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SURROGATE ACTIVE VIBRATION CONTROL OF A ROTATING SHAFT SUPPORTED BY MAGNETIC BEARINGS

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Abstract. *Active Magnetic Bearings (AMB) have a wide range of applications in industry. The rotor is levitated and supported by magnetic forces, which are generated by magnetic fields arising along the bearing structure. This allows non-contact operation, which favors the application of AMB in rotating machines as it eliminates overheating, friction, and wear of basic rotor materials. The magnetic forces generated for shaft levitation purposes are determined by using an active vibration control approach. The rotor is intrinsically unstable, and because of that, it is necessary to control the generated magnetic field to prevent the shaft from exceeding the safety limits of the bearings. In recent years, several works have been devoted to the development and implementation of controllers aiming to guarantee the robust stability of the system. Among the control techniques, the adaptive PID controller associated with fuzzy or neuro-fuzzy logic and sliding modes, has shown good results. However, such techniques often lead to high complexity concerning their development and experimental implementation. In this context, the present contribution is devoted to applying a Kriging surrogate to control a rotor supported by two AMBs. The proposed approach is evaluated by considering the rotor operating at different rotation speeds and unbalanced conditions.*

Keywords: *active magnetic bearing, Kriging surrogate model, vibration control, Kriging metamodeling*

1. INTRODUCTION

Bearings are machine elements responsible for supporting shafts in rotating machines. The rotational movement generates different loads and forces along the structure of the rotor that can generate damages. Therefore, bearings are used to prolong the machine's lifespan and ensure the maintenance of vibration parameters within the standards established by safety and operation norms (Harnoy, 2002).

Among the various types of bearings, the active magnetic bearing (AMB) has its functioning based on the principle of magnetic levitation. Its first application was presented by Habermann and Liard (1977) in reaction wheel applications in terrestrial satellites. Later, the development of electronics increased the implementation of magnetic bearings in the industrial field.

One of the advantages of using magnetic bearings is the fact that electromagnetic levitation is used for machine operation, resulting in contactless operation. There is no friction between the shaft and the bearing surfaces, therefore this contactless operation of AMB solves issues related to cooling, overheating and vacuum compared with the application of rolling and hydrodynamic bearings, which depend on lubrication factors (Schweitzer *et al.*, 2009). With the reduction of these issues, interventions for equipment maintenance become less necessary, thus increasing the operating time.

However, AMBs require a reliable power supply. Since their operation is based on generating a magnetic field, created by injecting an electric current into a magnetic coil, any failure in the power supply can lead to a structural collapse and breakage of the support bearings. therefore, the use of AMBs requires the presence of a passive auxiliary bearing (Guirao, 2012).

The unstable nature of the magnetic force generated to ensure the levitation of the shaft can cause damages to the rotor. This happens since the production of the associated magnetic field utilized can exceed the safety limits of the structure. To address this issue, the implementation of a closed-loop control system is required, along with a system of position sensors, filters, controllers and power amplifiers.

Therefore, several studies have been conduct to develop control techniques, ensuring the stability of rotating machines with active magnetic bearings, such as PID design (Yadav *et al.*, 2016; Sun *et al.*, 2018), sliding modes (Siqueira, 2013), fuzzy logic (Saha *et al.*, 2022) and backstepping (Yaseen *et al.*, 2022). At institutional level, studies have been conducted aiming at the implementation of controllers based on H_∞ norm, Optimal Control, and fuzzy logic using Kalman estimators to find modal states (Koroishi, 2013), Multiple Methods technique (Borges, 2016), adaptive PID and Kriging metamodel (Oliveira, 2019), and robust fuzzy and neuro-fuzzy (Carvalho, 2020).

In this work, a Kriging surrogate is proposed to control a rotor supported by two AMBs. This surrogate simplifies the controllers compared to more traditional control techniques, which present high development and experimental implementation complexity. The proposed approach evaluates the rotor operating at different rotation speeds and unbalanced conditions and the use of magnetic force as a substitute of the coefficients of stiffness of the bearing in the equation of movement.

2. FLEXIBLE ROTOR MODEL

Flexible rotors are part of a class of dynamic systems that have the following basic components: disks, flexible shafts, bearings, and seals. For the model, the unbalance mass must be considered, in addition to the forces generated by electromagnetic actuators, since they are external forces that excite the system.

The equation of motion for the rotor requires the calculation of kinetic and potential energy for all components of the system, selection of a method for system discretization, and application of Lagrange's equations on Eq. (1) (Lalanne and Ferraris, 1998).

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial q_i} = F_{qi} \tag{1}$$

where $\mathbf{N}(1 \leq i \leq N)$ is the number of degrees of freedom of the system $\mathbf{q_i}$ are the generalized coordinates, $\mathbf{F_{qi}}$ are the generalized forces, and $\mathbf{T}$ and $\mathbf{U}$ are the kinetic and potential energies of the components, respectively.

For this model, some assumptions are made:

- The disk is a rigid element, therefore it only possesses kinetic energy
- The shaft is represented as a beam element with a constant circular section and is characterized by both kinetic and potential energy where each element has two nodes and four degrees of freedom per node
- The bearings and seals can be represented by a set of linear springs and dampers.

The differential equation representing the dynamic behavior of a rotor is defined by Eq. (2).

$$\mathbf{M}\,\ddot{\mathbf{q}}(t) + \mathbf{\Omega G}\,\dot{\mathbf{q}}(t) + (\mathbf{K} + \dot{\mathbf{\Omega}}\mathbf{K_{st}})\,\mathbf{q}(t) = \mathbf{W}(t) + \mathbf{F_u}(t) + \mathbf{F_{AEM}}(t) \tag{2}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{G}$ is the gyroscopic matrix, $\mathbf{K}$ and $\mathbf{K_{st}}$ are related to the stiffness matrix, where the coefficients of the bearings present in the left term of the motion equation are replaced by the magnetic forces ($\mathbf{F_{AMB}}$) of the actuator on the right term. $\mathbf{q(t)}$ is the generalized displacement vector, Ω is the time-varying angular velocity, $\mathbf{W}$ is the system's weight force, $\mathbf{F_u}$ is the force due to unbalance.

3. ACTIVE MAGNETIC BEARING

For the modeling of the $\mathbf{F_{AMB}}$, it is necessary to understand how the acting force works and its influence on the structure. In this paper, the active magnetic bearing is considered as an electromagnetic actuator. The actuator consists in a device where an electric current will circulate, determining the intensity of the magnetic field. This field will create a closed loop, passing through the electromagnet itself, the air gap, and the rotor located in the center of the actuator, resulting in an attractive force between the elements made of ferromagnetic material, called as the reluctance force.

Morais (2010) proposed a methodology for obtaining a model of an electromagnetic actuator, where the ferromagnetic core is constructed using soft iron, aiming to better direct the magnetic field flux and thus reduce losses due to dispersion. By considering the symmetry of the equipment, it is possible to analyze only half of the magnetic circuit, as the fluxes are equal and its value is half of the flux circulating in the center of the electromagnet. The eletromagnetic actuator produce only atractive forces and values of eddy current are neglected during the modeling.

Therefore, the force provided by the actuator is defined on Eq. (3).

$$F_{AEM} = \frac{N^2 I^2 \mu_0 a f}{2\left((e \pm \delta) + \frac{b+c+d-2a}{\mu_r}\right)^2} \tag{3}$$

where $(\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}, \mathbf{f}, \mathbf{h})$ are geometric parameters of the structure, $\mu_\mathbf{r}$ and $\mu_\mathbf{u}$ are the magnetic permeability of the material and of the vacuum, $\mathbf{N}$ is the quantity of spiral coils, $\mathbf{e}$ is the gap and δ is the relative distance between the actuator and rotor. Therefore, $\mathbf{e} \pm \delta$ is the nominal gap of the structure.

Observing the equation above, $\mathbf{F_{AEM}}$ is proportional to the coil current and proportional to the inverse of the air gap of the actuator. It means that when the geometry consists of small air gaps and high currents the magnetic flux becomes saturated, increasing the nonlinearity of the magnetic force. So, for the modeling of a magnetic bearing, it is considered that the levels of magnetic flux are below a saturation level of the material, therefore, operation at higher levels is not recommended. The increase of the current results in a high cost of energy generation without the return of larges magnetic fluxes.

To overcome problems that are result of the non-linearities present on the system, an inverse model was developed by Hagopian and Mahfoud (2010) and it determinate the necessary current required for the full operation of the actuator Eq. (4). Its based on the control force, where in this paper was obtained by the force necessary to maintain the equilibrium of the rotor between the actuators and with the the gap variation and conditions of eccentricity.

$$I = \sqrt{2F_{AEM}\left((e \pm \delta) + \frac{b + c + d - 2a}{N^2 \mu_r a h}\right)^2} \tag{4}$$

4. KRIGING-BASED SURROGATE CONTROL

Here is proposed a controller to sustain the rotor, since the coefficients of stiffness of the bearings where added on the right term of the equation of movement, and also control the vibration of the structure. The approach used was based on surrogate modeling, where its vantage consists on simpler equations, eliminating the need of estimate gains, filters, weights and coefficients that are necessary for the implementation of controllers already used in many works.

The surrogate had its data obtained from sets of shaft displacements in relation to the bearing, these based on different eccentricities. With these values, using the equilibrium of forces of the system, were obtained the currents necessary to sustain the rotor. This relation between displacements and currents generated the surrogate for all four axis of actuators. It is expected to found the relation between these variables to be linear because of the need of use below the saturation level of the magnetic materials.

For a bigger understanding of the Kriging surrogate generated, its definition can be found in Eq. (5). $\hat{\mathbf{y}}$ is a approximated function, where $\mathbf{f}(\mathbf{x})$ is a generic polynomial function and $\mathbf{Z}(\hat{\mathbf{x}})$ is the stochastic contribution, also called correlation function. Therefore, $\hat{\mathbf{y}}$ is the controlled variable that will be send to the actuator.

$$\hat{y}(x) = f(x) + Z(x) \tag{5}$$

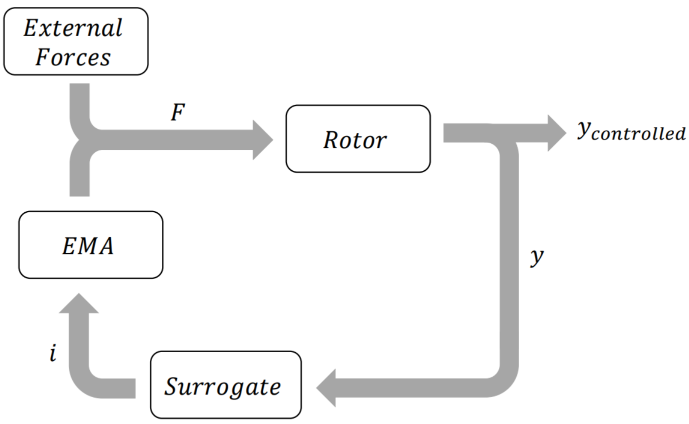

Figure 1. Control system scheme.

Here, $\mathbf{x}$ is related to the rotor displacements and $\hat{\mathbf{y}}$ is the approximated current for the electromagnetic actuator. It is worth highlighting the good practice of normalizing the set of input and output data samples during the development of the surrogate, with the aim of preventing its ill-conditioning (Lophaven *et al.*, 2002).

The covariance matrix $\mathbf{Z}(\mathbf{x})$ is responsible for generating localized deviations in the system response through interpolations at the collected sample points and can be indicated by Eq. (6) where $\sigma^\mathbf{2}$ is the process variance and $\mathbf{R}$ is the spational correlation function found in Eq. (7).

$$Cov[Z(x), Z(y)] = \sigma^2 R(\theta, x, w) \tag{6}$$

$$R(\theta, x, w) = \prod_{j=1}^{k} R_j(\theta_j, x_j, w_j) \tag{7}$$

where θ is the unknown correlation parameters used to modeling the surrogate, $\mathbf{p}$ and $\mathbf{q}$ are input vectors and $\mathbf{k}$ is the number of inputs. $R_j(\theta_j, x_j, w_j)$ is the correlation function, that can be linear, Gassian, exponential and cubic. It is also importante to highlight that the variables $\mathbf{p}$ and $\mathbf{q}$ are samples utilized for the surrogate model, therefore are displacements of the rotor.

In Fig. 2 and 3 is possible to see how the surrogate was capable of reproduce the linear behavior between displacement and current, confirming the possibily of an implementation of a controller based on the technique.

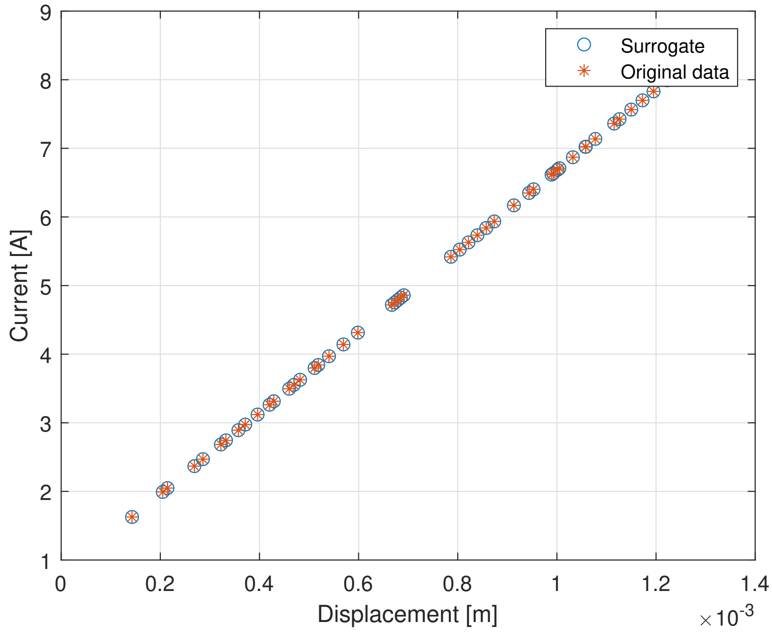

Figure 2. Kriging surrogate on axis X.

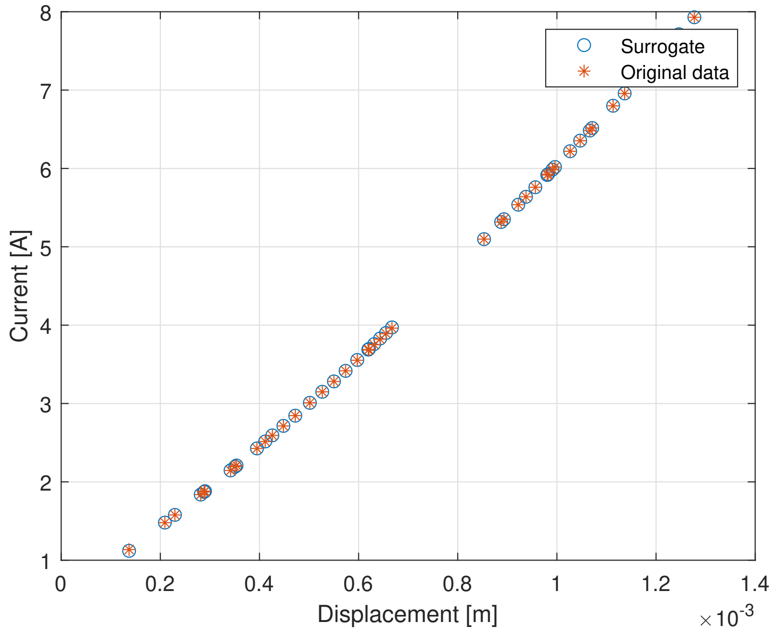

Figure 3. Kriging surrogate on axis Y.

5. RESULTS AND DISCUSSIONS

From the displacement and current data obtained to generate the surrogate, the rotor model was implemented in Matlab/Simulink©, which contains a disk and two magnetic bearings and also the structure of the controller based on

Kriging. It is also important to mention that a bias current of 5.0 A was used for numerical analysis purposes to study the system behavior and without the presence of stiffness coefficients for rotor stability.

Initially, it was verified whether the structure maintains amplitudes close to zero without the presence of the gravitational force and unbalance forces typically found in any rotating machine. In Fig. 4, it is possible to visualize amplitudes close to 10^{-5} m and 10^{-6}m, indicating that the magnetic actuator was able to ensure stability for both axis, however in the X-axis, the position was not located at the center of the bearing. Therefore, certain improvements are required for the X-axis.

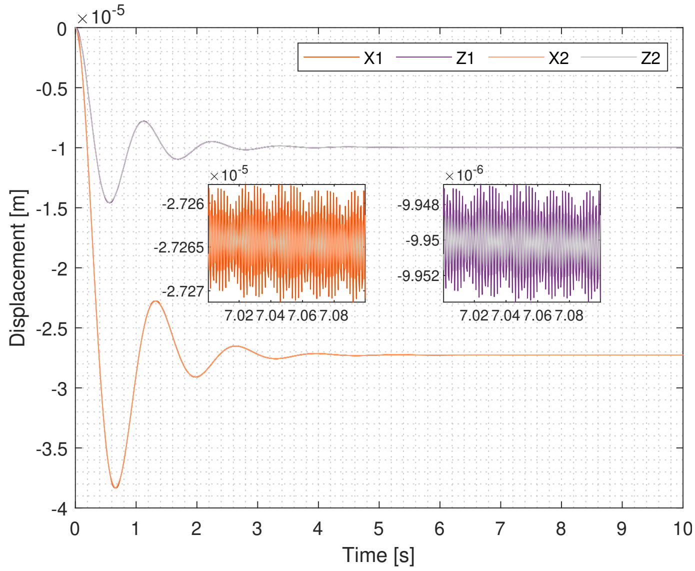

Figure 4. AMB without weight and unbalance forces.

In a second analysis, the presence of unbalance forces were added, but the weight of the structure was still not considered in order to assess its behavior and the performance of the Kriging controller. It was observed that after the transient period of the simulation, the controller was able to bring the structure to the center of the bearing. However, there is a need for improvement in terms of vibration amplitude, especially in the uncoupled bearing of the rotor, indicated by X2 and Z2 in Fig. 5. In the coupled bearing, amplitudes in the order of μm r were observed.

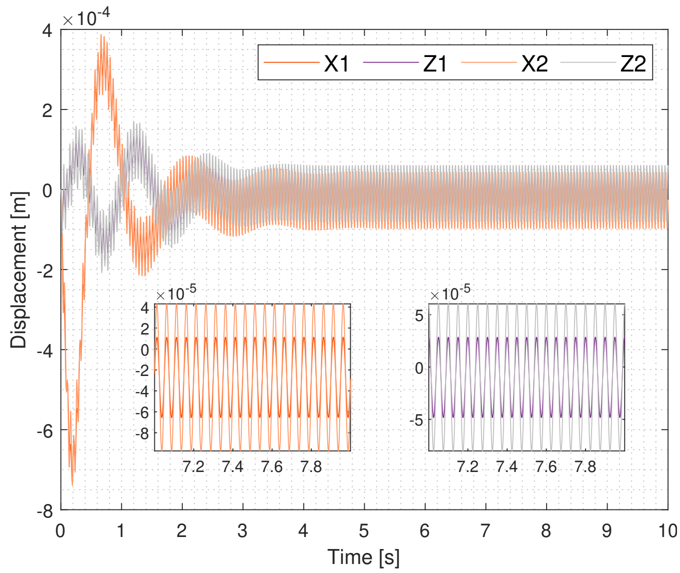

Figure 5. AMB without weight and with unbalance forces.

In a final analysis, the weight force and unbalance force were added to the system. With the obtained results, it is possible to analyze that in the X-axis, the positioning of the shaft relative to the center of the bearing was still ensured by the Kriging-based control, along with the vibration amplitude. However, the issue of amplitude still persisted. As for the Z-axis, there is a stability in the system's vibration, however with larger amplitudes, and there is also a failure of the controller to bring the axis to the center of the bearing, as its shows on Fig. 6-7.

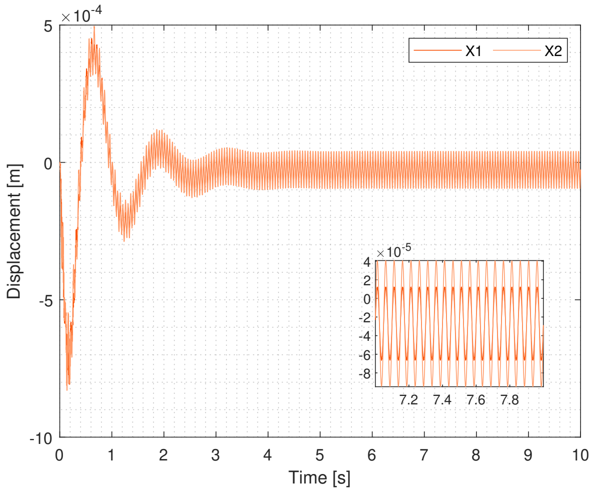

Figure 6. AMB with weight and unbalance forces on X.

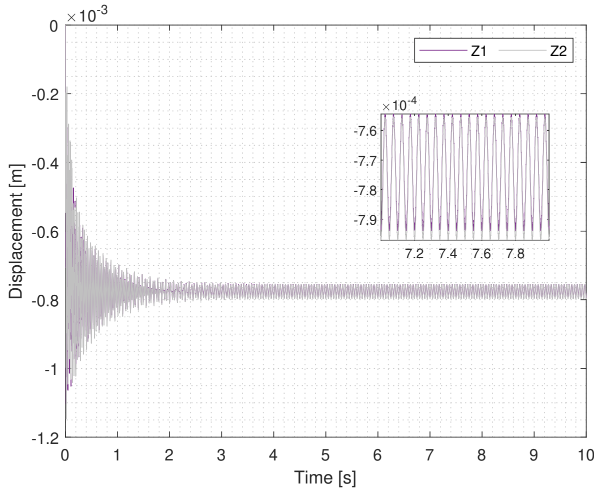

Figure 7. AMB with weight and unbalance forces on Z.

In this condition with the presence of the weight force, several factors can be attributed to the failure of the controller to bring the shaft to the center of the bearing. Firstly, the geometry of the actuator may not be robust enough to achieve magnetic levitation without the presence of any roller bearing associated. Additionally, although the surrogate is capable of representing the linear relationship between displacement and current (as shown in this paper), the controller developed that generates the actuation current and sends it to EMA, the magnetic force generated, when entered on the right side of the equation, may not provide the necessary actuation for complete rotor support in the presence of the weight.

Therefore, these results need to be further investigated to refine and improve the data already obtained in this work.

6. CLOSING REMARKS

The surrogate model proposed intended to evaluate the relation between displacements of the shaft and corresponding control currents, aiming the guarantee of the vibration of the rotor. The model of the rotor also had its bearing stiffness on the right side of the motion equation represented by the magnetic force, replacing the common values of coefficients presents on literature. The results show that the use of pure magnetic force to maintain the vibration levels of the rotor at values close at μm is promising but the presence of weight causes an offset in relation the center of the bearing. It shows the need of improvement at the implementation of the actuators in the model to get better levels of amplitude, guarantee of position at its center and consequently security of the operation.

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