Disturbance Rejection Control Scheme for Optical Disk Drive Systems

J. Leyva-Ramos, M. G. Ortiz-Lopez, and L. H. Diaz-Saldierna

Instituto Potosino de Investigación Cientifica y Tecnologica, San Luis Potosí, S.L.P. 78216, Mexico

A disturbance rejection control scheme is developed for optical disk drive (ODD) systems. Disturbances acting on these servo systems inherently contain significant periodic components that cause tracking errors of a periodic nature. Such disturbances can be effectively rejected by employing a modified repetitive compensator. The proposed control scheme overcomes the drawback of typical internal-model-based repetitive control schemes, which cancel repeatable disturbances but amplify disturbances at other frequencies. A sufficient stability criterion is developed when the proposed control scheme is used in a closed-loop system. Some practical guidelines are also given for tuning the control scheme. A comparison of the control scheme with and without the modified repetitive compensator shows significant improvement of the tracking performance of the proposed scheme.

Index Terms—**Internal model principle, optical disk drive (ODD) system, periodic disturbances, repetitive control.**

I. Introduction

REPETITIVE control arises as a practical solution for tracking or disturbance rejection of periodic signals and is based on the well-known internal mode principle [1]. This principle states that the controller output can track a class of reference commands without a steady error if the generator, or the model, for the reference is included in the stable closed-loop system. The development of repetitive control was motivated by a design of a magnetic power supply for a proton synchrotron; however, first theoretical work describing the stability of repetitive control for linear systems can be found in [2] and for nonlinear systems in [3].

Since then a great number of applications and new developments can be found in different areas such as mechanics, robotics, and electronics. An optical pickup actuator must have a high bandwidth servo to follow the disk fluctuations [4], [5]. Ingenious approaches have been proposed in order to change their structural dynamics to reduce vibrations; see [6]–[8] and the numerous references within. The optical disk drive system, e.g., CD or DVD player, has various disturbances such as the disk surface vibration, eccentric vibration, radial vibration, and resonance caused by the actuator itself. These disturbances contain significant periodic components appearing at a known fundamental frequency corresponding to the disk rotational velocity and higher harmonics. Because periodic disturbances have a crucial effect on tracking control performance, it is imperative to attenuate them effectively in order to achieve the required tracking accuracy. Disturbance observers have been used for rejecting disturbances as well as improving the tracking performance [9]–[11]. Numerous control strategies have been proposed to design a controller for the track-following system of an optical disk drive. Tools from robust control, sliding mode control, linear quadratic Gaussian (LQG) control, H_∞-control and estimation theory using a discrete Fourier transform have been effectively used to diminish the influence of sinusoidal disturbances even in the presence of uncertainties of the actuator [12]–[16].

Repetitive control is especially useful for read-out of information in an optical disk drive (ODD) system where the laser beam spot should be positioned precisely on the track within a specified tracking error bound in the presence of external disturbances. A conventional repetitive compensator and a controller designed using robust control tools have been proposed for optical disk drives [17]. The above is used to overcome the uncertainties of the plant as well as the periodic disturbances that appear in these systems.

In repetitive control, a simple delay line in a proper feedback array can be used to reproduce an infinite number of poles on the imaginary-axis leading to a system dynamics of infinite dimension [18]. The delay line can be reproduced in analog or digital form. Typically, the delay line is added in the forward pathway producing phase changes of 360°. When the delay is added in the feedback pathway, the phase changes between 90° and −90°; therefore, it is much better for controller design. Furthermore, when a feedforward pathway is included into the above scheme [19], a set of infinite resonant filters, given at the corresponding harmonics, is reproduced plus a set infinite notch filters. A compensator given by a bank of resonant filters is required in repetitive schemes. In this paper, such a compensator is used to reject disturbances that appear in optical disk drive systems.

In this paper, a modified repetitive compensator is proposed for the track-following servo system of an optical disk drive. A conventional repetitive compensator cancels out repeatable disturbances but amplify disturbances at other frequencies. The modified repetitive compensator will introduce notch filters between the resonant peaks, the above will allow the possibility of having higher gains in the controller which results in better disturbances rejection characteristics. One important issue that may affect the stability, when using repetitive compensators, is the phase change. The conventional repetitive compensator provides changes in phase between 180° to −180°, whereas the modified repetitive compensator provides phase changes from 90° to −90°; therefore, a robust controller is easier to design. The flexibility of the proposed design technique is seen by simulation.

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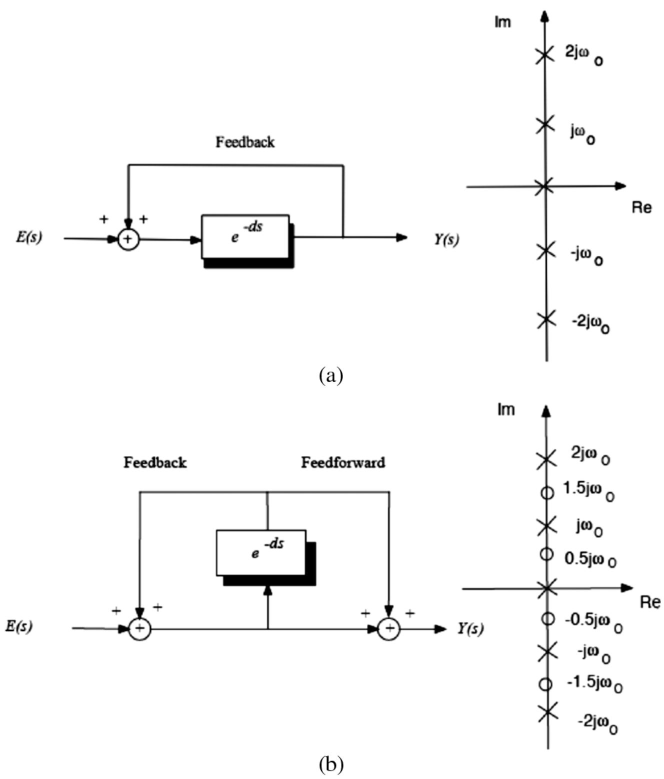

Fig. 1. Continuous-time models and pole-zero locations for the repetitive compensators: (a) conventional, and (b) with feedforward modification.

The notation in this paper is as follows. L^{-1} means the inverse Laplace transform. A function $g(t)$ is called an L_2 denoted by $g(t) \in L_2$ if $\int_0^\infty g(t)^2 dt < \infty$. A rational function or matrix is said to be stable if it is analytic in the closed right-half complex plane. The set of all proper and real rational stable transfer matrices $p \times m$ are denoted by $RH^{m \times n}$. The infinity norm of $G(s) \in RH_\infty$ is defined by $\|G\|_\infty \triangleq \sup_\omega \overline{\sigma}[G(j\omega)]$, where $\overline{\sigma}(\cdot)$ denotes the larger singular value of the matrix.

The remainder of this paper is organized as follows. Section II gives a brief description on the characteristics of the modified repetitive compensator. In Section III, the stability conditions are given when the repetitive scheme is implemented in a closed-loop system. In Section IV, the implementation of the modified repetitive compensator in an optical disk drive system is given. Section V concludes the paper.

II. Modified Repetitive Compensator

In the traditional way, repetitive schemes consist of a single delay in the forward (conventional) or feedback pathways. A modification for the above schemes consists in the addition of a feedforward pathway using the existent delay. The above modification will introduce zeros between the pair of poles, therefore, improving the selective nature of the conventional repetitive scheme. The continuous-time models of the conventional and modified repetitive compensators, including the pole-zero location, are shown in Fig. 1.

The transfer function for the repetitive compensator with feedback-feedforward scheme is given by

$$R(s;d) = \frac{1 + e^{-ds}}{1 - e^{-ds}} \tag{1}$$

where $Y(s)$ is the output, $E(s)$ is the input, and d is a positive real number representing the time delay.

For the transfer function $R(s;d)$, the poles can be found from the expression $e^{-ds} = 1$. Notice that the complex function $e^{-ds}|_{s=j\omega} = 1$ for $d\omega_0 = 2\pi k$ where $k = \{0, \pm 1, \pm 2, \ldots, \pm\infty\}$. Thus, the repetitive compensator with feedforward contains all harmonics of the fundamental. Therefore, the fundamental frequency of repetitive compensator is $\omega_0 = 2\pi/d$, the delay of repetitive scheme can be computed as $d = 1/f_0$ where $\omega_0 = 2\pi f_0$. Notice that by nature of transfer function (1), the zeros lie exactly in the middle frequency points between two consecutive poles.

It is clear that, the above compensator generates an infinite set of peaks centered at the harmonic frequencies. Moreover, thanks to the presence of the zeros, notch filters appear between two consecutive poles. Since the resulting expression contains poles and zeros, the set of peaks and notches are in the theory of infinite gain ($+\infty$ dB at the resonant frequencies and $-\infty$ dB at the notches). The repetitive compensator given by (1) can also be rewritten as an infinite sum of resonant filters as follows [19]:

$$R(s;d) = \frac{2}{d}\left\{\frac{1}{s} + \sum_{k=1}^{\infty}\left(\frac{2s}{s^2 + (k\omega_0)^2}\right)\right\}. \tag{2}$$

The above expression is easily derived using hyperbolic functions. This expression shows that this scheme reproduces exactly a set of infinite resonant filters at the harmonic frequencies plus a pole at the origin; therefore, it is the appropriate scheme to be used for harmonic compensation.

The corresponding Bode plots for the conventional and modified repetitive compensators are shown in Fig. 2. It is clear that the conventional repetitive compensator has valleys between the resonant peaks with magnitude of approximately -6 dB. On the other hand, the modified repetitive compensator exhibits notch filters, which would allow a better selectivity and the possibility of providing higher gains at the resonant frequencies.

The repetitive compensator above mentioned is not ready to be used in real application yet. There is a need to add damping to all the poles/zeros by slightly shifting them to the left of the imaginary axis. As a consequence of this simple pole/zero shifting process, the peaks amplitude becomes bounded. This shifting process is realized as follows: $\tilde{R}(s) = R(s + a; d)$ for $a > 0$. Notice that this is equivalent to multiply the exponential function by a gain factor $K = e^{-da}$. Henceforth, for a gain $0 < K < 1$ the poles/zeros move to the left. Moreover, it is easy to show that the gains of the resonant peaks at the resonant frequencies, originally of infinite magnitude, reach now a maximum magnitude of $(1+K)/(1-K)$ while at the notch filters reach a minimum magnitude of $(1+K)/(1-K)$.

The modified repetitive compensator, depicted in Fig. 3, includes a simple low-pass filter (LPF). This modification restricts

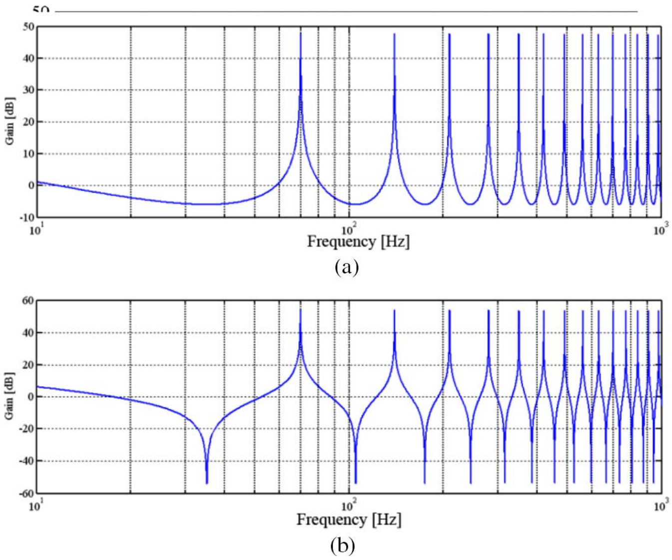

Fig. 2. Bode plots for the repetitive compensators: (a) conventional, and (b) with feedforward modification.

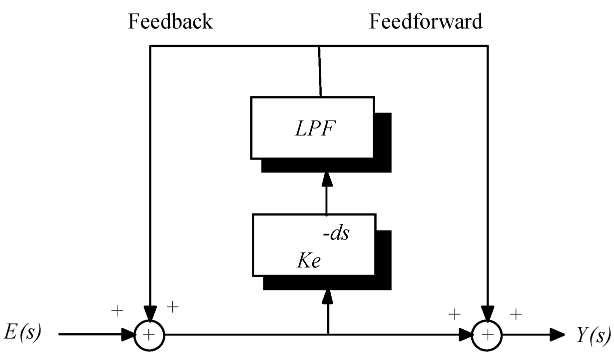

Fig. 3. General repetitive compensator with feedforward.

the bandwidth of the compensator but is necessary to provide stability robustness as it will be discussed in the next section.

III. Stability Analysis of the Closed-Loop System

The corresponding stability analysis, when the modified repetitive compensator is implemented in a closed-loop system, is now given. In this section, sufficient conditions for stability are stated in terms of the small gain theorem. The repetitive compensator with feedforward depicted in Fig. 4 has the following transfer function $(1+f(s)e^{-d_1 s})/(1-f(s)e^{-d_1 s})$ where $f(s)$ is a low-pass filter $K/(\tau s+1)$ with $K<1$. The gain K is generated as a consequence of the slightly shifting of poles and zeros, it is only important to point out that $|f(s)|<1$ for the reasons mentioned in the last section. The signals $Y_p(s)$, $R(s)$, and $E(s)$ correspond to the Laplace transforms of the output $y_p(t)$, the reference $r(t)$ and the error $e(t)$ of the repetitive scheme, respectively. The transfer function $G_p(s)\in RH_\infty^{nxn}$ denotes the transfer matrix for the plant of the system, $G_c(s)\in RH_\infty^{nxn}$ denotes the transfer matrix for the controller designed to provide stability to the closed-loop system and $G(s)=G_c(s)G_p(s)$.

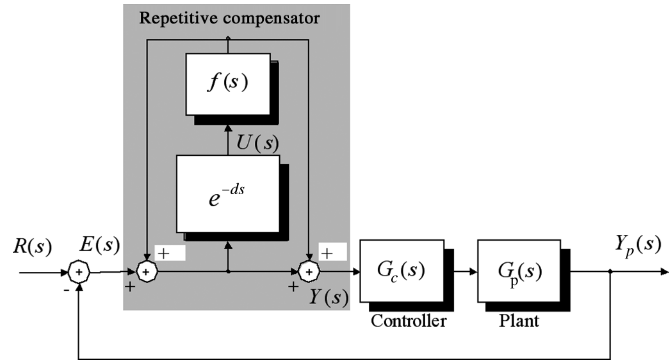

Fig. 4. General repetitive control system for harmonics compensation.

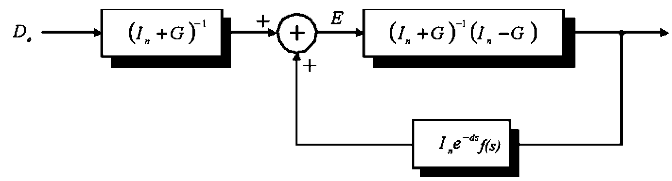

Fig. 5. Equivalent system for the closed-loop system.

For the closed-loop system shown in Fig. 4, the following relations are obtained:

$$E(s)=R(s)-Y_p(s) \tag{3}$$
$$Y_p(s)=G(s)Y(s)+\tilde{Y}_p(s) \tag{4}$$
$$Y(s)=E(s)+2f(s)U(s) \tag{5}$$
$$U(s)=e^{-ds}\left(E(s)+f(s)U(s)\right)+\tilde{U}(s) \tag{6}$$

where the terms $\tilde{Y}_p(s)$ and $\tilde{U}(s)$ correspond to the Laplace transforms of the responses for initial conditions of $G(s)$ and $e^{-ds}I_n$ respectively.

The stability of the repetitive control system can be studied by transforming the system to an equivalent one using the guidelines given in [2]. Using (3), (4), (5), (6), the following expression is obtained $(I_n+G(s))E(s) = e^{-ds}f(s)(I_n-G(s))E(s)+D_e$, i.e.,

$$E(s)=e^{-ds}f(s)(I_n+G)^{-1}(I_n-G)E(s)+(I_n+G)^{-1}D_e \tag{7}$$

where D_e is given by

$$D_e=\left(1-f(s)e^{-ds}\right)\left(R(s)-\tilde{Y}_p(s)\right)-2f(s)G(s)\tilde{U}(s). \tag{8}$$

The corresponding block diagram for the above representation is shown in Fig. 5.

Let us now discuss the stability condition for the closed-loop system using the repetitive scheme considering BIBO stability for the equivalent system described by (7). The small gain theorem [20] will be used to test robust stability. Suppose that all elements of $r(t)$ are bounded and continuous periodic signals of period d. This assumption yields that $L^{-1}[1-f(s)e^{-ds}]R(s)$ is bounded for $0\le t\le d$ and 0 for $t>d$. This fact, together with (1) and (7), implies that the equivalent exogenous input $L^{-1}[(I_n+G(s))^{-1}D_e]$ is an L_2 function under the assumption of asymptotic stability of $(I_n+G(s))^{-1}G(s)$. The next proposition gives sufficient error convergence conditions.

Proposition 1: For the repetitive control system shown in Fig. 4, if

$$(I_n+G(s))^{-1}\,G(s) \text{ is stable} \tag{9}$$

and

$$\left\| f(s)\,(I_n+G(s))^{-1}\,(I_n-G(s)) \right\|_{\infty} < 1 \tag{10}$$

then

$$e(t) = L^{-1}\,[E(s)] \in L_2 \tag{11}$$

for $r(t)$ bounded and continuous, the error of the system is bounded.

Proof: Let us assume that $(I_n+G(s))^{-1}$ belongs to RH_∞. Hence, $(I_n+G(s))^{-1}(I_n-G(s))$ belongs to RH_∞. Since the induced L_2 norm of $L^{-1}[G(s)]$ is less than or equal to $\|G(s)\|_\infty$ and $|e^{(-j\omega L)}|=1$ for all ω, the result follows from the small gain theorem.

Remark 1: The introduction of the low-pass filter $f(s)$ will help to satisfy condition (10). The proper selection of the $f(s)$ is crucial for the stability of the closed-loop system.

The sensitivity properties can be studied for the scalar case by finding the sensitivity function [20] of the transfer function $Y_p(s)/R(s)$ to changes in the forward path transfer function $\tilde{R}(s;d,K)G_c(s)G_p(s)$. When this sensitivity function is computed results in

$$S_G(s) = \left(1+\tilde{R}(s;d,K)G_c(s)G_p(s)\right)^{-1}. \tag{12}$$

Remark 2: It is clear that due to the high gains at the resonant frequencies, the repetitive compensator will produce notch filters at these values, which shows that the closed-loop system is less sensitive at these frequencies.

IV. Repetitive Control for an Optical Disk Drive

Optical disks are used to storage large amounts of data; however, reproducing data with high speed and high accuracy is not an easy task because the track to follow becomes very narrow. For the operation of an optical disk drive system, a step motor is used for the coarse tracking motion and a voice coil motor (VCM) for the fine tracking. Our major concern is the fine tracking motion of the VCM. The later consists in the following components [9], [10]: (a) the focusing/tracking voice coil motor (VCM) driver; (b) the VCM; and (c) a RF amplifier that generates the focusing/tracking error signal from the optical spot reflected on the optical disk, see Fig. 6. In the case of a DVD tracking servo, the optical spot must follow the track within 0.1-μm residual tracking error in the face of disturbances.

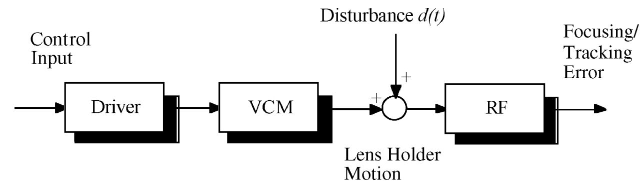

Fig. 6. Block diagram for the fine tracking motion of the VCM.

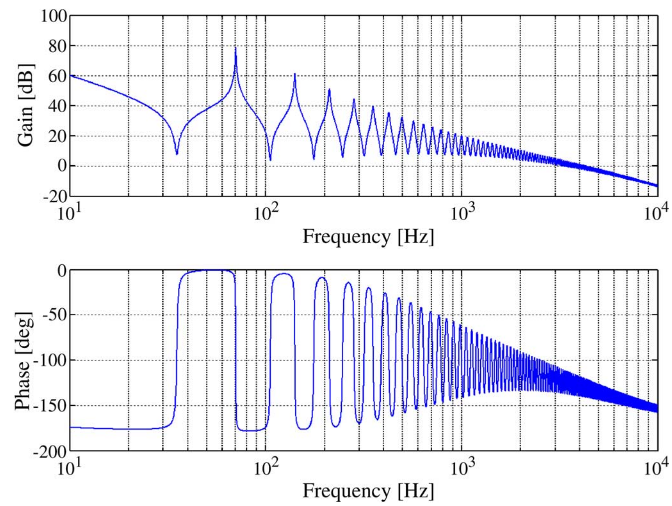

Fig. 7. Bode plot of the open-loop transfer function of the system with the repetitive compensator: (top) gain and (bottom) phase.

The real plant can be modeled as a fifth-order transfer function; however, the poles of the driver and RF amplifier can be neglected due to the high frequency dynamics. Thus, the fifth-order plant can be approximate by a second-order nominal plant. The nominal plant used for the repetitive controller design has the following form:

$$G_P(s) = \frac{k}{(s/\omega_n)^2+2\zeta(s/\omega_n)+1}[\text{Volt/Volt}] \tag{13}$$

where k is the dc gain of the real plant, ζ is the damping ratio of the VCM and ω_n is the undamped natural frequency of the VCM. For instance, the VCM for a DVD 12× ODD system (manufactured by Samsung Electronics Company) can be represented as a second order system with crossover frequency of 70 Hz ($\omega_n = 2\pi\times 70\ \text{rad/s}$) and damping coefficient $\zeta = 0.158$ as follows:

$$G_P(s) = \frac{34400}{(s/440)^2+2(0.158)(s/440)+1}. \tag{14}$$

where the quantity 34400 contains the gains of the driver, VCM and RF amplifier.

In order to design the corresponding repetitive compensator, a stabilizing controller has to be designed such that proper gain

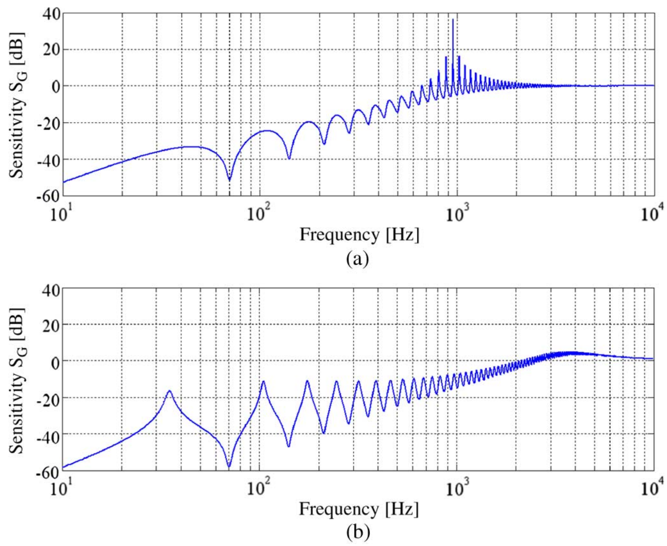

Fig. 8. Resulting Bode plots of the closed-loop sensitivity with: (a) a conventional repetitive compensator, and (b) the modified repetitive compensator.

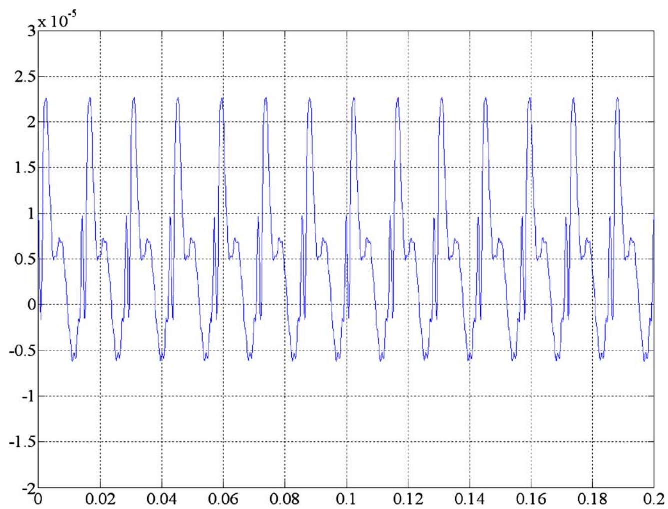

Fig. 9. Disturbance signal $d(t)$ used in simulation (5 $\mu\mathrm{m/div}$), (Time: 0.02 s/div).

and phase margins are obtained. A stabilizing controller designed for this particular case is

$$G_C(s) = 0.1162 \times \frac{5.2 \times 10^{-7}s^2 + 7.182 \times 10^{-4}s + 1}{8.488 \times 10^{-6}s^2 + 0.1601s + 1} \quad (15)$$

which is a lead-lag network that provides a closed-loop system with 46.3° phase margin. As a robustness measure, the minimum distance of the Nyquist plot to -1, for the open-loop transfer function, is given by $d = 1/\|G_C G_P\|_\infty = 0.636$.

The closed-loop system is required to attenuate a disturbance of the following form $d(t) = 5 + \sum_{i=1}^{11} c_i \sin(2\pi \times 70(\mathrm{i})\mathrm{t} + \theta_{\mathrm{i}})$ $\mu\mathrm{m}$ where $c_i = 9/i$ and $\theta_i = 4\pi/i$. The disturbance signal comprises of a constant and eleven harmonics of the spindle frequency 70 Hz. It can be noticed that the magnitudes and phases for the different harmonics are not the same. The gain of the overall open-loop transfer function, including the modified repetitive compensator, is plotted in Fig. 7. It is worth noting that high gain peaks appear at the harmonic components of the fundamental frequency 70 Hz, and that their magnitudes decrease with increasing frequency due to a low-pass filter with a transfer function given by $f(s) = 0.9/(6.5 \times 10^{-4}s + 1)$. The crossover

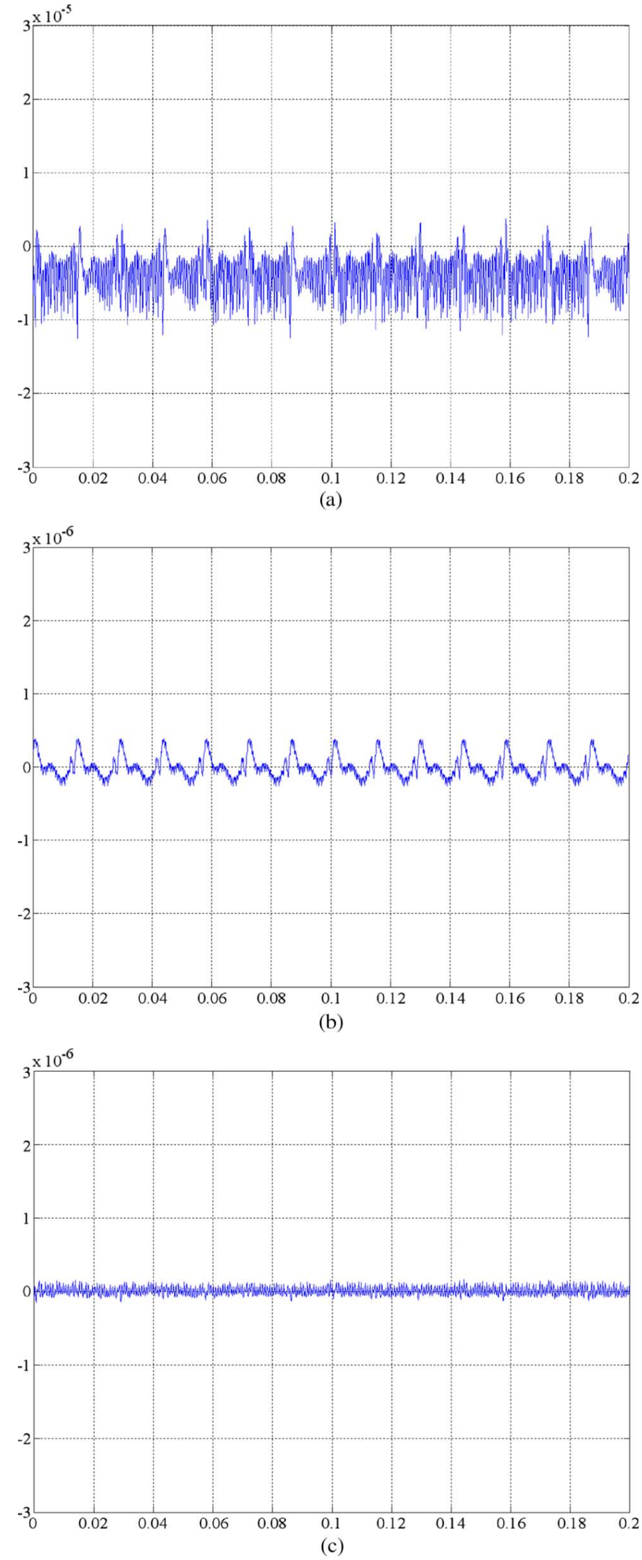

Fig. 10. Resulting tracking error with: (a) stabilizing controller, (b) stabilizing controller plus a conventional repetitive compensator, (c) stabilizing controller plus the modified repetitive compensator. ($10\,\mu\mathrm{m/div}$, $1\,\mu\mathrm{m/div}$, $1\,\mu\mathrm{m/div}$), (Time: 0.02 s/div).

frequency for the overall open-loop transfer function is about 4000 Hz.

The corresponding Bode plots for the closed-loop sensitivity for both repetitive compensators are depicted in Fig. 8. The closed-loop sensitivity with the conventional repetitive compensator shows higher gains than the modified repetitive compensator at the disturbance frequencies. The conventional repetitive compensator produces high peaks in the closed-loop sensitivity at frequencies near 1 kHz, this due to the fact this compensator produces wide changes in phase. On the other hand, the closed-loop sensitivity using the modified repetitive compensator has a smooth behavior at high frequencies.

Fig. 10 shows the time evolution of the disturbance signal used in simulation. The peak value of the disturbance is about 22.5 $\mu\mathrm{m}$. Now, a comparison of the resulting flying height errors without and with the repetitive compensators is given. Fig. 10(a) shows the tracking error obtained by simulation when only the stabilizing controller is used; this signal contains also a constant. Now a conventional repetitive compensator is enable, the time evolution is shown in Fig. 10(b). It is clear that an attenuation of the perturbation is obtained, which shows that the compensator is effectively working. Fig. 10(c) shows the time evolution when the modified repetitive compensator is used. It is obvious that the tracking error is further reduced when the designed repetitive compensator is employed. As a consequence, the modified repetitive compensator reduces the tracking error up to 1.2% of the tracking error given when only the stabilizing controller is used. This further reduction in the tracking error is important when reading data in ODD systems. The constant that appears in the tracking error of Fig. 10(a) is attenuated due to the pole in the origin that is produced by the repetitive compensators.

V. Concluding Remarks

Disturbances that affect the proper operation of the ODD systems are mainly: disk surface vibration, eccentricity vibration, radial vibration and resonance. These disturbances can effectively be rejected using a repetitive compensator with feedforward pathway, which produces an infinite set of resonant filters that can be tuned exactly at the harmonic components of the disturbances. All the resonant filters plus the pole at the origin are implemented at once using a single time delay which in turn will produce a system dynamics of infinite dimension; therefore, the stability of the closed-loop system has to be studied. It is shown that the modified repetitive compensator provides a practical and easy approach for compensation of periodic disturbances. Due to the high performance that can be obtained using the proposed repetitive compensator, it is suitable for fine tracking motion in ODD systems where the residual tracking error should be maintained at a low value.

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