# Controlling Magnetic Bearing Systems with a Digital Signal Processor

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## Outline

First, the succession of magnetic bearing systems designed at the Institute of Mechanics in Zürich is retraced briefly with special emphasis on the control aspects. The most recent examples make use of the digital signal processor.

The main body of the paper contains a detailed description of the magnetic bearing control of our first DSP controlled system, a highly elastic rotor. Experimental results permit to assess the advantages of the new control device. Future possibilities of magnetic bearing control layout are shortly indicated.

## 1. Short Survey of Magnetic Bearing Projects at the Institute of Mechanics

The succession of magnetic bearing projects at the Institute of Mechanics in the last few years can serve as an example for some typical trends. The list is not complete.

Our first project was a rigid rotor built for purely experimental purposes. The system includes analog power amplifiers bought as standard laboratory equipment, analog control and premagnetizing coils. All these features contribute to give a relatively simple, easy to handle system.

Different control strategies were tried for this project. They include state feedback with differentiators for the velocity signals, Luenberger observer for the velocities and decentralization. The results proved that such a drastically simplified control can give very satisfactory system performance. Furthermore, the robustness of the observer for velocity was clearly demonstrated for this rigid body application. A similar type of observer is also used for magnetic levitation vehicles.

The next system is the centrifuge for liquid-cristal epitaxy experiments. It was presented by Bauser et al. /1/ in this symposium. The one attribute changed here is mainly the elongated rotor shape, resulting in non-neglectable structural elasticity.

The bearing-sensor arrangement and the stiffness requirements of the bearing were such, that the simple analog control of the first rotor could be applied here as well. However it became apparent that for other applications the control would have to be more powerful and more sophisticated

The first digitally controlled magnetic bearing system was then designed. This was again a rigid rotor. The 8-bit microprocessor handles two decoupled control channels at a sampling rate of about 1 kHz. New switched-type power amplifiers were employed, we also experimented with digital gap sensors based on CCD arrays. The bearing characteristics was linearized on the software side instead of the hardware side. This means that special linearizing coils and the constant current power supplies could be eliminated.

For later projects, the controller power was increased by introducing 16-bit microprocessors. This development made it possible to consider more demanding control algorithms. Therefore, a digital controller was used for the experimental setup of the project on elastic rotors. It uses two 16-bit processors. This project is described below in detail. The same rotor-bearing system was later used for the first DSP application for magnetic bearing control. To complete this survey, some of the other recent projects are mentioned.

An elastic rotor-bearing system was built for a university in Hamburg. Improvements mainly on the software side made it possible to achieve the desired results in a short time. The specifications required operation at several critical speeds. This rotor with a shaft thickness of only 8 mm can operate at five bending critical speeds up to its operational speed of 7200 rpm . The control is with two general-purpose microprocessors.

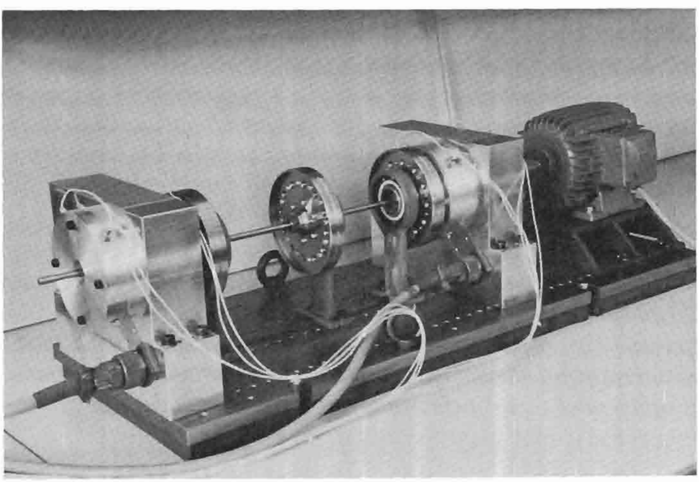

**Fig. 1: Elastic rotor: Shaft thickness 8mm, 7200 rpm, 5 critical speeds.**

For other projects now under way, attention turned to the sensors and the amplifiers. Switched power amplifiers are used for the milling spindle project, where a high bearing load is required. The rotational speed reaches 40000 rpm. The controller was first implemented with single-chip processors and is now being changed to a DSP. The final results and evaluations for this project are not yet available.

Due to the good results of the first DSP control, the same controller hardware will be used for the very high speed rotor project.

New sensing principles have been or are successfully being tested, one of them being the flux-density measurement in the bearing. This also opens up new possibilities for the mechanical rotor-system design as well as for the control strategy. We also aim at integrating the amplifier properties in the system modelling and control design.

## 2. The Elastic Rotor Project

The advantages of magnetic bearings for vacuum technology or high rotational speed are obvious. Less obvious, but just as interesting are the possibilities for the damping of structural vibration modes. To demonstrate this capability, a highly elastic test rotor was equipped with contact-free electromagnetic bearings.

The critical speed vibrations can be directly influenced through the relative damping of the supporting bearings. A thorough investigation of the mathematical, mechanical as well as the control theoretical aspects of this problem is available in the thesis of Salm /2/.

The controller was first implemented on two 16-bit microprocessors with a sampling rate of 400 microseconds and a time-lag between input and output signal of 250 microseconds. The effect of time-lag inherent to any digital controller is now shortly discussed.

The Effect of Time-Lag:

The primary goal is to produce a damping force. The measured signal, from which this force must be produced, is a position signal. This means that the controller transfer function will have to have a positive phase between input and output signal, no matter what control strategy is applied. Naturally, time delay in the controller always makes a negative contribution to the phase angle which increases with the frequency. The shorter this time-lag, the higher the frequency up to which a damping force can be exerted.

For the high-frequency range, excitation is avoided by providing a low gain of the controller. If the gain is sufficiently low, the natural damping present in all mechanical system will overcome the residual exciting force component.

Therefore the microprocessor system used first with the time lag of 250 microseconds, as mentioned, made it necessary to provide a carefully designed analog low-pass filter with a cutoff frequency at about 400 Hz. A speed of about 5000 rpm could be reached.

The time lag of the DSP controller of about 40 microseconds (including AD-conversion time) made it possible to do without this filter. It then became possible to reach a rotational speed of 10000 rpm with the unbalanced elastic rotor and to operate it at four critical speeds. The greater part of this 40 microsecond time-lag is not due to the DSP, but is used for the AD-converters.

## 3. The Digital Signal Processor (DSP)

As indicated by the name, the digital signal processor is a special purpose microprocessor. It can perform the specific tasks it is designed for faster by a factor of about 10 to 20 compared with a typical general purpose microprocessor. The power of a single processor is also superior to a single transputer, whose advantages become effective mainly in multi-processor systems. There are now integer and floating-point DSP's available.

The relative importance of DSP's versus general purpose microprocessors is growing rapidly in a wide range of applications. DSP's are also used in many low-cost mass products like CD-players or toys. The applications cover not only the obvious fields telecommunications and image processing, but more recently also the area of controllers for industrial machinery.

There are already some compilers for high-level language programming of DSP's available, but the resulting code is not yet optimal Therefore, at this time we have to rely on assembler programming for the fast parts of the control algorithm.

Summing up what has been said up to here, it seems to be a logical step to apply the DSP for magnetic bearing control as we have done in the project now being described is some more detail.

## 4.1 The Control: Theory

It is sensible to start a discussion on magnetic bearing control with the basic concepts of mechanical **stiffness** and **damping**. These two force components will somehow show up in the input variable of the control plant, i.e. the rotor to be supported.

The most obvious way to obtain these forces is to feed back a position signal with a classical **proportional-differential** controller. For the selection of stiffness and damping coefficients, one can use engineering judgement or refer to some of many publications on magnetic bearings, e.g. /2/, /3/ or /4/ .

The main difficulty is, as in the continuous case, the **differentiating** path. As minimal time-lag is a fundamental requirement, algorithms with small computation-needs are favoured. The simple **difference sequence** can often be applied successfully. The main drawback of this method is the relatively large amount of noise present in such a differentiating path, especially for short sampling periods. There is a very simple and obvious method to overcome this particular problem: The time step for the difference sequence can be increased to an integral **multiple of the sampling period.** It can be noticed that this most simple method can give good results for many of applications.

Of course, in some cases **higher order** algorithms can be necessary. Which method is best will depend on a given practical application. Polynomial approximations of second order have so far been applied successfully in some of our projects, in the present one as well.

But even in the case of a first order algorithm, i.e. an algorithm using only one time-lag element, there are additional possibilities. The algorithms mentioned up to now are all so-called finite-impulse-response (**FIR**) algorithms. The parameters are all in the feedforward path of the controller (fig. 2), which corresponds to the numerator of the z-transfer function.

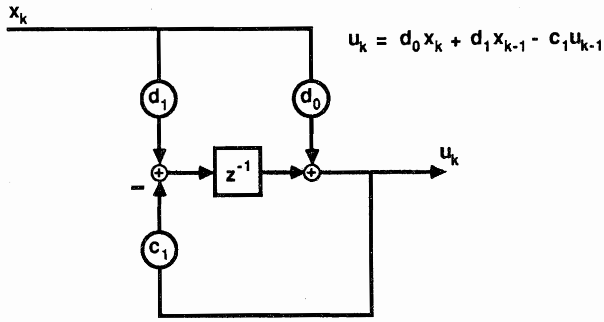


**Fig.2: General first-order compensator**

The parameters in the internal feedback path have not yet been used. For a general case implementation, the parameter called $c_1$ in Fig. 2 is not zero. This results in a system which the filter specialists call "infinite impulse response" (**IIR**). The name is self explaining. For such algorithms, the parameters cannot be interpreted as easily as before in terms of stiffness and damping, except in some special cases.

One such special case is the digitally implemented **PID** algorithm. The integrating feedback path will have the effect of a position independent of the load, i.e. a statically infinite stiffness up to the maximum bearing force.

Another way to obtain an IIR algorithm by applying the stiffness-damping concept is by using a **local Luenberger-observer** to obtain an approximation for the velocity signal. This can even be done with a first-order algorithm.

A third method is to **transform a continuous** PD or PID controller of any order from the Laplace-domain to the **z-domain** and to obtain the corresponding difference equations. Many textbooks on sampled control can be consulted on this method. Frequency domain methods are also presented by Kanemitsu et al. /6/.

A most interesting and much more generalized method has been presented by **Larsonneur and Herzog** /5/ earlier in this symposium.

Up to now, we have only discussed **single-channel** control. The control systems engineer of course first sees the **multi-input multi-output** system represented by any magnetic bearing problem with more than one degree of freedom. We also investigate the corresponding control strategies. For the case of continuous control, the question is treated in depth in /2/. Most results can be generalized to discrete-time controlled systems. I will therefore not go into details here and only mention some possibilities.

**State-feedback** gives of course very nice results. One simplification which can usually be done at neglectable cost to the controller performance is the **decentralization** of the feedback.

The main problem is the fact, that not all state variables are measured. The derivation of velocities has been treated with the single-channel control. A fully coupled **Luenberger observer** can be used to derive the unknown state variables from a mathmatical model of the plant. Such an observer could also be used to obtain the amplitudes of the **bending modes** from a reasonably reduced model of an elastic rotor.

In this way, it would be possible to actively and selectively exert damping for the system modes. We have made first simulations with this kind of controller. The results so far indicate that a relatively parameter-sensitive system is obtained. Furthermore, the number of on-line calculations for such an observer increases by an order of magnitude and seems to be at the limit of what our current fixed-point arithmetic DSP can do. However, research in this area is being pursued, especially in conjunction with interesting new model reduction techniques /7/.

A very promising solution seems again the approach of a generalized **optimal dynamic feedback** compensator with predefined structure, as presented in /5/. It is a considerable extension and generalization to sampled systems of continuous-time control methods described in /3/ and in /8/. Application is expected in the near future.

For the current project, the goal was not sophisticated control, but on testing the new hardware and software with a simple, well known algorithm. It seems that some decisive advantages of the new controller can be made out clearly even when from the control design point of view a very simple design is used.

## 4.2 The Control: The Algorithm

The DSP is designed to compute summation expressions as they appear in the following general digital control formula of n-th order.

$$u_k = \sum_{i=0}^{n} d_i * x_{k-i} - \sum_{i=1}^{n} c_i * u_{k-i} \qquad (1)$$

where k is the numbering of the sampling steps, $u_k$ is the output variable at the time $T_s*k$ , $x_k$ is the input variable and $d_i$ are constant coefficients.

Address calculation and data multiplications operate simultaneously. This brings the time for one multiplication down to one processor cycle (or 200 nanoseconds in our case). The operands are 16 bits each, the accumulator is 32 bits, the data from and to the converters is 12 bits only. Therefore, no scaling problems have occured so far in our magnetic bearing applications.

The high sampling rates achievable are above 50 kHz (20 microseconds). For this application, a single DSP is used for four or five channels. The converters need about 25 microseconds conversion time. Faster converters are easily available when needed. Therefore the minimal sampling time for five channels is roughly **80 microseconds** (12 kHz). This is high enough to actively control the first few mechanical vibration modes of such rotor systems.

As mentioned before, short sampling times in conjunction with simple difference-sequence algorithms make it necessary to consider multiples of the sampling time for the step-length. Therefore, the formula (1) is generalized to

$$u_k = \sum_{i=0}^{n} d_i * x_{k-i*m} - \sum_{i=1}^{n} c_i * u_{k-i*m} \qquad (2)$$

with the integer m.

This control algorithm has to be programmed in assembler. In order to implement this quite general formula for a varied set of parameters, **ringbuffers** for the values of input and output variables ( x and u respectively ) are used. These ringbuffers can also serve for analysis purposes on-line or off-line. They contain a record of the system and control behavior, also after termination of the control program. The length of the ringbuffers is limited only by the available memory which in our case goes up to 64 kbytes .

The use of such ringbuffers has proved to be very valuable both for the program flexibility and for data analysis, which can be done e.g. by graphics.

## 4.3 The Control: Hardware & Software

Our colleagues at the Institute of Electronics have developed a **DSP card** for IBM compatible PC's with the Texas Instruments DSP, a dual port RAM, interfaces and a **software development package**. All of this is now commercially available, along with custom-made analog interface cards. Separate converters are used for each channel. We did not have to develop any electronic circuits ourselves.

The **service program** loading all the parameters and the programs to the DSP card can be written in Pascal on the PC. The two programs, the service program for the PC and the assembler routine for the DSP are now shortly described.

From the **screen display** of the service program the user can choose various functions like starting or stopping the DSP, loading another program, changing or computing new control parameters including the sampling time, calibrating the sensors by directly addressing the converters, examining the ringbuffers etc. From this list, it should become understandable that much more programming effort is put into the Pascal program than into the assembler routine.

The **assembler routine** consists mainly of a loop computing a new output for every channel and every time-step. One important feature is the fact, that the time lag is minimized by making all the calculations not using the newest input value **before or during the AD conversion**. This means that after the reading of the AD-converter value, only one more multiplication and addition has to be done to get the newest value of the output variable.

The mathematical output variable $u_k$ can be used for the ringbuffer. For the actual output to the DA-converter, some additional processing is necessary. This consists mainly of adding the **offset currents** for linearizing of the force-current characteristics, checking for saturation of the actuators and selecting the proper output channels according to the sign of the output variable.

All these tasks for five channels and the converter operation are interlocked in such a way as to **minimize the time-lag**. Therefore the channels are not sampled simultaneously, as is usually assumed for the theoretical system description. This must be taken into account when simulating the system behaviour. On the other hand it would certainly not be the sensible thing to do to degrade system performance by increasing time-lags just in order to get an easier theoretical system description.

## 5. Results

The control has been realized as described above. Hardware and software have fully met the expectations. A controller with two general purpose microprocessors and a time-lag of 250 microseconds has been replaced by a system with a single DSP and a time-lag of 40 microseconds. This represents an increase in power by a factor of about 12.

The elastic rotor system could be operated without analog filter, which made it possible to reach 10000 rpm compared with about 5000 rpm in the earlier implementation. These results will be presented in detail at the coming conference on rotordynamics /4/.

Our institute subsequently presented magnetic bearing applications with this type of controller at two industrial fairs. The DSP controller has been chosen for several current projects.

## 6. Conclusions

Digital signal processors are **well suited for magnetic bearing** applications. They are built specifically for such a control task. In the case of magnetic bearing control, the requirement of minimal time-lag seems more important than minimal sampling time. Therefore a single DSP can be used for many control channels.

The assembler programming has not been a major drawback, as the control function is relatively simple. For future applications with more sophisticated control algorithms it will be highly desirable to use high level programming languages, which produce efficient code. Such languages are now being developed. New projects will use floating point processors, which are now becoming widely available. **Industrial applications** can become feasible as the cost for stand-alone applications are falling.

It seems too early, to decide whether transputers will replace DSP's in the field of magnetic bearing control. There are indications that transputers show advantages for other mechatronic applications like robotics, where multi-processor systems and high-level programming are crucial.

## 7. References

/1/ E. Bauser, G. Schweitzer, H.P. Strunk, A. Traxler: "Centrifuge for Epitaxial Growth of Semiconductor Multilayers", First Int. Symp. on Magnetic Bearings, ETH Zürich, June 1988

/2/ J. Salm: "Eine aktive magnetische Lagerung eines elastischen Rotors als Beispiel ordnungsreduzierter Regelung grosser mechanischer Systeme", Prom ETH 8465, Zürich 1987 / VDI-Fortschrittberichte, Reihe 1, Nr. 162,1988

/3/ H. Bleuler: "Decentralized Control of Magnetic Bearings", Prom ETH 7573, 1984

/4/ H. Bleuler, J. Salm: "Active Electromagnetic Suspension and Vibration Control of an Elastic Rotor with a Signal Processor", 4th Int. Conf. on Vibrations in Rotating Machinery, Heriot-Watt University, Edinburgh, Sept. 1988

/5/ R. Larsonneur, R. Herzog: "Optimal Design of Structure-Predefined Discrete Control for Rotors in Magnetic Bearings (SPOC-D), First Int. Symp. on Magnetic Bearings, ETH Zürich, June 1988

/6/ Y. Kanemitsu, M. Ohsawa, K. Watanabe: "Active Control of Flexible Rotor Suspended in Magnetic Bearings", First Int. Symp. on Magnetic Bearings, ETH Zürich, June 1988

/7/ O. Matsushita, H. Bleuler: "Modelling for Flexible Mechanical System", First Int. Symp. on Magnetic Bearings, ETH Zürich, June 1988

/8/ W. S. Levine, M Athans: "On the Determination of the Optimal Constant Output Feedback Gain for Linear Multivariable Systems", IEEE Trans. on Automatic Control, Vol. AC-15, febr. 1970, pp 44-48