Simulation Investigation of a Soft Hydraulic Artificial Muscle

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Abstract. This paper presents a soft hydraulic artificial muscle (SHAM) design, which replaces the cylinder, rod and piston in traditional hydraulic cylinder with soft structures. The presented muscle has the advantages of high output force level and good adaptability to environment. Modelling and simulation are conducted after introducing the working principle of the SHAM. Simulation results show that the output force can be as large as 160N with 0.8MPa input pressure. The effect of mixed air into the working fluid has also been investigated and discussed. Above advantages make the SHAM perfect for applications such as exoskeletons.

1. Introduction

Soft robotics is an innovation-concentrated research area in which many researchers and engineers are interested. Soft actuator is an important aspect of soft robotics that drive the robots to achieve various of motions. Among kinds of soft actuators, artificial muscle (AM) is widely employed for the advantages of elegant structure, relatively low cost, good safety and large output force level [1-3].

Mckibben pneumatic artificial muscle (PAM) has longest history and best popularity in application. The Mckibben PAM, firstly proposed by Joseph L. Mckibben, uses fiber reinforced rubber cylinder as its main structure. The longitude and latitude directions of the fiber both have angles between the axis of the cylinder. When inflated with pressure air, the cylinder expands radially and this will lead to its decrease in length. The main advantages of Mckibben PAM are its low cost and high output force level. While the main disadvantages of Mckibben PAM include its high stiffness when inflated and its short contraction interval.

Based on the traditional Mckibben PAM, many researchers developed variety of novel designs of AMs. Juan Yi et al. introduced origami intro the design of the cylinder of AMs. The design overcome the short working interval problem of traditional Mckibben PAM. Experiments showed that the origami based AM can achieve 150N force output with 50% contraction ratio under 100kPa pressure [4]. Lee Belding et al. developed an AM based on a plastic cylinder with several slits [5]. A balloon is placed in the plastic cylinder. When inflated with pressure air, the cylinder expands radically and this will lead to its decrease in length. The working principle is much like Mckibben PAM, while it has longer working interval. In addition, changing the single chamber structure of Mckibben PAM to multi chamber structure is another hot topic in this field. Novel actuators such as twisting PAM, pneumatic fingers, pneumatic grippers have been developed according to this method [6-10].

Besides the Mckibben based PAMs, many other structures have also been proposed to achieve either higher contraction interval or good compliance. Jackson Wirekoh et al. developed a flat PAM employing multi chamber structure based on fiber reinforced silicon rubber [11-12]. The PAM is especially suitable
for human-robot interface applications such as exoskeletons. Kwanghyun Han et al. invented a high contraction ratio PAM with a belt-cylinder based structure. The PAM can reach a contraction ratio as high as 183% and a response of 1Hz [13]. However, the width of the PAM is too large during contraction, which limits its potential application.

Other design of novel PAMs have also been proposed with novel manufacturing methods such as 3D printing [14]. However, how to achieve long contraction interval and high level output force at the same time is still a big problem in the research of this area.

This paper proposes a novel design concept a AM, which is called soft hydraulic artificial muscle (SHAM) design based on traditional hydraulic cylinder,. The design allows high working pressure, which results in high output force; traditional rigid cylinder material is replaced by soft rubber, which will increase its adaption to environment. The contents of the paper are as follows: Firstly, the working principle of SHAM is introduced; then the modeling process of SHAM is given; the simulation results are analyzed, which validates the design concept; finally, the results of the paper are concluded.

2. Working principle of SHAM

As shown in Fig.1, the soft hydraulic muscle is consist of two top caps, some O-rings, a left port, a soft piston, a piston core, a Ni-Ti alloy wire, a right port and an end cap. The two top caps are mounted together by three radially uniformly distributed screws. There is a central hole in each top cap, through which the Ni-Ti wire can just go through. There is a groove for the O-ring on each top cap to seal the working liquid from the clearances of top cap-soft cylinder and top cap- alloy wire. The left port is mounted on side of the soft cylinder to charge and discharge the working liquid to the left chamber of the muscle; The right port is also mounted on the side of the soft cylinder to charge and discharge the working liquid to the right chamber of the muscle. For the piston, which is composed of a soft piston and a piston core, works like the piston in a traditional hydraulic cylinder. The end cap is mounted on the right end of the soft cylinder. The top and end caps are fixed by pipe hoops around the soft cylinder.

From above introduction, it can be understood that the working principle of the soft hydraulic muscle is much like that of a traditional hydraulic cylinder. The advantage of the designed soft hydraulic muscle compared with traditional hydraulic cylinder made of rigid parts is it can adapt to the shape of its working environment (Fig.2). The advantage of the designed soft hydraulic muscle compared with traditional pneumatic muscles is it can generate a higher force, which is because the hydraulic principle allows higher working pressure.
The modeling work of the soft hydraulic muscle mainly concentrates on the motion analysis on soft piston assembly based on the Newton’s Second Law, which can be expressed as follows:

$$m \frac{d^2 x}{dt^2} + D \frac{dx}{dt} = (p_L - p_R) A - F_L - f$$

(1)

In the equation, \(m\) and \(x\) are the mass and displacement of soft piston assembly (soft piston and piston core), \(D\) is the damping ratio, \(p_L\) and \(p_R\) are the pressures of left and right chambers, \(A\) is the working area of the piston assembly, \(F_L\) is the load force and \(f\) is the friction force.

Another mainly concentrated analysis is the pressure of left and right chambers. As the analysis method is same, only the pressure of the left chamber is given as follows:

$$\frac{dp_L}{dt} = \frac{E}{V + Ax} \left( Q - A \frac{dx}{dt} \right)$$

(2)

In the equation, \(E\) is the equivalent modulus of working fluid, \(V\) is the initial volume of left chamber and \(Q\) is the inlet flowrate into the left chamber.

The simulation model is established in Matlab/Simulink based on above equations.

3. Simulation results

The simulation results of output force variations with different percentages of air mixed into the working fluid (hydraulic oil) are shown in Fig.3. The simulation was conducted by giving a stepping input pressure of 0.8MPa, which is a normal pressure of pneumatic systems. As shown in the figure, the output force reaches as large as 160N with 0.8MPa input pressure. The dimensions of the soft hydraulic muscle are 200mm in length and 16mm in diameter. This validates the advantage of high output force level mentioned above. It can also been concluded from the figure that with higher percentage of air mixed into the working fluid, the response time becomes longer. That is because more air mixed into the working fluid, the equivalent modulus \(E\) of the working fluid becomes smaller. When there is 1% mixed...
air, the response time is about 0.006s; while when there is 20% mixed air, which is common in low pressure open hydraulic systems, the response time increases to about 0.04s.

Fig.3 Simulation results of output force with 0.8MPa step input pressure and different percentages of mixed air into the working fluid

Although the simulation data was achieved without considering that in a real hydraulic system, a step pressure is hard to realize. The simulation results do indicate that when using the designed SHAM, we must assure that the mixed air is reduced to minimum.

4. Conclusions
This paper presents a soft hydraulic artificial muscle design based on traditional hydraulic cylinder. The presented muscle has the advantages of high output force level and good adaptability to environment. The advantages are validated through modeling and simulation in Matlab/Simulink. Simulation results show the muscle has good potential to be used in applications such as exoskeletons.

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