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Neural Network Optimization of Design Parameters of Stewart Platform for Effective Active Vibration Isolation

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Abstract: In several engineering applications vibration isolation must be carefully considered, as the vibration propagating into or out of the system can significantly degrade the performance. A passive isolation limits the magnification at resonance, at the same time it reduces the high frequency attenuation where as Active Vibration Isolation (AVI) resolves this conflict. Stewart Platform (SP) has been investigated by many researchers, as an AVI system which can isolate vibrations in all 6 degree of freedom. This study focuses on design parameter optimization of SP for AVI. The SP is modeled in MATLAB and design parameter optimization is carried out using Neural Network. The optimal configuration is effective in providing low amplitude at corner frequency and good attenuation at high frequency of >40 dB. Finally, the model developed in MATLAB is validated using Tao configuration.

Key words: Active vibration isolation, Stewart platform, neural network, frequency, investigated

INTRODUCTION

Vibration is one of the vital factors that affect the performance of advanced manufacturing systems, such as ultra-precision machining, micro-manufacturing platform, semiconductor manufacturing equipment and so on (Li *et al*., 2012). The growing need for a better pointing accuracy of instruments connected to spacecraft have lead many researchers to develop a ultra quiet isolation platforms as space observation systems and communication systems involve very rigorous performance requirements (Lin and McInroy, 2006; Skullestad, 2003; Doug *et al*., 1998).

Vibration isolation is a topic that has received a great deal of attention over the past few decades because of wide variety of problems, including vibrating machinery, civil structure in earthquakes and sensitive spacecraft. The problem of isolating the harmful vibration should be carefully taken into account in systems which increasingly need very quiet environment. Vibration is generally regarded as a multiple Degree of Freedom (DOF) phenomenon that is the disturbing force may emerge from different directions (Yang *et al*., 2009b).

There are two main cases where vibration isolation is essential (Hanieh, 2003), the operating machinery can generate an oscillating disturbance (force) propagating into the supporting structure. The disturbance can be introduced by the supporting structure propagating into the sensitive equipment.

Passive isolation is mostly suited for several application, in which one or more stages of spring-mass-damper system are brought in the propagation path. Passive isolation limits the amplification at resonance but reduces the high frequency atteunation. The parameter of the passive isolation system are so adjusted to compromise the amplification, at resonance and high frequency attenuation. To attain simultaneously a low amplification at resonance and high frequency attenuation AVI is considered (Preumont *et al*., 2007).

In order to overcome the disadvantage of conventional passive vibration isolation and achieve satisfactory vibration isolation performance in all 6 DOF, AVI using a SP has become the focus of research recently (Preumont *et al*., 2007; Hauge and Campbell, 2004; Cheng *et al*., 2004; Ren *et al*., 2004).

Many researchers have focused in the area of control methodologies and its effectiveness for specific applications in multi DOF vibration isolation (Yang *et al*., 2009a; Wang and Zhang, 2009; Yun and Li, 2011), this study concentrates on design optimization of SP without varying the control parameters. Design parameter optimization of SP for AVI is carried using Neural Network (NN).

STEWART PLATFORM MODEL DEVELOPED IN MATLAB/SIMULINK FOR AVI

The Stewart platform is a classic parallel manipulator which consists of 2 platforms linked by 6 extensible limbs (actuators) with joints at either end. The fixed platform is called the base frame and the movable platform is called

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the top platform which has 6 DOF relative to the base frame. Figure 1 shows a spatial 6 DOF, 6 Spherical Prismatic Spherical (SPS) parallel manipulator, known as the Stewart platform. About 6 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.

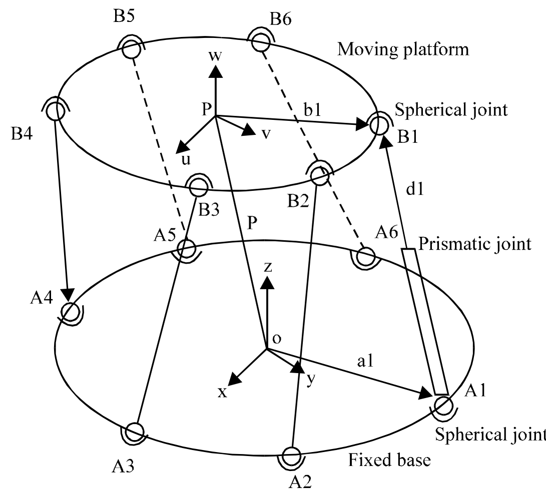

Fig. 1: Spatial 6 DOF, 6 SPS parallel manipulator

Model of the 6 DOF vibration isolation system: 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.

In the present study, active vibration isolation of foundation from machinery vibration is modeled. The vibrating machinery is 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 is carried out using MATLAB/SIMULINK.

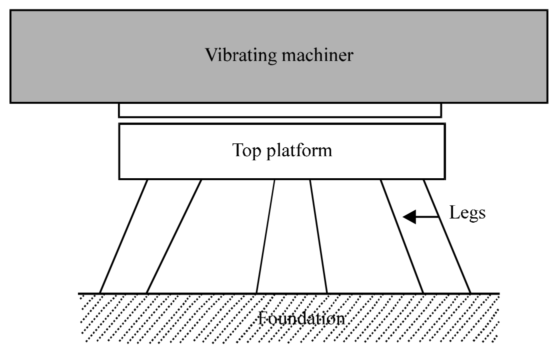

Fig. 2: Stewart platform for isolating foundation from machinery vibration

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 Fig. 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, ${}^{A}R_{B}$ of the moving platform. ${}^{A}R_{B}$ for a RPY (Roll, Pitch and Yaw) wrist is given by:

$$ {}^{A}R_{B} = \begin{bmatrix} \cos\theta_2.\cos\theta_3 & \sin\theta_1.\sin\theta_2.\cos\theta_3 - \cos\theta_1.\sin\theta_3 & \cos\theta_1.\sin\theta_2.\cos\theta_3 + \sin\theta_1.\sin\theta_3 \\ \cos\theta_2.\sin\theta_3 & \sin\theta_1.\sin\theta_2.\sin\theta_3 + \cos\theta_1.\cos\theta_3 & \cos\theta_1.\sin\theta_2.\sin\theta_3 - \sin\theta_1.\cos\theta_3 \\ -\sin\theta_2 & \sin\theta_1.\cos\theta_2 & \cos\theta_1.\cos\theta_2 \end{bmatrix} \quad (1) $$

Where, θ_{1-3} are the roll, pitch and yaw motions, respectively. As shown in Fig. 1, let $a_i = [a_{ix}\ a_{iy}\ a_{iz}]^T$ and ${}^{B}b_i = [b_{iu}\ b_{iv}\ b_{iw}]^T$ 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 ith limb of the manipulator can be written as:

$$ \overline{A_iB_i} = p + {}^{A}R_{B}.{}^{B}b_i - a_i \quad (2) $$

The length of the ith limb is obtained by taking the dot product of the vector $\overline{A_iB_i}$ with itself and:

$$ d_i^2 = \left[p + {}^{A}R_{B}.{}^{B}b_i - a_i\right]^T \left[p + {}^{A}R_{B}.{}^{B}b_i - a_{ic}\right] \quad \text{for } i = 1,2,\ldots,6 \quad (3) $$

Where, d_i denotes the length of the ith limb. Expanding Eq. 3 yields:

$$ d_i^2 = p^Tp + \left[{}^{B}b_i\right]^T\left[{}^{B}b_i\right] + a_i^Ta_i + 2p^T\left[{}^{A}R_{B}.{}^{B}b_i\right] - 2p^Ta_i - 2\left[{}^{A}R_{B}.{}^{B}b_i\right]^T a_i \quad (4) $$

For the inverse kinematics problem, the position vector p and rotation matrix ${}^{A}R_{B}$ 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 Eq. 4 gives:

$$ d_i = \pm\sqrt{p^Tp + \left[{}^{B}b_i\right]^T\left[{}^{B}b_i\right] + a_i^Ta_i + 2p^T\left[{}^{A}R_{B}.{}^{B}b_i\right] - 2p^Ta_i - 2\left[{}^{A}R_{B}.{}^{B}b_i\right]^T a_i} \quad (5) $$

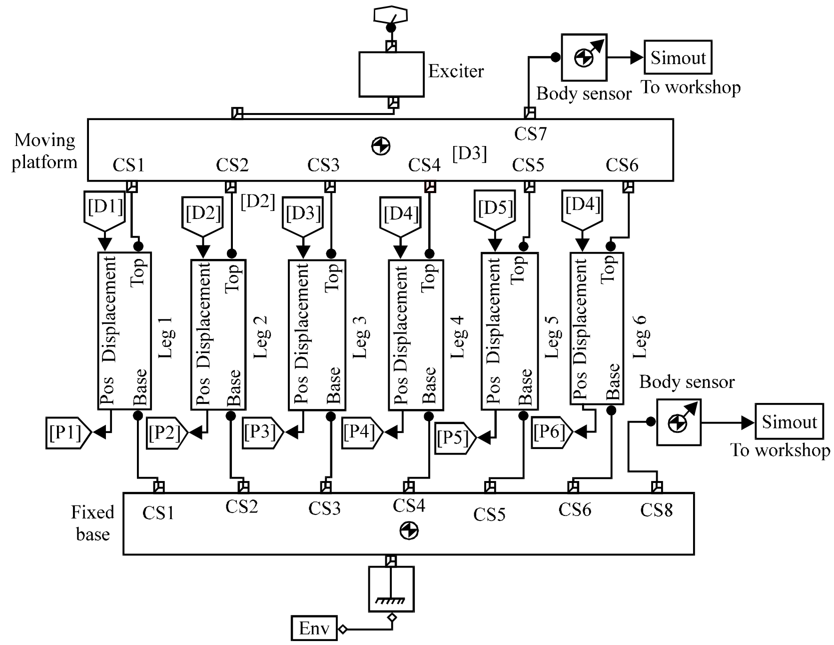

Fig. 3: Model for the 6 DOF AVI system

Fig. 4: Stewart platform at SASTRA University

Equation 5 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 is modelled in MATLAB/SIMULINK. 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. 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, there by isolating the foundation from machinery vibration.

The overall model: An overall model of the AVI system based on Stewart platform is shown in Fig. 3. 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.

Modelling was carried out considering the configuration details of the working model of a Stewart platform, developed at SASTRA University, India (Baig and Pugazhenthi, 2010). Figure 4 shows the physical model based on which MATLAB/SIMULINK 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 Fig. 5. In order to arrive at an optimal design, the physical design parameters of the Stewart platform are varied keeping the control aspect of the model a constant. The control chosen was a simple PID controller and the controller gain was also kept constant.

The goal of active vibration isolation is to have low amplitude at corner frequency (T_r) and provide good attenuation of 40 dB decade^{-1} at high frequency.

So, the researcher have coined a new index, termed as transmissibility index for AVI, α as given by:

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

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

Neural Network was used to optimize the design parameters of the SP for AVI. Training of NN was carried by the 500 different input and corresponding output from Baig and Pugazhenthi (2011). Feedforward Multi-Layer Perceptron (MLP) network was used; training function that updates weight and bias values is according to Levenberg-Marquardt optimization (Trainlm). Figure 6 shows the regression plot of NN prediction of transmissibility versus actual transmissibility, the NN prediction was usually accurate with correlation of coefficients of 95.59%.

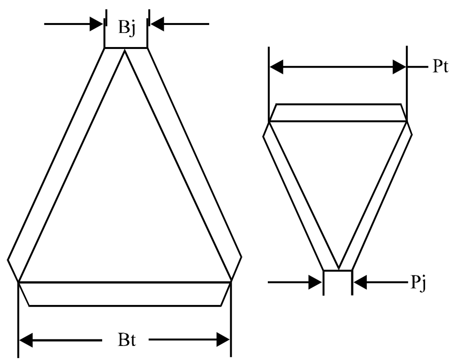

Fig. 5: Base and mobile platform of Stewart platform

After training the NN, randomly generated design parameters were given as the input to the network and transmissibility index for AVI, α is obtained. The design parameters for maximum value of α are the optimal design parameters of SP for AVI. The optimal design parameters of the Stewart platform for 6 DOF AVI for SASTRA model, thus found using NN is: B_t = 0.38 m, B_j = 0.07 m, P_t = 0.16 m, P_j = 0.05 m and h = 0.48 m.

Using the optimal design configuration of SASTRA model, the MATLAB/SIMULINK model is run with and without AVI control and the transmissibility is plotted in Fig. 7. For the SASTRA configuration the resonance occurs at 2.7 Hz. Without AVI control the transmissibility is high at resonance (36 dB) and high frequency attenuation is only 14 dB at 100 Hz which shows a compromise between transmissibility at resonance and high frequency, a typical characteristic of passive isolation. With AVI control there is a smaller peak of 8.7 dB at resonance and high frequency attenuation is -48 dB at 100 Hz. It is evident that optimal design configuration of the SP results in effective isolation.

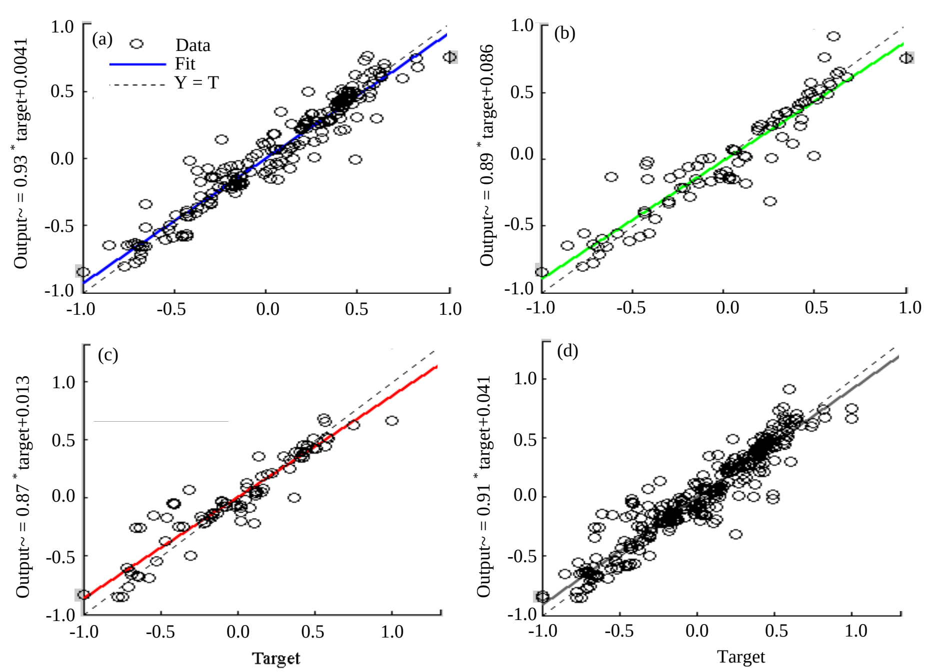

Fig. 6: Regression plot of NN prediction of transmissibility vs. actual transmissibility

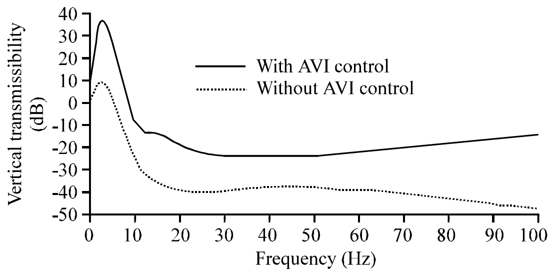

Fig. 7: Transmissibility with and without AVI for SASTRA model

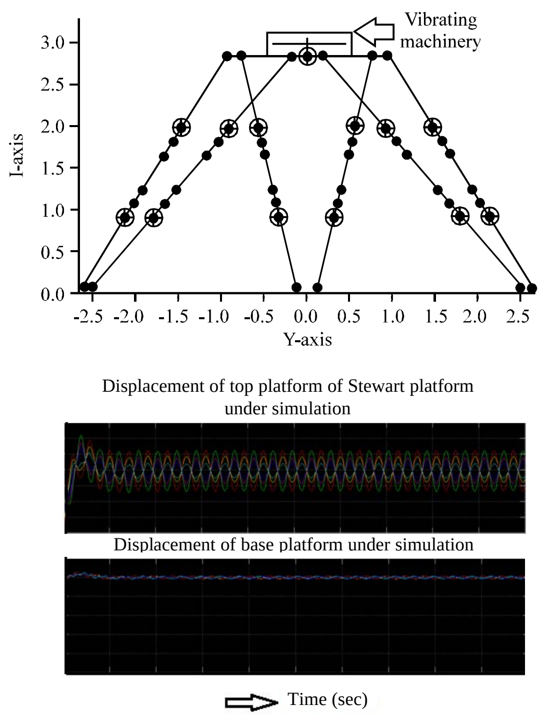

Fig. 8: MATLAB simulation results

Figure 8 shows the snap shot visuals of MATLAB simulation for the optimal configuration of SASTRA model, the displacement plot of top platform and base of Stewart platform clearly indicates its effectiveness in isolating harmful vibration of the vibrating machinery placed at the top of the platform.

VALIDATION

In order to validate the NN based optimization model for the AVI developed in MATLAB/SIMULINK, Yang *et al*. (2009b) research study is considered and parameters adopted are given in Table 1. The MATLAB/SIMULINK model is configured with the parameters of Tao. Different sets of design parameters are fed to the model and corresponding transmissibility

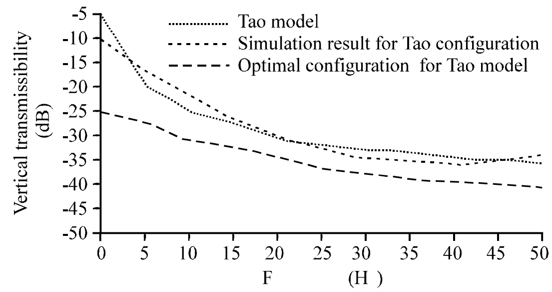

Fig. 9: Transmissibility for Tao model

Table 1: Tao model parameters

Tao model parameters	Values
Mass of the payload, m	12.4 kg
Moment of inertia of the payload to the centroid, $I_x = I_y$	0.157 kg m^2
I_z	0.313 kg m^2
Radius of the upper plate r_p	0.2 m
Radius of the lower plate r_b	0.5 m
Platform height h	0.28 m
Central angle between the adjacent joints with the symmetric distribution, θ	30°
Moving mass of the strut m_i	1 kg
Stiffness coefficient k_i	2.0×10^3 N m^{-1}
Damping coefficient b_i	19.1 kg sec^{-1}

$B_t = 0.75$ m, $B_j = 0.5$ m, $P_t = 0.3$ m, $P_j = 0.2$ m and $h = 0.28$ m

Table 2: Optimal design configuration for Tao model for effective isolation

Parameters	Dimension (m)
Height (h)	0.42
Base triangle distance (B_t)	0.85
Distance between the joints of base (B_j)	0.09
Moving platform triangle distance (P_t)	0.35
Distance between the joints of moving platform (P_j)	0.07

values is obtained from simulation of the model. These sets of input design parameters and corresponding α are used to train the NN. Then optimal configuration for the Tao model is obtained from NN. Figure 9 shows displacement transmissibility in Z direction for Tao model, the MATLAB/SIMULINK model was able to predict same transmissibility as seen. The transmissibility for the optimal design parameters for Tao model as predicted by NN is plotted and a low transmissibility is achieved at resonance and as well, at high frequency with same control parameters. It is evident that by choosing the correct design parameters the transmissibility can be reduced. The optimal parameters for Tao model is tabulated in Table 2.

EFFECT OF DESIGN PARAMETER ON TRANSMISSIBILITY

The design optimization of Stewart platform for AVI is considered by evaluating the effect of realistic design parameters B_j, B_t, P_j, P_t and h. The effect of these parameters on transmissibility is plotted in Fig. 10-14. The

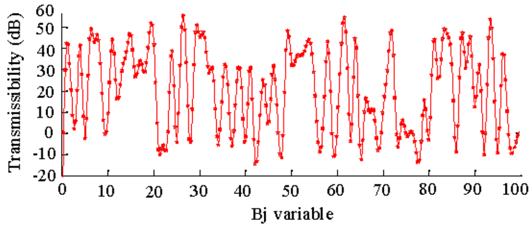

Fig. 10: Effect of base joint distance (B_j) on transmissibility

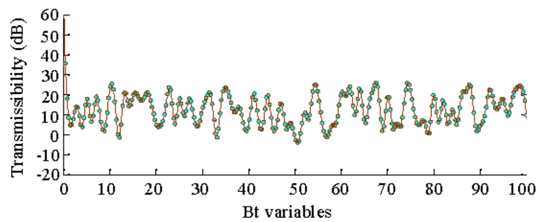

Fig. 11: Effect of base triangle distance (B_t) on transmissibility

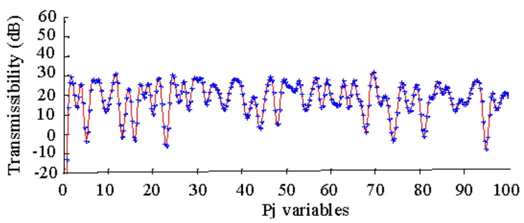

Fig. 12: Effect of platform joint distance (P_j) on transmissibility

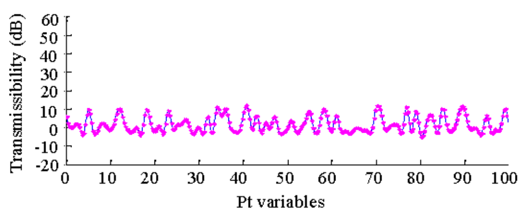

Fig. 13: Effect of platform triangle distance (P_t) on transmissibility

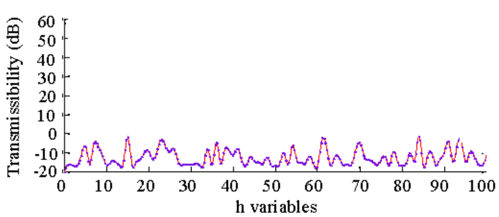

Fig. 14: Effect of height of the platform (h) on transmissibility

overall percentage effect of these parameters is tabulated in Table 3. The Base joint distance (B_j) and Platform joint distance (P_j) influence more on the transmissibility of the isolation platform compared to other parameters. The percentage effect of design parameters on transmissibility is tabulated in Table 3.

Table 3: Percentage effect of design parameters on transmissibility

Parameters	Effect on transmissibility (%)
Distance between the joints of base (Bj)	38.48
Distance between the joints of moving platform (Pj)	23.82
Base triangle distance (Bt)	18.10
Height (h)	10.11
Moving platform triangle distance (Pt)	9.47

CONCLUSION

The neural network 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 greater than -40 dB in the vicinity of 100 Hz for the model developed in MATLAB/SIMULINK. The model developed in MATLAB/SIMULINK is validated with Tao configuration. It is also proved through simulation results that by choosing optimal design parameters of SP the transmissibility can be reduced by keeping the same control parameters.

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