

# Improvement of Dynamic Characteristics during Transient Response of Force-sensorless Grinding Robot by Force/Position Control

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**Abstract**—This research aims to achieve a new grinding robot system that can grind an object into desired shape with force-sensorless feed-forward control. In order to grind the target object into desired shape with sufficient accuracy, the hand of the robot arm have to generate desired constrained force immediately after the grindstone being contacted with the metal object to be ground. However, a time delay arises in the transition of constrained force while the hand of a robot arm generates desired constrained force stemming from a first-order time delay caused by dynamics in motors. This paper suggests some methods how to improve transient response of constrained force that influences shape-grinding accuracy directly. Results observed by real grinding experiment have confirmed how our proposed method effectively improved to shorten the time delay of constrained force.

**Index Terms**—force-sensorless grinding, constrained force, robot.

## I. INTRODUCTION

Many researches have discussed force control methods of robots for constrained tasks. Most force control strategies use force sensors [1]-[3] to obtain force information, where the reliability and accuracy are limited since the work-sites of the robot are filled with noise and thermal disturbances, reducing the sensor's reliability. On top of this, force sensors could lead to the falling of the structure stiffness of manipulators, which is one of the most essential defects for manipulators executing grinding tasks. To solve these problems, some approaches that don't use force sensor have been presented [4]-[8]. In this paper, we discuss about grinding task of robot that have grinder as an end-effector. To ensure the stabilities of the constrained motion, those force and position control methods have utilized Lyapunov's stability analysis under the inverse dynamic compensation [5], [6]. Their force control strategies have been explained intelligibly in books [7] and recently interaction control for six-degree-of-freedom tasks has been compiled in a book [8].

Those former classical robot controlling approaches can be classified into two broad categories [6]: impedance control and hybrid (force/position) control. In impedance control, a prescribed dynamic relation—between the robot end-effector's force exerting to an object constraining the end-effector, and

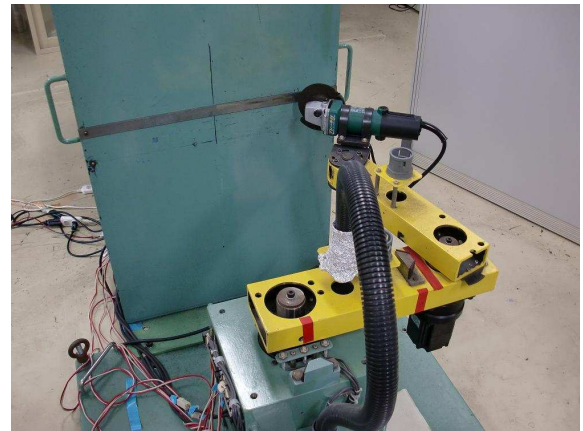


Fig. 1. Grinding Robot

position displacement toward the direction vertical to the object's surface—is sought to be maintained [9]. In hybrid control, the end-effector's force is explicitly controlled in selected directions and the end-effector's position is controlled in the remaining (complementary) directions [1].

In the classified categories, our force/position control approach is named as Constraint-Combined Control, which will be introduced later detailedly, belonging to model based hybrid control of rigid robot in hard contact with rigid environment.

The work-piece used for the grinding by the robot in this paper is iron, of which the spring constant of deformation against unit force is so huge to the extent that we can ignore the deformation of the work-piece caused by the constrained force with robot's end-effector since the grinding force exerted by the grinder to the work-piece is no more than 10 to 20 [N]. So the contact process of the grinder can be just thought as non-dynamical process but a kinematical one, so the prerequisite that there is no motion occurred in vertical direction to the surface to be ground could be undeniable. Therefore, in our research we don't use the time-differential equation of motion to describe constrained vertical process of the grinder contacting to the work-piece. Oppositely, we consider an algebraic equation as the constraint condition to analyze this contacting motion. Based on this algebraic equa-

tion, we have proposed Constraint-Combined Force Controller, which has the ability to achieve the force control without time delay if the motors ideally should generate required torques without time delay [1]-[13], where, force error will not be affected by the dynamical motion along to the surface in non-constraining direction [11], [12]. The Constraint-Combined force/position control method without using sensors can be thought to be essentially different from methods proposed so far [6]-[9].

Eq. (1), which has been pointed out by Hemami [10] in the analysis of biped walking robot, denotes also algebraic relation between the input torque  $\tau$  of the robot and the constrained force  $f_n$ , when robot's end-effector being in touch with a surface in 3-D space:

$$f_n = a(q, \dot{q}) - B(q)\tau, \quad (1)$$

where,  $q$  and  $\dot{q}$  are state variables.  $a(q, \dot{q})$  and  $B(q)$  are scalar function and vector one defined in following section. A strategy to control force and position proposed in this paper is also based on Eq. (1). Contrarily to Peng's Method [5] that has used Eq. (1) as a force sensor to estimate  $f_n$ , we used the equation for calculating  $\tau$  to achieve a desired constrained force  $f_{nd}$  [11] - [13].

In this paper, position and force control performances of our new controller [11] are confirmed by grinding experiments, especially on the view point that the force control space and the position control space are divided into orthogonal spaces being complement each other, that is, force space is defined by range space of  $B$  and the other is null space of  $B$ , that is  $(I - B^+B)$ .

The problem to be solved in our approach is that the mathematical expression of algebraic constraint condition should be defined in the controller instead of the merit of not using force sensor. Our grinding controller requires on-line estimation of constraint algebraic condition—the  $a(q, \dot{q})$  and  $B(q)$  in Eq. (1) include the mathematical descriptions of constraint condition  $C(r(q)) = 0$  that will be detailed in the next section—, which is changed since the grinding is the action to alter the constraint condition in nature. So, in this paper, we estimate the object's changing surface in real time using the grinder as a touch sensor. In order to give the system the ability to grind any working object into any shape, we focus on how to update the estimation constraint condition in real time, obtaining the result that spline function is best for on-line shape estimation. Based on the above preparation we conducted a continuous shape-grinding experiment to evaluate the proposed shape-grinding system, which aims for grinding to desired shape without force sensor, having confirmed the effectiveness of improving the transient responses of contact force by reshaping the time profile of the desired constrained force with several varieties.

## II. ANALYSIS OF GRINDING TASK

Generally speaking, the grinding power is related to the metal removal rate—weight of metal being removed within unit time—, which is determined by the depth of cut, the

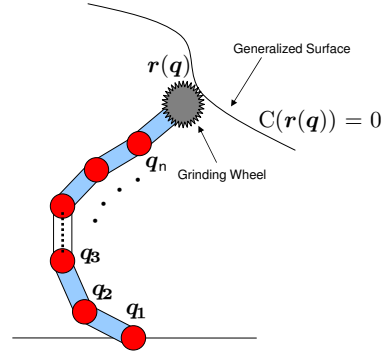


Fig. 2. Grinding Robot Model

width of cut, the linear velocity of the grinding wheel, the feed rate and so on. There are many empirical formulae available for the determination of grinding power, and the desired force trajectory can then be planned according to the power. The constrained force  $f_n$  is exerted on the workpiece in the perpendicular direction of the surface, and is a significant factor that affects ground accuracy and surface roughness of workpiece. The value of it is also related to the grinding power or directly to the tangential grinding force as

$$f_t = K_T f_n, \quad (2)$$

where,  $K_t$  is an empirical coefficient,  $f_t$  is the tangential grinding force.

## III. MODELING

An photo of the experiment device is shown in Fig. 1. A concept of grinding robot of constrained motion is shown in Fig. 2.

Constraint condition  $C$  is a scalar function of the constraint, and is expressed as an algebraic equation of constraints as

$$C(r(q)) = 0, \quad (3)$$

where  $r$  is the position vector from origin of coordinates to tip of grinding wheel and  $q$  is angles of motors.

The grinder set at the robot's hand is in contact with the constrained surface, which is modeled as following Eq. (4),

$$M(q)\ddot{q} + h(q, \dot{q}) + g(q) + D\dot{q} = \tau + J_C^T f_n - J_R^T f_t, \quad (4)$$

$$J_C^T = \frac{\left(\frac{\partial C}{\partial q}\right)^T}{\left\|\frac{\partial C}{\partial r}\right\|}, \quad (5)$$

$$J_R^T = \frac{\left(\frac{\partial r}{\partial q}\right)^T \dot{r}}{\|\dot{r}\|}, \quad (6)$$

where  $M$  is a  $n \times n$  matrix,  $h$  is centrifugal and coriolis

force vector,  $\mathbf{D}$  is viscous friction coefficient matrix,  $\mathbf{g}$  is gravity vector.  $f_n$  is the constrained force associated with  $C$  and  $f_t$  is the tangential disturbance force. Moreover,  $\mathbf{J}_C^T$  is time-varying coefficient vector translating  $f_n$  into each joint disturbance torque and  $\mathbf{J}_R^T$  is time-varying coefficient vector transmitting the tangential disturbance force  $f_t$  to joint disturbance torque. The dynamic equation represented by Eq. (4) must follow the constraint condition denoted by Eq. (3) during the contacting motion of grinding. Differentiating Eq. (3) by time twice, we have the following condition of the robot's grinder keeping in contact with the work-piece to be ground,

$$\left[ \frac{\partial}{\partial \mathbf{q}} \left( \frac{\partial C}{\partial \mathbf{q}} \right) \dot{\mathbf{q}} \right] \dot{\mathbf{q}} + \left( \frac{\partial C}{\partial \mathbf{q}} \right) \ddot{\mathbf{q}} = 0. \quad (7)$$

Above constraint condition represents an algebraic condition of  $\ddot{\mathbf{q}}$  that have to be determined dependently following to  $\mathbf{q}$  and  $\dot{\mathbf{q}}$ .

Putting  $\ddot{\mathbf{q}}$  in Eq. (7) and  $\ddot{\mathbf{q}}$  in Eq. (4) to be determined identically so as to the solution of  $\mathbf{q}$  and  $\dot{\mathbf{q}}$  of Eq. (4) comply simultaneously with the constraint condition Eq. (7), the solution  $\ddot{\mathbf{q}}$  and  $f_n$  could be uniquely determined. The following Eq. (8) is the resulted solution of  $f_n$  [11]-[13],

$$f_n = a(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{B}(\mathbf{q})\mathbf{J}_R^T f_t - \mathbf{B}(\mathbf{q})\boldsymbol{\tau}. \quad (8)$$

Where  $m_c$ ,  $a(\mathbf{q}, \dot{\mathbf{q}})$  and  $\mathbf{B}(\mathbf{q})$  are

$$m_c \triangleq \left( \frac{\partial C}{\partial \mathbf{q}} \right) \mathbf{M}^{-1} \left( \frac{\partial C}{\partial \mathbf{q}} \right)^T, \quad (9)$$

$$a(\mathbf{q}, \dot{\mathbf{q}}) \triangleq m_c^{-1} \left\| \frac{\partial C}{\partial \mathbf{r}} \right\| \left\{ - \left[ \frac{\partial}{\partial \mathbf{q}} \left( \frac{\partial C}{\partial \mathbf{q}} \right) \dot{\mathbf{q}} \right] \dot{\mathbf{q}} + \left( \frac{\partial C}{\partial \mathbf{q}} \right) \mathbf{M}^{-1} (\mathbf{h} + \mathbf{g}) \right\}, \quad (10)$$

$$\mathbf{B}(\mathbf{q}) \triangleq m_c^{-1} \left\| \frac{\partial C}{\partial \mathbf{r}} \right\| \left\{ \left( \frac{\partial C}{\partial \mathbf{q}} \right) \mathbf{M}^{-1} \right\}. \quad (11)$$

Substituting Eq. (8) into Eq. (4), the equation of motion of the constrained robot dynamics (as  $f_n > 0$ ) can be rewritten as

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) = \mathbf{J}_C^T a(\mathbf{q}, \dot{\mathbf{q}}) + (\mathbf{I} - \mathbf{J}_C^T \mathbf{B})\boldsymbol{\tau} + (\mathbf{J}_C^T \mathbf{B} - \mathbf{I})\mathbf{J}_R^T f_t. \quad (12)$$

Solutions of above dynamic equation always satisfy the constrained condition, Eq. (7), then accordingly  $\mathbf{q}$  satisfies Eq. (3).

#### IV. FORCE AND POSITION CONTROLLER

Reviewing the dynamic equation Eq. (4) and constraint condition Eq. (3), it can be found that as the number of links are 2, the number of input torque is 2 and it is more than that of the constrained force, i.e., 1. From this point and Eq. (8) we can claim that there is a redundancy of the number of the constrained force against the number of the input torque  $\boldsymbol{\tau}$ . This condition is much similar to the kinematical redundancy. Based on the above argument and assuming that, the parameters of the Eq. (8) are known and its state variables

could be measured, and  $a(\mathbf{q}, \dot{\mathbf{q}})$  and  $\mathbf{B}(\mathbf{q})$  could be calculated correctly, which means that the constraint condition  $C = 0$  be prescribed or measured correctly. As a result, a control law is derived from Eq. (8) and can be expressed as

$$\boldsymbol{\tau} = -\mathbf{B}^+(\mathbf{q})\{f_{nd} - a(\mathbf{q}, \dot{\mathbf{q}}) - \mathbf{B}(\mathbf{q})\mathbf{J}_R^T f_t\} + \{\mathbf{I} - \mathbf{B}^+(\mathbf{q})\mathbf{B}(\mathbf{q})\}\mathbf{k}, \quad (13)$$

where  $\mathbf{I}$  is a  $n \times n$  identity matrix,  $f_{nd}$  is the desired constrained forces,  $\mathbf{B}(\mathbf{q})$  is defined in Eq. (11) and  $\mathbf{B}^+(\mathbf{q})$  is the pseudoinverse matrix of it,  $a(\mathbf{q}, \dot{\mathbf{q}})$  is also defined in Eq. (10) and  $\mathbf{k}$  is an arbitrary vector used for hand position control, which is defined as

$$\mathbf{k} = \left( \frac{\partial \mathbf{r}}{\partial \mathbf{q}} \right)^T \{ \mathbf{K}_P(\mathbf{r}_d - \mathbf{r}) + \mathbf{K}_V(\dot{\mathbf{r}}_d - \dot{\mathbf{r}}) \}, \quad (14)$$

where  $\mathbf{K}_P$  and  $\mathbf{K}_V$  are gain matrices for position and the velocity control. The position and velocity control is executed through the redundant degree of range space of  $\mathbf{B}$ , that is null space of  $\mathbf{B}$ ,  $\{\mathbf{I} - \mathbf{B}^+ \mathbf{B}\}$ .  $\mathbf{r}_d$  is the desired position vector of the end-effector along to the constrained surface and  $\mathbf{r}$  is the real position vector on it. Eq. (14) describes the required torque to achieve  $f_{nd}$  firstly with the minimum norm torque. We have to set  $\mathbf{K}_P$  and  $\mathbf{K}_V$  with a reasonable value, otherwise high-frequency response of position error will appear. The controller presented by Eq. (13) and Eq. (14) assumes that the constraint condition  $C = 0$  be known precisely as we can see  $a(\mathbf{q}, \dot{\mathbf{q}})$  and  $\mathbf{B}(\mathbf{q})$  include constraint condition  $C$  in Eq. (10) and Eq. (11) respectively, even though the grinding operation is a task to change the constraint condition. This looks like a contradiction, so we need to observe time-varying constraint conditions in real time by using grinding tip as a touch sensor.

The time-varying condition is estimated as an approximate constrained function by position of the manipulator grinder used as touch sensor to presume the ground surface shape. The estimated condition is denoted by  $\hat{C} = 0$  (in this paper, “ $\hat{\phantom{x}}$ ” means the presumption of unknown constraint condition). Hence,  $a(\mathbf{q}, \dot{\mathbf{q}})$  and  $\mathbf{B}(\mathbf{q})$  including  $\partial \hat{C} / \partial \mathbf{q}$  and  $\partial / \partial \mathbf{q} (\partial \hat{C} / \partial \mathbf{q})$  are changed to  $\hat{a}(\mathbf{q}, \dot{\mathbf{q}})$  and  $\hat{\mathbf{B}}(\mathbf{q})$  as shown in Eq. (16) and Eq. (17). They were used in the estimation experiments of the unknown constrained condition. As a result, a controller based on the estimated constrained condition is given as

$$\hat{\boldsymbol{\tau}} = -\hat{\mathbf{B}}^+(\mathbf{q})\{f_{nd} - \hat{a}(\mathbf{q}, \dot{\mathbf{q}}) - \hat{\mathbf{B}}(\mathbf{q})\mathbf{J}_R^T f_t\} + \{\mathbf{I} - \hat{\mathbf{B}}^+(\mathbf{q})\hat{\mathbf{B}}(\mathbf{q})\}\mathbf{k}, \quad (15)$$

$$\hat{a}(\mathbf{q}, \dot{\mathbf{q}}) \triangleq m_c^{-1} \left\| \frac{\partial \hat{C}}{\partial \mathbf{r}} \right\| \left\{ - \left[ \frac{\partial}{\partial \mathbf{q}} \left( \frac{\partial \hat{C}}{\partial \mathbf{q}} \right) \dot{\mathbf{q}} \right] \dot{\mathbf{q}} + \left( \frac{\partial \hat{C}}{\partial \mathbf{q}} \right) \mathbf{M}^{-1} (\mathbf{h} + \mathbf{g}) \right\}, \quad (16)$$

$$\hat{\mathbf{B}}(\mathbf{q}) \triangleq m_c^{-1} \left\| \frac{\partial \hat{C}}{\partial \mathbf{r}} \right\| \left\{ \left( \frac{\partial \hat{C}}{\partial \mathbf{q}} \right) \mathbf{M}^{-1} \right\}. \quad (17)$$

Fig. 3 illustrates a control system constructed according to the above control law that consists of a position feedback



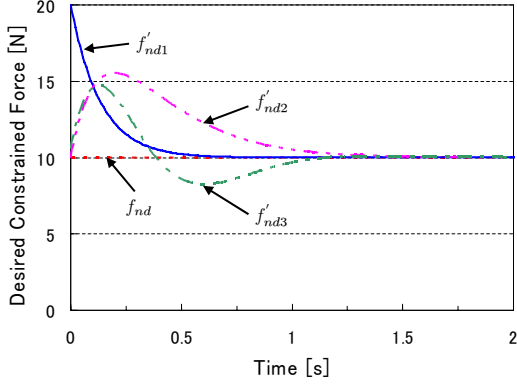


Fig. 5. Desired Constrained Force

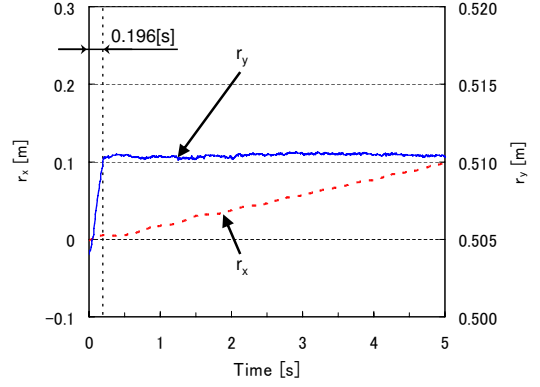


Fig. 7. Position Data  $r_x, r_y$  ( $f_{nd} = 10$  [N])

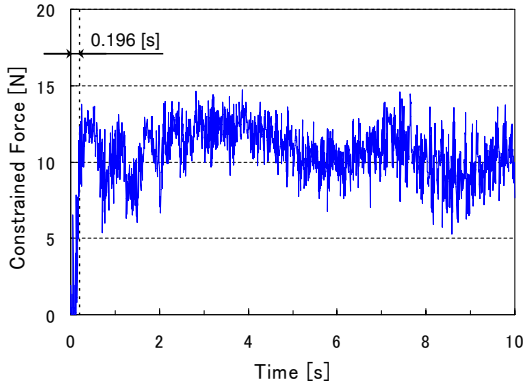


Fig. 6. Time Profile of Constrained Force when Step input Desired Force  $f_{nd} = 10$  [N] is given to The Controller being given by Eq. (15)

by a force sensor set between grinder and robot end-effector. In addition, the depicted force is calculated by averaging 10 times of touching motion experiments. The dotted line of 0.203 [s] shows the time delay defined in the previous section.

#### D. Modified Desired Force $f'_{nd3}$

We consider Eq. (23) as new desired constrained force.

$$f'_{nd3} = f_{nd}(1 + \alpha t e^{-wt} \cos(\omega t)). \quad (23)$$

Desired constrained force  $f_{nd}$  is given as 10.0 [N], coefficient  $\alpha$  is given as 16.0, weight  $w$  is given as 10.0 and angular frequency  $\omega$  is given as 8.0 [rad/s] in Eq. (23). Fig. 11 represents constrained force time profile. The dotted line of 0.217 [s] shows the time delay.

#### E. Comparison of Experiment Results

In this section, we compare Figs. 6, 9, 10 and 11. Table I represents a rising time  $T$  and an error calculated by averaging constrained force. The average force error, we call it in this paper as error rate  $R$  [%] was given by,

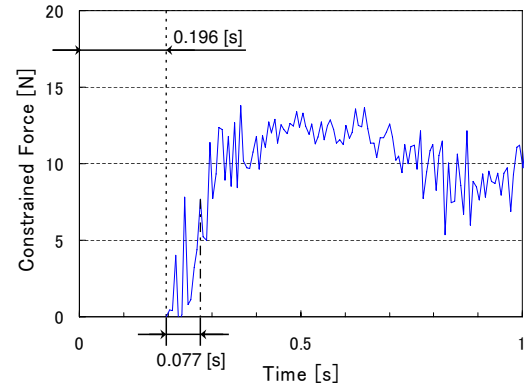


Fig. 8. Expansionary Figure of Fig. 6

$$R = \frac{100}{T f_{nd}} \int_0^T |f_{nd} - f_n| dt, \quad (24)$$

which represents average deviation force  $f_{nd}$ , and listed in right column of Table I. In Table I, the row of  $f_{nd}$  indicates the data of rising time  $T$  and error rate  $R$  on the condition that stop input  $f_{nd} = 10$  [N] is given at time  $t = 0$ . The other rows are on conditions of  $f'_{ndi}$  ( $i = 1, 2, 3$ ) being given, where the time-varying desired force profiles  $f_{nd}, f'_{ndi}$  are shown in Fig. 5. The new desired force time profiles  $f'_{ndi}$  are inspired by the force response result of  $f_{nd}$  shown in Fig. 6.

Table I shows that rising time for all condition ( $f'_{nd1}, f'_{nd2}, f'_{nd3}$ ) has been improved than the case of  $f_{nd}$  being given, where the rising time has been shorten to 0.007 [s] in any case of modified desired force;  $f'_{nd1}, f'_{nd2}, f'_{nd3}$ , from 0.035 [s] in case of constant desired force value,  $f_{nd} = 10$  [N]. On the both view points of Error rate and Rising time,  $f'_{nd3}$  is best.

## VI. CONCLUSION

In this paper, we have done some force-sensorless grinding experiments using the grinding robot system. We have confirmed about the first-order time delay has arisen in the force

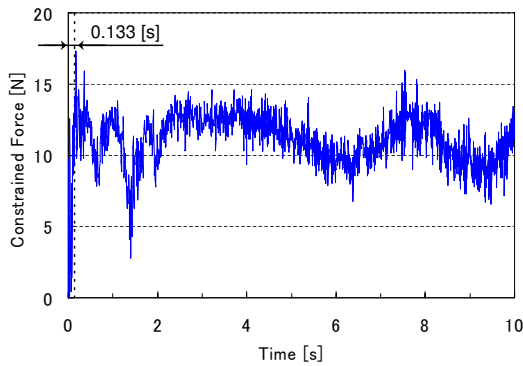


Fig. 9. Experiment Result ( $f'_{nd1}$ )

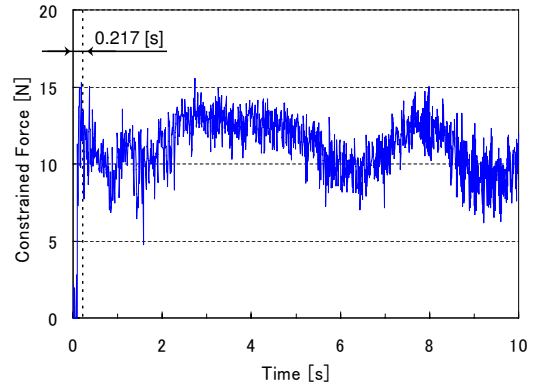


Fig. 11. Experiment Result ( $f'_{nd3}$ )

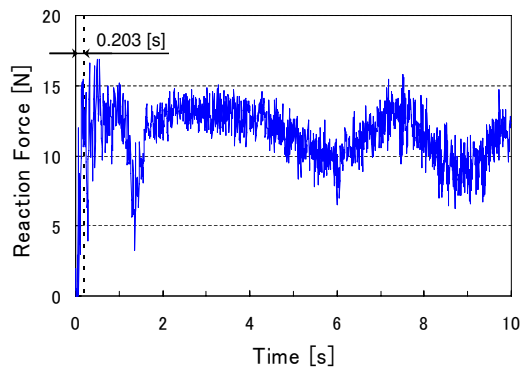


Fig. 10. Experiment Result ( $f'_{nd2}$ )

control. The desired constrained forces with three different kinds which changed by time have been given to improve the first-order time delay.

The rise time could be improved about to 1/5 in all the experiment results. Here, we have used Eq. (23) to show the result which has minimum error. In future, I'm going to do experiments of force-sensorless continuous sharp grinding using Eq. (23) in the force control.

Moreover, the thing for which it is checked whether it is what the cause of vibration of the analysis of movement or the experiment results of desired constrained force which arises in the collision depends on angle  $q_1$  since the edge of a grinder and the thing to be ground collide and vibration occurs as a future subject when grinding is started is mentioned.

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TABLE I  
COMPARISON OF RESULTS

	Rising Time $T$ [s]	Error Rate $R$ [%]
$f_{nd}$	0.077	12.4
$f'_{nd1}$	0.042	15.9
$f'_{nd2}$	0.028	24.3
$f'_{nd3}$	0.014	9.3

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