Flexible Motion Realized by Force-free Control: Pull-Out Work by an Articulated Robot Arm

Daisuke Kushida, Masatoshi Nakamura, Satoru Goto, and Nobuhiro Kyura

Abstract: A method for force-free control is proposed to realize pull-out work by an industrial articulated robot arm. This method achieves not only non-gravity and non-friction motion of an articulated robot arm according to an exerted force but also reflects no change in the structure of the servo controller. Ideal performance of a pull-out work by the force-free control method was assured by means of simulation and experimental studies with a two-degree-of-freedom articulated robot arm.

Keywords: Articulated robot arm, flexible motion, force-free control, pull-out work.

1. INTRODUCTION

Robot arms are used in various industries and throughout numerous fields for many purposes, and as such their rigidity must be adaptive to suit a variety of objectives. For instance, in the case of cutting and welding, the rigidity of robots must be kept high, because high accuracy of the robot arm tip locus is essential [1-5]. Alternatively, in the case of pull-out work, assembly or grinding, the rigidity of robots must be kept low, because flexible motion by external force is vital [6-7]. However, as almost all industrial articulated robot arms are designed with high rigidity for convenience of positioning and contouring, they are not exactly suitable for pull-out work. To attain flexible motion of robot arms for industry use, a flexible device is attached to the tip of the robot arm, or a torque limit is induced to the joint actuator, which is called "servo float method" [6]. However, the flexible device is limited to movement in a vertical direction due to the effect of gravity and can therefore only perform certain works. Execution of these works is difficult using the industrial articulated robot arms because the servo controllers of the robot arms must be changed. Other methods for impedance control and those for compliance control have been proposed to reduce the rigidity of robot arms [9-10]. However, these methods are also difficult to carry out by industrial articulated robot arms, because of algorithm complexities and required controllers' modifications.

In this paper, a method for force-free control is proposed to realize pull-out work by an industrial articulated robot arm. This method does not require any changes to the structure of the servo controller. Ideal performance of a pull-out work by the force-free control method was assured by simulation and experimental studies.

2. FORCE-FREE CONTROL FOR THE REALIZATION OF FLEXIBLE MOTION

2.1. Flexible motion

Operations such as cutting and welding can be easily performed by using industrial robot arms. These operations are carried out through contour control in that the tip of the robot arm moves along a given path, and point-to-point (PTP) control in that the tip moves between previously assigned points. These operations are tractable as the rigidity of the robot arm advances. Therefore, the industrial robot arms and the NC machine tools are designed with high rigidity.

Until recently, control of a contact force has been required in order to carry out assembling, handling, inlaying, pull-out work and grinder operations. And yet, it is difficult to control the contact force if the robot arm possesses a high degree of rigidity. From this view, low rigidity for industrial robot arms is required to control the contact force.

Conversely, flexible motion is also required for

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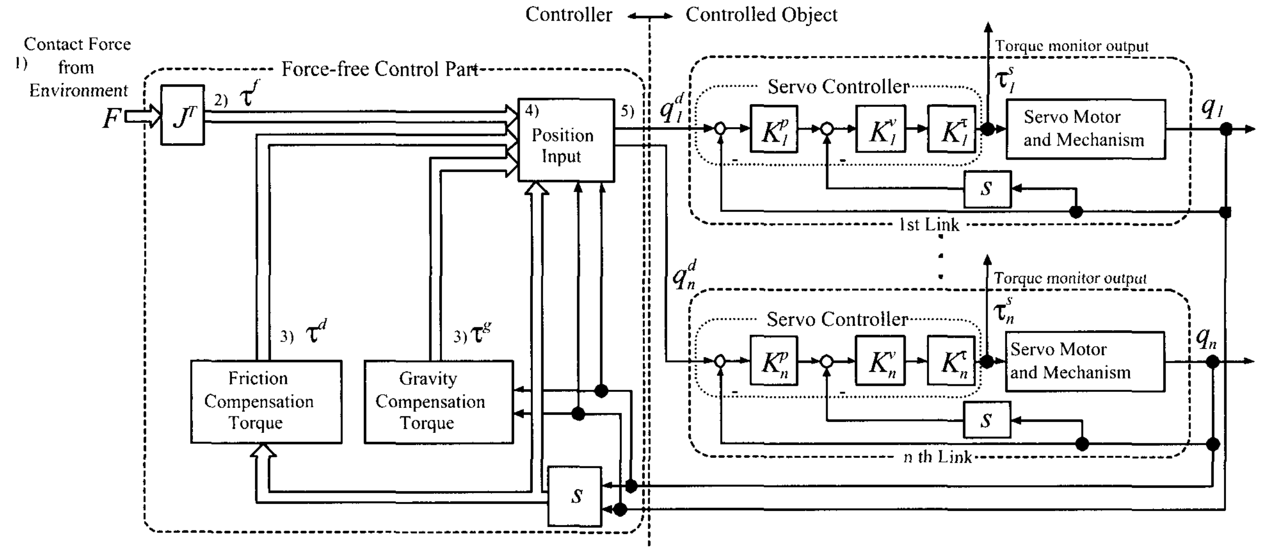


Fig. 1. Block diagram of industrial articulated robot arm and force-free control.

safe operation as in the case of contact between the robot and human operator. Generally, an emergency shutdown switch is built-in to the servo controller. When an operator becomes squeezed between the tip of the robot arm and the environment, an emergency halt becomes more dangerous. If the robot arm can be actuated with flexibility, the operator is released from this precarious situation.

Some of the problems have been solved by particularly designed robots or remodeling of robots. However, countless industrial robot arms are manufactured for general purpose, and such robot arms have a lower cost compared with those of the special purpose robots. From this view, flexible motion by general purpose industrial robot arms is required.

2.2. Present status of flexible motion in industry

A servo controller of the industrial robot arm includes a position loop and a velocity loop. Input to the industrial robot arm is usually the joint position of each link. Hence, the industrial robot arms should be considered as the combination of the mechanism of the robot arm and the servo controller.

Recently, studies concerning the force control of industrial robots have been developed rapidly and their achievement has been of major concern. Numerous force control methods for the change of rigidity in robot arms such as impedance control [9], compliance control [10] and servo float method [6] have been proposed. These methods are apparently adequate to meet the requirements of force control. However, to apply these methods in industry, there are difficulties that must be overcome. For general purpose robots including the servo controller, these methods require adjustment of the control strategy in the servo controller. Modification of the servo controller is almost impossible on the user side, and modification by the manufacturer requires a vast sum of money. Presently, methods available for realization of flexible contact between the tip of the robot arm and the environment involve attaching a flexible device on the tip of the robot arm.

The servo float method, developed by the Yaskawa Co. [6], realizes flexible contact force without the use of flexible devices. This method limits the torque of each joint by setting the contact force. In the servo float method, setting of the contact force is complicated according to the applications. Furthermore, the servo float method requires modification of the servo controller by the manufacturer; hence the cost of such a system is very high.

This paper proposes force-free control for flexible motion of general purpose industrial articulated robot arms without modification of the servo controller, and the proposed force-free control is applied to pull-out work, which is one of the flexible works.

2.3. Flexible motion realized by force-free control

Force-free control, which has been proposed by authors previously, can attain non-gravity and non-friction motion of industrial articulated robot arms. Although the robot arm is actuated by the attached motor, the robot arm performs directly under the external force.

Generally, "Impedance Control" [9] is employed in order to realize objective contact force. It is constructed based on mechanical impedance, which is assumed to exist between the tip of the robot arm and the external object. Therefore, impedance control mainly considers the tip flexibility of the robot arm. In contrast, force-free control refers to the flexibility of the tip as well as to the total exerted force of the robot arm by use of a torque monitor [11]. Therefore, force-free control realizes more flexible motion on the robot arm compared with impedance control. Here, the meaning of force sensorless stated in this paper refers to executing flexible motion of the present industrial robot arms by minimum equipment, and does not deny the force sensor. Force sensorless is not an advantage of the force-free control but rather one of its merits. In this paper, force-free control only considers the tip's force because the tip of the robot arm is important for pull-out work. The mathematical explanation of force-free control is described below.

The industrial articulated robot arm is constructed by the articulated robot arm mechanism and the servo controller. The servo controller is shown on the right hand side of Fig. 1 [12], where, K_i^p, K_i^v and K_i^τ (i=1,$\cdots$,n) represent the position of loop gain, velocity loop gain and torque constant, respectively. The symbols q_i^d, q_i and τ_i^s (i=1,$\cdots$,n) are the inputs of joint angle, output of joint angle and input torque to the robot arm, respectively. Symbol i stands for the link.

The dynamic equation of the industrial articulated robot arm including the servo controller is given by [7]

$$\begin{aligned}&H(\boldsymbol{q})\ddot{\boldsymbol{q}} + D\dot{\boldsymbol{q}} + \mu\,\mathrm{sgn}(\dot{\boldsymbol{q}}) + \mathbf{h}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \mathbf{g}(\boldsymbol{q})\\ &= K^{\tau}\left[K^{v}\left\{K^{p}\left(\boldsymbol{q}^{d}-\boldsymbol{q}\right)-\dot{\boldsymbol{q}}\right\}\right],\end{aligned} \tag{1}$$

where $H(\boldsymbol{q})$ is the inertia matrix, $D\dot{\boldsymbol{q}}$ and $\mu\,\mathrm{sgn}(\dot{\boldsymbol{q}})$ are the friction terms, $\boldsymbol{h}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is the coupling nonlinear term, $\boldsymbol{g}(\boldsymbol{q})$ is the gravity term [7] and $\boldsymbol{q}=[q_1,\cdots,q_n]^T$. Besides, K^p is a diagonal matrix of K_i^p, K^v is a diagonal matrix of K_i^v and K^τ is a diagonal matrix of K_i^τ.

A block diagram of force-free control for the industrial articulated robot arm is shown in Fig. 1. Inputs of joint angle $\boldsymbol{q}^d\,(=[q_1^d,\cdots,q_n^d]^T)$ in order to realize force-free control are obtained by solving the right side of equation (1) as [7]

$$\boldsymbol{q}^{d}=\left(K^{p}\right)^{-1}\left\{\left(K^{v}\right)^{-1}\left(K^{\tau}\right)^{-1}\left(\boldsymbol{\tau}^{f}+\boldsymbol{\tau}^{g}+\boldsymbol{\tau}^{d}\right)+\dot{\boldsymbol{q}}\right\}+\boldsymbol{q}, \tag{2}$$

where $\boldsymbol{\tau}^f\,(=[\tau_1^f,\cdots,\tau_n^f]^T)$ is the joint torque corresponding to the external force on the tip of the robot arm. Symbol $\boldsymbol{\tau}^g\,(=[\tau_1^g,\cdots,\tau_n^g]^T)$ is the gravity compensation torque and $\boldsymbol{\tau}^d\,(=[\tau_1^d,\cdots,\tau_n^d]^T)$ is the friction compensation torque. Here, joint torque corresponding to the external force at the tip of the robot arm is obtained by [8]

$$\boldsymbol{\tau}^{f}=\boldsymbol{J}^{T}\boldsymbol{F}, \tag{3}$$

where $\boldsymbol{F}$ is the external force and $\boldsymbol{J}$ is the Jacobian matrix. The friction compensation torque ($\boldsymbol{\tau}^d$) is calculated by obtaining coefficients of viscous damping and coulomb friction from the experiment as follows:

$$\boldsymbol{\tau}^{d}=D\dot{\boldsymbol{q}}+\mu\,\mathrm{sgn}(\dot{\boldsymbol{q}}), \tag{4}$$

where D is the coefficients of viscous damping matrix, μ is the coefficients of coulomb friction and $\mathrm{sgn}(\dot{\boldsymbol{q}})$ means a sign of $\dot{\boldsymbol{q}}$. And the gravity compensation torque ($\boldsymbol{\tau}^g$) is obtained by calculating in real-time from a posture of the robot arm by

$$\boldsymbol{\tau}^{g}=\boldsymbol{g}(\boldsymbol{q}). \tag{5}$$

Hence, the flexible motion of the industrial articulated robot arm is realized by inputting the joint position ($\boldsymbol{q}^d$) to the servo controller.

Here, $(K^p)^{-1}$, $(K^v)^{-1}$, and $(K^\tau)^{-1}$ must employ the identical value as the inverse of servo gain K^p, K^v, and K^τ, which are already set up within the servo controller. Therefore, if servo gains are changed, it is also necessary to change $(K^p)^{-1}$, $(K^v)^{-1}$, and $(K^\tau)^{-1}$ of force-free control simultaneously. In this case, the influence by change of the servo gains is compensated by $(K^p)^{-1}$, $(K^v)^{-1}$, and $(K^\tau)^{-1}$, and the action of force-free control has no variance. However, a manipulator's action is affected when the servo gains of either force-free control or servo controller are fluctuated.

Here, the flow of the force-free control is explained briefly. 1) Contact force ($\boldsymbol{F}$) is detected by the force sensor, 2) the detected force is converted to joint torque ($\boldsymbol{\tau}^f$) by solving equation (3), 3) the friction compensation torque ($\boldsymbol{\tau}^d$) and the gravity compensation torque ($\boldsymbol{\tau}^g$) are generated from position output and velocity output of the servo motor by solving equations (4) and (5), 4) the position input ($\boldsymbol{q}^d$) is generated by solving equation (2), 5) finally, the position input ($\boldsymbol{q}^d$) is brought to the input of the servo controller. Those are general expressions of the flow of force-free control. But actually, $\boldsymbol{\tau}^f$ is obtained by use of torque monitor directly [11], $\boldsymbol{\tau}^d$ is determined from the step response of joint velocity and τ^g is calculated beforehand from the measured relationship between the gravity torque and the posture of the robot arm.

According to the procedure, force-free control is realized. The key point of the method is the realization of force-free control by inputting the appropriate position to the servo controller without modification of the servo controller. Besides, the robot arm would realize the optimal motion by the external force because the inertia of the robot arm can be changed by modifying the output of the torque monitor.

The force-free control is not a force controller at the tip of the robot arm but the realization of non-gravity and non-friction motion by following the generated joint torque according to the external force of the robot arm.

Here, the algorithm of force-free control closely resembles stiffness control. Stiffness control is the same control technique as impedance control, which generates a control input to realize an ideal mechanical impedance model. Damper and mass are set to zero. In the case of force-free control, a servo motor realizes a torque equivalent to the external force by performing reverse operation of the servo system. If necessary, gravity torque and friction torque will be added to the torque equivalent of the external force. Therefore, although force-free control and stiffness control perform similar action in the above derivation, the concept and algorithm differ from each other.

3. PULL-OUT WORK BY FORCE-FREE CONTROL

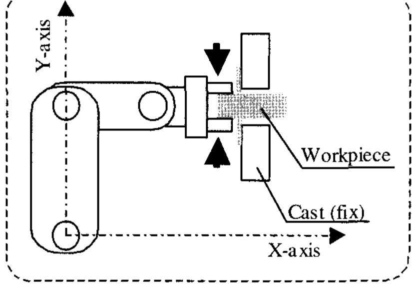
3.1. Purpose of pull-out work

A schematic of pull-out work and the sequence of pull-out work motion are shown in Fig. 2. This depiction shows the base of the first link and the cast as fixed. Pull-out work means that the workpiece, which is held by the robot arm, is pulled out by the push-rod, and it is usually used in the aluminum casting industry. The operational sequence is as follows: a) the hand of the robot arm grasps the workpiece, b) the workpiece is pushed out by the push-rod, and c) the workpiece is released by the force from the push-rod. The motion of the robot arm requires flexibility in order to follow the pushed workpiece.

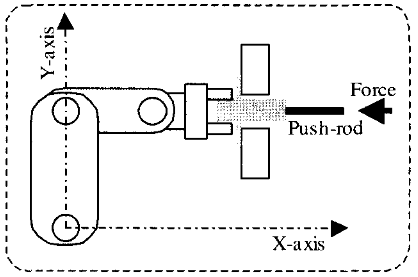
3.2. Condition for simulation and experiment

The structure of an industrial articulated robot arm used in the experiment is shown in Fig. 3. The articulated robot arm (Performer-MK3s, YAHATA ELECTRIC MACHINERY MFG, CO., LTD.) has the following specifications; link lengths being $l_1 = 0.25$[m], $l_2 = 0.215$[m], $l_3 = 0.2$[m], and masses of the links being $m_1 = 2.86$[kg], $m_2 = 2.19$[kg], $m_3 = 1.46$[kg].

(a) Grasping the workpiece



(b) Pushing the workpiece



(c) Flexible motion of robot arm

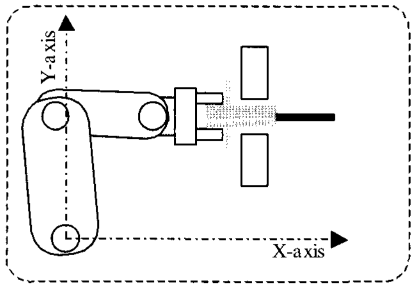


Fig. 2. Conceptual flow chart of pull-out work.

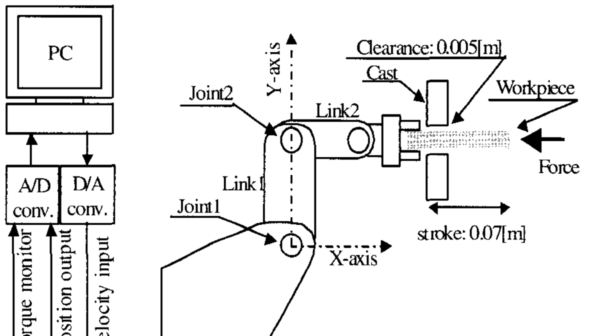


Fig. 3. Construction of experimental equipments.

Firstly, τ^f, which corresponds to the external force ($\mathbf{F}$), was detected by the torque monitor [11]. Next, the friction compensation torque (τ^d) was determined from step response of joint velocity beforehand, and the gravity compensation torque (τ^g)

was calculated from the measured relationship between gravity torque and the posture of the robot arm. After that, the position input ($\boldsymbol{q}^d$) of the robot arm was generated from accumulated torque by solving equation (2). The procedure was carried out using a personal computer and the generated position input ($\boldsymbol{q}^d$) was brought into the servo controller through a D/A converter. Hence, the robot arm was actuated by the torque, which was generated from the position input in the servo controller. Here, the third link is synchronized depending on first and second links to maintain the horizontal posture of the third link. Here, the estimation of the friction compensation torque ($\boldsymbol{\tau}^d$) poses a very difficult problem. In the present condition, the estimation of friction has not been performed completely. Subsequently, the friction compensation torque ($\boldsymbol{\tau}^d$) is not carried out enough. If over-compensation occurs, the robot arm reacts superfluously to slight external force, and then the moving velocity increases and diverges.

Sampling interval was Δt=0.001 [s], simulation time was 5 [s], position loop gains were $K_1^p = K_2^p$ = 25 [1/s], velocity loop gains were $K_1^v = K_2^v$ = 150 [1/s], torque constants were K_1^τ = 0.104 [Nm/(rad/s^2)], K_2^τ = 0.006 [Nm/(rad/s^2)], clearance between the workpiece and the cast was 0.005[m], stroke of pull-out was 0.07[m], coefficients of viscous damping were D_1 = 4.68 [Nms/rad], D_2 = 2.72 [Nms/rad], and coefficients of coulomb friction were μ_1 = 0.5 [Nm], μ_2 = 0.5 [Nm]. Coefficients of viscous damping and coefficients of coulomb friction were determined by the step response of joint velocity. Various simulations were carried out with different values of coefficients.

The initial position of the tip of the second link was set to (0.25, 0.31) [m], and the workpiece was pushed by the push-rod to the X-axis direction.

3.3. Results of pull-out work

In this paper, the proposal and implementability of force-free control are the primary points, while the comparison with other techniques is adjunctive. Therefore, experimental results are shown first, and then simulation results of comparisons with other methods are shown.

The experimental result of pull-out work by force-free control is shown in Fig. 4. Fig. 4 (a) and Fig. 4 (b) indicate external force along the X-axis and Y-axis to workpiece by the push-rod, respectively, (c) and (d) show the torques of joint 1 and joint 2, respectively, (e) and (f) show the positions of joint 1 and joint 2, respectively, and Fig. 4 (g) depicts the locus of the tip of link 2.

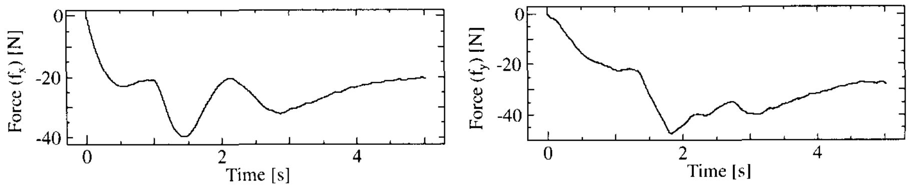
In Figs. 4 (a) and (b), the external force was calculated from the torque monitor output by use of equation (3), in (c) and (d), joint torque, which is in accordance with the external force and friction compensation torque, was obtained by torque monitor based on reference [11], in (e) and (f), joint angles are followed by joint torques, and in (g), locus does not exceed the clearance until pull-out work is completed. Here, the start point of the locus is shifted from the initial position, because the locus is obtained from kinematics by use of detected joint locations. Usually, the tip of the link is not directly measured by sensor, therefore the tip position is estimated by use of the above technique in industry.

This guarantees the realization of pull-out work with the industrial articulated robot arm based on force-free control.

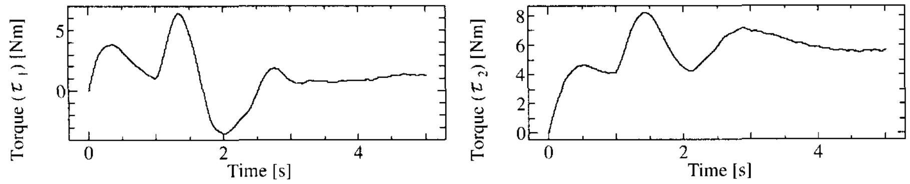
Next, the proposed method of the force-free control was compared with the servo float method (untuned case and well tuned case). The servo float method [6], which is the control method of contact force obtained by introducing torque limit in the servo controller, realizes the pull-out work in industry. The servo float method is required to set the contact force between the tip of the robot arm and the environment so that a robot arm may manage optimal pull-out work. The motion of the robot arm depends on the set torque limit according to the set contact force and as such, the servo float method requires troublesome tuning of the contact force. As well, change in the servo controller structure is required in order to appropriately use the servo float method on an industrial general purpose robot. Hence, comparison between force-free control and servo float method is done by means of simulation. Here, the clearance between the workpiece and the cast is 0.001[m], and the stroke of pull-out is 0.16 [m].

Simulation results of the pull-out work using the three methods are shown in Fig. 5. The first column of the graphs show the results using the untuned servo float method, the second column shows the results obtained by the tuned method, and the third column shows the results from the force-free control method. These methods realize the ideal action according to the theory because they are performed in numerical simulation. Fig. 5 (a1), (b1) and (c1) show the external force of the workpiece by the push-rod, Fig. 5 (a2), (b2) and (c2) demonstrate the joint torque of the first link, Fig. 5 (a3), (b3) and (c3) illustrate the joint torque of the second link, and Fig. 5 (a4), (b4) and (c4) show the locus of the tip of the robot arm. In the case of the untuned servo float, limit forces in X and Y-axis directions were 1.5 [N] and 0.0 [N], respectively. In the tuned servo float, those forces were 0.5 [N] and 0.0 [N], respectively.

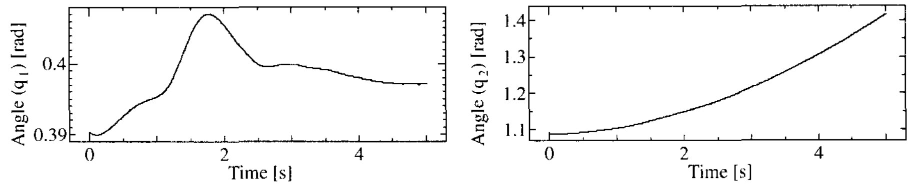
In Fig. 5 (a1), (b1) and (c1), the force from the push-rod is added to the workpiece gradually during



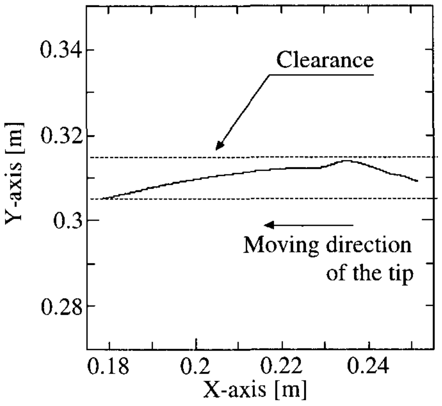
(a) Force along X-axis. (b) Force along Y-axis.



(c) Torque of joint 1. (d) Torque of joint 2.



(e) Position of joint 1. (f) Position of joint 2.



(g) Locus of the tip of link 2.

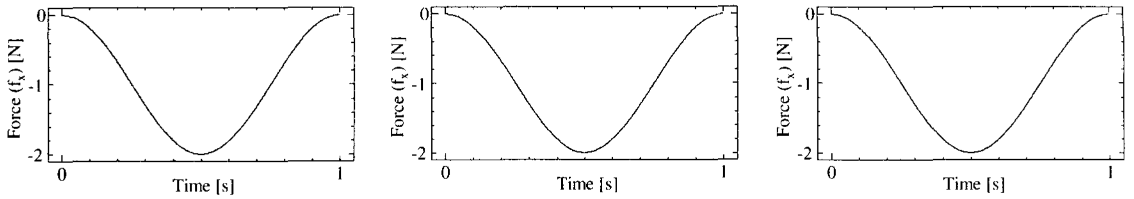
Fig. 4. Experimental result of pull-out work by force-free control.

pull-out work. Fig. 5 (a2), (a3), (b2) and (b3) show the realization of torque limit of each joint torque according to the set contact force in the Cartesian coordinates. In Fig. 5 (a4), (b4) and (c4), the tip of the robot arm is moved according to the external force. In particular, in (b4) and (c4), sufficient results of pull-out work were obtained. Here, in the results of the force-free control, the length of the locus is longer than other results for the same external force. This means that the force-free control is the most efficient among the three methods. Since joint torque contains impulse-like noise, the locus is wavy.

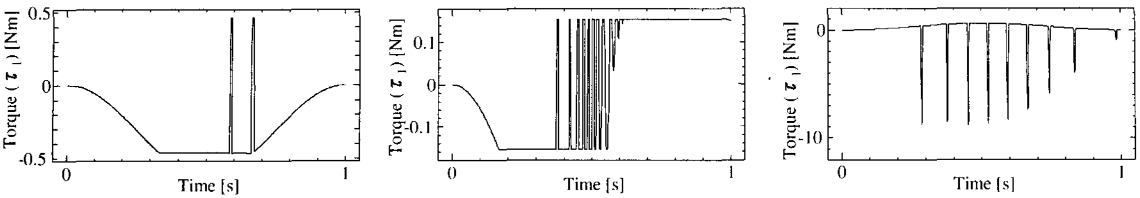
4. DISCUSSION

4.1. Appropriate performance of chattering phenomenon

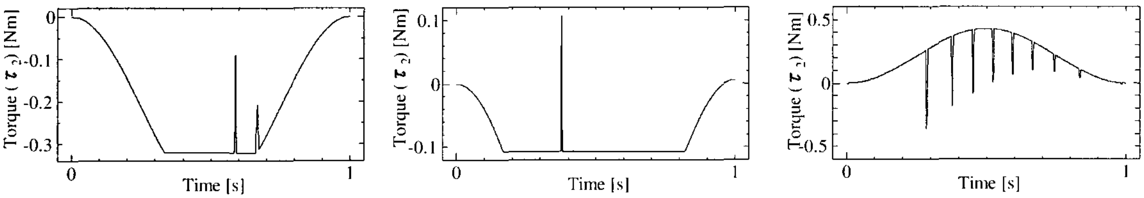
In Fig. 5 (a4), (b4) and (c4), the tip of the robot arm moves not only in the X-axis direction but also in the Y-axis direction despite the fact that force is added only in the X-axis direction. This is due to the mechanism of the articulated robot arm in which the motion is based on the rotation of links. The direction of the locus of the tip of the robot arm is not the same as the directions to the external force. Hence, the tip of the robot arm follows a curved path, and the contact between the workpiece and the cast is unavoidable. Besides, in Fig. 5 (c4), the locus of the tip of the robot arm is a wavy line. The tip of the robot arm deviates from the direction of the external force, then, the workpiece collides with the cast. The tip of the robot arm is influenced by the reaction force from the cast. Therefore, the robot arm is actuated following the external force and the reaction force based on force-free control. By repeating this procedure, the locus of the tip of the robot arm has become a wavy line. Consequently, the chattering phenomenon has occurred. Here, whether the upper or lower part of



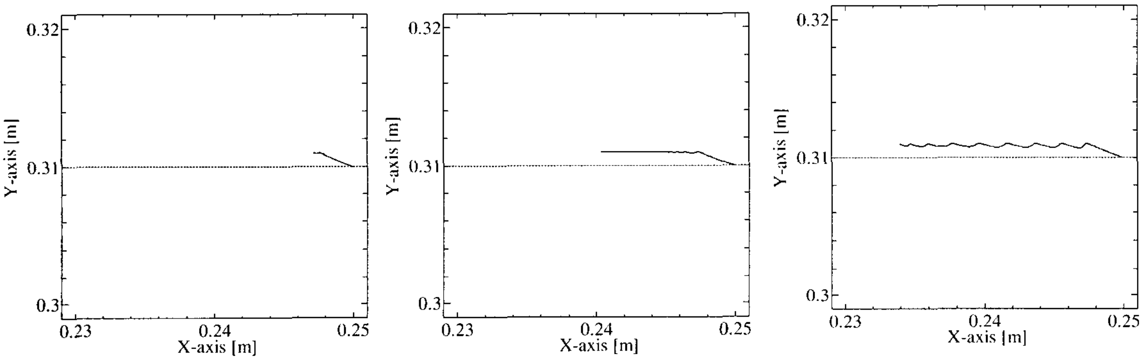
(a1) External force. (b1) External force. (c1) External force.



(a2) Joint torque of link 1. (b2) Joint torque of link 1. (c2) Joint torque of link 1.



(a3) Joint torque of link 2. (b3) Joint torque of link 2. (c3) Joint torque of link 2.



(a4) Locus. (b4) Locus. (c4) Locus.

Fig. 5. Simulation results of flexible motion based on the proposed method of force-free control by comparing the servo float method (The initial point of the tip of the robot arm was x_0=0.25[m] and y_0= 0.31[m], and the external force $f_x = \cos(2\pi t) - 1$ [N] is added to the tip of the robot arm).

the cast is contacted, change occurs with the initial position at the tip of the robot arm. This phenomenon seems to affect accuracy in a negative manner. However, the operation is carried out without any problem, because the robot arm is actuated as escaping to the direction of the contact force from the environment including the reaction force from the cast. Therefore, the robot arm can perform the task according to the above characteristics. The chattering phenomenon is an important factor to succeed the pull-out work. The phenomenon in Fig. 5 (c4) is better than that of Fig. 5 (b4) because, if the workpiece is rubbed against the side of the cast as in Fig. 5 (b4), accuracy of the workpiece deteriorates by shaving the side of the cast. If clearance becomes small, the chattering phenomenon will become intense and the execution of smooth work will become difficult. Moreover, if servo gains set up are low in order to prevent chattering, the extraction itself will no longer be performed since extraction work is accomplished through chattering. It is the same case with the servo float method, which is already used in the technique discussed. Therefore, the chattering problem is not the demerit of force-free control.

4.2. Comparison between force-free control and servo float

Fig. 5 (b4) shows the servo float method under the tuned contact force by the trial and error manner. Here, the pull-out work is realized almost completely by the servo float method. But, the force-free control can realize pull-out work with greater accuracy compared to the servo float method. The length of the locus in Fig. 5 (b4) is shorter compared with the re-

Table 1. Comparison between force-free control and servo float method.

	Force-free control	Servo float
(i) Contact force tuning	No need	Need
(ii) Contact force	Zero	Setting by designer
(iii) Response	Sensitive	Exceed the set contact force
(iv) Flexibility	Every direction	Depending on the set contact force
(v) Property	For flexible motion control	For contact force control

sult in Fig. 5 (c4). This indicates that the working efficiency of the force-free control is higher than that of the servo float method. In other words, the force-free control can reduce operating time. In addition, the force-free control does not require any changes in the control strategy of the servo controller whereas the servo float changes the servo controller causing increase in cost.

Characteristics of the force-free control and the servo float method are summarized in Table 1. (i) Force-free control does not require tuning of the contact force, unlike in the case of the servo float method. This is caused by a difference in the concept concerning both methods. The servo float method is developed to bound the contact force, but the force-free control method is developed to realize flexible motion by external force. Therefore, the servo float method requires tuning of maximum force output, which is similar to the contact force in the Cartesian coordinate. If maximum force output is set at zero, as in the case of force-free control, the servo float method cannot output the force, because of torque output depending on the maximum force output. Hence, the servo float method requires tuning in every different work. (ii) The contact force between the tip of the robot arm and the environment: in force-free control, the contact force is always zero, just as in the servo float method that is set by the designer. Hence, the servo float method requires tuning of set contact force. In other words, the role of the servo float method is not to control the flexibility but to control the contact force. (iii) The force-free control is sensitive to the external force. The servo float method actuates the robot arm when the external force exceeds the set contact force. Actually, the servo float method can be set at zero contact force. However, the length of locus of the tip of the robot arm is short as in Fig. 5 (a4). Therefore, the servo float method requires greater force in order to realize the pull-out work. (iv) The force-free control method has flexibility if external force is added to every part of the robot arm. However, the servo float method depends on the set contact force to the tip of the robot arm. (v) From such point of view, the property of the force-free control is more suitable for flexible motion control compared with the servo float method.

Here, there is impedance control with the position feedback loop. This method and the force-free control method have been constructed under the same concept. However, although impedance control depends on a mechanical impedance model, force-free control depends on a servo system. Both methods differ from each other.

These discussions indicate that force-free control was effectively applied to the pull-out work and realization of the pull-out work of the robot arms is guaranteed.

4.3. Other applications of force-free control

Effectiveness of force-free control for the pull-out work was guaranteed. In industry, robot arms are used in various applications and force-free control is required such as in the instance of the realization of direct-teaching for robot arm control. Generally, teaching of industrial articulated robot arms is carried out by use of operational equipment known as a teach-pendant. Smooth teaching can be achieved if the direct-teaching is appropriate. Here, in the direct-teaching the robot arm is moved by an operator manually. Direct-teaching is problematical due to the friction of joints and the existence of high gear ratios, and the fact that the controllers are already built in. Furthermore, the robot arm is strained by manual force during teaching. Non-gravity and non-friction conditions are desirable for the implementation of direct-teaching. From such point of view, force-free control is especially applicable for the direct-teaching.

In addition, by monitoring each joint torque according to the external force of the robot arm, the robot arm will actuate an escape when contact occurs between the tip of the robot arm and a human operator or the environment. Hence, force-free control can also improve the safety surrounding works with a human operator.

5. CONCLUSION

Realization of the pull-out work of the industrial articulated robot arms was achieved. In the pull-out work, rigidity of the robot arms must be kept low. Hence, force-free control was applied to the pull-out work. Realization of the pull-out work was guaranteed by the simulation and the experimental results. The pull-out work using force-free control can be applied in industry, because there are no requirements regarding change of the hardware.

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