DEVELOPMENT OF A HYDRAULIC MASTER-SLAVE SYSTEM FOR TELE-ROBOTICS

HAPTIC DISPLAY DEVICE FOR USAGE OF A HYDRAULIC SERVO-SYSTEM

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In this study, we deal with a bilateral master-slave system for tele-robotics composed of electro-hydraulic servo-systems. In a teleoperated master-slave system, the master has to play two roles, firstly as a reference input device to the slave and secondly as a haptic display device. The term "haptic display" indicates a function by which the operator can feel a force fed back from the slave. In order to produce a haptic display composed of hydraulic servo-systems, we must solve a problem called back-drivability, in which an actuator in a hydraulic servo-system cannot be operated freely by manual means. As a practical solution to this problem, we propose a driving method of actuator that uses a force sensor attached to the actuator. Furthermore, as an application of the haptic display proposed, we construct a bilateral master-slave system composed of electro-hydraulic servo-systems. Experimental results of the manipulating motion of the system are given.

Keywords: Hydraulic Servo-system, Master-slave System, Haptic Display, Tele-robotics

1 INTRODUCTION

In a teleoperated manipulation system, the operator needs not only a visual representation but also a haptic representation of a system existing in a remote place. Those devices of haptic display, at present, have problems, such as insufficiencies in the display functions and complications in their constitutions.

A conceptual illustration of a teleoperated manipulation system for this study is given in Fig. 1. The figure shows that the system is constructed as a master-slave system and that both manipulators

Proc. of 1st FPNI-PhD Symp. Hamburg 2000, pp. 467-474

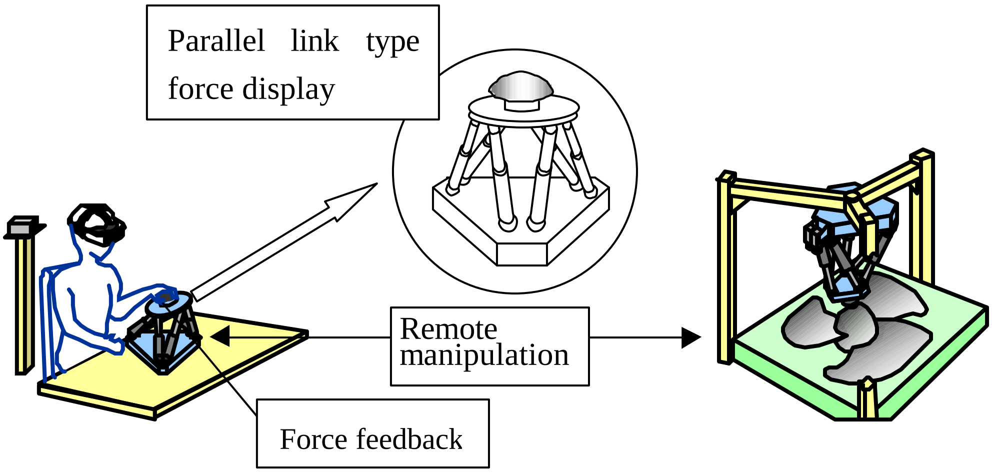


Figure 1: Master-slave system for remote control

for the master and the slave consist of six-DOF parallel link (Stewart Platform) type actuators. Moreover, it is illustrated that a machine tool for grinding is implemented at the end-effecter of the slave manipulator. In a teleoperated master-slave system as shown in Fig. 1, the master has to play two roles, firstly as a reference input device to the slave, and secondly as a haptic display device. Here, the term "haptic display" means a function that allows the operator to feel a force that is fed back to him from the slave.

This research deals with a remote-control system applicable to the machining fields, such as grinding, polishing, assembling, and shaping. In machining works that require high speed, high power, and high rigidity in the operation, the attributes of hydraulic actuators make them suitable for these applications. In this study, therefore, we deal with a master-slave system composed of parallel links by hydraulic cylinders. The parallel links treated here are assumed to be of one-DOF, instead of six-DOF for general use, because we mainly are concerned with developing a new haptic display device.

2 A NEW DRIVING METHOD OF HYDRAULIC SERVO-SYSTEM BY MEANS OF A FORCE SENSOR

In order to produce a haptic display applicable to hydraulic servo-systems, we must solve a problem called back-drivability, in which an actuator in a hydraulic servo-system cannot be operated freely by means of a manual force. The problem is caused mainly by the operating principle of the servo-valve. Due to this problem, the operator has such difficulty that he is unable to drive the system manually, by operating, for example, a cylinder or a servo-valve. As a practical solution to this problem, we propose a driving method of hydraulic servo-system using a manual force. Figure 2 shows a schematic diagram of a system equipped by the proposed method. As seen in the figure, the constitution of the system is almost similar to that of conventional hydraulic servo-systems. A uniqueness of this system is that it has a force sensor (a strain gauge), which is attached through a flat spring at the inertial load of the system. The system can be driven by a manual force in the following manner: first, the operator inputs a command force to the system manually by making contact with the flat spring (hereafter called the operating plate). Subsequently, the command signal detected by the force sensor is sent to the servo amplifier for driving the servo valve. As a consequence, the piston moves to the direction of the input force.

3 EXPERIMENTAL INVESTIGATIONS

3.1 Hydraulic System with Haptic Display

Dealing with the system in Fig. 2, we investigate experimentally the function of the haptic display. In this experiment, a load-force for feeding back to the operator needs to be produced in the system. For this purpose, the system in Fig. 2 was rearranged into the one shown in Fig. 3. In the new system, a spring of stiffness k was set to the cylinder for simulating a load-force. This spring is not actual but virtual, provided by means of a computer program. In the equilibrium state of the system, the mass-load is located at a distance of 10 mm from the spring-end.

The principles of the system's operation are as follows. First, the piston starts to move by getting an operating-force F_{op} from the operator, and soon it contacts the virtual spring after stroking 10 mm.

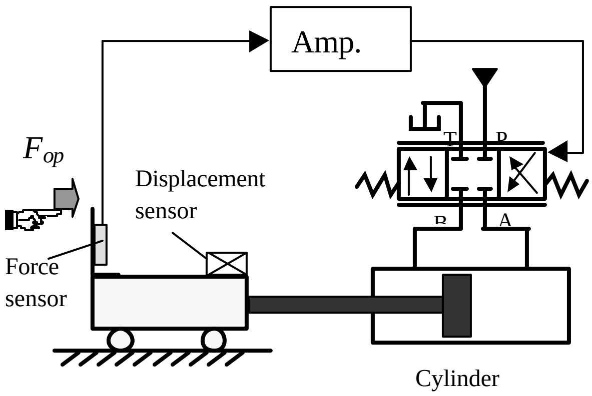


Figure 2: Hydraulic servo system

(Driving method by manual force)

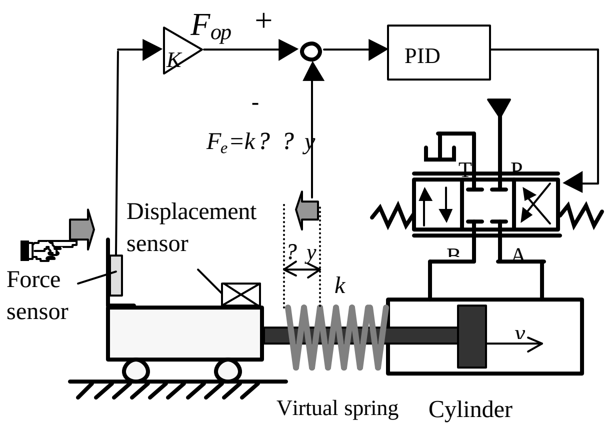


Figure 3: Hydraulic force-display

Subsequently, a further stroke of Δy brings about a reaction force $F_e (= k\Delta y)$. Therefore, by controlling F_e so as to follow F_{op} in the control system, the operator can feel the reaction force of the virtual spring. As for the control algorithm for the controller, we adopted a PID controller. Experiments were performed under these conditions: 1 ms sampling rate, 3.5 MPa supply pressure.

Figure 4 (a), (b) show two results of experiments for investigating a function of the force display, where the stiffness k of the virtual spring was set at k=4 [kN/m] in Fig. 4(a) and k=0.4 [kN/m] in Fig. 4(b). In the figures, time responses of both reaction force F_e and operating force F_{op} are indicated together with that of the displacement of piston y. The result in Fig. 4(a) shows that the piston is harder to move beyond the position y=10 mm by the influence of a strong reaction force of stiffness k. Accordingly, in this experiment the operator was able to feel as if he had contacted a hard spring. On the other hand, the result in Fig. 4(b) shows that the piston can move easily beyond y=10 mm as a consequence of a soft reaction force of stiffness k. In this experiment, the operator was able to feel as if he had contacted a soft spring.

As a result, it was verified experimentally that the one-DOF hydraulic system developed in this study was useful as a haptic display.

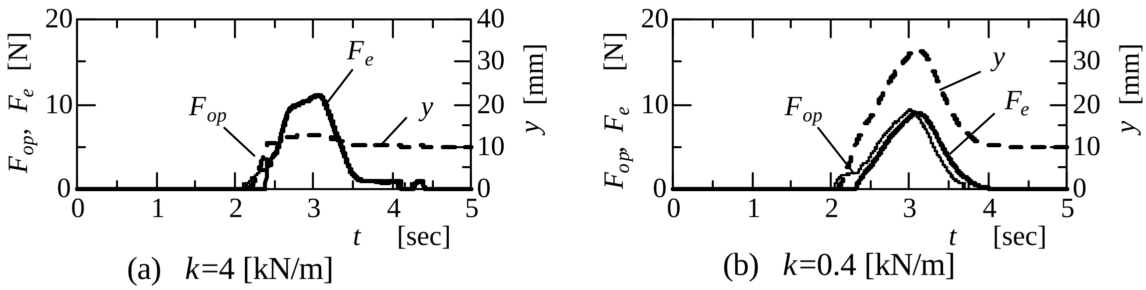


Figure 4: Experimental result of hydraulic force-display

3.2 Master-slave Hydraulic System with Haptic Display

To realize a teleoperated manipulation system as shown in Fig. 1, it is necessary to constitute a master-slave system, in which the master and the slave correspond, respectively, to a haptic display and an actuating manipulator. In this section we therefore discuss a master-slave hydraulic system equipped with the new haptic display proposed.

3.2.1 System Constitution

In Fig. 5, a schematic diagram of the experimental apparatus for the present study is shown. The total system consists of a master system and a slave system. The operator's force F_{op}, detected by a force sensor, is sent to the computer in order to actuate a master-side piston. In the slave system, a spring of stiffness k is attached at a frame of apparatus for simulating a load-force of operation. To detect the load-force, a force sensor is set at the inertial load through a plate spring. Two displacements of pistons in master and slave x_m, x_s, and two forces $F_{op}(=F_m), F_s$ are detected by each sensor and then sent to the computer. Subsequently, two control inputs u_m and u_s for actuating the master and the slave are calculated in the computer, according to a bilateral algorithm. For an algorithm of each controller for the master and slave, a proportional control algorithm was adopted. The sampling time was chosen to be 1 ms. In the experiment, two kinds of stiffness k, that is k=0.4 and 1 [kN/m], were tested. With respect to servo-valves and cylinders for constructing two servo-systems in the master and the slave, different types were adopted intentionally between the two systems. Namely, the master-slave system was tested in the experiment for a system with rather different dynamic characteristics between the master and the slave.

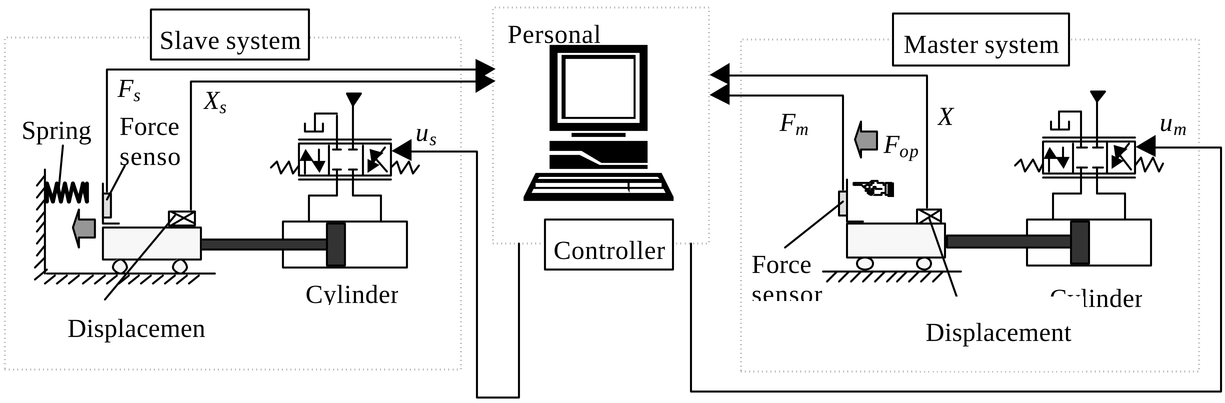


Figure 5: Diagram of experimental apparatus

3.2.2 Construction of master-slave type hydraulic system

We adopt here a bilateral control methodology for controlling the master-slave system. Concerning system constitutions for bilateral control, the following four types are well known as representative ones:

- (a) Symmetric position servo type
- (b) Force reflection type
- (c) Force reflecting servo type
- (d) Parallel control type.

Figs. 6 (a) to (d), respectively, show the block diagrams for those four types. In contrast to these types, an improved parallel control is shown in Fig. 6(e). We adopted the improved parallel control in this study as a suitable one for master-slave hydraulic systems, modifying slightly the symmetric and displacement feedback type proposed by Sato. This type can also be conceived as a simple modification of the parallel type (d). That is, the system is modified by adding a feedback loop of the displacement error between the master and the slave to the slave system. The purpose of the modification is to impose a good adaptability to a master-slave system with different dynamics between the master and slave. As a result of the modification, it is expected that the slave system can be controlled in good agreement with the reference input from the master.

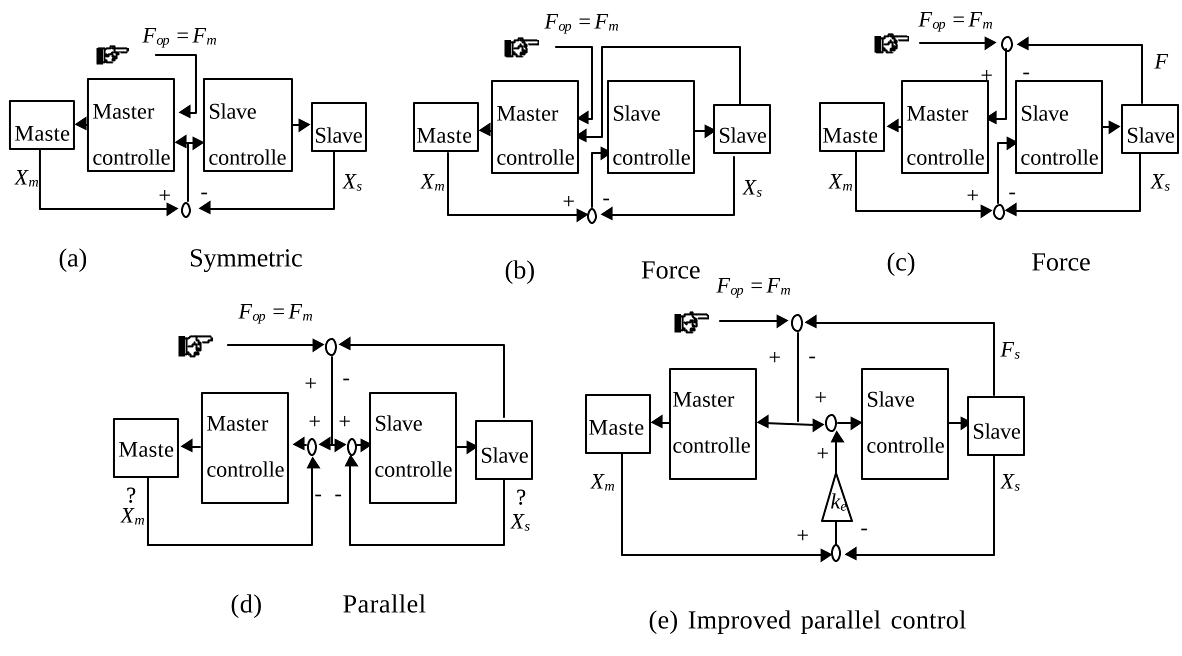


Figure 6: Bilateral control methods applied for hydraulic force-display

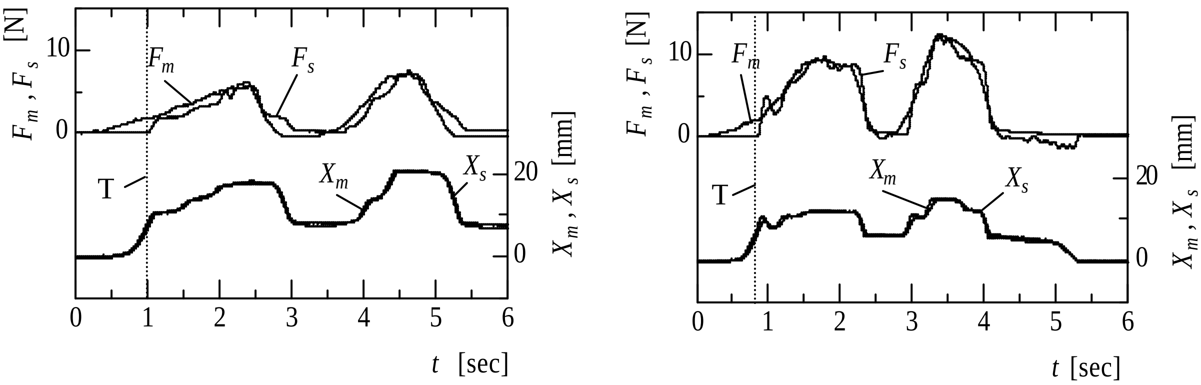
3.2.3 Experimental Results

In the master-slave system shown in Fig. 5, we adopt two types of bilateral controls, that is, a force reflecting servo type and an improved parallel control method. By comparing the haptic functions between two types of systems, we investigate experimentally the applicability of the proposed system. In the experiment, time responses of two forces F_m and F_s were measured together with those of two displacements X_m and X_s.

First, response curves for the force reflecting servo system are shown in Figs. 7 (a) and (b). These figures correspond, respectively, to the results for the soft spring (*k*=0.4 [kN/m]) and the hard spring (*k*=1 [kN/m]). Observing Fig. 7(a), we see that the slave force F_s is detected almost at the instant that the slave touches the spring, (that instant is denoted in the figure by the T mark). Subsequently, the force F_s is controlled in good agreement with the master force

F_m as seen in the figure. In this experiment, the operator was able to feel a softness of spring through the sensing function of the haptic display. On the other hand, Fig. 7(b) shows that the response curve of F_s is accompanied by a tendency toward vibration. The vibration appears from the instant that the slave touches at the spring. In addition, the tendency of such a vibration affects the wave forms of displacements X_m and X_s. In this experiment, it was difficult to control the system stably.

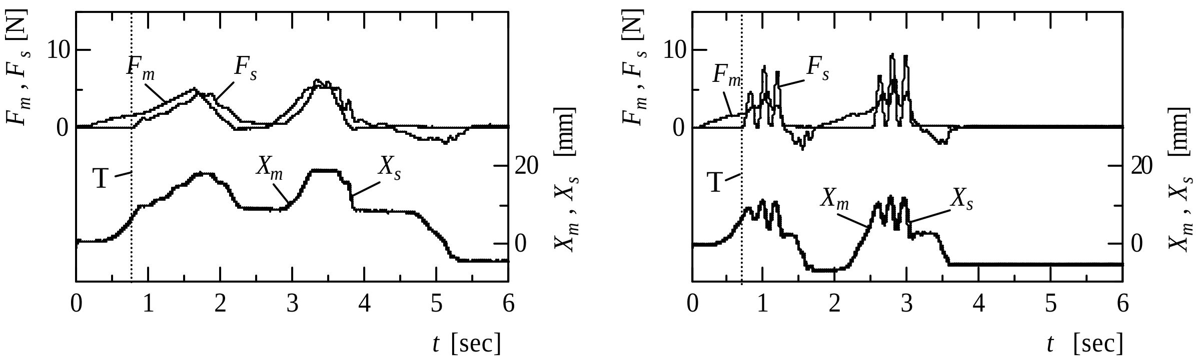
Secondly, the same kinds of results as seen in Fig. 7 are shown in Figs. 8 (a) and (b) as a result of the improved parallel control. Comparing Fig. 8(a) with Fig. 7(a), we see that both results coincide well with each other. The operator in this experiment was able to feel a softness of spring as in the previous experiment in Fig. 7(a). Furthermore, the result for the hard spring in Fig. 8(b) is



(a) Soft spring (k=0.4 (b) Hard spring (k=1 [kN/m])

Figure 7: Experimental results of force reflecting servo type

improved distinctly compared with the result in Fig. 7(b). The system was kept stable in this experiment under various system conditions. As a result, the operator was able to feel a hardness of spring. Correspondingly, it is observed in Fig. 8(b) that the amount of piston displacement is smaller than that in Fig. 8(a), in spite of the fact that a larger force than that in (a) is given to the system.



(a) Soft spring (k=0.4 [kN/m]) (b) Hard spring (k=1

Figure 8: Experimental results of improved parallel control method

4 CONCLUSIONS

In the first place, for the use of hydraulic servo-systems, we proposed in this study a haptic-display device. The function of the haptic display in this device is generated in terms of a control algorithm through a force sensor. The proposed device was applied to a one-DOF hydraulic system and tested to confirm its applicability. It was verified in the experiment that the operator of the system was able to drive a piston manually with ease. Furthermore, the operator was able to feel sensitively the reaction forces caused by virtual load-springs.

In the second place, we constituted and investigated a master-slave hydraulic system equipped with the haptic display proposed, taking into consideration an application to tele-robotics. As a method for controlling the system, we adopted an improved parallel control algorithm. By adopting the algorithm, it was confirmed that the system was controlled with good dynamic performance and that an operator of the system was able to feel sensitively the load forces caused in the working environment.

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