Development of 6DOF Force Feedback System with Pneumatic Parallel Mechanism

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Abstract: In this paper, it is presented the development of a new type force feedback system. It is based on a 6-DOF Stewart parallel mechanism[1] which has six pneumatic actuated cylinders. The thrust force of each cylinder is controlled by PWM control for the solenoid valve and it is actualized by PIC controller. When the pneumatic actuator is controlled, it must be considered the influence on the compressibility of air. For this problem, we guarantee the control characteristics by the effect of the accumulator. It is confirmed that the thrust force of the cylinder can be applied to the pneumatic parallel mechanism, and is presented the experimental result of force control for vertical direction.

Keywords: stewart type parallel mechanism, six degree of freedom, PWM control

I. INTRODUCTION

For the patients afflicted with paralysis, the rehabilitation aid by the physical therapist is necessary. In recent years, the number of the paralyzed patients is increasing due to some reasons, like the adult disease, traffic accident and aging, and the shortage of the physical therapist becomes a new social problem. Thus, it is required the rehabilitation support technology. Corresponding to the patients with various paralysis symptoms, it is necessary for the rehabilitation equipment to support the multiple degree of freedom movement[2] [3].

We note the Stewart type parallel mechanism and consider applying it to the rehabilitation equipment for the wrist or hand paralysis. This mechanism achieves six degree of freedom motion and has two characteristics that are high power and high rigidity. Therefore, it is useful for the wrist or hand rehabilitation equipment. The multiple motion of this mechanism can be achieved by the coordinated telescopic motion of six actuated cylinders. The power source of the cylinder is hydraulic pressure, pneumatic or servomotor. We choose the pneumatic cylinder since this actuator has a flexible characteristics due to the compaction property of the air and therefore it actualizes friendly and soft rehabilitation aid for the patients.

In this paper, it is presented the development of the force feedback system which generates the feedback force through the pneumatic parallel mechanism. This system will be a base technology of the rehabilitation equipment for the wrist or hand paralysis. The pneumatic parallel mechanism is designed by 3DCAD and made a prototype model. Control of the thrust force of each pneumatic cylinder is actualized by PWM control for the solenoid valve. The PIC is used to the controller for the PWM control. When the pneumatic actuator is controlled, it must be considered the influence on the compressibility of air. For this problem, the control characteristics are guaranteed by the effect of the accumulator.

This paper consists of six sections. This section is introduction. Next section shows the configuration of the force feedback system. In 3rd section, the design of the parallel mechanism and the developed prototype model are presented.

The detail of force control of the pneumatic cylinder is denoted in section 4. In section 5, the result of the force control experiment for unit cylinder is presented. And then, for the parallel mechanism which has the six cylinders, the experimental results for vertical direction motion are presented

Ⅱ. SYSTEM CONFIGURATION

Figure 1 shows the configuration of the force feedback system. It mainly consists of the pneumatic parallel mechanism and the personal computer. As shown in Fig.2, there is a gripper on the platform of the pneumatic parallel mechanism and it can be moved in 6-DOF direction by hand. Each cylinders of the parallel mechanism has a position detector detects the cylinder length. The PC calculates the attitude of the parallel mechanism by solving the direct kinematics of the parallel mechanism with the data of each cylinder length. With the calculation result, the PC draws a simple moving object which shows the harmonic motion with the parallel mechanism in the virtual working space on the display.

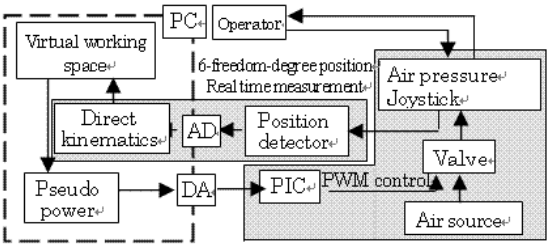


Fig.1. Configuration of force feedback system

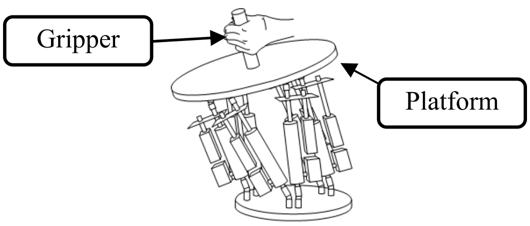


Fig.2: Pneumatic parallel mechanism with gripper on the platform

When the moving object in the virtual space contacts some kind of obstacle as shown in Fig.3, PC calculates the virtual reaction force and sends the control signals to the six PIC controllers, respectively. Each PIC controller controls two solenoid valves on one air cylinder of the parallel mechanism by PWM. The one solenoid valve is used for the pushing force of the cylinder and the other is for the pulling force. The resultant force of six cylinders is equivalent to the virtual reaction force. Then, the operator feels the reaction force generated in the virtual space at his hand.

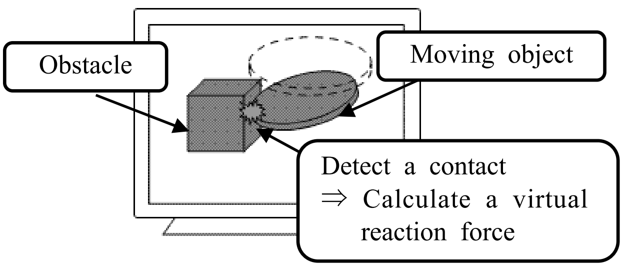


Fig.3: Contact the obstacle in a virtual space

Ⅲ. PROTOTYPE MODEL OF PNEUMATIC PARALLEL MECHANISM

In this section, a prototype model of the pneumatic parallel mechanism for the use of the force feedback system is presented. The left figure in Fig.4 is the 3D CAD design image of the prototype model. This mechanism has 6-DOF motion, namely, translational motion along x-axis (surge motion), y-axis (sway motion) and z-axis (heave motion), and rotational motion about x-axis (roll motion), y-axis (pitch motion) and z-axis (yaw motion). The right figure of Fig.4 is the overall view of the prototype model and Fig.5 is close up of one of the pneumatic cylinders. It has a position detector and two solenoid valves. The bottom end of cylinder is connected to the bottom base by a universal joint. The upper end of cylinder is connected to the platform by a spherical magnetic joint. The reason of using the magnetic joint for upper joint is that if unexpected huge force acts on gripper, the platform uncouples from the upper joints and therefore the destruction of the parallel mechanism is averted.

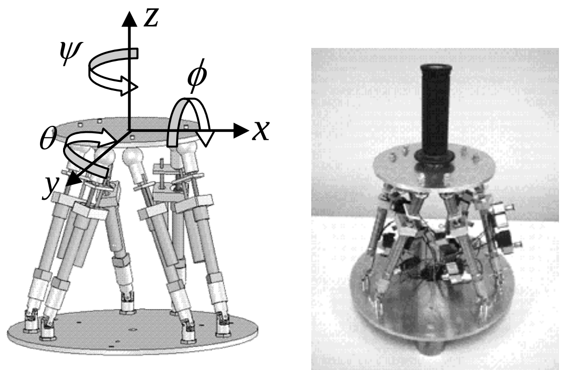


Fig.4: CAD image and overall view of Prototype model

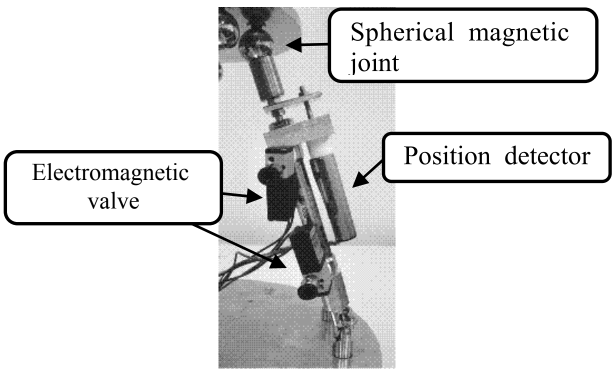


Fig.5: Close up of the pneumatic cylinder

Ⅳ. FORCE CONTROL OF PNEUMATIC CYLINDERS

The force control of each pneumatic cylinder of the prototype model is actualized by regulating the supplied airflow. The airflow is regulated by PWM control for the solenoid valve. As shown in Fig.6, the PWM (Pulse Width Modulation) is a modulation method that is tuning ON time for the pulse wave at a constant cycle by changing the modulation rate. Where, let τ denotes the modulation rate, T denotes one constant cycle and T_{on} denotes ON time in T, τ is described as

$$\tau = \frac{T_{on}}{T}.$$

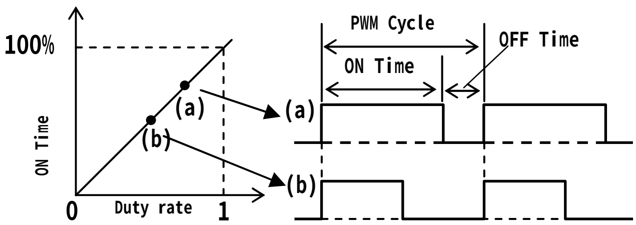
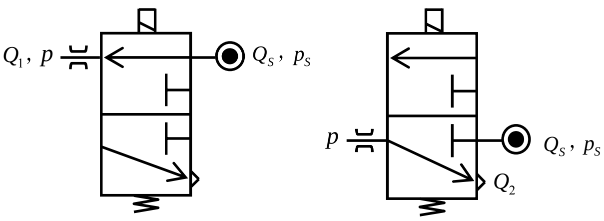


Fig.6: PWM wave and Duty rate

By the PWM signal, opening-closing time of the solenoid valve is tuned, and thereby supplied airflow for pneumatic cylinder is regulated. Figure 7(a) and (b) show turn-on and off of three-way solenoid valve, respectively.



(a) ON (b) OFF

Fig.7: Three way solenoid valve

Figure 8 is the circuit of the force control of the pneumatic cylinders. The duty rate τ decided by PC is converted to analog signal (voltage) through the DA convertor. The analog signal is input into PIC controller. The PIC generates PWM signal and sends it to two solenoid valves. The one valve is used for the pushing force of the cylinder and the other is for the pulling force. The relation between the average control pressure and the modulation rate τ of PWM is written as

$$p = p_s \frac{\tau^2}{\tau^2 + (1-\tau)^2}, \tag{1}$$

where, sign p_s is supply pressure. From Eq. (1), thrust force F of the cylinder is given by

$$F = \eta A p_s \frac{\tau^2}{\tau^2 + (1-\tau)^2} \tag{2}$$

where, A is an area of the pushing side or pulling side of the cylinder, and η is a load factor.

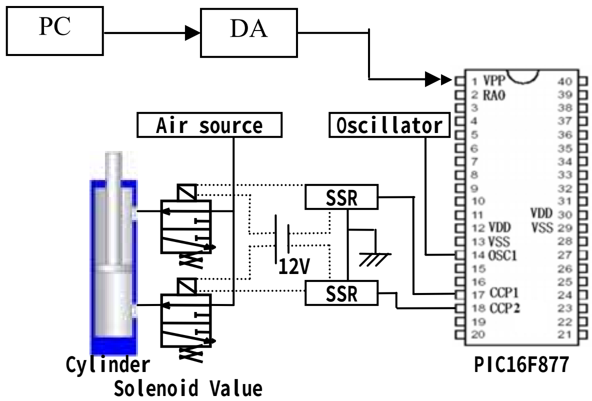


Fig.8: Control Circuit

Ⅴ.EXPERIMENTAL RESULTS

In this section, the experimental results of force control of the prototype of pneumatic parallel mechanism are presented. At first, the average control pressure for the change in the modulation rate τ of PWM is measured. Figure 9 is the overview of the experiment and Fig.10 shows the result where the supply pressure is adjusted to 0.15MPa and the pipe length between the solenoid valve and the manometer sets 50mm.

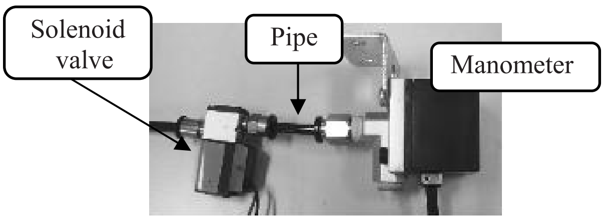


Fig.9: Measurement of air pressure

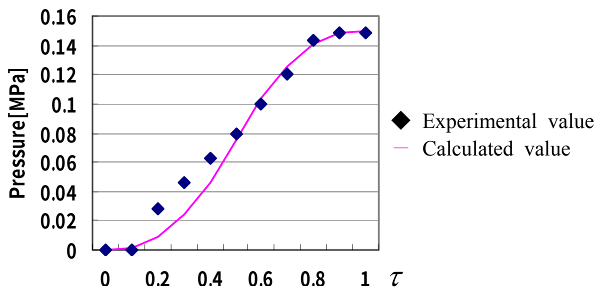


Fig.10: Pressure (pipe length 50mm)

It shows the difference between the measurements and predictions by Eq.(1). For the result, we try to improve the control performance by using the effect of the accumulator. Figure 11 is the result where the pipe length between the solenoid valve and the manometer set 500mm to increase the accumulator. As shown in Fig.11, the control performance is improved, and therefore it was known that when the volume between the solenoid valve and the cylinder is small, the compressibility of air influences the pressure characteristic. And it is understood that the force characteristic is depend on the capacity of the accumulator.

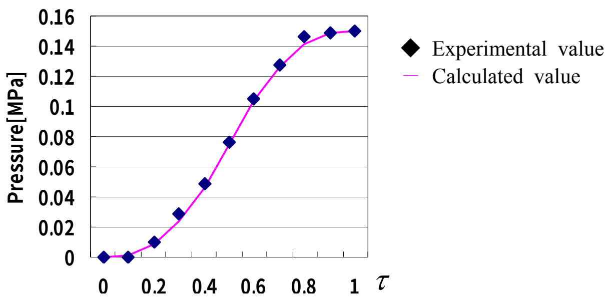


Fig.11: Pressure (pipe length 500mm)

Next, the experimental results of force control of the pneumatic mechanism are shown. Figure.12 is over view of the experiment. The force sensor (0～100N) consists of the strain gauge, and the force in z-direction is measured. The force generation of the parallel mechanism for z-direction is that the same modulation rate is given for solenoid valves of six cylinders.

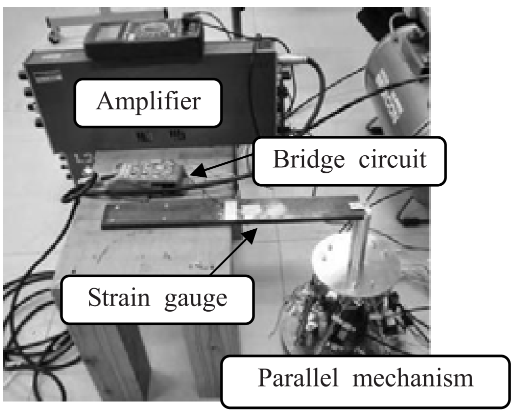


Fig.12: Experiments with the parallel mechanism

Figure 13 shows the results of experiment. Where the posture is adjusted to be neutral position (cylinder expansion and contraction 15mm) and the supply pressure is 0.15Mpa. The calculated value is summation of each thrust force of 6 cylinders in vertical direction obtained thrust from Eq.(2). The prediction agrees well with the measurements, and it is known that z-axis force control is possible. A force of approximate 60N is generated when the supply pressure is 0.15Mpa, and it is understood the enough force experienced by man is generated.

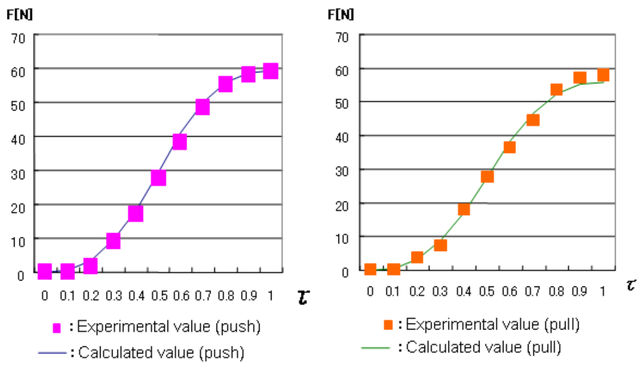


Fig.13: Force control of parallel mechanism

Ⅵ. CONCLUSION

The prototype model of pneumatic parallel mechanism for use of the force feedback system has been developed, and the 6-DOF force control was achieved. The conclusion is shown below.

(1) The compressibility of air can be compensated with accumulator, and the control characteristic of the thrust force of the cylinder has been improved.

(2) The pneumatic 6-DOF parallel mechanism was developed. The push and pull force control in z-axis was evaluated by the experiment, and it was confirmed that the force control by the PWM control was possible.

References

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