Dynamic Decoupling and Load Desensitization of Direct-Drive Robots by Current Feedback

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Abstract

Direct-drive robots have excellent features including no backlash, small friction, and high mechanical stiffness. However, dynamic coupling among joints as well as nonlinear effects become more prominent than traditional robots with reducers. Another critical issue is that the robot becomes more sensitive to the change of load. In this paper, we develop a simple current feedback scheme for reducing the influence of dynamic coupling and load sensitivity on the direct-drive robots. The method is implemented on a 2 d.o.f. planar direct-drive robot. Then the validity of the method is demonstrated through experiments.

1 Introduction

Direct-drive robots, in which special high torque motors are directly coupled to their load, have many advantages over their traditional counterparts. The robots have no backlash, very small friction and high mechanical stiffness, all of which enable high accuracy and high speed manipulation[1].

As the speed increases, however, complex dynamic behavior becomes more prominent in the direct-drive robot. Dynamic coupling among multiple joints as well as nonlinear effects such as Coriolis and centrifugal forces become more prominent than traditional robots with reducers. Furthermore, the drive systems become sensitive to the change of inertial load because of the direct coupling of the motors to the arm links[2].

A variety of design and control methods have been addressed, including feedforward compensation[3], adaptive control[2], arm design for decoupled and configuration-invariant inertia[4], torque feedback control[5], These methods have reduced or eliminated the dynamic coupling and load sensitivity.

In this paper, a simple current feedback scheme is presented in order to reduce the high load sensitivity and the dynamic coupling for multiple joint direct-drive robots. In this scheme, all the parameters of controller are kept constant in spite of the change of system parameters such as inertial load.

It is impossible to completely eliminate the influence of interactions and load sensitivity for an arbitrary frequency range. Nevertheless, it will be possible to broaden the frequency range which are not affected by the change of inertia through an appropriate modification of the feedback gains of control system. Thus, if we make the bandwidth wider than normal operation speeds, system responses will not be influenced by the change of inertial load at normal operation speeds.

We derive the condition for the bandwidth to be kept wide enough, even though the inertia increases in a certain range. We use a root locus technique to illustrate the effects of inertia change upon the system dynamics.

For a multiple d.o.f. robot, interactions are caused by inertia matrix as shown in section 4. Thus, one can make the system dynamics independent of the inertia at normal speeds. Namely the system is dynamically decoupled. The method is then applied to brushless DC motors. Recently, brushless DC motors are widely used for actuators of direct-drive robots. The load desensitization method is implemented on a 2 d.o.f. planar direct-drive robot with brushless DC motors. Finally the validity of the method is proved through experiments.

2 Load Desensitization

Fig.1 shows the equivalent block diagram of a 3 phase, Y-connection brushless DC motor with position feedback. Here, k_t, L, R, represent, respectively, the torque constant, inductance, and electric resistance of each phase of the motor. H represents inertia including the load, and K_p, K_v, K_I represent position, velocity, and current feedback gains, and k_{pre}, k_A are gains of the pre amplifier and the power amplifier, respectively.

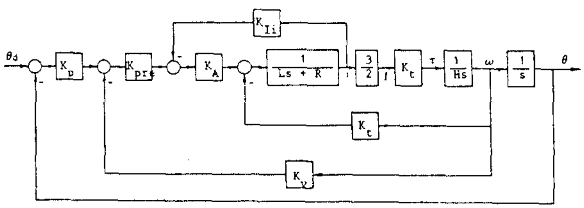

Fig.1 Block diagram of single link drive system

For this system, the transfer function from position input θ_d to position output θ is represented as

$$\frac{\theta}{\theta_d} = \frac{A_0}{A_3 s^3 + A_2 s^2 + A_1 s + A_0} \quad (1)$$

where

$$\begin{aligned} A_3 &= LH \\ A_2 &= H(R + K_I k_A) \\ A_1 &= \frac{3}{2} k_t (K_v k_{pre} k_A k_t) \\ A_0 &= \frac{3}{2} K_p k_{pre} k_A k_t \end{aligned}$$

Suppose that the coefficients A_3, A_2 including the inertia H are zero in equation (1). Then the system becomes a 1st order system, and the dynamics of the system will not be influenced by the inertia or the change of it. However, it is impossible to make the coefficient A_3 completely zero. So we consider to make the coefficients A_3, A_2 sufficient small so that the response of the system may not be influenced by the inertia or the change of it at a normal speed range. Then the system will be desensitized for the change of inertial load at normal operation speeds.

Usually, the coefficients A_3, A_2 are considerably high for most servo systems. For a large A_2, the bandwidth becomes narrow when the inertial load increases. Therefore, the system response will be influenced by the interactions and load change even at low speeds. In the next section, we derive the condition on the control system that can maintain a wide bandwidth in spite of some increase of the inertia. We also discuss how to select the feedback gains for the load desensitization.

3 Control System Design

We investigate how the poles of the system vary depending on the inertial load. To this end, we draw root loci for inertia H as parameter. Fig.2 shows a typical root locus of the direct-drive system described above. Note that the complex roots are dominant and that the complex roots move towards the imaginary axis as the inertia increases. Therefore, the bandwidth becomes narrower. A 3rd-order system with large A_2 has this pattern of root locus.

If we make the coefficient A_2 appropriately small, the root locus differs from Fig.2. Fig.3 depicts the root locus for small A_2. In Fig.3, it should be noted that the dominant pole is a real single root, and it moves away from the imaginary axis as the inertia increases. Then the bandwidth becomes wider. However, we should determine the value of A_2 by considering the stability of the system, because the system may be unstable if A_2 is too small.

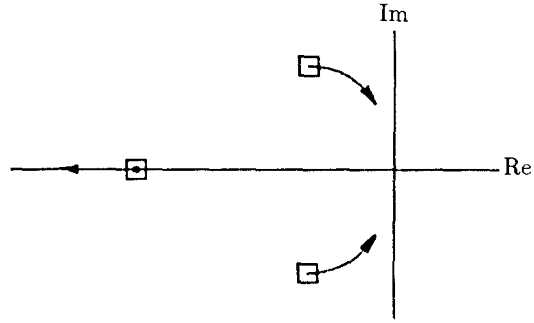

Fig.2 Root locus *for inertia as parameter* in case of *large* A_2

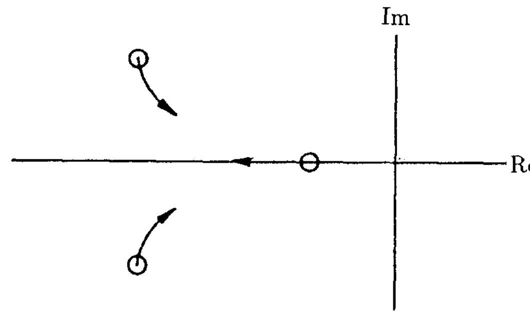

Fig.3 Root locus *for inertia as parameter* in case of *small* A_2

The $\alpha - \beta$ diagram by Siljak[6] is a convenient tool in determining feedback gains in relation to the system response. To depict the curve, equation (1) should be normalized as given by equation (2),(3). In the $\alpha - \beta$ diagram, constant σ, constant ζ and constant ω_n are plotted.

$$\frac{\theta}{\theta_d} = \frac{1}{S^3 + \alpha S^2 + \beta S + 1} \quad (2)$$

$$= \frac{\sigma \omega_n^2}{(S+\sigma)(S^2 + 2\zeta\omega_n S + \omega_n^2)} \quad (3)$$

where

$$S = \frac{1}{\sqrt[3]{A_0/A_3}} s$$

$$\alpha = \frac{(A_2/A_3)}{\sqrt[3]{A_0/A_3}}$$
$$\beta = \frac{(A_1/A_3)}{\sqrt[3]{(A_0/A_3)^2}}$$

The diagram is given by Fig.4.

Parameters α and β change when the inertia of system changes. We plotted the loci of α,β in Fig.4, as the inertia changes. The loci departed from the left top side move to the right bottom as the inertia increases. In the region where $\alpha > \beta$, σ is larger than ω_n. The root locus corresponding to this region has been given by Fig.2. In the region where $\alpha < \beta$, σ is smaller than ω_n. The root locus for this was shown in Fig.3. Therefore, to maintain a desired bandwidth, it is desired that α is no larger than β even when the inertia load becomes maximum.

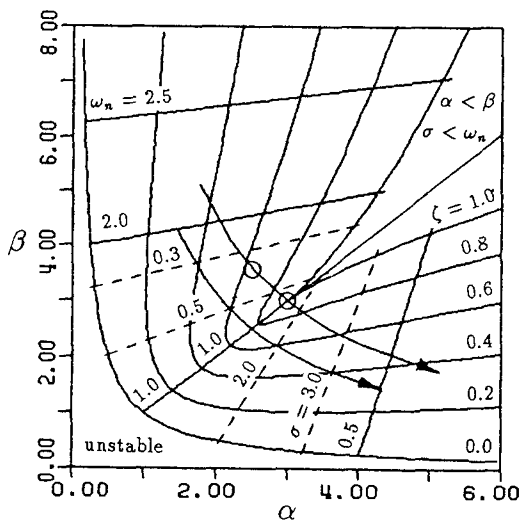

Fig.4 $\alpha - \beta$ diagram

From Fig.4, it follows that the stability is poor if β is much larger than α. Therefore, we need to tune the system so that β may not become too larger than α even when the inertia becomes minimum. Actually the ratio of maximum inertia to minimum is not larger than 2. In the case of CMU DD Arm, that ratio for a proximal joint was around 1.57. For example, if we set the gain to be $\alpha = 2.38, \beta = 3.78$ at the minimum inertia, α and β becomes 3 at twice inertia of minimum. Hence the system is held stable for minimum or maximum inertia.

In this paper, we determine the controller parameters to be α=β at the maximum value of the anticipated inertia load. Then it is guaranteed that β does not exceed α for maximum inertia, and β may not become too larger than α for half of maximum inertia.

The above method of control system design requires that the coefficient A_2 small enough to satisfy the condition on α and β. In order to make the parameter A_2 small, we employ positive current feedback. As for the bandwidth, we need to make parameter A_3 small, because the bandwidth is approximately in proportion with $\sqrt[3]{A_0/A_3}$. Since A_3 is given by LH, the inductance of the motor should be minimized.

4 Dynamic Decoupling

If we ignore the nonlinearity of arm dynamics for the sake of simplicity, the joint displacements of a d.o.f. robot is given by

$$\theta = G\theta_d \tag{4}$$

where, θ_d, θ represents the input, the output vectors respectively. And the transfer matrix G is given by

$$G = [A_3 s^3 + A_2 s^2 + A_1 s + A_0]^{-1} A_0 \tag{5}$$

where A_i are $n \times n$ square matrix for n d.o.f. robot, and given by

$$\left.\begin{aligned} A_3 &= diag[L]H \\ A_2 &= diag[R + K_I k_A]H \\ A_1 &= diag[\tfrac{3}{2}k_t(K_v k_{pre} k_A k_t)] \\ A_0 &= diag[\tfrac{3}{2}K_p k_{pre} k_A k_t] \end{aligned}\right\} \tag{6}$$

In equation (6), only H is not a diagonal matrix. So the interactions among joints are due to inertia matrix. However, as mentioned in section 3 the system dynamics can be independent of the inertia matrix. Note that the system is decoupled because matrices A_1 and A_0 are diagonal.

5 Experiments

We built a 2 d.o.f. planar direct-drive robot whose actuators are 3-phase brushless DC motors. First, we attempted load desensitization by positive current feedback. Fig.5 shows step response for single a link. As shown in the figure, the response is almost not changed in spite of inertia increase if we take positive current feedback. However if we don't take positive current feedback the response varies largely depending on the inertial load as shown in Fig.6.

The second experiment was on the dynamic decoupling for a 2 d.o.f. planar direct-drive robot. The reference positional input was zero for joint 1, while a step input was applied to joint 2. And then the output position of joint 1 was observed. As shown in Fig.7, joint 1 was rotated 0.0176 rad due to the dynamic interaction. However, the interaction was almost eliminated with positive current feedback as shown in Fig.8.

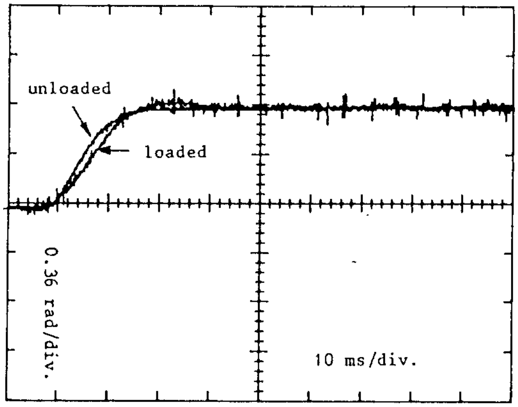

Fig.5 Positional step response of single link system *with positive current feedback*

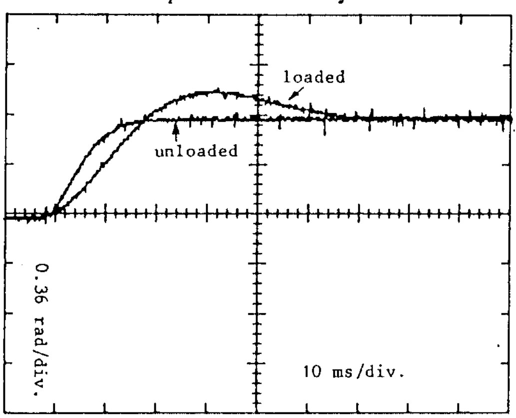

Fig.6 Positional step response of single link system *without positive current feedback*

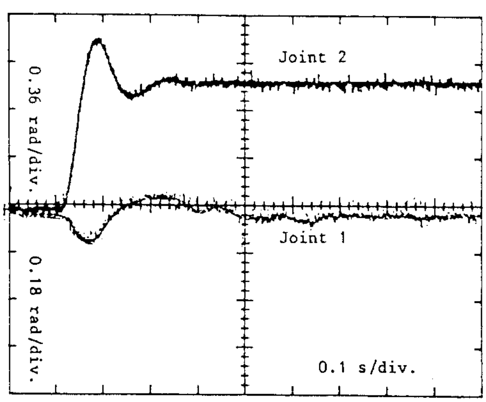

Fig.7 Interaction test for 2.d.o.f. direct-drive robot *without positive current feedback*

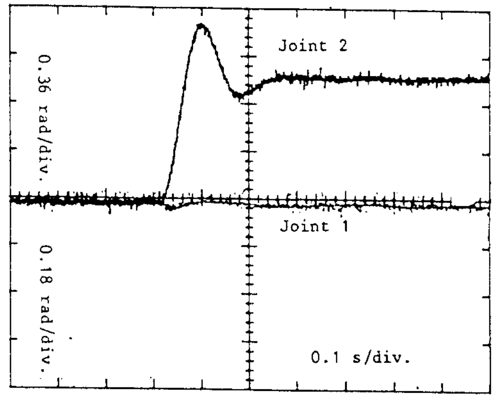

Fig.8 Interaction test for 2.d.o.f. direct-drive robot *with positive current feedback*

6 Conclusion

Dynamic decoupling and load desensitization of direct-drive robot by current feedback have been presented. The control system was designed by using the $\alpha-\beta$ diagram and root loci as inertial parameter. The method was implemented on a 2 d.o.f. planar direct-drive robot with brushless DC motors. Validity of the method was proved through experiments.

References

[1] H. Asada and T. Kanade: Design of Direct-Drive Mechanical Arms, Trans. of ASME, Journal of Vibration, Stress and Reliability in Design, Vol.105, No.3, pp. 312-316 (1983).

[2] H. Asada and K. Hara: Load Sensitivity Analysis and Adaptive Control of a Direct-Drive Arm, 1986 American Control Conference.

[3] T. Suehiro and K. Takase: A Manipulation System Based on Direct Computational Task-coordinate Servoing, Journal of the Robotics Society of Japan, Vol3, No.2, pp.11-21 (1985).

[4] H. Asada and K. Youcef-Toumi: Decoupling of Manipulator Inertia Tensor by Mass Redistribution, Proceeding of the ASME Mechanisms Conference (1984)

[5] K. Kosuge, H.Takeuchi and K. Furuta: Control of Robot Arms using Torque Sensors, Proceeding of SICE'87 (1987).

[6] D. Siljak: Nonlinear Systems, John Willey & Sons, New York (1968).