Appendix

Design of Force Control Gain $K_f$ and Damping Gain $K_v$

In this appendix, we explain the design of the force controller based on the frequency characteristics. The design is done using the equivalence between the explicit force control algorithm and the impedance control algorithm. As an example of the proposed force controller design, we present the design of the force controller so as to reduce the gain of the transfer function $G_{dirt}(s)$ at the frequency of the disturbance force to less than $a(dB)$.

From eq.(23), we have

$$G_{dirt}(s) = K' \cdot (1 + Ts) \cdot \frac{w_n^2}{s^2 + 2\xi w_n s + w_n^2}, \quad (26)$$

where

$$K' = \frac{1}{1 + K_f}, \quad w_n = \sqrt{K_d M_d}, \quad \xi = \frac{D_d}{2\sqrt{M_d K_d}}. \quad (27)$$

In order to reduce it to $a(dB)$, we obtain the relation as follows:

$$K' = \frac{1}{1 + K_f} = 20 \log_{10} a. \quad (28)$$

Rewriting this equation, we have

$$K_f = 10^{-a} - 1. \quad (29)$$

Fig.13 Bode diagram of $G_{dirt}(s)$ ($K_f = 0.78 K_v = 0.0, a = -5(dB)$)

Using this equation, we can design the force control gain $K_f$.

However, as shown in fig.13, when the frequency of the disturbance force is close to the resonance frequency, the magnitude of $G_{dirt}(s)$ at the frequency of the disturbance force can not be reduced to less than $a(dB)$ due to the resonance peak. Therefore, in order to reduce it to $a(dB)$, we have to modify the frequency characteristics shown in fig.13 to the one that do not have the resonance peak as shown in fig.7. Then, as shown in the third term of eq.(26), in order to suppress the resonance peak, we design $\xi$ appropriately. Substituting this $\xi$ to eq.(27), from eq.(21), (22) and (27), we obtain the desired impedance parameters $M_d, D_d, K_d$. Substituting these parameters into eq.(25), we have the desired damping gain.