Six-degree-of-freedom hexapods for active damping and active isolation of vibrations

Article *in* Journal de Physique IV (Proceedings) · December 2002

DOI: 10.1051/jp4:20020473

3 authors:

Ahmed Mohammed Abu Hanieh

Birzeit University

Mihaita Horodinca

Gheorghe Asachi Technical University of Iasi

A. Preumont

Université Libre de Bruxelles

Journal de Phisique IV, vol 12, Pr11-41, December 2002

SIX-DEGREE-OF-FREEDOM HEXAPODS FOR ACTIVE DAMPING AND ACTIVE ISOLATION OF VIBRATIONS

First author : **Ahmed Abu Hanieh**
e-mail : aabuhani@ulb.ac.be

Second author : **Mihaita Horodinca**
e-mail : hmihaita@email.ro

Third author : **André Preumont**
e-mail : andre.preumont@ulb.ac.be

Same address for the three authors:

Universite Libre de Bruxelles
SCMeRo (CP 165/42)
50 Av. Roosevelt
1050 Bruxelles
Belgium
Tel : +32 2 650 26 87
Fax : +32 2 650 46 60

Journal de Phisique IV, vol 12, Pr11-41, December 2002

Ahmed Abu Hanieh, Mihaita Horodinca and André Preumont

Abstract : As future astronomic missions will require more and more stringent resolution requirements, the high demand for an environment clean of vibrations and disturbance appears. This also leads to the need for high precision steering devices for fine pointing of sensitive optics with the highest possible accuracy. Several methods exist to reduce vibration levels: the first consists in isolating the sensitive system from the perturbation and the second in damping the structure vibration modes. Therefore, two Stewart platforms have been designed, manufactured and tested. The first is a soft hexapod that provides 6 degree-of-freedom (DOF) active isolation and the second is a stiff hexapod that provides active damping to whatever flexible payload attached/mounted to it. In addition, both hexapods have steering capabilities.

1. INTRODUCTION

The two robots presented in this paper are based on the cubic configuration of Stewart platform [9], more details about cubic configuration are shown in [1]. The legs of the soft hexapod consist in soft electro-dynamic actuators. This hexapod consists mainly of two plates connected to each other by six legs. Each leg of the soft Stewart platform contains a voice coil electro-dynamic linear actuator, a force sensor and two flexible joints. This Stewart platform is aimed to be used in active vibration isolation. Only active control can achieve simultaneously high isolation performances (–40 *dB/decade* attenuation rate at high frequency) and the stabilisation of the suspension modes. The system is based on a spring mass device with minimum passive damping, provided with pure force generators, collocated vibration sensors and a decentralized control law. A positioning/pointing control layer can also be added to the system.

The second Stewart platform uses high-stiffness piezoelectric actuators in each leg. The legs of this Stewart platform consist of a piezoelectric amplified actuator, a force sensor and two flexible tips. Using universal or spherical joints here is avoided to achieve high resolution without backlash or friction. This hexapod is made to act as a vibration damping interface from one side and a precision pointing device from the other side. Using a mechanical truss structure as a payload, the platform showed high authority in active damping of the vibrations. Another application for this hard actuator hexapod is the high-precision pointing device for space applications. The kinematics of the hexapod helps to amplify the motion of the mobile platform (more details about kinematics are discussed in [2, 10, 12]). Although the stroke of the actuator does not exceed 55 µm the translation and rotation strokes of the upper platform are 90,103 and 95 *m*m in the *x*, *y* and *z* directions respectively and 1300, 1150 and 700 *m*rad around the *x*, *y* and *z* directions respectively.

2. SOFT STEWART PLATFORM

The design of this soft Stewart platform is based on the cubic configuration where the two main plates here are two aluminium triangles connected to each other by means of six active struts. Each strut consists mainly of a voice coil actuator, a force sensor and two flexible joints as shown in Fig.1. Fig.2 shows the hexapod; where Fig.2(a) is a side view showing the inclination angles of the legs according to the cubic configuration and Fig.2(b) is a general view showing the triangular plates and their connection to the legs. In the design of this soft system, one should take into account many parameters particularly the design and manufacturing of the current carrying coils, the membranes and the flexible joints.

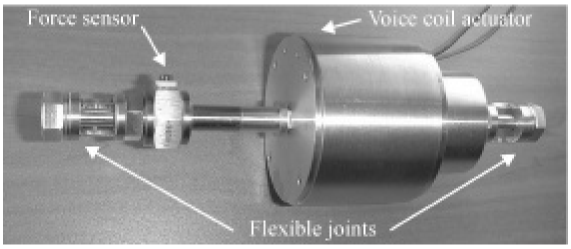

Figure 1: The active leg assembly of the soft Stewart platform

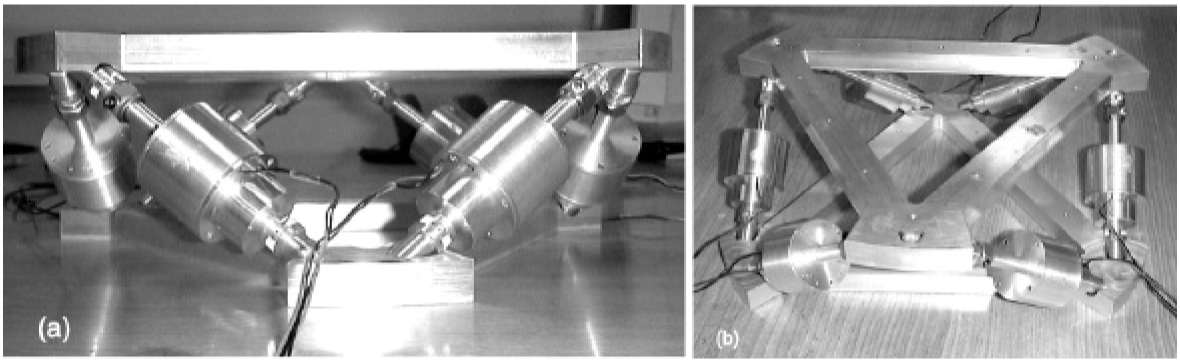

Figure 2: Soft Stewart platform. (a): side view, (b): General view of the hexapod

2.1 Active strut design

The voice coil actuator integrated in the leg consists of a permanent magnet and a current carrying coil. The permanent magnet is a radial polarity toroid magnet with a ferromagnetic metal core manufactured by BEI KIMCO. The current carrying coil has been developed and manufactured in house because of its significant contribution in the passive damping content in the form of eddy current [3]. Looking over at the previous designs, we find in [5] that the design include the effect of this damping in the system in spite of its high influence on the high frequency attenuation. On the contrary, in [8], a carbon fiber composite material has been used to construct the coil holder (bobbin) in order to minimize the eddy current and thus reducing the passive damping. The new contribution in our design is that we could get rid of this problem completely by simply winding the coil and sticking the turns to each other using a special strong adhesive without having any holder from any kind. In order to align the coil and the magnet up together, a set of components and connections are manufactured and installed as shown in the exploded view in Fig.3. To allow the current carrying bobbin to move freely through the air gap of the permanent magnet in the actuator, an alignment system is needed [4, 5]. Two *Beryllium Copper* flexible membranes have been designed and manufactured at the ULB to achieve the following characteristics: (*i*) low axial stiffness, (*ii*) high radial stiffness, (*iii*) no friction or backlash, (*i*v) non-magnetic characteristics and, eventually, (v) light weight and small size. To connect each leg to either the upper or the lower plate, flexible joints are designed, tested and manufactured at the ULB, (deep discussion about flexible joints is shown in [6]).

These joints behave like spherical joints, but with the following characteristics: (*i*) high axial and shear stiffness, (*ii*) low bending and torsion stiffness and (*iii*) minimum friction and backlash.

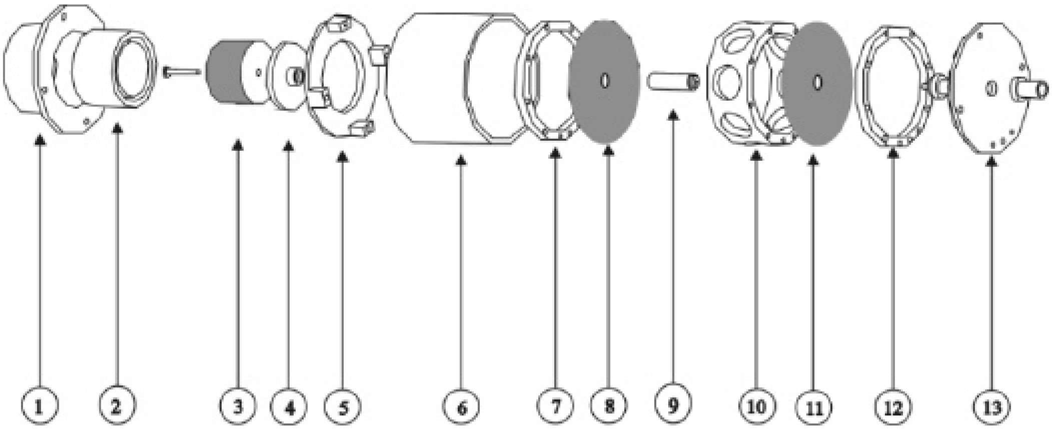

Figure 3: Exploded view of the actuator. (1): Magnet holder, (2): Magnet, (3): coil, (4): Coil backplate, (5): Magnet-membrane spacer, (6): Envelope, (7): Spacer-1, (8): Membrane-1, (9): Central rod, (10): Membrane spacer, (11): Membrane-2, (12): Spacer-2, (13): Cover

2.2 Finite element model

To predict the behaviour of the hexapod in a comprehensive way, a finite element model is built and simulated using SAMCEF finite element software. The flexible joint is modelled as a super element, the actuator is modelled as another super element. Two flexible joints and one actuator are assembled to form one leg of the hexapod. The six legs are configured according to the requirements of the cubic configuration and the upper mobile platform is modelled and assembled to the legs. The lower plate is considered to be fixed to the ground, therefore, no representation of this plate to be seen in the model. Looking at the results of the finite element model, we see that the first piston (bounce) mode is at 2.9 Hz, the two tilt modes are at 3.2 Hz, the twist mode is at 6.5 Hz and, eventually, the two shear modes of the mobile plate are at 9.5 Hz (see Fig.4). In addition to the six responsive modes in the frequency band 2.9-9.5 Hz, local modes of the legs appear in the frequency band 72–115 Hz.

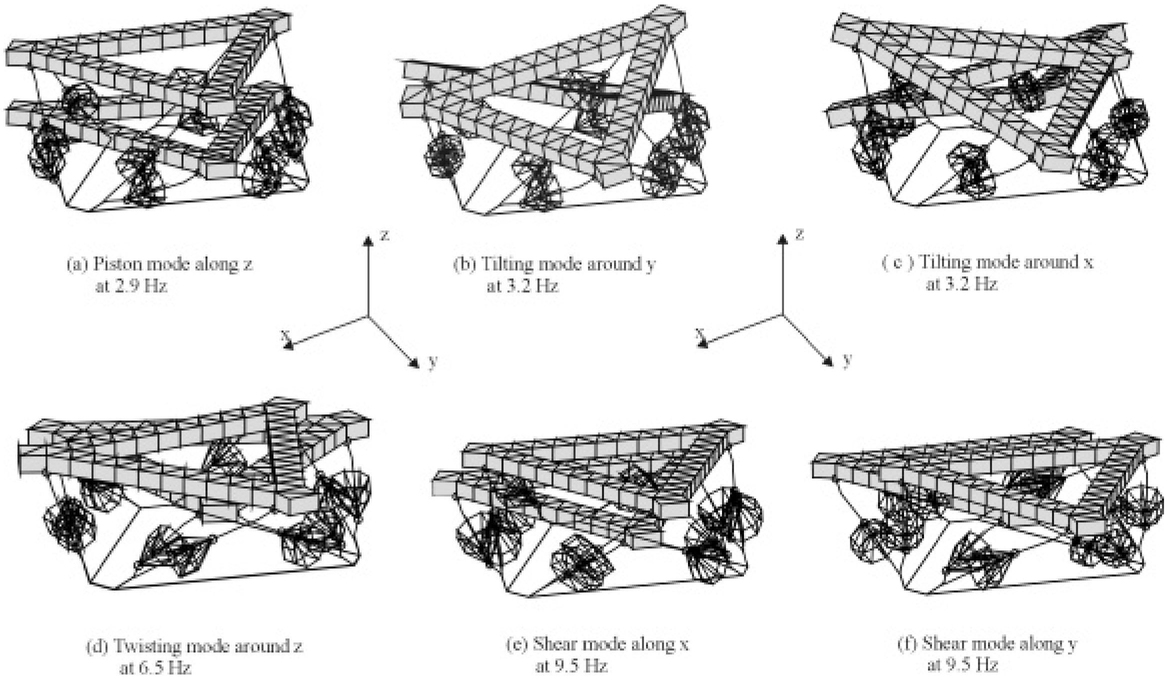

Figure 4: Mode shapes of the first six modes as seen in the finite element model

2.3 Preliminary experimental results

The Stewart platform has been installed on the working table to be tested. As far as this hexapod is designed and addressed to space applications, no internal stiffness has been taken into account to compensate for the weight of the mobile plate. However, as the membranes of the actuators are not stiff enough to hold the mobile plate in the ground test, there was a need to compensate for the gravity force by using external suspension springs. It has been avoided to use internal springs integrated in the legs so as not to increase the corner frequency of the system which reduces the isolation performance. The system is excited using a proof mass shaker; the signal produced is a random white noise with a frequency range between 1 to 1600 Hz. The open-loop frequency response function (FRF) is taken between the input signal to the actuator and the conditioned signal out of the force sensor. Fig.5 shows the FRF measured in one of the legs. From this FRF, one can see the low frequency rigid body modes of the mobile plate between 3.3 and 8.5 Hz. The decentralized integral force feedback control strategy has been used to damp these responsive modes (more about this control technique can be found in [7]). A low frequency zero appears here at 2.5 Hz resulting from bending stiffness of the flexible joints. The existence of this zero close to the modes reduces the performance of the active control. Another band of modes appear at high frequency around 1000 Hz. These modes represent the local bending, torsion and shear modes of the triangular plate constituting the mobile platform. The existence of these modes induces no effect on the system because they are located far enough from the corner frequency of the system (4.5 Hz) which results in isolating the disturbance of these modes. The peaks we see in the open-loop FRF (Fig.5) are not the only natural frequencies of the hexapod, but there is another band of modes ranges between 65 to 115 Hz but they cannot be observed by the force sensors and, thus, we do not see them in the open-loop FRF. These modes are the local natural frequencies of the legs and have the ability to deteriorate the sharpness of the high-frequency roll-off decreasing the isolation performance.

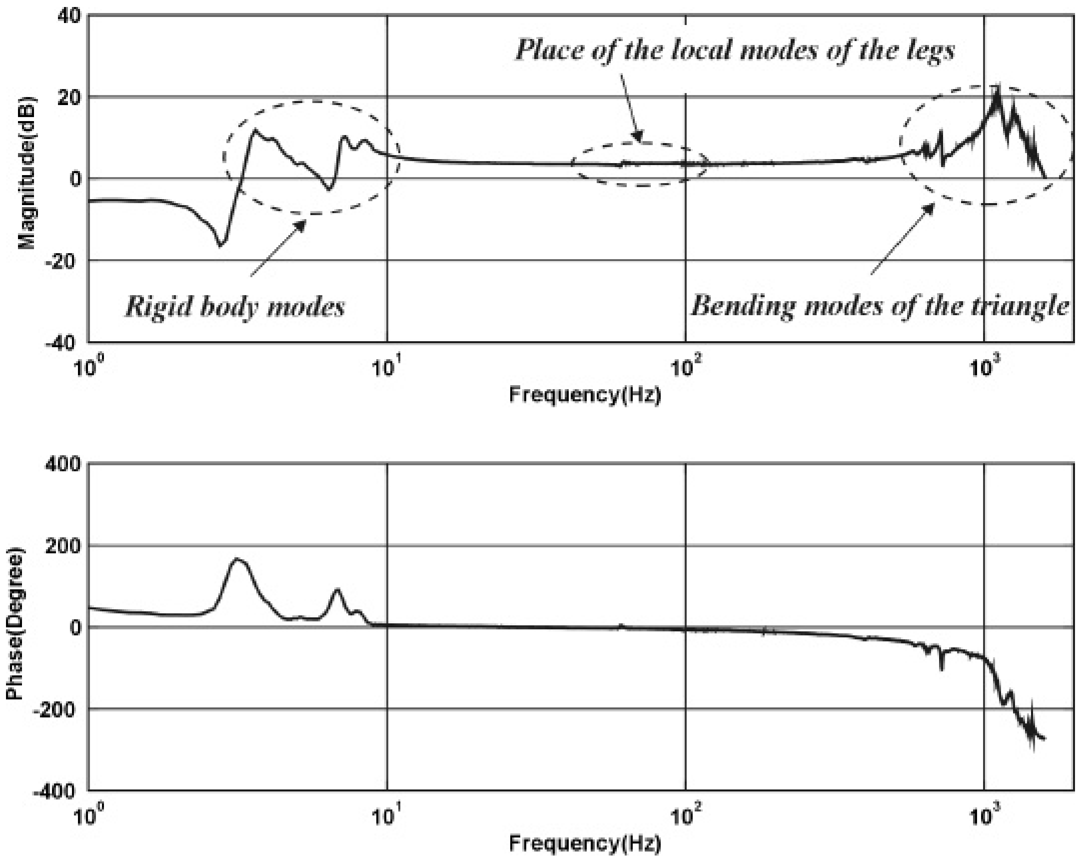

Figure 5: Open-loop FRF between the input signal to the actuator and the output signal from the force sensor in one leg of the Stewart platform

3. STIFF STEWART PLATFORM

In this part, a stiff active damping interface is proposed. It can be used either as a support for payloads or to connect arbitrary substructures. It has the ability to introduce damping in the mechanical system attached to it while remaining stiff. The active interface consists of a six-degree of freedom Stewart platform; a standard hexapod with a cubic architecture. Each leg of the active interface is made of a linear piezo electric actuator, a collocated force sensor and flexible tips for the connection with the two end plates. The control architecture is based on six local/decentralized Integral Force Feedback controllers. By providing the legs with strain or elongation sensors, this active interface can also be used as an interface with infinite stiffness at low frequency (i.e. for machine tools), a 6 d.o.f. Positioning and steering device for space applications as well as a micro vibration isolator.

3.1 The hexapod assembly

Fig.6(a) shows a picture of the complete Stewart platform and Fig.6 (b) shows the same but with removing the upper plate. The two plates are circular aluminium plates connected to each other by six active legs; the legs are mounted in such a way to achieve the geometry of cubic configuration. Each active leg consists of a force sensor (B&K 8200) and an amplified piezoelectric actuator (Cedrat Recherche APA50s) as shown in Fig.7. To avoid the problems of friction and backlash in the joints, flexible tips were used instead of spherical joints. These flexible tips have zero friction, zero backlash, high axial stiffness and relatively low bending stiffness. The existence of this bending stiffness makes a limitation for the control authority because it shifts the transmission zeros to a higher frequency, which will decrease the damping effect expected from each closed-loop pole.

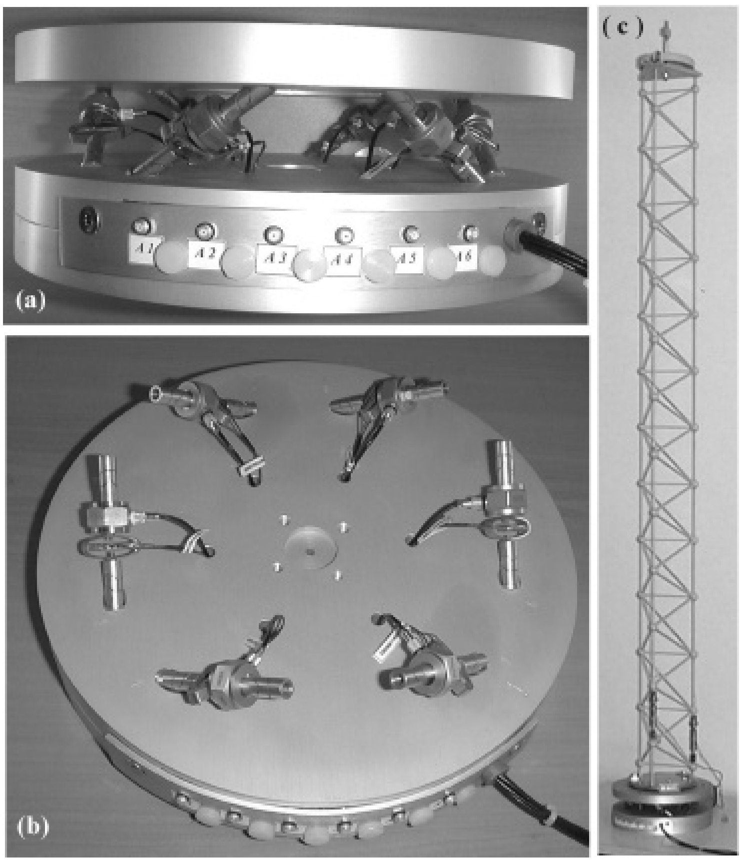

Figure 6: The Stiff Stewart platform (a): complete hexapod (b): the hexapod with the upper plate removed, (c): test set-up

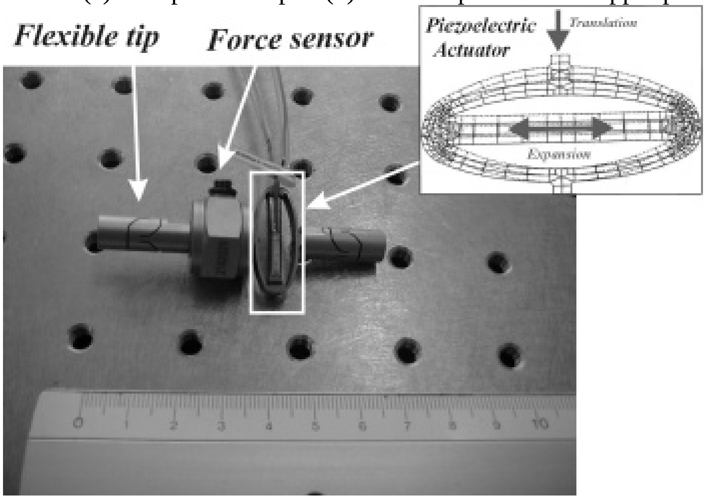

Figure 7: The active leg assembly of the stiff Stewart platform

3.2 Active damping results

In order to evaluate the damping performances of the interface, the hexapod is connected to a flexible payload, a 150 cm long steel truss structure (see Fig.6 (c)). Decentralized Integral Force Feedback control scheme was applied to the experimental system. The six independent controllers have been implemented on a DSP board. The six loops have been closed separately and, although the control loops were independent, the feedback gains used in all the loops are identical. Fig.8 presents some experimental results. The time response shows the signal from one of the force sensors located in the legs; the truss is subjected to an impulse at middle height, without then with control. The frequency responses (with and without control) are obtained between a perturbation signal applied to the piezo actuator of one leg and its collocated force sensor. One can see that fairly high damping ratios can be achieved for the low frequency modes (4-5Hz) but also significant damping in the high frequency modes (40-90Hz). Unfortunately, the results on the torsion mode were disappointing, probably due to the flexion stiffness in the flexible tips. The experimental results were consistent with the predictions calculated from the FEM. The modes and mode shapes taken from the FEM model are shown in Fig.9 where v is the fraction of strain energy.

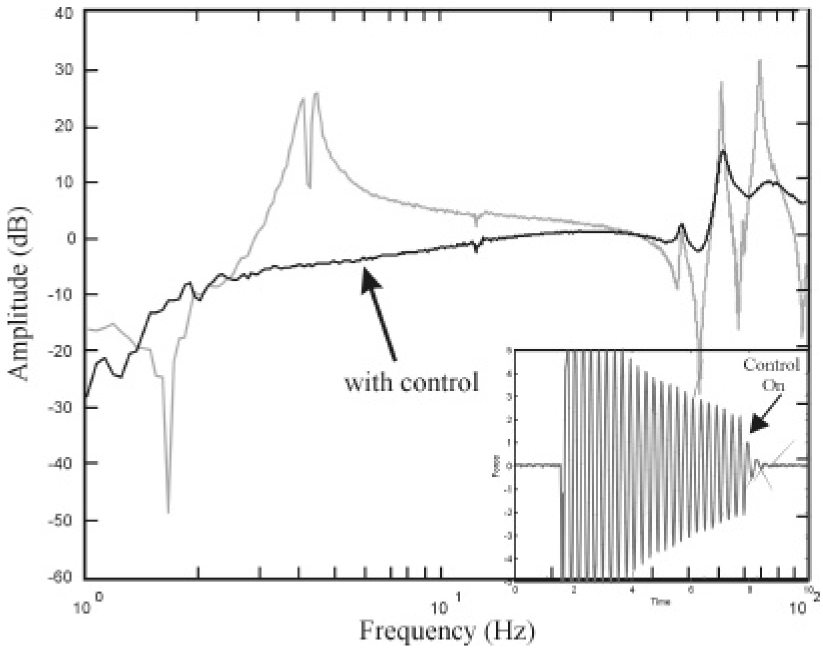

Figure 8: Experimental time response and FRF of the truss mounted on the active interface.

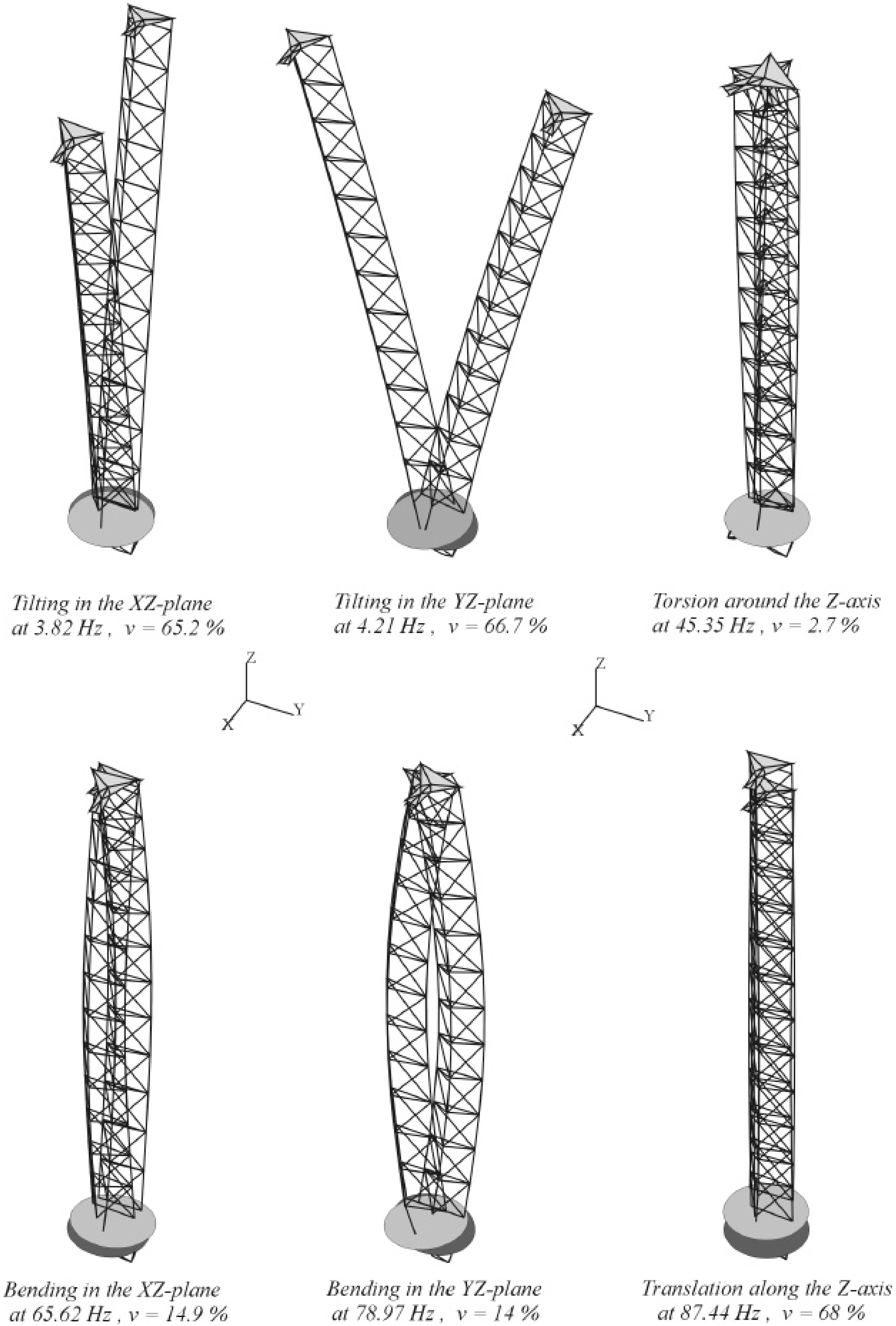

Figure 9: Modes and mode shapes of the active interface with a truss as a payload

4. CONCLUSION

This paper described two new generations of soft and stiff mount Stewart platforms. In a brief discussion we tried to show the design, assembly and configuration of the two hexapods. The control technique applied to the stiff hexapod proved to give good active damping authority on the low frequency modes as well as the high frequency ones. Regarding the soft hexapod, our discussion was concentrated on the design and technological aspects. The design and manufacturing of the flexible joints proved to have high influence on both; the active suppression of vibrations induced by the low frequency suspension modes and the active isolation of vibrations caused by high frequency excitations. On the other hand, a good design of the actuator and the flexible membranes can contribute significantly in increasing the isolation of vibrations provided to the system.

Acknowledgment

This work was supported by the Inter University Attraction Pole IUAP-V on Advanced Mechatronics Systems.

References

1. Z.J. Geng and L.S. Haynes, Six degree-of-freedom active vibration control using the Stewart platforms, *IEEE Transactions on Control Systems Technology*, 2(1): 45-53, March 1994.
2. A. Abu Hanieh, A. Preumont & N. Loix, piezoelectric Stewart platform for General purpose Active damping and precision control, *9th European Space Mechanism and Tribology Symposium*, September, 2001. Liege , Belgium.
3. A. Preumont, *Vibration control of active structures*, 1st. ed., Kluwer Academic Publishers, 1997
4. J.E.McInroy, J.F.O'Brien and G.W.Neat, Precise, fault-tolerant pointing using a Stewart platform, *IEEE/ASME Transactions on Mechatronics*, 4(1): 91-95, March 1999.
5. J. Spanos, Z. Rahman & G. Blackwood, A soft 6-axis Active vibration isolator, *Proceedings of the American Control Conference*, 412-416, June, 1995.
6. D. Thayer, J. Vagner, A. von Flotow, C. Hardham and K. Scribner, Six-axis vibration isolation system using soft actuators and multiple sensors, *AAS*, 064: 497-506, 1998.
7. A. Preumont, A. Francois, F. Bossens and A. Abu-Hanieh, “Force feedback versus acceleration feedback implementation in active vibration isolation”, *Journal of sound and vibration*, accepted for publication in 2002.
8. J. Fochage, T. Davis, J. Sulivan, T. Hoffman & A. Das, Hybrid active/passive actuator for spacecraft vibration isolation and suppression, *SPIE*, 2865:104-122, March 1996.
9. D. Stewart, A platform with six degrees of freedom, *Proc Instn Mech Engrs*, 180 (15): 371-378, 1965 - 1966.
10. J.P. Merlet, An algorithm for the forward kinematics of general parallel manipulators, *IEEE*, 1991.
11. C. Reboulet and T. Berthomieu, Dynamic models of a six-degree of freedom parallel manipulators, ICAR'91, 1153-1157, Pisa, June 1991.
12. K.H. Pittens and R.P. Podhorodeski, A family of Stewart platforms with optimal dexterity, *Journal of Robotic Systems*, 10(4): 463 - 479, December 1993.