ADVANCED FLEXURE STRUCTURES IN ACTIVE HIGH-ACCURACY AND LARGE BANDWIDTH MECHANISMS

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ABSTRACT - *Over several years CSEM has developed an advanced technology of flexure structures based on monolithic elastic components capable of the main kinematic functions required in precision mechanisms: linear guiding, rotation, motion amplification and reduction. The various types of monolithic flexure structures can further be combined very efficiently in order to achieve more complex motions such as two-axis rotation. These monolithic components allow the realisation of compact mechanisms that are free from all effects associated with friction, backlash and wear, and are particularly suited to the implementation of very fast controlled motions, as well as to the correction of perturbations in association with sensing and control modules with large bandwidth. The integrated "smart" structures that are the outcome of this design process have outstanding characteristics of accuracy, linearity and control bandwidth. The paper illustrates some recent flexure structures developments at CSEM and outlines the comprehensive know-how involved in this technology.*

1. INTRODUCTION

Conventional kinematic linking between mechanical parts in relative motion, such as slides and rotating bearings, suffer from a number of limitations: friction, stiction, wear, backlash, machining accuracy of the surfaces in contact, fretting or even cold welding under vacuum conditions, where special lubrication or surface coating may be necessary.

Flexure technology is not affected by these effects. It relies on deformable structures which constitute flexible bridges between stiff structural parts. It can be applied with advantage to all mechanisms where the amplitude displacement range remains moderate, for instance in the field of high resolution actuators, of isostatic suspensions used to compensate thermal effects, of mechanical impedance adapters (lever motion transmission devices), or in the field of vibration control systems. In each of these cases it can provide the maximum accuracy and stability without friction, stiction, wear or backlash and with minimal hysteresis.

Flexure technology allows for several functions to be integrated in a few monolithic structures, that can be substituted to complex kinematic assemblies. In addition, monolithic integration opens the way to:

- Simpler integration, guaranteed alignments

- Miniaturization, leading the way to integrated micro-mechanisms
- Higher reliability, particularly valuable for space mechanisms

Over several years CSEM has developed a particular capability of conceiving and modeling flexure mechanisms of great geometrical complexity and has acquired a comprehensive and very mature flexure structure technology which emcompasses much more than the bare utilization of flexible elements in mechanisms and covers in particular all the critical design issues of high-performance active mechanisms:

- Frictionless motion transmission, in many cases with amplitude reduction or amplification. Guiding accuracy and linearity.
- Minimizing mechanism mass and volume.
- Modal analysis and frequency response. Reduction of unwanted dynamic effects by balancing and damping
- Manufacturing technology issues, in particular applicable to complex monolithic structures.
- Various technology issues relating to surface quality and treatments, as well as material fatigue.

Historically the main field of applications of flexure structures is found in precision mechanisms. An earlier example is found in the micropositioning device shown in figure 1. In this case the motion time constant to be is of about one second, which limited the problem to geometrical and quasi-static effects.

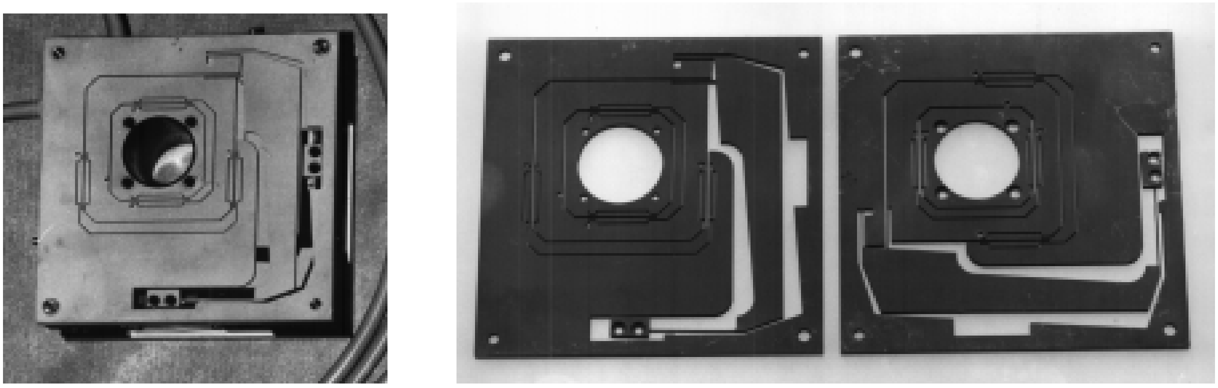


Fig. 1: Micropositioning stage for an optical fiber system. The mechanism is constituted by two monolithic components (each one machined for a single plate such that it forms a system of multiple levers linked by flexure blades) which provide the guiding and reduction of the motion, as well as a complete uncoupling between the two main directions.

Today, however, the requirements for state-of-the-art flexure based mechanisms are more and more demanding in terms of dynamic bandwidth. While Fig. 1 illustrates well the sophisticate geometry implemented in modern flexure components, the manufacturing, lifetime, overall reliability aspects as well as considerations related to dynamic behavior take a larger and larger importance in state-of-the-art mechanisms and require innovative solutions even when geometrically simple flexure elements are implemented.

Consider for instance the classical compensated parallelogram which is frequently used for accurate linear guiding. This simple geometry has been developed into a monolithic component (Fig. 2) manufactured in aluminium alloy, suitable for a variety of designs that need the accurate linear guiding of an actuator or sensor.

The profile cutting is performed by electro-discharge machining (EDM): a particular EDM process was thereby selected in order to ensure the desired homogeneity of stiffness characteristics along the blades as well as the surface quality. The latter aspect is related particularly to the fatigue life, which is ultimately one of the very few real limitation of such flexure structures.

Fig. 2: A monolithic "hairpin" compensated parallelogram. The size of the baseline model is about 4 cm and its motion range is ±1 mm but the concept is scaleable both to smaller and large dimensions.

Another important aspect in the use of flexure structures concern spurious resonance modes and frequency response. Compensated flexure parallelograms experience beside their fundamental mode, various higher order modes which will be excited at higher frequencies and can be quite undesirable for large frequency bandwidth applications. To reduce these unwanted dynamic effects, selective damping devices have been developed and patented, which are located at the “hairpin” heads.

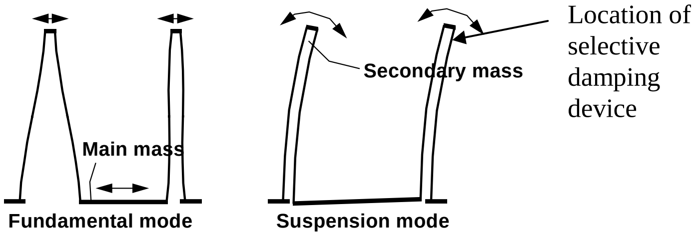


Fig. 3: The fundamental mode and of one of the main disturbing modes.

2. FLEXURE STRUCTURES AND ACTIVE MECHANISMS

Flexure structures find more and more applications as the key component of large bandwidth active and adaptive systems in which one or more of the following characteristics are required:

- Frictionless guiding, driven only by kinematic and stiffness constraints
- Uncoupling of degrees of freedom, which allows the making of isostatic structural systems, which are often the most direct way to a structural solutions and are also simpler to conceive and to predict.

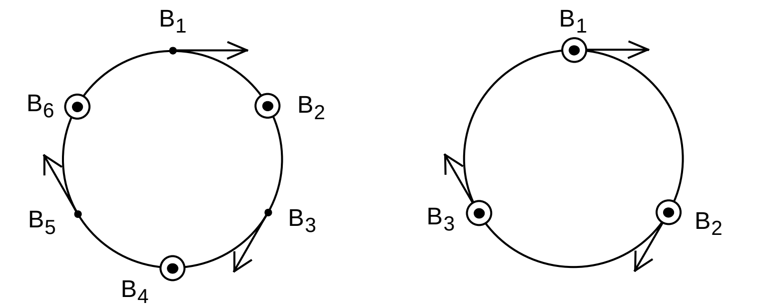
- Motion amplification and reduction. In particular, the case occurs frequently in which the optimal ranges of the most suitable actuator, measuring devices and desired actuated motion at the interface, each taken individually, are widely different. The structural/mechanical components should then ideally be able to reconciliate these different ranges without loss of individual resolution or performance in the sensing, control and actuator stages. This implies the implementation of frictionless motion guiding/amplification/reduction stages as part of the intended system.

The following examples drawn from some recent projects will illustrate how these concepts are actually implemented in state-of-the-art active mechanisms.

3. MECHANICAL ELASTIC ELEMENT FOR DAMPING AND ISOLATION (MEDI)

We describe here a flexure-based mechanical element designed as the main component of an isolation and damping interface between a spacecraft main structure and an optical terminal for inter-satellite laser beam communication.

For any solid in space, the position of the load interface is controlled by six independent degrees of freedom (DoF) which may be conveniently defined by one-dimensional translations of six attachment points B_1 to B_6 (see Fig. 4A) or by two-dimensional translations of three attachment points B_1 to B_3 Fig. 4B). Damping and isolation can then be achieved by transmitting separately the relative motion of the attachment point along the relevant direction.



A. Control by six 1-DOF units B.Control by three 2-DOF units

Fig. 4: Two possible configurations for 6-DoF load position definition

Consider the mechanism schematically represented in Fig. 5: a monolithic flexure structure, essentially planar, is used to transmit a vertical vibration of the load interface through flexure hinges and a lever into a suitable isolator/damper unit. The lever will generally allows adapting the optimum range of the isolator/damper unit to the actual amplitude of vibration. In order to avoid the hyperstatic overdetermination of the 6-DoF support (Fig. 4), each single-degree-of-freedom mechanism must also provide the uncoupling of all other DoF's by assigning them a much lower stiffness than along its main direction. The flexure hinges that allow the function of the lever also provides the uncoupling of X-translation and Z-rotation. Additional flexure blades are obtained by reducing the thickness of the plate along the B-B junction, thus effectively uncoupling also the Z-translation and the X- and Y-rotations.

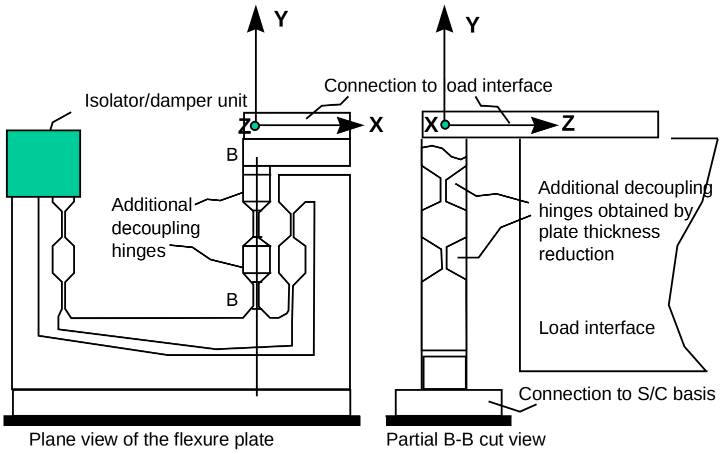


Fig. 5: Basic concept for a single-degree-of-freedom isolation/damping element

For this particular project, the configuration of Fig. 4B was preferred and implemented by a mechanical interface component combining stiffness and damping properties along two translation DoF's, in practice combining two single-DoF elements in one.

This 2-DoF element is illustrated in figure 6 below. Its main component is a flexure structure by which the two in-plane displacements at the load interface are:

- uncoupled with respect to each other and with respect to the other DoF's,
- transmitted and amplified to two linear electromagnetic actuators, which act as passive dampers.

Also the support of the two linear actuators consist of a compensated flexure parallelogram, so that the entire mechanism is free from spurious friction or wear effects of any kind.

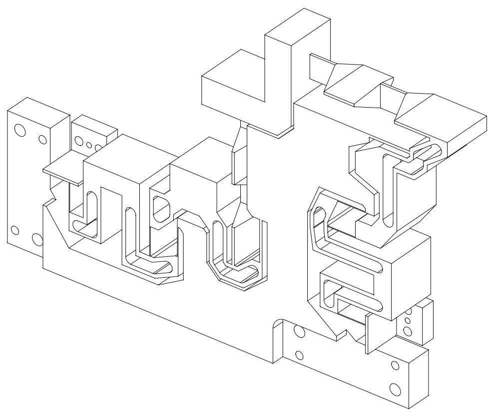


Fig. 6: 2-DoF Mechanical Element for Damping and Isolation (MEDI). Right, a drawing of the rather complex monolithic flexure structure which provides both the uncoupling and the amplification functions of the MEDI.

4. TWO-AXIS TILT FINE POINTING ASSEMBLY MECHANISM

In the field of inter-satellite optical communications, a pivotless tip-tilt mechanism implementing the frictionless support of three linear actuators with a 3-rod suspension allows a fine pointing mirror to combine the high static deflection range with high frequency bandwidth and step response performance required by the acquisition and tracking functions.

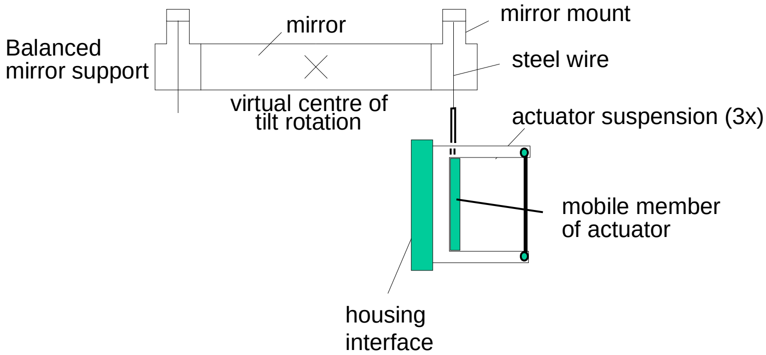


Fig. 7: Principle of 2-axes mirror suspension

The main technical specifications for this mechanism were two-axis deflection of an optical beam of 10 mm in diameter over a optical steering angle of +/-100 mrad, with a resolution above 1/20'000 and a small signal bandwidth of above 1 kHz. The design was aimed at a small compact module (300 g / 300 cm^3).

Three linear actuators are placed in a star configuration and drive the mirror frame through intermediate steel wire flexible rods. The center of rotation of the mirror and its frame coincide with their center of gravity. The three actuators are of the mobile magnet type and are suspended with the monolithic "hairpin" flexure parallelogram as already illustrated in Fig. 2. In this case the issue of stray resonances is particularly critical and is solved by selective damping.

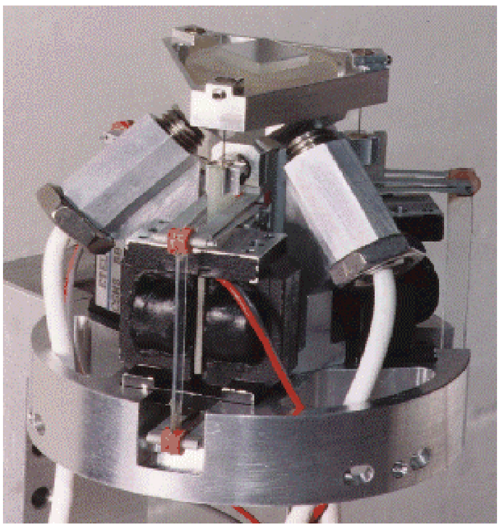


Fig. 8: Photograph of two-axis tilt fine-pointing assembly prototype

This is just one example of various fast 2-axes tip-tilt devices developed and built by CSEM for various purposes.

Fig. 9 illustrates another mechanism: here a lever amplification and the guiding of the three actuator are provided by flexure pivots located opposite to the mirror suspension.

Fig. 9: Illustration of an ultra-fast tip-tilt device for a special purpose printing machine

With this particular system a dynamic bandwidth is achieved by means of a state space controller with a Bessel filter characteristic and a cutoff frequency of 2kHz. The total mechanical tilt angle is ± 10°, and the maximum step deflection is about 2% of total tilt range. The achieved accuracy is about 1:80’000.

5. ACTIVE COMA-FREE SECONDARY MIRROR

This project concerned an active secondary mirror (M2) unit to achieve active high pointing stability of large spaceborn telescopes. The main technical requirements for the M2 mechanism were: the coma-free rotation around a point situated some 200 mm behind the secondary mirror apex, the tip/tilt resolution (better than 1:50’000) implied to sense displacements in the nano-meter range, and a minimum bandwidth for vibration rejection of more than 100 Hz.

The concept developed by CSEM (fig. 9) is based on two coaxial cylinders connected by transverse (flexible) membranes, acting as a double reduction lever for the transmission and inversion of two-axis transverse motion from an actuator ring to the M2 mobile mirror stage. By suitable choice of the reaction mass, the transverse reaction induced by any commanded M2 motion on the telescope structure is compensated by the inverse motion of the actuator ring. The lever reduction factor is set equal to 10, corresponding to a mass of the order of 50 grams, for a M2 mobile stage mass of 500 grams. The ring is moved by four push-pull voice coil actuators, two per axis in order to include redundancy, within a transverse range of ± 500 μm corresponding to ± 250 μrad full tilt angle about twa axes.

In order to achieve tip-tilt rotation, the M2 mirror stage is further guided by four concentric rods pointing to the virtual center of the coma-free rotation point. A very high axial rotation stiffness is obtained by attachment to the lever cylinders without other structure. This combination has the advantage of maintaining the suspended mass to a minimum and the overall system can be contained into a very reduced volume.

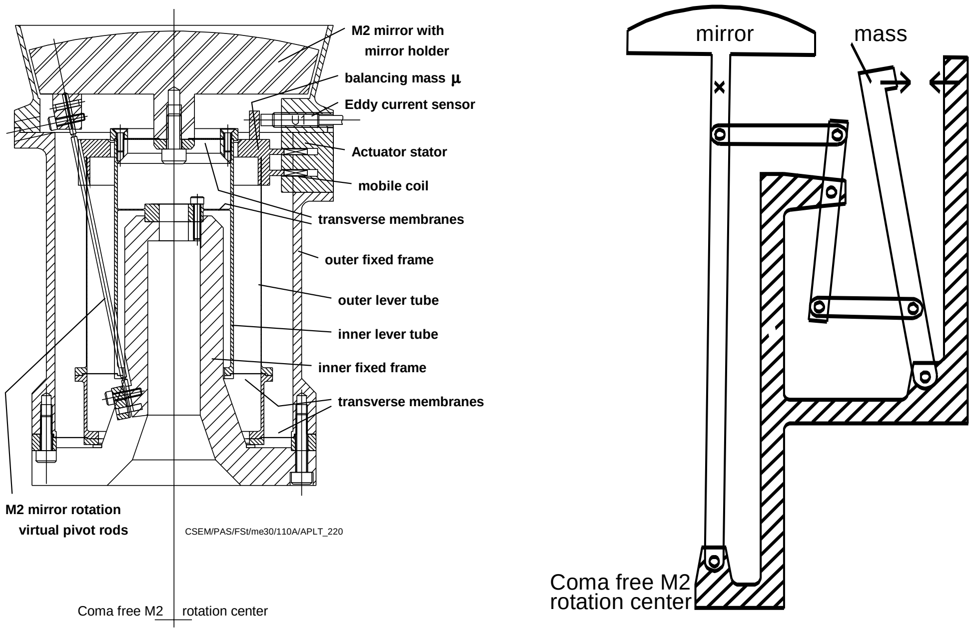


Fig. 10: Basic flexure kinematics of the coma-free secondary mirror unit: note that the rotation point is far outside the envelope of the system. Right, the corresponding kinematic theoretical mechanism, which if based on stiff members and hinges would require a much large volume

6. HIGH-ACCURACY CORNER CUBE MECHANISM

A critical part of any optical interferometric instrument is the delay line, which allows the phase adjustment of the two light beams before their coherent combination. This generally requires one or more optical surfaces, often in form of a corner cube reflector, which have to move linearly to create or correct an optical path difference between both arms of the interferometer. The trajectory of this reflector must be controlled to an accuracy better than the wavelength.

The development of such a device has been commissioned to CSEM by EUMETSAT (European organization for the exploitation of Meteorological Satellites) for the IASI (Infrared Atmospheric Sounding Interferometer) instrument developed for the next generation European meteorological satellite METOP.

The IASI CCM (Corner Cube Mechanism) is an active device which must fulfill a number of very severe kinematic and mechanical requirements. The linear motion of the corner cube reflector shall be driven with a periodic motion in which alternating strokes must have a velocity of 130 mm/s with a maximum variation of ± 1 mm/s. The most critical design driver is the lateral deviation allowed from the ideal straight line which is required to be less than 2 micrometer on the short term. The CCM also has very demanding reliability and lifetime requirements as it is deemed to operate for about a billion cycles of alternating motion.

The design is illustrated in fig. 11. The prescribed accurate linear guiding is achieved by means of a flexure structure in form of a compensated parallelogram constituted by two machined membranes in high-strength copper-beryllium alloy.

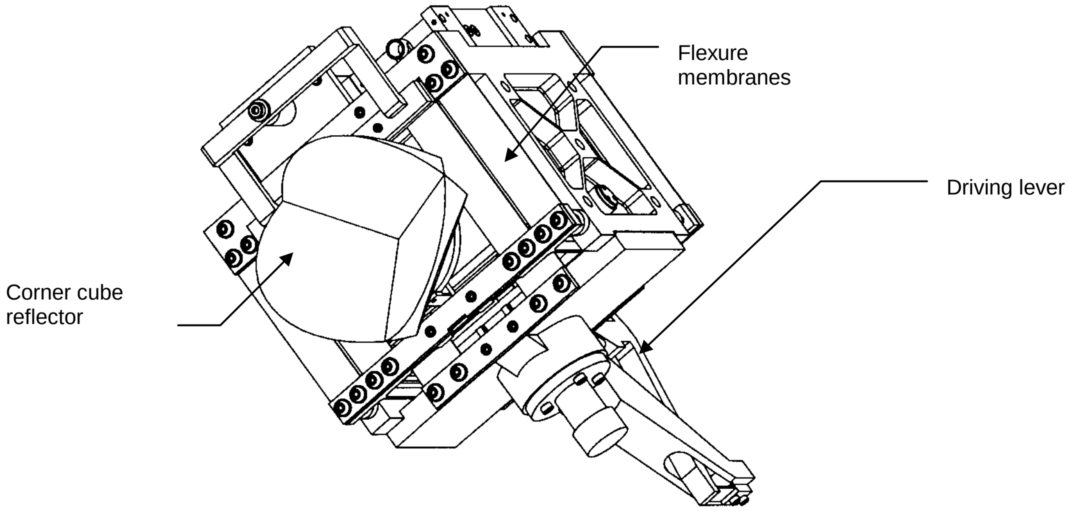


Fig. 11: IASI Corner Cube Mechanism

An innovative aspect is given by an additional driving lever with flexure blades which constrains the motion of the parallelogram in order to dramatically decrease the remaining error caused by the inevitable manufacturing and assembly tolerances. Indeed without the driving lever the lateral deviation can be expected to be several tens micrometers. The particular implementation of this flexure driving lever concept is in the meantime object of a patent application by CSEM.

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