FLEXIBLE BEARINGS FOR HIGH-PRECISION MECHANISMS IN ACCELERATOR FACILITIES

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Abstract

While in conventional mechanical bearings motion is obtained by sliding or rolling between solid bodies with the resulting mechanical non-linearities, flexible bearings rely on the elastic properties of matter allowing several advantages to be obtained. Combining flexible bearings with adequate actuators and sensors allows thus nanometric positioning resolutions to be obtained.

In this paper, the basic principles of compliant mechanisms design methodology are presented. To illustrate the approach, some examples taken from aerospace and astronomical applications are described. Several compliant mechanisms used at the Swiss Light Source synchrotron facility are then presented.

1 INTRODUCTION

Flexible bearings are an alternative to conventional mechanical bearings. While in the latter motion is obtained by a sliding or rolling motion between two (or more) solid bodies with the resulting mechanical non-linearities (friction, pre-sliding displacement, ...), flexible bearings rely on the elastic properties of matter and are thus characterized by several advantages:

- high precision
- no friction
- no hysteresis
- no wear
- no need for lubrication
- no risk of jamming
- no backlash
- possibility of monolithic manufacturing and thus of "design for no assembly"
- main sources of errors are systematic and therefore simple control laws can be used
- reduced costs.

On the other hand, flexures do present some limitations related to their physical principles:

- limited stroke
- limited load capacity
- presence of restoring forces
- complex kinematics.

Although the basic principles of flexible bearings have been known for several decades, the design methods that could be found in literature have long remained fragmented. Only recently the interests for flexures and

their applications has grown leading to a more systematic treatise of the respective design methodologies [1], [2], [3]. A resulting tendency towards the usage of flexures in high- and ultra-high precision devices (e.g. robots and manipulators) and in applications in hostile or ultra-clean environments (temperature variations of hundreds of degrees, cryogenic temperatures, high radiation levels, high- and ultra-high vacuum, high vibration levels, …) is also evident.

Many examples of usage of flexures-based devices can recently be found in space instruments embarked on satellites, but increasingly also at accelerators facilities around the world in mechanisms used to position with high resolutions and accuracies the optical components.

It is also relevant that the progress in wire electro-discharge machining (EDM) techniques allows nowadays the manufacturing of complex flexures-based monolithic mechanical structures having several degrees of freedom (Fig. 1) with an excellent surface quality. This in turn leads to longer fatigue lifetimes of the considered components.
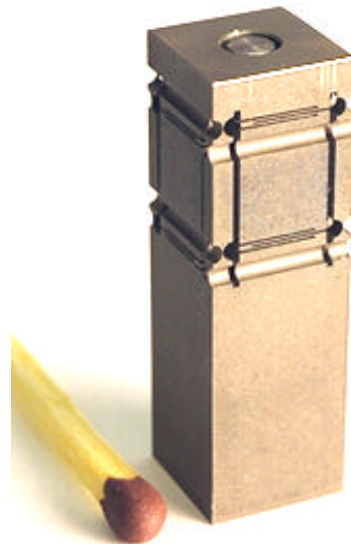

Figure 1: Monolithic X-Y stage machined by wire EDM. This part is composed of 16 notched circular flexure hinges with a thickness of 30 μm

The aim of this paper is to illustrate the mechanical design principles of flexures-based compliant mechanisms. A presentation of several design cases of

ultra-high-precision mechanisms based on flexures will follow. These examples relate to space and astronomical projects realized by the Centre Suisse d'Electronique et de Microtechnique (CSEM), as well as devices applied at the new Swiss synchrotron radiation facility SLS situated at the Paul Scherrer Institut (PSI).

2 DESIGN OF COMPLIANT MECHANISMS

2.1 Long Stroke Compound Kinematics Principle

The compound rectilinear stage (Fig. 2) is a common structure used as a linear translation bearing. Its kinematics results in a stroke doubling that of a simple parallel translator, as well as in a significant reduction of the vertical parasitic movement. The device is, however, still characterised by an intrinsically parasitic degree of freedom (DOF) that can be excited by external bads or dynamically due to fast movements. A classical solution to this problem consists in using a slaving lever ("servo"), which couples the motion of the mobile bloc to that of the intermediate stage (Fig. 3). The resulting planar kinematics has thus a single DOF, which corresponds to the desired rectilinear translation of the mobile bloc.
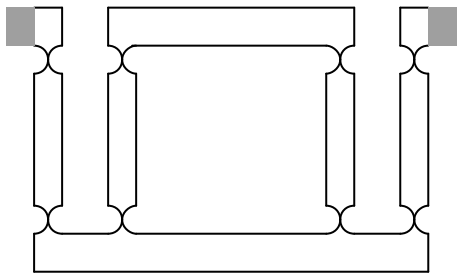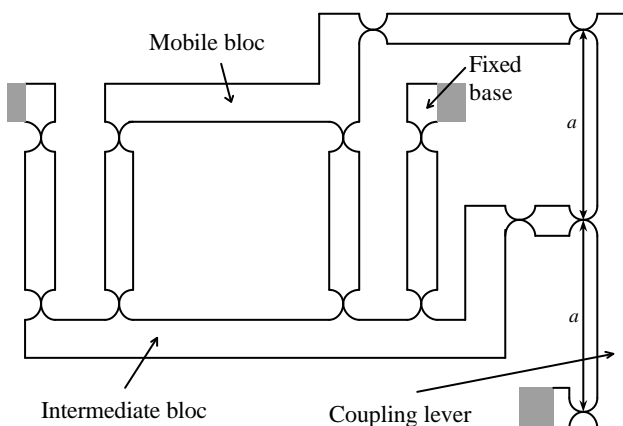
Figure 2: Compound rectilinear stage (2 DOF)

Figure 3: Compound rectilinear stage with coupling lever (1 DOF)

A compliant mechanism based on the compound rectilinear stage is used as the axial translator for an interferometer linear delay line developed at CSEM. This device, called the Corner Cube Mechanism (Fig. 4 and 5), allows a corner cube reflector to be moved over a ± 12 mm range with a lateral off-axis error smaller than

1 µm. The apparatus allows bi-directional full stroke movements to be performed at a 2.3 Hz rate. It will work continuously for at least 5 years on METOP-type satellites (Fig. 6) allowing to measure the earth's atmospheric spectrum and thus to estimate the dependence of the temperature and humidity values on the altitude.
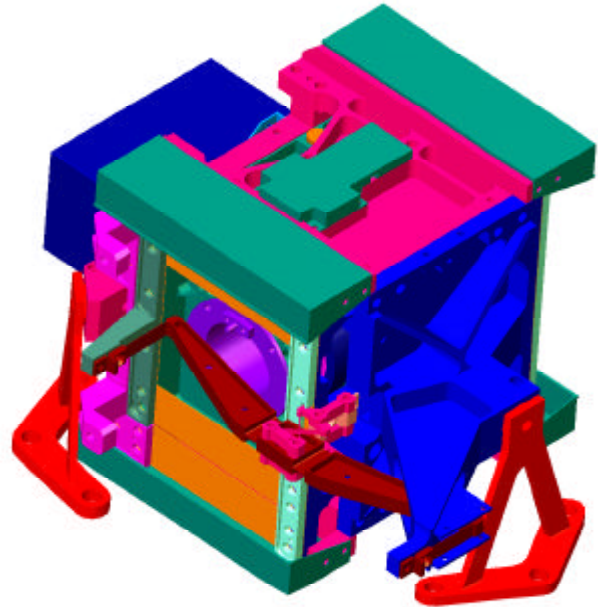

Figure 4: CAD drawing of the Corner Cube Mechanism (CCM)

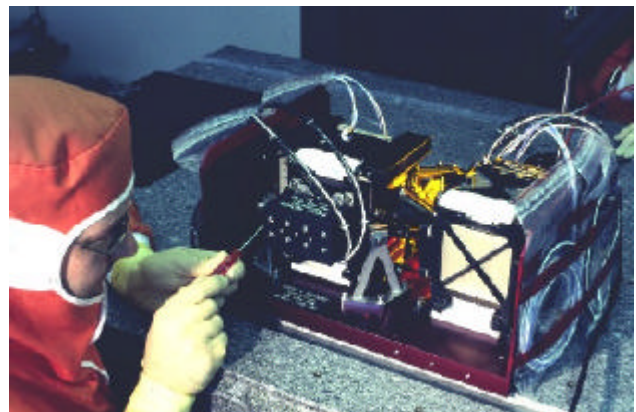Figure 5: Electro-discharge machined coupling lever of the CCM

Figure 6: Final assembly of the CCM for the IASI instrument of the METOP satellite taking place at CSEM

The same kinematic principles were applied also in the design of a rotational bearing (Fig. 7) developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) [2]. Although in this case the slaving arrangement is not as simple as for the lever of Fig. 3, the employed slaving kinematic chain still couples the rotation of the intermediate central bloc to that of the mobile bloc. The occurrence of the problems outlined above is thus avoided, while the experimentally achieved radial stiffness of the pivot is increased by a factor nine. The resulting monolithic pivot has a stroke of $\pm$ 15°.
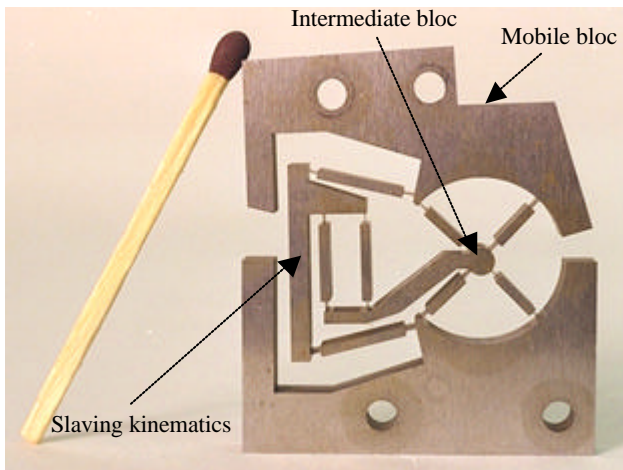

Figure 7: Monolithic long stroke ($\pm$ 15°) flexible pivot with slaving mechanism

2.2 Stiffness Compensation Principle

Flexible bearings produce a restoring force when they are moved away from their nominal position. For some applications this linearly increasing force can become a limiting factor. In that case, preload springs can be used to tune the stiffness of the bearing. The principle is shown on the test set-up of Fig. 8. The natural stiffness of parallel spring stages can be therefore tuned to values close to zero, producing an ideal translation bearing.

The stiffness compensation principle is applied on the monolithic device (Fig. 9) realized by wire EDM. Fig. 10 shows how the preload compensates for the restoring force of the translation bearing. It should be noted that making use of this principle allows also the power consumption of the actuators to be drastically reduced.

2.3 Parallel Kinematics Principle

Flexures can be combined into multi-degrees of freedom parallel kinematic structures to obtain complex high-precision compliant mechanisms. The field selector mechanism of the Nasmyth Adaptive Optics System (NAOS) used at the Very Large Telescope (VLT) in Paranal, Chile (Fig. 11) has 3 DOFs ($Z-\theta_X-\theta_Y$). It is driven by three mobile magnets linear actuators that are attached to the base. The mobile magnets are guided by compound parallel spring stages. Flexible rods are used as ball bearings connecting the mobile mirror to the actuators. A flexible membrane is used to bloc the undesired DOFs of the mobile mirror ($X-Y-\theta_Z$).
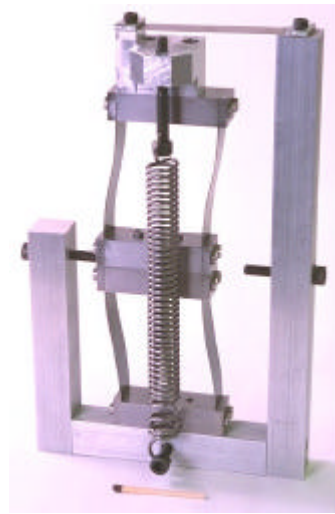

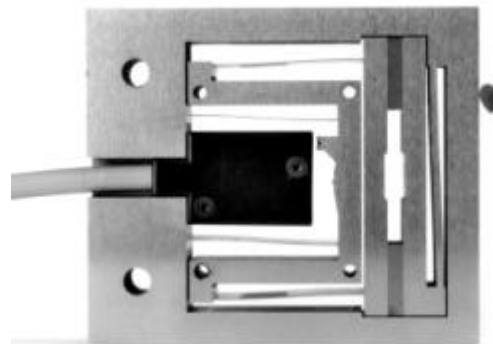Figure 8: Test set-up of a tuneable-stiffness parallel spring translator

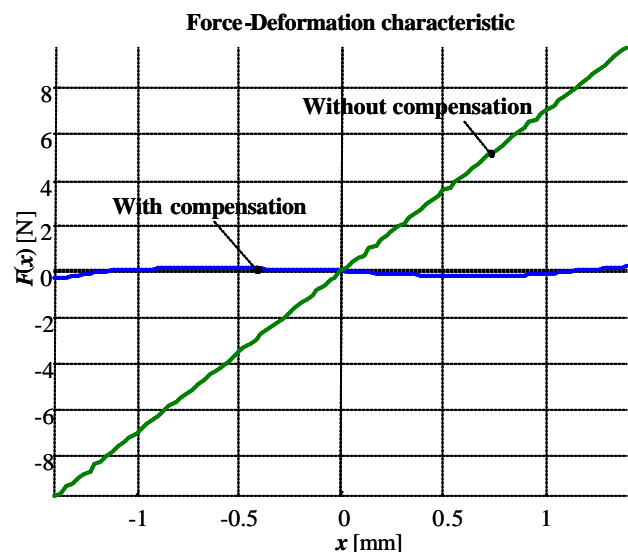Figure 9: Monolithic tuneable-stiffness parallel spring stage

Figure 10: Force-deformation characteristic of the tuneable-stiffness parallel spring mechanism of Fig. 9
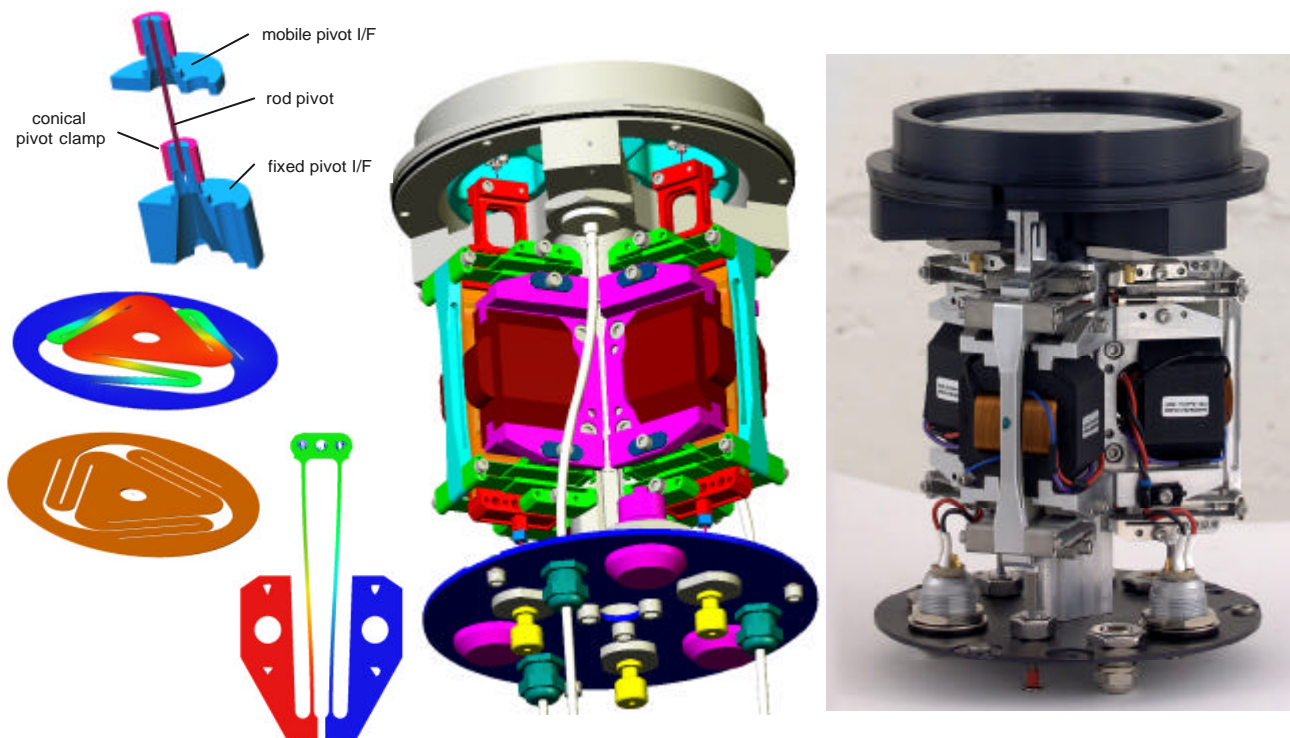
Figure 11: CSEM's Tip-Tilt-Piston field selector used at the VLT in Chile. The mobile mirror is driven to select a sub-pupil of the VLT's field of view, collecting the light of a bright star on the NAOS. Mirror diameter: 85 mm; tilt amplitude: ± 6°; angular resolution: 0.62"; rise time for a 0.24° step: 40 ms

3 COMPLIANT MECHANISMS USED AT THE SWISS LIGHT SOURCE (SLS) SYNCHROTRON RADIATION FACILITY

The technological characteristics of synchrotron radiation and other accelerator facilities pose severe challenges in terms of the stability and reproducibility of the beam position. This implies strict requirements on the positioning mechanisms for the respective optical elements. In fact, the latter must be used in ultra-high vacuum (UHV) and meet concurrently additional environmental constrains (thermal variations, vibrations,…), while allowing resolutions and accuracies in the nanometric and micro-radian range to be achieved.

On the other hand, as evidenced before, compliant mechanisms offer the needed high-precision coupled with UHV, radiation and high or cryo-temperature compatibility. They are also characterized by simple, reliable and maintenance free design.

This section presents several examples of compliant mechanisms used at the SLS facility.

3.1 High Heat Load Monochromator Crystal Mount – Materials Science Beamline

The crystal mount for the first monochromator crystal of the SLS materials science (MS) beamline (Fig. 13) was realized in a framework of a collaboration with the Hamburger Synchrotronstrahlungslabor (HASYLAB) at DESY. This Si (111) crystal absorbs up to 1.1 kW of power with peak power densities approaching 3 W/mm^2,

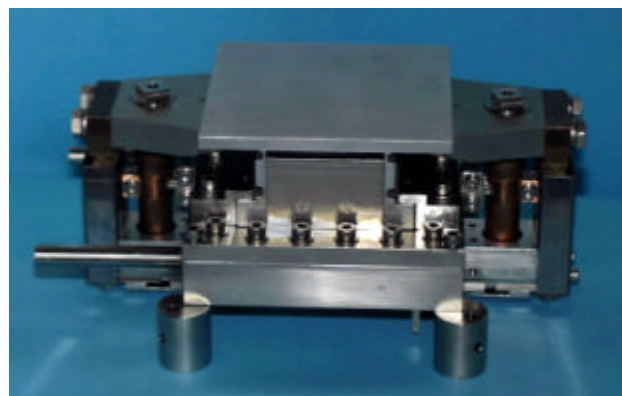posing thus severe challenges in attaining the required positional stability.

Figure 12: First monochromator crystal mount for the SLS MS beamline produced in the PSI workshops

The adoption of elastic hinges in the mount allows in this case to decouple the crystal from its support structure, while concurrently permitting the adaptation of its shape to be obtained. In fact, the compensation of the convex bowing of the reflection surface induced by the heat load on the crystal is achieved by mechanically loading the wing-like sections of the top crystal plate (Fig. 13). The supports of the actuating lever arms comprise a set of flexural elements as well, assuring thus the respective longitudinal and transversal compliance.

The numerical evaluation of the performances of the device, as well as the operational experience on the

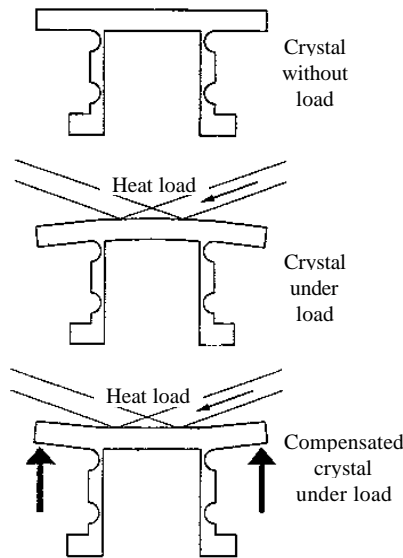beamline so far, prove the complete suitability of the adopted concepts in the foreseen working conditions.

Figure 13: Compensation of thermal deformations of the monochromator crystal [4] (courtesy of HASYLAB)

3.2 In-Vacuum Dynamic Mirror Bender – Protein Crystallography Beamline

The in-vacuum vertical focusing rhodium-coated fused silica mirror, placed on the same optical table and downstream of the double crystal monochromator of the SLS protein crystallography (PX) beamline, was developed in collaboration with the European Synchrotron Radiation Facility (ESRF). The mirror is dynamically bendable providing radiuses of curvature in the 400 - 12000 m range, while concurrently has to guarantee excellent stability and reproducibility [5].
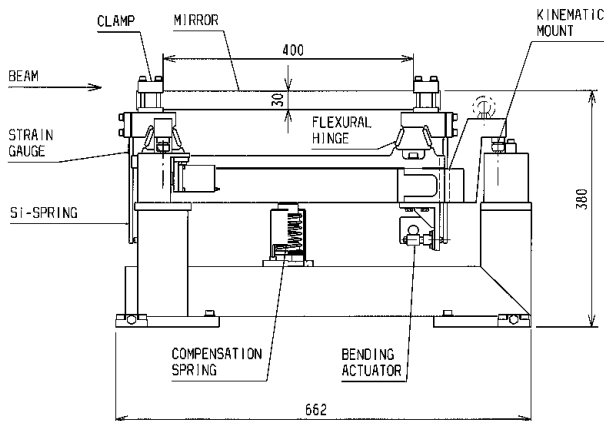

Figure 14: Mechanical design of the in-vacuum flexural hinge-based dynamic mirror bender for the SLS PX beamline

The needed bending moments are applied independently at the mirror ends (which makes possible the eventual attainment of asymmetric - e.g. aspherical - mirror bending) through hysteresis-free Si-springs (Fig.

14). The necessary rotational degrees of freedom and the uncoupling of the mirror from its basement are assured through a set of wire EDM machined flexure hinge-based joints (fig. 15). The whole mechanism is positioned on the table via a motorised kinematic mount arrangement.

Figure 15: Detail of the flexural hinges on the mirror support

First experiences at SLS show that a slope reproducibility of the order of 0.1 µrad with an angular rms stability of the order of 2.5 nrad can be obtained with the adopted configuration [5].

3.3 Sagittal Crystal Bender – Protein Crystallography Beamline

The PSI patented crystal bender [6] allows the sagittal bending of the second monochromator Si (111) crystal of the SLS PX beamline to be obtained. The adopted design provides, in fact, an elegant way of achieving the dynamic micro-focusing of undulator radiation in the horizontal plane.

In this case the bending is achieved by means of 4 motorized micrometer screws and compliant elements-based lever arms (Fig. 16).
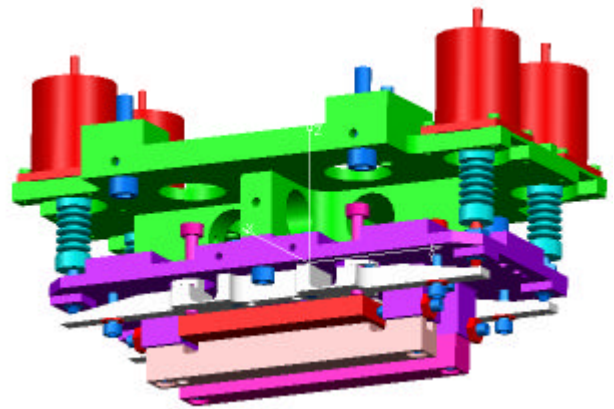

Figure 16: Sagittal crystal bender for the SLS PX beamline

First tests with this arrangement show that at 10 keV a 6 mm beam can be focused to 20 µm with an efficiency greater than 90%. Dynamic focusing was also demonstrated.

Moreover, together with the vertical focusing bender illustrated above, the micro-focusing of the beam in the PX beamline to the designed values (10 x 25 µm^2) was reached. A 0.1 eV energy reproducibility of the monochromator was also achieved [7].

3.4 Flexible Taper Transition – In-Vacuum Undulators

In the framework of a collaboration with the SPring-8 synchrotron facility in Japan, a flexible taper transition for in-vacuum undulators was realized [8]. This compliant beryllium-copper (CuBe) structure provides a smooth transition between the vertical aperture of the adjacent fixed taper section and the movable in-vacuum magnet carrying beams of the undulator (allowing the insertion device gap movements), thus minimizing any impedance discontinuity (Fig. 17).

The number and thickness of the notch transitions of the flexible taper have been optimised via non-linear FEM analysis to increase the respective fatigue lifetime to the 10^5 cycles region.

In a further development step, the longitudinal compliance of the arrangement was assured by adopting a parallel spring translator. This allows then the eventual axial-stresses-induced yielding due to the differential thermal expansion of the UHV chamber with respect to the magnet carrying beams during bake-out to be avoided. The usage of the parallel spring translator does induce a small asymmetry in the behaviour of the lower and upper flexible transition halves, due to the parasitic vertical displacement of the ends of the springs in the µm range. This effect has, however, a negligible influence on the stress-strain behaviour of the taper itself.

Numerical simulations have also allowed to establish that, although during the undulator gap scans and the bake-out procedure the flexible blades assuring the smooth transition between the flexible taper and the vacuum flange are slightly deformed, the resulting stress levels are negligible.
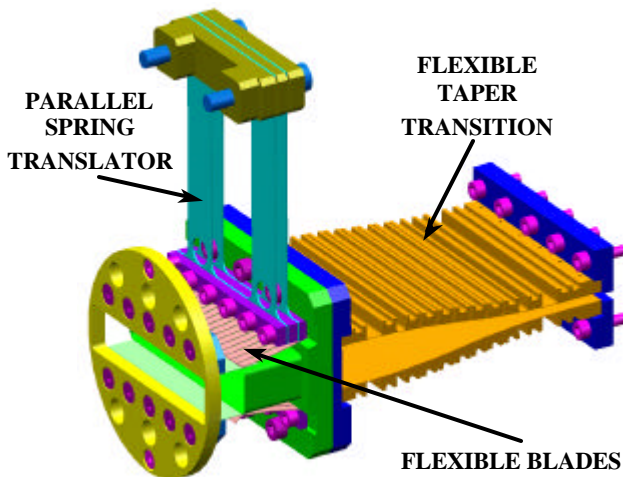

Figure 17: Flexible taper transition for in-vacuum undulators

The prototype of the newly developed assembly including wire EDM machined flexible tapers is being tested to establish empirically the fatigue lifetime of the device, but also to evaluate the potential occurrence of wear at the spring-translator-to-flexible-taper connection or at the surface of the flexible blades. Other effects that could not be taken into account during the numerical optimisation (e.g. effects induced due to the fabrication and heat treatment procedures) will also be evaluated.

Depending on the outcome of the experimental assessment, the concepts developed in the framework of the flexible taper design could then be adopted also for the SLS storage ring scraper device.

4 COMPLIANT MECHANISMS AT OTHER SYNCHROTRON RADIATION FACILITIES

At many other synchrotron radiation facilities, flexible bearings and the resulting compliant mechanisms are increasingly becoming a widely adopted design standard to meet the needs for high-precision positioning devices for the optical elements. Some examples are briefly outlined below.

At the centre for X-ray lithography in Wisconsin (USA) compliant mechanisms were applied in the case of an X-Y micropositioning stage ($100 \times 100 \ \mu m^2$ range, 10 nm resolution, first eigenfrequency in the 100 Hz range) for use with a scanning X-ray microscope [9].

At the Elettra facility in Italy, a mirror manipulation unit was developed that allows the pitch and jaw of a plane mirror to be remotely controlled with an accuracy better than 0.1 mrad (Fig. 18) [10].
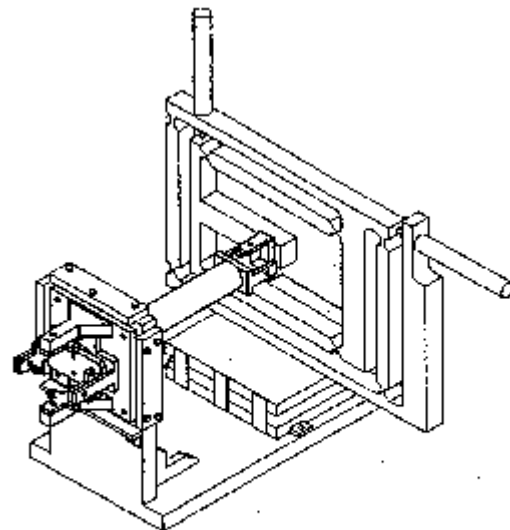

Figure 18: Mirror manipulator at Elettra, Trieste (I) [10] (courtesy of Elettra)

Mechanisms based on wire EDM machined flexible bearings have also been applied to bend Bragg-crystals or multilayers with µrad accuracy, with a high level of know-how developed in this frame at ESRF [11], [12], [13], [14]. It should be noted here that even the sagittally bent crystal can in some cases be a compliant structure on its own, since a ribbed crystal allows to approach as much as possible a smooth cylindrical shape, while concurrently minimizing twisting and anticlastic bending (i.e. the bending of the crystal in the meridional direction) [13].

More recently, flexures-based compliant devices have also been used at the APS (Argonne, IL, USA), where a "high-stiffness weak-link mechanism" produced via lithographic techniques is used to position an assembly of monochromator crystals obtaining a meV bandpass. The mechanism itself is constituted by a series of notched bars in a circular configuration that allows to retain all the advantages of flexural bearings outlined above (in fact, a resolution of the order of 20-50 nrad was achieved with a motion range of a couple of degrees), while on the other hand the overconstrained assembly seemingly limits all the parasitic motions and increases substantially the dynamic stability of the device [15].

At the BESSY facility in Berlin (D), a compliant flexible parallelogram mirror manipulator for a switching mirror unit was developed. The device allows to achieve 1.5 µm positioning resolutions over a 50 mm range with a reproducibility of 5 µm and extremely small parasitic motions [16]. Another flexible hinges-based compliant mechanism is used at the same facility for the manipulation of the refocusing mirror, allowing resolutions of 0.8 - 5 µrad and 0.5 µm to be obtained over motion ranges of respectively ± 100 µrad to ± 2° and ± 1 mm [17].

At BESSY is in development also a monolithic flexible mirror support for the infrared beamline with two independent perpendicular rotational DOFs that intersect at the mirror surface. An overconstrained arrangement is again used to limit the parasitic DOFs, while guaranteeing high dynamic stiffnesses (Fig. 19) [18].
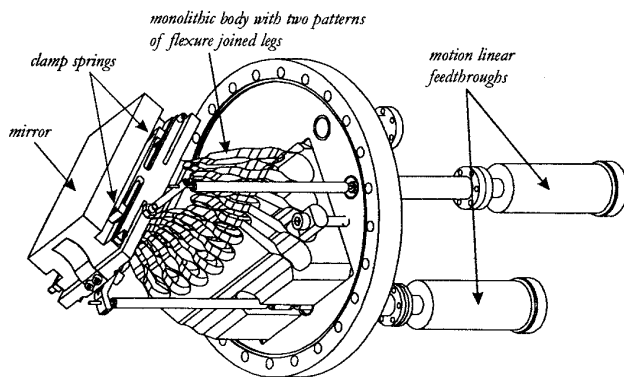

Figure 19: Monolithic two-rotational-DOFs mirror manipulator [18] (courtesy of BESSY)

5 CONCLUSION

Flexible bearings make the design of a new generation of high- and ultra-high-precision mechanisms possible. Realized applications with typical positioning resolutions in the range of 10 to 100 nm (respectively 0.02 to 1 µrad), amplitudes of 0.1 to 50 mm (respectively 1 mrad to several degrees) and working bandwidths of 1 to 150 Hz have been presented in this work.

Mastering the design of complex flexible structures as well as the interactions at the system level between the

- mechanical structure
- actuators
- sensors
- electronics
- control algorithms

allows, in fact, to benefit from the proposed compliant mechanisms approach in the design of accelerator equipment and instrumentation.

6 ACKNOWLEDGMENTS

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