www.s2is.org
International Journal on Smart Sensing and Intelligent Systems
ISSN 1178-5608

FEEDFORWARD CONTROL OF TEMPERATURE-INDUCED HEAD SKEW FOR HARD DISK DRIVES

Yong Xiao[1], Chi Zhang[2], Xiaoyu Ge[1] and Peiqi Pan[1]

[1]College of Information Engineering, Shenyang University of Chemical Technology, China

2 Ningbo Institute of Technology, Zhejiang University, Ningbo, China

Emails: pg01639835@ntu.edu.sg

Submitted: Jan. 7, 2012 Accepted: Feb. 9, 2012 Published: Mar. 1, 2012

Abstract In hard disk drives (HDDs), head skew error among multiple heads is calibrated during manufacturing process, and will be implemented prior to head switching seeks. In operational environment, additional head skew deviation due to temperature drift may be observed, which could introduce heavy handling burden for feedback controller along with unacceptable noise to HDD customers. Therefore, a thorough analysis of head skew variation against temperature is carried out in this paper. With help of accurate estimation of head skew based on drive temperature, smart feedforward control strategy during drive startup is embedded. Experimental results demonstrating its effectiveness to enhance drive performance are given.

Index terms: Head skew deviation, hard disk drives, calibration, and temperature coefficient.

I. INTRODUCTION

With the progress of information technology (IT), more advanced storage devices to accommodate the unprecedented expansion of information and the rapidly changing IT environment are needed [1]. Magnetic and optical recording storage devices, such as hard disk drive (HDD) and optical disk drive (ODD), are the best candidates for satisfying these demands and requirements, as its cost per terabyte is only about 1/3 to 1/50 of solid-state storage devices [2]. Motivated by the increasing capacity of HDD, multi-disk writing (MDW) technology emerges to combine two or more transducer heads capable of reading and writing bits of data to/from two or more stacked storage discs, which are sharing a common axis of rotation within a storage media drive [3, 4]. The transducer heads are each attached to an actuator arm in a stack of actuator arms and are intended to be vertically aligned so that the transducer heads align with the same relative position on each corresponding storage disc. Exact vertical alignment of the transducer heads in the phase of assembly is actually impossible. Then, a certification process is normally developed to adapt the MDW-related discrepancies, so that high servo performance for head switching seeks using feedforward control can be obtained [5]. Moreover, a lot of servo feedback control algorithms were also reported to further enhance drive performance in the literatures [6, 7].

In response of an environmental event (e.g., a shock, head stack tilt and temperature drift), the transducer head alignment may be disrupted, which means that head skew probably deviates from the calibrated value in factory. As a result, control performance will be degraded at aspects of track-seeking and track-following. The former deals with the motion control of the HDD heads between tracks in minimum time [8], and the latter with maintaining the HDD heads on the center of the tracks [9, 10]. To solve this problem, a full recalibration of head alignment is required from point of view of design. However, it is impractical for shipped drives due to constraint of time to ready (TTR). Then, a method of quick power on check is proposed to compensate the permanently deviated head skew with acceptable penalty of TTR margin [11]. The major concern for recalibration is the acoustic issue, as it is becoming more and more sensitive to home theater users. The third solution is to probably adjust the triggering threshold of recalibration according to field temperature, so that frequent recalibration can be avoided. Unfortunately, large head skew deviation in this case is never reduced, which will rely on feedback controller for error elimination, although TTR for storage media drives operating at different temperature is relatively satisfactory.

It is recognized that the drive is typically certified at a preset temperature (e.g., 40-50 degrees Celsius), where the best drive performance is normally guaranteed by design. In reality, the head skew deviation of the storage media drive is somehow dependent of the ambient condition. This is especially true for the event of temperature drift, and happens on small and compact storage media drives with limited cooling capability (e.g., mobile drives) [12]. Then, acoustic issue and long access time during recalibration are related to significant residual of head skew caused by occasional temperature change [13]. As well, system intelligence is highly desired for automation industry [14, 15], and feedforward control could render advantage of shorter settling time than feedback control, given that variation of the controlled object is predictable. Therefore, smart calibration of temperature coefficients for head skew deviation is developed in this paper, and accurate estimation of the temperature-sensitive head skew trajectory can be realized. As a result, feedforward control strategy through on-chip temperature sensing technology is embedded to servo startup, so that recursive recalibration for occasional head skew deviation can be avoided, and its impact on TTR is also negligible.

The remaining of this paper is organized as follow. Section II describes the basic knowledge of head skew. Section III analyzes the head skew deviation related to temperature drift. In Section IV, calibration strategy of temperature coefficients and its implementation procedure are presented, the effect of which is verified by experimental results in Section V. Finally, conclusions are given in Section VI.

II. RAW HEAD SKEW

Raw head skew refers to the radial position difference of relevant heads, as depicted in Figure 1. The transducer heads are each attached to an actuator arm in a stack of actuator arms also, so that the transducer heads align with the same relative position on corresponding storage discs with a common axis of rotation.

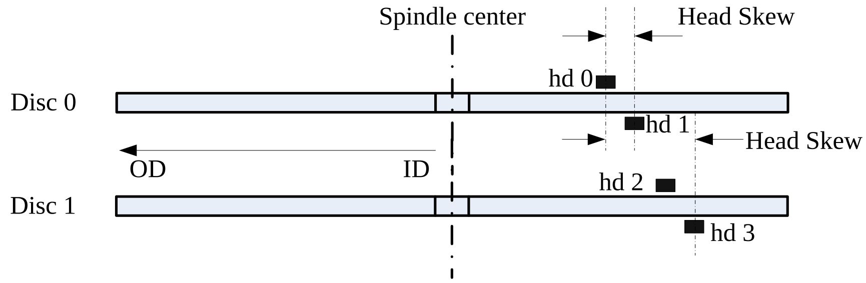


Figure 1. Sketch of raw head skew

Then, raw head skew can be described by

$$RHS(hd_i, hd_j, cyl) = RP_j(cyl) - RP_i(cyl) \quad (1)$$

where hd_i and hd_j are the physical source and destination heads, cyl indicates the servo cylinder number over which source head is flying, RP_i and RP_j represent radial positions of source and destination heads involved in the head switching operation.

Clearly, head skew at a certain cylinder is invertible, which is equivalent to:

$$RHS(hd_i, hd_j, cyl) = -RHS(hd_j, hd_i, cyl) \quad (2)$$

Moreover, head skew across heads can be decomposed into sequential head skews, as given by:

$$RHS(hd_i, hd_j, cyl) = RHS(hd_i, hd_{i+1}, cyl) + \cdots + RHS(hd_{j-1}, hd_j, cyl) \quad (3)$$

With increasing demand of high storage capacity, multiple discs and heads are required to be assembled into one drive, instead of stressing track per inch (TPI) and/or bits per inch (BPI). Study reveals that raw head skew post drive assembly is varying linearly against servo cylinders from outer disc (OD) to inner disc (ID), as shown by the upper plot of Figure 2 for a 4-head drive. Then, head skew calibration is embedded in the drive certification, and an appropriate polynomial could be easily fitted with help of offset adjustment, the result of which is illustrated by lower plot of Figure 2.

As a result, feed-forward control of head skew can be implemented for subsequent head switching seeks, by means of polynomial evaluation with input parameter of cylinder number, as given by:

$$RHS(hd_i, hd_j, cyl) = PolyEva(c_i, cyl) + \cdots + PolyEva(c_{j-1}, cyl) \quad (4)$$

where c_i denotes polynomial coefficients of head skew from hd_i to hd_{i+1}, $PolyEva$ is the evaluation function of polynomial.

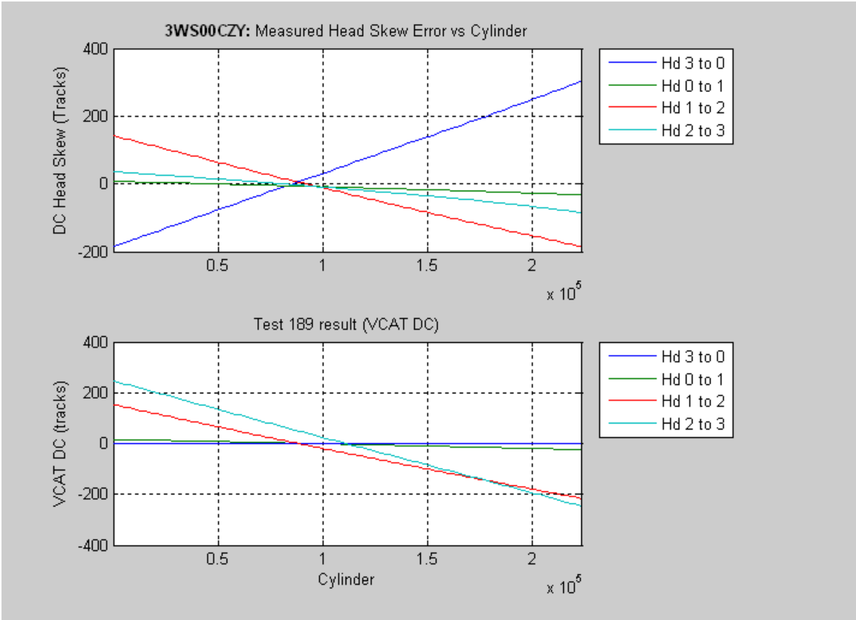


Figure 2. Raw head skew and its fitted curve during certification

III. TEMPERATURE-INDUCED HEAD SKEW

HDD is typically certified at a preset temperature (e.g., 40-50 degrees Celsius), and satisfactory drive performance is guaranteed. Then, residual of head skew should be around zero. In reality, customers are sometimes frustrated by low read/write efficiency and loud noise generated at cold temperature. This is because the ambient condition is changing significantly from that of certification. In other words, if the drive is operating at extreme temperature, large position error and high actuator current post head switching is present, which results in heavy load for servo controller to handle such exceptions. Further study shows that this kind of position error is temperature-sensitive. In this case, head skew estimation based on (4) is inaccurate, and the deviation of head skew is related to drive temperature, as shown in Figure 3. Note that the residual of head skew is collected at a fixed servo cylinder ($cyl = 100000$), and H3->0 indicates that head is switching from number 3 to 0.

By defining the deviation of head skew due to temperature drift as THS, it has

$$THS(hd_i, hd_j, cyl, T_c) = 0 \tag{5}$$

where T_c is the certification temperature in factory.

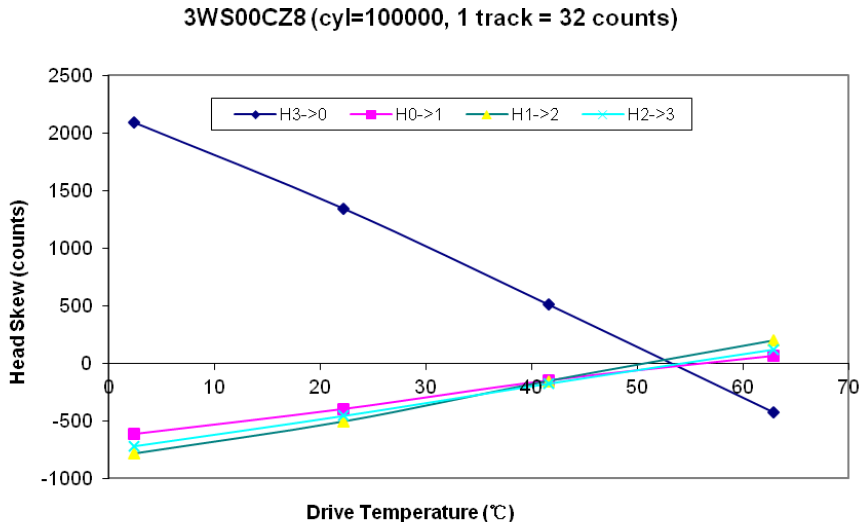


Figure 3. Temperature-induce head skew variation

Clearly, perfect compensation of head skew with expression (4) at 53℃ can obtained, as head skew deviation for this drive is neglectable. Nevertheless, large head skew deviation, around 65 tracks, could be present if the drive is powered up at cold temperature. Then, high pitch of noise will be generated by drive actuators. Furthermore, drive may fail to get ready in case that the deviation exceeds a certain threshold.

IV. CONTROL STRATEGY

Figure 3 also shows that temperature-induced head skew is varying linearly against ambient temperature T. Then, feedforward control of such deviations could be realized by:

$$THS(hd_i, hd_j, cyl, T) = THS(hd_i, hd_j, cyl, T_c) + k_{ij} * (T - T_c) \tag{6}$$

where k_{ij} is the temperature coefficient of head skew.

Combining equations (5) and (6) yields a simplified control law,

$$THS(hd_i, hd_j, cyl, T) = k_{ij} * (T - T_c) \tag{7}$$

Note that temperature of certification T_c is known, so adjustable parameters of compensation are drive temperature T and temperature coefficients k_{ij}. In order to achieve higher drive performance, temperature coefficients k_{ij} for each drive can be calibrated in factory, so that drive-drive variation can be taken into consideration. As certification time contributes to the manufacturing cost of drive, the embedded procedure of calibration should be optimized. The simplest way is to measure one group of head skew deviations THS at a temperature rather than T_c for each head switching operation, as shown in Figure 4. Then, temperature coefficients can be estimated by:

$$k_{ij} = \frac{THS(hd_i, hd_j, cyl, T_s) - THS(hd_i, hd_j, cyl, T_c)}{T_s - T_c} \quad (8)$$

or

$$k_{ij} = \frac{THS(hd_i, hd_j, cyl, T_s)}{T_s - T_c} \quad (9)$$

where T_s represents a specific temperature for coefficient calibration of head skew.

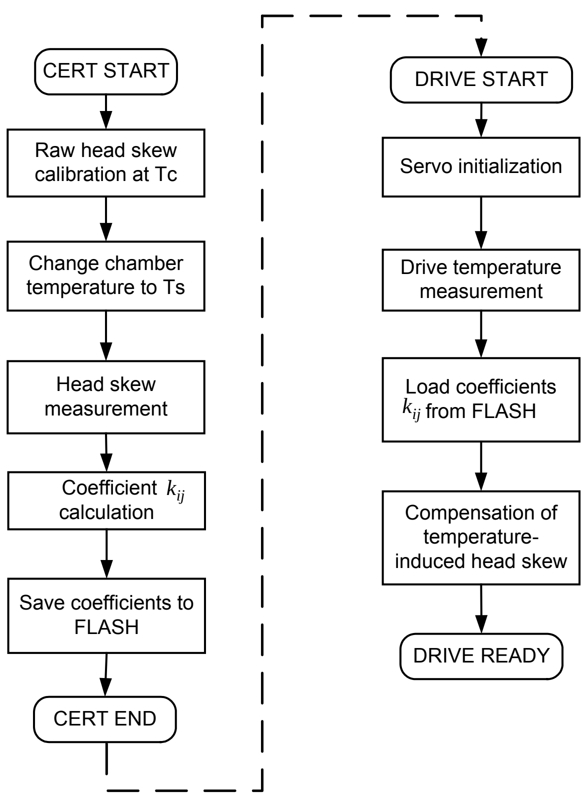


Figure 4. Flowchart of head skew calibration

Once temperature coefficients are calibrated and saved to drive FLASH, compensation of temperature-induced head skew could be implemented during next drive startup according to expression (6), given that drive temperature is updated appropriately.

V. EXPERIMENTAL VERIFICATION

In this experiment, 4 fresh drives with serial numbers: 3WS00CYP, 3S00CZ5, 3WS00CZ8 and 3WS00CX are chosen for functional test. First, MDW calibration is carried out at temperature $T_c = 50$ ℃, so that raw head skew are completely compensated. Then, gradually sweep chamber temperature and measure head skew deviation THS . The results shown in Figure 5 demonstrate that head skew deviation is varying linearly against drive temperature. Finally, based on equation (9), temperature coefficients for each drive can be calculated, as summarized in Table I.

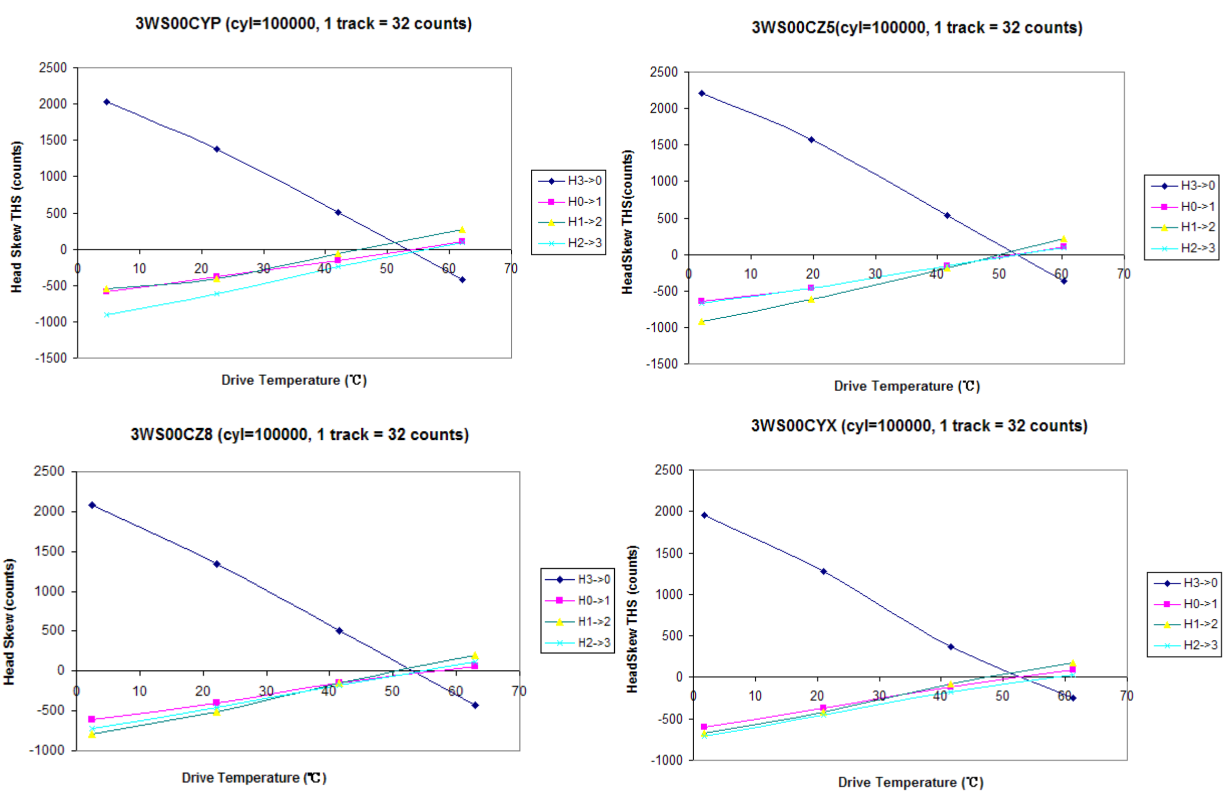


Figure 5. Head skew deviation against drive temperature

Table I also illustrates that the coefficient variation for different drives is insignificant, which means that online calibration of temperature coefficients can be avoided. Instead, hard coded coefficients are implemented for all drives, so that shorter certification time and lower manufacturing cost can be obtained. Figure 6 shows the head skew residual when compensation of temperature-induced head skew deviation is equipped, and $k_{30} = -331$, $k_{01} = 95$, $k_{12} = 128$ and $k_{23} = 113$ are set for respective head switching sequence. Clearly, the peak value of head skew residual with the proposed strategy is reduced by 90%, which will guarantee good drive performance in extreme operational conditions without any concern of acoustic issue and long TTR. It must be pointed out that the performance can be further improved with penalty of longer certification time if temperature coefficients for each drive are individually calibrated, as a full process in Figure 3 is performed.

Table I. Calibrated temperature coefficients

	Temperature coefficients				Statistic	
Head switching	3WS00CYP	3WS00CZ5	3WS00CZ8	3WS00CYX	Mean	1-sigma
H3->H0 (k30)	-341	-353	-333	-296	-331	24.25
H0->H1 (k01)	97	102	90	93	95	5.49
H1->H2 (k12)	114	156	130	113	128	20.06
H2->H3 (k23)	140	104	111	99	113	18.45

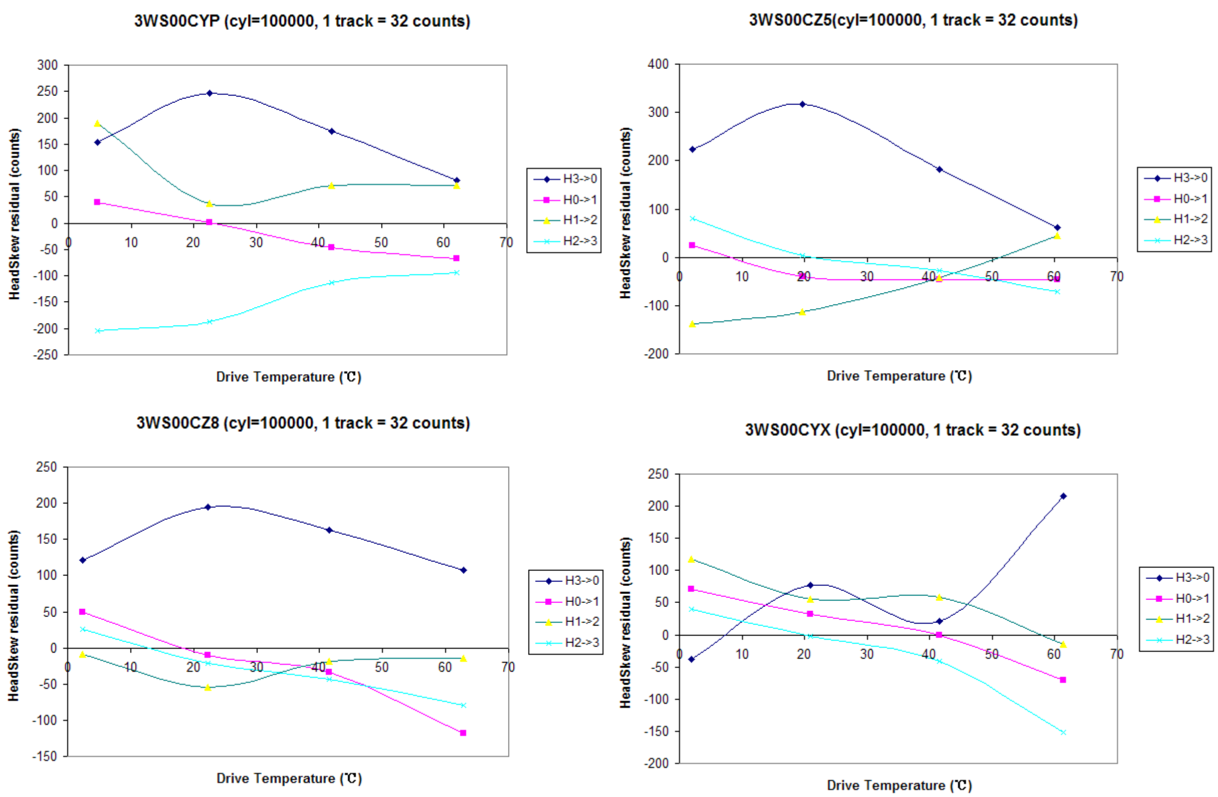
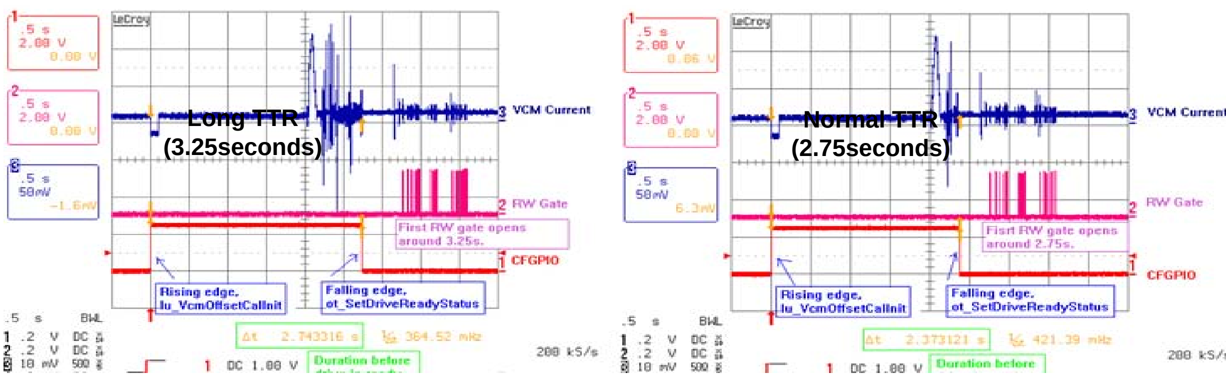


Figure 6. Head skew residual with temperature compensation

Figure 7(a) shows the startup performance of drive 3WS00CYP at cold temperature when the proposed temperature compensation is absent. Clearly, long TTR around 3.25 seconds is obtained. This is because head skew deviation at -15 ℃ is above recalibration threshold (30 tracks or 960 counts), and the quick power on recalibration can not be avoided, which will typically consume 0.5 seconds along with loud recalibration noise. However, TTR of this particular drive will recover to normal value (2.7seconds, for example) if the feedforward control of temperature-induced head skew is activated, as illustrated by Figure 7(b). In other words, such drives are able to automatically trace the change of ambient condition, and concerns of acoustic issue and TTR are eliminated.



(a) (b)

Figure 7. TTR Comparison for drive operating at cold temperature:
(a) without compensation; (b) with compensation

VI. CONCLUSIONS

In this paper, temperature-induced head skew for hard disk drives is formulated, and calibration strategy of temperature coefficients during certification is proposed. With embedded feedforward control, significant head skew deviation can be effectively reduced, so that drive performance in terms of TTR and acoustic noise at extreme conditions can be enhanced, which has been verified by experimental results.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contribution of Natural Science Fund of Ningbo (Grant no: 2011A610107), as well as Dr. Ruili Wang and reviewers' comments.

REFERENCES

[1] K. S. Park, Y. P. Park, N. C. Park, “Prospect of recording technologies for higher storage performance,” *IEEE Transactions on Magnetics*, vol. 47, no. 3, 2011.

[2] Y. Hori, Y. Kanai, K. Taima, “An audiovisual content recorder using a removable hard disk drive,” *IEEE Transactions on Consumer Electronics*, vol. 56, no. 4, pp. 2324-2329, 2010.

[3] Y. Uematsu, M. Fukushi, K. Taniguchi, “Development of the pushpin free STW [servo track writer],” *IEEE Transactions on Magnetics*, vol. 37, no. 2, pp. 964-968, 2001.

[4] T. Yaada, M. Fkushi, H. Suzuki, etc, “Servo track writing technology,” *FUJITSU Scientific & Technical Journal*, vol. 42, no. 1, pp. 93-102, 2006.

[5] Yong Xiao, Yujun Pang, Xiaoyu Ge, etc, “Compensation of shock-induced head skew for hard disk drives,” *Procedia Engineering*, vol. 16, pp. 65-71, 2011.

[6] Y. L. Chow, F. L. Lewis, V. Venkataramanan, etc, “Disturbance and friction compensations in hard disk drives using neural networks,” *IEEE Transactions on Industrial Electronics*, vol. 57, no.2, pp. 784-792, 2010.

[7] T. Semba, M. T. White, F. Huang, “Adaptive cancellation of self-induced vibration,” *IEEE Transactions on Magnetics*, vol. 47, no. 7, pp. 1958-1963, 2011.

[8] M. R. Graham, and R. A. de Callafon, “An iterative learning design for repeatable runout cancellation in disk drives,” *IEEE Transactions on Control System Technology*, vol. 14, no. 3, pp. 474-482, 2006.

[9] H. Fujimoto, “RRO compensation of Hard Disk Drives with multirate repetitive perfect tracking control,”, *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 3825-3831, 2009.

[10] T. Atsumi, A. Okuyama, M. Kobayashi, "Track-following control using resonant filter in Hard Disk Drives,", *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 4, pp. 472-479, 2007.

[11] Y. Xiao, C. Zhang, X. Y. Ge, etc, "Reliable recalibration of DC head skew in hard disk drives,", in *Proceeding of 2011 International Conference on Modelling, Identification and Control*, Shanghai, China, pp. 26-29, 2011.

[12] J. Y. Chang, "Thermal analysis and design of disk-spindle radial repeatable runout in spinning data storage devices," *IEEE Transactions on Magnetics*, vol. 47, no. 7, pp. 1855-1861, 2011.

[13] F. Gao, W. Z. Lin, C. W. Lee, etc, "Numerical hard disc drive seek acoustic transfer analysis and experimental validation", *IEEE Transactions on Magnetics*, vol. 45, no. 11, pp. 4945-4949, 2009.

[14] M. Y. Tsai and T. S. Liu, "Sliding mode based fuzzy control for positioning of optical pickup head," *International Journal on Smart Sensing and Intelligent Systems*, vol. 3. no. 2, pp. 304-321, 2010.

[15] M. Rahmat, S. M. Rozali, N. A. Wahab, etc, "Application of draw wire sensor in position tracking of electro-hydraulic actuator system," *International Journal of Smart Sensing and Intelligent System*s, vol. 3. no. 4. pp. 736-755, 2010.