SELF-TUNING CONTROL FOR MAGNETIC BEARINGS

Hannes Bleuler
Institute of Industrial Science, University of Tokyo
Jong Up Jeon
Toshiro Higuchi
Dep. of Precision Machinery, University of Tokyo
Hirochika Ueyama
Koyo Seiko Co. Ltd., Osaka

ABSTRACT

Auto-calibration and auto-tuning for a magnetic bearing system of an industrial turbo-molecular pump (TMP) is presented. The control program is able to calibrate and levitate a system autonomously and then to fine-tune the controller according to some desired stiffness-damping characteristics. Practical issues on auto calibrating are discussed. The basic time constants of the plant are determined automatically in order to find a first stabilizing control autonomously. The tasks of the designer are 1.) to make the choice of operating ranges of all the components and to match those ranges and 2) to give a realistic goal on desired stiffness and damping. Other fine-tuning criteria and autonomous determination of stability ranges of feedback parameters are also investigated.

1. INTRODUCTION

The calibration and tuning of an AMB controller is still a tedious and fairly delicate procedure requiring much time and expert knowledge by an experienced and skilled engineer. With the increasing number of industrial applications, there is a strong incentive to reduce the burden of work required for putting in operation every single AMB system.

On the other hand, a magnetic bearing system with a digital controller offers, through its sensors and actuators, a wide range of possibilities for adaptation, parameter identification, controller tuning and automated optimization.

The inherent possibilities towards the goal of autonomous controller calibration and tuning are investigated in this paper. The vision for the future is the following: At the design stage of a new system, the expert (who can also be very much computer-aided) must make the basic choices on power requirements, signal ranges, time constants and other specifications of the AMB components necessary to perform a given task. The system is then manufactured, assembled and connected. From now on, the control program takes over to put the system into operation.

This paper will analyse the problems which must be solved in order to meet the vision. Several important parts of the procedure have been realized and are currently being tested on different systems. The main results presented concern auto-calibrations, open-loop identification, autonomous realization of first stabilizing controllers and then fine tuning of such controllers. Experimental results where obtained for a commercial TMP system with an experimental DSP controller.

2 AUTO CALIBRATIONS

Connections, Position Offsets, Vertical / Horizontal

Before the controller itself can be operated, the correct offsets and bias currents must be set throughout the system. This can be automated in a straight-forward manner for magnetic bearing systems. As a standard procedure, the rotor is pulled around in the auxiliary bearings by applying a sinusoidal current to the bearings. The same experiment is performed for half and full peak current amplitude. Several checks can thus be made: The connections of amplifiers and sensors are tested. The program can decide whether all connections made, the order is correct, the rotor is horizontal or vertical and whether the sensors operating. It can even be checked sensors are to be adjusted mechanically and whether the amplifications are correct. The program must be told the assignment of the radial x-/y-directions to the output channels, the rest can be determined autonomously. The result at this stage is a diagnosis of the connections and position offsets for the sensors. There is even a possibility of determining either the linearity of the sensors or the roundness of the auxiliary bearing. Both cannot be tested at the same time, but the user has the possibility of checking one of the two assuming the other one is known.

Bias Currents

Next come the bias currents. This is an extremely important system parameter as it determines the open-loop poles of the system and the achievable stiffness. It can therefore not be determined directly, an iterative procedure is necessary. For a first try, values of 30 % of full range are proposed. Later on, this can be modified, mainly depending on the stiffness achieved. If the desired stiffness could not be reached, than the bias current should be augmented to 50% of full range. If it was easily achieved, a lower value might be tried. The designer is usually able to give a range of preferred values, so the system should just look for a value at the lower end of this range. If the rotor was found to be horizontal, the bias current must be increased in the coils carrying the rotor weight.

A fine-tuning of the bias currents can nicely be done after the PD-controller operates: When sweeping through different values of the proportional feedback. the equilibrium position will vary very sensitively to asymmetries in the actuators. The fine-tuning of the bias currents of negative and positive coil is done in such a way, that the equilibrium-position stays independent of the proportional feedback coefficient.

3 IDENTIFICATION & CONTROL DESIGN

Accurate identification of actual AMB systems has proven to be a difficult task. Some parameters are known accurately:

- geometry (location of bearings, sensors)
- rotor mass, center of mass and moments of inertia

As a simplification for the present discussion only a one-degree-of-freedom system is considered. Extension of the results to the multi-degree-of-freedom system is straight forward since only the well known parameters are involved in this extension.

However, the most basic system parameter the value of the open-loop poles $\sqrt{k_s/m}$ with the force-displacement factor k_s and the equivalent mass m is difficult to measure.

This parameter can be estimated from a relay-control (bang-bang control) experiment. The force-current factor must be determined beforehand. The static value of k_i can be identified quite accurately using the known rotor weight. For this experiment, the rotor has to be placed in horizontal position.

Figure 1 shows the bang-bang-controller and figure 2 shows a measurement result. The rotor is actually moving over the full range of x touching the auxiliary bearing at the peak-values. Nevertheless, the vibration being close to sinusoidal in shape, its frequency gives a meaningful estimate of the open-loop system eigenvalues.

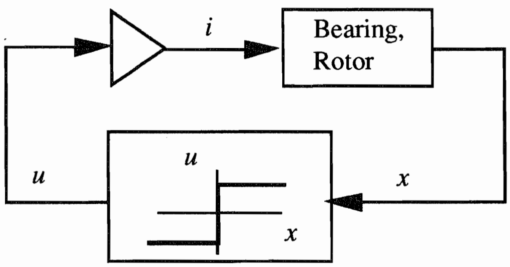

Fig. 1 Bang-bang controller for system time-constant identification

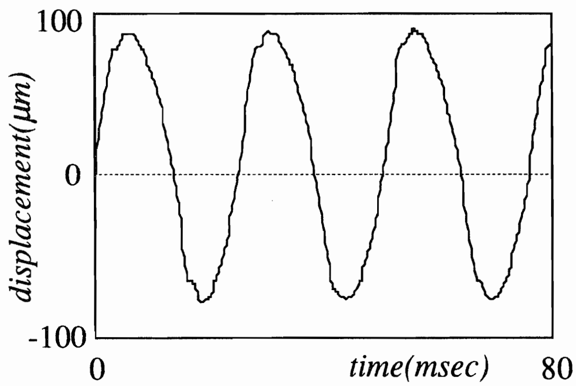

Fig. 2 Measurement result of magnetic bearing with bang-bang control used for time-constant identification.

For an actual system, several such experiments are performed with the different bearings in order to obtain information about the multi parameter system. As mentioned earlier, knowledge about the geometry of the rotor is used at this stage for a correct interpretation of the multi-variable data.

Furthermore, the output value of the bang-bang controller is adjusted in an iterative procedure using theoretical knowledge about the interplay of air-gap, bias current, force-displacement and force-current factors.

Once the force-displacement factor k_S has been identified in this manner, a first stabilizing PD-control can be found autonomously. Well suited is a minimum-energy controller which attempts to stabilize the system without changing its speed, that is while conserving the absolute value of the open-loop poles.

Once stabilization has been achieved, an optimization procedure is started. Different approaches are used. The most direct method is to aim at desired stiffness and damping coefficients supplied by the user. Currently on trial is a minimization of an actually measured integral-square cost function. Further information on the system is extracted from the measured step response. A good evaluation of the robustness of the achieved control is obtained by an automatic determination of the range of P-D parameters.

Finally, depending on the result, the complete procedure can be restarted by going back to the bias current adjustment. The over-all autonomous start-up and tuning flow-chart of the algorithm is given in Figure 3

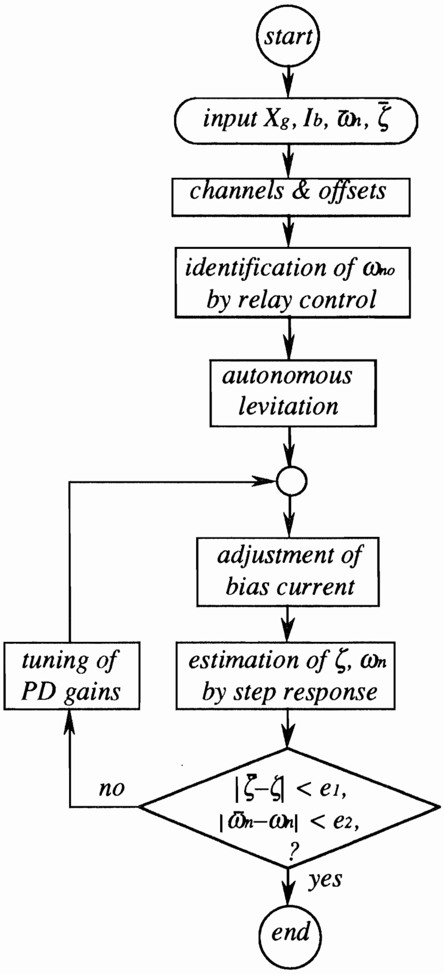

Fig. 3 Autonomous start-up and tuning algorithm for an AMB controller

EXPERIMENTAL SYSTEM

The experimental system used for these experiments is an industrial turbo-molecular pump for ultra-high vacuum. The commercial analog controller was replaced by a digital control with a floating point signal processor. Experiments are being done with current and voltage control. It is the same system used for sensorless bearing control in /1/, the nominal data is given there. Figures 4 and 5 show the system.

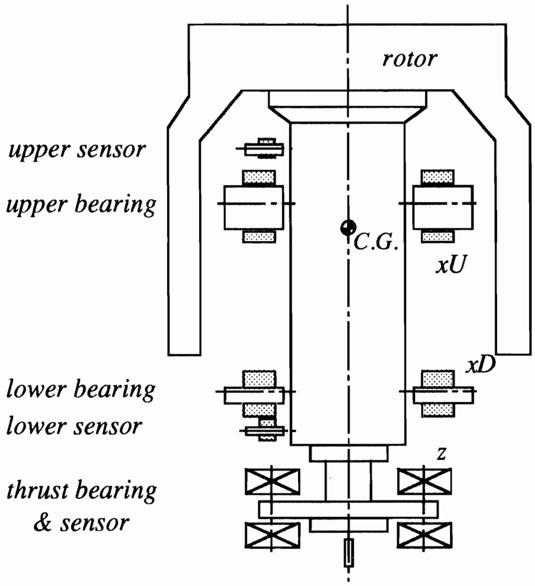

Fig. 4 Turbo-molecular pump rotor

Fig. 5 Photograph of the TMP

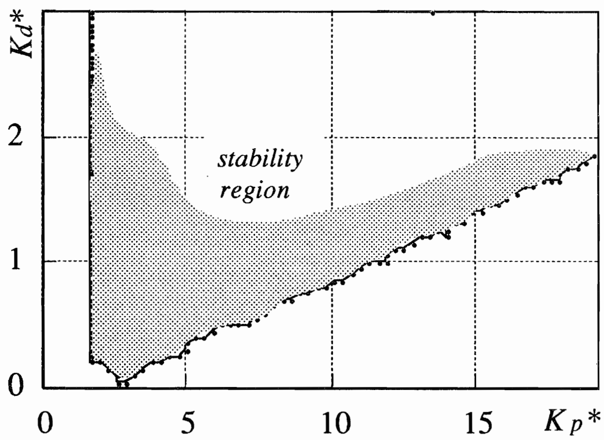

Fig. 6 On-line measurement of the stability-region in the feedback-parameter plane

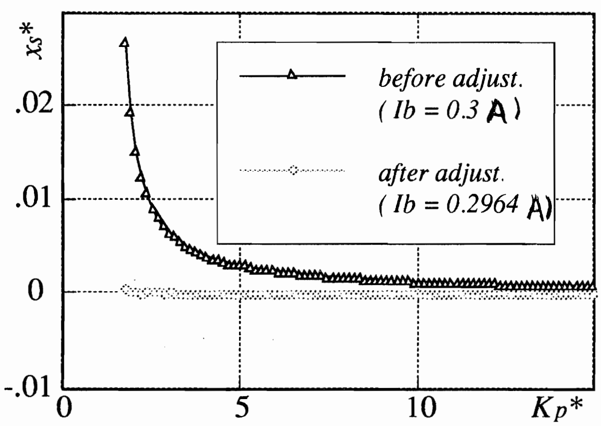

Fig.7 Bias Current Adjustment.

Figure 6 show a measurement of the stability area in the P-D-plane. Figure 7 shows data from the adjustment of the bias current. The high sensitivity of a symmetric bearing behavior to the bias currents is clearly visible. An adjustment of 1.2% only of the bias currents of the positive and negative coil had such a strong effect.

CONCLUSION

The goal of this work is to come up with a program for the DSP which would allow automated start-up and self optimization when connected to an newly assembled AMB system. Some parameters such as mass and geometry are easy to be determined accurately, they are directly used. Other parameters, mainly the force-current and the force-displacement factors are usually not accurately known beforehand. They are automatically identified on-line and directly used for the tuning of a controller.

The self-tuning control program may assume that the given system is designed right. Specifically, this includes the following assumptions:

- The bearing layout and size are suitable
- The sensor-range and sensitivity are adequate, the voltage-ranges of the signals, the AD-DA-converters and the power amplifiers fit together.

The procedures exposed here have been tried out with an industrial AMB system. They may help reducing the cost of realizing magnetic bearing applications.

Acknowledgment

The generous endowment of the Toshiba Chair of Intelligent Mechatronics at the IIS is greatly acknowledged.

References

/1/ Mizuno, Bleuler, Tanaka, Komatsu, Ueyama, Hashimoto, Kucera: An Industrial Application of Sensorless Magnetic Bearings. 4th Int. Symp. on Magn. Bearings, ETH Zurich/ICMB, Aug.1994