CHAPTER 6: RESULTS AND DISCUSSION

Important results obtained during the optimization of design parameters of Stewart platform for AVI are discussed in this chapter. The two categories of isolation are separately presented. Section 6.1 considers the results of design optimization of Stewart platform while isolating machine vibration being transmitted to the foundation and section 6.2 concentrates on the results of design optimization of Stewart platform for isolating sensitive equipment from vibrating floor.

6.1. AVI OF FOUNDATION FROM MACHINERY VIBRATION

In this case of isolation heavy vibrating machine is kept on top of the platform and the goal is to isolate the foundation from the vibration generated by the machine. Isolation of the body of a spacecraft from the vibration generated by an engine is one of the real world examples. Initial investigation into the optimization of design parameters have been carried out using GA based algorithm by keeping MATLAB simulation in the loop and later by using an efficient neural network prediction. During the course of optimization the five design parameters of Stewart platform are varied and all other parameters such as control parameters, inertial parameters of the platform and the machine mounted are all kept constant. A SIMULINK model is run each and every time and the transmissibility is calculated. The changes in leg length of the Stewart platform due to extension/retraction of linear actuators in the legs while isolating the machinery vibration are captured in a snap shot during simulation and shown in Fig. 6.1. The figure shows the length of all the six legs as calculated by inverse kinematic equation, the actual leg length during simulation and deviations between the calculated and actual leg lengths during simulation. The plot shows that the legs of the Stewart platform follow the expected course as calculated by the inverse kinematic equation with negligible deviations.
6.1. Effect of Design Parameters on AVI of Foundation

The effect of design parameters of Stewart platform considered for optimization is studied. The parameters studied are: B_t-Base triangle distance, B_j-Base joint distance, P_t-Platform triangle distance, P_j-Platform triangle distance, h-Height of the platform. The effects of these parameters are studied at two different frequencies both at resonance (2.7 Hz) and at a high frequency of 100 Hz, to analyse the quality of isolation in terms of amplitude reduction at resonance and high frequency attenuation. One by one, a parameter under consideration alone is varied keeping the other parameters constant at their respective optimal values.

a) Effect of Base Joint Distance (B_j) on Transmissibility at Resonance

The effect of base joint distance on transmissibility is shown in Fig. 6.2. As the distance between the joint increases the transmissibility at resonance also increases,
hence it is evident that minimum is the distance between the joints, lower is the peak at resonance. Hence, distance between joints at base may be fixed at minimum, based on the physical size of the universal joints so as to accommodate them without interference.

![Graph showing the effect of base joint distance on transmissibility at resonance](image)

**Fig. 6.2. Effect of B_j on Transmissibility at Resonance**

b) **Effect of Base Triangle Distance (B_t) on Transmissibility at resonance**

The effect of base triangle distance on transmissibility is shown in Fig. 6.3. The transmissibility was high for B_t values less than 48 cm and remains almost constant thereafter. Hence the B_t value can be kept greater than or equal to 48 cm as there is no change in transmissibility, even if B_t is increased. This aspect of larger base triangular distance is particularly attractive when mounting machine of huge size and weight, which requires broader base.
c) **Effect of Platform Joint Distance** ($P_j$) **on Transmissibility at resonance**

The effect of platform joint distance on transmissibility is shown in Fig. 6.4. As the distance between the joint increases the transmissibility at resonance also increases, hence it is evident that minimum is the distance between the joints, lower is the peak at resonance. The minimum distance between joints at platform is to be decided considering dimensions of spherical joint, in order to avoid any hindrance in assembly.
d) **Effect of Platform Triangle Distance (Pt) on Transmissibility at resonance**

The effect of platform triangle distance on transmissibility is shown in Fig. 6.5. Transmissibility at resonance is minimal for minimum platform triangle distance. With increase in the platform triangle distance, the transmissibility at resonance also increases. As both Pt and Pj should be minimised to have a reduced transmissibility, a trade-off is to be done and this is reflected in the optimization results presented in chapter 5, wherein the optimal values of Pt and Pj are found to be 16 cm and 5 cm respectively.

![Fig. 6.5. Effect of Pt on Transmissibility at Resonance](image)

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e) **Effect of Height of the Platform (h) on Transmissibility at resonance**

The effect of height of the platform on transmissibility is shown in Fig. 6.6. Transmissibility at resonance is minimal for a range of values of height of platform. Height of the platform is an important parameter when selecting SP for AVI, as it ensures stiffness while carrying huge machine. Transmissibility at resonance will be in the acceptable range if the height of the platform is between 42 and 52 cm.
The behaviour of AVI system is different at high frequency when compared to that at resonance. At high frequency it is desired that transmissibility is always less than 1. As the ratio of amplitude of vibrating machine to isolated platform is in fraction, when expressed in decibels (logarithmic of amplitude ratio), it is always negative. Hence, the individual effects of the design parameters are also studied at high frequency and are presented in the subsequent sections.

f) Effect of Base Joint Distance (Bj) on Transmissibility at high frequency

The effect of base joint distance on transmissibility is shown in Fig. 6.7. As the distance between the joint increases the transmissibility at 100 Hz also increases, hence it is evident that minimum is the distance between the joints, better is the attenuation at high frequency of 100 Hz. Therefore, the base joint distance needs to be smaller to reduce transmissibility at resonance as well as to have good high frequency attenuation. This is the reason for optimized value of Bj being 7 cm.
g) **Effect of Base Triangle Distance (B_t) on Transmissibility at high frequency**

The effect of base triangle distance on transmissibility is shown in Fig. 6.8. The transmissibility was minimal, for B_t = 38 cm. For values of B_t less than 38 cm and greater than 40 cm, the transmissibility is higher. Even though the value of B_t at resonance was required to be greater than 48 cm, the effect of B_t at high frequency has a profound effect on optimal configuration of SP. This is seen in the optimal configuration of SP with B_t value of 38 cm.
h) **Effect of Platform Joint Distance (Pj) on Transmissibility at high frequency**

The effect of platform joint distance on transmissibility is shown in Fig. 6.9. As the distance between the joint increases the transmissibility at high frequency also increases, hence it is evident that minimum is the distance between the joints, better is the attenuation at high frequency. A similar effect of Pj has been observed at resonance and got reflected in optimization results with a Pj value of 5 cm.

![Graph showing effect of Pj on transmissibility at 100 Hz](image)

**Fig. 6.9. Effect of Pj on Transmissibility at 100 Hz**

i) **Effect of Platform Triangle Distance (Pt) on Transmissibility at high frequency**

The effect of platform triangle distance on transmissibility is shown in Fig. 6.10. Transmissibility at high frequency is minimal for minimum platform triangle distance. As we increase the platform triangle distance, the high frequency attenuation remains unchanged till a particular value of Pt (less than 32 cm) and high frequency attenuation gets degraded subsequently and transmissibility increases. The effect of Pt at resonance as well as at high frequency is similar, requiring it to be lower which resulted in a lower Pt value in the optimal configuration of 16 cm.
j) Effect of Height of the Platform (h) on Transmissibility at high frequency

The effect of height of the platform on transmissibility is shown in Fig. 6.11. High frequency attenuation is found to be good and in the acceptable range if the height of the platform is between 40 and 50 cm. The effect of height at resonance called for a height between 42 and 52 cm. The optimal height from the ANN results is 48 cm, which is validated through these effects.

Fig. 6.10. Effect of $P_t$ on Transmissibility at 100 Hz

Fig. 6.11. Effect of $h$ on Transmissibility at 100 Hz
6.2. AVI OF SENSITIVE EQUIPMENT FROM FLOOR VIBRATIONS

In this case of isolation sensitive equipment is kept on top of the platform and the goal is to isolate the equipment from the floor vibrations. This kind of AVI of sensitive equipment is needed in the field of micro-manufacturing, high-resolution measurement, etc. Similar to the case of AVI of foundation discussed in section 6.1, initial investigation into the optimization of design parameters of SP have been carried out using GA based algorithm with SIMULINK model being simulated within the loop for computing transmissibility index. Sensory data from the base of the Stewart platform is taken as input to the inverse kinematic equation, leg lengths required to counteract vibration from the base and isolate the sensitive equipment are computed.

6.2.1. Effect of Design Parameters on AVI of Equipment

In this case also, the individual effects of the design parameters are studied at two different frequencies, one at resonance of 2.7 Hz and the other at high frequency of 100 Hz. Each design parameter is varied and its effect on transmissibility is studied by keeping the other design parameters at optimal values.

a) Effect of Base Joint Distance ($B_j$) on Transmissibility at resonance

The effect of base joint distance on transmissibility is shown in Fig. 6.12. As the distance between the joints at the base of the SP increases the transmissibility at resonance also increases. Hence, a minimum possible joint distance is to be adopted. Thus, the optimized value of $B_j$ is 9 cm.
The effect of base triangle distance on transmissibility is plotted in Fig. 6.13. The transmissibility at resonance is minimal for values of base triangle distance ranging from 25 to 35 cm. The transmissibility increases with any further increase in $B_t$. Hence, for the given set of other optimal design parameters, variation within the range of 25 to 35 cm of $B_t$ does not affect the AVI. The optimal value of $B_t$ (25 cm) found by ANN is thus validated.
c) **Effect of Platform Joint Distance (P\textsubscript{j}) on Transmissibility at resonance**

The effect of platform joint distance on transmissibility is studied by varying P\textsubscript{j} in steps of 0.5 cm and the same is shown in Fig. 6.14. In order to avoid interference of spherical joint at the platform, the lowest possible distance between the adjacent joints is taken as 5 cm. As the distance between the joint increases the transmissibility at resonance also increases, hence it is evident that the minimum is the distance between the joints, lower is the peak at resonance.

![Fig. 6.14. Effect of P\textsubscript{j} on Transmissibility at Resonance](image)

**d) Effect of Platform Triangle Distance (P\textsubscript{t}) on Transmissibility at resonance**

The effect of platform triangle distance on transmissibility is shown in Fig. 6.15. Transmissibility at resonance is minimal for platform triangle distance of 12 cm. Any further increase in platform triangle distance results in higher transmissibility.
e) Effect of Height of the Platform (h) on Transmissibility at resonance

The effect of height of the platform on transmissibility is shown in Fig. 6.16. Transmissibility at resonance is minimal for a range of values of height of platform. Transmissibility at resonance will be in the acceptable range if the height of the platform is between 58 and 63 cm.
f) Effect of Base Joint Distance (B_j) on Transmissibility at high frequency

The effect of base joint distance on transmissibility is shown in Fig. 6.17. Transmissibility at high frequency is minimum for values of base joint distance around 10 cm resulting in high frequency attenuation of more than 40 dB. A similar effect of B_j on transmissibility has been seen at resonance and hence the optimal value is placed at 9 cm.

![Transmissibility vs Base Joint Triangle](image)

Fig. 6.17. Effect of B_j on Transmissibility at 100 Hz

g) Effect of Base Triangle Distance (B_t) on Transmissibility at high frequency

The effect of base triangle distance on transmissibility is shown in Fig. 6.18. The transmissibility has been found to be minimal for B_t = 25 cm. For values of B_t less than 25 cm and greater than 25 cm, the transmissibility increases. At resonance also B_t of 25 cm has been found to yield lower transmissibility. Therefore, the value of h in the optimal configuration of SP stands at 25 cm agreeing with the results.
h) **Effect of Platform Joint Distance (P\textsubscript{j}) on Transmissibility at high frequency**

The effect of platform joint distance on transmissibility is shown in Fig. 6.19. For P\textsubscript{j} less than 10 cm, higher is attenuation at high frequency. For higher values of platform joint distance, transmissibility increases and attenuation suffers. The requirement of P\textsubscript{j} at resonance has also been to have minimal distance between spherical joints. Hence, the optimal value is found to be 6 cm.
i) **Effect of Platform Triangle Distance \((P_t)\) on Transmissibility at high frequency**

The effect of platform triangle distance on transmissibility is shown in Fig. 6.20. Transmissibility at high frequency is minimal for minimum platform triangle distance. As we increase the platform triangle distance, the high frequency attenuation remains unchanged till 15 cm of \(P_t\) and high frequency attenuation becomes poor afterwards. Combined effect of \(P_t\) at resonance and at high frequency results in the optimal value being 12 cm.

![Fig. 6.20. Effect of \(P_t\) on Transmissibility at 100 Hz](image)

j) **Effect of Height of the Platform \((h)\) on Transmissibility at high frequency**

The effect of height of the platform on transmissibility is shown in Fig. 6.21. High frequency attenuation will be high and will be in the acceptable range if the height of the platform is between 58 and 63 cm, similar effect has been seen at resonance. The optimal height of the platform is found to be at 60 cm.
6.3. Effect of Stiffness on AVI of SP

A plot of stiffness against height of the Stewart platform is shown in Fig. 6.22. Stiffness increases with increase in height initially and then it decreases. The working height of the platform should satisfy workspace and singularity constraints. Generally, a cubic configuration ensures better AVI compared to non-cubic configuration for same control strategy because cubic configuration ensures orthogonality and symmetry in all the directions (Geng and Hyanes, 1994). On the other hand, it is required to have a stiff platform while isolating foundation from machinery vibration (Preumont et al., 2007). Therefore, the optimized height of the Stewart platform found in the current research is between the height of the stiff platform and height of cubic configuration as depicted in Fig. 6.22. The optimal height of 48 cm offers moderate value of stiffness within the work volume of the Stewart platform satisfying the geometric constraints of both reachable joint angles and attainable leg lengths.

It is required to have a soft platform while isolating sensitive equipment from vibrating floor (Preumont et al., 2007). The optimal height of the platform for AVI of sensitive equipment from vibrating floor has been found to be 60 cm, this height
offering a low value of stiffness. The height of the platform thus optimized is in between the height of the soft platform and the height of cubic configuration as shown in Fig. 6.22.

![Graph showing the effect of stiffness on various platform heights](image-url)

**Fig. 6.22. Effect of Stiffness**