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Tape drive track following using cascade control

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Abstract: Ultra-precise positioning of the recording head over the data tracks is required to achieve the aggressive track density scaling envisioned for future tape storage systems. The track-follow control system is responsible for reducing the misalignment between the tape and the head created primarily by lateral motion of the flexible medium. The challenge of improving the track-following accuracy becomes even more difficult in the presence of external vibration disturbances. Typically, position error signal (PES) information is measured at the tape head using pre-formatted servo information and is used in a feedback controller during track-following to maintain the position of the read/write elements at the desired position during tape transport. In this paper, a track-follow scheme is introduced in which a high-bandwidth low-noise position sensor is used in conjunction with the position information read back by the head from preformatted servo patterns on the tape. A cascade control configuration is proposed, in which first an inner loop is designed based on the actuator position information provided by the sensor. The high-bandwidth and low-noise characteristics of the sensor enable a high closed-loop bandwidth of the inner system that effectively compensates for external vibration disturbances. Subsequently, using a cascade structure, a PES-based controller is designed that compensates for the lateral tape motion disturbances. Simulation and experimental results are presented that illustrate the performance of the proposed scheme compared to a conventional PES-based track-follow control system.

Keywords: Magnetic tape storage, cascade control, H∞ control

1. INTRODUCTION

Magnetic tape drives are the current technology of choice for disaster recovery and long term archiving applications and are also used extensively for back-up and restore applications. The continued success of tape for these applications arises from its low total cost of ownership and very high reliability. In order to remain successful, it is critical to maintain tape's cost advantage by continuing to scale the cartridge capacity and areal density of tape systems at least as fast as the capacity scaling of hard disk drives. Tape systems such as linear tape open (LTO[1]) generations 1 through 5 achieved capacity increases by scaling both linear density and track density by roughly equal factors. However, the capacity gains of more recent systems such as LTO generation 6, have been achieved by scaling track density much more aggressively than linear density. In the future, this trend of modest linear density increases is likely to continue, and capacity scaling will have to be achieved through aggressive track density scaling (Argumedo et. al., 2008; Cherubini et. al., 2011; INSIC Tape Roadmap, 2012). In order to enable such aggressive track density scaling, the performance of the track follow system of future tape drives will have to be dramatically improved (Lantz et. al., 2012).

The track-follow control system in tape drives is responsible for reducing the misalignment between the tape and the head during read and write operations. Misalignment arises primarily from lateral motion of the flexible medium as it is streamed over the read/write head. The challenge of improving the track following accuracy in tape systems is further aggravated by the wide range of conditions in which tape drives must operate. For example, magnetic tape is used extensively for the collection of seismic data on ships used for oil exploration. In such environments the tape drive is exposed to external vibrations that give rise to additional track following disturbances that must be compensated for by the control system.

In modern tape systems, the position of the head relative to the tape is measured using servo information that is pre-formatted onto the tape during manufacturing. This position signal derived from this servo information is used in a feedback controller during tape transport to correct tape head misalignments. Feedforward control schemes have been investigated that use information from micro electro-mechanical (MEMS) based accelerometers to enhance the closed-loop track-follow accuracy in the presence of vibration disturbances (Pantazi and Lantz, 2013). In this paper, a track-follow scheme is introduced in which a high-bandwidth low-noise position sensor is used in conjunction with the position information read back by the head from the servo patterns on the tape. A cascade control configuration is proposed, in which an inner loop is designed based on the actuator position information provided by the sensor. The high-bandwidth and low-noise characteristics of the sensor enable a high closed-loop bandwidth of the inner system that effectively compensates for external vibration disturbances. A second PES-based controller is then used to compensate for lateral tape motion disturbances. Simulation and

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experimental results are presented that illustrate the performance of the proposed scheme compared to a conventional servo pattern only based track-follow control system.

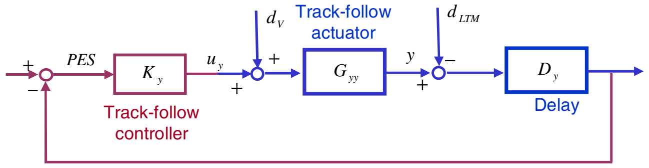

Fig. 1. Block diagram of the tape drive track-follow control system.

2. TRACK-FOLLOWING IN TAPE DRIVES

The track-follow control system in tape drives adjusts the lateral position of the head actuator using a position error signal (PES), which measures the error between the target track location on the tape and the position of the head. The PES information is derived from servo patterns that are preformatted on the tape media during manufacturing and read back during tape transport using dedicated servo readers. A block diagram representation of the closed-loop system responsible for the lateral head positioning is shown in Fig. 1. The lateral dynamics of the head actuator are captured by the transfer function G_{yy}. Figure 2 shows the experimentally obtained frequency response of the track-follow actuator measured with the servo pattern and with an optical sensor. The actuator has well defined dynamics that are dominated by the fundamental resonance at approx 100 Hz. The delay observed in the phase response data captured using the servo pattern at a tape speed of 2 m/s, is not part of the actuator response but corresponds to the measurement delay depicted by D_y in Fig. 1. The measurement delay is mainly determined by the servo pattern format and the tape speed as discussed in Lantz et. al., (2012).

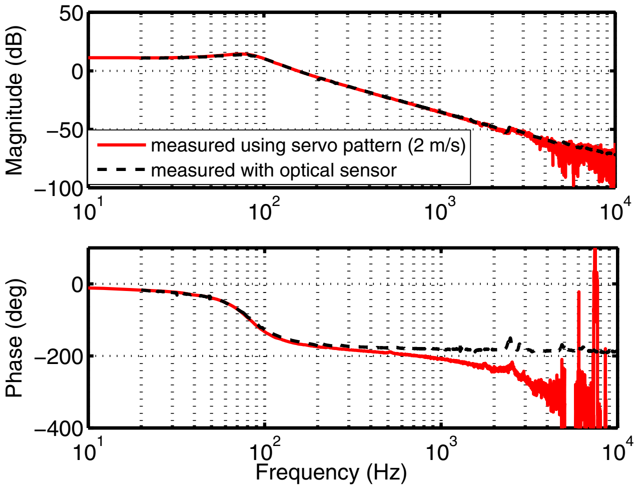

Fig. 2. Head actuator frequency response measured with the servo pattern at 2 m/s and with an optical position sensor.

There are two main disturbance inputs that affect the track-follow performance, as shown in the block diagram of Fig. 1. Lateral tape motion (LTM) of the flexible medium, d_{LTM} in Fig. 1, is the main disturbance in track-following during normal operating conditions. The second type of disturbance that must be considered arises from external vibrations of the drive that occur under some operating conditions and is indicated by d_v in Fig. 1. Figure 3 shows the power spectral density of the LTM measured using dedicated servo readers and the servo pattern information pre-formatted on the tape. LTM is mainly created by mechanical imperfections of the tape path components such as rollers and reels. The mechanical source and the operating tape speed determine the spectral characteristics of the LTM disturbances as illustrated in Fig. 3. A more detailed description and discussion of LTM characteristics can be found in Pantazi et. al. (2012).

Achieving the track-following accuracy that will be required for future tape systems becomes more challenging during operation under vibration conditions. Figure 4 shows a typical vibration profile in terms of the acceleration input to the tape drive system that describes the vibration conditions under which the drive is required to operate. To experimentally characterize the performance under vibration conditions, a vibration test system is used to create external disturbances in the lateral direction according to the acceleration profile. The vibration system consists of a shaker (TIRA Exciter 200N, TIRA Power Amp 500VA) that generates the external disturbances, an accelerometer (Endevco 2222C and Endevco 133 Signal Conditioner) that measures the applied acceleration and a vibration controller (Data Physics) that ensures the application of the vibration profile based on the acceleration measurement. A spectrum of the accelerometer output captured during a typical vibration test is also shown in Fig. 4 for comparison.

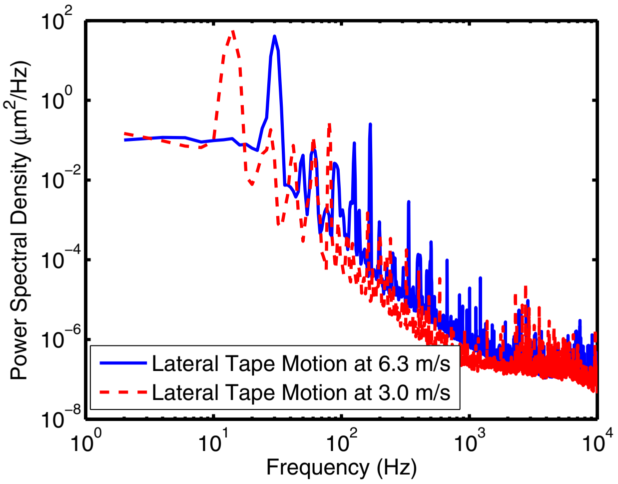

Fig. 3. Power spectral density of lateral tape motion measured at 6.3 m/s and 3.0 m/s.

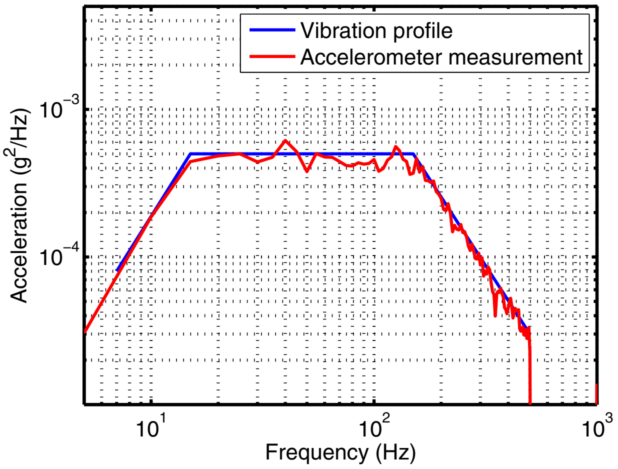

Fig. 4. Typical vibration profile and power spectral density of the acceleration applied during a typical vibration test.

The bandwidth requirements of the track-follow control system are set by the frequency characteristics of the LTM and the external vibration disturbances, denoted as d_{LTM} and d_v, respectively in the block diagram of Fig. 1. In the conventional one-degree-of-freedom closed-loop system, deviations from the target track location created by the LTM and the external disturbances are both measured by the PES. The feedback controller K_y uses the measured PES to generate the control current u_y that drives the head actuator. The closed-loop bandwidth that can be achieved is limited by the resulting higher sensitivity to position measurement noise as well as effects that arise from the measurement delay. Operation at low tape speeds increases the time required to generate a lateral position estimate from the servo pattern and therefore increases the loop delay.

3. TRACK-FOLLOWING USING CASCADE CONTROL

The performance of the conventional one-degree-of-freedom control system can be improved by decoupling the requirements of the LTM and the vibration disturbance compensation. To achieve this, a high-bandwidth low-noise position sensor is introduced that measures the position of the head actuator with respect to tape drive frame. The position measurement from the sensor is used in conjunction with the PES information read back from the head. The additional position information enables a cascade control configuration where the design requirements of the two controllers are decoupled.

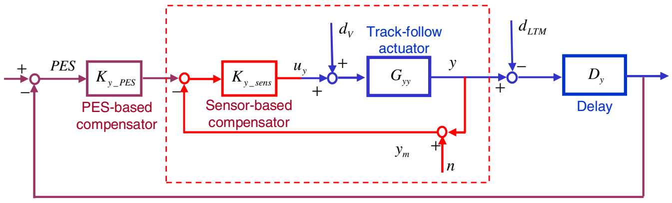

Fig. 5. Cascade control configuration.

A block diagram of the cascade control configuration is depicted in Fig. 5. An inner loop is designed (indicated by the dotted lines) that makes use of the additional position measurement y_m provided by the position sensor. The sensor-based feedback controller K_{y_sens} is designed to increase the bandwidth of the track-follow actuator, reduce uncertainties and minimize the effects of external vibrations on the actuator position y. The use of the position sensor to increase the actuator bandwidth provides the additional benefit of reducing the effect of measurement noise on the closed loop track follow performance. To achieve the control design goals, the external sensor must provide a high bandwidth and low noise position measurement and a sufficiently large position measurement range, ideally comparable to the actuator range of motion. These requirements on the position sensor are very important in achieving accurate positioning.

To compensate for the LTM disturbances a PES-based controller K_{y_PES} is designed and connected in a cascade control configuration. The output of the controller K_{y_PES} provides the reference input to the inner loop controller K_{y_sens}. An advantage of this cascade implementation is that it clearly decouples the requirements and the design of the two controllers. First the controller K_{y_sens} is designed to minimize the effects of d_v on the actuator output y and then K_{y_PES} is designed to minimize the effects of d_{LTM} on PES.

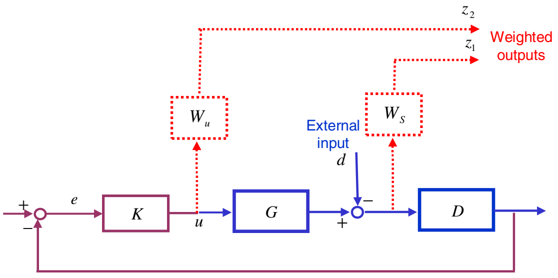

Fig. 6. Block diagram of the H_∞ control formulation.

An H_∞ control design approach is employed to independently design the two controllers in the cascade control configuration. The block diagram of the H_∞ control formulation is depicted in Fig. 6. Two weighting functions, W_S and W_u, are used to describe the requirements on the closed-loop system. W_S captures the closed-loop bandwidth requirements and W_u ensures that the control signal u is within allowable limits. The H_∞ optimization problem is formulated using the general control configuration (Skogestad and Postletwaithe, 1996). In this configuration, the exogenous input is $w=[d]$, the exogenous output is $z=\begin{bmatrix} z_1 \\ z_2 \end{bmatrix}$, the sensed output is e and the control signal is u. The H_∞ control design problem is to find a stabilizing controller K such that $\|T_{zw}\|_\infty < \gamma$, where γ is a constant approx. equal to 1. T_{zw} is the closed-loop transfer function matrix relating z with w. For the control design of the sensor-based controller K_{y_sens}, a second-order model of the track-follow actuator that captures the fundamental resonance was used as the plant G. The measurement delay in the inner loop is negligible, therefore in this problem formulation the delay D was set to 1. A model that captures the inner-loop response was used as the plant for the subsequent design of the PES-based controller K_{y_PES}. In this case, the delay D corresponds to the servo pattern delay. The decoupling requirements of the cascade control architecture are expressed in terms of the weighting functions W_S and W_u in the control formulations of the sensor-based and the PES-based controllers. Specifically, a high-bandwidth controller is required in the inner-loop system and a high gain controller at low frequencies is required for tracking the LTM in the outer loop. Figure 7 depicts the magnitude response of the W_S weighting function that corresponds to the sensor-based and the PES-based control designs.

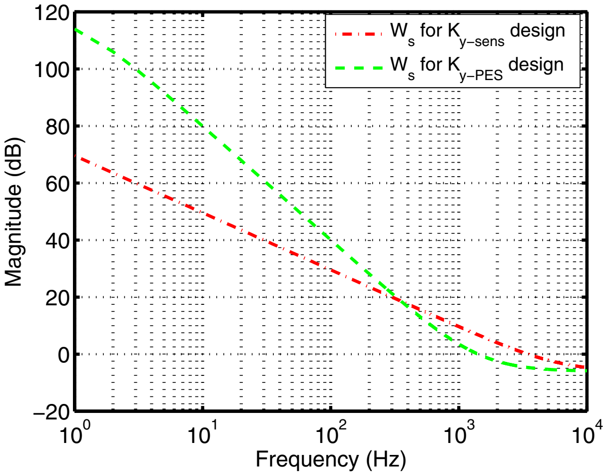

Fig. 7. Magnitude response of the weighting function W_S for the sensor-based and the PES-based control design.

Using the H_∞ synthesis, a 3rd order controller is obtained for K_{y_sens} and a 7th order controller is obtained for K_{y_PES}. The magnitude response of the resulting controllers is shown in Fig. 8. As can be seen in the figure, the task of increasing the actuator closed-loop bandwidth is assigned to the K_{y_sens} controller, whereas the tracking of the low-frequency LTM is assigned to the K_{y_PES} controller. For comparison, Fig. 8 also presents the magnitude response of the one-degree-of-freedom controller K_y shown in the block diagram of Fig. 1, which was also designed using a similar H_∞ control design approach.

The benefit of the proposed control structure can be further illustrated by comparing the response of the track-follow actuator model and the inner closed-loop system shown in Fig. 9. As mentioned above, the bandwidth of the track-follow actuator is determined by the fundamental resonance mode at approx. 100 Hz. The response of the inner closed-loop system shows that we can extend the bandwidth up to approx. 1.5 kHz using the external position sensor.

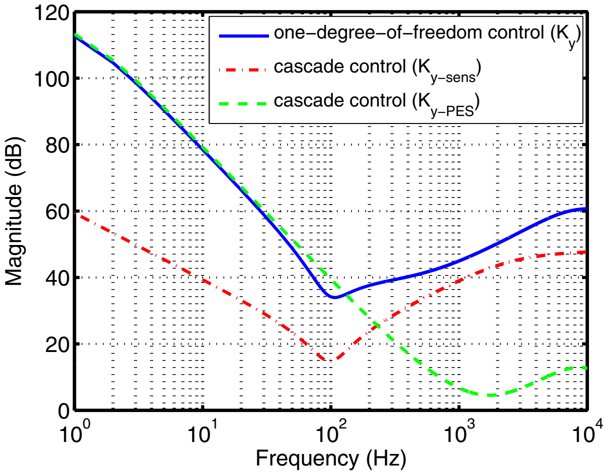

Fig. 8. Magnitude response of controllers K_{y_sens}, K_{y_PES} and K_y.

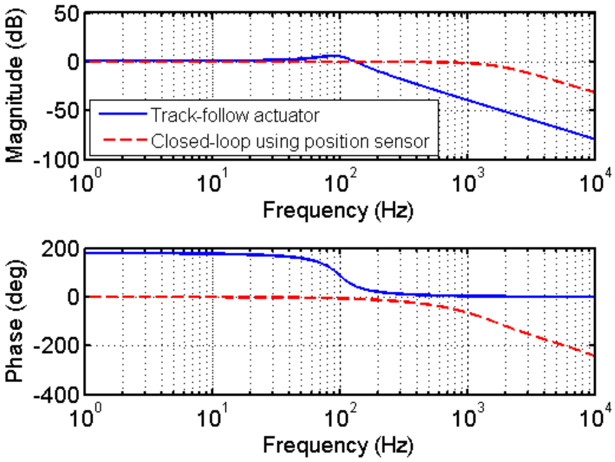

Fig. 9. Comparison of magnitude and phase response of the track-follow actuator model and the inner closed-loop system.

4. PERFORMANCE RESULTS

The performance of the proposed cascade control is evaluated using an external optical position sensor (MTI 2100 Probe Module). The optical probe provides a high-resolution measurement of the track-follow actuator position. The actuator and the optical probe setup are shown in the photograph of Fig. 10. Other position sensors can be used for the inner loop control system such as a giant magnetoresistance-based (GMR) position sensor (Tuma et. al., 2013). A GMR-based sensor has the capability of providing high-bandwidth and high-resolution position measurement. In this paper we present experimental and simulation results using the optical position sensor shown in Fig. 10.

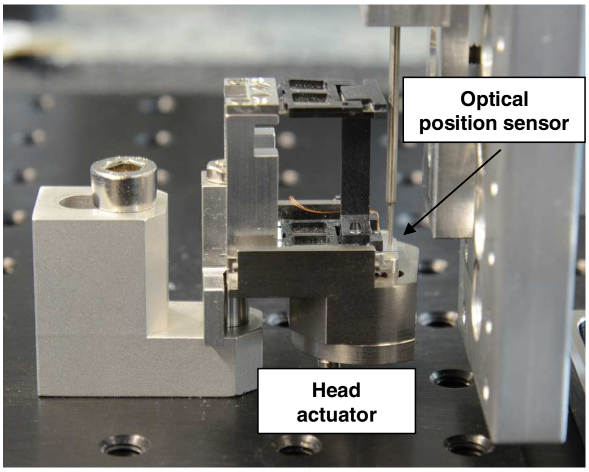

Fig. 10. Photograph of the track-follow actuator with the optical position sensor.

The K_{y_sens} controller designed based on the H_∞ approach was implemented in a digital signal processor hardware platform using a sampling period of 20 µs. Figure 11 shows the experimentally identified closed-loop transfer function of the inner closed-loop system using the optical sensor. The analytical response corresponding to this transfer function is also shown. It can be seen that there is a very good agreement between the two. The –3 dB bandwidth based on the closed-loop transfer function from the reference to the output is approx. 1.5 kHz as shown in Fig. 11.

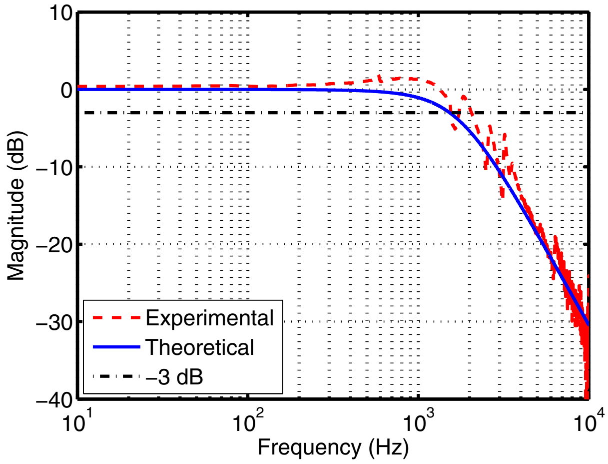

Fig. 11. Analytical and experimental closed-loop frequency response using the optical position sensor.

The proposed cascade control scheme was simulated using experimentally captured waveforms. Specifically, the LTM and vibration disturbances were estimated from closed-loop data captured using the vibration test system. The measurement noise signal of the optical sensor was captured by keeping the actuator in a fixed position. Identified models for the actuator and the PES measurement delay systems were also utilized. The simulation results show that the proposed technique provides significant improvement in the PES performance, especially in the presence of external vibrations. Specifically, Fig. 12 shows the simulation results of the closed-loop PES under vibration conditions with the one-degree-of-freedom PES-based controller and with the cascade control based jointly on PES and the position sensor. Figure 13 shows a comparison of the power spectral density of the closed-loop PES for the two cases. It can be observed that most of the improved performance is in the frequency area of the vibration disturbances where the sensor-based inner loop enhances the performance of the system. The performance in terms of the 1σ PES is 250 nm with the one-degree-of-freedom PES-based control and 63 nm using the additional position sensor and the cascade control configuration, a reduction in track following errors of approximately 74%.

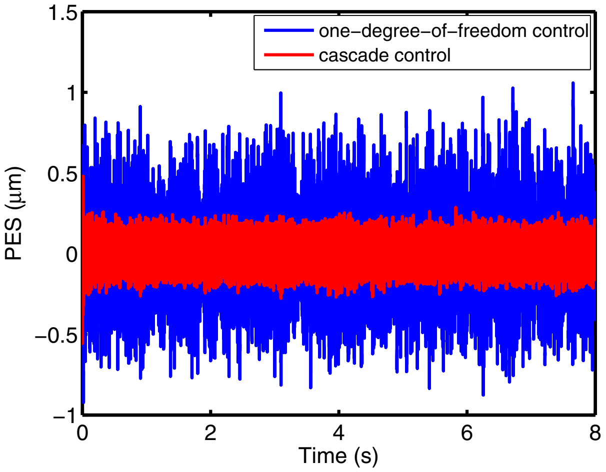

Fig. 12. Simulated closed-loop PES under vibration conditions of the one-degree-of-freedom PES-based control system and the cascade control system based jointly on PES and an optical position sensor.

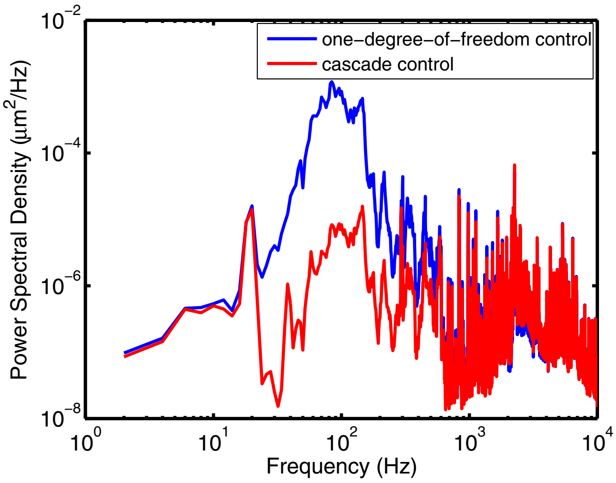

Fig. 13. Power spectral density of the data of Fig. 11 comparing the spectra of the simulated closed-loop PES under vibration conditions of the one-degree-of-freedom PES-based control system and the cascade control system based jointly on PES and the optical position sensor.

6. CONCLUSIONS

Improving the track-following performance of tape drives during operation in the presence of external vibrations will be essential to achieving the aggressive track density scaling required for the continued scaling of tape cartridge capacity. The cascade control structure introduced here which combines information from a high-bandwidth low-noise position sensor with the position information generated from servo patterns on the tape provides a promising approach to achieving this goal. Performance simulations based on experimental data demonstrated a 74% reduction in track-following errors under vibration conditions using the new scheme compared to a conventional controller that uses only information from the tape servo pattern. The low noise and high bandwidth characteristics of the sensor used for the inner loop are essential to achieving such performance improvements.

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