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An Identification Experiment for Simultaneous Estimation of Low-Order Actuator and Windage Models in a Hard Disk Drive

Riccardo Antonello, Roberto Oboe
Dept. of Mechanical and Structural Engineering
University of Trento
via Mesiano 77, 38050 Trento, Italy
E-mail: {antonelr,oboer}@ing.unitn.it

Raymond A. de Callafon
Dept. of Mechanical and Aerospace Engineering
University of California at San Diego
9500 Gilman Drive, La Jolla CA 92093-0411 USA
E-mail: callafon@ucsd.edu

***Abstract*— This paper describes an identification experiment designed in order to simultaneous estimate low-order parametric models for the servo actuator and windage disturbance dynamics of hard disk drives. The challenging identification issues imposed by the experiment, namely the closed loop operating conditions and the low-complexity requirements about the estimated models, are overcome by using an identification method that has been recently developed by one of the authors and called "extended two-stage method". The experiment is carried out on a commercial 3.5 in, 7200 rpm hard disk drive operating in standard track following mode and with his own cover, so that realistic working conditions for the servo actuator and the internal airflow pattern inducing windage are reproduced. Low order, control relevant actuator and windage models are estimated using the proposed identification method. The effectiveness of the method is assessed by comparing its results with those obtained using standard parametric and non-parametric identification methods.**

I. INTRODUCTION

In a modern hard disk drive (HDD) data is magnetically stored on the surface of one or several spinning disks (platters), along concentric and ideally circular patterns called tracks. Data is read and written by means of a read-write head mounted on the tip of a flexible suspension. The suspension is moved across the disk surface by a servo actuator, which is responsible of aligning the head with the target track. Alignment accuracy is a key aspect for improving storage density and data transfer rate in HDDs, and it must be guaranteed in face of several internal and external disturbances affecting the position of the head and causing off-track motions (*run-out errors*) [1]. As reported in [2], the most detrimental disturbance during track following mode is the windage noise, which arises from the interaction of the head suspension and the airflow produced by the spinning disks. The windage can be reduced with a careful mechanical design (i.e. by choosing properly the disk diameter, the position and aerodynamics of the actuator, the properties of the enclosure, the disk materials, the air pressure in the enclosure) and by choosing low spinning rates for the platters. However, the last option contrasts with the requirement of improving access rate to stored information. Therefore, windage effects on head position must be reduced mainly with the aid of a high precision servo control.

The design of an effective servo control for disturbance rejection in track following mode is usually done by employing model-based control design techniques: thus, the knowledge of meaningful models of both the servo actuator and the disturbance affecting the head position is required.

While obtaining a realistic model for the servo actuator is a rather easy task [3], the derivation of a significant windage model for control design purposes is not trivial. Computational flow models such as those derived in [4], [5], [6] are too complex to be useful for control design. Moreover, they focus on the flow pattern between co-rotating disks instead of providing relevant information for control tuning, such as the interaction of air flutters with the head suspension. The effect of such interaction is to excite the resonant modes of the suspension, thus inducing vibrations that are detrimental for positioning accuracy.

A more viable way to estimate meaningful models for controller tuning purposes consists of exploiting identification-based modeling techniques [7]: this is the modeling approach adopted in this paper. In particular, this paper describes an identification experiment aimed to simultaneously estimate low-order, control-design relevant models of the servo actuator and windage dynamics. In order to reproduce realistic operation conditions, a standard 3.5 in, 7200 rpm commercial drive has been used for the experiment. Since the nature of airflow depends on the air pressure and the geometry of the chamber within the hard disk case, the experiment has been carried out on a drive operating with its own cover. The windage disturbance has been characterized during normal track following mode and the internal servo controller has been used to stabilize the head on a target track.

In order to address the issue of estimating low order models of both plant and output disturbance dynamics from data collected under closed loop conditions, the identification method developed in [8] has been exploited. This method, called *extended two-stage method*, differs from previously available closed loop, control-oriented identification methods

[9], [10], [11], [12], because it allows to take control over the orders of both plant and disturbance models, and not just the plant model.

The remainder of this paper is organized as follows: details about experiment design and organization are given in Section II. Section III describes briefly the extended two-stage identification method and its properties. Section IV illustrates the identification results obtained for the commercial hard disk drive used in the experiment. Finally, some concluding remarks are given in Section V.

II. EXPERIMENT DESIGN

The experiment has been designed in order to collect meaningful and realistic data for modeling both the actuator and windage dynamics. In order to make the experiment easily reproducible, it has been avoided the use of spinstands or similar dedicated and expensive hardware: instead, the experiment has been carried out on a standard 3.5 in, 7200 rpm commercial drive, using a minimal amount of external electronics and instrumentations.

An important issue when dealing with windage modeling consists of identifying how it affects the head positioning error. This is usually done by pulling its effect apart from the effects induced by other disturbance sources [2]. One way to separate the positioning error induced by the windage disturbance from the the sensor noise due to the built in position sensor consists of using an external position sensor: in the experiment, a Polytec OFV 300 Laser Doppler Vibrometer (LDV) has been used to measure absolute head displacements. In order to let the head accessible to the laser beam of the LDV, a lateral opening has been made on the cover of the hard disk drive. The internal environment has been preserved against external pollutants by applying a transparent glass slide on the lateral hole. The experimental device is depicted in fig.1.

Fig. 1. Modified hard disk drive used in the experiment. A lateral opening has been made on the case in order to let the read/write head accessible to the reference laser beam of the LDV. A transparent glass slide applied on the hole protects the drive against dust.

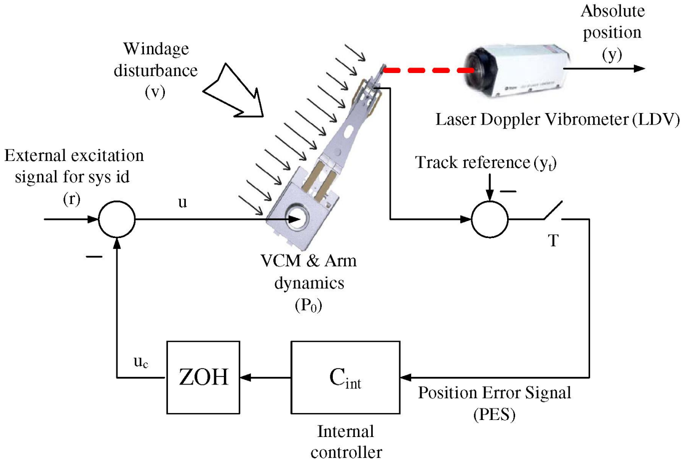

Fig. 2. Structure of the experiment. Plant and windage dynamics are characterized during normal track-following mode of operation, while the internal track-following controller C_{int} is running. A laser doppler vibrometer (LDV) is used to measure absolute radial displacement of the read/write head.

The models have been derived in order to being representative of the track following mode of operation: the read/write head has been positioned on a suitable track (located around the middle/outer diameter of the hard disk drive platter) so that the laser spot of the LDV could be easily shone on the side of the head, and the internal controller has been exploited to stabilize the system around the selected position. The position signal retrieved by the LDV in such conditions contains actually a repetitive component, which is due to the irregular physical shape of the track to be followed and to spindle induced vibrations, and a non-repetitive component, which can be assumed to be produced by air turbulence.

The experiment setup is similar to those of related works such as [13], [14], in which an LDV is used for indirect, non contact measurement of the head position. However, some differences should be pointed out: firstly, the disk drive operates with his own cover and in a closed environment, so that the air flow during the experiment corresponds to that found in a commercial drive under normal working conditions. This situation differs from that of [14], where an open (i.e. without cover) drive experiment is described. Secondly, the experiment proposed in this paper is carried out under closed loop control, using the internal servo controller as stabilizing controller, instead of an external one as in [13]. This simplifies the preparation of the experimental setup; however, it introduces additional side effects to take care of. In particular, the internal controller stabilizes the head position with respect to the track center instead of an absolute reference, as in the case of an external feedback control based on LDV measurements. Hence, the position signal is affected by a repetitive component due to the irregular shape of the track to be followed. Furthermore, adaptation mechanisms implemented in the servo control make the whole system time varying.

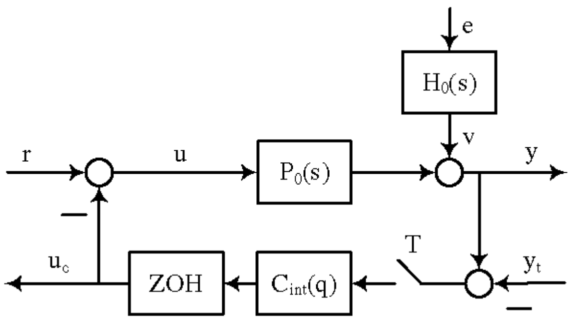

Fig. 3. Block diagram of the experiment.

During the experiment, a least square procedure has been employed to fit a sum of harmonics, synchronous with disk rotation, to LDV position measurement, assuming to collect a fixed number of samples at each disk rotation. Subsequently, the repetitive component, i.e. the sum of harmonics, has been removed from the position signal to obtain the non-repetitive component induced by windage. Moreover, time varying effects due to adaptive mechanisms have been neglected, in order to make the identification problem feasible: this assumption normally holds when the adaptation mechanism is much slower than the experiment duration.

The block diagram in fig.3 shows the configuration of the experiment: $P_0(s)$ denotes the actuator dynamics (composed of voice-coil motor, the E-block and the suspension), while $v(t)$ denotes the windage disturbance (which is assumed to be the output of a shaping filter driven by white noise $e(t)$). $C_{int}(q)$ represents the internal digital controller during track following mode, with q denoting the unit time-shift operator ($q\,u(t) = u(t+T)$). The sampling clock has period T and it is synchronized with the disk rotation, so that a fixed number of samples are collected at each disk rotation. The signal $y(t)$ is the absolute head position as measured by the LDV, while $y_t(t)$ denotes the track reference, so that their difference is the positioning error measured by the built-in position sensor. For identification purposes, an external excitation signal $r(t)$ has been injected in the hard disk, by summing it with the actual control signal $u_c(t)$ provided by the internal controller. A 16 bit A/D acquisition board has been used to collect samples of $y(t)$, $r(t)$ and $u(t)$, with the same sampling clock of the internal controller.

A full discrete-time version of the system depicted in fig.3 can be derived by taking discrete-time equivalents $P_0(q)$, $H_0(q)$ of $P_0(s)$, $H_0(s)$: this can be done by considering sampled signals only, and by removing repetitive components as described before. Referring to a full discrete-time systems, it follows that:

$$y(t) = P_0(q)u(t) + v(t)\,, \qquad v(t) = H_0(q)e(t) \tag{1}$$

where $e(t)$ is a white noise with variance λ, $u(t) = r(t) - C(q)y(t)$ and $C(q)$ represents an "equivalent" controller with input $y(t)$ and output $u_c(t)$. Hence the closed loop system is governed by:

$$y(t) = \bar{P}(q)r(t) + \bar{H}(q)e(t) \tag{2}$$

where $\bar{P}(q) = P_0(q)S_0(q)$, $\bar{H}(q) = H_0(q)S_0(q)$ are the closed-loop actuator and windage dynamics and $S_0(q) = (1 + C(q)P_0(q))^{-1}$ is the sensitivity function.

III. IDENTIFICATION METHOD

The problem addressed in this paper is to simultaneously estimate approximate parametric models $P_\theta(q) \doteq P(q,\theta)$, $H_\theta(q) \doteq H(q,\theta)$ of both actuator dynamics $P_0(q)$ and windage dynamics $H_0(q)$, given the input/output measurements $Z^N = \{r(t), u(t), y(t) \,:\, t = kT,\, k = 1\ldots N\}$ obtained under closed loop conditions, as explained in previous section. The order and accuracy level of estimated models must be geared for design of an effective, yet simple servo-control for disturbance rejection (*control relevant modelling*).

Several closed loop identification methods have been introduced in the literature so far [11], [10], [15], but they don't deal with the issue of simultaneous estimation of *low order*, control relevant plant and disturbance models. Recently, this issue has been reconsidered and solved in [8] by extending the standard two-stage method for closed loop identification [7]. In this paper, we make use of such method to successfully solve the aforementioned identification problem.

A. Description of the method

The extended two-stage method presented in [8] is based on the standard two stage method, which has been introduced in order to overcome one of the major drawbacks of closed loop identification, namely the correlation of the unmeasurable noise with any of the signals in the feedback loop, and in particular the plant input [9]. The innovation introduced with the extended two-stage method is to allow control over the order of the estimated disturbance model, in addition to the order of plant model, as in the standard two-stage method case.

The identification procedure is composed by two steps:

1) in the first step, a standard open-loop identification of the closed-loop transfer functions $\bar{P}(q)$, $\bar{H}(q)$ is performed on the basis of the closed-loop signal $r(t)$ (excitation signal) and $y(t)$ (plant output). The estimated models $\bar{P}_*(q)$ and $\bar{H}_*(q)$ are used to compute the closed-loop prediction error:

$$\varepsilon_{cl}(t) = \bar{H}_*^{-1}(q)\ \big(\, y(t) - \bar{P}_*(q)\, r(t)\,\big) \tag{3}$$

which is a realization of the white noise $e(t)$ in the feedback loop of fig.3. The models $\bar{P}_*(q)$, $\bar{H}_*(q)$ are only used for filtering purposes and they don't affect the complexity of the final approximate models, so no specific restrictions on their orders are imposed.

2) In the second step, the reference signal $r(t)$ and the prediction error $\varepsilon_{cl}(t)$ are filtered by an estimate $S_*(q)$ of the sensitivity function $S_0(q)$ to form the filtered signals

$$u_f(t) \doteq S_*(q)\, r(t)\,, \qquad \varepsilon_f(t) \doteq S_*(q)\, \varepsilon_{cl}(t) \tag{4}$$

If the controller transfer function $C(q)$ is known, an estimate of the sensitivity function can be retrieved by using the relation $S_*(q) = 1 - C(q)\,\bar{P}_*(q)$, where $\bar{P}_*(q)$ is the the closed-loop actuator model obtained in the first step of the method. When the controller transfer function is unknown, the knowledge of the plant input signal $u(t)$ is required, so that the sensitivity function can be estimated as the transfer function from the reference signal $r(t)$ to the input signal $u(t)$.

As suggested by (2), the filtered signals $u_f(t)$, $\varepsilon_f(t)$ can be both considered as measured inputs of a 2-inputs, 1-output MISO system with output $y(t)$. Then, by choosing an output error (OE) model structure [7] of the type:

$$y(t) = [P_\theta(q)\ H_\theta(q)] \begin{bmatrix} u_f(t) \\ \varepsilon_f(t) \end{bmatrix} + e_1(t) \qquad (5)$$

with $e_1(t)$ white noise, a standard open-loop prediction-error identification method based on the minimization of the 2-norm of the output error can be exploited to estimate low-order approximate models $P_\theta(q)$ of plant dynamics and $H_\theta(q)$ of disturbance dynamics.

As in the two-stage method, de-correlation of the unmeasured noise $e(t)$ and the plant input $u(t)$ is achieved by generating a disturbance free plant input, using the external reference input $r(t)$ (uncorrelated with the noise) and a high-order model of the transfer function from the injection point of $r(t)$ to the plant input. The innovation introduced with the extended two-stage method consists of embedding $H_\theta(q)$ in the plant dynamics of the OE model structure (5), thus allowing complete control over its order.

B. *Properties of method*

Since the extended two-stage method is explicitly designed in order to estimate low-order approximations of both plant and disturbance dynamics, it is interesting to analyze the approximation level achieved by the method. The asymptotic bias distribution of the transfer function estimates, i.e. the misfit between the limiting model and the true system, plays an important role in evaluating the identification accuracy, especially when the true system does not belong to the model set [12]. An expression of the bias distribution is usually derived by looking at the frequency-domain expression for the 2-norm of the prediction error.

The following theorem summarizes the most general situation for the extended two-stage method:

Theorem 1: Suppose that $\bar{P} = P_0 S_0$, $\bar{H} = H_0 S_0$ are not consistently estimated in the first step of the method, that is: $\bar{P}_* \neq \bar{P}$, $\bar{H}_* \neq \bar{H}$. Then, for $N \to \infty$ the two-norm minimization of the prediction error associated with the OE model (5) is equivalent to:

$$\begin{gathered} \min_\theta \textstyle\int_{-\pi}^{\pi} |(P_0 - P_\theta)S_0 + \dots \\ \dots + (\bar{P}_* - \bar{P})(P_\theta C + H_\theta(1 - C\bar{P}_*)\bar{H}_*^{-1})|^2\, \Phi_r + \cdots \\ \cdots + |(H_0 - H_\theta)S_0 + \cdots \\ \cdots + H_\theta \left[S_0 - (1 - C\bar{P}_*)\bar{H}\bar{H}_*^{-1}\right]|^2\, \Phi_e\, d\omega \qquad (6) \end{gathered}$$

where P_θ and H_θ denote the models estimated in the second step of the method, Φ_r and Φ_e denote the spectrum of the excitation signal $r(t)$ and the unmeasured white noise $e(t)$, respectively, and $\omega = 2\pi f T$ is the normalized angular frequency.

Proof: Please refer to [8], Theorem 1. ■

The result of the theorem is more appealing when consistent estimates of the transfer functions $\bar{P}$, $\bar{H}$ are obtained in the first step of the method. In this special case, the theorem specializes as follows:

Corollary 1: Suppose that $\bar{P} = P_0 S_0$, $\bar{H} = H_0 S_0$ are consistently estimated in the first step of the method, that is: $\bar{P}_* = \bar{P}$, $\bar{H}_* = \bar{H}$ Then, for $N \to \infty$ the two-norm minimization of the prediction error associated with the OE model (5) is equivalent to:

$$\min_\theta \int_{-\pi}^{\pi} |P_0 - P_\theta|^2 |S_0|^2 \Phi_r + |H_0 - H_\theta|^2 |S_0|^2 \Phi_e \, d\omega \quad (7)$$

Proof: The result follows immediately by substituting $\bar{P}_* = \bar{P}$, $\bar{H}_* = \bar{H}$ into (6) and by using the identity $S_0 = 1 - C\,\bar{P}$. ■

The sensitivity function S_0 acts as a frequency weight in the identification criterion (7): in particular, the higher the sensitivity is, the more accurate the approximation is. This is a remarkable property when estimated models are used for control design purposes, because a higher modeling accuracy is needed where the feedback loop is more sensitive.

The bias of the estimation can be further tuned by properly shaping the spectrum of $r(t)$ and by choosing an independent parametrization of the plant and disturbance models (i.e. by splitting up the parameter vector $\theta = [\alpha^T\ \beta^T]^T$ and defining the parametric models $P_\alpha(q)$ and $H_\beta(q)$) in order to avoid that the plant model bias affects the disturbance model estimation and viceversa.

Regarding the modeling accuracy, it can be noted from (7) that consistent models are estimated when the true system belongs to the model set, i.e. when there exists a parameter θ such that $P_\theta = P_0$ and $H_\theta = H_0$.

IV. EXPERIMENTAL RESULTS

The experiment setup described in Sec.II has been implemented in order to gather relevant data for model identification, namely the data set $Z^N = \{r(t), u(t), y(t) : t = kT,\ k = 1 \dots N\}$ containing samples of the external reference signal $r(t)$, the servo actuator command $u(t)$ and the head displacement measurement $y(t)$ (provided the LDV) (see Sec.III). The sampling time of the acquisition board has been synchronized with the master-clock of the hard disk drive servo controller (sampling frequency: $F_s = 52.80\ kHz$), so that a constant number of samples were acquired at every disk rotation (equals to the number of servo sectors [1] in each track: $N_{servo} = 440$). Repetitive components on both $u(t)$ and $y(t)$ have been estimated by fitting a sum of harmonics, synchronous with disk rotation frequency, to the collected data. Then, repetitive-component free signals have been used for system identification.

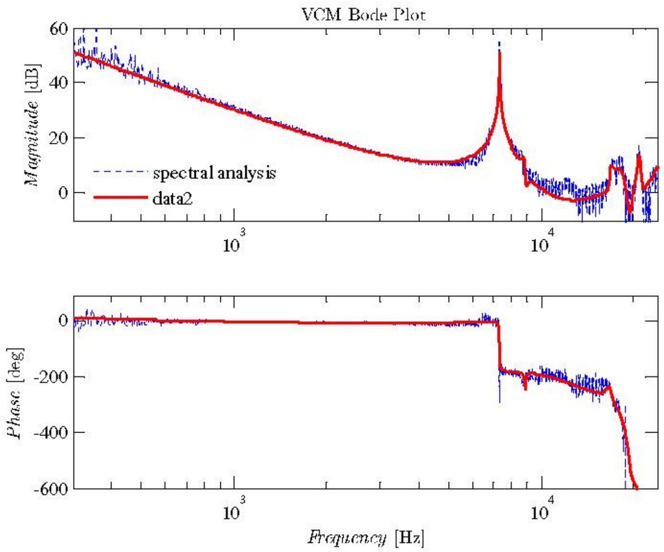

Fig. 4. Bode plot of the 14^{th} order actuator model obtained using the extended two-stage method. Spectral estimate of the actuator dynamics is shown for validation purposes.

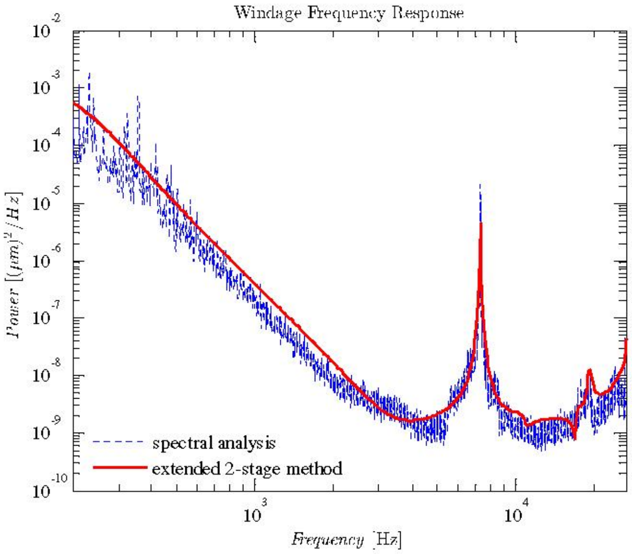

Fig. 5. Estimation of the windage disturbance spectrum $\Phi_{vv}(e^{j\omega}) = \left|H_0(e^{j\omega})\right|^2 \Phi_{ee}(e^{j\omega})$ obtained using the extended two-stage method. Spectral estimate of the windage dynamics is shown for validation purposes.

Two different parametric estimation methods have been tested on the same data set (composed of $N = 80000$ preprocessed samples) - the extended two-stage method and the standard direct method [7] - with the purpose of identifying low-order approximated parametric models $P_\theta(q)$, $H_\theta(q)$ of the servo actuator and windage dynamics ($P_0(q)$, $H_0(q)$, respectively). The following parametrization has been chosen for $P_\theta(q)$, $H_\theta(q)$:

$$P_\theta(q) = \frac{b_n\, q^{-n} + b_{n-1}\, q^{-n+1} \cdots + b_1\, q^{-1} + b_0}{q^{-n} + a_{n-1}\, q^{-n+1} \cdots + a_1\, q^{-1} + a_0} \tag{8}$$

$$H_\theta(q) = \frac{q^{-n} + c_{n-1}\, q^{-n+1} \cdots + c_1\, q^{-1} + c_0}{q^{-n} + d_{n-1}\, q^{-n+1} \cdots + d_1\, q^{-1} + d_0} \tag{9}$$

$$\begin{aligned}\theta = [&a_{n-1}, \cdots a_1,\, a_0,\, b_n, \cdots b_1,\, b_0\\ &c_{n-1}, \cdots c_1,\, c_0,\, d_{n-1}, \cdots d_1,\, d_0]\end{aligned}$$

For the first step of the extended two-stage method, a 28^{th} order ARMAX model has been selected to estimate the closed loop actuator and windage dynamics ($\bar{P}(q)$ and $\bar{H}(q)$, respectively). In the second step, a 22^{th} order ARMAX model has been used to estimate the loop sensitivity function $S_0(q)$. Finally, the servo actuator and windage dynamics have been approximated with 14^{th} order models.

For comparison purposes, a model of the same order has been estimated using the direct method. In the direct method, closed loop identification of plant and disturbance dynamics is performed by employing a standard open loop prediction error minimization method, regardless of the presence of feedback.

Models derived with either the extended two-stage method or with the direct method have been validated by using results of spectral analysis as a reference. The non-parametric estimates $\widehat{P}(e^{j\omega})$, $\widehat{H}(e^{j\omega})$ of the actuator and windage dynamics have been derived according to the following equations:

$$\widehat{P}(e^{j\omega}) = \frac{\widehat{\Phi}_{ry}(e^{j\omega})}{\widehat{\Phi}_{ru}(e^{j\omega})} \tag{10}$$

$$\widehat{\Phi}_{vv}(e^{j\omega}) = \left[\widehat{\Phi}_{yy}(e^{j\omega}) - \frac{|\widehat{\Phi}_{ry}(e^{j\omega})|^2}{\widehat{\Phi}_{rr}(e^{j\omega})}\right] \frac{\widehat{\Phi}^2_{rr}(e^{j\omega})}{|\widehat{\Phi}_{ru}(e^{j\omega})|^2} \tag{11}$$

where $\widehat{\Phi}_{vv}(e^{j\omega}) = |\widehat{H}(e^{j\omega})|^2\, \widehat{\Phi}_{ee}(e^{j\omega})$ and $\widehat{\Phi}_{rr}$, $\widehat{\Phi}_{yy}$, $\widehat{\Phi}_{vv}$ denote the estimates of auto-spectrums of $r(t)$, $y(t)$ and $v(t)$, respectively, while $\widehat{\Phi}_{ru}$, $\widehat{\Phi}_{ry}$ are estimates of cross-spectrums. Relevant auto-spectrum and cross-spectrum have been obtained using a digital signal analyzer (DSA).

Parametric and non-parametric identification results are shown in fig.4-7. In fig.4 the Bode plot of the 14^{th} order parametric model $P_\theta(q)$ estimated with the extended two-stage method is compared with the spectral analysis results; the same comparison is reported in fig.6 for direct identification results. Figures 5 and 7 show the estimates of the windage disturbance spectrum $\Phi_{vv}(e^{j\omega}) = \left|H_0(e^{j\omega})\right|^2 \Phi_{ee}(e^{j\omega})$ obtained with the extended two-stage method and the direct method, respectively. As for the servo-actuator models, the results are validated using spectral analysis.

As expected, in the same experimental conditions and with the same model orders requirements, the extended two stage method performs better than the direct method, yielding more consistent, less biased estimations.

V. CONCLUSIONS

The paper has described an identification experiment that allows to estimate low-order parametric models of both servo actuator and windage dynamics in a hard disk drive. In order to reproduce realistic working conditions, the experiment has been carried out on a commercial drive while operating in

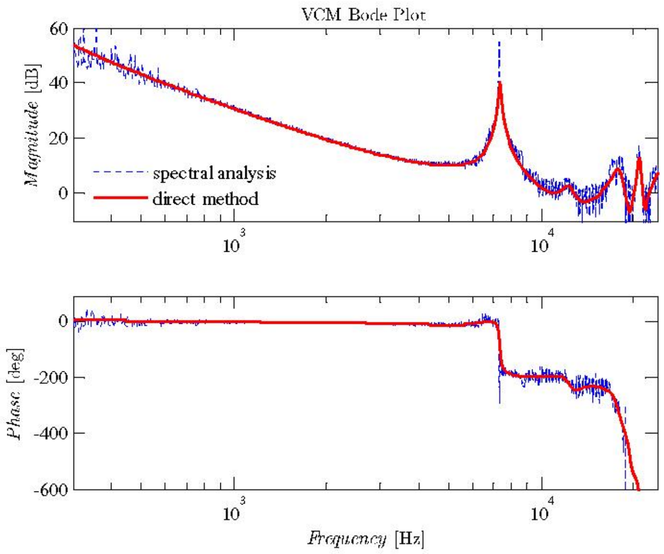

Fig. 6. Bode plot of the 14^{th} order actuator model obtained using the direct method. Spectral estimate of the actuator dynamics is shown for validation purposes.

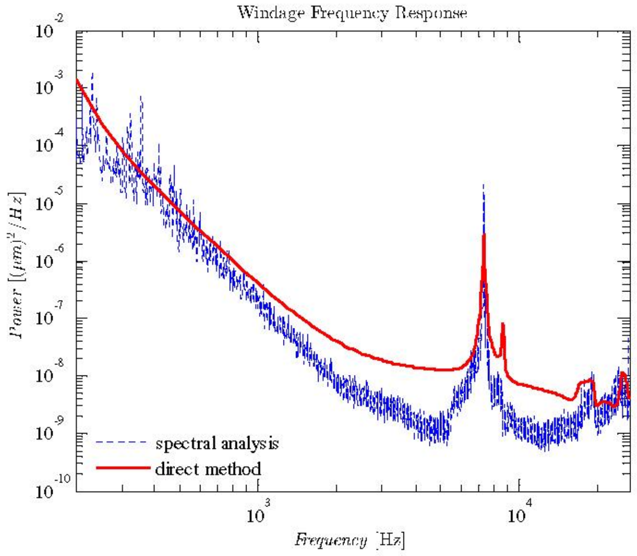

Fig. 7. Estimation of the windage disturbance spectrum $\Phi_{vv}(e^{j\omega}) = \left|H_0(e^{j\omega})\right|^2 \Phi_{ee}(e^{j\omega})$ obtained using the direct method. Spectral estimate of the windage dynamics is shown for validation purposes.

standard track following mode, under the supervision of its internal servo controller. A lateral opening has been made on the external case of the drive to perform interferometric measurement of the head position. However, the disk has operated under "closed case" conditions, so that the airflow pattern during the experiment matches that one encountered during normal operating conditions.

The identification has been performed by employing a recently developed closed loop identification method, called extended two-stage method, that is specifically geared for the simultaneous estimation of low order plant and disturbance dynamics on the basis of closed loop data. Since modeling accuracy is weighted by the sensitivity function of the control loop, the estimated models are particularly suited for control design purposes and they can be used for tuning the windage-induced vibrations rejection capabilities of the servo controller, thus improving positioning accuracy and enabling further increasing of recording density.

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