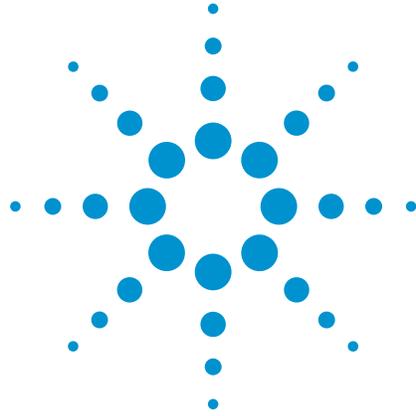


Agilent PC-Based Hard Disk Storage Testing Platform for Position Error Signal Generation and Servo Control on Spindrive

By: Wai Ee Wong (A*STAR Data Storage Institute, Singapore 117608, Singapore)



Abstract

The hard disk drive storage industry is driven to increase data storage density, with increasing tracks per inch (TPI) and bits per inch (BPI) on the recording media. In the development of higher density recording, high-speed testing of magnetic heads and media in engineering and manufacturing environments has traditionally focused on spindrives and disk head testers. This paper describes a high-performance Servo control system for enhancement of spin stand Servo performance. This PC-based system uses a multifunction I/O card for controller output and an Agilent Acqiris high-speed digitizer card capable of sampling the frequency-encoded Servo pattern at 500 MS/s. The PC, running under the Linux operating system, uses the Goertzel algorithm decoding scheme to calculate the position error signal (PES) at a 15-kHz update rate for feed-back control. The control signal drives a custom-made lead zirconate titanate (PZT) actuator, which moves the suspension and thus the read/write head. A proportional and integral (PI) type Servo controller supports a 1.1-kHz Servo bandwidth, producing a 21.9% improvement of the positioning accuracy of the spindrive[1].

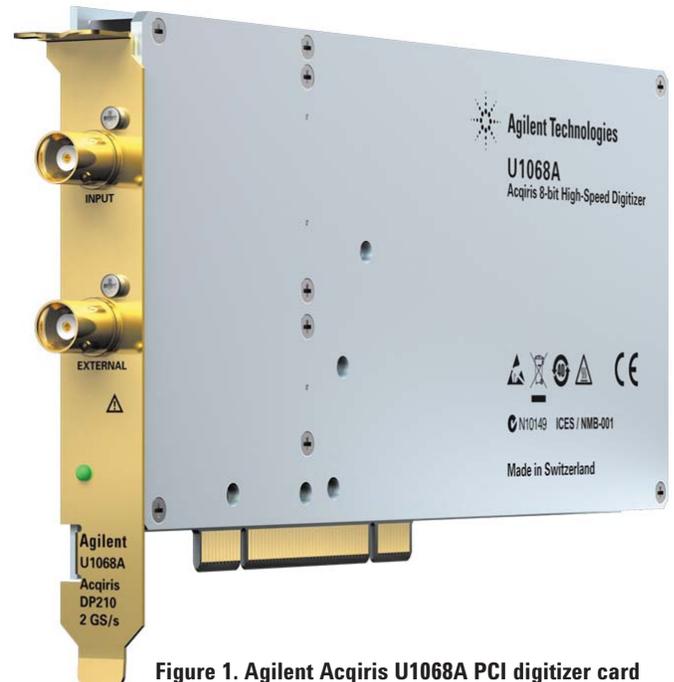


Figure 1. Agilent Acqiris U1068A PCI digitizer card



Agilent Technologies

1. Introduction

In disk drive industry, spindles or disk head testers are often used for high-speed testing of magnetic heads and media in both engineering and manufacturing environments [2]. It is a system designed to mount and test HDD components (specifically heads, head stacks, disks, and channel, when used together with a read/write analyzer), simulating the conditions found in the actual HDD. Traditionally, low vibration mechanisms such as low nonrepeatable runout air-bearing spindle motors have been used, and thus, spin stand Servo has been tasked to track the thermal shift and DC drift of the mechanical fixture. However, the disk drive industry has been targeting at achieving above 1 Tb/in² areal density, which requires a position accuracy of about 400,000 tracks per inch. Track mis-registration caused by disk vibration, suspension vibrations, and air-bearing spindle motor non-repeatable runout, all in a few nanometer ranges, cannot be ignored anymore; a more precise Servo system is thus essential.

One viable solution to overcome these limitations is to add a microactuator or use active suspension on the read/write heads assembly. This microactuator, designed for submicrometer motions, can increase the bandwidth of the Servo positioning system. Previously, researchers have proposed various types of secondary stage microactuators to hard disk drive Servo positioning systems. All those works show significant improvements in disk drive Servo positioning systems by introducing microactuators [3]. However due to high cost and reliability issues, it is not widely employed in commercial hard disk drives (HDDs). Attention has been diverted to micro-actuation mechanisms in magnetic recording spindles recently [4],[5]. However in their setup, external sensors such as an optical sensor is used, hence, the Servo system developed cannot be directly applied to HDDs, which have a position error signal (PES) channel.

As in hard disk drive Servo systems, the essential tasks in a spin stand Servo system are to obtain the PES, execute the control algorithm, and update the control output at desired frequency so that the read/write head is positioned correctly with respect to the data written on the media. In our setup, we add an external Servo system on to an existing spin stand for fast deployment of spin stand Servo as well as using as a platform for testing advance Servo technology.

This PC-based system uses a multifunction I/O card for control signal output and an Agilent Acqiris high-speed U1068A digitizer card for sampling the frequency-encoded Servo pattern (FESP) at 500 MS/s. Goertzel algorithm decoding scheme is implemented in the PC to calculate the position error signal (PES). Based on a 3-GHz CPU PC, we are able to achieve 15-kHz PES update rate for feedback control under Linux Redhat 9.0 operating system (OS), which has a lower latency compared to Window XP OS. A custom-made PZT actuator is design and fabricated to move the suspension and thus the read/ write head and a low hump proportional-integral (PI) controller is designed to close the Servo loop.

With this external control system, high Servo bandwidth of 1.1-kHz and 21.9% improvement of the positioning accuracy on the existing spin stand has been achieved. Since the PES is computed with the PC, dedicated PES generation hardware is unnecessary. Furthermore, various PES generation schemes as well as advanced Servo control algorithms can also be tested on the spin stand.

2. System Configuration

In this paper, a commercial spin stand [2] is used. The existing spin stand consists of piezoactuators with piezo range from 12 to 16.6 μm and linear scale of resolution of 0.5 nm, and first mode natural frequency at less than 200 Hz [6]. Due to the stacked stage design, the achievable Servo bandwidth is less than 50 Hz, which is unable to compensate for any major repeatable runout (RRO) harmonics and only deals with once-a-round thermal expansion caused off-track disk vibration. To improve the Servo performance, the spindles' head cartridge is modified to integrate a small piezo actuator near to the read/write head and used as the precise positioning device to drive the suspension. A close-up view of the modified head cartridge with piezo chip actuator is shown in Figure 1.

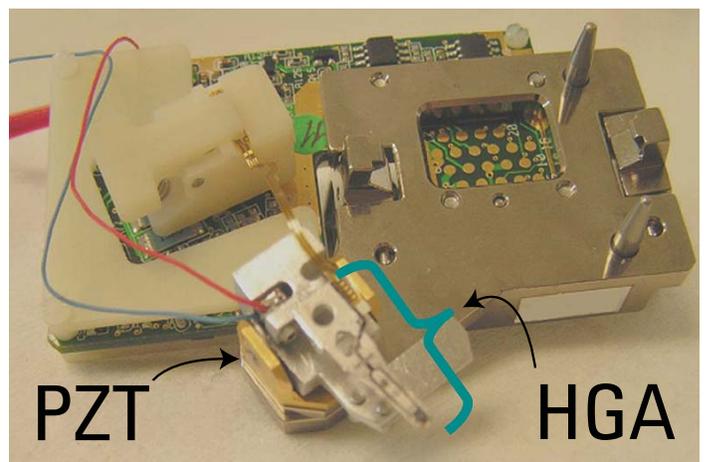


Figure 1. Head cartridge with piezoelectric actuator.

Figure 2 shows the block diagram of the overall PC-based Servo system architecture. The PC system will calculate the position error signal based on the digitized readback signal at each Servo sector interval and computes the control signal for reader Servo control. The readback signal is obtained and digitized by an Acqiris DP210 high sampling rate digitizer card from the spin stand setup. The single-channel card features a 2 GS/s sampling rate with an acquisition memory from 256 kpoints up to an optional 4 Mpoints, depending on user requirements, for recording complex signals over long periods of time, an essential component for maintaining fast sampling rates and timing resolution. The card's flexibility provides exceptional testing benefits to engineering and manufacturing applications.

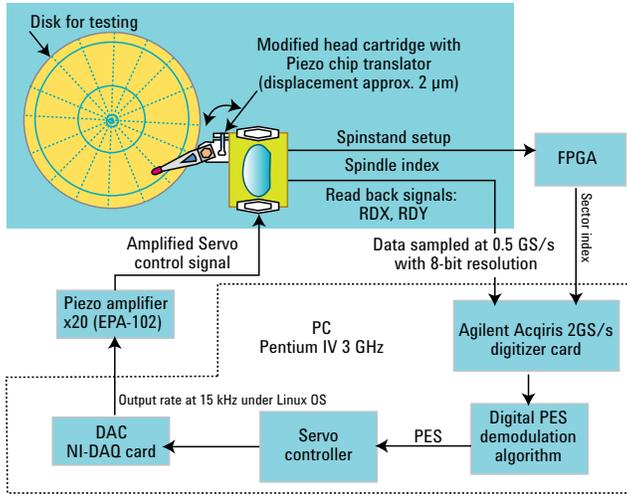


Figure 2. Architecture of spin stand Servo system.

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An external clock generator circuitry is used to trigger the PC-based Servo system to acquire the Servo signal and compute the PES at every sector. In addition, a multifunctional I/O card is used for conversion of the digital control signal and providing the external reference for system performance measurement. In the setup, 40 Gbit/in2 read/write head is used for the experiment, with the write head's width about 12.5 μm , and the read head's width about 8.2 μm . A 2.5" disk is used and spun at 4000 rpm.

The controlled plant basically consists of four components, namely, piezo amplifier, PZT chip actuator, head cartridge base, and a non-active suspension with the head gimbal assembly (HGA). With smaller load mass and actuation nearer to the actual read/write head, the resonance can be pushed further up the frequency range and thus provides a much higher bandwidth actuation mechanism. As can be seen from the frequency response measured from the generated PES versus the input exciting swept sine as shown in Figure 3, we see that the PZT head cartridge plant model has the first structural resonance at 4.2-kHz with a displacement range of about 140- μm .

3. Dual-Frequency PES Formulation via Goertzel Algorithm

The default Servo pattern within the spin stand is based on amplitude detection which has been widely used to determine the off-track position of the read/write head with respect to the disk media [2]. In this paper, a frequency-based Servo pattern is proposed for the Servo pattern layout on the spin stand, where a Servo pattern of alternating transitions is written on each Servo track at different frequency. As the frequency-based Servo pattern is fabricated at the same tangential position, the Servo burst overhead can be reduced as much as 50% as compared to conventional Servo pattern [7]. Besides the reduced complexity in the writing of frequency-based Servo pattern as compared to phase-based Servo pattern, the scheme itself is not as critical to the timing jitter errors encountered since the magnitude of the frequency components is used for demodulation.

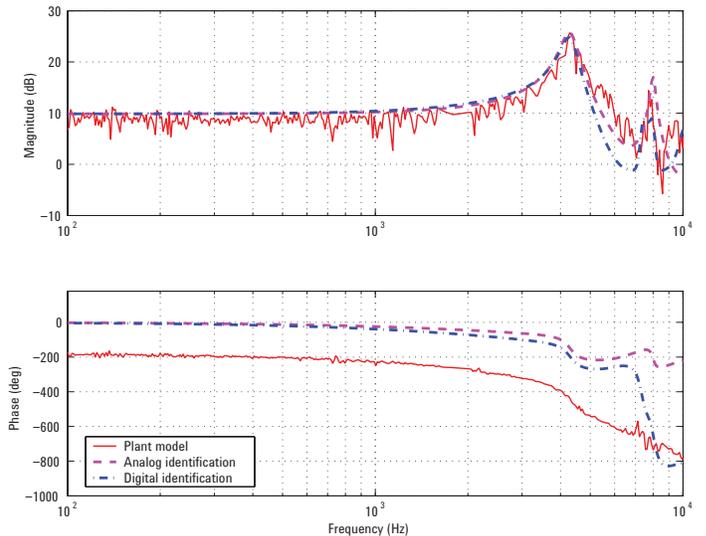


Figure 3. PZT micro-actuator with head cartridge frequency response and identified model.

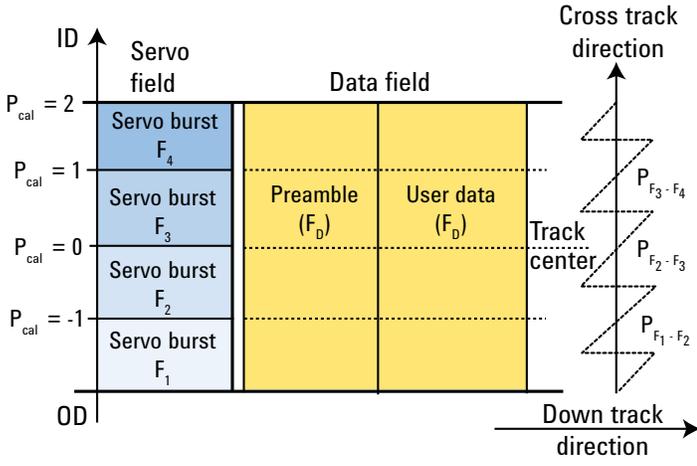


Figure 4. Multiple -frequency Servo burst pattern.

Due to the limitation of current setup and for testing purpose, only in-phase multiple-frequency Servo pattern written at narrower track pitch is suggested, as illustrated in Figure 4. With more frequencies written, the linear portion of each individual position signal can be combined to construct the linear Servo control range wider and diminish the positioning error due to overshooting at the final access stage. Thus, such a pattern will incur less Servo burst overhead as well as ease of finding the offset direction.

In this paper, Goertzel algorithm is proposed to determine the relative amplitude of each frequency components F_i (where $i = 1, \dots, 4$). The Goertzel algorithm is derived from the Discrete Fourier Transform (DFT) methodology and exploits the periodicity of the phase factor $e^{j2\pi k/N}$ to reduce the computational complexity associated with the DFT, as the fast Fourier transform (FFT) does. The Goertzel algorithm is more efficient than the FFT in computing an N -point DFT if less than $\log_2 N$ DFT coefficients are required. The number of multiplication required based on the Goertzel algorithm is only $(Ns + 4)$, whereas the DFT requires as least $(4Ns + 4)$ for the detection of two frequency components. Thus, it is commonly used to detect tones for the dual tone multifrequency (DTMF) applications [8].

The Goertzel algorithm can be derived from the DFT equation and implemented as a second-order IIR bandpass filter, as shown in Figure 5.

The relative amplitude of the frequency will be as follows:

$$G_k = \sqrt{q^2(n) + q^2(n-1) - 2\cos\left(\frac{2\pi k}{N}\right)q(n)q(n-1)}$$

where

$$q(n) = x(n) + 2\cos\left(\frac{2\pi k}{N}\right)q(n-1) - q(n-2)$$

and

$$k = N \frac{f_o}{f_s}$$

The number of samples is defined as N , f_0 is the required frequency and f_s is the sampling frequency. For accurate estimation, every frequency of interest should be an integer factor of the sampling rate. Thus, k has to be an integer, and the resolution of this algorithm to differentiate between required frequencies is given by f_s/N .

Based on the identification of each frequency Servo bursts components within the sampled readback Servo signal, the percentage offset with respect to the center of the Servo track for F_1 and F_2 can be computed as

$$PES_{F_1 - F_2} = \frac{G_1 - G_2}{G_2 + G_2}$$

The computed individual frequency cross-track functions are normalized to eliminate the positioning offsets with respect to the Servo signal's strength at different frequencies. Following which, individual frequency components computed with Goertzel algorithms are calibrated and identified to determine the corresponding position signal to be fed to the Servo controller module. A block diagram of the computation flow is as shown in Figure 6.

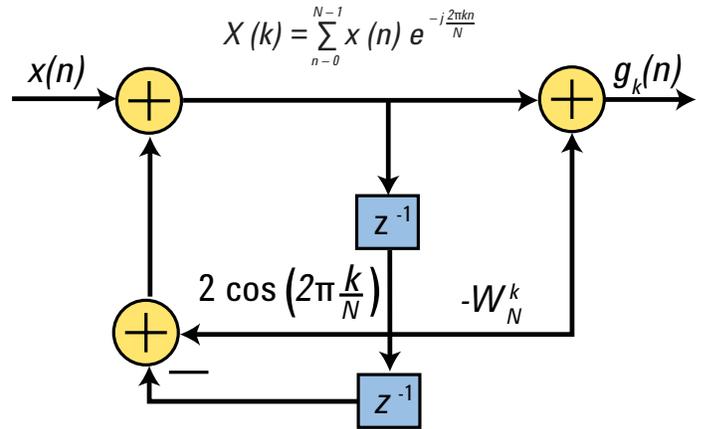


Figure 5. Goertzel 2nd order filter block diagram: $W_N^k = e^{-j\frac{2\pi k}{N}}$

4. Servo Pattern Configuration and PES Performance

For the 4-frequency case, the detection of the 1st and 2nd largest frequency components in the readback signal will determine the read head's position and the appropriate range for computation of PES. In this setup, Servo frequency of 31.25-MHz, 25-MHz, 20-MHz and 12.5-MHz are written on the disk media starting from the outer diameter, at Servo track width of 9 μ inch respectively. The sampling rate of the the Agilent Acqiris U1068A digitizer card is set at 500 MS/s, and the number of sample points per Servo sector is 400, which indicates frequency resolution of 1.25 MHz for Goertzel detection. Cross track measurement of the normalized Goertzel computation for each Servo frequency and the calibrated PES measurement are shown in Figure 7 and Figure 8 respectively. The Servo signal consists of two fundamental Servo frequencies, whereas the data channel portion contains single frequency preamble signal for synchronization at the beginning of each data field. This user data frequency is usually higher than the Servo frequency and it is set at 300 MFlux/S as seen in Figure 9.

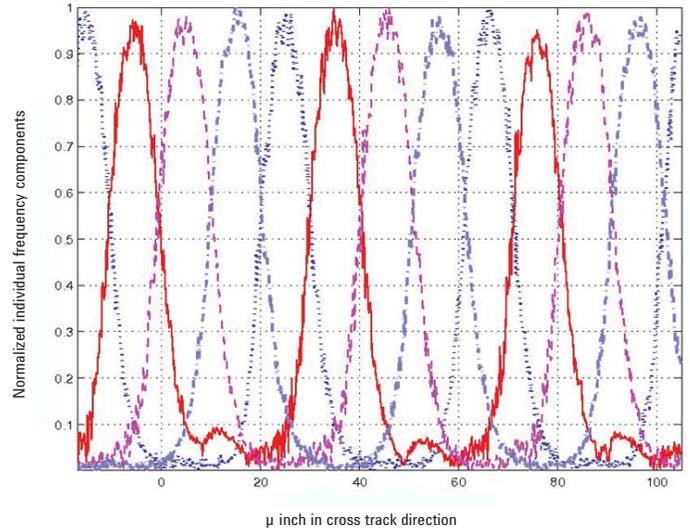


Figure 7. Normalized Goertzel computation of Servo pattern F1, F2, F3, F4.

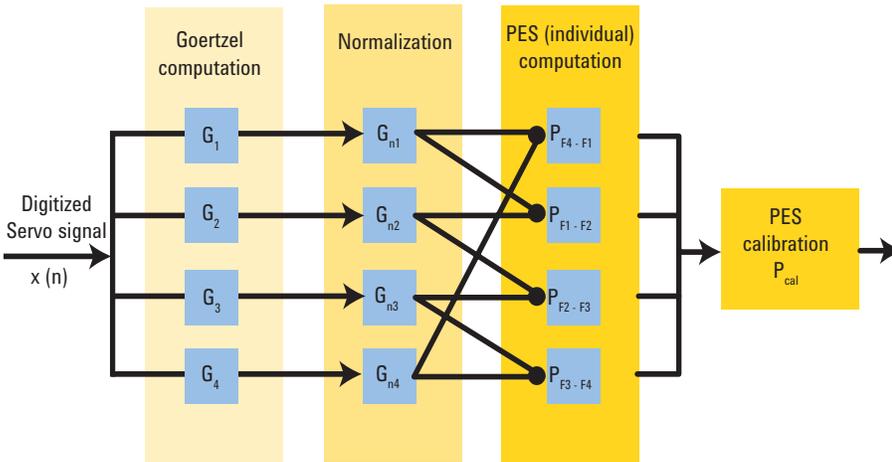


Figure 6. Block diagram of PES generation and calibration process.

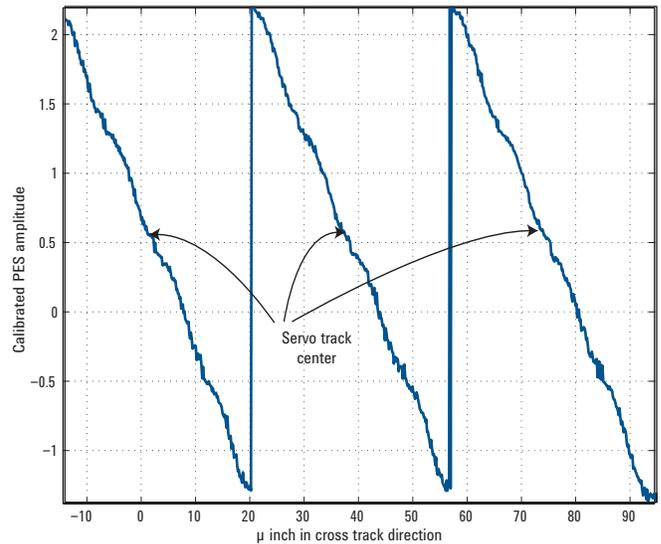


Figure 8. Calibrated PES function.

The overall execution time includes data acquisition, data transfer, PES generation, control algorithm and control signal output time. The processing time for the PES generation is proportional to the number of data points taken for computation. A breakdown of the approximate time taken for each component based on a Pentium 3-GHz PC system with Linux OS (Redhat 9.0) platform is shown in Table 1. Comedi Driver (0.7.68) and Comedi library (0.7.18) [10] are used to control the NI DAQ card and the Redhat version 2.9 driver is used to drive the Agilent Acqiris U1068A card. The time taken for each loop is about 62 μ s and thus the maximum achievable Servo update rate can be set at 15-kHz. The spindle speed is set at 4000 RPM, which is 15 ms per revolution. With the timing interval set at 65 μ s, there will be 230 sectors per revolution.

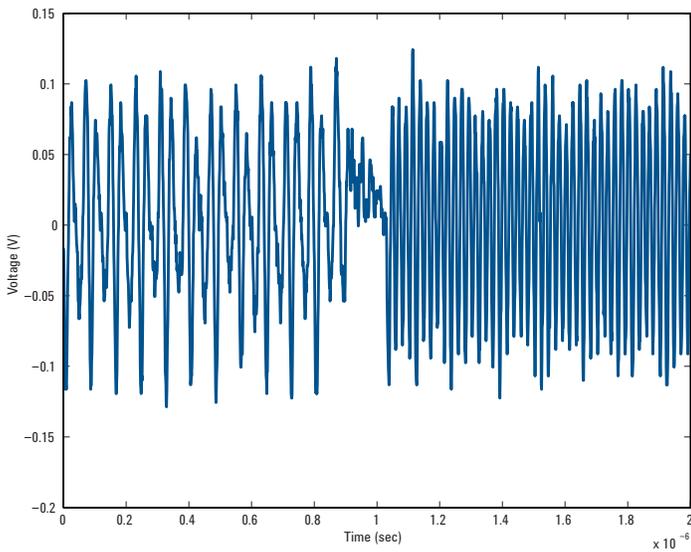


Figure 9. Readback signal of Servo pattern and preamble.

Sequence	Approximate timing in Windows® (μsec)	Approximate timing in Linux (μsec)	Remarks
Start acquisition	40	3	Activate Agilent digitizer
Get reference input	80	3.5	ADC from NI DAQ card
PES computation	120	8.2	Based on 400 sample points
PES calibration	5	< 1	Calibrate PES
Controller	5	< 1	< 11th order controller
Sampled data transfer	140	37	PCI transfer to PC RAM
Control signal output	10	3.5	DAC through NI DAQ card

Table 1. Timing breakdown of individual reader Servo control program components.

5. Spin stand Servo Control Implementation

A near perfect modeling (NPM) of micro-actuators [3] is proposed to suppress the sensitivity hump by constructing a flat virtual model of the plant, together with a Proportional and Integral (PI) controller to close the Servo loop, as shown in Figure 10. The plant model of the PZT actuator, as shown in Figure 3, can be viewed as a pure unity gain up to a high frequency after pre-multiplying with the inverse of this plant model.

The PI controller is designed in continuous time and converted to discrete form as follows:

$$C_{PI}(z) = k_p + \frac{k_i}{\frac{2}{T_s} \cdot \frac{z-1}{z+1} + 10}$$

where PI parameters $k_p = 0.12$, $k_i = 2400$ and control sampling time, $T_s = 65 \mu$ s, in cascade with an inverse plant model, which is the approximate inverse of the identified and digital transfer function of the plant model.

$$C_{NPM}(z) = 0.23948 \frac{(z - 0.4418)(z^2 + 0.3261z + 0.81)}{(z - 0.05733)^2(z - 0.0002835)}$$

As can be seen from Figure 11, the peak value of the sensitivity transfer function ($1/(1 + C(z)P(z))$) is about 4.5 dB and Servo bandwidth is about 1050 Hz. The improvement is mainly by the suppression of the first five RRO components as can be seen from the power spectrum plot of the PES with and without the controller activated in Figure 12 and Figure 13 respectively.

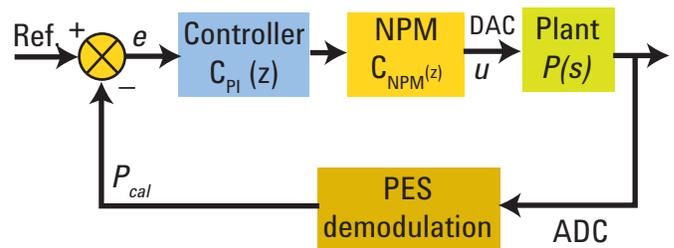


Figure 10. Block diagram of Servo control system.

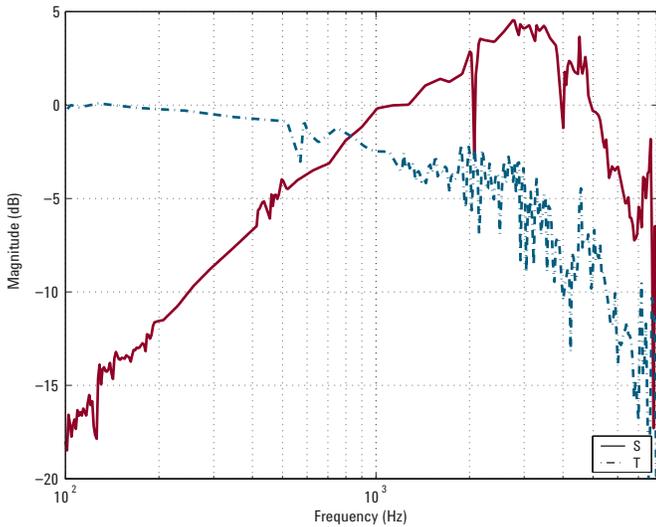


Figure 11. Sensitivity (S) and complementary sensitivity (T) functions based on PI controller.

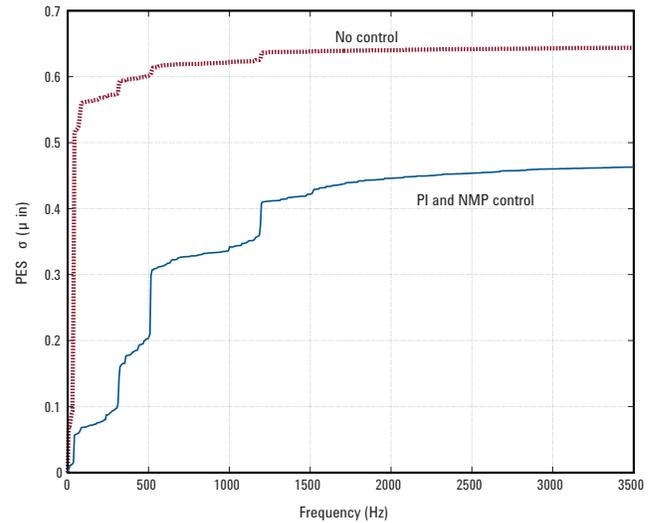


Figure 14. PES 3 σ value frequency at different frequency with and without Servo control.

As can be seen from Figure 11, the peak value of the sensitivity transfer function ($1/(1+C(z)P(z))$) is about 4.5 dB and Servo bandwidth is about 1050 Hz. The improvement is mainly by the suppression of the first five RRO components as can be seen from the power spectrum plot of the PES with and without the controller activated in Figure 12 and Figure 13 respectively.

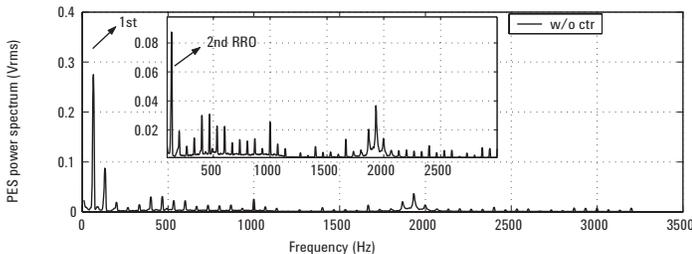


Figure 12. Power spectrum of PES without Servo control.

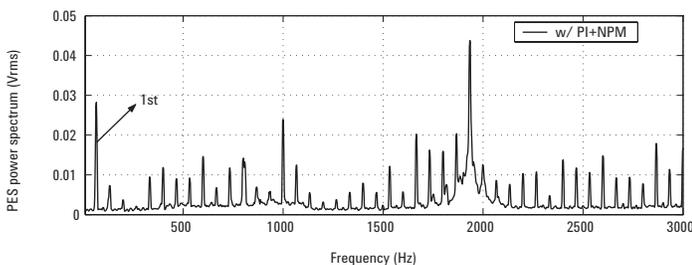


Figure 13. Power spectrum of PES with Servo control.

6. Conclusions

The PC-based Servo control system, which allows flexibility, fast deployment, and programming ease, has been implemented successfully on a commercial spin stand. The PC-based control system samples at 500 MS/s using an Agilent Acqiris PCI digitizer card and a multifunction NI DAQ card under Linux OS platform. A combination of frequency-encoded Servo pattern and Goertzel decoding scheme is used to generate the PES.

Total PES computation and processing time, which is about 62 μ s (5% due to non-real time PC setup), has been attained. With 230 Servo sectors per revolution and spindle speed at 4000 RPM, the PES sampling rate is 15 kHz. Together with the PES demodulation and low-mass piezo-based head cartridge designed, a closed-loop Servo bandwidth of 1050 Hz has been achieved for spin stand Servo control and 21.9% reduction of disturbances has been achieved as compared without Servo control.

The experimental dynamic testing and control implementation reveals that the proposed designs can be used for precise micro actuation spin stand for ultra high recording density. Thus, the added-on piezo actuator to the spin stand head cartridge is a viable solution to the Servo control problem for high track density magnetic recording on spin stand.

We note that the time taken to initiate and transfer the data to PC for PES calculation incurs much of the overhead. To further improve the Servo update rate, computation of PES within FPGA is a feasible choice. In [9], Agilent Acqiris cPCI card which has an on-board FPGA (Model: U1080A) is used to generate the PES and Servo update rate can be increased to 300 kHz.

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