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TECHNICAL PAPER

A robust adaptive feedforward method for the compensation of harmonic disturbances

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Abstract Most of disk drives suffer from various disturbances that degrade read–write performances. As the track density rapidly increases, basic drive functions may fail even with a small scale disturbance in a normal operating environment. For the reason, an accurate identification of the repeatable runout (RRO) of a hard disk drive has been one of the most important tasks for the successful servo designs in modern hard disk drive integration. Extensive research efforts have been dedicated for the compensation of the runouts and produced many successful strategies to minimize the influences to the critical basic drive functions. Primarily for the simple implementation and the cost reduction in the actual drive development and manufacturing, most of the developed methods being used in the actual drive integration are preferred to be formulated on time domain or frequency domain with very basic limited functions. The primitive frequency domain approaches usually require extensive calculations and large physical memories. In the present work, a RRO compensation method that combines advantages of the transient Fourier coefficients (TFC) and the least mean square (LMS) update is introduced. Combining the two methods in a proper fashion, the present work provides many benefits for the drive design and outperforms the previous compensation methods. The proposed method requires significantly less amount of computational work and physical memories compared to the conventional runout compensation methods. And it also provides effective frequency component selectivity so that the compensation resources are to be concentrated to a specific problem reason. Comprehensive frequency domain formulation of the method followed by a series of experimental test results is provided in the present article.

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1 Introduction

The growing demand of higher data storage density and the increasing necessity of lower manufacturing cost in the hard disk drive industry have shed light on the development of many new schemes for the reduction of position error signal (PES). Aggressive researches have been done and yielded many innovative PES reduction methods since they are directly related to both drive performance and manufacturing cost. Therefore in order to be adopted for a volume production the developed schemes are to be not only functionally effective but also yet more inexpensive.

Although most of disturbance sources causing PES can be well defined and characterized, no single remedy that works for reduction of both repeatable and non-repeatable is available. A well coordinated strategic effort must be made for the successful reduction of the overall PES because of the following reasons. The first, to ascertain the effectiveness of a method for the reduction of PES in the high density drive integration, it is necessary to obtain a firm understanding of how those disturbances are related under varying operating conditions. The second, highly coupled dynamic relation hampers clear identification of dominant runout since it varies as drive platform changes (Akagi et al. 2005).

Since drive servo can fail or its performance can be severely degraded by the repeatable runouts (RRO) causing repeatable PES (RPES), controlling the disturbance effects within a certain limit has been one of the most important issues of the hard disk drive (HDD) servo system design. As a result, extensive research activities have been dedicated for the compensation of the RRO (Jia et al. 2005; Oh et al. 2005; Cao et al. 2000; Sacks et al. 1995; Zhang et al. 2000; Kawafuku et al. 2004; Sidman 1991; Shepherd et al. 2000; Shu 2000). Most of previous popular methods for the compensation are formulated and implemented in time domain approach. Although the time domain approach may benefit from its modest mathematical formulation procedure, it apparently loses efficiency due to a lengthy averaging process carried over the time which could be a direct burden on the drive manufacturing cost. In addition, it might be more vulnerable to errors in identification of plant or control systems. Recently, many drive platforms have been adopting frequency domain RRO compensation methods nevertheless most of them are still formulated with a primitive FFT technique that still consumes extensive amount of computational resources and physical memories (Oh et al. 2005).

In the present work, an efficient RPES compensation method formulated with a combination of the transient Fourier coefficients (TFC) and the least mean square (LMS) methods is presented. Having the TFC approach reinforced by the LMS, this work differs from the previous publication that adopts a basic FFT analysis (Oh et al. 2005).

Servo tracks of a hard disk drive are supposed to be concentric perfect circles. In reality, however, they are normally rather crooked in actual drives since various mechanical defects of the drive components are written in to servo tracks during servo pattern writing processes. The written-in irregularity so called written-in RRO causes RPESs that should be attenuated for the successful read–write functions. There could be two antithetical concepts for the runout compensatory action. It is either diligently ''following'' the irregularities of the circular paths or deliberately ''ignoring'' them (Akagi et al. 2005; Shepherd et al. 2000; Shu 2000). The proposed method starts from the concept of the latter approach that commands the drive servo to purposely ignore some irregularities of a data track. It consists of the following two steps. The first, PES is collected at each revolution. Then on each revolution the RRO is to be reconstructed by the TFC method. In the next step, the determined Fourier coefficients are to be updated with the proposed LMS method for refining the RRO. In the present article, the reconstructed RRO information is referred to ''pre-characterized''. Equipped with the ''pre-characterized'' wave form information, the controller is allowed to ignore the irregularities of the actual written servo tracks. As a result, read–write action could be done with respect to the RRO compensated tracks so that the control effort and PES could be minimized. For the write mode, the performance is usually much better than for the read mode. The RRO compensation concept is depicted in Fig. 1.

Even without the second step of refining the RRO information, the proposed method provides superior performances to the conventional time domain approaches. In essence, the proposed method significantly improves RRO identification performance, uses less physical memory, and reduces computational efforts compared to the previous methods thanks to the combination of advantages of the two methods.

This paper is organized as follows. Identification of the repeatable runout is provided in Sect. 2. Fourier wave form of the repeatable runout is synthesized by the TFC method and an update rule formulated with LMS is introduced in Sect. 3. Drive level experiments are performed to demonstrate the effectiveness of the proposed method. Comparative studies between the proposed and the conventional work are also given in Sect. 4.

2 Repeatable runout identification

2.1 Characterization of repeatable runout

Generic concept of the RRO compensation referred to cancellation of the harmonic components of distur-

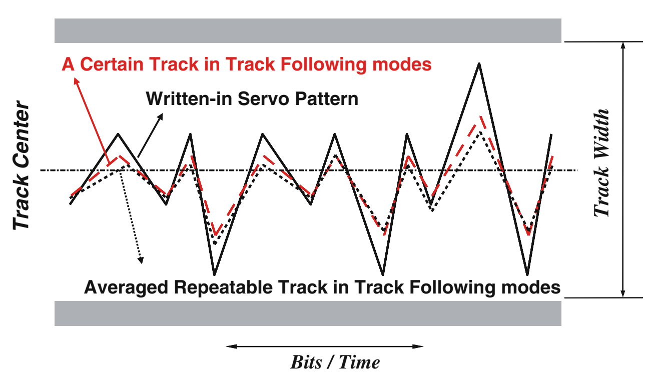


Fig. 1 Runout compensation

bances is well covered by many publications and patents (Oh et al. 2005; Cao et al. 2000; Sacks et al. 1995; Zhang et al. 2000; Kawafuku et al. 2004). Maintaining high quality compensatory action, precise identification and characterization of the periodic disturbances are of importance.

Identification of the RRO could not be directly achieved from the measured PES. In order to obtain refined RRO information from the measured PES, the signal is collected and averaged on each sector of a track while disk spins. There might be many different averaging schemes available for this step such as weighted or simple linear average. By completion of the step, the non-repeatable information might be averaged-out and the remaining information should asymptotically converge to the repeatable portion provided that a sufficient number of averages are taken. Finally for constructing the "usable" runout information, the averaged PES should be multiplied with the inverse of the error sensitivity function that is a function of plant $\boldsymbol{P}$ and controller $\boldsymbol{C}$ as shown in Fig. 2.

Apparently, the more number of averages provides the better quality of the RRO identification. In other words, a usable RRO pattern can be acquired by a series of averaging of PES measured on each track. It is however obviously an immediate burden on drive manufacturing time and cost.

Adding the "pre-characterized" RRO ($\hat{d}_{\mathrm{rro}}$) to the actual instantaneous PES (e), the controller is forced to ignore a certain portion of RRO so that the overall amount of calculation effort could be reduced. The "pre-characterized" RRO is constructed by isolating Non-repeatable runout (NRRO) contribution from total disturbances and the information is recorded at some tracks on which RPES exceeds the design specification. When the servo system needs to follow a track especially for the write mode, the stored "pre-characterized" RRO information of the track is firstly sought and referenced for the RRO compensation.

In order to generate the "pre-characterized" RRO, most of the current methods take simple arithmetic averages of the disturbances over the time as disk spins. Although the simple time domain averaging might guarantee efficacy of RRO compensation and simplicity of formulation, the efficiency of the method in terms of reduction of manufacturing cost is not well established.

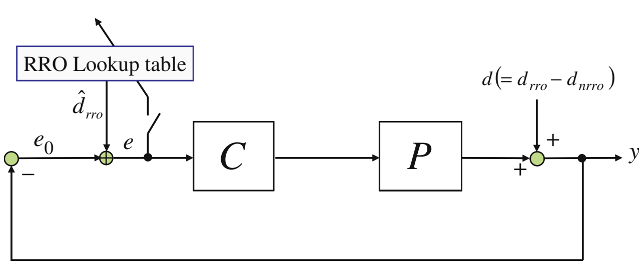


Fig. 2 HDD servo loop with RRO compensation

2.2 Fourier wave form synthesis

Having formulated on frequency domain with Fourier coefficients, the proposed method provides the following advantages. First, frequency selection for RRO compensation is possible so that a specific frequency component could be chosen and suppressed independently. Second, computational cost is relatively inexpensive in the actual drive integration since the method carries only the final summation of the errors for constructing the coefficients whereas other methods using similar approach have to memorize entire history of the update.

The first step of the proposed work begins with the Fourier representation of RPES. Discrete format of the RPES, can be expressed in

$$e_r(nT_\mathrm{s}) = \lim_{N_\mathrm{rev}\to\infty} e_r(nT_\mathrm{s}, N_\mathrm{rev}) \tag{1a}$$

and

$$e_r(nT_s, N_\mathrm{rev}) = \frac{1}{N_\mathrm{rev}} \sum_{p=0}^{N_\mathrm{rev}-1} e(nT_s + pN_\mathrm{sector}T_s), \tag{1b}$$

where N_rev and N_sector are number of disk revolutions and number of sectors, respectively. And the RPES is also given by

$$e_r(nT_\mathrm{s}) = \sum_{k=1}^{\infty} [w_s(k)\sin(\omega_k nT_\mathrm{s}) + w_c(k)\cos(\omega_k nT_\mathrm{s})] \tag{2}$$

where $w_s\ (k)$ and $w_c\ (k)$ are Fourier coefficients of RPES at kth harmonic frequency ω_k, T_s sampling time, $n =$ 1, 2, 3, ... refers to discrete sample times. Hence the "pre-characterized" discrete RRO, $\hat{d}_\mathrm{rro}(nT_\mathrm{s})$ can be expressed in the form of

$$\hat{d}_\mathrm{rro}(nT_\mathrm{s}) = \sum_{k=a}^{a+b} [v_s(k)\sin(\omega_k nT_\mathrm{s}) + v_c(k)\cos(\omega_k nT_\mathrm{s})], \tag{3}$$

where $\hat{d}_\mathrm{rro}(nT_\mathrm{s})$ is summation of the RRO from 'a' times of the rotation frequency ω_a to 'b' times of the rotation frequency ω_b. By adding the limit 'a' and 'b' at this step, it enables frequency selection and makes the RRO identification more efficient. As a result,

$$\begin{Bmatrix} v_c(k) \\ v_s(k) \end{Bmatrix} = \frac{1}{S_\mathrm{r}^2(k)+S_\mathrm{i}^2(k)} \begin{bmatrix} S_\mathrm{r}(k) & -S_\mathrm{i}(k) \\ -S_\mathrm{i}(k) & -S_\mathrm{r}(k) \end{bmatrix} \begin{Bmatrix} w_c(k) \\ w_s(k) \end{Bmatrix}, \tag{4}$$

where S is error sensitivity function of the system shown in Fig. 1, $S_\mathrm{r}(k)$ and $S_\mathrm{i}(k)$ are real and imaginary part of the error sensitivity function at the kth harmonic frequency, respectively.

The Fourier coefficients of the ‘‘pre-characterized’’ RRO at kth harmonic frequency, $v_s(k)$ and $v_c(k)$ can be determined by the Fourier coefficients of RPES at kth harmonic frequency, $w_s(k)$ and $w_c(k)$. In other words, the ‘‘pre-characterized’’ RRO can be reconstructed through the identification of $w_s(k)$ and $w_c(k)$. Note that the determined Fourier coefficients $v_s(k)$ and $v_c(k)$ may contain NRRO contributions if they are calculated using disturbances acquired over the insufficient number of revolutions.

3 Determination of the Fourier coefficients

3.1 Transient Fourier coefficients

The Fourier coefficients $w_s(k)$ and $w_c(k)$ should be identified accurately to guarantee successful function of the ‘‘pre-characterized’’ RRO. From the definition of Fourier transformation,

$$E(l) = \frac{1}{N}\sum_{n=0}^{N-1} e_r(n)\mathrm{e}^{-j2\pi\frac{l}{N}n} = E_\mathrm{real}(l) + jE_\mathrm{imag}(l). \tag{5}$$

The Fourier coefficients at a frequency $l = \omega_k N T_\mathrm{s}/2\pi$ can be determined as follows;

$$\begin{aligned} E(l)|_{l=\omega_k N T_\mathrm{s}/2\pi} &= \frac{1}{N}\left(\sum_{n=0}^{N-1} e_r(n)\cos(\omega_k n T_\mathrm{s}) - j\sum_{n=0}^{N-1} e_r(n)\sin(\omega_k n T_\mathrm{s})\right) \\ &= \frac{1}{2}(w_c(k) - jw_s(k)) \end{aligned} \tag{6}$$

where $e(n)$ and $E(l)$ represent time domain and frequency domain components of RPES, respectively. The sample length N is greater than the sample length of one revolution. Thus the real component, E_real (l), and the imaginary component, E_imag (l) can be Fourier coefficients $w_c(k)/2$ and $-w_s(k)/2$ by means of $l = \omega_k N T_\mathrm{s}/2\pi$. At a certain time t = N_p T_s, the ‘‘TFCs’’ are to be determined by using the frequency analysis with the correlation method. It is given by,

$$u_s(k, N_\mathrm{rev}, N_p) \equiv \frac{2}{N_p}\sum_{n=0}^{N_p-1} e_r(n, N_\mathrm{rev})\sin(\omega_k n T_\mathrm{s}), \tag{7}$$

$$u_c(k, N_\mathrm{rev}, N_p) \equiv \frac{2}{N_p}\sum_{n=0}^{N_p-1} e_r(n, N_\mathrm{rev})\cos(\omega_k n T_\mathrm{s}). \tag{8}$$

Note that the Eqs. 7 and 8 are merely a simple summation of the RPES data. Therefor it uses significantly less amount of physical memory compared to the previous methods (Oh et al. 2005; Ljung 1999).

If the RRO is expressed by

$$d_\mathrm{rro}(t) = D\cos(\omega_k t), \tag{9}$$

then the RPES can be represented by

$$e_r(n, N_\mathrm{rev}) = D\left|S(\mathrm{e}^{j\omega_k})\right|\cos(\omega_k n T_\mathrm{s} + \varphi) + \varepsilon(n T_\mathrm{s}), \tag{10}$$

where $\varphi = \arg\left(S(\mathrm{e}^{j\omega_k})\right)$ and ε $(nT_\mathrm{s}$ $)$ stand for an error caused by either the noise or the various uncertainties. Then, the TFC u_c $(k$, N_rev, $N_p)$ can be expressed by

$$\begin{aligned} &u_c(k, N_\mathrm{rev}, N_p) \\ &= \frac{2}{N_p}\sum_{n=0}^{N_p-1} D\left|S(\mathrm{e}^{j\omega_k})\right|\cos(\omega_k n T_\mathrm{s} + \varphi)\cos(\omega_k n T_\mathrm{s}) \\ &\quad + \frac{2}{N_p}\sum_{n=0}^{N_p-1}\varepsilon(nT_\mathrm{s})\cos(\omega_k n T_\mathrm{s}) \\ &= D\left|S(\mathrm{e}^{j\omega_k})\right|\cos(\varphi) + D\left|S(\mathrm{e}^{j\omega_k})\right|\frac{1}{N_p}\sum_{n=0}^{N_p-1}\cos(2\omega_k n T_\mathrm{s} + \varphi) \\ &\quad + \frac{2}{N_p}\sum_{n=0}^{N_p-1}\varepsilon(nT_\mathrm{s})\cos(\omega_k n T_\mathrm{s}), \end{aligned} \tag{11}$$

Note that the second term of Eq. 11 converges to zero at 1/2 period of ω_k whereas N_p diverges to infinity, and so does the third term by one period of ω_k if ε $(nT_\mathrm{s}$ $)$ does not contain a pure periodic component of frequency ω_k. Similarly,

$$\begin{aligned} &u_s(k, N_\mathrm{rev}, N_p) \\ &= D\left|S(\mathrm{e}^{j\omega_k})\right|\sin(\varphi) + D\left|S(\mathrm{e}^{j\omega_k})\right|\frac{1}{N_p}\sum_{n=0}^{N_p-1}\sin(2\omega_k n T_\mathrm{s} + \varphi) \\ &\quad + \frac{2}{N_p}\sum_{n=0}^{N_p-1}\varepsilon(nT_\mathrm{s})\sin(\omega_k n T_\mathrm{s}). \end{aligned} \tag{12}$$

Therefore the Eqs. 11 and 12 imply that the Fourier coefficients could be directly determined at the end of the first period of ω_k which is $N_p = 2\pi/(\omega_k T_s)$. Note that this provides substantial benefits over the previously published methods in terms of reducing drive process time since it does not requires a lengthy data collecting procedure for determination of the Fourier coefficients. And it is the principal contribution of the present work. In other words, reconstructing the RRO information could be done with one disk revolution data set. The TFCs determined with small number of revolutions may still include NRRO contributions that could be eliminated by adding an update process which is described in next section.

3.2 Fourier coefficient updates with LMS algorithm

Once the Fourier coefficients are initially determined using Eqs. 11 and 12, the proposed method refines them using the following LMS algorithm.

$$w_s(k)_{m+1} = w_s(k)_m + \eta \frac{1}{N_p} \sum_{n=0}^{N_p-1} \frac{\partial e_r^2(n, N_{\mathrm{rev}})}{\partial w_s(k)}, \tag{13}$$

$$w_c(k)_{m+1} = w_c(k)_m + \eta \frac{1}{N_p} \sum_{n=0}^{N_p-1} \frac{\partial e_r^2(n, N_{\mathrm{rev}})}{\partial w_c(k)}. \tag{14}$$

where subscript m is the number of update steps and η is a update constant, respectively. Hence the update rule used for the Fourier coefficients of Eq. 2 is given by

$$w_s(k)_{m+1} = w_s(k)_m + 2\eta \frac{1}{N_p} \sum_{n=0}^{N_p-1} e_r(n, N_{\mathrm{rev}}) \sin(\omega_k n T_s), \tag{15}$$

$$w_s(k)_{m+1} = w_s(k)_m + 2\eta \frac{1}{N_p} \sum_{n=1}^{N_p} e_r(n, N_{\mathrm{rev}}) \sin(\omega_k n T_s), \tag{16}$$

Then the update equations can be expressed in term of the TFCs.

$$w_s(k)_{m+1} = w_s(k)_m + \eta u_s(k, N_{\mathrm{rev}}, N_p), \tag{17}$$

$$w_c(k)_{m+1} = w_c(k)_m + \eta u_c(k, N_{\mathrm{rev}}, N_p), \tag{18}$$

and these update equations are convergent (Snyder and Hansen 1990) when

$$0 < \eta < 1/\lambda_{\max}, \tag{19}$$

where $\lambda_{\max}$ is the biggest eigenvalue of the following autocorrelation matrix and it is independent of frequency.

$$\lambda_{\max} = \max\left(\lambda\left(E\begin{bmatrix} \sin^2(\omega_k n T_s) & \sin(\omega_k n T_s)\cos(\omega_k n T_s) \\ \cos(\omega_k n T_s)\sin(\omega_k n T_s) & \cos^2(\omega_k n T_s) \end{bmatrix}\right)\right). \tag{20}$$

Besides the convergence characteristics could be expressed as (Snyder and Hansen 1990),

$$0 < \eta < 1/2, \text{over-damped}; \tag{21}$$

$$\eta = 1/2, \text{critically damped}; \tag{22}$$

$$1/2 < \eta < 1, \text{under-damped}. \tag{23}$$

Consequently, a value of η equals to $1/2\lambda_{\max}$ (=1/2) will generally yield the fastest overall convergence rate.

In the present work, the Fourier coefficients are initially determined by the TFC method and they are updated using the LMS algorithm. Associating the two methods provides fast determination of the coefficients and also guarantees fast convergence to the repeatable components. In essence, the proposed method is proven that it requires significantly less number of revolutions to characterize the RRO compared to the conventional approaches. And this effectiveness elects the key contribution of the present work. In the following section, a series of the experimental verification is to be provided.

4 Experimental verifications

Two sets of verification tests are given in this section. The first, using a 3.5 in. 7,200 rpm drive, the controlled PES values by the proposed and the conventional time domain method are compared. For a successful demonstration of superiority of the present work, three different RRO compensation methods are tested. The first, RPES is compensated by the conventional time domain approach. The second, it is compensated by only the TFC method that might shows improved efficacy compared to the first case. The last, the RPES is compensated by the combination of the TFC and the LMS method which shows the best results. Next, for the verification of the consistency of the proposed method, the sample size is expanded to five drives and the same tests are repeated.

For the first case, the Fig. 3 shows RPES of a drive at an outer disk (OD) track without any adaptive RRO

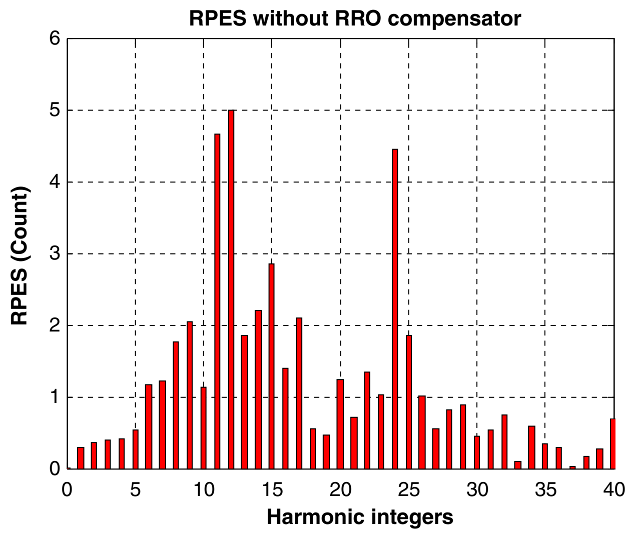


Fig. 3 RPES on an OD track without RRO compensation (8.4 *counts*)

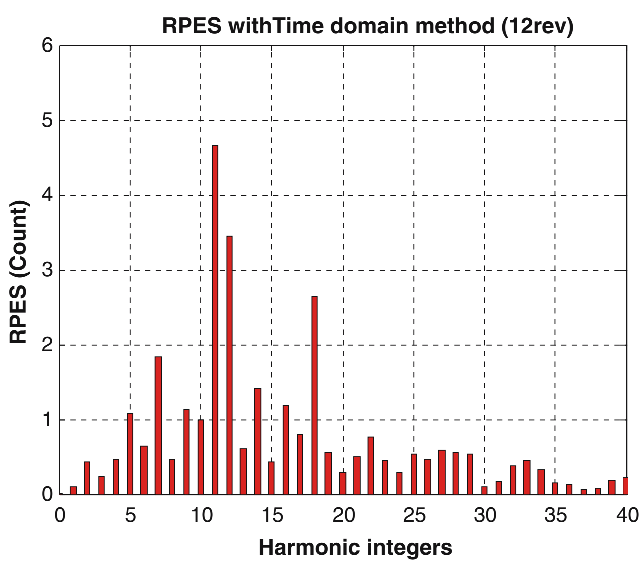


Fig. 4 RPES on an OD track with time domain RRO compensation method (12 revolutions, 5.5 *counts*)

compensatory action. In the figure the overall PES level is about 8.4 *counts*. The term "*count*" a PES unit used in the present paper represents 1/512 of a track width. An improved RPES profile with the conventional time domain RRO compensation method is presented in Fig. 4. In this method, the pre-characterized RRO is constructed in time domain with sector by sector averages during 12 disk revolutions. Some of the frequency peaks such as 11× still maintain significant energy level. However the overall PES level has reduced down to 5.5 *counts*.

In the next example shown in Fig. 5 that represents the second case, RRO compensation for the frequency components from 5× to 50× using the data collected only for two disk revolutions by the TFC is provided. The compensated RPES is 6.7 *counts*. Similarly Fig. 6 illustrates that the RPES compensated by the TFCs using data collected for three disk revolutions is reduced to 5.5 *counts*. Applying the advantages of the TFC method to the RRO compensations as shown in the previous tests, it is much more effective than the conventional time domain method.

On the other hand, although the TFC method provides a superior performance as shown in the previous tests, it apparently requires more number of revolutions for data collections in order to improve the identified RRO pattern accuracy. The more number of disk revolutions of course guarantees the higher accuracy in the RRO compensation. It is however directly affecting manufacturing cost of the drives. Acquiring the improved accuracy of the TFC method, the data collection period was expanded to five revolutions and the result of the RRO compensation with the five revolutions is provided in Fig. 7. Note that no significant RPES improvement is monitored compared to result shown in Fig. 6 that uses only three disk revolutions. This is because the convergence rate of the Fourier coefficient is saturated.

Recognizing the limitations of the TFC method, combination of the method with the LMS update rule provides a better convergence of the Fourier coefficients. In other words, the TFC method works for the

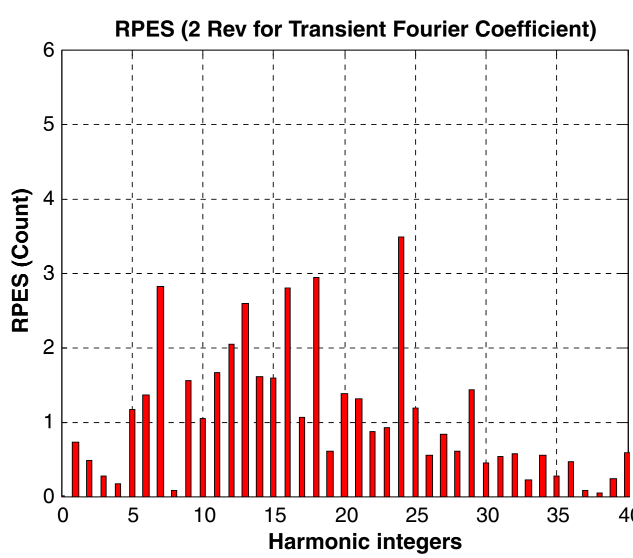


Fig. 5 RPES on an OD track with the proposed RRO compensation method (two revolutions for transient Fourier coefficients only, 6.7 *counts*)

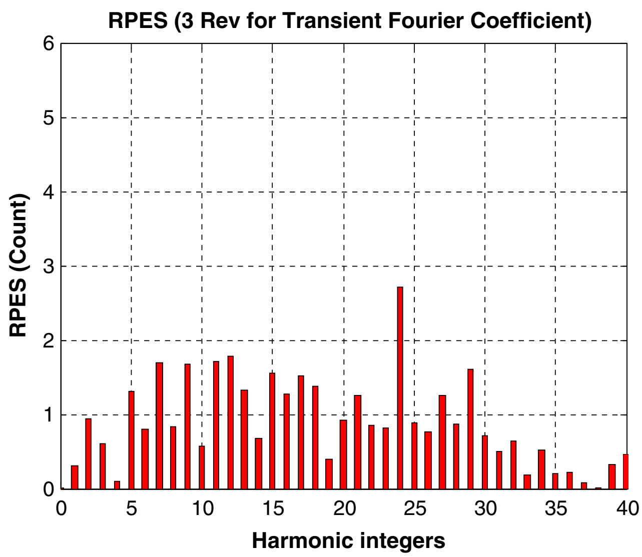


Fig. 6 RPES on an OD track with the proposed RRO compensation method (three revolutions for transient Fourier coefficients only, 5.5 *counts*)

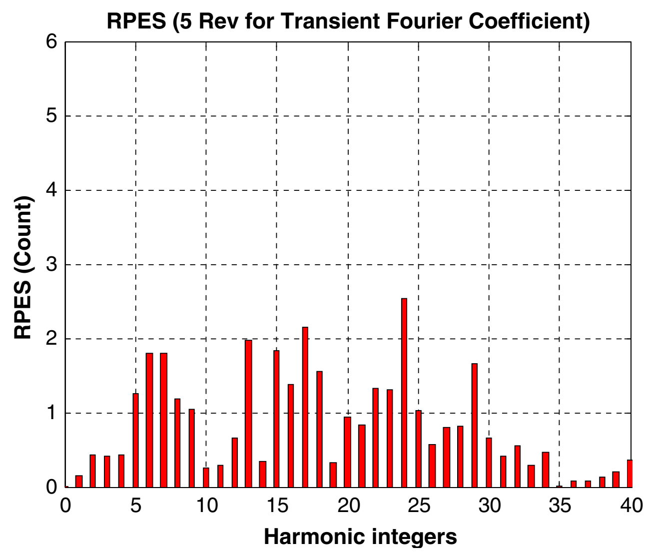


Fig. 7 RPES on an OD track with the proposed RRO compensation method (five revolutions for transient Fourier coefficients only, 5.4 *counts*)

determination of the initial values of the coefficients and the LMS update refines the initial values for yielding accurate coefficients. This situation constructs the third case.

In Fig. 8, the RPES compensated by the combination of the TFC and the LMS updates is presented. In the example, five disk revolutions (three revolutions for the TFC method and another two revolutions for the LMS update method) are used to construct the pre-characterized RRO. The RPES level is decreased to 4.8 *counts* and most of the frequency peaks are successfully suppressed. Comparing the test case shown in Fig. 7, the improvements are significant. For the demonstration of the superior RPES compensatory performance of the present work, a test case result that comes out with only four disk revolutions is presented in Fig. 9. Although only four revolutions are used for the construction of the Fourier coefficient, two revolutions for the TFC method and another two for the LMS, the RPES level is only 4.9 *counts* and no dominant frequency peak is monitored. As a result, data collections during at most two disk revolutions for the TFC method might be sufficient to determine the initial conditions and another two revolutions used for the proposed LMS update improves the accuracy.

In Fig. 10, the sample size has been expanded to five drives for the consistency verification of the proposed method. Basically the same test sequence used for Figs. 3, 4, 5, 6, 7, 8, and 9 are duplicated for the five drives. The x-axis of the figure represents RRO compensation methods at various disk revolutions and the y-axis shows corresponding repeatable PES levels of the five drives. The first column of the figure shows PES levels of the five drives without any RRO compensation applied. The RPES levels of all the five drives are above 8 *counts*. The second column shows the RPES level when the simple time average method using data collected for 12 disk revolution is applied. The RPES levels of the case are about 6 *counts*.

The third column represents the RPES when the TFC method is used instead of the time averaging.

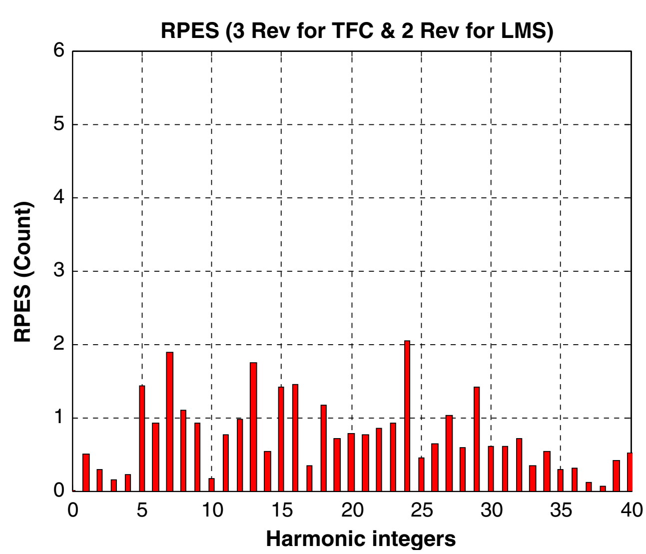


Fig. 8 RPES on an OD track with the proposed RRO compensation method (three revolutions for transient Fourier coefficients and two revolutions for LMS adaptation, 4.8 *counts*)

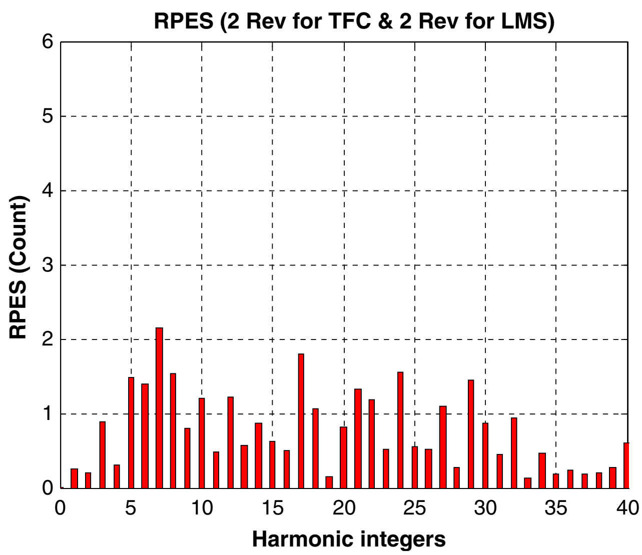


Fig. 9 RPES on an OD track with the proposed RRO compensation method (two revolutions for transient Fourier coefficients and two revolutions for LMS adaptation, 4.9 *counts*)

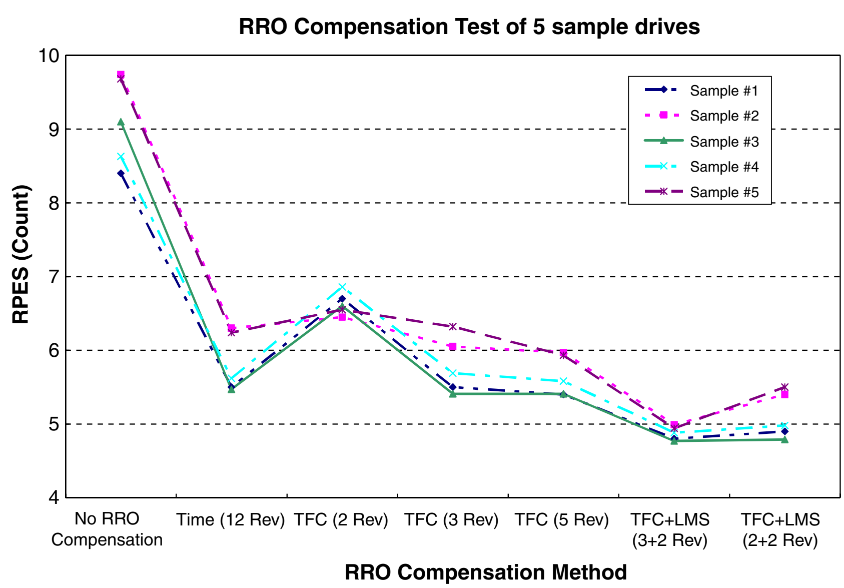
Even though the coefficients are determined by the data collected for only two disk revolutions, the RPES level has been reduced below 7 *counts*. As expected, increasing the number of disk revolution for the data collection, the RPES levels of all five drives decrease as shown in next columns. With the five disk revolutions for the TFC determination, the RPES levels come down to 5.5 *counts*.

The sixth column noted as "TFC + LMS" shows the RPES levels of those drives when both the TFC and the LMS are adopted. Comparing to the case of TFC with five disk revolutions presented in the fifth column, the combination of the TFC and the LMS shows better RPES reduction performance despite the same number of disk revolutions used for the data collection. The RPES levels of all sample drives are controlled under 5 *counts* which is almost a half of the PES of non-controlled situation. In the last column, although four disk revolutions (one revolution less than the previous case) are used for the combination of the TFC and the LMS, the error correction performances are not aggravated. The RPES correction performance of the proposed method that uses only four disk revolutions for the data collection shows superior performance compared to the simple time average scheme which consumes 12 disk revolutions.

5 Conclusion

In the present work, a combination of the TFC method to the LMS update algorithm provides a superior repeatable runout compensatory performance at minimum cost. Having the TFC method for the determination of initial values, it benefits not only to improve the drive manufacturing process time but also to reduce the amount of physical memories allocated for the identification of RRO. Meanwhile the LMS update method works for refining the RRO information and also notably enhances the convergence speed of the proposed method. In essence, the proposed method guarantees the accurate RPES compensation with moderate cost.

Fig. 10 RRO compensation performance test with five sample drives (*x-axis* RRO compensation method, *y-axis* RPES level)



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