EXPERIMENTAL FAULT DETECTION IN ROTATION SYSTEM USING STATE OBSERVERS BY LMIS

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Abstract. Rotating systems have many applications in wide-ranging industrial contexts. The breakdown of this equipment results in economic wastes or leads to dangerous situations. To avoid such problems is very important, and it can be done through tools that inform about the inform about the existence of faults, as well as, about their progress in time. A review of the modeling process used for rotor-support-structure shows that the finite element method is the major method employed. In this paper, with the aid of well defined theoretical models, obtained using the finite element technique, and the state observer method for the identification and location of faults it is possible to monitor the parameters of a rotor-support-structure system, including the foundation effects. In order to improve safety, these parameters must be supervised that the occurrence of failures or faults can. The state observers were designed using Linear Matrix Inequalities (LMIs). Finally, experimental results (using for this a rotation system in the mechanical vibrations laboratory at Ilha Solteira’s Mechanical Engineering Department) demonstrate the effectiveness of the methodology developed.

Keywords: Rotation System, Fault Detection, State Observers, Linear Matrix Inequalities (LMIs)

1. INTRODUCTION

Nowadays one of the most dominant concerns of the industry is to maintain its systems operating without sudden stops. Due to this constant concern new techniques of fault detection and location in mechanical systems submitted to dynamic loads have been developed. Since the introduction of the state observer's theory by Luenberger (1964), many methodologies have been proposed for condition monitoring of the machines using the state observers' technique (Ge et al, 1987; Elmas et al, 1996). Even so, most of the methodologies using state observers are intended for solving control problems and detecting possible faults in sensors and instruments (Clark, 1978; Watanabe et al, 1982). Moreover, many works are theoretical, without any experimental verification of the developed methodologies (Park et al, 2001; Trinh et al, 1998; Frank et al, 1991). The state observers' technique can reconstruct the non-measured states or can estimate the values of difficult access points in the system. Thus, the faults at these points can be detected without the knowledge of measured data, hence, monitoring them through the reconstructions of their states (Luenberger, 1964). This technique consists of developing a model for the system to be analyzed and to compare the output at the observer with the output of the system. In order to supervise the process, a set of observers is mounted where each observer is dedicated only to an instrument or physical parameter of this system. For fault detection in the system, an observer of global state is projected first. The global observer has the role of verifying if the system is working properly without any indications of faults, because in this observer’s assembly the same system matrix of the mechanical system is used in the analysis. Thus, the global observer can detect a possible fault or irregularity in the system if the system’s response is not coincident with the global observer’s response. In detecting a possible fault, the next step would be to locate such fault, which is the reason why robust observers are used. Thus, a bank of observers is set up, where each observer is dedicated to a physical parameter of the system.

In practice, the mathematical models representing the behavior of the systems, are not free of unknown disturbances and of variations in their own parameters. In most state observers’ projects, the parameters of the system are known or can be identified through some specific methods found in the literature. In cases where the parameters are not accurately known or where they are subject to changes during the operation of the system, the observer’s response can supply an incorrect estimate of the reconstructed states, therefore inducing certain permanent mistakes that assume the false alarms in the faults detection and location. Therefore, this paper proposes the development of a methodology for faults detection and location in mechanical systems with relation to the structure of the mechanical system, i.e., with relation to the variation of the system parameters, as stiffness and damping and a rotor system using the state observers' technique in order to avoid false alarms and unnecessary stops of mechanical systems.

2. LINEAR MATRIX INEQUALITIES (LMIS)

The history of LMIs in the analysis of dynamical systems goes back more than 100 years. In 1890, when Aleksandr Mikhailovich Lyapunov presented his work, introducing the Lyapunov Theory (Boyd et al,1994). He showed that the differential equation:
\[ \dot{x}(t) = Ax(t) \]  

is stable (all the trajectories converge to zero), if and only if there is a positive-definite matrix \( P \) such that:

\[ A^T P + PA > 0 \] \hspace{1cm} (2)

The inequation given by Eq. (2) is known as the Lyapunov inequality. Currently, LMIs have been the object of study by many important researchers around the world: control of continuous and discrete systems in time (Ghaoui et al, 2000), optimal control and robust control (VanAntwerp et al, 2000; Silva et al, 2004), model reductions (Assunção, 2000), control of nonlinear systems, theory of robust filters (Palhares, 1998), systems identification, control with variable structures (Teixeira et al, 2000), control using Fuzzy model (Teixeira et al, 2000), detection, location and quantification of faults (Abdalla et al, 1999; Abdalla et al, 2000; Wang et al, 2007).

3. STATE OBSERVERS USING LMIS

A state observer is defined by:

\[ \left\{ \begin{align*} \hat{x}(t) & = [A]x(t) + [B]u(t) + [L](y(t) - \hat{y}(t)) \\ \hat{y}(t) & = [C_{me}]\hat{x}(t) \end{align*} \right. \] \hspace{1cm} (3a) \hspace{1cm} (3b)

Where:

- \( [A] \in \mathbb{R}^{n \times n} \) is the dynamical matrix;
- \( [B] \in \mathbb{R}^{n \times p} \) is the input matrix;
- \( [C_{me}] \in \mathbb{R}^{k \times n} \) is the measure matrix;
- \( n \) is the order of the system, \( p \) the number of inputs \( \{u(t)\} \), \( k \) the number of outputs \( \{y(t)\} \);
- \( [L] \) is the observer matrix;
- \( \hat{y}(t) \) is the output of the observer;
- \( \hat{x}(t) \) is the state vector of the observer.

In this case, the study of stability of the state observer is attained by using the following LMIs:

\[ P(A - LC_{me}) + (A - LC_{me})^T P < 0 \] \hspace{1cm} (4)

\[ P > 0 \]

Where:

- \( P = P^T \);
- \( [A - LC_{me}] \) is the observability matrix.

It is necessary to perform some manipulations of Eq. (5), after these manipulations, we get:

\[ PA - PCLC_{me} + A^T P - C_{me}^T L^T P < 0 \] \hspace{1cm} (5)

Multiplying both sides of Eq. (6) by \( P^{-1} \), the following is obtained:

\[ AP^{-1} - LC_{me}P^{-1} + P^{-1}A^T - P^{-1}C_{me}^T L^T < 0 \] \hspace{1cm} (6)

Calling \( X = P^{-1} \) and \( G = P^{-1}L = XL \), we arrive at:

\[ AX + XA^T - G C_{me} - C_{me}^T G^T < 0 \] \hspace{1cm} (7)

\[ X > 0 \]

where \( X = X^T \). Note that \( P^{-1} \) exists, because \( P > 0 \), in other words every eigenvalues of \( P \) are different from zero or the best bigger that zero.

Considering the decay rate:
The gain of state observer is given by:

\[ L = X^{-1} G \]  

4. STATE OBSERVERS’ METHODOLOGY

Many control systems are based on the supposition that the full state vector is available for direct measurement, but in practice, all the variables are not always available, and the variables that are unavailable for direct measurement must be estimated.

Therefore, control systems using state observers can reconstruct the non-measured states or estimate the values of difficult access points in the system. However, the necessary condition for this reconstruction is that all the states should be observable (Luenberger, 1964; D’Azzo et al, 1988).

Figure 1 shows a logical diagram for faults detection and location in mechanical systems using the state observers’ technique.

![Figure 1. Observation System.](image)

In the system of Fig. 1, when a certain component begins to fail, the state observer is capable of quickly detecting the influence of this fault, because the observer is quite sensitive to any incipient irregularity that appears in the system. The state observer is a group of ordinary first-order differential equations that represents the same response as that of the real system, when it is working properly. Therefore, the idea is to use this effect for the state observer to detect and locate possible faults in a mechanical system.

In this set of observers, the role of the global observer is to verify if the system is working properly, without any indications of faults, because this observer uses the same system matrix of the mechanical system analysis. Thus, the global observer can detect a possible system fault or irregularity in the analysis if the system’s response is not coincident with the global observer’s response.

If a possible fault is detected, the next step would be to locate such fault, and that is why robust observers are used. The robust observers are projected by partly removing the parameters subject to faults in their dynamic matrix.

Therefore, the robust observer’s response that approaches the response of the faulty system will be the responsible observer for the location of this possible system fault.

There still are possibilities for one or more parameters to fail at the same time. In this case, the solution would be to design robust state observers to all parameters subject to failures.

Finally, it is the Unit of Logical Decision (ULD) that collects and analyzes the difference between the real system and the designed state observers, in order to detect and locate faults or irregularities in the system. This unit also analyzes the progression of possible system faults, and activates, when necessary, an alarm system. This alarm system can be ready to be activated when a determined variation occurs in a certain parameter.

5. EXPERIMENTAL RESULTS

With the objective of verifying the effectiveness of the methodology of fault detection and location in the rotation system, a rotor system was devised in the Mechanical Engineering Department (DEM/FEIS). For simulating the stiffness of the seals and of the foundation, the rotation system was mounted on the bars perpendicular to the rotor’s
axel, which could in the future provide the possibility for altering the stiffness of the set seals and foundation for the simulation of a possible fault. The system considered is shown in Fig. 2.

![Figure 2. Mechanical system mounted.](image)

A scheme of system showed in Fig. 3 is represented in Fig. 2.

![Figure 3. Representative scheme of rotor system to finite element mounted on lumped foundation.](image)

The numerical value of the physics parameters of the rotation system without faults are shown in Tab. 1.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Numerical values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seals + Foundation</td>
<td>( K_{xx1} = 60667.79 \text{N/m}; K_{xx2} = 56212.83 \text{N/m}; K_{xx3} = 53992.56 \text{N/m} )</td>
</tr>
<tr>
<td>Disks</td>
<td>( M_1 = 0.32 \text{ kg}; M_2 = 1.4 \text{ kg}; d_1=100\text{mm}; d_2=150.00\text{mm}; e_1=5.00\text{mm}; e_2=10.00\text{mm} )</td>
</tr>
<tr>
<td>Shaft</td>
<td>( L_1=10.90\text{mm}; L_2=11.83\text{mm}; L_3=12.77\text{mm}; L_4=11.32\text{mm}; L_5=11.98\text{mm}; d_1=10.0.0\text{mm}; d_2=14.0.0\text{mm}; d_3=15.0.0\text{mm}; d_4=15.0.0\text{mm}; d_5=14.0.0\text{mm} )</td>
</tr>
<tr>
<td>Bearing</td>
<td>( m_1=0.15 \text{ kg}; m_2=0.20 \text{ kg}; m_3=0.15 \text{ kg} )</td>
</tr>
</tbody>
</table>

To simulate a possible fault in the system represented by Figure 4, some screws were relaxed in order to reduce the stiffness of the seals+foundation. So the real fault system showed a percent lost of 4.90% of \( K_{xx2} \). Firstly, it was projected the global state observer. The results are showed in Tab. 2.

<table>
<thead>
<tr>
<th>Percent Lost</th>
<th>Real system with fault of 4.90% of ( K_{xx2} )</th>
<th>Real system with fault of 4.90% of ( K_{xx2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00%</td>
<td>1.8406X10^-006</td>
<td>8.3918X10^-006</td>
</tr>
<tr>
<td>2.00%</td>
<td>3.7170X10^-006</td>
<td>1.6868X10^-006</td>
</tr>
<tr>
<td>3.00%</td>
<td>5.6300X10^-006</td>
<td>2.5429X10^-006</td>
</tr>
<tr>
<td>4.00%</td>
<td>7.5817X10^-006</td>
<td>3.4076X10^-006</td>
</tr>
<tr>
<td>5.00%</td>
<td>9.5725X10^-006</td>
<td>4.2811X10^-006</td>
</tr>
<tr>
<td>6.00%</td>
<td>1.1604X10^-006</td>
<td>5.1635X10^-006</td>
</tr>
<tr>
<td>7.00%</td>
<td>1.3677X10^-006</td>
<td>6.0549X10^-006</td>
</tr>
<tr>
<td>8.00%</td>
<td>1.5793X10^-006</td>
<td>6.9554X10^-006</td>
</tr>
<tr>
<td>9.00%</td>
<td>1.7954X10^-006</td>
<td>7.8653X10^-006</td>
</tr>
<tr>
<td>10.00%</td>
<td>2.0161X10^-006</td>
<td>8.7845X10^-006</td>
</tr>
</tbody>
</table>
Analyzing the results present by Tab. 2, it was observed that the global state observer was projected correctly, which can be seen by the RMS difference between output of real system without fault and output of global state observer.

Table 3. Results obtained for global state observer projected.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00%</td>
<td>1,5639X10^{-007}</td>
<td>1,2726X10^{-007}</td>
<td>1,3942X10^{-007}</td>
<td></td>
</tr>
<tr>
<td>2.00%</td>
<td>1,5399X10^{-007}</td>
<td>9,5295X10^{-008}</td>
<td>1,1968X10^{-007}</td>
<td></td>
</tr>
<tr>
<td>3.00%</td>
<td>1,5158X10^{-007}</td>
<td>6,2879X10^{-008}</td>
<td>9,9519X10^{-007}</td>
<td></td>
</tr>
<tr>
<td>4.00%</td>
<td>1,4917X10^{-007}</td>
<td>2,9998X10^{-008}</td>
<td>7,8949X10^{-007}</td>
<td></td>
</tr>
<tr>
<td>5.00%</td>
<td>1,4675X10^{-007}</td>
<td>3,3571X10^{-008}</td>
<td>5,7976X10^{-008}</td>
<td></td>
</tr>
<tr>
<td>6.00%</td>
<td>1,4433X10^{-007}</td>
<td>3,7197X10^{-008}</td>
<td>3,6666X10^{-008}</td>
<td></td>
</tr>
<tr>
<td>7.00%</td>
<td>1,4191X10^{-007}</td>
<td>7,1531X10^{-008}</td>
<td>1,5549X10^{-008}</td>
<td></td>
</tr>
<tr>
<td>8.00%</td>
<td>1,3950X10^{-007}</td>
<td>1,0637X10^{-008}</td>
<td>1,0803X10^{-008}</td>
<td></td>
</tr>
<tr>
<td>9.00%</td>
<td>1,3710X10^{-007}</td>
<td>1,4173X10^{-007}</td>
<td>3,2201X10^{-008}</td>
<td></td>
</tr>
<tr>
<td>10.00%</td>
<td>1,3473X10^{-007}</td>
<td>1,7761X10^{-007}</td>
<td>5,5451X10^{-008}</td>
<td></td>
</tr>
</tbody>
</table>

Analyzing the results of Tab. 3, it was observed that a fault was detected in the system. This can be observed by the RMS difference between the real system’s observer and state observers’ output (1,5877X10^{-007}). In the Tab. 3, they were observed two possible fault’s interval (between lost of 4.00% and 5.00% for $K_{XX2}$ and 7.00% and 8.00% for $K_{XX3}$). For the best analysis, they were projected robust observers for these intervals.

Through the Fig. 4, the fault of 4.90% of $K_{XX2}$ could be located.

6. CONCLUSIONS

With the results obtained, it was possible to say that the methodology developed was validated. The technique of fault detection using state observers consists in the capacity of state observer of reconstruction the states not measured or values proceeding from points of difficult access in the system. It was verified necessity to choose the parameters
citizens the fault for the construction of robust observers to these parameters, therefore certain components exist that need a constant accompaniment due to its great requests or constant fault, then, for these parameters are mounted with a system of alarms that would generate a curve of trends. A restriction in the developed methodology exists that is the fact of the system to be observable with the number of carried through measures. In case that this does not occur, it must be made other measures until the system if becomes observable.

7. ACKNOWLEDGEMENTS

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