure, and the length of the tube.

However it has been reported in literature that the accuracy of the previous model of the tube is about 80 %. An improved model which could provide a higher accuracy is attempted further. To improve the model of Smart fluid damper behaviour, the model is extended by introducing an elastic energy of inner tube.

dWin = dWout + VrdW

Where

V_r: Volume occupied by the inner tube

W: Strain energy density function

From the previous analysis of input work and output work

$$P^1 dV = - F\, dL + V_r dW$$

Alternatively

$$F = - P^1 \frac{dV}{dL} + V_r \frac{dW}{dL}$$

For simplicity, the rubber tube will be assumed to behave as a solid. The strain energy function of the Smart fluid damper W could be expressed as a function of the first invariant of strain.

$$W = \frac{\mu_r}{2}(I_1 - 3)$$

Where

μ_r : Shear modulus for infinitesimal deformations

I1: Strain invariants

And the same can be expressed as follows

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

In which

λ_I (i=1,2,3) are the principle stretches

$$\lambda_1 = \frac{L}{L_o}$$

Where

L: Instantaneous length of the tube

D: Instantaneous diameter of the tube

L_O: Initial length of the tube

D_O: Initial diameter of the tube

Hence W can be expressed as

$$W = \frac{\mu_r}{2}\left(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3\right)$$

Alternatively

$$W = \frac{\mu_r}{2}\left(\left[\frac{L}{L_o}\right]^2 + \left[\frac{D}{D_o}\right]^2 + \left[\frac{D_o L_o}{D\,L}\right]^2 - 3\right)$$

From the geometry model, the diameter of the tube could be expressed in terms of length of tube.

$$D^2 = \left(\frac{b^2 - L^2}{\pi^2 n^2}\right)$$

Therefore strain energy density of inner tube W is determined by using the equation.

$$W = \frac{\mu_r}{2}\left(\left[\frac{L}{L_o}\right]^2 + \left[\frac{b^2 - L^2}{D_o^2 \pi^2 n^2}\right] + \left[\frac{D_o^{\,2} L_o^{\,2} \pi^2 n^2}{L^2 (b^2 - L^2)}\right] - 3\right)$$

The derivative strain energy density regarding the length

$$\frac{dW}{dL} = \frac{\mu_r}{2}\left[\frac{2L}{L_o^{\,2}} + \frac{-2L}{D_o^2 \pi^2 n^2} + \frac{-2D_o^{\,2} L_o^{\,2} \pi^2 n^2 (b^2 - 2L^2)}{L^3 (b^2 - L^2)^2}\right]$$

Therefore, the force output of the Smart fluid damper could be expressed

$$F = P^1\left(\frac{3L^2 - b^2}{4\pi n^2}\right) + \frac{V_r \mu_r}{2}\left[\frac{2L}{L_o^{\,2}} + \frac{-2L}{D_o^2 \pi^2 n^2} + \frac{-2D_o^{\,2} L_o^{\,2} \pi^2 n^2 (b^2 - 2L^2)}{L^3 (b^2 - L^2)^2}\right]$$

Following design inputs are considered for design calculations.

L_O: Initial length of the tube = 200 mm = 0.2 m

D_O: Initial diameter of the tube = 10 mm = 0.01 m

b: Uncoiled length of fibre = 220 mm = 0.22 m

θ: Angle of Fibre wound = 30^0

t_O: Thickness of inner tube = 0.3 mm = 0.0003 m

Goal is to design Smart fluid damper so as to achieve a force of 100 N. To accomplish this goal it is required to estimate

L: Instantaneous length of the tube

n: Number of turns

D: Instantaneous diameter of the tube

p: Pressure required to achieve the above mentioned force

Outcome of design calculations is summarized in table 1.

Table 1 Summary of design calculations

Sl. No.	Description	Value
1.	Instantaneous length of the tube	0.1905 m
2.	Number of turns	3
3.	Instantaneous diameter of the tube	0.012 m
4.	Pressure required to achieve the above mentioned force	2 bar

IV. MATLAB CODES FOR DESIGN AND SIMULATION OF SMART FLUID DAMPER

It is planned to develop a code in MATLAB software for designing the Smart fluid damper and subsequently simulation. The necessary formulation, which is derived in previous section, is required to be converted in form of code. The intention behind developing the code is to enable the user to use this code as a hand calculator, which just takes the inputs from the user and within no time gives the output there by avoiding getting the desired output through usage of formulae.

Simulation is done with the help of code developed in MATLAB software so as to bring out the variation of force with respect to design parameters which are as follows

- Initial length of the tube
- Initial diameter of the tube
- Uncoiled length of fibre
- Angle of Fibre wound
- Thickness of inner tube

Variation of Force with Initial Length of Tube obtained from simulation runs is shown in fig. 2.

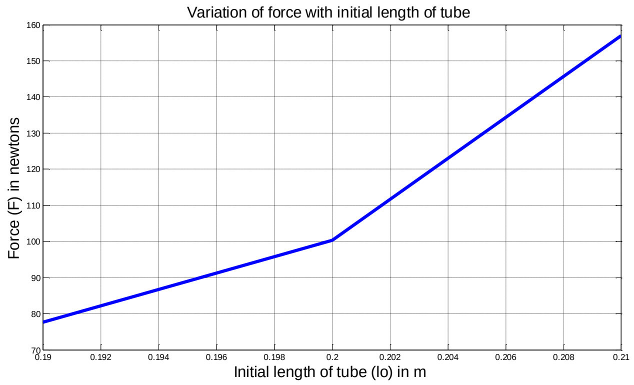

Fig. 2. Variation of Force With Initial Length Of Tube

- Force varies in direct proportion to variation in initial length of tube
- Which means by increasing initial length of tube, force of Smart fluid damper increases and vice versa

Variation of Force with Initial Diameter of Tube is shown in fig. 3.

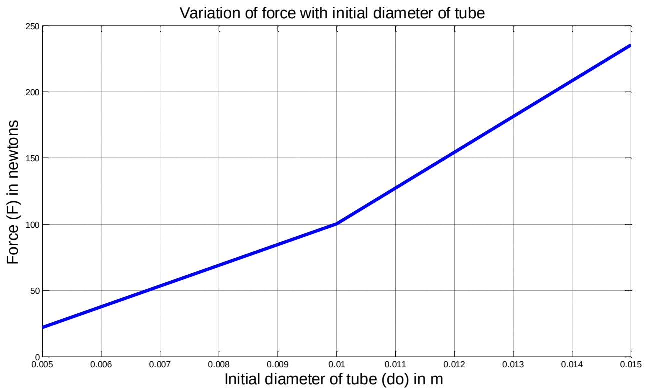

Fig. 3. Variation of Force with Initial Diameter of Tube

• Initial diameter of tube also has direct proportional relation with force

Variation of Force with Uncoiled Length of Fibre is shown in fig. 4.

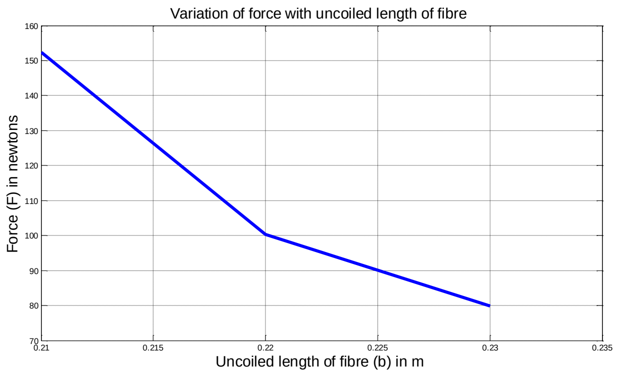

Fig. 4. Variation of Force with Uncoiled Length of Fibre

• Unlike earlier design parameters, uncoiled length of fibre has inverse relation with force.

• Increasing uncoiled length of fibre, force decreases.

Variation of Force with Angle Of Fibre Wound is shown in fig. 5.

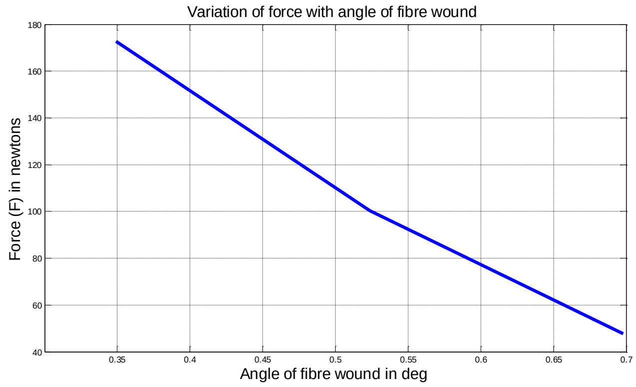

Fig. 5. Variation of Force with Angle of Fibre Wound

• Angle of fibre wound has inverse relation with force.
•Which means increasing the angle, force decreases.

Variation of Force with Thickness of Inner Tube is shown in fig. 6.

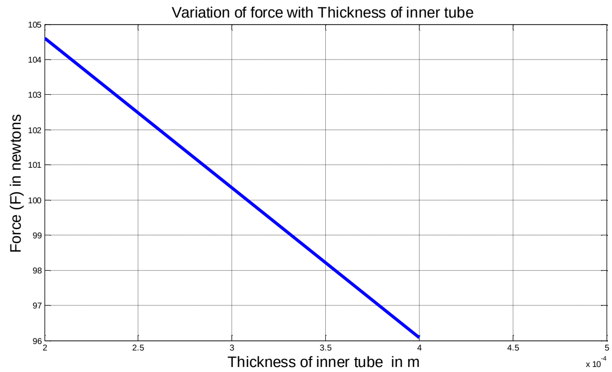

Fig. 6. Variation Of Force with Thickness Of Inner Tube

• Thickness of inner tube also has inverse relation with force.

Variation Of Force with With Pressure is shown in fig. 7.

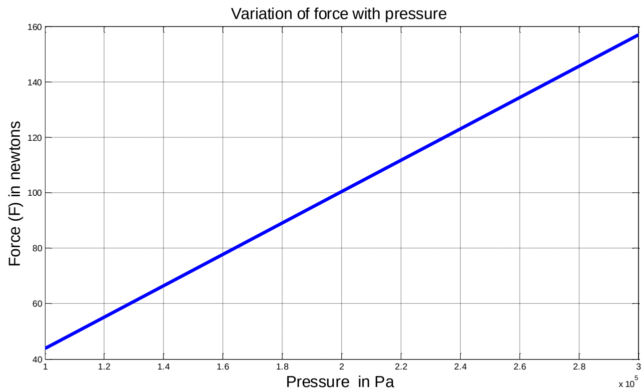

Fig. 7. Variation of Force with pressure

• Force varies in direct proportion to variation in pressure

• Which means by increasing pressure, force of Smart fluid damper increases and vice versa

V. CONCLUSION

A novel Smart fluid damper is designed in this work which will have a low value of static friction. The intention behind developing MATLAB code is to enable the user to use this code as a hand calculator, which just takes the inputs from the user and within no time gives the output there by avoiding getting the desired output through usage of formulae.End of the exercise simulation exercise conveys a message that to have an optimum design of Smart fluid damper one need to chooze higher values for initial length and diameter and pressure and lesser values for uncoiled length of fibre, thickness of tube and angle of fibre wound.

ACKNOWLEDGMENT

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