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Mechanical behaviour of tape springs used in the deployment of reflectors around a solar panel

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ABSTRACT

In order to increase the production of power on small satellites, solar panels are commonly deployed and, in some cases, reflectors are added to improve the concentration factor on solar cells. In this work, reflectors are deployed by the means of compliant mechanisms known as tape springs. Their attractive characteristics are, among others, their passive behaviour, their self-locking capacity, their elastic deformations and their robustness. However, their mechanical behaviour is highly nonlinear and requires thorough analyses in order to develop predictive numerical models. It is shown here through parametric studies that the nonlinear behaviour of a tape spring is mainly governed by its geometry. Thus, for each specific application, its dimensions can be determined in order to minimise two critical features: the maximum stress affecting the structure and the maximum motion amplitude during deployment. In this paper, an optimisation procedure is proposed to meet these requirements.

1. Introduction

In deployable structures, various types of mechanisms can be used to connect the different bodies. The most common ones are usually composed of kinematic joints and have to be combined with a motor to perform the deployment stage. Nonetheless, compliant systems have been developed and proved reliable in various engineering applications [1]. In this present work, the inherent characteristics of tape springs, belonging to this last category, are exploited in a space application.

By definition, some elastic energy is stored during their folding and is then naturally released during deployment in order to reach an equilibrium configuration. Although two equilibrium states may exist [1], only the straight one is sought in the following studied cases. The deployment stage is thus completely passive and self-actuated, requiring no external source of energy as opposed to the most common joints. Compared to these latter, other significant advantages can be pointed out. No lubricant is needed since the motion results from the deformation of structural components only and not from the sliding between contact surfaces. Thus, the risks of outgassing and contamination are reduced in space environment. The structural simplicity of tape springs is also a strong asset since it greatly improves the robustness and limits the possibilities of failure during folding and deployment.

The complexity of tape springs comes from their highly nonlinear mechanical behaviour. First of all, according to the sense of bending, different deformed configurations are encountered. For example, the equal sense is characterised by some torsion, while in the opposite sense, the structure is not affected by any transverse displacements. Then, for a critical value of the rotation angle, the tape spring is submitted to buckling which induces the formation of a fold and a sudden drop in the stiffness. Finally, due to the non-superposition of the loading and unloading paths, the dynamic evolution is affected by some hysteresis which, after a certain number of cycles, leads to the self-locking of the structure.

Wüst [2], Rimrott [3] and Mansfield [4] derived the theoretical relationship between the applied rotation angle and the associated bending moment. Various analytical models were developed: in [5], tape springs are represented as two rigid bodies of variable length interconnected by a mobile hinge; in [6], a variational approach expressed in terms of potential energy is used to perform quasi-static analyses; in [7,8], a one-dimensional planar rod model with a flexible cross-section is investigated. Numerous finite element analyses exploiting shells were also achieved. For example, static analyses of a large variety of tape springs can be found in [9], while dynamic analyses focusing on the self-locking phenomenon, on the impact of the numerical and structural dampings, and on three-dimensional tape springs are available in [10,11] and [12] respectively. Finally, experimental studies were performed to either validate analytical or finite element analyses. Static and dynamic tests can be found in [5,13] and [5,14,15] respectively.

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The choice of the application studied in this paper was made by taking into consideration the growing interest in the development of technologies for small satellites of less than 200 kg. The intended purpose is the launch of numerous missions requiring both a low budget and a short period of design. Regarding the on-board power consumption of the electronic equipment, it is generally not possible or enough to cover the external surface of the satellite with solar cells. The most common solution is then to deploy solar panels on the sides of the satellite once it is jettisoned from the rocket. Furthermore, adding reflectors along the solar panels concentrates the sunlight on the solar cells and thus, in theory, the geometric concentrator factor can be doubled and the area of the solar panels can be reduced. This system, however, requires the folding of the panels and the reflectors in order to integrate the satellite inside the confined space of the fairing, hence the use of tape springs.

For space systems, the use of reflectors has been investigated since the nineties [16]. The V-trough concentrators were first integrated on the solar panels of the PanAmSat Galaxy XI satellite and, a few years later, they were exploited on the Boeing BSS-702 Satellite Bus with limited success due to the contamination of the reflecting surfaces and the shrinkage of the reflectors alignment system [17]. More recently, JAXA launched the small spacecraft REIMEI equipped with single lateral reflectors on each solar panel (Fig. 1) which gave satisfactory results according to their last report [18].

The use of reflectors is then not unusual to increase the performance of solar panels and deploying them with tape springs shows promising advantages. A particular deployment procedure exploiting the self-actuated and the self-locking properties of tape springs can be found in [19] where they provide the driving torques to classical hinges. In the present work, however, the hinges connecting the reflectors to the solar panels are only composed of tape springs and not combined to any additional classical hinges.

An extensive analysis is then required to prove their efficiency for this type of applications. During folding and then deployment, the most critical parameters are the maximum stresses affecting the structure and the maximum motion amplitude. Regarding the former, its value must be kept under the yield limit in order to remain in the elastic regime and prevent irreversible deformations, while for the latter, which is only relevant during deployment, any collision with the other elements of the spacecraft must be avoided. To fulfil these requirements, the geometry of the tape springs has to be adapted to each specific situation. Since several parameters can be modified, it is proposed in this work to address this problem by the means of an optimisation procedure exploiting the results of finite element models.

The layout of this paper is as follows. In Section 2, the problem to be solved is defined, along with the geometric characteristics and the material properties of the tape springs. Then, in Section 3, their theoretical behaviour is recalled. In Section 4, the features of the finite element analyses and models are described. In Section 5, parametric studies are performed by varying some geometric parameters. The impact of the thickness and the radius of curvature are assessed. In Section 6, the optimisation procedure is performed to minimise the stresses and the motion amplitudes, while the complete deployment of the reflector will be discussed in Section 7. Finally, the conclusions of this work are drawn in Section 8.

2. Definition of the problem

The problem studied in this work is the deployment of a reflector around a fixed solar panel. In its folded configuration, it is located on the top of the panel. The reflective membrane is square of side 200 mm and, with its frame, has a mass of 0.4 kg. In its deployed configuration, the angle formed with the solar panel reaches 120° as recommended in [19]. The hinge is composed of two tape springs, whose orientation will be determined in the last part of this study.

The geometry of a tape spring is completely characterised by four parameters: its length L, its thickness t, its subtended angle α and its transverse radius of curvature R. Regarding the reference frame used in this work, the x-axis coincides with the longitudinal axis of the tape spring, the y-axis with its transverse axis and the z-axis is along the height. All these elements are represented in Fig. 2. Furthermore, only straight tape springs, that is without any initial longitudinal curvature, are considered in this paper. However, applications with curved tape springs can be found in [14].

In a spacecraft the available space is strictly limited and the one devoted to the hinges of the reflectors is most likely to be determined at an early stage of the spacecraft design. Here, the tape springs length is fixed to 50 mm, while for their cross-section, their width $w = 2R\sin\alpha/2$ and their height $h = R(1 - \cos\alpha/2)$ cannot exceed 25 mm and 10 mm respectively. A schematic representation of the deployed reflector is given in Fig. 3, along with the maximum dimensions accepted for the tape springs. Notice that in order to simplify the model, all the connections between the different components (tape springs – solar panel, tape springs – reflector) will be considered as perfectly rigid.

Throughout the simulations, the thickness t, the radius of curvature R and the subtended angle α are the remaining design variables. Regarding the material composing the tape springs, its properties are fixed *a priori* in order to limit the complexity of the design problem in these first analyses, furthermore in space applications, the choice of materials is anyway limited due to constraining requirements on contamination. The chosen material used throughout this work is the beryllium copper. Its properties are given in Table 1 where E is the Young's modulus, ν is the

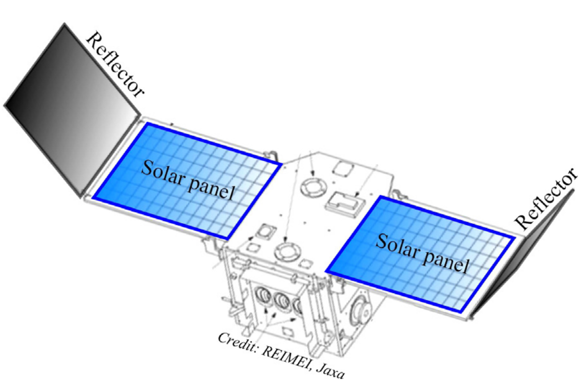

Fig. 1. Deployed configuration of the reflectors on the spacecraft REIMEI (modified illustration from [18]).

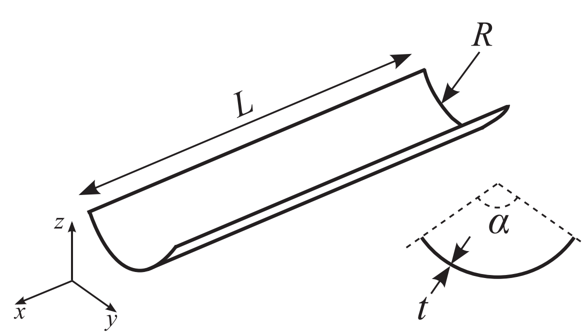

Fig. 2. Geometric characteristics of a tape spring with the length L, the thickness t, the subtended angle α and the transverse radius of curvature R.