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Double Actuator Unit with Planetary Gear Train for a Safe Manipulator

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***Abstract*—Control of a robot manipulator in contact with the environment is usually conducted by the direct feedback control system using a force-torque sensor or the indirect impedance control scheme. Although these methods have been successfully applied to many applications, simultaneous control of force and position cannot be achieved. Furthermore, collision safety has been of primary concern in recent years with emergence of service robots in direct contact with humans. To cope with such problems, redundant actuation has been used to enhance the performance of a position/force controller. In this paper, the novel design of a double actuator unit (DAU) composed of double actuators and a planetary gear train is proposed to provide the capability of simultaneous control of position and force as well as the improved collision safety. Since one actuator controls position and the other actuator modulates stiffness, DAU can control the position and stiffness simultaneously at the same joint. The torque exerted on the joint can be estimated without an expensive torque/force sensor. DAU is capable of detecting dynamic collision by monitoring the speed of the stiffness modulator. Upon detection of dynamic collision, DAU immediately reduces its joint stiffness according to the collision magnitude, thus providing the optimum collision safety. It is shown from various experiments that DAU can provide good performance of position tracking, force estimation and collision safety.**

I. INTRODUCTION

A robot manipulator operating in free space can be controlled by the conventional position control scheme. In this case, a manipulator usually has high stiffness for improved positioning accuracy. When the manipulator contacts or collides with the external environment, however, such high stiffness may cause damage to not only the manipulator but also the environment. When the manipulator moves while contacting with the external environment, accurate force control is required to ensure safe and smooth movement. Force control of a manipulator is usually executed directly by the feedback control system using a force/torque sensor. This approach suffers complicated algorithms and use of an expensive sensor. Force control can also be implemented indirectly by the stiffness control method in which the contact force is indirectly controlled by adjusting the displacement of a linear spring in proportion to the external force [1],[2]. There are some limitations to improving the performance of a force/position controller using the passive elements because the system performance depends heavily on their mechanical characteristics.

In recent years, service robots started to work in the living space, so the collision safety problems between a human and the robot have been of great concern. To cope with this problem, various research efforts have been directed toward the development of a safe manipulator. The approach based on redundant actuation has recently received considerable attention. The redundantly actuated systems can be used to improve not only the performance of a force/position controller but also collision safety. Bicchi developed the variable stiffness unit (VSU) which could control the joint stiffness by changing the mechanical impedance during the task [3],[4]. The VSU, which was composed of double actuators for implementation of the agonist and antagonist, controlled the position and stiffness simultaneously by adjusting the direction and magnitude of the torques generated by the two actuators. Khatib improved the response performance of a force/position controller, as well as collision safety by using the distributed actuation approach. This approach used two actuators connected in parallel; one is the high torque-low frequency actuator placed at the base and the other is the low torque-high frequency actuator at the joints of the manipulator [5]. However, its implementation was not easy because of its size and the manipulator design was complicated since two actuators must be connected with the manipulator in parallel.

In this paper, the novel design of a double actuator unit (DAU) composed of double actuators and a planetary gear train is proposed to cope with such problems. Since one actuator (called a positioning actuator) controls position and the other actuator (called a stiffness modulator) modulates stiffness, DAU can control the position and stiffness simultaneously at the same joint. This unit can implement force control of a manipulator more easily and increase the collision safety during the external collision. The torque exerted on the joint can be estimated without an expensive torque/force sensor by using the encoders installed at each actuator. DAU is capable of detecting the dynamic collision by monitoring the speed of the stiffness modulator. Upon detection of dynamic collision, DAU immediately reduces its joint stiffness according to the collision magnitude, thus providing collision safety.

The remainder of this paper is organized as follows. Section II introduces the operating principle of a double actuator unit (DAU) in detail. The position controller and force controller based on this DAU are presented in section III. Section IV

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deals with how to improve collision safety using DAU. The performance of DAU is verified by several experimental results in section V. Finally, section VI presents conclusions.

II. DOUBLE ACTUATOR UNIT

DAU (Double Actuator Unit) using a planetary gear train proposed in this research can control both position and stiffness independently. Section II.A presents the concept of a double actuator mechanism and II.B explains the operating principle of a planetary gear train. Section II.C deals with DAU based on a planetary gear train and II.D considers the gear ratio of DAU.

A. Double actuator mechanism

To improve the performance of the position and force control of a manipulator, the position and stiffness should be controlled simultaneously. Because it is impossible to control the position and stiffness at the same time by using only one actuator, some systems adopt redundant actuation, which utilizes more actuators than the number of DOFs required by the system.

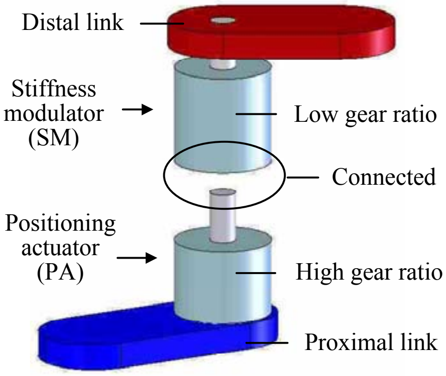


Fig. 1 Double actuator mechanism.

The double actuator mechanism shown conceptually in Fig. 1 is also based on redundant actuation. The double actuator mechanism is composed of two actuators; one for position control, called a positioning actuator (PA), and the other for stiffness control, called a stiffness modulator (SM). In this mechanism, the output shaft of SM rotates relative to the body of PA since the body of SM is connected together to the output shaft of PA. In this research, a novel design of the double actuator unit (DAU) based on a 2 DOF planetary gear train is proposed to reduce the size and weight of the double actuator mechanism shown in Fig. 1.

B. 2 DOF planetary gear train

In contrast to an ordinary gear train, which has a single input and a single output, a planetary gear train can have two inputs and a single output. The simple planetary gear train sketched in Fig. 2 consists of a sun gear in the center, a planet gear, a planet carrier, and an internal ring gear. The sun gear, ring gear and planet carrier all rotate about the same axis. The planet gear is mounted on a shaft in the planet carrier, which meshes with both the sun gear and the ring gear. The motion of a planet carrier (output) is determined by the combined motion of the sun gear (input 1) and ring gear (input 2).

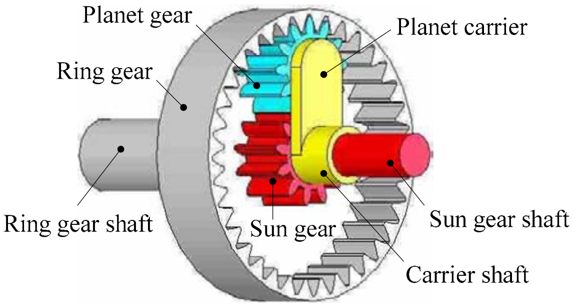
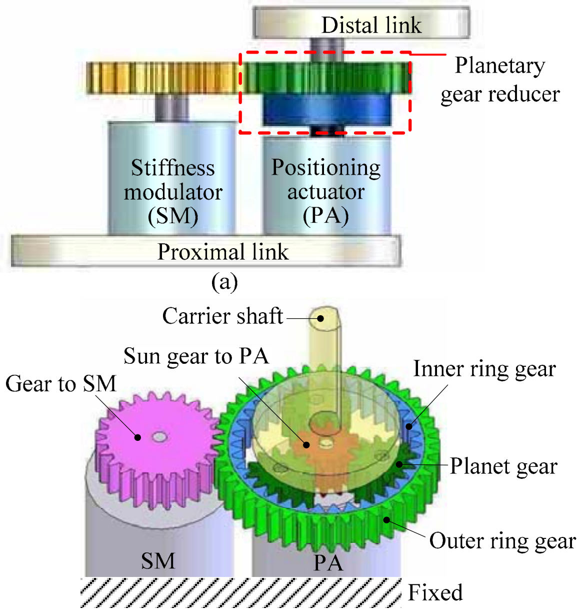


Fig. 2 Planetary gear train.

C. DAU based on planetary gear train

In this research, the 2 DOF characteristics of a planetary gear train are exploited to implement a novel design of DAU. DAU is mainly composed of PA (positioning actuator), SM (stiffness modulator) and a planetary gear train, as shown Fig 3(a). The planetary gear train used in DAU is illustrated in Fig. 3(b). As explained before, the sun gear (connected to the PA shaft) and the outer ring gear (connected to the SM shaft through the spur gear) function as the inputs to DAU, whereas the carrier as its output. As shown in Fig. 3, both bodies of PA and SM are fixed to the proximal link and the carrier shaft is attached to the distal link.



(b)

Fig. 3 DAU; (a) DAU based on planetary gear train, (b) planetary gear train.

D. Gear ratio of DAU

Since the power of DAU is transmitted by a planetary gear train and functions of two actuators are divided into position control and stiffness control, the selection of the gear ratio is very important. With the spur gear connected to the SM shaft fixed, the gear ratio r_P associated with position control can be expressed by

$$r_P = \frac{\omega_C}{\omega_{PA}} = \frac{N_S}{N_{RI} + N_S} \tag{1}$$

where ω_{PA} and ω_C are the angular speed of PA and the carrier, and N_S and N_{RI} are the number of teeth of the sun gear and the internal ring gear, respectively. High gear ratio of a position control part, which is beneficial to positioning accuracy, can be obtained by the multi-stage planetary gear train. Its gear ratio is then determined by the products of the gear ratios of each stage. For example, if the gear ratios are 6:1, 5:1, 6:1 and 5:1 for each stage of the 4-stage planetary gear train, then the resulting gear ratio is 900:1.

On the other hand, with the sun gear connected to the PA shaft fixed, the gear ratio r_{SM} associated with stiffness control can be given by

$$r_{SM} = \frac{\omega_C}{\omega_{SM}} = \frac{N_{RO}}{N_{SMG}} \cdot \left(1 - \frac{1}{r_P}\right) \tag{2}$$

where ω_{SM} is the angular speed of SM, and N_{SMG} and N_{RIO} are the number of teeth of the spur gear (attached to the SM shaft) and the outer ring gear, respectively. Low gear ratio of a stiffness control part is advantageous to soft manipulation.

The gear ratio of PA and SM can be selected in consideration of the desired position accuracy and stiffness. A high gear ratio is good for PA, whereas a low gear ratio is beneficial to SM, because the functions of two actuators can be easily divided in terms of the gear ratio.

III. POSITION AND STIFFNESS CONTROL

DAU based on a planetary gear train can control the position and stiffness independently. In this section, the position and stiffness control using DAU are explained in detail and the motion of a planetary gear train is examined during the position and stiffness control.

A. *Position control using DAU*

The motion of the planetary gear train is shown in Fig. 4 when the link rotates to the desired position, $\theta_{PA,d}$, in free space by controlling PA. If PA rotates counterclockwise (CCW), then the sun gear attached to the PA shaft also rotates CCW(i) but the planet gears rotate CW(ii). Suppose the SM shaft is locked. Since the ring gear meshing with the spur gear is also fixed in this case, the carrier rotates CCW(iii). As a result, the link attached to the carrier rotates CCW, thereby reaching the desired position.

The position control of PA can be achieved by PID control, in which the position of PA is controlled until the error between the desired position ($\theta_{PA,d}$) and the current position (θ_{PA}) measured by the encoder becomes 0.

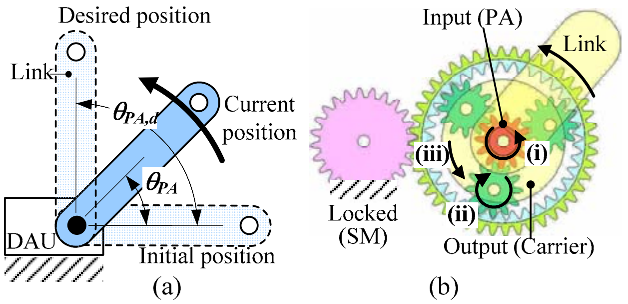


Fig. 4 Position control using DAU; (a) position control of link, (b) gears in motion during position control.

B. *Stiffness control using DAU*

Suppose that the link needs to exert a contact force F_C on the object located at θ_{ob}, as shown in Fig. 5(a). This task is composed of position control and subsequent force control. First, the link is controlled to move to the desired position (θ_{ob}) at which it barely touches the object θ_{ob} by means of the position control scheme mentioned before. Once the link contacts the object, PA cannot rotate any more, so rotation of the carrier attached to the link is constrained.

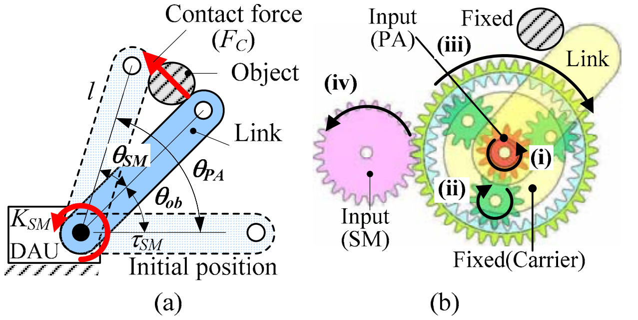


Fig. 5 Stiffness control using DAU; (a) stiffness control of link, (b) gears in motion during stiffness control.

Figure 5(b) shows the motion of DAU during stiffness control. As PA rotates CCW, the sun gear attached to the PA shaft rotates CCW(i) and the planet gears meshing with the sun gear rotate CW(ii). Then the ring gear rotates CW and transmits the torque to SM(iii) because the carrier is constrained when the link contacts with the object. Therefore, the ring gear causes the spur gear joined to SM to rotate CCW(iv). The angular displacement θ_{SM} of the back-drivable SM occurs.

$$\theta_{SM} = \theta_{PA} - \theta_{ob} \tag{3}$$

Then, the output torque of DAU τ_{SM} is given by

$$\tau_{SM} = F_C \cdot l = K_{SM} \cdot \theta_{SM} \tag{4}$$

where K_{SM} is the joint stiffness which can be set by a user. Supposing the length of the link is l, the contact force F_C between the link and the object can be obtained by (4). The torque τ_{SM} can be expressed by multiplying the torque constant $K_{T,SM}$ by the current i_{SM} supplied to SM as follows.

$$\tau_{SM} = F_C \cdot l = K_{T,SM} \cdot i_{SM} \tag{5}$$

When the angular displacement θ_{SM} occurs, the relation between the desired joint stiffness K_{SM} and the current i_{SM} can be described by (4) and (5) as follows:

$$i_{SM} = \frac{K_{SM} \cdot \theta_{SM}}{K_{T,SM}} \tag{6}$$

For example, when K_{SM} = 0.1Nm/deg, $K_{T,SM}$ = 2Nm/A, l = 0.1m and θ_{Ob} =30°, if the desired contact force of 2N is exerted, θ_{SM} must be 2° from (4). The position of PA θ_{PA} is 32° from (3) since the position of the object θ_{Ob} does not change during the motion. Therefore, PA rotates 32°, the angular displacement θ_{SM} is 2°. Substituting the stiffness and angular displacement into (6) yields the current of 0.1A. The torque of 0.2Nm is then generated by SM, which is predicted by (5).

IV. COLLISION SAFETY

A. Safety criterion

The safety criterion can be divided into static and dynamic collision. Static collision means that the collision speed between the robot arm and a human is low (e.g., below 0.6m/s). The human pain tolerance for static collision can be expressed by

$$F \le F_{\text{limit}} \tag{7}$$

where F_{limit} is the injury criterion value which has been suggested as 50N by several experimental researches [6].

To represent the human safety associated with the dynamic collision of DAU, the head injury criterion (HIC) used to quantitatively measure the head injury risk in car crash situations is adopted in this research [7].

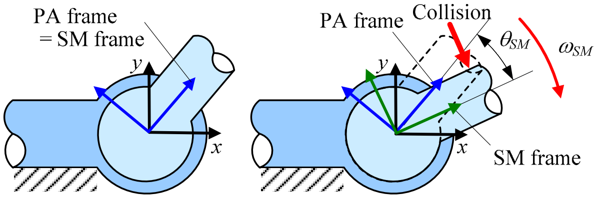
$$HIC = T\left(\frac{1}{T}\int_0^T a(t)dt\right)^{2.5} \tag{8}$$

where T is the final time of impact and $a(t)$ is the acceleration in the unit of the gravitational acceleration g.

The damages caused by static collision are not critical in most cases. In contrast to static collision, dynamic collision frequently occurs in a daily life and may lead to serious injury or even deadly situations. Consequently, in this research only the dynamic collision is considered.

B. Safety against dynamic collision with stiffness control

There is a close relation between the manipulator stiffness and collision safety. Collision safety can be achieved by an immediate reduction in stiffness upon detection of collision. The proposed DAU in this research has such capability of detecting collision and reducing its stiffness, thus enabling collision safety.



(a) (b)

Fig. 6 Frames of PA and SM; (a) before collision, (b) after collision.

Figure 6 represents the frames related to the shafts of PA and SM for the DAU-based system. The two frames are coincident with each others before collision, as illustrated in Fig. 6 (a). After collision, however, the SM frame rotates together with the link connected to the SM shaft and the difference between the two frames occurs. In this situation, the angular velocity of the SM frame can be used for collision detection. That is, DAU can detect the collision when the angular velocity of SM, ω_{SM}, is larger than some pre-determined critical velocity, ω_o, as follows:

$$\omega_{SM} \ge \omega_o \tag{9}$$

The critical velocity can be set to any value depending on the tasks. In this research the critical velocity is set to170deg/s (3rad/s) when the collision occurs at the end of the 20 cm link. This velocity was chosen because humans feel threatened [8],[9] at the sight of the robot moving at this speed. In other words, the manipulator should move slower than this speed to avoid both the physical injury and fear. After DAU detects the collision, it needs to changes the stiffness K_{SM} to a lower value to provide collision safety

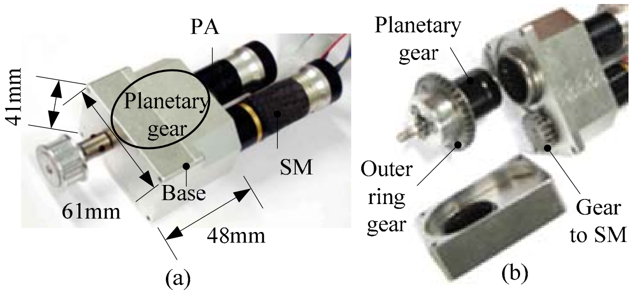
$$K_{SM} = K_{SM}^o - \beta_{vel} \cdot \Delta\omega \tag{10}$$

where K^o_{SM} is the initial stiffness of SM, β_{vel} is the proportional constant depending on the application, and $\Delta\omega = \omega_{SM} - \omega_o$.

For example, suppose ω_o is 170deg/s, K^o_{SM} is 1.5Nm/deg and β_{vel} is 0.01. If the link rotates at a speed of 270deg/s at the instant of collision, DAU detect the collision since its angular velocity is faster than the critical velocity. The stiffness of the manipulator is then reduced abruptly to 0.5Nm/deg by (10) and the collision safety is attained by this lowered stiffness.

V. EXPERIMENTS

The prototype of DAU based on a planetary gear train shown in Fig. 7 was constructed to conduct various experiments related to the performance of DAU. In this DAU, both actuators are mounted on the base, so electrical wires of actuators do not twist. Furthermore, it is possible to adjust the gear ratio of the planetary gear train depending on the applications, thereby optimizing the system size. The DAU uses two 20W BLDC motors. PA has 4-stage planetary gear trains and the gear ratio of each stage is approximately 5:1. SM has its own gear reducer and the output shaft is connected to the spur gear which has a gear ratio of 2:1. Therefore, the gear ratio of the position control part of DAU is 690:1, while that of the stiffness control part is 103:1. Various experiments have been conducted to evaluate the performance of position tracking, force estimation and collision safety of the proposed DAU.

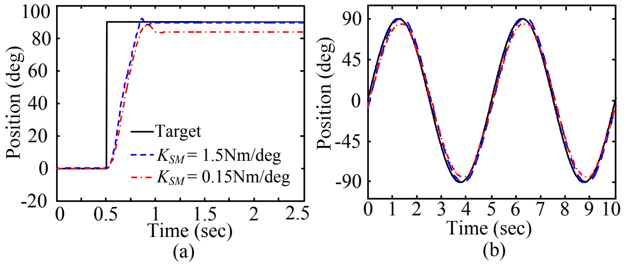


(a) (b)

Fig. 7 Prototype of DAU based on planetary gear train; (a) DAU, and (b) components of DAU.

A. *Position tracking*

The link is connected to the output shaft of DAU to verify the positioning accuracy under a load. A load of 500g was attached at the endpoint of the link, which is placed 20cm apart from the output shaft of DAU. In the experiment for position tracking, the link was commanded to track the step and sinusoidal reference inputs with the stiffness of SM set to 0.15Nm/deg and 1.5Nm/deg. Figure 8(a) shows the unit step response with an amplitude of 90º and Fig. 8(b) shows the response to a sinusoidal input with an amplitude of 90º and a period of 5 sec. Some errors between the reference input and the actual position occurred when the joint stiffness of SM was to a low value. However, such position errors can be reduced by increasing the joint stiffness of SM. Therefore, DAU can ensure high positioning accuracy for a robot arm by increasing its stiffness.



(a) (b)

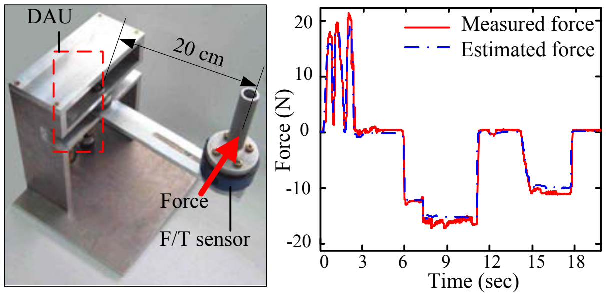
Fig. 8 Response of DAU-based system subject to (a) step input and (b) sinusoidal input.

B. *Force estimation*

Figure 9(a) shows the experimental setup to verify the performance of force estimation using DAU. A force/torque sensor is installed at the endpoint to directly measure the force exerted on the link. If the force is exerted on the link, the angular displacement of SM occurs. The force acting on the link can be given by

$$\tau_e = F_e l = K_{SM} \cdot \theta_{SM} \tag{11}$$

where F_e is the estimated force acting on the link and l is the length of the link. The joint stiffness K_{SM} was set to 2 Nm/deg in the experiment.



(a) (b)

Fig.9 Force estimation; (a) Experimental setup for estimate contact force using encoder (b) comparison between measured and estimated forces.

The force was randomly applied to the link during 3sec and then maintained for a while to an opposite direction. The measured and the estimated forces show a good agreement, as shown in Fig. 9(b). Therefore, DAU can accurately estimate the force acting on the link without an additional force/torque sensor.

C. *Collision safety*

Some experiments for dynamic collision were conducted for the robot arm equipped with DAU. For dynamic collision, a plastic ball of 1.5kg moving at a velocity of 3m/s was forced to collide with the end of the 20cm link, as shown in Fig. 10. The acceleration of the ball was measured by the accelerometer mounted at the ball. Two experimental conditions were tested: one for constant joint stiffness and the other for varying stiffness upon detection of collision.

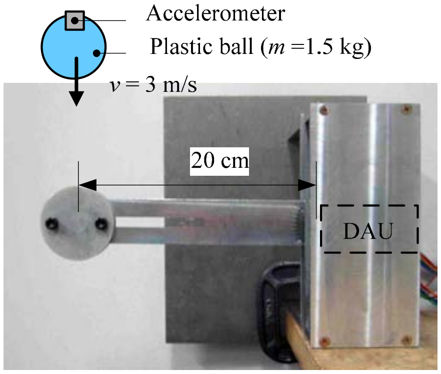
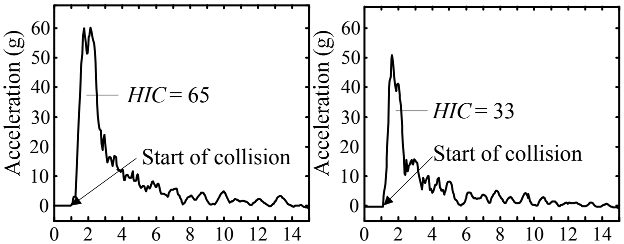


Fig. 10 Experimental setup for the dynamic collision.

When the initial joint stiffness K_{SM} was set to 2Nm/deg, Fig. 11 shows the measured acceleration at the plastic ball. When the joint stiffness was kept constant, as shown in Fig. 11(a), the acceleration of the ball reached a peak value of 60*g*. The dynamic collision safety can be verified in terms of *HIC* defined by (8) and the *HIC* value was computed as 65, which is less than 100. When the joint stiffness was allowed to vary according to (10), the acceleration of the ball reached a peak value of 50g and the *HIC* value was computed as 33, which was less than the case of constant stiffness. Therefore, the robot arm with DAU can provide collision safety between a human and the robot by reducing the joint stiffness appropriately upon detection of dynamic collision.



(a) (b)

Fig. 11 Experimental results for dynamic collision of DAU; acceleration vs. time in case of (a) constant stiffness, and (b) variable stiffness.

VI. CONCLUSIONS

A double actuator unit (DAU) was proposed in this research to enable force and position control to be conducted simultaneously for a single joint. The performance of position tracking, force estimation, and collision safety were investigated through a series of experiments. From this research, the following conclusions are drawn.

(1) DAU can control the position and force simultaneously for a single DOF joint by exploiting the features of a planetary gear train.

(2) The torque exerted on the joint of DAU can be estimated by the encoder information without an expensive force/torque sensor. Force control can be conducted by using the estimated force and torque information.

(3) DAU can detect both static and dynamic collision and reduce the joint stiffness immediately, thus offering the capability of collision safety even for severe dynamic collision.

The proposed DAU in this research can be used for a variety of applications requiring stable force control, such as hands and legs of a humanoid robot, as well as the safe manipulators requiring collision safety. DAU can also improve its safety feature by using other sensors to detect the object before collision.

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