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Experimental study of disk vibration reduction via stacked disks

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Abstract

In order to improve the position accuracy of testing and manufacturing equipments such as spin stand and servo track writer with minimal mechanical alternation, a stacked-disk approach whereby more than one normal recording media are stacked together for reading and writing on the disk surfaces is studied. Two 3.5-inch recording media are stacked together to test the effectiveness of reducing the vibrations and improving the position accuracy. The position error signals (PES) are measured and analyzed at different rotational speeds of 7200, 8400 and 10,200 rev/min. The results show that the dual-disk stack can reduce the amplitude of the PES by over 30% when the rotating speed is above 8400 rev/min.

1. Introduction

To support higher track per inch (TPI) density hard disk drive (HDD), the positioning accuracy of the test equipments such as spin stand and servo track writer has to be increased. Spin stand is a commonly used equipment for magnetic recording component testing [1]. Servo track writer (STW) [2–4] is to pattern the recording media with servo information for the HDD servo system. In both cases, spindle motor and disk vibrations [5–9] affect the positioning accuracy and limit how close adjacent tracks can be placed together, and thus restrict the TPI number that can be achievable. In Ref. [10], damped laminated disks were used to reduce the amplitude of rocking modes by sandwiching a viscoelastic layer in between two aluminum layers to increase disk damping. Deeyiengyang and Ono [11] investigated the effect of suppressing resonance amplitude of disk vibrations by applying a squeeze film damping. In addition to the laminated disks and the squeezed air bearing plate methods, other active methods such as active control approaches [12,13] and active servo added to spin stand [14] are proposed to deal with the vibrations. Over the years there has been a great interest in patterned media using technologies such as nano-imprint [15], which eliminates the need of STW. However, such potential approaches to achieve dimensions of less than 100 nm will have to resolve issues such as high production throughput in a cost-effective manner. In view of these, in this paper we propose an approach with minimal mechanical alternation. That is to stack more than one normal recording media together for reading and writing on the disk surfaces.

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A spin stand is used to investigate the effect of suppressing the disk vibration by stacking disks. The vibration reduction results for a 3.5-inch dual-disk stack (two disks stacked together) servo writing process on the spin stand are presented. Experimental results of the position error signal (PES) and the axial disk vibrations are obtained and analyzed at the spindle rotational speed of 7200, 8400 and 10200 rev/min. It is shown that the dual-disk stack can reduce PES 3σ value by over 32% as compared to single disk case. We also verify that written disk surface's contacting with another disk surface for stacking the two disks will not damage the media recording property. This further justifies that the disk stacking approach can be applied as a simple way of achieving higher TPI on spin stand and similar systems such as off-line servo track writers or multi-disk servo track writers.

2. Experimental process

The commercial spin stand is employed to test heads and media and demonstrates the achievability of servo performances [14]. Here we use a Guzik spin stand (Model no. 1701A) to evaluate the effectiveness of dual-disk stack in position accuracy improvement. Position errors based on the readback signal can be generated through our external digital PES channel [16]. The disk vibrations in the axial direction are also measured at the outer diameter (OD) region of the disk via laser doppler vibrometer (LDV).

In the experiment, the spindle motor is spinning at 7200, 8400 and 10,200 rev/min, respectively, and the size of the aluminum disk is 3.5-inch of 0.8 mm thickness. Two such disks are stacked together and mounted on the spindle motor of the spin stand, which is shown in Fig. 1. The experimental process is described as follows.

Step 1: Stack two disks together and mount on the spin stand.

Step 2: Spin the motor and write servo information on the top disk surface.

Step 3: Read back the written information and obtain the PES.

To write servo information on the disk surface in between the two disks, the spindle motor is stopped and the written surface of the disk is flipped over, following which, steps 1–3 are repeated.

Next, we shall show the effectiveness of disk vibration reduction and thus improvement of position accuracy by using the stacked disks.

3. Position accuracy improvement via dual-disk stack

The disk vibration in the axial direction of the single disk and the dual-disk stack are measured via LDV. The measurement point is at the outer diameter (OD) region. In addition, the position error signals are collected for both the single disk and the dual-disk stack conditions. To evaluate the improvement of position accuracy, $M = 20$ traces of the position error signal are collected and denoted by PES_i $(i = 1, \ldots, M)$. For each trace, 5002 sampled data is collected via an oscilloscope, i.e. the length of PES_i is 5002. The repeatable

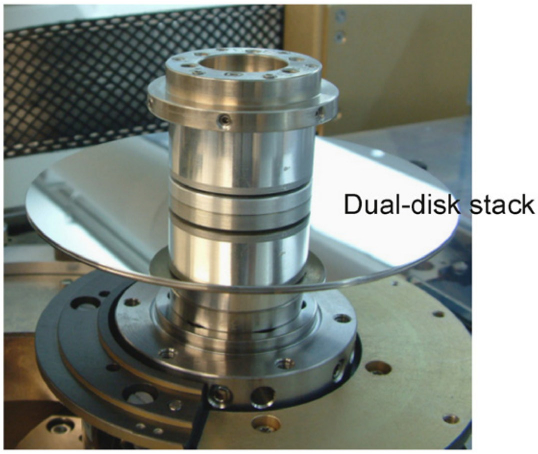

Fig. 1. Disk and spindle on the spin stand.

runout (RRO) and the nonrepeatable runout (NRRO) [4] are thus given by

$$\mathrm{RRO} = \frac{1}{M}\sum_{i=1}^{M} \mathrm{PES}_i, \quad \mathrm{NRRO}_i = \mathrm{PES}_i - \mathrm{RRO}.$$

3.1. Position accuracy improvement at 7200 rev/min

Tested disk vibration results of the dual-disk and the single disk are shown in Fig. 2. Besides the harmonics with respect to the spindle speed, the disk vibration modes can be seen clearly as denoted by T1–T9. It is found that the frequencies of the disk vibration modes T1–T9 are shifted and their amplitudes are reduced apparently. The vibration modes are all shifted 40 Hz to higher frequencies.

The power spectra of the RRO and NRRO, computed from the collected PES data, are shown in Figs. 3 and 4. As seen in Fig. 3, except for the first harmonic, other dominant harmonics before the 11th harmonic are

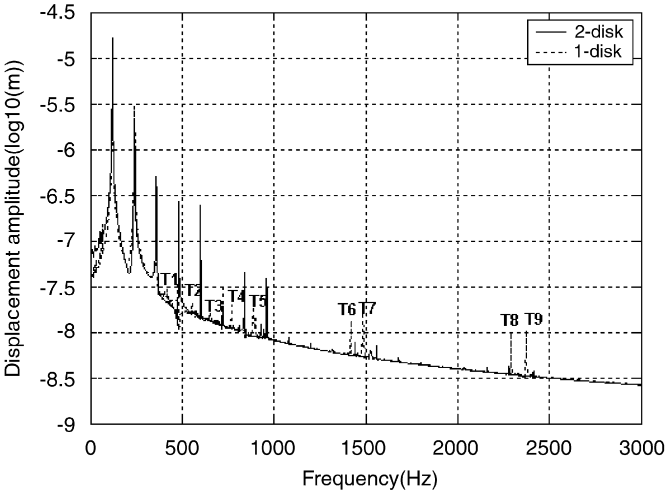

Fig. 2. Comparison of single- and dual-disk axial vibrations measured via LDV at 7200 rev/min.

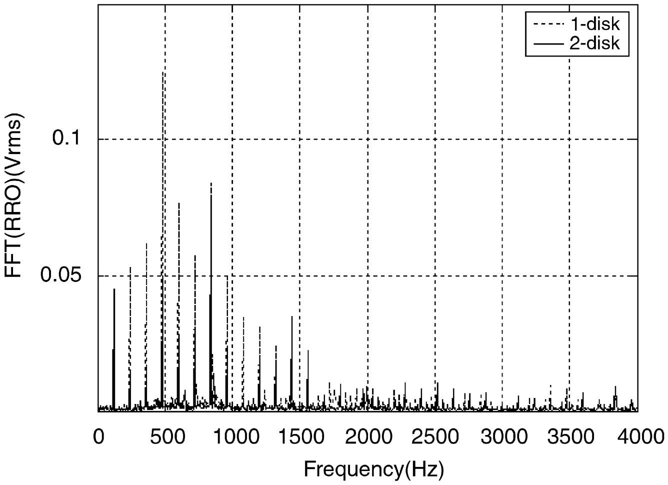

Fig. 3. Comparison of single- and dual-disk RRO power spectrum at 7200 rev/min (23% improvement of σ value).

all reduced. In Fig. 4, we can observe that almost all the reduced disk vibration modes T1–T9 in Fig. 2 are reflected in NRRO. The other peaks indicated by S1–S4 can be identified to be caused by slider vibrations. They are both lowered significantly, which may be due to better slider-disk interaction. It is noted that the peak S2 for the single disk case is shifted to S3 in the dual-disk case. This randomly happens and the writing process at a different time may cause such a shifting. This phenomenon can be seen in other testing results which will be shown later.

The standard deviations (or σ values) of RRO, NRRO and PES are obtained. It turns out that the σ value of RRO is reduced by 23%, NRRO by 18%, and the PES σ value is reduced by 21%. Fig. 5 shows time sequences of PES in both cases and the amplitude reduction is seen apparently.

3.2. Position accuracy improvement at 8400 rev/min

The disk or the dual-disk stack is rotating at 8400 rev/min, and the disk vibrations in the axial direction are shown in Fig. 6. It can be seen that the amplitudes of the vibration modes are all reduced with a shift in frequencies, as indicated by T1–T6.

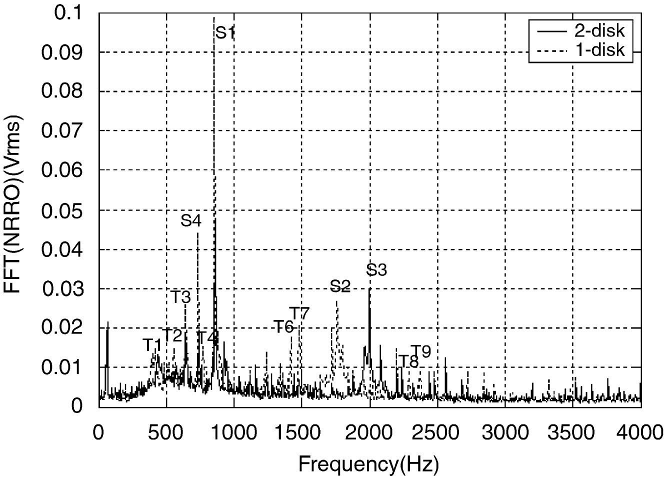

Fig. 4. Comparison of single- and dual-disk NRRO power spectrum at 7200 rev/min (18% reduction of σ value).

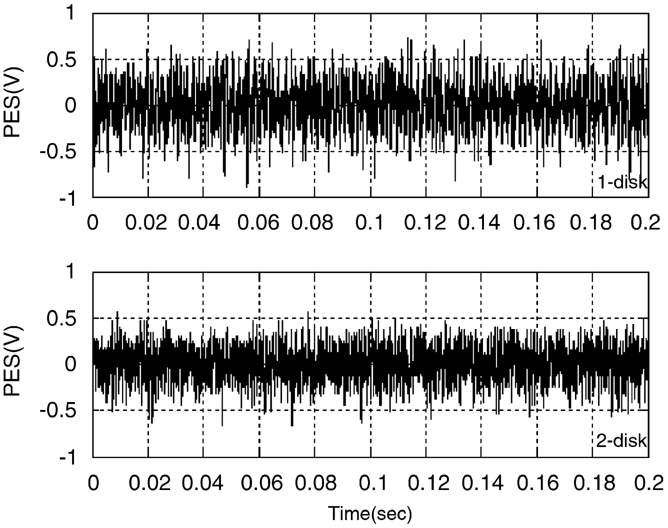

Fig. 5. Comparison of single- and dual-disk PES in time domain at 7200 rev/min (21% reduction of σ value).

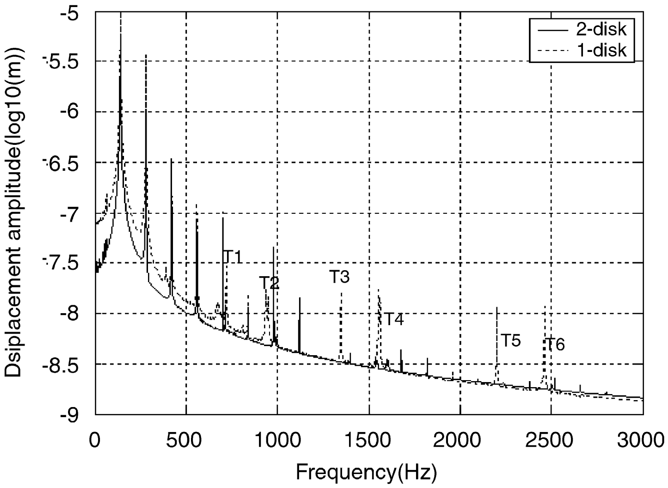

Fig. 6. Comparison of single- and dual-disk axial vibrations measured via LDV at 8400 rev/min.

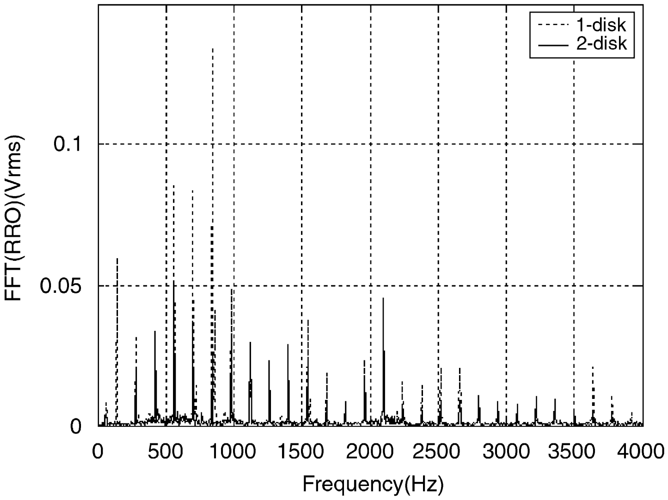

Fig. 7. Comparison of single- and dual-disk RRO power spectrum at 8400 rev/min (41% improvement of σ value).

The power spectra of the RRO and NRRO are calculated from the tested PES and shown in Figs. 7 and 8. Fig. 7 shows that almost all the first seven harmonics are decreased and as a result, the σ value of RRO is reduced by 41%. In Fig. 8, the corresponding T1–T6 in Fig. 6 can be found and they are all suppressed in the case of the dual-disk stack. Notice that S1 is reduced significantly, but cannot be traced in the tested disk vibrations in Fig. 6. This further verifies that S1 is caused by the disk–slider interaction. The corresponding S4 cannot be found in this case, while T1 appears very close to S4 location. The resultant σ value of NRRO is improved by 28%, and PES by 38%. Fig. 9 shows the comparison of single- and dual-disk PES in time domain, and the amplitude of PES in the case of the dual-disk stack approach is much lower as compared to conventional single-disk approach.

3.3. Position accuracy improvement at 10,200 rev/min

A higher rotational speed of 10,200 rev/min is performed on both dual-disk stack and single-disk cases. Fig. 10 shows the obtained disk axial vibration by LDV. The modes T1–T6 are quite obvious with the amplitude reduced and the frequencies shifted higher. Figs. 11 and 12 show the power spectrum of RRO and

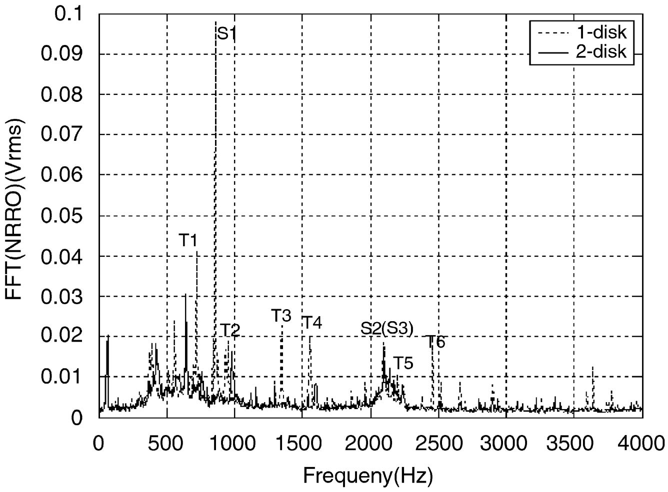

Fig. 8. Comparison of single- and dual-disk NRRO power spectrum at 8400 rev/min (28% reduction of σ value).

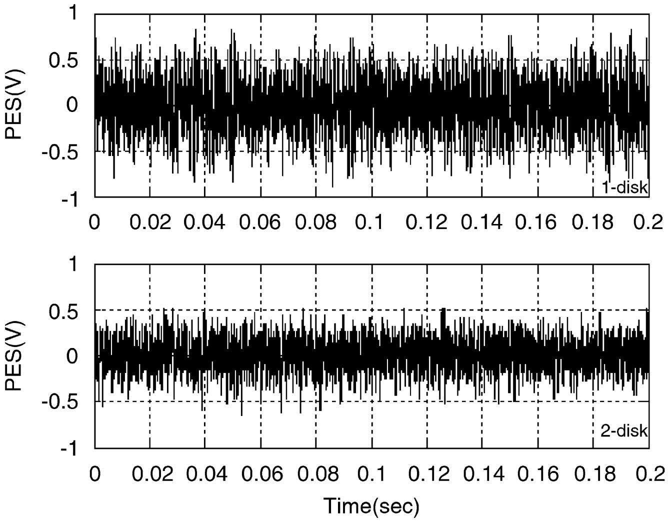

Fig. 9. Comparison of single- and dual-disk PES in time domain at 8400 rev/min (38% reduction of σ value).

NRRO. The third and fifth harmonics are significantly reduced as seen in Fig. 11. Fig. 12 reflects the corresponding disk vibration modes T1–T6 in Fig. 10. As for the slider-related vibrations, S1 is reduced significantly again and S2 and S3 are shifted, while S4 cannot be seen at all in Fig. 12.

As a result, the σ value of RRO is improved by 33%, NRRO by 27%, and PES by 32%, compared with that of the single-disk approach. Fig. 13 shows the comparison of PES in time domain, and it is observed that the amplitude of PES in the case of the dual-disk stack is decreased.

The reduction of disk vibration amplitude is evaluated from Figs. 2, 6 and 10 and tabulated in Table 1 for different rotational speeds. The improvement of σ values of RRO, NRRO and PES are also summarized in Table 1. Remarkable improvement is achieved for every rotational speed. It can be seen clearly from the table that the best improvement is obtained when operating at 8400 rev/min. The second best result obtained is performed at 10,200 rev/min, where the dual-disk stack approach leads to an improvement of 32% in position accuracy.

For all cases, we have observed remarkably reduced amplitude of the disk vibration and its reflection in positioning accuracy improvement via the dual-disk stack. This indicates that the stacked disk is a simple way

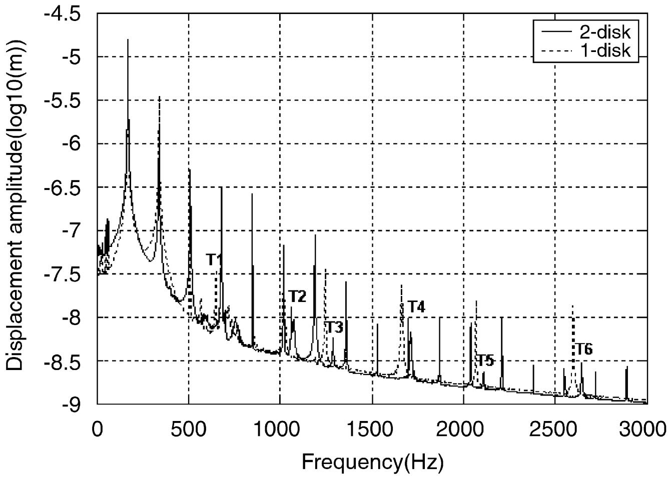

Fig. 10. Comparison of single- and dual-disk axial vibrations measured via LDV at 10,200 rev/min.

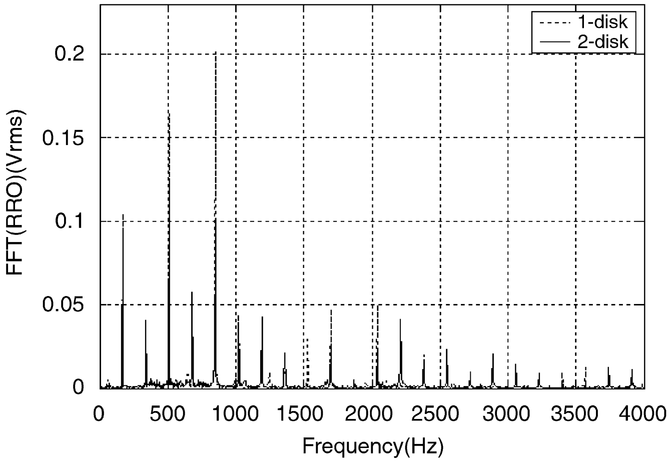

Fig. 11. Comparison of single- and dual-disk RRO power spectrum at 10,200 rev/min (the third and fifth harmonics reduced significantly, 33% improvement of σ value).

of reducing the disk vibrations in spin stand tests particularly where single-disk surface is accessed. In Figs. 2, 6, and 10, we have also observed the frequency shifting of disk vibration modes.

From theoretical point of view, the maximum amplitude of disk vibration is as follows [6]:

$$V_{\text{disk}} \propto \frac{\rho R^4 \omega^2}{t^3 E d}, \tag{1}$$

where R is the disk outer radius, ρ is the gas density, ω is the angular speed, t is the disk thickness, E is the disk substrate Young's modulus, and d is the disk substrate damping. Eq. (1) indicates that the disk vibration is inversely proportional to t^3. Denote x' as the corresponding parameter of x of the dual-disk stack. Thus assuming the change of E is negligible, and considering $t' = 2t$,

$$V'_{\text{2-disk}} \propto \frac{\rho R^4 \omega^2}{8 t^3 E d'} \tag{2}$$

which means that $V'_{\text{2-disk}} < V_{\text{disk}}$ when $d' > \frac{1}{8}d$. The experimental results verified the amplitude reduction of the disk vibration.

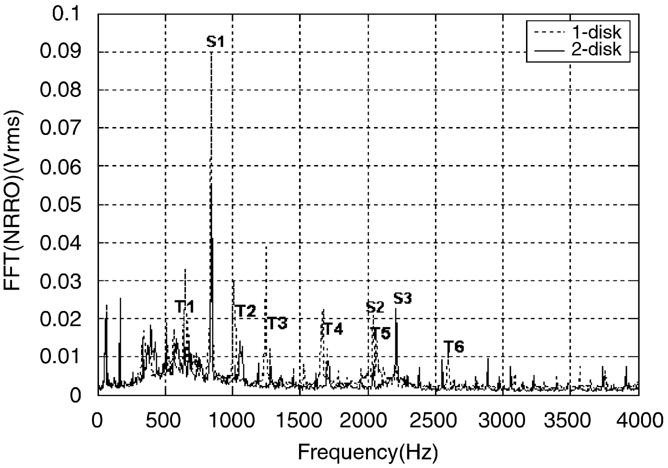

Fig. 12. Comparison of single- and dual-disk NRRO power spectrum at 10,200 rev/min (27% reduction of σ value).

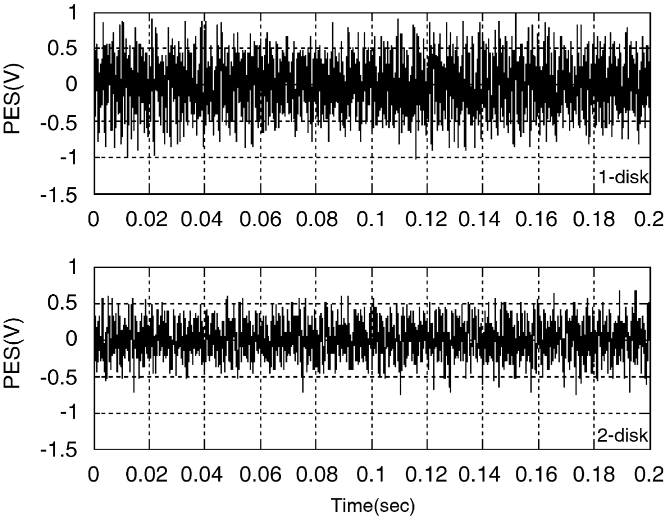

Fig. 13. Comparison of single- and dual-disk PES in time domain at 10,200 rev/min (32% reduction of σ value).

Table 1
Reduction of σ values of PES, RRO and NRRO and disk vibration amplitude with stacked disks compared with single disk

Speed (rev/min)	% reduction of σ values			% reduction of disk vibration amplitude
	RRO	NRRO	PES	
7200	23	18	21	24
8400	41	28	38	45
10,200	33	27	32	35

On the other hand, it is known that the natural frequency of disk vibration mode is defined by [7]

$$f_{mn} = \frac{\lambda_{mn}^2}{2\pi R^2}\left[\frac{Et^3}{12\gamma(1-v^2)}\right]^{1/2}, \tag{3}$$

where f_{mn} is the natural frequency of the (m, n) mode, γ is the mass per unit area of the disk, v is the Poisson's ratio, and λ_{mn} is the dimensionless frequency parameter which is generally a function of the boundary conditions on the plate, the ratio of the inner to outer diameter, and Poisson's ratio. Denote Ω as the rotational speed of the disk, the frequency of the disk vibration mode [7]

$$f = f_{mn} \pm n\Omega. \tag{4}$$

Assuming the change of v is also negligible, and considering $t' = 2t$, $\gamma' = \gamma$,

$$f'_{mn} = 2\sqrt{2}\frac{\lambda'^2_{mn}}{2\pi R^2}\left[\frac{Et^3}{12\gamma(1-v^2)}\right]^{1/2} \tag{5}$$

which implies some shifting of the disk vibration modes as can be seen in the experimental results.

In addition to the doubled thickness, the mechanical properties such as d and λ_{mn} [6,7] are certain to change correspondingly after stacking two disks. Further research for details on how the stacked disks change these properties is significant.

To verify that written disk surface's contacting with another disk surface for stacking the two disks does not damage the tracks written, five sets of multi-frequency servo pattern were written on the stacked disk surface. Fig. 14 shows that the track profile of the previously written servo tracks can still be read back. As such, the proposed process can be used for reducing the disk vibration on both disk surfaces for reading and writing, such as multi-disk servo track writers [3]. In addition, such a disk vibration reduction approach can be used as an alternative or complement technique to the air shroud design [11] and the active control approaches [12,13] to further improve positioning accuracy.

4. Conclusions

This paper reports a marked improvement of the position accuracy due to the vibration reduction by stacking two disks together. We have shown an over 30% reduction of PES 3σ when the 3.5″ stacked-disk rotating speed is above 8400 rev/min. It has been verified that the approach of stacking two disks together can

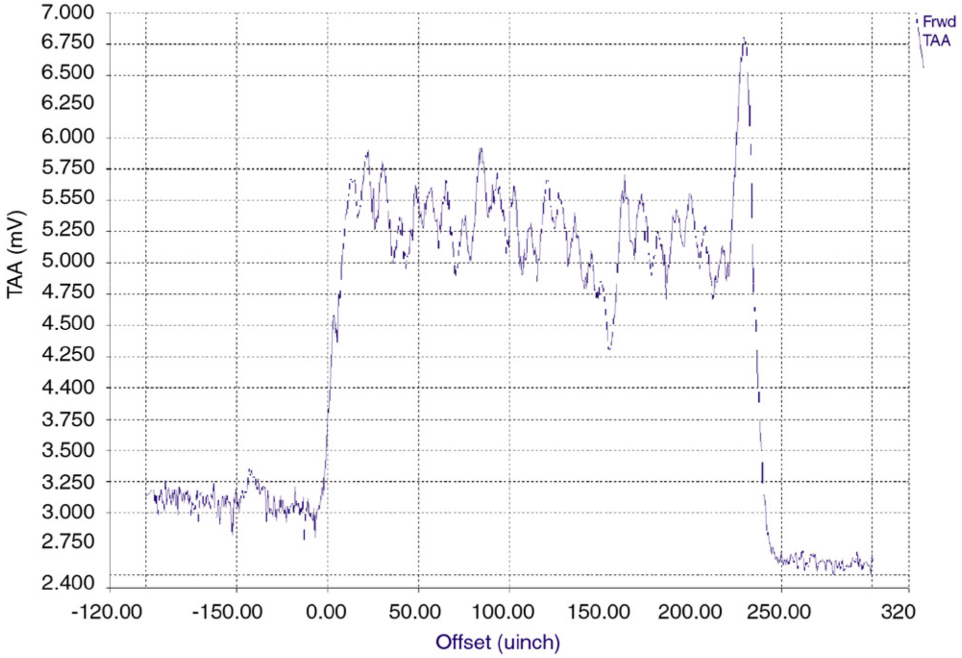

Fig. 14. Readback track profile of the several servo tracks on the spin stand.

be used as a low cost method to achieve high TPI on spin stand, and can also be adopted in media servo track writing for disk vibration reduction and higher positioning accuracy.

References

[1] Guzik Company Website [Online], Spin Stand Products Information, 〈http://www.guzik.com〉.

[2] H. Ye, V. Sng, C. Du, J. Zhang, G. Guo, Radial error propagation issues in self servo track writing technology, *IEEE Transactions on Magnetics* 38 (5) (2002) 2180–2182.

[3] K. Takashi, Y. Uematsu, T. Yamada, M. Kamimura, M. Fukushi, Y. Kuroba, HDD servo technology for media level servo track writing, *IEEE Transactions on Magnetics* 39 (2) (2003) 851–856.

[4] C. Du, J. Zhang, G. Guo, Disturbance modeling and control design for self-servo track writing, *IEEE/ASME Transactions on Mechatronics* 10 (1) (2005) 122–127.

[5] Y.-B. Chang, D.-K. Park, N.-C. Park, Y.-P. Park, Prediction of track misregistration due to disk flutter in hard disk drive, *IEEE Transactions on Magnetics* 38 (2) (2002) 1441–1446.

[6] W.E. West Jr., U. Ummethala, F. Aguirre, Disk vibration induced TMR: thicker is better, IDEMA Insight 1998.

[7] J.S. McAllister, Characterization of disk vibrations on aluminum and alternate substrates, *IEEE Transactions on Magnetics* 33 (1) (1997) 968–973.

[8] J.Y. Shen, C.W. Tseng, I.Y. Shen, Vibration of rotating disk/spindle systems with flexible housing/stator assemblies, *Journal of Sound and Vibration* 271 (3–5) (2004) 725–756.

[9] S. Lim, Finite element analysis of flexural vibrations in hard disk drive spindle systems, *Journal of Sound and Vibration* 233 (4) (2000) 601–616.

[10] B. Heo, I.Y. Shen, Taming disk and spindle rocking by damped laminated disks—an experimental study, *IEEE Transactions on Magnetics* 35 (5) (1999) 2304–2306.

[11] S. Deeyiengyang, K. Ono, Suppression of resonance amplitude of disk vibrations by squeeze air bearing plate, *IEEE Transactions on Magnetics* 37 (2) (2001) 820–825.

[12] G. Guo, J. Zhang, Feedforward control for reducing disk-flutter-induced track misregistration, *IEEE Transactions on Magnetics* 39 (4) (2003) 2103–2108.

[13] G. Guo, J. Zhang, Control strategies for writing servo tracks narrower than 5 micro inches, *Proceedings of the 2003 JSME-IIP/ASME-ISPS Joint Conference on Micromechatronics for Information and Precision Equipment (IIP/ISPS Joint MIPE'03)*, Yokahama, Japan, June 16–18, 2003, pp. 1–5.

[14] L. Feng, W.E. Wong, C.L. Du, C. Duan, G.X. Guo, T.C. Chong, W.C. Ye, Stretching servo performances on a spin stand, *Proceedings of the American Control Conference 2004*, Boston, USA, 30 June–2 July, 2004, pp. 1159–1164.

[15] T. Ishida, K. Miyata, T. Hamada, H. Hashi, B. Yasuaki, K. Taniguchi, A. Saito, Magnetic printing technology-application to HDD, *IEEE Transactions on Magnetics* 39 (2) (2003) 628–632.

[16] W.E. Wong, L. Feng, G. Guo, W. Ye, A. Al-Mamun, Implementation of a servo positioning system on spin stand, *Proceedings of the 29th Annual Conf. of the IEEE Industrial Electronics Society*, IECON, November 2003, pp. 2114–2119.