Static Analysis on Suitable Arrangement of Tubes of Low-Cost Control Valve Using Buckled Tube

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***Abstract*—Due to its potential to improve human health care and various of the treatments equipment, power assisted nursing care systems have received positive attentions from the global community and also gaining huge demands from the mainstream industry. In such a control system, wearable actuators and control valves are required to be mounted on the human body. Generally, the performance and cost of the pneumatic wearable rehabilitation device depends on the cost and performance of the valve. Therefore, the optimal design of the valve for precise control is required. In this paper, the proposal of the static model and analysis of the servo valve using buckle tubes developed before are described.**

***Index Terms*—low-cost servo valve, using buckled tube, Static analysis**

I. Introduction

Recently, rehabilitation devices in power assisted nursing care systems [1], [2] have received much attention. In such a wearable control system, a wearable actuator and a small-sized control valve that can be mounted on the human body are required [3]-[7]. As taking account of development of a wearable control valve that can drive pneumatic actuators to support the multi-degrees of freedom of human motion, the cost and dimension of the valve will be serious problems. In the previous study, a low-cost and small-sized servo valve using buckled tube was proposed and tested [8]. In the next step, it is necessary to investigate the static characteristics of the valve by changing the arrangement of buckled tubes. In this paper, static analytical model and static analysis of the valve for the optimum design will be discussed.

II. Small-Sized Control Servo Valve Using Buckled Tube

A. Construction of the Servo Valve Using Buckled Tube

Fig. 1 shows the construction of a servo valve using buckled tubes. The valve consists of two buckled soft polyurethane tubes (SMC Co. Ltd. TUS0425: inner diameter of 2.5 mm, outer diameter of 4.0 mm), a small-sized RC servo motor (GWS Co. Ltd. PICO/STD/F), an acrylic valve holder and an acrylic tube holder disk. Two buckled tubes are used for supply and exhaust. In the initial condition, the buckling tubes are held by the acrylic rotary disk so that each of buckled angles is 65.7 degrees in clockwise and counterclockwise with radius of about 5 mm from the motor shaft, respectively. Then, each end of the supply and exhaust port is fixed at the tube holder. The alternative arrangement of two buckled tubes helps to decrease the reaction torque for the motor.

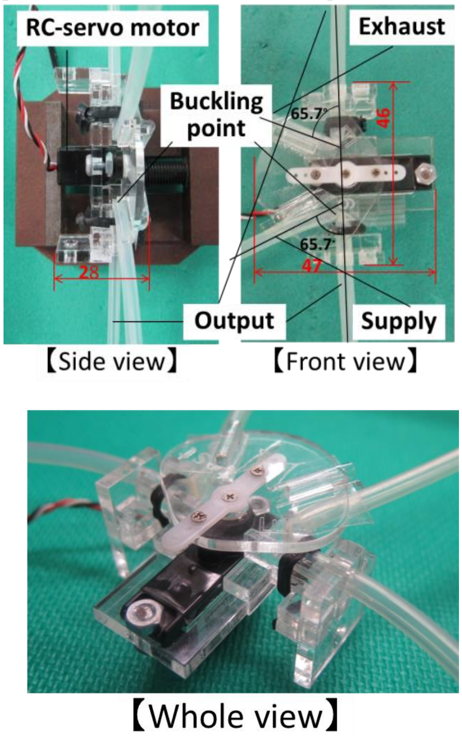

Figure 1. Improved servo valve using buckled tube.

B. Operating Principle of the Servo Valve

The operating principle of the valve is as follows. When the servo motor rotates clockwise, the buckled angle of exhaust tube is decreased and at the same time the buckled angle of supply tube is increased. Then, it causes the increasing of the sectional area in the supply tube by releasing the bending force at the buckling point, while the bending force acted on the buckling point of the exhaust tube is increasing. By increasing the buckled force, the exhaust tube closed surely. The mass and the

Manuscript received July 1, 2014; revised June 11, 2015.

doi: 10.18178/ijmerr.4.3.222-225

cost of this valve are suitable for a wearable device. The mass of this proposed valve is very small, that is 22 g. The estimated cost of the valve is extremely low, that is about 9 US dollars. The mass of tested valve is 22.5 g. The volume is about 60 cm3, with 47 mm length, 28 mm width and 46 mm height.

III. Analytical Model of the Valve

Fig. 2 shows the model of two buckled tubes in the tested valve using the buckle tubes. The model consists of the disk driven by the motor and two buckled tubes that have specific arrangement of tubes as shown in Fig. 2. The equivalent equation of torque between the restoration torque from buckled tubes and the generated torque of the motor is given by

$$J_M \frac{d^2\theta}{dt^2} + b_T \frac{d\theta}{dt}\left(\tau_{MR} - \tau_{ML}\right) = \tau_M \tag{1}$$

where τ_M , τ_{MR} and τ_{ML} are the motor torque and the torques that the buckled tubes act to the motor and generated by the restoration force from the left and right side tube, respectively. In addition, from tube's geometrical configuration as shown in Fig. 2, the equations about buckled tubes are given as follows.

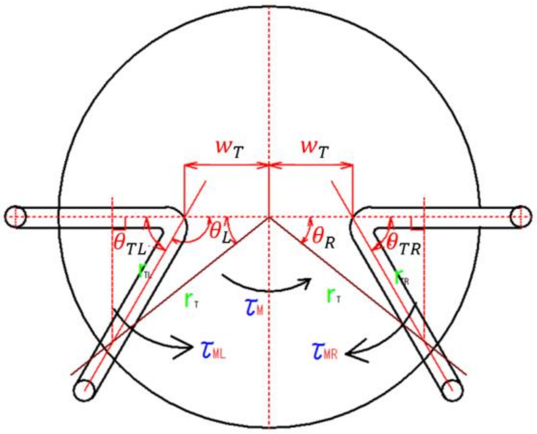

Figure 2. Improved servo valve using buckled tube.

Firstly, the buckling angels of the right and the left tube θ_{TR} and θ_{TL} are given by the following equations, where r_T and w_T are the distance (radius and width) from the central axis of the motor to the fixed point of the right/left tube and to the buckling point of the right/left tube, respectively.

$$\theta_{TR} = \tan^{-1}\left(\frac{r_T \sin(\theta_{R0} - \theta)}{r_T \cos(\theta_{R0} - \theta) - w_T}\right) \tag{2}$$

$$\theta_{TL} = \tan^{-1}\left(\frac{r_T \sin(\theta_{L0} + \theta)}{r_T \cos(\theta_{L0} + \theta) - w_T}\right) \tag{3}$$

The torques τ_{MR} and τ_{ML} due to the restoring force of the each buckled tube applied to the central axis of the motor are given by the following equations.

$$\tau_{MR} = \tau_{TR} \frac{r_T}{r_{TR}} \cos(\theta_{TR} - \theta_{R0} - 2\theta) \tag{4}$$

$$\tau_{ML} = \tau_{TL} \frac{r_T}{r_{TL}} \cos(\theta_{TL} - \theta_{L0} + 2\theta) \tag{5}$$

where τ_{TR} and τ_{TL} are the generated restoration torques at the buckling point of the right and left buckled tube. In addition, r_{TR} and r_{TL} are the distance from the buckled points to the fixed points of each buckled tube and are expressed by the following equations.

$$r_{TR} = \frac{r_T \sin(\theta_{R0} - \theta)}{\sin(\theta_{TR})} \tag{6}$$

$$r_{TL} = \frac{r_T \sin(\theta_{L0} + \theta)}{\sin(\theta_{TL})} \tag{7}$$

Then, the flow rate of Q_S and Q_a of buckled tube in each supply port (left) and exhaust port (right) are given as following equations.

$$Q_S = A_R \cdot P_S \sqrt{\frac{2}{RT}} \cdot f\left(\frac{P_O}{P_S}\right) \tag{8}$$

$$Q_a = A_L \cdot P_O \sqrt{\frac{2}{RT}} \cdot f\left(\frac{P_a}{P_O}\right) \tag{9}$$

Each opening area A_R and A_L of both tubes are expressed as function of the buckling angle. P_a, P_O and P_S are the atmospheric pressure, output pressure and supply pressure, respectively. R and T are the gas constant and absolute temperature, respectively. $f(z)$ is the function that express the state of flow, and are expressed given by the following equations.

$$f(z) = \sqrt{\frac{\kappa}{\kappa - 1}\left(z^{2/\kappa} - z^{(\kappa+1)/\kappa}\right)} \quad (0.528 \le z \le 1) \tag{10.1}$$

$$f(z) = \sqrt{\frac{\kappa}{\kappa + 1}\left(\frac{2}{\kappa + 1}\right)^{2/(\kappa-1)}} \quad (0 \le z < 0.528) \tag{10.2}$$

where κ is the specific heat ratio, and κ =1.4.

Based on the equations from (1) to (10) as mentioned above, static characteristics of the valve such as the relation between motor angle and output flow rate are possible to be calculated and predicted by changing the arrangement of the two buckled tube.

IV. Fundamental Experiments for Parameters Identification

In the Eqs. (2), (3), (8) and (9), it is not easily to analytically determine the relation between the buckling angle θ_{TR} and θ_{TL} with respect to the restoration force τ_{TR} and τ_{TL} and the tubes opening area A_R and A_L . So, it is necessary to investigate these relations as an empirical formula. In the experiment, the restoration torque from each buckled tube was calculated by investigation of relation between the buckled angle and the restoration force of the tube. Fig. 3 shows the relation between the restoration torque (Nm) and the buckling angle (deg.). Based on the experimental result, the relation between the buckling angle θ_T and τ_T can be approximated by following equation.

$$\tau_{Ti} = 0.066e^{-0.032\theta_{Ti}} \tag{11}$$

By using Eq. (11) and the model mentioned above, the relation between the maximum motor torque and the restoration torque from buckled tube can be simulated for various arrangements of the tubes. When the restoration torque is larger than the maximum motor torque, we can understand that the saturation is occured. Secondly, in order to investigate the relation between the opening area and the buckled angle of the tube, the relation between the mass flow rate and buckled angle as shown in Fig. 4 had been investigated. In the experiment, the supply pressure of 500 kPa was applied and the flow rate was measured by using digital flow meter (SMC Co. PFMB7201-C8-A-M, 1*l*/min). In this figure, y axis shows mass flow rate, x axis shows buckled angle (deg.) and the symbols show the average results of three times measurements.

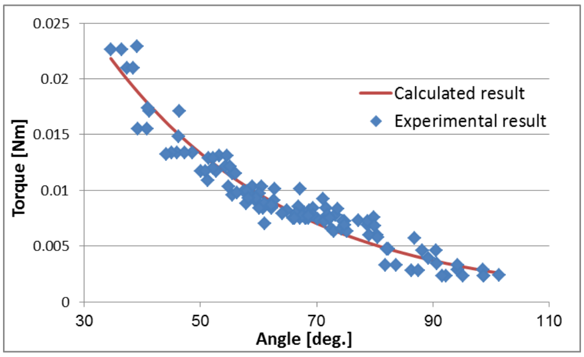

Figure 3. Relation between buckled angle and restoration torque

Secondly, in order to investigate the relation between the opening area and the buckled angle of the tube, the relation between the mass flow rate and buckled angle as shown in Fig. 4 had been investigated. In the experiment, the supply pressure of 500 kPa was applied and the flow rate was measured by using digital flow meter (SMC Co. PFMB7201-C8-A-M, 1l/min). In this figure, y axis shows mass flow rate, x axis shows buckled angle (deg.) and the symbols show the average results of three times measurements.

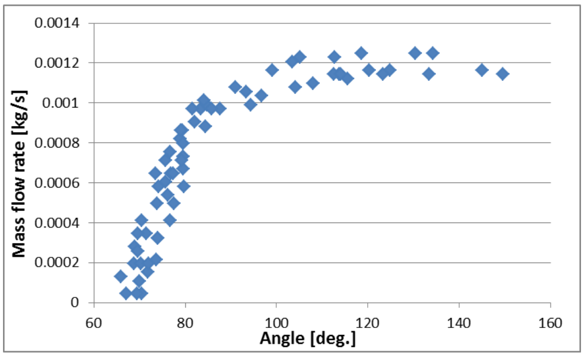

Figure 4. Relation between buckled angle and mass flow rate

Based on the results as shown in Fig. 4, the relation between the opening area and the buckled angle of the tube was calculated by using Eqs. (8), (9), and (10.2). Fig. 5 shows the relation between the opening area (mm^2) and the buckled angle (deg.) of the tube. As same as the previous result, the relation between the output flow rate and buckled angle of the tube was also defined as following approximated equations.

$$A_i = 0.845\left(1 - e^{-0.105(\theta_{Ti} - 68.9)}\right) \quad (i = R, L) \tag{12}$$

By using these empirical formulae and the model mentioned above, the static relation between the motor angle θ_M and output flow rate $Q_S - Q_A$ of the valve will be estimated by changing the distance w_T from the motor center axis to the buckled point of the left and right of the tubes and the initial buckled angle of the tube can be evaluated. In order to confirm the validity of the proposed model, experimental results using the actual equipment and calculated result based on the analytical model of the output flow rate with respect to the motor rotation angle θ were compared.

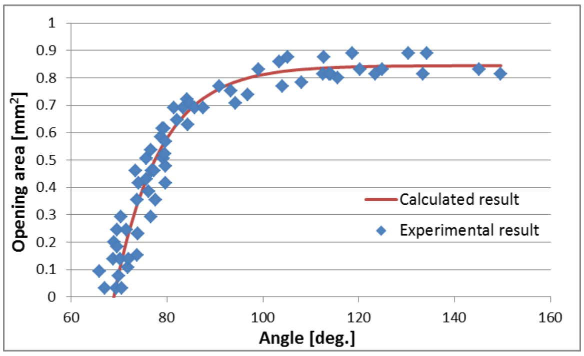

Figure 5. Relation between buckled angle and opening area

Fig. 6 shows the result of comparison between calculated and experiment results. In Fig. 6, symbols and solid line show the experimental and calculated result, respectively. From the Fig. 6, it can be found that the calculated results using the model agrees well with the experimental results. Therefore, the validity of the proposed model is confirmed.

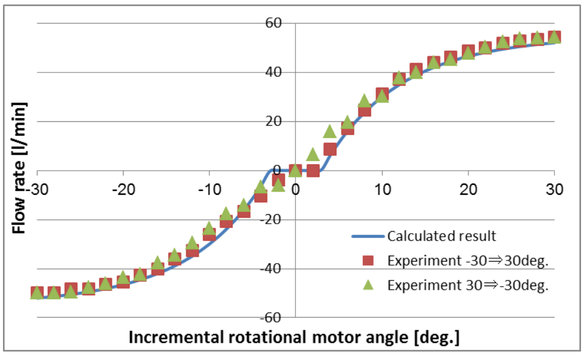

Figure 6. Relation between buckled angle and mass flow rate

V. Conclusions

This study can be summarized as follows. The analytical model of the servo valve using buckled tube is proposed. As an identification of system parameters, the relation between restoration torque and opening area with respect to the buckling angle of the tube are investigated. The empirical formulas of these relations can be obtained.

Finally, by comparing the experimental and calculated relationship between the motor rotational angle and output flow rate of the valve, it can be concluded that the proposed model was valid to estimate the static characteristics by changing the design parameter of the valve. As our future works, a theoretical analysis of valve dynamics for optimal design and an investigation of value body for practical use will be performed.

ACKNOWLEDGMENT

Finally, we express thanks that this work was supported in part by MEXT in Japan through a QOL Innovative Research Program (2012-) and Grant-in-Aid for Scientific Research (C) (Subject No. 24560315).

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