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ORIGINAL ARTICLE

Improvement of force-sensorless grinding accuracy with resistance compensation

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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 control. In order to grind the target object into desired shape with sufficient accuracy, the hand of the robot arm has to generate desired constrained force immediately after the grindstone being contacted with the metal object to be ground. Based on the algebraic equation, we have proposed constraint-combined force controller, which has the ability to achieve the force control without time delay if the motors should ideally generate required torques without time delay. In this paper, the relation between contacting force and grinding resistance force have been derived analytically and the relation is used for grinding force control, having brought improved grinding force accuracy.

Keywords Grinding · Robot · Force control · Force-sensorless

1 Introduction

Industrial robots are used for many purposes, i.e., welding, assembling and grinding operations. This research aims to achieve a new grinding robot system that can grind an object into desired shape with force-sensorless feed-forward force control.

Many researches have discussed force control methods of robots for constrained tasks. The conventional control strategies use force sensors [1, 2] 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 falling of the structure stiffness of manipulators, which is one of the most essential defects of manipulators executing grinding tasks. To solve these problems, some approaches that do not use force sensors have been presented [3–7].

In this paper, we discuss about grinding task of robot that has disk grinder as an end-effector. Our grinding robot (Fig. 1) is two link SCARA manipulator with a control period of 6 ms. The work-piece used in this paper is iron, whose spring constant of deformation against unit force is so huge 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 15 N in case that human conducts grinding task by hand. 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 do not use the time-differential equation of motion to describe constrained vertical process of the grinder contacting to the work-piece. Contrarily, we consider an algebraic equation as the constraint condition to analyze this contacting motion.

Based on this algebraic equation, we have proposed constraint-combined force controller (CCFC), which has the ability to achieve the force control without time delay if the motors

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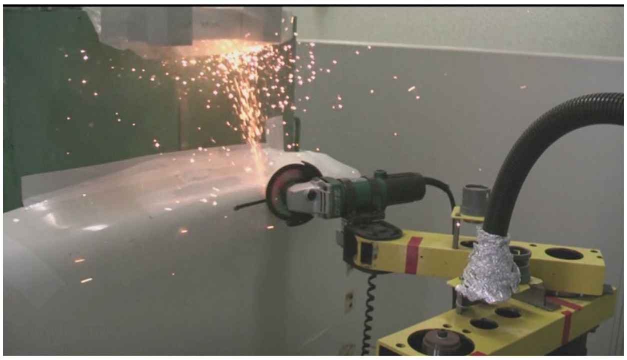

Fig. 1 Robot during grinding operation

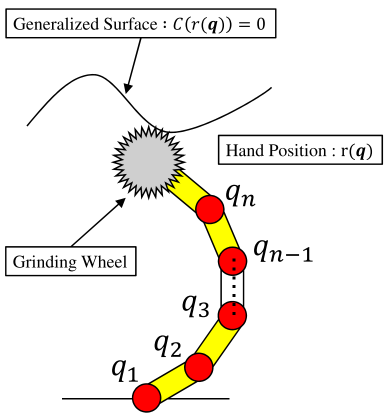

Fig. 2 Grinding robot model

should ideally generate required torques without time delay [9–11], where force error will not be affected by the dynamical motion along to the surface in non-constraining direction. The constraint-combined force/position control method without using sensors is essentially different from methods proposed so far [5–8].

The joint angles and angular velocities can be detected easily but the frictional force and frictional grinding coefficient that influence the contacting force control results are difficult to measure correctly. In this paper, the grinding resistance coefficient is obtained by experiments and it is confirmed that appropriate grinding control has been performed by compensating the influences from grinding resistance force to contacting force of the grinder.

2 Modeling of contact dynamics

A 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

$$C(\boldsymbol{r}(\boldsymbol{q})) = 0, \tag{1}$$

where $\boldsymbol{r}(m \times 1)$ is the position vector from origin of coordinates to tip of grinding wheel and $\boldsymbol{q}(n \times 1)$ is joint angles. The grinder set at the robot's hand is in contact with the material that is to be ground. The equation of motion of grinding robot is modeled as following Eq. (2) [9–11]:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}\dot{\boldsymbol{q}} = \boldsymbol{\tau} + \boldsymbol{J}_C{}^T f_n - \boldsymbol{J}_R{}^T f_t, \tag{2}$$

$$\boldsymbol{J}_C{}^T = \frac{\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)^T}{\left\| \frac{\partial C}{\partial \boldsymbol{r}} \right\|}, \quad \boldsymbol{J}_R{}^T = \left(\frac{\partial \boldsymbol{r}}{\partial \boldsymbol{q}}\right)^T \frac{\dot{\boldsymbol{r}}}{\|\dot{\boldsymbol{r}}\|}, \tag{3}$$

where $\boldsymbol{M}$ is a $n \times n$ matrix, $\boldsymbol{h}$ is centrifugal and coriolis force vector, $\boldsymbol{D}$ is viscous friction coefficient matrix, $\boldsymbol{g}$ is gravity vector. f_n is the constrained force associated with C and f_t is the tangential disturbance force caused by grinding. Moreover, $\boldsymbol{J}_C{}^T$ is time-varying coefficient vector translating f_n into each joint disturbance torque and $\boldsymbol{J}_R{}^T$ is time-varying coefficient vector transmitting the tangential disturbance force f_t to joint disturbance torque. The equation represented by Eq. (2) must follow the constraint condition given by Eq. (1) during the contacting motion of grinding. Differentiating Eq. (1) by time twice, we have the following relation among $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ that should be maintained during contacting motion with the work-piece to be ground,

$$\left[\frac{\partial}{\partial \boldsymbol{q}}\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\dot{\boldsymbol{q}}\right]\dot{\boldsymbol{q}} + \left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\ddot{\boldsymbol{q}} = 0. \tag{4}$$

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

Putting $\ddot{\boldsymbol{q}}$ in Eq. (4) into $\ddot{\boldsymbol{q}}$ in Eq. (2) to be determined identically so as the solution of $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$ of Eq. (2) to comply simultaneously with the constraint condition Eq. (4), the solution $\ddot{\boldsymbol{q}}$ and f_n could be uniquely determined. The following Eq. (5) is the resulted solution of f_n [9–11],

$$f_n = a(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{B}(\boldsymbol{q})\boldsymbol{J}_R{}^T f_t - \boldsymbol{B}(\boldsymbol{q})\boldsymbol{\tau}, \tag{5}$$

where m_c, $a(\boldsymbol{q}, \dot{\boldsymbol{q}})$ and $\boldsymbol{B}(\boldsymbol{q})$ are:

$$m_c \triangleq \left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)^T, \tag{6}$$

$$a(\boldsymbol{q}, \dot{\boldsymbol{q}}) \triangleq m_c{}^{-1}\left\|\frac{\partial C}{\partial \boldsymbol{r}}\right\|\left\{-\left[\frac{\partial}{\partial \boldsymbol{q}}\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\dot{\boldsymbol{q}}\right]\dot{\boldsymbol{q}} + \left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}(\boldsymbol{h} + \boldsymbol{g})\right\}, \tag{7}$$

$$B(q) \triangleq m_c^{-1}\left\|\frac{\partial C}{\partial r}\right\|\left\{\left(\frac{\partial C}{\partial q}\right)M^{-1}\right\}. \quad (8)$$

Substituting Eq. (5) into Eq. (2), the equation of motion of the constrained robot dynamics (as $f_n > 0$) can be rewritten as:

$$M(q)\ddot{q} + h(q,\dot{q}) + g(q) = J_C{}^T a(q,\dot{q}) + (I - J_C{}^T B)\tau + (J_C{}^T B - I)J_R{}^T f_t. \quad (9)$$

Solutions of above dynamic equation always satisfy the constrained condition, Eq. (4), then accordingly q satisfies Eq. (1).

3 Force and position controller

In the following discussions of grinding task, we assume that $m = 2$, $n = 2$, C is scalar function, since we use two link manipulator as a experimental device. Putting the above assumptions and Eq. (5) into consideration we can claim that there is a redundancy of the number of the constrained force, one, against the number of the input torque $\tau = [\tau_1, \tau_2]$. This condition is much similar to the kinematical redundancy. Based on the above argument and assume that, the parameters of Eq. (5) are known and its state variables could be measured, and $a(q,\dot{q})$ and $B(q)$ 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. (5) and can be expressed as:

$$\tau = -B^+(q)\{f_{nd} - a(q,\dot{q}) - B(q)J_R{}^T f_t\} + \{I - B^+(q)B(q)\}k, \quad (10)$$

where I is a 2×2 identity matrix, f_{nd} is the desired constrained forces, $B(q)$ is defined as Eq. (8) and $B^+(q)$ is the pseudoinverse matrix of it, $a(q,\dot{q})$ is defined as Eq. (7) and k is an arbitrary vector used for hand position control, which is given as:

$$k = \left(\frac{\partial r}{\partial q}\right)^T \{K_P(r_d - r) + K_V(\dot{r}_d - \dot{r})\}, \quad (11)$$

where K_P and K_V are gain matrices for position and the velocity control. The position and velocity control is conducted through the redundant degree of range space of B, that is null space of B, specifically $\{I - B^+B\}$. r_d is the desired position vector of the end-effector along to the constrained surface and r is the real position vector on it. K_P and K_V is needed to be set with a reasonable value, otherwise high-frequency oscillation of position error may appear.

The controller presented by Eqs. (10) and (11) assumes that the constraint condition $C = 0$ be known precisely as we can see $a(q,\dot{q})$ and $B(q)$ include constraint condition C in Eqs. (7) and (8), 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 constraint condition is estimated as an approximate constrained function by the 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, "∧" means the presumption of unknown constraint condition). Hence, $a(q,\dot{q})$ and $B(q)$ including $\partial\hat{C}/\partial q$ and $\partial/\partial q(\partial\hat{C}/\partial q)$ are changed to $\hat{a}(q,\dot{q})$ and $\hat{B}(q)$. 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

$$\tau = -\hat{B}^+(q)\{f_{nd} - \hat{a}(q,\dot{q}) - \hat{B}(q)J_R{}^T\hat{f}_t\} + \{I - \hat{B}^+(q)\hat{B}(q)\}k, \quad (12)$$

where $\hat{f}_t$ is estimated friction force. It can be found from Eqs. (5) and (12) that the constrained force always equals to the desired one explicitly if the estimated constraint condition equals to the real one, i.e., $C = \hat{C}$ and $f_t = \hat{f}_t$. This is based on the fact that force transmission is an instant process.

4 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 width of cut, the linear velocity of the grinding wheel, the feed rate and so on. There are many empirical formula 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 work-piece in the perpendicular direction of the surface, and is a significant factor that affects ground accuracy and surface roughness of work-piece. The value of it is also related to the grinding power or directly to the tangential grinding force as:

$$f_t = K_t f_n, \quad (13)$$

where K_t is an empirical coefficient, f_t is the tangential grinding friction force. Here in this discussion, the estimated friction force $\hat{f}_t$ in Eq. (12) is assumed to be given as

$$\hat{f}_t = \hat{K}_t f_{nd}. \quad (14)$$

5 Considering grinding resistance

In the previous section, we mentioned that the input τ can be determined through q, $\dot{q}$ and f_t observed. When the tangential grinding friction force estimated by Eq. (14) is used in the control law, Eq. (12), and further substituting the result into

Eq. (5), the relationship between the constrained force f_n and the target constrained force f_{nd} is

$$f_n = f_{\mathrm{nd}} + \boldsymbol{B}(\boldsymbol{q})\boldsymbol{J}_R^T(f_{\mathrm{t}} - \hat{K}_{\mathrm{t}} f_{\mathrm{nd}}). \tag{15}$$

Therefore, it can be understood from Eq. (15) that the second term on the right side corresponds to the friction force error made by the difference between actual friction force f_{t} and estimated friction force $\hat{K}_{\mathrm{t}} f_{\mathrm{nd}}$. $\boldsymbol{B}(\boldsymbol{q})\boldsymbol{j}_R^T$ is determined by $\boldsymbol{q}$. The error between the actual constrained force f_n obtained from the experimental result and the desired force f_{nd} is considered to be proportional to $(f_{\mathrm{t}} - \hat{K}_{\mathrm{t}} f_{\mathrm{nd}})$ given the condition that the changing of $\boldsymbol{q}$ is limited in small extent.

When defining $\Delta f = f_{\mathrm{nd}} - f_n$, Eq. (15) can be changed into

$$\Delta f = \boldsymbol{B}(\boldsymbol{q})\boldsymbol{j}_R^T(\hat{K}_{\mathrm{t}} f_{\mathrm{nd}} - f_{\mathrm{t}}). \tag{16}$$

Considering that the change of the manipulator's shape during grinding dose not large, $\boldsymbol{B}(\boldsymbol{q})\boldsymbol{j}_R^T$ seems to be generally constant.

In this report, the tangential grinding force that reduces the error of the constrained force is obtained from the experiment, by determining the correct coefficient $\hat{K}_{\mathrm{t}}$ to have the Δf to minimized. The control performance is confirmed in the next section.

6 Experiment

Figure 3 shows experimental environment. Our robot is two link SCARA manipulator with a control period of 0.6 ms. The work-piece is iron. Figure 4 shows the appearance of placed work-piece.

6.1 Determination of grinding resistance coefficient

The desired grinding force is set as constant, and the grinding resistance coefficient $\hat{K}_{\mathrm{t}}$, which has been explained in Sect. 4, is changed as a experimental parameter. The appropriate $\hat{K}_{\mathrm{t}}$ can be determined from the following experiment. With the condition that the change of the robot posture can be thought to be constant, the target grinding force is set to $f_{\mathrm{nd}} = 10$ N, the grinding resistance coefficient $\hat{K}_{\mathrm{t}}$ is changed by 0.1 from 0.1 to 0.6. Then the average grinding force $f_n$values was examined. Figure 5 shows the average value of the grinding force at each grinding resistance coefficient. The grinding resistance of $\hat{K}_{\mathrm{t}}$ to achieve the desired grinding force 10 N is estimated as 0.192 that is the intersection of the approximate straight line $F_n = 8.05\hat{K}_{\mathrm{t}} + 8.45$ and $F_n = 10$ as shown in the graph of Fig. 5 with the numerical data shown in Table 1.

Fig. 4 Work-piece

6.2 Verification of derived grinding resistance

An arbitrary desired grinding force can be achieved by control using the determined grinding resistance coefficient. In order to verify the validity of the grinding resistance coefficient $\hat{K}_{\mathrm{t}}$, grinding experiment was conducted by changing the value of the desired grinding force f_{nd} from 6 to 10 N, with the actual grinding force was measured.

$\hat{K}_{\mathrm{t}}$ was set to 0.192 and other experimental environments and conditions were the same as in the previous section, and only the desired grinding force f_{nd} was changed. Grind feed speed is 20 [mm/s] and grinding operation time is 10.0 s. The result is shown in Table 2. It shows the error

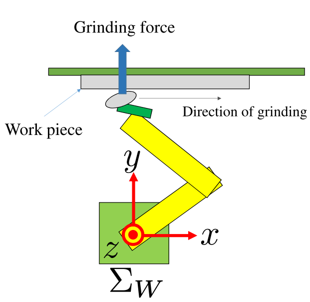

Fig. 3 Schematic diagram of experimental environment

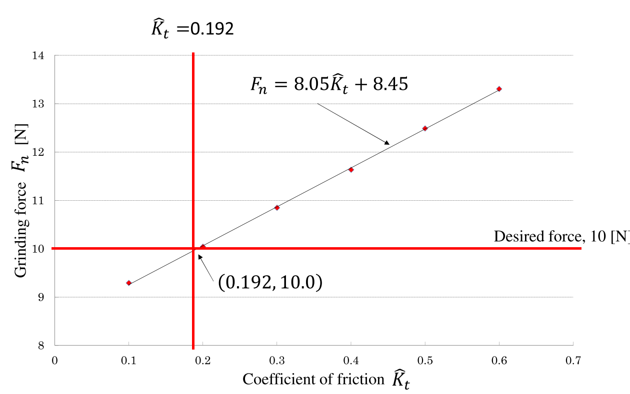

Fig. 5 Forces on each grinding resistance coefficient

between the average value of the actual grinding force and the desired value. And in Fig. 6, the time profile transition of the actual grinding forces during grinding are shown. The desired force is depicted by dashed line. The thin solid line means the measured grinding force and the dark solid line means the moving average with the time span of 6 ms. In Fig. 7, the transition of the grinding force from 6.0 to 6.1 s is shown by expanding the range of time from Fig. 6. From Fig. 7, it has been found that the grinding force has been roughly controlled to the desired values although irregular outliers are generated due to the influence of contacting motion grinding surface and grinding wheel. The data from 6.0 to 6.1 s is generally similar to the data form 0 to 10 s. Figure 8 shows that the grinding force is roughly controlled to desired value throughout the experiment.

Table 1 Error between target grinding force and measured force on each grinding resistance coefficient $\hat{K}_t$

$\hat{K}_t$	f_n(N)	$f_{nd} - f_n$(N)
0.1	9.30	−0.70
0.2	10.05	0.05
0.3	10.85	0.85
0.4	11.63	1.63
0.5	12.49	2.49
0.6	13.31	3.31

Table 2 Error between measured grinding force and target

f_{nd} (N)	f_n (N)	$f_n - f_{nd}$ (N)
6	6.19	0.19
7	7.15	0.15
8	8.22	0.22
9	8.94	−0.06
10	10.13	0.13

From Eq. (15), it is expected that the error between the actual grinding force obtained from the experimental result and the desired value becomes proportional to $(f_t - \hat{K}_t f_{nd})$. From Fig. 5, it can be confirmed that the error between the actual grinding force and the desired one appears in the linear against $\hat{K}_t$. From Figs. 6 and 7, the force time profile obtained by using the controller given by Eq. (12) can be improved by adjusting $\hat{K}_t$ into empirically trustful value, 0.192.

7 Conclusion

In this report, the effect of grinding resistance on grinding force was described. Calculating that the appropriate value of $\hat{K}_t$ is 0.192 from the approximate straight line of the graph of $\hat{K}_t$ and the error of force control, the validity of the true value of $\hat{K}_t$ is verified by conducting grinding with varying the desired grinding force, having confirmed that the average

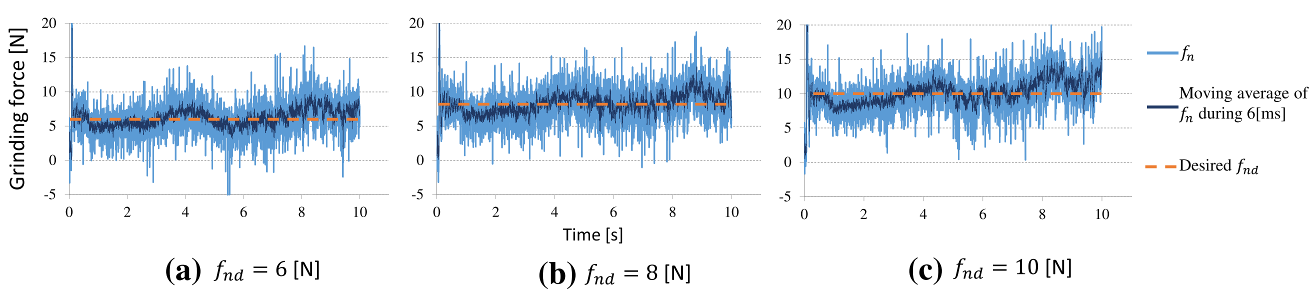

Fig. 6 Experimental result f_n

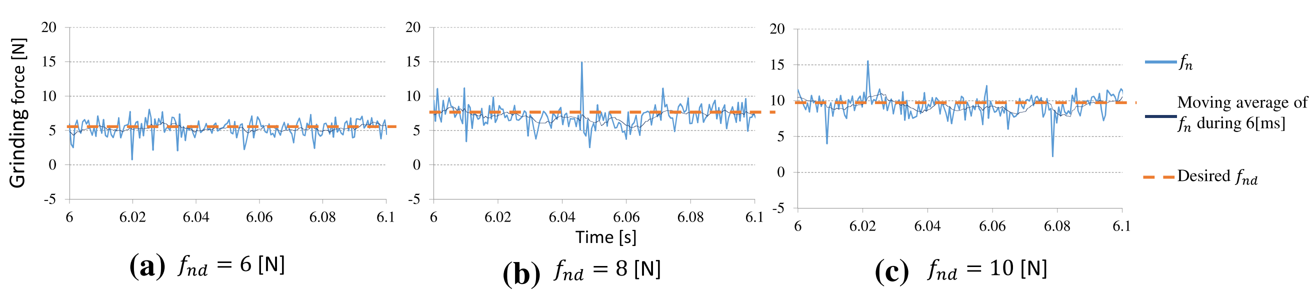

Fig. 7 Experimental result f_n from 6 to 6.1 s

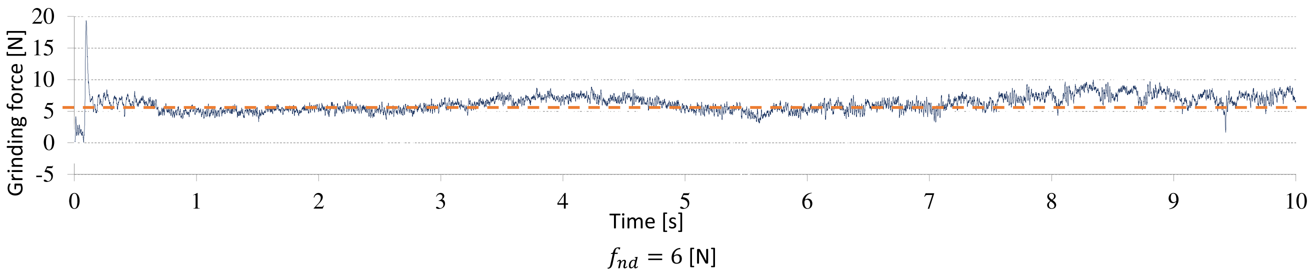

Fig. 8 The moving average of f_n is especially shown. It has been found that the grinding force has been roughly controlled to the desired value

value of the grinding force was controlled to the desired force roughly.

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