The cylindrical joints application in spatial suspension possibility

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Abstract. The paper considers the implementation of a spatial oscillation protection system to reduce low-frequency oscillational oscillation and impacts. The existing oscillation protection approaches are generalized. A variant of the spatial oscillation protection system based on oscillation isolation devices with cylindrical joints is proposed. A preliminary assessment of the physical model’s practical implementation feasibility and the physical analogue’s implementation is given. An algorithm for determining the mobility criteria by the matrix determinant values of the Plucker coordinates on the screw method basis is considered.

Introduction

Natural and man-made shock processes lead to the broadband oscillation effects’ emergence. As a rule, energy impacts of low power are absorbed by the structural elements. To absorb high-power oscillations, a set of oscillation and seismic protection measures is required. If the frequencies coincide with the resonant frequencies of the spatial structures, undesirable amplitudes increase. Among the problems and the theory tasks of seismic protection and oscillation protection at low frequencies, which are considered in numerous works all over the world, the issues of spatial oscillation protection, the selection of the system’s physical characteristics ratio are less developed compared to the analysis and synthesis of the vertically mounted oscillation isolators’ dynamic characteristics. Most researchers consider one-dimensional systems using motion-limited guiding mechanisms. As a rule, small displacements of vertically arranged insulators without additional energy absorption systems in the low-frequency range are considered. The difficulty of absorbing the infrasonic and low-frequency range of frequencies makes various rubber cushioning materials ineffective at low frequencies (0.01-100Hz). The use of broadband elastic rubber or polymer elements leads to an increase in suspension travels without providing energy absorption in the critical frequency range. The acoustic noise reduction from the use of polymeric materials sometimes leads to an increase in the infrasonic range oscillations.

In this regard, it seems relevant to consider the issue of spatial oscillation protection, taking into account the geometry of the oscillation protection elements’ arrangement. The solution to the problem is complicated by the complexity of describing the system in space at the engineering solutions’ level. The problem under consideration is the geometric problem of optimal synthesis. It consists in the search for the optimal arrangement of elements in space and the selection of their physical...
characteristics. Three approaches are used to solve this problem. In the framework of the first approach, the force action arising in the oscillation protection system is considered as control. In this approach, the task of creating an oscillation protection system is reduced to the task of creating an effective regulator, based on the oscillation protection system’s ultimate capabilities estimates. However, in practice it is not always possible to implement the required regulatory system according to the found control law [1,2]. In this approach, it is especially difficult to take into account the inertial motion transducer’s inertial properties, which creates an effect in the low-frequency range of frequencies. The second approach is based on the oscillation protection system’s optimal transfer function construction in a linear and nonlinear setting. This approach focuses on the displacement and shock overloads’ assessment at the attachment points, taking into account the system’s flexibility [3]. The third approach is to optimize the parameters which structure is given [4]. In this case, nonlinear programming and parametric optimization methods are used. The tasks are solved, as a rule, numerically, therefore, the role of analytical solutions has been repeatedly emphasized by the leading experts in the optimal design of structures [1,2,3].

Results
The model describing its own dynamic properties employs the techniques developed at the Institute of Mechanical Engineering of the Russian Academy of Sciences, which are based on the principle of using Plücker coordinate matrices and helical number elements. A feature of this method is a more simplified variation of the elements’ rotation angles in space and the choice of their installation location. The implementation of such an approach in a Cartesian coordinate system complicates the analytical calculations and increases the errors in engineering calculations. The use of Plücker coordinate matrices in assessing the system’s mobility makes it possible to estimate the kinematic stability degree. The use of Plücker coordinate matrices to determine the uniform dynamic properties for active oscillation protection systems makes it possible to solve the problem of tuning the system to different frequency ranges and relative damping areas, making the technique universal in terms of searching for extrema of damping, stiffness, and relative inertia functions. Creation of passive constructive solutions based on the models using the theory of screw reckoning makes it possible to implement the adjustable oscillation protection systems by controlling their frequency and damping characteristics due to the optimal arrangement of the oscillation isolation elements in space and the selection of their relationships and physical characteristics. Thus, the oscillation protection model described by the Plücker coordinates matrices built on the screw numeration basis should solve the problem of designing an oscillation isolation system for the selected structure. To solve the optimization problem, as a rule, the criterion is the minimum mass and dimensions of the oscillation protection element; to solve the seismic protection problem, the criterion will be the optimal absorption of pulse energy during the known movements satisfying the oscillation isolation system’s stability condition.

The seismic perturbation feature is the complex nature of the object’s movement, the attachment point’s mobility in the horizontal and vertical direction with a predominance of horizontal displacement at large amplitudes of oscillations [5].

To free a given frequency range from natural frequencies, it is necessary to introduce elastically inertial relations with respect to relative displacement into the matrix of OPD Plücker coordinates. The method of freeing the frequencies by localizing the frequency spectrum is a particular task of controlling the Rayleigh system’s spectrum. The spectrum localization problem’s solution is possible using ball joints due to the oscillations’ pseudo-independence implementation. If we assume that the side effects do not exceed 10% of the oscillations along the main axis of the oscillation isolator. One of the options for the spatial structures’ implementation is the construction of linear conservative systems based on the given frequency dependences of the input dynamic compliance and transmission coefficient based on the method of the electrical circuits and electromechanical analogies’ synthesis “star – delta” [6].
A general approach to the object’s movement as a solid body as a link in a mechanism using the movement of relative helical axes with movement relative to several given positions in space based on spherical trigonometry. Using the screws theory allows the mechanical quantities taken as the system parameters to be described as the elements with a force effect and a torque simultaneously. And the use of Plücker matrices to operate with these screws with real and dual quantities as the components of screw quantities.

In this case, the oscillation protection system becomes a special case of the parallel kinematics’ mechanism, the studies of which are devoted to [7, 8]. If so, it can be assumed that the model under study, like any mechanism of parallel kinematics, can have singular points at large displacements at which the oscillation protection system will seizure. Let us introduce the assumption that the operation of our mechanism lies outside the stability loss areas and seizure is not possible.

To unleash the oscillations, we introduce the model, the conditions for the axes’ coincidence of the oscillation isolators with the mass center axes are introduced, which are widely known by the method of “inclined supports” used in aircraft construction. This gives an opportunity to solve the problem of reducing the natural frequencies to a narrow range and reducing the connectedness of the oscillations.

The task of constructing a model is reduced to solving several subtasks.

- The problem of assessing kinematic mobility
- Development of the individual system components’ models at attachment points
- Definition of criteria for assessing the dynamic properties
- Development of methods for accounting the dynamic properties by kinematic parameters

Each individual rigid element of oscillation protection is represented by a rod with the ends fixed on a solid body with a rigid base using spatial hinges. The position of the oscillation protection systems’ axes remains unchanged and is characterized by the unit vector \( \vec{e}_i \) position of a unit vector in space relative to the coordinate system XYZ characterized by the unit vector of the Plücker coordinate matrix [9,10],

\[
a^T = [\cos \alpha_i \cos \beta_i \cos \gamma_i \quad l_i \quad m_i \quad n_i]
\]  

(1)

Where

\[l_i = \eta_i \cos \gamma_i - \zeta_i \cos \beta_i\]
\[m_i = \xi_i \cos \alpha_i - \zeta_i \cos \alpha_i\]
\[n_i = \zeta_i \cos \beta_i - \eta_i \cos \alpha_i\]
\[\cos \alpha_i = \sin \gamma_i \cos \lambda_i\]
\[\cos \beta_i = \sin \gamma_i \sin \lambda_i\]
\[\cos \gamma_i = \cos \gamma_i\]

\(\xi_i, \zeta_i, \eta_i\) – are the coordinates of the upper hinges’ centers

\(\gamma_i\) – is the angle between axis Z and the oscillation isolator axis

\(\lambda_i\) – is the angle between the direction of the axis X and the projection of the oscillation isolator axis

\(l_i, m_i, n_i\) – are the vector moments relative to the axes XYZ.

The coordinate axes’ origin and rotation transfer do not affect the Plücker coordinate matrix and its determinant. The stability degree of the object placed on the oscillation isolators is characterized by the absolute value of the Plücker coordinates matrix determinant. The maximum value of the matrix determinant corresponds to the most stable object’s state.

The dependence of the angular and linear movements of the object in the vector form \(X\) relative to the coordinate system XYZ to the Plücker coordinate matrix \(A\) will correspond to the velocity vector \(\Delta V\). The force impact on structural elements is a product of velocity vectors \(\Delta V\) on the matrix of static stiffness \(C_0\) at the oscillation isolators’ attachment points. That is, the force impact \(F\) can be represented as a transposed matrix of Plücker coordinates \(A^T\) on the integral displacements’ vector.
\[
A^T = \begin{bmatrix}
\cos \alpha_1 \cos \beta_1 & \cos \gamma_1 & l_1 & m_1 & n_1 \\
\cos \alpha_2 \cos \beta_2 & \cos \gamma_2 & l_2 & m_2 & n_2 \\
\cos \alpha_3 \cos \beta_3 & \cos \gamma_3 & l_3 & m_3 & n_3 \\
\cos \alpha_4 \cos \beta_4 & \cos \gamma_4 & l_4 & m_4 & n_4 \\
\cos \alpha_5 \cos \beta_5 & \cos \gamma_5 & l_5 & m_5 & n_5 \\
\cos \alpha_i \cos \beta_i & \cos \gamma_i & l_i & m_i & n_i
\end{bmatrix}
\]  
(2)

For an object on elastic oscillation isolators, the following ratios of velocity and displacement vectors are valid

\[
\Delta V = A \cdot X 
\]  
(3)

\[
\Delta V = F_{\Delta V} \cdot C_0^T 
\]  
(4)

\[
\Delta V = F_{\Delta V} \cdot B_0^T 
\]  
(5)

\[
F_{\Delta V} = G_0 \int_0^t \Delta V dt 
\]  
(6)

\[
F = A^T F_{\Delta V} \tau 
\]  
(7)

The diagonal matrix of the oscillation isolators’ elastic elements has the form (8). We believe that the oscillation isolators in question do not transmit the moments, and the forces depending on the oscillation isolators’ stiffness are concentrated in the oscillation isolators’ mass center

\[
C_0 = \begin{bmatrix}
C_1 & 0 & 0 & 0 & 0 \\
0 & C_2 & 0 & 0 & 0 \\
0 & 0 & C_3 & 0 & 0 \\
0 & 0 & 0 & C_4 & 0 \\
0 & 0 & 0 & 0 & C_5 \\
0 & 0 & 0 & 0 & C_i
\end{bmatrix}
\]  
(8)

The diagonal matrix of the oscillation isolators’ shock-absorbing elements is described by the matrix

\[
B_0 = \begin{bmatrix}
b_1 & 0 & 0 & 0 & 0 \\
0 & b_2 & 0 & 0 & 0 \\
0 & 0 & b_3 & 0 & 0 \\
0 & 0 & 0 & b_4 & 0 \\
0 & 0 & 0 & 0 & b_5 \\
0 & 0 & 0 & 0 & b_i
\end{bmatrix}
\]  
(9)

In the simplest case, when there are six oscillation isolators located along three coordinate axes and compensating for movements and moments independently of one another. The parameters’ optimization is reduced to the analysis of the matrix 6X6 determinant extrema.

In practice, statically indeterminate systems often occur with an arbitrary number of oscillation isolators significantly more than six [9].

In this case, the form’s transposition is

\[
F = [A^T \times C_0 \times A] \times X \tau
\]  
(10)

Where \( C = [A^T \times C_0 \times A] \).

The spatial oscillation protection systems considered in works 1 and 2 were oriented towards the use of ball joints (Figure 1). This made it possible to vary the angles in three planes. To solve the oscillation protection problem using ball joints, it is enough to use 6 oscillation isolators.
Let us consider the solution to the problem using the cylindrical joints.

In this case, the suspension system will undergo restrictions on one of the planes.

In place of the spherical joints used in [9–11], we apply the spatial (cylindrical) joints. In this case, the use of six oscillation isolators will not be enough to ensure the stability of the structure. The analysis showed that using the supports’ slopes in one plane, the features of increasing stiffness by triangular trusses, the eight-rod oscillation isolation system with four symmetrically located triangular elements can be considered as promising (Figure 2). A similar technical solution loses to a six-rod statically determinate system in terms of weight characteristics. Adjusting the angles to the mass center axis in the place of the mass center will lead to the additional torques’ emergence, which is compensated by a more rigid arrangement of the oscillation isolators. Placement inside the inertial converting blocks [12] will reduce the impact and ensure high efficiency under shock loads.

The use of cylindrical hinges with a partial possibility of rotation requires high requirements for the structure’s symmetry. With small oscillations of the system 6, the supports 2 should work as pivotally motionless. When large displacements are pivotally movable with the action along the curved linear guides 9, (the guides are not shown).

In this case, a contradiction arises since only one reaction can occur in a pivotally movable support. In such a support, a rotation of the section, linear movement in one of the directions is permissible. For example, for the movable support 11 shown in Figure 2, the horizontal movement is permissible, but
the vertical movement is not possible. Thus, one vertical reaction arises in the support. The use of curved profiles is possible as guides. This will resolve the contradiction in both horizontal and vertical displacements under the seismic impact [5].

A feature of the oscillation protection system was the distance from the mass center to the mounting points of the suspension 3. Figure 2 shows the difference in the placement of the suspension with spherical hinges of the support 10 from the supports with cylindrical hinges 11. It is optimal to position the smaller-sized objects with a circular shape along the axes passing through the mass center in this case, the suspension system requires special structural protective and decorative solutions. An example of such placement is the support 1. The frequency is according to the associated forms x, y, z are determined from the ratio 11:

\[-\omega^2 \cdot M_{x,y,z} + C_0 = F\]

For the proposed solution, the Plücker coordinate matrix A will have a dimension [6x8], stiffness matrix $C_0$, damping $B_0$, inertia $M_{x,y,z}$ dimension [8x8] respectively.

Assessment of kinematic mobility additional inertia signs are determined from the ratios considered in a previously published work [12]. Figure 3 shows a prototype of a physical model. Resilient prototype elements with rigidity $2 \times 10^6$N/m according to the proposed layout provide the sufficient system’s stability. Evaluation of the prototype fault tolerance showed that the failure of two vertical oscillation isolators leads to an increase in displacements by 20%. Failure of three oscillation isolators or two, entering a bunch of oscillation isolators, leads to loss of system stability. In the physical model proposed for further studies, the stiffness of the oscillation isolators should increase to $5 \times 10^5$N/m elastic and inertial elements will be introduced. It is also planned to develop an original oscillation test bench based on two EGV-10 oscillation stands.

**Figure 3.** Prototype physical model of spatial suspension.

**Summary**

There are methods of the supports’ inclined installation in which isolation of both angular and translational movements is possible. The algorithm for choosing the dynamic parameters has been proposed. The option of creating a statically indeterminate spatial oscillation protection system will require the creation of locking mechanisms to ensure the bonds’ release at large horizontal amplitudes and the implementation of the guides ensuring the free return of the oscillation protection systems’ guides. It may be necessary to implement the hydro-elastic stops with the built-in oscillation isolators to effectively dampen the oscillation protection system when breaking the elastic ties with the soil.

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