Servo Track Writing Technology

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To increase the recording density of hard disk drives (HDDs), it is indispensable to improve the servo track writing (STW) technology that writes the servo positioning information used to position the magnetic recording head onto the data track. Previously, it was popular to write the servo tracks by using the HDD's own head and positioning it using an external actuator. Recently, however, the demand for higher productivity and STW quality has been growing, and a new method is needed. As a manufacturer of HDDs, Fujitsu is developing various STW technologies to meet this need. This paper introduces the major STW methods and requirements for STW and then describes the factors that reduce STW quality. Then, it describes media STW and magnetic printing STW, which are typical external writing methods.

1. Introduction

High-density recording requires improvements in positioning accuracy on the data track. The track pitch of current hard disk drives (HDDs) is from 220 to 250 nm, which is about 3/4 of the track pitch of next-generation DVDs. The track pitch will continue to be reduced in the future as the recording density of HDDs increases.

The magnetic head is positioned on the data track by the servo based on servo positioning information recorded magnetically on the disk, and the quality of this information greatly affects the positioning accuracy of the HDD. The servo track writing (STW) process, which writes the servo positioning information to the disk, is a unique technology in HDDs. Currently, the main STW method is to write the servo positioning information in the same way that data is written using the HDD's magnetic head or an outside magnetic head.[1] This method requires a lot of time and equipment and is very different from the methods used for optical disks such as DVDs, which have molded servo positioning information. To reduce the cost of HDDs, it is necessary to reduce the amount of time needed to write this information.

We have therefore analyzed the problems of current STW and developed a new STW technology.

This paper introduces the major STW methods and requirements and describes the factors that reduce the STW quality. Then, it describes media STW and magnetic printing STW, which are typical external writing methods, and compensation by HDDs for differences in servo track trajectories.

2. STW methods

Table 1 shows several methods of STW.

The STW methods are primarily classified as external writing, which writes the positioning information when the disk is outside the HDD, and internal writing, which writes the information when the disk is inside the HDD using the HDD's own head.

The internal writing method is further

Table 1
Classification of servo track writing methods.

Writing method	Positioning	STW method
External writing	External positioning	Media STW Magnetic printing
Internal writing	External positioning	Push-pin, Mirror-on Non-contact push-pin
	Internal positioning	Rewrite STW Self STW

classified into: 1) positioning the head using an optical encoder or laser interferometer system and an external positional scale and 2) positioning the head onto an internal positional scale.

Furthermore, in the hybrid method, the HDD rewrites the servo positioning information after a disk containing temporary servo positioning information that was written outside the HDD is installed in the HDD. From the viewpoint of the final STW quality, this method is classified as an internal writing method.

The media STW and magnetic printing STW described in this paper are classified as external writing methods.

3. STW requirements

There are three important requirements in STW: high quality, high productivity, and low equipment costs. The quality strongly depends on the following points regarding the accuracy of the servo track:

1) Circularity of the servo track.

When the servo track is not perfectly circular, Repeatable RunOuts (RROs), which are synchronous with the spindle rotation, occur when the servo positioning information is demodulated.

2) Positional accuracy relative to the adjacent track.

This influences the Write to Write Track Misregistration (TMR).

3) Linearity of the demodulated position error signal to the track offset.

This affects the servo control and the appropriateness of judgments to suspend writing when an unacceptably large off-track error occurs.

4) Noise in the demodulated position error signal.

This noise appears as Non-Repeatable RunOut (NRRO) when the servo positioning information is demodulated by the HDD. NRRO is asynchronous with the rotation of the spindle.

To reduce the influences described in 1) to 4), various techniques are used during and after demodulation within the HDD. Moreover, the quality is greatly influenced by the pattern of the servo positioning information.

4. Factors that reduce STW quality

4.1 Factors that reduce servo track circularity

Excluding the quality of the magnetic printing, the main factors that reduce the circularity of the servo track are as follows:

1) Asynchronous vibration during STW such as vibration of the spindle, disk, head suspension, head arms, and base plates.
2) Positioning accuracy of the STW actuator.
3) Rotation-synchronous variations in the amplitude variations during STW and HDD operation (HDD eccentricities).
4) Non-uniform magnetic characteristics and other flaws in the medium's magnetic properties that cause media noise and other problems.

The mechanical conditions required for internal writing using the HDD's head are almost the same as the conditions required during normal HDD operation. Therefore, it is difficult to reduce the mechanical disturbances described in 1).

A reduction in rotational speed brings significant reductions of mechanical disturbances in an HDD because the biggest components of disturbance are disk flutter, head arm vibration, and suspension vibration caused by turbulence around the disk. However, the rotational speed of the disk can only be lowered a small amount;

otherwise, because the heads of all HDDs have a gas dynamic bearing slider, a stable flying height, which has the biggest influence on the magnetic recording characteristics, cannot be secured.

In this respect, because there are few restrictions of the mechanism and power consumption, various measures can be applied for the media STW method to write outside the HDD. These measures are described in Section 4.

However, the problem described in 3) inevitably occurs in the external STW method.

4.2 Problems with quality of STW using external positional scale[2)]

Next, we describe some of the problems with the quality of STW when an external positional scale is used and then describe methods for using external positional scales in external and internal writing methods.

The write head cannot follow the medium because it is positioned according to the encoder coordinates without any relation to the motion of the disk. However, following high-frequency vibration such as disk flutter using a feedback control system for an internally written positional scale is difficult, and forced following might reduce the positioning accuracy. Therefore, it is generally vibration in the low-frequency region below the rotational frequency that causes differences between the results of external and internal positioning systems. In the hydrostatic bearing of an external STW device and in the hydrodynamic bearing of recent HDDs, a low-frequency resonant peak of the half-speed whirl is easily generated by air as the disk rotates. However, the biggest influence in HDDs that use ball bearings is the retainer (cage) vibration. **Figure 1** shows the axial runout spectrum of a disk in the low-frequency region. This asynchronous, low-frequency vibration is a major problem during STW. However, it is not a problem during normal HDD operation because the feedback control system can compensate for it (**Figure 2**) and it is masked by low-frequency windage disturbances.

The servo tracks, which are written on 100 to 200 servo sectors arranged on the circumference at equal intervals, are usually concentric circles. When one of these tracks has been written, the head must be moved radially in order to write the next track, which causes a discontinuity between the beginnings and ends of tracks (**Figure 3**). This results in a position error signal series that cannot be removed from the disturbance vibration waveform by using a rectangular window function.

In general, this problem occurs when the head passes over a discontinuity because the start and end sectors at STW are not recognized when

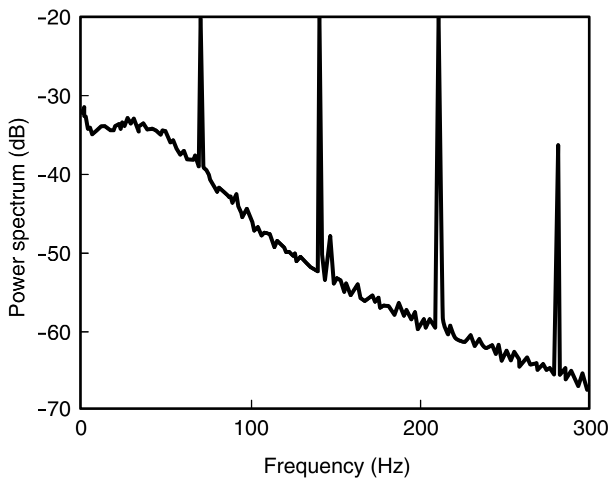
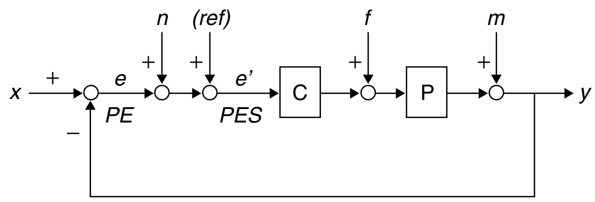


Figure 1
Axial runout spectrum of HDD spindle assembly.
Rotational frequency is 70 revolutions per second.



x : Target, *e* : Following error, *PE* : Position Error,
n : Demodulation noise, *ref* : Reference,
e' : Following error signal, *PES* : Position Error Signal,
C : Controller, *f* : Force disturbance, *P* : Plant,
m : Vibration disturbance, *y* : Output

Figure 2
Block diagram of HDD track-following feedback loop.

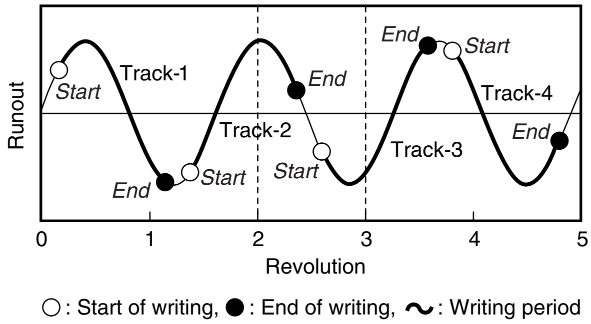


Figure 3
Start and end points of servo track writing.

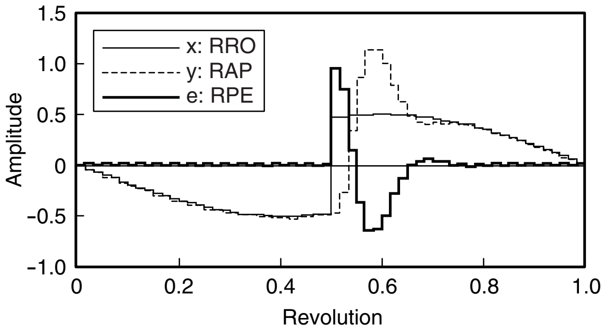


Figure 4
Repeatable runout (RRO) written by STW, repeatable absolute position (RAP), and repeatable position error (RPE) as responses in HDD operation.

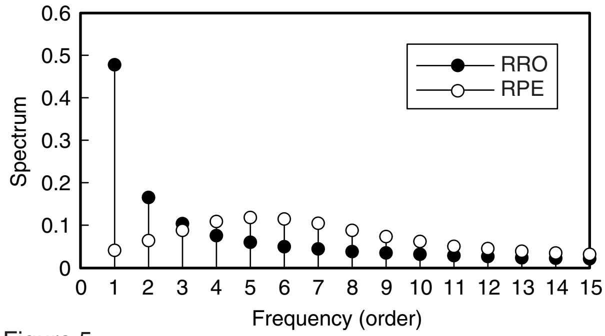


Figure 5
Spectra of RRO and RPE.

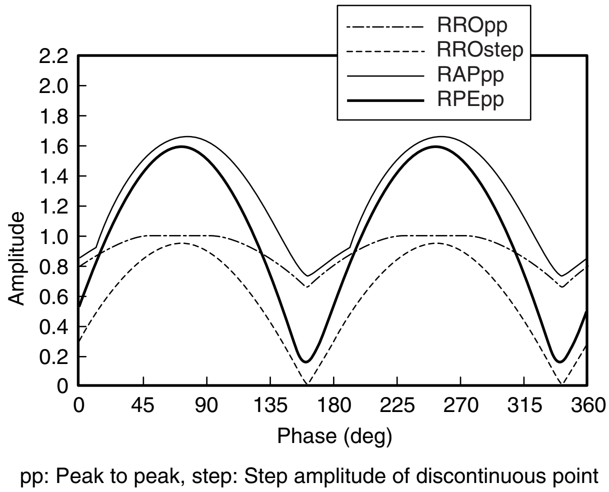


Figure 6
RPE amplitude vs. RRO phase at start of writing.

feedback control is performed to follow the servo track on the media.

Figure 4 shows the RRO written at STW, repeatable absolute position (RAP), and repeatable position error (RPE) with the feedback control system when this low-frequency vibration is written at STW. The zero-crossing frequency of the open-loop transfer function of the control system in this example is about 5.4 times the rotational frequency. Because the asynchronous component at STW becomes a synchronous component of RRO in the HDD, the position error signal is a RPE. The RPE amplitude greatly depends on the phase of the low-frequency vibration at the start of servo track writing. **Figure 5** shows a spectrum similar to leakage in the discrete Fourier transform. The fourth and subsequent RROs are amplified by the feedback control and appear as RPE.

Figure 6 shows the positioning error amplitude versus phase at the beginning of writing when a sinusoidal pattern that was written during STW is input to the servo system. The RPE amplitude is maximum at (1-fc/fr)π from the start of writing, where fr is the spindle rotation speed and fc is the disturbance vibration frequency. In this example, the maximum amplitude is about 10 times larger than the minimum.

Figure 7 shows the maximum and minimum RPE/RRO versus the disturbance frequency at STW. In the phase in which RPE/RRO is minimum, a characteristic very close to the sensitivity function is obtained. On the other hand, the RPE amplitude when the servo is positioned on an RRO

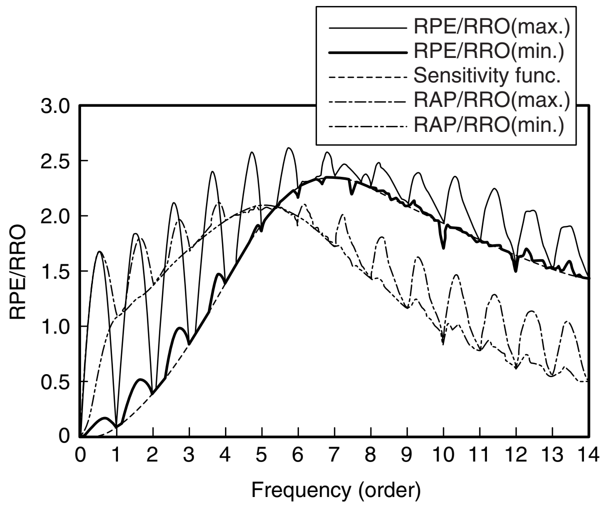


Figure 7
Maximum and minimum RPE/RRO vs. NRRO frequency.

that was written in the worst phase is small in the vicinity of the harmonics of the rotational frequency and rises to a peak in the interharmonic regions. Moreover, the skirt extension due to “leakage” is large in the low-frequency region, and the RPE amplitude that extends to the high-frequency region is amplified near the peak of the sensitivity function.

It can be said that the influence of the problem of STW quality on an external positional system is large because the frequency of the retainer vibration of the ball bearing and frequency of the fluid bearing’s half-speed whirl are about half of the rotational frequency.

It is also possible to suppress low-frequency spindle vibration during STW to some degree by sensing the vibration and performing feedforward control.

On the other hand, if disturbances from the external environment are excluded, the disturbances during STW of an internal positional scale are thought to be almost the same as the disturbances of normal operation.

5. Media STW

The purposes of media STW are to improve the productivity and the efficiency of clean room usage. In media STW, two or more disks are stacked onto a spindle and the servo positioning information is written to them (**Figures 8** and **9**). An improvement in STW quality can be expected because media STW eliminates the restriction on HDDs that was described in Section 3. This section introduces the measures we applied to improve the quality of media STW.

Many of the mechanical disturbances are flow-induced vibrations, which are caused by air flowing around the disk. These disturbances are similar to those that occur during normal operation and cause not only disk flutter but also arm/suspension vibration.

The influence of the windage disturbance can be dramatically reduced by reducing the disk rotational speed. It is difficult to decrease the rotational speed of HDDs because it is usually designed to secure the best flying height at the operational speed, and if we can disregard productivity because a suitable air bearing surface (ABS) design for the STW rotational speed can be used, we can select an arbitrary STW rotational speed for just the STW head.

Disk flutter is the largest windage disturbance and can be reduced by reducing the space between the disk and squeeze plate and reducing the shroud gap. The design of an HDD is restricted by the parts interference margins at assembly and the increase in power consumption due to windage. On the other hand, these restrictions can be considerably eased in an external STW device. **Figure 10** shows the disk flutter spectrum for various gaps between the squeeze plate and disk surface. **Figure 11** shows the spectrum of disk flutter when the distance between the disk edge and shroud is reduced. As can be seen, reducing the distance can significantly suppress the flutter.

In addition, because high-speed seek performance is not required in the STW actuator, the actuator and suspension can be made more rigid. The low-frequency disturbance that acts on the actuator’s moving parts can be reduced by increasing the actuator’s moment of inertia.

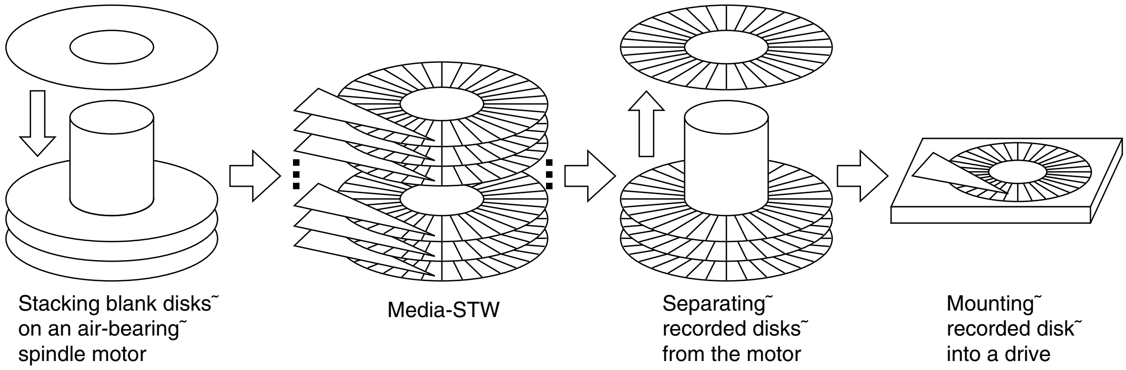


Figure 8
Media servo track writing. After writing servo signals on magnetic disks, the disks are separately mounted in the drive.

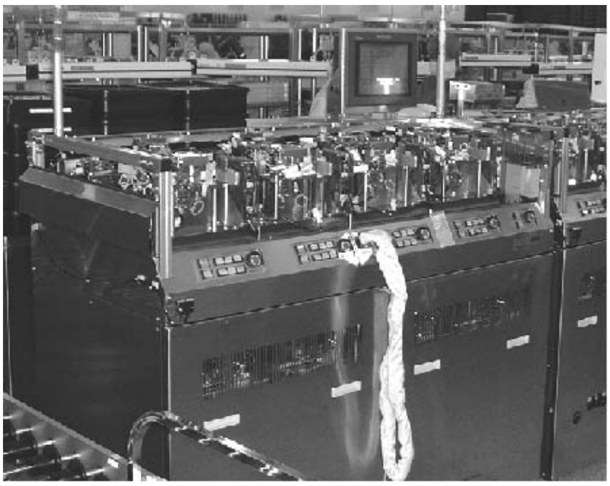


Figure 9
Media servo track writers.

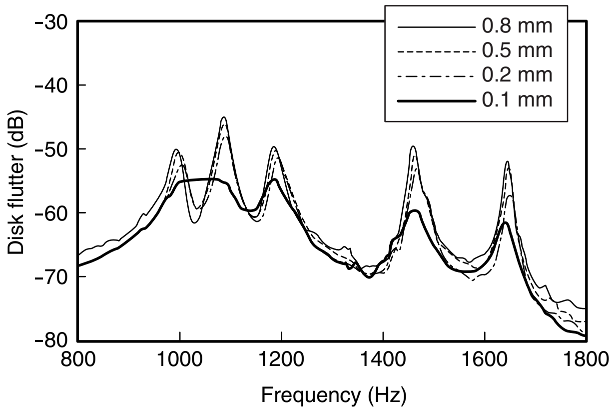


Figure 10
Disk flutter reductions for various squeeze plate gaps.

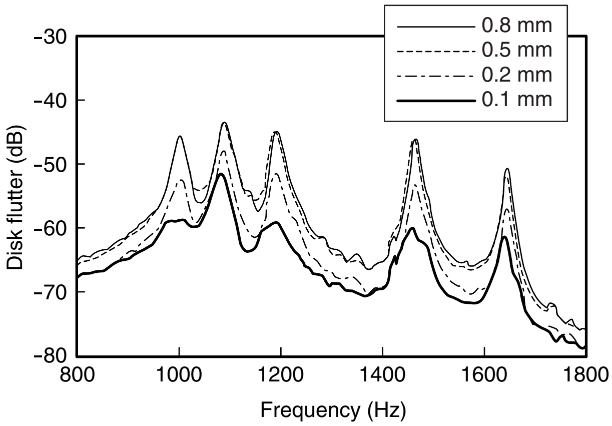


Figure 11
Disk flutter reductions for various shroud gaps.

6. Magnetic printing STW[3)]

Magnetic printing uses a master disk that has a ridge/groove servo pattern covered by a soft magnetic layer. The servo pattern is transcribed to the disk medium using an external magnetic field to reverse the magnetization of the parts of the disk medium that correspond to the grooves on the master disk.

Although there is an STW method of rewriting the servo pattern by using the head of the HDD based on the temporary transcribed servo pattern, many of the accuracy improvements cannot be obtained from magnetic printing because the final STW quality depends on the disturbances inside the HDD. Therefore, we tried to directly transcribe the final servo pattern that is formed on an HDD. This section describes the result of installing a transcribed magnetic disk in an HDD.

The transcribed servo pattern is a phase pattern composed of straight lines and is thought to be suitable for electron beam drawing. **Figure 12** shows a magnetic force microscopy (MFM) image and the readback waveform of the transcribed medium. **Figure 13** shows a readback signal image of a servo sector with a head offset.

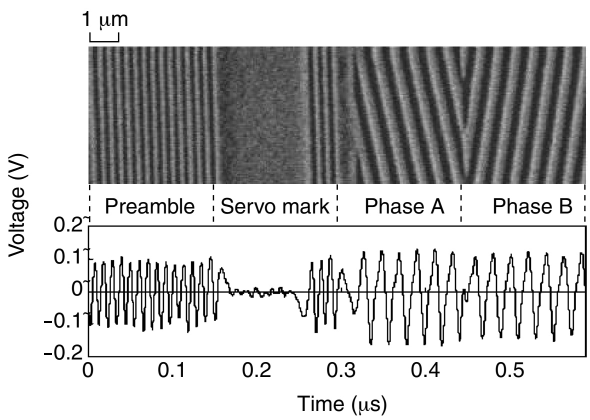


Figure 12
MFM image of printed pattern and its readback signal.

In a commercial 38.5 kTPI HDD, track follow control is done by removing the first-order eccentricity with feedforward control. **Figures 14 (a)** and **14 (b)** show the minimum, maximum, and mean values of the position error signal (PES) of adjoining tracks for each sector of this type of HDD. The mean value is usually called the RPE. The RPEs of Track *n* and Track *n*+1 were, respectively, 22% and 23% of the track pitch and were considerably large compared with typical HDDs. **Figure 14 (c)** shows the differences between the PESs of Track *n* and Track *n*+1. The difference between each RPE was 3% or less of the track pitch. The intertrack interference was small, and there was sufficient accuracy from the viewpoint of Write To Write TMR because adjacent tracks remained parallel even though there were large variations in the trajectories of RPEs.

7. Compensation for HDD servo track trajectory differences[4)]

This section describes a problem that occurs in HDDs when external writing is done with the media STW and magnetic printing STW described above and the compensation of differences in trajectories. The servo track trajectory does not always coincide with the rotation trajectory of an

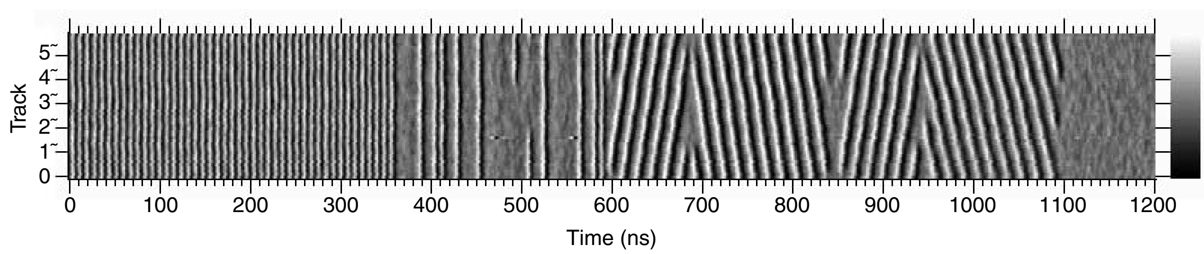


Figure 13
Readback signal image of servo sector.

externally written disk when it is mounted in an HDD after media STW and magnetic printing STW. This difference in trajectories consists of a first-order shift from the center of the disk and also higher-order eccentricities.

Figure 15 shows a system that compensates for these eccentric components in an actual HDD.

The first-order eccentricity is caused by unavoidable misalignments that occur during assembly and is much larger than the higher-order eccentricities. **Figure 16** shows the phase and amplitude of the compensation current for first-order eccentricity compensation at various positions. We used an observer-based RRO compensation technique to estimate the rotation vector of the RRO compensation current in each zone. The rotation vector of the first-order RRO in each zone is stored in the parameter table and used for first-order eccentricity compensation.

Electromagnetically induced vibration of the spindle motor, the trajectories of the fluid bearing, and the distortion of the clamped disk generate higher-order RROs. We used repetitive control to obtain the compensation value of these higher-order RROs. **Figure 17** shows the PES spectrum when a rotation-synchronous component is suppressed by repetitive control. We averaged the voice coil motor (VCM) current generated by repetitive control on several tracks in each zone and stored the results in a table. We then used the results to generate the feedforward compensation current (**Figure 18**).

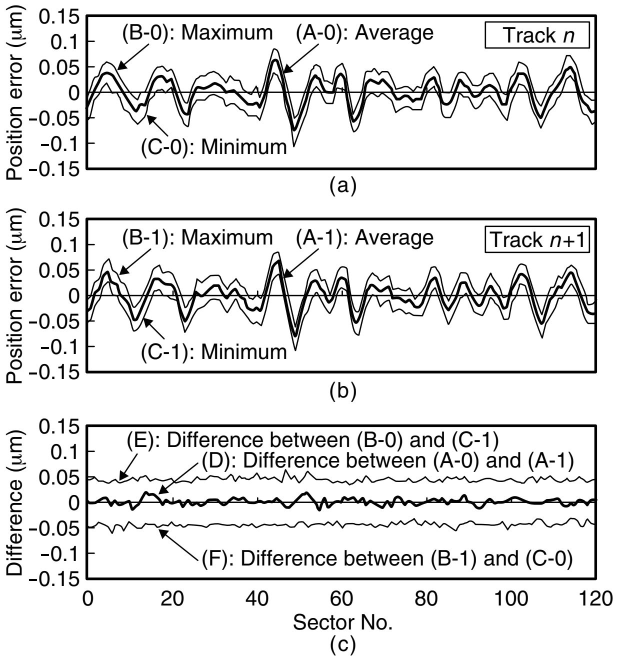


Figure 14
Position error signals of adjacent tracks and their differences. (a) Track *n*. (b) Track *n*+1. (c) Difference between (a) and (b).

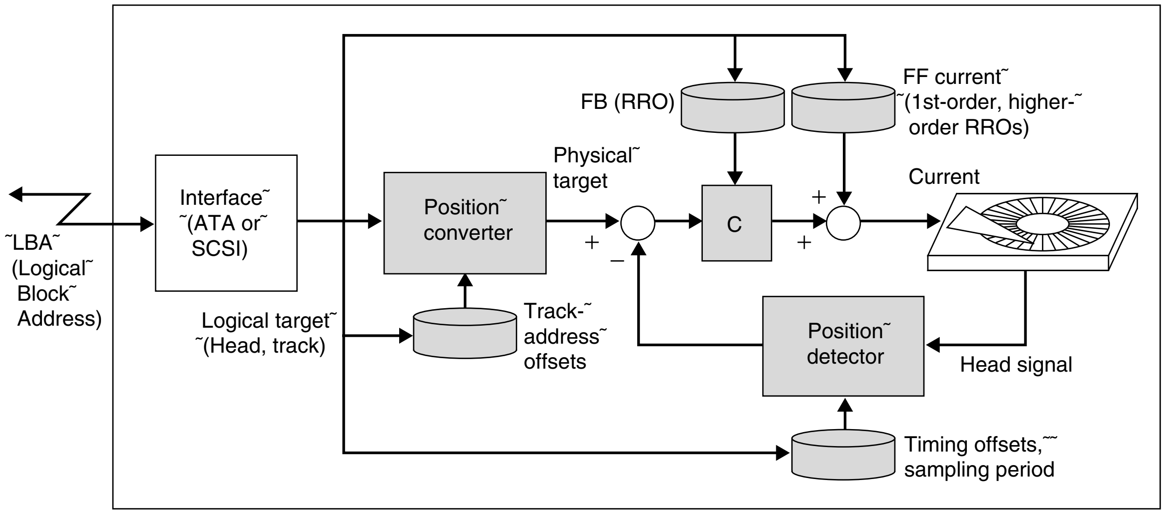


Figure 15
Block diagram of servo controller for HDDs with media-STW disks.

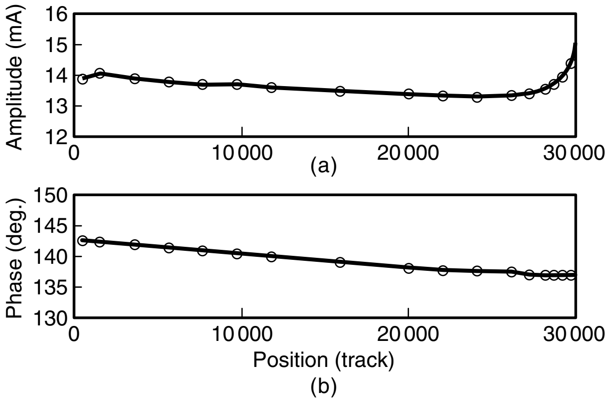


Figure 16
First-order RRO feed-forward current of HDD. Amplitude (a) and phase (b) are different for each track address.

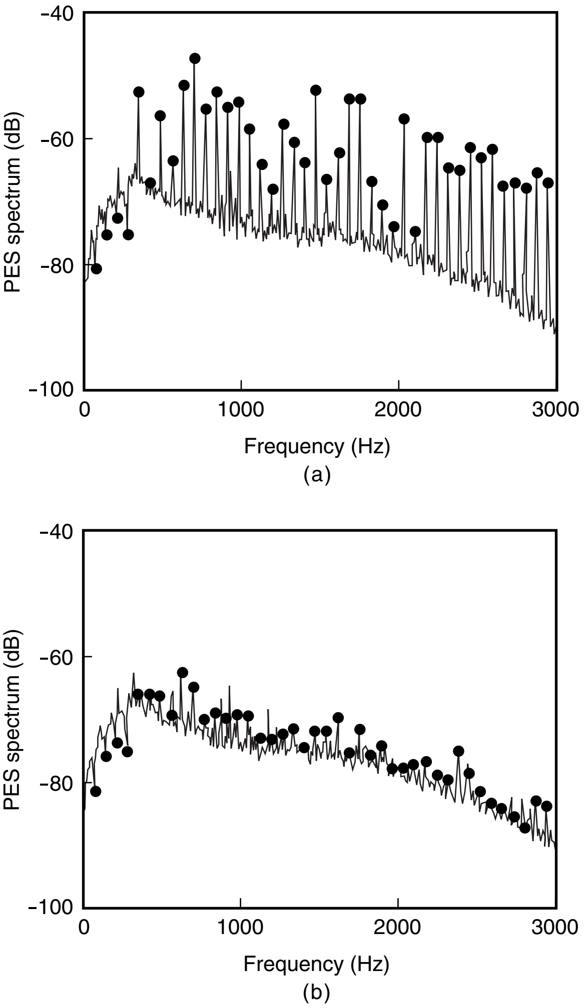


Figure 17
Power spectrum of HDD position error signal with (a) normal controller and (b) controller using feedforward current generated by repetitive controller.

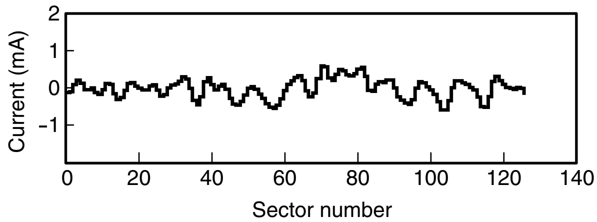


Figure 18
Feedforward current generated by calibration of higher-order RROs.

8. Conclusion

In this paper, we considered the factors that determine the accuracy of the servo track in an HDD. We showed that certain factors have a large influence on low-frequency vibration during STW. We then described various methods for reducing the mechanical disturbances during media STW and obtaining an excellent STW quality. We confirmed that the magnetic transcript method, which does not use a head, produces adjacent tracks that are satisfactorily parallel, although the value of RRO is large. It is necessary to compensate for the first-order and higher-order eccentricities generated by these external STW methods by controlling the HDD.

The demand for the STW quality needed to achieve high-density recording in the future is expected to make external STW much more important, and the need for newer STW technologies will continue in the future.

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