Controller Design of Piezoelectric Milliactuator for Dual Stage System
이중 구동 시스템을 위한 압전 밀리엑추에이터의 제어기 설계

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ABSTRACT

To reach high areal density, less track pitch is expected and more servo bandwidth is required. One approach to overcoming the problem is by using dual stage servo system. For this system, we have suggested new milliactuator based on the shear mode of piezoelectric elements to drive the head suspension assembly. In this paper, we introduce milliactuator and controller design method, PQ method. PQ method reduces the controller design problem for DISO (dual-input/single-output) systems to two standard controller design problems for SISO (single-input/single-output) problems. The first part of PQ method directly addresses the issue of actuator output contribution, and the second part allows the use of traditional loop shaping to achieve the overall system performance. This paper shows how to employ the PQ method to meet aggressive close-loop performance specifications for a disk drive system with a VCM and piezoelectric milliactuator.

요 약

고밀도, 고정밀의 정보저장기를 실현하기 위해서 높은 서보대역이 요구되고 있다. 이러한 요구조건을 만족시키기 위해서 이단구동시스템이 도입되었다. 이 시스템은 기존의 VCM을 조동구동기로, 추가적인 밀리엑츄에이터를 미동구동기로 사용하는 것이다. 이를 위해 우리는 압전형 밀리엑츄에이터를 서스펜션부에 설계하였다. 이러한 시스템의 제어를 위하여 PQ 제어 방법을 도입하였으며, 이 방식은 이중입력/단일출력 시스템을 두개의 단일 입출력 시스템으로 단순화시키는 것이다. 이 논문은 PQ 제어 방식을 적용시켜 설계하고, 설계된 제어기의 성능 평가로써 기존의 HDD의 PES을 받아서 외란제어 능력을 평가하는 것이다.

1. Introduction

The areal recording density of HDD (hard disk drives) has been increasing by about 100% a year. In order to reach high areal density, less track pitch is expected and more servo bandwidth is required. To achieve so high the track density, one possible solution that can provide higher bandwidth is dual stage actuator system.

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The dual stage actuator system consists of a VCM (voice coil motor) as the primary stage and a milliactuator as the secondary stage. The high bandwidth secondary stage combining with the primary stage will increase the whole system's servo bandwidth, and the high track density is achieved in HDD. Therefore, the precise head positioning control can be realized.[5, 6]

The dual stage actuator system can be classified by energy conversion or location of the secondary actuator. The three types of electrical to mechanical energy conversion methods are electromagnetic, electrostatic and piezoelectric type. Another various types of the dual actuator systems are divide into four groups: moving slider, head, slider, suspension, slider and suspension.[8]

In dual stage servo system, only total output of the two actuators is usually available for the servo controller. Accordingly, the dual stage actuator is a DISO(dual-input/single-output) system, and the servo controller is a SIDO (single-input/dual-output) system. MIMO (multi-input/multi-output) controller is a special case. MIMO controller design method is applied to the design of the dual stage servo system, such as LQR, H_∞, μ-synthesis. However, these control methods usually results in high order controllers, which are hard to implement on the actual HDD.

The master-slave method tries to treat this MIMO design as a series of SISO designs. However, this method assumes that very little interaction takes place between VCM loop and milliactuator loop. Actually, there is an interaction between the two loops, which interferes system performance. The PQ method reduces the controller design problem for DISO(dual-input/single-output) problems systems to two standard controller design problems for SISO (single-input/single-output) problems. The first part of the PQ method directly address the issue of actuator output contribution as a function of frequency, and the second part allows the use of traditional loop shaping to achieve the overall system performance.[1~4]

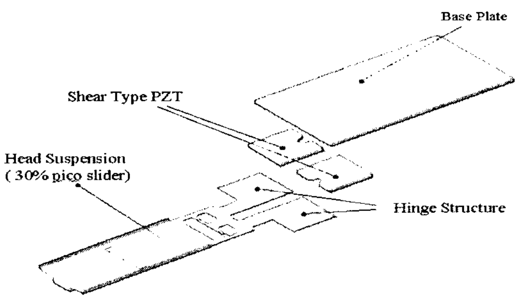


Fig. 1 Shear mode piezoelectric milliactuator

In this paper, we use a piezoelectric milliactuator for dual stage systems, as shown in Fig. 1. Our piezoelectric actuator is based on the shear mode of piezoelectric elements to drive the head suspension assembly. The dual servo system is applied by PQ method.

2. Shear Mode Piezoelectric Milliactuator

2.1 Piezoelectric Suspension

Maintaining the trend towards higher track densities in HDD, it is required that track following servo system has to increase servo bandwidth for reliable storage device. However, track density increase is limited by servo bandwidths. The system bandwidth is limited by the mechanical resonance of actuator. For increasing mechanical resonance of actuator, piezoelectric suspension should have higher stiffness in the lateral direction and has compliance in the vertical direction. Satisfying these trade-off characteristic of the suspension, optimal design process is utilized. And the shear type PZT is introduced. The shear type PZT does not depend on dimensions of the element, but depends on the shear mode PZT type coefficient and the number of layers.

Due to these efforts, our milliactuator is able to have higher bandwidth and stability of the head/slider.[7, 9]

2.2 Design of Suspension for Milliactuator

We have suggested new milliactuator base on the shear mode of piezoelectric elements to drive the head suspension assembly. Securing enough servo bandwidth, piezoelectric suspension has higher stiffness in the lateral direction and has compliance in the vertical direction. To trade off between lateral stiffness and vertical flexibility is considered the optimizing design parameters. To satisfy these properties, we design channel structure for lateral stiffness, and sidebending height, groove structure for compliance. Also, the hinge structure of the milliactuator is designed on the spring region for adding a vertical flexibility.

The sensitivity analysis is utilized in optimal design. Beam width, beam length, groove margin, spring length, and side bending height are selected by design variables. Cantilever mode, 2nd torsion mode, and sway mode are selected by target variables.

Figure 2 shows the structure of a piezoelectric milliactuator. The piezoelectric milliactuator consists of a suspension, hinge structure, PZT, and base plate.

The lateral natural frequency of the piezoelectric milliactuator is 10 Hz, which can achieve higher

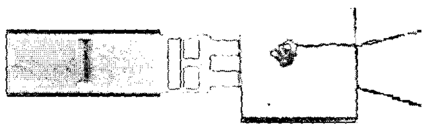


Fig. 2 Milliactuator embedded suspension

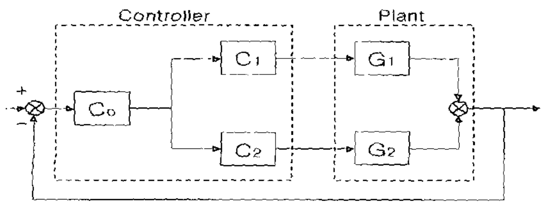


Fig. 3 Block diagram for general DISO system

bandwidth about 2 kHz our desired frequency for dual stage actuator systems.

3. Controller Design

3.1 Introduction of PQ Method

PQ method is control method that can construct compensator, systematically. PQ method reduces the controller design problem for dual-input/single-output (DISO) systems to two standard controller design problems for single-input/single-output (SISO) problems. The first part of PQ method directly address the issue of actuator output contribution and the second part allows the use of traditional loop shaping to achieve the overall system performance. Most linear time-invariant feedback systems consisting of a DISO system with a single-input/dual-output (SIDO)compensator can have the block diagram form as shown Fig. 3.[2]

G_1 represents the dynamics of the coarse actuator, and G_2 represents the dynamics of the secondary actuator in Fig. 3.

Next step is to define $P = G_2/G_1$. Compensator Q is designed to stabilize the plant (P) with unit feedback as shown Fig. 4. The response of the dual system is dominated by the out put of G_2 until when the frequency is equal to 0 dB crossover frequency. If the outputs are

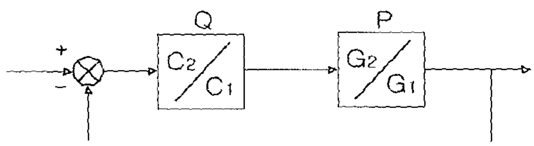


Fig. 4 Block diagram of the PQ feedback system

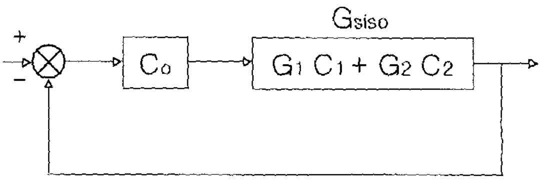


Fig. 5 Block diagram of the SISO system

about 180 degrees out of phase when magnitudes are nearly equal, the dual stage system will be interface each other, and total output magnitude will drop considerably owing to destructive interference. To avoid destruction between VCM and milliactuator, a sufficient phase margin should be considered in designing the control scheme.

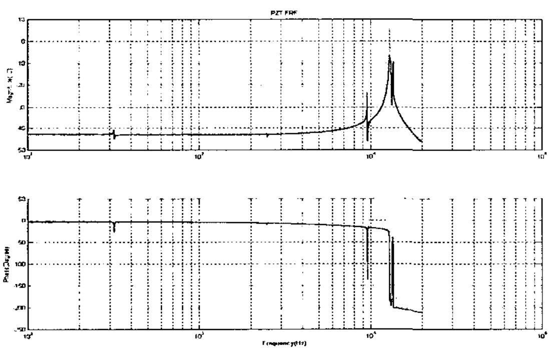
Next, C_1 and C_2 is designed to address the issues of stable zeros, relative output, and destructive interference. Once, C_1 and C_2 have been selected, then, $G_{siso} = G_1C_1 + G_2C_2$ is defined. If $C_1=1$ is settled, the structure of the PQ method is the same as the master-slave method. However, PQ method is clearly considered relative output contribution and the stability of the zeros of the parallel loop.

The design of C_0 is equivalent to design of a compensator for the SISO system in Fig. 5. At this point, the method for the design of the SIDO compensator for the DISO system proceeds as a standard SISO design problem.[3]

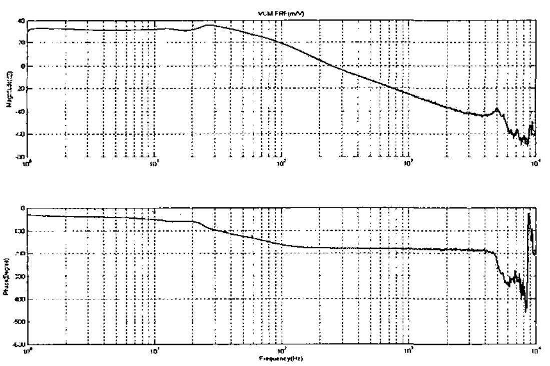
Lastly, the compensator C_0 is designed for the parallel system having frequency response G_{siso} with loop shaping technique.

3.2 Controller Design

Figure 6 shows the experimentally obtained frequency responses of G_1 (piezoelectric milliactuator) and frequency responses of G_2 (VCM). Dashed line displays a simple modeling for controller design as shown Fig. 6. Then, P is defined as shown Fig. 7(a). The 0 dB, crossover frequency should be chosen some reasons that are based on estimation limits of the runout of the

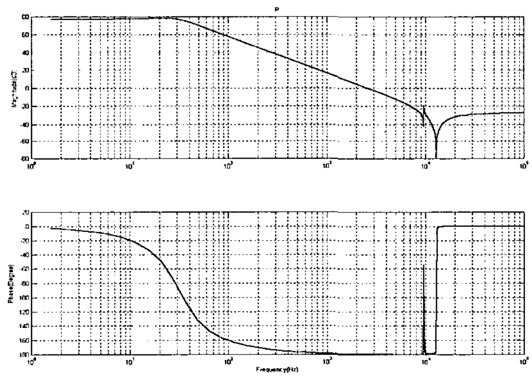


(a)

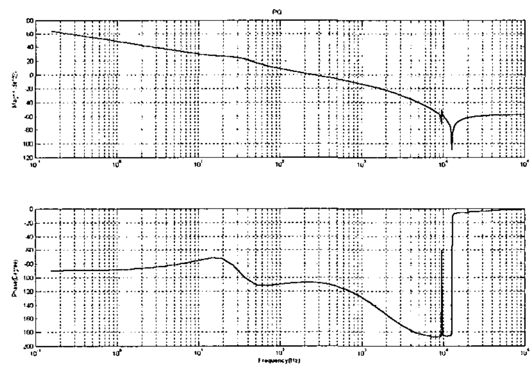


(b)

Fig. 6 Frequency response of (a) G_1 and (b) G_2



(a)



(b)

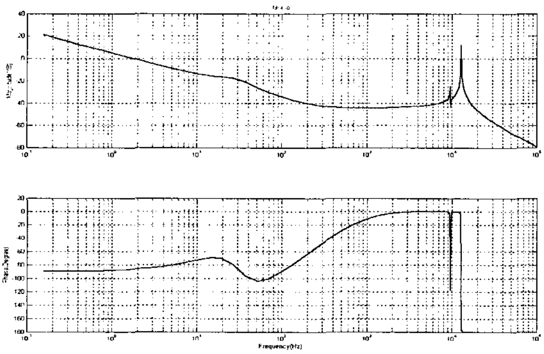
Fig. 7 Bode plot of (a) P and (b) PQ rotating disk at that frequency and saturation limits of the piezoelectric milliactuator. The crossover frequency should be low to achieve large error rejection contribution by using the fine actuator but not so low that the fine actuator is exceeds its range. So, we chose a 250 Hz, 0 dB crossover frequency. The design specifications for systems as follows: 1) zero steady error for a constant disturbance, 2) phase margin is over 30 degree, 3) sensitivity function 0 dB crossover frequency is over 1500 Hz, 4) disturbance rejection at 100 Hz is over 52 dB.[(2)]

Fig. 7(a) shows the frequency response of P. The design of Q uses loop shaping techniques with satisfied the design specifications. Q includes a PI controller with break frequency at 240 Hz to ensure zero steady state error, and that VCM will dominate the response at low frequency. Q also includes a phase lead compensator to increase phase margin, about 100 degrees at the crossover frequency. As our design specification, the margin of the PQ feedback system is over 60 degrees. Q is :

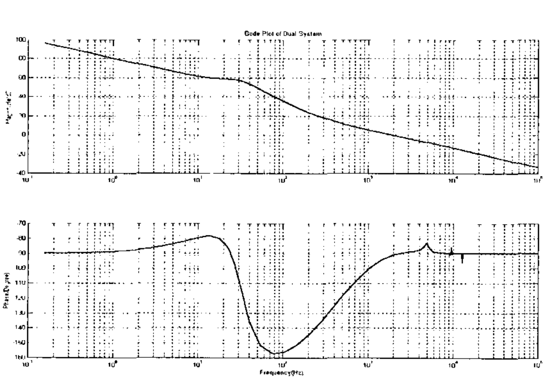
$$Q=\frac{0.03047s^3+1277s^2+5.073e005s+5.061e007}{s^3+30000s^2+2.25e008s}$$

Figure 7 (b) shows the frequency response of PQ. The resulting compensator Q is satisfied with design specification, then $C_1 = 1$, and $C_2 = Q$ is selected.

Figure 8(a) shows the bode plot of $G_{siso} = G_1C_1 + G_2C_2$. The next step is to design C_o. G_{siso} looks like G_2 at low frequency, and also looks like G_1 at high frequency. The objective for the compensator for G_{siso} is to reduce the resonance peaks and obtain desired bandwidth. The cascade of two notch filters and lag



(a)



(b)

Fig. 8 Bode Plot of (a) G_{siso} and (b) $G_{siso}C_o$

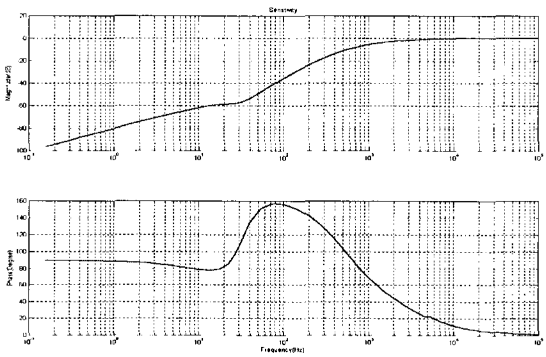


Fig. 9 Sensitivity function

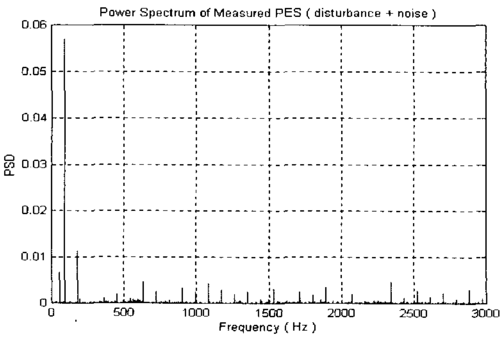


Fig. 10 PSD of PES(disturbance + noise)

compensator is chosen. C_o is to be :

$$C_o = 38.5 * \left\{ \frac{s^4 + 489.6s^3 + 1.02e10s^2 + 2.17e12s + 2.40e19}{2.63e-6s^5 - 0.49s^4 + 1.36e5s^3 - 1.75e9s^2 + 4.65e14s + 1.63e17} \right\}$$

Fig. 8(b) shows the bode plot of $G_{siso}C_o$. The 0 dB crossover frequency is 2 kHz with phase margin of 89.557 degree.

Fig. 9 shows the sensitivity function for dual stage actuator system. The 0 dB crossover frequency is about 2 kHz. And its attenuation is 80 dB.

4. Disturbance Rejection

In order to read or write the desired data without error, the head has to be positioned the track center while the read or write process is over. This is the major part of the track-following servo controller.

The error from mechanical-electrical disturbance is called runout. The runout is classified RRO (repeatable runout) proportioned by the fixed number of the disk rotating and NRRO (non-repeatable runout) related to the disk rotating number. The PES (position error signal) is obtained the static summation of the RRO and NRRO.

$$\text{PES} = \sqrt{\text{RRO}^2 + \text{NRRO}^2} \tag{1}$$

The Fig. 10 presents the example of the PES

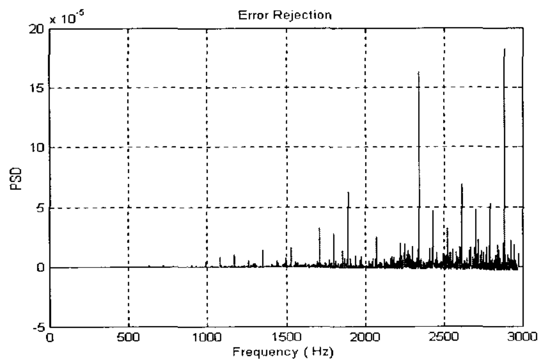


Fig. 11 PSD of error Rejection

for HDD. The specification of the HDD is as follows: *a)* the rotational speed of the spindle is 5400rpm *b)* the track density is 6900 tpi *c)* the recording density is 132,938 bpi *d)* the servo sectors are 66 numbers. Hence, the sampling frequency of the track following servo system in this HDD is 5970 Hz and the Nyquist frequency is 2970 Hz.

The most effective RRO element is generally appears at first or second natural frequency which is 90 Hz or 180 Hz using 5400 rpm motor. These periodic RRO elements are somehow attenuated by the repeatable runout compensator. However, the three more RRO is not decreased the runout compensator.

To separate the disturbance from the overall PES, the three assumptions are considered. First, the noise n is white noise. The period is about 90Hz. The Fig. 4.22 shows the NRRO elements of the disturbance. The NRRO is achieved that it is extracted from the total disturbance. The major NRRO are disk mode vibration, bearing effect, vibration mode of HGA and so on. However, the effect of these elements is different from various disk specifications.

The error-rejection capability of a servo scheme is measured by its sensitivity function. The error rejection capability related power spectrum of the PES is expressed as equation.[2]

$$S_{pes} = |S|^2 (S_w + S_d + S_n) \tag{2}$$

where, S is plant sensitivity function, S_w is PSD (power spectral density) of the force disturbance, S_d is PES of the position disturbance, and S_n means PSD of the noise. As the S_w is ignored, the sensitivity function of the final controlled plant is as Fig. 11. This figure shows most outer disturbance is decreased below the 2 kHz.

5. Conclusion

This paper shows dual stage actuator system and a developed controller design method, PQ method. Dual actuator system consists of VCM which is used as a primary stage, and milliactuator actuator which is used as a secondary stage. As a secondary actuator, new milliactuator based on the shear mode of piezoelectric elements has been suggested to drive the head suspension assembly. The lateral natural frequency of the piezoelectric milliactuator is 10 Hz. This can make higher bandwidth about 2 kHz, which is desired frequency for dual stage actuator systems.

The PQ method reduced the compensator design from DISO to two SISO problems. The first part of PQ method directly address the issue of actuator output contribution and the second part allows the use of traditional loop shaping to achieve the overall system performance.

In this paper, the dual stage actuator system has higher bandwidth, 2 kHz, and higher attenuation, 80 dB. The disturbance from PES is used to confirm the disturbance rejection performance of the dual stage actuator. There are many approaches for dual stage actuator, and this PQ method is very useful in servo controller design.

Acknowledgement

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