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Frequency Adaptive Control Technique of Compact Disk Drives for Rejecting Periodic Runout [1]

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Abstract

This paper proposes a novel adaptive controller for rejecting the periodic runout of a track following system in the compact disk drives. The control objective is to attenuate adaptively the specific frequency contents of runout disturbances without amplifying its rest harmonics. Being depends on the position of the disk, the proposed controller is applicable to both the spindle modes of constant linear velocity (CLV) and constant angular velocity (CAV) for various operation speeds. The experimental results show that the novel control strategy leads to a satisfactory performance in terms of the reduction of tracking error of compact disk drives.

1 Introduction

In this paper, a novel Frequency Adaptive Control Technique (FACT) aims to eliminating the periodic runout effect on the track-following system in the optical disk drives is proposed. Compare to the widely used Adaptive Feedforward Cancellation (AFC) [1, 2, 3] schemes which are suitable for the cases that the disk running at single angular velocity, the proposed method provides a single runout cancellation structure to apply to the variable speeds requirement of the CAV and CLV modes. The FACT controller along with the original feedback ones are implemented in a single FPGA device to validate its application for a compact disk drive.

2 Algorithm of FACT

The FACT setup is realized in a plug-in configuration as shown in Fig. 1, in which the proposed algorithm is illustrated in the dash-line box. The track-following system, which composed of fine actuator $G_f(s)$ and coarse actuator $G_c(s)$, effected by the periodic runout $d(t)$ is controlled by the feedback controllers $C_f(s)$, $C_c(s)$ as well as the output $v(t)$. In the FACT box, $e(t)$ is first filtered by a low pass filter, and then been sampled at N equally spaced points for each complete rotation of the disk.

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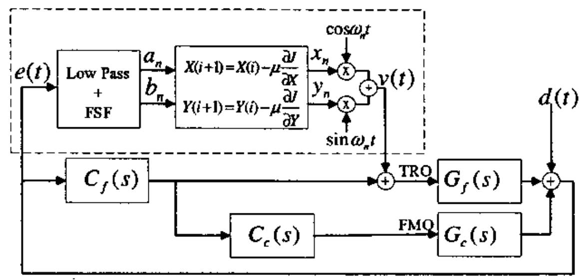

Fig. 1: Periodic runout rejection for Optical Disk Drives

2.1 Periodic Runout Identification

A bank of Frequency Sampling Filter (FSF) [4] defined as,

$$\begin{aligned} H_n(z) = \tfrac{1-z^{-N}}{1-W_N^n z^{-1}} &= 1 + W_N^n z^{-1} \\ &+ W_N^{2n} z^{-2} + \cdots + W_N^{n(N-1)} z^{-(N-1)} \end{aligned} \tag{1}$$

where $W_N^n = exp(j\frac{2\pi n}{N})$ and $n = 0, 1, \cdots, N-1$.

Theorem 1. Let ω_1 be the fundamental frequency, and the periodic signal $e(t)$ denoted as

$$e(t) = \sum_{n=1}^{M} (a_n \cos\omega_n t + b_n \sin\omega_n t) \tag{2}$$

where M is the highest harmonic order, $\omega_n = n\omega_1$, and a_n, b_n are variables to be identified. For the input $e(t)$ be sampled at N values for each period, and the output of each filter described as

$$\xi_n(k) = H_n(z)e(k) = \frac{N}{2}(\alpha_n + j\beta_n) \tag{3}$$

where, $n = 1, 2, \cdots, M$, then the variables a_n and b_n in (2) can be identified on-line as

$$\begin{cases} a_n = \alpha_n \cos\omega_n t + \beta_n \sin\omega_n t \\ b_n = \alpha_n \sin\omega_n t - \beta_n \cos\omega_n t \end{cases} \tag{4}$$

and the least value of N is $N = 2M + 2$.

It's worth noticing that not the full bank filters but only the M filters are needed to be implemented.

2.2 Adaptation Formulation

Let the output $v(t)$ designed as

$$v(t) = \sum_{n=1}^{M} (x_n \cos\omega_n t + y_n \sin\omega_n t) \tag{5}$$

where, the on-line adaptation of variables x_n and y_n are to be formulated, and the vectors A, B, X and Y as $A = [a_1\, a_2 \cdots a_M]^T$, $B = [b_1\, b_2 \cdots b_M]^T$, $X = [x_1\, x_2 \cdots x_M]^T$, $Y = [y_1\, y_2 \cdots y_M]^T$, where, a_n, b_n are given by (4) and x_n, y_n are variables described in (5). The penalty function J is defined as the total energy of $e(t)$ at ω_n such that

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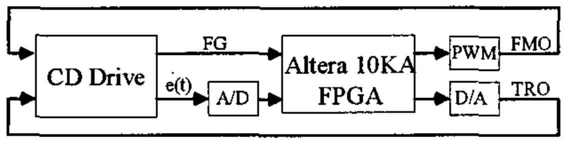

Fig. 2: Periodic runout rejection for Optical Disk Drives

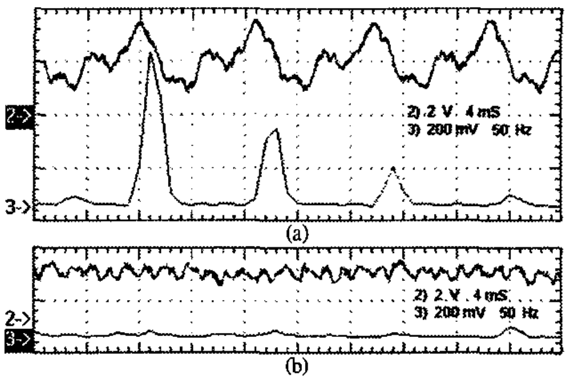

Fig. 3: TS (ch2) and PS (ch3) of $e(t)$ for disk running at 6,780 RPM. (a) FACT off; (b)FACT on.

$$J = \frac{1}{2}(A^TA + B^TB) \tag{6}$$

According to the gradient descent algorithm [5], we have

$$\begin{cases} X(i+1) = X(i) - \mu\dfrac{\partial J}{\partial X} \\ Y(i+1) = Y(i) - \mu\dfrac{\partial J}{\partial Y} \end{cases} \tag{7}$$

where, the adaptation gain $\mu > 0$ such that the descendent of J is guaranteed. For system with input as $v(t)$ and output as $e(t)$ expressed as

$$\frac{e(s)}{v(s)} = \frac{G_f}{1 + G_fC_f + G_cC_cC_f} \doteq \frac{G_f}{1 + G_fC_f} = W(s)$$

and let $W(j\omega_n) = W_r(\omega_n) + jW_i(\omega_n)$, we have (8)

$$a_n + jb_n = \{W_r(\omega_n) + jW_i(\omega_n)\}(x_n + jy_n) \tag{9}$$

and

$$\begin{aligned} \frac{\partial a_n}{\partial x_n} &= W_r(\omega_n), \quad \frac{\partial a_n}{\partial y_n} = -W_i(\omega_n) \\ \frac{\partial b_n}{\partial x_n} &= W_i(\omega_n), \quad \frac{\partial b_n}{\partial y_n} = W_r(\omega_n) \end{aligned} \tag{10}$$

Substitute the gradients of J as,

$$\frac{\partial J}{\partial X} = \Phi_{ax}A + \Phi_{bx}B, \quad \frac{\partial J}{\partial Y} = \Phi_{ay}A + \Phi_{by}B \tag{11}$$

leads to the adaptation law in (7) as

$$\begin{cases} x_n(i+1) = x_n(i) - \mu[W_r(\omega_n)a_n + W_i(\omega_n)b_n] \\ y_n(i+1) = y_n(i) - \mu[-W_i(\omega_n)a_n + W_r(\omega_n)b_n] \end{cases}$$

with $n = 1, 2, \cdots, M$. (12)

3 Experimental Results

The experimental results show the successful runout rejection when the disk operating at the high-speed CAV mode and the slow CLV mode. Fig. 2 shows the experimental setup in which the FG accounting for the disk position decoder signal. For the disk is running at 6,780 RPM, Fig. 3 shows the time series (ch2)

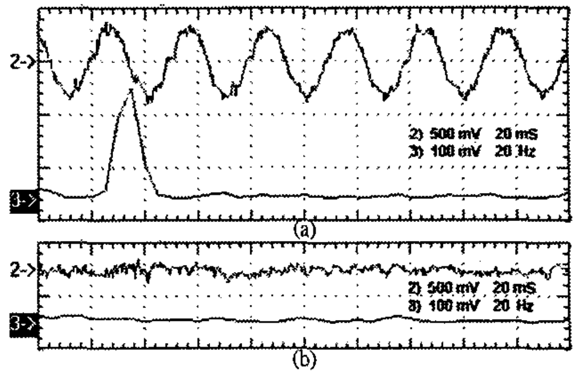

Fig. 4: TS (ch2) and PS (ch3) of $e(t)$ for disk running at CLV. (a) FACT off; (b)FACT on.

and power spectrum (ch3) of $e(t)$. It is clear that, in (a), there are significant steady error up to 3th order harmonics which equivalent to the maximum of $0.1\mu m$ runout, while, in (b), the harmonic contents are completely canceled through the FACT. When the disk running at slower CLV mode, Fig. 4 shows the dominant fundamental harmonic has been canceled completely.

4 Conclusion

A novel frequency adaptive control technique is proposed and examined on a compact disk drive. Both the theoretical and experimental results show that the periodic runout harmonics can be rejected simultaneously and efficiently for both CAV and CLV spindle modes under variable playing speed. The rejection devoted to some candidate harmonic components will not influence the uncompensated ones. In view of application requirement, the proposed FACT can be extended for the runout rejection to various compact disk drives, such as CD-ROM, CD-RW or DVD-ROM drives.

References

[1] S. W., J. L. Zhang, and T. S. Low, "Effieient implementation of adaptive feedforward runout cancellation in a disk drive," *IEEE trans. on Magnetics*, vol. 32, no. 5, pp. 3920–3923, 1996.

[2] Y. O. and H. I., "Repeatable runout compensation for disk drives using multi-loop adaptive feedforward cancellation," in *Proceedings of the SICE Annual Conference*, pp. 29–31, July 1998.

[3] H. S. Lee, "Implementation of adaptive feedforward cancellation algorithm for pre-embossed rigid magnetic disks," *IEEE trans on Magnetics*, vol. 33, no. 2, pp. 2419–2423, 1997.

[4] R. R. Bitmead, "Adaptive frequency sampling filters," *IEEE transactions on Acoustics, Speech and Signal Processing*, vol. Assp-29, pp. 684–693, June 1981.

[5] T. J. Sutton and S. J. Elliott, "Active attenuation of periodic vibration in nonlinear systems using an adaptive harmonic controller," *Journal of Vibration and Acoustics*, pp. 355–362, July 1995.

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Modelling Modal Based Sensors for Oscillatory Systems[1]

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Abstract

In this short paper we very briefly describe a class of sensors which have proven very useful in control problems for distributed parameter systems. These sensors, which provide approximate point evaluation for infinite dimensional systems, also rapidly damp high frequency oscillations. The sensors are obtained as convolution integrals over small spatial regions with kernels that possess rather interesting properties. In this short work we will very briefly describe the kernels, give some of their important properties. We expect that the underlying kernels will find many applications in other areas where there is a desire to have smooth compactly supported sensors that rapidly damp the effects of high frequency modes. In particular, these kernels can be used as efficient small-scale spatial mollifiers with efficient spectral filtering properties in computational fluid dynamics. For complete details we refer to our forthcoming paper [1].

1 Introduction

In many important practical problems in applied mathematics and engineering applications to distributed parameter systems it is desirable to model approximate point evaluation sensors with special properties. Often such sensors are described by convolution operators with kernels given by an approximate delta sequence. In our recent work [1] we have discovered a special class of such sensors that are particularly well suited to problems of output regulation in which a parabolic type problem is to be controlled so as to have an output track (or reject) the output of a highly oscillatory hyperbolic system. Examples include the problem of controlling a flexible structure in order to reject an unknown disturbance (noise) generated by a exogenous system of hyperbolic type, for example an acoustic system. For such systems it is desirable to have sensors providing approximate point measurements as outputs which can be processed in order to design a regulator that will suppress the undesired noise. Many other types of applications arise as general problems in output regulation of distributed parameter systems with infinite dimensional exosystems. For problems of output regulation when the plant to be regulated is of parabolic type and the exosystem generating signals to be tracked or disturbances to be rejected is also infinite dimensional and of hyperbolic type one is often confronted with a serious difficulty in computing the desired feedback law. The difficulty comes from the fact that parabolic systems tend not to support rapid oscillations while hyperbolic systems usually support modes of increasing oscillation. To deal with this problem it is desirable to design sensors for the hyperbolic exosystem that damps high order oscillations at a sufficiently fast rate [1]. This requirement stems from explicit formulas for the feedback gain as obtained in our recent works [2, 3].

Our main point in this work is the modelling of a class of one parameter families of output operators $Q_\rho^{(m)}$ that approximate point evaluation and also rapidly damp high order oscillations. We are particularly interested in sensors that arise as convolution with a smooth compactly supported kernel function and among such functions we are interested in exponentially damping high order oscillations. The output operators presented here have the form

$$y(t) = (Q_\rho^{(m)} w)(t) = \int_0^1 k_\rho^{(m)}(\xi_0 - \xi) w(\xi, t)\, d\xi, \quad (1)$$
$$\xi_0 \in (0,1), \quad 0 < \rho < 1,$$

where, for example, $w(\xi, t)$ might represent the solution to a wave equation. The kernel functions $k_\rho^{(m)}$ are derived as examples from a class of so-called *Schwartz type test functions* described in [4]. We note that there are no explicit examples given in [4]. One of the major results of the work [1] is the discovery of explicit examples of functions in the classes defined in [4] and presented in Section 2.

2 The Kernels and Their Properties

In order to describe our results we first present some notation and elementary facts from the theory of Schwartz type test functions and their Fourier transforms [4]. We denote by $C^\infty(\mathbb{R})$ the space of infinitely differentiable functions on the real line $\mathbb{R}$ and by $\mathcal{S}$ the subspace of rapidly decreasing functions. We denote by $C_0^\infty(\mathbb{R})$ the subspace of $\mathcal{S}$ consisting of functions in $C^\infty(\mathbb{R})$ with compact support. The Fourier transfor-

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