Analysis and Modeling of Tap-Water/Pneumatic Drive McKibben Type Artificial Muscles

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Abstract—This study is concerned with comparative analyses and modeling of both tap-water and pneumatic drive McKibben type artificial muscles. McKibben type pneumatic artificial muscles have been widely used in various fields, especially medical and welfare fields. On the other hand, tap-water drive muscles are proposed because conventional pneumatic muscles require a compressor to generate compressed air. In this paper, to examine some static and dynamic characteristics of them such as contraction ratio, time-delay, and time constant, an experimental setup, which can be used to control the tap-water and pneumatic drive muscles, is constructed and then the differences on the characteristics of them are examined by comparative analyses. It is useful to investigate the characteristics in order to figure out the availability and suitable applications of them. In addition, difference on modeling are investigated by using system identification technique. As a result, the identified model of the pneumatic drive muscle is more complex than the model of the tap-water drive muscle because of nonlinearity due to compressibility of working medium.

Index Terms—McKibben type artificial muscle, tap-water drive system, pneumatic drive system, modeling

I. INTRODUCTION

Recently, medical and welfare devices strongly require a connection with mechatronics and robotics, such as power assist systems and rehabilitation systems [1]-[3]. In the devices, soft actuators are used because high human-friendliness, flexibility, and light-weight are essential issues [4]. As one of such soft actuators, McKibben artificial muscles is well-known. They consist of an inner rubber tube, nylon sleeves, and two end connecters as shown in Fig. 1. The advantages of them are 1) high power-to-weight ratio, 2) light-weight due to the structure and materials, and 3) high flexibility. On the other hand, the disadvantages are follows: 1) low control performance due to high nonlinearity, 2) low contraction ratio, which means small stroke and it is less than 30% in general, and 3) low dynamic characteristics.

Generally, McKibben type artificial muscles are driven by pneumatic drive systems because pneumatic drive systems have lots of advantages, such as easy-to-use, light-weight, and compact [5], [6]. In addition, the systems have back drivability, which is useful for medical and welfare devices, and compressed air is basically clean. Thus, as a safeness and cleanliness points of view, the drive systems are one of the suitable systems for the devices. Unfortunately, this leads to degrade the control performance of the muscles because the pneumatic drive systems have strong nonlinearity due to high compressibility of air compared with other drive systems.

Figure 1. Structure of McKibben type artificial muscle

In this paper, another drive system is also proposed. It is a tap-water drive system, which uses only a tap as a power source, and it means 100% oil-free system. As mentioned before, cleanliness is very important for medical and welfare applications and then the system is suitable for the devices. Moreover, the system can remove air compressors from whole system because it need only a tap. This is great benefit for the devices.

Tap-water drive system has been applied to some industrial fields, such as food processing, pharmaceutical, and nursing-care machineries. In particular, rehabilitation devices use McKibben type artificial muscles driven by tap-water as actuators [7], [8]. From the related works, it is confirmed that the muscles can be controlled well by tap-water drive systems. However, quantitative analyses and comparison between tap-water and pneumatic drives have not been investigated yet.
In this paper, we carry out some experiments to examine the characteristics of both tap-water and pneumatic drive artificial muscles under same experimental conditions and then derive both parametric models. Finally, we compare both control performance by using same a control scheme, which is PI control, and show the difference of the performance between the tap-water and pneumatic drive muscles.

II. McKIBBEN TYPE ARTIFICIAL MUSCLE

McKibben type artificial muscles were proposed and developed by McKibben in 1950s [9] and have been widely used to various applications. Fig. 2 shows a structure of the muscles. When working fluid or compressed air are supplied to the muscle, the muscle contracts depending on the supply pressure. Fig. 3 shows the muscle displacement – supply pressure characteristics while pneumatic driving. The characteristics has relatively strong hysteresis as shown in Fig. 3. This is a reason why the control performance of the muscle is degraded.

Figure 2. McKibben type artificial muscle (FESTO)

Figure 3. Muscle displacement – supply pressure characteristics of the pneumatic drive muscle under no-load condition

III. COMPRISON OF TAP-WATER AND PNEUMATIC DRIVE MUSCLES

To examine static and dynamic characteristics of both tap-water/pneumatic drive muscles, an experimental setup is constructed. The experimental setup consists of two proportional valves (Koganei Co. Ltd., KFPV300-2-800) which can be used to both hydraulic and pneumatic drive systems, a pressure sensor (KYOWA ELECTRONIC INSTRUMENTS CO., LTD., PVL10KD), a load cell (KYOWA ELECTRONIC INSTRUMENTS CO., LTD., LUX-B-2KN-ID). Notice that the experimental setup can be used to both tap-water/pneumatic drive muscles under same experimental conditions. In addition, to make a variable load system, a pneumatic cylinder (SMC corporation, CG5LN32SR-200), and an electro-pneumatic proportional valve (SMC corporation, VER2000) are used in the setup. Operating the valve by feedbacking an output of the load cell, the load connecting the muscle, which is equivalent to the generated force of the pneumatic cylinder, can be adjusted arbitrary. Figs. 4 show the experimental setup.

In addition, although the static characteristics was examined, it is not enough to get the performance of both muscles because there are no experimental results of dynamic characteristics.

Table I shows differences of characteristics between tap-water and pneumatic drive muscles. Notice that these experimental results are obtained from same experimental setup under same experimental conditions.

The contraction ratio and contraction force of both muscles are almost same levels and then it is shown that
such static characteristics of both muscles are not different much. This is reasonable because related works showed same results about it. On the other hand, some dynamic characteristics such as time-delays and time constants show different results. The time-delay of the pneumatic drive muscle is approximately one sixth of the time-delay of the tap-water drive muscle, and the time constant of the pneumatic one is approximately one seventh of the other. This is because orifices of the valves used in these experiments are same and it means that flow rate of pneumatic one is larger than of the other. Under same conditions, flow rate of typical pneumatic drive systems is more than tenfold of typical water hydraulic drive systems in general. Thus, it is confirmed that static characteristics of them are almost same levels although characteristics of used valves have dominant effects on dynamic characteristics of them.

### IV. MODELING OF TAP-WATER AND PNEUMATIC DRIVE MUSCLES

To derive parametric models of both muscles, we apply system identification technique [10] to modeling of them. The muscles have strong nonlinearity and there are no established mathematical models [11]-[13]. In this study, we aim to obtain simple model to be used as a nominal model for model-based control schemes.

![Figure 5. Input and output data for tap-water drive muscle](image)

In system identification, only input and output data are used to identify systems. Fig. 5 shows time-series of input and output data for the tap-water drive muscle. Note that the input is applied voltage for the valve and the output is measured displacement of the muscle.

A following equation shows an identified model of the muscle derived by system identification.

\[
G_w(z) = \frac{0.0824}{z^2 - 1.765z + 0.7819}
\]  

(1)

where \( G_w(z) \) is a discrete-time transfer function of the tap-water drive muscle, \( z \) is a time-shift operator that satisfies \( z(k) = x(k+1) \). Fig. 6 shows a comparison of the simulated displacement by the identified muscle model (1) with the measured displacement by the experiment.

![Figure 6. Comparison of simulated and experimental results (Tap-water drive muscle)](image)

The output of the obtained model (1) shows a good agreement with measured output by experiment. Thus, the relatively simple model, which is described as a discrete-time second-order transfer function, can be derived.

To compare differences on modeling of both muscles, same identification method is applied to the pneumatic drive muscle. An identified model of the pneumatic drive muscle is expressed as,

\[
G_a(z) = \frac{0.01909z^{-3} - 0.01086z^{-2} - 0.01118 + 0.004816}{z^4 - 3.227z^3 + 4.126z^2 - 2.503z + 0.6059}
\]  

(2)

where \( G_a(z) \) is a discrete-time transfer function of the pneumatic drive muscle. Fig. 7 shows a comparison of the simulated displacement by the identified muscle model (2) with the measured displacement of the pneumatic drive muscle.

![Figure 7. Comparison of simulated and experimental results (Pneumatic drive muscle)](image)

Compared with the model of the tap-water drive muscle, the identified model (2) has more complex structure. It is caused by characteristics of air, especially compressibility and dynamics of temperature change. Therefore, it is confirmed that there is a considerable difference between the tap-water and pneumatic drive muscles on modeling. In other words, the tap-water one is
suitable or easy-to-use for applications of model-based control schemes and it is expected to achieve high control performance.

V. CONCLUSIONS

This study is concerned with comparative analyses and modeling of both tap-water and pneumatic drive McKibben type artificial muscles. To examine some static and dynamic characteristics of them, an experimental setup, which can be used to control the tap-water and pneumatic drive muscles, is developed. From static and dynamic experiments and comparative analyses, it is confirmed that the dynamic characteristics of the pneumatic drive muscle, such as a time-delay and a time constant, are better than the characteristics of the tap-water drive muscle although the contraction ratio and force of them are almost same levels. On the other hand, from a view point of modeling, the identified model of the tap-water drive muscle is simpler than the model of the other. This is because difference of the characteristics of compressed air and tap-water. The obtained results can be used to apply model-based control schemes to a displacement control system of both tap-water and pneumatic drive systems.

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