Simulation Research on Hydraulic Stewart Force Feedback Master-Slave System

Hou Jingwei, Zhao Dingxuan, Zhao Ying, Cui Yuxin
College of Mechanics Science and Engineering
Jilin University,
Changchun, China
e-mail: houjw@jlu.edu.cn

***Abstract*— a virtual prototype program of hydraulic Stewart force feedback master-slave system is developed to solve the modeling problems when plant developing and controller design. The following work is done based on the Stewart manipulator simulation program built in Matlab/SimMechanics platform: 1. Master/slave force feedback control framework is built based on the relationship between force on cylinders and upper platform.; 2. A new Stewart platform with load force model on the upper platform hydraulic servo system is built as the slave hand. The validity of the functions is verified by simulation experiment.**

Keywords- Numerical simulation; Hydraulic servo-system; Stewart platform; force feedback; Master-slave control;

I. INTRODUCTION

The model-based virtual prototype for machine production and control system design is a new research field rises with the development of computer technology in recent years. As the virtual prototype may provide accurately dynamics simulation with CAD modeling so it has been widely used in many large companies [1]. Boeing Company, USA is the first to take advantage of virtual prototyping technology applied to manufacturing of aircraft. NASA applies virtual prototyping technology to simulate the force and movement of the rocket in the Martian environment to successfully complete the development of the Mars probe [2].

In the field of parallel robot, the application of virtual prototyping technology may eliminates the need for manufacturing a real physical prototype, which greatly shorten the development cycle and reduce the costs for design work. YOU Shi-ming [3] created a 6-SPS parallel robot virtual prototype model by the ADAMS tool. With the kinematics simulation analysis in the virtual prototype, important theoretical references are provided for the optimization of the structure design and control system development. Wang etc. designed a virtual prototyping for a 6-SPS parallel robot by Matlab Simulink and SimMechanics[4].

In 2000, Kudomi, Muto etc. [5] established a hydraulic driven Stewart-type master-slave force feedback system. Both the master hand and the slave hand of the system are Stewart parallel mechanisms. In the system, the operator operates a grinding robot by master-slave control to avoid the operator to work in the full location harmful dust. To improve the system's load performance, our group in Jilin University has done many work [6,7] to improve the designation. A matlab/Simmechanics program is developed to simulate the master hand in paper [8]. Here in this paper, the master-slave system is all simulated and two problems are mainly focused on: 1. to simulate the master-slave control framework in virtual prototype as is used in actual system. 2. To simulate the environment force which is set on the slave hand.

In this paper, we introduced the master-slave system in Section 2, and then the simulation program was introduced in Section 3; we did an experiment to test its function and validity in Section 4.

II. THE HYDRAULIC STEWART MASTER-SLAVE SYSTEM

A. *The hydraulic Stewart master-slave system*

The hydraulic Stewart master-slave system is shown in Figure 1. it is mainly composed of two parts：the master site shown in the left figure is a hydraulic Stewart force display operated by the operator and the slave site shown in the right figure is a hydraulic Stewart platform equipped with a grinding tool (M11GA, Minitor CO.LTD) to perform tasks at the work spot. As a force display, the master hand has the same shape of the slave hand, which is characterized by the need to accurately feel the force from the operator through a six-dimensional force sensor on its upper platform and to be able to provide displacement as a reference of the slave platform. The slave hand is used for grinding work so the platform should provide a larger carrying capacity of the completion of the grinding work. So six linear force sensors are mounted on the hydraulic cylinders to sense the rod force, and finally the six-dimensional force on the platform and working environment interact is got by the method of force compose.

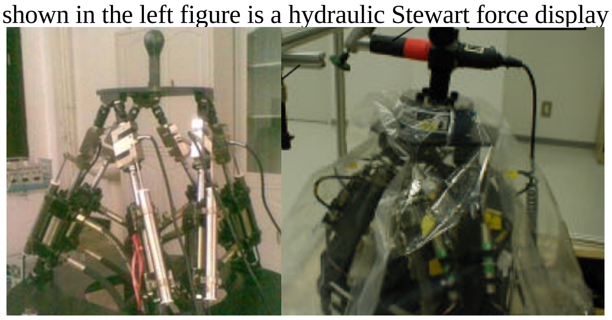

Figure 1. The hydraulic Stewart manipulator

B. The master-slave algorithm

Ability to the platform of free movement is the first issues to consider. So a bilateral servo strategy which has good operational performance is applied, as is shown in Figure 2. The main manipulator is used as the force input device. Due to the friction of the piston, it is difficult for the operator to move it depending on his force. So the force Fm, which is applied by the operator to the master hand, is detected by force sensor to drive the movement of the force display. Meanwhile, the master hand needs to display the reaction force that applied to the hand manipulator by the work object. The manipulator of the master hand should be driven according to the calculation data of the result of $K \times (F_m + S \times F_s)$. K is a constant rate.

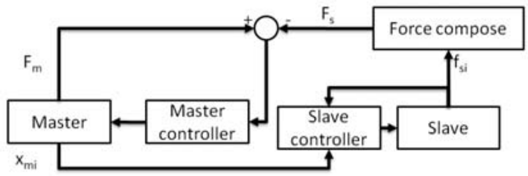

Figure 2. the master-slave algorithm

When the master hand moves, the slave hand tracks the movement of the master hand through the position information that is feedback from the master side. When the slave hand is unload, F_s is small, it is mainly the force composition of inertial force, Coriolis force and coupling force joint force. When the upper platform encounters resistance imposed by the job object, the driving forces of each link become obviously, the composition of forces is the composition of all the forces and will be send to the master side as feedback force.

III. THE SIMULATION PROGRAM

The virtual prototype is design mainly for two purposes: 1. to avoid damage in the hardware environment when designing the force feedback controller. 2. As the slave part is complex, to design prototype directly may prone to high cost and error. Since the current master and slave site are near, so the research is mainly focused on the impact of the master and slave hand, and the time delay that often talked in many papers will not be included.

A. The component of the simulation program

The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

Based on the master-slave system and the control algorithm in the second part, we developed a simulation program by matlab/SimMechanics, as is shown in Figure 3. The system consists of four parts –Operator simulator, Trace generator, trace generator, master controller, Master plant, slave controller, slave plant, inverse dynamic calculator and force composer.

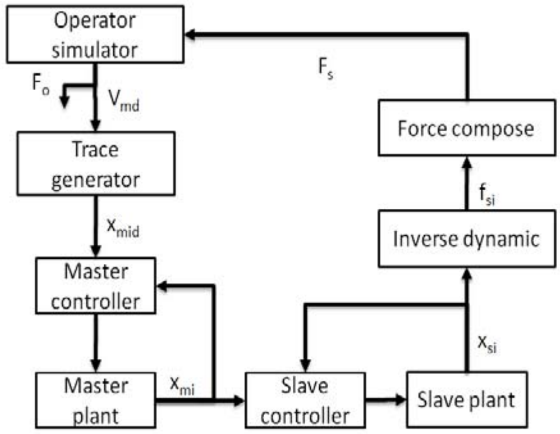

Figure 3. the simulation system

First, in the Operator Simulator part, according to the operator’s intention and the force on the slave upper platform Fs, the expected platform trajectory Vmd is generated and be input to the trace generator. Then the expected displacements of each connecting rod of the master hand xmid (i=1~6) is generated in Trace generator. In the master controller, a PID controller is designed to complete the close-loop control for the master hand according to xmid and the actual displacements xmi which is fed back from the virtual prototype. xmid is input to the slave controller, the slave controller includes a PID controller which is designed according to xmid and the actual displacement of the slave hand prototype to follow the trajectory of the master hand. At the same time, the synthesized force of the link forces are feedback to the master hand as the environment force. The system uses a serial method in which the slave hand follows the motion of the master hand, rather than sent the Vmd directly to the master hand and the slave hand (the method called a parallel method), the main purpose is to avoid the error accumulation of displacement between the two sites.

The prototype control system framework inherited the real system’s framework to make the slave hand to follow the master hand’s movement. The desired trajectory of the main hand is generated based on the operator’s intension and the effect that the slave force applied to the operator.

B. Mathematics model of the hydraulic system

To simulate the dynamical system of the servo valve controlled hydraulic cylinder, the following mathematics model is built and realized by matlab/simulink. The equation of motion of the servo valve is given by Eq. (1).

$$i = k_a u$$
$$\frac{d^2 x}{d t^2} + 2\zeta\omega_n \frac{d x}{d t} + \omega_n^2 x = k_v \omega_n^2 i \qquad (1)$$

The equation of motion of the piston is given by Eq. (2).

$$\left.\begin{aligned} m\ddot{y}_s + b\dot{y}_s &= a_p p_L \\ p_L &= p_a - p_b \end{aligned}\right\} \quad (2)$$

The relations for flow rate qL are given by Eqs. (3) and (4).

$$q_L = k_x x - k_p p_L \quad (3)$$

$$q_L = a_p \dot{y}_s \quad (4)$$

The parameters are as the following:

a_p : cross-sectional area of piston [m^2]
a_{pa},a_{pb}: area of piston [m^2]
b : Viscous damping coefficient of piston [Ns/m]
k_a : Gain of servo amplifier [mA/V]
k_x , k_p: Flow rate gain, pressure gain [m^2/s], [m^4/kg]
k_v : Gain of servo valve [m/mA]
m_u : Mass of upper platform [kg]
m_p : Mass of piston [kg]
m_c : Mass of cylinder [kg]
p_a , p_b:Pressures in piston chambers [Pa]
q_L ,p_L: Flow rate, load pressure [m3/s],[Pa]
T : Gain [-]
u : Control input [V]
x : Displacement of spool [m]
ζ : Damping ratio [-]
ω_n : Natural angular frequency [rad/s]

Consequently the mathematical model of the slave system is represented by Eq. (1) to Eq. (4). With a Laplace transform, the equations can be expressed as Transfer Fun components in the Simulink library. The hydraulic subsystem is shown in Figure 4.

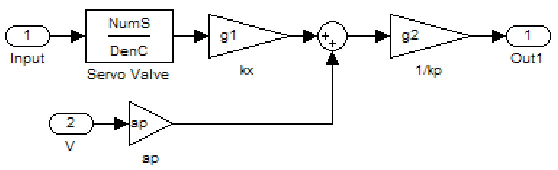

Figure 4. The hydraulic subsystem

In order to simulate the load force on the upper platform of the slave hand, a load force system by SimMechanics which consists of a connecting rod, a judgment device, and the grinding force model is developed. One end of the connecting rod is fixed on a prismatic block by a universal joint; another end is on the upper platform. As the grinding force generally includes only the tangential force and the normal force from two directions, the load force can be generated by adjusting the positions of the ends and the force input to the cylindrical block. Figure 5 shows the load force generator, the left figure is the in program, and the right figure shows the convex hull figure by simMechanics.

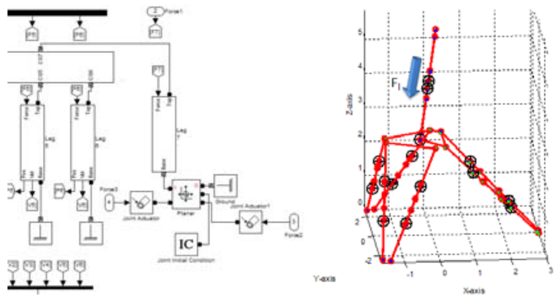

Figure 5. environment force generator

We used a simplified dynamic model for cylindrical grinding, which is calculated based on applied power. U is the Specific grinding energy, Z is the grinding rate, and grinding power is

$$P = UZ \quad (5)$$

The radial grinding force F_a is 0, the tangential grinding force is

$$F_t = \frac{P}{V_s} \quad (6)$$

Vs is grinding speed, the normal grinding force is

$$F_n = kF_t \quad (7)$$

k is the ratio of F_n and F_t.

IV. SIMULATION EXPERIMENT

To test the functions including motion following, force feedback and dynamic character of the program. We did an experiment to compare between the force results of every cylinder by calculating manually and those from the program when the upper plate is at three different positions and orientations.

The parameters used in the program are shown in Table 1.

TABLE I. THE PARAMETERS IN THE SIMULATION PROGRAM

$k_a = 1.0mA/V$	$k_v = 0.144\times10^{-3}mA/V$
$\omega_n = 354rad/s$	$\zeta = 0.1$
$w = 4.8\times10^{-3}m$	$m_c = 80.1kg$
$b = 44.3Ns/m$	$m_u = 173.2kg$
$m_p = 124.3kg$	$k_p = 5.09\times10^{-3}m^4s/kg$
$k_x = 3.03\times10^{-6}m^2/s$	$a_{pb} = 0.76\times10^{-5}m^2$
$a_{pa} = 1.26\times10^{-5}m^2$	

The following experiment is done: The master hand is set to move at the trajectory of

$$\begin{cases} x = 0.5\sin(t+\pi/2) \\ z = 3 \\ y = 0 \end{cases} \quad (8)$$

And the grinding process will begin when the x position of slave hand x>0.1.

The result is shown in Figure 6, the (1)~(6) are the forces and torques on x,y,z directions, The (7) shows all the forces on the legs, and (8) is the x position of the master and slave hand's upper platform. The deep line is the master hand's and the light line is the slave hand's.

In the results, the area between a and b are force free time, the slave hand moves without the load force, and the feedback force is the composition of inertia force and Coriolis force. At this time, the operator feels only small force. As the slave platform is moving at the speed of triangle functions, the feedback force are similar to triangle functions, as is shown in (7).

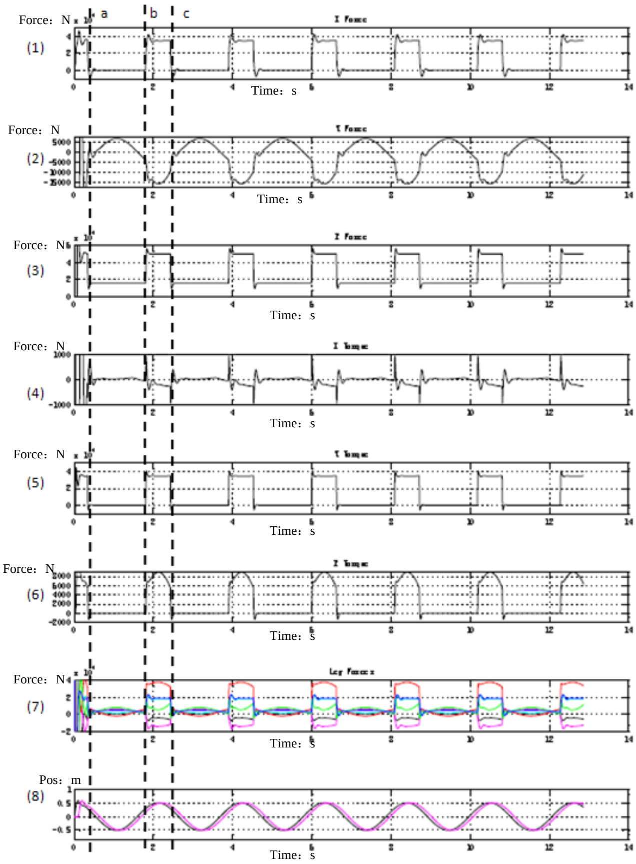

Figure 6. Force calculation experiment result in scope

In the area between b and c, the grinding begins, the upper platform are affected by the tangential force from x direction and the normal force from z direction. Because of the coupling force of the parallel machinery and the forces from cylinders, the operator may feel small forces and torques from other directions. These are very small compare to the x force z force and y torque.

From the result, we can see that the motion following function was realized even when the slave hand work with load force, and the feedback force decrypts the force on the upper framework accurately. We can see the functions on simulating the master –slave framework and the dynamical system with hydraulic servo system and load force generator are realized very well.

V. Conclusions

A simulation program for virtual prototype of hydraulic Stewart force feedback master-slave system is developed for control strategy design. In this paper, based on the achievements of Stewart research, we developed a master-slave system and did experiments to test the validity of the simulation results and the performance on calculating the work state of the motion simulator during work process. The result shows that simulate master-slave system program is validate and the program can be used widely for the research work on hydraulic Stewart platform.

Acknowledgment

This work was financially supported by the Jilin University basic scientific research expenses (450060481048, 450060481333) GFY101000068.

References

[1] LI Zheng-wen ZHANG Guo-liang ZHANG Wei-ping JIN Bin.A Simulation Platform Design of Humanoid Robot Based on SimMechanics and VRML. Procedia Engineering Vol.15 (2011),p.215 – 219.

[2] DU Ping-an YU De-jiang YUE Ping. Research on Technology and Methodology Architecture of Virtual Prototyping Technology. JOURNAL OF SYSTEM SIMULATION . Vol.19(2007): p.3447-3451.

[3] YOU Shi-ming, CHEN Si-zhong, LIANG He-ming.Kinematics and Dynamics Simulation of PMT Based On ADAMS. Computer Simulation, Vol.22 (2005), p.181-185.

[4] Huang Qitao, Han Junwei He Jing feng. Dynamics Modeling of a Six-degree-of-freedom Parallel Platform and its Analysis. Mechanical Science And Technology. Vol. 25(2006)4 p.382-385.

[5] S. Kudomi, H. Yamada, T. Muto. Development of a hydraulic parallel link type of force display, Proc. 5th JHPS Inter. Symp. on Fluid Power. (2002) p.471-476,.

[6] Chen Tiehua, Zhao Dingxuan, Zhang Zhuxin. Design of Master-slave Manipulators System and Bilateral Servo Control Strategy. Transactions of the Chinese Society for Agricultural Machinery. Vol.12 (2008) p.141-145.

[7] Hou Jingwei Zhao Dingxuan Gong Mingde.Strategy-switching Control for Hydraulic Force Bilateral Servo System when Catching Objects.Transactions of the Chinese Society for Agricultural Machinery, Vol.43 (2012): p.190-194.

[8] Hou Jingwei, Zhao Dingxuan Numerial research on Numerical Simulation Research on Hydraulic Stewart Force Feedback Manipulator.ICACMVE2011, Shanghai 2011, p.5-9.