Majalah

LAPAN

VOL. 1 NO. 3 JULI - SEPTEMBER 1999 ISSN 0126-0480

DITERBITKAN OLEH :

LEMBAGA PENERBANGAN DAN ANTARIKSA NASIONAL

Jl. Pemuda, Persil No. 1, Jakarta 13220, INDONESIA

Active Vibration Control of Rocket RX-250-LPN Payload Structures

Lilies M. Goenardi, Mujtahid, Setiadi*) Salam Ginting**)

RINGKASAN

Seperti telah dilaporkan, ada kemungkinan muatan roket LAPAN gagal berfungsi karena getaran yang terlampau besar selama fase awal peluncuran. Tujuan dari makalah ini adalah untuk menyelidiki kemampuan mengontrol getaran secara aktif pada muatan RX-250 LPN selama peluncuran. Makalah ini juga berfungsi sebagai proses awal sebelum melakukan percobaan pengendalian getaran secara aktif di laboratorium dinamika struktur. Dalam analisa, muatan dan strukturnya dimodelkan sebagai sistem masa dengan satu derajat kebebasan. Sistem struktur diberi rangsangan pada pangkalnya oleh penyambung roket-muatan berupa percepatan dalam koordinat modal. Sensor mengukur akibat dari percepatan tersebut dalam sistem, dan memberikan input balik pada pengendali. Untuk mengevaluasi efektivitasnya, digunakan 3 macam pengendali *yakni Active Vibration Absorber* (AVA), state estimator dengan menggunakan metoda *Pole Placement* (PP), dan pengontrol *Linear Quadratic Gaussian* (LQG). Kemampuan tiap pengendali diuji untuk melihat kemampuannya dalam meredam getaran pada muatan roket. Sebagai pengendali jenis baru, kombinasi antara AVA & LQG digunakan untuk meningkatkan kemampuan AVA ketika massa yang digunakan amat kecil.

ABSTRACT

As it has been reported that there was a possibility of LAPAN rocket payload function failure due to excessive vibrations during lift-off. It is the purpose of this paper to investigate the feasibility of controlling actively vibrations of rocket RX-250-LPN payload structure during the launch and throughout its flight. This paper also serves as a preliminary process before conducting an active vibration control experiment in the Structural Dynamics Laboratory. In the analysis the payload and its structures were modeled as a single-degree-of-freedom lumped mass system. The structural system is excited at the base by the rocket-payload base interface acceleration in modal coordinates. The sensor measures response acceleration of the system, then it is fed back to the controller. In order to evaluate the effectiveness, three types of controllers, based on Active Vibration Absorber (AVA), state estimator by using Pole Placement (PP) method, and Linear Quadratic Gaussian (LQG) regulator, were designed for active vibration control process. Performance of each controller is presented to show the possibility of using the active control method to reduce vibrations of rocket payload structures. A new controller, a combination of AVA and LQG controller is introduced to improve the performance of AVA controller when the AVA controller mass used is very light.

1. INTRODUCTION

It is well understood that a rocket undergoes vibrations during the flight. Sustaining vibrations in the rocket can cause a loss of a rocket as reported for the German V-2 rockets in the World War II. In the investigation, it was found out that panel flutter was the cause of the rocket failure. (Annonym, 1996). In subsonic wind-tunnel experiment conducted in LAPAN-Rumpin, it was observed that at high angle of attack and speed near transonic region, the rocket experienced high amplitude vibrations that could lead to failure.

---

*) Research Engineer, Structural Dynamics Laboratory
**) Head, Structures and Mechanics Division

An extreme environment during lift-off can also impose great dangers on the rocket and its payload inside. It has been suspected that one of LAPAN's rocket payload on-orbit malfunctions was due to detrimental jitters from motor rocket ignition. This case has brought an attention to the importance of vibration control in our rocket system to preserve the rocket and its payload designed missions.

Active control as one of the available methods to control vibrations of structures has gained a wide acceptance in the world. It can be traced by an extensive amount of research that has devoted to discuss this method. The difficulty to estimate the exact mass, damping and stiffness of an absorber that meet the actual operating environment in passive vibration control has made the active control more attractive. The strong point of the active control is its ability to adapt to unpredicted changes in its working environment. However, the active control has a setback for being dependent on its electronic equipment performance.

In active control method, a controller plays a very important role since it serves as the brain that commands the incoming signal and the necessary input to be delivered. The controller can be designed based on the control theories that are available these days. In 1992, Brunner et al presented a second-order acceleration feedback controller that acts as an active vibration absorber (AVA). This controller that guarantees stability is model-independent for collocated accelerometers and actuators. (Bisplinghoff and Ashley, 1962). Glauser et al (1996) applied this AVA controller in their study of active vibration control of STS-41 satellite during the lift-off period. Their results showed that the system with this controller was effective to suppress vibrations and to reduce frequency response peak of five-degree-of-freedom satellite system during the lift-off. (Brunner et.al., 1992).

This paper examines the feasibility of using active control method to suppress vibrations of rocket RX-250-LPN payload during the lift-off and its flight. The payload and its structures are modeled as a single-degree-of-freedom (SDOF) structural system, which is randomly excited at the base. In vibration suppression process a controller to regulate the input and output is developed. Three types of controllers, which are Active Vibration Absorber (AVA), a state estimator or an observer with Pole-Placement (PP) method, and Linear Quadratic Gaussian (LQG) regulator, are compared to find the best one. A brief theory of each controller is given in the section 3. The time histories of the controller responses and amplitude peak reductions are presented to show their effectiveness in suppressing the vibrations. Since the performance of AVA controller is reduced when the controller mass used is very light. A new controller, a combination of the AVA and LQG controllers is developed to improve the vibration suppression. This type of controller was utilized by Belvin et al (1992) in Phase-0 CSI Evolutionary Model (CEM) test bed for the study of LOS and active vibration suppression. (Lee-Glauser et.al., 1996). The response using this controller is presented and compared to that of AVA controller and LQG.

2. MATHEMATICAL MODEL

As aforementioned the rocket payload is described by a SDOF lumped-mass system as shown in Figure 2-1. At the base, the structure is subjected to an excitation force, which is a function of launcher-payload base interface acceleration. The equation of motion is given as following

$$m\ddot{q} + d\dot{q} + kq = f \quad \text{.........} \; (2\text{-}1)$$

m, d, and k are payload mass, damping and stiffness respectively.   and q are modal coordinate acceleration, velocity and displacement vectors while f is modal coordinate excitation force. Dividing by the mass, m, equation (2-1) can be simplified by

$$\ddot{q} + \frac{d}{m}\dot{q} + \frac{k}{m}q = \frac{f}{m} \quad \text{...........} \; (2\text{-}2)$$

If the natural frequency is defined as $\omega_n^2 = k / m$, viscous damping factor is given by $\zeta = \frac{1}{2\omega_n}\frac{d}{m}$ and launcher interface acceleration, $\ddot{u}_1 = \frac{f}{m}$ then the equation of motion can be rewritten in term of natural frequency and viscous damping vectors.

$$\ddot{q} + \frac{d}{m}\dot{q} + \frac{k}{m}q = \frac{f}{m} \quad \text{.........} (2\text{-}3)$$

Transforming the second-order equation of motion into first-order equation in state-space form by letting $z = \begin{Bmatrix} q \\ \dot{q} \end{Bmatrix}$

$$\dot{z} = Az + Bu \quad \text{........} (2\text{-}4)$$

Where A, B and u are given by the followings

$$A = \begin{bmatrix} 0 & 1 \\ -\omega_n^2 & -2\zeta\omega_n \end{bmatrix}; B = \begin{bmatrix} 0 \\ 1/m \end{bmatrix}; u = f \quad \text{...........} (2\text{-}5)$$

Let acceleration response measured by a sensor is defined as

$$\ddot{q} = \begin{bmatrix} -\omega_n^2 & -2\zeta\omega_n \end{bmatrix} \begin{Bmatrix} q \\ \dot{q} \end{Bmatrix} + \ddot{u}_1 \quad \text{..} (2\text{-}6)$$

Then in terms of state-space form it becomes

$$y = Cz \;;\; C \text{ is } \begin{bmatrix} -\omega_n^2 & -2\zeta\omega_n \end{bmatrix} \text{..........} (2\text{-}7)$$

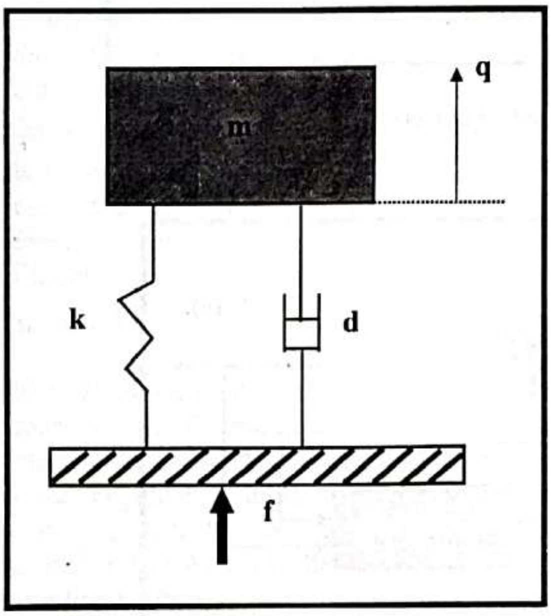

Figure 2-1 : MATHEMATICAL MODEL OF ROCKET PAYLOAD STRUCTURES

3. ACTIVE CONTROL LAW

3.1 Active Vibration Absorber (AVA) Controller

The purpose of this method is to design a second-order acceleration feedback controller that function as an active vibration absorber. (Bisplinghoff and Ashley, 1962). This controller can be imagined as a virtual dynamic system consists of mass, spring and dash pot attached to the actual dynamic system (plant) at the location of the sensors/actuators. Relationship between the plant and the controller is shown in Figure 3-1. The objective of the controller is to augment the damping in the targeted mode. Letting $q_c = q_a - q$ the controller equation can be written as

$$m_c\ddot{q}_c + d_c\dot{q}_c + k_c q_c = -m_c y \quad \text{.......} (3\text{-}1)$$

$$u = k_c q_c + d_c \dot{q}_c \quad \text{.......} (3\text{-}2)$$

In a state-space form, the controller equation is given by

$$u = C_c\bar{z} + D_c y \quad \text{............} (3\text{-}3)$$

$$u = C_c\bar{z} + D_c y \quad \text{..........................} (3\text{-}4)$$

where

$$A_c = \begin{bmatrix} -k_c^0/m_c & -d_c^1/m_c \end{bmatrix}; B_c \begin{bmatrix} 0 \\ -1 \end{bmatrix}$$

$$C_c = \begin{bmatrix} k_c & d_d \end{bmatrix} \;;\; D_c = \begin{bmatrix} 0 \end{bmatrix}; \bar{z} = \begin{Bmatrix} q_c \\ \dot{q}_c \end{Bmatrix}$$

y is the output of plant, which is fed to the controller while it is the output of the controller that acts a control input to the plant. The closed-loop system of this active vibration absorber can be described in Figure 3-2. Thus, it is necessary to find the values of controller mass, dash pot and spring that will stabilized the closed-loop system . Similar to passive vibration absorber method, the frequency of active absorber is set equal to the frequency of the mode wished to be controlled i.e. $\omega_c^2 = \omega_n^2 = k_c / m_c$. Then, the value of d_c can be determined by using root locus method.

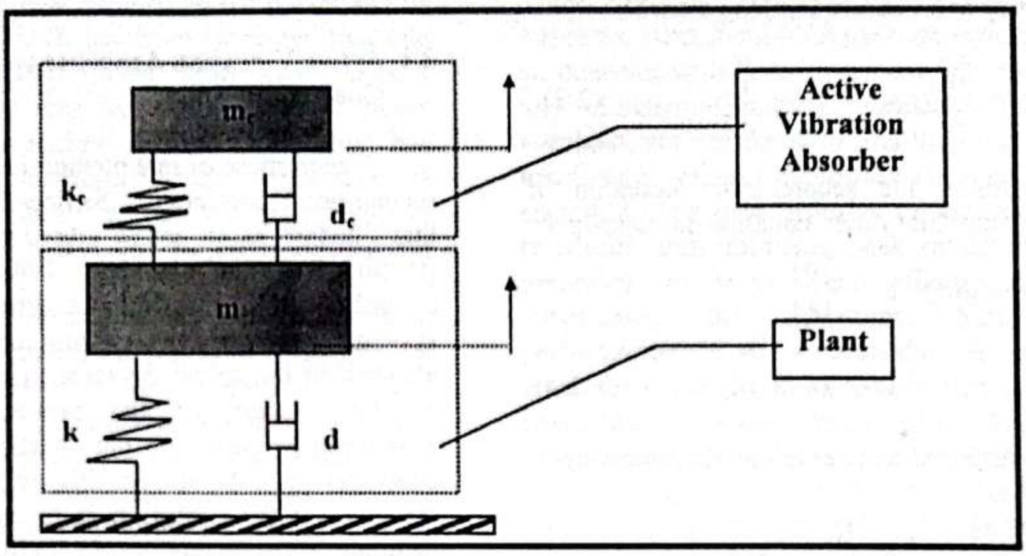

Figure 3-1 : ROCKET PAYLOAD MODEL AND AVA CONTROLLER.[2]

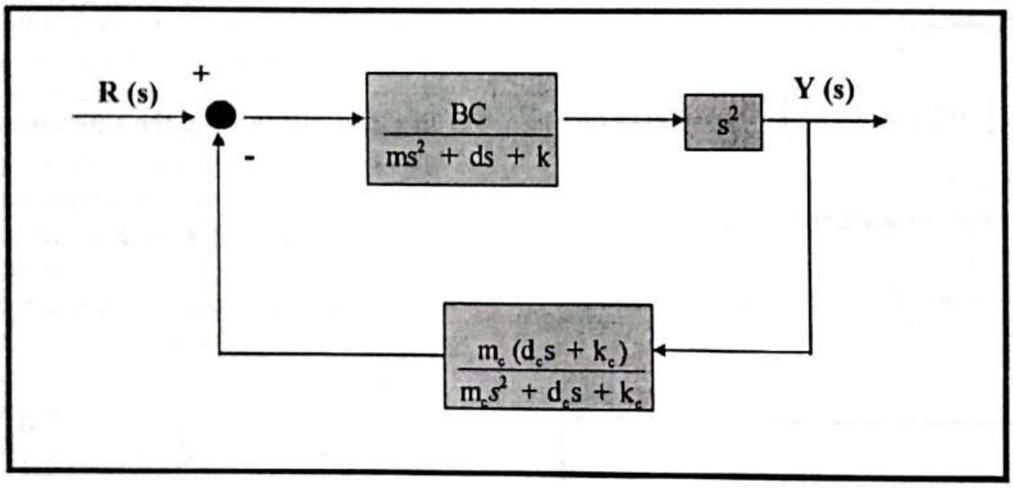

Figure 3-2 : ACTIVE VIBRATION ABSORBER CLOSED-LOOP BLOCK DIAGRAM.[3]

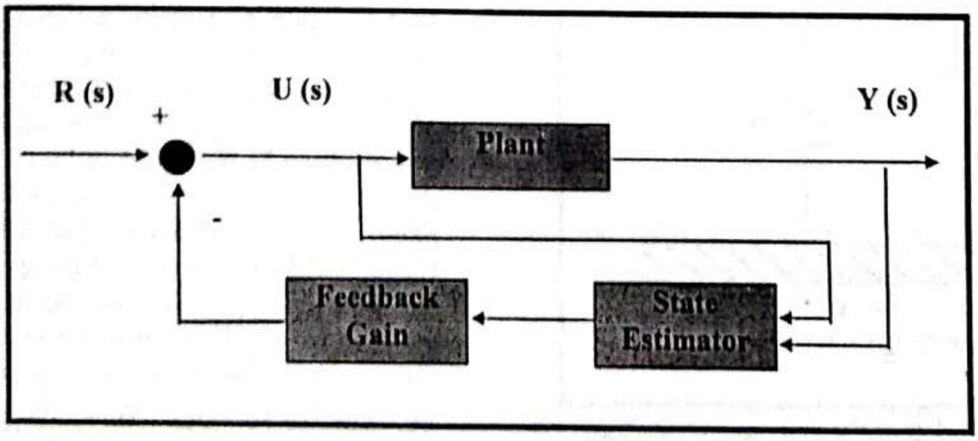

Figure 3-3 : CLOSED-LOOP SYSTEM WITH STATE ESTIMATOR.[3]

3.2 State Estimator or Observer

The second type of controller used to suppress vibration of rocket payload is a controller constructed from estimating the states of the plant to be controlled. The controller called state estimator or observer is assumed to have dynamics of the same type as those of the plant. (Belvin et.al, 1992). The state estimator equations are defined as follow

$$\dot{\hat{z}} = A_0 \hat{z} + B_0 u + Gy \quad \text{............(3-5)}$$

where A_0, B_0 and G are chosen such that $\hat{z}$ is an accurate estimate of state z. In other words, the error $e = z - \hat{z}$ goes to zero as $t \to \infty$. In order to do so, the estimated states have to fulfill the following criterion

$$\frac{\hat{z}(s)}{u(s)} = \frac{z(s)}{u(s)} \quad \text{.....................(3-6)}$$

It means that the transfer function from input u to the estimated states has to be equal to the transfer function from input to the actual states. Utilizing the derived equations in reference 3, finally the expression for the estimator equation is given by

$$\dot{\hat{z}} = (A - GC)\hat{z} + Bu + Gy \quad \text{....(3-7)}$$

Matrices A, B and C are plant system matrices while G can be determined by using Pole-Placement (PP) or Ackerman's method. It is desired to have stable poles in the characteristic equation of the estimator $|sI - A + GC| = 0$; i.e. the poles are in the left plane. In vibration control process, the estimated states z are utilized to generate the feedback command in the closed-loop as in Figure 3-3, which is expressed by

$$u = -K\hat{z} \quad \text{....................................(3-8)}$$

Here K is the feedback gain matrix, as in the case of G, determined by Pole-Placement method such the closed-loop real eigenvalues have negative values. From the equations above, it can be seen that active vibration absorber (AVA) controller can be thought as an observer/estimator by setting G equal to B_c and K equal to C_c.

3.3 Linear Quadratic Gaussian (LQG) Regulator

Let process/actuator w and sensor v noises are disturbances that exist in the plant, therefore the equations become

$$\dot{z} = Az + Bu + \Gamma w \quad \text{................(3-9)}$$

$$y = Cz + v \quad \text{.............................(3-10)}$$

The input noises are assumed to be independent, zero mean, Gaussian white noise with constant intensity Ξ and ψ respectively.[5] Since sometimes disturbances, which tend to destabilize rather than stabilize the system, are present in vibration control process, thus, it is necessary to have a controller that accounts them. Such well-known controller is called Linear Quadratic Gaussian (LQG) regulator. This regulator similar as in Figure 3-3 consists of a Kalman state estimator and state feedback gain, which is usually determined by linear optimal control theory. This theory trades off the output performance and control effort to obtain the control u that minimizes a cost function below.

$$J_{LQG} = E\left\{ \lim_{T \to \infty} \left[\int_0^T \left(z^T(t) Q z(t) + u^T(t) R u(t) \right) dt \right] \right. \quad \text{..(3-11)}$$

where Q is positive semi-definite state weighting and R is positive definite control weighting. Since the noises satisfy

$$E(w) = E(v) = 0;\ E(ww^T) = \Xi;\ E(w^T) = \Psi \quad \text{....(3-12)}$$

a Kalman state estimate $\hat{z}$ that minimizes the steady-state error covariance below can be constructed[6]

$$P = \lim_{T \to \infty} E\left\{ [z - \hat{z}][z - \hat{z}]^T \right\} \quad \text{.........(3-13)}$$

The LQG regulator state-space equation becomes

$$\dot{\hat{z}} = [A - LC - BK]\hat{z} + Ly \quad \text{..(3-14)}$$

$$u = -K\hat{z} \quad \text{........................(3-15)}$$

where L is Kalman filter gain, which can be determined by solving Riccati's equation as, follows

$$AP + PA^T - (PC^T)\Psi^{-1}(CP) + \Gamma\Xi\Gamma^T = \quad \text{.........(3-16)}$$

So that the filter gain is defined

$$L = \Psi^{-1} CP \quad \text{.......................(3-17)}$$

4. SIMULATION ANALYSIS

The effectiveness of each controller in suppressing the vibrations of 20-kg rocket payload excited at the base during the lift-off and throughout its flight is studied in this section. The payload natural frequencies based on experimental result conducted in Structural Dynamics Lab are 4 Hz, 6.25 Hz, and 8.75 Hz with viscous damping coefficients are set to be 0.02. Excitation input, which is in form of payload base interface acceleration, is simulated for a length of time 50 seconds. The first six seconds represent the lift-off period that extends from the motor rocket ignition time to the burn-out time. The time history of random payload base interface acceleration is given in Figure 4-1. The time histories of closed-loop responses for each frequency are given in Figure 4-2, 4-3 and 4-4. In these graphs, open-loop peak magnitude at fre-quency 4 Hz is reduced about 20 dB by this system followed by the system with controller using Pole-Placement (PP) method about 15 dB. Reduction of the peak by the system using AVA controller is the smallest about 15 dB. As the natural frequency increases, performance of AVA controller also improves. On the other hand, the effectiveness of the system with state estimator decreases when the placed poles are kept constant as the frequency to be controlled increases. The open loop peak magnitude reduction for these three frequencies are shown in Figure 4-5, 4-6 and 4-7. The required control input to suppress vibrations for each type of controller at the frequency of 8.75 Hz is given in Figure 4-8. The AVA controller mass used to attenuate these vibrations is 1 kg and the damping force constant is 5000 N/m. When a light AVA controller mass and small damping force are applied, the degrading performance can be compensated by using a new controller called AVA-LQG. This controller is similar with LQG regulator that consists of Linear Quadratic Regulator (LQG) state feedback gain and an AVA observer in place of Kalman filter. A system with this AVA-LQG controller shows a good performance not only when the AVA mass is light. However, it is advised not to use high input and state weighting constants since it can destabilize the closed-loop response (Figure 4-9).

5. CONCLUSION

A simple SDOF rocket payload model is used to investigate the feasibility of active control in suppressing the vibrations first three natural frequencies of the payload during the lift-off and the flight. The system with three different types of controllers, such as AVA controller, PP estimator, LQG regulator has been studied and compared. Based on the presented results, it can be concluded that the system with LQG regulator is the most effective in actively controlling the vibrations of the rocket payload. Besides, it requires lower control input than the systems with other two controllers. A combination of AVA and LQG controllers offers a better performance for a second-order controller in the active control of rocket payload vibrations during the lift-off and throughout its flight.

6. REFERENCES

1. Annonym, 1996, *Matlab HelpDesk*, The MathWorks Inc., Ver. 5.
2. Bisplinghoff, R. L., and H. Ashley, 1962, *Principles of Aeroelasticity,* John Wiley, pp. 419.
3. Brunner, A. M., Belvin W. K., Horta L. G., and J. N. Juang, 1992, *Active Vibration Absorber for CSI Evolutionary Model : Design and Experimental Results*, Journal of Guidance, Control, and Dynamics, Vol. 15, No.5, pp. 1253-1257.
4. Belvin, W. K., Elliott K. B, and L. G. Horta, 1992, *A Synopsis of Test Results and Knowledge Gained From the Phase-0 CSI Evolutionary Model*, Proceedings of Fifth NASA/DoD Control-Structures Interaction Technology Conference, NASA CP 3177, pp. 489-508.
5. El Ghaoui, L., Carrier A., and A. E. Jr. Bryson, 1992, *Linear Quadratic Minimax Controller,* Journal of Guidance, Control, and Dynamics, Vol. 15, No. 4, pp. 953-961.
6. Hagood, N. W., 1992, *Average-Cost Based Robust Structural Control*, Proceedings of Fifth NASA/DoD Control-Structures Interaction Technology Conference, NASA CP 3177, pp. 639-664.

7. Juang, J. N., and M. Phan, 1992, *Robust Controller Designs for Second-Order Dynamic System : A Virtual Passive Approach*, Journal of Guidance, Control, and Dynamics, Vol. 15, No. 5, pp. 1192-1198.

8. Lee-Glauser, G., Ahmadi G., and J. B. Layton, 1996, *Satellite Active and Passive Vibration Control During Lift-off*, Journal of Spacecraft and Rockets, Vol. 33, No.3, 1996, pp.428-431.

9. Philips, C. L., and R. B. Harbor, *Feedback Control System*, Prentice-Hall International, 1996, Chap. 10.

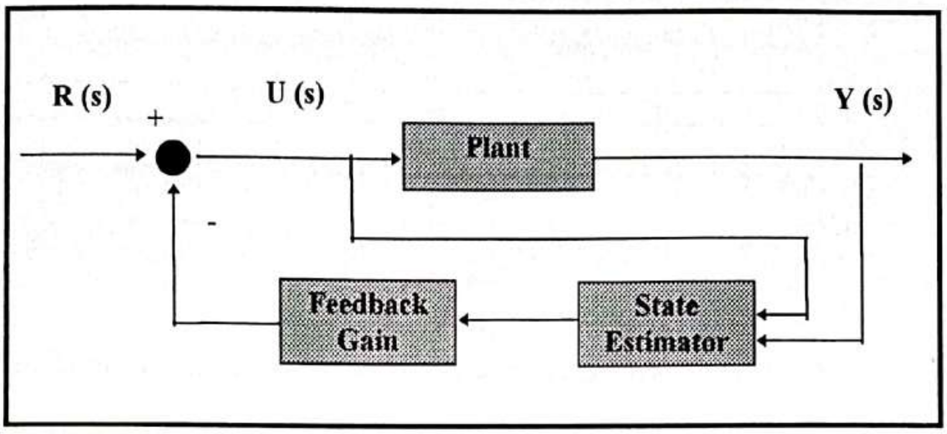

Figure 3-3 : CLOSED-LOOP SYSTEM WITH STATE ESTIMATOR.[3]

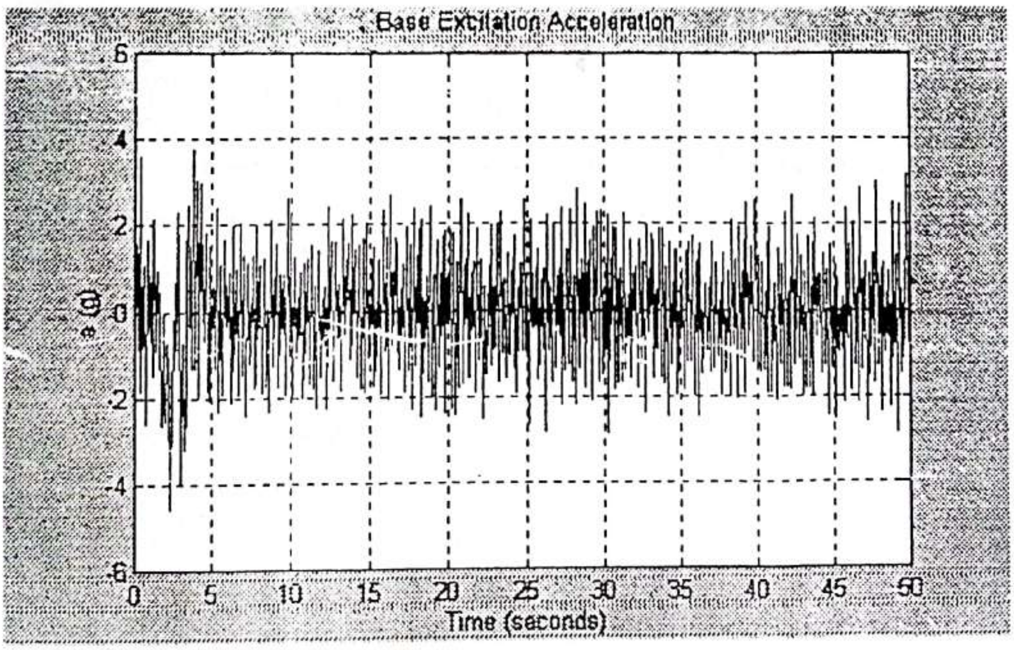

Figure 4-1 : ROCKET-PAYLOAD BASE INTERFACE SIMULATED ACCELERATION

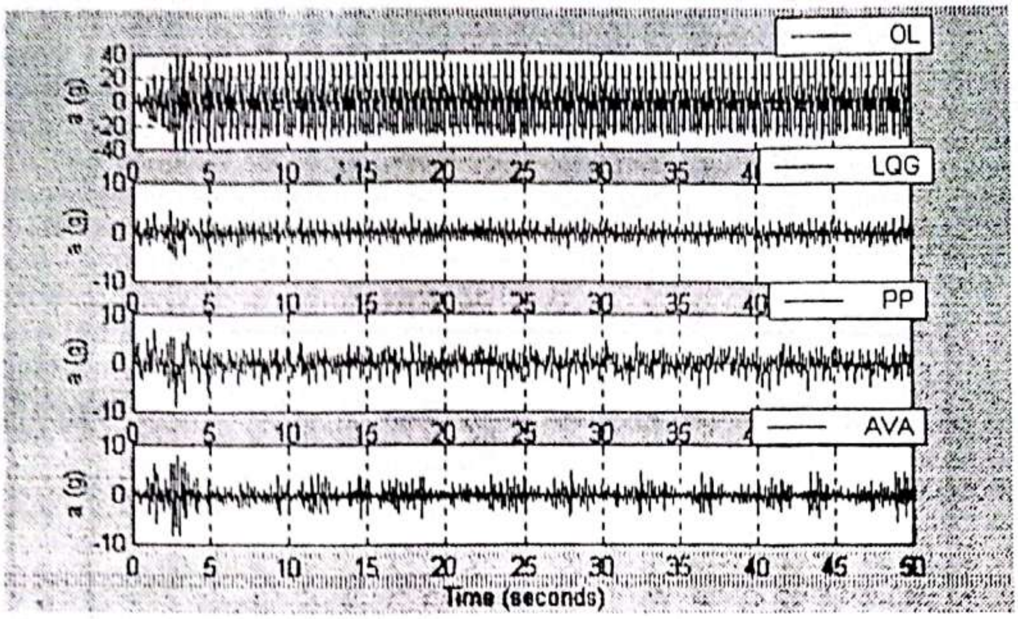

Figure 4-2 : ROCKET PAYLOAD CLOSED-LOOP RESPONSE AT THE FREQUENCY 4.00 Hz

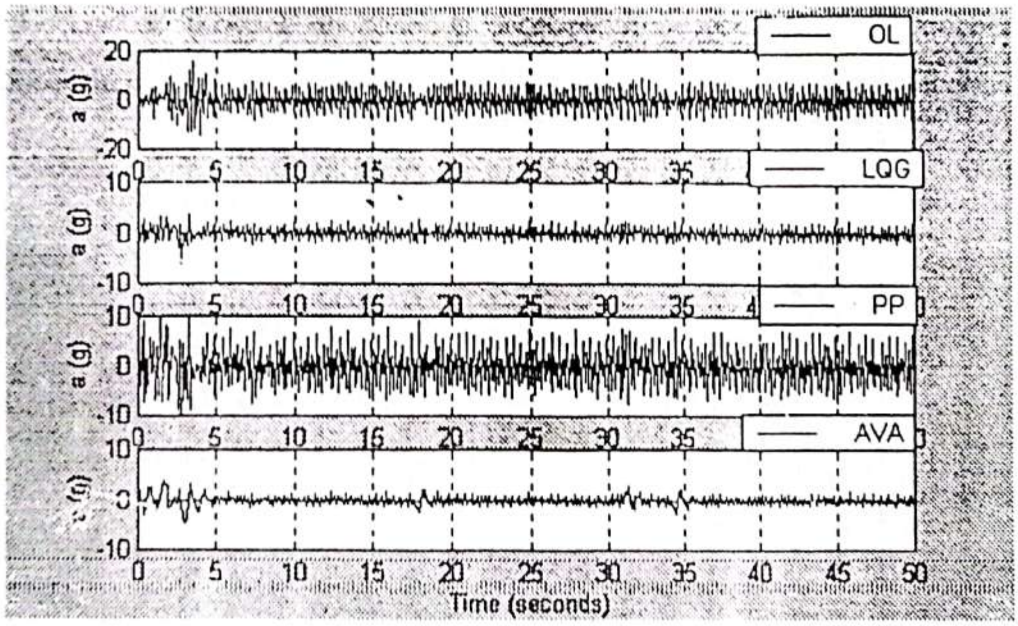

Figure 4-3 : ROCKET PAYLOAD CLOSED-LOOP RESPONSE AT THE FREQUENCY 6.25 Hz .

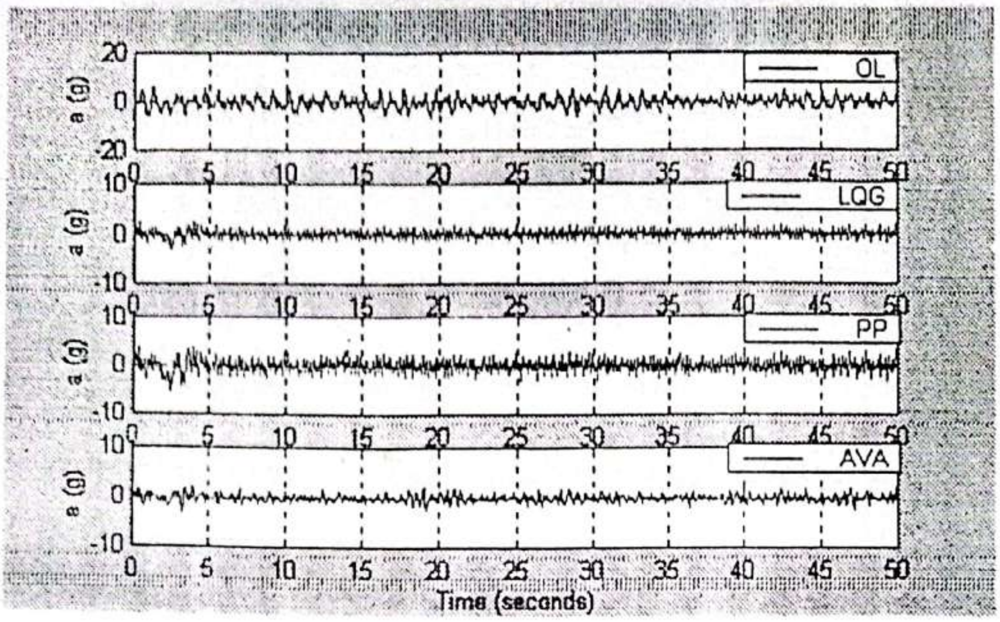

Figure 4-4 : ROCKET PAYLOAD CLOSED-LOOP RESPONSE AT THE FREQUENCY 8.75 Hz

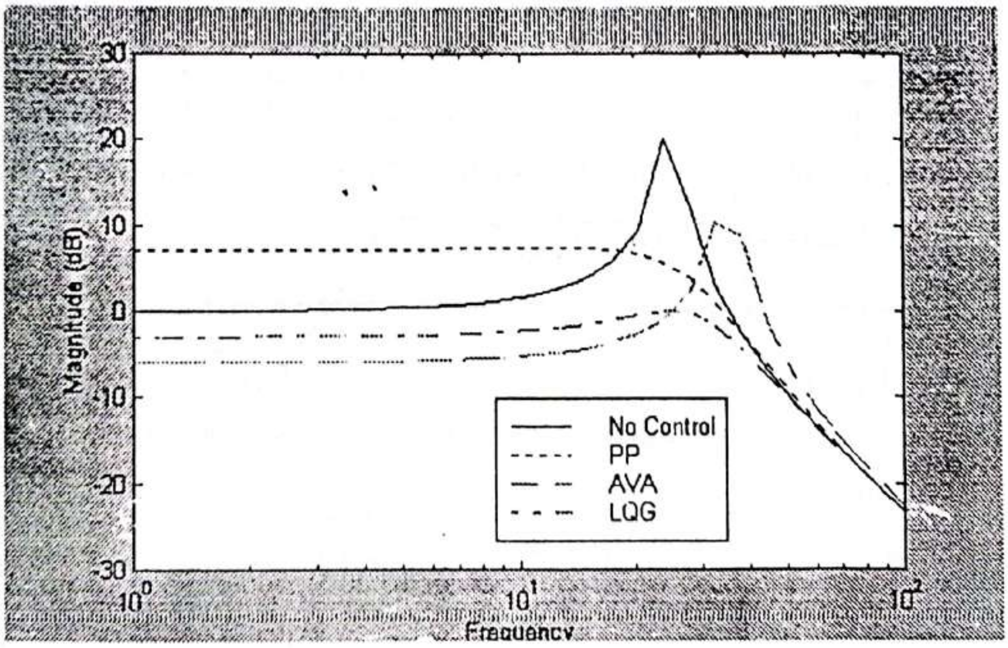

Figure 4-5 : CLOSED-LOOP PEAK MAGNITUDE REDUCTION AT THE FREQUENCY 4.00 Hz

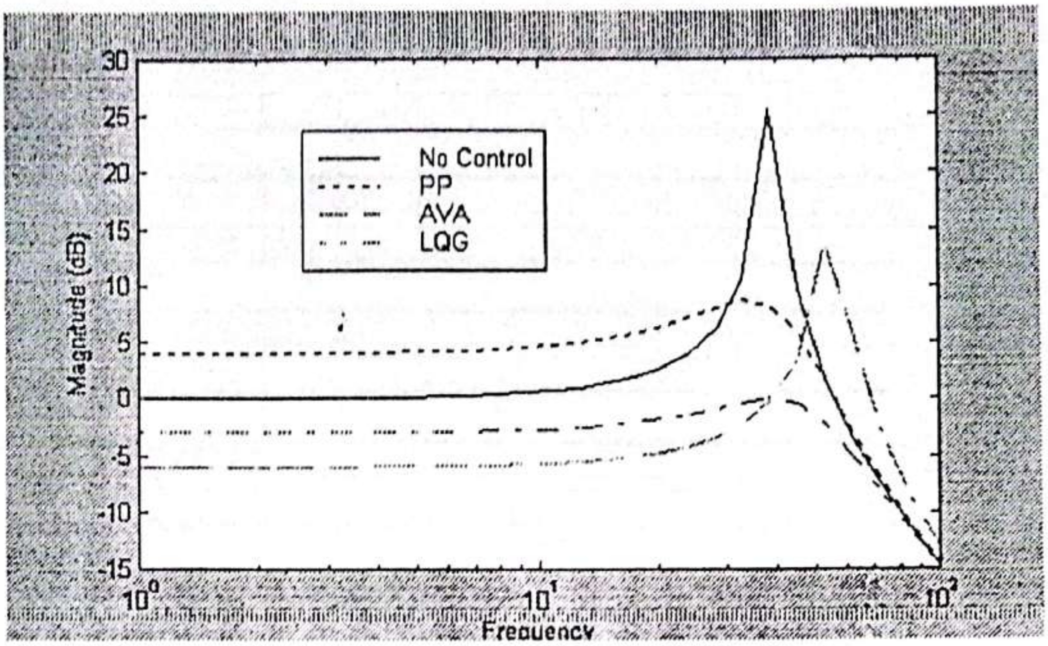

Figure 4-6 : CLOSED-LOOP PEAK MAGNITUDE REDUCTION AT THE FREQUENCY 6.25 Hz

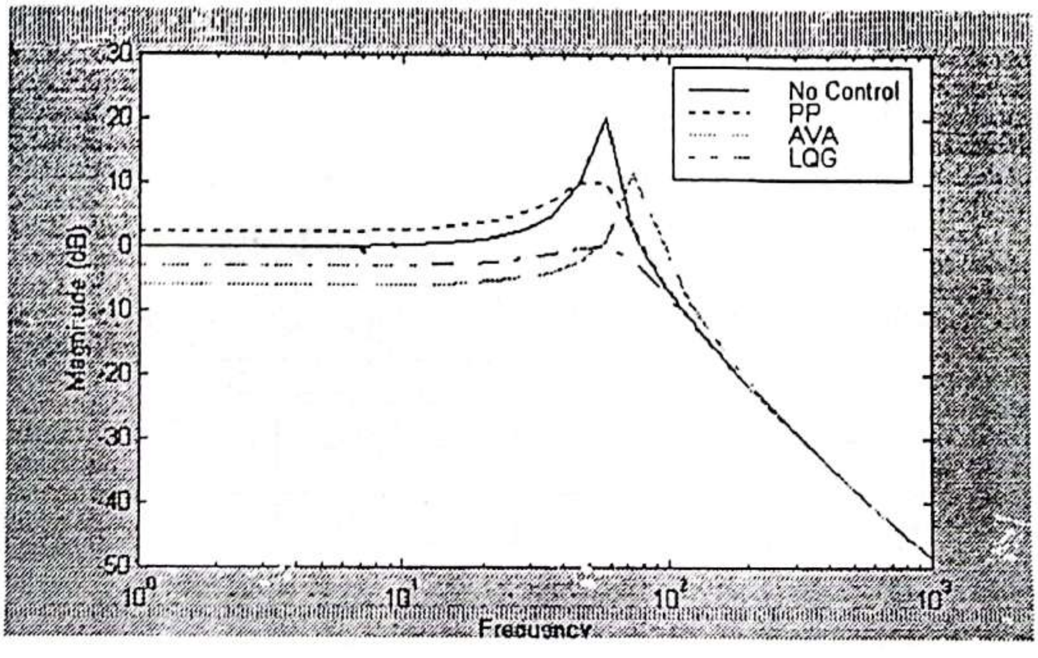

Figure 4-7 : CLOSED-LOOP PEAK MAGNITUDE REDUCTION AT THE FREQUENCY 8.75 Hz

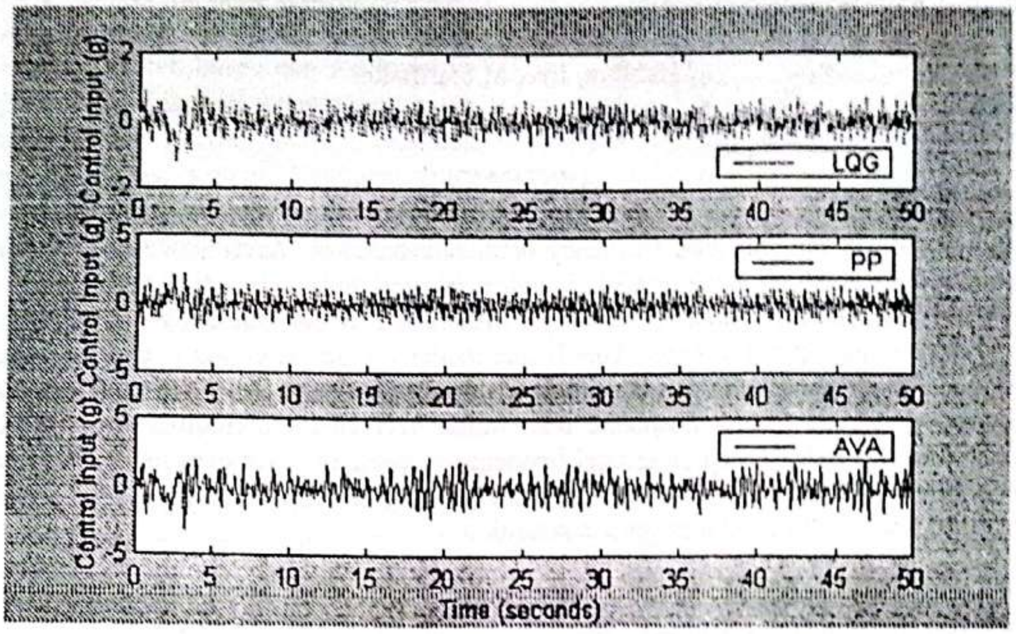

Figure 4-8 : REQUIRED CONTROL INPUT AT THE FREQUENCY 8.75 Hz

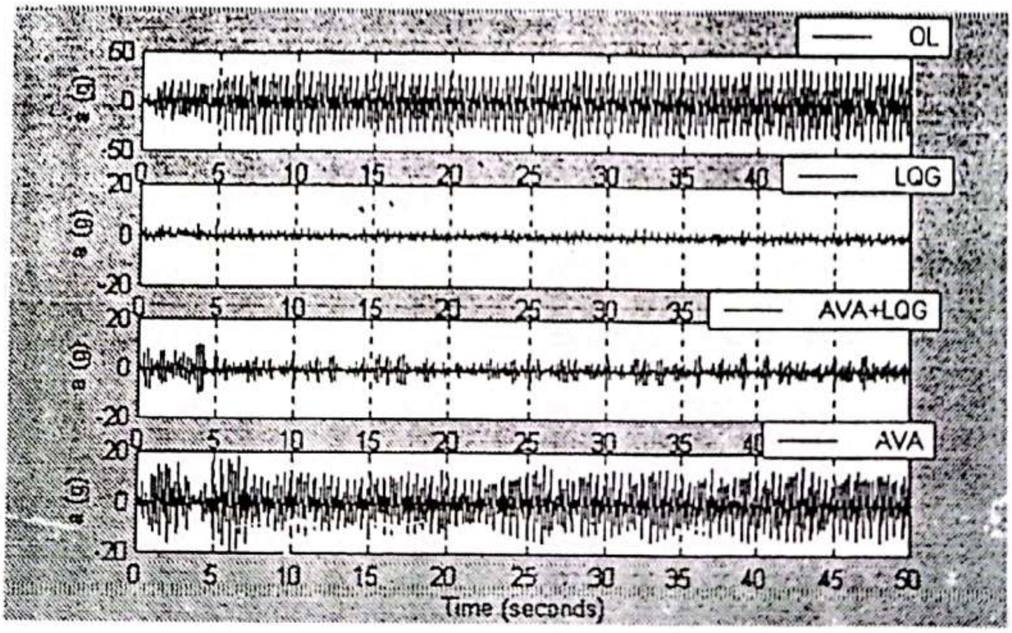

Figure 4-9 : CLOSED-LOOP RESPONSE WITH LIGHT AVA CONTLOLLER MASS AT THE FREQUENCY 4 Hz