Capability of Designing a Novel Fluid Damper Using a McKibben Actuator

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ABSTRACT

Flow fluid between moving parts is providing the damping force. Such characteristic can be utilized to build fluid dampers for a wide variety of vibration control systems. Most previous works have studied the application of fluids damper in pistons/cylinders actuator, where the kinetic energy of a vibrating structure can be dissipated in a controllable fashion. The reduction of the friction can cause a sudden jump in the velocity of the movement. Stick-slip friction is present to some degree in almost all actuators and mechanisms and is often responsible for performance limitations. To overcome this problem, this report investigates the capability of designing a fluid damper that seeks to reduce the friction in the device by integrating it with a McKibben actuator. It is also reduced the total weight of such damper. In this paper, the concept of McKibben actuator has been reviewed, the modelling of device made is also presented. Also, the model has been validated experimentally. It is founded that the model predicts the behavior of the test rig with accuracy 85%. Also, the total weight could be reduced to 50% from the original weight.

Keywords: Viscus fluid, Stick-slip friction, McKibben actuator.

1 Introduction

A vibration isolator is a device inserted between the source of vibration and the primary device to reduce unwanted vibration [1]. The basic constituents of anti-vibration devices are the resilient load-supporting means and the energy dissipation means or the damping elements. Damping force exists if there is a relative velocity between two ends of the damper, and it refers to three types which are coulomb, viscus and material damping. In a coulomb damping, energy is absorbed via sliding friction (friction between rubbing surfaces that are either dry or have insufficient lubrication) [2]. Viscous damping is an energy loss occurs in liquid lubrication between moving parts or in a fluid forced through a small opening by a piston [3, 4]. A material damping where the material is deformed due to an applied force, and some energy is absorbed and dissipated by the material due to the friction between the its internal planes [5].

The majority of anti-vibration devices have studied the application of fluids damper in piston and cylinder actuator, where the kinetic energy of a vibrating structure can be dissipated in a

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controllable fashion. Although the friction has a positive effect in the damping devices, the dry sealing friction makes a vibration transmission to the equipment; this tiny vibration may cause poor accuracy for sensitive devices [6]. Friction could have a bad effect on the system when applied force is close to overcoming the static friction. The behaviour is called stick-slip motion. Stick-slip motion occurs at close to zero velocity and is in the form of a sudden jerking motion. Typically, the static friction coefficient between two surfaces is larger than the kinetic friction coefficient. If an applied force is large enough to overcome the static friction, the friction reduces from static to dynamic friction. The reduction of the friction can cause a sudden jump in the velocity of the movement. Stick-slip friction is present to some degree in almost all actuators and mechanisms and is often responsible for performance limitations [7]. Using a McKibben actuator instead of a hydraulic actuator could reduce the friction in the device. Such actuator has advantages over cylinder and piston dampers for instance: high power/weight ratio and low cost, also there is no stick-slip phenomena in such actuator [8]. This report investigates the possibility of designing a fluid damper by using a McKibben actuator instead of piston and cylinder actuator.

2 McKibben Actuators

The McKibben actuator is a device that converts fluid pressure to force; it consists of an internal rubber tube inside a braided mesh shell. When the inner tube is pressurized, the internal volume of the actuator changes causing the actuator to expand or contract axially as shown in Figure 1. The McKibben actuator is usually used to mimic the behaviour of skeletal muscle [9]. It is also used in medical equipment [10] and industrial applications [11]. Although the working fluid in a McKibben actuator is usually air, there are some applications using water as a working fluid, especially in exoskeleton devices and devices working in a water medium, such as an actuator for an underwater robot introduced by Kenneth et al. [12]. Shan et al. developed a variable stiffness adaptive structure based upon fluidic flexible matrix composites (F2MC) and water as the working fluid [13]. The fibres in an F2MC actuator can be placed at any one angle or combination of angles. This material can be designed to bend and it also provides a greater axial force.

The advantages of the McKibben structure tubes are that it uses inexpensive and readily available materials, and it can easily be integrated into a structure. A McKibben actuator also offers others advantages such as being light weight and with low maintenance costs when compared to traditional cylinder actuators [13]. A comparison of the force output of a pneumatic McKibben actuator and a pneumatic cylinder was made, and the result shows that the McKibben actuator produces a higher ratio of power to weight than the pneumatic cylinder actuator [8].

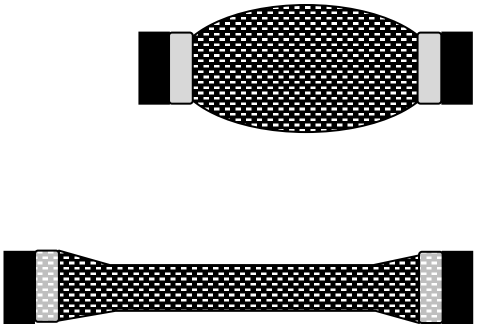


Figure 1: Concept of McKibben actuator.

3 Modelling of McKibben Actuator

To predict the behaviour of the test rig under static load, there is no effect of viscous damping of the valve, and the test rig could be modelled similar to a McKibben actuator. The variable parameters of this device are: a force applied to the test rig, internal pressure of the McKibben tube, type of internal material, and length of the McKibben tube. There are several techniques used for predicting the behaviour of this actuator and to provide a relationship between variable parameters. The technique of energy analysis, where input work (W_{in}) is equal to the output work (W_{out}), will be used in this research. It is assumed the shape of the McKibben tube is cylindrical. By neglecting the effect of the inner tube at this stage, the input work is done on this actuator by applying compressed air; this air moves the inner rubber surface, so the work is:

$$dW_{in} = P'dV \qquad (1)$$

Where: dV volume change, and P' gauge pressure. The output work from this pressure is tension in the actuator, which leads to a decrease in the length of the tube:

$$dW_{out} = -FdL \qquad (2)$$

Where: F axial force, and dL axial displacement. From the principle of virtual work, we could reach to the next expression [13]

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

Where: n number of turn, and b uncoiled length of fibre. Now, the effect of elastic energy of inner tube will be accounted. So,

$$dW_{in} = dW_{out} + V_r dW \qquad (4)$$

Where: Vr the volume is occupied by the inner tube, and W is the strain energy density function. From the previous analysis of input work and output work:

$$P'dV = -FdL + V_r dW \qquad (5)$$

To determine the strain energy density of the inner tube, the rubber tube will be assumed to behave as a Neo–Hookean solid. The strain energy function of the actuator W could be expressed as a function of the first invariant of strain [14].

$$W = \frac{\mu_r}{2}[I_1 - 3] \qquad (6)$$

μ_r is the shear modulus for infinitesimal deformations [14], and I_1 strain invariants which could be expressed:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \qquad (7)$$

λ_i (i=1,2,3) are the principle stretches. $\lambda_1 = \frac{L}{L_0}$, $\lambda_2 = \frac{D}{D_0}$ and $\lambda_3 = \frac{1}{\lambda_1\lambda_2}$.

Where L and D, are instantaneous length and diameter, while L_0 and D_0, are initial length and diameter of the tube, respectively. The diameter of the tube could be expressed in terms of length of tube [12]:

$$D^2 = \frac{b^2 - L^2}{\pi^2 n^2} \qquad (8)$$

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

$$W = \frac{\mu_r}{2}\left[\frac{L^2}{L_0^2} + \frac{b^2 - L^2}{D_0^2\pi^2 n^2} + \frac{D_0^2 L_0^2 \pi^2 n^2}{L^2(b^2 - L^2)} - 3\right] \qquad (9)$$

The derivative strain energy density regarding the length:

$$\frac{dW}{dL} = \frac{\mu_r}{2}\left[\frac{2L}{L_0^2} + \frac{-2L}{D_0^2\pi^2 n^2} + \frac{-2D_0^2 L_0^2 \pi^2 n^2 (b^2 - 2L^2)}{L^3(b^2 - L^2)^2}\right] \qquad (10)$$

Therefore, the force output of the actuator could be expressed:

$$F = P'\left(\frac{3L^2 - b^2}{4\pi n^2}\right) + \frac{V_r \mu_r}{2}\left[\frac{2L}{L_0^2} + \frac{-2L}{D_0^2\pi^2 n^2} + \frac{-2D_0^2 L_0^2 \pi^2 n^2 (b^2 - 2L^2)}{L^3(b^2 - L^2)^2}\right] \qquad (11)$$

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

4 Experimental Work

The rig used in this research is shown in Figure 2; it consists of a McKibben tube, valve and accumulator. The McKibben tube 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 valve at another end. Pressurizing the McKibben tube could be achieved at the top of the accumulator. By applying force to the end of the volume of actuator is changed, consequently the pressure inside tube is increased. Then, the fluid is able to flow in and out of the tube, and energy is eliminated through the viscous effect of the controlled valve. The total weight of such device is less than the half weight of similar piston/cylinder damper, the same results were found in previous researches [12-13].

To validating of the model, the isotonic test was carried out in this report. The actuator was loaded to known load, then internal pressure was increased 0.5 bar increments, and the internal pressure P, length of tube L are recorded. Changing in the pressure is causing to chaining length of the actuator. So, these parameters are governed by equation 11.

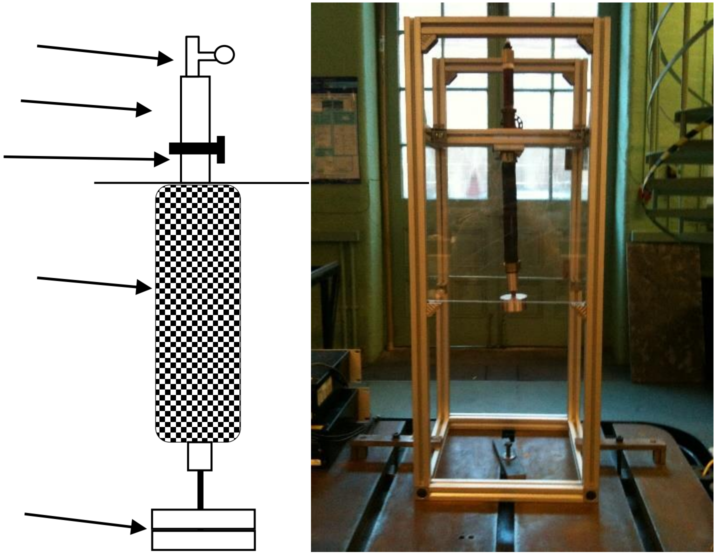
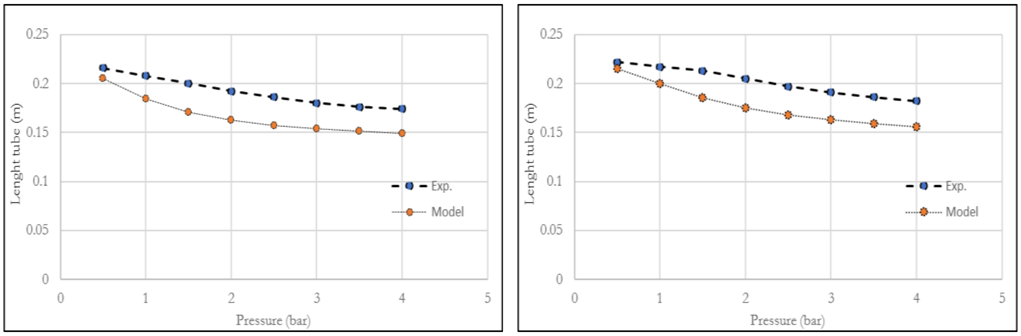


Figure 2: Test rig.

The length of McKibben actuator was 0.12m with diameter 0.011m. when uncoiled fibre the Length was 0.138m. Such actuator has 2.15 turns. The inner tube was made by rubber with thickness is 0.0003m and Shear modulus is 0. 6MPa.The procedures were examined at two constant loads which are 25N and 50N. Figure 3 shows the experimental results which are compared with the modelling results at a constant load. The figures show the model gives acceptable results in comparison with experimental data. Although there are differences between the modelling results and experimental results, the accuracy of this model is above 85%.



a b

Figure 3: Model and experimental result of rig: a) force is 25N; b) force is 50N.

To minimize these differences, it is important to consider the realistic shape rather than ideal cylindrical shape, also to account the force losses in the system due to friction between fibres and friction between the inner tube and outer tube.

Moreover, it is noticed, the model is shown to have less accuracy at low pressure, and the error is bigger when applying higher loads. To minimize such error, the end effects of the tube should be captured. The end effects changes in the output of the force at the length limits. When the actuator is reaching the length saturation L_s (length saturation), the stretching will be occurring in the fibres; therefore, the output force will be dependent on stiffness of the fibre material. While the force is zero if the length of actuator is less than minimum length L_m, this model is shown in next equations [15].

$$F = \begin{cases} P^{'}\left(\frac{3L^2 - b^2}{4\pi n^2}\right) + \frac{V_r \mu_r}{2}\left[\frac{2L}{L_0^2} + \frac{-2L}{D_0^2 \pi^2 n^2} + \frac{-2D_0^2 L_0^2 \pi^2 n^2 (b^2 - 2L^2)}{L^3 (b^2 - L^2)^2}\right] + K_f (L - L_s) & L > L_\mathrm{m} \\ 0 & L < L_\mathrm{m} \end{cases} \tag{12}$$

Where: K_f stiffness of fibre material.

5 Conclusions

Flow fluid is considered as one of the most superior means of control of vibration, and there are many of applications which profit from the characteristics of viscus fluid, which have been employed successfully. However, a conventional fluid damper has dry sealing frictions which cause a vibration transmission to the equipment. To reduce the friction in a device, a McKibben actuator could be used instead of a hydraulic actuator. Also, using such actuator could be reduced more than half of total weight of devices. A model of a McKibben actuator has been developed and then, it is validated experimentally. The model predicts the behaviour of the test rig with accuracy about 85%.

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