Investigation of Current-Based Dynamic Force Measurement with Active Magnetic Bearings

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ABSTRACT

Many processes involving rotating machinery could benefit from the continuous feedback of the forces applied to the bearings that support the machinery. Such a system could be used to provide diagnostics for process monitoring in a manufacturing application or to provide force feedback in other devices. In order to stand up to the demands of an industrial or harsh field environment the force measurement system would ideally be robust, inexpensive, and readily applicable to any AMB (Active Magnetic Bearing) system. To meet these goals, dynamic load data would be provided using monitored currents and positions only, without the use of Hall probes. This paper presents the first step towards developing a technique and algorithm for achieving dynamic current-based force measurement with AMBs. The proposed measurement system is based on a simple force equation developed from magnetic circuit theory which has been modified to accommodate an "effective current" to account for errors due to both current and speed-dependent loss mechanisms. The modified model presented here is not physics-based but determined by curve fitting the magnetic-circuit force model to known force data for a single load and bias current case at multiple speeds. Known force data was obtained from force transducers mounted under a bearing. This empirically determined model was then used for comparison to force transducer data for other load, speed, and bias current cases. If all of the data is polled the average error is 4% with a worst-case error of 21%. System dynamics caused modeling problems for the data collected at 3000 RPM, if errors in this speed range are neglected, the average error is 2.8% with a worst-case of 6.8%. The results of this study demonstrate that a speed-dependent AMB force model is possible, and set the groundwork for future investigations.

INTRODUCTION

The ability of a magnetic bearing to concurrently support and monitor a load facilitates significant improvements for machine condition and performance monitoring as well as information for process control in manufacturing applications. Several researchers have demonstrated this force measurement capability; the current state of the art relies on additional hardware in the form of Hall probes to gauge the magnetic flux present in the air gap. Although this often leads to reliable force data, the use of Hall probes is not necessarily appropriate for all applications. For example, physically harsh environments may pose problems for such techniques due the delicate nature of Hall probes. The research presented here is part of an effort to provide dynamic force data by analyzing information that is inherent to a typical magnetic bearing system: coil current and rotor displacement. The research was carried out on a small high-speed laboratory rotor that was modified to allow for the direct measurement of bearing forces for comparison to magnetic bearing data. Figure 1 shows a picture of the rotor in which the modifications are evident. In particular, the outboard bearing was mounted onto two force transducers, the inboard bearing and motor were mounted on spacers to match the height of the outboard bearing. The transducers allow acquisition of the reaction forces experienced by the outboard bearing that can be used to verify the accuracy of magnetic bearing current-based force measurement techniques under investigation. The authors are unaware of any other study comparing AMB force measurement techniques with actual measured bearing forces.

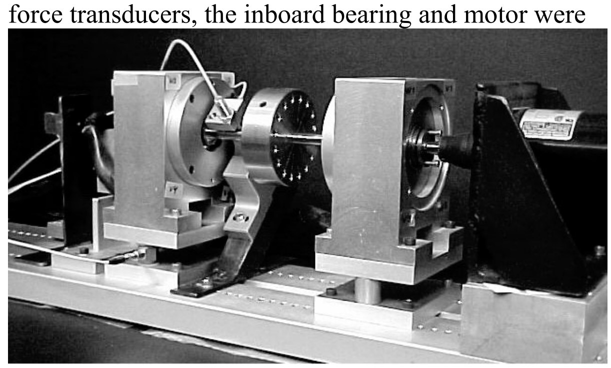

Figure 1: Laboratory Rotor

Most AMB techniques for force measurement rely on Hall probes because they are capable of direct flux measurements and as such are not affected by hysteresis and eddy currents. This is particularly important when measuring rapidly changing loads, such as those observed in a rotating system, where significant portions of the measured control current will be required to overcome these magnetic losses. Aenis (2000), for example, chose to use Hall probes over a current and displacement-based model when developing frequency response functions related to the operation of a centrifugal pump. In a similar study concerning journal bearings, Knopf (1998) also showed that Hall probes were the better choice for force measurements on a dynamic system. Imlach (2000) was able to improve the accuracy of his Hall probe measurements for use in a rocket thrust measurement system by developing gap-dependent fringing factors. The accuracy of the new fringing factor model was facilitated by the Multi-Point Method (MPM) for identification of field gaps as developed by Kasarda (2000).

Although the above methods are capable of providing accurate dynamic force data, their reliance on Hall probes could lead to difficulties in some cases. For instance, failed probes may not be easily serviced since they must be placed in the air gap. Furthermore, the addition of Hall probes represents an increase in system cost and complexity.

The potential difficulties with flux probes combined with the readily available nature of coil current and rotor displacement data serves as a motivation to develop dynamic force measurement using only magnetic bearing system data. The first question to be answered is: can data from a variety of conditions, including speed variation, bias current variation, and dynamic load variation, be fit to a common model that produces reasonably accurate results? Recognizing that such a model would need to account for dynamic effects such as saturation and hysteresis may dictate the approach of developing a complex model that accounts for these and other system inefficiencies. Our initial approach in an attempt to characterize trends associated with magnetic phenomena is to modify the bearing force model to include a formulation for an effective current in place of a simple measured current. The parameters describing the effective current in the new model were optimized so that variation between the modeled force and the force transducer measurements was minimized based on one initial set of measurement data. Additional data from a variety of load conditions and bias current conditions was then modeled using the optimized parameters to predict the bearing force. Although this requires knowledge that is not typically available (force transducer measurements) it does demonstrate that a reasonably good model can be made to fit multiple dynamic data scenarios using only one set of AMB system data.

APPROACH

A typical axis of an AMB system, such as those used to gather the data presented in this paper and depicted in Figure 2, consists of a pair of opposing electromagnets. This configuration is referred to as a double acting actuator because the load can be shifted in either direction of the actuator axis.

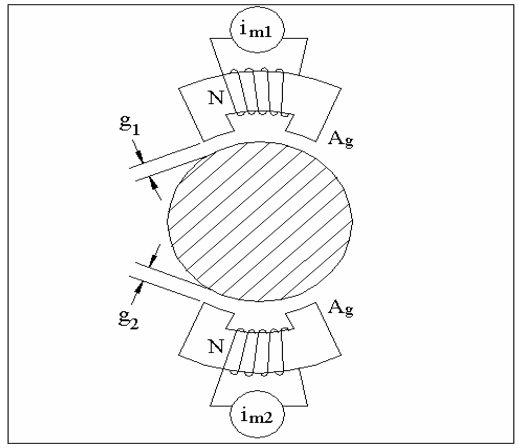

Figure 2: Double-acting magnetic actuator

The net force of a double-acting actuator such as the one illustrated in Figure 2 is the difference between the forces produced by the top and bottom magnets. Based on magnetic circuit theory, the relationship between force, air gaps, and current for a double-acting actuator can be represented as

$$F_{th} = \varepsilon \cdot k_{th} \left(\frac{i_{m1}^{\;2}}{(2g_1 + b_{th})^2} - \frac{i_{m2}^{\;2}}{(2g_2 + b_{th})^2} \right) \qquad (1)$$

where k_{th} is a proportionality constant, i_{m1} and i_{m2} are the measured currents in the opposing coils, g_1 and g_2 are the upper and lower air gaps, b_{th} is the equivalent iron path length of the actuator, and ε is a derating factor (Baun, 1996). The proportionality constant, k_{th}, can be calculated from the geometry of the actuator and is given by

$$k_{th} = \mu_0 A_g N^2 \qquad (2)$$

where μ_0 is the permeability of a vacuum ($4\pi*10^{-7}$ H/m), A_g is the area of a single pole face, and N is the number of coils per actuator. The equivalent iron path length is represented as

$$b_{th} = L_i / \mu_r \qquad (3)$$

where L_i is an approximation of the mean distance the magnetic flux must travel through the actuator core, and μ_r is an approximation of the relative permeability of the magnetic material. The derating factor, ε, accounts for uncertainties in the model due to such effects as fringing and leakage. For the results presented here, the derating factor was set to unity since we assumed our model parameters would account for non-ideal effects.

The idealized model in Equation 1 shows that the force generated by a given coil is a function of the proportionality constant k_{th}, the measured coil currents i_{m1} and $i_{m2,}$ the air gaps g_1 and g_2, and the equivalent iron path length b_{th}. Of these terms, $k_{th,}$ and b_{th} are constants associated with a particular bearing setup. Of the remaining parameters $i_{m1,}$ $i_{m2,}$ $g_{1,}$ and $g_{2,}$ the coils currents i_{m1} and i_{m2} are directly observable in most standard AMB systems in the field without additional hardware. The actual bearing gap can be inferred from proximity sensors and knowledge of the bearing geometry. However, this does not take into account variations in gap due to thermal effects, misalignment, or final machinery assembly tolerances. Future work will include incorporation of MPM calibration techniques for identifying field gaps (Kasarda [2000]).

The force model shown in Equation 1 assumes that all of the measured currents i_{m1} and i_{m2} are available for use in generating magnetic flux. In the case of a dynamic load there will be a difference between the measured currents and the current that is available for use in generating magnetic flux due to parasitic losses such as hysteresis and eddy currents. Therefore, a form of Equation 1 that incorporates an "effective" current, i_e may offer improved force measurement accuracy. Although we chose not to develop a rigorous physical model of effective current at this time, we did expect that the effective current would be a function of the measured current and the rotor speed. Based on these assumptions we proposed the following equation for determining effective current, based loosely on the expected effects of projected loss sources:

$$i_e = i_m - p_1 i_m - p_2 i_m \omega - p_3 i_m^2 \omega^2 \tag{4}$$

where i_e is the effective current, i_m is the measured current, and ω is the rotor speed. The parameters p_1, p_2, and p_3 are not known *a priori* and were determined for the initial data set by using the known force values provided by the transducers.

Predicted AMB force for the remaining data was then determined by augmenting Equation 1 with Equation 4, assuming the parameter values determined from the initial data set. This model force was then compared to its associated transducer data.

EXPERIMENTAL SETUP

Test data was generated using a high-speed laboratory rotor supported by AMBs as shown in Figure 1. The system consists of two eight-pole, 35 mm stator inner diameter heteropolar design AMBs with a digital PID controller manufactured by Revolve Magnetic Bearings, Inc. Additional specifications are as follows; 0.381mm nominal air gap, 12 lb_f maximum rated load per bearing, 9.5mm shaft, 200mm bearing span. The outboard bearing was mounted on ICP type force transducers to allow monitoring of the bearing reaction force. Each transducer has a 10 lb_f capacity (PCB Model 208C01). The inboard bearing and motor were mounted on spacers to maintain alignment. This rig allowed us to observe the magnetic bearing control signals and the force transducer output for a variety of system conditions.

The system conditions that were varied were rotational speed, bias current, and dynamic load. Speed was varied from 2000 to 9000 RPM via the motor controller. Bias currents were changed using the AMB controller; bias currents of 1.3, 1.5, and 1.7 Amps were applied. The different dynamic load scenarios were achieved by inserting various unbalance masses into the disk. In addition to the 0g added unbalance mass case, unbalance masses of 0.4g, 0.6g, 0.8g, and 1.0g were added to the disk to vary the dynamic loading. The conditions imposed on the rotor during testing are summarized in table 1.

Table 1: Summary of Rotor Test Conditions and Resulting Dynamic Load (lb)

Load Scenario	Bias Current (Amps)	Speed (RPM)							
		2000	3000	4000	5000	6000	7000	8000	9000
Case 1 0g added	1.3	0.42	0.83	1.3	1.6	2.17	2.79	3.15	3.12
	1.5	**0.43**	**0.79**	**1.26**	**1.63**	**2.3**	**2.98**	**3.32**	**3.23**
	1.7	0.45	0.74	1.21	1.61	2.4	3.12	3.46	3.3
Case 2 0.4g added	1.3	0.46	0.97	1.56	1.96	2.73	3.53	4.12	4.32
	1.5	0.48	0.91	1.5	1.99	2.9	3.8	4.4	4.52
	1.7	0.49	0.87	1.44	1.97	3.02	3.99	4.61	4.66
Case 3 0.6g added	1.3	0.5	1.04	1.68	2.14	2.95	3.89	4.6	4.92
	1.5	0.49	0.98	1.63	2.18	3.15	4.22	4.94	5.18
	1.7	0.49	0.91	1.55	2.15	3.28	4.43	5.19	5.35
Case 4 0.8g added	1.3	0.54	1.12	1.82	2.37	3.26	4.27	5.14	5.6
	1.5	0.53	1.05	1.76	2.41	3.49	4.64	5.54	5.93
	1.7	0.52	0.98	1.67	2.38	3.64	4.9	5.84	6.16
Case 5 1.0g added	1.3	0.55	1.2	1.95	2.63	3.55	4.66	5.65	6.22
	1.5	0.53	1.12	1.89	2.58	3.8	5.11	6.14	6.66
	1.7	0.52	1.04	1.8	x	2.84	5.43	6.47	6.96

As described earlier, an initial set of data was used to provide input to determine the model parameters shown in Equation 4. The data that makes up the initial set is set in boldface in the table and consists of the 0g added load case operating with bias currents of 1.5 Amps across the full range of speeds.

PARAMETER ESTIMATION

The parameters in Equation 4 were optimized using an augmented Equation 1 where currents i_{m1} and i_{m2} were replaced by expressions for their respective effective currents based on Equation 4. The expression for effective current incorporates three parameters, p_1, p_2, and p_3, whose values were unknown at the outset. These parameters were determined using an initial data set consisting of constant load and bias current selections at all seven test speeds (0g added load; bias currents of 1.5 Amps; full range of speeds). Measured current and displacement data for the initial data set were used as inputs to the augmented equation so that a force value could be calculated for each selected speed, assuming arbitrary parameter values. Each parameter was then assigned a range so that numerous force values could be calculated for each of the seven speeds in the initial data set. Each calculated force for a given speed was then compared to the force transducer data associated with that speed. The set of parameters p_1, p_2, and p_3 which caused the least percentage error over all seven test points of the initial data set were chosen as the parameters of record to be used in Equation 4 for the purpose of modeling the remaining data. The final parameter values are as follows:

$p_1 = 0.48$
$p_2 = -1.6e\text{-}5$
$p_3 = -3.1e\text{-}11$

so that Equation 4 becomes:

$$i_e = i_m - (0.48)i_m + (1.6e-5)i_m\omega + (3.1e-11)i_m^2\omega^2 \quad (5)$$

A cursory examination of Equation 5 shows that this model predicts effective current to *increase* as rotor speed increases. This is counter to expected behavior since eddy currents and hysteresis, which represent a parasitic loss of current, at least initially increase as speed increases (until skin effects may come into play). It is apparent that the model in Equation 5 does not reflect expectations; this is likely due to a faulty proposed model (Equation 4) forcing an overcompensation by the optimization routine to account for current magnitude effects. Although this is clearly an issue and is under active consideration, the technique does demonstrate that a variety of dynamic load scenarios can be accurately predicted using a single mathematical model as will be shown in the next section.

EXPERIMENTAL RESULTS

Force transducer measurements for a variety of data sets as listed in Table 1 were generated for comparison to the AMB predicted force. Figure 3 shows the dynamic loads from the force transducers for all the speed and load cases associated with the middle bias current case (1.5 Amps).

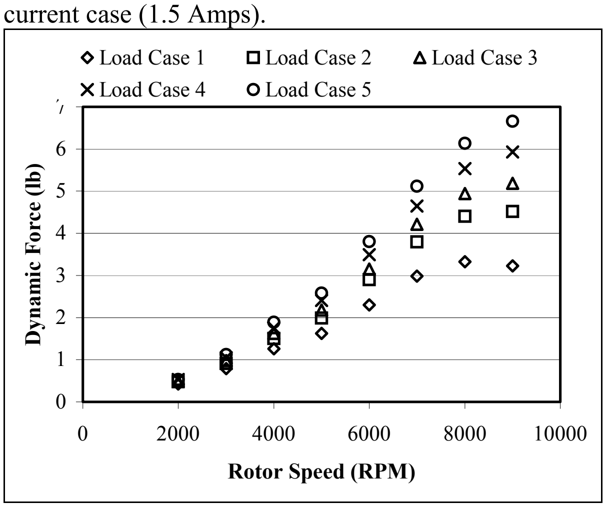

Figure 3: Dynamic Force Values Measured by Force Transducers for the 1.5 Amp Bias Cases

Figure 3 is fairly typical of the other bias current cases and can be considered representative. As expected, the unbalance masses used to create the five dynamic load cases are more effective as speed increases. At lower speeds it is difficult to achieve a variety of dynamic loading using unbalance masses. The rotor/bearing system was well damped; a well damped system critical speed exists in the vicinity of 3000 RPM. The location of this system critical speed varied with the magnitude of the bias current.

If the measured currents are used directly in the force model, large errors occur. This is illustrated in Figure 4 for all three bias current cases associated with load case 1 (no added unbalance).

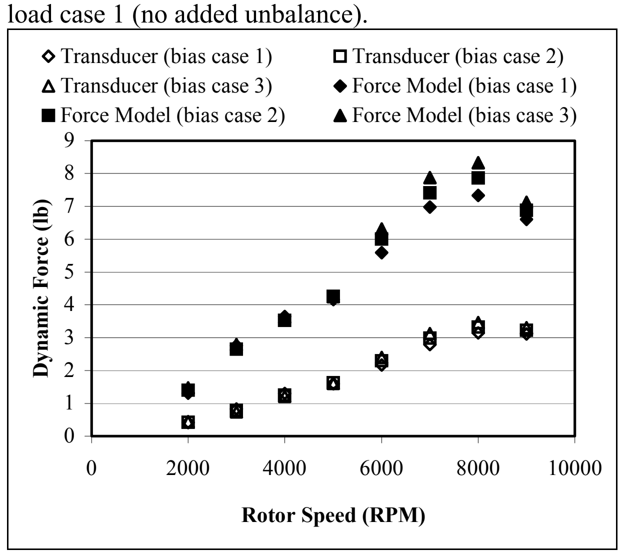

Figure 4: Transducer Force and AMB Force (from an Unmodified Model; Based on Total i_m) for the 0g Added Unbalance Data Set

Figure 4 shows that unacceptably large errors occur between unmodified model data and transducer data.

The measured currents and displacements from the 1.5 Amp bias current data set shown in Figure 4 were used as inputs in the procedure described earlier to determine the parameters p_1, p_2, and p_3 in the effective current equation (Equation 4).

Once the parameters were optimized, the force model in Equation 1 utilizing the effective current expression in Equation 4 was used to determined predicted AMB forces in the remaining data sets as shown in Table 1.

An example data set consisting of transducer force data and predicted AMB forces for the load case when unbalance is 0.6g and for three bias current settings of 1.3, 1.5, and 1.7 Amps through a speed range of 2000 – 9000 RPM is presented in Figure 5.

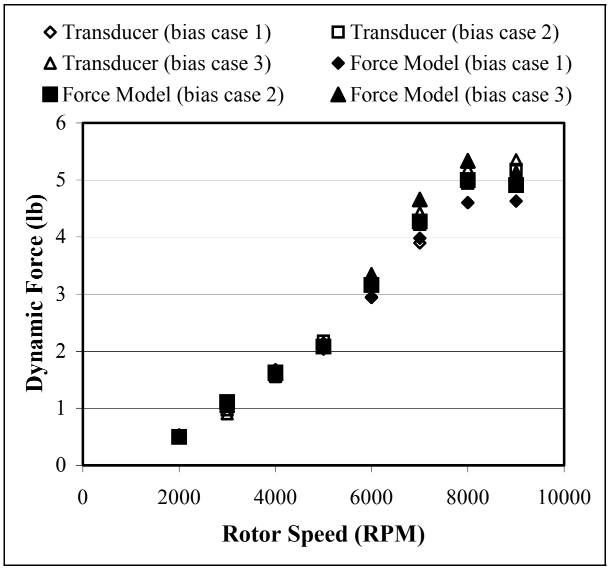

Figure 5: Comparison of Transducer Data and Model Data (based on i_e) for all Bias Settings of Load Case 3 (0.6g Added Unbalance)

A very good fit with an average error of 4.1% and maximum error of 16.8% between the AMB predicted forces and measured transducer data is shown in Figure 5 for this load case. The maximum error percentages occur at the 3000 RPM case. If the 3000 RPM speed cases are neglected, the average error is 2.8% with a maximum error of 5.9%. Figure 5 demonstrates that an effective current based AMB force model provides a significant improvement in accuracy as compared the force model that relies solely on measured currents.

In order to better judge the effective current model, the error percentages between the transducer readings and the forces determined by the model were calculated for all load cases throughout the speed range. Figures 6, 7, and 8 show the resulting error plots for bias currents of 1.3, 1.5, and 1.7 Amps respectively. It should be noted that there is a system critical speed at approximately 3000 RPM that appears to be affecting the accuracy at the 3000 RPM cases for all test scenarios. This is possibly due to motion in the force transducers as part of the system response but this has not been characterized at this writing.

Errors for all load and operating speed cases for a bias current of 1.3 Amps are shown in Figure 6. Except for the 3000 RPM outliers, all of the AMB model force values are within ±6.8% of the associated transducer values for bias currents of 1.3 Amps. The average error for this case is 3.5%. The worst-case error at 3000 RPM is 7.6%.

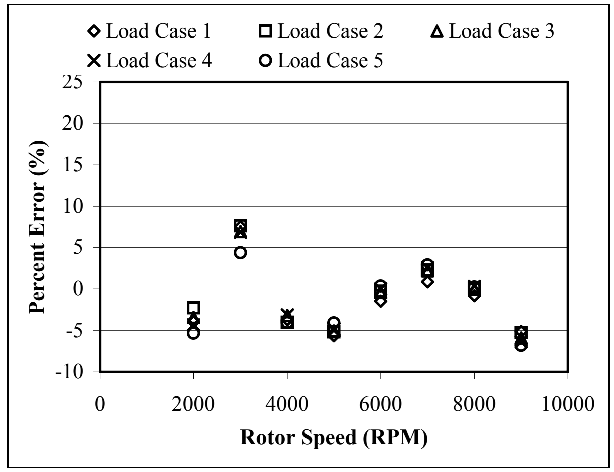

Figure 6: Model Error for Bias Case 1 (1.3 Amps)

The error trends for the bias current setting of 1.5 Amps for all load and speed cases are shown in Figure 7. Except for the 3000 RPM outliers, all of the AMB model force values are within ±6.8% of the associated transducer values for bias currents of 1.5 Amps. The average error for this case is 2.3%. The worst-case error at 3000 RPM is 13.6%

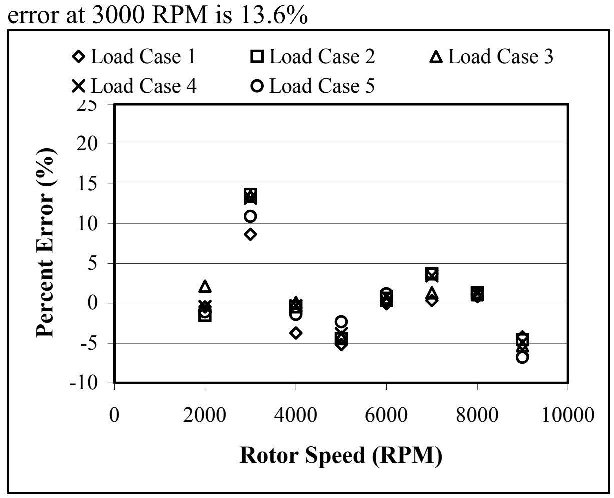

Figure 7: Model Error for Bias Case 2 (1.5 Amps)

The error trends for the bias current setting of 1.7 Amps for all load and speed cases are shown in Figure 8. Except for the 3000 RPM outliers, all of the AMB model force values are within ±6.4% of the associated transducer values for the for bias current of 1.7 Amps. The average error for this case is 3%. The worst-case error at 3000 RPM is 21%.

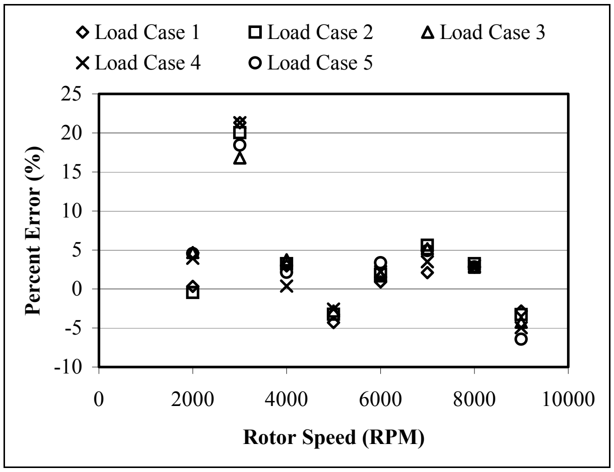

Figure 8: Model Error for Bias Case 3 (1.7 Amps)

As mentioned earlier, we suspect that a system resonance, possibly related to the way in which the AMB bases are mounted to the transducers, was in play near the 3000 RPM speed. Bias current changes may have contributed to changes in the system stiffness and damping parameters. Such changes could have been enough to cause significant variation in the system response at 3000 RPM, making modeling difficult in that region. In any case, it is clear that some phenomena are occurring at this speed that we have not unaccounted for.

In broad strokes, if all of the data is considered, the average error is 4% and the worst-case error is 21%. If the data associated with 3000 RPM is neglected the average error is reduced to 2.8% and the worst-case error becomes 6.8%.

CONCLUSIONS

A force measurement alternative that requires only the control currents and rotor displacements readily available from an AMB control system would have clear advantages over Hall probe-based techniques. Traditional difficulties with such an approach have been related to correctly determining how much of the input current contributes to creating lift force versus how much is required to counter parasitic losses.

We have successfully demonstrated that a mathematical model based solely on current and position data can successfully predict dynamic forces in a magnetic bearing. Although the chosen model does not appear to represent the underlying physical processes, it remains significant that it *can predict dynamic forces for multiple speeds and loads* and the results shown here lay the foundation for *a priori* determination of an accurate current-based force measurement technique. The model developed here has been shown to fit a range of data that includes variations in speed, bias current, and dynamic load. Over the test conditions the model is able to predict forces to within 4% on average although some cases have as much as 21% errors. If outliers associated with the 3000 RPM critical speed are neglected, the model prediction statistics improve to an average of 2.8% with a worst case of 6.8%.

Although the errors in force measurement presented here are still greater than those typically associated with Hall probe techniques, they are small enough to suggest that an accurate current based force measurement method is possible.

Future work includes the incorporation/development of a more rigorous physics based model and of the development of a system identification approach to determining model parameters without the use of force transducer data. This work includes an experimental component using a new larger test apparatus currently under development that includes the ability to vary parameters such as rotor lamination thickness and air gaps to facilitate the characterization of parasitic loss effects on AMB force measurement techniques.

ACKNOWLEDGEMENTS

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