Acta Astronautica 111 (2015) 323–333

Contents lists available at ScienceDirect

Acta Astronautica

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

Importance of structural damping in the dynamic analysis of compliant deployable structures[☆]

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ARTICLE INFO

Article history:
Received 15 October 2014
Received in revised form
16 January 2015
Accepted 5 March 2015
Available online 11 March 2015

Keywords:
Tape springs
Nonlinear analysis
Structural dissipation
Deployable structures
Compliant structures
Shells

ABSTRACT

Compliant mechanisms such as tape springs are often used on satellites to deploy appendices, e.g. solar panels, antennas, telescopes and solar sails. Their main advantage comes from the fact that their motion results from the elastic deformation of structural components and the absence of actuators or external energy sources. The mechanical behaviour of a tape spring is intrinsically complex and nonlinear involving buckling, hysteresis and self-locking phenomena. In the majority of the previous works, dynamic simulations were performed without any physical representation of the structural damping. These simulations could be successfully achieved because of the presence of numerical damping in the transient solver. However, in this case, the dynamic response turns out to be quite sensitive to the amount of numerical dissipation, so that the predictive capabilities of the model are questionable. In this work based on numerical case studies, we show that the dynamic simulation of a tape spring can be made less sensitive to numerical parameters when the structural dissipation is taken into account.

1. Introduction

With the extensive development of small satellites and cubesats dedicated to low-cost missions, the mass reduction of the components is paramount. However, the power reduction due to the miniaturisation of electronic equipment does not follow the same downward slope. Thus, covering only the external surface of the satellite with solar cells might not provide enough power and be too restrictive, hence the necessity for a reliable but cheap and simple means to deploy large solar panels. This, however, brings another major problem that must be solved: the packaging of large structures into the confined space inside the fairing of launch vehicles. In order to address these challenges, deployable structures have been developed and a brief listing of the most common structures can be found in [1]. This paper will focus on those belonging to the compliant mechanisms category and in particular on tape springs.

A tape spring is a thin strip curved along its width commonly known as a Carpenter tape and used in the everyday life as tape measures. Nowadays, it finds applications in the space domain for the deployment of appendices such as solar panels, antennas, telescopes and solar sails. Since they belong to the category of compliant mechanisms, they rely only on elastic energy that is stored during the folding and then naturally released when deployed. Indeed, a possible equilibrium state when the tape spring is free of constraints is the straight configuration, which is sought as a deployed configuration for many space applications. This characteristic also brings forward the fact that no source of external energy is required for the deployment and hence the passive and self-actuated behaviours of these devices.

[☆] This paper was presented during the 65th IAC in Toronto.

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http://dx.doi.org/10.1016/j.actaastro.2015.03.003
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Their motion results from the deformation of structural components only and not from the sliding between contact surfaces as in usual hinges or prismatic joints. It implies that tape springs do not require any lubricant to ensure a motion without jamming, which is advantageous in order to avoid outgassing and contamination in space. The structural simplicity of tape springs is also beneficial, since, without taking into account the supports, a tape spring consists of a single component and thus does not require any assembly procedure. The robustness is then greatly improved compared to more common mechanisms and it limits the possibilities of failure during deployment.

Regarding the mechanical behaviour of tape springs, it is complex and highly nonlinear, but stays in the elastic regime for the most commonly used materials such as BeCu. Regarding other materials, a limit that the ratio between the transverse radius and the thickness must satisfy can be found in [2] to avoid any plastic deformation during folding.

The complexity is further increased due to the existence of nonlinear phenomena such as buckling which induces the formation of a fold in the deformed configuration and the non-superposition of the loading and unloading paths leading to hysteresis and self-locking.

The mathematical background describing the theoretical relationship between the rotation angle and the resulting bending moment was first developed by authors such as Wüst [3], Rimrott [4] and Mansfield [5]. More recently, new analytical models were combined to numerical studies and experiments for validation. In [6], the static bending moment-angle relationship was numerically computed for a large variety of tape springs. In a next work [7], the dynamic deployment was investigated and it allowed representing a folded tape spring as two rigid bodies of variable length connected to each other with a mobile hinge. Between this 2D discrete model and finite element simulations with shells, an intermediate model was developed in [8] based on 1D planar rods with a flexible cross-section. Quasi-static analyses of the folded configuration submitted to end loads were also performed in [9] and correctly predicted thanks to a variational technique. Finally, more complex and compact three dimensional foldings can be obtained and were studied, first analytically in [10], then experimentally in [11,12].

Tape springs can also be combined to form tape spring hinges [13]. A generic one called MAEVA was developed by the CNES and 01dB-Metravib [14] and was successfully used to deploy solar panels, antennas and masts on the six MYRIADE micro-satellites [15]. Experimental analyses were performed, along with finite element simulations. Recently, a more precise study of the dynamic behaviour and the self-locking phenomenon was carried out in [16].

In the majority of the previous works, finite element dynamic simulations of tape springs were performed without any physical representation of the structural damping, with the notable exceptions of [17,18]. In the former, the viscoelastic material properties of a reinforced polymer are integrated in the finite element model under the form of a Prony series. The goal was to determine the impact of the temperature, the folding rate, the creep recovery and the relaxation during storage on the behaviour of the tape spring. On the other hand, [18] does not directly concern tape springs, but analyses foldable flattenable tubes which are also characterised by buckling and hysteresis phenomena. The structural damping is in this case based on the Rayleigh model with the particularity that the damping factor is variable according to the state of the structure. Otherwise, the simulations could be successfully achieved because of the presence of numerical damping in the transient solvers. However, as it will be proven further in this paper, the dynamic response turns out to be quite sensitive to the amount of numerical dissipation. The predictive capabilities of the models are then questionable. Furthermore, in the analytical model developed in [7], it was shown that viscous damping terms needed to be introduced in order to match the numerical results to the experiments. The aim of this work is then to determine if adding structural damping can make the simulator less sensitive and if numerical damping is always required. The choice is made to represent the structural dissipation by Kelvin–Voigt models in order to keep the simulations as simple as possible.

The layout of this paper is as follows. In Section 2, the geometric characteristics of a tape spring are described. Then in Section 3, the general features of the finite element models and the resolution strategy are explained. In Section 4, the theory ruling the bending behaviour of tape springs is recalled. In Section 5, the effect of numerical and structural dampings in the generalised-α method is analysed on a one-degree-of-freedom model and compared to the analytical solution. In Section 6, the impact of the numerical damping on the bending behaviour of a tape spring is studied in the case of a dynamic deployment. In Section 7, structural damping is added in the same model. Finally, the conclusions of this work are drawn in Section 8.

2. Geometric characteristics

The geometry of a tape spring is defined by means of five parameters: its length L, its thickness t, its subtended angle α, its transverse radius of curvature R and its longitudinal radius of curvature R_L. All these elements are represented in Fig. 1.

For the most common applications and the structures studied in this paper, the tape springs are straight without any longitudinal curvature. In other cases, they would be referred to as curved tape springs [19].

Regarding the ratio between the length and the width, a lower limit of five will be respected in order to reduce the local end effects due to the boundary conditions [5].

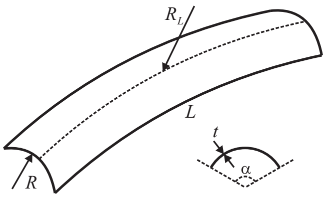

Fig. 1. Geometric characteristics of a tape spring with the length L, the thickness t, the subtended angle α, the transverse radius of curvature R and the longitudinal radius of curvature R_L.