N94- 35839

HIGH PERFORMANCE DATA ACQUISITION, IDENTIFICATION, AND MONITORING FOR ACTIVE MAGNETIC BEARINGS

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p. 6

SUMMARY

Future Active Magnetic Bearing systems (AMB) must feature easier on-site tuning, higher stiffness and damping, better robustness with respect to undesirable vibrations in housing and foundation, and enhanced monitoring and identification abilities. To get closer to these goals we developed a fast parallel link from the digitally controlled AMB to Matlab[1], which is used on a host computer for data processing, identification and controller layout. This enables the magnetic bearing to take its frequency responses without using any additional measurement equipment. These measurements can be used for AMB identification.

INTRODUCTION

Active Magnetic Bearing systems have already shown their feasibility in various applications [1]. Thanks to the progresses in AMB control [3],[6], the number of demanding AMB applications is growing fast. For that reason, there is a strong need for tools and facilities which enable rapid and cost effective prototyping.

A MATLAB INTERFACE FOR DIGITALLY CONTROLLED AMBs

We implemented digital AMB control on a fast TMS320C25 digital signal processor board (DSP) which enables stand-alone operation of the final AMB application. For installation and optimization purposes a fast parallel link to a host PC can be plugged onto the signal processor board. For the putting into operation of new AMB prototypes and for on-site tuning we developed a powerful Matlab-based environment on the host PC. This enables us to use all of Matlab's built-in facilities: numerics, signal processing, graphics, as well as the extensibility offered by available toolboxes on control, robust control and system identification.

[1] Matlab is a trademark of The MathWorks Inc. and has become an industrial standard software package for numerical computations.

The *low level* interface layer between Matlab and the AMB application basically consists of two commands for data reading from and writing to specified memory addresses of the signal processor board. This low level interfacing is implemented using Matlab's MEX facility of calling compiled and dynamically linked C subroutines.

With the *mid-level* interface layer between Matlab and the AMB controller board specific memory addresses no longer have to be kept in mind. Variables on the AMB controller board can be accessed by *name*, see figure 1, through a hidden cross reference table. This cross reference table not only manages the bookkeeping of memory addresses and variable names, but also enables the use of vector and matrix objects with *variable* size. This is particularly important for loading or changing controller state space matrices.

The *high level* Matlab interface layer incorporates tools for taking time history measurements of AMB controller variables, see figure 1. Frequency response measurements can be effectuated by a sine wave sweep. The sine wave is generated in the AMB signal processor program. It is completely configurable; i.e. frequency, amplitude, and excitation variables are controlled through the interactive Matlab user interface. We extended this measurement procedure for the multivariable case (MIMO). This is particularly useful for measuring radial couplings between different bearing planes. Finally, the high level Matlab interface automatically performs the controller parameter scalings needed for the fixed-point DSP board. Although floating point DSP boards have gained influence in the last few years they are still relatively expensive for industrial applications. Automatic controller parameter scaling eliminates some of the disadvantages caused by fixed point processing.

```
ts = 1000;
tmsvar('tsamp', ts);      % Writing to an AMB controller variable.
ts = tmsvar('tsamp');     % Reading back an AMB controller variable.
Ac = [0 1; 0 0];
tmsvar('a_cntr', Ac);     % Writing a matrix valued variable.
xt = scope('x');          % Time history of an AMB controller variable.
plot(xt);
```

Figure 1: Matlab access of AMB controller variables.

IDENTIFICATION OF MAGNETIC BEARING SYSTEMS

The aim of AMB identification consists in deriving a mathematical model of a magnetic bearing system by carrying out a (finite) number of input/output experiments. Frequency domain input/-output experiments (sine wave excitation with spectral analysis of the responses) are perfectly suitable for filtering out noise and non-linear phenomena.

A) Identification using much a–priori knowledge

The frequency domain measurements can be used to determine the numerator and denominator coefficients of the AMB plant using least square methods. In the case of voltage controlled magnetic bearings the plant transfer function can be accurately described by a third order system with no (finite) transmission zeros:

$$G(s) = \frac{1}{a_3 s^3 + a_2 s^2 + a_1 s + a_0}$$

Figure 2 shows the least square identification of a voltage controlled magnetic bearing (VCMB).

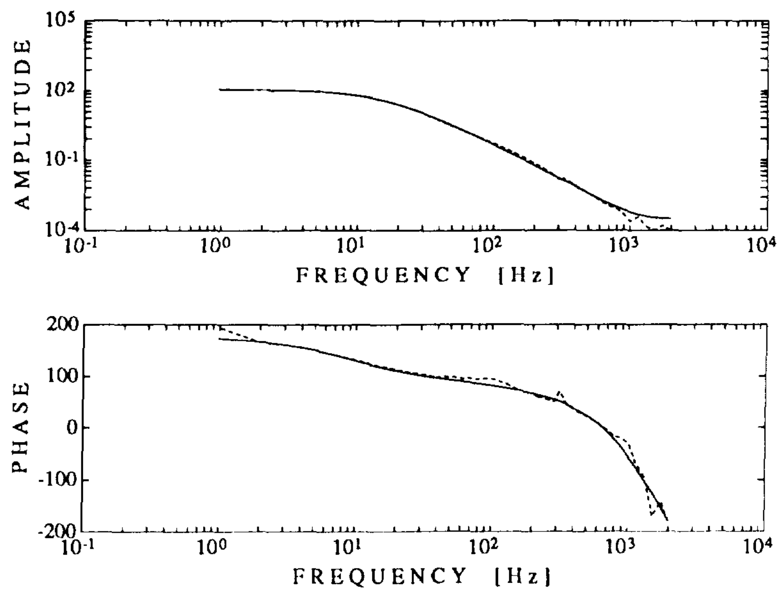

Figure 2: Solid: identification result, Dashed: measured frequency response of a VCMB.

The measured transfer function in figure 2 which relates displacement to input voltage was taken on a magnetically levitated tube spindle. In some cases it is useful to determine the bearing dynamics as a separate block. Since the modelling of the rotor is very accurately known in most cases, the parameter associated with the bearing dynamics can be identified using the overall frequency response measurements and the known rotor dynamics; see figure 3. This approach takes maximum use of available a–priori knowledge.

B) "Robust Identification Methods" using little a–priori knowledge

It is desirable that an identification algorithm be "stable" under small measurement noise or small perturbations of the data. For example, Lagrange interpolation (fitting a polynomial of minimal degree through the data) is known *not* to have this property. Figure 4 shows this bad behaviour of Lagrange interpolation. The noisy measurement data (marked with o) causes large oscillations of the identification output (solid curve). Although the identification error evaluated at the measurement points remains small, the deviation between the original transfer function (dashed) and the identification output (solid) is important. Robust identification seeks to prevent this salient bad behavior.

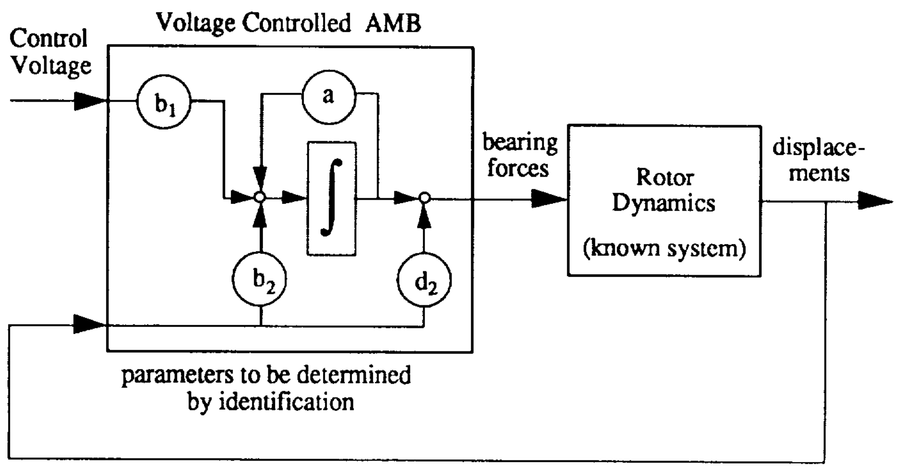

Figure 3: Identification of a voltage controlled magnetic bearing plant.

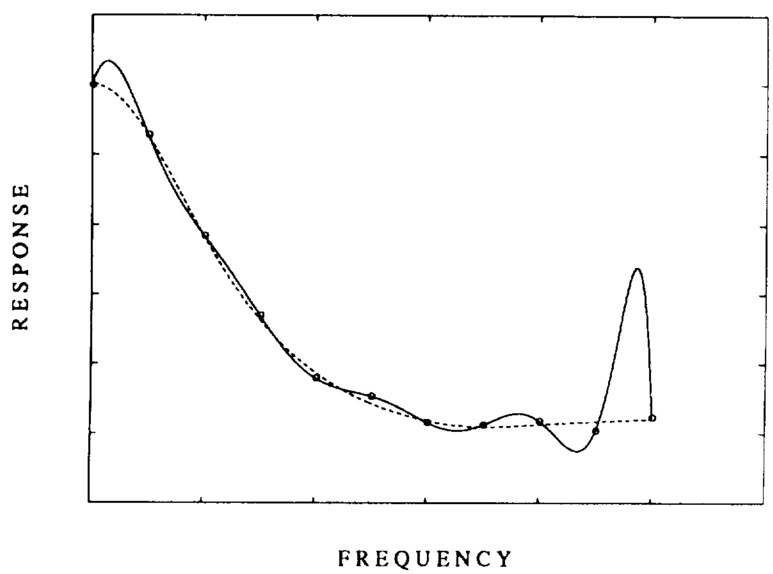

Figure 4: Robust identification seeks to prevent large sensitivities w.r.t. noisy data.

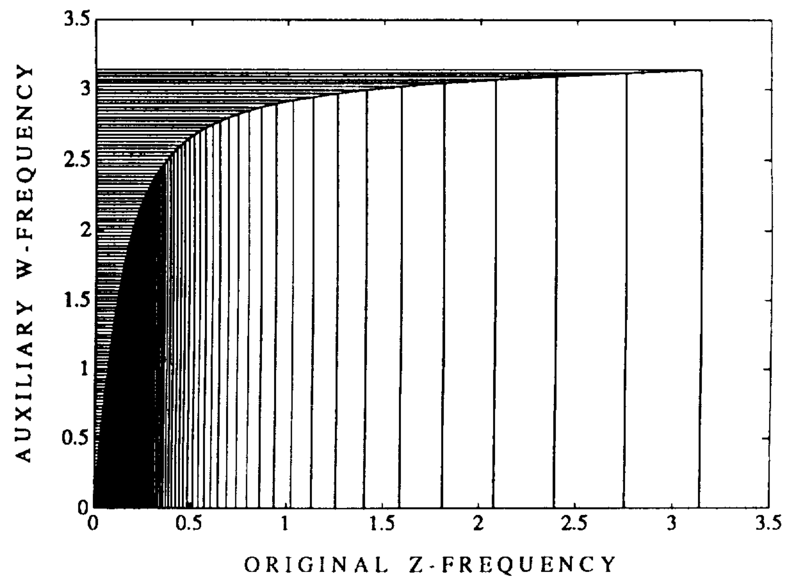

Figure 5: Bilinear frequency stretching.

The mathematical framework of "robust identification" and various identification algorithms were proposed recently in literature [4], [5], [7]. Most of these algorithms consist of two steps. In the first step, the frequency points are transformed to an impulse response function $\sum_{-N}^{+N} h_k z^k$ using inverse FFT and windowing functions. In the second step, the anti–causal part of the impulse response is approximated by a stable function using Nehari extension. Both steps can be easily implemented in Matlab since they rely only on standard matrix computations. The following section reports some of our experience with this identification approach.

When using methods [4], [5], [7] to identify a voltage controlled magnetic bearing of a tube spindle, we realized the following three points:

- Usually, the sampling rate is quite fast, compared to the open–loop system dynamics. For identification in the z–plane a very high number N of terms in the impulse response function $\sum_{-N}^{+N} h_k z^k$ is needed for accurate results. We lessened this problem by applying a bilinear transform which maps the unit disc $\{|z| < 1\}$ onto a unit disc $\{|w| < 1\}$ in a new w–plane. An equally spaced w frequency grid $w_k = e^{i\varphi_k}$ corresponds to an irregularly spaced z frequency grid, which in turn is closely spaced at low frequencies and more loosely at high frequencies; see figure 5. This bilinear transform allows us to diminish the number N of terms in the series $\sum_{-N}^{+N} \tilde{h}_k w^k$. After carrying out the identification in the w plane, the result is transformed back to the z–plane.

- The fast roll–off rate of transfer functions from voltage controlled magnetic bearings (60 dB/decade) causes an important *relative* identification error at high frequencies. Generally, an identification procedure achieving small *relative* error would be desirable. We used frequency weightings to incorporate this requirement.

- The methods proposed in [5], [6] are only applicable to stable systems. Since magnetic bearings are unstable plants one could identify closed-loop functions, e.g. the sensitivity function $S(s) = (1 - P(s) \cdot C(s))^{-1}$, and determine plant $P(s)$ using the known controller $C(s)$. This approach [8] ends up with a pole-zero cancellation which is a numerically delicate operation. Therefore, we preferred to identify the unstable plant and to replace the Nehari step in [5], [6] by a model reduction [2] of the two-sided impulse response $\sum_{-N}^{+N} \tilde{h}_k w^k$.

These three realizations allowed us a successful first step in "robust identification" of magnetic bearing systems. The detailed identification results will be published soon in a separate paper. Further investigations are required in order to determine for which cases which identification procedure, and which a-priori knowledge yields the "best" result.

SUMMARY

A Matlab-based environment for AMB prototyping and on-site tuning was developed. This environment includes tools for frequency response measurements and AMB identification. These tools proved extremely valuable for increasing the efficiency and reducing the costs of AMB prototyping and on-site tuning.

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