Performance Assessment of a Self-bearing Motor: an Application of ISO 14839

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***Abstract* — Two different controllers have been applied for the stabilization of a self-bearing motor prototype existing at LASUP/UFRJ (Laboratory of Applied Superconductivity – Federal University of Rio de Janeiro): a PID controller and a LQR controller. This paper compares the performance of those controllers based on criteria described on the ISO 14839 standard, which establishes requirements for AMB (Active Magnetic Bearing) applied to turbo machinery.**

I. INTRODUCTION

A. *Performance assessment for AMB controllers*

Controllers are essential for the operation of active magnetic bearings, due to their intrinsic instability. As many different control strategies have been applied, some articles have addressed the question on which controller is the best. Various performance criteria have been used, like: analysis of phase plane trajectories [1], sensitivity analisys[2], step response [3], etc.

Standard ISO 14839 has been proposed as a performance evaluation procedure for turbo-machines, aiming to be an answer to the lack of consensus on how to evaluate magnetic bearings applied to turbo machines [4]. This paper addresses this technique, applied to a self-bearing motor.

B. *LASUP self-bearing prototype*

LASUP self-bearing motor has been assembled as shown in Figure 1 below, having two 4-poles 2 phase motors. Although structured to have an upper and a lower radial bearing, only the upper magnetic bearing was used for the experiments, being the lower radial bearing, as well as the axial bearing, implemented by a ball bearing. Phase A of the motor is used for positioning, though generating some torque, while phase B is just applied for torque generation.

C. *Control structure*

For the stabilization of this self-bearing motor, two different controllers were designed and implemented: a PID controller [5] and a LQR controller [6]. Both controllers were realized using a DSP (Digital Signal Processor).

The question posed is "which controller is the best ?". In order to address this point, various performance criteria may be proposed, as mentioned before, provided the objective of the AMB is defined. For the purpose of this paper, the performance evaluation criterium used was the criterium proposed by ISO 14839 [4].

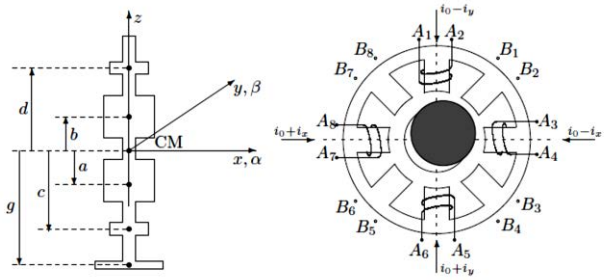

Figure 1. Self-bearing prototype geometry and fase coil arrangement.

II. ISO 14839 PERFORMANCE EVALUATION APPROACH

ISO 14839 Part II proposes a procedure to evaluate the vibration level that naturally arises in the turbo machine operation, defining acceptable displacements, calculated in terms of the minimum clearance established for the considered equipment. For that purpose ISO 14839 uses the definitions of ISO 7919-1 related to vibration zone guidelines for oil-film bearings. The definitions of each zone are as follows.

- ***Zone A:*** *The vibratory displacement of newly commissioned machines would normally fall within this zone.*
- ***Zone B:*** *Machines with vibratory displacement within this zone are normally considered acceptable for unrestricted long-term operation.*
- ***Zone C:*** *Machines with vibratory displacement within this zone are normally considered unsatisfactory for longterm continuous operation. Generally, the machine may be operated for a limited period in this condition until a suitable opportunity arises for remedial action.*
- ***Zone D:*** *Vibratory displacement within this zone is normally considered to be sufficiently severe to cause damage to the machine.*

ISO 14839 sets the maximum displacements in terms of C_{min}, minimum radial clearance, as presented in table I.

ISO 14839 Part III describes the steps for the evaluation of the stability margin, proposing the usage of random signal to be injected in the closed loop, to measure the plant sensitivity transfer function (1). Then, the standard proposes stability indexes based on the sensitivity transfer function, as shown in table II.

TABLE I. DISPLACEMENTS ZONE LIMITS

Zone	Displacement D_{max}
A/B	< 0.3 C_{min}
B/C	< 0.4 C_{min}
C/D	< 0.5 C_{min}

$$G_S(s) = \frac{G_P(s)G_C(s)}{1 + G_P(s)G_C(s)} \qquad (1)$$

TABLE II. STABILITY ZONE LIMITS

Zone	Sensitivity peak
A/B	3 (9.5 dB)
B/C	4 (12 dB)
C/D	5 (14 dB)

III. Experimental Data

A. *Data gathering*

For the purpose of performance evaluation, a pseudo-random binary signal (PRBS) was generated in the DSP, and made available at a DSP output. This signal was added to the self-bearing motor position measurement, as shown in figure 2.

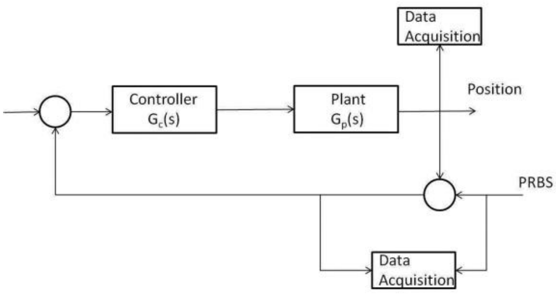

Figure 2. Data acquisiton arrangement

The series of position measurements were recorded, as well as the PRBS testing input and the PRBS added to position signal, in order to generate the performance figures refered by ISO 14839, namelly, the maximum displacement of the rotor axis from the central position, and the sensitivity. Data was recorded on a digital osciloscope, as may be seen in figures 3a and 3b below, showing experimental results for operation at 1800 rpm, both for X axis and Y axis displacements, for sample 1 of three experiments.

B. *Performance analysis*

In order to apply ISO 14839, experiments were conducted using the LASUP prototype, and time series were acquired for the different experiments. An example of such time series plot, showing its maximum value, is presented in figure 4.

Figure 3a. Time series for X, 1800 rpm. Yellow – PRBS signal. Blue – Output signal

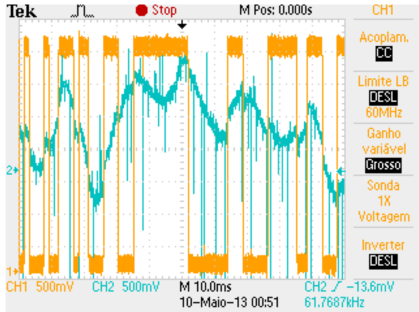

Figure 3b. Time series for Y, 1800 rpm. Yellow – PRBS signal. Blue – Output signal

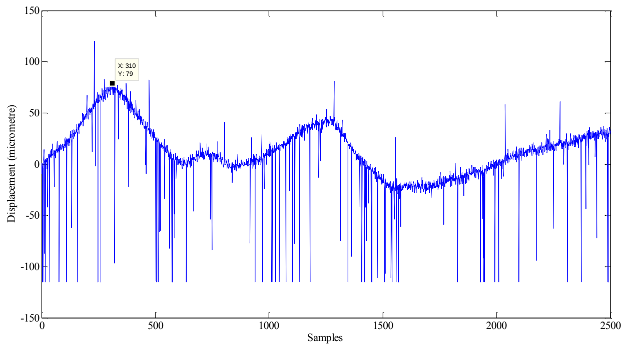

Figure 4. Time series for Y, 1800 rpm

Three experiments were conducted with the self-bearing motor operating at 1800 rpm, and times series were collected for X and Y positions, as shown in figure 2, in order to calculate de maximum displacement, and also series for the PRBS and position added to PRBS were recorded, so that sensitivity transfer function data could be calculated.

IV. Performance Assessment

The analysis of experimental data, according to ISO 14839, was conducted in two steps: first, generate and analise data for the maximum displacement calculation, and then process data for the sensitivity evaluation.

A. *Displacement analisys*

Experimental data for displacements in the X and Y directions was submitted to MATLAB in order to calculate total displacement as

$$D(k) = \sqrt{(X(k)^2 + Y(k)^2)} \qquad (2)$$

Plotting such series, as shown in figure 5, its maximum could be determined for each of the series. This data is shown on table I, for the three experiments using each controller.

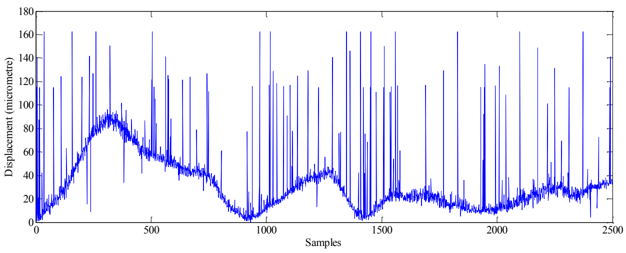

Figure 5 Displacement D(k) for LQR control at 1800 rpm

TABLE III. DISPLACEMENT FIGURES

Experiment	Maximum displacement (µm)
LQR 1800/1	74
PID 1800/1	94
LQR 1800/2	86
PID 1800/2	90
LQR 1800/3	68
PID 1800/3	87

This result can be graphically displayed, as in figure 6 below, showing that, regarding this figure of merit, the LQR controller has a better performance.

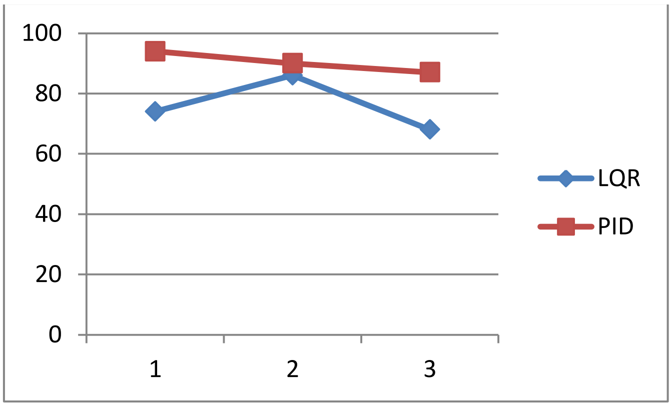

Figure 6 Maximum displacement, at 1800 rpm

B. *Sensitivity analisys*

Plant sensitivity, as defined by equation (1), was obtained by submitting experimental time series, for the three experiments, to MATLAB *etfe()* function in order to develop sensitivity Bode diagrams. Such Bode diagrams, for both controllers, are presented in figure 7. In the same figure, zone limits, defined in the standard ISO 14839, are shown as colored straight lines.

Those Bode diagrams show that LQR controller satisfies the gain limit for C/D zone, while PID controller does not satisfy the stability margin for none of the zones.

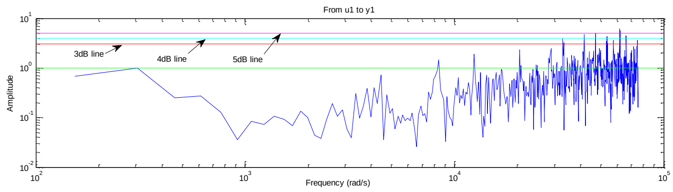

Figure 7a. Sensitivity for LQR serie, showing stability zone limits

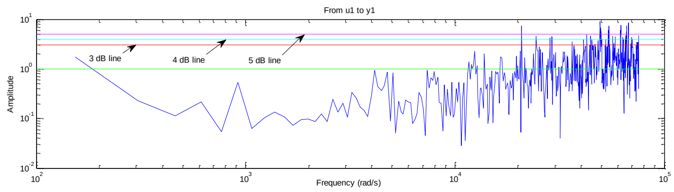

Figure 7b. Sensitivity for PID serie, showing stability zone limits

V. PERFORMANCE CRITERIA AS TUNNING CRITERIA

Previous paragraphs have led to the conclusion that the PID controller has, regarding the maximum displacement value, presented a performance poorer than the performance obtained with the LQR controller. A natural question arises: could the PID controller by retuned to display a better performance?

With that in mind, the self-bearing motor, controlled by the PID algorithm, was operated with different values for the PID proportional gain, beginning with the original gain, and the experimental data was analyzed regarding the maximum displacement.

Table III shows the displacement figures, and figure 8 displays graphically the performance obtained for each tested proportional gain.

TABLE IV. DISPLACEMENT FIGURES

Proportional gain	Maximum displacement (µm)
50	73
80	71
100	68
120	65

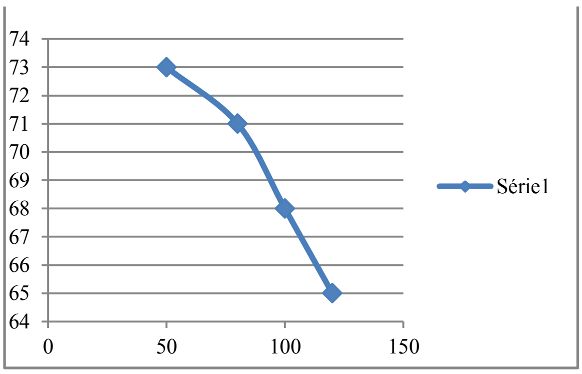

Figure 8 Maximum displacements for various PID proportional gains

As may be observed, increasing the proportional gain, the displacement is reduced, thus displaying a better performance for the plant. Nevertheless, a question should be posed regarding the stability of the new controller parameter: is the system still stable? Has the stability margin worsened with the new gain?

The ISO 14839 criteria address this sensible question by analyzing not only the error, but also the system stability. For the larger gain, the sensitivity Bode diagram was also obtained, and is shown in the figure 9.

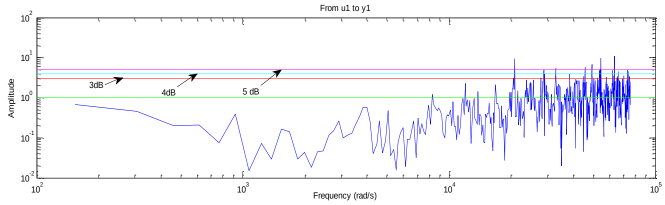

Figure 9a Sensitivity Bode diagram for original controller, showing stability zone limits

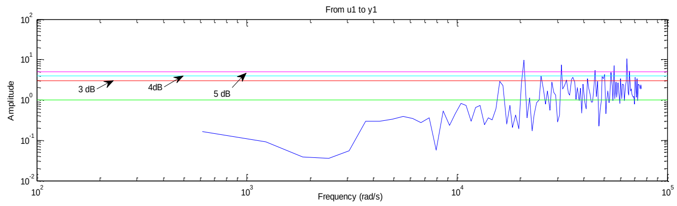

Figure 9b Sensitivity Bode diagram for optimized controller, showing stability zone limits

As can be observed, the stability margin has been reduced but not drastically, the system remaining stable for this point of operation.

VI. CONCLUSION

For the LASUP prototype, with position control applied to the upper rotor, running at 1800 rpm, the LQR controller shows a better performance than the PID controller, when considering the requirements of the ISO standard 14839. Frequency domain data shows that both controllers should be retuned in order to attain a better stability margin, according to the mentioned ISO norm.

A retuning of the PID controller, done in order to obtain better results in the sense of a reduction of maximum displacements, has shown to be feasible. Nevertheless, caution should be taken, as stability may be affected by this procedure. Ideally, one should consider a continuous monitoring of plant performance, calling the attention of operators, should the controller require retuning.

It should be stressed that those requirements are set for AMB´s applied to turbo machinery, meaning that different applications may require different performance requirements, as stressed by the very ISO 14839 standard.

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