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Experimental Evaluation of A Cylinder Actuator Control using McKibben Muscle

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Abstract: There has been an increased interest in applying pneumatic muscle actuator (PMA) in robotic systems because of its low weight and high compliant characteristics. On the other hand, pneumatic muscle actuator (PMA) is gaining attention in robotic applications because of its low weight and high compliant characteristics. It is known that the McKibben muscle is different from the fluidic cylinder actuator in that the cylinder was unstable in its position and in its velocity in an open-loop system unlike the McKibben that is stable in its position. The modeling and control of McKibben muscle as the actuator for the cylinder are crucial because it is known to have non-linear response, hysteresis and small stroke. In this project, a single acting cylinder model which would have uncontrolled extension to push direction by compressed air, is actuated and controlled using a PMA. The system is designed with two 1.3mm-diameter McKibben muscles attached to the cylinder. Open loop control was used and the result shows that the PMA is able to control the cylinder with good performance.

Keywords: McKibben muscle, artificial muscle, pneumatic muscle actuator, cylinder actuator, soft robotic

1. Introduction

Actuators are used in machineries in different application to facilitate the movement where human either is not capable of or requires great effort to perform. There are many types of actuators such as pneumatic, hydraulic and electrical actuators. Type of actuator to use depends on the installation space, cost, and types of application. Pneumatic and hydraulic actuators usually consist of a piston housed in a hollow cylinder [1]. Therefore, they are also commonly referred to as cylinder actuator.

Pneumatic cylinder actuator is widely used in areas where safety, cost and pollution are a concern such as chemical industries and medical applications [2]. There is also another type of pneumatic actuator where pressured air is used to control the contraction and relaxation of an artificial muscle - internal bladder coated by a braided mesh shell - or otherwise known as McKibben muscle [3]. The McKibben actuator has been gaining attention in robotic community because of its low weight and high compliant characteristics [4]. For example, A. A. M. Faudzi discussed how those

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**Corresponding author: athif@fke.utm.my* characteristics has helped in the development of a Giacometti robot utilizing the muscle to achieve a maximum walking speed of 0.05 m/s [5]. Besides that, a soft amphibious robot – a robot which could walk on sand and in water, and on flat or inclined plane – and soft manipulator – snake-like body structure with pick–and-place ability – have also been developed using the actuator [5][6].

It is argued that the McKibben muscle is different from the fluidic - pneumatic or hydraulic - cylinder actuator in an open-loop system. Unlike the McKibben actuator which is stable in its position, the fluidic cylinder is unstable in its position and in its velocity [8]. Because of this advantage, it is interesting to study the effect of replacing direct fluidic source with McKibben muscle in a cylinder actuator system.

1.1 Cylinder Actuator Control

There are many control strategies employed to control the position of a pneumatic cylinder actuator, for example, sliding mode control [9], pulse width modulation [10], feedback-fuzzy hybrid [11] and predictive functional controller [12]. However, they share the same problem: it is difficult to achieve an accurate position control [13]. This is due to the compressibility of air. Therefore, most of its application is focused on single – initial and final - position control.

1.2 The Present Research

Using McKibben muscle, it is possible to design an accurate multiple position actuator [14] [15]. Previous research shows that the maximum contraction that can be achieved by the muscle is 20% when supplied by 0.3 MPa pressure [16]. This represents a problem because the actuator needs to be much longer than the distance it needs to cover. For example, to move a load for 2 cm, the muscle needs to be at least 10 cm. This would normally mean a long housing to fit the muscle and is therefore impractical. To solve this problem, a pulley system is proposed in this paper. This would allow a long muscle to be slotted in a tight space.

The remainder of the paper is organized as follows. In section 2, the cylinder actuator structure and specification including 3D CAD design and McKibben muscle description are presented. Section 3 discusses the static analysis of the CAD design and contraction and displacement result of the actuator. The paper concludes with a brief evaluation and suggestions for future work in section 4.

2. Methodology

2.1 Experimental Design

A prototype of cylinder actuator was designed using Solidworks® (Figure 1) and fabricated using 3D printer. The design took into consideration the maximum length the piston should move, the muscle’s length, and the placement of the spring and its hooks. The spring was chosen based on its expansion length and having a spring constant such that it would be able to return the piston to its original location after being actuated. There was ample gap between the actuator and its track so that the actuator could move freely while being guided by the track. As the prototype’s piston was lightweight, a thin muscle should be enough to pull it. However, our prototype used two muscles to simulate a real-life application. The muscles’ individual length was long enough such that when they fully contracted, the piston would move to its final position.

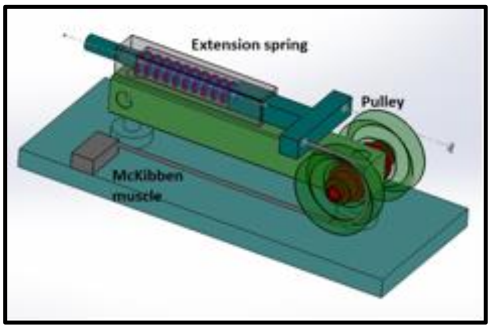


Fig. 1 - Solidworks drawing of the prototype

2.2 Design Analysis

It is important to design the prototype right before it goes to production to avoid unnecessary cost. In one well-known study, it was found that 80% of unnecessary cost could be avoided by design changes compared to just 20% by production engineering changes [17]. One of the most commonly used methods to evaluate the CAD design is by doing linear static analysis. Its purpose is to simulate what happens when the design is subjected to a particular load. This would enable the design to be improved, for example by removing material where it is not being utilized and strengthen areas with high stress [18]. Therefore, a static analysis using Solidworks Simulation has been carried out. Two simulations were performed; horizontal force and vertical force. Physical and mechanical properties of the material used in the simulation are shown in Table 1.

Table 1 Properties of the material used in the simulation

Property	Value
Material	Steel
Elastic Modulus	200000000000 N/m^2
Poisson's Ratio	0.29
Shear Modulus	77000000000 N/m^2
Mass Density	7900 kg/m^3
Tensile Strength	420507000 N/m^2
Yield Strength	351571000 N/m^2
Thermal Expansion Coefficient	0.000015 K^{-1}
Thermal Conductivity	47 W/(mK)
Specific Heat	420 J/(kgK)

2.3 Apparatus

Two McKibben muscles with outer diameter of 1.3 mm were used. Each of them was attached to a tube that connected them to the compressor. The attachment process was done carefully to avoid any air leakage. PTFE tape, Loctite 401 glue and a stick with fine tip were used. The tape was applied on the muscles' surface so that inserting them into the tube was easier. The glue was applied inside the tube, around the tape and through the tube-muscles gap using the stick. The stick had fine tip so that the glue spread properly inside the tube and sipped into the gap. Using thick tip would risk air leakage, because the glue might not be applied properly.

An Agilent DC power supply was used to provide 24V supply to pressure sensor. A compressor was used to supply the air pressure. It was connected to an air filter and a pressure regulator. The experiment setup is shown in Figure 2.

2.4 McKibben Muscles

A considerable amount of literature has been published on McKibben muscles' design and specifications. These studies investigated the design of various outer diameters, ranging from 1.3 mm up to 40 mm [19] and various braided structures [20]. In this study, thin soft McKibben muscles with outer diameter of 1.3 mm which has been developed previously were used. The braided angle was 18˚ - less than contraction cutoff angle of 55˚ - and therefore would contract when pressure is applied [21].

Fig. 2 - Experiment setup

2.5 Procedures

Three experiments were conducted. The first one was to measure the contraction of the muscle when pressure was varied. The second was to measure the displacement of the piston when actuated by the muscles. The third was to measure the free-load contraction.

For the first experiment, the muscle's end that was connected to the pressure supply was fixed while the other end that was sealed was let to move freely (Figure 3). Pressure sensor was connected to the regulator to measure the pressure coming into the muscle. Pressure was increased incrementally using regulator. The reading on the pressure sensor and the muscle's length were recorded. The experiment was repeated until 0.4 MPa.

For the second experiment, to conduct the experiment easier, the piston was separately connected to the actuators. However, because the piston was lightweight, a guide was built around it so that it would not be off-track when pulled (Figure 4). The procedures then followed the first experiment. For the third experiment, the piston was removed (Figure 5) and similar procedures from the first experiment were repeated. The difference between amount of contraction-without-load and amount of the displacement was observed.

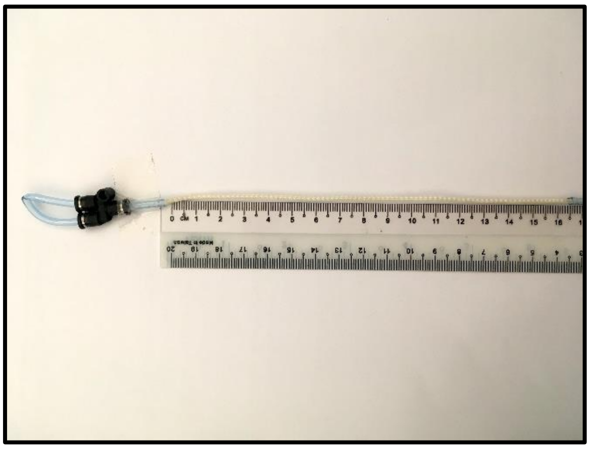


Fig. 3 - First experiment

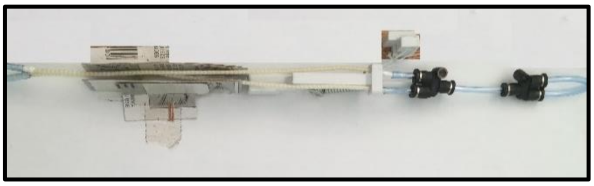


Fig. 4 - Second experiment

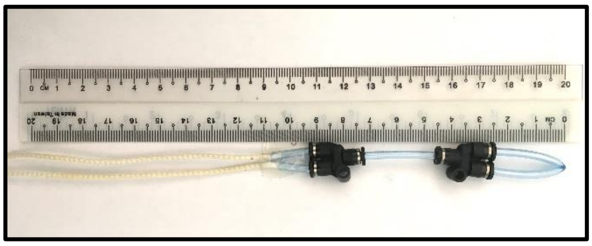


Fig. 5 - Third experiment

3.0 Results and Discussion

3.1 Solidworks Simulation

A static analysis using Solidworks Simulation has been done to simulate the performance of the design under expected force. The results are shown in Table 2 and Table 3.

Table 2 Displacement result of Solidworks static study

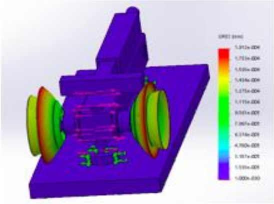
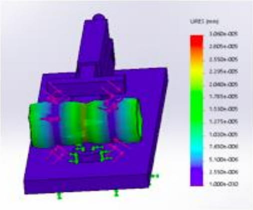
Type of force	
Horizontal	Vertical
 Maximum displacement: 1.912 x 10^{-4} mm	 Maximum displacement: 3.06 x 10^{-5} mm

Table 3 Stress result of Solidworks static study

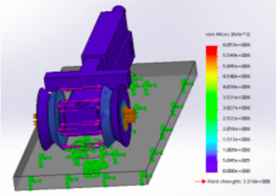
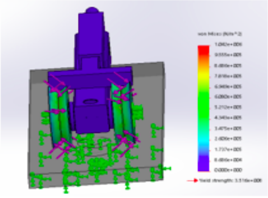
Type of force	
Horizontal	Vertical
 Maximum von Mises: 1.264 x 10^{-6} N/m^2	 Maximum von Mises: 8.582 x 10^{-5} N/m^2

Table 2 shows the displacement result. Horizontal forces show more areas with high displacement compared to vertical forces. However, both are within the limit with maximum displacement of 1.912 x 10^{-4} mm (horizontal) and 3.06 x 10^{-5} mm (vertical) respectively. On the other hand, stress analysis shows more area of high stress at vertical. However, they are both still within limit. Based on the result, it can be shown that the design is able to withstand the requirements set earlier.

3.1 Contraction and Displacement

Figure 6 shows the contraction of the McKibben muscle versus applied pressure. The muscle's length is 16.8 cm. The maximum contraction is 3.1 cm, which gives the maximum contraction ratio of about 0.18. The ratio is about the same as previous literatures.

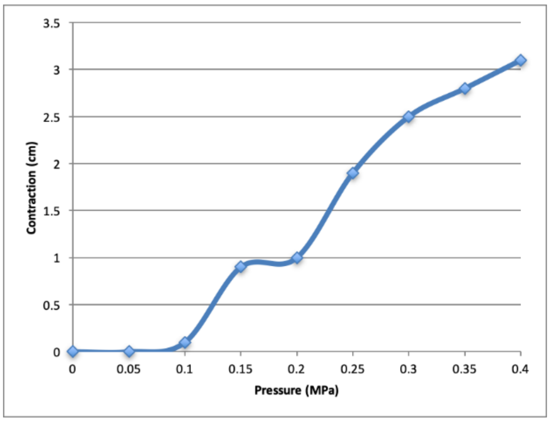


Fig. 6 - Contraction (cm) vs air pressure (MPa)

Figure 7 shows the displacement of the piston and the contraction of the two muscles-without-load versus applied pressure. From the experiment, the higher the contraction, the more displacement the piston underwent. This then translated to lower muscle contraction and thus lower piston displacement. This is because higher contraction happens at higher pressure and the higher the pressure, the more static force is produced (Figure 8). However, the displacement and the contraction values are not the same. This is to be expected because in our open-loop control system, additional force required to pull the piston was not compensated with an increased pressure because there was no feedback involved. To make the displacement equals to the contraction, closed-loop system as in Figure 9 should be used.

Figure 6 also shows that the maximum displacement is much lower than the maximum contraction. In our experiment, we limited the maximum pressure used to be 4 bar. This is because we were worried that applying more pressure would damage the 1.3 mm muscle. However, to allow for higher maximum displacement, larger-diameter muscle should be used so that higher maximum pressure and thus higher static force could be applied [22]. Besides that, using longer muscle could also increase the maximum displacement. Our results also indicate that McKibben muscle is able to position control a cylinder actuator by varying the applied pressure. Therefore, by replacing direct fluidic source with McKibben muscle in a cylinder actuator system, multiple position control could be achieved.

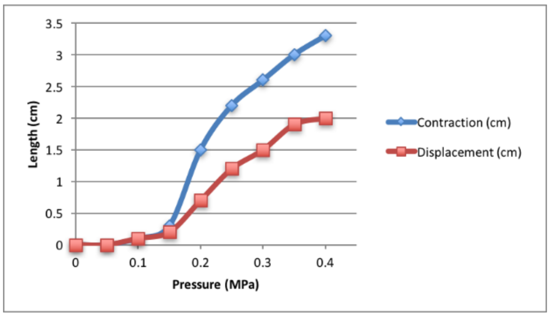


Fig. 7 - Piston displacement (cm) and muscle contraction (cm) versus air pressure (MPa)

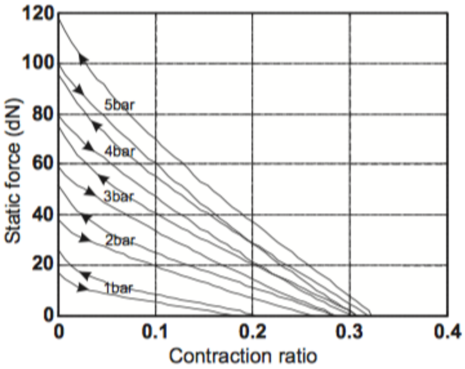


Fig. 8 - Typical static force of a McKibben muscle [4]

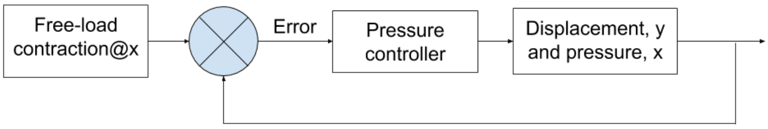


Fig. 9 - A closed-loop control system to compensate additional force required with increased load

4.0 Conclusion

This study sets out to determine the performance of a single acting cylinder actuator employing McKibben muscles as its actuator in place of conventionally-used compressed air. To achieve this, a 3D-printed prototype has been developed. The prototype's CAD design was evaluated using Solidworks static analysis tool to look for any design improvement. The prototype was then tested using open-loop control. Results showed that the piston position can be controlled to a maximum displacement of 2 cm. These findings suggest that in general, using McKibben muscle allows multiple position control in a cylinder actuator system. An implication of this is the possibility of using McKibben actuator for fine cylinder actuator position control.

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