Active Magnetic Bearing System Identification using Current-Position Perturbation

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Abstract: Active magnetic bearings (AMBs) are currently in operation in many commercial applications including industrial turbo machines [1] as well as turbo molecular pumps. Since AMBs have important advantages over conventional bearings, new applications of this technology are developed yearly in fields such as commercial heating and air conditioning and space based rotary equipment. A notable advantage of AMBs is the ability to act concurrently as a means of bearing support and as a shaft force sensor. Sensing the force (or reaction) that is applied to the AMB stator through the shaft rotor is achieved by measuring information about the AMB's magnetic field. This capability has the potential to facilitate advanced health monitoring techniques as well as facilitate improvements in the continuous control of processes used in the production of microfibers and in detailed metal processing [1]. Quality control for such applications can be directly linked to real-time rotor force evaluation.

Some researchers have examined the force sensing capability of magnetic bearings by using Hall effect sensors in air gaps between bearing stator and rotor components. In this approach, measured magnetic flux densities are used in force equations to determine applied bearing reactions. Other researchers have employed methods based on measuring magnetic flux density in the bearing electromagnets from electric current data to determine applied bearing reactions, thus eliminating the need for additional sensor hardware. Limitations with both methods include assumptions in the force model associated with leakage, fringing, heterogeneity of magnetic material, and non-uniformity of axial and radial air gaps due to manufacturing tolerances. Misalignment and thermal issues encountered in the field also affect model accuracies [2]. Most magnetic force models assume that these effects are negligible and/or non-measureable. The research presented in this paper introduces a new in situ approach for bearing system identification in an effort to improve magnetic force models and is based on measurement of current and position perturbations. The paper also includes initial proof-of-concept static verification of the proposed method.

Keywords: AMB, Parameter Identification, AMB Force Measurement

Nomenclature

<u>Symbol</u>	<u>Description</u>
F_v	v axis magnetic force
μ_0	magnetic permeability of air (constant)

A	area of one pole face
N	number of coils of one pole face
i_{vt}	v-axis top coil current
i_{vb}	v-axis bottom coil current
g_{vt}	effective radial air gap at top of AMB along v-axis
g_{vb}	effective radial air gap at bottom of AMB along v-axis
g_{v0}	effective radial air gap along v-axis with rotor at geometric center ($g_{vt}=g_{vb}$)
b_{th}	equivalent iron length of stator and rotor
I_{bias}	bias current
v_0	rotor offset along v-axis
α	angle between centerline of AMB horseshoe and pole face (22.5°)

Introduction

The methodology presented in this paper extends the application of earlier system identification models based on examination of current perturbation only, collectively referred to as Multi-Point Methods (MPMs) [2,3]. These techniques involve perturbing a bearing current via a controller bias current and measuring subsequent responses to determine an AMB's magnetic center [3] and effective air gap [2]. The new method presented here is a current-position perturbation method which extends the MPM by examining the system response by *perturbing both bearing current and bearing position* thus improving system identification. The ultimate goal of this work is to improve force measurement techniques based on bearing current measurements, but the technique has implications for field evaluation as well. The identification technique makes use of the controller's ability to support a load at a specific location for any bias current setting within the operating envelope of the system [1]. Fig. 1 is a schematic of the magnetic bearing used in this research.

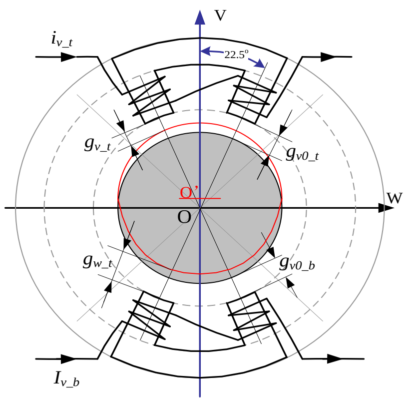

Figure 1 – Geometry of 8 Pole (4 shown here) Radial AMB Magnetic Horseshoe

The AMB used in this study consists of two 4 pole magnetic horseshoes, one along the v-axis and one along the w-axis. For a given load and position along the v-axis, a change in the bias current I_{bias} will result in a corresponding change in the controller current pair i_{vt} and i_{vb} maintaining the rotor at the operational set-point v_1. A bias current-perturbation method can establish a quadratic equation in one variable identifying the rotor origin [3]. This method assumes that the effective gap, g_o, is known in the force model (Eq. 2). The force model is established by equating the force along the v-axis (w-axis) for two independent bias current settings per Equation 1 [3]:

$$F_{v1} = F_{v2} \tag{1}$$

$$\frac{i_{vt1}^2}{[g_{v0}-(v_0+v_1)\cos\theta]^2}-\frac{i_{vb1}^2}{[g_{v0}+(v_0+v_1)\cos\theta]^2}=\frac{i_{vt2}^2}{[g_{v0}-(v_0+v_2)\cos\theta]^2}-\frac{i_{vb2}^2}{[g_{v0}+(v_0+v_2)\cos\theta]^2} \tag{2}$$

The nominal gap along v-axis and w-axis may not be the same due to system uncertainties. The current-position perturbation method presented here considers the rotor origin and effective gap as unknowns. The gap along v-axis and w-axis is identified independently of these two quantities.

In order to verify the proposed method, four separate force cases are determined which have different rotor positions and/or bias current pairs. To establish a set of two simultaneous equations in two unknowns, at least four perturbations are needed. These perturbations can be realized by changing current pairs, rotor position, or both.

Application of the MPM shows that not all equation pairs established by these perturbations have a unique solution. For example, if only current-perturbation is used (i.e. rotor position is assumed to remain unchanged), the resulting equations are ill-conditioned. When simultaneous equations in two unknowns are established by current-position or position perturbation, a wide range of solutions can result within error limits. This paper presents proof-of-concept experimental verification of results obtained from analytical computations using the current-perturbation approach. Advantages of the proposed current-position perturbation method include:

- Origin location and air gap are identified without prior knowledge of actual AMB geometry.
- System uncertainties (discussed previously) are considered. It is assumed that these factors affect the upper and bottom AMB gaps equally.
- System can have different effective gaps along v-axis and w-axis due to the circularity and rotor assembling error.
- Lamination coefficient is considered to be unknown and can be calibrated from the known load.

Magnetic Force Model

The configuration of a standard 4-pole radial active magnetic bearing horseshoe is showed in Fig. 1 for the v-axis. A model that assumes each magnetic axis acts independently is used to describe the magnetic force applied to the rotor. Namely,

$$F_V = 0.25\mu_0 AN^2\left[\frac{i_{vt}^2}{g_{vt}^2}-\frac{i_{vb}^2}{g_{vb}^2}\right]\cos\alpha \tag{3}$$

$$\begin{cases} F_V = 0.25\mu_0 AN^2\left[\dfrac{i_{vt}^2}{(g_{v0}-(v_0+v))^2}-\dfrac{i_{vb}^2}{(g_{v0}+(v_0+v))^2}\right]\cos\alpha \\ F_W = 0.25\mu_0 AN^2\left[\dfrac{i_{vt}^2}{(g_{w0}-(w_0+w))^2}-\dfrac{i_{vb}^2}{(g_{w0}+(w_0+w))^2}\right]\cos\alpha \end{cases} \tag{4}$$

Where, $\mu_0 AN^2$ is a constant proportional to the magnetic force. Control current i_{vt} and i_{vb} and rotor position v and w are provided by the controller and are inputs into the model. The outputs are the magnetic forces F_v and F_w. v_0 and w_0 are defined as rotor effective origin coordinates and the displacement of the rotor center is measured relative to the geometric center of the AMB stator. g_{v0} and g_{w0} are defined as the initial effective gaps for the v and w axes respectively when the rotor is located at the effective center (top gap equals to the bottom gap: $g_{vt} = g_{vb}$ *and* $g_{wt} = g_{wb}$). In essence, the purpose of this research is to identify the rotor origin (v_0, w_0) and initial effective gaps (g_{v0}, g_{w0}) describe above.

Usually, the rotor location is specified via a position sensor coordinate system. The origin of this sensor coordinate system does not coincide with the geometric origin of stator. Other factors, such as eccentricity, and non-axial alignment may lead to changes in rotor origin location. In determining the origin all effects indicated above are accounted for.

The effective gap (g_{v0}, g_{w0}) is affected by factors indicated previously. When the rotor is located at the geometric origin (v_0, w_0), the effective gap of the top AMB actuator and bottom actuator are the same ($g_{vt} = g_{vb} = g_{v0}$, $g_{wt} = g_{wb} = g_{w0}$). When the rotor is located at position of (v,w), the effective air gap can be described as: $\begin{cases} g_{vt} = g_{v0} - (v_0 + v) \\ g_{vb} = g_{v0} + (v_0 + v) \end{cases}$ and $\begin{cases} g_{wt} = g_{w0} - (w_0 + w) \\ g_{wb} = g_{w0} + (w_0 + w) \end{cases}$.

Once the effective gap and origin are determined, Eq. 4, in conjunction with the current and position provided by the controller, may be used to calculate the reaction applied to the stator by the rotor shaft.

Current-Position Perturbation Algorithm

The identification technique used in this research relies upon an MPM [1]. Along the v-axis, for a given load and position, a change in the bias current will result in a change in the controller current pair i_{vt} and i_{vb} maintaining the rotor at set-point v_1. The bias current perturbation method generates multiple pairs of controller currents (i_{vti}, i_{vbi}) in order to infer system information to calculated force. As was discussed previously, bias current-perturbation methods establish n quadratic equations in n unknowns allowing the rotor origin to be established. The effective gap is considered known in these equations but may change due to system uncertainties.

Although the perturbation method seems mathematically feasible, the equations will be 4th order (or higher) with 2 unknowns if the pair of perturbation positions selected are not symmetric. Fig. 2 is a set of force model solutions determined from application of the current-position perturbation approach. The v-axis effective gap (left axis) ranges from 600 to 1000 μm, and the v-axis origin (right axis) ranges from -100 to 100 μm with a step of 1 μm. Results demonstrate that there is a wide range series of solutions for a given RMS error limit of 5.0 x 10^{-5} μm (vertical axis). It does not provide a unique solution for a given set of system inputs so there are multiple gap and origin combinations that are solutions to the force equation.

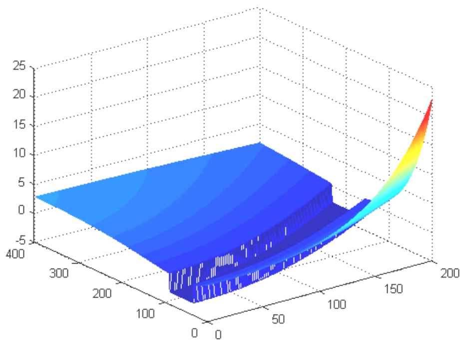

Figure 2 – Solution Space (Current-Position)

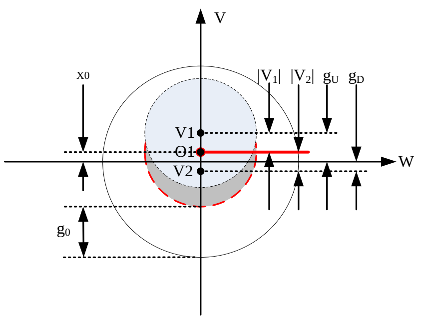

Figure 3 –Position Pairs (v-Axis)

In order to determine a unique solution for a given set of force equation inputs, a set of symmetrical position pairs along the v-axis are selected, (v_1,-v_1) and (v_2,-v_2), as shown in Fig. 3. Along the v-axis, a current-position perturbation is performed with current pairs (i_{vt11}, i_{vb11}, i_{vt12}, i_{vbi2}) and position pair (v_1,-v_1). The following equations result:

$$\frac{i_{vt11}^2 - i_{vt12}^2}{\left(g_{v0} - v_0\cos\alpha - v_1\cos\alpha\right)^2} = \frac{i_{vb11}^2 - i_{vb12}^2}{\left(g_{v0} + v_0\cos\alpha + v_1\cos\alpha\right)^2} \tag{5}$$

The perturbation is repeated with the same current pairs and position pair (v_2,-v_2). Resulting in the following,

$$\begin{cases} \dfrac{g_{v0} - v_0\cos\alpha - v_1\cos\alpha}{g_{v0} + v_0\cos\alpha + v_1\cos\alpha} = \sqrt{\dfrac{i_{vt11}^2 - i_{vt12}^2}{i_{vb11}^2 - i_{vb12}^2}} = P_A \\ \\ \dfrac{g_{v0} - v_0\cos\alpha - v_2\cos\alpha}{g_{v0} + v_0\cos\alpha + v_2\cos\alpha} = \sqrt{\dfrac{i_{vt21}^2 - i_{vt22}^2}{i_{vb21}^2 - i_{vb22}^2}} = P_B \end{cases} \tag{6}$$

Eq. 6 can be re-written as:

$A \cdot X = C$, where

$$A = \begin{bmatrix} (1-P_A), & -(1+P_A) \\ (1-P_B), & -(1+P_B) \end{bmatrix}, X = \begin{bmatrix} g_{v0} \\ v_0\cos\alpha \end{bmatrix}, \quad C = \begin{bmatrix} (1+P_A)\cos\theta \\ (1+P_B)\cos\theta \end{bmatrix}, \quad X = A^{-1}C \tag{7}$$

Eq. 7 is a linear first order system with effective gap g_{v0} and effective origin v_0 as unknowns.

The effective rotor origin is the location for which the current-position method returns effective offset values of zero for each axis: (v_e,w_e) = (0,0) [3]. In general, the effective origin will not coincide with the system (geometric) origin. The effective origin location is found by manually changing the rotor offset via the system controller so that the effective rotor position is (0,0). The initial bearing rotor position coincides with the center of the back-up bearing which coincides with the system coordinate origin: (v_s,w_s) = (0,0). The current-position MPM is first applied at this initial location to determine the corresponding position in effective coordinates (v_e, w_e). Initially, the effective rotor offset will probably be non-zero. The effective coordinates are used as an error signal to estimate a more correct rotor position. The rotor is moved to new location according to the error estimate. Usually, multiple iterations of rotor position adjustment are required to allow the origin and effective gap to converge to a final value within an error tolerance.

Test Apparatus

The AMB experimental apparatus used to verify the proposed method is shown in Fig. 4. Although the platform is comprised of two radial AMBs, only one is used during initial tests. The inboard bearing (left bearing in Fig. 4) is used as a simple support by suspending it magnetically at system coordinate (0,0). By hanging various masses on the balance disk, different bearing loads are produced, resulting in a reaction envelope. The AMBs used in the study consist of two four-pole magnetic horseshoes and are connected to a digital PID controller. The bearings have a load capacity of 53.4 N and a saturation current of 3.0 A. The inner diameter of the stator is 35 mm, with a nominal diametric gap of 0.762 mm. External proximity probes are used to quantify rotor displacement along the v and w axes.

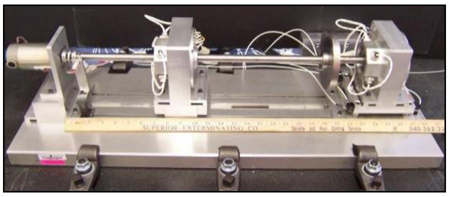

Figure 4 - Experimental Test Platform for AMB Force Measurement

Current and position pairs are the only inputs required to characterize the AMB system. Before starting the experiment, both the position sensor and current DAQ are calibrated in situ using a multi-meter having 0.1% error (within 0-3A) and a micrometer having 0.25% error (within 0.2 inch).

Experimental Results

Experiments described in the previous section provide verification of the proposed method of current-position perturbation. Parameters are identified experimentally using three bias current pairs. Position pairs of ±20μm (equal to one third of the radial distance between rotor and back-up bearing) are selected and 10 iterations are preformed for each experiment. Table 1 shows the mean average from the 10 iterations.

Table 1 – Result of Current-Position Perturbation Method for Three Bias Pairs

No.	Bias(A)	Perturbation Position Pairs (μm)		Origin Position (μm)		Effective Gap (μm)	
		v_1	w_1	v_0	w_0	g_{v0}	g_{w0}
1	1.4/1.5	±20	±20	35.08	-9.63	778.71	765.11
2	1.4/1.6	±20	±20	31.75	-10.72	778.84	753.00
3	1.5/1.6	±20	±20	28.77	-12.03	768.96	778.43
	Average			31.87	-10.79	775.50	765.51

Results indicate that origin error is within ±4 μm and effective gap error is within ±20 μm. The mean gap predicted by the method along v-axis and w-axis is within 13 and 3 μm, respectively, of the nominal mechanical gap of 762 μm. The consistency of the results for different cases, and the measured gap compared to nominal gap demonstrate the method's validity. Differences between gap values are accounted for in this proposed method. Results from Experiment 2 in Table 1 are shown in Table 2.

Table 2 Results for 10 Iterations

No.	Rotor Origin(μm)		Effective Gap(μm)	
	v_0	w_0	v-axis	w-axis
1	31.92	-7.18	784.44	765.42
2	33.67	-11.06	813.22	782.07
3	30.47	-9.75	746.59	732.63
4	31.41	-11.40	858.65	728.96
5	31.58	-10.73	759.45	695.12
6	32.08	-9.92	773.46	742.76
7	31.46	-10.78	738.01	709.65
8	31.96	-11.78	773.46	850.73
9	31.56	-12.71	747.11	743.12
10	31.43	-11.91	793.98	779.59
Ave	31.75	-10.72	778.84	753.00

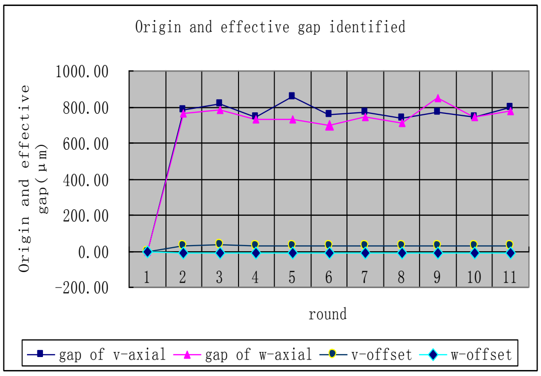

Figure 5 – Rotor Origins and Effective Gap Values for Outboard AMB

Fig. 5 shows rotor origin and effective gap values for the outboard AMB obtained from the proposed method for 10 iterations. Origin and effective gap values converge to their respective mean values with one iteration. The observed undulations (iterations 2 to 11) are caused by current and position sensor error. By comparison, other previously discussed MPM methods may require 10 or more iterations to converge to origin and effective gap mean values.

Rotor Position Perturbation

Another experiment, using a bias current pair of 1.4/1.6A and ±20μm position pairs is preformed for 10 iterations to verify the accuracy of the parameters found previously. Tab. 3 shows the results of this experiment. In addition, in order to determine if the initial rotor position affects parameter values, these experiments are preformed with the rotor at randomly selected initial points. As shown in Tab. 3, initial rotor location has only a minor affect on effective gap and rotor origin.

Table 3 – Effect of Different Initial Rotor Positions on Parameter Values

No.	**Bias (A)**	**Initial Position (μm)**		**Origin Position (μm)**		**Effective Gap (μm)**	
		v_1	w_1	v_0	w_0	g_{v0}	g_{w0}
1	1.4/1.6	0	0	35.68	-11.70	775.10	759.16
2	1.4/1.6	30	30	33.47	-10.82	775.54	765.76
	1.4/1.6	-10	-30	37.22	-13.39	769.21	757.20
4	1.4/1.6	2.78	-36.88	32.87	-11.57	779.69	762.36
Average				34.81	-11.87	774.89	761.12

Rotor Reassembly

A final experiment is performed after removal and re-attachment the outboard AMB rotor. The parameter values obtained from this experiment are shown in Tab. 4.

Table 4 – Parameter Values after Rotor Re-assembly

No.	Bias(A)	Perturbation Position Pairs (μm)		Origin Position (μm)		Effective Gap (μm)	
		v_1	w_1	v_0	w_0	g_{v0}	g_{w0}
2	1.0/1.4	±30	±30	-48.25	12.34	771.83	750.74
3	1.0/1.4	±40	±40	-47.45	12.16	783.58	773.25
4	1.0/1.4	±50	±50	-48.84	12.99	768.89	754.84
2	1.2/1.4	±30	±30	-46.96	13.98	774.61	773.73
3	1.2/1.4	±40	±40	-46.25	13.92	767.99	761.20
4	1.2/1.4	±50	±50	-46.94	13.15	771.47	767.79
	Average			-47.45	13.09	773.06	763.60

Several bias current and initial position pairs are shown in Tab. 4. The calculated origin significantly changes after re-assembly due to reorientation of the rotor but the effective gap is close original its value (within 5μm) prior to disassembly.

Conclusion

A system identification method, based on perturbations of both AMB current and rotor position, has been introduced in this paper. This method allows in situ identification of radial gap and rotor origin position. Accuracy and robustness of this method is demonstrated through repeated experimental verification involving several combinations of current/position settings and rotor origin initial positions. Also, the rotor is removed and then replaced to determine affects on calculated parameters. The expected gap from mechanical measurements, based on the mean average of the values reported in Tables 1, 3, and 4, is 775 μm and 763 μm, for g_{v0} and g_{w0}, respectively. Corresponding standard deviations are 1.3 μm and 2.2 μm. The nominal diametric gap is 762 μm, resulting in errors of 1.7% and 0.1% for the v and w axes, respectively.

Similarly the mean for origin points, v_0 and w_0 for all tests are 33.3 μm and -11.3 μm, respectively, with standard deviations of 2.1 μm and 0.8 μm. The consistency among the various experiments allows confidence that the approach works for system identification and is intended only to introduce the approach. Future work and publications will include force measurements determined from application of this approach.

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