International Journal of the Physical Sciences Vol. 6(30), pp. 6882 - 6890, 23 November, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.1450
ISSN 1992 - 1950 © 2011 Academic Journals

Full Length Research Paper

Design optimization of an active vibration isolation system

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Accepted 11 October, 2011

Several engineering systems require isolation of sensitive equipment from foundation vibrations or isolation of the foundation from machinery vibrations. Even though passive vibration isolation systems are effective in reducing the amplification at resonance, high frequencies attenuation is poor. Active vibration isolation (AVI) systems are being used for eliminating this problem. AVI is essential in multiple axes for precision control of a wide range of space-borne structures and also for a few earth-based systems of high precision. This paper presents a methodology of design optimization of a six degree of freedom AVI system based on Stewart platform. The design optimization is carried out using genetic algorithm by subjecting the model developed in 'MatLab'.

Key words: Stewart platform, active vibration isolation, genetic algorithm.

INTRODUCTION

Many applications in precision engineering such as wafer stepper lithography machines, atomic force microscopes, space telescopes and interferometers, laser communication systems, etc., need a careful vibration isolation of the system. Traditionally, the problem of vibration propagation is tackled by passive mounts. Passive isolation consists of one or several stages of mass-spring-damper systems in the propagation path. Passive damping is effective in limiting the amplification at resonance, but it tends to reduce the high frequency attenuation of the isolation system.

AVI can resolve this conflict, achieving simultaneously a low amplification at resonance and a large attenuation at high frequency. Hence, there has been considerable research activity devoted to develop AVI schemes. Zhang et al. (2002) developed a model for the vibration isolation of micro manufacturing platform. The model developed is to overcome vibrations of the ground, the movement of the instrument on the platform. Huang et al. (2003) made practical investigation into an active vibration isolation system. The isolation system was a four-mount structure and the system was effective in isolation over a wide range of frequency.

Yang et al. (2004) have developed a vibration isolation system for marine diesel engine. Marine diesel engine is a major source of vibration that needs an isolation system to reduce vibration transmission to the hull. Apart from improving passenger and crew comfort, there is a need to contain the generation of acoustic noise from the hull. Such acoustic noise creates a severe detection hazard in naval vessels and also becomes problematic for civil vessels, such as those used by fisheries.

Jia-Yush et al. (2005) developed an AVI for a large stroke scanning probe microscope. Extensive research is also being done in developing control methodologies for the AVI systems (Andrew et al., 2006; Wen-Hong et al., 2006; Farshidianfar et al., 2011). Multi degree of freedom (DOF) vibration isolation is essential for the precision control of a wide range of space-born structures as well as earth-based systems. Kerber et al. (2007) developed a feedback controller for a commercially available multi DOF AVI system with electro-dynamic actuators.

Jason et al. (1994) have used Stewart platform for developing six DOF active vibration control. Stewart platform has several features which make them particularly attractive for six DOF active vibration control. They use the minimum number of linear actuators to provide six DOF motions. Considerable efforts are on, for utilizing the concept of Stewart platform for six DOF AVI

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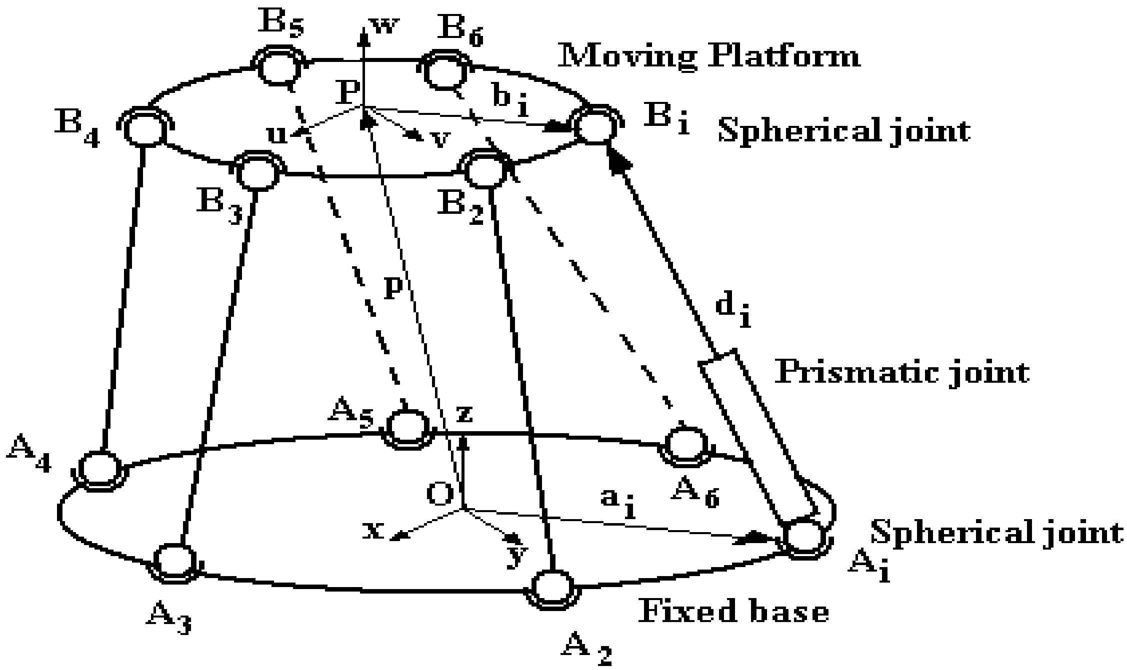

Figure 1. Spatial six DOF, six SPS parallel manipulator.

(Doug et al., 1998; Hauge and Campbell, 2004; Yuan et al., 2004; Ren et al., 2004; Preumont et al., 2007). Even though many researchers have focused in the area of control methodologies and its effectiveness for specific applications, but there has not been any attempt made to optimize the design configuration of Stewart platform for the best isolation effectiveness. The authors have attempted to fill this void. The objective of this work is to develop a methodology for arriving at the optimal design parameters of the AVI system based on Stewart platform.

Stewart platform

The Stewart platform is a typical parallel manipulator, which consists of two platforms connected by six extensible limbs (actuators) with joints at either end (Lung-Wen 1999). The fixed platform is called the "base frame" and the movable platform is called the "top platform", which has six DOF relative to the base frame. Figure 1 shows a spatial six DOF, six spherical prismatic spherical (SPS) parallel manipulator, known as the Stewart platform. Six identical limbs connect the moving platform to the fixed base by spherical joints at points B_i and A_i, i = 1, 2, …., 6, respectively. It has to be noted that in Figure 1, the attachment points A_i for i = 1 to 6 are sketched in a plane on the fixed base. Similarly, B_i for i = 1 to 6 are sketched in a plane on the moving platform.

For a general Stewart platform, however, these attachment points do not necessarily lie in the same plane. There are 14 links (n) connected to 6 prismatic joints (j) and 12 spherical joints. Hence, the number of DOF of the mechanism is:

$$F = \lambda(n - j - 1) + \sum_i f_i = 6(14 - 18 - 1) + (6 + 3\times 12) = 12 \qquad (1)$$

However, there are 6 passive degrees of freedom associated with 6 SPS limbs. Therefore, the moving platform possesses 6 DOF. It has to be noted that a SPS limb can be replaced by a spherical prismatic universal (SPU) limb without compromising the overall DOF of the mechanism. In the present work, an SPU limb has been modeled.

MODEL OF THE SIX DOF VIBRATION ISOLATION SYSTEM

There are two main cases where vibration isolation is necessary (Abu, 2003):

1. The operating equipment can generate an oscillating disturbance (force) propagating into the supporting structure.
2. The disturbance can be generated by the supporting structure propagating into the sensitive equipment.

The main principle of vibration isolation is to place an isolation stage in the vibration transmission path, so as to prevent the transmission of vibratory forces between them.

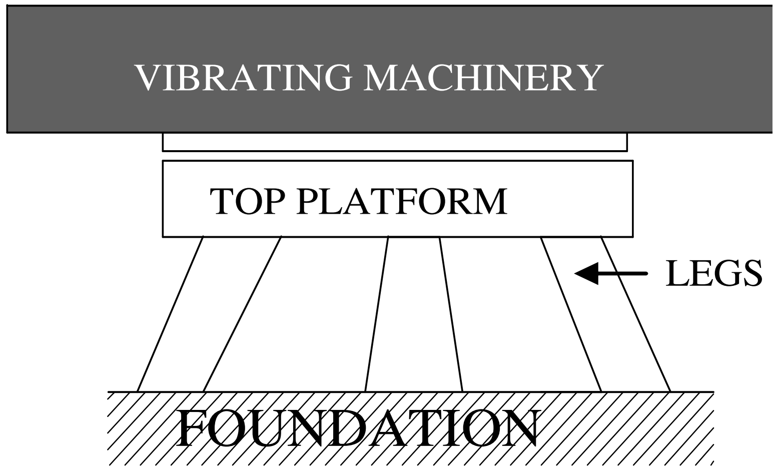

Figure 2. Stewart platform for isolating foundation from machinery vibration.

In the present work, active vibration isolation of foundation from machinery vibration was modeled. The vibrating machinery was kept on the top platform and the legs of the manipulator could be utilized to isolate the base from harmful vibrations. An active controller takes the signals from the top and sends these signals to the actuators of the manipulator to actuate in the opposite direction, thus isolating the foundation from vibration. Figure 2 depicts the model of utilizing Stewart platform for isolating foundation from vibrating machinery. Modeling of the Stewart platform for AVI was carried out using MatLab.

INVERSE KINEMATICS OF STEWART PLATFORM

In order to find the required displacements of the legs of Stewart platform to counter any disturbance, inverse kinematics is to be performed. From Figure 1, the transformation of the moving platform with respect to the fixed base can be described by the position vector *p* of the centroid, P and the rotation matrix, ${}^AR_B$, of the moving platform. ${}^AR_B$ for a Roll, Pitch and Yaw (RPY) wrist was given by:

$$ {}^AR_B = \begin{bmatrix} \cos\theta_2.\cos\theta_3 & \sin\theta_1.\sin\theta_2.\cos\theta_3 - \cos\theta_1.\sin\theta_3 & \cos\theta_1.\sin\theta_2.\cos\theta_3 + \sin\theta_1.\sin\theta_3 \\ \cos\theta_2.\sin\theta_3 & \sin\theta_1.\sin\theta_2.\sin\theta_3 + \cos\theta_1.\cos\theta_3 & \cos\theta_1.\sin\theta_2.\sin\theta_3 - \sin\theta_1.\cos\theta_3 \\ -\sin\theta_2 & \sin\theta_1.\cos\theta_2 & \cos\theta_1.\cos\theta_2 \end{bmatrix} \quad (2) $$

where θ_1, θ_2 and θ_3, are the roll, pitch and yaw motion, respectively.

As shown in Figure 1, let $a_i = [a_{ix}\ a_{iy}\ a_{iz}]^T$ and ${}^Bb_i = [b_{iu}\ b_{iv}\ b_{iw}]^T$ be the position vectors of point A_i and B_i in the coordinate frames A and B, respectively. The vector loop equation for the i^{th} limb of the manipulator can be written as:

$$ \overline{A_iB_i} = p + {}^AR_B.{}^Bb_i - a_i \quad (3) $$

The length of the i^{th} limb was obtained by taking the dot product of the vector $\overline{A_iB_i}$ with itself and,

$$ d_i^2 = \left[p + {}^AR_B.{}^Bb_i - a_i\right]^T\left[p + {}^AR_B.{}^Bb_i - a_i\right], \quad \text{for i} = 1,2,....,6 \quad (4) $$

where d_i denotes the length of the i^{th} limb. Expanding Equation 4 yields:

$$ d_i^2 = p^Tp + \left[{}^Bb_i\right]^T\left[{}^Bb_i\right] + a_i^Ta_i + 2p^T\left[{}^AR_B{}^Bb_i\right] - 2p^Ta_i - 2\left[{}^AR_B{}^Bb_i\right]^Ta_i \quad (5) $$

For the inverse kinematics problem, the position vector *p* and rotation matrix ${}^AR_B$ of frame B with respect to A are given and the limb lengths d_i, i = 1, 2… 6, are to be found. The square root of Equation 5 gives:

$$ d_i = \pm\sqrt{p^Tp + \left[{}^Bb_i\right]^T\left[{}^Bb_i\right] + a_i^Ta_i + 2p^T\left[{}^AR_B{}^Bb_i\right] - 2p^Ta_i - 2\left[{}^AR_B{}^Bb_i\right]^Ta_i} \quad (6) $$

Equation 6 is the inverse kinematic equation, where d_i is the required displacements in each leg corresponding to the disturbance in the mobile platform. Inverse kinematic equation was modeled in MatLab and is as shown in Figure 3. The position and orientation changes of mobile platform are taken as the input to the model and the required change in length of each leg are computed.

MODELING OF A SINGLE LEG

Each leg was modeled as an SPU limb as shown in Figure 4. The spherical joint was attached to the top platform, universal joint to the base of the manipulator and prismatic joint is the active joint in each leg of the

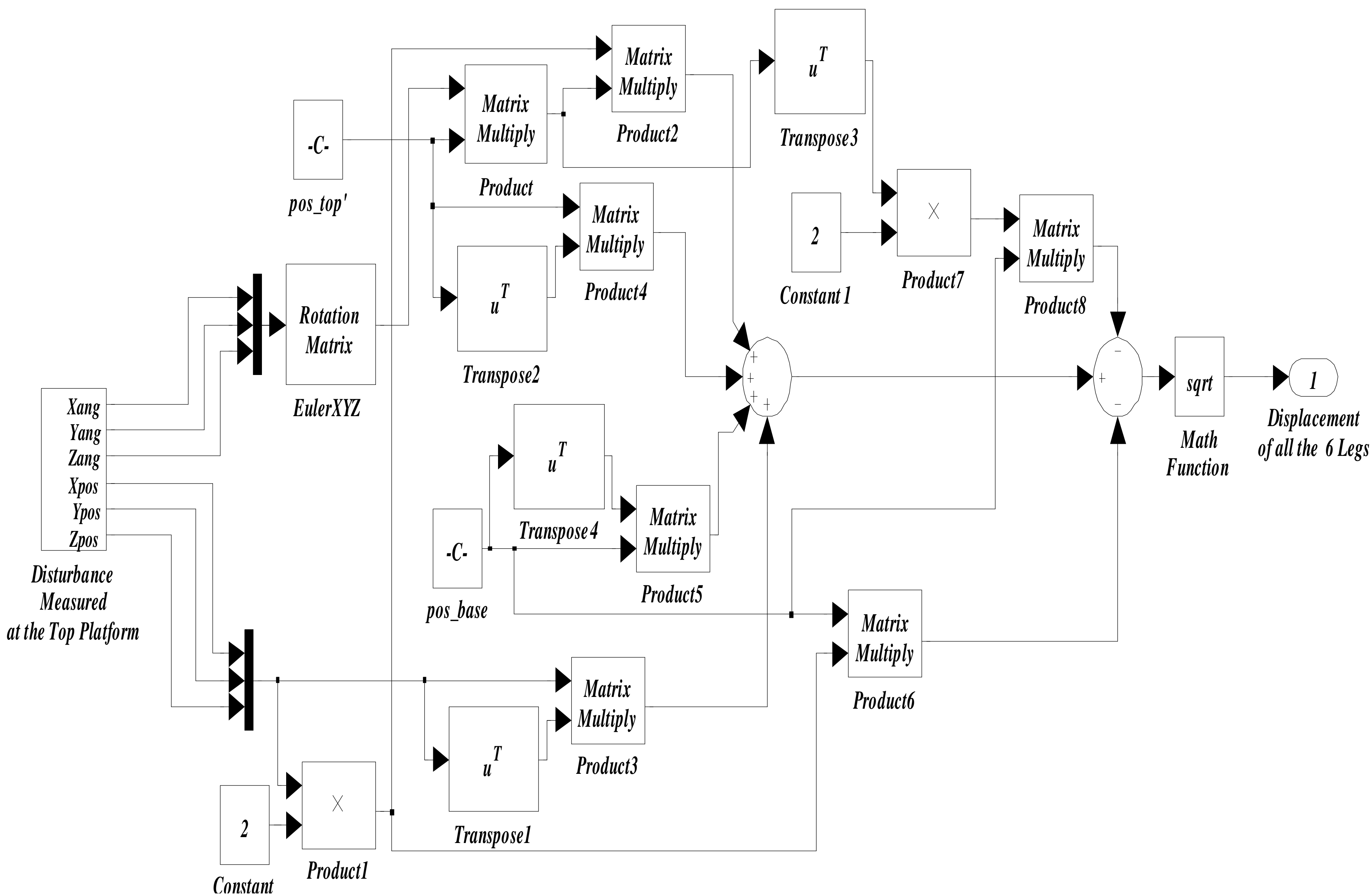

Figure 3. Inverse kinematic equation model in MatLab.

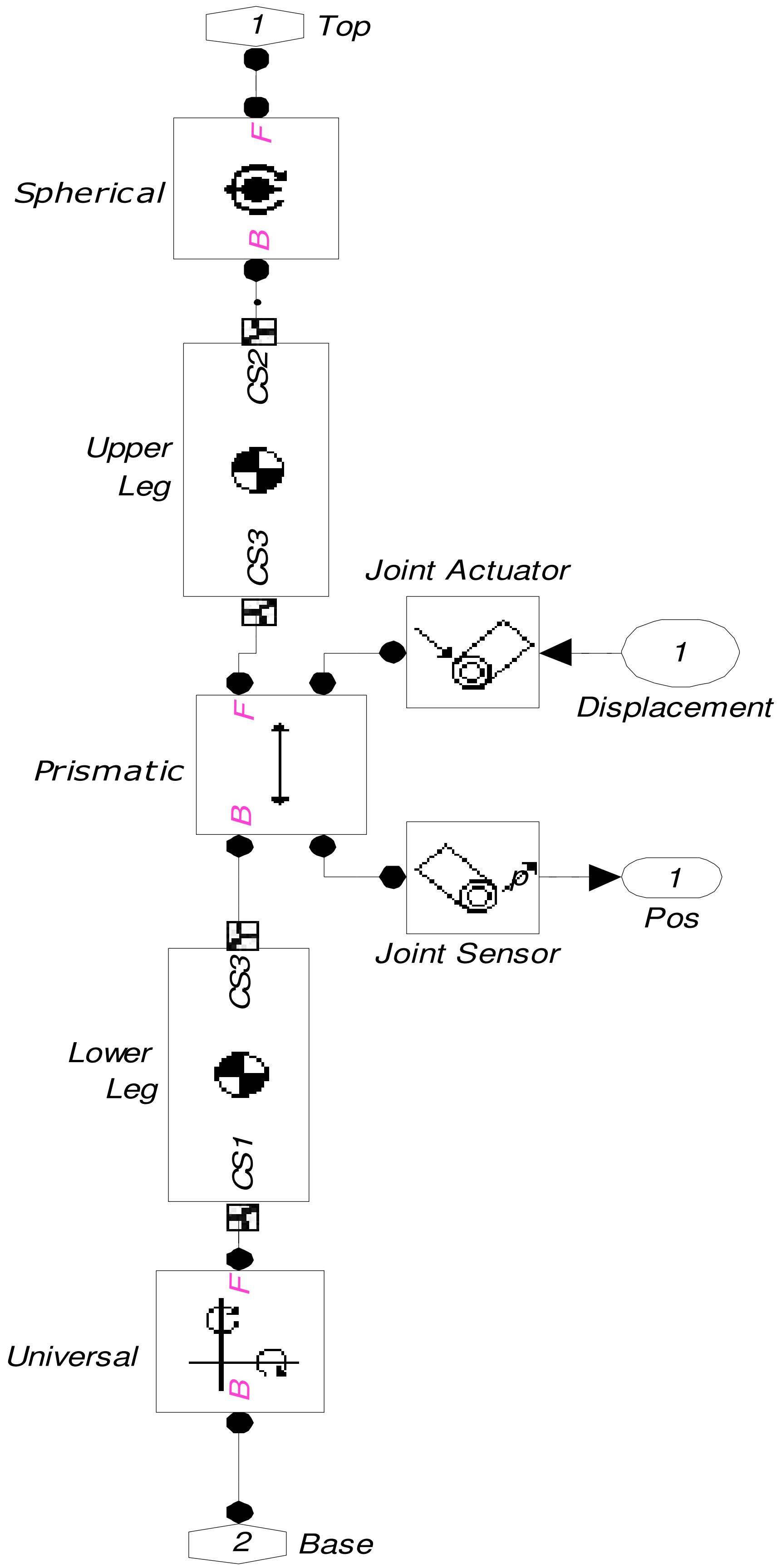

Figure 4. Model of a single leg.

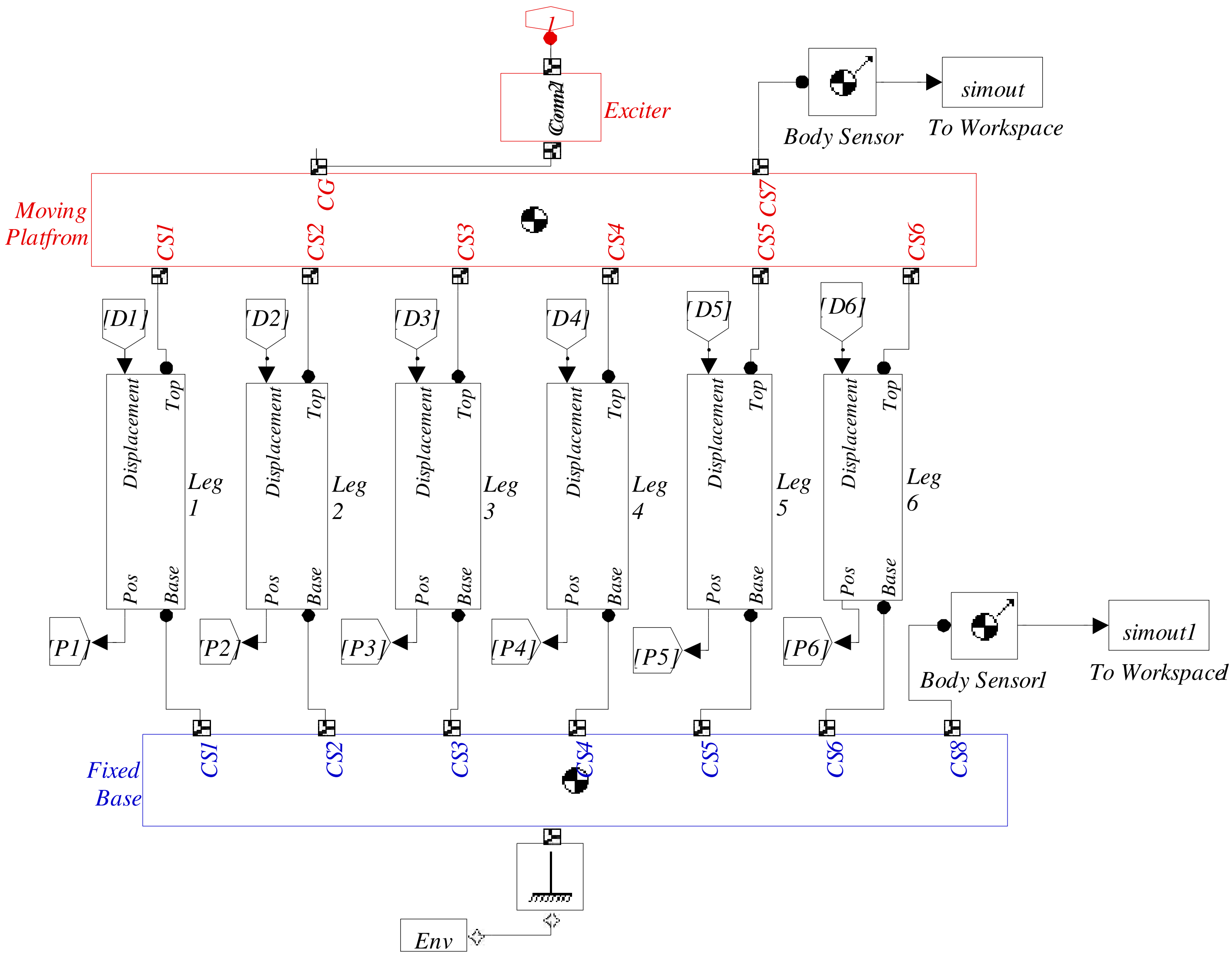

Figure 5. Model for the 6 DOF AVI system.

manipulator. An active controller takes the signals from the top platform and sends to the prismatic actuators of the manipulator to actuate in the opposite direction, thereby isolating the foundation from machinery vibration.

THE OVERALL MODEL

Extending the model of a single leg, an overall model of the AVI system based on Stewart platform is as shown in Figure 5. The exciter acts as the source of disturbance giving input to the inverse kinematic equation model, which calculates the desired changes in leg lengths to actively isolate the base platform from the vibration given by the exciter on the moving platform.

Modeling was carried out considering the configuration details of the working model of a Stewart platform, developed at SASTRA University, India (Rahmathulla and Pugazhenthi, 2010). Figure 6 shows the physical model based on which MatLab model was created to explore the benefits of Stewart platform for AVI.

DESIGN OPTIMIZATION

The objective is to find the optimal design parameters which govern the performance of Stewart platform for AVI. Realistic physical parameters of Stewart platform considered for optimising the configuration of Stewart platform for AVI are: base triangle distance (B_t), base joint distance (B_j), mobile platform triangle distance (P_t), mobile platform joint distance (P_j) and height of the Stewart platform (h) as shown in Figure 7. In order to arrive at an optimal design, the physical design parameters of the Stewart platform varied keeping the control aspect of the model a constant. The control chosen was a simple proportional integral derivative (PID) controller and the controller gain was also kept constant.

In order to quickly search for the optimal design parameters, genetic algorithm (GA), an evolutionary search technique has been employed. Heuristics of GA are broadly applied to generate useful solutions for optimization and search problems with natural evolution. These heuristics start with a set of solutions called the initial population, and then new populations were created gradually through three genetic processors of selection, crossover and

Figure 6. Stewart Platform at SASTRA University.

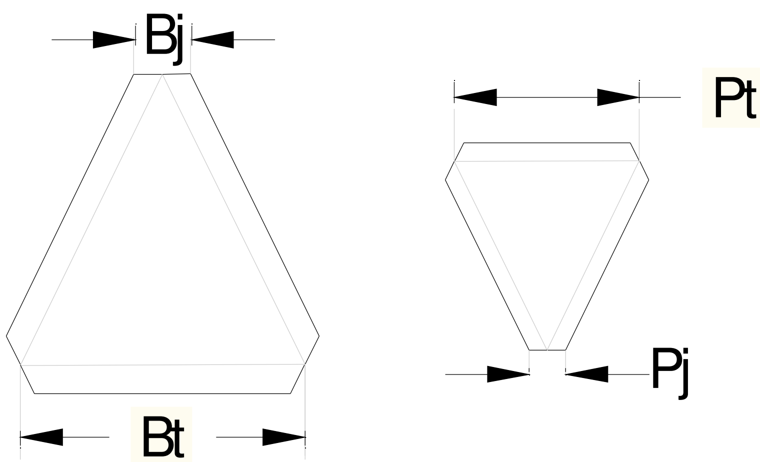

Figure 7. Base and mobile platform of Stewart Platform.

mutation (Peng and Pu, 2011).

The goal of active vibration isolation is to have low amplitude at corner frequency (T_r) and provide good attenuation of -40 dB/decade at high frequency. So, the authors have coined a new index, termed as transmissibility index for AVI, α is given by

$$\text{Transmissibility index for AVI, } \alpha = \frac{\text{Transmissibility at corner frequency } (T_r) \text{ in dB}}{\text{Transmissibility at high frequency in dB}} \qquad (7)$$

The higher the value of α, the better the isolation will be (assuming that the high frequency transmissibility will always be on the negative side). For the sake of calculation, the high frequency is considered to be 100 Hz for the present model.

The steps adopted in the implementation of genetic algorithm for finding the optimal values of the design parameters are furnished as follows:

Step 1: A population size of 40 chromosomes and number of generations of 1,000 are initialized.

Step 2: Chromosomes representing the design parameters considered for optimization (that is, B_t, B_j, P_t, P_j and h) are randomly generated.

Step 3: Inverse kinematics was performed for each set of design parameters to find the lengths of legs.

Step 4: Magnitude of lengths of legs were checked for geometric constraints.

Step 5: When geometric constraints were satisfied, Simulink model with the set of design parameters were run for evaluating the effectiveness of the Stewart platform for AVI.

Step 6: The transmissibility ratio at different frequencies for the model was evaluated.

Step 7: Fitness value for all chromosomes was computed, and the best one with the maximum value was identified.

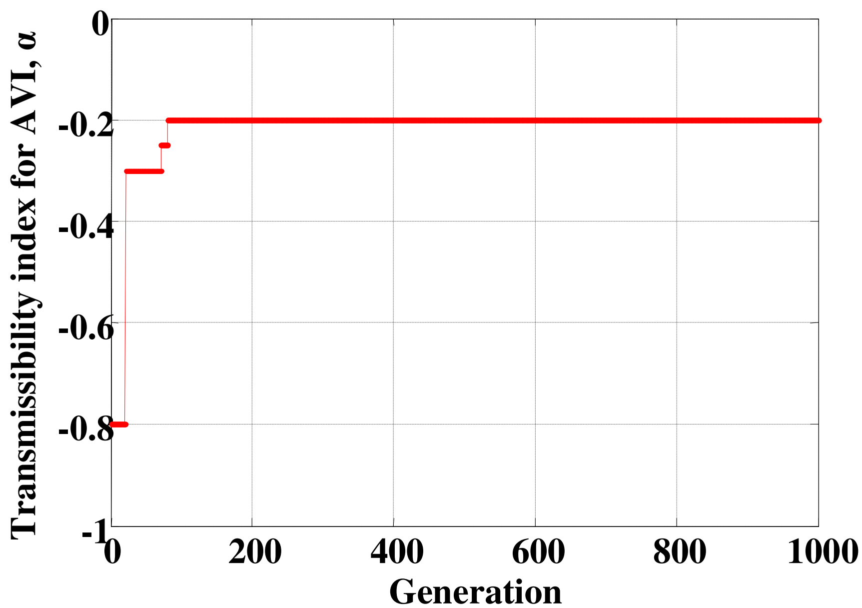

Figure 8. Transmissibility index for AVI, α.

Table 1. Optimal design parameters.

Parameter	Value (m)
Height (h)	0.46
Base triangle distance (Bt)	0.35
Distance between the joints of base (Bj)	0.10
Moving platform triangle distance (Pt)	0.15
Distance between the joints of moving platform (Pj)	0.09

Step 8: Reproduction operation was performed.
Step 9: Crossover of random pairs of chromosomes was done with a probability of 0.8.
Step 10: Bitwise mutation was performed with a probability of 0.05 on the chromosomes.

These result in a new set of chromosomes for the next generation. Steps 3 to 10 were repeated for all the generations.

The best transmissibility ratio for AVI is updated for each generation. At the end of the complete search, corresponding to the maximum transmissibility index, the optimal design parameters are identified. Figure 8 shows the convergence of transmissibility index over 100 generations.

The optimal design parameters of the Stewart platform for six DOF AVI were thus found using GA as given in Table 1.

SIMULATION RESULTS

Simulation results corresponding to optimal design parameters as shown in Table 1 are used to draw transmissibility plot in Figure 9. It shows the transmissibility plot for optimal configuration of the Stewart platform with and without AVI control. It is evident from the plot that the optimal configuration has low amplitude at the corner frequency and good attenuation at high frequency of more than -40 dB.

Conclusion

The design optimization of 6 DOF AVI system based on Stewart platform has been carried out. The optimal configuration is effective in providing low amplitude at corner frequency and good attenuation at high frequency of more than -40 dB in the vicinity of 100 Hz. The effectiveness of the Stewart platform for active vibration isolation was demonstrated by modeling the 6 DOF AVI system based on Stewart platform using MatLab.

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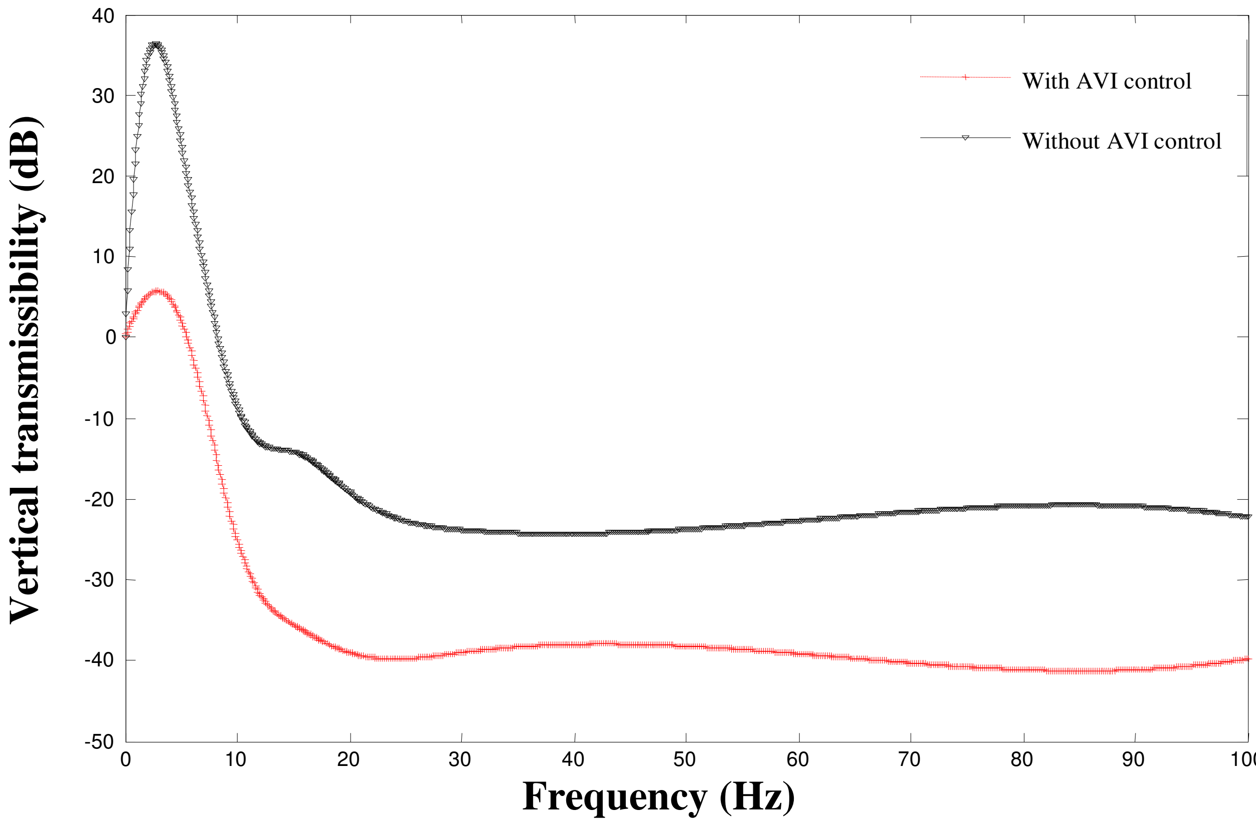

Figure 9. Transmissibility curve with and without AVI control.

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