Mechanical Systems and Signal Processing 101 (2018) 1–25

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Experimental and numerical investigation of the nonlinear dynamics of compliant mechanisms for deployable structures

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ARTICLE INFO

Article history:
Received 20 February 2017
Received in revised form 30 May 2017
Accepted 2 August 2017

Keywords:
Tape springs
Nonlinear dynamics
Finite element simulations
Structural damping
Experimental tests
Model correlation

ABSTRACT

This paper studies the dynamics of tape springs which are characterised by a highly geometrical nonlinear behaviour including buckling, the formation of folds and hysteresis. An experimental set-up is designed to capture these complex nonlinear phenomena. The experimental data are acquired by the means of a 3D motion analysis system combined with a synchronised force plate. Deployment tests show that the motion can be divided into three phases characterised by different types of folds, frequencies of oscillation and damping behaviours. Furthermore, the reproducibility quality of the dynamic and quasi-static results is validated by performing a large number of tests. In parallel, a nonlinear finite element model is developed. The required model parameters are identified based on simple experimental tests such as static deformed configurations and small amplitude vibration tests. In the end, the model proves to be well correlated with the experimental results in opposite sense bending, while in equal sense, both the experimental set-up and the numerical model are particularly sensitive to the initial conditions.

1. Introduction

Compliant mechanisms rely on the deformation of flexible structural components to produce motion. Based on this behaviour, several advantageous characteristics can be put forward compared to common kinematic joints: the storage of energy creating a restoring force, the deformations staying in the elastic regime, the small number of required parts, often limited to a single one, the limited impact or absence of assembly procedure, the absence of gap affecting the accuracy in measurement systems, the combination of the guiding and motor functions, and the absence of friction resulting in the absence of wear and lubrication [1]. In terms of applications, compliant elements can be found in various domains, for example in constant-force mechanisms [2], in electrical contacts [3], in robotic orthoses [4], in grippers [5], in the auto-focusing mechanism of cameras [6], in atomic force microscopes [7] and in deployable structures [8]. Finally, compliant mechanisms can be designed using topology optimisation methods [1,5,9].

High-fidelity structural models are then required to reach a detailed understanding of compliant mechanisms characteristics and predict their evolution in various situations. In order to reach a high level of accuracy, experimental data are essential to provide inputs for the models and validate their resulting outputs. In this work, an experimental and numerical

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http://dx.doi.org/10.1016/j.ymssp.2017.08.006
0888-3270/

investigation is performed on compliant mechanisms called tape springs, whose nonlinearity is mainly geometric due to their transverse curvature. Even though they generally operate in the elastic regime, their behaviour is characterised by geometrically nonlinear phenomena such as buckling, the formation of folds and hysteresis, some energy being dissipated every time a fold disappears. In the end, these characteristics lead to attractive features for deployable structures such as self-actuation and self-locking in the unfolded configuration.

Tape springs are mainly used in space deployable structures for satellites. Indeed, they represent simple, autonomous, robust and easy-to-integrate components compared to common mechanisms usually composed of several kinematic joints set into motion by the means of motors. Successful uses of tape springs can be found in several space missions such as the six MYRIADE micro-satellites for the deployment of solar arrays, antennas and masts [10] or the MARS EXPRESS spacecraft for the deployment of a long wavelength antenna [11] and will be found in future missions such as SOLAR ORBITER for the deployment of a radio and plasma wave antenna or NORSAT-1 for the deployment of an AIS (Automatic Identification System) receiver. They are also considered as support structures for the deployment of Cassegrain telescopes [12], inflatable structures [13] and solar sails [14,15].

The inherent characteristics of tape springs exploited in these applications are the following. First of all, when deformed to reach their folded configuration, the deformations stay in the elastic regime, provided that the geometric and material parameters satisfy a design constraint [16]. The stored elastic energy is then responsible for a residual bending moment that leads to a passive and self-actuated deployment until the tape springs reach their equilibrium state which, in the context of this work, is the straight stress-free configuration. In some other applications, several stable configurations may coexist [8]. Furthermore, compared to kinematic joints which usually imply some sliding between contact surfaces while in motion, the deployment of tape springs only leads to the deformation of structural elements. The use of lubricant is then irrelevant in this case and the risks of outgassing or contamination are limited in space. At the buckling point, one observes a transition from a configuration characterised by a high stiffness to a folded one associated with a low stiffness. Because of this low post-buckling stiffness, large motion amplitudes can be encountered and have to be constrained in order to avoid collisions with other components. Likewise, the shocks created by the formation or the disappearance of folds have to be monitored to limit the interference with other sensitive instruments. Finally, several tape springs can easily be combined to form a hinge with characteristics specific to the application at hand, showing thus the versatility of these compliant mechanisms. For example, the MAEVA hinge is composed of three tape springs with alternate orientations [17] (Fig. 1), Boesch et al. designed a hinge with four pairs of tape springs, each one being composed of a long and a short element [18] (Fig. 2). The assets of tape springs can also be found in hinges consisting of thin walled tubes with longitudinal holes which are called integral slotted hinges [11,19] (Fig. 3).

To capture and predict the nonlinear behaviour of tape springs, analytical developments, finite element analyses and experimental tests are performed. Theoretical developments were first derived by Wüst [20], Rimrott [21] and Mansfield [22]. Various analytical models were developed afterwards: in [23], tape springs are represented as two rigid bodies of variable length interconnected by a mobile hinge; in [24], a variational approach expressed in terms of potential energy is used to perform quasi-static analyses; in [25,26], a one-dimensional planar rod model with a flexible cross-section is investigated; in [27], a viscoelastic analytical model representing three aspects (stowage, stability and deployment) of bistable tape springs is developed; in [28,29], the equations of motion for the deployment of solar panels with tape springs are derived through a path-dependent path identification method combined with dynamic equations and based on a rigid multi-body theory in [30].

Regarding finite element models, comprehensive quasi-static analyses were performed in order to understand the impact of the geometric and material parameters on the relationship linking the bending moment and the rotation angle in the case of a single tape spring [16,31] or of integral slotted hinges [32] and nonlinear dynamic analyses were performed to capture the nonlinear phenomena (buckling, hysteresis, self-locking) characterising the deployment of tape springs in a planar motion [33,34] and in a 3D-space [35].

Experimental tests, usually combined with finite element models used for the initial design or the correlation of the full deployment simulation, can be found in [23,36] for single tape springs, in [17,18,37] for hinges composed of multiple tape springs, in [11,32] for the deployment of integral slotted hinges and in [13] where tape springs are used as structural stiffeners for inflatable structures. The experimental data on the bending moment are collected in these works by the means of strain gauges without any correlated information on the configuration [36], or of load cells while the rotation angle is controlled and the motion kept planar [17,37,38]. Regarding displacements, the most common solution is to capture the motion with high-speed cameras and then post-treat the images [16,18,23,32], which limits the experimental results to a 2D-space unless several cameras are used at the same time. Finally, in [10,17], the dynamic tests had the particularity to be performed either on an air cushion table or during 0-g flights to approach microgravity conditions.

To the best of our knowledge, the accurate measurement of complete 3D motions and loads during deployment tests has not yet been achieved for the quantitative analysis of the structural response of tape springs and for the validation of detailed numerical models. In this work, an experimental set-up is then designed and submitted to deployment tests. To perform dynamic acquisitions, a 3D motion analysis system combined with a synchronised force plate are proposed. Furthermore, the experimental tests are repeated a large number of times in order to assess the reproducibility of the tape spring behaviour and of the measurements.