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

Wataru Kobayashi, Shujiro Dohta, and Tetsuya Akagi
Department of Intelligent Mechanical Engineering, Okayama University of Science, Okayama, Japan
Email: {kobayashi, dohta, akagi}@are.ous.ac.jp

Kazuhisa Ito
Department of Machinery and Control Systems, Shibaura Institute of Technology, Saitama, Japan
Email: kazu-ito@shibaura-it.ac.jp

***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.

Manuscript received January 10, 2017; revised April 10, 2017.

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.

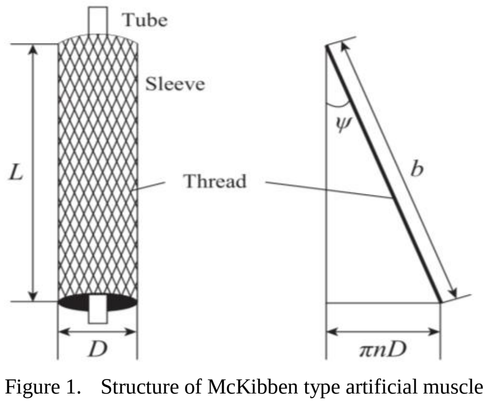


Figure 1. Structure of McKibben type artificial muscle

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.

doi: 10.18178/ijmerr.6.6.463-466

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)

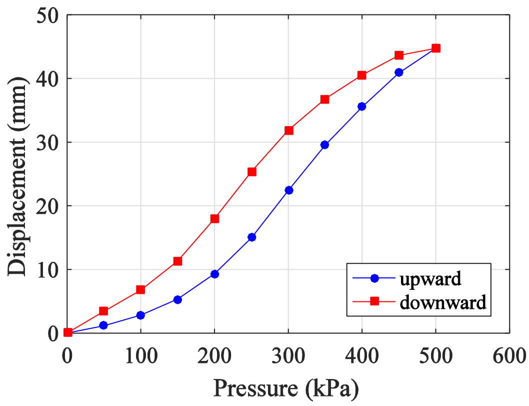


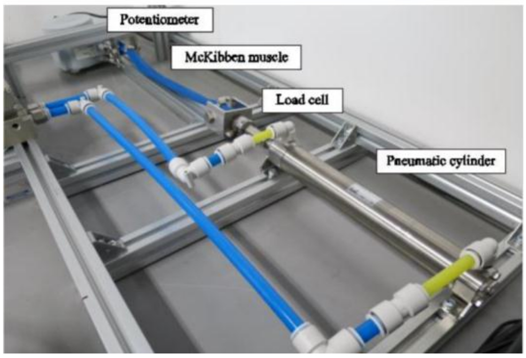
Figure 3. Muscle displacement – supply pressure characteristics of the pneumatic drive muscle under no-load condition

In related works, it was shown that the characteristics of the muscle while tap-water driving had almost same tendency as pneumatic one. However, both experiments have not been carried out under same experimental conditions and there was no comparison between tap-water and pneumatic drive muscles by using the same experimental setup. Note that the experimental setup here means control valves, hydraulic/pneumatic circuits, and pressure and displacement sensors.

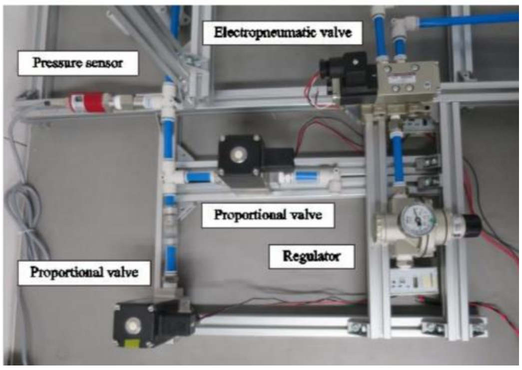
In addition, although the static characteristics was examined, it is not enough to get the performance of both muscles because there are no experimental results of dynamic characteristics.

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.



(a) Tap-water/pneumatic drive circuit



(b) Variable load system with cylinder and proportional valve

Figure 4. Experimental setup for tap-water/pneumatic drive muscle

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.

TABLE I. COMPARISON OF PNEUMATIC AND TAP-WATER DRIVE MUSCLES

	Pneumatic drive	Tap-water drive
Max. contraction ratio (%)	23.7	25.3
Max. contraction force (N)	13.7	15.1
Time-delay (s)	0.04	0.25
Time constant (s)	0.12	0.87

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.

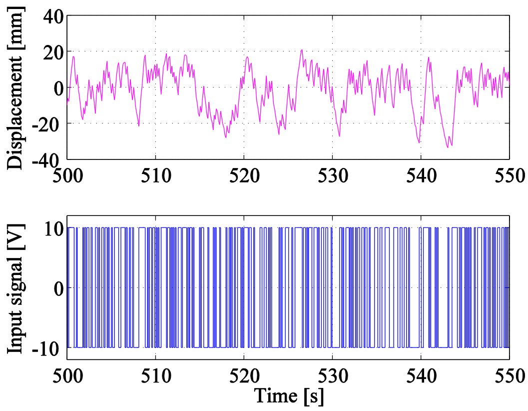


Figure 5. Input and output data for tap-water drive muscle

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.

$$G_w(z) = \frac{0.0824}{z^2 - 1.7652z + 0.7819} \quad (1)$$

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

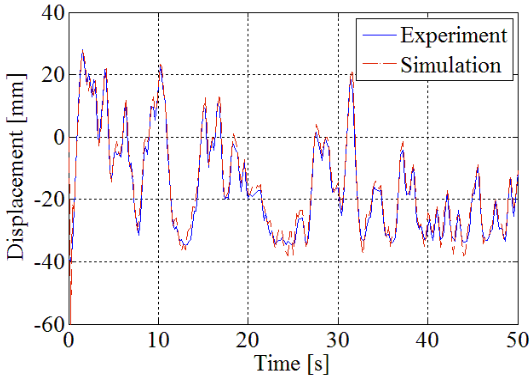


Figure 6. Comparison of simulated and experimental results (Tap-water drive muscle)

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,

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

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.

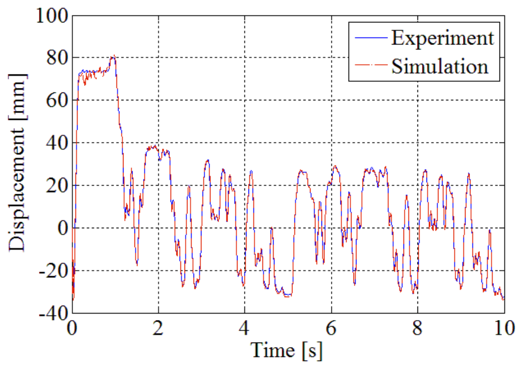


Figure 7. Comparison of simulated and experimental results (Pneumatic drive muscle)

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.

Acknowledgment

This research was supported by the MEXT in Japan through a Financial Assistance Program for QOL Innovative Research (2012-2016) and a Grant-in-Aid for Scientific Research (C) (Subject No. 24560315 & 16K06202).

References

[1] M. A. M. Dzahir, T. Nobutomo, and S. I. Yamamoto, "Development of body weight support gait training system using pneumatic mckibben actuators-control of lower extremity orthosis," in *Proc. 35th Annual International Conference of Engineering in Medicine and Biology Society*, 2013.

[2] Y. L. Park, *et al*., "Design and control of a bio-inspired soft wearable robotic device for ankle-foot rehabilitation," *Bioinspiration & Biomimetics*, vol. 9, no. 1, 2014.

[3] T. Noritsugu and T. Tanaka, "Application of rubber artificial muscle manipulator as a rehabilitation robot," *IEEE/ASME Transactions on Mechatronics*, vol.2, no.4, pp. 259-267, 1997.

[4] B. Tondu and P. Lopez, "Modeling and control of McKibben artificial muscle robot actuators," *Control Systems*, vol. 20, no. 2, pp. 15-38, 2000.

[5] S. Yamamoto, *et al*., "Development of pneumatic gait assist system," in *Proc. International Conference on Complex Medical Engineering*, pp.1337-1340, 2007.

[6] T. Miyoshi, *et al*., "Robotic gait trainer in water: Development of an underwater gait-training orthosis," *Disability and Rehabilitation*, vol. 30, pp. 81-87, 2008.

[7] W. Kobayashi and K. Ito, "Development of gait-training orthosis with water hydraulic mckibben muscle," in *Proc. 12th International Symposium on Fluid Control, Measurements and Visualization*, 2013.

[8] W. Kobayashi, K. Ito, and S. Yamamoto, "Displacement control of water hydraulic mckibben muscles with load compensation," *JFPS International Journal of Fluid Power System*, vol. 8, no. 2, pp. 107-112, 2015.

[9] H. F. Schulte, "The characteristics of the McKibben artificial muscle," *The Application of External Power in Prosthetics and Orthotics*, vol. 874, pp. 94-115, 1961.

[10] L. Ljung, *System Identification*, Birkhäuser Boston, 1998.

[11] T. Vo-Minh, *et al*., "Cascade position control of a single pneumatic artificial muscle-mass system with hysteresis compensation," *Mechatronics*, vol. 20, no. 3, pp. 402-414, 2010.

[12] D. B. Reynolds, *et al*., "Modeling the dynamic characteristics of pneumatic muscle," *Annals of Biomedical Engineering*, vol. 31, no. 3, pp. 310-317, 2003.

[13] A. Pujana-Arrese, *et al*., "Modelling in modelica and position control of a 1-DoF set-up powered by pneumatic muscles," *Mechatronics*, vol. 20, no. 5, pp. 535-552, 2010.

Wataru Kobayashi is currently an assistant professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Shibaura Institute of Technology in 2015. His research interests are robust control theory and aqua drive system; especially rehabilitation and life support systems.

He is a member of The Japan Society of Mechanical Engineers (JSME), The Society of Instrument and Control Engineers (SICE), The Japan Fluid Power System Society (JFPS), and The Society of Life Support Engineering (SLSE).

Shujiro Dohta is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He is also currently a Vice-president of Okayama University of Science.

He joined Okayama University of Science as a research associate on 1974. Then, he became an Exchange Faculty of Wright State University, U.S.A. from 1984 to 1985. He received his doctor degree in Engineering from Kobe University in 1990. His major in mechatronics is focusing on the development of robotics, wearable devices for rehabilitation purpose. Prof. Shujiro Dohta is currently a member of The Japan Society of Mechanical Engineers (JSME), The Society of Instrument and Control Engineers (SICE), The Robotics Society of Japan (RSJ), and The Japan Fluid Power System Society (JFPS).

Tetsuya Akagi is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Okayama University of Science in 1998.

He started at Tsuyama National College of Technology, Japan as a research associate on 1998. Then, he joined Okayama University of Science as a lecturer from 2005. He received Young Scientists' Prize from Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. His research interests include mechatronics and robotics; especially wearable control systems using microcomputers and wearable control devices such as flexible pneumatic actuator, soft sensor and wearable control valve.

Kazuhisa Ito is currently a full professor at the Department of Machinery and Control Systems, Shibaura Institute of Technology. He received his B.E. (1993), M.E. (1995), and D.E. (2001) degrees in Mechanical Engineering from Sophia University, JAPAN.

His current research interests include controller design for nonlinear systems and its application to mechanical systems; especially control/ energy saving performance improvement of aqua drive system, and agriculture engineering.

He is a member of The Japan Fluid Power System Society, The Society of Instrument and Control Engineers, and Japanese Society of Agricultural, Biological and Environment Engineers and Scientists.