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Energy regenerative hose-free pneumatic actuator

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ABSTRACT

Pneumatic actuators in general require an air-compressor, valves, and pneumatic hoses. This makes them difficult to be used on mobile apparatus. To solve this problem, we previously developed a new gas source that uses the electrolysis/synthesis of water through an ion-exchange membrane. The developed gas source uses a gas/liquid reversible chemical reaction and controls the generation/absorption of gas through an electric current supplied to the membrane.

In this paper, we present a control method for the energy-regeneration cycle and perform theoretical and experimental studies to verify its power consumption. This energy-regeneration control method is applied to an actuator, and it works successfully with a power consumption improvement of approximately 20% compared to that without energy-regeneration. Furthermore, we successfully develop a hose-free pneumatic rubber actuator with this control method.

1. Introduction

Pneumatic actuator needs air-supply-hoses, and it is controlled by an air-compressor and solenoid valves [1]. This driving system is not suitable for portable uses, and there are limitations with regards to the potential installation locations. Previously, to realize portable pressure sources, many types of pressure-generation devices have been proposed and tested. For example, conventional studies have used phase transitions of carbon dioxide on a triple point [2], gas-absorption/releasing of hydrogen storing alloys [3], or irreversible chemical reactions [4–7]. Comparison of these devices is shown in Table 1. However, it is difficult for these pressure sources to realize precise pressure control. In addition, most of these pressure sources work by generating the gases from chemical materials mounted in the tank and releasing them, which is essentially the same as a kind of gas holder. Further, the energy efficiency is low because energy is wasted when compressed air is released into the atmosphere in the pressure decreasing state. Till date, the energy-regeneration concept has not been realized for improving the power consumption of pneumatic actuators.

To control pressure precisely, we focus on the reversible gas/liquid chemical reaction in the previous report [8], which is shown in the Formulae (1) and (2), or (3). Reactions of Formulae (1) and (2) take place at the anode side and cathode side, respectively. Combining either reaction pair yields the same overall decomposition/composition of water (Formula (3)). The standard electrode potential for the electrolysis of water is theoretically 1.23 V [9],

$$4H^{+}+4e^{-} \leftrightarrow 2H_2 \tag{1}$$

$$2H_2O \leftrightarrow O_2+4e^{-}+4H^{+} \tag{2}$$

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

The reaction that we used is the electrolysis/synthesis of water. As shown in these formulae, the amount of gas generated is directly proportional to the electric charge. Therefore, by controlling the electron flow, the generated/absorbed gas rates, or the pressure, can be controlled precisely, both in the generation and absorption states. Our study uses an ion-exchange membrane (Nafion) to control the reversible reaction, which has the same structure as a polymer electrolyte fuel cell (PEFC). Previously, Neagu et al. developed an actuator that was based on a similar concept [10,11]. However, their actuator was developed only for use on micro-electro-mechanical systems (MEMS), and its response was slow.

In our previous paper [8], we have investigated the response characteristics to develop a prototype pressure source with practical speed. We have also highlighted the potential of energy-regeneration during gas absorption in the report because it works as a fuel cell during the gases-to-water state. However, in the previous report, we have applied the gas generation/absorption principle to control the pressure in a rigid vessel but not to real actuators, and have not realized energy-regeneration. In this paper, we present the development of a pneumatic rubber actuator in which the gas

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Table 1
Evaluation of earlier portable pressure source studies for pneumatic actuator.

Required properties	Working principle		
	Phase transition on triple point [2]	Hydrogen storing alloy [3]	Irreversible chemical reaction [4–7]
Electrical control of gas	Disable	Enable	Disable
Gas generation/synthesis using reversible reaction	Enable	Enable	Disable
Energy-regeneration	Disable	Disable	Disable

generation/absorption device is installed. It works successfully as an air-supply-hose-free actuator, and the energy-regeneration also works well. We also present theoretical and experimental studies to verify its power consumption and achieve good results.

2. Proposed hose-free actuator with energy-regeneration

2.1. Structure of actuator

Fig. 1(a) illustrates the structure of the proposed hose-free pneumatic actuator. The sectional view is illustrated in (b) and (c) along with its working. It consists of a silicone rubber envelope filled with water and an ion-exchange membrane (Nafion) which separates the silicone rubber envelope into two chambers. Thin electrodes are fabricated on both sides of the ion-exchange membrane, and gas generation/absorption reactions occur by applying a current to the electrodes.

The (b) and (c) shows the basic working principle of this actuator. On applying the electric current to the electrodes, oxygen and hydrogen gases are generated on each electrode with the electrolysis of water, resulting in the inflation of the rubber envelope as shown in (c). Connecting the electrodes makes the actuator return to the initial state as shown in (b). The ion-exchange membrane absorbs the gases at each electrode, causing the synthesis of water and resulting in a decrease in pressure and deflation of the actuator. During the gas absorption state, the ion-exchange membrane works as a fuel cell generating electrical energy, which can be stored by an electric charger and used as a secondary pressurization energy. This will be able to decrease the power consumption.

This working principle enables a precise control of pressure along with energy-regeneration, which have not been achieved in previous studies shown in Table 1. In our previous work [8], the energy is wasted during the gas absorption state when the electrodes are shortened to decrease the pressure. In this paper, we propose a novel energy regenerative hose-free pneumatic actuator with energy-regeneration to reuse the stored energy as driving energy.

2.2. Driving sequence of energy-regeneration actuator

This section explains the driving sequence of the proposed energy-regenerative hose-free pneumatic actuator (see Fig. 2). Based on this sequence, the power consumption is discussed theoretically and experimentally in Sections 3 and 4, respectively.

The initial state of this cycle is shown in Fig. 2(a). The internal pressure of pneumatic actuator is shown with a pressure gauge. Fig. 2(b) shows the state as the pressure increases, which is realized with water electrolysis by applying current using an external current supply. Fig. 2(c) shows the constant-pressure state, which is realized by stopping the electron flow by disconnecting the external current supply. Fig. 2(d) represents the energy-recovering state, which is realized with water synthesis as the actuator works as a PEFC. The regenerated electrical energy is stored in the capacitors connected in parallel as shown in Fig. 2(d). In the actuator, the generated gases are absorbed and the pressure decreases. This energy-recovering state continues to work until the voltages of PEFC and the capacitors are balanced. This means that the internal pressure does not decrease as much as the initial pressure of 0 kPaG of the energy-recovering state (d). Therefore, a shortening state (e) is required to decrease the pressure to the initial pressure of 0 kPaG. The next pressure increasing state using the energy recovered from the capacitors is illustrated in Fig. 2(f), where the parallel connection of capacitors is converted to a series connection to increase the voltage to make it suitable for water-electrolysis in the next step. The electrical energy in the capacitors in series works as a current supply to increase the pressure with the water electrolysis. If the capacitor energy does not sufficiently increase the pressure, the actuator is connected to an external current supply as shown in Fig. 2(g), and gas generation is continued to increase the pressure to the desired pressure.

The actuator realizes two working cycles of the inflation/deflation during this driving cycle from (a), (b), (c), (d), (e), (f), (g), (c), (d), (e), again to (a) in Fig. 2. The first part of the sequential cycles from (a) to (f) is shown as Flow1 in Fig. 2, while the following part from (f) to (a) is shown as Flow2. The energy-recovering state (d) appears twice while the capacitor-driving state (f) appears only once during this driving cycle. This is because the pressure increase in state (f) would be small if it appears every working cycle because the voltage increase with one energy-recovering state (d) would not be high enough. This is an essential driving sequence of this actuator which we call the double-recovering cycle, and we discuss the actuator motion drive with this cycle in this paper.

3. Theoretical analysis

Power consumption of this actuator with no load, or the loss energy for self-moving, is discussed theoretically in this section. It is an essential parameter in the discussion on the actuator efficiency. It is calculated for two cases: conventional driving case without the energy-regeneration of the previous paper as well as that with the energy-regeneration, and the effectiveness of the energy-regeneration is discussed.

3.1. Electrical modeling of actuator

The electrical model of the actuator is shown in Fig. 3, which can work as a charge/discharge device [12]. We used the battery model of Baba et al., because it is the simplest model compared with other battery models, and it shows good agreement with our experiment as is shown in Fig. 4. This chart displays the experimental results of current response in the states (b), (c), and (e), which are shown in Fig. 2. The current values of the theoretical model match the measured values. The circuit constants, $C_A = 0.5$ F, $R_1 = 3.9\ \Omega$, $C_1 = 0.7$ F and $R_2 = 1.5\ \Omega$, which were obtained by fitting the current values of the model to the measured values in the experiment during the states (b), (c), and (e) in Fig. 2.

3.2. Power consumption

The power consumption during the driving cycle shown in Fig. 2 is calculated as the sum of the energy supplied to the actuator in the states (b) and (g). The supplied energy in (b) is always constant; however, the energy in (g) depends on the charge level in (f).