FAULT DETECTION IN MECHANICAL SYSTEMS THROUGH THE METHODOLOGY OF THE STATE OBSERVERS

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Abstract. *The development of new techniques of detection and localization of fault in mechanical systems submitted dynamic shipments has evolved very in the last years in function of the necessity each bigger time of the industries in keeping the equipment in functioning without abrupt stops. To guarantee this functioning the mechanical systems have that to be supervised, therefore the riots in normal operation cause a deterioration of the performance of the system or even though they take the dangerous situations. In this case, fault in these points without knowledge of its measures can be detected, being able to monitor them through the reconstructions of its states. This technique consists of developing a model for the system in analysis and comparing the output esteem with the measured output. The idea is to mount a bank of observers to supervise the process, where each observer is dedicated only to an instrument or physical parameter of this system. One of the great advantages in if using to the methodology of the state observers, to monitor the system, is the necessity of if knowing only one signal of reply of the system, presenting resulted satisfactory in the detection of fault. In this paper, with the aid of welldefined theoretical models and the state observer method for the identification and location of faults it is possible to monitor the parameters of a mechanical systems. In order to improve safety, they must be supervised such that occurrence of failures or faults can be repaired as quickly as possible.*

Keywords*: state observers, mechanical systems, faults.*

1. INTRODUCTION

One of the great concerns of the industry nowadays is to keep its equipment in functioning without that hung-up occur. With this constant concern, one observes in the last times the development of new techniques of detection and localization of fault in mechanical systems submitted dynamic shipments. In order to guarantee the functioning of the mechanical systems with security, these must be supervised and be monitored so that the fault are cured fastest possible, therefore if not, the riots in normal operation can even though take to a deterioration of the performance of the system or the dangerous situations.

The tools for theoretical analysis of the current dynamic systems sufficiently are sophisticated the point to be able to simulate complex models in modern computers, however, exist great difficulties in the prediction of the dynamic behavior of certain structural components and in diagnose of fault due the inexactly of the theoretical or same model for the difficulty of measurement of some variable of the system.

The state observers can reconstruct the states not measured or the values proceeding from points of difficult access in the system. Being thus, fault in these points without the knowledge of its measures can be detected, being able to monitor them through the reconstructions of its states. The existing methodologies using observing of state are in its majority destined to decide problems of control and detection of possible fault in sensors and instruments.

It has two decades approximately that the problem of detection of fault has been studied for researchers, where basically has used techniques through observers of states in control systems and/or methods of esteem of parameters. Some of the most used methodologies using can be mentioned models in systems of control or the detection of fault in sensors and instruments, as: dedicated observers of Luenberger, observers, detection through filters, robust consistency of space, observers for unknown inputs.

The technique of the state observers consists of developing a model for the system in analysis and comparing the output esteem with the measured output. The mathematical models that in the practical one represent the behavior of the systems are not free of unknown disturbances and variations in the proper parameters. In the majority of the projects of state observers, the parameters of the system are known or can be identified through some found specific methods in literature. In cases where the parameters are not known with exactness or are citizens the changes during the functioning of the system, the reply of the observer it can supply a incorrect estimate of the reconstructed states provoking errors of permanent regimen, that take the false alarms in the detection and localization of fault. In the last years, the problem of the parameter variation in the project of state observers has been studied for innumerable researchers.

2. THEORETICAL BEDDINGS

The automatic control has played a basic role in the advance of engineering and science. Beyond the extreme importance in systems of space vehicles, robotic and similar systems of aiming of missiles, systems, the automatic control if has become of great importance and integrant part of the modern industrial processes and of production. System of control is an interconnection of components forming a configuration of systems that will produce a reply desirable do system, no which the base for the analysis of a system is formed by the supplied beddings by theory linear systems, that assumes a cause relation effect for the components of a system, no which the entered relation - output represents the relation cause effect do process.

2.1. System of control

A control system that keeps a preset relation enters the largeness of output and the largeness of reference, comparing them and using the difference as half of control, is said of system of control with retraction or system of control the closed mesh as it can be seen in Fig. 1. In control systems the closed mesh, the operating signal of error, that is the difference enters the signal of input and the signal of retraction, excites the controller in order to reduce the error and to bring the value of the output signal for a desired value.

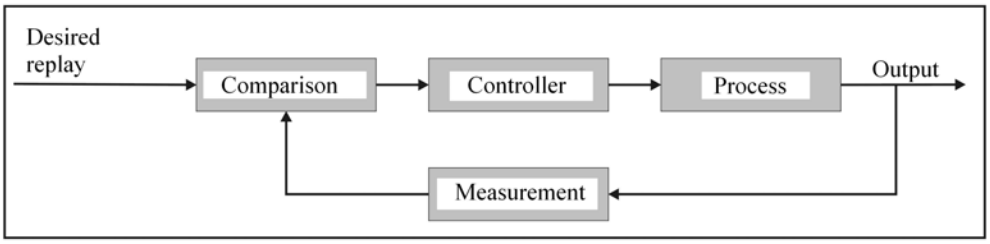

Figure 1. System of control of closed mesh.

The systems, in which the output signal does not influence in the action of control, is called control systems the open mesh. Of a general form, in the control systems the opened mesh, the signal of output of the system is not measured nor sent in return for the comparison with the input signal; this type of controller uses a control actuator to get the desired reply, as shown in Fig. 2.

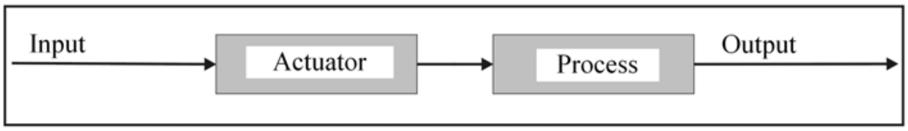

Figure 2. System of control of open mesh.

2.2. Controllability and Observability

The concepts of controllability and observability are of great importance in the study of control and the esteem of dynamic systems. The controllability concept is related to the existence of a possible law of control capable to transfer the initial state of a system to one another state in a finite time. In similar way, the observability concept is related to the existence of possible algorithm esteem the variable of state from the available variable.

Controllability: system is said completely controllable in the instant t_0 if is possible by means of an excitement $\{u(t)\}$ not restricted, to transfer to the system of the initial state $\{x(t_0)\}$ to any another state $\{x(t_f)\}$ in a finite time $t_f > t_0$. Moreover, if the system is controllable for any instant t_0 and initial state $\{x(t_0)\}$, then the system is said completely controllable. A vector of control excitement is said not restricted when it does not have limitations how much its amplitude.

Observability: A system is said observable in the instant t_0 if is possible to determine the initial state $\{x(t_0)\}$ from the reply $\{y(t)\}$ of the system during a time interval $t_0<t<t_f$.

2.3. Representation in the state space

The state of a system, used in the projects of a system of control in the domain of the time, is a set of variable such that the knowledge of the values of these variable and the functions of input, with the equations that describe the dynamics, to the future states and the future output of the system supply. The state of a system in one instant t is described in terms of a set of values of the state variable [x_1(t), x_2(t)..., x_n(t)] of a system. The state of a system is described for a set of distinguishing equations first-class written in function of the state variable, Eq. (1).

$$\begin{aligned}
\dot{x}_1(t) &= a_{11}x_1(t)+a_{12}x_2(t)+......+a_{1n}x_n(t)+b_{11}u_1(t)+.....+b_{1m}u_m(t)\\
\dot{x}_2(t) &= a_{21}x_1(t)+a_{22}x_2(t)+......+a_{2n}x_n(t)+b_{21}u_1(t)+.....+b_{2m}u_m(t)\\
&\vdots\\
\dot{x}_n(t) &= a_{n1}x_1(t)+a_{n2}x_2(t)+......+a_{nn}x_n(t)+b_{n1}u_1(t)+.....+b_{nm}u_m(t)
\end{aligned} \tag{1}$$

in which,

$$\{\dot{x}(t)\} = dx/dt$$

This system of distinguishing equations can in accordance with be presented in the matrical form the Eq. (2).

$$\frac{d}{dt}\begin{bmatrix} x_1(t)\\ x_2(t)\\ \vdots\\ x_n(t)\end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n}\\ a_{21} & a_{22} & \cdots & a_{2n}\\ \vdots & \vdots & \cdots & \vdots\\ a_{n1} & a_{n2} & \cdots & a_{nn}\end{bmatrix}\begin{bmatrix} x_1(t)\\ x_2(t)\\ \vdots\\ x_n(t)\end{bmatrix} + \begin{bmatrix} b_{11} & \cdots & b_{1m}\\ \vdots & & \vdots\\ b_{n1} & \cdots & b_{nm}\end{bmatrix}\begin{bmatrix} u_1(t)\\ \vdots\\ u_m(t)\end{bmatrix} \tag{2}$$

in which,

$$\{x(t)\} = \begin{bmatrix} x_1(t)\\ x_2(t)\\ \vdots\\ x_n(t)\end{bmatrix}$$ is the state vector;

$\{u(t)\}$ is the vector of the input signals.

Of this form, the equation of state can in accordance with be represented the Eq. (3).

$$\{\dot{x}(t)\} = [A]\{x(t)\} + [B]\{u(t)\} \tag{3}$$

in which,

[A] is a square shaped matrix n x n called state matrix or dynamic matrix;
[B] is a matrix n x m call of matrix of inputs.

The outputs of a linear system can be related with the variable of state and the signals of input for the output equation, Eq. (4).

$$\{y(t)\} = [C_{me}]\{x(t)\} + [D]\{u(t)\} \tag{4}$$

in which,

{y(t)} is the set of the output signals;
[C_{me}] is the output matrix;
[D] is the matrix of direct transmission.

2.4. State Observer

Initially, the state observers had been considered and developed for Luenberger and after that perfected by proper it. The theory of the observers has been extended for some research to include systems varying in the discrete time, discrete systems and random systems. Since of 1964, the observers have formed an integral part of numerous projects of systems of control of which a small percentage have been informed of explicit form.

The simplicity of its project and its resolution makes of the observer a attractive component of the general project, mainly for the fact to reconstruct states not measured. Had its practical utility, the observers offer a theoretical glamour without equal. Its theory intimateness is related the basic concepts of the linear system of controllability, observability, dynamic reply and stability. This theoretical wealth made of the observer a attractive seek area. Almost all system is an observer. Ahead of this, it is considered initially, for example, the problem to observe a free system that is, a system without no input. In case that the outputs of the system are used as entered to monitor another system, this as system will almost always go to serve as an observer of first in which the its state will tend to locate a linear transformation. Such situation meets represented by Fig. 3.

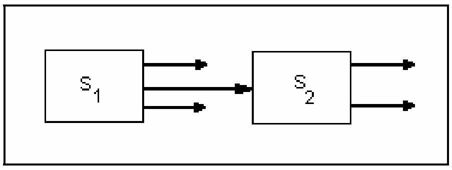

Figure 3. A simple observer.

This result forms the base of the theory of the observer and explains because much freedom in the project of an observer exists. The technique of the state observers consists of developing a model for the system in analysis and comparing the output esteem with the measured output.

The idea is to mount a bank of observers to supervise the process, where each observer is dedicated only to an instrument or physical parameter of this system. It is verified, however, that the parameters of the system can vary during the process due to specific characteristics of some materials or to the proper natural consuming of the components. This can all cause to false alarms, compromising the functioning of the system. Another important factor is the knowledge of the inputs, in view of that nor always it is possible to have random precision of the excitement forces and disturbances in the system.

The Fig. 4 represents the project of a state observer.

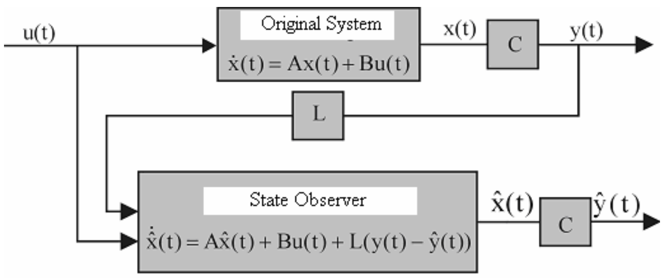

Figure 4. Definition of state observer.

in which,

[L] is the matrix of the observer.

2.5. Observers of global and robust state

In a mechanical system, where component determined one starts to fail, an observer of mounted global state for this system is capable to feel the influence of this imperfection of sufficiently fast form, therefore the observer of global state presents the same reply of the real system, leaving of the principle of that this is functioning in adjusted way, being the sufficiently sensible observer to any irregularity that to start to appear in the system.

The idea is to use the effect felt for the observer of global state to locate a possible imperfection in a mechanical system. Therefore, in order to detect and to locate possible fault in mechanical systems, it is calculated initially, if the system will be observable, an observer of global state for the detection of possible fault or irregularities in the mechanical system in question. The global observer is a set of usual distinguishing equations developed using the equations of Riccati, that answers accurately as the system in question, since that the system is functioning adequately without no indication of fault.

The following step is to calculate the robust determined observers of state parameters citizens the fault or for a numerical percentile variation of the parameters in order to locate the possible fault or irregularities of the system, or either, when indications of fault in the system exist, the curve of the robust observer to the parameter of the system with possible imperfection starts if to approach to the curve of the real system, therefore in the assembly of the robust observer a specific parameter, this exactly parameter is removed of the matrix dynamics of the system before the assembly of the observer. Through this approach of the curves it is possible to locate the fault of the system in question. In mechanical systems, a great possibility of one or more parameters exists to fail at the same time, then, in this in case that, it projects observing of state robust to all the parameters citizens the fault.

Also exist the possibility of the parameters citizens the fault to be located in the same position of the dynamic matrix [A]. Being thus, one works with a combination of the some components of the system in order to locate the origin of these fault.

In Fig. 5 to follow, one presents a project of a bank of observers used for the detection and localization of fault, where if {verifies the excitement force {f(t)}, the reply {y(t)}, the observer of global state and the robust observers of state to the possible parameters citizens the fault z_1....................z_n and the unit of logical decision.

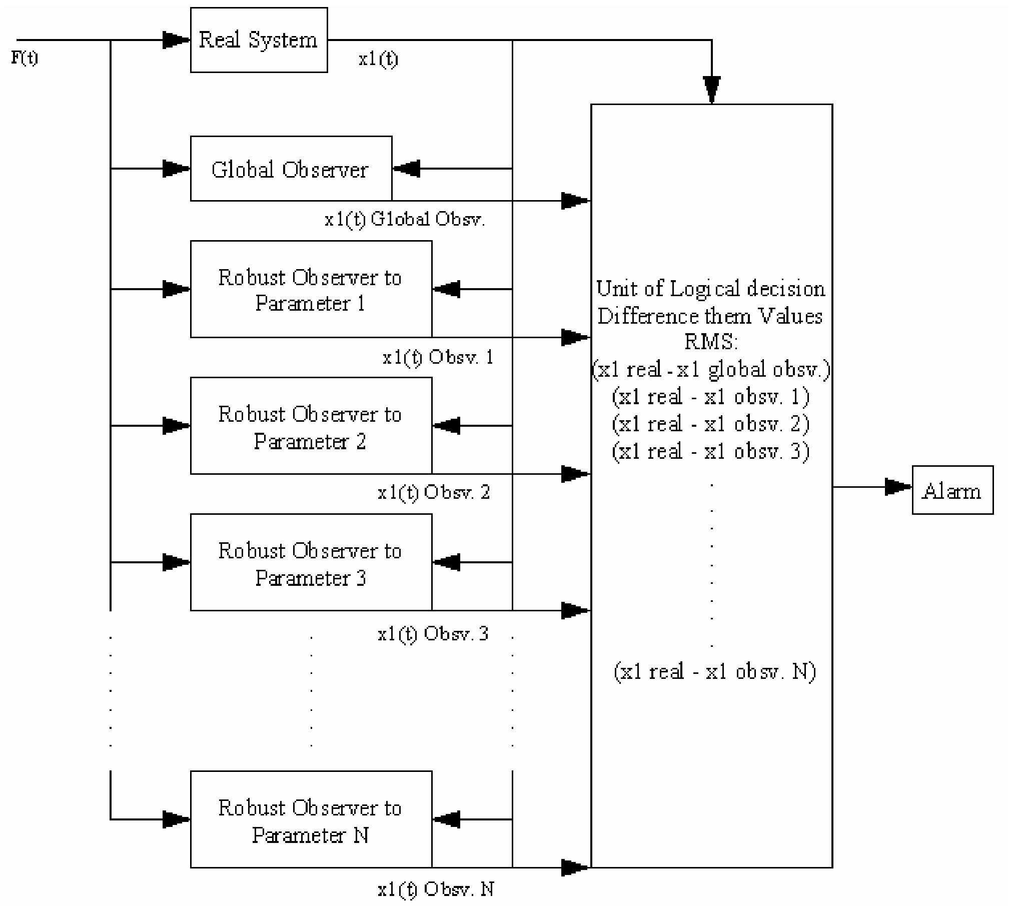

Figure 5. System of robust observation.

This bank of observers is constituted of the global observer who will go to analyze if the system in question possess some indication of imperfection or not, and of the robust observers of state to the parameters citizens the fault, that are used in order to locate the possible fault of the system. As much the global observer how much the robust observers receive the values from the excitement and the reply of the real system and after the resolutions of the sets of distinguishing equations, the gotten results is collected and analyzed in the unit of logical decision. The unit of logical decision first analyzes the difference of values RMS between the real system and the global observer, in order to detect some irregularity in the system. To follow, it analyzes the differences of values RMS between the real system and the robust observers to the parameters citizens the fault, locating the possible fault of the system. È in this unit that if analyzes the trend of the progression of an imperfection and is it that sets in motion when an alarm system will be necessary. The alarm system can be ready to be set in motion when to occur a percentile variation in one determined parameter, but this depends on the system which is being evaluated.

3. METODOLOGY

In order to verify the validity of the developed methodology using the method of the observers of state for the localization and quantification of the fault in mechanical systems, a mechanical system with 4 observed degrees of freedom as in Fig. 6 was considered, considering only loss in the stiffness k_3. Of this form the methodology mathematically consists of shape the system and through the project of robust observers to the parameters citizens the fault, to initiate the process of localization and quantification of the damage in the system. The analyzed mechanical system meets represented in Fig. 6.

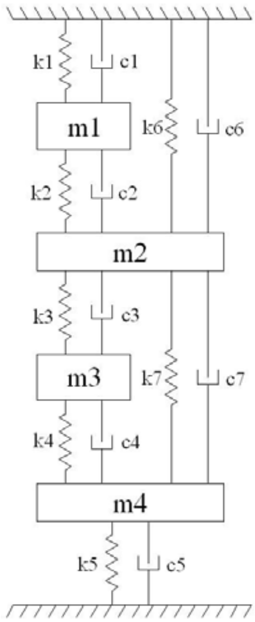

Figure 6. Mechanical system.

The table 1 presents the values of the physical parameters of the system.

Table 1. Physical parameters of the system.

Mass (kg)	**Stiffness (N/m)**	**Damping (N.s/m)**
$m_1 = 4$	$k_1 = 6000$	$c_1 = 40$
$m_2 = 5$	$k_2 = 6000$	$c_2 = 40$
$m_3 = 4$	$k_3 = 6000$	$c_3 = 40$
$m_4 = 5$	$k_4 = 6000$	$c_4 = 40$
	$k_5 = 6000$	$c_5 = 40$
	$k_6 = 10000$	$c_6 = 50$
	$k_7 = 10000$	$c_7 = 50$

Considering the following initial conditions $x_1 = 0{,}025\,m$, $x_2 = x_3 = x_4 = 0$, $\dot{x}_1 = 3m/s$ e $\dot{x}_2 = \dot{x}_3 = \dot{x}_4 = 0$. The time of sampling of points acquired of the reply it was of 1s. Thus, the reply of the system can be simulated, generating 1024 discrete points.

4. RESULTS

For the validation of the method in the localization of fault, an imperfection in the system with total loss in the stiffness was introduced k_3, and for this situation all had been considered as parameters citizens the parameters, with exception of the masses. Of this form, they had been constructed observing robust for the parameters: k_1, k_2, k_3, k_4, k_5, k_6, k_7, c_1, c_2, c_3, c_4, c_5, c_6, and c_7. First, were constructed to the global observer and after that the robust observers. To follow the results meet gotten.

The Fig. 7 represents the answers of the real system without imperfection and the global observer. Of this graph it can be observed that the global observer is compatible with the system, since the replies had been coincident. Demonstrated the validity of the gotten global observer

The Fig. 7 represents the answers of the real system with imperfection and the global observer. In this graph, the presence of an imperfection in the system can be observed, since the graphs of the answers had not been coincident. From the graph of the defective real system which parameter will be determined was modified, to result in such imperfection, being constructed a robust observer for each parameter subject to fails.

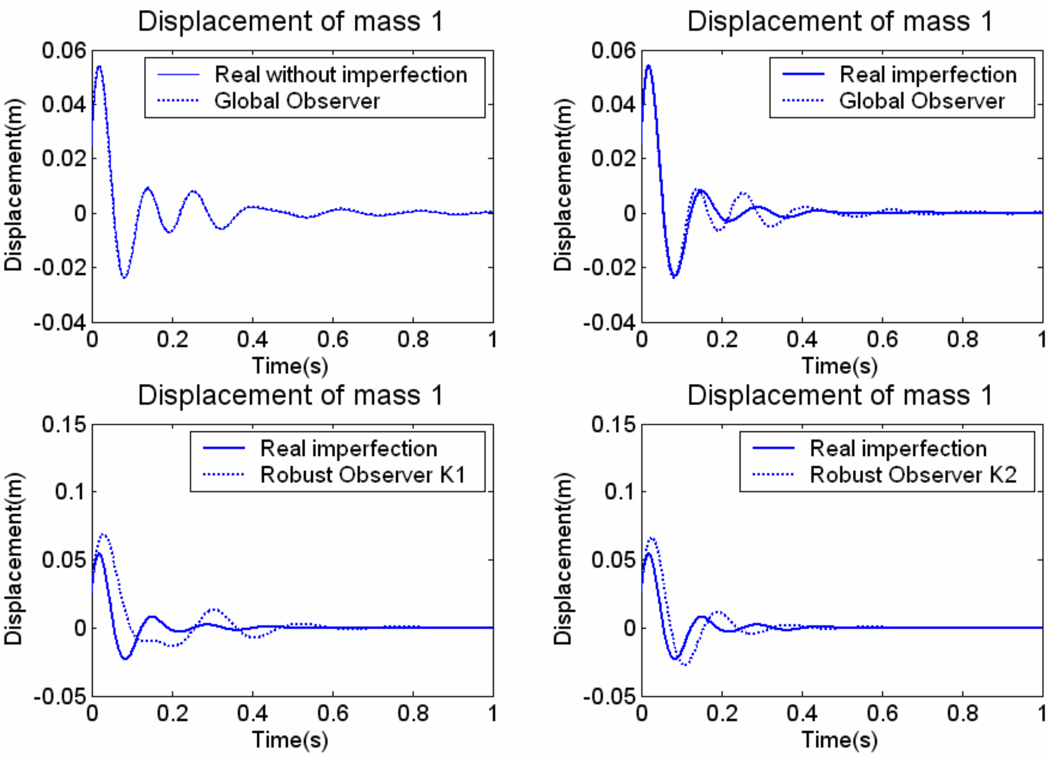

Figure 7. Response of system.

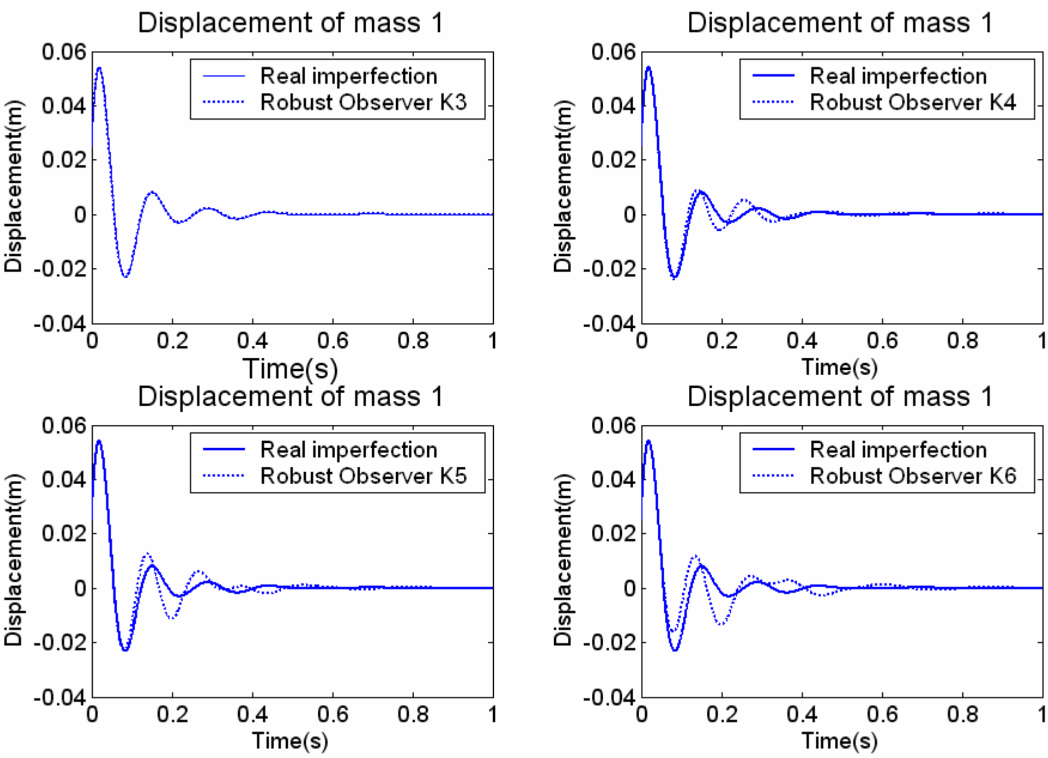

Figure 8. Response of system.

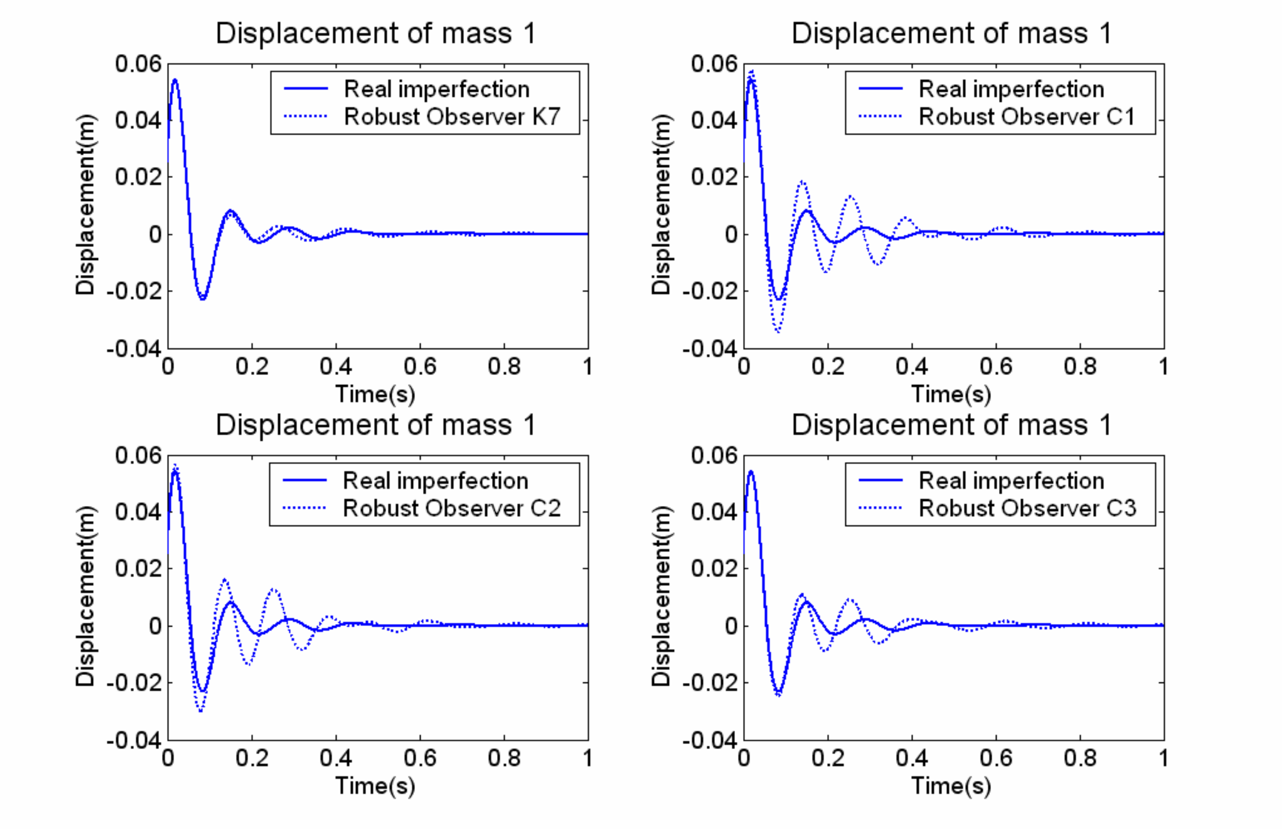

Figure 9. Response of system.

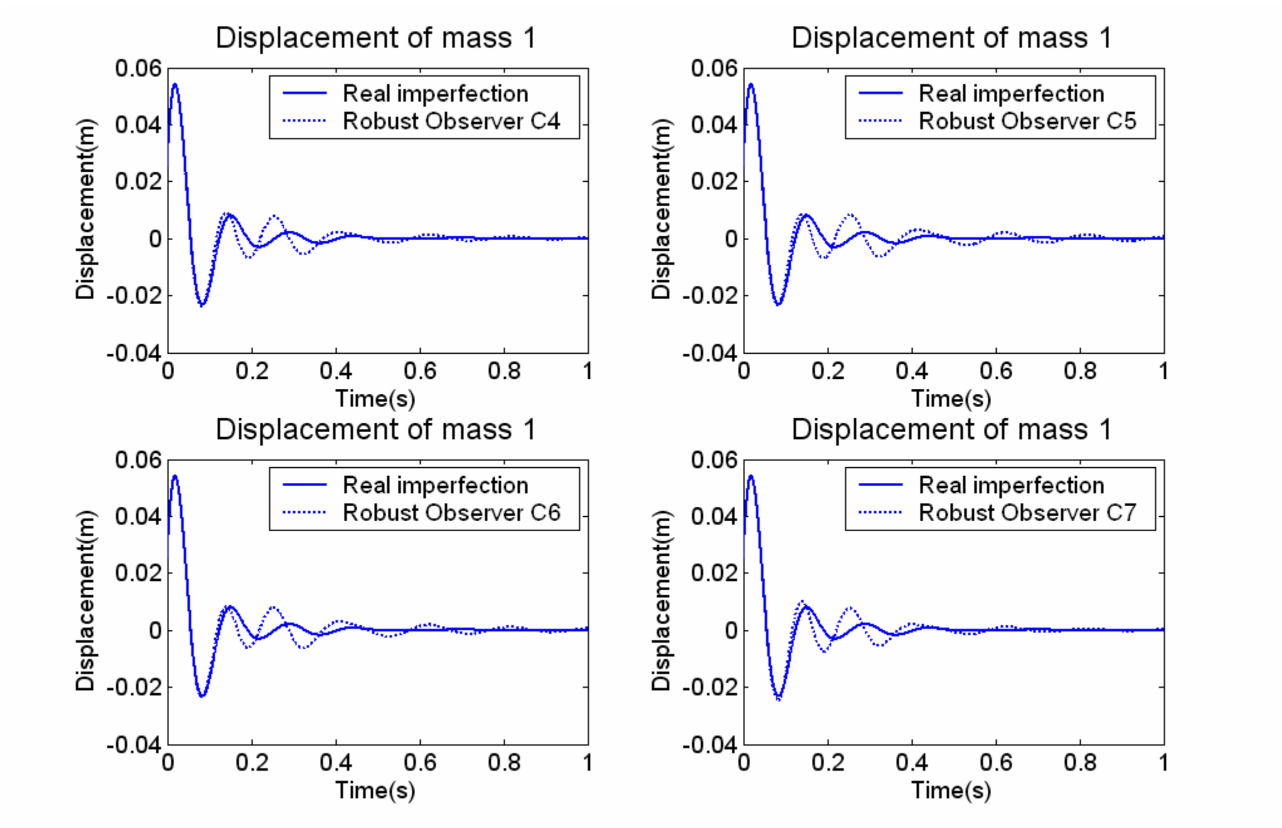

Figure 10. Response of system.

It is noticed that the curves distance themselves one of the other, being possible to detect a possible imperfection in the system, that in this in case that k_3 were the withdrawal of the parameter, but still was not possible to locate such imperfection. In the robust assembly do observing to a specific parameter, this exactly parameter is removed of first dynamics do system before of assembly do system. Knowing itself that when indications of fault in the system exist, the curve of the robust observer to the parameter of the system with possible imperfection starts if to approach to the curve of the real system, is possible to carry through an analysis in Fig. 7 to 10 in order to locate such imperfection. In the example simulated in question, wise person that the removed parameter of the dynamic matrix of the system was k_3 and this it is verified in Fig. 8, where both the curves are coincident, what it becomes possible to locate the imperfection.

In the remaining figures it is possible to verify that the curves if distance one of the other, this having to the fact of that the removed parameter of the system did not correspond to the parameter of the constructed robust observer, or either, in this in case that, the removed parameter was k_3, and can be verified this when it was located curve of the global real system simulated without k_3 with the curve of the robust observer the parameter k_3. Therefore, through this analysis "appearance" it is possible to verify the validity of the developed methodology.

The Table 2 presents the difference of values RMS of the displacement of the curves of the real system with and without imperfection and of the robust observers global and to the specific parameters.

Tabela 2. Diference of values RMS.

State Observer	Real System without imperfection	Real System with Imperfection
Global Observer	**1,4509e-018**	1,7646e-005
Robust Observer k_1	0,00057383	0,00057301
Robust Observer k_2	0,00041813	0,00041423
Robust Observer k_3	1,9199e-005	**4,4931e-018**
Robust Observer k_4	6,4688e-006	1,5341e-005
Robust Observer k_5	2,2505e-005	3,1409e-005
Robust Observer k_6	5,8096e-005	6,1199e-005
Robust Observer k_7	2,2401e-005	1,0328e-005
Robust Observer c_1	0,00012272	0,00012577
Robust Observer c_2	7,8434e-005	8,6769e-005
Robust Observer c_3	1,2949e-005	2,5094e-005
Robust Observer c_4	1,7273e-006	1,8606e-005
Robust Observer c_5	6,2191e-006	2,0827e-005
Robust Observer c_6	6,9744e-006	1,6424e-005
Robust Observer c_7	6,9744e-006	1,6424e-005

Analyzing the results of Table 2, it is observed validity of the method since the difference of value RMS of x_1 real without imperfection and x_1 of the global observer had presented small value extremely, demonstrating the validity of the result gotten for the global observer. While that for the system with imperfection, is observed that the lesser difference of value RMS occurred for the robust observer k_3, thus having found the imperfection in the system, since was considered loss of k_3 to simulate the imperfection in the system.

5. CONCLUSIONS

In the present work, a methodology for the localization of fault was developed saw observers of state in systems with parameter variations. The technique of detection and localization of state fault using observing can reconstruct 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 its great requests or constants 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. A system was considered mass-spring-shock absorber, in which total loss of the parameter was considered k_3, being that from the presented results, it was possible successfully to detect and to locate the parameter that was failing, validating the methodology developed.

Ahead of the gotten results, the validity of the methodology of the observers in the detection of fault in mechanical systems can be concluded, since the results had been sufficiently satisfactory, demonstrating the effectiveness of the developed methodology.

6. ACKNOWLEDGEMENTS

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