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MODELING, SERVO CONTROL AND MOTION PLANNING FOR HIGH TRACK DENSITY RECORDING

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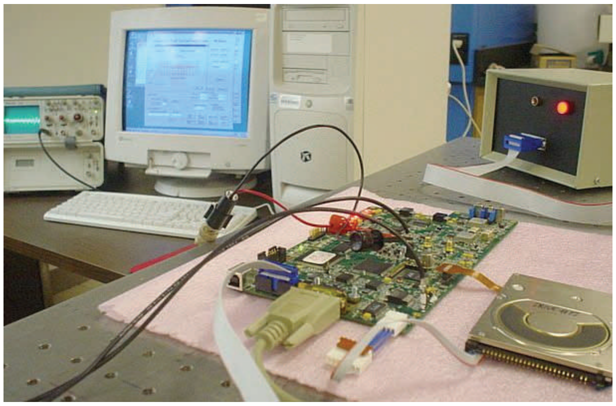
An essential component for high density and fast performance mechanical data storage systems is the ability to follow the physical tracks on which data exchange takes place. Data exchange in the form of reading and writing (magnetic) bits typically requires off-track positioning errors of a read/write element less than 10 percent of the actual track pitch. To give an indication of the position accuracy required, one of the latest developments in perpendicular recording technology used in modern hard disk drives, that remain to be an indispensable storage resource for digital appliances and recording equipment, have shown recording capabilities on an ultra-narrow track pitch of 65nm. Such ultra-narrow track pitches obviously places high demands on the performance and accuracy of the servo system needed to follow the physical tracks within less than 10nm accuracy.

The design problem of a high performance and robust servo system is an intricate trade-off determined by actual system dynamics (actuator bandwidth), incomplete knowledge of system dynamics (uncertainty and product variations) and disturbances (rotating media, windage, friction) acting on the system. The Advanced Motion and Servo Laboratory (AMSL) at the CMRR directed by Prof. de Callafon, focuses on the development of high performance and robust servo control algorithms by developing the tools and algorithms to improve the information on system and disturbances dynamics. Better information on system and disturbances dynamics can alleviate the intricate design problem and help tune servo control and motion planning algorithms to squeeze out the maximally achievable performance. The ultimate goal is to develop these methods in such a way that they can be integrated in the firmware of system, providing automatic identification and tuning for servo control.



Supported by partial funding from the Information Storage Industry Consortium (INSIC) TAPE and EHDR program, the AMSL houses several magnetic data storage experiments that include hard disk drives (HDD) and linear tape open (LTO) storage systems. The unique property of the experiments in the AMSL is the ability to measure an *in situ* magnetically coded off-track Position Error Signal (PES), while having the opportunity to inject independent excitation signals

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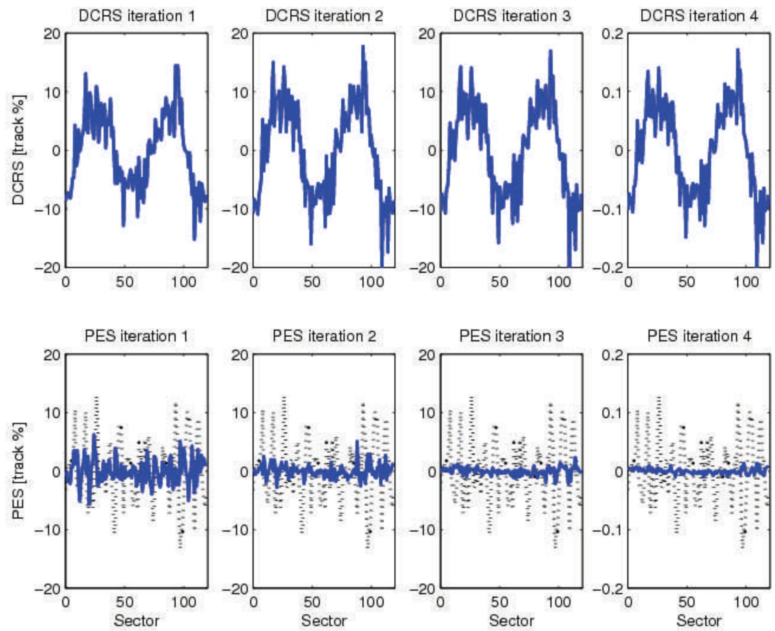
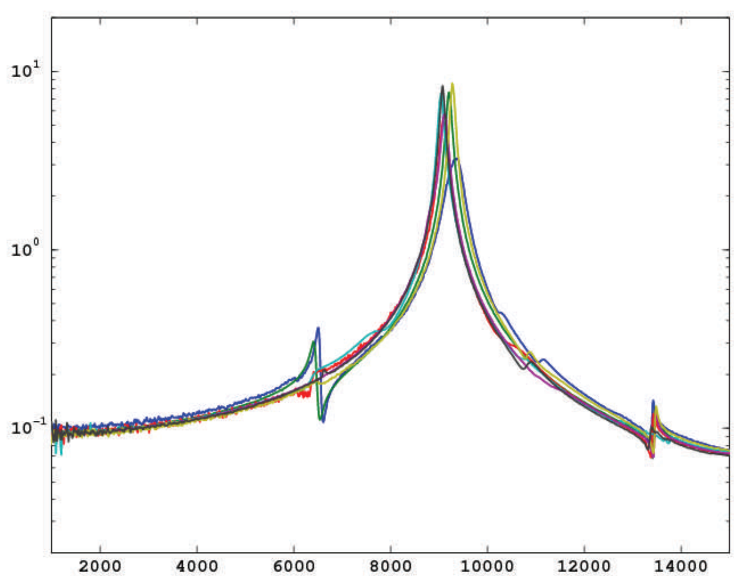
during servo operation. This allows Prof. de Callafon and his students to perform experiments that can unravel the dynamics of the servo actuator and characterize the spectrum of any stochastic disturbances (non-repeatable runout errors) that cause PES and limit servo performance. A recent publication in Automatica [1] summarizes the two-step identification procedure that allows estimation of models for actuator and disturbance dynamics, whereas collaborative work with Prof Oboe [2] has shown the successful implementation of this procedure on actual data obtained from a HDD system.



Independently, work funded by several gifts from Headway to the AMSL has unleashed the ability to target specific periodic disturbance (repeatable runout errors) typically seen in the rotating storage media of a HDD. By the development of an Iterative Learning Control algorithm, that only requires limited knowledge of the closed-loop response of a servo actuator, Prof. de Callafon and his student Matthew Graham were able to show in [3] how fast decay of all periodic disturbance components can be obtained. Progress of the actual measurement of the PES obtained from one of the HDD applications in the AMSL in the CMRR has been depicted in the figure on the left.



The experimental data obtained from several dual-stage actuators was also the basis of a study associated to model uncertainty due to product variabilities. Dual-stage actuators are much smaller and thus provide a larger dynamic range for high bandwidth servo, but bandwidth is limited due to uncertainties in the dynamic behavior of the actuator. Such variations can be seen in many practical situations where one servo control

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algorithm is required to work with a large set of possible variations in actuator dynamics [4]. Independent work with Prof. Oboe [5] and Prof. Horowitz [6] have shown how such variations can be modeled in a single model with both a unstructured and structured uncertainty description. A snapshot of the measured frequency responses used in this study of seven (same model) dual-stage actuators has been depicted in the figure on the right.

Recent work of the AMSL also includes the development of new frequency domain identification techniques that are distributed to sponsors via a Matlab® coded Graphical User Interface that are based on realization methods [7]. Realization methods are data-based modeling techniques that do not require optimization techniques to compute parameter estimates of models. Instead, straightforward matrix analysis techniques such as a Singular Value Decomposition or a QR factorization are needed to compute a state space realizations of a discrete-time actuator model.

Our most recent realization technique allows the estimation of full actuator actuator dynamics on the basis of simple step response experiments. The ability to perform repeated simple experiments and the absence of optimization code needed to compute parameter estimates brings the opportunity to code these estimation techniques directly in firmware much closer to reality. We are confident that automatic servo tuning based on actual *in situ* measurements from actuator and disturbance dynamics provides new opportunities towards designing optimal servo control algorithms that can minimize position error signals. With such enhanced modeling and servo control algorithms in place and encoded in firmware, ultra-narrow track pitches will provide less of challenge for future high density data recording systems.

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[2] R. Antonello, R. Oboe And R.A. de Callafon, "An Identification Experiment For Simultaneous Estimation Of Low-Order Actuator And Windage Models In A Hard Disk Drive," *IEEE International Symposium On Industrial Electronics*, Vigo, Spain, pp. 3102-3107, 2007.

[3] M.R. Graham, R.A. de Callafon, "An Iterative Learning Design For Repeatable Runout Cancellation In Disk Drives," *IEEE Transactions on Control Systems Technology*, Vol. 14, No. 3, pp. 474-482, 2006.

[4] M.R. Graham, R.A. de Callafon And L. Shrinkle, "Modeling And Low-Order Control of Hard Disk Drives with Consideration for Product Variability," *IEEE Transactions On Magnetics*, Vol. 42, No. 10, pp. 2588-2590, 2006.

[5] M. Rotunno, R. Oboe, R.A. de Callafon, "Modeling Product Variations In Hard Disk Drive Micro-Actuator Suspensions," *Microsystem Technologies,* Vol. 12, No. 9, pp. 803-813, 2006.

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[7] M. Claes, M.R. Graham and R.A. de Callafon, "Frequency Domain Subspace Identification of a Tape Servo System," *Microsystem Technologies*, Vol. 13, pp. 1439-1447, 2007