CURRENT LOOPS

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All industrial servo drives require some form of compensation often referred to as proportional, integral, and differential (PID). The process of applying this compensation is known as servo equalization or servo synthesis. In general, commercial industrial servo drives use proportional, and integral compensation (PI). It is the purpose of this discussion to analyze and describe the procedure for implementing PI servo compensation.

The block diagram of figure 1 represents dc and brushless dc motors. All commercial industrial servo drives make use of a current loop for torque regulation requirements. Figure 1 includes the current loop for the servo drive with PI compensation. Since the block diagram of figure 1 is not solvable, block diagram algebra separates the servo loops to an inner and outer servo loop of figure 2.

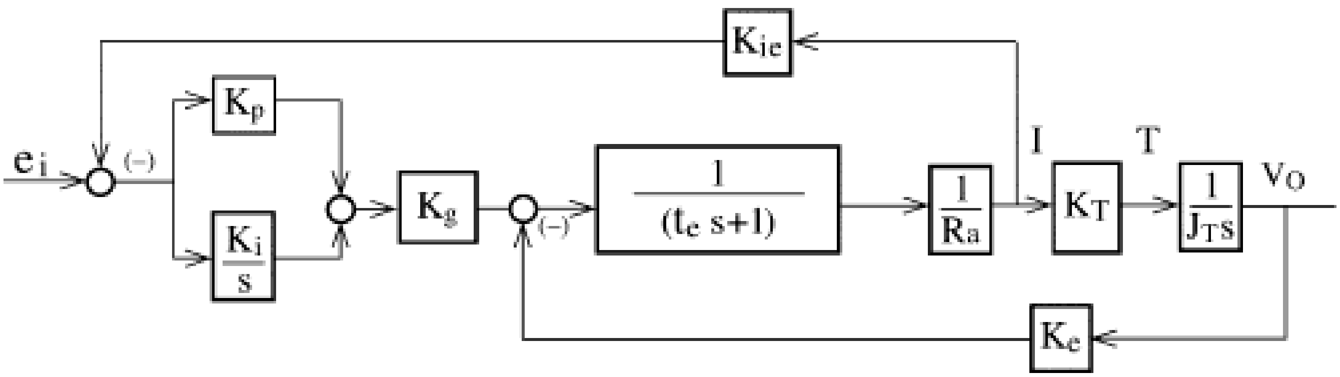

FIGURE 1 MOTOR AND CURRENT LOOP

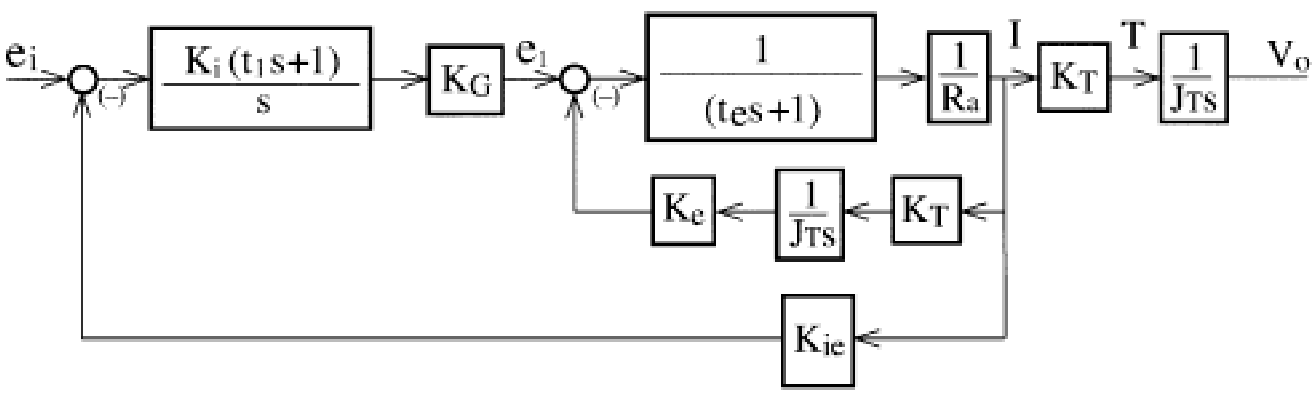

FIGURE 2 MOTOR AND CURRENT LOOP

For this discussion a worst case condition for a large industrial servo axis will be used. The following parameters are assumed from this industrial machine servo application:

Motor - Kollmorgen motor - M607B
Machine slide weight - 50,000 lbs
Ball screw: Length - 70 inches

Diameter - 3 inches
Lead - 0.375 inches/revolution

Pulley ratio - 3.333
J_T = Total inertia at the motor= 0.3511 lb-in-sec^2
t_e = Electrical time constant = 0.02 second = 50 rad/sec
$t_1 = t_e$
K_e = Motor voltage constant = 0.646 volt-sec/radian
K_T = Motor torque constant = 9.9 lb-in/amp
K_G = Amplifier gain = 20 volts/volt
K_{ie} = Current loop feedback constant = 3 volts/40A= 0.075 volt/amp
R_a = Motor armature circuit resistance = 0.189 ohm
K_i = Integral current gain = 735 amp/sec/radian/sec

The first step in the analysis is to solve the inner loop of figure 2. The closed loop response I/e_1= G/1+GH where:

$G = 1/R_a (t_e S+1) = 5.29/[t_eS+1]$ (5.29 = 14.4 dB)
$GH = 0.646 \times 9.9/[0.189 \times 0.3511[(t_eS+1)S]$
$GH = 96/S[t_eS+1]$ 96 = 39dB
$1/H = J_TS/K_e K_T = 0.3511S/0.646 \times 9.9$
$1/H = 0.054\ S$ (0.054 = -25 dB)

Using the rules of Bode, the resulting closed loop Bode plot for I/e_1 is shown in figure 3. Solving the closed loop mathematically :

$$\frac{I}{e_1} = \frac{G}{1+GH} = \frac{1}{R_a(t_eS+1) + K_eK_T / J_TS} = \frac{J_TS}{J_TR_aS(t_eS+1) + K_eK_T}$$

$$\frac{I}{e_1} = \frac{J_T\ S}{J_TR_at_eS^2 + J_TR_aS + K_eK_T} = \frac{J_T / K_eK_T\ S}{[(J_TR_a/K_eK_T)t_eS^2 + (J_TR_a/K_eK_T)\ S + 1]}$$

$$\frac{I}{e_1} = \frac{(.3511/.646\text{x}9.9)\ S}{t_mt_e\ S^2 + t_m\ S + 1} = \frac{0.054\ S}{0.01\text{x}0.02\ S^2 + 0.01\ S + 1}$$

where: $t_m = \frac{J_TR_a}{K_e\ K_T} = \frac{0.3511 \times 0.189}{0.646 \times 9.9}$ =0.01 sec, $w_m = 1/t_m$ = 100 ra/sec
t_e = 0.02 sec $w_e = 1/t_e$ = 50 rad/sec

For a general quadratic-

$$\frac{S^2}{w_r^2} + \frac{2\ delta}{w_r} S + 1$$

$w_r = [w_m\ w_e]^{1/2} = [100 \times 50]^{1/2}$ = 70 rad/sec

$$\frac{I}{e_1} = \frac{0.054S}{S^2/70^2 + (2delta/70)S + 1}$$

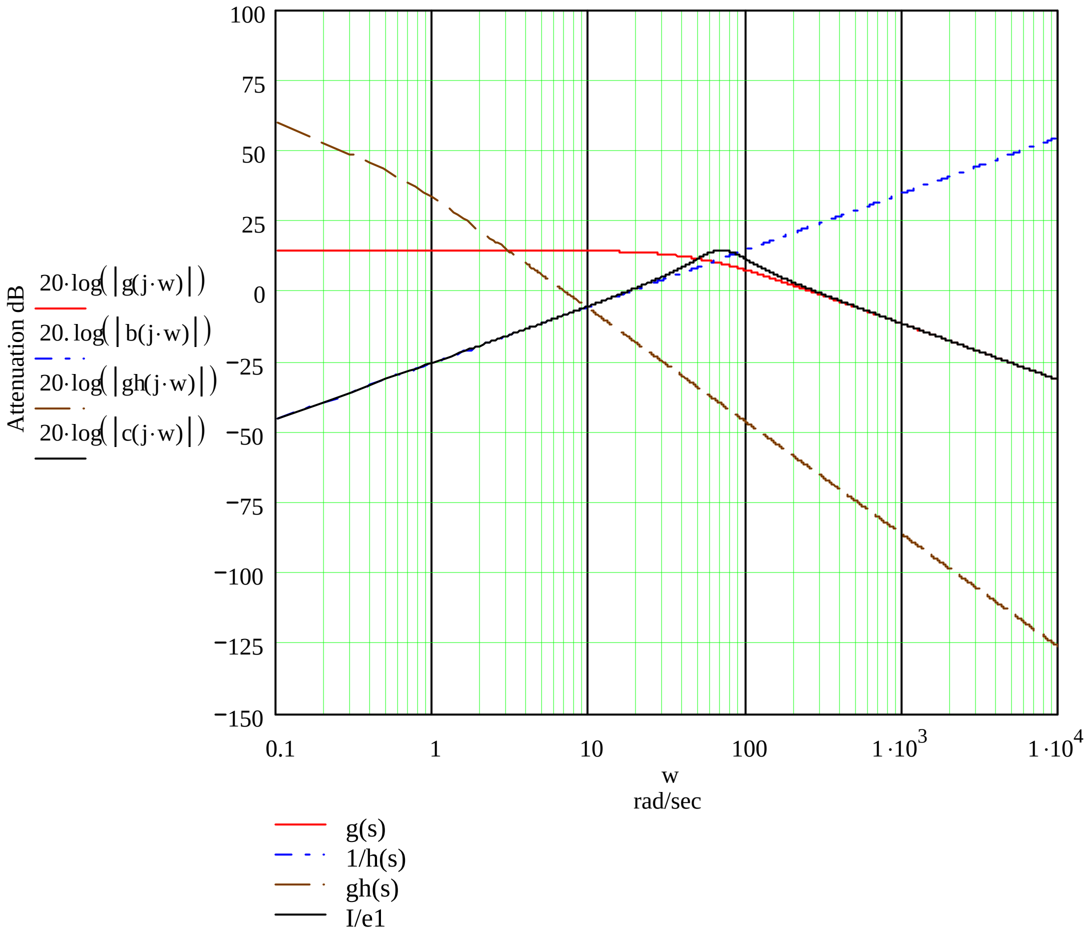

Fig 3 Current inner loop

Having solved the inner servo loop it is now required to solve the outer current loop. The inner servo loop is shown as part of the current loop in figure 4.

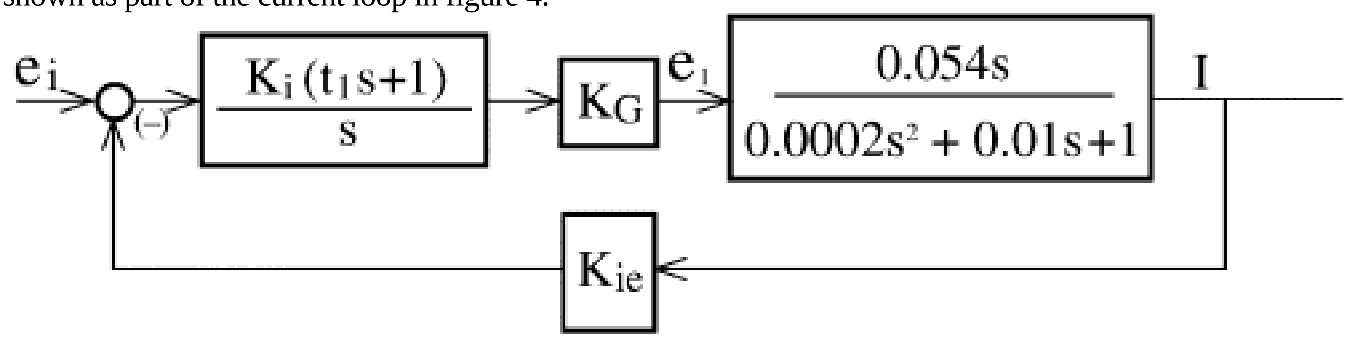

FIGURE 4 CURRENT LOOP

In solving the current loop, the forward loop, open loop, and feedback loop must be identified as follows:

The forward servo loop-

$$G = \frac{K_i\,K_G \times 0.054\,(0.02S+1)}{0.0002\,S^2 + 0.01\,S + 1} = \frac{735 \times 20 \times 0.054\,(0.02S+1)}{0.0002S^2 + 0.01\,S + 1}$$

$$G = \frac{794(0.02\,S+1)}{0.0002S^2 + 0.01S + 1} = \frac{15.88S + 794}{0.0002S^2 + 0.01S + 1}$$

Where: K_G =20 volt/volt
K_{ie} = 3/40 = 0.075 volt/amp
K_iK_G x 0.054 794 (58 dB)
K_i = 794/(20 x 0.054)=735

$$G = \frac{79{,}400S + 3{,}970{,}000}{S^2 + 50\,S + 5000}$$

The open loop-

$$GH = 0.075 \times \frac{79{,}400S + 3{,}970{,}000}{S^2 + 50S + 5000}$$

$$GH = \frac{5955S + 297{,}750}{S^2 + 50S + 5000}$$

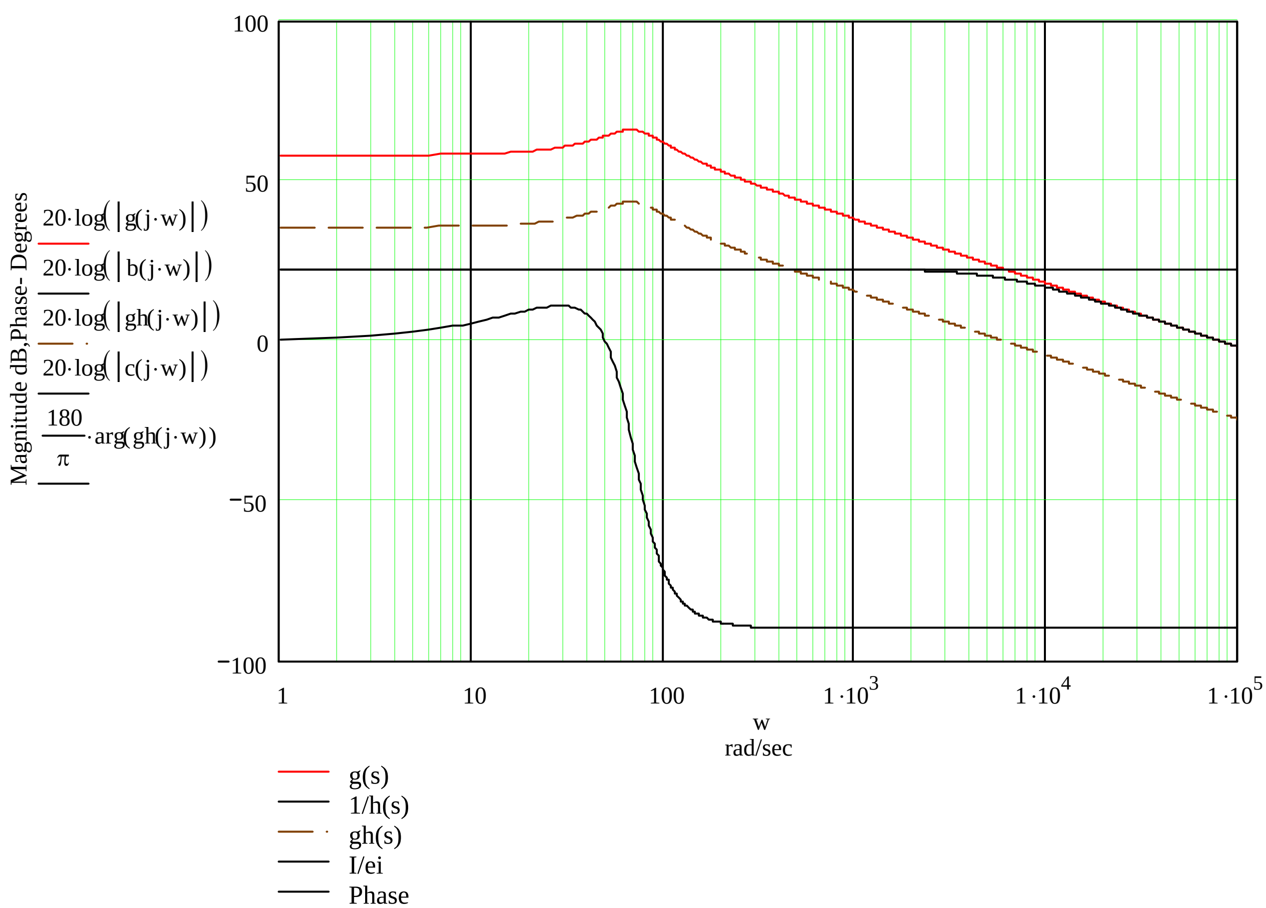

Fig 5 Current loop response

The feedback current scaling is-

$H = 3 \text{ volts}/40 \text{ amps} = 0.075 \text{ volts/amp} \qquad 1/H = 13.33 = 22.4 \text{ dB}$

The Bode plot frequency response is shown in figure 5. The current loop bandwidth is 6000 radians/second or about 1000 Hz, which is realistic for commercial industrial servo drives.

The current loop as shown in figure 5 can now be included in the motor servo loop with reference to figure 2 and reduces to the motor servo loop block diagram of figure 6.

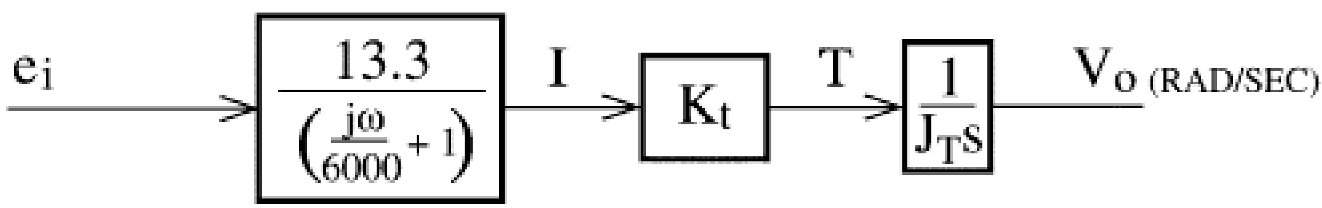

FIGURE 6

The completed motor servo loop has a forward loop only (as shown in figure 6) where:

J_T = Total inertia at the motor = 0.3511 lb-in-sec^2

K_T = Motor torque constant = 9.9 lb-in/amp

$$G = \frac{13.3 \times 9.9}{.3511S\left(\left(jw/6000\right)+1\right)} = \frac{375}{S(0.000166S + 1)} \quad (51.5 \text{ dB})$$

$$G = \frac{375}{0.000166S^2 + S + 0} = \frac{2{,}250{,}090}{S^2 + 6000S + 0}$$

$$\frac{v_o}{e_i} = \frac{K_T}{J_T\,S} \times \frac{|I|}{|v_i|} = \frac{9.9}{0.3511S} \times \frac{13.1(0.02S + 1)}{0.00000331S^2 + 0.02S + 1}$$

$$\frac{v_o}{e_i} = \frac{375\,(0.02S + 1)}{S\ 0.00000331\,(S + 50)(S + 5991)}$$

$$\frac{v_0}{e_i} = \frac{375\,(0.02S + 1)}{S\ 0.00000331 \times 50 \times 5991\,((S/50) + 1)(((s/5991) + 1)}$$

$$\frac{v_o}{e_i} = \frac{375\,(0.02S + 1)}{S\,(0.02S + 1)(0.000166S + 1)}$$

$$\frac{v_o}{e_i} = \frac{375}{S\,((jw/5991) + 1)}$$

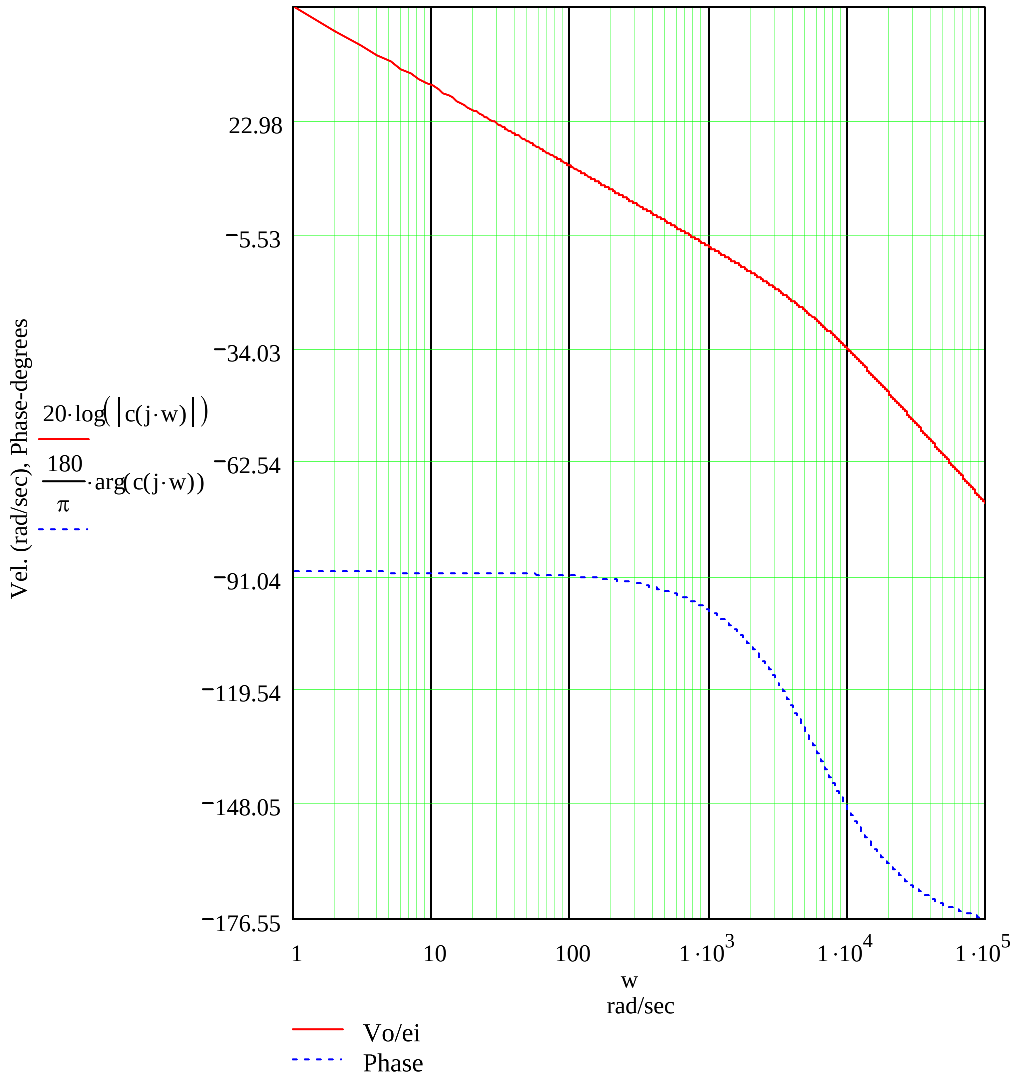

Fig 7 Mot.&I loop freq. response

The Bode frequency response for the motor and current loop is shown in figure 7. The motor and current closed loop frequency response, indicate that the response is an integration which includes the 6000 rad/sec bandwidth of the current loop. This is a realistic bandwidth for commercial industrial servo drives.