The Characteristics of Mckibben Muscle Based on The Pneumatic Experiment System

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Abstract: In the pneumatic experiment system in which Mckibben muscles are applied, the electropneumatic regulator provides gas pressure to Mckibben muscles. The structure of the electropneumatic regulator is analyzed, and that the electropneumatic regulator can stabilize its output gas pressure is pointed out. The stiffness expression of Mckibben Muscles is formulated from both its force model and the characteristic of the electropneumatic regulator. The process of gas pressure transmission with the whole pneumatic experiment system is investigated. The model of the gas pressure transmission based on the integrated pneumatic experiment system is established. The experiment is done to prove its validity. The result shows, that the inner pressure of Mckibben muscle doesn't vary when its length is changed by outer force, and there are bath a pure time delay and a raise course of gas pressure when Mckibben muscles are input by pressed air. The pure time delay comes from the turning on of the valve of the electropneumatic regulator, and the raise course corresponds with the filling process of the inner gas pressure of Mckibben muscle.

Keywords: Mckibben muscle; pneumatic experiment system; electropneumatic regulator; stiffness; gas pressure transmission

1. Introduction

Mckibben pneumatic artificial muscle (it will be called as Mckibben muscle later) is a kind of motion engine which is stimulated and can contract. It constructs with two layers-the inner layer rubber tube and the outer layer fiber wave. When the inner layer closed tube is input by pressed gas, the outer layer wave expands and shortens its two ends and then outputs pulling force[1-3]. Therefore, the electro-pneumatic regulator is necessary, which is capable of providing the required gas pressure. In this case, the whole pneumatic experiment system includes not only Mckibben muscles but also the electro-pneumatic regulator. But the former literatures usually didn't mention the electro-pneumatic regulator. Here the writer thinks that the integrated pneumatic system should include both Mckibben muscles and the electro-pneumatic regulator which will effect the characteristics of Mckibben muscles. This paper is just to investigate the characteristics of Mckibben muscles based on the integrated pneumatic experiment system.

2. Pneumatic experiment system

Fig.1 is an ordinary pneumatic experiment system. The computer-controlled electro-pneumatic regulator can output determined gas pressure. Mckibben muscle input by the pressed gas contracts and output pull force and then works on the load. The gas source is usually from a compressor. Obviously the experiment should mainly include both the electro-pneumatic regulator and Mckibben muscles.

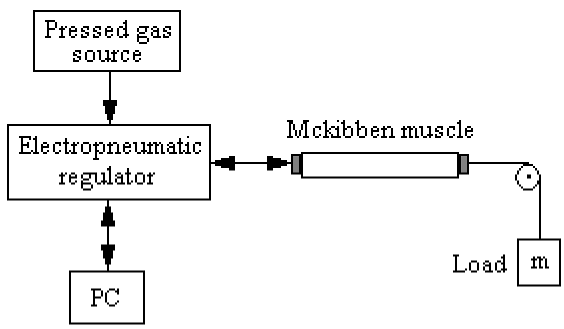

Fig.1 Pneumatic experiment system

Firstly let's discuss the electro-pneumatic regulator. It is a computer-controlled system which can output determined gas pressure. Its input is the electric current or electric voltage which's quantity can be controlled by the computer, and the output gas pressure is proportional to the current or the voltage within definite field. It has multiple output channels for the practical need. Every output channel can output a gas pressure proportional to the input. Fig.2 is just the principle block diagram related one channel. Thereinto, the control circuit can control all the channels. From Fig.2, every channel consists of the control circuit, two electromagnetism proportion valves, and one pressure sensor. The pressure sensor measures the output gas pressure and feedback it to the control circuit. Accordingly, a closed feedback loop is made up. It is not difficult to understand that the closed loop can automatically regulate and restrain the out gas pressure when it changes because of the later links. This is why the electro-pneumatic regulator can output stable gas pressure. The compressor provides the pressed gas input to the electro-pneumatic regulator. The magnitude of the gas pressure should be larger than the maximal output gas pressure.

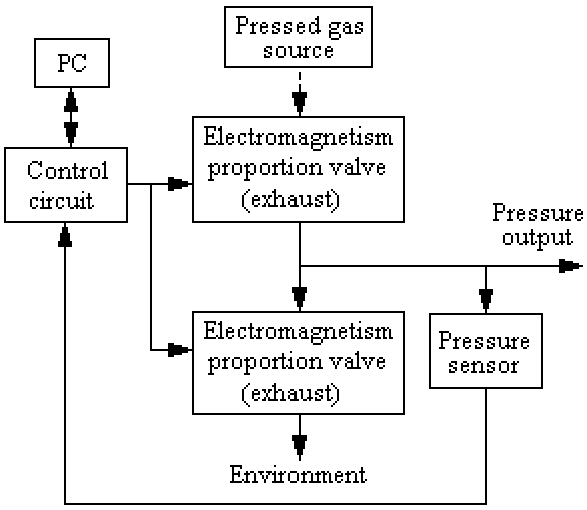

Fig.2 Principle figure of the electropneumatic regulator

3. The stiffness of Mckibben muscle

There have been many papers discussed the characteristics of Mckibben muscle itself, especially its force characteristic[4-6]. But few paper mentioned its stiffness. Mckibben muscle changes its shape when acting, a little like the spring. To the spring, its stiffness is constant within definite field. To Mckibben muscle, how about its stiffness? Now let’s discuss this problem.

The basic concept of the stiffness is the needed force making a shape change in unit length. It is just the differential of force to length in actual calculation. Based on the concept, th stiffness of Mckibben muscle is the differential of its output force to its length. To Mckibben muscle, there has been clear conclusions about the force characteristic especially its static force characteristic. Different literatures gave the same ideal force output expressions. Some of them gave revisory ones for idiographic products of Mckibben muscles[7-8]. In this paper the ideal force output characteristic will be used to discuss the stiffness.

The force characteristic expression is

$$F=Pb^2(3L^2/b^2-1)/(4\pi n^2) \qquad (1)$$

Thereinto, F is the force output, P is the input gas pressure, and L is the current length of Mckibben muscle. Both b and n are structure parameters and they keep constant. Formula (1) expresses that the force output of Mckibben muscle is proportional to gas pressure, and is nonlinear to the length.

Based on both the stiffness and its force characteristic of Mckibben muscle, the stiffness k is

$$\begin{aligned} k&=\mathrm{d}F/\mathrm{d}L \\ &=\mathrm{d}[Pb^2(3L^2/b^2-1)/(4\pi n^2)]/\mathrm{d}L \\ &=Pb^2(3L^2/b^2-1)/(4\pi n^2)\mathrm{d}P/\mathrm{d}L + 3PL/(2\pi n^2) \end{aligned}$$

There are two items in the above formula. Generally, $\mathrm{d}P/\mathrm{d}L$ in the first item is very difficult to calculate, because the inner pressure has to change with its volume varying to enclosed gas. To Mckibben muscle, if the related valve is shut up after some pressed gas is input, its inner gas becomes enclosed, and its length change must make its inner volume change, consequently its inner pressure P will change. Based on the above analysis to the electro-pneumatic regulator, the inner pressure actually as the controlled object, together with the related channel of the electro-pneumatic regulator, constitute a enclosed loop control system. In practice, the inner pressed gas can exchange its mass with the regulator. It is not an enclosed gas. The sensor in the channel of the regulator will send feedback signal about the change immediately to the control circuit when the inner pressure varies because of some outer factors. Then the control circuit will make the related electromagnetism proportion valve act. Then definite gas will be input to or output from Mckibben muscle, so as to stabilize the inner pressure. Some experiments have clearly proved that. The inner pressure changes instantly and recover to the former immediately when the length of Mckibben muscle is enforced to change after determined gas pressure is input. Therefore it can get

$$dP/dL=0$$

So, the stiffness of Mckibben muscle is

$$k=3PL/(2\pi n^2) \tag{2}$$

Based on the formula (2), there is conclusion that the stiffness of Mckibben muscle is not constant. It is proportional to gas pressure, and is proportional to the length too. Larger the pressure, larger the stiffness. The stiffness at the beginning of contraction is larger than the one after contraction under the condition of the constant inner pressure. This is quite different from the spring with constant stiffness. Just like he spring, there is a length field within which the expression (2) is correct. Because there is a length field in the force expression (1), and the length field is just the normal operation field of Mckibben muscle.

Formula (2) express that the stiffness of Mckibben muscle has finite volumes within its normal operation field. In another word, the force needed to change its length is not very large. Just because there is so called “compliance” which means that the shape is easy to be changed by the outer force, the robot actuated by Mckibben muscles is related safe to human when contact with it[9-10].

4. The model of gas pressure transmission in Mckibben muscle

Mckibben muscle is stimulated. In another word, it contracts after gas pressure is input and then output force. So the gas pressure is greatly related with the output force. Formula (1) has proved that the output force is proportional to the input gas pressure. Therefore, the transmission of the gas pressure will greatly effect the forming of the contraction force of Mckibben muscle. To a factual pneumatic experiment system, the opening of the gas valve of the electropneumatic regulator has definite time delay, and different valves have different delays. To the familiar valve products, the time delay is usually less than 50ms. For simple calculation, it can be considered as a pure delay less than 50ms. The actual delay in the used electropneumatic regulator is about 30ms. In addition, the diameter of Mckibben muscle is usually much larger than the one of the gas transmission tube. So the gas pressure inputting to Mckibben muscle can’t be stepped. It should have a very complicated rise course. For simple dealing with, the course is considered as one-order inertia link. Its rise time will be much larger than the delay of the electropneumatic regulator. Probably it can be a few hundred milliseconds[7,11] and the ideographic quantity is related with the inner volume of Mckibben muscle. Based on the above analysis, the opening of the gas valve considered as the pure delay, and the gas pressure transmission from the output port of the gas valve to the inerior of Mckibben muscle as one-order inertia course, the input pressure P can be expressed as

$$P(t) = P_0\,(1-e^{-(t-T\mathrm{d})/Tc})\,u(t-T_\mathrm{d}) \tag{3}$$

Thereinto, P_0 is the static volume, T_d is the time delay of gas valve, and T_c is the time constant of the one-order inertia course.

A experiment is conducted to validate the above conclusion. Because of that it is different to directly measure the inner pressure of Mckibben muscle, a measurement of its pull force is done to validate the formula (3) indirectly. Fig.3 shows the comparison between the pull force model and the experiment data in which the used Mckibben muscle has a nominal length 300mm and nominal diameter 20mm, under the condition of that P_0 equals to 0.5MPa and L keeps 300mm. Besides, the time delay of the electropneumatic regulator is 30ms and the time constant of the one-order inertia course is 260ms. From the formula (1), The pull force F and the gas pressure P will change in the same way if L keeps constant. From fig.3, the raise course of the gas pressure is consistent with the experiment on whole. Then it infers that the gas pressure transmission model expressed by formula (3) is basically close to the factual system. This model will greatly consult the design of the control algorithm of Mckibben muscle.

From fig.3, the opening time delay of the electropneumatic is much less than the gas pressure filling time to mckibben muscle. Scanning he whole gas pressure transmission, according to the pull force model, the gas pressure gets to 90% of the stable volume at about 600ms.

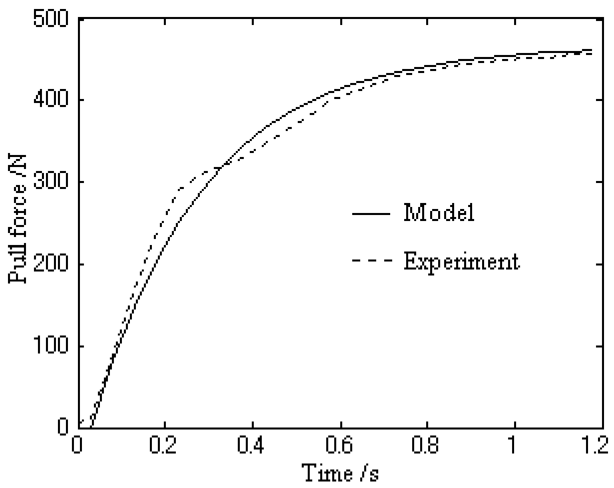

Fig.3 Comparison between the model and the experiment

5. Conclusion

In factual applications of Mckibben muscles, to a typical pneumatic experiment system, usually the electropneumatic regulator is used to control the gas pressure. Based on the whole system, the stiffness of Mckibben muscle is proportional to both its gas pressure and its length. Enforcing to change its length, its inner gas pressure doesn't change. When gas pressure input, there is a time delay of several hundred milliseconds because of both the delay of the gas valve of the electropneumatic regulator and the filling course of the inner gas pressure of Mckibben muscle. And the filling course is much larger than the delay of the gas valve.

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