Application Note 4109

A guide to the design of current feedback control

Introduction

FAN8024D/BD/CD is 4-CH motor drive IC and FAN8025G3 is 5-CH motor drive IC, which both are suitable for optical media applications and have current feedback channels.
We will describe the current feedback controller for actuators in optical media system with our motor ICs. Then, show how to calculate controller gains and external component values by easy equations.
Finally add test results of simulation and experiment.

1. Current Control Overview

In general, controlling the motor position and speed signifies controlling the armature current.
It is because motor torque is proportional to armature current. The electrical equation of DC motor is given as follows;

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \qquad (1)$$

where,
Va: terminal voltage,
Ia: armature current,
Ra: motor winding resistance
La: motor winding inductance
Ea: Back-EMF voltage of motor that is proportional to angular velocity

When the mechanical time constant is lager than electrical time constant, transfer function of above equation could be simply stated as below:

$$A_M(S) = \frac{I_a(S)}{V_a(S)} = 1/L_a * \frac{1}{s + \omega_M} \qquad (2)$$

$$\text{where, } \omega_M[\text{red/sec} = \frac{R_a}{L_a} \qquad (3)$$

The characteristic of this equation looks like first order LPF.(ω_M means natural frequency of motor.)
To control current of motor(or another load) voltage mode or current mode can be used. Decision making between current and voltage mode is related to the natural frequency and system bandwidth. Now let's examine natural frequencies of some actuators in the optical-media applications.

Table. 1 Armature electrical characteristics of actuators of Optical-media

		Resistance [Ω]	Inductance [μH]	Natural bandwidth [Hz]
Model1	Tracking	17.9	124.9	22.8KHz
	Focus	18.5	228.5	12.9KHz
Model2	Tracking	4.0	12.4	51.3KHz
	Focus	4.4	38.5	18.2KHz
Model3	Tracking	4.3	15.6	43.9KHz
	Focus	5.17	73.6	11.2KHz
HDD VCM		14	11.4mH	195.5Hz
Remark		Measured in condition of 1KHz, 0.1V		

In a word, on some applications where required system bandwidth is lower than actuator's natural frequency, there is no need to use current feedback control.
For example, when the system requiring dynamics is 30KHz, the tracking actuator of Model2 can be operated by voltage mode control like fig.1, because the natural frequency of this actuator is much higher than requiring dynamics.

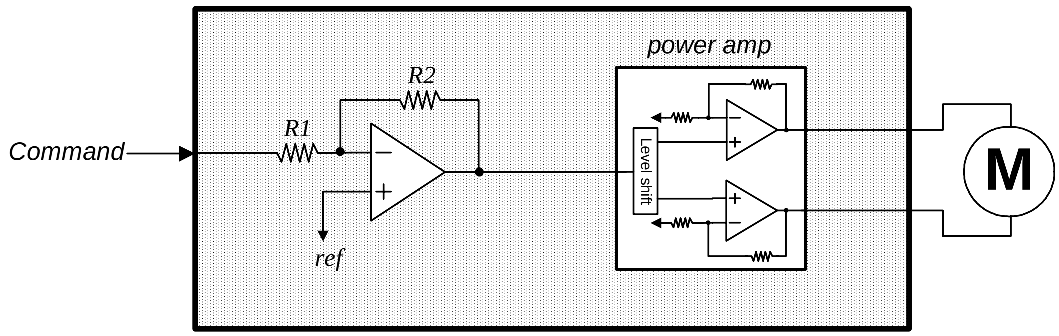

Figure. 1 Voltage mode controller in DC motor driver of Optical-media application

In the fig.1 the power amp is typical BTL (Balanced Transformer Less) architecture and linear drive of upper and lower power transistor gives linear voltage to the motor. This scheme assumes one point; the current will rapidly follows the voltage so the motor speed or position could be controlled within required system bandwidth. According to the case of Maker1 40X CD-ROM set in table 1, if the system need more than 30KHz in system bandwidth, general voltage mode control would show poor performance because natural frequency of load motor itself becomes the performance barrier to the total system. When the required system bandwidth is increased and the natural frequency of the load motor is so slow, the outer control system must control the current directly for precise load control.

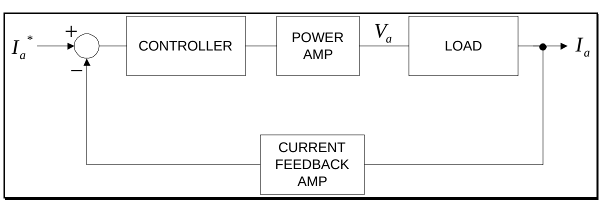

Figure.2 The block diagram of current feedback control

Fig. 2 illustrates typical current feedback control system. The controller block regulates current error which is come from current command minus real load current to zero. This is done by canceling the delay effect of load. This will be explained in detail in the following paragraphs.

2. Current Feedback Controller in FAN8024/FAN8025

Fig.3 illustrates the application circuit for current feedback controller. The input signal is applied to Vin/Sref pin, and across voltage of the sensing resister, Rs, is a feedback to error amplifier. The feedback network consists of external component, Rent, C and internal resistor, Rin, R2. In Fig.3, Vx1 is a reference voltage converted from Vin through current conveyor. From now on it will be expressed as command current. Fig. 4 is s-domain transfer function of above block diagram.
Let's assume the following.

$$H(s) = A_E(s) \cdot 2 \times A_p(s) \cdot A_M(s) \quad (4)$$

$$G(s) = R_s \cdot A_s(s) \quad (5)$$

$$T(s) = H(s) \cdot G(s) \quad (6)$$

T(s) is open loop gain of above system and characterizes the closed loop system

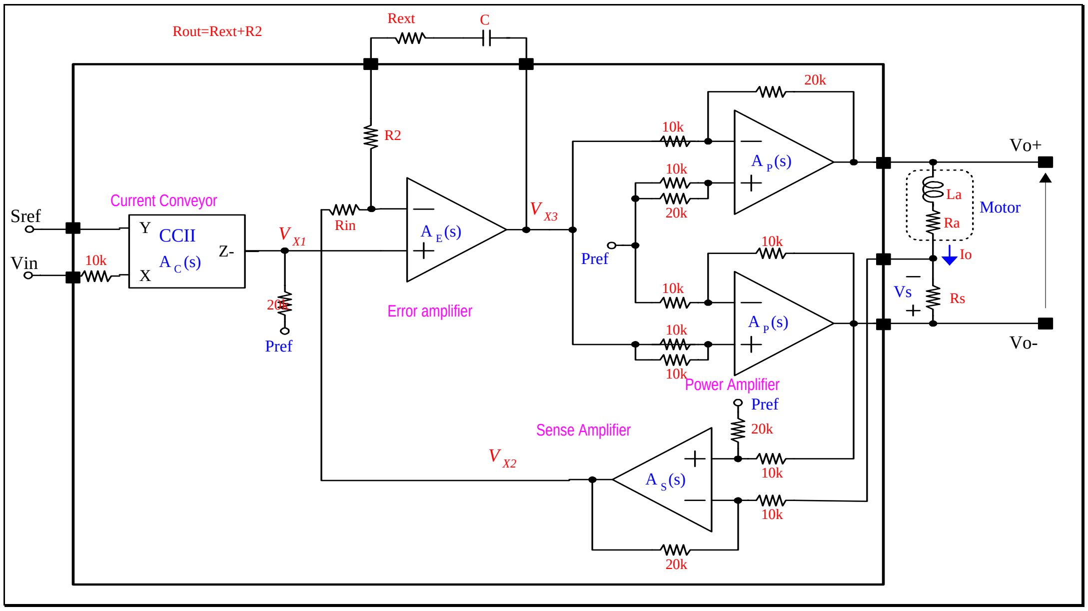

Figure. 3 Current feedback controller in FAN8024/FAN8025

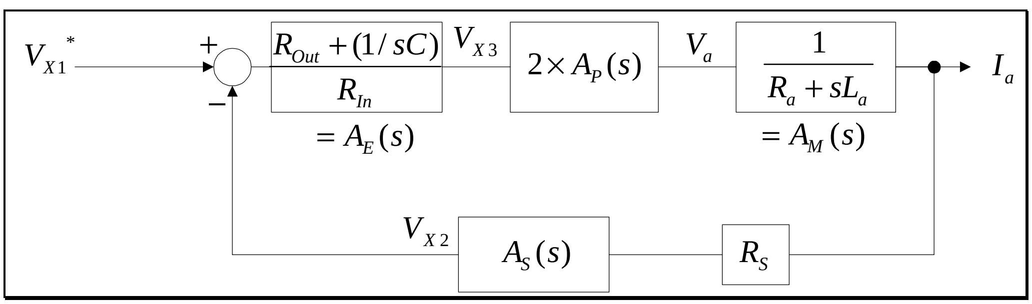

Figure. 4 Current feedback control system block diagram of FAN8024/FAN8025

According to the above definitions and negative feedback theory, closed loop transfer function could be arranged as follow.

$$T_{CL}(s) = \frac{I_a}{V_{X1}} = \frac{H(s)}{1+T(s)} \qquad (7)$$

For an easy analysis, equation 7 could be changed to unity gain feedback system

$$T_{CL}(s) = \frac{1}{G(s)} \cdot \frac{T(s)}{1+T(s)} \qquad (8)$$

New transfer function can be rearranged as Fig. 5.

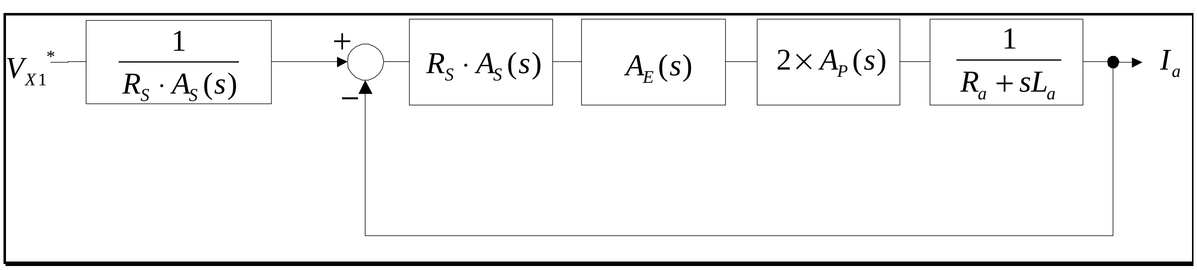

Figure. 5 Revised current feedback control in FAN8024/FAN8025

Let's assume the following two factors for an easy analysis.

Assumption 1. The bandwidth of power amplifier, Ap(s), is too wide that it doesn't affect the whole system dynamics. So, we can replace the transfer function of the power amplifier to constant. This is reasonable because the bandwidth of the power amplifier is far larger than the required system bandwidth.

(Ap(s)=Kpower)

Assumption 2. The bandwidth of sense amplifier, As(s), is wide also. As a result, we can define

As(s) as Ksense

With above assumptions, system block diagram could be simplified as below.

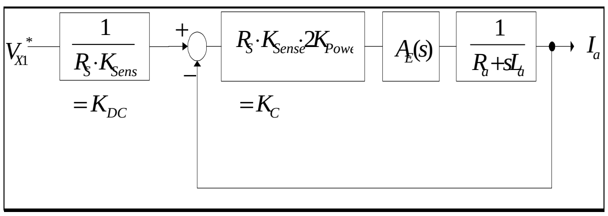

Figure. 6 Simplified current feedback control in FAN8024/ FAN8025

Because the fig.6 is unity gain feedback system, total DC gain is expressed as below.

$$K_{DC} = \frac{1}{R_S \cdot K_{Sense}} \qquad (9)$$

Let's define some constants to simplify the equation.

$$K_C = R_S \cdot K_{Sense} \cdot 2K_{power} \qquad (10)$$

3.Design of Current Feedback Controller

When the PI controller is used as a current controller, the transfer function and block diagram of PI controller are shown as below.

$$A_C(S) = K_P + \frac{K_I}{S} \qquad (11)$$

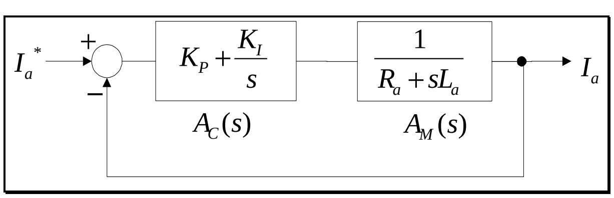

Figure. 7 Typical PI controller

The transfer function of above system can be converted to Pole Zero equation to define design parameter easily and the resulting diagram looks like fig.8. The Pole Zero representation has proportional gain, Kp, one Pole in origin and one Zero in pole point, ω_{PI}

$$\omega_{PI}[rad/sec] = \frac{K_I}{K_P} \qquad (12)$$

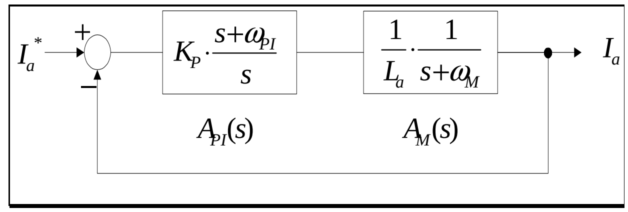

Figure. 8 Revised typical PI controller

The Kp and Ki gain are flexible values to achieve control system performance and the destination of current feedback control is to eliminate the delay effect of load dynamics. If ω_{PI} is equal to ω_M, then delay effect for load can be compensated by zero of PI controller and the loop gain becomes simply first order integration term. This means phase margin of loop gain is more than 90°. So, it is reasonable to give the closed loop bandwidth any value. If the Kp and Ki gains are generally selected, the natural frequency of load would be like in Assumption 3.

Assumption 3. Let $\omega_{PI} = \omega_M$, then following equation is derived.

$$\frac{K_I}{K_p} = \frac{R_a}{L_a} \qquad (13)$$

$$T_{PI}(s) = A_{PI}(s) \cdot A_M(s) = K_P / L_a \qquad (14)$$

The transfer function of closed loop can be represented as equation 15

$$T(s) = \frac{1}{1 + T_{PI}(s)} = \frac{1}{1 + S/\omega_C} \qquad (15)$$

$$\omega_C = \frac{K_P}{L_a} \qquad (16)$$

Where ω_C is bandwidth of the closed loop. Using equation 13 and 16, we can derive gain equations.

$$K_p = \omega_C \cdot L_a \qquad (17)$$

$$K_I = \omega_C \cdot R_a \qquad (18)$$

4. Calculation of External Component

The required system bandwidth and sensing resistor value are decided by the users. By using comparative method for fig. 4, 6 & 7, we can find out the followings.

$$K_P = K_C \cdot \frac{R_{Out}}{R_{In}} \qquad (19)$$

$$K_I = K_C \cdot \frac{1}{C \cdot R_{In}} \qquad (20)$$

When users want to realize the above controller with FAN8024/FAN8025, they should bear in mind the fact that input resistor, Rin, and feedback loop resister, R2, are already fixed with 7.5K. Using equations 19 and 20, the external component coefficient can be finally calculated as below.

$$R_{Out} = \frac{K_P \cdot R_{In}}{K_C} \qquad (21)$$

$$R_{Ext} = R_{Out} - R_2 \qquad (22)$$

$$C = \frac{K_C}{K_I \cdot R_{In}} \qquad (23)$$

Example)

The load impedance of Maker1 40X focus actuator: 18.5Ω . 228.5µH @1KHz,0.1V

Required system bandwidth: fc=60KHz,
Sensing Resister: Rs=0.5Ω
Let Rin=R2 =7.5KΩ .

$$\omega_C = 2 \cdot \pi \cdot f_c = 2 \cdot \pi \cdot 60 \times 10^3 = 37.7 \times 10^4 [rad/sec]$$

$$K_P = \omega_C \cdot L_a = 37.7 \times 10^4 \times 228.5 \times 10^{-6} = 86.14$$

$$K_I = \omega_C \cdot R_a = 37.7 \times 10^4 \times 18.5 = 697 \times 10^4$$

$$K_C = R_S \cdot K_{Sense} \cdot 2K_{Power} = 0.5 \cdot 2 \cdot 2 \cdot 2 = 4$$

$$R_{out} = \frac{K_P \cdot R_1}{K_C} = \frac{86.14 \times 7.5 \times 10^3}{4} = 161.5[K\Omega]$$

$$R_{Ext} = R_{Out} - R_2 = 161.5 - 7.5 = 153[K\Omega]$$

$$C = \frac{K_C}{K_I \cdot R_1} = \frac{4}{697X10^4 \cdot 7.5X10^3} = 76.5[pF]$$

5. Simulation

We simulate this system with MATLAB® which is a powerful and popular software to check a system easily.

Below is MATLAB® program to simulate the above system.

```
R_armature = 18.5;
L_armature = 228.5e-6; %focus actuator

Freq_system =60e3;% system requiring frequency,
60KhzOmega_system = 2*pi*60e3;
R1 = 7.5e3; % serial resistor

R2 = ((Omega_system*L_armature*R1)/4);
%feedback resistor
w=logspace(3,6,1000);
t= (0:1e-7:4e-5);

Motorsystem_num = [R_armature];
%DC-gain is set for unity gain
Motorsystem_den = [L_armature R_armature];

FBsystem_num = [Kp Ki];
FBsystem_den = [L_armature R_armature+Kp Ki];

Kp = Omega_system*L_armature
Ki = Omega_system*R_armature
R2_added=R2-7.5e3
%necessary resistor add to feedback loop
C = L_armature/(R2*R_armature)
% feedback capacitor
figure (1)
bode (Motorsystem_num,Motorsystem_den,w)

figure (2)
step (Motorsystem_num,Motorsystem_den),grid

figure (3)
bode (FBsystem_num,FBsystem_den,w)

figure (4)
step (FBsystem_num,FBsystem_den,t),grid
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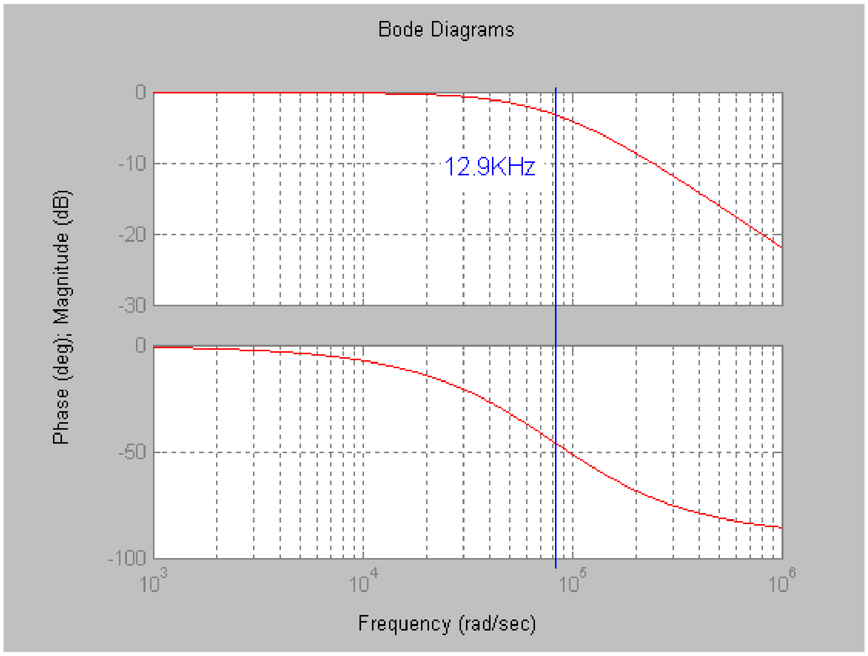

Figure.10 Bode plot of motor system itself
(Below 3dB point from the DC-gain is 12.9KHz that is natural bandwidth of motor)

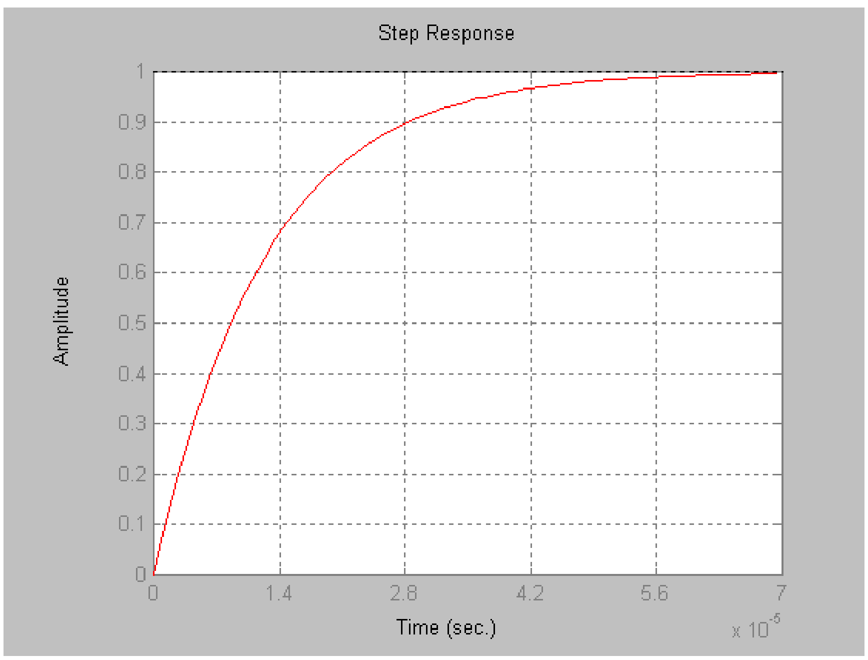

Figure.11 Step response of motor system itself

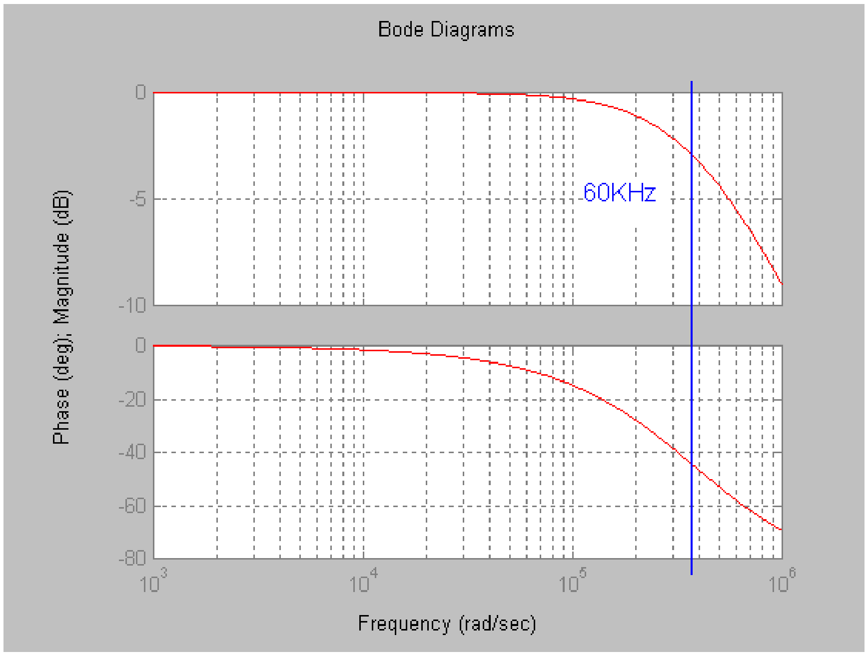

Figure. 12 Bode plot of current feedback control system
(Below 3dB point from the DC-gain is 60KHz that is system required dynamics)

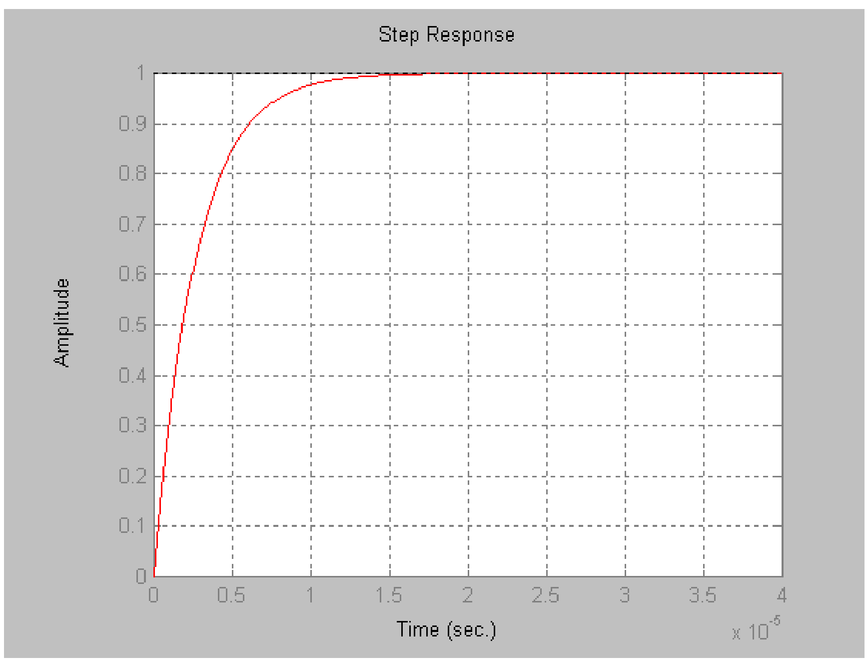

Figure. 13 Step response of current feedback control system

(Notice the time scale)

6. Experimental Result

This is a test with FAN8024/FAN8025 current feedback channel to verify current feedback performance.
After checking the motor dynamics with voltage mode channel, test is done by current feedback controller. And then compare the two results. Test condition is same as that of simulation but there are no exact real components; we use 157.5K for R2 and 66pF for C
Measuring instruments we used are listed below:

- Tektronics TDS460A digital oscilloscope
- Tektronics AM503B current probe amplifier
- Tektronics A6303 current probe
- Hewlett Packard 4194A Impedance/Gain Phase analyzer
- Hewlett Packard 33120A Arbitrary function generator
- Kikusu PAK35-10A DC power supply

4194A gain-phase analyzer can draw bode plot automatically. But both input and output are only voltages, bringing somewhat different in bode plot of gain since the current is measured with current probe amplified through current probe amplifier. We can only refer to trend of bode plot.

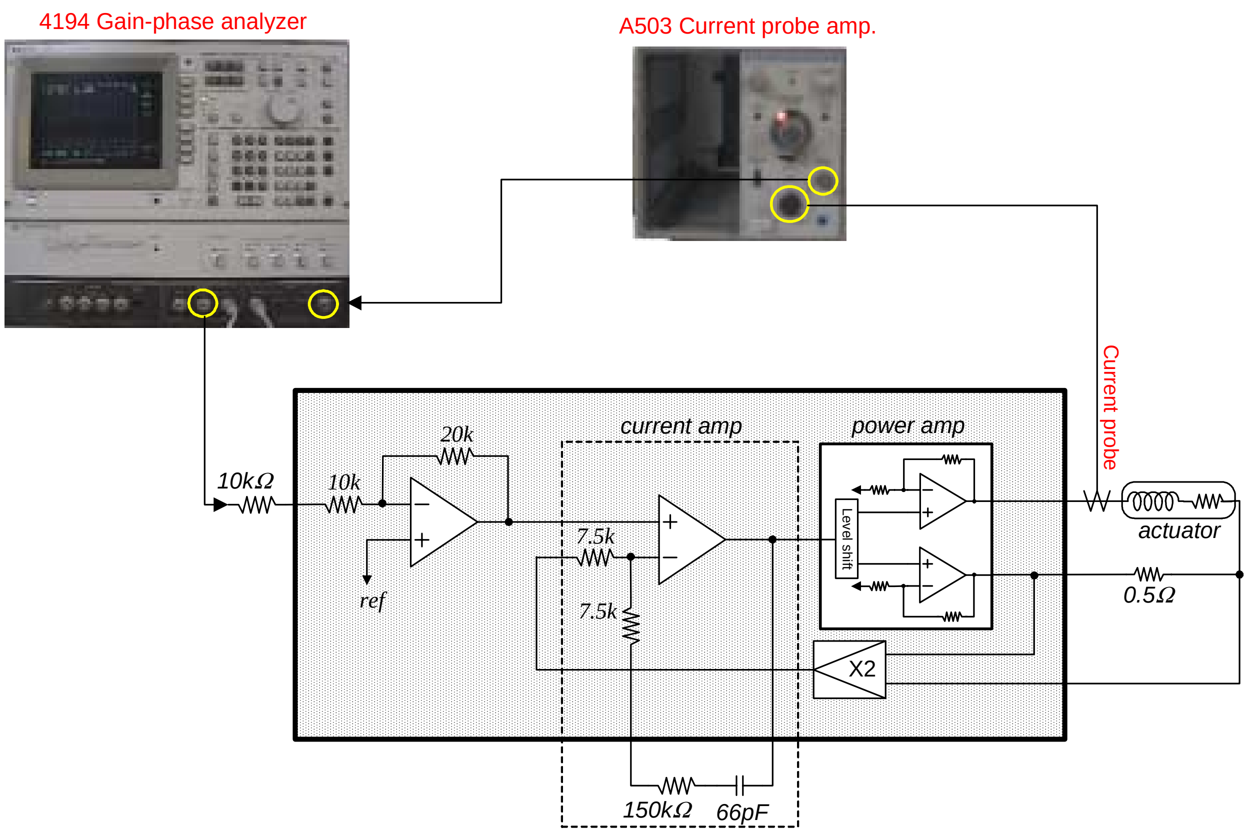

Figure. 14 Experimental setup using FAN8024/FAN8025 current feedback channel

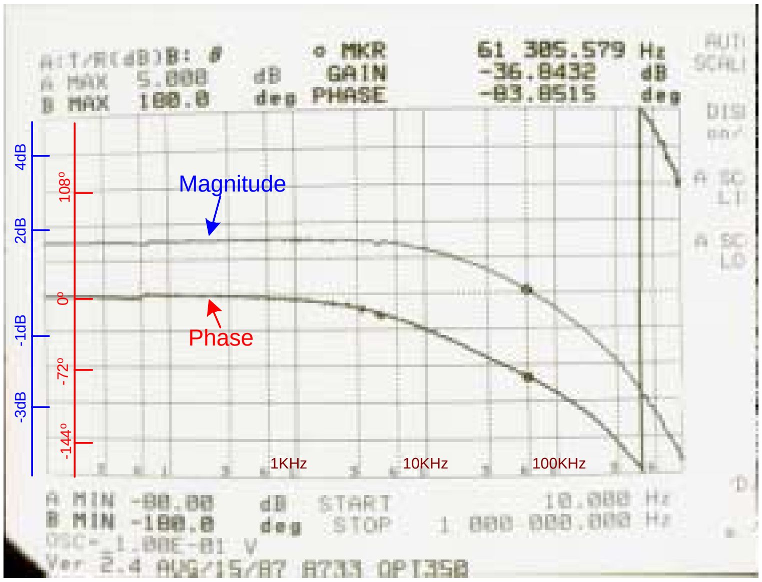

Figure. 13 Frequency response of tested actuator with FAN8024/FAN8025(voltage mode control)

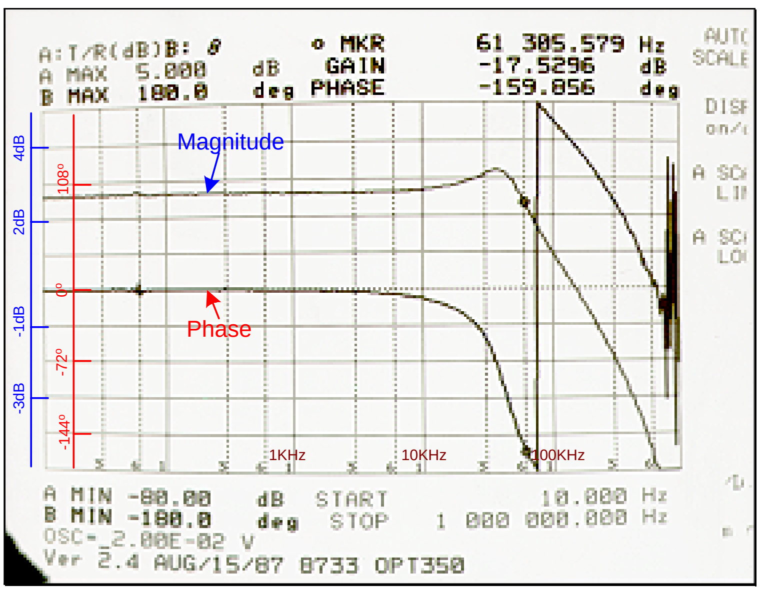

Figure. 14 Frequency response of tested actuator with FAN8024/FAN8025 (current feedback control)

7. Conclusion

Until now the controlling method of CD-media motor (actuators and loading motor etc.) is just in voltage mode which is very simple and easy to understand. But nowadays the system dynamics of CD-media (include CD-ROM, CD-RW, DVDP and DVD-ROM etc.) is increasing rapidly because the point edge multi media system needs huge data access. It means another controller (that is current controller) is needed to match the system dynamics without motor change. Under the current control system, transfer function become complicated and it is difficult to understand system intuitively. In this application note, we have described the current feedback controller of motor system and extracted the method of calculating the controller gains. With this method users can understand the system intuitively and extract the external component values from simple calculations.

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