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DEVELOPING A METHODOLOGY FOR FAILURES DIAGNOSTICS OF ROTATING SYSTEMS USING STATE OBSERVERS

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Abstract. *Increased competitiveness between companies have demanded higher operating speeds and shorter periods of equipment maintenance, therefore it is of utmost importance can extend the working life of equipment through the prediction of possible failures. The goal of this project was to develop a method which allows predicting failures in rotary system components, from a mechanical system used the technique of finite elements using beam elements with 4 degrees of freedom per node, to obtain the model of this system, and the use of state observers, which estimate states that are unknown and cannot be measured, it was possible to detect the faults. When a failure occurs there is a change in the parameters of the system, mass, rigidity, for example, and so the state observer method of kind robust can detect these alterations and associates them to some kind of failure. To make these comparisons and detect possible failures used the RMS value of the signals obtained in the time domain, this methodology has been tested experimentally and computationally and the results have been very satisfactory, from a failure in the system purposely created is possible to detect this failure by using the methodology already described.*

Keywords: *Fault Prediction, Finite Element, Observers of State, Rotating Systems, Numerical model.*

1. INTRODUCTION

Technological advances and increased competition between companies of recent years have demanded higher operating speeds and shorter periods of equipment maintenance. The increases in operating speeds imply the emergence of dynamic effects rarely seen in older equipment, but are now critical to the proper functioning of the various components of a machine (bearings, gears, shafts and all others). Shorter periods available for maintenance are a direct consequence of the necessity of the return of the investment in equipment, necessary for companies to remain competitive.

In this context appears predictive maintenance, which involves using of methods capable of predicting the life of a component without it being necessary to interrupt the operation of the equipment, thereby prolonging their useful life, and performing the replacement in a timely manner.

Many works are been performed using the finite element concepts and state observers. These methods are very recent, which grew with the advancement of computer technology and the increasing processing power of computers.

Using the Observer State, Melo (1998) develops a methodology for detection and location of faults in mechanical systems using the state observer of reduced order. Following this same principle Lemos (2004), using the technique of finite elements with the state observer, in his dissertation develops a methodology for detecting and locating faults in rotating systems considering their foundations. Also in rotating systems have Fernandes Junior (2011) who in his dissertation used a model to identify cracks in shafts of rotating systems with the use of state observers; all these studies have validated the effectiveness of the method.

2. MODEL SYSTEMS ROTATING

To obtain the general equations of rotating systems with the technique of finite elements, through the following steps:

- Calculate the kinetic energy, potential and virtual work for the elements of the system;
- Choice of numerical method of Rayleigh-Ritz;
- Application of Eq. (1) of Euler-Lagrange.

$$\frac{d}{dt}\left(\frac{\partial T(t)}{\partial \dot{q}(t)}\right)-\frac{\partial T(t)}{\partial q(t)}+\frac{\partial U(t)}{\partial q(t)}+\frac{\partial R(t)}{\partial \dot{q}(t)}=F_q(t) \tag{1}$$

where *T(t)* is the kinetic energy of the element, *U(t)* is the potential energy, R(t) dissipated energy, *F(t)* is the generalized force and *q(t)* is the vector of generalized coordinates.

The resulting equations are equations presented in differentials nodal coordinates corresponding to each element, to obtain the global model adds to the energy systems of constructing a generalized vector (Eq. 3), each nodal point of the system in question contains two rotational degrees of freedom of translation (*u* e *w*) and two rotational degrees of freedom (θ e Ψ). The vector of coordinates and the vector generalized is given by, respectively:

$$q_i(t)=[u_i(t) \quad w_i(t) \quad \theta_i(t) \quad \psi_i(t)]^T \tag{2}$$

$$q(t)=[q_1(t) \quad q_2(t) \quad \cdots \quad q_n(t)]^T \tag{3}$$

where $q_i(t)$ represents the coordinates of ith nodal point.

3. STATES OBSERVES

It is very important to know the state variables that represent a system, however, some of these are not measurable. Luenberger (1966) demonstrated that the states of a deterministic dynamical system can be estimated from knowledge of its inputs and some of its outputs.

Considering the system in state space in discrete time domain:

$$x(k+1)=Ax(k)+Bu(k) \tag{4}$$

$$y(k)=Cx(k) \tag{5}$$

wishes to obtain an estimate the state vector of the system, through the dynamic model discrete represented by:

$$\hat{x}(k+1)=A\hat{x}(k)+L(y(k)-\hat{y}(k))+Bu(k) \tag{6}$$

$$y(k)=Cx(k) \tag{7}$$

where *L* represents the gain matrix of the observer.

3.1 Fault detection with state observers

Was used two types of state observer, all full order and type identity, they are the Global observer states and Robust observer states. The observer global is a faithful copy of the original system model without fail, so it is possible to make a comparison between the parameters be listed experimental and parameters obtained from the global observer construction. From this information, the new focus is in the search parameter failure, which is performed by the construction of the robust observer to possible parameters of failure. This observer is constructed with a gradual change in its dynamic matrix to in respective parameters. Therefore, the operation failure location and quantification of the observer is complete when the comparison between the curve experimental and the curves constructed by the observer result in a difference that approaches zero.

To compare the curves of the dynamic behavior, in both the global or in robust observer uses the RMS (root mean square) of the vibratory response signal. One can calculate the RMS value as follows:

$$y_{rms}=\frac{1}{N}\sqrt{\sum_{i=1}^{N} y^2{}_i} \tag{8}$$

where y_i represents the i-th term of the signal discrete *y*, and *N* the total number of terms.

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4. DECISION LOGIC UNIT

The methodology created to perform the comparison of values using a statistical approach with a t-student distribution. Real systems in general have a natural variation of vibratory responses (or RMS value), and this variation should not be associated with system failures. From the samples of the system without fault can obtain a mean value and its standard deviation, the global observer is constructed such that the accompany average value of the system without fail.

A variation on the experimental measured value is considered significant if it is larger than the value of the global observer more deviation obtained by the t-student distribution with 95% reliability.

5. RESULTS

This section presents an application of experimental methodology created. From a real system with bearings, shaft and two unbalance disk, which is show in Fig. 1. Faults that are identified in this work are only present in the bearings.

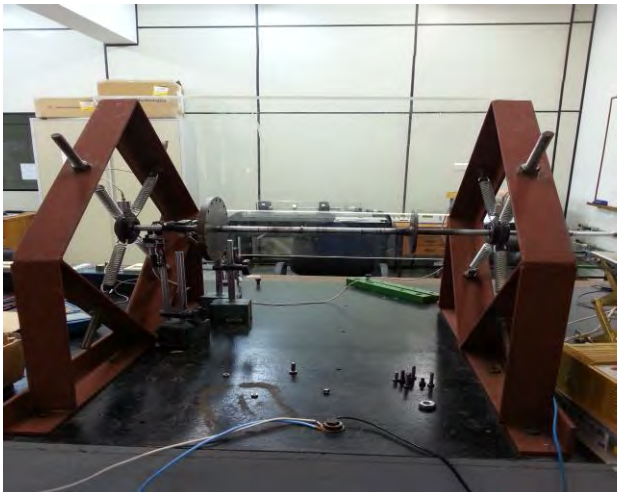

Figure 1. General overview of Experiment conducted.

Some simplifications are made in order to facilitate the obtaining and comparing data, the stiffness of the bearing is symmetrical, that is equal to the axes z e x (see Fig. 1), and experimental data are collected only in the *z* direction. The system is discretized into nine finite elements and ten knots, with 4 degrees of freedom per node for a total of 40 degrees of freedom. The Fig. 2 shows the discretized system model in the *x z* plane.

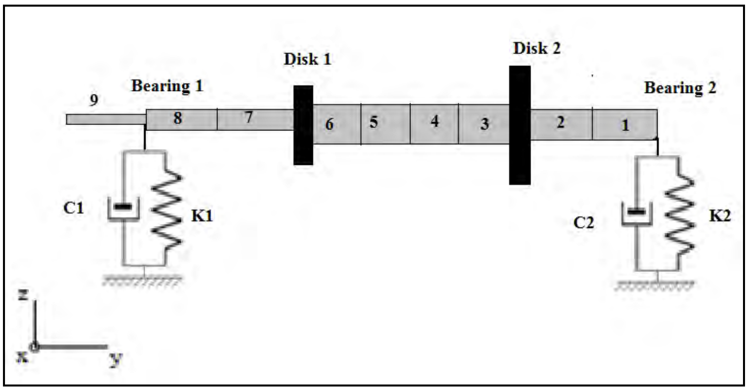

Figure 2. Equivalent Model Experiment.

The stiffness *K1*, *K2* and the damping *C1*, *C2* are obtained through an optimization function using the Quasi-Newton method, based on an input impulse in the system. Table 1 shows the parameters for the discretization as well as the properties of other elements (disc, bearings and shaft).

Table 1. Parameters of the Experiment

Density of the shaft material	ρ=7800 Kg/m^3
Modulus of elasticity	E = 210 G Pa
Poisson's ratio	v = 0.3
Diameter of the elements 1,2	$d_{1,2}$ = 0.0145 m
Length of elements 1,2	$L_{1,2}$ = 0.065 m
Diameter of the elements 3,4,5,6	$D_{3,4,5,6}$ = 0.0145 m
Length of elements 3,4	$L_{3,4}$ = 0.06m
Length of elements 5,6	$L_{5,6}$ = 0.0755m
Diameter of the elements 7,8	$D_{7,8}$ = 0.01395 m
Length of elements 7,8	$L_{7,8}$ = 0.0565m
Diameter of the element 9	D_9 = 0.01085 m
Length of elements 9	L_9 = 0.093m
Mass of Disc 1	M_{d1} = 0.287 Kg
Mass of Disc 2	M_{d2} = 1.9 Kg
Mass of bearing 1	M_{m1} = 0.4 Kg
Mass of bearing 2	M_{m2} = 0.43 Kg
Inertia of Disc 1	I_y = 0.004843 Kg.m^2 $I_x = I_z$ = 0.002495 Kg.m^2
Inertia of Disc 2	I_y = 0.0004801 Kg.m^2 $I_x = I_z$ = 0.0003411 Kg.m^2

The system is coupled to an electric motor through the element 9, it rotates at a constant speed of 820 rpm (approx. 13.6 Hz), and the excitation is made by a known mass unbalance on the disc 2. For a previous analysis, the system is simulated in order to identify their behavior in presence of faults, Fig. 3 shows the simulated signals for the bearings 1 and 2 without fail.

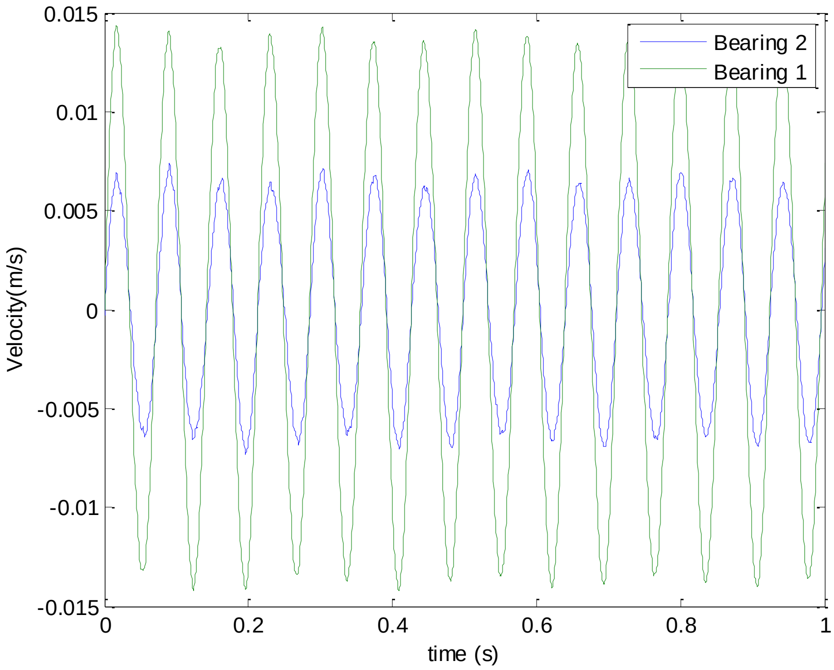

Figure 3 Simulated speeds the bearings 1 and 2.

For a variation of stiffness of the bearing 2 can note the influence on the RMS values of the other components, this influence depends on the dynamics of the system and physical parameters. The Fig. 4 shows the RMS values for each component simulated in many cases.

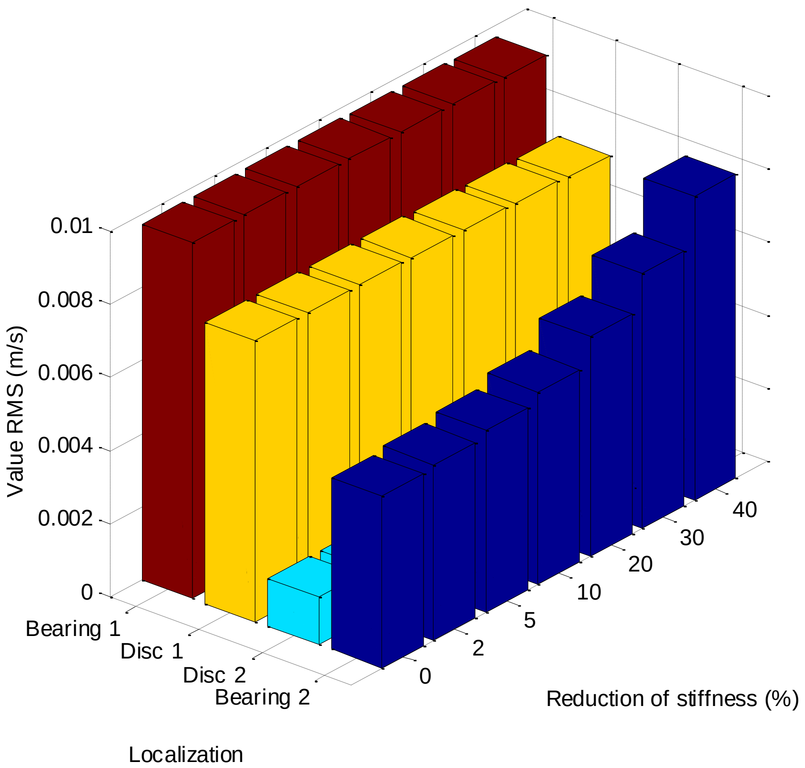

Figure 4. Influence of failures in RMS values.

The variation in the RMS value in the bearing 1, which failure present in the second bearing, was small as seen in Fig. 4, but depending on the system dynamic range that can be felt at all components. In the Disc 2 the failure can be felt change value RMS was 18% considering the most extreme case of 40% loss.

In the experimental part, a measure of the velocity signals in the direction z is show in Fig. 5. Because of the presence of many noises in the speed signal, it is processing through a bandpass filter whose cutoff frequencies are 11 and 15 Hz.

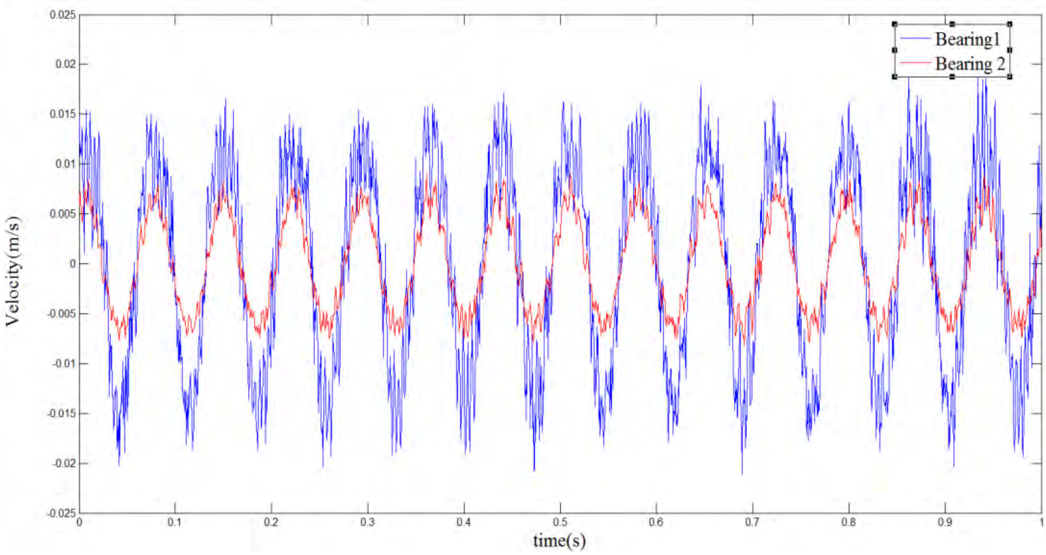

Figure 5. Experimental comparison velocity in the bearings.

After this filtering process, can calculate the RMS value of the signal from Eq. 8. We collected 9 velocity signals, for each bearing, Table 2 shows the values obtained from the RMS velocity signals, as well as the mean and its standard deviation. The global observer is constructed with the use of mean values following the dynamic system without fail.

Table 2. Experimental RMS values in the *z* direction.

Measure Number:	RMS values of velocity (m/s 1e-4)	
	Bearing 1	Bearing 2
1	3.1593	1.5245
2	3.1593	1.5245
3	3.1418	1.5364
4	3.1298	1.6086
5	3.1446	1.5407
6	3.1389	1.5337
7	3.1290	1.5494
8	3.1462	1.2761
9	3.1129	1.5052
Mean	3.1402	1.5110
Standard Deviation	0.0149	0.0926

From the construction of the global observer, a failure is imposed on the bearing 2, the springs that hold the bearing are held by screws, one of these is released in two different grip levels. The Fig. 6 shows the location where the screw is released in order to cause a failure.

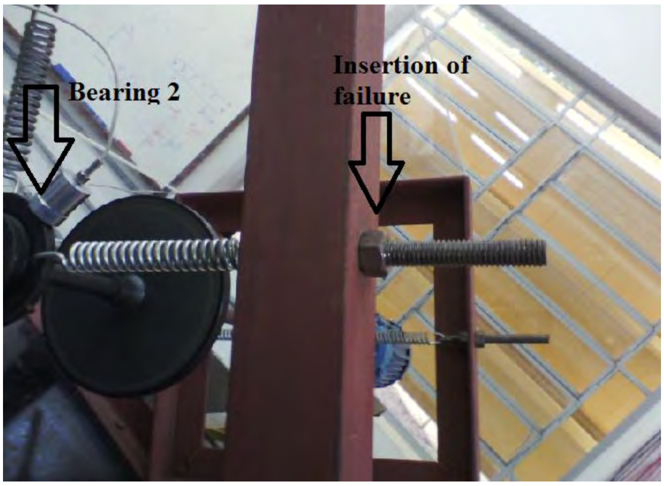

Figure 6. Mechanism for Fault Insertion.

Using a distribution t-student with 8 degrees of freedom, for a confidence interval of the 95%, the limits of RMS values considering the values of standard deviations in Table 2 are [3.1059 3.1746] for bearing 1, and [1.2975 1.7245] to the bearing 2, both in the *z* direction. An experimental value that is outside these limits is considered a failed system. The Table 4 presents the experimental RMS values in bearing 2 for the 2 levels of failure introduced, there were three measures for each failure level.

Table 4. RMS values experimental of the bearing 2 after insertion failure.

Measure Number:	LEVEL 1 m / s 1e-04	LEVEL 2 m / s 1e-04
1	1.7929	1.9337
2	1.7855	1.8773
3	1.7899	1.8566

The amounts relating to vibration signal of the bearing 2 presents outside acceptable limits obtained from the t distribution. Using a robust state observer, one can confirm that the fault lies in bearing 2, where the difference in RMS values tend to zero, and further quantify this failure as a loss of stiffness. Table 5 shows the experimental values of the measure number 1 for the two levels of failure, and their RMS values for each loss robust observer.

Table 5. RMS values for comparison of the robust observer.

Fault Level Value	Experimental (m / s)	Loss of Observer Robust the bearings 2 (m / s)				
		3 %	5 %	10 %	14.46 %	20.19%
1	1.7929e-04	1.5617e-04	1.5986e-04	1.6978e-04	1.7929e-04	1.9337
2	1.9337e-04	1.5617e-04	1.5986e-04	1.6978e-04	1.7929e-04	1.9337

The values in Table 5 show that for the fault level 1 loss of stiffness was 14.46%, and level 2 was 20.19%, both in bearing 2, in the direction of z. With the location of the failure by the global observer and with the quantification and location of the failure in the form of loss of stiffness, can better schedule maintenance. Intervention can be made thus that the failure is detected or, with the monitoring of the amount of loss stiffness, stipulating a limiting value and thus for example to keep the machine in operation longer.

6. FINAL REMARKS

The presented methodology for fault detection proves very effective, however, one must have a satisfactory model of the system and know the excitation forces. Its very important to know the answers of a system, so the application of state observers and so interstate because not all outputs of the system can be measurable. In the simulations, when the fault was introduced in the second bearing, the bearing was influenced not 1, because it stiffness's of bearings station in an order much smaller than the stiffness own shaft, but the change in stiffness alters the response of the failing component, even for small changes, so this method can be applied.

In the experimental test the methodology achieved success, when combined with statistical analysis of the variation of RMS values, using the t-student distributions. Now this method should be applied to more complex systems, for example gearboxes, to continue to validate the methodology.

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