An Integrated Mechatronics Approach to Ultra-Precision Devices for Applications in Micro and Nanotechnology

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Abstract

An effort to optimise both mechanical and electronic/control components of ultra-precision devices is presented. The considered mechanics is compliant, which overcomes the non-linearities of conventional devices. Design guidelines for hinge optimisation are given and a preliminary consideration of the scaling effects is performed. The developed control system is based on a rapid controller prototyping platform consisting of a Compact-PCI system running under the Linux RTAI real-time extension.

1. Introduction

Mechatronics is seen as the combination of mechanics, electronics, computer science and control. The focus of a mechatronics approach lies on the overall system behaviour, while the different components are seen as instrumental for obtaining the desired performances. In practice, the fact that the whole system is as good as its components is often forgotten. When considering dynamic behaviour as the most important issue, the impression that the model obtained from the identification procedure is valid in absolute terms often tends to prevail over the fact that different working conditions may produce unexpected results.

This work follows an approach aimed at overcoming these limitations via the optimisation of all system components. The mechatronics device

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considered here and shown in Fig.1 is based on optimised compliant mechanical structures for ultra precision positioning (e.g. for handling and assembly of microcomponents or for STMs or AFMs). In fact, given the absence of mechanical non-linearities [1], compliant mechanisms are advantageous in high precision applications, allowing simple control typologies to be applied. The architecture of a single degree-of-freedom (DOF) optimised integrated mechatronics device is hence described.

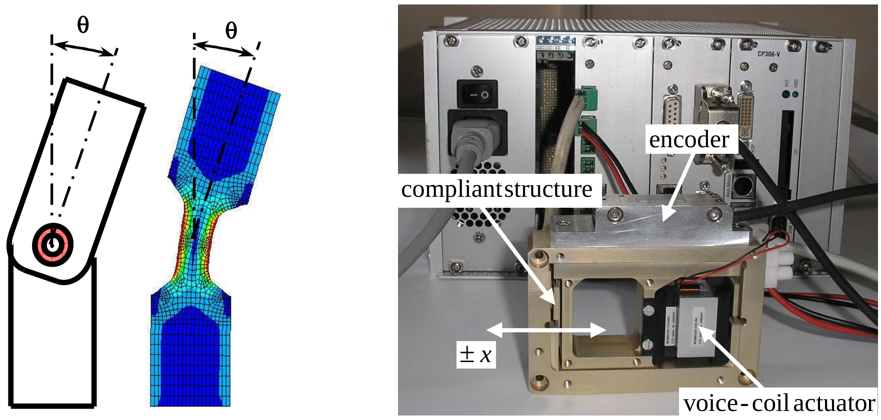

Fig. 1. Compliant joint and mechatronics device optimised in this work

2. Optimised mechanical structure

Mechanical aspects considered in the design process were the optimisation of the flexural hinge shapes (Fig. 2) in terms of compliance, strength and parasitic motions, as well as the scaling effects on the mechanical properties. Several hinge shapes were considered: the prismatic beam (P shape), the conventional right circular (RC) hinge, the optimal shapes obtained in classical mechanics (based on the authors indicated as the Grodzinski (G), Baud (B) and Thum & Bautz (TB) shape [2]), the optimised shapes obtained by coupling non-linear parametric optimisation algorithms with automatic FEM meshing and spline function generators like the optimised circular shape (OC shape), the optimised pure elliptical shape (OPE), the elliptical shape with $r_y = h_{min}/\pi$ (OEB) or the freeform optimised shape (FFO). Compliances around the primary hinge rotation DOF φ_z, as well as the transversal flexural (φ_y) and axial (x) directions were taken into account. It was thus established that the FFO and TB shapes will be the preferred choice when the goal is compliance maximisation along φ_z (Fig. 3a), while the G, B, OC and OEB shapes will be preferred when the parasitic shifts and the stress concentration in the axial and transversal directions are also important (Fig. 3b) [3].

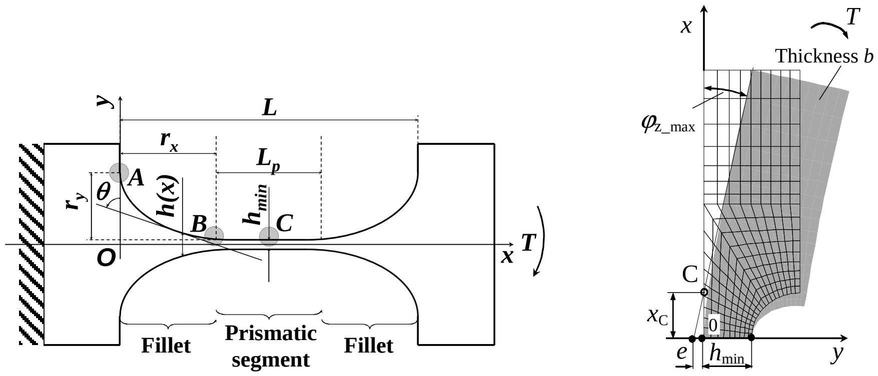

Fig. 2. Geometry of flexural hinge and parameterised shape for optimisation

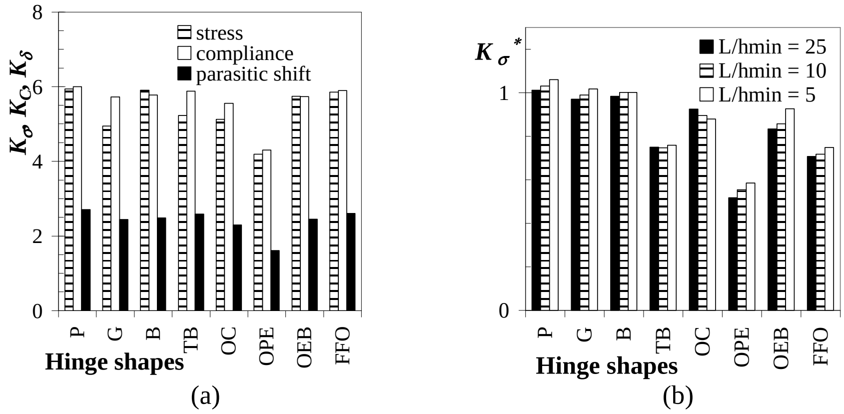

Fig. 3. Hinge behaviour along φ_z (a) and normalized stresses along φ_y (b)

When the considered applications are such that the dimensions of the mechanical structure must be minimised to nanometric levels, scaling effects on the entity of the mechanical characteristics must also be taken into account. In fact, it has been established that in the submicrometric domain the value of Young's modulus E can vary up to 70% with respect to its conventional value [4]. It is also known that the value of the Poisson coefficient ν is seldom known with an accuracy better than 20% [5], but its estimation at these dimensions has not yet been performed. An innovative methodology for determining ν is thus proposed here. The method is based on the calculation of the dynamic flexural response of Euler-Bernoulli-type cantilevers coupled with Von Kármán equations used to determine the variation of flexural stiffness of rectangular plates. In fact, the latter is a non-linear function of the deflection of the beam, varying from the value of E for plane strain (small loads) up to $E/(1-\nu^2)$ for plane stress (large load) conditions [6]. A seismic excitation of the cantilever with varying amplitudes will then result in an increment of the flexural stiffness, and thus of the frequency at which the response amplitude is maximal (Fig. 4). A suitable dimensioning of the cantilever of known E allows then a straightforward accurate determination of ν.

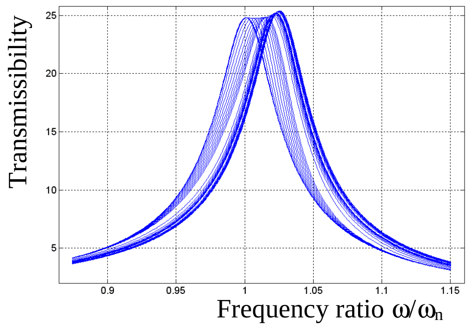

Fig. 4. Dynamic response of a micrometric silicon cantilever with $\nu = 0.22$

3. Actuators and sensors

Various actuating (DC micromotors, stepper motors, voice-coils, PZTs, inchworms, ultrasonic and inertial actuators) and feedback systems have been considered for the foreseen applications. Given the needed resolutions, accuracies and precisions, as well as the needed travel ranges, power requirements, ease of bidirectional control and large dynamic ranges, voice-coil actuators have been chosen. On the other hand, high resolutions and accuracies, excellent dynamic performances, large travel ranges and an easy integration with the compliant structure made optical encoders preferential over capacitive sensors, LVDTs and interferometric-based displacement measurement systems.

4. Control system

The control system is contained in a Compact-PCI rack with a power supply unit and a standard X86 processor computing board. The system exploits the results of the RTAI project (www.rtai.org), which offer real-time extensions of the Linux OS and interfaces with various CACSD tools (Matlab/Simulink or Scilab/Scicos). Within the same environment a graphical model can be prepared to feed the process with excitation signals and to retrieve data for the identification; the real-time application can send data to a remote PC, where the data is stored, displayed and analyzed.

The heart of the control system consists of two specially developed boards: a sinusoidal encoder signal interpolation board and a driver board for voice-coil motors. The three channel sinusoidal encoder interpolation board is built around a commercially available IC and it processes 1 Vpp sinusoidal signals. It is able to sample the inputs at a frequency of 500 kHz and to resolve 13 bits within a signal period. The three channel driver board has an output of up to 3.5 A per channel with a 16 bit resolution.
Other interface boards can be used as well: AD boards for various measurements or other Compact-PCI compatible boards. Their usage is immediate if the board is supported by the Comedi project (www.comedi.org); otherwise the drivers have to be written.
The initial integration of the control system with compliant mechanical structures allowed excellent performances with high flexibility and reliability at a limited cost. In fact, nanometric positioning accuracies (less than 15 nm) have been achieved in millisecond range time spans after a long (1 mm) range positioning step.

5. Outlook

The improvement in the design of the hinge shapes will be assessed with experiments. The objective is to accurately determine the stiffness of the structure as a function of the angle. Intuitively one would measure statically the dependence between motor currents and the resulting displacements and obtain the stiffness. However, this dependence is affected by the position-varying current-to-force characteristics of the actuator or by deviations due to the sensors' mounting inaccuracies. The tests on the structures will thus be based on the analysis of the resonance frequency at different positions. Precise estimates of the frequencies will be obtained using periodic excitation signals and the FFT analysis of the resulting data.

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