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DEVELOPMENT OF AGRICULTURAL HYDRAULIC ROBOT (Part I)
- Dynamic Characteristics and System Identification -

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ABSTRACT

We have developed an agricultural hydraulic robot to operate in the agricultural field. Using the robot, automatic harvesting experiments of watermelon were done. The results are as follows. First, the gripper should be modified its finger. Second, the manipulator and the gripper should be known precisely about dynamic characteristics of them in order to control adequately. Therefore, a new gripper was manufactured on trial by modifying its finger, and in order to know dynamic characteristics of the manipulator and the new gripper, the system identification was carried out with experiments.

INTRODUCTION

The population of farmer shows a decrease year by year and the advanced age increases. As the solution to these problems, it is effective to improve the production capacity of the agriculture by the agricultural robot with the higher control system and the intelligence. Therefore, we have developed the agricultural robot.

Comparing the industrial robot with the agricultural one, the industrial robot requires the higher controllability, the higher accuracy and the lower cost of maintenance. For these reason, the industrial robot is driven by the electric power. But the robot driven by the electric power has the low power/weight ratio, and it is difficult to supply the electric power stably in the agricultural field. On the other hand, the agricultural robot requires the high power and the stable power supply in order to practice hard labors, and the ability of traveling in the field. The robot driven by the hydraulic actuator has the high power/weight ratio, and it is easy to supply the robot with the stable power in the field. As the traveling equipment can use the same hydraulic system as the manipulator, the hydraulic robot has the advantages of combining the ability of traveling. For reasons mentioned above, we have employed the hydraulic actuator as the agricultural robot(Fig. 1).

This robot consists of a manipulator, a gripper, a traveling equipment and miscellaneous elements. Using this robot, the automatic harvesting experiments of watermelon as the heavy vegetable were done in order to investigate functions required as the agricultural robot. It was clarified that the manipulator should be improved on the operational speed and the shock at stopping, and that the gripper should be improved on the finger stiffness, the grasping force and positioning. To solve these problem, it was necessary to modify the finger of the gripper, and to know precisely the dynamic characteristics of the manipulator and the gripper in order to improve on the control method.

This study is described first about the manufactured robot on trial machine, and second about dynamic characteristics of the manipulator and the new gripper with the analysis of dynamics and the parameter identification.

ROBOT FOR EXPERIMENT

1. Manipulator

Figure 2 shows the dimension and the configuration of the hydraulic manipulator. The dimension of the manipulator is determined in order to operate in the same motion space as a manual operation. Rotational joints are used on all joints because of the wide application to various agricultural operations. The manipulator has 5 degrees of freedom, corresponding to a waist, a shoulder, an elbow and two wrists. Linkages of the robot are made out of the aluminum alloy in order to be lighter. For the purpose of the higher stiffness, the structure of the link is the hollow box. The mass of the manipulator is about 95kg. The lifting force at the end of the manipulator is more than 200N in order to handle fertilizer baggage and the heavy vegetable.

The hydraulic cylinders are employed at the joint 1, 2, 3 and 5, and a rotary actuator at the joint 4. The hydraulic motor is not employed, because it rotates fast at low torque and requires the transmission to the joints : It would result in increase of the mass and the size, and in inaccuracy caused by the backlash.

As the force of these actuators is enough to drive the joint directly without the transmission, the robot becomes more compact and lighter. Table 1 shows the driving method and the operation of each joint. If a cylinder should be used for driving the joint 2, it will become an obstacle in the motion area. So the joint 2 is driven by two cylinders. As for the joint 3, the side of a larger pressure area of the cylinder is arranged in the direction to lift up the link, the parallel linkages are employed.

2. Gripper

The former gripper is manufactured on trial to harvest a watermelon as a heavy vegetable. Figure 3 shows the outline of the gripper. It consists of four fingers, four pads, four wires and four springs, and is driven by a hydraulic cylinder. The fingers open by spring forces when the cylinder pushes four wires together, and close when it pulls them. Four Pads made of the pneumatic rubber ball are installed at the end of each finger in order to relieve the grasping shock, to reduce the contact pressure and to absorb the misalignment between fingers and fruit. Pads are connected by vinyl tubes so that the inner pressures of them can be kept the same pressure during grasping. This gripper is fixed at end of the manipulator, and harvesting experiments of watermelon are done. On the basis of results, a new model is manufactured on trial by modifying the fingers.

The new gripper is shown in Figure 4. It consists of 4 fingers made by the aluminum alloy. The finger shape is thin, and the silicone rubber is pasted on the part of each finger contacting with watermelon to relieve the grasping shock. The new model becomes lighter than the former one. Although the new gripper is driven in the same ways as the former one, the wiring of pull wires is improved to increase the grasping force. In addition to the improvement, the suspension mechanism is devised at the part connecting the gripper with the manipulator in order to absorb the shock and the misalignment at grasping watermelon.

3. ELECTRIC AND HYDRAULIC SYSTEM

The hydraulic circuit for the manipulator and the gripper is shown in figure 5. A hydraulic pressure-compensated pump is used, and its pressure is 3.5MPa. The cylinders installed at the joint 1, 2, and 3 of the manipulator are controlled by servo valves, and other actuators by proportional valves. The servo valve is driven by a solenoid, and is controlled by a signal voltage input. In order to control the flow rate in proportion to the signal voltage input, the position of spool is detected by L.V.D.T.(Linear Variable Differential Transformer), and the feedback control is employed to keep the aperture of the spool constantly. The signal voltage input is between -5V and 5V, and when its signal is 0V, the flow rate is zero. The sign of the signal voltage input determines the direction of the flow. The proportional valve is driven by two solenoid, and the position of the spool is not detected. The signal voltage input is between 0 and 5V, the direction of the flow is determined by the selection of the solenoid which should be driven.

The signal flow for control of the manipulator and the gripper is shown in figure 6. The whole control is done by a personal computer with Intel 80386SX. Rotary encoders are used as joint angle sensors. The resolution at each joint is 0.0879 deg./pulse.

DYNAMIC CHARACTERISTICS OF THE ROBOT

1. ANALYSIS

To improve on the control method, the dynamic model of the manipulator should be precisely known. Therefore, an analysis of the manipulator with 2 degrees of freedom, whose joints corresponded with the joint 2 and 3 in figure 2, was done. The 2 D.O.F manipulator is shown in figure 7. The link parameters based on the Denavit-Hartenberg notation are given by plans. In figure 7-a), let m_i, l_{gi} and I_i be the mass , the center of the mass and the inertia tensor matrix for the link i (i=1,2,3,4), respectively. In figure 7-b), let θ_1 and θ_2 be each angular displacement of the joint 2 and 3, respectively. The clockwise direction is taken to be positive.

To begin with, the dynamic equation of this manipulator is as follow.

$$\tau = M(\theta)\ddot{\theta} + h(\theta, \dot{\theta}) + g(\theta) \quad \cdots \text{Eq}(1)$$

where τ, M, h and g represent a joint torque vector(2×1), an inertia tensor(2×2), centrifugal and Coriolis forces(2×1) and a gravity torque vector(2×1), respectively.
Here, In the consideration of a friction force vector ζ at each joint axis Eq(1) can be rewritten as:

$$\tau = M(\theta)\ddot{\theta} + h(\theta, \dot{\theta}) + g(\theta) + \zeta(\dot{\theta}) \quad \cdots \text{Eq}(2)$$

Then, the dynamic characteristics of hydraulic cylinders must be considered. For this purpose, the relation between the hydraulic cylinder and the joint torque must be derived. P_{j1} and P_{j2} are respectively the bottom and the rod side of the pressure in the cylinder j, where j represents number of the joint (j=1, 2). A_{j1} and A_{j2} are the bottom and the rod side of the pressure area in the cylinder j. In consideration with a friction force between the sealing and the piston in the cylinder and the arrangement between the linkage and the cylinder, the joint torque τ_j is given by

$$\tau_1 = G_1(A_{11}P_{11} - A_{12}P_{12} - \eta_1 G_1 \dot{\theta}_1)$$
$$\tau_2 = G_2(A_{21}P_{21} - A_{22}P_{22} - \eta_2 G_2 \dot{\theta}_2) \quad \cdots \text{Eq}(3)$$

where G_j represents a linkage gain defined by the relative position between the linkage and the cylinder j.

Finally, using Eq(2) and Eq(3) can be rewritten as:

$$\tilde{\tau} = [\tilde{\tau}_1, \tilde{\tau}_2]^T$$
$$= \begin{bmatrix} A+B+2D\sin\theta_2 & B+D\sin\theta_2 \\ B+D\sin\theta_2 & B \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}$$
$$+ \begin{bmatrix} D\cos\theta_2 \cdot \dot{\theta}_2^2 + 2D\cos\theta_2 \cdot \dot{\theta}_1 \cdot \dot{\theta}_2 \\ -D\cos\theta_2 \cdot \dot{\theta}_2 \end{bmatrix}$$
$$+ \begin{bmatrix} E\sin\theta_1 - F\cos(\theta_1+\theta_2) \\ -F\cos(\theta_1+\theta_2) \end{bmatrix} \hat{g} + \begin{bmatrix} \zeta_1 \dot{\theta}_1 \\ \zeta_2 \dot{\theta}_2 \end{bmatrix}$$
$$+ \begin{bmatrix} \eta_1 G_1^2 \dot{\theta}_1 \\ \eta_2 G_2^2 \dot{\theta}_2 \end{bmatrix} \quad \cdots \text{Eq}(4)$$

where $\tilde{\tau} = [\tilde{\tau}_1, \tilde{\tau}_2]^T$ is the vector after subtracting the friction force in the cylinder from the joint torque τ, and $\hat{g}$ is the acceleration of gravity.

On identifying system parameters, it is unnecessary to obtain them individually, that is to say, following linear coupling parameters in Eq(4) should be identified.

$$A = m_1 l_{g1}^2 + m_3 l_{g3}^2 + m_4 l_1^2 + I_1 + I_3$$
$$B = m_2 l_{g2}^2 + m_3 l_2^2 + m_4 l_{g4}^2 + I_2 + I_4$$
$$D = m_3 l_2 l_{g3} - m_4 l_1 l_{g4}$$
$$E = m_1 l_{g1} + m_3 l_{g3} + m_4 l_1$$
$$F = m_2 l_{g2} + m_3 l_2 - m_4 l_{g4}$$

These parameters are estimated by the multiple regression.

As for new gripper, the analysis of the dynamic characteristics is also done. As it consists of the same fingers, the dynamic characteristics is analyzed on one finger. The dynamic equation of this gripper is as follow.

$$\tau_f = M_f(\theta_f)\ddot{\theta}_f + g_f(\theta_f) + k_f(\theta_f) + \eta_f(\dot{\theta}_f) \quad \cdots \text{Eq}(5)$$

where τ_f, M_f, g_f, k_f, and η_f represent a joint torque vector, an inertia, a gravity torque, a spring element, and a friction force, respectively. θ_f is the angular displacement of a finger joint. These parameters are estimated in the same method as the manipulator.

2. IDENTIFICATION EXPERIMENT

In the experiment of manipulator, the measuring points were pressures at the bottom and the rod side in cylinders, the acceleration at the end of manipulator and the each joint angular displacement. Experiments were done as follows.

1) Joint 3 only is driven, and joint 2 is fixed.
2) Joint 2 only is driven, and joint 3 is fixed.
3) Both Joint 2 and 3 are driven.

All signal voltage inputs to valves were rectangle waves. That a joint is fixed means that a joint is kept at a certain position by the feedback control. The joint torque was derived from the measured pressure and the pressure area in the cylinder. The joint angular acceleration was derived by dividing the measured acceleration by the length between the moving joint axis and the position of the accelerometer. The joint angular velocity was derived by the integration of the joint angular acceleration. Although the joint angular velocity could be calculated by the differentiation of the joint angular displacement, this method was not employed because of the larger error caused by the low resolution of the encoder.

As for the gripper, first, the strength of a finger was investigated by the load-strain experiment. Concerning the identification of the gripper, measuring points are pressures at the bottom and the rod side in the cylinder, the acceleration of finger, and the joint angular displacement. The signal voltage input to a proportional valve was rectangle waves. The joint torque, the joint angular acceleration, and the joint angular velocity were derived in the same method as the manipulator.

RESULTS AND DISCUSSION

Figure 8 shows as the phase of the signal voltage input, the angular displacement of the joint 3 and the acceleration about experiment 1). Figure 9 shows as the phase of the pressure changes and the angular displacement of the same experiment. It was founded that the joint is driven correctly in response to the signal voltage input. In figure 8, the acceleration at the end of manipulator was seemed to vibrate at the moment when the rotational direction of the joint changed. As shown in figure 9, this vibration was not caused by the spring element, but by the pressure change. It was clarified that the link was driven directly in response to pressure changes. In experiment 2) and 3), we could observe the same phases as experiment 1).

From the measured data, parameters of the manipulator were identified by the multiple regression. Each identified parameter is shown in Table 2. The torque of the joint 3 was calculated in use of these identified parameters, and it was compared with the joint torque calculated from the measured pressures as figure 10. As both of the calculated joint torque were quite similar to each other, it was judged that the identified parameters were valid. As the result of the parameter identification, the friction force at the joint axes of the manipulator did not influence the joint torque, but the friction force between the sealing and the piston did.

Following results was clarified by the experiment on the new gripper. Loading 42N weight on the end of finger, the stress at the weakest point was 2.2MPa. The finger was sufficiently strong. Figure 11 shows as the phase of the signal voltage input, the joint angular displacement, the displacement of the cylinder and the force of the cylinder. From the measured data, parameters of the gripper were identified by the multiple regression. Each identified parameter is shown in Table 3. As the result, the force of the cylinder was enough to drive against the mass and the inertia of the finger, but it was required for the valve to improve on the response to the signal.

CONCLUSIONS

From this study, we have results as follows.

1) Hydraulic manipulator and gripper are adequate for agriculture.
2) The friction force at joint axes of the manipulator can be ignored.
3) The friction force between the sealing and the piston in the cylinder has a influence on the joint torque.
4) Linkages of the manipulator can be regarded as the rigid body without the spring element.
5) The new gripper has higher stiffness and the grasping force.
6) The proportional valve is required to improve on the response to the signal.

REFERENCES

1. K.Namikawa, M.Umeda, M.Iida, and M.Suguri : WATERMELON HARVESTING HYDRAULIC ROBOT, Proc. of JICA-IPB 5THE Joint Seminar as International Conference on Engineering Application for the Development of Agriculture in the Asia and Pacific Region, pp B233-B240 (INDONESIA), October, 15, 1992

Table 1. Driving method and operation of each joint

JOINT	DRIVING METHOD	OPERATION
1	A HYDAULIC CYLINDER AND LINKS	REVOLUTION OF WAIST
2	TWO HYDAULIC CYLINDERS AND LINKS	REVOLUTION OF SHOULDER
3	A HYDAULIC CYLINDER AND LINKS	REVOLUTION OF ELBOW
4	A HYDAULIC ROTARY ACTUATOR	REVOLUTION OF WRIST 1
5	A HYDAULIC CYLINDER AND LINKS	REVOLUTION OF WRIST 2

Table 2. Identified system parameters of manipulator

A	9.1 [kgm^2]	ζ_1	0 [kgm^2/s]
B	5.3 [kgm^2]	ζ_2	0 [kgm^2/s]
D	-13.3 [kgm^2]	η_1	5123.5 [Ns/m]
E	10.2 [kgm]	η_2	1482.9 [Ns/m]
F	-4.9 [kgm]		

Table 3. Identified system parameters of gripper

M_f [$\times 10^{-3} kgm^2$]	g_f [$\times 10^{-1}$ Nm]	k_f [$\times 10^{-1}$ Nm]	η_f [$\times 10^{-2}$ Nms]
5.51	2.67	5.47	1.88

Fig. 1 Hydraulic robot

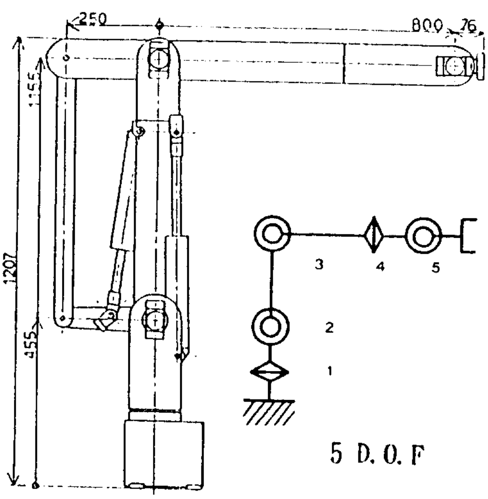


Fig. 2 Schematic diagram of manipulator

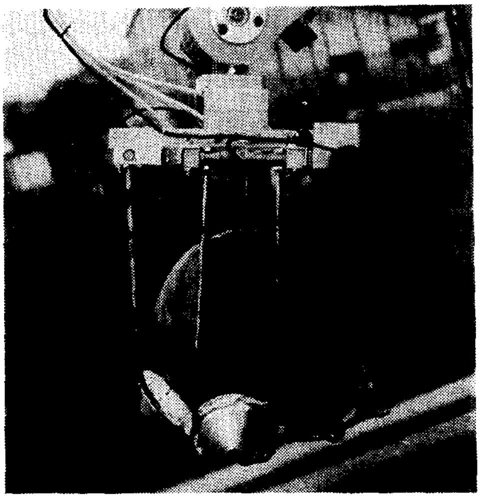


Fig. 3 Former gripper

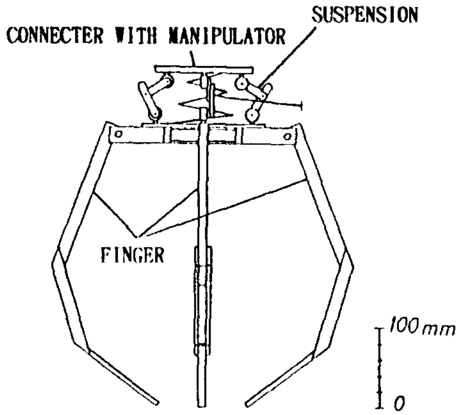


Fig. 4 Schematic diagram of new gripper

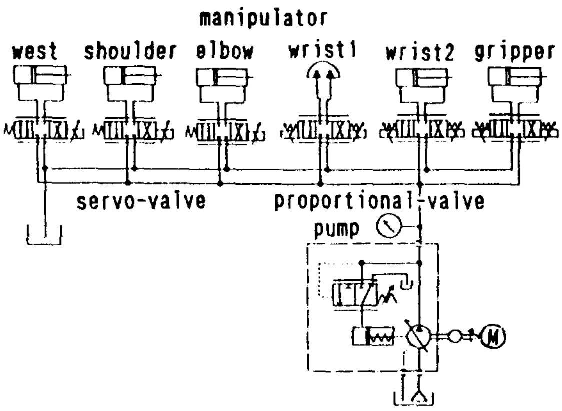


Fig. 5 Hydraulic circuit

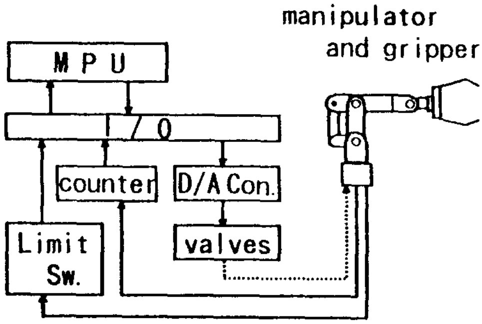
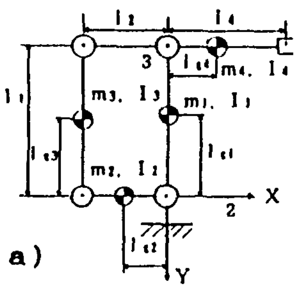


Fig. 6 Blockdiagram of drive circuit



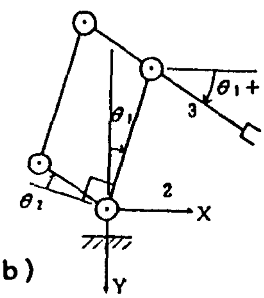


Fig. 7 Dynamic models a) Parameter b) Angular displacement

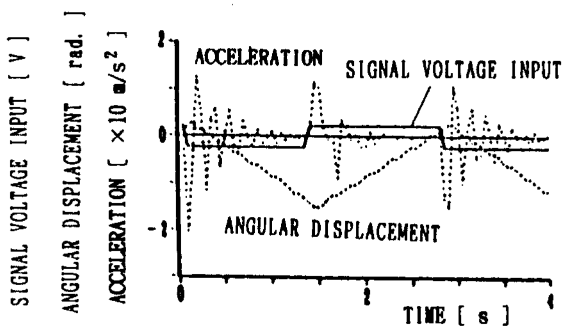


Fig. 8
Signal voltage input, angular displacement of joint 3 and acceleration at end of manipulator, when joint 3 was driven

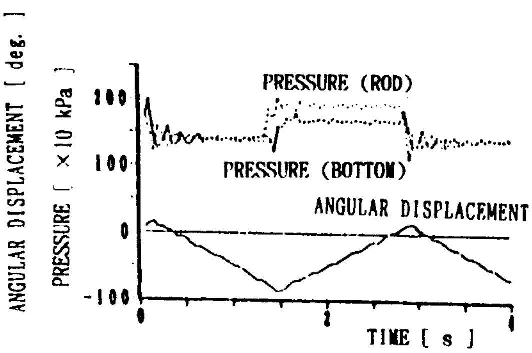


Fig. 9
Angular displacement of joint 3 and pressures in cylinder, when joint 3 was driven

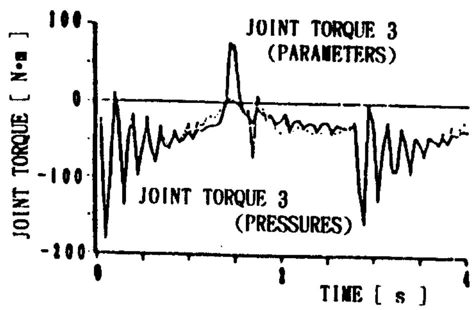


Fig. 10
Calculated torque 3 from measured pressures and calculated torque 3 from identified parameters

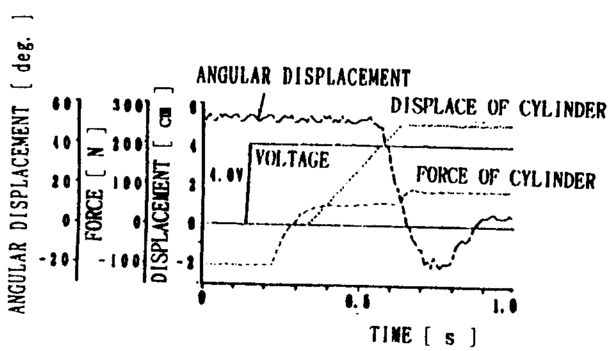


Fig. 11
Signal voltage input, angular displacement of finger, cylinder force and displacement of cylinder rod, when a finger was driven