Proceedings of the Second International Symposium on
Measurement and Control in Robotics (ISMCR '92)
Tsukuba Science City, Japan - November 15-19, 1992

Impedance Control of a Robot Manipulator Stabilized by PID Endpoint Motion Compensator

Taisuke SAKAKI*, Takanobu IWAKANE*, and Susumu TACHI**

*Yaskawa Electric Corporation.
2-1 , Kurosaki-shiroishi, Yahata-nishiku, Kitakyushu 806, Japan.
**RCAST, University of Tokyo.
4-6-1 Komaba, Meguroku, Tokyo, 153, Japan.

Abstract:
A new implementation of impedance control is proposed for a robot manipulator composed of torque-controlled actuators including reduction gears. A PID servo compensator of the arm endpoint motion, using wrist force sensor information, is applied to the torque-based impedance control method. The feasibility of the control system is verified by impedance control experiments with the manipulator.

Keywords: Force Control, Impedance Control, Torque-controlled Actuator

I. INTRODUCTION

Without sufficient safety equipment and devices, many operations are still unable to be carried out or accessed directly by a human. These operations include work in high radiation fields in nuclear power plants, undersea operations for ocean exploitation, fire fighting and rescue operations, during which extremely sophisticated and/or complex motions are necessary to be achieved by a machine as well as by a human operator. In consideration of such background, many projects have been directed toward establishing a robot technology with the capability of inspection, maintenance, rescue, and other highly complex operations.

The specifications required for such a robot are the multi-degree-of-freedom (d.o.f.) manipulators with maneuverability and adaptability the same as human arms, and the flexible operation capability with compliant force control and bilateral control. In the ARTRA (Advanced Robot Technology Research Association) project, dual-arm, four-fingered manipulators have been studied with the development of such new robot actuators [3,5,6]. The arm is composed of a 7 d.o.f. manipulator, and a 14 d.o.f. hand. The dual-arm system has 42 d.o.f. driven by 52 actuators, in total. Therefore, actuator size and weight are very important for these kinds of robots. Also, many such advanced robot systems are constructed as master-slave systems which are operated in bilateral mode. Force or torque control of actuators is required to drive the bilaterally controlled arms.

Therefore, there are two targets for such dexterous robots: one is on the actuator and the other is on force control method. The fundamental goals of the robot actuator is the minimization of its size and weight, and high torque performance. Robot actuators which have been most successfully implemented on industrial robots, are the motors connected to the arm joints by reducers with high reduction ratios, and controlled usually by velocity/position control. However, such robot systems have some disadvantages in their force control performance, which are mainly caused by reducer backlash and elasticity. On the other hand, a direct-drive (DD) motor has been developed as a robot actuator which executes precise torque and position control even in high-frequency regions. However, DD motors still have many problems because of their small torque/weight ratio. Therefore, a compact and torque controlled actuator has been a target in the ARTRA project. The torque/weight performance of the actuator developed in the project, is one-tenth that of conventional actuators. In addition, the actuator has precise torque controllability, whose linearity of reference/output torque is within 3 % of the rated torque.

As for another target for the dexterous robot, impedance control is one of the force controls of a manipulator to execute a stable contact task by dealing with the dynamic interaction of a robot and its environment[1-4,7]. Many control experiments have been achieved with direct-drive robots. However, there have been no impedance control methods suitable for the manipulator composed of the torque-controlled actuators. Those conventional impedance control methods cannot be implemented directly to the manipulator.

In this paper, a new implementation of impedance control of a robot manipulator using compact and torque-controlled electric actuators is proposed. A PID servo compensator of the arm endpoint motion using wrist force sensor information is applied to the torque-based impedance control algorithm. The feasibility of the control system is verified by impedance control experiments with a manipulator composed of torque controlled actuators.

This paper is organized as follows. In Section II, a new implementation method of impedance control is proposed. In Section III, impedance controllability is examined by some experiments of the manipulator composed of the actuators. In Section IV, the specifications of the method are discussed dealing with response and stability issues.

II. TORQUE-BASED IMPEDANCE CONTROL WITH SERVO COMPENSATOR

This section explains several problems of conventional impedance control methods when directly applied to the newly developed actuator, and proposes an impedance control algorithm suitable for the actuator to solve those problems.

There are two kinds of implementation methods of impedance control: one is the torque-based method, the other is the motion-based [7]. The torque-based method controls force of an end-effector compliant against the external motion of an object [2,3,4]. It has the advantage of stability in contact with a solid object. This is because the control algorithm which needs each joint motion but no force sensors on the arm endpoint, allows the actuator and sensor to satisfy their collocation [9]. The experiments of the impedance control, using acceleration feedback applied to a direct-drive arm, have shown the feasibility of the method by using a precise inner arm dynamics model and the torque control performance of the DD motor. The motion-based method controls motion of the arm endpoint against external force [1]. K.Furuta et al., have applied a virtual inner model following control to impedance control, which has robustness against arm model variation or other disturbances, and shows stability even for a target impedance with a small stability margin [11]. However, the control system may cause contact instability. This is because the system needs force sensor information on an end-effector, and actuators and sensors are noncollocated [9].

However, there is no impedance control method suitable for a manipulator composed of the newly developed compact actuators. Since the conventional torque-based method is equal to the model matching control for the target impedance, the control system has the same stability margin as the impedance model. The system may become unstable for an impedance model with a small stability margin, and the system is weak to the disturbance from modeling error or variation. The arm consisting of the new actuators may cause instability when the conventional torque-based method is directly applied to it, since the actuator reduction gears have non-linear friction and may generate arm modelling error or variation. Also, the motion-based impedance controls, which are available to be applied to a motion control unit used in conventional industrial robots, cannot be implemented in the arm with such torque-controlled actuators.

We will propose a new impedance control method with a PID servo compensator of an arm endpoint motion, using the external force information on the arm endpoint, applied to the conventional torque-based acceleration feedback method. The compensator regulates the endpoint motion to follow a virtual reference trajectory added to an earlier target trajectory. The virtual trajectory is created by both the external force information and the target impedance to realize the model dynamics against the force. Therefore, the manipulator dynamics are

$$T_a = M(\Theta)\ddot{\Theta} + h(\Theta,\dot{\Theta}) - J^T F_e \qquad (1)$$

where $M(\Theta)$, $h(\Theta,\dot{\Theta})$, J^T, Fe indicate inertia matrix, nonlinear term including gravity or Coriolis effect term, transposed Jacobian matrix, and external force vector. The actuator output torque Ta consists of the nonlinear compensation term [first term of (2)] and control term [second term U of (2)].

$$T_a = [\, M(\Theta)\ddot{\Theta} + h(\Theta,\dot{\Theta}) \,] + U \qquad (2)$$

The control term U for the target impedance (M_o, B_o, K_o) comprises the torque-based impedance control input U_o and the compensation term U_c to follow the virtual reference trajectory X_m by the external force F_e.

$$U = U_o + U_c \qquad (3)$$

U_o is the conventional torque-based impedance control input with using acceleration feedback.

$$U_o = J^T [\, M_o(\ddot{X}_d - \ddot{X}) + B_o(\dot{X}_d - \dot{X}) + K_o(X_d - X) \,] \qquad (4)$$

where X_d is an earlier target trajectory. And the following PID (or PD) feedback is applied as the compensator output U_c,

$$U_c = J^T [\, K_p (\ddot{X}_m - \ddot{X}) + K_v (\dot{X}_m - \dot{X}) + K_i \int (X_m - X) dt \,] \quad (5)$$

where X is the actual arm end point position, K_p, K_v, K_i are gains of the PID feedback. The reference trajectory X_m is derived from the target impedance, the target trajectory X and the external force F_e as follows.

$$\ddot{X}_m = \ddot{X}_d - M_o^{-1} [\, B_o (\dot{X}_m - \dot{X}_d) + K_o (X_m - X_d) - F_e \,] \quad (6)$$

The output torque T_a is applied to the actuators by the algorithm. The control block diagram is shown in Fig.1.

The proposed algorithm will show control stability for a target impedance even with a small stability margin. In the case where the target impedance is applied as

$$F_e = M_o (\ddot{X} - \ddot{X}_d) + B_o (\dot{X} - \dot{X}_d) + K_o (X - X_d) \quad (7)$$

the arm endpoint regulates motion error e along the following equation,

$$\ddot{e} + M_o^{-1} (B_o + K_v) \dot{e} + M_o^{-1} (K_o + K_p) e = 0 \quad (8)$$

The PD gains Kv, Kp help the system to control the error even with a target impedance with small parameters of Bo or Ko. The steady state error remains in the system applied only with Kv, Kp. The error will be regulated to zero in the system also with I gain, Ki. And the system can cancel the modelling error/variation or other disturbances. Note that although the torque-based control part Uo keeps stable contact on a rigid object, the PID servo compensator with high gains Uc may cause contact instability because of the actuator sensor noncollocation. In order to keep the contact stability, the compensator gains should be assigned low value against a rigid object and be assigned high value against a soft one, which will be discussed later.

III. IMPEDANCE CONTROL EXPERIMENTS

In this section, an experimental manipulator composed of the compact torque-controlled actuators is explained, and the feasibility of the proposed control system is verified by impedance control experiments with the manipulator.

3.1 Manipulator Composed of Torque-controlled Compact Actuators

The design goal of the actuator in the ARTRA project has been that the torque/weight performance of the actuator is one-tenth that of conventional actuators (Fig. 2), and the actuator has linearity of reference/output torque controllability. The proposed actuator has the following structure to satisfy the above specifications (See Fig.3) [3,5,6].

The motor of the actuator is a synchronous type AC servo motor with permanent magnets. The magnet material is a high-energy product rare-earth iron boron permanent magnet (maximum energy product is 35 MG-Oe or 278 kJ/m^3). The armature winding is the fractional slot-winding type. The number of slots per pole per phase is chosen between 0.5 and 1. The stator core is laminated vanadium permendur (50%Co-2%V) with high magnetic saturation flux density and low iron loss. Lighter structural materials such as aluminum or titanium alloy were used for the frame and shaft. Actuator configuration corresponding to the combination of the reducer and electric motor, is the built-in reducer type suitable for obtaining small size

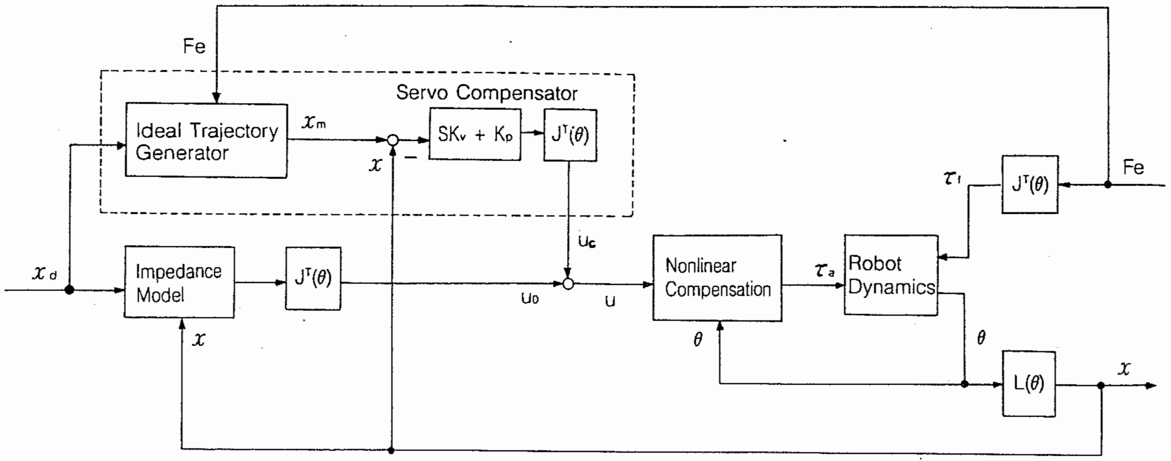


Fig.1 Proposed torque-based impedance control with servo compensator.

and light weight. Actuator compactness was also considered in a sensor integrated structure. A torque sensor mounted on the actuator output shaft to detect the output torque, a resolver, and a potentiometer are integrated with the motor.

The joint torque feedback loop is implemented to compensate the reference/output torque[3,5,8]. There is a trade-off between the compactness of an actuator achieved by high reduction ratios and its force controllability. A harmonic drive reduction gear is suitable for obtaining lighter weight. However, it generates nonlinear friction proportional to the reduction ratio (Fig.4). Because of the nonlinear friction and elasticity of the reduction gear, open loop torque control is difficult for the actuator. In fact, the friction torque of the actuator gear is 24 % of the rated torque of the motor. Therefore, the gear integrated motor is necessary to be designed to optimize a compact and lightweight actuator, implementing a joint torque feedback control to compensate for the output torque nonlinearity. The output torque information detected by the torque sensor is fed to the motor driver, and the nonlinearity of reference/output torque is compensated for by joint torque negative feedback of the driver. Figure 3 shows a torque sensor made of thin magnetic film mounted on the motor shaft. Figure 4 shows some experimental results on compensation of static and dynamic transfer characteristics by joint torque feedback. It results in the friction torque limited to 3.4 % of the rated torque in a static specification.

The manipulator of three degree-of-freedom comprises newly developed actuators. Figure 5 shows the structure of the experimental manipulator. The shoulder rotating joints have two d.o.f. and the elbow rotating joint has one d.o.f., three d.o.f. in total. The length of each link is 450 mm and 600 mm, respectively. The handling weight is 5.0 kg at a point 500 mm from the elbow joint. The entire manipulator configuration is made slim by using the proposed actuators. A six-axis force sensor is mounted on the arm endpoint to detect the external force. A personal computer is applied to obtain the information of each axis motion (angle, angular velocity) and external force, calculate an output torque in the impedance control algorithm, and send the command to the motor driver.

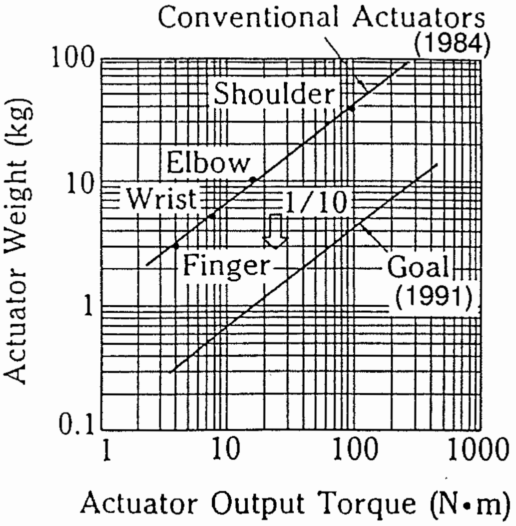
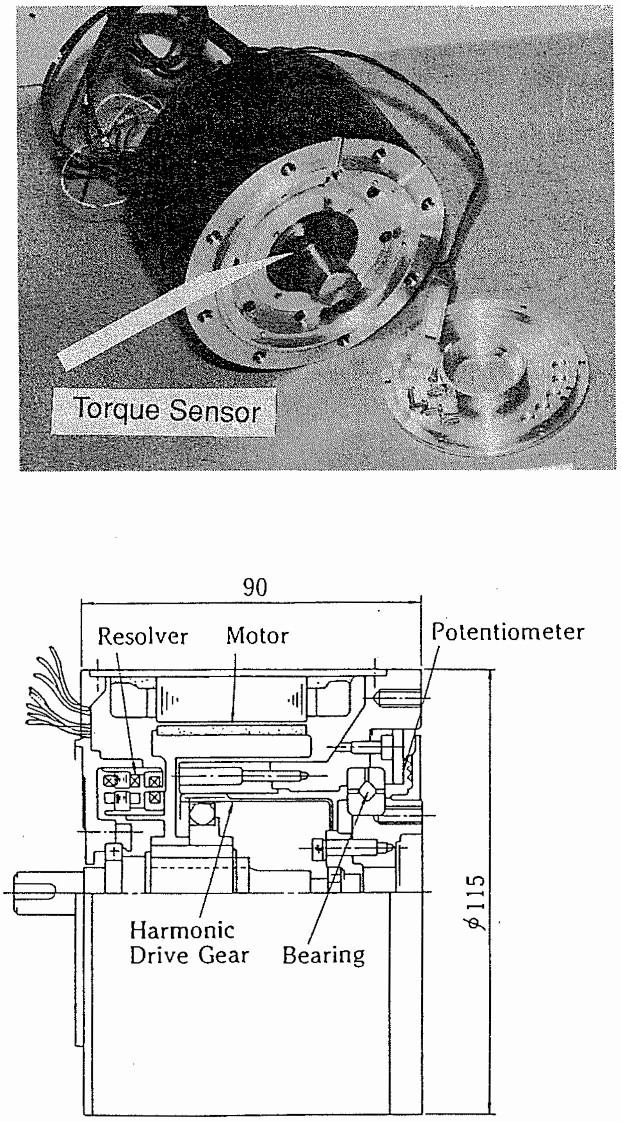


Fig.2 Goal of light-weight actuator proposed by ARTRA project.

3.2 Impedance Control Experiments of a Manipulator

The implementation of impedance control was

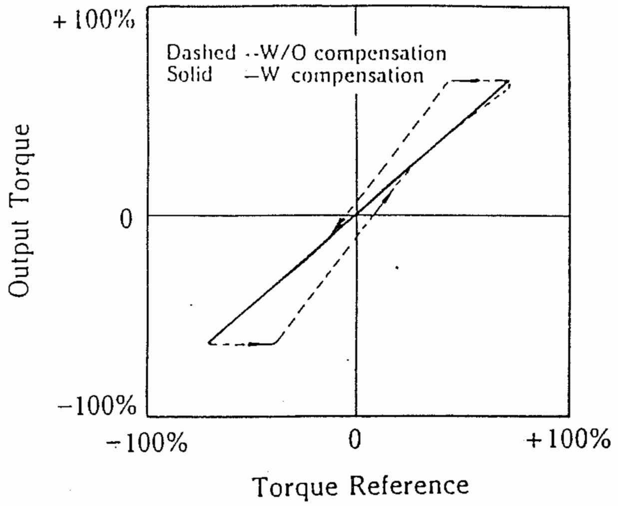


Rated Torque : T_R=120 N·m
Weight : W=3.3 kg
Reduction Ratio : R = 40

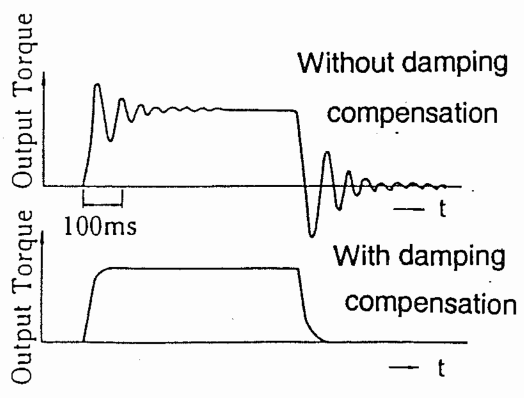
Fig.3 Torque-controlled compact actuator with torque sensor.

verified by some contact task experiments of the arm endpoint to compare its response and stability with those of the conventional torque-based impedance control (Fig.5). The purpose of the experiments was to examine the algorithm to operate stably with a target impedance with a small stability margin, and to see robustness against arm model error/variation or other disturbances. One of the shoulder joints was fixed in the experiments so that the manipulator had two d.o.f. in a vertical plane. The target impedances of the arm endpoint were set in horizontal and vertical axes. The target impedance in the horizontal axis was fixed as (inertia = 1.2 kg, frequency = 1.2 Hz, damping ratio = 0.2) to position the arm endpoint in the direction, and the target impedance in the vertical axis was set as (inertia = 2.0 kg, frequency = 1.0 Hz, damping ratio = 0.4) as one with a larger stability margin and (inertia = 2.0 kg, frequency = 1.0 Hz, damping ratio = 0.1) with a smaller one to generate some compliance in the direction. After applying the load of 0.5 kg on the end-effector, vibrations of the arm end position in the vertical direction were measured as step responses.

Figure 6 indicates the experimental results of the step responses. Figures (a) show larger error of transient response and steady state of the conventional torque-based method without compensations. Figures (b) in the proposed method with a PD compensator, which regulates the system to follow the ideal trajectory for external force with frequency of 2.0 Hz and damping ratio of 0.7. Their transient responses are better than of the conventional one, (a). The steady-state errors in (b) are reduced more than in (a), but still remain. Figure (c) are the results of the proposed control with a PID compensator, in which an integral feedback is also



(a) Static torque transfer characteristics.



(b) Dynamic torque transfer characteristics.

Fig.4 Static and dynamic torque control performance with joint torque feedback.

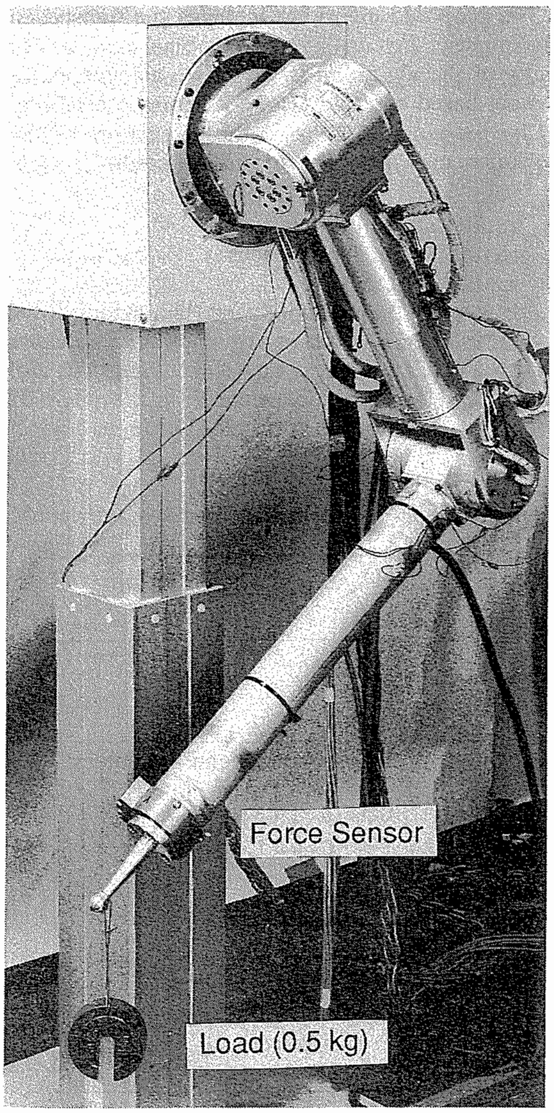


Fig.5 Manipulator composed of torque-controlled compact actuators and force sensor.

included in the PD one. In addition the transient responses are achieved as well as the case of the PD compensator in (b); the steady-state errors are completely removed.

IV. DISCUSSION

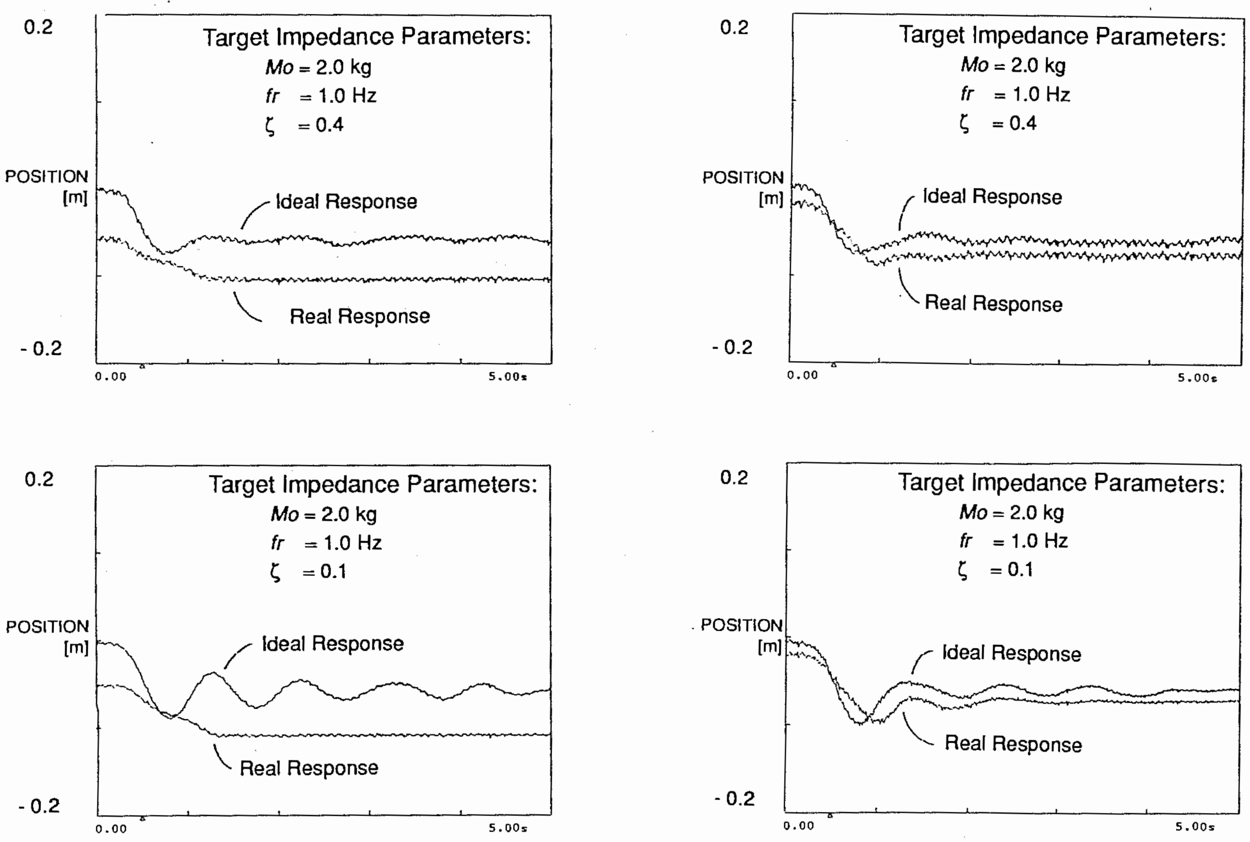
The characteristics of the proposed method are as follows,

(1) It becomes available to set a target impedance with a small stability margin by a PID compensator in addition to the conventional torque-based impedance control. The integral compensator of the PID controller works to reduce the steady state error from the disturbance of the modeling error or variation.

(2) The proposed algorithm includes the transposed Jacobian matrix, but no inverse Jacobian matrix. The simplicity of the algorithm is useful to achieve a real time sensor-based control. Also, a kinematic instability caused by the singular point in the calculation of the inverse kinematics, never occurs in the control system [11].

(3) The actuators used in the experimental manipulator, are compact and have static linearity of torque controllability. However, their dynamic torque control performance is still lower (20 Hz) than DD motors (500 Hz), and nonlinear friction of reduction gears may cause arm model error or variation[3]. Therefore, the proposed impedance control algorithm are necessary to be applied to the manipulator to cancel those frictions or disturbances, keeping dynamic response of impedance control instead of other impedance control methods applied usually to a DD robot without gears or to an industrial robot with a motion control unit and high reduction gears.

(4) The manipulator with the proposed algorithm may often cause instability in contact with a rigid environment. It is because actuators and sensors are noncollocated in the part of the compensator output Uc to control actuator torque in each joint by using force sensor information on the arm endpoint. Conversely, the part of the conventional torque-based impedance control output Uo, does not cause such instability. It satisfies actuator-sensor collocating to control actuator torque only by using each joint motion. Therefore, there is a trade-off between dynamic response and stability in the applied impedance control. The simulation in Fig.7



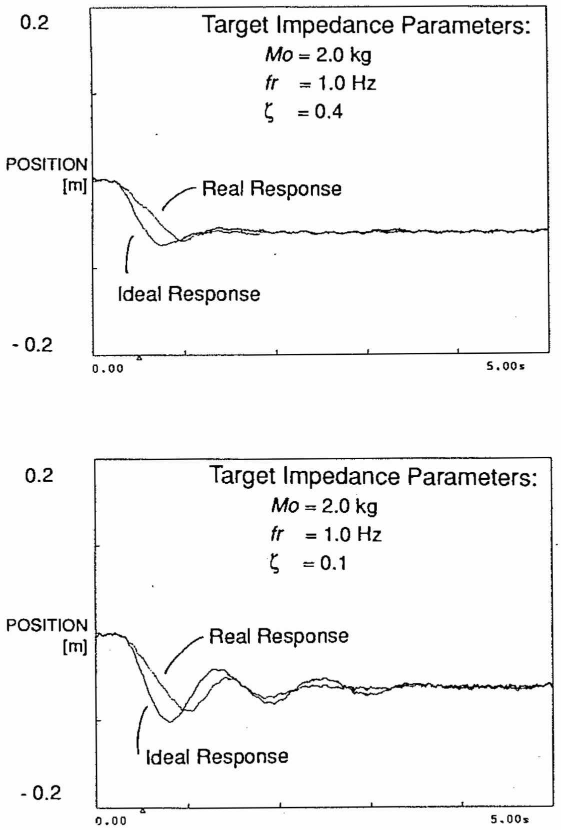
(a) Without compensators

(b) With PD compensator

Fig.6 Experimental results of impedance control with/without servo compensator. (a) and (b) shows the simulation results of contact stability of the proposed impedance control. Increase of the compensation gains moves zero into instability region, and it will cause contact instability. One of the strategies to solve the problem will be to keep the gains of the compensator small during transient contact, and to raise the gains gradually after confirming the steady state of contact.

V. CONCLUSIONS

A new implementation of impedance control has been proposed and applied to a manipulator composed of small, lightweight and torque-controllable actuators. A PID servo compensator of the arm endpoint motion using wrist force sensor information, has been added to the torque-based impedance control. The feasibility of the control system was verified by impedance control experiments with the manipulator. The transient response capability rises and steady-state error decreases in the proposed system more than in the conventional one. The strategy to avoid contact instability was also discussed.



(c) With PID compensator

Fig.6 Experimental results of impedance control with/without servo compensator. (c)

REFERENCES

[1]N.Hogan,"Impedance control part I-III," ASME Trans., March, 1985.

[2]S.Tachi, T.Sakaki and H.Arai, "Impedance control of a direct drive manipulator without using force sensors," Proc. ISMCR'90, Houston, 1990.

[3]T.Sakaki, T.Iwakane, "Impedance control of a manipulator using torque-controlled light-weight actuators," IEEE IAS Annual Meeting, pp.1438-1444, Dearborn,1991.

[4]Y.Inoue, T.Matsumoto, T.Sakaki and T.Iwakane, "Impedance control using decoupling control of a direct drive arm," Int. Power Electronics Conference in Tokyo, 1990.

[5]H.Inokuchi, T.Iwakane and T.Matsumoto, "Electric actuator for advanced robot manipulators," '91 ISART, 1991.

[6]T.Iwakane et.al, "Special issues on advanced robot -- Power source technology," Yaskawa Denki, Vol.55, No. 2, 1991.

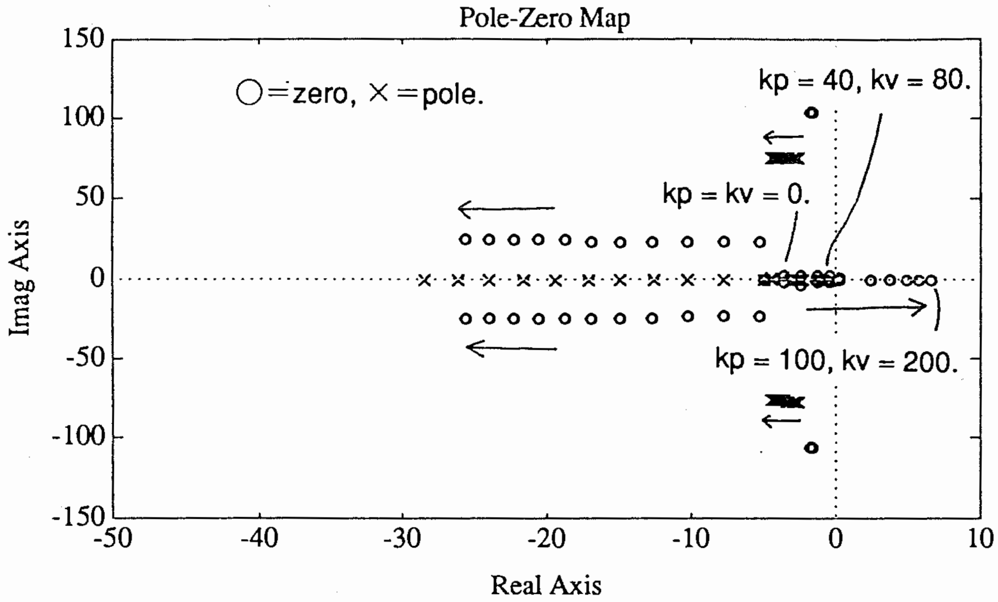
[7]D.A.Lawrence, "Impedance control stability properties in common implementations," IEEE Int. Conf. Rob. & Autom.,1988.

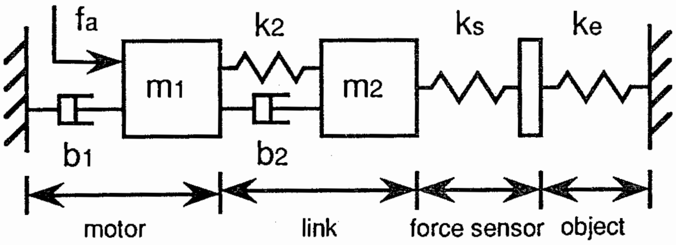
[8]J.Y.S.Luh, W.D.Fisher and R.P.C.Paul, "Joint torque control by a direct feedback for industrial robots," IEEE Trans. Automatic Contr., Vol.AC-28, No.2, 1983.

[9]S.D.Eppinger, and W.P.Seering, "Three dynamic problems in robot force control," IEEE Int. Conf. on Rob. & Autom., 1989.

[10]K.Furuta, K.Kosuge, O.Yamono, and K.Nosaki, "Robust control of robot manipulator with nonlinearity," Robotica, Vol.2. pp.75-81, 1984.

[11]C.H.An, C.G.Atkeson, and J.M.Hollerbach, "Model-Based Control of a Robot Manipulator," MIT Press, 1988.





manipulator dynamics with link dynamics contact with object

m1 = 2.97
b1 = 22.8
m2 = .88
b2 = 2.28
k2 = 4209
ks = 5000
ke = 10000
mo = 4
bo = 40
ko = 100

Fig.7 Simulation results of contact stability of proposed impedance control (with PD servo compensator).