Position Control and Explicit Force Control of Constrained Motions of a Manipulator for Grinding Tasks

福井大学
工学部 研究報告
第44巻 第2号
1996年9月

Position Control and Explicit Force Control of Constrained Motions of a Manipulator for Grinding Tasks

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(Recieved Aug. 30, 1996)

On the basis of a detailed analysis of the grinding process, motions of the constrained dynamic system of a grinding robot is modeled in this report. In the model, the constrained generalized forces are included and expressed as an obvious function of the state and input generalized forces. Thereafter, a control law is presented by taking the advantage of the redundancy of input generalized forces to the constrained forces. A controller is then constructed without involving any force feedback sensors. Simulations have been done for justificating the feasibility of the controller by taking an articulated planar two-link manipulator as an example. Results show the effectiveness of the controller.

1. Introduction

In pace with the advancement of mechanical manufacturing technology on automaticity and flexibility, more and more robots have been introducing into various fields in industry for kinds of tasks. Welding and spray painting robots that without contaction with objects are widely used and are very successful in application. Assembly, measurment and deburring robots that with little contacting forces with circumstances have also been applied and successful examples are not rare. However, in the case that much bigger contact forces have to be dealt with, for instance, for grinding task, the application of a robot is at least sparse if not none[2]-[3].

It is well known that robots, particularly articulated types, are very dextrous and have large operating volumn. Hence, it is reasonable to introduce such kinds of robots more extensively into manufacturing so as to perform some machining operations that are too expensive or too difficult for a machine tool to do. On the other hand, compare with a machine tool, the characteristics of robots on stiffness, damping and vibration-proofing are somewhat poor. Therefore, much sophisticated design and control strategies have to be developed.

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It is one of the effective strategies to simultaneously control the position and force for constrained motions of robots. Many researches have been engaged on such control of robots and all of the force control strategies include force sensors[2],[5]. However, joint-mounted force sensors now available for obtaining force information are limitted by the reliability and accuracy as being employed in worksite where noises are everywhere. Although the wrist or hand mounted force sensors are more sensitive and easier to use than joint sensors, they pose challenging problems in mechanical design, electronics and communications[5]. For these reasons, a new strategy for simultaneously controlling the position and force of a grinding robot without using any force sensors is presented in this report.

The strategy is based on two facts that have been ignored for a long time. One of them is that the force transmission process is an immediately finished process for a rigidly structured manipulator as the acceleration being determined by state variables and input gerneralized force while the occurence of velocity and position is a time-consuming process. Another is that there is some dynamic redundancy for the input generalized forces comparing with the constrained generalized forces as force control as well as position control are needed at the same time.

In what follows, the grinding tasks are firstly analyzed in Section 2. In Section 3, the constrained dynamic system of a grinding robot is modeled with Lagrangian dynamics by including constrained forces, and the constrained generalized forces are expressed as an obvious function of the input generalized forces(torques and/or forces) and the state of the system. Then based on the above-mentioned two facts a controller without involving any force sensor is therefore constructed in Section 4, which is different from the traditional ones. In Section 5, a planar two-link manipulator is considered, and simulations are carried out to verify the feasibility of the theory and the controller presented.

2. Analysis of Grinding Task

There are four kinds of grinding processes in common use including vertical surface grinding, horizontal surface grinding, internal grinding and cylindrical grinding, as shown in Fig.1. A grinding machine usually can only perform one or two of these processes because of kinematical limitation. However, all of these four kinds of tasks can be finished by a single robot manipulator for its dexterity on movement. As performing grinding tasks, the grinding wheel will come into contact with the environment, i.e., the workpiece. The particular set of contacting surfaces, generally the surfaces being ground, will form a set of constraints to the motions of the wheel. As for vertical surface grinding operation shown in Fig.1(a), the grinding wheel in contact with a surface of the workpiece is not free to move through that surface, which forms a position constraint, and also, the wheel connot freely apply arbitrary force tangent to the surface in order to avoid being over worn or even broken, which forms a force constraint. Situations of constraints for other kinds of grinding tasks are shown in Fig.1(b), (c) and (d).

In general, for each task configuration, a generalized surface can be defined in a constraint space having N degrees of freedom, with position constraints along the normals to this surface and force constraints along the tangents. Desired motions of position and force patterns in a task configuration should be specified according to these constraints. The desired motions also occur along the tangents and normals to the generalized surface, for instance, the desired force should be specified along surface

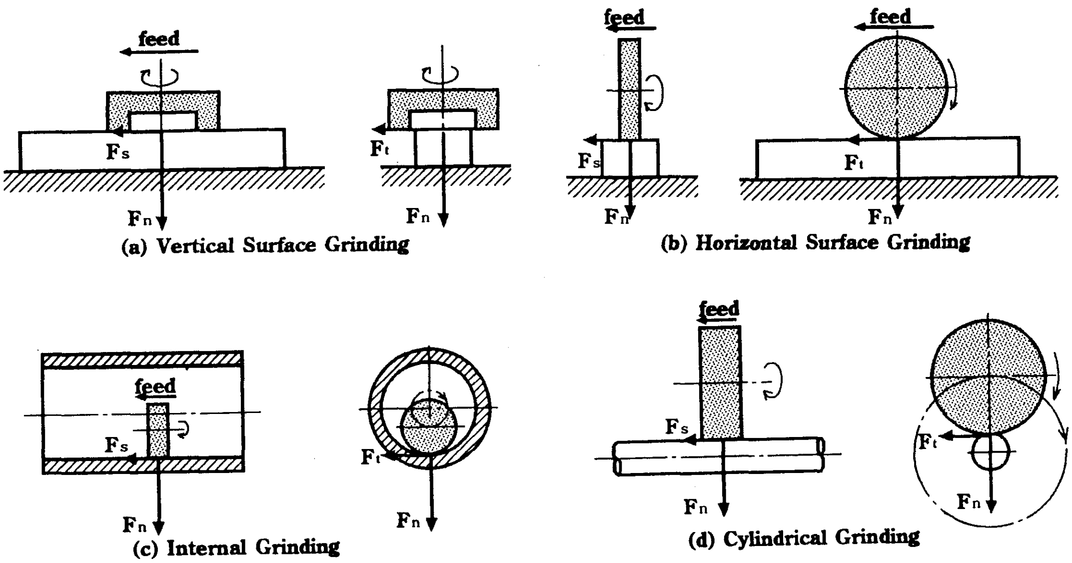

Fig. 1 . Types of Grinding Tasks.

normals, and desired position along tangents for the above-mentioned constraints(also refer to Fig.1).

In general, the desired grinding position trajectory is given by processing drawings for each procedure that has taken the grinding allowance into consideration. As for forces(refer to Fig.1), the desired values should be determined carefully for different grinding conditions. Generally speaking, the grinding power is related to the metal removal rate(volumn or weight of metal being removed within unit time) that determined by the depth of cut, the width of cut, the linear velocity of the grinding wheel, the feed rate and so forth. 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 tangential grinding force F_t has direct relationship with the driven power of grinder, which mainly causes the change of grinding temperature and thermal deformations and can be expressed as(refer to [4], p.38),

$$F_t = 9.8 \times 60 \times 102 \frac{N}{V} \quad (N), \tag{1}$$

where, $N(kW)$ is the grinding power, $V(m/min)$ is the linear velocity of the grinding wheel.

The normal grinding force F_n is acted in the direction perpendicular to the surface. It is a significant factor that affects grinding dimensional accurate and surface roughness of workpiece in application. The value of it is also related to the grinding power or directly to the tangential grinding force as

$$F_n = K_F F_t, \tag{2}$$

where, K_F is a coefficient and usually is about two or so (for detailed values, refer to [4] or other literatures available).

The axial grinding force F_s is propotional with the feed rate, and is much smaller than the former two.

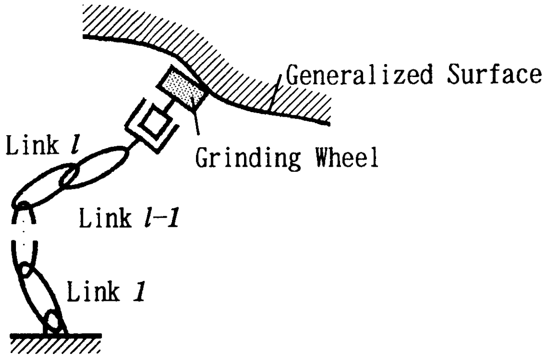

Fig. 2. A Grinding Robot.

For grinding task, the normal force and tangential velocity are the most important two factors. To improve grinding quality, it is usually desired that the normal force and the tangential velocity are constant.

Because grinding is a kind of precision machining method, for a robot to do so, force control is necessary in addition to position control. Usually, as force control being carried out, force sensor is an essential element. However, sensors pose many challenging probloms as the above-mentioned. Therefore, a way is proposed in the following to obtain force information by calculation rather than by using force sensors.

3. Modelling of Constrained Dynamic Systems

Hemami and Wyman[1] have addressed the issue of control of a robot during constrained motion and examined the problem of control of biped locomotion constrained to motion in the frontal plane. Although the objective of them was to control the position coordinates of the biped rather than generalized forces of constraints, their constrained dynamic equation included the item of generalized forces of constraints. For this reason, the system of the grinding manipulator shown in Fig.2 is modelled as following with Langrangian equations of motion including the constraint forces by refering what Hemami has done:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \left(\frac{\partial L}{\partial q}\right) = \boldsymbol{\tau} + \left(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}}\right)^T \boldsymbol{\Gamma}, \tag{3}$$

where , L is the Lagrangian, $\boldsymbol{q}$ is l generalized coordinates, $\boldsymbol{\tau}$ is l inputs, $\boldsymbol{C}$ is r independent constraints, and expressed as a constrained equation,

$$\boldsymbol{C}(\boldsymbol{q}) = \mathbf{o}, \tag{4}$$

$\boldsymbol{\Gamma}$ is an r vector with the ith component γ_i being the force of constraint associated with the ith component of $\boldsymbol{C}$. Eq.(3) can be derived to be

$$\boldsymbol{M}(\boldsymbol{q})\ddot{q} + \boldsymbol{H}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau} + \left(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}}\right)^T \boldsymbol{\Gamma}, \tag{5}$$

where $\boldsymbol{M}$ is an $l \times l$ matrix $\boldsymbol{H}$ and $\boldsymbol{G}$ are l vectors. The state variable $\boldsymbol{x}$ is constructed by adjoining $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$: $\boldsymbol{x} = (\boldsymbol{x}_1, \boldsymbol{x}_2)^T = (\boldsymbol{q}, \dot{\boldsymbol{q}})^T$. The state-space equation of the system are

$$\begin{aligned} \dot{\boldsymbol{x}}_1 &= \boldsymbol{x}_2, \\ \dot{\boldsymbol{x}}_2 &= -\boldsymbol{M}^{-1}(\boldsymbol{H}(\boldsymbol{x}_1, \boldsymbol{x}_2) + \boldsymbol{G}(\boldsymbol{x}_1)) + \boldsymbol{M}^{-1}\left(\boldsymbol{\tau} + \left(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{x}_1}\right)^T \boldsymbol{\Gamma}\right), \end{aligned} \tag{6}$$

or in the compact form,

$$\dot{x} = F(x, \tau, \Gamma), \tag{7}$$

where the dimension of x is $n = 2l$. In order to control the system (7) with constraints (4) , it can be done firstly by differentiating the constraint equation (4) twice with respect to time and rewriting the result in terms of x:

$$D(x)\dot{x} = \mathbf{o}, \tag{8}$$

where, $D(x)$ is an $r \times n$ matrix whose rows span the r-dimensional space to which the constrained motion of the system is orthogonal. Premultiplying Eq.(7) by $D(x)$ derived from Eq.(8),

$$D(x)F(x, \tau, \Gamma) = \mathbf{o}. \tag{9}$$

This is a set of r linear equations in the r unknown constrained forces Γ. Eq.(9) can be uniquely solved for Γ as a function of the state x and input τ,

$$-[\frac{\partial}{\partial q}(\frac{\partial C}{\partial q})\dot{q}]\dot{q} + (\frac{\partial C}{\partial q})M^{-1}(H(q,\dot{q}) + G(q)) - (\frac{\partial C}{\partial q})M^{-1}\tau = [(\frac{\partial C}{\partial q})M^{-1}(\frac{\partial C}{\partial q})^T]\Gamma. \tag{10}$$

Because the $r \times r$ matrix

$$(\frac{\partial C}{\partial q})M^{-1}(\frac{\partial C}{\partial q})^T$$

is positive definite, it is consequently invertible. In this case, Γ can be worked out from Eq.(10) as

$$\Gamma = \Gamma(x, \tau), \tag{11}$$

or in a detailed form

$$\begin{aligned} \Gamma &= [(\frac{\partial C}{\partial q})M^{-1}(\frac{\partial C}{\partial q})^T]^{-1}\{-[\frac{\partial}{\partial q}(\frac{\partial C}{\partial q})\dot{q}]\dot{q} + (\frac{\partial C}{\partial q})M^{-1}(H(q,\dot{q}) + G(q))\} \\ &\quad -[(\frac{\partial C}{\partial q})M^{-1}(\frac{\partial C}{\partial q})^T]^{-1}\{(\frac{\partial C}{\partial q})M^{-1}\}\tau \\ &\triangleq a(x_1, x_2) - A(x_1)\tau, \end{aligned} \tag{12}$$

where, $a(x_1, x_2)$ is an $r \times 1$ vector representing the first item in the expression of Γ, and $A(x_1)$ is an $r \times l$ matrix that represents the coefficient matrix of τ in the same expression. Eqs.(7) and (11) form a constrained system that can be controlled with the following method. The above two Eqs.(7) and (11) with Γ=0, describe the unconstrained motion of the system.

Substituting the Eq. (12) into Eq.(6), the state equation of the system including the constrained force (as $\Gamma > 0$) can be rewritten as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= -M^{-1}[H(x_1, x_2) + G(x_1) - (\frac{\partial C}{\partial x_1})^T a(x_1, x_2)] + M^{-1}[\tau - A(x_1)\tau]. \end{aligned} \tag{13}$$

Note that the solution of these dynamic equations will always satisfy the constrained equation (4) so that the normal position error will always be zero.

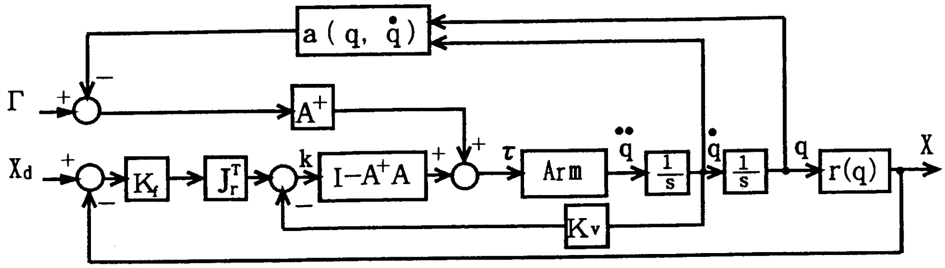

Fig. 3. Controller.

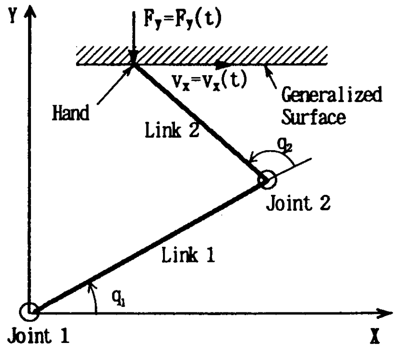

Fig. 4. A Planar 2-link Grinding Manipulator.

4. Controller

By reviewing the dynamic equation (3), it can be found that as $r < l$ the number of input generalized forces is greater than that of the constrained forces. From this point of view we can say that there is some dynamical redundancy between the input torques and a part of output—the constrained forces. This phenomenon is much similar to the kinematic redundancy of redundant manipulator. Based on this argument and the two facts mentioned in Section 1, a control law is presented and can be expressed as

$$\tau = -A^{+}(x_1)(\Gamma_d - a(x_1, x_2)) + (I - A^{+}(x_1)A(x_1))k, \qquad (14)$$

where I is an identity matrix, Γ_d is the desired constrained force, i.e., the F_n in Eq.(2) in Section 2, $A(x_1)$ is defined as in Eq.(12) and $A^{+}(x_1)$ is the pseudoinverse matrix of it, $a(x_1, x_2)$ is also defined as in Eq.(12) and k is an arbitrary vector which is defined as

$$k = J^T(q)K_f(X_d(q) - X(q)) - K_v\dot{q} \qquad (15)$$

where $J^T(q)$ is the transposed Jacobian matrix of the manipulator, K_f is a coefficient matrix that is applied to control the position by using the redundant degree of freedom, $X_d(q)$ is the desired position vector and $X(q)$ is the practical position vector of the end effector, and K_v is a joint velocity gain matrix.

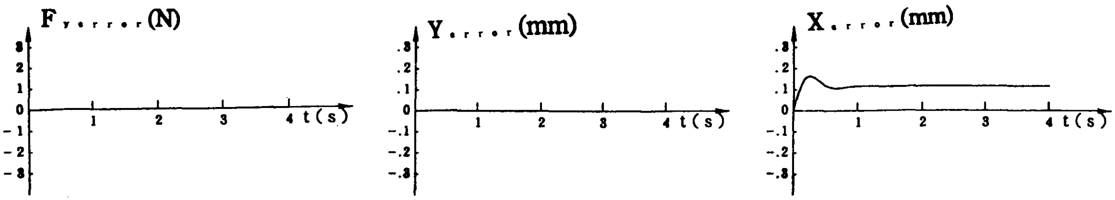

Fig. 5. Constant Tangential Velocity and Constant Normal Force Control.

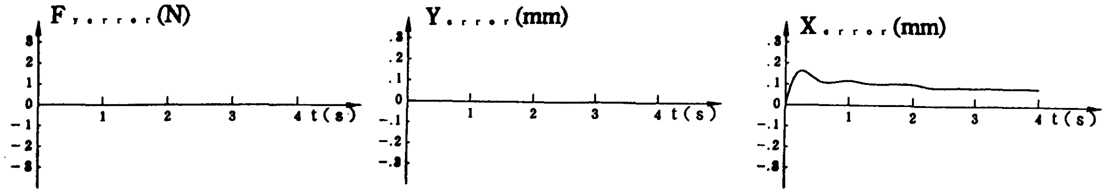

Fig. 6. Constant Tangential Velocity and Step Normal Force Control.

Fig.3 illustrates a control system constructed with the above control law that consists of a position control loop and a force control loop. The controller coorporates the idea proposed in the Section 3, i.e., by using the terms of computed constrained force Γ for control rather than sensing one.

It can be found from Eqs.(14) and (12) that the constrained force always equals to the desired one. This is based on the fact that force transmission is an instant process. Additionally, because the constrained equation constrains the normal position, which makes the normal position error always be zero.

5. Simulations

A planar two-link manipulator is applied for simulation so as to examine the behaviour of the proposed controller. The goals were to examine the feasibility of the method as well as the constrained dynamic equations with regard to the accuracy and stability.

The model of grinding robot manipulator is shown in Fig.4 and the constrained dynamic eqaution of the manipulator is formulated in the form of Eq.(13). A controller as shown in Fig.3 is applied. The parameters of the robot are: length of link 1 is 0.5m, mass of link 1 is 5kg, length of link 2 is 0.4m and mass of link 2 is 4kg. The boundary of the constraint, i.e., the tracked trajectory is $Y = 0.5m$(as $X \geq 0.1m$).

Fig.5 shows the constant velocity control in X direction(tangential direction) and constant force control in Y direction(normal direction). The initial velocity and force are zero, the desired velocity in X direction is $v_{xd} = 0.0025m/s$ and the desired force in Y direction is $F_{yd} = -1N$. The gains of the controller are respectively $K_{f1} = K_{f2} = 1500$ and $K_{v1} = K_{v2} = 20$. It can be seen that the position error in Y direction is always zero($Y_{error}(t) = 0$) and the desired force can always be achieved($F_{yerror}(t) = 0$, i.e., $F_y = F_{yd}$) while there is a small stationary error in X direction($X_{error}(t) = X_d - X = 0.117mm$, as $t \geq 1.8s$).

Fig.6 depicts the simulation result of the constant velocity control in X direction as the force in Y

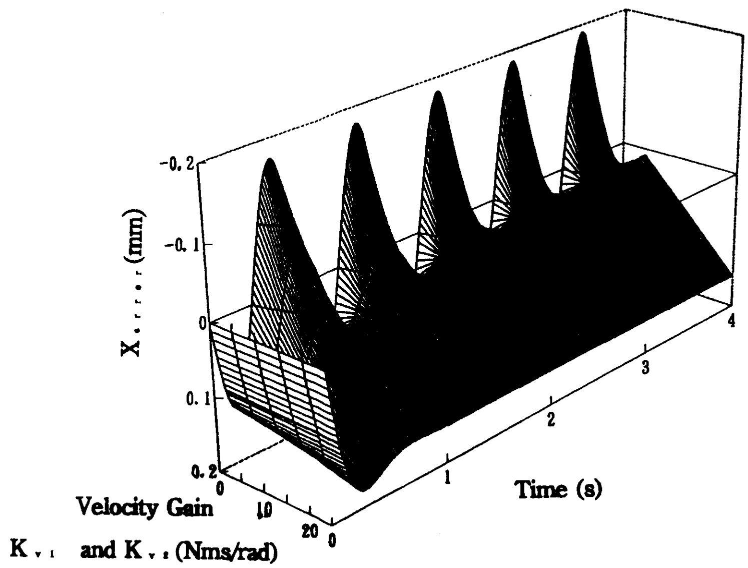

Fig. 7. Effect of K_v of Controller on X_{error}(as $K_{f1} = K_{f2} = 1500$).

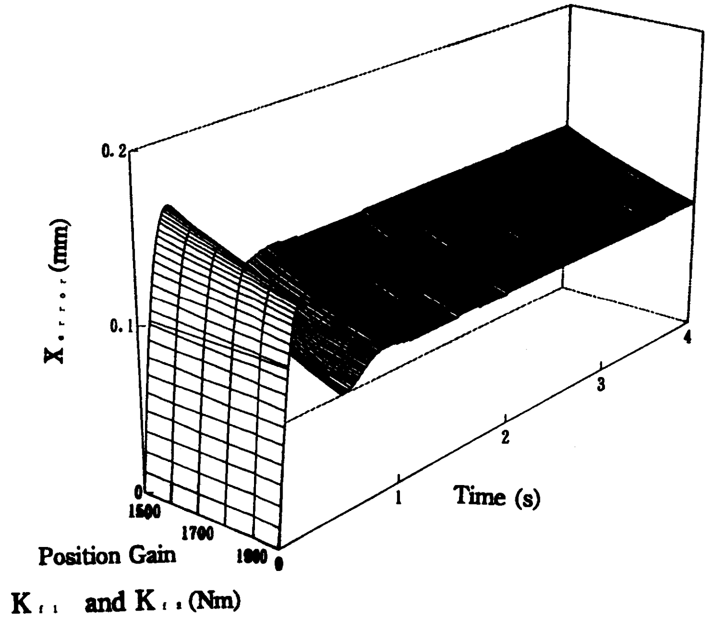

Fig. 8. Effect of K_f of Controller on X_{error}(as $K_{v1} = K_{v2} = 20$).

direction changed steply. The initial velocity and force are zero, the desired velocity in X direction is also $v_{xd} = 0.0025m/s$ and the desired force in Y direction is $F_{yd} = -1N(0 < t \leq 1s)$, $F_{yd} = -2N(1s < t \leq 2s)$ and $F_{yd} = -3N(t > 2s)$. The gains of the controller are the same with the above situation. It can also be found that the position error in Y direction is always zero and the desired force can always be achieved while there is a small stationary error in X direction($X_{error} = X_d - X = 0.090mm$, as

$t \geq 2.3s$).

Figures 7 and 8 demonstrate the effect of the gains of the controller on the tangential position error while performing constant velocity control in X direction and constant force control in Y direction. The initial velocity and force, the desired velocity in X direction and the desired force in Y direction are the same as the first case(Fig.5). While the position error and force error in Y direction are always zero, the position error in X direction is changed with different gains. As shown in Fig.7, when $K_{v1} = K_{v2} = 0$, the tangential error X_{error} vibrates harmonically; and when $K_{v1} = K_{v2}$ increased from 0 to $25[Nms/rad]$, the amplitude decreased and offset error of X_error increased.

Fig.8 shows the effect of the position gains of the controller on the tangential error X_{error} as $K_{v1} = K_{v2} = 20[Nms/rad]$. It can be seen that as the position gain increased from $K_{f1} = K_{f2} = 1500$ to $2000[N/m]$(the system becomes unstable when the position gains turn to surpass this range), the amplitude as well as the offset error decreased.

6. Conclusions

The constrained dynamic equations of a manipulator are derived and the constrained forces are expressed as an obvious function of the state and inputs. The presented methodology allows computation of the forces, as an alternative to sensing. Hence, the system is controlled with no force sensor. The control law presented is constructed by taking the advantage of the dynamical redundancy of constrained systems. The controller designed with this control law can be used for simultaneous control of force and position. Simulation with a planar 2-link manipulator show that the desired force is always achieved and the position error in normal direction is always zero while there is a small stationary error in tangential direction.

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