Servo Synthesis for an Optical Pick-up Head with Tilt Compensation

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Abstract: The new DVD optical heads are equipped with tilt control mechanism to compensate for the disk tilt. From the servo point of view, the tilt control shares the same push-pull tracking error (PPTE) signal from the optical head and are compensating the same control goal. In addition, the system exhibits highly nonlinear characteristics due to the change in the lens tilt. This study derives the optical head nonlinear dynamic model based on the Newtonian mechanics. The model indicates that the nonlinear effects mainly arise from the variation in the lens tilt. With reasonable approximations, it is possible to separate these nonlinear factors and lump them into a system variation term. The popular μ synthesis procedure is then used for the controller design.

Keywords : Optical disks, Nonlinear systems, Robust control, Uncertainty

1. INTRODUCTION

Digital versatile disk drives now-a-day usually contains 4.7 Gbytes of data. The newer Blue-Ray Disk (BD) and Advanced Optical Disk (AOD) hold up to 27 and 20 Gbytes, respectively. The track pitch on the DVD disk is 1.6 μm per track. To hold the amount of data, it can be seen that the track pitch on the new BD or AOD would be a few hundred nanometers. The DVD optical head company researchers have noticed the influence of disk wobble on the reflection of the laser beam, and have introduced active tilt control as an effective way of compensating for the DVD tracking error.

The DVD optical head assembly is usually composed of two pairs of coils: one for focusing and the other for fine tracking. The optical head enabling active tilt control will implement an additional tilt actuator coil alongside the focusing coil. The tilt coil has the same winding structure as the focusing coil except the windings are reversed to produce equal and opposite forces. The dynamic behavior of the optical head is then more complicated. The commercial chip set to handle the three degree-of-freedom servo relies on separate control loops to simplify the controller structure; however, the coupling effects will obviously affect the servo performance. The previous results in this area are quite limited. Active tilt control on an optical disk drive reduces jitter and improves the signal-to-noise ratio of the read back signal. In addition, the DVD optical head often uses high numerical aperture (NA) to reduce the size of the laser spot. The tilt control on a high NA optical head and also improves the signal quality. There are, however, weaknesses on using active tilt control. First, the crosstalk's among the three control axes become more serious with the introduction of the tilt control. Second, there is still a lack of tilt control chipset available. Therefore, active tilt represents an increase in the production cost.

A majority of the literature have focused on the mechanical and optical design of the three dimensional optical head (Ishibashi, *et al.*, 1996, Yoshimura, *et al.*, 1996, Namoto, *et al.*, 1997, Tateishi, *et al.*, 1999, Takamine, *et al.*, 1999, Son, 2001, Watanabe, 2002, Furukawa, 2002). There is also some discussion on how to obtain measurement signal from the tilt control optical heads (Sarigoz, 1998), but only until recent have people stated to discuss the tilt servo issue in the DVD system (Yamada, *et al.*, 1999, Yamada, *et al.*, 2000, Bittanti, *et al.*,2002). Most results have treated the tilt control problem with separate control and showed that tilt control improved the signal jitter. It is also interesting to note that only until very recent have people started discussing the nonlinear dynamic behavior of the tile control system (Paul, *et al.*, 2003). This result used nonlinear control and is difficult to implement with the standard DVD controller chipset.

This paper proposed a 6 degree-of-freedom system modeling for the tilt control optical head. The nonlinear effect of the tilt control optical head arises mainly from the tilt angle variation. To overcome this difficulty, the authors took a careful examination and are able to separate the nonlinear behavior from the nominal model. The system can be expressed with the familiar linear fractional transformation and apply the linear control for the control. The controller is easy to implement, and the simulation results show that the control is effective under tilt angle variations.

2. THE SYSTEM MODEL

Figure 1 shows the schematics of the DVD optics.

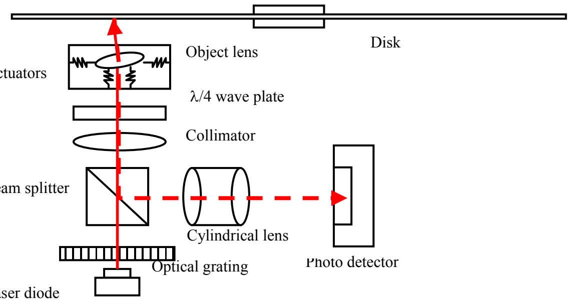

Figure 1. DVD optics

The laser light from the laser diode is focused on the disk surface by adjusting the object lens. The reflected light is then gathered by the same object lens and sent to the photo detector to convert the reflected signal into electrical signal. The cylindrical lens varies the shape of the reflected laser beam spot with different focal length and allows the detection of the focusing error. The vertical movement of the object lens is usually sufficient to maintain focus of the beam when the disk surface is in good condition. When there is too much tilt on the disk surface it would be necessary to also bent the laser beam by tilting the object lens.

According to the ECMA specifications, the maximum amount of allowable disk tilt in the radial direction is α = 0.80°, and the maximum allowable tilt in the tangential direction is α = 0.30° (DVD specifications, 2001). This specification provides us with a bound on the magnitude of tilt angle to be expected. As discussed in (Sarigoz, *et al.*, 1998), it is possible to use the push-pull tracking error (PPTE) signal to determine the amount of disk bent. They have also shown that this error can be corrected by properly changing the optical lens tile angle, and the signal gitter gains significant improvement.

Figure 2. Tilt control and focusing actuator coil

For the optical head with tilt control, the tilt coil is usually located on the same plane as the mass center to produce a close to pure torque on the focusing lens. From Newton's law of motion, the translational motion of the lens system can be described as:

$$
\begin{aligned}
&F_x - K_x x = M\ddot{x} \\
&F_y - K_y y - Mg = M\ddot{y} \\
&F_z - K_z z = M\ddot{z}
\end{aligned} \tag{1}
$$

where K_x, K_y, K_z are the spring constants of the wires suspending the object lens. The gravity force can be neglected by setting $F_y - Mg = F_y{}'$.

The rotational motion of the system is then

$$
\begin{aligned}
&\sum M_x = \dot{H}_x - H_y\omega_z + H_z\omega_y \\
&\sum M_y = \dot{H}_y - H_z\omega_x + H_x\omega_z \\
&\sum M_z = \dot{H}_z - H_x\omega_y + H_y\omega_x
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
&\sum M_x = I_{xx}\ddot{\theta}_x - I_{yy}\dot{\theta}_y\dot{\theta}_z - I_{zz}\dot{\theta}_y\dot{\theta}_z \\
&\sum M_y = I_{yy}\ddot{\theta}_y - I_{zz}\dot{\theta}_z\dot{\theta}_x - I_{xx}\dot{\theta}_z\dot{\theta}_x \\
&\sum M_z = I_{zz}\ddot{\theta}_z - I_{xx}\dot{\theta}_x\dot{\theta}_y - I_{yy}\dot{\theta}_x\dot{\theta}_y\ ,
\end{aligned} \tag{3}
$$

where the products of inertia are set to zero by assuming the torques are acting on the principal axes. From the coil design the torque acting on the *x* and *y* axes are zero (figure 3), and there are only translational motion in the *x* and *y* directions.

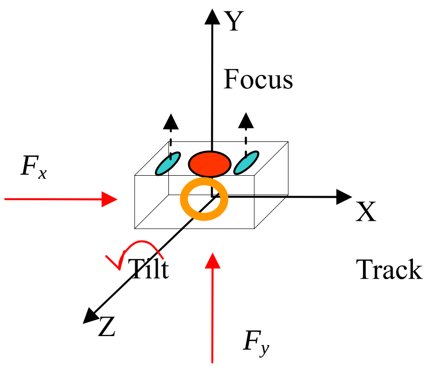

Figure 3. The motion of the object lens

Then (3) can be simplified to be

$$\sum M_z = I_{zz}\ddot{\theta}_z\ . \tag{4}$$

For the case when the lens is in the horizontal position, the electromagnetic force of the coil from Kirchhoff law gives

$$F_{(x,y,\theta)} = n_m B_m l_m i_m = \frac{n_m B_m l_m}{R_m}\left(V_m - K_{mvs}\dot{q}_{(x,y,\theta)}\right), \tag{5}$$

where n_m is the number of turns, B_m is the magnetic flux density, and l_m is the effective coil dimension.

Combining equations (1), (4) and substitute the forces and torque from (5), one obtain

$$\begin{aligned}
\ddot{x} &= -K_{mvs,x}\frac{n_x B_x l_x}{MR_x}\dot{x} - \frac{K_x}{M}x + \frac{n_x B_x l_x}{MR_x}V_x \\
\ddot{y} &= -K_{mvs,y}\frac{n_y B_y l_y}{MR_y}\dot{x} - \frac{K_y}{M}x + \frac{n_y B_y l_y}{MR_y}V_y \qquad (6) \\
\ddot{\theta}_z &= -K_{mvs,\theta_z}\frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}}\dot{\theta}_z - \frac{K_\theta}{I_{zz}}\theta_z + \frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}}V_{\theta_z}
\end{aligned}$$

Writing the equations in the system form, one obrain

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{y}\\ \ddot{y}\\ \dot{\theta}\\ \ddot{\theta}\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{K_x}{M} & -\frac{K_{mvs,x}n_x B_x l_x}{MR_x} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{K_y}{M} & -\frac{K_{mvs,y}n_y B_y l_y}{MR_y} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -\frac{K_{\theta_z}}{I_{zz}} & -\frac{K_{mvs,\theta_z}n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}} \end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ y\\ \dot{y}\\ \theta\\ \dot{\theta}\end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \frac{n_x B_x l_x}{MR_x} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{n_y B_y l_y}{MR_y} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{R_{\theta_z} I_{zz}} \end{bmatrix}\begin{bmatrix}V_x\\ V_y\\ V_{\theta_z}\end{bmatrix}$$

$$\mathbf{y} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}\mathbf{x}$$

The transfer function matrix is thus

$$\begin{bmatrix}Y_x\\ Y_y\\ \Theta\end{bmatrix} = \begin{bmatrix} \dfrac{\frac{n_x B_x l_x}{MR_x}}{s^2 + \frac{K_{mvs,x}n_x B_x l_x}{MR_x}s + \frac{K_x}{M}} & 0 & 0 \\ 0 & \dfrac{\frac{n_y B_y l_y}{MR_y}}{s^2 + \frac{K_{mvs,y}n_y B_y l_y}{MR_y}s + \frac{K_y}{M}} & 0 \\ 0 & 0 & \dfrac{\frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}}}{s^2 + \frac{K_{mvs,\theta_z}n_{\theta_z} B_{\theta_z} l_{\theta_z}}{MR_{\theta_z}}s + \frac{K_{\theta_z}}{M}} \end{bmatrix}\begin{bmatrix}U_x\\ U_y\\ U_\theta\end{bmatrix}$$

(7)

The result is useful for the system identification.

When the object lens is moved away from the zero position and tilted, the forces acting on the lens can be represented in figure 4, and the equations of motion can now be represented as:

Track, Focus, Tilt actuator action

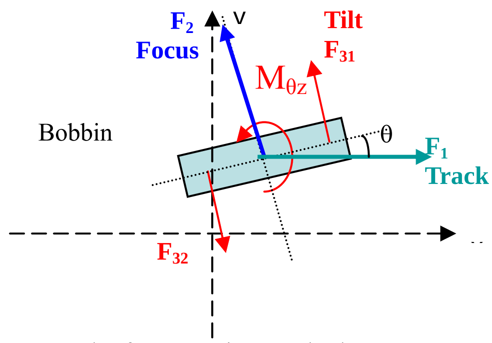

Figure 4. The forces acting on the lens

$$\sum F_x = F_1 - F_2\sin\theta + F_{31}\sin\theta - F_{32}\sin\theta - K_x x = M\ddot{x}.$$

Note that F_{31} and F_{32} are equal in magnitude and opposite, one can write

$$\ddot{x} = -K_{mvsx}\frac{n_x B_x l_x}{MR_x}\dot{x} - \frac{K_x}{M}x + \frac{n_x B_x l_x}{MR_x}V_x + K_{mvsy}\frac{n_y B_y l_y}{MR_y}\dot{y}\sin\theta - \frac{n_y B_y l_y}{MR_y}V_y\sin\theta$$

. (8)

Similarly, for y and θ_z to obtain

$$\ddot{y} = -K_{mvs,y}\frac{n_y B_y l_y}{MR_y}\dot{y}\cos\theta - \frac{K_y}{M}y + \frac{n_y B_y l_y}{MR_y}V_y\cos\theta$$

(9)

$$\ddot{\theta} = -K_{mvs,\theta_z}\frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}}\dot{\theta} - \frac{K_{\theta_z}}{I_{zz}}\theta + \frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}}V_{\theta_z}$$

(10)

The system equation becomes now

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{y}\\ \ddot{y}\\ \dot{\theta}\\ \ddot{\theta}\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{K_x}{M} & -\frac{K_{mvs,x}n_x B_x l_x}{MR_x} & 0 & \frac{K_{mvs,x}n_x B_x l_x}{MR_x}\sin\theta & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{K_y}{M} & -\frac{K_{mvs,y}n_y B_y l_y}{MR_y}\cos\theta & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -\frac{K_{\theta_z}}{I_{zz}} & -\frac{K_{mvs,\theta_z}n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}} \end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ y\\ \dot{y}\\ \theta\\ \dot{\theta}\end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \frac{n_x B_x l_x}{MR_x} & \frac{n_x B_x l_x}{MR_x}\sin\theta & 0 \\ 0 & 0 & 0 \\ 0 & \frac{n_y B_y l_y}{MR_y}\cos\theta & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{R_{\theta_z} I_{zz}} \end{bmatrix}\begin{bmatrix}V_x\\ V_y\\ V_{\theta_z}\end{bmatrix}$$

(11)

The system transfer function now becomes

$$\begin{bmatrix}Y_x\\ Y_y\\ \Theta\end{bmatrix} = \begin{bmatrix} \dfrac{\frac{n_x B_x l_x}{MR_x}}{s^2 + \frac{K_{mvs,x}n_x B_x l_x}{MR_x}s + \frac{K_x}{M}} & G_{11}(s)\frac{R_x n_y B_y l_y}{R_y n_x B_x l_x}\sin\theta\left(K_{mvs,y}sG_{22}(s) - 1\right) & 0 \\ 0 & \dfrac{\frac{n_y B_y l_y\cos\theta}{MR_y}}{s^2 + \frac{K_{mvs,y}n_y B_y l_y\cos\theta}{MR_y}s + \frac{K_y}{M}} & 0 \\ 0 & 0 & \dfrac{\frac{n_{\theta_z} B_{\theta_z} l_{\theta_z}}{I_{zz}R_{\theta_z}}}{s^2 + \frac{K_{mvs,\theta_z}n_{\theta_z} B_{\theta_z} l_{\theta_z}}{MR_{\theta_z}}s + \frac{K_{\theta_z}}{M}} \end{bmatrix}\begin{bmatrix}U_x\\ U_y\\ U_\theta\end{bmatrix}$$

(12)

where $G_{11}(s)=\dfrac{\dfrac{n_x B_x l_x}{MR_x}}{s^2+\dfrac{K_{mvs,x} n_x B_x l_x}{MR_x} s+\dfrac{K_x}{M}}$, and

$$G_{22}(s)=\frac{\dfrac{n_y B_y l_y \cos\theta}{MR_y}}{s^2+\dfrac{K_{mvs,y} n_y B_y l_y \cos\theta}{MR_y} s+\dfrac{K_y}{M}}.$$

It is clear that the coupling effect due to lens tilt can become significant with the variation of the tilt angle θ.

3. SYSTEM IDENTIFICATION

The system identification is carried out with the random noise identification function by an HP35663 structure analyzer. An eddy current proximity sensor placed 0.5 cm away from the optical head lens measures the output displacement. The lens is covered with a thin aluminum foil to induce the sensor current. The input noise is set to a 160 mV signal around a 1.4V dc. The proximity sensor is capable of picking up lens displace. The tilt angle is then measured by the PPTE variation when the optical head is not moving.

Figure 5 shows the frequency response of the focusing system.

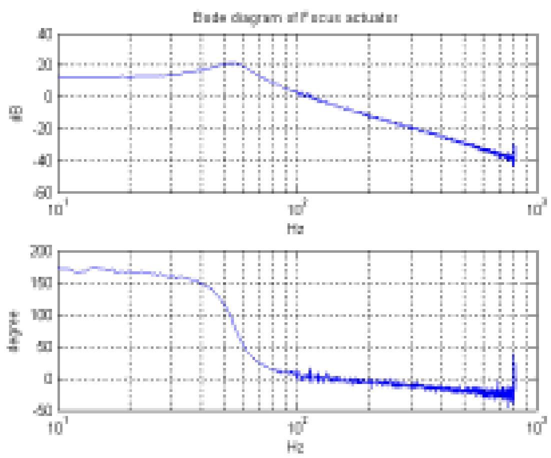

Figure 5. Frequency response of the focusing system.

There is an obvious resonance at 53 Hz with 10 dB peak. The frequency fit transfer function is

$$G_f(s)=\frac{-405956.6}{s^2+94.34s+113048.4}. \tag{13}$$

The frequency response of the fine tracking servo is shown in figure 6.

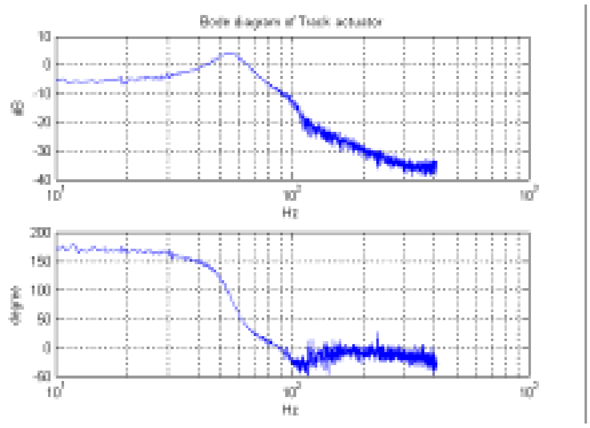

Figure 6. The frequency response of the fine tracking servo.

The 53 Hz resonance is still obvious with 12 db peak. The curve fit transfer function is

$$G_{ft}(s)=\frac{-58124.1}{s^2+98.08s+117997.8}. \tag{14}$$

Figure 7 shows the frequency response of the lens tilt system. The first obvious resonance now moved to 102 Hz with 10 dB peak. The curve fitted transfer function is

$$G_t(s)=\frac{-40367.5}{s^2+334.35s+465606.9}. \tag{15}$$

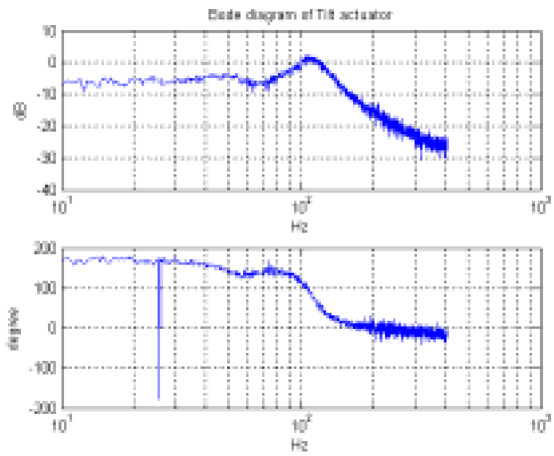

Figure 7. The frequency response of the tilt control system.

The overall system can now be written as

$$\begin{bmatrix} Y_x \\ Y_y \\ \Theta \end{bmatrix}=\begin{bmatrix} \dfrac{-581241}{s^2+98.08s+1179978} & \dfrac{-4057062}{s^2+98.08s+1179978}\sin\theta\left(\dfrac{9418\cos\theta s}{s^2+94.34\cos\theta s+113484}-1\right) & 0 \\ 0 & \dfrac{-4059566\cos\theta}{s^2+94.34\cos\theta s+1130484} & 0 \\ 0 & 0 & \dfrac{-403675}{s^2+334.35s+4656069} \end{bmatrix}\begin{bmatrix} U_x \\ U_y \\ U_\theta \end{bmatrix} \tag{16}$$

By approximating the small angle sinusoidal function with θ, and treat the cosine function as 1, one can approximate equation (16) with

$$\begin{bmatrix} Y_x \\ Y_y \\ \Theta \end{bmatrix}=\begin{bmatrix} \dfrac{-581241}{s^2+98.08s+1179978} & G_{12}(s) & 0 \\ 0 & \dfrac{-4059566\cos\theta}{s^2+94.34\cos\theta s+1130484} & 0 \\ 0 & 0 & \dfrac{-403675}{s^2+33435s+4656069} \end{bmatrix}\begin{bmatrix} U_x \\ U_y \\ U_\theta \end{bmatrix},$$

(17)

where

$$G_{12}(s) = \frac{-38209409.9\theta s}{s^4 + 192.4s^3 + 240299s^2 + 2{,}22\times10^7 s + 1.33\times10^{10}} - \frac{-405706.2\theta}{s^2 + 98.08s + 117997.8}$$

.

It is now possible to represent the system as uncertainty terms caused by the tilt angle θ and apply the familiar μ control synthesis.

4. CONTROLLER DESIGN

By lumping the magnitude of the tilt angle obtained from the ECMA specification into the system, one can normalize the tilt angle uncertainty term with a single normalized uncertainty term, Δ. In addition, three separate uncertainty terms are introduced to represent the unmodeled dynamics in the three input channels. The control system loop thus becomes as shown in figure 8, and one can now apply the familiar μ synthesis procedure for the controller design (Skogestad and Postlethwaite, 1996).

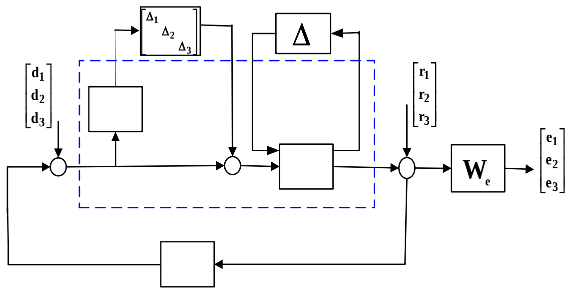

Figure 8. The uncertainty system representation.

The system identification results are very accurate in the low frequency region; however, there are measurement noises in the high frequency region. Because the optical head needs to operate with a bandwidth close to 3 KHz, the weighting function for the input uncertainty, W_u, is designed as shown in figure 9.

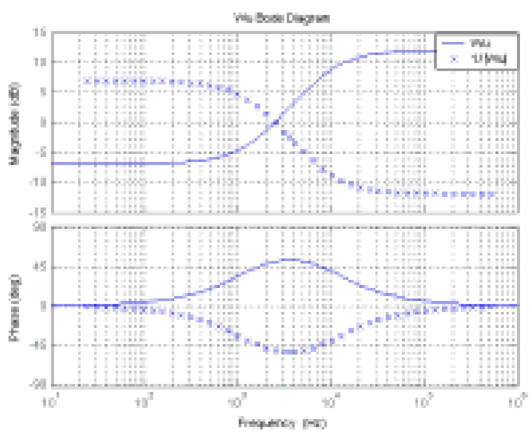

Figure 9. The weighting function for the input uncertainty

Accordingly, the performance specification is designed as shown in figure 10.

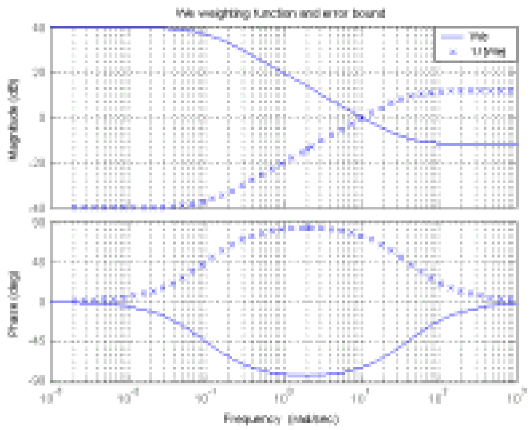

Figure 10. The performance specification for the system.

Because the system measures three outputs to produce three manipulating inputs, the controller is a three by three transfer function matrix. Due to the space limitation, the control transfer function matrix will not be included here. We just mention that the controller are linear time invariant controllers and are easily implemented with the commercial digital signal processors.

5. SIMULATION RESULTS

Figure 11 shows the system response to a step command when the tilt angle is set to zero. The signals are tracking response, focusing response, and tilt angle, respectively. One can see that the signal all follows the commands and settles within very short transient periods.

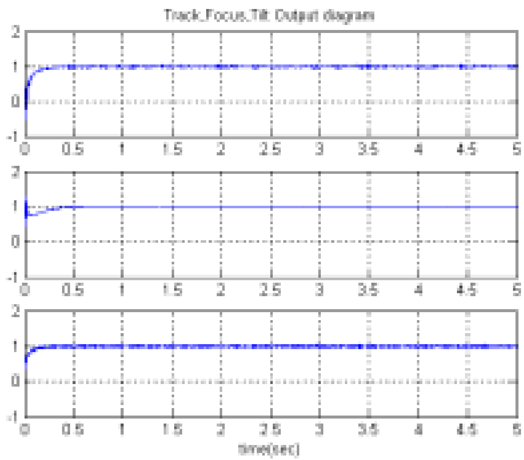

Figure 11. The system response under no tilt condition.

To examine the capability of the system under the tilt condition, we introduce a tilt angle of ±0.0052° and subject the system to an external disturbance of 25 Hz with 0.2V amplitude. The disturbance signal is to simulate the situation when the DVD is at work with a disk that are placed with an eccentricity.

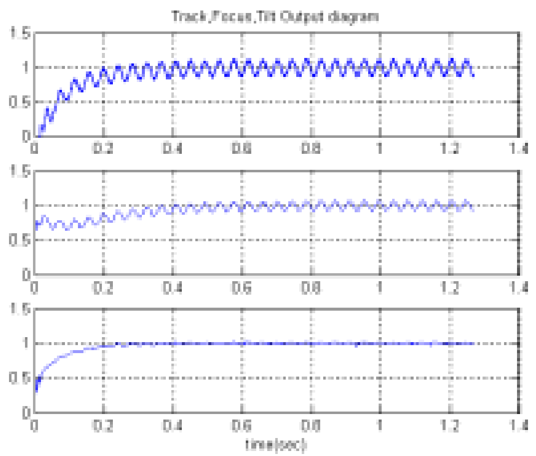

Figure 12. The system response with tilt angle and external disturbance.

The responses, again, are tracking signal, focusing signal and tilt angle, respectively. It is observed that the system can still manage to control the responses and settle the signals within 500 ms, even though some residual disturbance remains observed. The tilt angle does not significantly affect the servo performance. These results are expected because the design setup has specified the fact that there maybe a tilt angle change with 0.8° variation. Even though the system representation has been simplified, one still expect the μ controller to be able to handle the system variation.

6. CONCLUSIONS

This paper derived the nonlinear dynamic behavior for the DVD optical head with tilt control. A system model was then expressed in terms of the lens tilt angle. The system identification model validated the model. It is noted that the tilt angle nonlinearity can be separated out and the system could then be formulated into a standard LFT formulation. The μ synthesis procedure then calculated the multivariable controller. The simulation results showed that the μ control still achieve the control goal when the lens experience severe tilt.

7. ACKNOWLEDGEMENTS:

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