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| Title | Hose-Free Pneumatic Bags-Muscle Driven by Gas/Liquid Conversion |
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| Citation | Proceedings of the 2016 IEEE/SICE International Symposium on System Integration, Vol. , No. , pp. 616-621 |
| Pub. date | 2016, 12 |
| DOI | https://doi.org/10.1109/SII.2016.7844067 |
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# Hose-Free Pneumatic Bags-Muscle Driven by Gas/Liquid Conversion

Tatsuhiro Hiramitsu[1], Akira Wada[2], Koichi Suzumori[1], Hiroyuki Nabae[1], and Gen Endo[1]

***Abstract*— Pneumatic artificial muscles have unique advantages such as high compliance, high ratio of power to mass, and easy manufacturing. These advantages are different characteristics from electric motors and hydraulic actuators, therefore pneumatic artificial muscles are expected to be applied to new robotic systems such as muscle suits and exploration robots. On the other hand, they require an air compressor, valves, and air supply hoses, making the multi DOF pneumatic robot systems large and complicated. In existing studies, we proposed a novel driving principle that does not require air compressors, valves, nor air supply hoses. Its actuation was based on the reversible chemical reaction of water electrolysis/synthesis using a polymer electrolyte fuel cell (PEFC). In this paper, we demonstrate a pneumatic artificial muscle which can be driven without air supply hoses, by applying the principle mentioned above to a bags-muscle which is a plastic pneumatic artificial muscle. The results of the driving experiments show that the proposed pneumatic artificial muscle can be successfully controlled by electric current.**

## I. INTRODUCTION

Pneumatic artificial muscles have some unique advantages, for instance they do not have electric motors neither hydraulic actuators. This brings as a consequence high ratio of power to mass, high compliance, easy manufacturing, and low cost. For these reasons, they are expected to be applied to new robots such as muscle suits and exploration robots [1][2]. Especially, high compliance is an important factor for devices with pneumatic artificial muscles because it is possible to achieve compact mechanisms with few parts that are able to develop complex motions [3][4][5].

In general, these robots have multi DOF of motion, and we need to configure the multi DOF pneumatic artificial muscle systems. Pneumatic artificial muscles are suitable for uses in multi DOF systems since pneumatic artificial muscles allow the excessive force with soft deformation when they are interfered with objects. On the other hand, an air compressor, air valves, and air supply hoses are required, and the systems get to be complicated and large. As a result, the robots using multi pneumatic artificial muscles have open problems: limitation in operation ranges, high cost, and loud noise. In addition, there is a tendency that control system is complicated. This is due to the fact that miniaturization is difficult compared with electrical systems.

Existing studies attempted to solve these problems [6][7][8]. For example, Ikuta, Ichikawa, Suzuki, and Yamamoto proposed a Band Pass Valves drive system that valves open within only the specified pressure range by using two valve elements [6]. Using this driving principle, they demonstrated a multi hydraulic system that is driven with one hose. Meanwhile, Nishioka, Suzumori, Kanda, and Wakimoto proposed a multi DOF pneumatic system whose control signal is transmitted with an air hose which applies the air pressure for the driving [7]. With this driving method, valves are opened by resonance with applied compressional wave.

In our existing report, we proposed a novel pneumatic rubber actuator using reversible chemical reaction of water, which does not require air supply hoses. We can change gas pressure chambers by the electrolysis/synthesis reaction of water with the PEFC built in actuators. Therefore, it is the greatest feature that the actuator is controlled with only electric wires. A rubber soft actuator successfully worked electrically operating in a response time of several seconds [9]. As compared with the case of using a conventional compressor, these actuators can be controlled by a quiet and compact system, moreover, it achieved regeneration which recovers the energy of the synthesis reaction of water [10]. However, the actuator reported in the existing paper was a balloon type actuator, which works with the expansion of a rubber bag just like a balloon, and the rigid PEFC was used in it. To apply the actuators to multi DOF pneumatic artificial muscle systems such as robots, muscle-like actuators with contracting motion and with flexible structure are required. They are also required to be driven with low flow rate and low pressure air.

In other paper, one of the authors has proposed bags-muscles, a kind of artificial muscles consisting of several serially connected bag units made of plastic film [11]. This muscle contracts in the axial direction and has flexibility in the bending direction because each bag unit is connected to allow to bend each other.

In this paper, we apply the gas/liquid conversion drive to the bags-muscles. This actuator does not needs air supply hoses using electrolysis/synthesis reaction of water. This paper describes the working principle, the actuator design, and the experimental results.

## II. WORKING PRINCIPLES OF THE GAS/LIQUID CONVERSION DRIVE

### *A. Principle of Operation of the Internal Gas Pressure Source*

Thre gas/liquid conversion driving method [12] utilizes the electrolysis/synthesis of water as shown in (1), where

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the pressure in the chambers of the actuator is controlled by electrical current.

$$2H_2O \longleftrightarrow 2H_2 + O_2. \tag{1}$$

Electrolysis/synthesis reactions of water are achieved through PEFCs, which can be miniaturized and operated at room temperature. Fig. 1 shows the basic working principle of the electrolysis/synthesis using a PEFC. The PEFC consists of five layers; two platinum membranes working as electrodes, two carbon papers working as catalysts, and a solid polymer membrane: Nafion®(DuPont™).

Eacn gases: hydrogen gas and oxygen gas are generated on each surface of the PEFC; hydrogen is on the positive electrode and oxygen is on the negative electrode. When the potential difference is applied between the electrodes by connecting a power supply to PEFC, protons move interior of the ion-exchange membrane, resulting in the decomposition of water to generate hydrogen/oxygen gases on each surface of the cell. The reaction is shown in (2) and Fig. 1(a).

$$2H_2O \longrightarrow 2H_2 + O_2. \tag{2}$$

In contrast, when the electrodes are connected with a resistance, there are hydrogen and oxygen gases surround electrode, and then water synthesis reaction occurs. This reaction is shown in (3) and Fig. 1(b).

$$2H_2 + O_2 \longrightarrow 2H_2O. \tag{3}$$

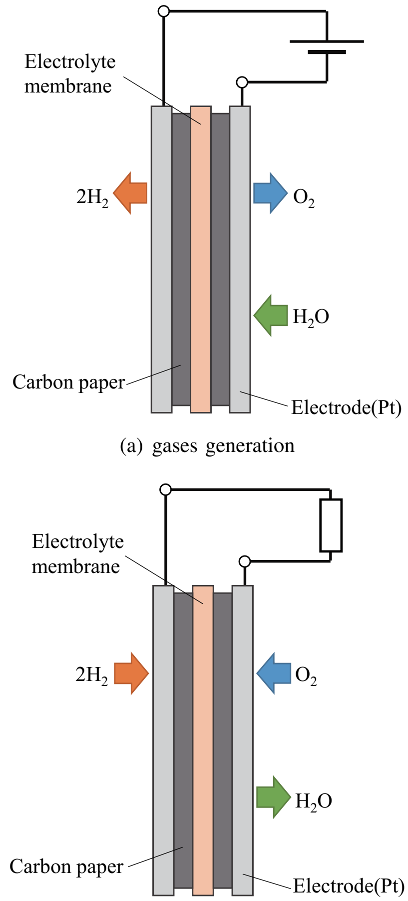
These reactions are reversible and they occur in a closed chamber. The change in gas volume due to the chemical reactions in closed chamber results in gas pressure change and pneumatic actuators drive.

### B. Hose-Free Expansion Type Soft Actuator

In the previous study [13], we have achieved an expansion type soft actuator utilizing the gas/liquid conversion drive. Fig. 2 shows the expansion type soft actuator driven by the gas/liquid conversion. The actuator consists of a PEFC, 12.5 mm long and 25 mm wide, which is covered with silicone rubber membranes (KE-1603, Shin-Etsu Chemical Co., Ltd.). The silicone rubber chamber is filled with pure water and is separated to two rooms by the PEFC for two gases, respectively to avoid their mixing. As shown in Fig. 2, this actuator is driven by applying the voltage of 2.9 V to the electrodes. As shown in Fig. 3, the actuator expands 2.4 mm in thickness direction.

### C. Bags-Muscles

One of the authors developed a bendable and very lightweight pneumatic artificial muscle named bags-muscle, which is made of plastic films such as polyethylene [11]. The bags-muscle shown in Fig. 4 is fabricated by welding plastic films to form chained small bag-like units. Fig. 4(a) and Fig. 4(b) show the bags-muscle in the initial state and deformed state, respectively. Bags-muscles can be driven at the pressure of less than 50 kPa.



(a) gases generation

(b) gases absorption

Fig. 1. Driving principle of electrolysis/synthesis of water with PEFC

It is a salient feature that this actuator can work in a bending state even if bag-like units contain rigid parts, because each unit is flexibly connected to each other. We can fabricate compact mechanisms without jut out machine elements such as hydraulic cylinders. Furthermore, we achieve the robot system that can perform complicated motions by redundant using actuators which have lightweight bodies and high compliance.

## III. DESIGN OF HOSE-FREE BAGS-MUSCLES

### A. Structure of the Muscle

Bags-muscles are fabricated by thermally welding polyethylene films to grid shapes. The structure is composed of bag-like inflatable units, and chambers of adjacent units are connected with air supply lines which conducting wires go through.

During gas absorption, the positive and negative electrodes need to be surrounded by hydrogen and oxygen respectively because of the PEFC function as a fuel cell. In order to avoid mixing hydrogen and oxygen gases, each unit of the proposed bags-muscle has two chambers divided by a partition sheet. The polyethylene film for the sheet has a rectangular cutout for installation of the PEFC. The gap between the polyethylene film and set cells is sealed with

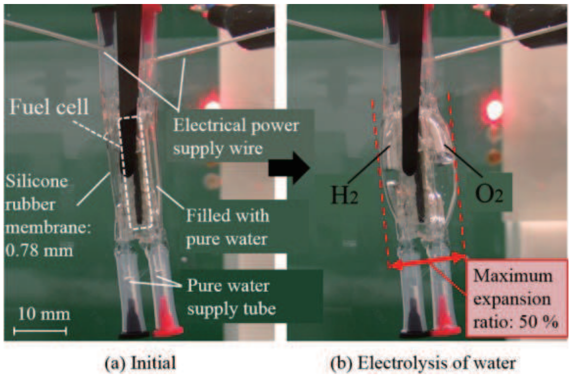



Fig. 2. Gas/liquid exchanging expansion type actuator [13]

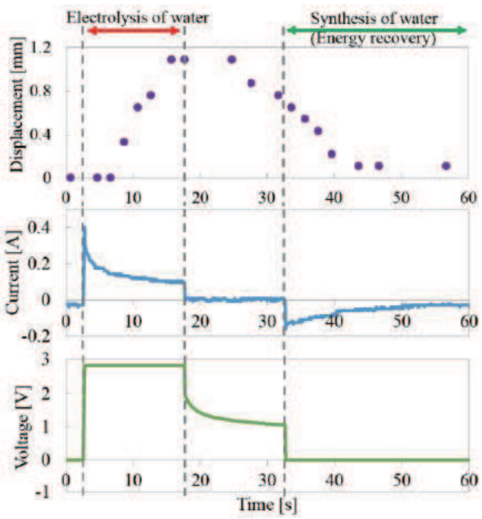
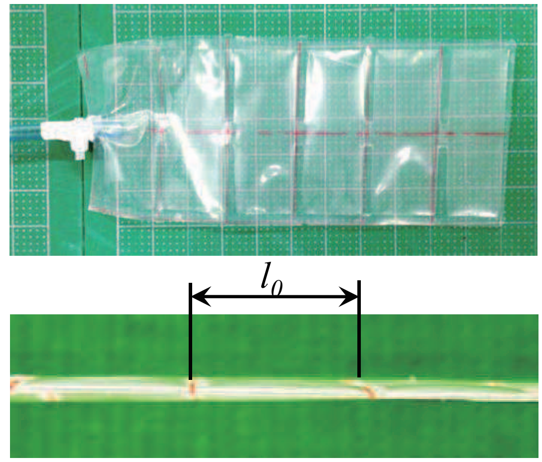
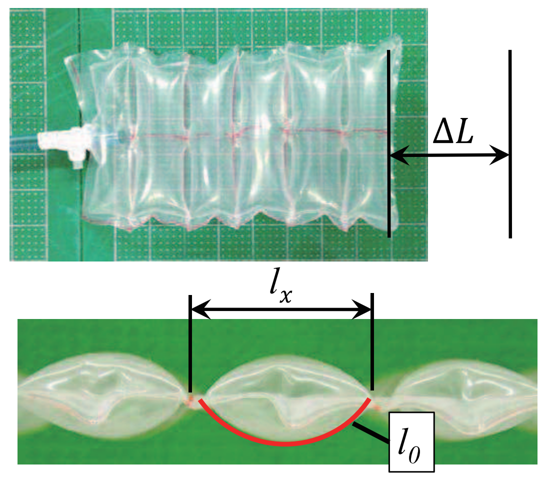



Fig. 3. Results of driving experiment of the expansion type actuator with sequence control (applied voltage for gas generation: 2.9 V). Measured displacement, current, and voltage [13]




(a) initial state




(b) contraction

Fig. 4. Contraction of a bags-muscle which applied air pressure is 20 kPa

hot melt adhesive. The chambers of fabricated bags-muscles are filled with pure water.

### B. Fabrication Process

Fig. 5 shows a fabrication process of the bags-muscle which the gas/liquid conversion drive is applied to. In this time, we use a commercially available PEFC (a) which is processed to have a width of 25 mm and a length of 12.5 mm, mass of 0.9 g. The PEFC consists of three components: a proton-exchange membrane, porous catalyst layers, and platinum mesh electrodes (FCSU-023, Horizon Fuel Cell Japan). Our previous study indicates that the reaction rate cell is strongly affected by pressure for fixing electrodes. (b) In this paper, we adopt commercially available plastic clips to pinch the electrodes. (c) Tin plating wires are arranged between a PEFC and a plastic clip in order to stabilize the contact between platinum electrodes of PEFCs and conducting wires. (d) A polyethylene film is cut to a rectangular shape of 35 mm in width and 100 mm in length, and then PEFCs are fixed at each hole. (e) We fix conducting wires that are copper foils of 5 mm width between a clip and tin-plated wires. (f) Hot melt adhesives seal gaps between the partition film and the PEFCs. We sandwich the composite part which is previously (Fig. 5(c)) described using two polyethylene films of width 35 mm, length 100 mm, in addition (g) we thermally weld at four sides and space between the cells. Fig. 6(a) shows the prototype of the gas/liquid conversion drive bags-muscle and Fig. 6(b) shows a structure of a bags-like unit. Finally, the four bags-like units are filled with pure water. An bag-like unit of this fabricated actuator consisted of two chambers, therefore we refer to this muscle as dual chamber types.

It is predicted that motions of dual chamber types are inhibited by a partition film as compared to existing bags-muscles[11]. Thereby, we prepare a bags-muscle has not a partition film that is made by the fabrication process in Fig. 5 without process (d) and process (f). We refer to this partition less actuator as single chamber types.

## IV. DRIVING EXPERIMENTS

### A. Experimntal System

We conducted a driving experiment of the prototype bags-muscle. The gas/liquid conversion are controlled by current

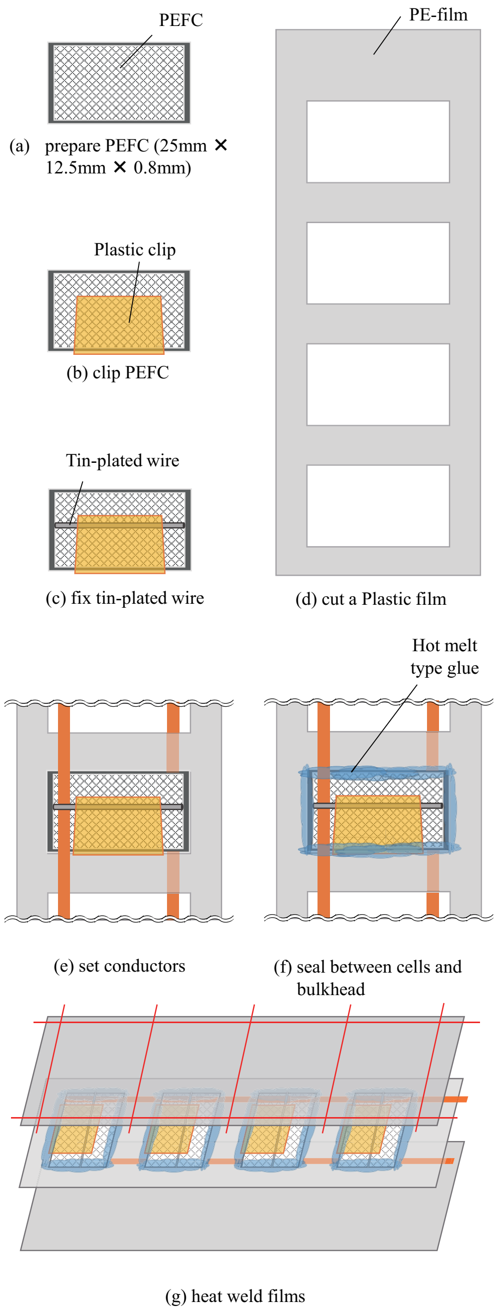



Fig. 5. Fabrication process of a gas/liquid conversion drive bags-muscle

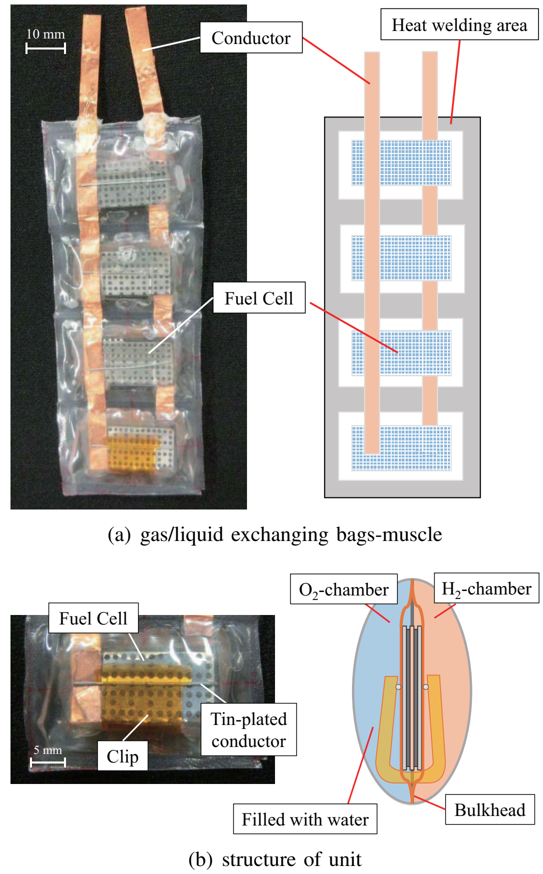



Fig. 6. Structure of the prototype gas/liquid conversion drive bags-muscle. PEFCs are built into each of contractile units.

through a PEFC. As shown in Fig. 7, we change a circuit connected to the PEFC to switch the following three operating phases.

1) **Phase A: gases generation**
   By connecting a power supply to the PEFC, Oxygen/hydrogen gases are generated and the pressure inside the actuator increases.
2) **Phase B: suspension**
   The electrodes of the PEFC are insulated from each other to stop the drive of the PEFC.
3) **Phase C: gases absorption**
   By connecting a resistor to the PEFC, oxygen/hydrogen gases are absorbed to decrease the internal pressure of the actuator.

We measured the amount of contraction by image processing and observed the current and voltage applied to the terminals that are connected to the PEFC, with the hanging down muscle which is loaded by a weight of 30 g attached on the tip.

We also carried out the same experiment with single chamber type muscles which is not loaded, in order to indicate how much the gas/liquid conversion drive muscles can contract at the maximum. Reactions of hydrogen and oxygen occur in a single chamber because single chamber type muscles have no plastic film for parting. Fig. 8 shows schematic structures of unit chambers on a sectional view.

### *B. Experomnt Conditions and Results*

Fig. 9(a) shows the experimental result of the single chamber type muscle, Fig. 9(b) shows the experimental result of the dual chamber type muscle. The figures show voltage values between the terminals, current values, and amounts of the contractions. At this time, we set time of each phase as follows; phase A: gas generation is 60 s, phase B: stop is 30 s, and phase C: gas absorption is 120 s.

During phase A: gas generation, water was decomposed into gases and pressure in chambers increased, therefore that the bags-muscle contracted. Contrary to this, gases are

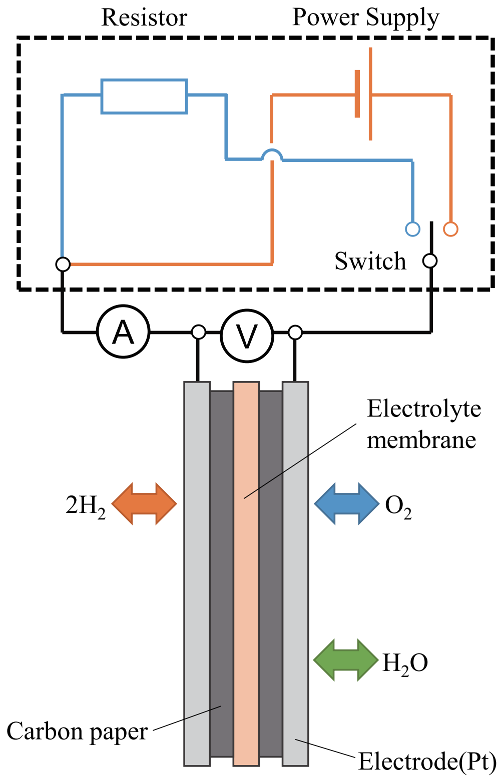
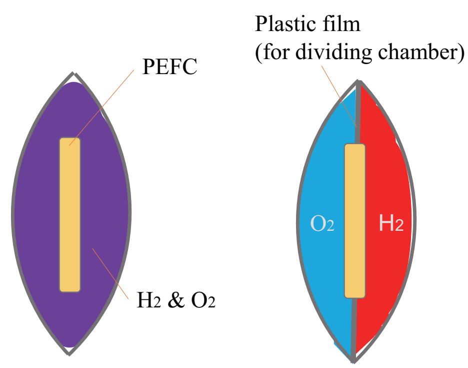
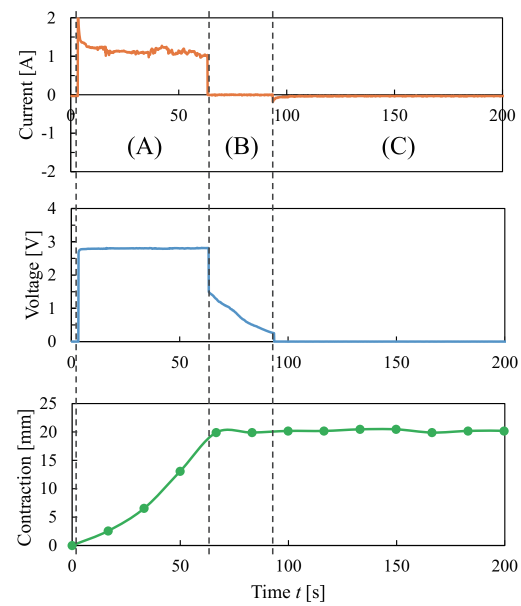



Fig. 7. Experimental system for gas/liquid conversion drive

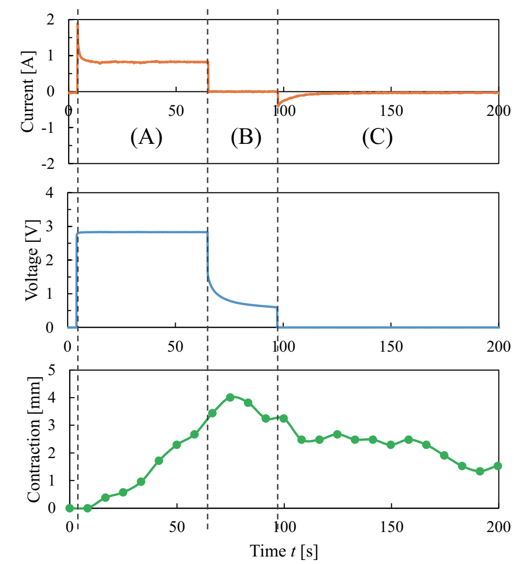



(a) single chamber (b) dual chamber

Fig. 8. Schematic figure of two chamber styles




(a) single chamber with no-loaded




(b) dual chamber with 30 g loaded

Fig. 9. Result of driving experiment of gas/liquid conversion drive bags-muscles with sequence control (applied voltage for gas generation: 2.9 V). Measured displacement, current, and voltage

combined into water and decreasing pressure during phase C: gas absorption, therefore that the bags-muscle returned to the initial form.

From graphs of contraction of Fig. 9, we confirmed that the single chamber type achieved approximately 20 mm contraction, and the dual chamber type muscle contracted approximately 4 mm by gas pressure generation. An amount of contraction of the single chamber type is comparable to a conventional bags-muscle. In contrast, the dual chamber type's amount of contraction is approximately 20 % of conventional's. This is because the partition film for dividing the chamber prevents a movement of the bags-muscle.

Meanwhile, negative current values can be observed after 93.6 s with the dual chamber type. Considering that, phase C: the synthesizing reaction of water from the gases was surely occurred. The current per unit area of the electrode was as follows: expansion type [14] is $474\ \mathrm{A/m^2}$, single chamber type is $896\ \mathrm{A/m^2}$, and dual chamber type is $652\ \mathrm{A/m^2}$. These differences are caused by the difference of cell's structure: the distance between two platinum mesh electrodes of the PEFC is closer by being pressed the PEFC, the reactivity is higher. In this time, cells are pressed by plastic clips. For the future, further consideration will be needed for effective pressurizing in order to improve the reaction rate of PEFCs. For example, it is already confirmed that much gases are generated when pressed by plastic screw.

## V. CONCLUSIONS

We have developed a hose-free pneumatic artificial muscle driven by gas-liquid reversible reaction. The reaction occurs in PEFCs built in the bags-muscle, that is a kind of an artificial muscle made of plastic films and works with low air pressure. Driving the proposed bags-muscle requires no air supply hoses, no valves, and no compressors, but it can be driven by electric current control. This is the only pneumatic artificial muscles without air supply hoses to the best of our knowledge. In general, electrical wires are thin compared to air supply hoses, and a control system for electric drive can be small and simple. For these reasons, the developed muscle has a big potential for multi DOF pneumatic artificial muscle systems.

Experimental results show that the motion of the developed muscle can be controlled by electric current. The single chamber actuator achieved approximately 20 mm contraction, however the returning to the initial state do not occurred. The dual chamber actuator that has two internal chambers separated for hydrogen and for oxygen gases works well with 4 mm in stroke and 30 g in load weight. Reversible current is also measured during releasing motion, which means the water synthesis works well.

While the response time is very long with the prototype, the surface improvement of the PEFC can solve this problem. Moreover, we believe that presented muscles will be able to generate contraction force and stroke as similar to that in conventional bags-muscles by reconsidering arrangement of cells.

## ACKNOWLEDGMENT

This research was supported by MEXT KAKENHI Grant Number JP26249028.

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