Compensation of Shock-induced Head Skew for Hard Disk Drives

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Abstract

Head skew among multiple heads in hard disk drives (HDDs) is normally calibrated in factory, and is applied by servo controller to estimate position of destination head for head switching seeking. In response to operating or non-operation shock, additional head skew error across stroke may be introduced, which could degrade drive performance in terms of long access time and acoustic issue. In this paper, a quick check method of head skew error during servo startup is proposed, where a sector-dependent filtering scheme for reliable head skew calibration is developed. Test result demonstrating the effective compensation of shock-induced head skew is summarized.

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1. Introduction

Nowadays, Magnetic Hard Disk Drives (HDDs), as depicted in Fig. 1, are used widely in many ways, and are becoming more important for our society than ever, due to the fact that the cost of HDDs per Terabyte storage capacity is only about 1/3 to 1/50 of solid-state storage devices [1]. Also, demand of storage capacity is increasing drastically [2], which renders a lot of challenges in the technical field of HDDs. Among them, two renowned control problems have been defined: track-seeking and track-
following [3]. The former deals with the motion control of HDD heads between tracks in minimum time, while the latter with maintaining HDD heads on the center of the tracks.
In the manufacturing process of HDDs, servo tracks along with encoded servo bursts are written in via servo track writer (STW). The STW may comprise a multi-disc writer (MDW) having a plurality of dedicated servo writing heads for higher efficiency of production [4]. Then, assembly of the disc into the final drive base is followed. Nevertheless, the ex-situ disk writing process could result in additional position and/or timing error, compared with in-situ disk writing technology. The reasons may include discrepancy between actual drive spinning center and written-in MDW track center, as well as assembly tolerance of head stack. Therefore, drive makers have developed a few calibration methods to compensate various MDW-related errors [5]. Among them, head skew calibration is one of the key processes, so that head skews are well compensated as if the servo bursts are written in-situ.

On the other hand, in the case that HDDs encounter operating or non-operating shock or vibration in mobile usage, head skew error across stroke may drift away from the calibrated values in factory. The resultant AC portion of head skew is independent of radial head position and could be successfully addressed by the adaptive feedforward cancellation (AFC) algorithms [6-8] or iterative learning control (ILC) [9]. The major concern is DC portion of head skew, as it may cause unacceptable noise issue, long access time, or long time to ready (TTR) if servo controller fails to tackle such large position errors during head switching seeking [10].

Therefore, power on quick check of DC head skew during servo startup is formulated, so that additional DC head skew error is properly compensated, and drive will behave as normal as long as servo is able to get ready. It is realized that sector-dependent AC position error may be dominant, which may deteriorate convergence of DC head skew. For this, a filtering algorithm of DC head skew is also...
proposed. Whenever the preset recalibration threshold is exceeded, compensation of DC head skew will take in effect, with one-time penalty of longer TTR than that during normal servo startup. The remainder of this paper is organized as follows. Section 2 describes head switching quick check strategy, and Section 3 discusses head skew filtering algorithm. In Section 4, experimental results are demonstrated, and finally conclusion is drawn in Section 5.

2. Head Switching Quick Check

Head skew is decomposed into AC and DC components, as described by

\[ \text{HeadSkew}(hd) = DCHS(hd) + ACHS(hd) \times \sin \theta \]  

(1)

where \( hd \) denotes head number, \( \theta \) is the phase of sample, \( \theta = 2\pi \times \frac{n}{N_s} \), servo sector \( n = 0,1,2,\cdots, N_s -1 \), \( N_s \) is the total servo sector per revolution, as illustrated in Fig. 2.

AC head skew is related to eccentricity of MDW tracks, and is calibrated in factory through Virtual Concentric Aligned Tracks (VCAT) test. DC head skew is regarded as the radial position error between the two heads for a drive with multiple heads/discs, as depicted in Fig. 3. During calibration, raw DC head skew errors across stroke (from outer disc to inner disc) are measured, and a 4th order polynomial could be formulated with proper offset adjustment, so that feedforward control of DC head skew can be implemented prior to every head switching seeking. Moreover, an adaptive head skew compensation table is used to tackle the fitting residual of head skew over physical heads.

Fig. 2 Typical embedded servo track layout

Fig. 3 Illustration of DC head skew error between two heads
Due to operating or non-operating shock, head skew might drift away from the factory-calibrated value, causing drive failure to get ready. For this, a scheme of power on quick check is developed, where intensive head switching seeks are performed after servo is initialized. Then, decision of head skew recalibration will be made and excessive head skew variation could be compensated. The learning algorithm of DC head skew is given by

\[
DCHS(hd,k) = DCHS(hd,k-1) - Gain \times OES(hd,k)
\]  

(2)

where \(k\) is the sequence number of head switching, \(OES\) represents valid position error post head switching, or observer error sample between demodulation position and predicted position. Ideally, \(OES\) should be zero if compensation of position error is perfect, \(Gain(<1)\) denotes the learning gain.

Notice that DC head skew in equation (2) might fail to converge due to a dominant AC portion of \(OES\). Fig. 4(a) shows the results of a 4-head drive, 5WX09ZSX (640G, 5400 rpm), at ten power cycles post non-operating shock test. Clearly, DC head skew error is evidently fluctuating against power cycle, and peak-peak value can reach 700 tracks for head switching from 3 to 0 or 1 to 2, which is not true in any situation. Further study shows that such inconsistency is caused by the dominant AC portion of head skew, as demonstrated in Fig. 4(b), where head switching seeks are always performed at one particular sector. In this case, position error \(OES\) is not independent of servo sector, and iteration of DC head skew error couldn't converge. In another word, the result of quick check based on equation (2) is not reliable. Such inconsistency will definitely cause recursive or unnecessary recalibration during power on if a recalibration threshold of 30 tracks is set, for example. Therefore, head skew filtering strategy is proposed.

![Fig. 4. (a) DC head skew error during different power cycle; (b) DC head skew error collected at fixed sector](image)

3. Head Skew Filtering Algorithm

Fig. 4 (b) also shows that head switching seeks should be sequentially done at two fixed sectors, which are separated by half a revolution. For instance, given that first group of head switching seeks is fixed at the \(n^{th}\) sector, the DC head skew error can be derived by

\[
DCHS_1(hd,k) = DCHS_1(hd,k-1) - Gain \times OES(hd,k,n)
\]  

(3)

Next, adjust servo sector to \(n + N_s / 2\), and collect the second DC head skew error.
Finally, the actual DC head skew error can be calculated by

\[ DCHS = \frac{(DCHS_1 + DCHS_2)}{2} \]  

where AC portion of head skew is automatically eliminated, as \( \sin(\theta + \pi) = -\sin(\theta) \) in equation (1).

Flowchart of servo startup is illustrated in Fig. 5, where recalibration of DC head skew is embedded. The downside of this algorithm is long servo startup time or TTR, as double head switching seeks at two respective servo sectors are involved. Then, one can increase the learning gain slightly, so that convergence of DC head skew error would take few servo samples.

4. Verification Test

Experiments with the proposed compensation scheme are carried out on the problematic drive (5WX09ZSX) with 288 servo sectors, while sectors 0 and 144 in Fig. 6(a) are chosen for head switching check. The DC head skew error is stable and repeatable over ten random power cycles, as shown in Fig. 6(b). Obviously, variation of DC head skew for all heads is significantly reduced to around 1 track, from previously hundreds of tracks. Therefore, satisfactory drive performance post non-operating shock can be achieved as long as DC head skew recalibration is completed. For this particular drive, the DC head skew recalibration after quick check is performed, as the preset threshold (30 tracks) is exceeded.
5. Conclusion

This paper has presented a novel DC head skew quick check scheme, where two fixed sectors for head switching seeks are scheduled in order to remove the AC component from position error. Verification test on a commercial drive has demonstrated its effectiveness and reliability with penalty of long servo TTR. Furthermore, the recalibration parameters can be saved to drive FLASH via non-volatile method, so that recursive recalibrations can be avoided, and drive will operate as normal for all subsequent power cycles.

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