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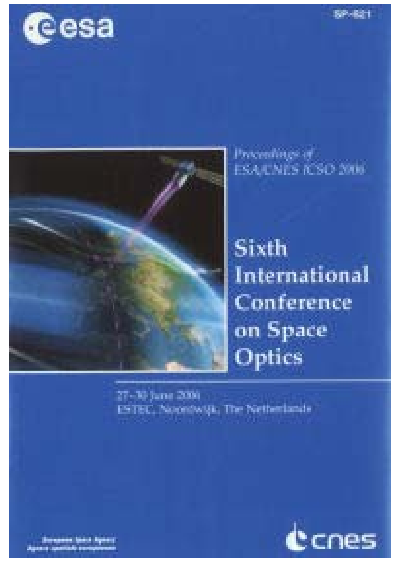

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A TAPE-SPRING HEXAPOD FOR DEPLOYABLE TELESCOPES: DYNAMICS

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ABSTRACT

An hexapod based telescope concept whose legs are deployable has been investigated in order to stow the secondary mirror during launch and to self-deploy it in orbit The main advantages of this concept are: a reduced volume for launch with high reduction of passive stability requirements, mass and inertia reduction inducing an agility gain. The positioning errors are corrected thanks to the vertical displacement of the hexapod feet and the final optical performance is reached thanks to adaptive optics. The paper presents the first steps towards the optimal design of a breadboard and the method developed to model the dynamic behaviour of such a structure with highly deformed flexible elements and validated with the results of sine vibration testing of the hexapod. The following part deals with the evaluation of its deployment and correction capabilities.

1. INTRODUCTION

In the close future of spaceborne observation missions, many challenges come into light like multi-pupil instrument conceived as free-flyers for optical aperture synthesis or Extremely High Resolution systems with large dimensions and high agility requirements. Facing the performance requirements of such missions, deployable structures with adaptive optics become almost compulsory.

Adaptive optics, which could be used to correct nowadays solutions can also be used to compensate for the positioning uncertainties of a deployable structure. For this, one must be sure that this optical technique is able to work after a deployment. This means that the passive part of the instrument is precise enough to allow picture shooting. A way to insure this precision is to use an active structure capable of correcting its geometry in compliance with adaptive optics requirements.

The main advantages of a deployable and active telescope structure, compared to classical hyper-stable telescope structures, are:

1. a reduced volume during launch allowing large systems design,
2. a very strong reduction of dimensional stability requirements during launch as the geometric instabilities of the structure after deployment will be corrected,
3. a strong mass and inertia reduction which leads to an agility gain of the system.

However, once in orbit, these lightweight structures will have to insure a very high stability of mirrors and this induces new design considerations. In order to pave the way to future space telescope design, Alcatel Alenia Space Research Department is studying innovative telescope structural concepts. One of them is a telescope structure based on an hexapod with deployable tape-spring legs.

Tape-springs have the advantage of a low cost and an ease-to-use. But, over all, such steel thin curved strips offer a very simple concept with elastic behaviour and a natural tendency to put themselves in their deployed configuration. Deployment of a rigid-panel[4], Collapsible Rib-Tensioned Surface [5] and high-resolution deployable telescope[6] are some applications using the folding of tape-springs in order to make simple self-locking hinges. Several joints have also been developed like tape-spring rolling hinges[7]-[8], Aerospatiale "Adele" patented hinge, and Astro / JPL NASA Hinge. Another way to use it is based on the coiling of the strip instead of folding with the same principle as carpenter's tape-measure like thin-walled tubular booms and deployment cassette for bi-STEM[9]. In such mechanisms, the cross-section forms a complete circle with some overlap. In the dealt application, innovation lies in the fact that deployment of the hexapod is provided by using six specific linear actuators in which tape-springs are coiled around a hub. Such coiling tape-spring mechanisms have already been applied to robotic applications [10].

This paper presents the design of an hexapod breadboard. It refers to a finite-element model used to predict its dynamic behaviour which has been updated using a numerical and experimental modal analysis[1]. The second part of this article links the modes shapes to the desired optical end application. Then, it deals with the characterisation of the deployment reproducibility performed with support of ESA Innovative Triangle Initiative.

2. DEPLOYMENT CONCEPT

For launch, the structure is compacted thanks to 6 legs made with tape-springs. The M2 mirror is stowed by a mechanism which withstands the major part of the vibration loads without any strong dimensional requirement. In this configuration, the tape-springs which are coiled around a hub offer a strong volume reduction.

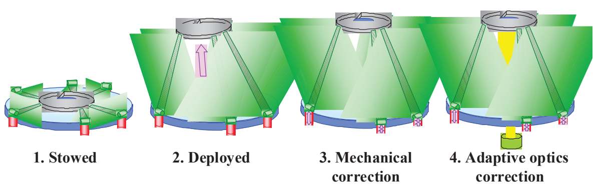


Fig. 1: Deployment stages

Once in operational orbit, the stowing mechanism is released and the 6 legs autonomously reach their full length configuration bringing the M2 mirror from the stowing point to a deployed point defined by the final length of the 6 legs and by the structure geometrical and mechanical defects. After deployment, the 6 vertical actuators located under the hexapod feet can be used to compensate for deployment errors that are evaluated thanks to a dedicated measuring system. This stage of mechanical correction of the structure can also be used to correct the long-term instabilities and thermo-elastic deformations.
Once corrected, the structure allows the acquisition of images. Even if their quality is reduced, it is sufficient to use adaptive optics which then allows to reach the full performance of the instrument.

3. DESIGN OF AN HEXAPOD BREADBOARD

This investigation follows a first work lead in collaboration between Alcatel Alenia Space Research and INRIA Sophia Antipolis and dedicated to the development of an optimal geometric algorithm for the definition of an hexapod [3]. A structural hexapod concept using tape-spring legs for deployment and vertical actuators under its feet for control has been defined. Then, in order to make a half-meter high demonstrator a set of ranges for the design variables (leg length, platform and base plate diameter, junction separation angles) has been entered into the optimal design algorithm to compute a set of solutions optimizing correction workspace and accuracy. This set has been examined with secondary criteria like hexapod stiffness to identify the design variables to make a demonstrator. As a result, this mechanical architecture is lightweight, stiff and designed to be highly fault tolerant.

Tape-spring actuators have been developed by IWF TU Braunschweig[10] which already used them for robotic applications. These mechanisms contain a rotating roll module in which the tape-spring is flattened and coiled. Because of this induced stress, the tape-spring naturally tends to go out to recover its natural curved section. Inside the roll module, a fixed axis is connected to the cradle by a ball bearing. The coiling device has an internal coil-spring which helps the self-deployment when the locking system is released.
The coilers also have an internal deployment length tuning mechanisms which was used to deploy the same length on each leg.
The active wrist concept used for this hexapod implies the use of one spherical joint at the top and one universal joint at the base of each leg which means that 2 DOF are required at the base of the tape-spring and 3 DOF at its top. For the base junction, an hinge made of two ball bearings and the coiling of the tape-spring have been used as two degrees of freedom in rotation. The top junction is constituted with an axis mounted on two ball bearings, a thin metallic flexural blade and with the torsion of the tape-spring itself.
The hexapod is composed of a base-plate on which 6 linear stages are mounted on 90° brackets and a platform representing the M2 mirror held by the 6 tape-springs . The linear stages support the bottom junctions and allow vertical displacements of the coiling mechanisms on a 16 mm stroke with a 20 µm resolution. The intersection of the rotational axes and the hinge axes at the top and base junction have been precisely placed at the positions computed by the optimal design algorithm.

4. HEXAPOD MODELING

The method developed to model the dynamic behaviour of such a structure with highly deformed flexible elements is detailed in [1]. The deployed hexapod model is composed of six flexible parts representing the tape-spring legs connected to two rigid bodies platforms (see Fig. 2). The structure is designed on a cyclical geometry with three couples of two tape-springs put back to back (orientated with opposite curvature). Modelling the hexapod in its deployed configuration is achieved thanks to a multi-body software (MSC-ADAMS) and the ANSYS FEM code.

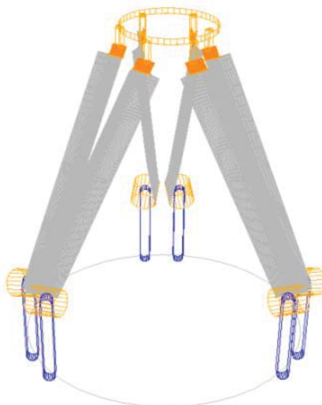


Fig. 2: Deployed hexapod model.

One relevant notice is that, in this modelling technique, the flattened section of the tape-springs induced by the coiling around the drum and the associated internal stresses have been taken into account. The boundary conditions are well known to have strong influence on mode shapes and then its was necessary to represent the effect of pre-stress.

A naturally curved tape-spring has been flattened in a large-displacement non-linear finite element analysis in order to evaluate with precision the shape, the internal stresses and further modal behaviour of the tape-spring. A reduced model of the flattened tape-spring has been generated using the component mode synthesis (CMS) from Craig and Bampton reduction[12] which allows to reduce the computation for solving the dynamic model. An equivalent pre-stress state has been applied to the reduced model to simulate the stress stiffening. The comparison between modal analysis of the full pre-deformed model and the condensed pre-stressed model showed good correlation. Then, six reduced models of the legs have been entered in the system model of the hexapod.

5. HEXAPOD MODAL BEHAVIOUR

The hexapod has been excited on a dynamic shaker along vertical and two lateral axes in the 0 to 200 Hz range. Tests have been performed with low input accelerations between 0.2 and 1.4g in order to identify the modal behaviour. The hexapod has been equipped with six pilot accelerometers near the feet, three tri-axial accelerometers on its platform and two couples of accelerometers on two tape-springs.

Amplitude and phase data from accelerometers gave information about the mode shapes and frequencies. The following table presents the frequencies and the participations of the hexapod first modes.

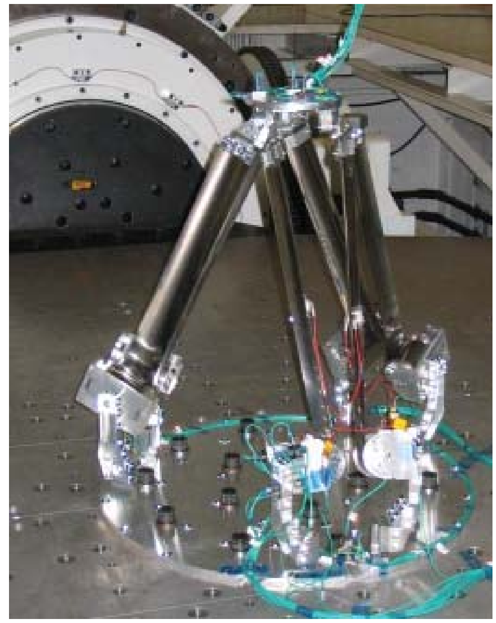


Fig. 3: hexapod on shaker

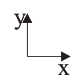
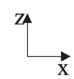
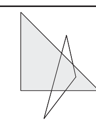
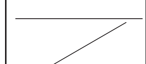
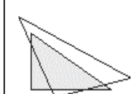
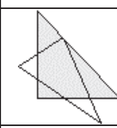
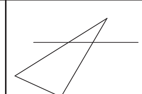
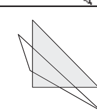
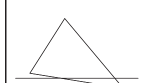
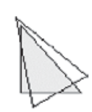
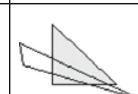
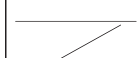
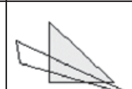
Resonant frequencies	Contribution of the mode shapes	Top view 	Lateral view 
17.8 Hz	Tilt (80%) Twist (15%) Pumping (5%)		
45.7 Hz	Pumping (70%) Twist (30%)		
~ 55 Hz 48<f<60 Hz	Tilt (50 %) Twist (50%)		
80.3 Hz	Tilt (78 %) Twist (20%)		
91.8 Hz	Pumping (60%) Twist (35%) Tilt (5%)		
96.5 Hz	Tilt (70%) Pumping (20%) Twist (10%)		
118 Hz	Pumping (60%) Twist (30%) Tilt (10%)		

Table 1: Natural frequencies and associated mode shapes.

Tests showed that the resonance behaviour of this hexapod depends on the combination of natural mode shapes mostly pumping, tilt and torsion (Fig. 4).

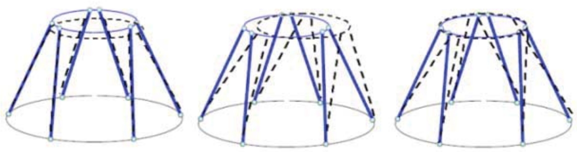


Fig. 4: Natural mode shapes: pumping, tilt and torsion.

The model described in §4 has been used to compute the modal behaviour. Modelling the structure allows highlighting components and the sets of coupling between legs that participate to the global movement of the upper platform. The modelling results show a good correlation with test results[1] and validates the modelling method.
One exception is the first mode about 18 Hz which doesn't appear in the FEM modal analysis. This mode is most probably due to slight variations in tape-springs deployed length which induce a tilt in the platform orientation. This tilt is excited and generates this mode under the first global mode of the hexapod. We can think that this mode which could have an important effect on the line of sight of the instrument can be moved to higher frequencies by a better integration of elements and positioning of the platform.
At this time, this hexapod is a plain breadboard designed to evaluate the reproducibility of a deployment thanks to tape-springs but the mass of its platform is representative of an equipped M2 mirror (about 600 g). Internal Alcatel Alenia Space studies have shown that, for optical aperture synthesis to which this kind of structure can be devoted, for example, the most important misalignment for image quality is defocus (pumping).
With a first pumping mode over 45 Hz, the sine test shows that this demonstrator exhibits an interesting potentiality to be designed with a high stiffness. A telescope based on this concept should then be easily dynamically decoupled from AOCS control loops typically between 0 and 10 Hz, from thermo-elastic deformations which are low frequency disturbances (<0.001 Hz) that will be corrected thanks to the vertical linear actuators. The decoupling from mission micro-vibrations (inertia wheels, active cryo-coolers…) will be achieved by tailoring the first pumping mode, through the optimal design algorithm with the positioning of junctions and thanks to the design of the hexapod elements.
For the development of future deployable structure demonstrators using tape-springs, we will focus, in particular, on constitutive materials and geometry of the tape-springs (curvature radius, width, thickness, composite lay-up) and flexible blades which have proved[1] having a strong influence on deployment stability and correction capability.

This modelling technique development is a first step toward towards the dynamic design of a representative breadboard. The same technique linked to the deployment kinetics modelling will also be used to evaluate the stability of the platform on discrete positions along the deployment path in order to identify and control the influent parameters of a safe deployment. The on-ground deployment testing of such structures is a challenge as the gravity compensation can't be complete and perfect. Then, the development of modelling techniques is mandatory to design such structures and to control their deployment kinematics.

6. CORRECTION CAPABILITY

With support of ESA Innovative Triangle Initiative (ITI), deployment tests have been performed on the prototype in Alcatel Alenia Space testing facilities. The hexapod deployment repeatability and the platform positioning have been evaluated by using photogrammetry with an about 10 µm precision.
After a series of 23 deployments, the maximal translational and rotational deviations are 240 µm and 820 µrad. The corresponding average values are 140 µm and 420 µrad. The average and maximal defocus errors are 74 µm and 135 µrad. It is relevant to notice that the maximal deviations are included in the workspace guaranteed by optimal design for further corrections of the upper platform position.
Then correction tests have been performed. These consisted in:

- identifying the jacobian matrix of the hexapod by performing unitary actuations of each foot and measuring the associated platform displacement,
- performing platform displacements thanks to a set of actuations calculated with the previous jacobian matrix,
- comparing the actual displacement to the theoretical one.

A statistical evaluation of a theoretical displacement named $disp_{49}$ has been calculated thanks to a Monte-Carlo stochastic simulation. This simulation considers the deviations on unitary actuations and displacement measures used for the evaluation of the jacobian matrix, the deviations on the actuations for $disp_{49}$. The mean value and standard deviation of $disp_{49}$ are compared to the measure and its theoretical precision.

	dX (µm)	dY (µm)	dZ (µm)	dθX (µrad)	dθY (µrad)	dθZ (µrad)
<$disp_{49}$>	-958	-25	-18	-72	602	-32
1 σ ••err	*9*	*10*	*5*	*92*	*92*	*93*
Test 49	-946	-29	9	-47	590	-51
1σ ••err	*5*	*5*	*5*	*94*	*94*	*94*
Difference	*12*	*4*	*27*	*25*	*12*	*19*

Table 2: Comparison between test and model

With this test, the hexapod proves its capability to make imposed large displacements within the correction workspace of the hexapod with a precision about 30 µm RMS and 34 µrad RMS. This precision is obtained with 20 µm resolution actuators.
As a second stage correction, adaptive optics will be used to reach the performance of the instrument. The phase diversity technique[13], for example, is know to correct errors whose amplitude is about the wavelength of the signal. This implies that the first stage mechanical correction of the platform position can have a precision below one micrometer for visible light application. This concept has shown a good potential to perform displacements with a precision close to the actuators resolution. To reach the adaptive optics correction precision, we will have to develop high-precision low-force clearance-less junctions, use finer actuators and make more precise measures for calibration.

7. CONCLUSION

A modelling technique to represent the behaviour of a deployed hexapod equipped with six tape-springs legs linked to the platform has been developed. It uses MSC-ADAMS and ANSYS reduced models of the flattened tape-springs. These reduced models have been pre-stressed in order to correctly simulate the hexapod behaviour. This dynamic behaviour is highly governed by the stiffness of the flexural blades required by the hexapod control along 6 DOF. The hexapod modal behaviour is characterized by a low-level sine test. It highlights coupling interactions between different subsystems corresponding to the flexural blades and tape-springs and shows that this concept presents a good potential to design stiff and lightweight structures that could be decoupled from base disturbances.
With a better understanding of the dynamic modelling of such flexible structures, this paper presents the preliminary investigation about the stability of an hexapod platform. The same technique linked to the deployment kinematics modelling will be used to evaluate the stability of the platform along the deployment path in order to identify and control the influent parameters. This way, the deployment of any hexapod with given parameters should be modelled and controlled.
The hexapod has also shown that its deployment repeatability is good enough to be corrected and that this correction can be made with a precision about 30 µm RMS. To make this structure compliant with a space optical application, more precise actuators will have to be used and new high-precision junctions to be developed. The design of new CFRP tape-springs will also be investigated in order to reduce the sensitivity of the hexapod to thermo-elastics disturbances and to control their deployment by tailoring their actuation moment.

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