FORCE CONTROL OF ROBOT MANIPULATOR USING FUZZY CONCEPT

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ABSTRACT

An approach to robot force control, which allows force manipulations to be realized without overshoot and overdamping while in the presence of unknown environment, is given in this paper.

The main idea is to use dynamic compensation for known robot parts and fuzzy compensation for unknown environment so as to improve system performance. The fuzzy compensation is implemented by using rule based fuzzy approach to identify unknown environment. The establishment of proposed control system consists of following two stages. First, similar to the resolved acceleration control method, dynamic compensation and PID control based on known robot dynamics, kinematics and estimated environment compliance is introduced. To avoid overshoot the whole control system is constructed overdamped. In the second stage, the unknown environment stiffness is estimated by using fuzzy reasoning, where the fuzzy estimation rules are obtained priori as the expression of the relationship between environment stiffness and system response.

Based on simulation result, comparisons between cases with or without fuzzy identifications are given, which illustrate the improvement achieved.

1.INTRODUCTION

Robotic manipulation may be divided in two ways: moving freely in the work space and dynamically interacting with the environment under constraints. Conventional PID control with dynamic compensation is sufficient when motions of robots are unconstrained and the necessary information about dynamics of robot arms, actuators and kinematics is available. As for the force control, various methods have been proposed in the literature[1-3]. An overview is given by[4]. The common tendency of these papers is trying to introduce dynamic and kinematic compensations as precisely as possible to satisfy the precise requirements for various manipulation. However, dynamic and kinematic compensation may fail to work in accordance with force control requirements due to the lack of perfect models about the robot arm, actuators and the environment the robot interacts with. In most cases these uncertainties are

(1) uncertainties of robotic mechanism, mainly the unmeasurable friction coefficients including both viscous and static ones of actuators and links
(2) uncertainties caused by the unknown parameter changes, e.g. the variation of payloads
(3) uncertainties due to the lack of the priority knowledge concerning the environment, such as the stiffness of environment and the exact position of contact surface
(4) uncertainties existed in measurements, including the sensor resolution and noises in external and internal sensors

In this paper, our discussion will concentrate on the third kind of uncertainties. Since the precise quantitative control fails to obtain good performance when uncertainties exist, it is natural then to imitate human operators under the same circumstance. Based on the heuristic experience, human operators can complete complex manipulation with ambiguous information, although it may not be very well in the sense of accuracy or optimization. Note that in most of robotic manipulations, the control can be allowed "coarse" before approaching the desired destination. Therefore system performance can be improved without losing other properties.

Based on this conception, the rule based fuzzy control method is introduced, which implements human like control by introducing knowledge based fuzzy compensation into control systems to provide efficient solution in the case that stiffness of the environment is unknown a priori. The application of fuzzy approach to servo control system has been reported[5]. As for the multi degree of freedom robot arms, the intuition and experience based fuzzy control can not be directly applied to because of the complexity of the robotic mechanisms and the environment. Therefore it is necessary for the control system to incorporate both the dynamical, kinematic compensation control function` and the knowledge based heuristic control function.

In this paper, the combination of a modified resolved acceleration position/force control and a fuzzy control are introduced investigated. In section 2, the precise model of an n joints robotic arm and actuators is given. In section 3, discussion on the dynamic compensation for hybrid position/force control is given to the case the accurate information is available. Due to the excising ambiguities around the environment,the dynamic compensation method may result in the deterioration in control performance. An rule based fuzzy compensation is then proposed in Section 4, which consists of a set of rules that implement relevant knowledge into the control system, and apply the fuzzy reasoning to acquire the appropriate control adjustment. Section 5 examines several simulation results to show the improved control performance. Conclusions are presented in Section 6.

2. MODELING OF ROBOT ARMS

Based on the Lagrangian formulation, it is easy to derive the dynamics of a robot arm. For convenience, considering a nonredudant robot arm with n joints that can be expressed by following equations.

$$J_M(q)\ddot{q} + h(q,\dot{q}) + g(q) + C_v\dot{q} + C_q sgn(\dot{q}) + C_s(I-sgn(|\dot{q}|)) = \tau - J^T f \quad (1)$$

where $\ddot{q}\in R^n$ are the vectors defining joint accelerations, $\tau\in R^n$ is the vector of joint input torques come from actuators, $f\in R^n$ is the vector of contact forces that the environment acts upon the end point of the robot arm in the Cartesian coordinate frame, $J_m(q)\in R^{n\times n}$ denotes the nonsingular inertia matrix, $h(q,\dot{q})$ represents the Coriolis', centrifugal forces, $g(q)\in R^n$ represents the gravitational forces, $J(q)\in R^{n\times n}$ is the Jacobian matrix and $J^T(q)$ is its transpose; C_v, C_q and $C_S\in R^n$ are the viscous, coulomb and static friction coefficient matrices of the joints respectively. Usually the motor inductances are small enough to be neglected in practice. Therefore the following brief form is obtained

$$R_a i + K_e q = v_a \quad (2)$$
$$D\ddot{q} + \omega = K_t i \quad (3)$$

where $K_t i=\tau$ is the torque,

$$D = J_a + J_M \quad (4)$$
$$\omega = h + g + (C_v+B_v)\dot{q} + (C_q+B_q)sgn(\dot{q}) + (C_s+B_s)(I-sgn(|\dot{q}|)) - J^T f \quad (5)$$

3. HYBRID CONTROL WITH RESOLVED ACCELERATION

The control input of the proposed resolved acceleration position/force control is of

$$\tau = \omega + DJ^{-1}\left[(I-S)x^* + SK_{eq}^{-1}f^* - \dot{J}\dot{q}\right] \quad (6)$$
$$x^* = \ddot{x}_d + K_{PD}(\dot{x}_d-\dot{x}) + K_{PP}(x_d-x) \quad (7)$$
$$f^* = \dot{f}_d + K_{FD}(\dot{f}_d-\dot{f}) + K_{FP}(f_d-f) \quad (8)$$

Matrices K_{PD} and K_{PP} are the servo joint D gain and P gain of position control, K_{FP} is the P gain of force control. S is a diagonal matrix that determines which axes are to be force controlled and which are to be position controlled. For simplicity, in the paper we assume $S=diag(0_{n-m} I_m)$. I, I_m are the unit matrices. 0_{n-m} represents the zero matrix. K_{eq} is the equivalent stiffness of environment and force sensors. $\dot{f}$ can be calculated as $K_{eq}\dot{x}$. Using the dynamic relation (2) and dynamic control (6), we get following relationship in Cartesian space.

$$\eta = (I - S)\eta_p + S\eta_f = 0 \quad (9)$$
$$\eta_P = (\ddot{x}_d-\ddot{x}) + K_{PD}(\dot{x}_d-\dot{x}) + K_{PP}(x_d-x) \quad (10)$$
$$\eta_f = (\dot{f}_d-\dot{f}) + K_{FD}(\dot{f}_d-\dot{f}) + K_{FP}(f_d-f) \quad (11)$$

It is obvious that the complex nonlinear dynamics is fully compensated and the robotic arm system is decoupled, i.e. $S\eta_f=0$ and $(I-S)\eta_p=0$ are satisfied simultaneously. The feedback gain matrices pair K_{FD} and K_{FP}, K_{PD} and K_{PP} are specified such that the linearized second order system (10) and (11) achieve critical damping responses. In this case, the P gains and D gains have the following relations.

$$K_{FD}^2 = 4K_{FP} \quad (12)$$
$$K_{PD}^2 = 4K_{PP} \quad (13)$$

4. FUZZY DYNAMIC COMPENSATION

In the hybrid position/force control, the additional information about the equivalent stiffness is needed to realize the complete nonlinear compensation. In practice it is seldom that K_{eq} is available. Therefore in this section we first design an overdamping controller to avoid overshoot or oscillation, then adding a fuzzy compensation to speed up system response as fast as possible. Here we only consider the regulator problem in the hybrid position/force control, thus only the constant position reference x_d and force reference f_d are under consideration.

4-1. Overdamped dynamic compensation

Supposed the equivalent stiffness K_{eq} ranges from K_{min} to K_{max} which are known boundaries. In order to avoid overshoot in hybrid position/force control, the control input is designed according to the most stiff case. Therefore, the dynamic compensation (6) is of the form

$$\tau = \omega + DJ^{-1}\left[(I - S)x^* + SK_{et}^{-1}f^* - \dot{J}\dot{q}\right] \tag{14}$$

where K_{et} is selected equal to K_{max}. This design will, however, result in such problem as system responses along constrained coordinates are extremely delayed due to the low gain property. By substituting (14) into (9) yielding

$$\eta_f = -\dot{f} - K_{FD}\dot{f} + K_{FP}(f_d - f) = \left(I - K_{et}^{-1}K_{FP}\right)(f_d - f) \tag{15}$$

that is, the force controlled subsystem in Cartesian space has a second order transfer function:

$$\left(s^2 I + K_{FD}s + K_{eq}K_{et}^{-1}K_{FP}\right)f(s) = f_d/s \tag{16}$$

Whenever $K_{eq} < K_{et} = K_{max}$ the system will be characterized as an over damped one.

4-2. Consideration of fuzzy compensation

To speed up system responses, a reasonable consideration is to identify the equivalent stiffness K_{eq} from system responses. In practice it is difficult to identify the equivalent stiffness directly from system responses due to the high nonlinearity of robot mechanisms and the wide range that the environment stiffness would be. On the other hand, with dynamic compensation the system behaves an overdamped system of second order as show in (16).

Therefore there is a possibility of approximately estimating unknown equivalent stiffness. In detail, a set of predetermined fuzzy rules is established. Each of these rules provides a sample that describes the relationship between the output of a second order system and the unknown stiffness in a particular situation. These rules are then combined to form a decision table for the fuzzy dynamic compensation. Finally, based on the fuzzy set theory an approximate reasoning is used to evaluate present system responses and derive appropriate control operation

The design procedure of fuzzy dynamic compensation, including both establishment of fuzzy rules and choosing fuzzy reasoning, is briefly explained below. For simplicity only a scalar force controlled subsystem is considered. However, the results can be easily extended to multi-variable force control subsystem of the hybrid position/force cases.

4-3. Implementation of fuzzy dynamic compensation

Reference Model

A reference model (17) with critical damping and proper frequency is selected in order that fast system responses can be achieved without overshoot.

$$f(s) = 1/s\left(s + 2\xi\omega s + \omega^2\right) \tag{17}$$

The PD gains of the force controlled subsystem are designed such that the real system responses are the same as the reference if no environment uncertainties are existed.

Sample set

Suppose the unknown equivalent stiffness K_{eq} varies from $K_{eq(min)} = 10^2$[N/m] to $K_{eq(max)} = 10^5$[N/m]. To investigate how the equivalent stiffness influences the system behaviors, the range of the stiffness is divided into ten sample levels $\underline{W}$ = {*VS, So, QS, RS, LS, N, LH, RH, QH, H*} as follows.

$K_{eq} = 100$	→	*VS*	(Very Soft)
$K_{eq} = 500$	→	*So*	(Soft)
$K_{eq} = 1000$	→	*QS*	(Quite Soft)
$K_{eq} = 1800$	→	*RS*	(Rather Soft)
$K_{eq} = 3000$	→	*LS*	(a Little Soft)
$K_{eq} = 5000$	→	*L*	(Normal)
$K_{eq} = 8000$	→	*LH*	(a Little Hard)
$K_{eq} = 12000$	→	*RH*	(Rather Hard)
$K_{eq} = 3\times10^4$	→	*QH*	(Quite Hard)
$K_{eq} = 1\times10^5$	→	*H*	(Hard)

Substituting the ten sample value into the real system model and let the estimated $K_{et} = 10^5$, then the system response of the force controlled coordinate will be characterized by

$$y(s) = 1/s\left(s + 2\zeta_i\omega_i s + \omega_i^2\right) \tag{18}$$

where i=1,···,10 corresponding to the ten levels of the stiffness from "VS" to "H" . The influences from K_{eq} can then be investigated in detail:

$$\omega_i = \sqrt{K_{FP}K_{eq}K_{max}^{-1}} \tag{19}$$

$$\zeta_i = \frac{K_{FD}}{2\sqrt{K_{FP}K_{eq}K_{max}^{-1}}} = \sqrt{\frac{K_{max}}{K_{eq}}} \tag{20}$$

It is clear that except for the case K_{eq} ="H" , all the damping coefficients $\zeta_i>1$. By using the reference models, system response $y_W(t_j)$ at any moment t_j can be calculated previously corresponding to each sample level

$$W \in \underline{W} = \{VS, So, QS, RS, LS, N, LH, RH, QH, H\}.$$

Quantization of system states

Owning to the over damping property, the system states f are simply quantized without considering the sign. In this paper , to restrict the number of control rules, ten fuzzy subsets

$$\underline{Y} = \{VS, Sm, QS, RS, LS, M, LB, RB, QB, B\}$$

are used to evaluate system states with respect to the sample levels of the equivalent stiffness. The abridged words in $\underline{Y}$ represent "Very Small", "Small","Quite Small","Rather Small","a Little Small","Medium", "a Little Big","Rather Big","Quite Big",and"Big" respectively.

It is easy then to extract the quantitative relationship among the fuzzified system state y and the stiffness K_{eq} from the equation (18). Those relationship are finally concluded in following rule form so as to facilitate the real time approximate reasoning

$$\text{IF } y(t_j) \text{ is } Y_W(t_j) \text{ THEN } K_{eq} \text{ is } W \tag{21}$$

where $Y_W(t_j) \in \underline{Y}$ and $W \in \underline{W}$.

Approximate reasoning

The environment stiffness is calculated by using following approximate reasoning. First the system output measured by force sensor at moment t_j is normalized as

$$y(t_j) = |f(t_j)/f_d|.$$

Suppose the output is located between two neighboring sample states $Y_{W'}(t_j)$ and $Y_{W''}(t_j)$ where W' and W'' belong to $\underline{W}$ and $W' < W''$. Then the coincidence of $y(t_j)$ with $Y_{W'}(t_j)$ and $Y_{W''}(t_j)$ are calculated as follows

$$\mu_{Y_{W'}(t_j)}[y(t_j)] = F_1\{[y(t_j) - Y_{W'}(t_j)] / [Y_{W''}(t_j) - Y_{W'}(t_j)]\} \tag{22}$$

$$\mu_{Y_{W''}(t_j)}[y(t_j)] = F_2\{[y(t_j) - Y_{W'}(t_j)] / [Y_{W''}(t_j) - Y_{W'}(t_j)]\} \tag{23}$$

where $F_1(\cdot)$ and $F_2(\cdot)$ are membership functions. Figure 1 shows the selected membership function of trigonometric type. The equivalent stiffness is estimated approximately as

$$K_{et} = \left\{K_{eq}(W')\mu_{Y_{W'}(t_j)}[y(t_j)] + K_{eq}(W'')\mu_{Y_{W''}(t_j)}[y(t_j)]\right\}/\Delta \tag{24}$$

$$\Delta = \mu_{Y_{W'}(t_j)}[y(t_j)] + \mu_{Y_{W''}(t_j)}[y(t_j)] \tag{25}$$

where $K_{eq}(W')$ and $K_{eq}(W'')$ represent the numerical value of the equivalent stiffness at sample levels W' and W''. In order to mitigate sampling deviation or measurement noise, it is necessary to sample system outputs over some period, which leads to establish a large sample set for approximate reasoning at different sampling moment t_j. To restrict the sample number in the sample set, only a few of reference samples are given previously at several fixed moment $\{t_j\}$. The necessary sample amongst two moment t_j and t_{j+1} is interpolated through following on-line calculation.

$$\forall t \in [t_j, t_{j+1}], \quad \forall W \in \underline{W}$$

$$Y_W(t) = \frac{Y_W(t_{j+1}) - Y_W(t_j)}{t_{j+1} - t_j}(t - t_j) + Y_W(t_j) \tag{25}$$

5. SIMULATION RESULTS

To investigate the effectiveness of the resolved acceleration position/force control and fuzzy compensation proposed in this paper, a robotic arm with three rotating joints is used(Figure 2). The first link is supposed to rotate around Z axe with the radius being zero. The second and third links are supposed to move inside one plane perpendicular to the X-Y plane.

5-1.Simulation condition

The length of the three links are 0.1[m], 0.5[m], and 0.5[m] respectively. The inductances of servomotors are (0.0017L, 0.0009L, 0.0009L) which is small enough to be ignored. The equivalent stiffness is assumed varying from $K_{eq(min)} = 10^2$[N/m] to $K_{eq(max)} = 10^5$[N/m]. The end point of robot arm is initially rest at point (0.4, 0, 0) in Cartesian space; the desired point is (0, 0.5, 0). The robotic arm contacts the environment along the Z direction and keep free motion in X and Y axes. The feedback gain matrices for P control and D control are selected as

$$K_{PP} = diag(25,\ 25,\ 25)$$

$$K_{PD} = diag(10,\ 10,\ 10)$$

$$K_{FP} = diag(100,\ 100,\ 100)$$

$$K_{FD} = diag(20,\ 20,\ 20)$$

that specify both position and force control responses in Cartesian space to be a critical damping one with their frequencies being $\sqrt{K_{PP}} = 5$ and $\sqrt{K_{FP}} = 10$ rad/sec respectively. The reference model for force control part is therefore determined. The sampling period is 1[msec].

5-2. Simulation Results

Figure 3 shows the case where directions X and Y are chosen to be position controlled and direction Z to be force controlled. The equivalent stiffness is exactly known as 15000[N/m]. With resolved acceleration position/force control, system shows perfect critical damping responses both among the position controlled and force controlled coordinates. From figure 4 we can observe that the system behaves nearly the same as figure 3 although the equivalent stiffness changes from 15000[N/m] to 1500[N/m] and 150[N/m]. On the other hand, figure 5 shows that system outputs are greatly delayed when the conservative initial estimation of equivalent stiffness $K_{et}=K_{max}=10^5$[N/m] is far more large than the real value K_{eq}.

The movement of robot arm along z coordinate with fuzzy compensation is illustrated in Figure 6. The fast the system response is required, the smaller the sample moment t_j should be. For simplicity we only select two sample moment t_1=0.1[sec] and t_2=0.15[sec]. Therefore totally 20 fuzzy rules are used. Figure 6 shows the force control result where the trigonometric type membership function of Figure 1 is used. The estimated equivalent stiffness K_{et} are about 16213.5[N/m], 1538.5[N/m] and 153.9[N/m] when the real K_{eq} are 15000[N/m], 1500[N/m] and 150[N/m] respectively.The estimated value is about 2%-10% higher than the true value. The reason is that, in (26) a linear approximate is used to represent a curve which is essentially a convex function of time t. Therefore the fuzzy reasoning gives a conservative estimation to the equivalent stiffness, which just satisfies both requirement of speeding up the system response and avoiding overshoot. From figure 6 one can confirm that the force controlled subsystem shows the critical damping property in the case the fuzzy compensation is added.

6. CONCLUSION

In this paper, the resolved acceleration position/force control with the rule based fuzzy dynamic compensation has been presented and applied to the hybrid position/force manipulation. The basic consideration and brief control design procedures were introduced, and the control performances have been shown through several simulation examples. The trade-off between the fast system response and no overshoot is achieved by introduction both the accurate dynamic compensation which is based on the exact model, and the approximate dynamic compensation which is implemented with heuristic control rules.

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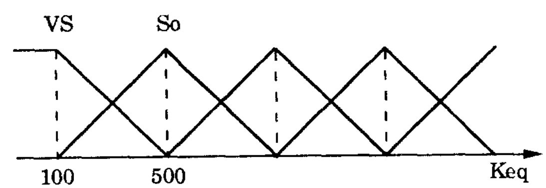


Figure 1. Membership function of trigonometric type

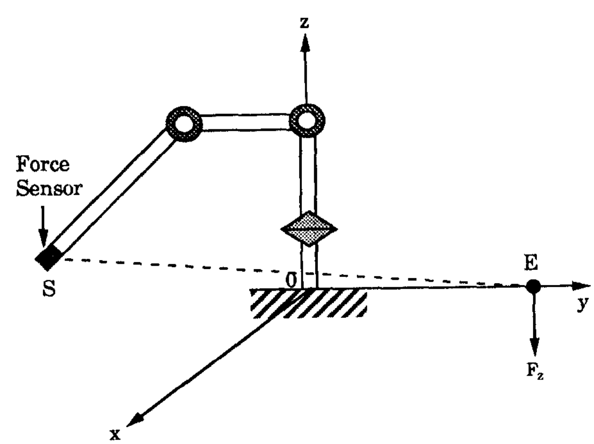
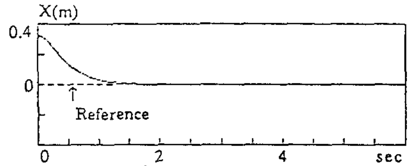
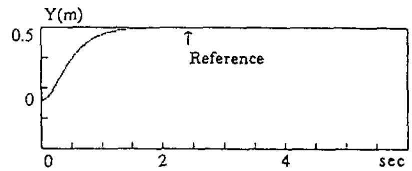


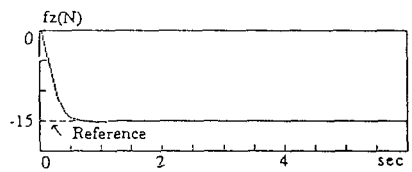
Figure 2. Robot arm of 3 D.O.F. in Cartesian space



(a) System response along X coordinate in position control

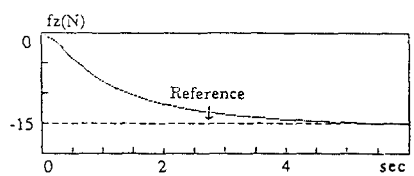


(b) System response along Y coordinate in position control

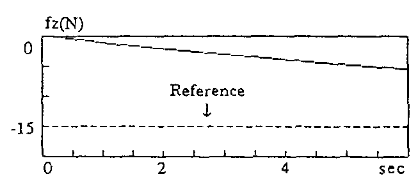


(c) System response along Z coordinate in force control
w.r.t. k_{eq}=15000N/m

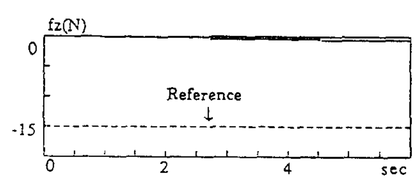
Figure 3. System response of resolved accleration position/force control with exact dynamic compensation
(Ket = Keq(max) = 15000[N/m])



(a) Force response along Z coordinate
k_{eq}=15000N/m
k_{et}=k_{max}=10^5N/m

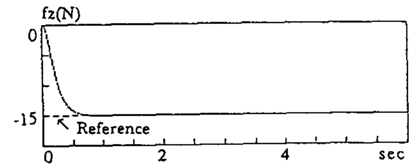


(b) Force response along Z coordinate
k_{eq}=1500N/m
k_{et}=k_{max}=10^5N/m

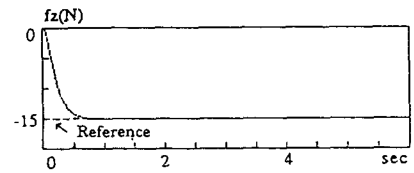


(c) Force response along Z coordinate
k_{eq}=150N/m
k_{et}=k_{max}=10^5N/m

Figure 5. System response of resolved accleration position/force control using maximum equivalent stiffness

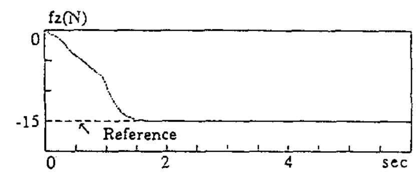


(a) Force response along Z coordinate
k_{et}=k_{eq}=1500N/m

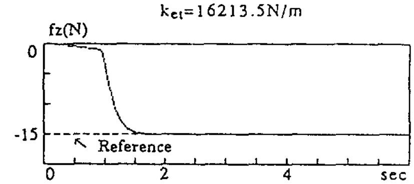


(b) Force response along Z coordinate
k_{et}=k_{eq}=150N/m

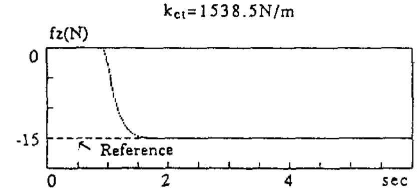
Figure 4. System response of resolved accleration position/force control using equivalent stiffness



(a) Force response along Z coordinate
k_{eq}=15000N/m
k_{max}=10^5N/m
k_{et}=16213.5N/m



(b) Force response along Z coordinate
k_{eq}=1500N/m
k_{max}=10^5N/m
k_{et}=1538.5N/m



(c) Force response along Z coordinate
k_{eq}=150N/m
k_{max}=10^5N/m
k_{et}=153.9N/m

Figure 6. System response of resolved accleration position/force control with fuzzy compensation