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IMPROVED VIBRATION SUPRESSION VIA HIERARCHICAL FUZZY CONTROL

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Abstract: In this paper a hierarchical control scheme is proposed to improve vibration suppression using an electro-mechanical system based in the lever principle. The hierarchical control consists of two controllers, a LQG/LTR and a fuzzy system, that present high efficiency under different operation conditions and a supervisor based on fuzzy logic that combines the control signals from each one of the controllers to obtain superior performance in a wide range of operating conditions. Digital simulation was used to evaluate the performance of this control scheme during tracking reference under several disturbances.

Keywords: Hierarchical control, Supervisor, Fuzzy logic, LQG/LTR, Vibration suppression.

1. INTRODUCTION

Industrial environments are usually subjected to the influence of vibrations, which are generated by a variety of sources such as machines and load transportation equipments for example. On the other hand, some of the devices require high precision positioning to operate properly, and the quality of the final product is strongly influenced by many factors that can cause negative impacts. Mechanical vibrations, in most cases transmitted through the floor, are one of the most frequent causes of problems in industrial processes that demand high precision. Hence, those industrial equipments need to be isolated from this type of disturbances. In addition to this problem, some industrial operations require the equipment, or part of it, to track a previously determined trajectory. Applications where it is desired to control vibrations range from home appliances and automobiles to space applications and nuclear power plants (Campbell and Crawley, 1994; Tamai and Sotelo Jr., 1995; Denoyer and Kwak, 1996; Bai and Lim, 1996; Jones *et alii*, 1996; Slicker *et alii*, 1996; Oshiro *et alii*, 1997; Holzhüter, 1997).

From the point of view of a control designer, the two aforementioned problems present particular difficulties, which may be expressed by different design specifications. Several design options can be found in the literature to make a control system that satisfies performance specifications such as tracking and disturbance rejection. These approaches normally focus on a trade off between these two conflicting objectives. Consequently, the designed control may not be the best for any one of the objectives separatelly.

With the technological advance, it is possible nowadays to implement sophisticated control schemes in real time. A simple DSP, microcomputer, or microcontroller, can be used to implement them. In fact, one can have more than one control algorithm running simultaneously to generate different control signals while a supervisor algorithm combines these signals to supply an improved control signal in a wide range of operation conditions.

This paper proposes a Mamdani fuzzy system as a supervisor that mixes signals from a LQG/LTR robust controller and a Takagi-Sugeno-Kang fuzzy controller. Each one of these controllers has good performance in certain operational conditions. The aim is to conceive a fuzzy supervisor that allows an advantageous combination of the two control signals. In the present work the supervisor's task is to determine the ideal proportion of the action provided by the controllers in each operational condition. Section 2 presents an overview of the electro-mechanical system and a linear mathematical model for it. In section 3 the LQG/LTR and the Fuzzy controller design are briefly revised. In section 4, the system responses shown in the section 3 are used in the fuzzy supervisor design. Section 5 shows the results of digital simulations using the hierarchical control scheme, and finally, in section 6 the conclusions are presented together with some possible further research topics.

2. THE ELECTRO-MECHANICAL SYSTEM

The proposed electro-mechanical system consists of a lever supported in two points. The main support has a DC servo-actuator to provide vertical displacements that are used for vibration suppression. The other support is passive, consisting of a spring and a damper. The lever is assumed to have a payload on the non-supported extremity. The objective is to reduce the transmission of vibrations between the baseplate, which can be the floor, and the payload. This is achieved by using the DC servo-actuator in such a way as to produce displacements that oppose the effects of the undesirable disturbances.(see fig. 1).

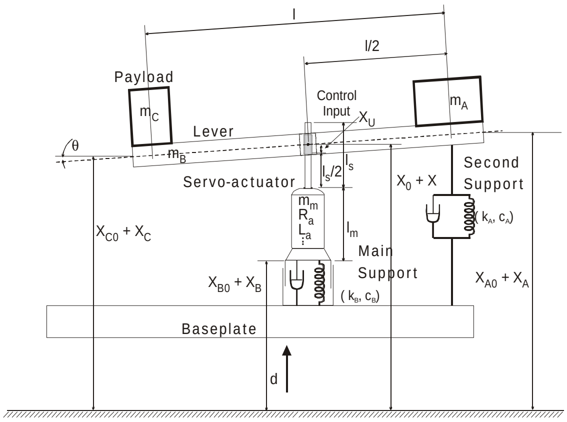


Fig. 1. The proposed electro-mechanical system.

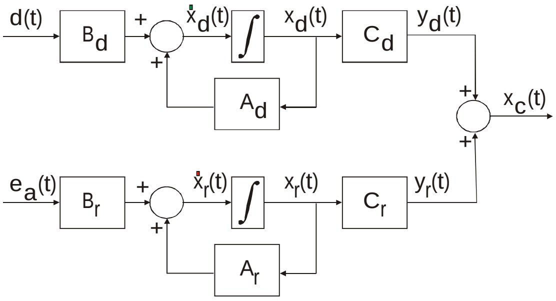


Fig. 2. Block diagram model of the system.

A dynamical linear model for the physical model presented in fig. 1 may be represented in the form of block diagram, as one can see in the fig 2. Mathematically, this model can be described by the equations (1) and (2).

$$\begin{aligned} \dot{\mathbf{x}}_R &= \mathbf{A}_R\mathbf{x}_R + \mathbf{B}_R\mathbf{u}_R \\ Y_R &= \mathbf{C}_R\mathbf{x}_R \end{aligned} \qquad (1)$$

$$\begin{aligned} \dot{\mathbf{x}}_D &= \mathbf{A}_D\mathbf{x}_D + \mathbf{B}_D\mathbf{u}_D \\ Y_D &= \mathbf{C}_D\mathbf{x}_D \end{aligned} \qquad (2)$$

where:

$$\mathbf{A}_R \approx \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -88{,}98 & -10{,}59 & -8{,}90 & -1{,}06 & 0{,}85 & 0{,}08 \\ -1{,}90 & -4{,}76 & -0{,}19 & -0{,}48 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -25{,}32 \end{bmatrix}$$

$$\mathbf{B}_R \approx \begin{bmatrix} 0 & 0 & 0{,}08 & 0 & 0 & 323{,}41 \end{bmatrix}^T$$

$$\mathbf{C}_R = \begin{bmatrix} 1 & -2.5 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{A}_D \approx \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ -88{,}98 & -10{,}59 & -8{,}90 & -1{,}06 & 88.98 \\ -1{,}90 & -4{,}76 & -0{,}19 & -0{,}48 & 1.90 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{B}_D \approx \begin{bmatrix} 0 & 0 & 8{,}90 & 0{,}19 & 1 \end{bmatrix}^T$$

$$\mathbf{C}_D = \begin{bmatrix} 1 & -2{,}5 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{u}_R = e_a \text{ and } \mathbf{u}_D = d$$

Further details about the system model can be found in Araújo and Yoneyama, 2001

3. THE CONTROLLERS

In order to close the control loop, the system output $x_c(t)$ is measured and compared with a reference value. The result is the tracking error that constitutes the input to the controller. Then, the controller produces a control signal $e_a(t)$ that drives the system in such a way as to satisfy the given performance specifications.

Two controllers were designed for this system: a LQG/LTR robust controller (Araújo *et.al.*, 2001b) and a fuzzy controller (Araújo *et.al.*, 2001a). These controllers have presented good performance but in different regions of operation.

3.1 The LQG/LTR Controller.

Araújo *et.al.* (2001b), proposed a LQG/LTR controller for this system where a Kalman filter gain matrix, $\mathbf{K_f}$, was adjusted to meet the objective of stability robustness and obtain the target filter loop (TFL). Then, a full-state feedback regulator gain matrix, $\mathbf{K_C}$, was determined via cheap control technique in the framework of linear quadratic regulator (LQR) problem (Doyle and Stein, 1979; Doyle and Stein, 1981).

Both the optimal state feedback regulator (LQR) and the Kaman filter exhibit good properties of infinite gain margin, at least ± 60° phase margin and ½gain reduction margin both for SISO (Safonov and Athans, 1977) and MIMO systems (Safonov *et al.*, 1981). It might be expected that LQG compensator would also generally exhibit good robustness and performance characteristics. Unfortunately this may not be always so. A counterexample by Doyle (1978) illustrates the possibility of the lack of guaranteed robustness. Fortunately, by following the procedure LTR (Stein and Athans, 1987) these properties can be recovered. By manipulating the weighting matrices it can be shown (Doyle and Stein, 1981) that the return ratio at the output can be made converge to the Kalman filter return ratio.

The gain matrixes $\mathbf{K_f}$ and $\mathbf{K_C}$ determined by the Araújo *et.al.* (2001b) and used in this work are given by:

$$\mathbf{K}_f = \begin{bmatrix} 107{,}28 \\ -0{,}19 \\ 5.76\times10^{3} \\ -22{,}25 \\ 6{,}45\times10^{4} \\ 1{,}60\times10^{6} \end{bmatrix} \quad \text{and} \quad \mathbf{K}_C = \begin{bmatrix} 9{,}68\times10^{3} \\ -2{,}50\times10^{4} \\ 250{,}26 \\ -711{,}09 \\ 3{,}25 \\ 0{,}27 \end{bmatrix}^T$$

With this LQG/LTR controller the system presented not only stability robustness and fast response but also good reference tracking and disturbance rejection. However, this performance was obtained by using large gains, which, in turn, lead to large control signals. In the other hand, if one modifies the LQG/LTR design to obtain smaller gains, the system performance with the new controller would not be satisfactory. Hence a protection device, such as a saturator, needs to be used together with the LQG/LTR controller, to guarantee the integrity of the servo-actuator.

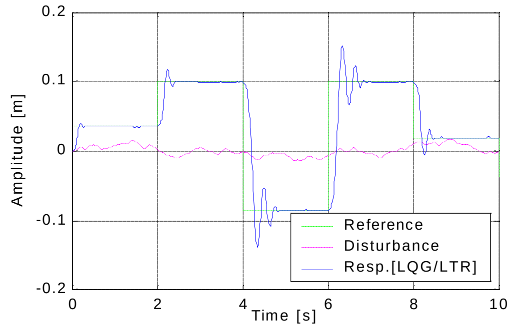


Fig. 3. System response with LQG/LTR controller.

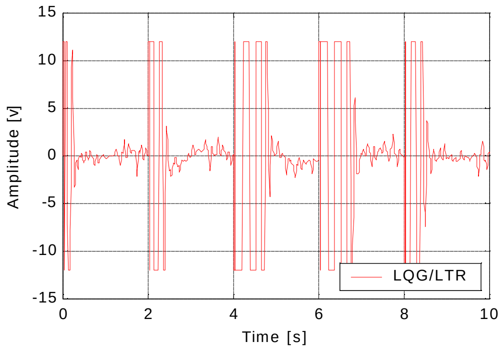


Fig. 4. Saturated control signal with the LQG/LTR robust controller.

A typical operational condition was chosen for the digital simulations. In this condition, a sequence of steps with duration of 2 seconds and random amplitudes between 0.1 and –0.1 meters were used as reference signal and a white noise with limited band signal with amplitude not larger than 0,02 meter in absolute value, has been used as disturbance. The system response with the LQG/LTR controller is shown in fig 3 and the saturated signal control is shown in fig 4.

3.2 The Fuzzy Controller.

Araújo *et.al.* (2001a), designed a fuzzy controller for this same system using a Takagi-Sugeno-Kang (TSK) fuzzy model where the inputs are the tracking error *e(t)* and its derivate *de(t)/dt* and the output is the control signal, respectively. The inputs membership functions and the rules base can be seen in figs. 5 to 7, while the TSK output functions are given in the tab 1.

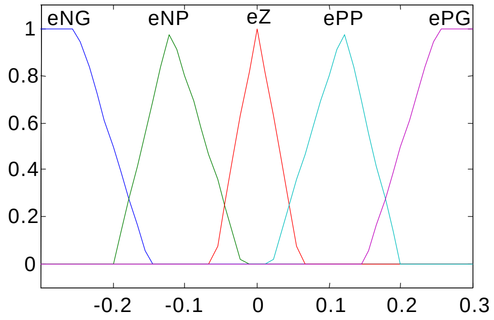


Fig. 5. Membership functions of the input *e(t)* of the fuzzy controller.

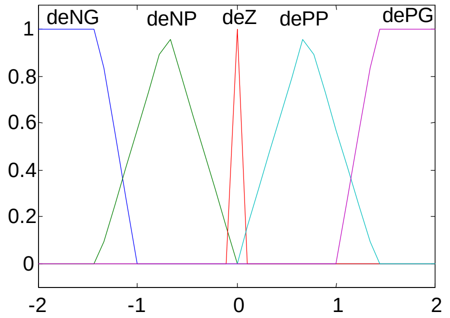
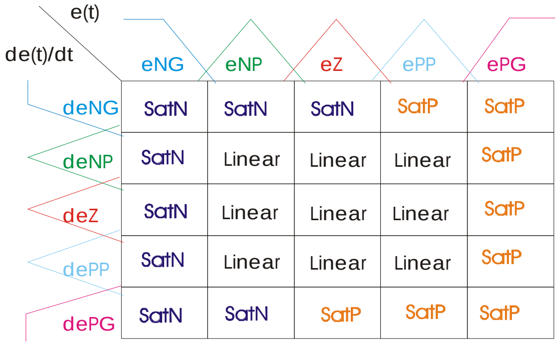


Fig. 6. Membership functions of the input *de(t)/dt* of the fuzzy controller.



de(t)/dt \ e(t)	eNG	eNP	eZ	ePP	ePG
deNG	SatN	SatN	SatN	SatP	SatP
deNP	SatN	Linear	Linear	Linear	SatP
deZ	SatN	Linear	Linear	Linear	SatP
dePP	SatN	Linear	Linear	Linear	SatP
dePG	SatN	SatN	SatP	SatP	SatP

Fig. 7. The rules base to fuzzy inference of the fuzzy controller.

The fuzzy controller was evaluated under the same operational conditions used with the LQG/LTR controller, and the corresponding results can be seen in fig. 8 and 9.

Table 1 TSK output function

Function Name	Function Parameters $[e(t)\ de(t)/dt\ 1]\mathrm{x}[a_1\ a_2\ a_3]^T$
SatP	$[0\ 0\ 12]^T$
SatN	$[0\ 0\ -12]^T$
Linear	$[100\ 10\ 0]^T$

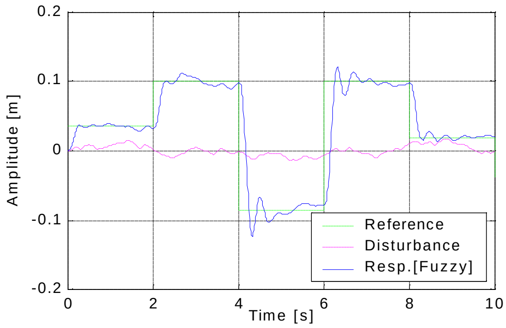


Fig. 8. System response with the fuzzy controller.

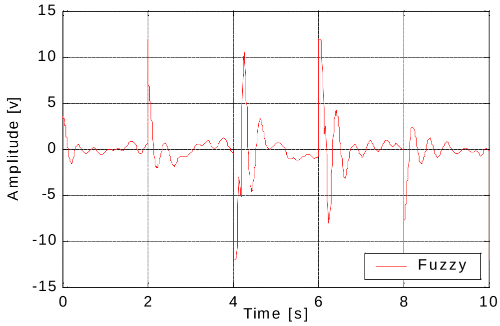


Fig. 9. The control signal with the fuzzy controller.

4. THE HIERARCHICAL FUZZY SCHEME

Comparing the figs. 3 and 4 with the figs. 8 and 9, one can see that the fuzzy controller can reduce tracking error more smoothly and without saturating the servo-actuator. On the other hand, the LQG/LTR controller present good robustness in terms of rejecting disturbances and the system response with the LQG/LTR is faster than with the fuzzy controller.

Now, the fuzzy supervisor is required to combine these two controllers to obtain a control signal that present better performance then when each of them are used separately. A Mamdani model was chosen for the design of the supervisor. Simulations were carried out to build the knowledge base, which provided information for the selection of the memberships function (fig 10, 11 and 12) and also to construct the rules base (fig 13).

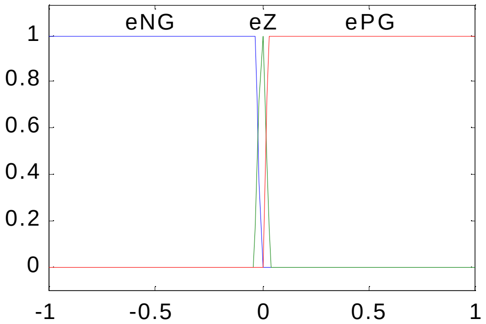


Fig. 10. Membership functions of the input *e(t)* of the fuzzy supervisor.

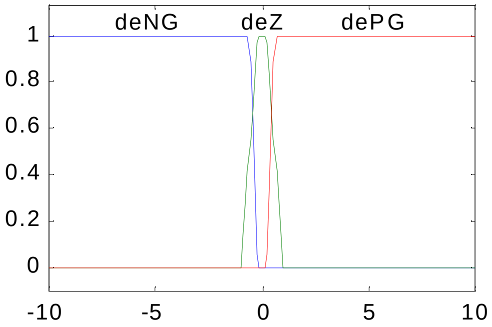


Fig. 11. Membership functions of the input *de(t)/dt* of the fuzzy supervisor.

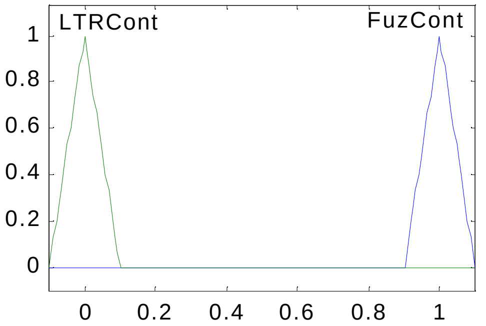


Fig. 12. Membership functions of the output of the fuzzy supervisor.

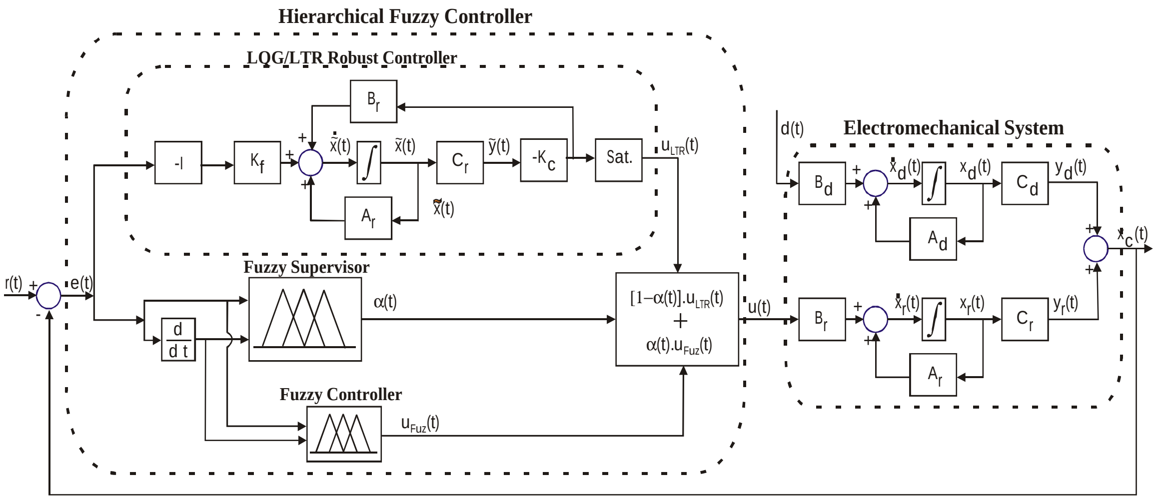
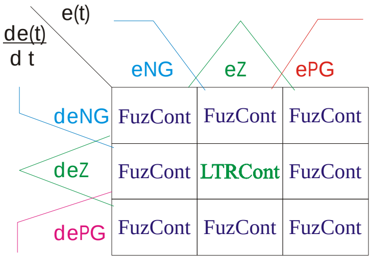


Fig 14. Block diagram of the complete system



$\frac{de(t)}{dt}$ \ e(t)	eNG	eZ	ePG
deNG	FuzCont	FuzCont	FuzCont
deZ	FuzCont	**LTRCont**	FuzCont
dePG	FuzCont	FuzCont	FuzCont

Fig. 13. The rules base to fuzzy inference of the fuzzy supervisor.

The supervisor inputs are the same inputs as those used in the fuzzy controller: the tracking error and its derivate. The output is a value in the closed set [0,1] that represents the weight of the output signal of the fuzzy controller in the control signal of the hierarchical control scheme, which will be injected into the plant. The weight of the output of the LQG/LTR controller is obtained as the complementary value of the first weight, in the same set (fig. 14).

5. RESULTS

The system, controlled by the proposed hierarchical fuzzy controller (HFC), was evaluated by simulations. The fig. 15 show the system response under the same operational conditions that were used before to evaluate the others controllers. The control signal generated by the HFC corresponding to this response can be seen in the fig.16.

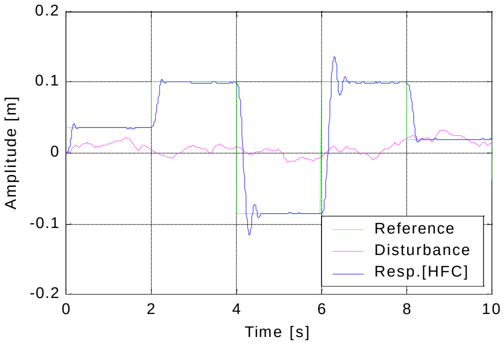


Fig. 15. System response with the HFC controller.

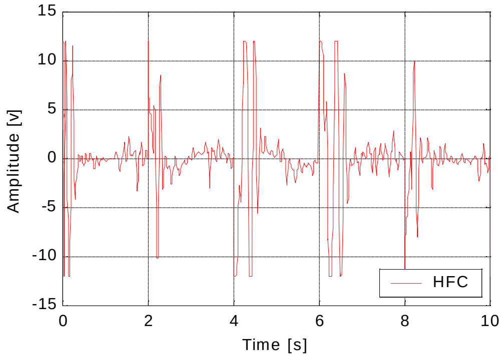


Fig. 16. The control signal with the HFC controller.

In fig. 17 one can see the output of the supervisor ($a(t)$). When $a(t)$ is 1 the control signal generated by the HFC is just the control signal of the fuzzy controller and when it is 0 the control signal of the HFC is equal to the saturated control signal of the LQG/LTR controller.

In order to compare the three controllers a reference a single step with 0.1 meters of amplitude and 2 seconds of duration was used as the reference as the disturbance, a white noise with limited band was used.

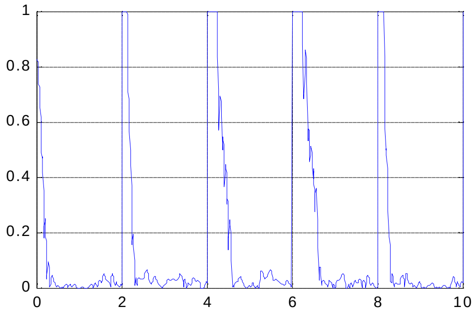


Fig. 17. The output of the fuzzy supervisor.

In the fig. 18 one can see the system response with the three controllers. Comparing the three responses, it is clear that the system response with the HFC can be smoother than the response with the fuzzy controller and it can be also faster than the response with the LQG/LTR controller. Besides, this response compares favorably in terms of robustness with respect to LQG/LTR alone.

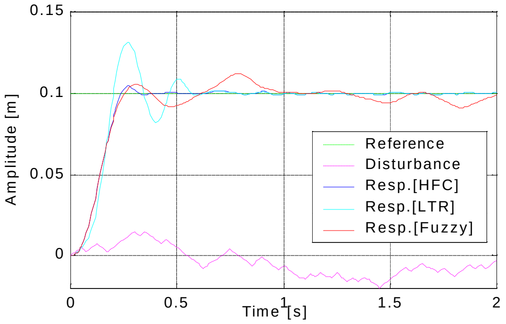


Fig. 18. Comparing the system responses.

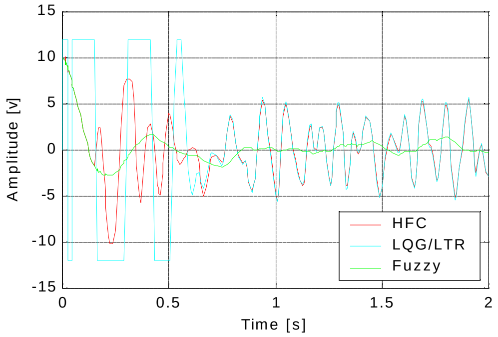


Fig. 19. Comparing the control signals.

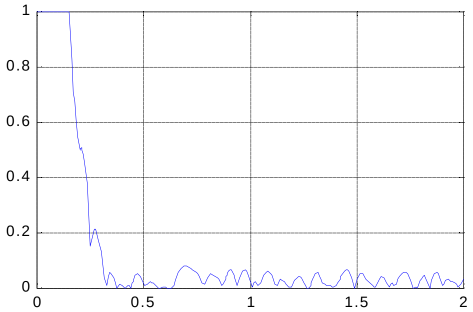


Fig. 20. The output of the fuzzy supervisor.

By analyzing the figs. 19 and 20, it can be noticed that during periods of time where the fuzzy controller present a good performance, the HFC signal control is closely related to it. In others regions, where the LQG/LTR controller presents better performance, the HFC signal control approximates more the signal generated by LQG/LTR. In the remaining interval the supervisor combines the two control signals to improve the overall system performance.

6. CONCLUSIONS

A hierarchical fuzzy control scheme was proposed. In this scheme, a fuzzy system of Mamdani type was used as supervisor to combine two control signals originating a new control signal that is used to drive an electro-mechanical system for purposes of vibration isolation. The two auxiliary control signals are generated by a LQG/LTR robust controller and a fuzzy controller and each one of these present some of the desired features. The supervisor is then required to combine hierarchically the control signal of each controller in such a way as to improve the system by taking advantage of the good characteristics of each one of these controllers.

The hierarchical controller presented satisfactory performance when compared with the two controllers used separately. The simulation results were evaluated in three different situations; 1. When the control signal is equal to the signal generated by the LQG/LTR controller ($a(t)$ » 1), 2. When the control signal is equal to the signal generated by the fuzzy controller ($a(t)$ » 0) and, 3. When the control signal is a combination of these two signais ($0 < a(t) < 1$). In situations 1 and 2 the behavior of the system were already known (Araújo *et.al.*, 2001a; Araújo *et.al.*, 2001b). The situation 3 turned up to be more remarkable. In this case the control signal is the linear combination of two signals generated by non linear systems, a LQG/LTR with saturation and a fuzzy system with two inputs and one output, and the formal mathematic analysis may be very intricate, although the simulation showed that in this situation the system response present good behavior. It was always satisfactorily in terms of being smooth and fast. In the next steps of this research, it is expected to incorporate adaptive law in the supervisor, using neurofuzzy techniques.

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