Experimental characterisation of tape spring nonlinear compliant mechanisms

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Summary. Tape springs are compliant mechanisms used as alternative to kinematic joints, for example, in deployable space structures. To reach a detailed understanding of their highly nonlinear behaviour, involving buckling, the formation of folds, nonlinear vibrations and hysteresis, an experimental set-up is designed. Dynamic and quasi-static tests are performed, as well as small amplitude vibration tests and large amplitude deployments in order to collect data in a broad variety of cases. The acquisition equipment consists of a 3D motion analysis system which triangulates the position of active markers and a force plate. The reproducibility of the acquisitions is assessed and the parameters affecting the measurements are identified. In the end, a finite element model is developed and correlated with the experimental results.

In deployable structures, compliant mechanisms such as tape springs are used as an alternative to common mechanisms composed of kinematic joints. Their main assets rely on a passive and self-actuated deployment, an elastic behaviour, the self-locking of the structure in the deployed configuration, the absence of lubricant leading to a reduction of the outgassing and contamination risks in space environments, and an improved robustness due to the structural simplicity.

The complexity in the use of tape springs is due to their highly nonlinear mechanical behaviour illustrated in Figure 1, which describes the evolution of the bending moment measured at the clamped extremity of the tape spring when the bending angle is controlled at the other end. Nonlinearities become especially apparent when the bending angle exceeds a particular limit defined by the tape spring geometry and material which triggers a buckling phenomenon. It leads then to the formation of a fold and, according to the sense of bending, different deformed configurations with specific characteristics in terms of stiffness and deployment are encountered. The nonlinearities also imply the non-superposition of the loading and unloading paths which introduces some hysteresis in the motion and results in the self-locking of the structure [1].

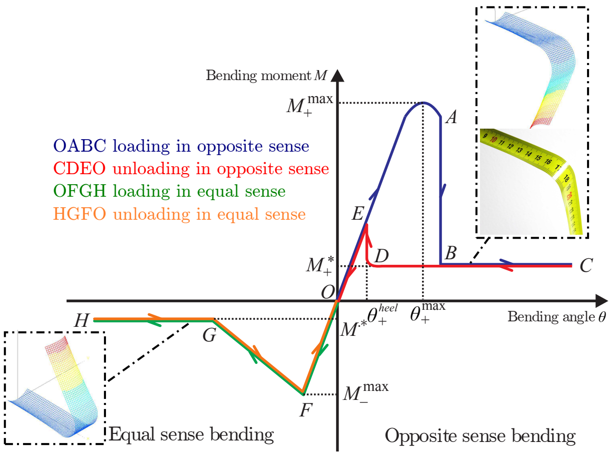

Figure 1: Theoretical nonlinear behaviour of tape springs [2].

High-fidelity finite element models can be used to reach a detailed understanding of all these characteristics and predict the actual behaviour of tape springs. In this work, an experimental set-up is designed to capture these nonlinear phenomena, to identify the modelling parameters such as the structural damping [3], and to validate the associated finite element model. It consists of two tape springs in parallel connected on one side to a fixation support and on the other one to a dummy appendix by the means of interfaces (Figure 2). The acceptable mass at the free end of the set-up is limited in order to allow passive deployments of the structure in both senses of bending. Due to geometric and material uncertainties affecting the set-up, that mass is evaluated after a series of parametric analyses.

Commonly, to collect data on this type of experimental set-up involving large amplitude motion, lasers or cameras are used. In this work, a 3D motion analysis system from CODAMOTION, usually devoted to human motion analysis, is exploited. Each scanner is able to triangulate the position of active markers with an accuracy reaching up to $0.3\ mm$ and an acquisition frequency of $800\ Hz$ (Figure 3). To complete this system, a force plate from KISTLER composed of four built-in piezoelectric sensors is located under the fixation support of the experimental set-up to collect information on the forces and moments affecting it. A threshold of $250\ mN$ allows performing accurate measurements even in the case of low loadings and the acquisition frequency reaches up to $4\ kHz$.

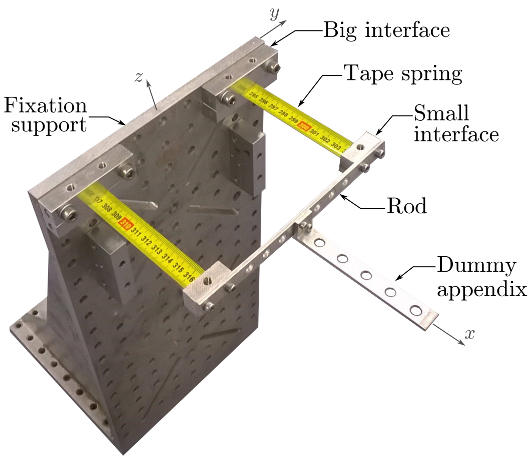

Figure 2: Experimental set-up.

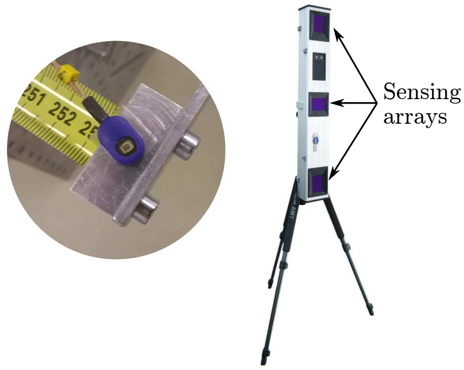

Figure 3: Acquisition equipment from CODAMOTION (marker and scanner).

The experimental tests are divided into two main categories. The first one consists of dynamic deployment tests involving large amplitude motions. Starting from a folded downwards configuration, passive deployments are triggered by the residual moments in the tape springs and the structure is left free to oscillate until it reaches its equilibrium configuration. Different cases are studied by adding or removing the dummy appendix from the experimental set-up and by starting with an initial folding of the tape springs in opposite or equal sense of bending. These tests allow, for example, capturing the evolution of the bending angle of the tape springs as illustrated in Figure 4 where 50 acquisition curves are superimposed and show a good reproducibility. In terms of forces, their evolution is more complex (Figure 5), but can nonetheless be directly linked to the motion by, for example, identifying the load peaks which are associated to changes of curvature in the tape springs. The second category of tests consists of quasi-static tests allowing to characterise the buckling of the tape springs. By applying a force in the middle of the rod of the experimental set-up, the behaviour illustrated in Figure 6 is captured and matches the theoretical behaviour described in Figure 1.

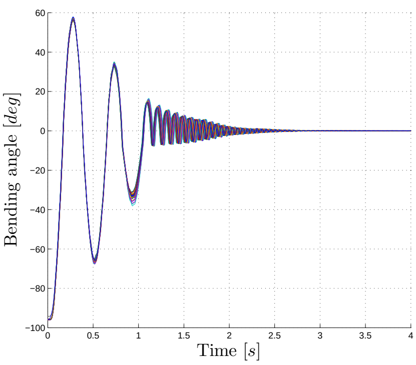

Figure 4: Evolution of the bending angle during deployment tests.

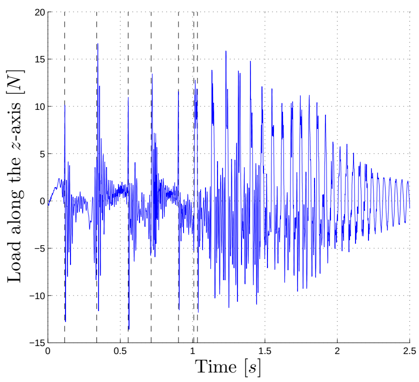

Figure 5: Evolution of the vertical force during a deployment test.

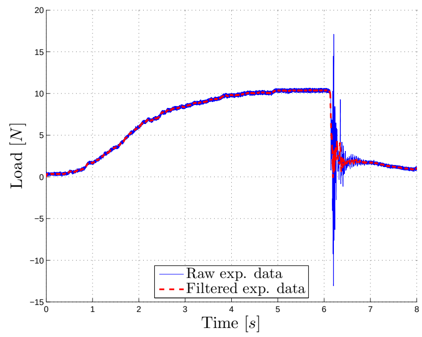

Figure 6: Quasi-static test.

Each type of tests is repeated in order to have a large panel of data. The quality and the reproducibility of these data are then assessed with the help of statistical considerations. Thus, the sensitivity of the experimental results to several parameters, such as the accuracy of the set-up building or the accuracy of the folded configuration before deployment, can be identified. Furthermore, the impact of these characteristics can be compared between the different studied cases mentioned previously (with and without the dummy appendix, with an initial folding in opposite and equal sense).

Finally, specific experimental tests are performed to identify the parameters required to developed an equivalent finite element model. This model is then validated by confirming the good correlation between the numerical and the experimental results.

References

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