論文 한국정밀공학회지 제12권 제7호 1995. 7
Journal of the Korean Society of Precision Engineering Vol. 12. No7. July. 1995.

컴퓨터 하드 디스크 드라이브에서 헤드 위치의 정밀서보제어를 위한 구조변경

정 진 태*

A Structural Modification for the Precise Servo Control of the Head Position in a Computer Hard Disk Drive

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ABSTRACT

본 논문에서 컴퓨터 하드 디스크 드라이브의 헤드 위치 정밀서보제어를 위한 하드 디스크 드라이브의 구조변경을 연구하였다. 구조변경을 위하여 충격 햄머를 이용한 모우드시험을 수행하였으며, 실험에 의한 전기적인 Bode plot을 얻었다. 전기적인 Bode plot과 기계적인 주파수응답함수를 비교하여 전기적인 Bode plot에 나타나는 피크들의 원인을 규명하였고, 모우드해석을 바탕으로 Bode plot상의 피크의 크기를 줄이고 고주파영역으로 옮기기 위해서 베이스 구조물을 수정하였다. 이러한 구조변경을 통해 하드 디스크 드라이브의 헤드위치 서보제어 특성을 개선하였다.

Key Words : Structural Modification(구조변경), Modal Test(모우드 시험), Servo Control(서보제어), Electrical Bode Plot(전기적 Bode Plot), Computer Hard Disk Drive(컴퓨터 하드 디스크 드라이브)

1. Introduction

One of very popular data storage devices in a computer system is a hard disk drive (HDD) which has a development trend toward high copacity, small form factor, fast data access time and more reliability. A HDD has major mechanical parts such as the base, cover, spindle motor, voice coil motor (VCM), actuator and disks as seen in Fig. 1 The actuator consists of heads/suspensions, arm and a coil while the VCM consists of a coil and a couple of magnets and yokes.

In a computer hard disk drive, data are read or written on a spinning circular hard disk by heads which are positioned by a rotary moving coil actuator. The position of the head in the actuator is controlled by a servo control algorithm. When the servo control algorithm is designed for a HDD, the

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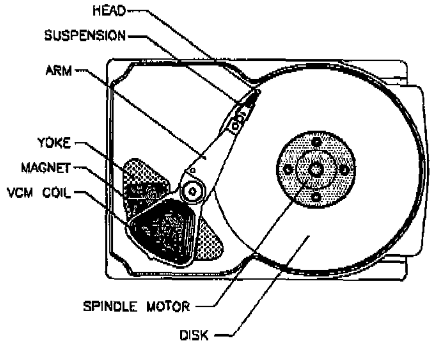

Fig. 1 Configuration of a computer hard disk drive.

electrical Bode plot is very useful.

The electrical Bode plot is affected by the mechanical system because the Bode characteristics of the servo control are closely related with the dynamic performance of a structure. Generally speaking, high frequency peaks in a Bode plot are mechanical contributions while low frequencies peaks are electrical. However, all the mechanical resonance peaks do not show up in the electrical Bode plot, because the Bode characteristics are influenced by only the mechanical resonance frequencies which have a great role in the in-plane motion. This in-plane motion results in the relative displacement between the target head position and the target track, which is often called the off-track. The off-track generates the position error signal(PES).

The modal test with an impact hammer is useful to identify natural frequencies and mode shapes of mechanical structures. This test is easy to handle, appropriate for a small structure like the HDD, and especially essential to identify the mode shapes of each part of a whole structure under the assembled condition. Use of the sine sweep method is very hard to identify the mode shapes of a single part in a whole system under the assembled condition: for example, a cover or base of a HDD.

In this study, the electrical Bode plot is compared with the mechanical transfer function from the modal test to identify the peaks in the electrical Bode plot for the servo control system of the HDD. Furthermore, the structural modification is carried out to improve the electrical Bode characteristics, based upon the natural frequency and mode shape of the HDD base.

2. Electrical and Mechanical Frequency Response Functions

A very practical and important approach to analysis of a system is the frequency response method which gives us insight to design the servo control system of the HDD and to modify the HDD structure. The frequency response of a system is defined as the steady-state response of the system to a sinusoidal input signal. The sinusoid is an input signal and the resulting output signal for a linear system is also sinusoidal in the steady-state; it differs from the input wave form only in amplitude and phase angle.[1]

An advantage of the frequency response method is the ready availability of sinusoid test signals for various ranges of frequencies and amplitudes. Thus the experimental determination of the frequency response of a system is easily accomplished and is the most reliable and uncomplicated method for the experimental analysis of a system. The unknown transfer function of a system can be deduced from the experimentally determined frequency response of a systme.[2,3]

Both the mechanical and electrical frequency responses functions are considered to improve the servo control characteristics of the HDD. The mechanical frequency response functions are obtained by the impact test while the electrical frequency response is obtained by the electrical sine sweep test. Furthermore, the analysis of frequency response functions leads to the modal analysis which gives us the information on structural modification of the HDD.

2.1 Electrical Frequency Response Plot: the electrical Bode plot

The electrical frequency response function for the servo control of the HDD is often represented by the Bode plot. With a servo control algorithm, the position of the head is controled on the hard disk which has data tracks. Fig. 2 shows the measurement system for the Bode plot of the head position control. The input of the system is the sinusoidal current from the function generator while the output is the PES for off-track between the target head position and the target track on the disk. The function generator provides the sign sweep of the current signal. The output signal which is detected by the head is amplified by the amplifier. With these signals, the frequency response function, i.e., the Bode plot is obtained by using the spectrum analyzer (HP3563A).

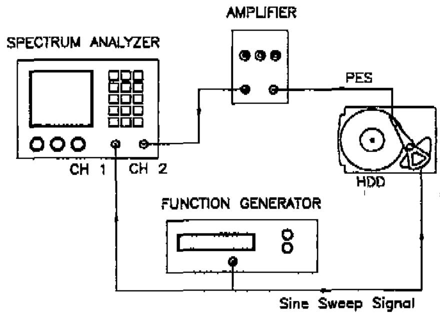

Fig. 2 Measurement system of the electrical Bode plot for the servo control of the HDD head position.

The Bode plot of the open-loop transfer function for the HDD servo control system contains much information about the behavior of the closed-loop system. The plot is easily generated even for higher-order systems and it allows the proper control gain to be selected simply by adjusting the scale factor on the plot. The Bode plot is the logarithmic plot which is widely used alternative to the linear Cartesian and polar forms because it is a particularly descriptive form of logarithmic plot to represent frequency response data.[4] Suppose that the open-loop transfer function in the frequency domain $G(j\omega)$ can be written by

$$G(j\omega) = |G(\omega)|e^{j\phi(\omega)} \tag{1}$$

where j is equal to $\sqrt{-1}$ and $\phi(\omega)$ is the phase angle. The natural logarithm of (1) is

$$lnG(j\omega) = ln|G(\omega)| + j\phi(\omega) \tag{2}$$

The logarithm of the magnitude is normally expressed in terms of the logarithm to the base 10:

$$\textit{Logarithmic gain} = 20\log_{10}|G(\omega)| \tag{3}$$

where the unit is decibel (dB). The Bode plot is a diagram where the logarithmic gain in dB and the phase angle $\phi(\omega)$ are plotted versus the frequency.

In the analysis of Bode plot for the HDD servo control, we often confront the aliasing problem. Sampling for the digital data analysis is usually performed with equally spaced intervals. The problem then is to determine an appropriate sampling interval. Sampling at points which are too far apart leads to confusion between the low and high frequency components in the original data. This problem is called the aliasing. It constitutes a potential source of error which does not arise in direct analog data processing, but is inherent in all digital processing which is proceeded by an analog to digital conversion. Assuming that a sampling interval is h, the highest frequency which can be defined by sampling at a rate of 1/h samples per second is 1/2h Hz. Frequency in the original data above 1/2h Hz will be folded back into the frequency range from 0 to 1/2h Hz, and be confused with data in this lower range. This frequency is called the Nyquist frequency or folding frequency given by

$$f_c = \frac{1}{2h} \tag{4}$$

For any frequency f in the range $0 \le f \le f_c$, the higher frequencies f_c which are aliased with f are defined by

$$f_a = 2nf_c \pm f \tag{5}$$

where n is an integer.[5]

2.2. Modal test of the HDD using the impact hammer

A popular modal test for a small structure such as the HDD is through use of an impact hammer. Although this type of test places greater demands on the analysis phase of the measurement process, it is a relatively simple means to obtain the mode shapes and natural frequencies. The equipment consists of an impact hammer, an accelerometer, two amplifiers and a spectrum analyzer. Usually, a set of different tips and heads of an impact hammer serve to extend the frequency and force level ranges for testing a variety of different structures. The useful range may also be extended by using different sizes of impact hammers.[6]

To take the modal test with an impact hammer, a measurement system is set up as shown in Fig. 3. The HDD under the assembled condition is hung with a rubber band to get rid of the boundary effects: that is, the free boundary condition is provided by this configuration. When the HDD is fixed on the fixture which is made of a solid material, the boundary effects may be introduced. Input signals are from a force transducer in the

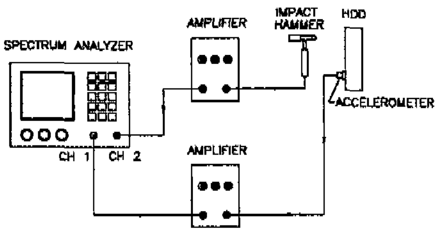

Fig. 3 Measurement system of the mechanical frequency response function for the HDD base under the assembled condition.

impact hammer while output signals are picked up by the accelerometer on the base of the HDD. Since these signals are very small charge quantities from piezoelectric elements, they need to be transformed into voltage signal and to be amplified: two conditioning amplifiers are used for this purpose. The input and output are connected to channels 1 and 2, respectively, of the spectrum analyzer (HP 3563A) which measures the mechanical frequency response functions.

During the measurement, two kinds of windows are used to obtain reliable mechanical frequency response functions: the forced window is used for the input signal while the exponential window is used for the output signal. It is well known that two signal processing problems inherent in the impacting test are noises and leakage. Noise can be a problem in both the force and response signals and is mainly a consequence of a long analyzer time record. Leakage is of most concern in the response signal and is a consequence of too short time record. These two problems may occur separately due to range of the test and the analyzer transform size.[7] Special force and exponential windows have been developed for impact testing to reduce noise and leakage.[8] The reference 8 discusses proper application of these windows while pointing out common errors. Guidelines are developed for setting the width of the force window and

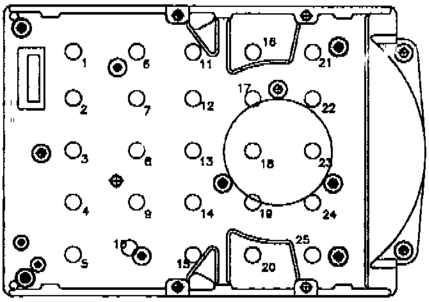

Fig. 4 Impact points on the HDD base in the modal analysis.

selecting the decay rate of the exponential window.

Fig. 4 shows the impact points on the base of the HDD and the accelerometer is attached on the point 3. The points in Fig. 5 are corresponding to the points in Fig. 4 if it is assumed that we look at the base from the top. It is important that the test should be performed under the assembled condition, because the boundary conditions are changed if only the base is separated and tested alone. Therefore, the base shown in Figs. 4 and 5 is put together with the cover, spindle motor and actuator.

The preliminary modal test for the structural dynamic resonance shows that there exist two natural frequencies in the range between 2 kHz and 4 kHz; namely, there is no resonance below 2kHz of the base under the assembled condition. Therefore, it is reasonable for the frequency response function to be measured in the frequency range from 2 kHz to 4 kHz because this helps to obtain more accurate test data.

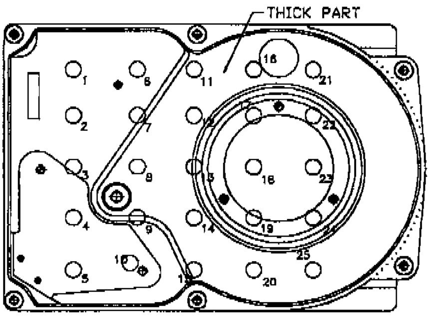

Fig. 5 Configuration of the impact points on the HDD base (shown from the top).

3. Analysis and Discussion

Fig. 6 shows the magnitude, i.e., gain of the electrical Bode plot which has two peaks at 2549 Hz and 3771 Hz in the high frequency region. The fluctuation in the low frequency region may be the effect from the electrical noise. Therefore, to improve the Bode characteristics, the peaks in the high frequency region should be removed or at least it is desirable that their magnitudes are reduced and shifted to the higher frequency region. In an ideal case, the curve in the gain-frequency diagram of the Bode plot should be a straight line.

Since the other parts of the HDD except the base, such as the actuator, suspension, cover and spindle motor, do not have resonance around the frequencies corresponding to the peaks shown in Fig. 6, a focus of the modal test is put on the base which has connction with the actuator. Fig. 7 is one of the mechanical transfer functions and the modal test result is summarized in Tables 1 and 2 which show that the first natural frequency is 2462 Hz and the second natural frequency is

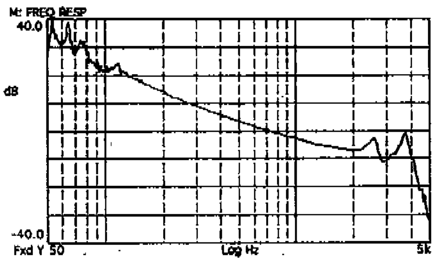

Fig. 6 Electrical Bode plot for the head position servo control in the HDD.

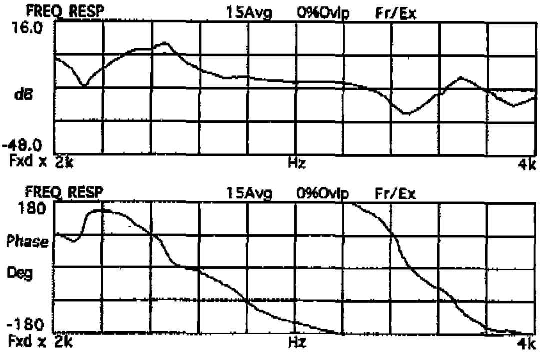

Fig. 7 Mechanical frequency response function of the base.

Table 1 Magnitudes and phase angles of the frequency response function for the first mode (2462 Hz).

Point	Magnitude (dB)	Phase angle (degree)	Point	Magnitude (dB)	Phase angle (degree)
1	5.95	42.08	14	29.46	68.77
2	21.01	-117.18	15	27.13	63.79
4	19.83	-136.2	16	27.85	58.38
5	23.20	70.55	17	31.84	70.53
6	31.13	59.54	18	26.64	79.34
7	17.27	78.15	19	18.09	58.05
8	9.74	168.19	20	18.25	57.98
9	16.05	162.42	21	-4.26	113.80
10	27.08	77.28	22	-0.86	-107.98
11	23.52	55.61	23	24.75	-120.59
12	29.64	64.11	24	11.96	-89.81
13	29.79	64.62	25	19.23	19.51

3615 Hz. Based upon the magnitudes and phases of the each point shown in Tables 1 and 2, the approximated mode shapes can be obtained. As number of the impact points increases, more accurate mode shapes is obtained. Figs. 8 and 9 show the first and second mode shapes, respectively, for the base of the HDD under the assembled condition. In these figures, the points on the cross sign (×) and the points on the circle sign (○) have the opposite signs of the phase angles each other. Using the magnitude and phase data, we can obtain the nodal lines which are drawn by the solid lines in Figs. 8 and 9.

Table 2 Magnitudes and phase angles of the frequency response function for the second mode (3615 Hz).

Point	Magnitude (dB)	Phase angle (degree)	Point	Magnitude (dB)	Phase angle (degree)
1	-10.15	-103.52	14	14.92	-93.83
2	11.74	74.92	15	6.82	-133.41
4	3.27	-18.20	16	12.90	133.59
5	8.93	-22.46	17	21.69	161.12
6	9.89	-38.74	18	6.71	-137.56
7	4.79	149.96	19	3.33	-116.50
8	-6.27	-30.52	20	1.24	-162.42
9	7.81	-51.48	21	-1.94	139.68
10	16.34	-47.62	22	-8.22	150.74
11	1.43	113.95	23	9.11	-126.84
12	12.95	122.08	24	5.79	127.95
13	6.45	105.96	25	8.14	169.01

Comparing the peak frequencies in the electrical Bode plot with the mechanical natural frequencies of the base under the assembled condition, they well coincide each other: the comparison between the frequencies of the electrical Bode plot and the natural frequencies is given in Table 3, which shows that the differences are less than 5%. Consequently, it is tentatively concluded that two peaks in the Bode plot are related with the mechanical resonance frequencies.

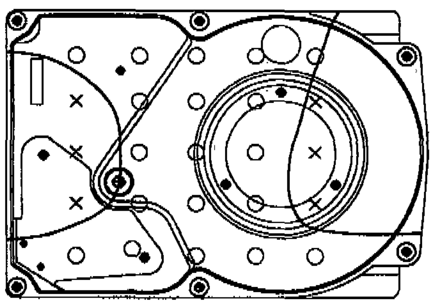

Fig. 8 First mode shape of the base under the assembled condition.

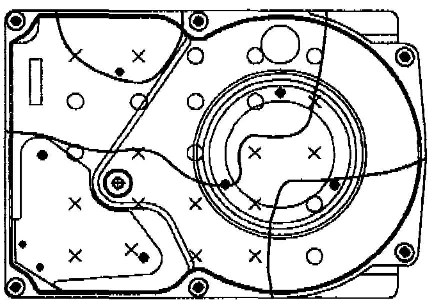

Fig. 9 Second mode shape of the base under the assembled condition.

Table 3 Comparison of the peak frequencies between the electrical Bode plot and the mechanical frequency response function.

	First Mode	Second Mode
Electrical Bode plot	2549 Hz	3771 Hz
Mechanical frequency response function	2462 Hz	3615 Hz
Difference	3.4 %	4.1 %

The aliasing problem often arises in the measurement of the Bode plot. Therefore, it is necessary to check whether the peaks in the electrical Bode plot are aliased peaks or not. The sampling frequency, f_s, of the HDD system is given by

$$f_s = N_t \Omega_s \qquad (6)$$

where N_t is the servo sampling track number and Ω_s is the rotating speed of the spindle motor in Hz. For the HDD considered in this study, the sampling track number and the spindle motor speed are 72 and 5400 RPM, respectively. Hence, the sampling frequency is calculated as f_s=6480 Hz. On the other hand, since the sampling frequency is double the Nyquist frequency f_c, the Nyquist frequency is equal to 3240 Hz. From (5) with n=1, the aliased frequencies of 2549 Hz are calculated as 3931 Hz and 9029 Hz while the aliased frequencies of 3771 Hz are 2709 Hz and 10251 Hz. The aliased frequencies, 9029 Hz and 10251 Hz, are beyond our interest because they are very high frequencies in the HDD structure. However, the aliased frequencies, 2709 Hz and 3931 Hz, are somewhat close to the peak frequencies in the Bode plot. In other words, the first peak seems to be an aliased peak of the second one in the Bode plot.

It is valuable to inverstigate why the resonances of the base affect the servo control characteristics, i.e., the Bode plot for the head position control of the HDD. As seen in Figs. 8 and 9, the nodal lines pass around the pivot point of the actuator and the center spindle motor. The opposite signs of the phase angles across these nodal lines result in the relative displacement between the head of the actuator and the disk on the spindle motor. Apparently, the relative displacement generates the off-track between the target head position and the target track on the disk so the off-track effect is detected as the PES which influences the Bode characteristics directly. It is noted that the point on the nodal line generally has no displacement for the normal direction. However, considering the relative in-plane displacement between the head and the disk, it is closely related with the sign changes for the phase angles of the points around the centers of the pivot and spindle motor. Fig. 8 shows that one of the nodal lines passes through the pivot area because the left part of the base shown in Fig. 8 is thinner than the part around the spindle motor. The other nodal line of the first mode passes through the spindle motor, which results in the in-plane displacement of the disk. Although the base part around the spindle motor is thicker than the left part, there exists a big hole for the spindle motor. Hence the nodal line passes through the spindle motor area. The similar discussion can be made for the second mode shape.

A structural modification is performed to improve the Bode characteristics of the head position servo control in the HDD system. A simple way to modify the base is to make it thicker; however, in a practical design it is not plausible because the form factor of the HDD is restricted for the mechanical compatibility. Moreover, other parts such as the voice coil motor and the actuator allow small room for the structural modification. Using the structural modification, it is desirable that those two peaks in the Bode plot are reduced

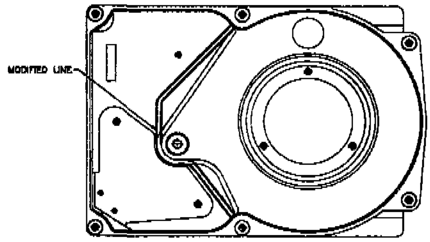

Fig. 10 Structural modification to reduce the effect of high frequency peaks in the electrical Bode plot.

in magnitude and they are shifted to higher frequency region. As shown in Fig. 5, the region of the base around the actuator pivot point is relatively flexible because the nodal lines are across this region. In order to reduce the effect of two peaks in Fig. 6, it is recommended to modify the structure as shown in Fig. 10 where thick solid lines indicate the modified shape of the thick part. Increasing the thick area around the pivot point provides more stiffness to the base plate which supports the spindle motor and actuator. This modification does not result in mechanical interference among the parts such as the actuator and VCM. With the modified base of the HDD, the electrical Bode plot is measured as seen in Fig. 11 which shows that the peaks in the high frequency region are shifted to 2989 Hz and 4004 Hz and that their magnitudes are reduced. Therefore, it is concluded

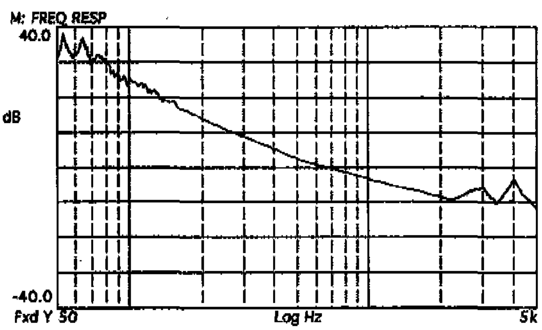

Fig. 11 Electrical Bode plot for the head position servo control with the modified base.

that the peaks of the electrical Bode plot in the high frequency region result from the mechanical resonance.

4. Conclusions

In this study, the electrical Bode plots and the mechanical frequency response functions are measured by the experiments in order to improve the servo control characteristics of the head position in the HDD. This paper identifies two high frequency peaks in the electrical Bode plot which result from the mechanical resonance of the HDD structure. The first and second peaks of the electrical Bode plot in the high frequency region are well matched with the peaks corresponding to the first and second modes, respectively, of the mechanical frequency response function.

To improve the dynamic characteristics of the system, the structural modification is performed for the base structure of the computer hard disk drive. This modification does not incur interference among parts such as the actuator and VCM but it provides sufficient stiffness to the base so that better performance of the head position servo control is obtained.

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