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# Modeling and Fuzzy Logic Control of an Active Reaction Compensating Platform System

*This article presents the application of the fuzzy logic (FL) concept to the active control of a multiple degree of freedom reaction compensating platform system that is designed and used for isolating vibratory disturbances of space-based devices. The physical model used is a scaled down two-plate platform system. In this work, simulation is performed and presented. According to the desired performance specifications, a full range of investigation regarding the development of an FL stabilization controller for the system is conducted. Specifically, the study includes four stages: comprehensive dynamic modeling of the reaction compensating system; analysis of the dynamic responses of the platform system when it is subjected to various disturbances; design of an FL controller capable of filtering the vibratory disturbances transmitted to the bottom plate of the platform system; performance evaluation of the developed FL controller through computer simulations. To simplify the simulation work, the system model is linearized and the system component parameter variations are not considered. The performance of the FL controller is tested by exciting the system with an impulsive force applied at an arbitrarily chosen point on the top plate. It is shown that the proposed FL controller is robust in that the resultant active system is well stabilized when subjected to a random external disturbance. The comparative study of the performances of the FL controlled active reaction and passive reaction compensating systems also reveals that the FL controlled system achieves significant improvements in reducing vibratory accelerations over passive systems.* *© 1995 John Wiley & Sons, Inc.*

## INTRODUCTION

The main objective of this article is to advance the effectiveness of vibration isolation systems. It is achieved by developing a new state-of-the-art control scheme, the fuzzy logic (FL) control system, for improving the performance of active vibration isolation systems.

In the past few decades, passive reaction compensating systems have played the dominant role for vibration isolation. These passive systems deal with the vibration originated from external disturbances then transmitted to the underlying structures. This vibration due to external disturbances may result in different degrees of interferences on the activities occurring on the underlying structures. Some typical real-world examples include: the isolation of vibratory disturbances due to robot maneuvers, astronaut mobility, or operating equipments against the main structure

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of a spacecraft; the isolation of ground vibration against sensitive electronic equipment; the isolation of machinery vibration against a ship structure; and the isolation of a car suspension's motion against rough terrain on a roadway, etc.

The simplest passive vibration isolation systems are formed by interposing a resilient material between a vibration object and its underlying foundation. Passive systems perform effectively in reducing vibration caused by the vibration object when the operating frequency of the object is high. However, their performance is serious degraded in the low frequency range, reported by Owen and Jones (1986). That is, at low operating frequency the passive systems will behave as a vibration amplifier instead of a vibration reducer.

In view of this shortcoming of the passive vibration isolation systems, active vibration isolation systems appear to be the only way to overcome the vibration isolation problem in the low frequency range. Although the benefits of using active vibration compensating systems are obvious, they require a high performance control system capable of handling all undesirable dynamic disturbances in an extremely short period of time. In particular, a robust control system that provides a wide range of dynamic disturbance compensating capability is the key to a vibration free dynamic environment. Toward this end some recent advancements in active vibration control schemes have been attempted. These recent schemes include a state space plus model velocity feedback control scheme proposed by Ross (1991); an active damping angular rate feedback control method developed by Owen and Jones (1986); and MIMO/SISO adaptive control algorithms contended by Sommerfeldt (1991), White and Cooper (1984), and Sommerfeldt and Tichy (1991), to list just a few.

Although the aforementioned active vibration control strategies have been able to reduce the level of vibration transmitted to the underlying structure to a certain extent, their limitations and performances are still far from being satisfactory.

Because most of the dynamic disturbances to be compensated are random and disorganized, the use of conventional control schemes, such as PID, adaptive, model reference control, and their combinations as mentioned above, will yield the following two major problems: it is difficult to identify and model the inputs for the control system, due mainly to the irregular nature of the dynamic disturbances; and even if the dynamic disturbances are identified and modeled properly, the computational burden of the developed control system for processing the rapid variations of random input conditions will be extremely heavy. Hence, it poses difficulty in realizing the control system in real time with currently available microelectronic devices. In view of these two problems, there is a need to develop a new control system with good intelligence and robustness such that it can cope with rapid varying vibratory disturbances in a real time manner.

To accomplish this, an FL algorithm that mimicks human thinking is proposed to develop control laws of the desired intelligent control system. Due to the fuzzy nature of the proposed control system, potential dynamic disturbances are identified and classified into groups. For each group of identified disturbances a unique control action will be taken to compensate for the undesirable disturbances. The control actions may be adjusted from time to time based on a set of adaptive fuzzy rules designed specifically for the platform system under study.

In addition, a comparative study of the dynamic responses of the platform system with and without active FL control is presented. It is evident that this FL control scheme not only simplifies the identified and algorithmic process of controller design, but also eases the complex calculations for control against the conventional control schemes. Furthermore, the simulation results show that the FL control scheme is robust in that it can cope with a wide range of disturbances and provides a satisfactory near-vibration free environment.

## DYNAMIC FORMULATIONS

To facilitate the control design process, the dynamic model of the multiple degree of freedom reaction compensating system is formulated. The dynamic formulation is derived in terms of spring force, primary plate motion secondary plate motion, and the simulated external disturbances such as impulses and step input. To make the dynamic model more comprehensive, the actuator dynamics are also considered.

The configuration of the two-plate system is shown in Fig. 1. The shapes of the top and bottom plates are circular with the bottom plate larger than the top plate. Three accelerometers are attached to the bottom plate. Each of them is located equally spaced from one another. For the ease of identification, symbols $C_1$, $C_2$, and $C_3$

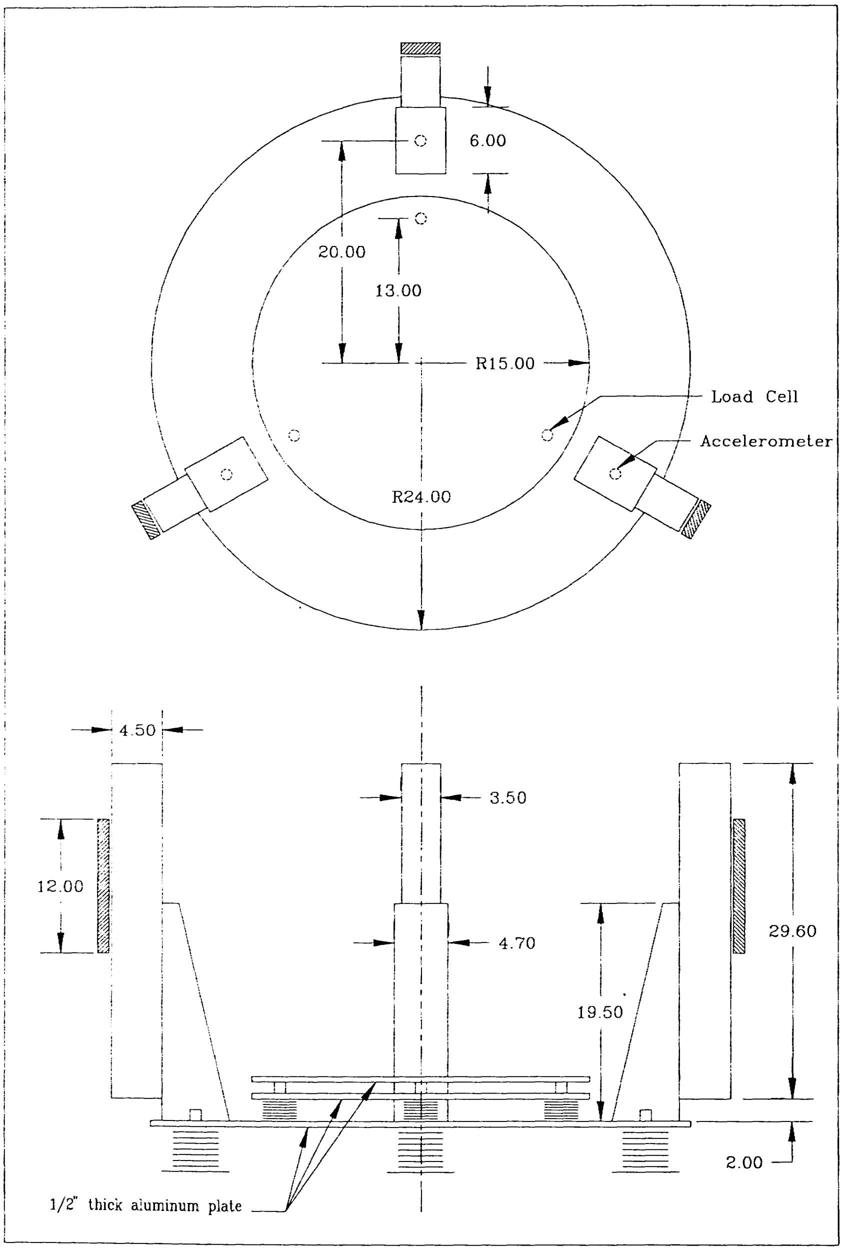


**FIGURE 1** Configuration of the platform system.

have been assigned to their locations, respectively (see Fig. 1). In collocation with each accelerometer is an actuator. The accelerometers are used to provide feedback signals to controllers that in turn use these signals to generate control actions for the actuators to reduce vibration of the plate. The bottom plate is coupled with its underlying structure by springs. Each of the springs is arranged in such a way that it is collocated with the location of the accelerometer. The top plate is coupled with the bottom plate through similar mechanical devices except for the absence of the accelerometer and actuator. The main reason that the two-plate platform system is preferred is that at high operating speed the two-plate platform system gives much improved vibration isolation. This is justified by a comparative study of the passive dynamic responses of the two different systems performed in the early stage of the project. Due to the space limitation, the detailed analysis for the justification is omitted.

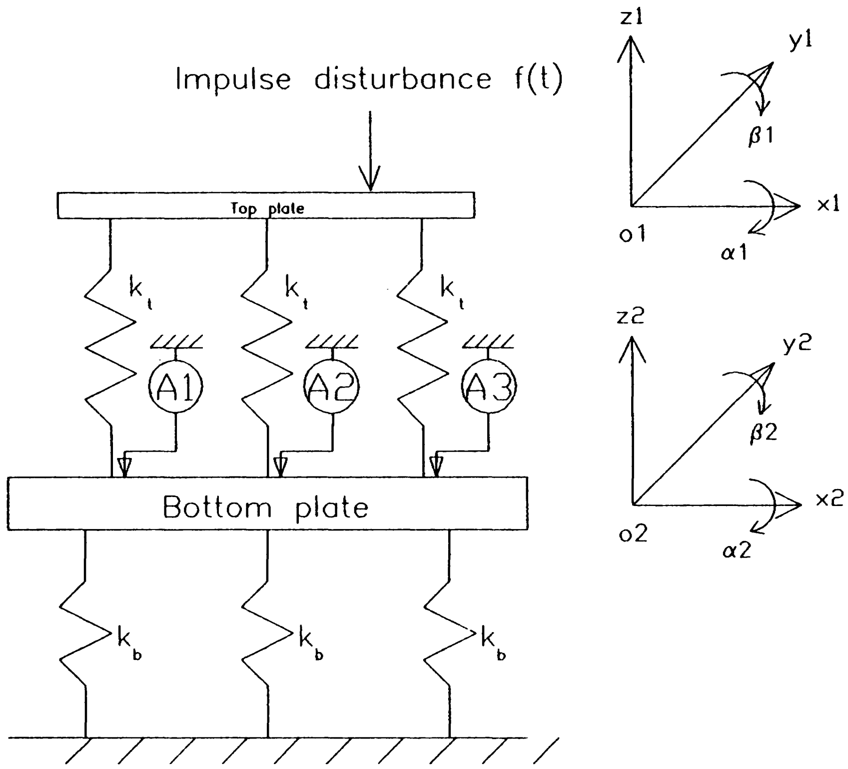


**FIGURE 2** Schematics of the platform system.

## Newton–Euler Formulation of Platform System

Figure 2 shows a schematic drawing of the two-plate reaction compensating platform system.

Following the conventional definition of coordinate systems, two relative coordinate systems, namely, $x_1y_1z_1$ and $x_2y_2z_2$ are defined for the top and bottom plates, respectively. These two relative coordinate frames are used to describe the kinematics of the plates. The assumptions made in the dynamic formulation are:

1. both plates are rigid;
2. both plates are not only subjected to yaws $\alpha$ and pitches $\beta$, but also vertical displacements $d$ of the centers of the plates;
3. the springs supporting static loads are linear.

Referring to Fig. 2, the variables corresponding to the 6 degree of freedom platform motion for the top and bottom plates are to be used. To simplify the dynamic model, the Newton–Euler equations of motion are linearized. Additionally, it is assumed that the rotational motion of the top and bottom plates are limited to a small angle during the motion process.

In a linearized model, the Newton–Euler equations of motion of the platform system are given by

$$M_t\ddot{z}_1 = -3k_tz_1 + 3k_tz_2 - k_t(y_{t1} + y_{t2} + y_{t3})\alpha_1 + k_t(x_{t1} + x_{t2} + x_{t3})\beta_1 + k_t(y_{b1} + y_{b2} + y_{b3})\alpha_2 - k_t(x_{b1} + x_{b2} + x_{b3})\beta_2 - f(t) \tag{1}$$

$$(M_b + 3M_c)\ddot{z}_2 = 3k_tz_1 - 3(k_t + k_b)z_2 + k_t(y_{t1} + y_{t2} + y_{t3})\alpha_1 - k_t(x_{t1} + x_{t2} + x_{t3})\beta_1 - [k_t(y_{b1} + y_{b2} + y_{b3}) + k_b(y_{c1} + y_{c2} + y_{c3})]\alpha_2 + k_t(x_{b1} + x_{b2} + x_{b3}) + k_b(x_{c1} + x_{c2} + x_{c3})]\beta_2 + u_1(t) + u_2(t) + u_3(t) \tag{2}$$

$$
\begin{aligned}
I_{x1}\ddot{\alpha}_1 = {} & y_{t1}k_t(y_{t3} - y_{t1})\alpha_1 - y_{t1}k_t(x_{t3} - x_{t1})\beta_1 \\
& - y_{t1}k_t(y_{b3} - y_{t1})\alpha_2 + y_{t1}k_t(x_{b3} - x_{b1})\beta_2 - y_f f(t)
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
I_{y1}\ddot{\beta}_1 = {} & k_t(2x_{t1} - |x_{t2}|)z_1 - k_t(2x_{t1} - |x_{t2}|)z_2 + k_t[x_{t1}(y_{t1} + y_{t3}) - |x_{t2}|y_{t2}]\alpha_1 \\
& -k_t[x_{t1}(x_{t1} + x_{t3}) - |x_{t2}|x_{t2}]\beta_1 - k_t[x_{t1}(y_{b1} + y_{b3}) - |x_{t2}|y_{b2}]\alpha_2 \\
& +K_t[x_{t1}(x_{b1} + x_{b3}) - |x_{t2}|x_{b2}]\beta_2 + x_f f(t)
\end{aligned}
\tag{4}
$$

$$
\begin{aligned}
I_{x2}\ddot{\alpha}_2 = {} & y_{t1}k_t(y_{t1} - y_{t3})\alpha_1 - y_{t1}k_t(x_{t1} - x_{t3})\beta_1 - [y_{t1}k_t(y_{b1} - y_{b3}) + y_{c1}k_b(y_{c1} - y_{c3})]\alpha_2 \\
& +[y_{t1}k_b(x_{b1} - x_{b3}) + y_{c1}k_b(x_{c1} - x_{c3})]\beta_2 + y_{c1}u_1(t) - y_{c1}u_3(t)
\end{aligned}
\tag{5}
$$

$$
\begin{aligned}
I_{y2}\ddot{\beta}_2 = {} & -k_t(2x_{t1} - |x_{t2}|)z_1 + [(2x_{t1} - |x_{t2}|)k_t + (2x_{c1} - |x_{c2}|k_2]z_2 \\
& -k_t[x_{t1}(y_{t1} + y_{t3}) - |x_{t2}y_{t2}]\alpha_1 + k_t[x_{t1}(x_{t1} + x_{t3}) - |x_{t2}|x_{t2}]\beta_1 \\
& +\{[x_{t1}(y_{b1} + y_{b3}) - [x_{t2}|y_{b2}]k_1 + [x_{c1}(y_{c1} + y_{c3}) + |x_{c2}|y_{c2}]k_b\}\alpha_2 \\
& -\{[x_{t1}(x_{b1} + x_{b3}) - [x_{t2}|x_{b2}]k_t + [x_{c1}(x_{c1} + x_{c3}) - |x_{c2}|x_{c2}]k_b\}\beta_2 \\
& -x_{c1}u_1(t) + x_{c2}u_2(t) - x_{c1}u_3(t)
\end{aligned}
\tag{6}
$$

where $f(t)$ is the excitation load (to simulate a person jumping) applied to the top plate. In this study, it is simulated to be an impulsive force of 100 lb for 0.5 s. Figure 3 shows the location on the top plate at which the impulsive force is applied.

The 2-D coordinates are (6.0, 12.0) with reference to the origin fixed at the center of the plate. $u_i(t)(i = 1, 2, 3)$ denote the force outputs of actuator 1, 2, and 3, respectively. In addition, it is assumed that the actuators used are high bandwidth. Therefore, the actuator dynamics are neglected in the derived dynamic formulation. In their state-space representation, Eq. (1) through (6) can be written as

$$
\dot{X}(t) = AX(t) + BU(t) + Cf(t)
\tag{7}
$$

where

$$
X = \begin{bmatrix} z_1 \\ \dot{z}_1 \\ z_2 \\ \dot{z}_2 \\ \alpha_1 \\ \dot{\alpha}_1 \\ \beta_1 \\ \dot{\beta}_1 \\ \alpha_2 \\ \dot{\alpha}_2 \\ \beta_1 \\ \dot{\beta}_2 \end{bmatrix}
\quad
A = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
a_{21} & 0 & a_{23} & 0 & a_{25} & 0 & a_{27} & 0 & a_{29} & 0 & a_{2b} & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
a_{41} & 0 & a_{43} & 0 & a_{45} & 0 & a_{47} & 0 & a_{49} & 0 & a_{4b} & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
a_{61} & 0 & a_{63} & 0 & a_{65} & 0 & a_{67} & 0 & a_{69} & 0 & a_{6b} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
a_{81} & 0 & a_{83} & 0 & a_{85} & 0 & a_{87} & 0 & a_{89} & 0 & a_{8b} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
a_{a1} & 0 & a_{a3} & 0 & a_{a5} & 0 & a_{a7} & 0 & a_{a9} & 0 & a_{ab} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
a_{c1} & 0 & a_{c3} & 0 & a_{c5} & 0 & a_{c7} & 0 & a_{c9} & 0 & a_{cb} & 0
\end{bmatrix}
\tag{8}
$$

$$
B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ b_{41} & b_{42} & b_{43} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ b_{a1} & 0 & b_{a2} \\ 0 & 0 & 0 \\ b_{c1} & b_{c2} & b_{c3} \end{bmatrix} \quad C = \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \\ 0 \\ -y_f \\ 0 \\ x_f \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{9}
$$

with

$a_{21} = -a_{23} = -3k_t/M_t$, $a_{25} = -k_t(y_{t1} + y_{t2} + y_{t3})/M_t$, $a_{27} = k_t(x_{t1} + x_{t2} + x_{t3})/M_t$,

$a_{29} = k_t(y_{b1} + y_{b2} + y_{b3})/M - t$, $a_{2a} = -k_t(x_{b1} + x_{b2} + x_{b3})/M - t$, $a_{41} = 3k_t/(M_b + 3M_c)$,

$a_{43} = -3(k_t + k_b)/(M_b + 3M_c)$, $a_{45} = k_t(y_{t1} + y_{t2} + y_{t3})/(M_b + 3M_c)$, $a_{47} = k_b(x_{t1} + x_{t2} + x_{t3})/(M_b + 3M_c)$,

$a_{49} = -[k_t(y_{b1} + y_{b2} + y_{b3}) + k_b(y_{c1} + y_{c2} + y_{c3})]/(M_b + 3M_c)$,

$a_{4b} = [k_t(x_{b1} + x_{b2} + x_{b3}) + k_b(x_{c1} + x_{c2} + x_{c3})]/(M_b + 3M_c)$, $a_{65} = -a_{67} = y_{t1}k_t(y_{t3} - y_{t1})/I_{x1}$,

$a_{69} = -a_{6b} = -y_{t1}k_t(y_{b3} - y_{b1})/I_{x1}$, $a_{81} = -a_{83} = (2x_{t1} - |x_{t2}|)k_t/I_{y1}$,

$a_{85} = [x_{t1}(y_{t1} + y_{t3}) - |x_{t2}|y_{t2}]k_t/I_{y1}$, $a_{87} = -[x_{t1}(x_{t1} + x_{t3}) - |x_{t2}|x_{t2}]k_t/I_{y1}$,

$a_{89} = -[x_{t1}(y_{b1} + y_{b3}) - |x_{t2}|y_{b2}]k_t/I_{y1}$, $a_{8b} = [x_{t1}(x_{b1} + x_{b3}) - |x_{t2}x_{b2}]k_t/I_{y1}$, $a_{a5} = y_{t1}k_t(y_{t1} - y_{t3})/I_{x2}$,

$a_{a7} = -y_{t1}k_t(x_{t1} - x_{t3})/I_{x2}$, $a_{a9} = -[y_{t1}k_t(y_{b1} - y_{b3}) + y_{c1}k_b(y_{c1} - y_{c3})]/I_{x2}$,

$a_{ab} = -[y_{t1}k_t(x_{b1} - x_{b3}) + y_{c1}k_b(x_{c1} - x_{c3})]/I_{x2}$, $a_{c1} = -(2x_{t1} - |x_{t2}|)k_t/I_{y2}$,

$a_{c3} = [(2x_{t1} - |x_{t2}|)k_t + 2x_{c1}k_b]/I_{y2}$, $a_{c5} = -[x_{t1}(y_{t1} + y_{t3}) - |x_{t2}|y_{t2}]k_t/I_{y2}$,

$a_{c7} = [k_{t1}(x_{t1} + x_{t3}) - |x_{t2}|x_{t2}]k_t/I_{y2}$, $a_{c9} = \{[x_{t1}(y_{b1} + y_{b3}) - |x_{t2}|y_{b2}]k_t + [x_{c1}(y_{c1} + y_{c3}) - |x_{c2}|y_{c2}]k_b\}/I_{y2}$,

$a_{cb} = \{[x_{t1}(x_{b1} + x_{b3}) - |x_{t2}|x_{b2}]k_t + [x_{c1}(x_{c1} + x_{c3}) - |x_{c2}|x_{c2}]k_b\}/I_{y2}$,

$b_{41} = b_{42} = b_{43} = 1/(M_b + 3M_c)$, $b_{a1} = -b_{a2} = y_{c1}/I_{x2}$, $b_{c1} = -b_{c3} = -x_{c1}/I_{y2}$, $b_{c2} = x_{c2}/I_{y2}$,

and $M_t$ = 71 lb = the mass of the top plate; $M_b$ = 90 lb = the mass of the bottom plate; $M_c$ = 70 lb = the mass of the actuator and corresponding components. Figure 4 shows some dimensions used in the parameters listed above.

## PASSIVE DYNAMIC RESPONSES OF PLATFORM SYSTEM

To look into the passive dynamic response of the simulated platform system, we analyze the variations of two principal dynamic variables; bottom plate acceleration, which results in adverse force propagating to the underlying structure; and bottom plate displacement, which indicates the actual movement of the base plate in absolute terms. Passive responses in terms of these two dynamic variables occurred at four different locations of interest on the top and bottom plates, namely the center and the three actuator locations, are studied and presented (Fig. 5).

In the dynamic simulation of the passive sys-

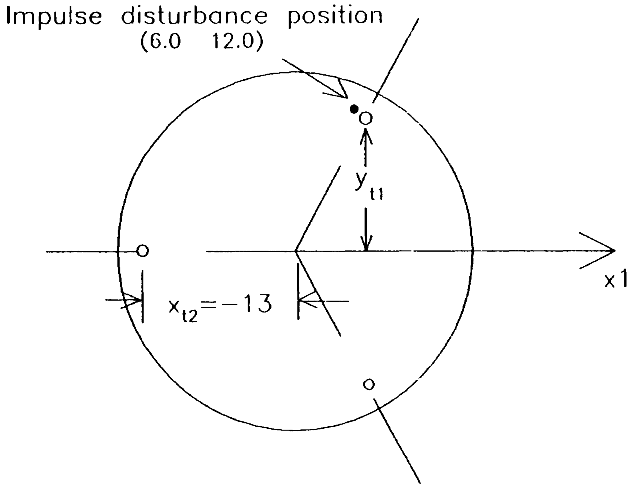


**FIGURE 3** Application point of an impulsive force.

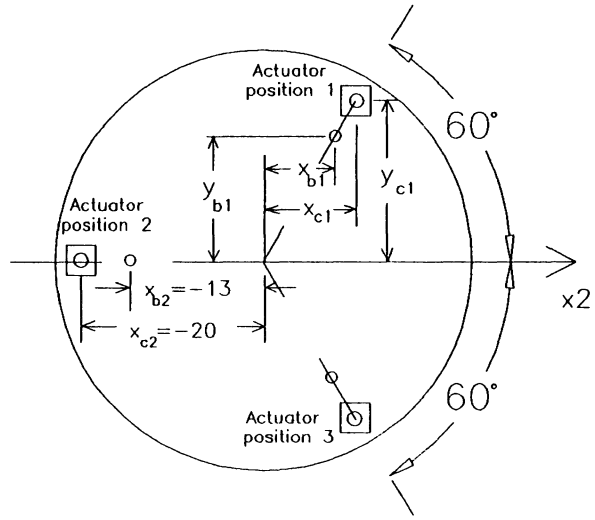


**FIGURE 4** Illustration of essential dimensions.

tem, the motion starts with an excitation of an impulsive force of 100 lb applied onto the top plate at (6.0, 12.0) for 0.5 s. The simulation results will be used later for comparison with controlled (active) simulation results.

To pursue the goal of generating a robust active reaction compensating platform system, an ideal dynamic model with zero bottom plate acceleration is created as a reference model. The compensator is then designed in such a way that the controlled system will be regulated toward the ideal model.

## FL CONTROLLER DESIGN

As mentioned in the previous section, the ideal active reaction compensating platform system behaves with zero accelerations on the bottom plate. Hence, the design of an FL controller focuses on finding controlled system characteristics approaching that of the ideal vibration isolation model.

In the existing platform system, the external disturbances will be generated by a person jumping or jogging on the tread pad sitting on the top

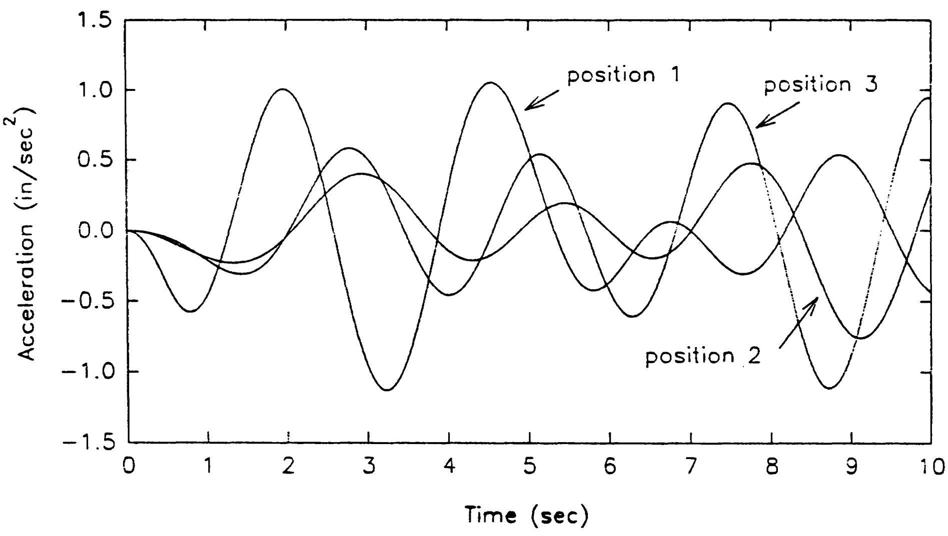


**FIGURE 5** Passive acceleration responses at actuator locations.

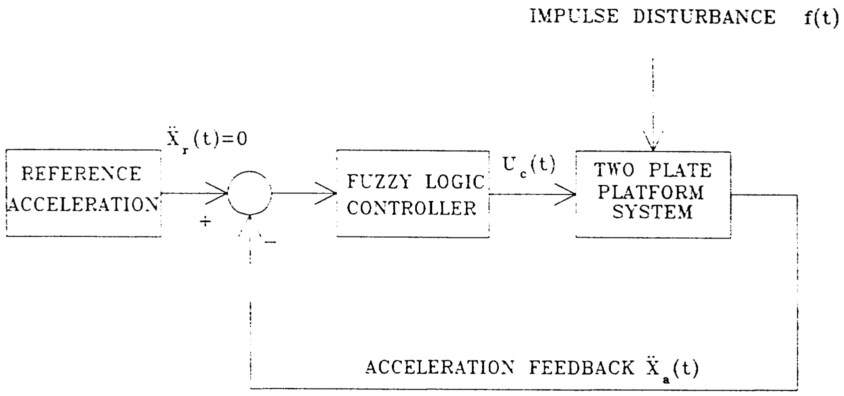


**FIGURE 6** Block diagram of the entire control system.

of the mounting plate. Hence, the disturbed actions can be multidimensional. However, the major disturbances transmitted to the supporting components are along the vertical axis ($z$ axis), which is one dimensional. Therefore, as long as we can control the three supporting components independently and simultaneously using a parallel control scheme, there is no need to control the moment disturbances along the other two axes ($x$ and $y$ axis). Because of this reason, separate control systems acting at the three actuation points by using the FL control scheme were designed.

## Desired Performance of FL Controller

As mentioned previously, the major control goal is to compensate for or completely eliminate the accelerations of the bottom plate of the platform system when subjected to external disturbances such as an excitation occurring on the top plate. Based on this control goal, a model reference FL controller was designed and the entire controlled system is illustrated by a block diagram in Fig. 6.

Referring to the figure, the measured accelerations of the bottom plate at the three actuator positions are used as the control feedback signals. After they are compared with the desired zero acceleration, the resultant error signals are then used to fire the fuzzy engine residing in the FL controller. The desired performance of the FL controller will be achieved when the detected accelerations reach the prespecified tolerances. The three actuators are controlled by three different FL controllers whose FL rule bases are set up independently, according to the passive dynamic responses at their respective locations.

## Architecture of FL Controller

The basic architecture of the designed FL controller is depicted in Fig. 7. Basically, it consists of four principal components: scaling, fuzzification, the decision making process, and defuzzification. The scaling factors map the controller inputs $e(t)$, $\Delta e(t)$ and controller output $\Delta u(t)$ to and from the normalized intervals in which the fuzzification and defuzzification processes take place. The controller inputs $e(t)$ and $\Delta e(t)$ are chosen to be the bottom plate acceleration error and its variation, respectively. The controller output $\Delta u(t)$,

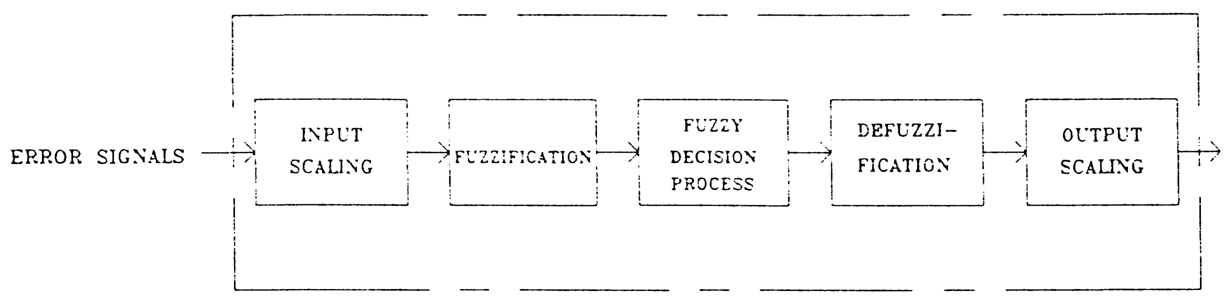


**FIGURE 7** Basic architecture of a fuzzy logic controller.

**Table 1. Designed Fuzzy Logic Rule Base**

| $\Delta e$ \ $e$ | NL | NM | NS | ZE | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | -3 | -3 | -2 | -1 | 0 | 1 | 2 |
| NM | -3 | -2 | -2 | -1 | 1 | 1 | 2 |
| NS | -3 | -2 | -2 | 0 | 1 | 2 | 3 |
| ZE | -3 | -2 | -1 | 0 | 1 | 2 | 3 |
| PS | -3 | -2 | -1 | 0 | 2 | 2 | 3 |
| PM | -2 | -1 | -1 | 1 | 2 | 2 | 3 |
| PL | -2 | -1 | 0 | 1 | 2 | 3 | 3 |

| | |
|---|---|
| -3 | NL |
| -2 | NM |
| -1 | NS |
| 0 | ZE |
| 1 | PS |
| 2 | PM |
| 3 | PL |

however, represents the resultant actuation force.

Fuzzification or quantization makes the measured controller inputs dimensionally compatible with the conditions of the knowledge-based rules, organized as a look-up table in Table I.

The knowledge base in turn, consists of two major components, a data base and an FL rule base. In the construction of the data base in this study, three sets of universe of discourses are defined with regard to the three actuators. Each set consists of three universe of discourses, for the inputs $e(t)$ and $\Delta e(t)$ as well as the output $\Delta u(t)$.

The universe of discourses for the two inputs are determined by using the passive dynamic acceleration responses of the bottom plate shown in Fig. 5. More specifically, the maximum/minimum amplitudes and slopes are utilized. However, the universe of discourses of the output $\Delta u(t)$ are determined based on the actuator's capability. These defined universe of discourses of the control variables are listed in Table II. In addition, they are further discretized into seven quantization levels. Then, a fuzzy set is defined by assigning grade membership values to each discretized segment. Figure 8 shows triangular shaped grade membership values that are used in this study.

As can be seen in the figure, seven linguistic variables are used corresponding to the peaks of the seven triangular membership functions. And the overlaps of two adjacent membership func-

**Table 2. Essential Parameters/Schemes Used in FLC Design**

| | |
|---|---|
| Rules | 49 |
| Membership Function | Tri-angle shapes |
| Linguistic Variables | Error e, change of error $\Delta$e, and incremental control output $\Delta$u |
| Universe of Discourse | Actuator 1:<br>e:(-1.0 1.0) m/sec$^2$<br>$\Delta$e:(-0.015 0.015) m/sec$^2$<br>$\Delta$u:(-20 20) lb<br>Actuator 2:<br>e:(-0.5 0.5) m/sec$^2$<br>$\Delta$e:(-0.005 0.005) m/sec$^2$<br>$\Delta$u:(-10 10) lb<br>Actuator 3:<br>e:(-0.8 0.8) m/sec$^2$<br>$\Delta$e:(-0.012 0.012) m/sec$^2$<br>$\Delta$u:(-15 15) lb |
| Relation for Each Rule (t-norm) | product |
| Linguistic Terms | NL negative large<br>NM negative medium<br>NS negative small<br>ZE zero<br>PS positive small<br>PM positive medium<br>PL positive large |
| Defuzzification | center-of-area defuzzification |
| Controller Output | u(t)=u(t-1)+$\Delta$u(t) |

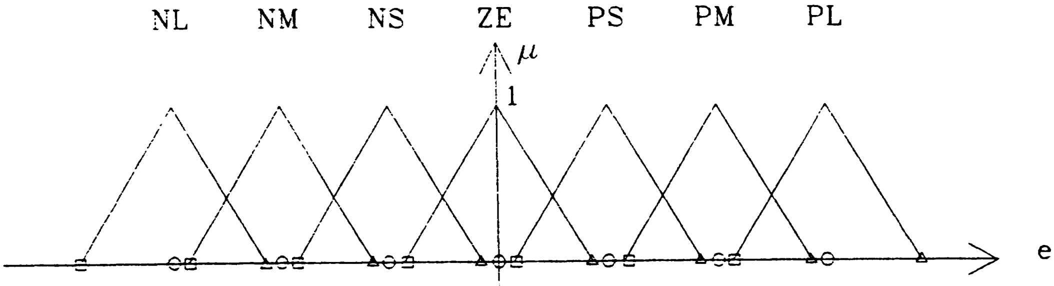


**FIGURE 8** Triangular shape membership function.

tions are uniformly determined to be 45°. This is then followed by the fuzzy decision making process performed by an inference engine that matches the conditions of all the rules and determines the partial degree of matching of each rule. Finally, it aggregates the weighted output of the rules, generating a possibility distribution of the values on the output universe of discourse.

The resultant fuzzy output sets are listed in Table I that defines the output of the controller for all possible combinations of the input signals. It is noted that each fuzzy variable is assigned a pertinent numerical integer definition in the range of (−3, 3). This will facilitate the off-line processing that will in turn shorten the required computation time of the control process.

In the derivation of fuzzy control rules, a heuristic method is used to analyze the dynamic behavior of the platform system. Basically, the control rules are derived in such a way that the deviation from a desired zero acceleration of the bottom plate will be corrected and the control goal can be achieved. Because the acceleration error and its variation are used as fuzzy inputs, the mirror image of the bottom plate acceleration responses (w.r.t. the horizontal axis) are to be analyzed.

By moving along the mirror-imaged curves of the acceleration responses, the magnitude and its corresponding slope of the bottom plate acceleration at each sampling time are discretized. This procedure is followed by the fuzzy decision process according to IF-THEN logic rules. Thus, the fuzzy outputs are obtained, as shown in Table I. Last, the defuzzification process summarizes this possibility distribution into a force point to be used by the actuators.

Some essential parameters and schemes used in the designed FL controller are listed in Table II.

## PERFORMANCE EVALUATION OF FL CONTROLLER

A PC-based computer motion simulation is performed to evaluate the performance of the vibration isolation platform system with the developed control process. To simulate the motion of the base plate, the dynamic equations of motion derived previously are calculated and solved by Newton's method.

A comparative study of the dynamic responses of the passive and active FL controlled platform system is carried out. Figures 9–11 show the time domain acceleration responses of the passive and the controlled system.

Referring to these figures, it is clear that the FL controller reduces the accelerations at each actuator position of the bottom plate by about 90% over the passive system. In addition, the comparative study is also extended to include the dynamic behavior of the center of the bottom plate, as shown in Figure 12.

The simulation results reveal that the acceleration of the center of the bottom plate, which is a critical measure of the performance of the entire platform system, is only slightly off against the desired zero acceleration line through the entire simulation history due to the compensation of the FL controller. This verifies that the developed FL controller is effective for the reduction of undesirable vibratory accelerations.

Moreover, comparisons of the displacement responses of the platform bottom plate between the passive and active controlled systems are made and the resultant simulations are shown in Figures 13–16.

In view of these four figures, the displacement responses of the platform bottom plate at the four critical positions all behave stably. It becomes clear that with the FL active control, all four

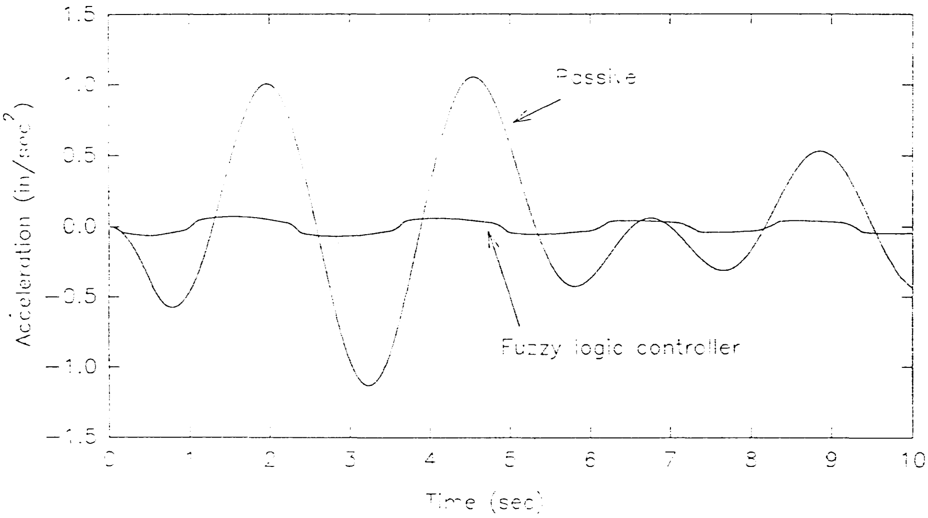


**FIGURE 9** Comparison of acceleration response at actuator 1.

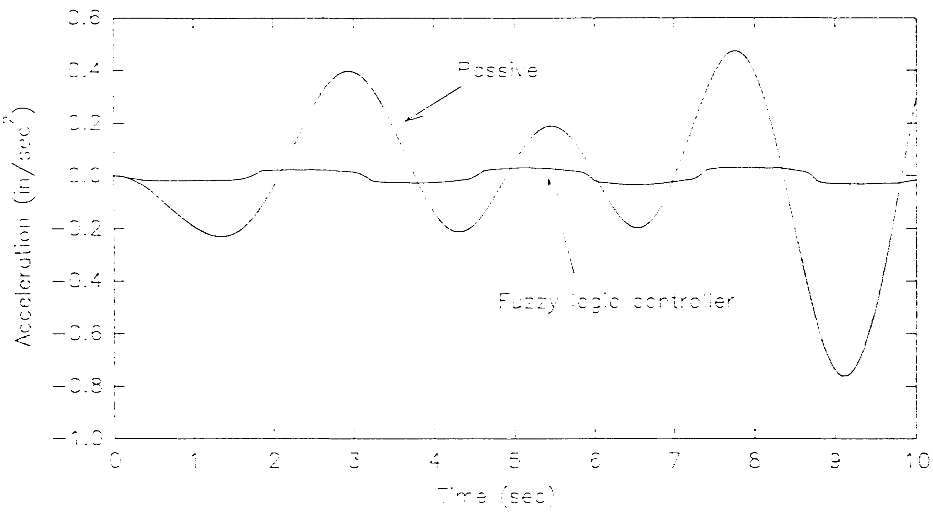


**FIGURE 10** Comparison of acceleration response at actuator 2.

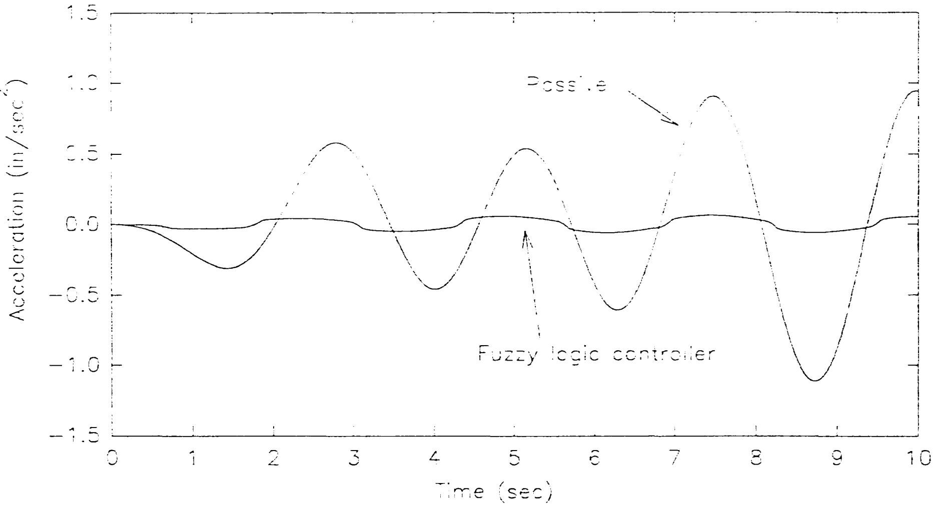


**FIGURE 11** Comparison of acceleration response at actuator 3.

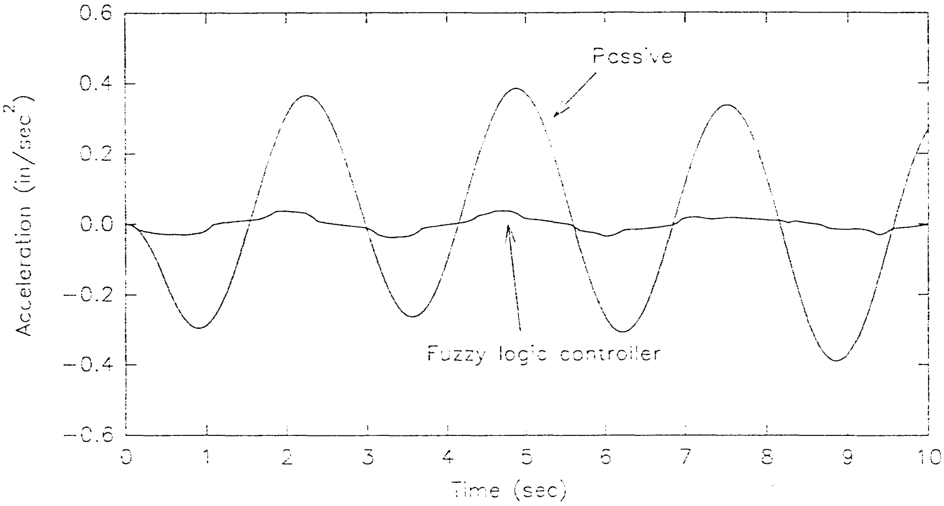


**FIGURE 12** Comparison of acceleration response at the center.

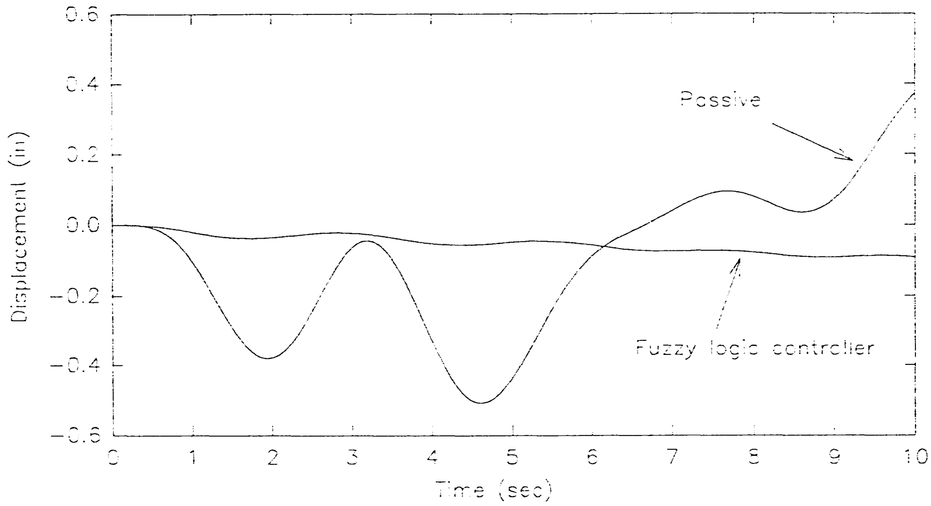


**FIGURE 13** Comparison of displacement response at actuator 1.

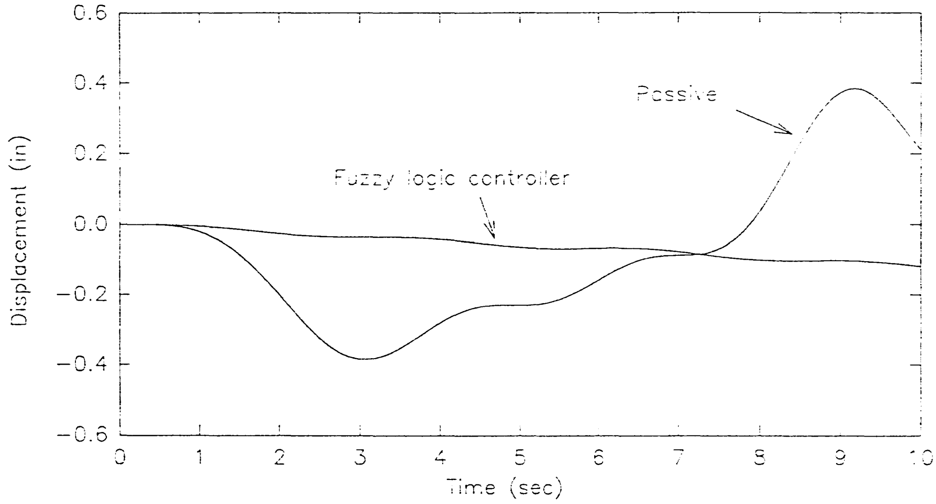


**FIGURE 14** Comparison of displacement response at actuator 2.

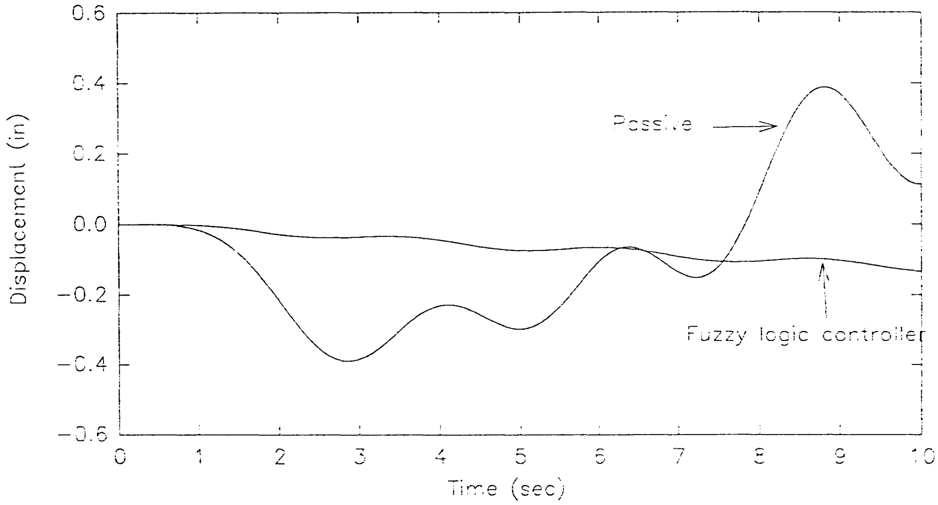


**FIGURE 15** Comparison of displacement response at actuator 3.

displacement responses stay around the zero displacement line through the entire simulation period, only with some ignorable offsets. This again demonstrates the effectiveness of the FL controller. That is, even though the displacement of the platform bottom plate is not used as an active control variable, the FL controller is able to cope with the vibratory displacements to a satisfactory extent. All in all it is evident that the developed FL controller results in remarkable improvements in dealing with the unstable dynamic behavior induced by external disturbances of the passive platform system. This implies that the FL controller is effective and the performance of the entire controlled system is satisfactory.

## CONCLUSION

In this article an active vibratory reaction compensation via a two-plate platform system was studied. An external excitation scenario of an impulsive force was applied to an arbitrarily chosen point on the top plate that induces the vibratory motion transmitted to the bottom plate via three coil springs. The required compensations for reducing the vibratory accelerations on the bottom plate were generated by an active FL controller.

In the first stage of the study, comprehensive dynamic formulations of the 6 degree of freedom platform system were formulated by applying the Newton–Euler method. Because the Newton–

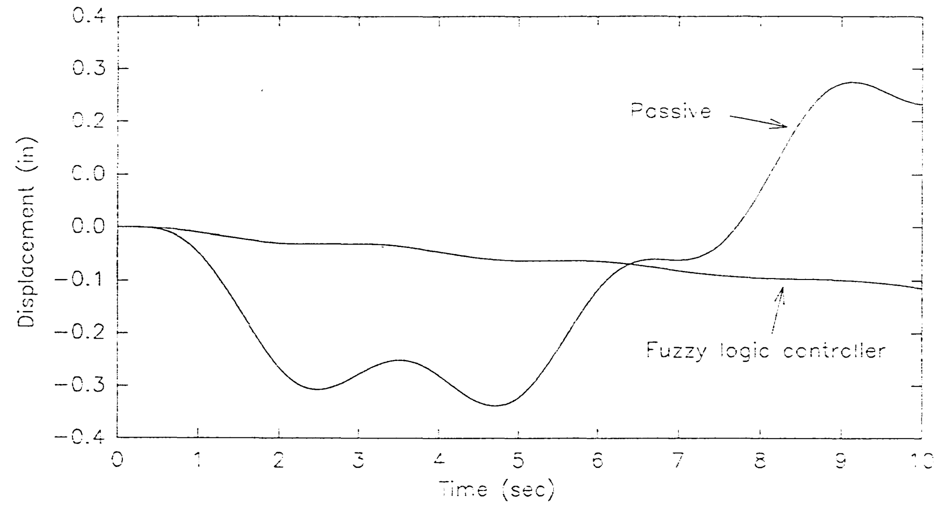


**FIGURE 16** Comparison of displacement response at the center.

Euler formulation is very structured and hence manipulated easily, it was further linearized and utilized for system dynamics and the control investigation. Based on the compensation requirement with a desired (reference) zero acceleration of the platform bottom plate, an FL controller was designed. Dynamic and control motion simulations were performed in terms of a comparative study of the passive uncontrolled and the active controlled platform system. The results showed that the designed FL controller possesses the following features, namely:

1. it is robust and hence less sensitive to the disturbance input variations;
2. it is easy to design and hence eliminates the tedious gain selection process required in conventional controller design;
3. its speed of response is rapid;
4. it is adaptive in that the fuzzy rule base is adjustable;
5. it is readily implementable by microelectronic devices because it uses logical operations.

In light of the comparative study shown in the simulation results, it was demonstrated that the designed FL controller could almost completely eliminate undesirable vibratory accelerations of the bottom plate induced by the specific impulsive disturbance. The effectiveness of the FL controller was further confirmed by viewing the significant reductions of the bottom plate's displacements shown in the comparative study.

With the presented satisfactory results, in phase II of the project presently underway, this study is being extended to include dynamic and control motion simulations: under different excitation scenarios of external disturbances; with system component parameter variations; with a nonlinear system dynamic model; and most importantly, the experimental verification of the developed fuzzy logic control scheme applied to the 6 degree of freedom reaction compensating platform system.

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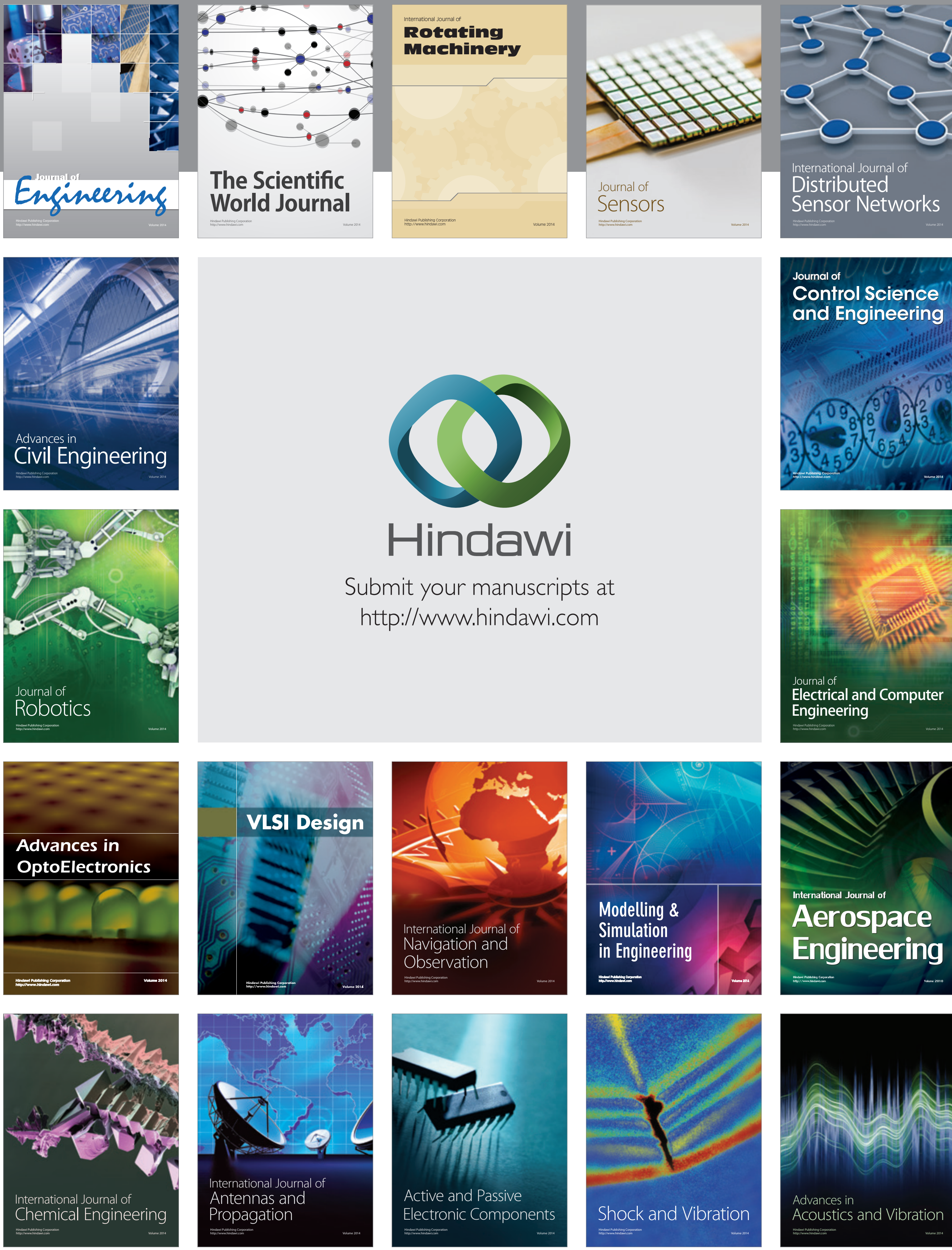
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