Development of Flexible Thin Actuator Driven by Low Boiling Point Liquid

Tetsuya Akagi, Shujiro Dohta, Shinsaku Fujimoto, Yasuyuki Tsuji, and Yuto Fujiwara
Department of Intelligent Mechanical Engineering, Okayama University of Science, Okayama, Japan
Email: {akagi, dohta, fuji}@are.ous.ac.jp, t13rm03ty@std.ous.ac.jp, t14rm05yf@ous.jp

***Abstract*—In this paper, an flexible thin actuator driven by low boiling point liquid that can generate large force in expansion was proposed and tested. The tested actuator is an envelope-type actuator that is made of laminating plastic sheets, low boiling point liquid and a flexible heater. The flexible heater is made of functional liquid using carbon nanotubes. In a preliminary experiment, by folding serial envelope-type actuators alternately, the actuator can generate the larger displacement towards a specific direction by using air pressure of about 100 kPa. The actuator was also able to drive the load of 490 N. In addition, the performance of the flexible thin actuator driven by the low boiling point liquid and the flexible heater was also investigated. As a result, it was confirmed that the tested actuator could be driven silently by using the fluidic power generated by the electric power.**

***Index Terms*—flexible thin actuator, low boiling point liquid, flexible heater, mobile rehabilitation device, silent movement**

I. Introduction

Due to the aging of Japanese society and the decreasing birth rate, an important problem to keep a quality of life (QOL) for the elderly has occurred [1]. Especially, the decrease in physical ability of the elderly will be concerned to increase in nursing care task. Therefore, the national budget for social welfare will be increased. In order to solve this problem, that is to improve a quality of life (QOL) for the elderly and the disabled and decrease the budget for nursing care, a simple rehabilitation device to keep their physical ability might be one of solutions. The actuator used in such a rehabilitation device requires lightweight, softness, small size and larger generated force that can support human body [2]-[4]. Therefore, many researchers are studying wearable actuators such as a McKibben artificial muscle [5]-[7]. The McKibben actuator can generate larger force that is more than 300 N by using the actuator whose diameter of 10 mm in the initial condition. However, the actuator can not work with long stroke. Maximum stroke is one fourth of the original length of the actuator. To get larger force by using other pneumatic actuator, larger sectional area of the actuator or higher pressure supplied to the actuator is needed. In ideal, a thin actuator that can generate larger force and displacement is required. Therefore, in our previous study [8], the envelope-type actuator driven by pneumatic pressure was proposed and tested as a flexible thin actuator. The actuator can be used as rehabilitation device for shoulder by being sandwiched it in armpit. In the next step, it is necessary to develop a portable fluid power source for wearable actuators. However an ordinary compressor on the market is bulky, heavy and noisy. Therefore, we aim to develop the compact and light-weight fluid power source that can be driven silently. The purpose of our study is to develop a flexible thin actuator driven silently by the fluidic power generated by the electric power such as small-sized battery. In order to develop the silent fluid power source, we paid attention to a low boiling liquid. In this paper, the flexible and thin heater that can be embedded into actuator will be also discussed. The united actuator with the flexible heater and its performance will be also described.

Manuscript received April 11, 2014; revised June 13, 2014.

II. Flexible Thin Actuator

A. Construction and Operating Principle

If a thinner actuator that can work with long displacement can be realized, it is useful to apply the rehabilitation or training devices. In our pervious study, we proposed and developed the thinner and lighter wearable actuator that can work toward a particular direction. Fig. 1 shows the construction of an envelope-type actuator. The actuator consists of four sheets of paper and plastic laminate films as shown in Fig. 1. The left figure in Fig. 1 shows the shape of paper A and B. The right figure shows the sectional structure of the actuator. The paper B works as a gusset in the actuator. The size of plastic laminate film is larger than the size of paper A and B. The plastic laminate films are bonded each other at the margin of the films with the exception of paper area. Then, the length of L_A, L_B and H in paper A and B is 90 mm, 110 mm and 40 mm, respectively.

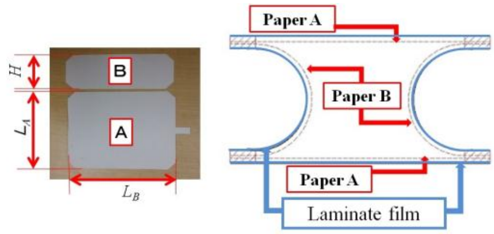

Figure 1. Inner structure of envelope-type actuator.

doi: 10.12720/ijmse.3.1.55-59

Fig. 2 shows the view of movement of the envelope-type actuator when the supply pressures of 30 kPa is applied. From Fig. 2, it can be seen that the thickness of the actuator was greatly deformed about 39 times from the initial thickness of 1.5mm with no supplied pressure to maximum thickness of 58.4mm. By using typical laminate films and paper that can be easily got on the market as a stationery, the actuator can be quickly and easily fabricated. The time for production of the actuator is several minutes.

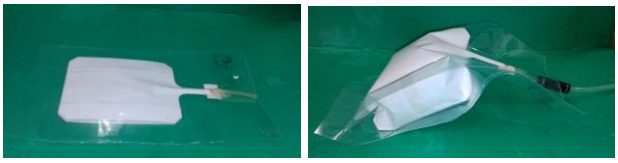

Figure 2. View of movement of tested actuator (Left: no supply, Right: supply pressure of 30 kPa).

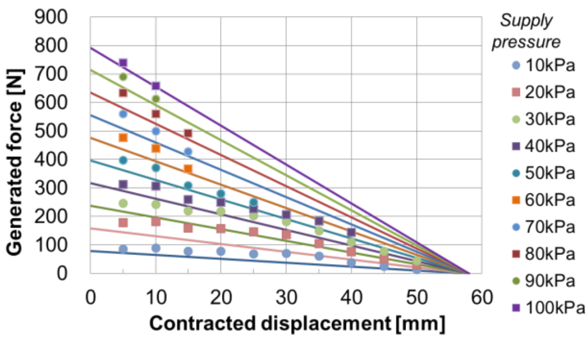

Figure 3. Relation between the contracted displacement and the generated force of the actuator.

Fig. 3 shows the relation between the contracted length and the generated force of the actuator in the case when the supply pressure was applied every 5 kPa from 0 kPa to the maximum pressure (burst pressure). Further, the relation between the displacement and generated force of the actuator was investigated. From Fig. 3, it can be seen that the maximum generated force of 657 N could be obtained in the case of supplied pressure of 100kPa. From these results, the following experimental relation between the displacement and the generated force of the actuator can be obtained.

$$F = A_0 P\left(1 - X / X_M\right) \quad (1)$$

where, F, A_0, P, X and X_M mean the generated force, equivalent sectional area, supplied pressure, displacement and maximum displacement of the actuator, respectively. In Fig. 3, the solid lines show calculated results using Eq. (1) with A_0=0.8$L_A L_B$=0.00792m^2 and X_M=2.9L_C=0.058mm. From Fig. 3, it can be seen that the proposed experimental relation expressed by Eq.(1) about the generated force and displacement of the actuator can predict well the static characteristics of the tested actuator.

B. Multi-Chamber Type Thin Actuator

In order to increase the displacement of the actuator, it is better to use many actuators by laminating with parallel. However, this type actuator needs many supplied tubes. It makes the construction to be complex. Therefore we proposed and tested a multi-chamber type thin actuator that the actuators with single chamber are connected in series with pressure supply line.

Fig. 4 shows the view and construction of the multi-chamber type thin actuator that two envelope-type actuators with single chamber are connected in series. By using the stick shaped silicon rubber in the bypass, it is possible to supply air to both pressure chambers without any extra tube. The bypass using the silicon rubber can send supply air smoothly even if the actuator and the bypass are bent.

Figure 4. Multi-chamber type thin actuator (Left: no supply, Right: supply pressure of 30 kPa).

Figure 5. Transient view of movement of the actuator that is to make two multi-chamber type thin actuators alternate (Time:0s, 15s, 39s).

Fig. 5 shows the transient view of the movement of the actuator using two multi-chamber type thin actuators. The actuator consists of two multi-chamber type thin actuators connected with four chambers in series. Both actuators are overlapped each other so as to make each actuator alternate. From Fig. 5, it is found that the actuator could be obtained a maximum displacement of 400 mm from the initial thickness of 15 mm. It corresponds about 27 times displacement of the original thickness. Furthermore, the working direction of the actuator can be held in the particular direction by overlapping each other alternately. The restricted directional motion of the actuator can be realized as follows. When the supplied pressure was applied to both thin actuators, by overlapping each other, two actuators twist so as to make rope shape. By this method, the stiffness of the actuator toward vertical direction becomes large according to the supplied pressure.

C. Analytical Model and Performance

Fig. 6 shows of the model of the tested actuator. From the experimental results and geometric configuration of the actuator as shown in Fig. 1, the following relationships can be obtained. L_A=4.5L_C, L_B=5.5L_C, A_0=0.8$L_A L_B$, X_M=2.9L_C. where L_C is a half-length of the gusset as shown in Fig. 6. From (1) and these relations, the following equation can be obtained.

$$F = 19.8PL_C{}^2 - 6.82PXL_C \quad (2)$$

By using (2), we can design the thin actuator. An example of designing the actuator using (2) is as follows. In the design, we assume that the purpose of the design is "to determine the dimensions of one actuator which can generate the displacement of 300 mm when the load of 500 N is applied by using four-chamber type actuator ". From (2) in the case of F=500 N, X=300/4=75 mm and P=200 kPa, the length L_C of 30mm is obtained. From these values, both lengths L_A of 135 mm and L_B of 165mm are obtained.

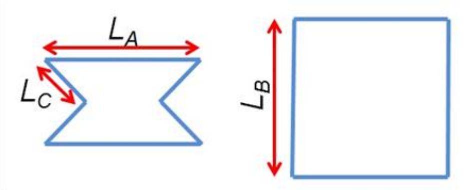

Figure 6. Basic shape of the envelope-type actuator.

Fig. 7 shows the transient view of the movement of the redesigned actuator using these parameters mentioned above when the actuator turns the load of 490 N. From Fig. 7, it is found that the actuator could turn the concrete block of 490 N. The tested actuator also generates the larger displacement of more than 300 mm.


Figure 7. Transient view of movement of the redesigned actuator when the actuator turns the load of 490 N (Time:10s, 20s, 34s).


Figure 8. Transient view of movement of the redesigned actuator when the actuator lifts the load of 490 N (Time:0s, 4s, 7s).

Fig. 8 shows the transient view of the movement of the actuator when it lifts up the concrete block of 520 N. As a result of this experiment as shown in Fig. 8, we confirm that the actuator has an ability of lifting up the load of 520 N. By using the proposed model, it is possible to easily design the actuator in order to get the desired generated force.

III. Flexible Actuator Using Low Boiling Liquid

A. *Low Boiling Point Liquid*

In order to develop the actuator driven by low boiling point liquid, the boiling point of the liquid is very important from the view point of the energy consumption and the response for heater. If the boiling point of the working liquid is higher, the larger electric power of the heater is required. In addition, from the view point of working liquid in a rehabilitation device, it must have safety, non-toxicity to the human body and harmless to the environment. Therefore, we select a functional liquid (3M^{TM} Co. Ltd., Novec™7000)[9] as a working liquid. Table I shows properties of Novec™7000. The liquid is a cleaning liquid for the electronic circuit board. The boiling point is 34 degrees centigrade. The liquid is nonflammable and nonpoisonous fluid virtually. The standard vapor pressure of 0.065 MPa is enough pressure to drive the envelope-type actuator. The high volume resistivity shows that the liquid can contact the electric heater directly during the high applied current.

TABLE I. Properties of Novec™7000

Boiling point (℃)	34	Specific heat (J/kgK)	1300
Freezing point (℃)	-123	Thermal conductivity (W/mK)	0.08
Vapor pressure (MPa)	0.065	Surface tension (mN/m)	12.4
Steam latent heat(kJ/kg)	142	Refractive index	1.26
Density (kg/m^3)	1400	Expansion coefficient (m^3/m^{3}K)	0
Absolute viscosity (Pa.s)	4.5×10^{-4}	Dielectric strength (kV)	40
Kinetic viscosity (cSt)	0.32	Volume resistivity (Ωm)	1×10^8

B. *Thin Flexible Heater*

To install the heater into the envelope-type actuator, the heater must be flexible and thinner. Therefore, we proposed and tested a flexible thin heater using the functional paint that includes carbon nanotubes. Fig. 9 shows the view and schematic diagram of the tested thin flexible heater. The heater consists of copper tape as an electrode, a functional paint (Future Carbon GmbH Co. Ltd., Carbon e-Therm PUR-120)[10] and plastic laminate films. The production method of the heater is as follows. First, two copper conductive tapes are pasted on a laminated film. Next, the laminate film is coated with Carbon e-Therm. Before drying the paint (Carbon e-Therm), the paint is covered with the laminated film from both sides. The size of the heater as shown in Fig. 9 is 60 x 65 mm. The thickness of the heater is 0.5 mm. The heater has flexibility. By laminating the plastic films from both sides, the heater has durability even if the heater is bent.

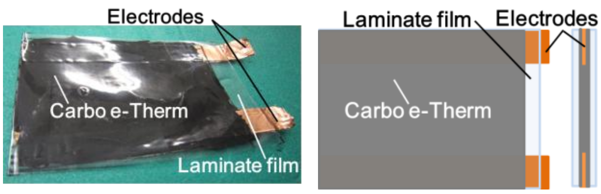

Figure 9. Flexible thin heater using Carbo e-Therm.

Fig. 10 shows the relation between the input voltage and the reaching temperature of the tested heater. In the experiment, the temperature was measured by the infrared radiation temperature meter (Custom Co. Ltd., CT-2000D). From Fig. 10, it can be seen that the maximum temperature of heater reached more than 250 degrees with input voltage of 10 V. It was also found that the temperature of the heater increased according to input voltage. The response time of the heater when the stepwise input voltage is applied is quite short, that is less than 1 second.

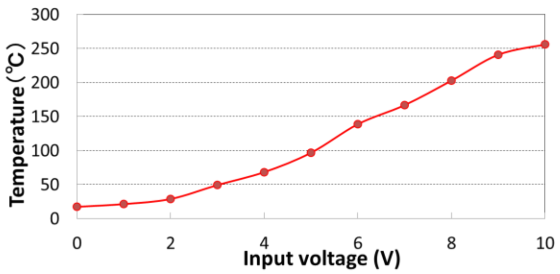

Figure 10. Relation between the input voltage and the reaching temperature of the tested heater.

C. *Flexible Actuator with Low Boiling Point Liquid*

Fig. 11 shows the construction of the flexible thin actuator with low boiling point liquid and flexible heater. The flexible heater is installed into the envelope-type actuator. To apply the voltage from the outside of the actuator, two copper tapes were connected with the heater. In the actuator, the low boiling point liquid with volume of about 50 cm^3 is also installed. The size of the actuator is 110 mm in length, 90 mm in width and 6 mm in thickness. The total mass of the actuator including the liquid is 80 g.

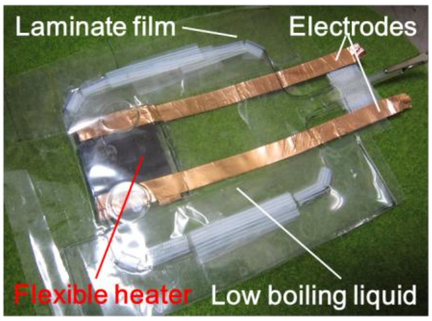

Figure 11. Construction of the flexible thin actuator with low boing point liquid and flexible heater.

Figure 12. Transient view of movement of the tested actuator when the input voltage of 10 V is applied (Time:5s, 10s, 15s).

Fig. 12 shows the transient view of the movement of the tested actuator when input voltage of 10 V was applied. Each figure shows the view of the actuator when 5, 10, 15 seconds from the beginning of starting to apply the voltage. It can be seen that the actuator reached at maximum displacement within 15 seconds. After stopping to apply the voltage, the actuator was contracted according to the decreasing the temperature of the liquid by natural cooling. We confirmed that the actuator did not make any sound during being driven.

Fig. 13 shows the transient response of the actuator when the input voltage is applied and then the actuator is cooled by the blower. In the experiment, the input voltage of 10 V was applied for 35 seconds. After 35 seconds from the beginning, the blower fan turned on for air cooling. Fig. 14 shows the transient response of the displacement of the actuator. It can be seen that the response time in expanding is about 35 seconds, the time for contraction of the actuator while cooling needs about 50 seconds. The slow response of the actuator is useful to apply the rehabilitation device. It is because that the rehabilitation device does not require the quick motion of the actuator. In rehabilitation, too slow speed of the given motion for patient will not cause problems. In addition, the actuator after contracting could return to the initial shape of the actuator naturally. The gusset also returns to the original shape even if it can not return naturally in the case that it is driven by pneumatic pressure. We confirmed that the function of the actuator is useful to apply the portable rehabilitation device from view point of repeatability of the actuator shape.

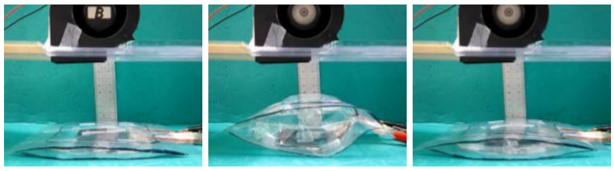

Figure 13. Transient view of movement of the actuator with cooler

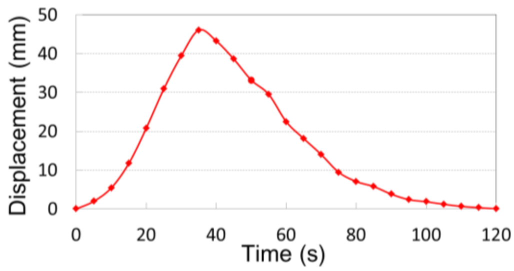

Figure 14. Transient response of the displacement of the actuator

IV. CONCLUSIONS

This study that aims to develop the wearable thin actuator driven by low boiling point liquid for portable rehabilitation device can be summarized as follows.

The flexible thin heater using the functional paint including carbon nanotubes was proposed and tested. The performance of the tested heater was also investigated. As a result, the maximum reached temperature of more than 250 degrees for immediately input voltage of 10 V could be obtained.

From view point of functionality and safety, the functional liquid Novec™7000 was selected as a working liquid of the actuator. By uniting the flexible heater and envelope-type actuator, the flexible thin actuator driven by fluidic power via electric power was proposed and tested.

The driving test of the proposed actuator was carried out. As a result, we confirmed that the tested actuator could be driven silently. We also confirmed that the tested actuator has suitable characteristics for portable rehabilitation device so as to return to its original shape after contracting it.

As our future work, the portable rehabilitation device using the tested actuators will be proposed and tested.

ACKNOWLEDGMENTS

Finally, we express our thanks that a part of this research was supported by a research-aid fund from the Ministry of Education, Culture, Sports, Science and Technology through a Financial Assistance Program for QOL Innovative Research (2012-) and a Grant-in-Aid for Scientific Research (C) (Subject No. 24560315).

REFERENCES

[1] Ministry of Internal Affairs and Communications, Statistics Bureau, Director-General for Policy Planning (Statistical Standards) & Statistical Research and Training Institute. Statistical handbook of Japan 2013. [Online]. Available: http://www.stat.go.jp/english/data/handbook/c0117.htm#c02

[2] T. Akagi and S. Dohta, "Development of wearable pneumatic actuator and multiport pressure control valve," *Journal of Robotics and Mechatronics*, vol. 17, no. 5, pp. 529-536, 2005.

[3] T. Akagi, S. Dohta, and M. Ihara, "Improvement of McKibben artificial muscle with long stroke motion and its application," *Journal of System Design and Dynamics*, vol. 4, no. 4, pp. 538-551, 2010.

[4] Y. Nagata, ed. *Soft Actuators-Forefront of Development*, NTS Ltd., 2004, pp. 291- 335.

[5] K. Yamamoto, M. Ishii, K. Hyodo, T. Yoshimitsu, and T. Matsuo, "Development of wearable power assisting suit," in *Proc. International Symposium on Fluid Control, Measurement and Visualization*, 2003, pp. 1-6.

[6] H. Kobayashi, T. Shiban, and Y. Ishida, "Realization of all 7 motions for the upper limb by a muscle suit," *Journal of Robotics and Mechatronics*, vol. 16, no. 5, pp. 504-512, 2004.

[7] T. Noritsugu, M. Takaiwa, and D. Sasaki, "Development of power assist wear using pneumatic rubber artificial muscles," *Journal of Robotics and Mechatronics*, vol. 21, no. 5, pp. 607-613, 2009.

[8] Y. Tsuji, S. Dohta, T. Akagi, and S. Noguchi, "Development of envelope-type pneumatic thin actuator," in *Proc. 12th International Symposium on Fluid Control, Measurement and Visualization*, 2013, pp. 1-7.

[9] 3M™ Novec™ 7000 Engineered Fluid (Catalog). [Online]. Available: http://solutions.3m.com/wps/portal/3M/en_US/Electronics_NA/Electronics/Products/Product_Catalog/

[10] Carbo e-Therm (Catalog). [Online]. Available: http://www.inno-x.ch/en/181/Heated-Coatings.htm

Tetsuya Akagi is currently a Professor of Intelligent Mechanical Engineering Department in Okayama University of Science, Japan. He has been working in this university since 2005. He received the Master of Engineering and the Doctor of Engineering from Okayama University of Science in 1995 and 1998, respectively. From 1998 to 2005, he was a faculty of Tsuyama National College of Technology, 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.

Shujiro Dohta is currently a Professor of Intelligent Mechanical Engineering Department in Okayama University of Science, Japan. He has been working in this university since 1974. He worked at Wright State University, USA, as an exchange faculty from 1984 to 1985. He received his Master of Engineering from Okayama University in 1974, and his Doctor of Engineering from Kobe University in 1990. His research interests include mechatronics and robotics, especially wearable control components such as flexible pneumatic actuator, soft sensor and wearable control valve.

Shinsaku Fujimoto is currently an associate Professor of Intelligent Mechanical Engineering Department in Okayama University of Science, Japan. He received the Master of Engineering and the Doctor of Engineering from Okayama University of Science in 1992 and 1995, respectively. From 1995, he was a faculty of Okayama University of Scienec, Japan. His research interests include control and robotics, especially biped robot using McKibben artificial muscle and power assisted wheelchair.

Yasuyuki Tsuji is a graduate student at Okayama University of Science. He received the Bachelor of Engineering from Okayama University of Science in 2013.

Yuto Fujiwara is a graduate student at Okayama University of Science. He received the Bachelor of Engineering from Okayama University of Science in 2014.