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# Experimental Fault Diagnosis in Systems Containing Finite Elements of Plate of Kirchoff by Using State Observers Methodology

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**Abstract.** This paper presents a methodology for detection and localization of faults by using state observers. State Observers can rebuild the states not measured or values from points of difficult access in the system. So faults can be detected in these points without the knowledge of its measures, and can be track by the reconstructions of their states. In this paper this methodology will be applied in a system which represents a simplified model of a vehicle. In this model the chassis of the car was represented by a flat plate, which was divided in finite elements of plate (plate of Kirchoff), in addition, was considered the car suspension (springs and dampers). A test rig was built and the developed methodology was used to detect and locate faults on this system. In analyses done, the idea is to use a system with a specific fault, and then use the state observers to locate it, checking on a quantitative variation of the parameter of the system which caused this crash. For the computational simulations the software MATLAB was used.

## 1. Introduction

The state observer's methodology consists on developing a model for the analyzed system and compares the estimated output with the measured output. The mathematical models which represent the behavior of the systems are not free of unknown perturbations and variations of the parameters. In the most of the state observer's designs, the parameters of the system are known or they can be identified by specific methods presents in the literature. In the cases in which the parameters are not known or they are subject to changes while the system working, the output of the observer may provide a incorrect estimation of the rebuild states, leading to false alarms in the detection and location of faults. In the last few years the problem of variation of the parameters in design of state observers have been studied by countless researchers [1-4].

According to Luenberger [5], the state observers can rebuild the states not measured or values from points of difficult access in the system. So, faults can be detected in these points without knowing its



values. The existing methodologies of state observers are designed to solve problems of control and detection of possible faults in sensors and instruments [6].

This work presents a methodology of fault detection and location in a system, which is similar to a simplified vehicular platform, by using of state observers.

## 2. Methodology

In the project of many control systems, it is considered that all the state variables are available for retroaction. However, in practices, there are situations that this is not real, so, it's necessary to estimate the state variables that are not available [7].

A state observer estimates the variables using the measurement of the outputs and control variables. According to Ogata [7], the state observers can be projected, if and only if, the observability condition is satisfied.

Considering the system defined by

$$\dot{x}(t) = A \cdot x(t) + B \cdot u(t) \quad (1)$$

$$y(t) = C \cdot x(t) \quad (2)$$

where  $A$ , of size  $n \times n$ , is the dynamical matrix,  $B$ , of size  $n \times r$ , is the input matrix and  $C$ , of size  $n \times n$ , is the output matrix, where  $n$  is the dimension of the system and  $r$  is the dimension of the inputs vector.

Admit that the state vector  $x(t)$  must approximate by the state vector  $\hat{x}(t)$  of the dynamic model

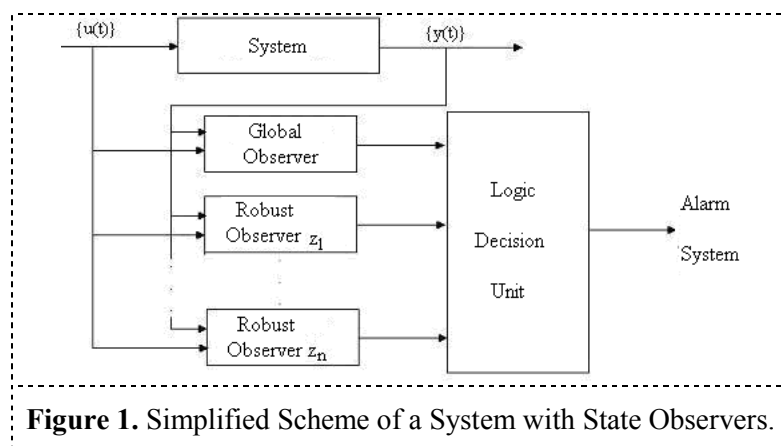
$$\dot{\hat{x}}(t) = A \cdot \hat{x}(t) + B \cdot u(t) + L \cdot (y - C \cdot \hat{x}(t)) \quad (3)$$

$$\hat{y}(t) = C \cdot \hat{x}(t) \quad (4)$$

which represents the state observer. The gain matrix  $L$  was determined using the Linear Quadratic Regulator (LQR).

## 3. Fault Detection By Using State Observers

The aim of this paper is the detection and location of faults in a system that is similar to a simplified vehicle platform. According to many recent papers [3-4,8], by For this purpose the methodology of state observers was used. For the fault detection in the system, it was projected a Global Observer. This Global Observer has the function of indicate a fault in the system. It was also projected a bank of Robust Observers, which has the objective of locate the positions of the fault in the system and its intensity. Figure 1 illustrates the mount scheme, using state observers.



**Figure 1.** Simplified Scheme of a System with State Observers.

The State Observers can rebuild the non-measured states of the system, so the Global Observer was used to simulate the dynamic behaviour of the system without any faults. The signal produced by the global observer is exactly the same of the output signal of the real system with no faults. In the case of a fault occur in any component of the system, the output signal produced by the global observer and

the real system will not be equal anymore, in this way the Logical Unit Decision will indicate the presence of a fault in the system, by comparing these two signals.

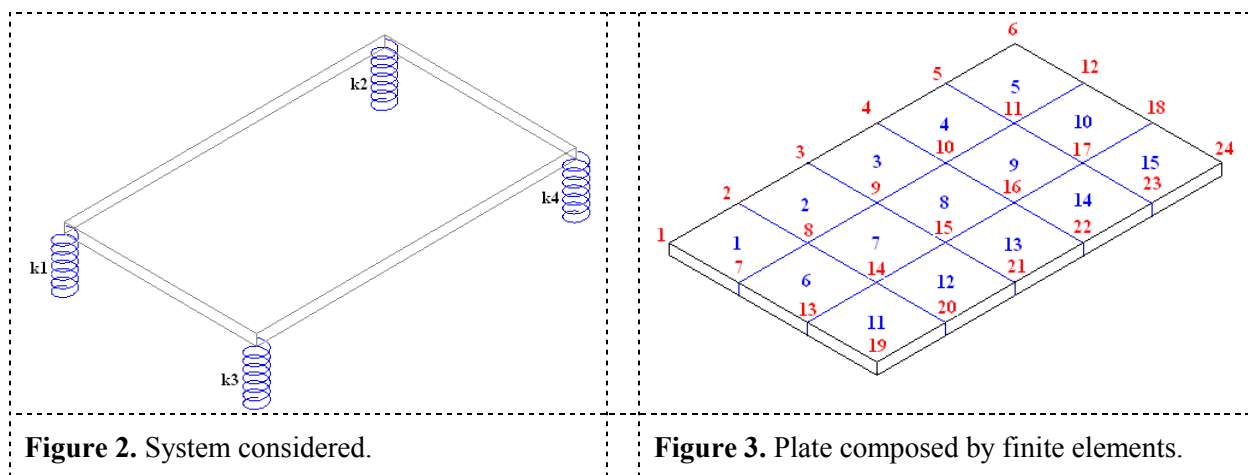
In the presence of a fault in the system, the global observer detects it, so becomes necessary the location of the component of the system in which the fault occurred. For this, a bank of Robust Observers is mounted for the system. In this bank, the observers are projected to estimate the outputs of the system for the case of specific faults in the many components of the system. There are utilized many observers, where each one represents a system with a fault in a determined component and a given percentage of fault. By this bank is possible to locate the fault in the system and its intensity.

#### 4. Finite Elements Method

The Finite Elements Method was used to determine the system's model. By using this method, mathematical models can be obtained for complex mechanical systems. The equations of this section are according to [9-11].

The motion equations of the system are obtained using the mass and stiffness matrices of the system. These matrices are obtained from the mass and stiffness matrices of the finite elements of the system. Now it will be shown the way that these matrices are obtained for the elements used in this paper, then these matrices will be used to obtain the mass and stiffness matrices of the entire system and these matrices will be used to determine the movement equations for the system.

Figure 2, shows the system utilized in this paper. The plate will be divided as the plate shown in figure 3.



The element that composed the plate presented in figure 3 is known as plate of Kirchoff. Some considerations will be adopted in the following theory:

1. The plate's thickness is small compared with the lateral dimension;
2. The plate's deflection is small comparing with its thickness and the inclination of the medium deflected plane is small compared with the unit;
3. The plate's deformation is such that, straight lines that are initially perpendicular to the medium surface, stay straight and perpendicular to the medium surface in the structure with the loading. This is the Kirchoff's Hypothesis;
4. There are no tensions in the medium surface of the plate.

The theory considered here, for which the above considerations are applied, is known as the Kirchoff-Love's Plate Theory, or classic plate theory. It will also be assumed that the material is homogeneous and isotropic. Using these considerations, the system presented in figure 2 can be represented by the equation 5.

$$M \cdot \ddot{D}(t) + K \cdot D(t) = Q \quad (5)$$

where  $Q$  is a vector of dimensions  $75 \times 1$ , which represents the forces and bendings applied to the system;  $M$  is the mass matrix;  $K$  is the stiffness matrix and  $D(t)$  is displacement vector.

## 5. Experimental Results

The studied system is shown in figure 4.



**Figure 4.** Experimental Apparatus.

The plate utilized was built with aluminum and its dimensions were 0.5m of length, 0.3m of width and 0.015m of thickness (how the thickness is equal to 5% of the smaller side of the plate, it was considered that this plate is a thin plate, so the plates of Kirchoff can be used). It was considered a density of  $2700\text{kg/m}^3$  for the aluminum. It was utilized an electric motor of Weg manufacturer, with a maximum rotation of 3380 rpm and a mass of 4 kg. This motor had a frequency regulator, which permits the control of the velocity of rotation.

There were supports for the springs screwed to the plate, where the springs were fixed. They were used springs with two different values of stiffness.

**Table 1.** Dimensions of the used springs.

d(m)	R(m)	k (N/m)	Fault (%)
0.003	0.0015	5437.884	0
0.0028	0.0014	4207.363	25

The springs in table 1 present high percentage of faults (25%), but in practices the faults are usually smalls, less then 10%. However, to build a spring with a loss of 10% of stiffness, for example, it would be necessary to made very small variations in its dimensions, so it was no possible to find a manufacturer of springs which provides this precision. Therefore it was chosen springs with a higher percentage of faults, so the springs could be made. For the computational simulation of the vertical movement of the apparatus shown in figure 6, it was used the model shown in figure 2 and the plate was divided in finite elements how is shown in figure 3. This configuration was chosen for a better distribution of motor weight and the forces of the springs in the dots.

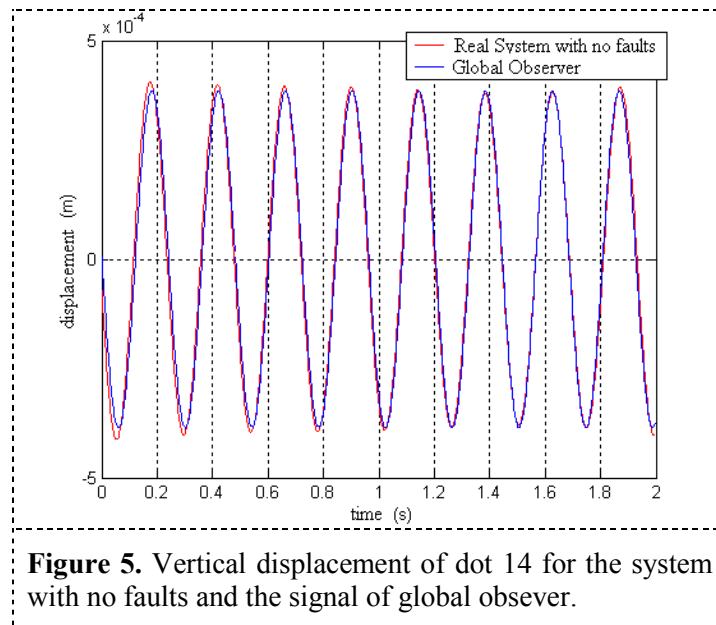
It was considered that the springs  $k_1$ ,  $k_2$ ,  $k_3$  e  $k_4$  were exactly beneath the center of elements 1, 5, 11 and 15, respectively. The motor was positioned on the center of the element number 8, so its mass was considered as a set of discrete masses distributed into the dots 9, 10, 15 and 16. The same was done to the masses of the supports of the springs, distributing then equally into the dots of the elements 1, 5, 11 and 15. For the forces applied by the springs, it was adopted a similar procedure of the distribution of the masses of the supports and the motor. The forces were equally distributed into the dots of the elements 1, 5, 11 and 15.

Although there were not any dampers in the experimental apparatus, the springs present a natural damping, so this damping was determined by the logarithmic decrement. For this purpose, it was applied impacts in the center of element number 8 and it was measured the decay of the amplitude of the vertical movement of the plate. It was obtained a value of 0.022 for the logarithmic decrement and, consequently a value of 3.685 N.s/m for the equivalent damping of the springs. How the springs were

in parallel, the value of the damping for each spring was 0.921 N.s/m. This value was used in the computational simulations, considering the dampers together with the springs.

For the movement of the plate, it was used a rotation of 1127 rpm (frequency of 20Hz) of the axis of the motor. It was also used an unbalanced mass of 0.05kg in a distance of 0.05m of the center of the axis. This force was distributed in the dots 10 and 16. How the plate was made of aluminum, the accelerometer was fixed by pasting a bronze support in the plate and then fixing the accelerometer by a screw. The accelerometer was positioned in the dot 14, so all the results presented in this section are for the vertical displacement of this dot.

For the signal acquisition, the accelerometer was connected to an amplifier, which was connected to an acquisition board DaqBook 112. The signal from DaqBook was sent to a computer that, together with software DasyLab, produced the visualization of the signal in the computer screen. The sample frequency was 500Hz. The software MATLAB was used for the design of the state observers that simulates the movement of the plate. A signal for the vertical displacement of dot 14 was generated by the global observer and compared with the signal from the accelerometer. The results are shown in figure 5.



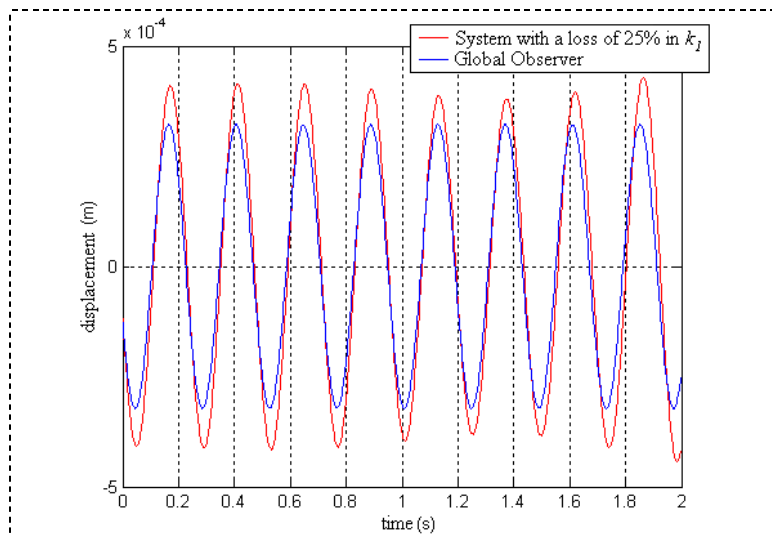
**Figure 5.** Vertical displacement of dot 14 for the system with no faults and the signal of global observer.

By figure 5, it can be seen that the signal from the global observer represents very well the signal from the experimental apparatus.

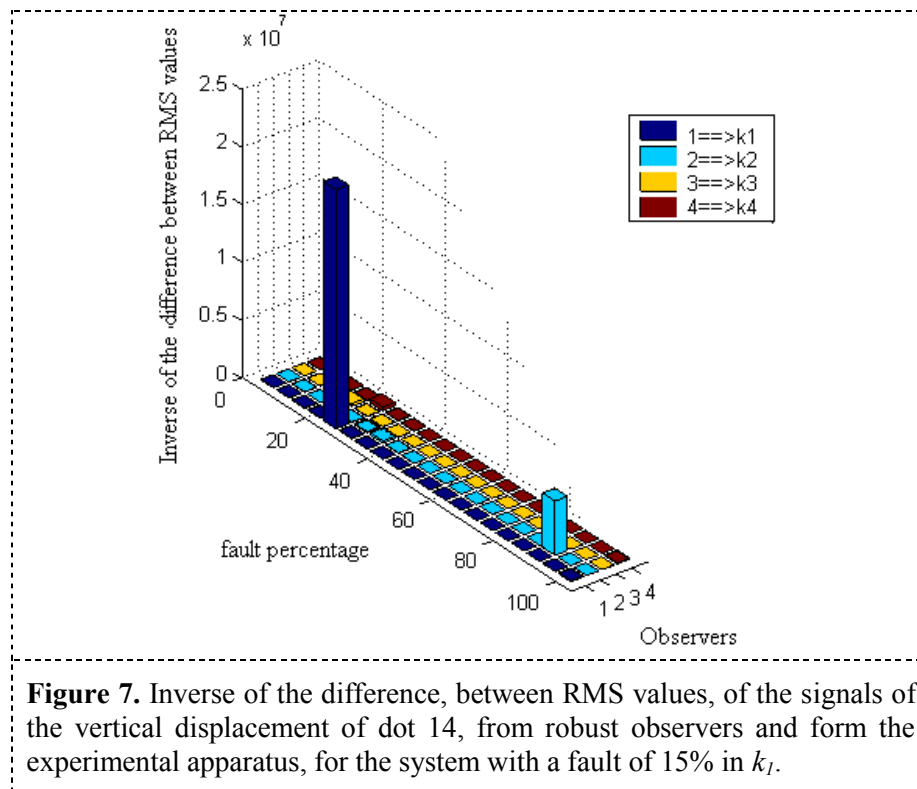
For the simulation of the system with faults, they were used the springs shown in table 1. These springs were positioned in specific positions and the vertical displacement of dot 14 was measured. The measured signal was compared with the signals from the bank of state observers. Initially the spring  $k_1$  was replaced by a spring with a loss of 25% of stiffness. The signal measured for the vertical displacement of the dot 14 and the signal of the global observer for the vertical displacement of this same dot are shown in figure 6.

In figure 6, it is possible to see a difference between the two signals, showing a fault in the system. Figure 7 below shows the inverse of the difference, between the RMS values, of the signal of the movement of dot 14 and the signals from the robust observers.

Figure 7 showed that the higher value occurs in the position 25% of robust observer  $k_1$ . This indicates that the signal from the robust observer to  $k_1$ , for a fault of 25%, is closer of the signal from the experimental apparatus, then the signal from any other robust observer. Therefore the difference between the RMS values of these two signals is smaller then the difference between any other RMS values from the experimental apparatus and the other observers. So the inverse of these differences produces a better visualization of the position of the fault (spring  $k_1$ ) and its intensity (25%).



**Figure 6.** Vertical displacement of dot 14 for the system with a fault of 25% in  $k_1$  and the signal of global observer.



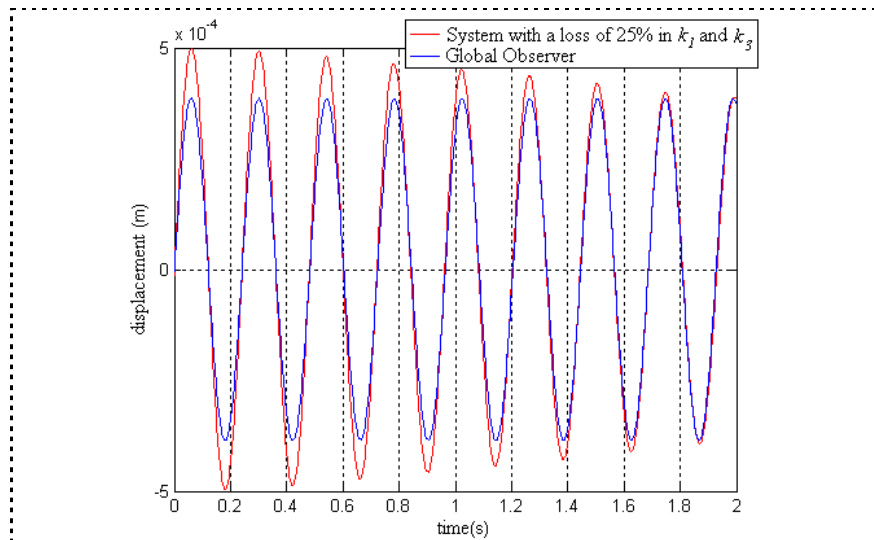
**Figure 7.** Inverse of the difference, between RMS values, of the signals of the vertical displacement of dot 14, from robust observers and from the experimental apparatus, for the system with a fault of 15% in  $k_1$ .

In sequence, both the springs  $k_1$  and  $k_3$  were replaced by springs with a loss of 25% in the stiffness. With the system functioning with these springs, the vertical displacement of the dot 14 was measured. The measured signal was compared with the signal from the global observer. These two signals are shown in figure 8.

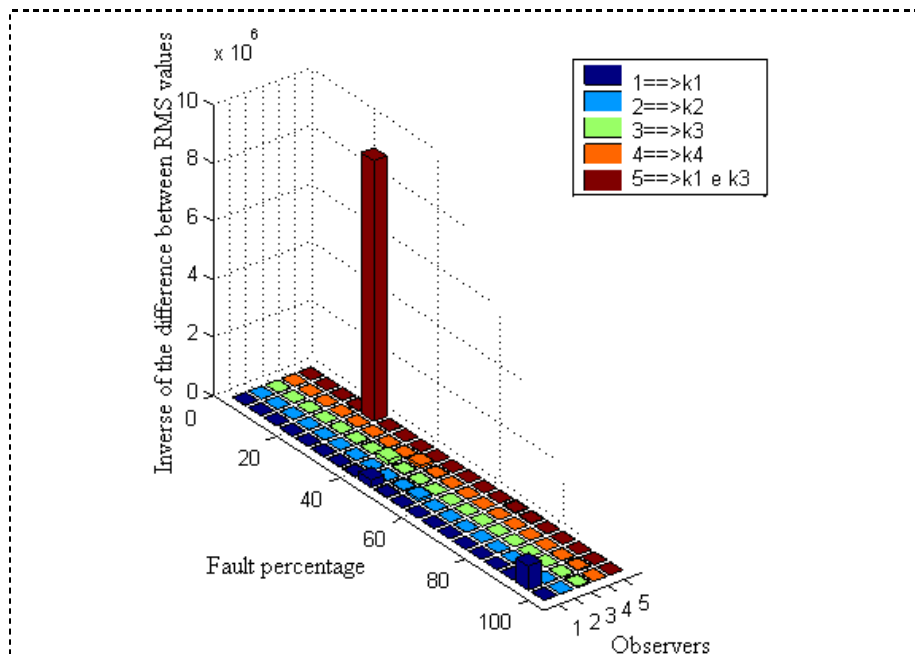
Figure 8 showed a large difference between the two signals, showing a fault in the system. Figure 9, below, presents the inverse of the difference, between RMS values, of the signals from this same system and from the robust observers.



By the figure 9, it was noticed that was necessary the introduction of a new observer, which represents the system with simultaneous faults on springs  $k_1$  and  $k_3$ . It's also verified that the higher value occurs in the position 25% of this observer. This means that the signal from the robust observer to  $k_1$  and  $k_3$ , for a fault of 25%, is the signal that is closer to the signal from the accelerometer, so the difference between the RMS values of these two signals is very smaller then the difference between the signal from the accelerometer and the other observers. The inverse of these values was done for a better visualization of the position of the fault. Therefore, is possible to locate the position of the fault (in springs  $k_1$  and  $k_3$  simultaneously), and its intensity (25%).



**Figure 8.** Vertical displacement of dot 14 for the system with 25% of fault in springs  $k_1$  and  $k_3$ , simultaneously, and from the global observer.



**Figure 9.** Inverse of the difference, between RMS values, of the vertical displacement of dot 14 from the system with faults of 25% in springs  $k_1$  and  $k_3$ , and the robust observers.



## 6. Conclusions

In this paper the methodology of the state observers was applied for the detection and location of faults in a model of platform that had a suspension system. The mathematical equations for the system used were determined by using the finite elements method.

By the presented results, it is possible to conclude that the state observer, projected by the Linear Quadratic Regulator (LQR) method, were efficient in the detection and location of faults in the system considered. Was verified that, for the system considered, the observers can detect and locate faults even that the measurement point is not close to the point where the faults occurs. It was also verified that the observers can detect and locate simultaneous faults in the system, that's the case when two springs presented faults at the same time.

Computational programs were developed, by the usage of the finite elements method, which allowed the simulation of the movement of the system and the detection and location of faults in a continuous system. The system used presented a very simplified suspension system. Although this system didn't present any parameter based on the parameters of a real vehicle, the computational programs can be expanded, in future works, to simulate the movement of a real vehicle.

The number of finite elements present on the plate could not be higher, because this would compromise the observability of the system.

## 7. References

- [1] Marano J H 2002 *Localização de falhas via observadores de estado em sistemas com variação de parâmetros* (Universidade Estadual Paulista, Faculdade de Engenharia de Ilha Solteira: Ilha Solteira).
- [2] Melo G P, Morais T S and Daniel G B 2005 Diagnosys of faults in mechanical systems with unknown inputs using proportional and integral state observers *Proceedings of International Congress of Mechanical Engineering - COBEM*.
- [3] Koroishi E H, Melo G P and Assunção E 2010 State Observer Using Decay Rate LMI Constraints for Fault Detection in Mechanical Systems *Ciência & Engenharia* 12-21
- [4] Koroishi E H and Melo G P 2012 Experimental Fault Detection in Rotation System Using State Observers by LMIs *Journal of Mechanics Engineering and Automation* 470-475.
- [5] Luenberger D G 1964 Observing the state of a linear system *IEEE Military Electronics* 74-80.
- [6] Koroishi E H, Borges A S, Cavalini Jr A A and Steffen Jr V 2014 Numerical and Experimental Modal Control of Flexible Rotor Using Electromagnetic Actuator *Mathematical Problems in Engineering (Print)*.
- [7] Ogata K 1998 *Engenharia de controle moderno* (Prentice-Hall do Brasil: Rio de Janeiro).
- [8] Melo G P and Lemos G F 2004 Fault Diagnosis in Rotation System Using well Conditioned State Observer *Proceedings of Conference on Structural Dynamics - IMAC*.
- [9] Azevedo A F M 1976 *Método dos elementos finitos* (Faculdade de Engenharia da Universidade do Porto)
- [10] Bathe K J 1976 *Numerical methods in finite elements analysis* (Prentice Hall: Englewood Cliffs).
- [11] Dawe D J 1984 *Matrix and finite element displacement analysis of structures* (Oxford: Clarendon).