AN INDUSTRIAL APPLICATION OF SENSORLESS MAGNETIC BEARINGS

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ABSTRACT

Application of the position sensorless active electromagnetic levitation to an industrial system, a turbo-molecular pump (TMP), is presented. Voltage is used as a plant input and current as the only measured plant output variable. A state estimator is implemented on a digital signal processor. The paper gives measurement results of the radial bearing system and modified dynamic equations for the thrust system taking account of strong influence of the eddy currents in the solid (non-laminated) rotor.

1. INTRODUCTION

There are several incentives to apply sensorless bearings for this application. It is a cost-critical application. A complete TMP is (very roughly) in the US $ 15 000 range. If five displacement sensors in the compact stator can be substituted by a more complex control program, the potential for cost reduction and increase in production volume is considerable. Saving the space of the sensors results in a shorter rotor which in turn has higher critical speed. This is a significant case of design constraints for this kind of machine usually designed to run below the first bending critical speed. As a third advantage, the static load capacity of the sensorless bearing is higher than for a comparable conventional bearing, thus permitting easy operation in vertical or horizontal rotor position. The work presented is a follow-up to the theory outlined in earlier papers /1,2,3,4/.

The system equations for one d.o.f. are

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{k_s}{m} & 0 & \frac{k_i}{m} \\ 0 & -\frac{k_b}{L} & -\frac{R}{L} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} e + \begin{bmatrix} 0 \\ \frac{1}{m} \\ 0 \end{bmatrix} w$$

where the state vector is $x=[x,v,i]^T$ (1)

(displacement, velocity and current), the input variable is voltage e and $w(t)$ is the load disturbance force. The parameters are equivalent mass m, inductance L resistance R, voltage-velocity factor k_b, force-current factor k_i, force-displacement factor k_s . Control is done as in /1,2,3,4/ by a full-order observer tuned on-line. Identified parameters may differ considerably from the nominal parameters given below.

2. DYNAMIC STIFFNESS

The experiments are done on an industrial turbo molecular pump with a magnetic bearing system from Koyo Seiko. The radial bearing system, where sensorless operation has been implemented successfully, has the following nominal data:

rotor mass (≠equiv. mass)		4235 g
rotor length		ca 200 mm
rotational speed	Ω	ca 48 000 rpm
force-current factor	k_i	ca 65 N/A
force-displacement factor	k_s	ca 84 N/mm
voltage-velocity factor	k_b	ca 111 N/A
resistance	R	6.6 Ohm
inductance	L	327 mH

A static load $w(t) = w_0 =$ constant is not observable from the current, the only available measurement in sensorless operation. Therefore, the current will return to its equilibrium value $i=0$ under such a distrubance. According to the linearized force-current-displacement equation

$$f = k_i\, i + k_s\, x \qquad (2)$$

the displacement will stabilize at $x = -w_0/k_s$. The negative sign means negative static stiffness, a typical characteristic of non-minimum-phase systems. This behavior at low frequencies is opposite to the behavior of usual magnetic bearing systems and also opposite to the behavior of a passive mechanical stiffness.

The negative sign for low frequencies is seen in the phase plot of fig. 1 and 2.

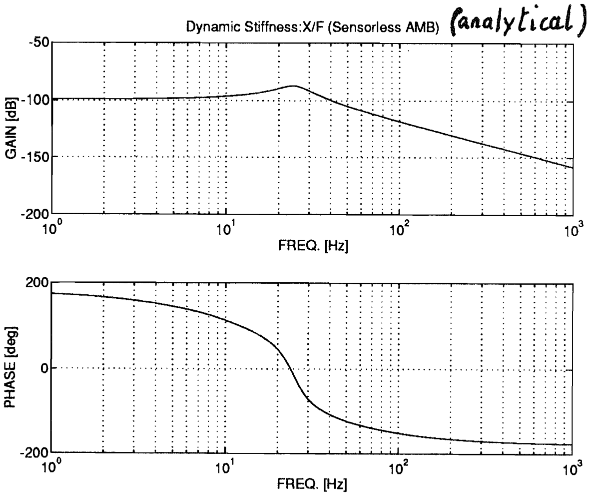

Fig. 1 Dynamic stiffness in sensorless operation

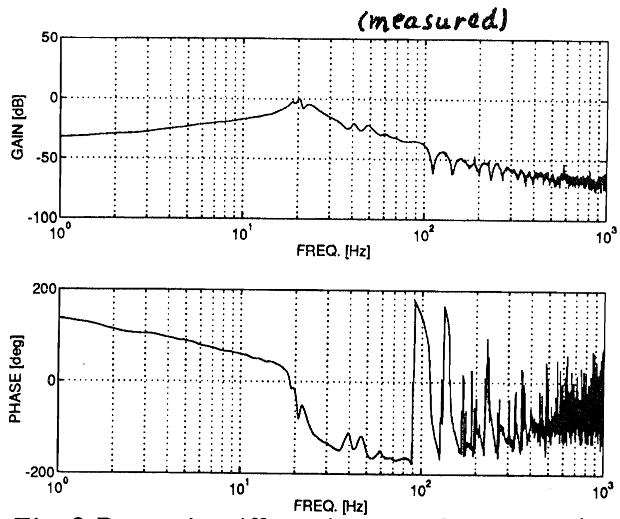

Fig. 2 Dynamic stiffness in sensorless operation

The high frequency dynamic stiffness is equal to the one of the normal magnetic bearing system shown in fig. 3.

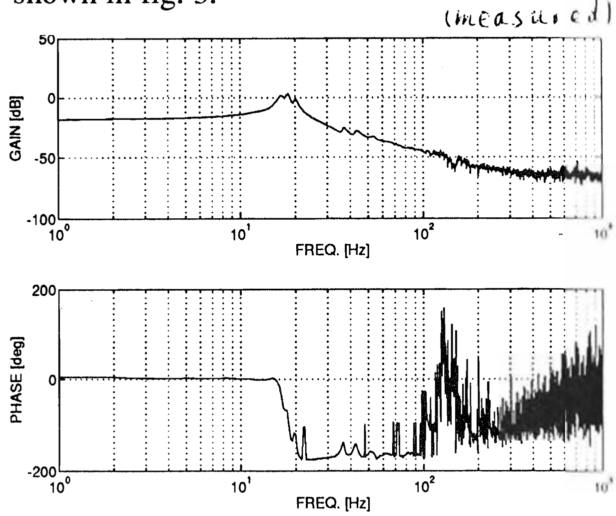

Fig.3 Dynamic stiffness of TMP with sensors

3. SENSORLESS BEARING FOR SOLID (NON-LAMINATED) CORE

As usual, there are laminations on the rotor at the radial bearings to reduce eddy current losses. The thrust bearing however consists of a soild disc. The resulting strong eddy currents act as an additional time-lag, they must be included in the dynamic model. A method proposed by Fukada, Kouya et al. /5,6,7/ is adapted here for the sensorless bearing. Additional parameters are introduced, indices 1 and 2 indicate the positive and negative side of the bearing shown in Fig.4.

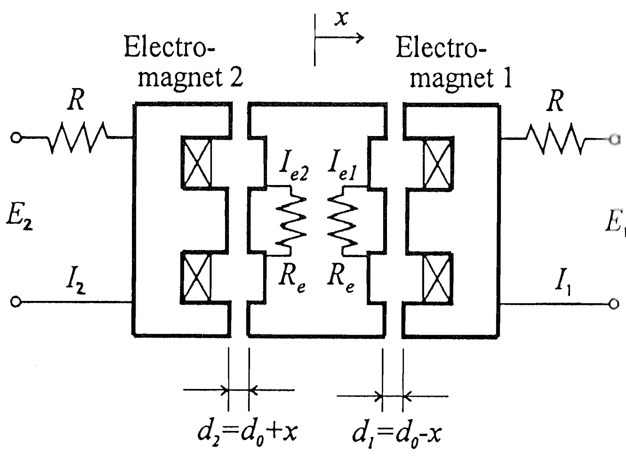

Fig. 4 AMB model including eddy currents

$$m\ddot{x} = F_1 - F_2 \tag{2a}$$

where $F_1=\frac{\Phi_1^2}{\mu_0 A}$ and $F_2=\frac{\Phi_2^2}{\mu_0 A}$ (3)

The equations of a single electromagnet are

$$E_1=RI_1+N\dot{\Phi}_1 \tag{4}$$

$$0=R_e I_{e1}+\dot{\Phi}_1 \tag{5}$$

$$NI_1+I_{e1}=R_{m1}\Phi_1 \tag{6}$$

$$R_{m1}\cong\frac{2d_1}{\mu_0 A} \tag{7}$$

where

- A : effective area of core
- μ_0 : permeability of air
- Φ_1 : flux
- E_1 : input voltage to magnet coil
- I_1 : current in magnet coil
- R : resistance of coil
- N : turns of coil
- R_m : magnetic resistance
- d : mean gap between magnet and rotor

Define the *quasi-current* as

$$Q=\frac{R_{m1}}{N}\Phi_1 \tag{8}$$

(statically $Q_1=I_1$, the coil current) and linearize as usual

$$E_1=E_0+e_1$$

$$Q_1=Q_0+q_1$$

$$R_{m1}=R_{m0}+r_{m1}=\frac{2d_0}{\mu_0 A}\;\frac{2x}{\mu_0 A} \tag{9}$$

With L' and k_b' defined as follows

$$L'=\frac{N^2}{R_{m0}}\left(1+\frac{R}{N^2R}\right)=L(1+\Delta) \tag{10}$$

$$k_b'=\frac{N^2I_0}{R_{m0}d_0}\left(1+\frac{R}{N^2R}\right)=k_b(1+\Delta) \tag{11}$$

$$\Delta=\frac{R}{N^2R_e} \tag{12}$$

one obtains

$$L'\dot{q}_1+Rq_1+k'_b\dot{x}=e_1 \tag{13}$$

and finally, with $q=q_1-q_2$, we obtain system (14)

$$\boldsymbol{x}=\begin{bmatrix}x\\ \dot{x}\\ q\end{bmatrix}\quad \boldsymbol{A}=\begin{bmatrix}0 & 1 & 0\\ \frac{2k_s}{m} & 0 & \frac{k_i}{m}\\ 0 & -\frac{2k'_b}{L'} & -\frac{R}{L'}\end{bmatrix}\quad \boldsymbol{B}=\begin{bmatrix}0\\ 0\\ \frac{1}{L'}\end{bmatrix} \tag{14}$$

This is equivalent to system (1) except for the modified parameters and the variable q (quasi-current) in place of current i. Using

$$q=(1+\Delta)i - e\,\Delta/R \tag{15}$$

system (14) is observable with current measurement alone, a position-sensorless operation is possible in principle according to (Fig. 5)

Even though model (14) has been used, at the time of manuscript submission the thrust bearing could not yet be operated in sensorless mode.

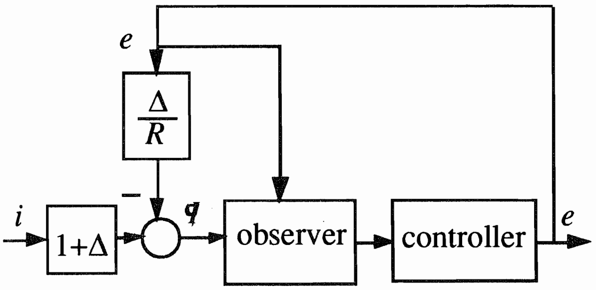

Fig. 5 Controller structure for position-sensorless magnetic bearing with solid rotor core.

Nevertheless, model (14) has been validated by experiments reported in the next section.

4. EXPERIMENTAL RESULTS ON THE INFLUENCE OF EDDY CURRENTS

A single-degree-of freedom system has been built specially for the purpose of measuring the influence of eddy currents with different "rotor"-cores. Measurement results are shown for three types of core materials, laminated silicon steel (transformer sheets), solid (non-laminated) soft iron and solid working steel S35C. The test-rotor has been fixed at an air-gap of 0.3mm and an additional coil of 150 turns was placed on the stator in order to directly measure the flux. The results shown are measurements at 5 Hz and 100 Hz with an AC current amplitude of 0.1 A superposed to a 0.3 A constant bias current. The phase lag between current and flux is a direct measure for the dynamic influence of the eddy current.

phase lag at	5 Hz	100 Hz
laminated Si-steel sheets	0.5°	3°
solid soft iron	7.5°	27°
solid steel S35C	6.5°	30.5°

Fig. 6 shows the measurement results.

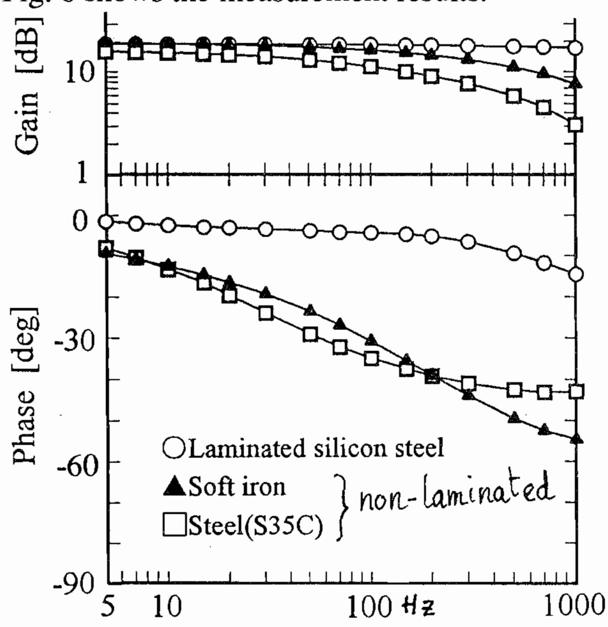

Fig. 6 Frequency response of flux to current

5. CONCLUSION

Posisiton-sensorless magnetic bearings based on current-measurement, voltage-amplifiers and a linearized plant model have been applied successfully to the radial bearings of an industrial turbo-molecular pump. This opens up the possibility for a real application of this type of bearings characterized among others by their negative static stiffness.

The problem of applying the same sensor-less control to a system with strong eddy-current influence, as e.g. the thrust bearing with its non-laminated rotor part, is analysed. A modified set of dynamic equations is proposed and validated experimentally. Experiments with the sensorless operation of the thrust bearing are not yet completed at the present time (June 1994).

Acknowledgements

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References

/1/ "Towards Practical Applications of Self Sensing Magnetic Bearings" Mizuno, Bleuler, Gähler, Vischer, 3.Int. Symp. Magn. Bearings, Washington. DC, Jul. 92

/2/ "A Geometric Approach to Control System Design of a Self Sensing Magnetic Bearing" Mizuno Bleuler, IFAC Conf Sydney Jul.93

/3/ "Self Sensing Active Magnetic Levitation", Vischer, Bleuler, IEEE Transactions on Magnetics, Vol 29, No2 March 1993

/4/ H. Bleuler, G. Schweitzer, A. Traxler, D. Vischer, D. Zlatnik "New Concepts for Cost Effective Magnetic Bearing Control", AUTOMATICA **30**:5, May 1994

/5/ Fukata S., Kouya et al.: Dynamic characteristics of Active Magn. Bearings. JSME Proc. **53**-490, 1987 pp1201-07 (Japanese)

/6/ Fukata S., Kouya et al.: Dynamic characteristics of Active Type Thrust Magnetic Bearing, JSME Proc. **56**-526 (1990) pp 180-185 (Japanese)

/7/ Sakamoto M.: Fundamental Research on Magnetic Bearings. Diploma Thesis, Inst. of Vocational Training, Sagamihara, Kanagawa Pref. 1987 (Japanese)