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Modeling and Designing a Power Assist Circuit Using Artificial Muscle

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Abstract

Artificial muscle actuators are used in various fields. Especially, they are applied to the power assist circuit to make use of their characteristics. The purpose of this paper is to model and analyze the power assist circuit using an artificial muscle actuator. As a result, it is found that the operating feeling of the power assist circuit depends mainly on the flow gain of the pneumatic servo valve. The required flow gain is calculated from the proposed model, and the experimental results agreed with the calculated results.

1 Introduction

Rubber artificial muscles as a pneumatic actuator are expected to apply to handling human being in hospitals [1]. Advantages of the artificial muscles are a light weight and a big output power, because it is made of a rubber tube and knitted fibers. The purpose of this paper is to investigate the model and the characteristics of a power assist circuit using an artificial muscle. Numbers of studies on controlling artificial muscle have been made and these results are reflected on robot control and so on[2]. In spite of numbers of studies on artificial muscles, a mathematical model including the compliance effect caused by the volume change is not considered. So, we propose a nonlinear model considering the variation of the compliance. On the other hand, in many cases pneumatic actuators are used as a power assist circuit. But, a design method for a pneumatic valve or actuator is not found. In this paper, the dynamics of the power assist circuit is examined and the calculation of the flow gain of the servo valve is possible using the proposed model which is linearized at equilibrium point. In fact, the power assist circuit is driven by two kinds of pneumatic servo valves which differ in flow gain. It is found that the difference in flow gain influences on operating and on characteristics of the power assist circuit. It is verified that calculation results of flow gain is correct through experiments.

Nomenclature

C : coefficient of viscous damping
C_v : specific heat at constant volume
d : diameter of the pulley
F : contraction force
F_b : generated force by finger
F_c : reference force of the artificial muscle
F_{fr} : friction force
G : mass flow rate
g : gravitational acceleration
h : heat transfer coefficient
K : power assist gain
K_s : spring constant of the assist circuit at input part

K_G : flow rate gain
L : initial length of the artificial muscle
l : length of the lever
M : mass of the weight
P : pressure in the artificial muscle
P_r : reference pressure
R : gas constant
S_h : heat transfer area
W : mass of the air
u : input voltage of the servo valve
V : volume of the artificial muscle
x : displacement of the finger
x_l : displacement of the lever
y : displacement of the artificial muscle
θ_a : atmospheric temperature
θ : temperature in the artificial muscle
ε : contraction ratio (y/L)

2 Mathematical model

2.1 Artificial muscle

Fig.1 shows the characteristics of the artificial muscle, showing the relation between the internal pressure and the contraction ratio when the load force is constant. It is seen that the artificial muscle has the hysteresis because of the creep of the rubber which depends on the contraction speed. It is difficult to include it in the model.

On the other hand, the theoretical equation for the artificial muscle is advocated, but the experimental results don't conform to it. So in this study, this theoretical equation is modified by adding the constant γ.

$$F = \alpha(1-\varepsilon)^2 P + \beta P + \gamma \tag{1}$$

The calculated results are drawn by broken lines in Fig.1. In the wide range, its results can correspond with averaged values of the hysteresis if coefficient is chosen appropriately.

Fig.2 shows the relation between the volume and the contraction ratio of the artificial muscle. The volume becomes 6 times larger than the initial volume when the contraction ratio is changed 0 to 0.25. It is found that the volume does not depend on the load force. This relation can be approximated by the following equation on contraction ratio.

$$V = D_1\varepsilon^2 + D_2\varepsilon + D_3 \tag{2}$$

Deriving the state equation of the gas, the following equation is obtained.

$$P\frac{dV}{dt} + V\frac{dP}{dt} = GR\theta + WR\frac{d\theta}{dt} \tag{3}$$

The energy equation is written as follows:

$$\frac{d}{dt}(C_v W\theta) = GR\theta_a + C_v G\theta_a - P\frac{dV}{dt} + hS_h(\theta-\theta_a) \tag{4}$$

The heat transfer coefficient is supposed constant: 80[W/m^{2}K] in the case of discharging and 120[W/m^{2}K] in the case of charging.

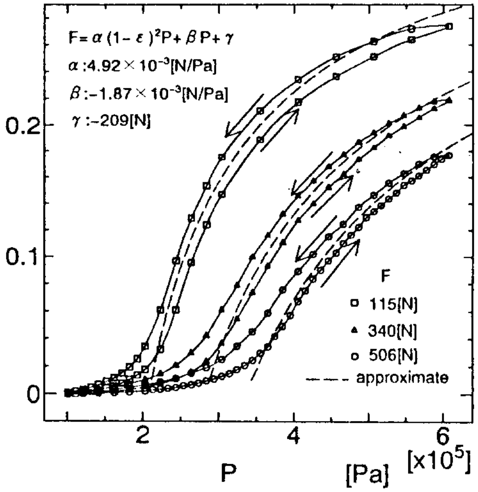


Fig.1 Characterisitics of the artificial muscle

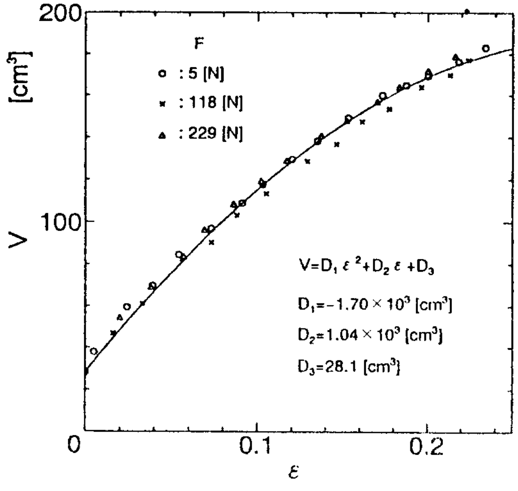


Fig.2 The relation between the volume and the constraction ratio

The heat transfer area is calculated from the volume and the displacement, assuming that the artificial muscle is cylindrical in any contraction ratio. The equation of the motion of the weight is expressed by following.

$$ML^2\frac{d^2\varepsilon}{dt^2} = F - LC\frac{d\varepsilon}{dt} - Mg - F_{fr} \qquad (5)$$

The coefficient of the viscous damping and the friction force are obtained from experiments.

2.2 Power assist circuit

The dynamic characteristic of the input part of the power assist circuit is much faster than that of artificial muscle. So, the force generated by the displacement of the finger can be written in the following equation.

$$F_b = K_s(x - x_l) = K_s\left(x - \frac{Ll}{2d}\varepsilon\right) \qquad (6)$$

If the object of the power assist is considered to amplify the human force, the force generated by artificial muscle can be written in the following equation.

$$F_c = KF_b \qquad (7)$$

Where K is named power assist gain. From Equation (1), the reference pressure is given by the following equation.

$$P_r = \frac{F_c - \gamma}{\alpha(1-\varepsilon)^2 + \beta} \qquad (8)$$

The flow rate can be calculated from the static pressure-flow characteristics because the response of the servo valve is very quick. So, flow gain is given by the following equation.

$$G = K_g(P_r - P) \qquad (9)$$

Fig.3 shows the block diagram concerning these variables.

3 Power assist circuit

3.1 Pneumatic servo valve

Two types of servo valves are used in order to examine the feeling of the operation.

The valve A, one of the two valves, is a nozzle flapper type. According to its catalog, the valve responds up to 100[Hz] and is fast enough to control the artificial muscle. The flow gain for pressure drop is 6.1×10^{-9}[kg/(Pa · s)] when supply pressure is 500[kPa].

The valve B, the other valve, is a pressure control type housed in two on-off valves for supply and exhaust. These two on-off valves regulate the output pressure to be linear, corresponding to the input voltage, using built-in pressure sensor. The flow gain is

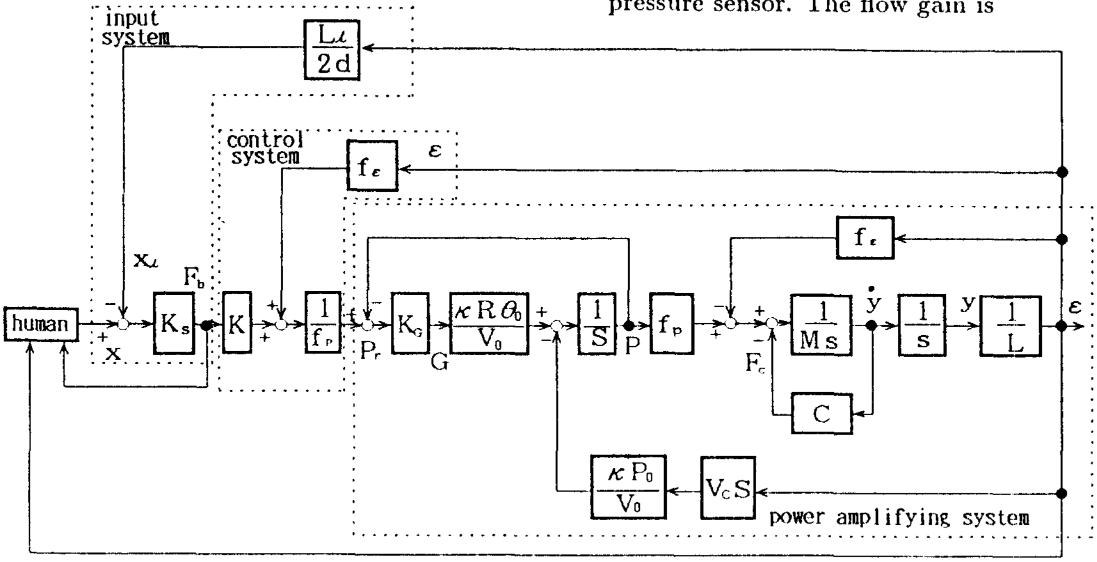


Fig.3 The block diagram of the power assist circuit

1.3×10^{-7}[kg/(Pa · s)] when valves are working. It is impossible to regulate the valve when the flow rate is too large. In this case, the flow gain is the impedance of the supply or exhaust valve. Taking into account the response of the artificial muscle, the dynamics of this valve is sufficient too.

3.2 Scheme of the system

The power assist circuit is constructed as shown in Fig.4. The purpose of this power assist circuit is to lift or to hold the weight naturally. Human moves the lever affixed strain gauges so that the force is generated in the input part. This force is amplified by artificial muscle and simultaneously returned to human to operate easily. As the input lever moves with the main lever, human can know the conditions of the system by the returned force or by seeing the weight. The weight is suspended at the end of the artificial muscle through the pulley. The length of the main lever is 300[mm] and the mass of the weight is 12[kg]. The inputs to the controller are the force measured by strain gauges and the displacement of the artificial muscle. The outputs from the controller to the servo valve after the reference pressure is calculated. The sampling time of the controller is 10[ms]. The generated force reduces gradually as the weight moves. Finally, the weight is stopped when the force balances the gravity of the weight. Table 1 shows the main parametersof the system.

4 Estimation of the mathematical model

We adopt step responses to estimate the model of the artificial muscle. Fig.5 indicates responses when a step signal is the input to the power amplifying system, which is a enclosed by broken line in Fig.3. In Fig.5, the responses are the inside pressure and the contraction ratio of the artificial muscle. Experimental results is in good agreement with calculated results, except that there is an offset between the displacement responses. Seeing Fig.1, we can notice that the hysyteresis is

Table 1 Parameters of the system

Mass	$M = 12$	[kg]
Coefficient of viscous damping	$C = 45$	[Ns/m]
Main lever length	$l = 0.3$	[m]
Coulomb friction	$F_c = 4.5$	[N]
Static friction	$F_s = 7.0$	[N]
Supply pressure	$P_s = 500$	[kPs]
Temperature	$\theta_a = 293$	[K]
Initial length	$L = 0.3$	[m]
Initial diameter	$d = 13$	[mm]
Power assist gain	$K = 20$	

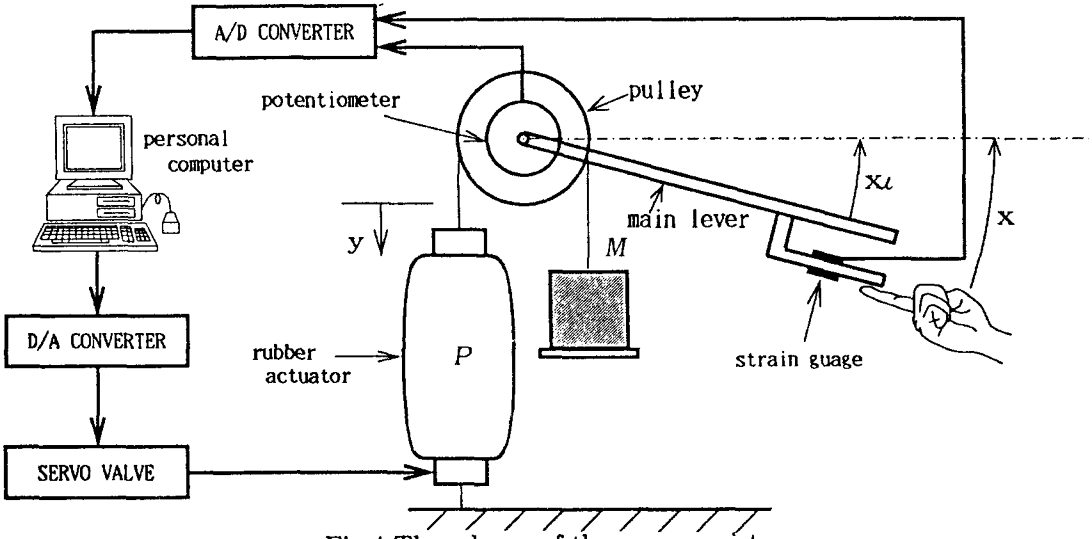


Fig.4 The scheme of the power assist circuit

big and the maximum difference between the contraction ratios for same pressure is 0.05. Consequently, this offset is caused by not cosidering the hysteresis in Equation (1).

5 Consideration for the required flow gain

The block diaphragm of Fig.3 is transformed into Fig.6, where the proposed model is linearized at equilibrium point. The transfer function G and H are as follows:.

$$G = \frac{\omega_1(s^2 + 2\zeta\omega_2 s + \omega_2{}^2)}{(s+\omega_1)(s^2 + 2\zeta\omega_2 s + \omega_2{}^2) + F_p\frac{\kappa V_c P_e}{V_o}s} \tag{10}$$

$$H = \frac{f_p/ML}{s^2 + 2\zeta\omega_2 s + \omega_2{}^2} \tag{11}$$

where:

$$\omega_1 = K_G\frac{\kappa R\theta}{V_o},\ \omega_2 = \sqrt{\frac{f_\varepsilon}{ML}},\ \zeta = \frac{C}{2\omega_2}$$

If human feels strange, there is a time delay between the force felt at the finger F_b and the force acting the weight F_c.

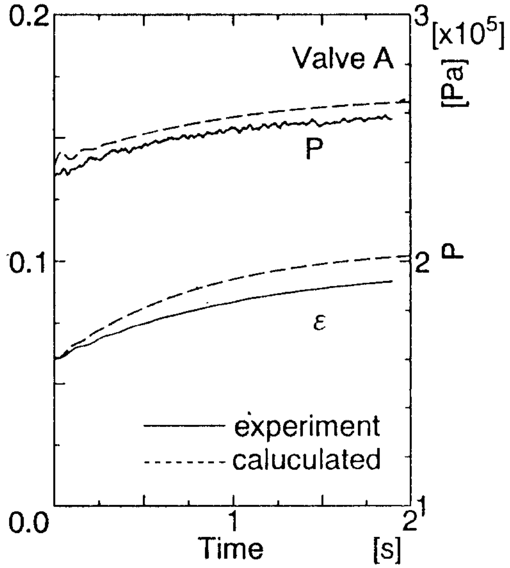


Fig.5 Step responses of the inside pressure and the constraction ratio

Fig.6 indicates the necessary condition that the band width of the transfer function G to be higher than the natural frequency ω_2 of the transfer function H. In other words, it is necessary that the dynamics of the pressure control system to be faster than the natural frequency which is determined by the mass of the weight and the characteristics of the artificial muscle. The degree of the time delay is determined by the volume of the artificial muscle and the flow gain of the servo valve. If the volume is determined on one contraction ratio , it is possible to calculate the flow gain to be faster than the natural frequency ω_2. Therefore, the requirement for the flow gain can be obtained from frequency responses at some equilibrium points. Fig.7 shows frequency responses when the equilibrium pressure is 400[kPa]. The natural frequency of the transfer function G is 4[Hz].

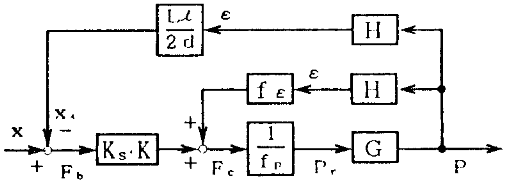


Fig.6 The transformed block diagram from Fig.3

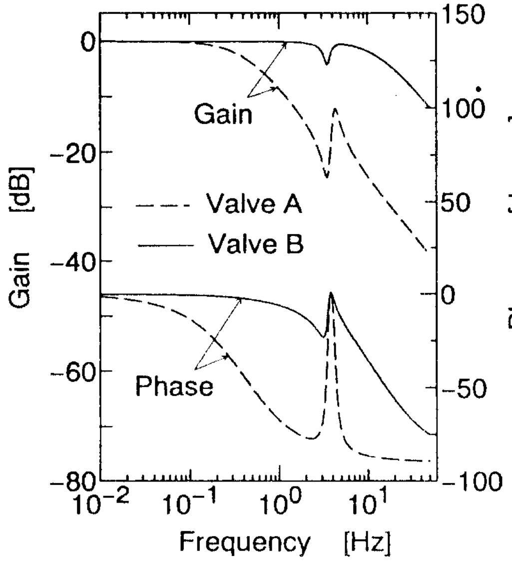
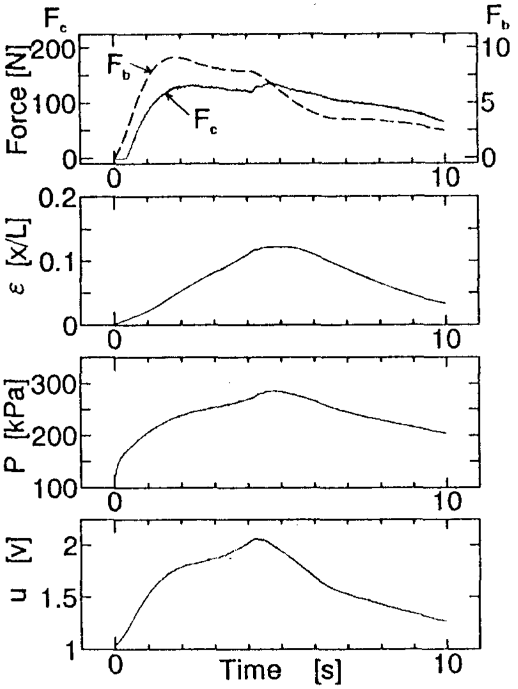
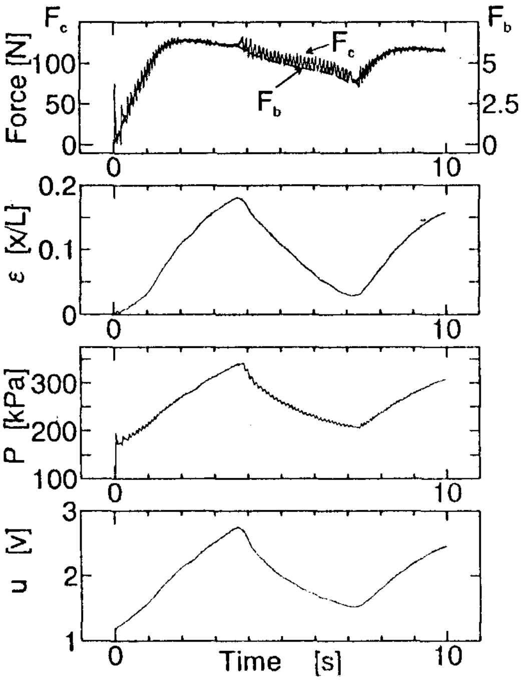


Fig.7 Frequency responses in the case of supply pressure 400[kPa]



(a)The case of valve A



(b)The case of valve B

Fig.8 Responses of the power assist circuit

The valve A does not satisfy the above necessary condition. But in the case of valve B, the pressure control system tracks up to the natural frequency ω_2, therefore good response on the power assist circuit is expected.

6 Responses of the power assist circuit

Fig.8 indicates responses of the power assist circuit. The force F_b is amplified 20 times larger than the force F_c. In the case of the valve A, human feels strange. Because the production of the feedback force F_c lags behind the target force F_b. Driving the valve B, the force F_c traces the force F_b very well. Feelings in operation is very good although the weight moves later than the finger. The ripple of the inside pressure is not problem at all since it does not influence the displacement of the artificial muscle. It is found that the result in the chapter 5 is correct. It is important to take into account not only the characteristics of the artificial muscle but also the flow gain of the servo valve.

7 Conclusions

We propose a model of the artificial muscle and apply it to the design of the power assist circuit. It is clear that the proposed model is good and useful for the design.

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