INTEGRATED ACTIVE MAGNETIC BEARINGS

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ABSTRACT

Three aspects of the structural and functional integration of electromagnetic bearings are presented: 1. In self-sensing bearings the rotor position is identified from the electric state variables directly at the power amplifiers. 2. The non-linearity of the magnetic force is compensated by software integrated in the digital controller. 3. Adaptive control and compensation strategies are realized to minimize resonance phenomena. The necessary design cycle for integrating the procedures into micro-computers is described as well.

INTRODUCTION

The market requirements for magnetic bearing systems, like high availability, reliability, simple handling and efficiency, can be fulfilled by integrating separate tasks, e. g.
– sensorless position detection of rotors (self-sensing magnetic bearing),
– consideration of non-linear properties of the components in the controller design,
– on-line adaptation of control parameters.

Today, most magnetic bearing systems are arranged to a mecano-electronic system by assembling the individual components (controller, power amplifiers, electromagnets, sensors, signal conditioning) additively. This conglomerate has some inherent disadvantages, like sensitivity, high maintenance expenditure, expensive production and limited load capacity, which considerably hinder a general acceptance and greater spreading. In order to reduce these disadvantages, magnetic bearing systems must be developed with the aim of both functional and structural integration to realize a compact, reliable, cheap and autonomous unit. Integrated mechatronic systems allow improved and completely new functions that were not realizable before.

A first type of integration is the structural or hardware integration as described in [Isermann, 1995]. As example the rotor position is identified by integrating the sensing system into the actuator using a micro computer. Two types of self-sensing magnetic bearings saving separate sensors are presented.

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A second type of integration is realized by information processing (functional or software integration) and based on modern methods of measurement and control. An example is the compensation of the non-linearities of the AMB components by the controller software which requires signal processing on higher levels.

As a second example for functional integration, the stiffness and damping of the AMB are adapted to the actual optimal operating point and even variable unbalance forces are compensated on-line. For this purpose, from measurable quantities non-measurable ones are determined via analytical relations.

The realization of these three tasks requires the consequent use of modern microelectronics as a hardware platform (chips with DSP, FPGA or ASIC), on which the problems' solutions are implemented as real-time algorithms. They must be adapted to the properties of the mechanical process by taking advantage of all programming language capabilities. This leads to process-coupled information processing with intelligent characteristics and to the functional integration of all components.

INTEGRATION OF THE SENSING SYSTEM INTO THE ACTUATOR

OPERATING PRINCIPLE

For stabilizing electromagnetic bearings, the rotor position must be detected. Usually contactless position sensors are used which cause a considerable part of costs. The system can be economized if the rotor position is identified from the electric state variables of the bearing magnets, [Vischer, 1988]. The basic idea of so-called self-sensing bearings is to analyze the current and voltage signals of the magnetic bearing coils with regard to their implicit information concerning the rotor position z.

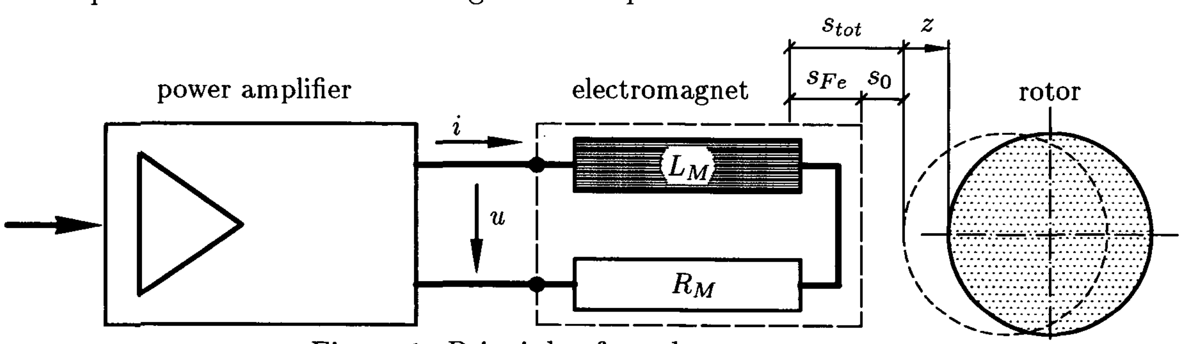

Figure 1: Principle of an electromagnet

The basis of self-sensing bearings are the relationships between the inductance L_M and the rotor displacement z (fig. 1),

$$L_M(z) = \frac{2k_M}{s_{tot} + z}, \tag{1}$$

as well as between the current i and the voltage u of the magnetic coil,

$$u = \frac{d(i\,L_M)}{dt} + i\,R_M. \tag{2}$$

Here the OHMic resistance of the AMB coils is taken into account by R_M and the material and geometrical characteristics of the electromagnets are summarized in the constant $k_M = n^2 \mu_L A_L / 4$. $s_{tot} = s_0 + s_{Fe}$ is the total gap in the center position ($z = 0$) consisting of the visible air gap s_0 and a fictitious part $s_{Fe} = l_{Fe}\mu_L / 2\mu_{Fe}$, which takes into account the losses along the electric flux course through the core material.

POSITION SENSING IN THE FREQUENCY DOMAIN

If electromagnetic bearings are supplied by pulse-width modulated power amplifiers the rotor position can be sensed in the frequency domain. The clock frequency $f_\Omega = \Omega/2\pi$ is very high (for example 75 kHz) compared to the frequencies of mechanical vibrations. Therefore, besides the quasistatic parts i_0 and u_0 the coil current i and the coil voltage u contain high-frequency parts, whereas due to its inertia the rotor doesn't perform high-frequency oscillations. Neglecting higher harmonics of the clock frequency,

$$i = i_0(t) + \hat{i}_\Omega\, e^{j\Omega t}, \quad u = u_0(t) + \hat{u}_\Omega\, e^{j\Omega t} \quad \text{and} \quad z = z_0(t) \tag{3}$$

is valid. Measuring the amplitudes of the clock-frequent electrical signals $\hat{i}_\Omega e^{j\Omega t}$ and $\hat{u}_\Omega e^{j\Omega t}$ available in the power amplifiers, the rotor position

$$z \approx \frac{2k_M\,\Omega}{\sqrt{\left|\hat{u}_\Omega/\hat{i}_\Omega\right|^2 - R_M^2}} - s_{tot} \tag{4}$$

can be estimated using the fundamental relationships (1) and (2). The extraction of the high frequency parts $\hat{i}_\Omega$ and $\hat{u}_\Omega$ of the signals is achieved with a specially designed circuit integrated into the power amplifier unit.

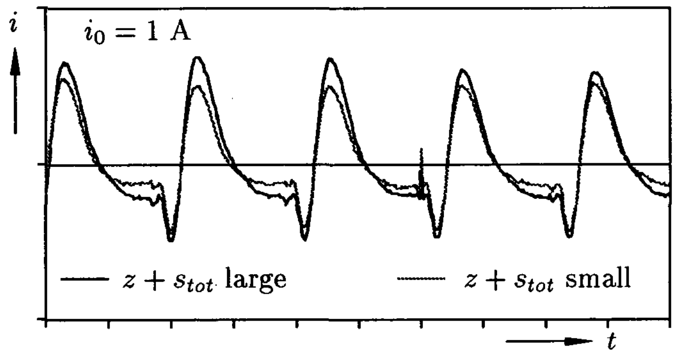

Figure 2: High-frequency component of the current for two different rotor positions

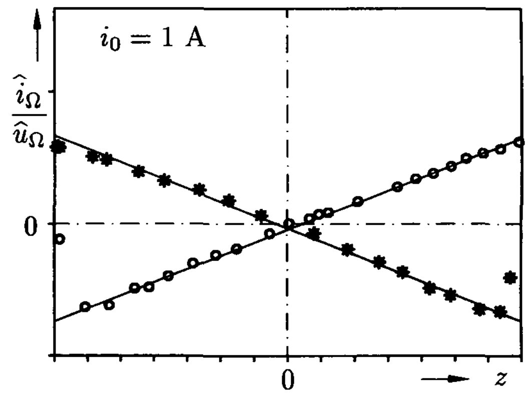

Figure 3: Identification signal

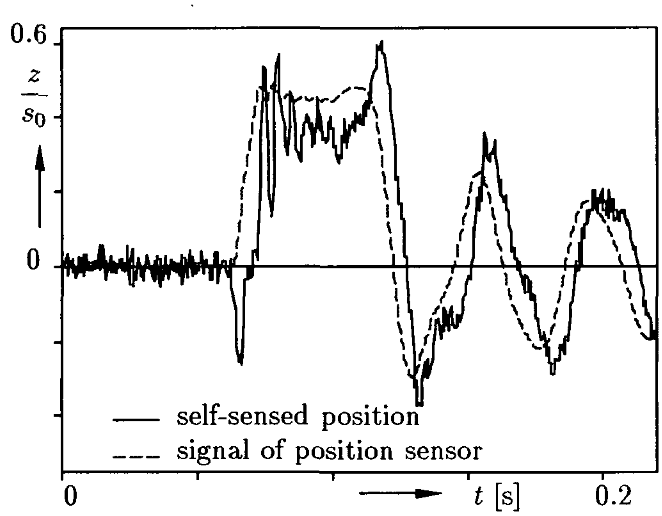

Figure 4: Quality of the self-sensed position

Measured results are shown in fig. 2 and 3. Fig. 3 shows that the estimated value $\hat{i}_\Omega/\hat{u}_\Omega$ is nearly linear to the rotor position for small currents ($i_0 = 1$ A). But some problems arose for large currents and for large rotor displacements. Fig. 3 and 4 compare the self-sensed rotor position to the conventional measured signal. Both time curves of fig. 4 agree in global behavior but the self-sensed signal has some high frequency disturbances. Improvements are still possible by advanced electronics.

POSITION SENSING IN THE TIME DOMAIN

A second method of self-sensing the rotor position works in the time domain as shown in fig. 5. Every control cycle is divided into three successive parts: During the measure cycle (1) the rotor position is determined, during the load cycle (2) the supporting current is supplied and during the set-back impulse (3) the magnetic material is brought back into a defined magnetic state for the next cycle.

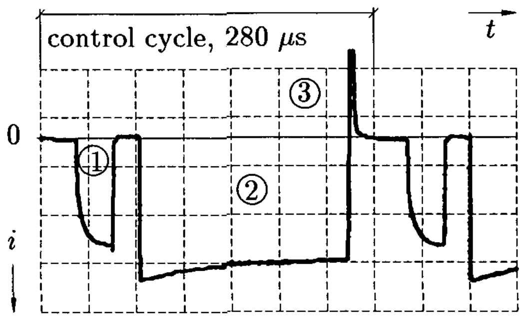

Figure 5: Control cycle

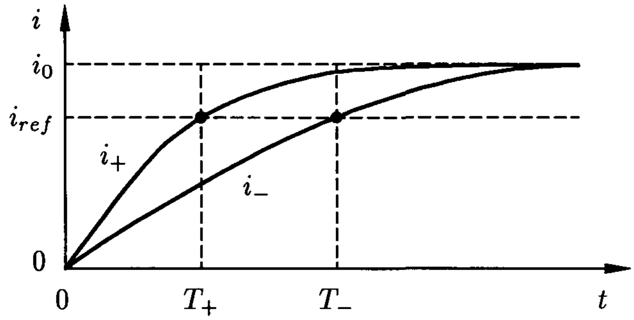

Figure 6: Measure cycle (z fixed)

For measuring the rotor position during cycle (1) a test voltage u_T is applied to the two opposite coils. As a result, the currents i_+ and i_- increase exponentially,

$$i_\pm = i_0 \left\{ 1 - e^{-t\,[R_M/L_{M\pm}(z)]} \right\} \quad \text{where} \quad i_0 = \frac{u_T}{R_M}, \quad L_{M\pm}(z) = \frac{2k_M}{(s_{tot} \pm z)}. \tag{5}$$

The times T_+ und T_- for reaching the reference value i_{ref} are different in the two coils (fig. 6). The time difference $\Delta T = T_- - T_+$ is used as measure for the displacement z,

$$z = \frac{K_T}{2\Delta T} \left[\sqrt{1 + \left(\frac{2\Delta T}{K_T} \right)^2} - 1 \right] s_{tot} \qquad \text{with} \qquad K_T = \frac{4k_M}{R_{tot}\, s_{tot}} \ln \left(\frac{i_0}{i_0 - i_{ref}} \right). \tag{6}$$

For small rotor displacements $|z| << s_{tot}$ even a linear relation between the rotor position z and the measurable time difference ΔT between the increasing time holds, $z \approx s_{tot}\, \Delta T / K_T$.

This principle was successfully realized in a model to demonstrate its functionality. A very lightweight ferrite rotor is supported contactless without separate distance sensors, [Meyer, 1995]. The quality of the measurement results depends significantly on the rotor material.

The on-line evaluation of the current and voltage signals in the power amplifiers is done by a micro-computer integrated in the power amplifier system.

SOFTWARE COMPENSATION OF NON-LINEARITIES

Most components of active magnetic bearing systems are non-linear making the entire system non-linear, [Laier et al., 1995]. Examples of inherent non-linearities are

- the non-linear force-current-displacement characteristic of the electromagnets,
- the flattening of the magnetization curve due to saturation of the core material,
- the hysteresis of the core material depending on frequency and amplitude and
- the limitations of the current's magnitude and slope due to the power amplifiers.

These non-linearities become strongly evident for large currents, high frequencies, large magnetic forces and small air gaps and restrict the working range of magnetic bearings. So, for example, the softening force-current characteristic and the limitation of the coil current yield resonance curves bending to the left (see fig. 11). This can result in jumps of the rotor-amplitude during run-up and run-down accompanied by transient vibrations. Due to the limited current slope the system can even become unstable, [Laier et al., 1995].

The essential non-linearity of active magnetic bearings results from the force-current-displacement-characteristic of the electromagnets. To reduce the effects of this non-linearity on the dynamic behavior normally pre-magnetization currents $i_V = i_{max}/2$ superposed by the control currents are permanently sent through all coils. The pre-magnetization currents bring with them high energy consumption even if no resulting magnetic force is necessary, like in the optimal operating point. Yet, only a rough linearization can be achieved by this method. For example, for a rotor deflection of half the gap the real magnetic force already deviates 12.5% from its linear approximation.

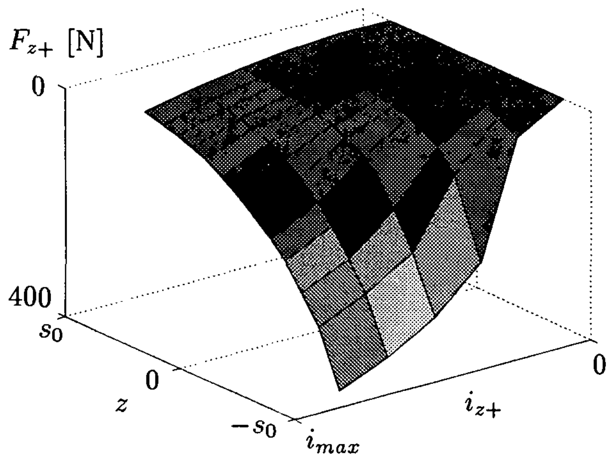

Figure 7: Measured force characteristic

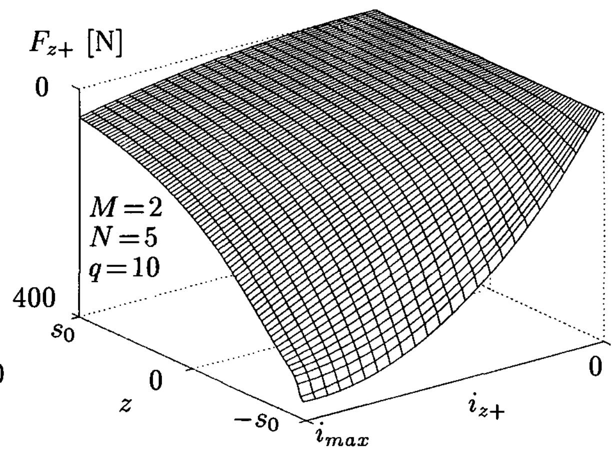

Figure 8: Approximate magnetic force

An alternative method to linearize the system can be realized by software using a two-component controller (fig. 9). The controller consists of a conventional part $f_R(z, \dot{z})$ and a post-connected compensator that *inverts* the magnetic force characteristic with regard to the current. The idealized non-linear magnetic force law

$$F_z(i_z, z) = F_{z+} - F_{z-} = k_M \left[\left(\frac{i_{z+}}{s_0 + z} \right)^2 - \left(\frac{i_{z-}}{s_0 - z} \right)^2 \right] \quad \text{with} \quad i_{z\pm} = i_V \pm i_z \qquad (7)$$

is not sufficiently exact because it neglects various important effects. Especially for small air gaps and large currents the actual forces are considerably smaller than the calculated ones due to the saturation. Therefore, the measured magnetic force characteristic (fig. 7) should be used instead of the idealized one. The measured field has to be approximated by a mathematical formula whose inversion is taken as compensator function. Following the ideal magnetic force law (7) a polynomial formulation with fixed polynomial limits M and N and exponent $1/q$ is chosen,

$$F_{z+}(i_{z+}, z) \approx \sum_{m=1}^{M} \sum_{n=0}^{N} c_{mn} \frac{i_{z+}^{\,m}}{(s_0 + z)^{n/q}} \,. \qquad (8)$$

The formulation is fitted to measured data by using the least squares method. The comparison of the measured force field (fig. 7) and its approximation (fig. 8) shows that the deviations are less than 10% of the maximal force even for the chosen very small polynomial order $M = 2$.

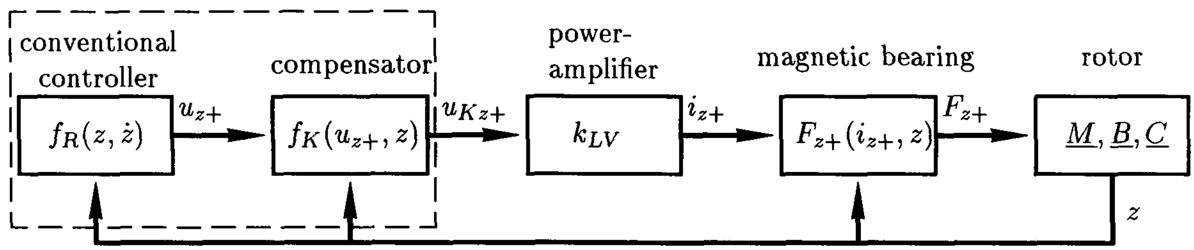

Figure 9: Control loop of an active magnetic bearing with compensator

The post-connected compensator determines a corrected control variable $u_{Kz+} = f_K(u_{z+}, z)$ depending on the previous control variable u_{z+} and the rotor displacement z so that the system as a whole is linear,

$$F_{z+} = k_{Fu}\, u_{z+} \,. \tag{9}$$

The force-displacement factor k_{Fu} can be chosen arbitrarily and for certain f_K the magnetic force even becomes independent of the rotor deflection z for constant currents. The relationship $i_{z+} = k_{LV}\, u_{z+}$ of the amplifiers between the control voltage u_{z+} and the current i_{z+} is linear. Therefore in case of $M = 2$ the inverse of equation (8) with regard to the current is achieved by

$$u_{Kz+}(u_{z+}, z) = \frac{1}{2\, k_{LV}\, a_2} \left\{ \sqrt{a_1^2 + 4\, k_{Fu}\, a_2\, u_{z+}} - a_1 \right\} \tag{10}$$

$$\text{with} \qquad a_1 = \sum_{n=0}^{N} \frac{c_{1n}}{(s_0 + z)^{n/q}} \,, \qquad a_2 = \sum_{n=0}^{N} \frac{c_{2n}}{(s_0 + z)^{n/q}} \,.$$

The inverse characteristic is stored on a micro computer so that the superordinate controller can access on-line. It is evident that the linearization in the whole field yields a strongly reduced magnetic force (in this case down to 70 N) because the force is limited by the maximal current at maximal air gap. A linearization in a smaller area achieves a larger value of k_{Fu} and so a larger maximal force. For large air gaps and high control values u_{z+} the power amplifier comes into saturation and, due to the limitation of the current, the force cannot be increased any more. The force-displacement characteristic has a bend that corresponds with the boundary curve at $i = i_{max}$ in fig. 8.

The linearization by software was tested in simulations as well as on a rotor test rig, [Hoffmann et al., 1997]. In order to show the effect of the non-linear magnetic force, the pre-magnetization was reduced significantly to $i_V = 0.25\, i_{max}$. Without compensator the quasi-stationary resonance curve bends to the left according to the softening characteristic and during run-up and run-down the typical jumps of the steady-state amplitudes occur, combined with transient oscillations (fig. 11). But with activated compensator the non-linear characteristic is totally compensated and the system behaves as a linear one. In simulations even the extreme case $i_V = 0$ was possible. But in practice the total reduction

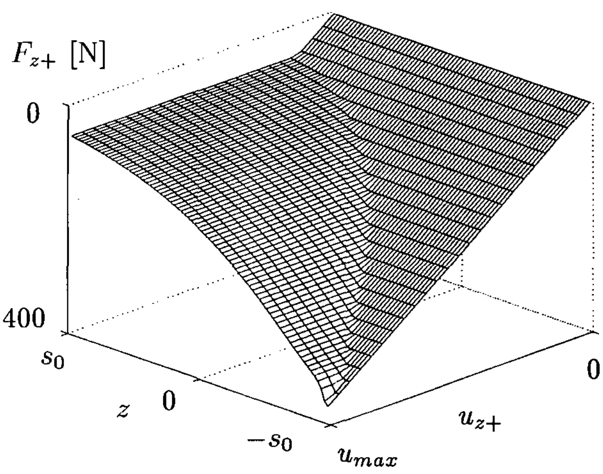

Figure 10: Partial linearization

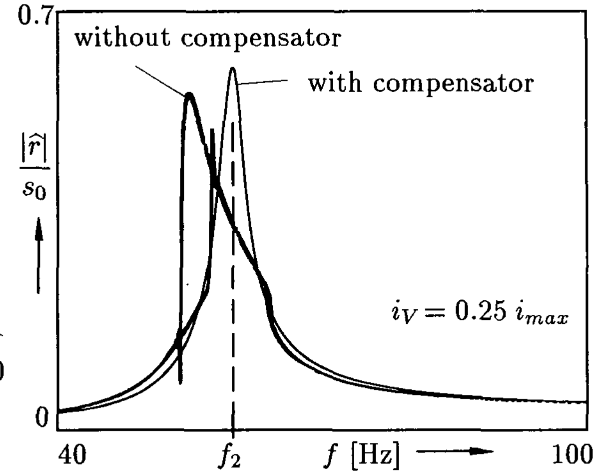

Figure 11: Unbalance response

of pre-magnetization to zero is not possible because the current slope is limited by the power amplifiers. In the experiment the rotor system became unstable for $i_V \leq 0.17\, i_{max}$.

The exact description of the process and the characteristic of the magnetic bearing is the crucial point for this functional integration by including a non-linear compensator into the controller.

INTEGRATION OF ADAPTIVE CONTROL SCHEMES

A further functional integration can be reached by implementing adaptive control schemes into the controller. This means that the parameters of the controller as well as the controller structure are changed during operation to adapt the stiffness and damping or to apply compensation forces onto the rotor by the electromagnets. Three techniques are known which are in particular, [Abraham et al., 1988]:

During *open-loop adaptation* the active stiffness of the electromagnets is switched at certain rotor speeds to the predetermined optimal value. Adaptation occurs in an open loop since only the input signal of the plant (rotation speed) is used. This method is easy to realize and fast but has the disadvantage that exact a priori knowledge about the rotor system is necessary and that system changes cannot be taken into account.

A higher performance can be achieved by the *closed-loop adaptation.* Depending on a measurable indicator, the controller parameters are updated continuously for getting optimal stiffness and damping which minimize the rotor vibrations (fig. 12). At a simple rotor the phase difference of the rotor deflections at the bearing and at midspan was used as indicator, [Abraham, 1992]. This process is insensitive to system changes and minor a priori knowledge about the system is necessary. However, finding and measuring an appropriate indicator can be difficult.

By the *compensation* method, undesired rotor vibrations are compensated by additional magnetic forces. The adaptation of the magnetic compensation forces (amplitude and phase) is done iteratively during operation so that system changes do not affect the success. For example, this was done for the unbalance excited rotor deflections which were minimized in a wide speed range (fig. 13). But the price for the zero rotor deflection at a certain position are large magnetic forces and rotor amplitudes in the magnetic bearings.

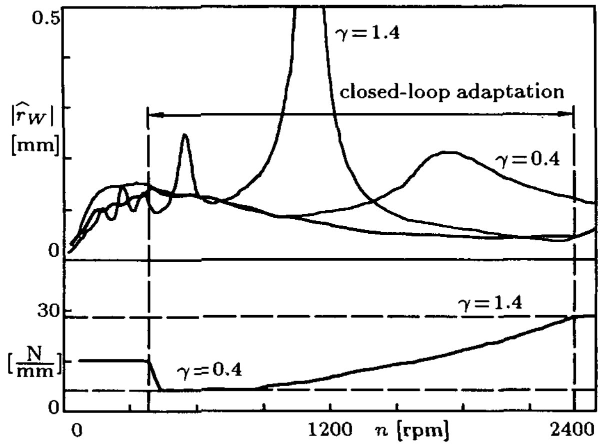

Figure 12: Unbalance response and magnetic stiffness with and without closed-loop adaptation

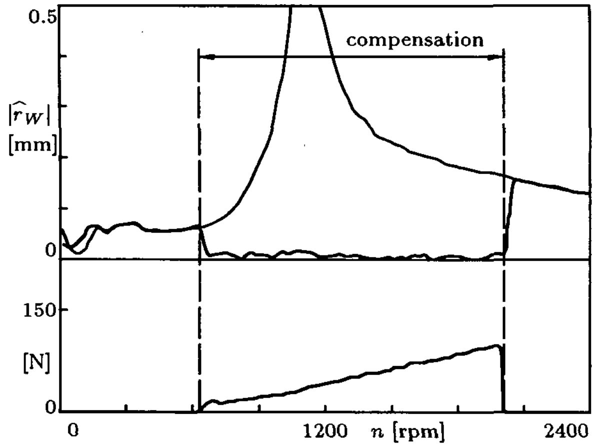

Figure 13: Unbalance response and magnetic compensation force without and with unbalance compensation

All three control procedures are implemented in the AMB system as modules and can be superimposed to the basic control. But the successful realization of these methods for multi-degee-of-freedom rotors requires powerful micro computers with integrated software.

MICROELECTRONICS FOR SYSTEM INTEGRATION

The functional integration is achieved primarily by using process knowledge in controller design. For the design of integrated magnetic bearings a complete view of the mechanic process and the electric and electronic components is required. The improvements and simplifications described in the previous sections are integrated in the design process. These additional tasks must not lead to a complex system because it has to meet certain time constraints. The signal and information processing units have to be realized by special microelectronic components and must be integrated within the process, actuator or sensor. This can be done with an application specific integrated circuit (ASIC).

The different tasks of the single components, like the sensing-system, information processing part or actuator can be realized with local hardware located in the vicinity of the magnetic bearing. Only supervising tasks like the changing of parameters are handled by a master controller while the slave operates stand-alone. This implies a detailed interface definition between the master and the slave component. Besides the decentralization of the controller and the relief of the master component, the smaller size of the final system is an advantage of microelectronic components like microcontrollers or ASICs.

Figure 14 shows the development and realization of hardware and software for integrated magnetic bearing systems. Both are efficiently realized with the aid of graphic design environments for mechatronic systems, [Le et al. 1997]. The graphic design environment supports implementation, realization and optimization of complex controller structures. The data flow oriented model of the magnetic bearing system including actuator, plant and sensor can be simulated within the design environment, a misbehaviour of the controller can be detected and removed early in the design process.

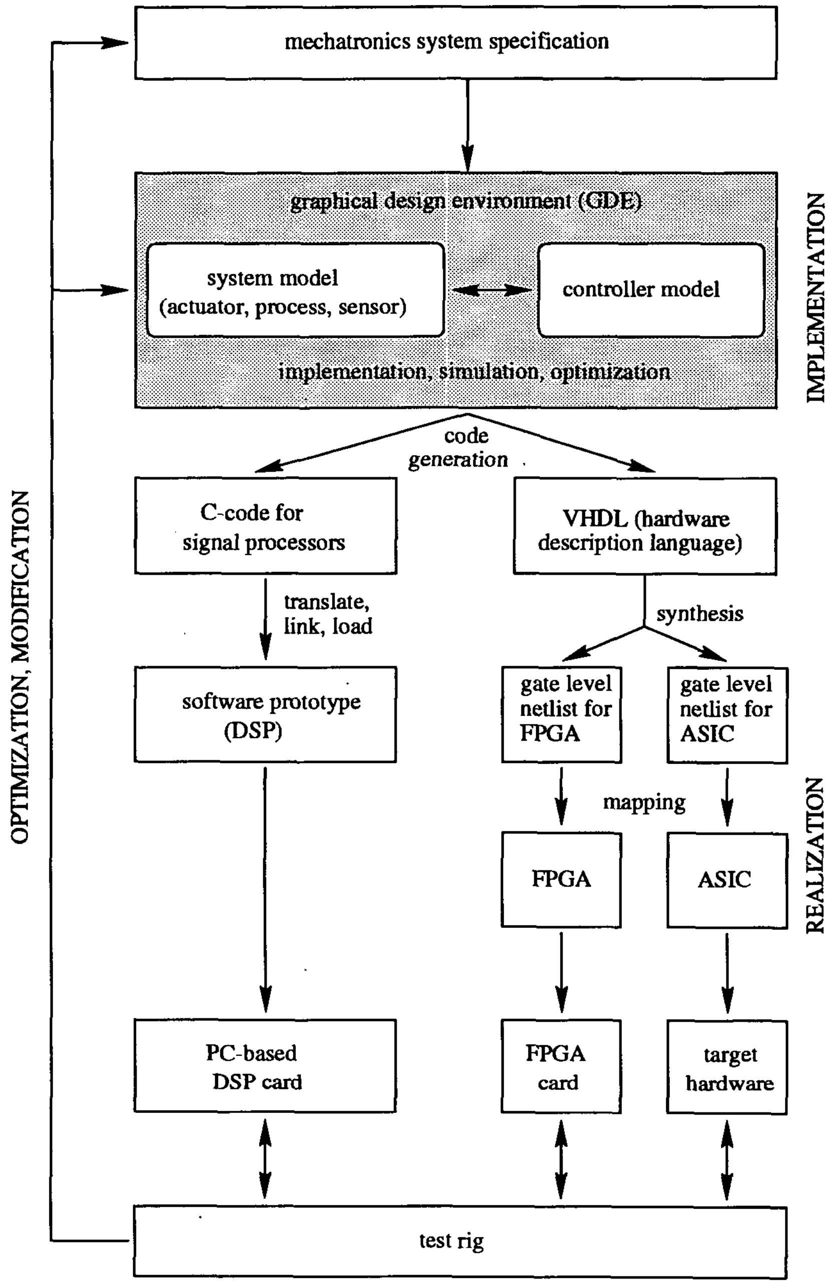

Figure 14: The Rapid Prototyping design flow

The physical realization of the control part is done in two ways. In a first step after the validation of all components, a software prototype is generated in a few seconds and transported to the target hardware located at the test rig. The specification of the controller is implemented with the tool Signal Processing WorkSystem (SPW). After successful simulation C code for signal processors is generated automatically. The C code is compiled, linked and transferred to a signal processor board located at the test rig for simulation purposes (hardware in the loop simulation). This fast generation of software prototypes enables the designer to modify the algorithms used and leads to a short development time. Furthermore all control algorithms can be tested under realistic conditions in order to select the optimal one for the magnetic bearing system.

The information processing part is realized in a second and final step in hardware by field programmable gate arrays (FPGAs) or application specific integrated circuits (ASICs) located within the power amplifiers. Besides the C code generation from the specification in SPW, VHDL code can be generated from the initial specification as well. This hardware description language enables the designer to map the functionality of the controller onto an FPGA that can be reconfigured if necessary, [Glesner et al., 1997]. Finally an ASIC is fabricated and put onto a printed circuit board within the power amplifier. Thus the final integrated magnetic bearing system consists only of the magnetic bearing itself and the power amplifiers including the ASIC controller.

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