DESIGN AND ANALYSIS OF A NOVEL HEXAPOD PLATFORM FOR HIGH-PERFORMANCE MICRO-VIBRATION MITIGATION

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ABSTRACT

Hexapod platforms for high-performance micro-vibration isolation are rarely integrated on a spacecraft due to several drawbacks they still present such as system complexity, considerable amount of added mass and need for control algorithm. This paper focuses on the design and analysis of a novel hexapod platform formed by six 2-collinear-DoF struts. Each strut is embedded with 2 Electromagnetic Shunt Dampers (EMSD) which is a semi-active damping technology that has been recently developed. This work starts with the evaluation of a bipod system with well-establish boundary conditions and it analyses its limitations. It then studies the isolation performance of a full hexapod in relation to different boundary conditions of the struts and their geometric configuration. This paper is intended as a first step toward the development of a new class of platforms that are specifically designed for micro-vibration mitigation.

INTRODUCTION

Hexapod platforms are regularly used nowadays for terrestrial applications such as flight simulators, fast pick-and-place robots, micro-surgical procedures and machine tooling. Also for space applications parallel manipulators have been identified as possible solutions to solve the requirement of high stability on board a spacecraft.

An ultra-quiet environment is indispensable for space systems with high-precision instruments (e.g. space interferometers and laser communication equipment). Such stability can be jeopardised by the micro-vibration disturbances that are produced by several on-board mechanisms, such as reaction wheels, momentum wheels and cryo-coolers [1-2]. In the attempt to isolate payloads from the noisy spacecraft bus, novel hexapod platforms have been designed and tested for space missions over the last few decades. Examples of such hexapod platforms are VISS (Vibration Isolation and Suppression System which had six passive viscous dampers [3]), SUITE (Satellite Ultraquiet Isolation Technology Experiment made of six active struts with embedded piezoelectric actuators [4]) and MVIS (Miniature Vibration Isolation System which combined passive and active isolation to obtain a hybrid solution [5]). Nevertheless, these mechanisms are rarely integrated in space missions due to some limitations and drawbacks that they still present such as dynamic complexity, considerable amount of added mass, need for control algorithm and sensors [6]. All these aspects, together with the limited isolation performance enhancement, have severely affected the use of hexapod platforms for high-sensitivity missions. Recently, the main research focus in the field of micro-vibration mitigation has been dedicated to the improvement of the strut isolation performance with the development of novel damping systems [7-11]. However, the performance of the isolation platform is determined not only by the damping mean embedded in each strut, but also by the design of the platform itself and the dynamic interaction between all its constitutive elements.

The optimisation of the platform geometry (e.g. change of strut length, angles and platform mass) has been extensively investigated in literature. In particular, the main objective is often the realisation of dynamic isotropy (i.e. first six modes, three translational and three rotational, to be at the same frequency) which simplifies the control algorithm in case of active struts and reduces the source of errors in the positioning. Although different approaches have been proposed to reach an optimised configuration, one of the common assumptions adopted to reduce the model complexity and the computational cost of the optimiser is to consider all the struts without mass. Such assumption is widely considered acceptable because for small displacements and low frequency range the effect of the strut inertia can be considered negligible. Nonetheless, it has been shown recently that such effect becomes actually dominant as the frequency range of interest increases [12] (e.g. up to 1 kHz in the case of micro-vibration mitigation).

This paper focus its attention on the limitations deriving from the commonly-used boundary conditions for a hexapod platform (all spherical/universal joints) in the context of micro-vibration isolation. The key aspect of this work is the inclusion of the strut mass in the analysis and the evaluation of its effect in the input-force attenuation at high frequency. The study is initially focused on a bipod system considered as one of the three identical elements forming a hexapod platform. Different boundary conditions are compared and a final configuration is identified that is capable of restoring the force TF to its ideal case (i.e. struts without
mass). Once the benefits of the proposed boundary conditions are verified on a bipod, the analysis is extended to a full hexapod platform to further corroborate the promising results in a 3D environment. Finally, a novel design for a planar joint for a micro-vibration load environment is proposed and tested.

BIPOD TESTING

The rationale for this work came after having tested and analysed a bipod configuration using the well-established boundary conditions of pin joints at both ends of the struts (see Figure 1). The single strut was designed so to have two highly-attenuated peaks in the force transfer function and to achieve at least -40dB of attenuation at 100Hz. The test with a vertical input force and a single strut was previously performed (Figure 2) and the results were compared with the analytical model. From Figure 3 it can be seen that the strut performed as expected until it reached 160Hz where local modes due to the membrane flexures were excited (it is noted that the flexure membranes were not optimised and so further improvement to push those local modes beyond 500Hz could be achieved).

However, when the bipod was assembled and tested, a different outcome was observed. The force transfer function was expected to be with similar features than the one of a single strut. Figure 4 shows instead the appearance of an undamped peak at about 58 Hz. After investigating the possible cause it was established that the culprit of this extra resonance was the pivot joints at the bottom of the struts and in particular their lateral stiffness. In fact, by adding the lateral stiffness of the joints (measured later because not provided in the datasheet) it was possible to replicate the test results with the Simulink model, as shown in Figure 4. Moreover, once the analytical model included all the correct inertia of the struts, a plateau behaviour was observed which was not considered before as (similarly to the literature) the strut inertia was initially neglected.

Figure 1. Bipod testing set up

Figure 2. Single strut test setup for vertical input force with mini-shaker

Figure 3. Comparison between test results and analytical model on a single strut vertical-force transfer function
Figure 4. Comparison between test results and analytical model on bipod configuration. By adding the translational stiffness of the joints in Simulink it was possible to replicate the test results.

**STRUT MODEL**

This section focuses on the comparison between ideal struts (i.e. massless struts) and real struts characterised by a mass and inertia. If single-DoF struts are considered (characterised only by a stiffness $K$ and no damping), the force transfer function for a bipod configuration would be represented by the blue curve in Figure 5. However, as the inertia is added to the system the aforementioned plateau effect can be observed. Such effect is due to strut inertia that causes shear force to be transmitted through the bottom pivot joint.

Figure 5. Comparison of the overall force TF between the ideal-strut case (i.e. massless struts) and the real-strut case

The mass/inertia of the strut cannot be eliminated, hence the best approach to deal with this limitation in the isolation performance would be to change the boundary conditions. As the issue is the lateral stiffness of the bottom joint, the first attempt to substitute the bottom pivot joint with a slider joint as shown in Figure 6. By doing this the bipod will still maintain its isostatic condition. In terms of the two direct transfer functions (i.e. vertical input-vertical output and horizontal input-horizontal output) this solutions completely eliminates the plateau effect. Therefore, these boundary conditions were initially included in the hexapod model.

Figure 6. Schematic representation of a bipod made of real struts and with the boundary conditions of pin at the top and lateral sliders at the bottom of the two struts

**HEXAPOD MODEL**

The hexapod model was developed both in ADAMS MSC and in Simulink as a mean of validation. Due to the 3D environment, the lateral slider became a planar joint in which apart from the lateral displacement in the plane perpendicular to the strut, also the rotation about the strut longitudinal axis is allowed. Figure 8 shows the vertical-input-vertical-output force transfer function for 2 types of boundary conditions: case (a) represents the traditional all-spherical joints, whereas in case (b) the planar joint is used at the bottom of the struts. The plots show the difference between the ideal struts and the real struts. As expected, it can be noticed that the inertia of the strut does not produce the plateau effect that is visible for the case (a).

The next step was to consider the 2-collinear-DoF strut and verify the transfer function matrix with the new boundary conditions.

Figure 7. Hexapod model developed in ADAMS MSC
Figure 8. Vertical-input-vertical-output force TF obtained through the hexapod model developed on ADAMS MSC. Ideal struts and real struts (i.e. with mass) are compared. a) hexapod with 6 universal joints at the top and 6 spherical joints at the bottom; b) hexapod with 6 universal joints at the top and 6 planar joints at the bottom (3 DoFs allowed which are the 2 translations in the plane perpendicular to each strut and 1 rotation about the strut longitudinal axis).

The hexapod model built with 2-collinear-DoF struts can be seen in Figure 9. The top platform was built on a diameter of 45 cm in order to be able to host 4 large reaction wheels. The dimension of the top platform corresponds to a specific length of the struts due to the cubic configuration (about 34 cm) and for this reason a lightweight rod was added to each strut.

By analysing the full transfer function matrix (6 by 6 matrix as the 6 inputs measured at the top platform and the 6 outputs measured at the bottom platform are the 3 components of the force and 3 components of the moments) it was possible to observe that several components are null, and that the 3 force transfer functions do not present a plateau as expected from the previous section. However, there are 5 components of the matrix (the 3 moment transfer function along the diagonal and the cross coupling components between the moments and the forces that are circled in Figure 10) that show the plateau effect, with values that hardly go below -20 dB. This phenomenon is still due to the fact that there is the strut mass that moves laterally (instead of rotating as before).

Therefore, further investigation was carried out and the strut configuration was modified as shown in Figure 11. In particular, the strut main mass is now clamped to the ground (with only the longitudinal motion allowed due to the prismatic joint) and the planar joint is placed on top of it. By doing this change, the overall behaviour of the transfer functions previously circled does not change, but given the lower mass that now moves above the planar joint (i.e. lightweight rod), the plateau value is considerably reduced and below -35 dB. Moreover, this new configuration is not dependent anymore on the strut mass, which can now be modified to be adapted for different purposes without affecting the overall isolation performance.

Figure 9. simulink model of the hexapod in the cubic configuration

Figure 10. Transfer function matrix. The six inputs and the six outputs are the 3 forces (Fx, Fy and Fz) and the 3 moments (Mx, My, Mz). The boundary conditions considered have produced several terms to be zero. However, the terms circled in red are those where major plateau effects can be seen which limit the isolation performance.
Figure 11. Evolution of the strut configuration. In this case the planar joint has been moved above the strut main structure thus reducing the moving inertia.

CONIC CONFIGURATION

The analysis of the different boundary conditions carried out on the cubic configuration revealed the inherent limitation that such configuration has over many terms of the transfer function matrix independently from the boundary conditions considered. By extending the investigation to different geometric configurations, a conic configuration was established as advantageous for micro-vibration purposes. This configuration is characterised by the top platform having an outer diameter that is half the one of the bottom platform. This comports that the 3 bipods are vertical, as shown in Figure 12. By using the same boundary conditions as the one reported in Figure 11, the transfer function matrix was built. As shown in Figure 13, the new configuration completely eliminates the plateau effect in the main diagonal terms (see Figure 14, and it reduces such effect for the cross coupling terms (i.e. TF51 and TF42) to about -50dB.

The main drawback of such configuration would be the increased height as the strut had a length of about 75cm and the top platform was at a height of about 50cm. Therefore, this configuration in its ideal state would considerably increase the volume envelope of the hexapod platform.

Nevertheless, it was noted that reducing the length of the struts (and so the height of the platform) while maintain the bipods aligned with the ideal sides of the bottom platform could have multiple benefits. First of all, the main diagonal terms do not change from the ideal case. Secondly, the reduced height of the whole platform, apart from reducing the volume envelope, would be also responsible for lowering the plateau at the cross-coupling terms.

Figure 12. Hexapod model developed in Simulink showing the full conic configuration.

Figure 13. Transfer function matrix associated with the hexapod in the conic configuration. There are only two terms (cross coupling between input moments and output forces) in which a plateau can be seen.

Figure 14. Transfer functions associated with the main diagonal terms of the hexapod in the conic configuration. The damping was not considered.
Figure 15. Hexapod model developed in Simulink showing the conic configuration with reduced height.

Figure 16. Hexapod model developed in Simulink showing the conic configuration with reduced height. Top view.

**ISOLATION PERFORMANCE**

Once the hexapod configuration was established, the damping was included by adding 2 EMSDs within each strut (one EMSD per half strut). Also, the ideal joints were made less ideal by considering the directions with zero stiffness to have more realistic values (e.g. lateral stiffness of planar joints to be around 300N/m).

Although this phase is still under investigation, the preliminary plots for the main-diagonal transfer functions look promising. The coils of the EMSDs are characterised by low resistance so their variation within the operational temperature range (i.e. -20°C to +50°C) is contained. Figure 17 and Figure 18 report the transfer functions of TF11, TF22 and TF33. This effect results in an isolation performance that does not change considerably with temperature. The main effect can be seen at low frequency where the amplitude of the first peak, although highly reduced, slightly changes.

**CONCLUSIONS**

The proposed hexapod platform is characterised by a conic configuration with reduced height (with respect to the ideal case) and with the inclusion of a planar joint within the strut. The main advantages of this solution are:

- The strut mass and dimensions can be changed without affecting the isolation performance.
- Platform easier to be assembled due to each bipod being in the vertical position.
- The upper platform dimensions can be easily changed by placing the 3 bipods accordingly.
- Height of the upper platform can be changed by varying the length of the connecting rods.
- Magnetic shielding (if required by the mission) could be attached directly to the ground.

The future work will include the development of a breadboard model of the fully-assembled hexapod and the assessment of the isolation performance with a real noise source.
REFERENCES


