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SELF-TUNING DIGITAL STATE CONTROLLER FOR ACTIVE MAGNETIC BEARINGS

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Abstract. State methods are well suited to control Active Magnetic Bearings for supercritical rotors and now digital state controllers implemented on a signal processor system are used by S2M. The mechanical design analysis of the rotor allows a computer-aided design of the optimal observer and controller. The tuning of the observer and controller is automatically done on the actual shaft by the signal processor, thus reducing time and increasing performances, reliability and maintainability of Active Magnetic Bearings.

Keywords. Active magnetic bearings, state variable control, self-optimisation, signalprocessor.

1. INTRODUCTION

The dynamic performances of Active Magnetic Bearings make them well suited to suppress vibrations of flexible shafts allowing them to pass successfully many critical speeds.

The development of digital signal processors gives the opportunity to implement economically complex state variable controls even for very fast rotors (up to 120,000 rpm). The use of state variable controllers in these applications is only possible with a computer-aided commissioning.

Therefore, this paper describes a self-tuning state variable control system for the active magnetic bearings. The necessary state variables are obtained by an observer using only the signals of the position detectors associated with the magnetic bearings. A signal processor system performs the automatic tuning procedure of the controller and observer by means of an identification procedure.

2. COMPUTER AIDED DESIGN OF ROTORS:

2.1. Initial design:

The mechanical design of rotors is always aided by computer using a finite element method. The undamped structure is described by its geometry and the mechanical properties of the materials. The modal method is used for solving the differential system: displacements are then linear combinations of a reduced number of modal deformations associated with the eigen frequencies. The computer gives the critical speeds, the evolution of the natural frequencies and modal damping with the rotation speed, and the associated dynamic deformations.
Using the computed eigenvalues and eigenvectors we can establish a state model (figure 1) of the free-free shaft (without bearings):

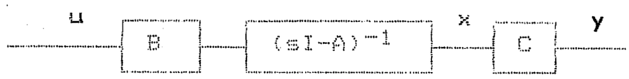

figure 1

$$x' = [A]\, x + [B]\, u$$
$$y = [C]\, x$$

where
x is the state vector (modal coordinates and derivative)
x' is the state vector derivative
y is the observation vector (positions at detectors locations)
u is the control vector (forces applied by the magnetic bearings)
A, B ,C are the state matrix of the system.

This mechanical model is completed by the filtering model (antialiasing filters and feedbacked power amplifiers). The negative stiffness of the electromagnets is corrected by an analog flux feedback in each amplifier in order to avoid non minimum phase system.

This modelisation allows optimisation of actuators and detectors positioning, and if necessary modifications of geometry or materials of the shaft. A first controller can be computed and its performances observed in simulation.

2.2. Modal analysis of the actual shaft:

When it is possible a modal analysis is done on the shaft just after manufacturing and before connecting with the stator. This analysis allows us to verify deviations from the initial design and reveals the influence of damping effects. On turbomachines rotors we can observe hysteretic damping.

This damping, due to the shrinkage of the different parts on the shaft, does not affect the magnitude of the resonances but gives phase rotations between excitation and measurement. The modelisation of this damping can be performed considering complex eigenvectors associated with the eigenvalues.

The transfer function $H_{ij}(w)$ between two nodes i and j at the frequency w is then:

$$H_{ij}(w) = \sum_{r=1}^{n} \Phi_{ri}\, \Phi_{rj} \,/\, (w_r^2 - w^2)$$

where Φ_{ri} and Φ_{rj} are the complex residues associated with the nodes i and j, for the eigen value w_r.

These complex residues cannot be used by the system analysis tools available today and an aproximative model of the phenomena with real parameters had been chosen. These parameters are identified from the measured transfer functions using a least squares method operating with complex values.

Fig 2 shows the geometry of an experimental flexible shaft, fig 3 the modal deformations computed with the finite elements modelisation, fig 4 the transfer function measured on the actual shaft and the response of the model identified with the least squares method.

The initial model can be updated and a better controller can be computed and tested in simulation and programmed in the digital signal processor.

But often the modal analysis is not possible on the free shaft and a self-commissioning procedure must be used on the machine implemented in a process.

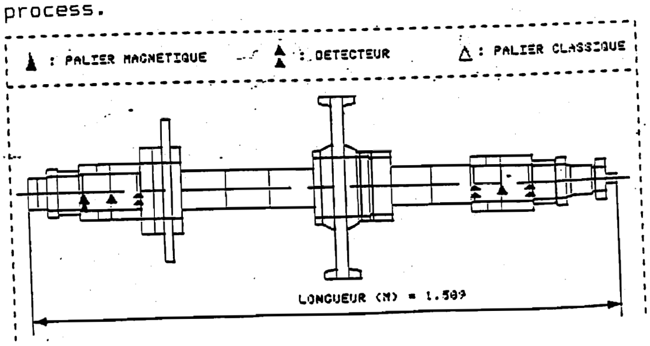

Figure 2

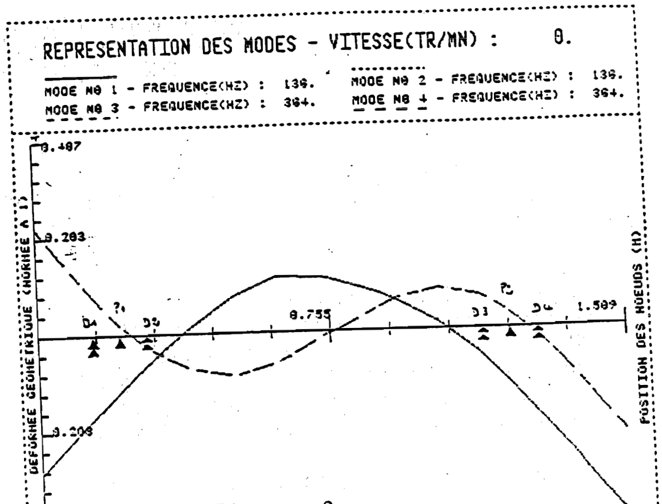

Figure 3

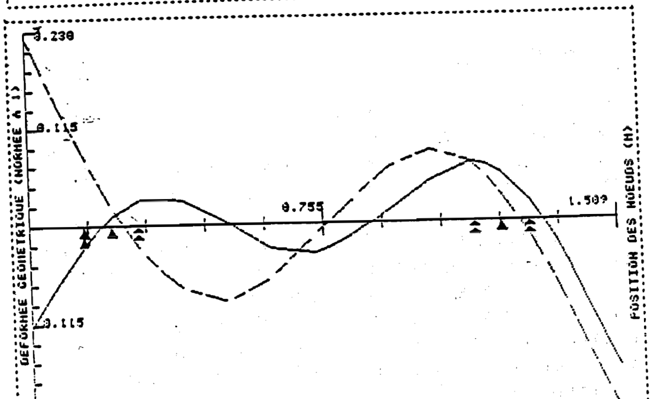

Figure 4

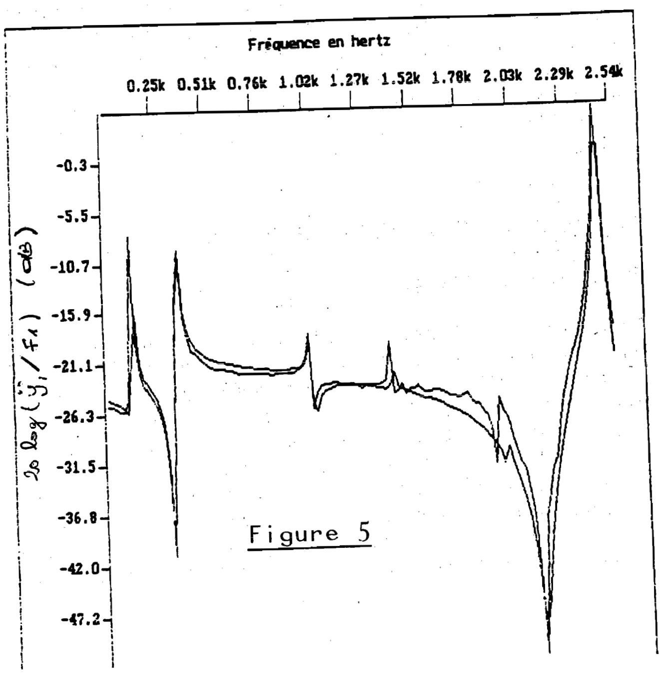

Figure 5

3. COMPUTER AIDED DESIGN OF THE CONTROLLERS:

3.1. Description of the state variable feedback controller:

The state controller consists of the weighted feedback of the modal state variables. The size of the model to use for the controller is determined by the rotation speed of the shaft. Generally, all the modes whose frequencies are under twice the rotation frequency must be damped. In order to have a good phase representation in the interesting bandwidth the complete model can be reduced using a residualisation method . After choosing the sampling frequency we compute the state transition matrix of the system and the state feedback vector F using the linear quadratic method (figure 6).

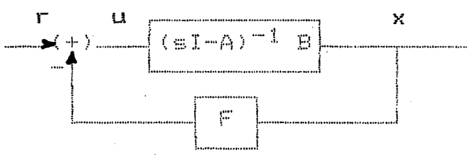

Figure 6

3.2. States observer configuration:

The state variables of the system are not all measurable. Only the position of the shaft is transmitted to the signal processor system. The remaining state variables, as well as the magnetic bearing force, must be computed by the observer. The error signal between the measured and the estimated shaft position (y_m-y_e) is feedbacked by the observer gain vector H.

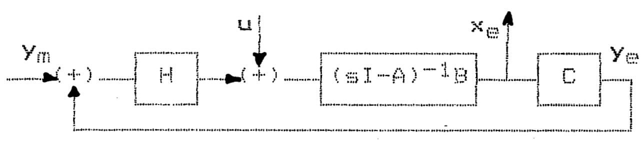

Figure 7

Dependent on the feedback coefficients, the observer error vanishes with an adjustable dynamic performance. The observer gain vector H is computed using Kalman Bucy Filter method.

3.3. Self-tuning control system:

Generally rotors of turbomachines are not available in their final state for modal analysis in laboratory. Then the commissioning of the controller has to be done on a rotor assembled with a complete machine using a self-optimisation procedure. The microcomputer which realizes the state control can compute the auto-commissioning without additional hardware costs.

In order to achieve a secure identification, an off-line procedure is selected. During this step, the shaft is supported by the magnetic bearings with very low stiffness, without damping the natural frequencies. The modal analysis operates automatically using magnetic bearings as actuators and position dectectors as sensors. The frequency response functions are determinated from the impulse response functions by means of a discrete Fourier transformation. Using the identification method described precedently the model parameters are corrected and then the state feedback vector F and the observer gain vector H can be computed and applied to the system. Finally, the integrators associated with each control loop are tuned until the step response of the closed loops matches a desired step response.

3.4. Disturbance observer:

Some machines require an unbalance control system. A digital synchronous observer using moving coordinates axes gives to the regulators information on the unbalance, allowing, for some applications, the rotation of the shaft around its inertial axis or, for other applications, forcing the rotation around the geometrical axis.

4. HARDWARE IMPLEMENTATION:

The system philosophy was conducted with several targets:

-Efficient man/machine interfaces for simple start-up and short repair times in the event of misfunctions,
-Easy adaptation on every rotor,
-Self commissionning of the controller,
-Access to internal system variables and parameters for monitoring and manual tuning,
-Provision for interfaces to serve host computers.

The system was designed using separate subsystem for regulation tasks and for monitoring tasks.

4.1. Regulation system:

The sensors signals are demodulated, filtered and digitized. These 12 bits information are transmitted to a signal processor which realizes state observers, state controllers, and unbalance observer.
The computed control signals are then transmitted, via D/A converters, to power amplifiers.

4.2. Monitoring system:

A microcontroller (for the "small" machines) or a microprocessor (for the other machines) is

interfaced with the digital signal processor system via a dual port RAM. A parallel link allows exchanges with a standard Personal Computer. This computer conducts the self-commissioning procedure from the identification phase to the parameters programming in EEPROM.
When the system is running, the PC allows monitoring of all parameters of the system (currents, deplacements, unbalance, speed of the rotor, temperatures...) and can execute a full diagnosis of the Active Magnetic bearings and its electronic. If necessary, a LCD panel on the electronic cabinet can display information on the machine status or failure diagnosis. Serial links can serve high order control levels.

5. CONCLUSION:

The use of the signal processor system permits the implementation of state variable controllers even for very fast rotors. A good dynamic performance of Active Magnetic Bearings is then achieved. The off-line identification procedure ensures a good model approximation, even if the shaft has a rather complex structure.

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