Electric Sail Static Structural Analysis with Finite Element Approach

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Abstract

The propulsive characteristics of an Electric Solar Wind Sail are usually evaluated using a simplified model in which all the sail tethers are coplanar and form a sort of rigid disk. However, the three-dimensional arrangement of the tethers is a fundamental information in the study of the spacecraft performance, and must be accounted for in refined mission analyses. In this paper, a Finite Element approach is chosen to estimate the deflected shape of the tethers, thus allowing important information on the structural response of the sail to be obtained. A parametric code is developed to perform a static analysis of an Electric Solar Wind Sail, whose requirements are given in terms of payload mass and characteristic acceleration. In particular, the tether structural response is investigated using three different beam models, which are compared in terms of accuracy and computational efficiency. The analysis is specialized to the noteworthy case of a Sun-facing sail that is placed at one astronomical unit distance from the Sun. The numerical results, which concern a set of possible sail configurations, are compared with those taken from analytical models.

Keywords: Electric solar wind sail, static structural analysis, finite element analysis, Sun-facing attitude

1. Introduction

The Electric Solar Wind Sail (E-sail) is a continuous low-thrust propulsion system for interplanetary navigation [1, 2]. An E-sail is composed of a number of centrifugally stretched thin tethers, which are electrically charged by an on-board electron gun [3]. The solar wind ions interact with the E-sail electric field, which deflects the proton flow so as to generate a propulsive acceleration; see Fig. 1.

The interest towards mission design using propellantless propulsion systems has significantly promoted the study of the E-sail behaviour in the interplanetary environment [4, 5, 6, 7, 8, 9]. In a preliminary mission design phase, the E-sail thrust may be estimated with a simplified model in which the tethers are assumed to be coplanar, and the E-sail takes the shape of a rigid disk [10]. The actual tether shape is however more involved, as it comes from a complex interaction between the stretching induced by the spacecraft spin and the inflection due to the solar wind dynamical pressure. As a result, tethers are arranged in a three-dimensional pattern, thus significantly affecting the E-sail propulsive performance [11].

In this context, several authors have already attempted to describe the actual E-sail shape with more accurate models, by addressing the problem either numerically or analytically. Toivanen and Janhunen [12, 13] have proposed an analytical model for the tether shape, which is based on the numerical solution of an integral equation similar to that of a classical catenary. According to such a model, the tether assembly describes a cone near the spacecraft main body, while a flat region occurs near the tips of the tethers. More recently, Bassetto et al. [14] have dealt with the problem of evaluating the equilibrium shape

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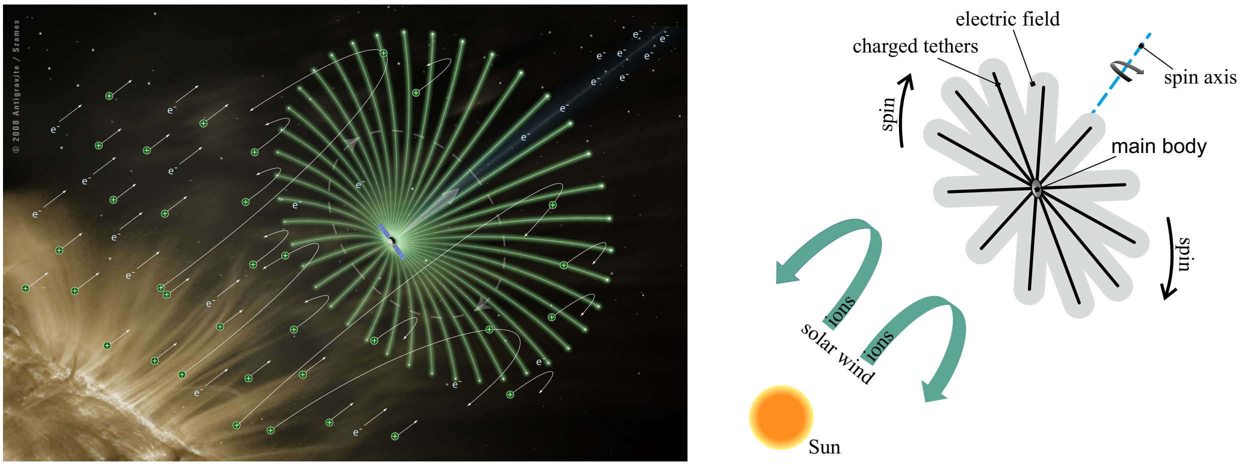


(a) Artistic rendering. Courtesy of Alexandre Szames, Antigravité (Paris).

(b) Schematic draw.

Figure 1: E-sail conceptual sketch.

of a Sun-facing sail (that is, an E-sail whose nominal plane is perpendicular to the Sun-spacecraft line), proving that the shape of each tether may be described by a logarithmic function. Moreover, Ref. [15] has proposed closed-form relationships for the E-sail thrust and torque vectors, based on the assumption that the tethers maintain the aforesaid logarithmic shape even when the sail pitch angle is different from zero, albeit sufficiently small. Instead, Yamaguchi and Miyata [16] have determined the tether equilibrium shape using a numerical approach in order to formulate an advanced solar wind force model.

An accurate description of the sail shape may be achieved by adequately modelling the structural behaviour of the tethers, which are similar to extremely slender beams. The intrinsic shear-bending stiffness of each tether is very low and, as such, is not sufficient to counteract the bending effect due to the solar wind dynamical pressure. The tethers remarkably improve their structural performance when subjected to the axial pre-tensioning induced by the centrifugal forces. However, such a pre-tensioning must stay below the yielding stress of the material and, therefore, the spacecraft spin rate is a trade-off value between stiffness enhancement and structural strength of the tethers. The resulting pre-tensioning is relatively low, thus making the structural response of the tethers highly non-linear. The nature of such a non-linearity is intrinsically geometrical. In fact, the changes in geometry as the structure deflects must be considered in formulating the constitutive and equilibrium equations that define the (complex) structural problem. The effectiveness of the model is also closely related to the accuracy in managing the non-linear behaviour of the structure, and in describing all of the external forces as "follower" loads. The latter are forces whose action lines are continuously updated in response to large tether deflections .

In this paper, a Finite Element (FE) approach is used to estimate the deflected shape of the tethers, thus allowing important information on the structural response of the E-sail to be obtained. Despite the dynamical nature of the problem, the results of the proposed procedure are restricted to the static case, which is a fundamental step for a proper set-up of more complex dynamical simulations. In particular, great effort is devoted to the development of strategies capable of overcoming the problems related to the strong non-linearities, while avoiding the use of oversimplified models, or fictitious numerical stabilizations. The tether deflected shape predicted by the discussed static models is also compared with the analytical solutions available in the recent literature, in order to obtain an effective validation of the simulation results. In fact, recent studies have dealt with the dynamical analysis of an E-sail through FE, assuming very simplified structural models for the tethers. For example, Ref. [17] has analyzed the stiffening effect induced by the E-sail spin rate using a dumbbell model under the assumption that the tethers are extensible but not bendable. Reference [18] has studied the E-sail dynamics assuming each tether to be equivalent to a single beam with the characteristics of a revised Euler-Bernoulli beam. Moreover, Li et. al. [19] have developed a high-fidelity multi-physics model to investigate the coupling between the E-sail orbital motion and its attitude dynamics.

The tether bending is suitably taken into account in the proposed approach, and different beam models are tested and compared in terms of final results and computational efficiency. To that end, the FE commercial software ABAQUS 6.14 [20] is used, due to its effectiveness in managing strongly non-linear analyses and its parametric modelling approach. The versatility of ABAQUS 6.14 is enhanced by the interaction with the Python language. A general numerical code is developed to perform static analyses of an E-sail with a given configuration and pitch angle, the latter being defined as the angle between the Sun-spacecraft line and the normal to the sail nominal plane. The E-sail configuration is based on the mass budget model proposed by Janhunen et al. [21], whereas the numerical results refer to a heliocentric distance of one astronomical unit and a Sun-facing attitude (that is, with a zero pitch angle), in order to obtain a straightforward comparison with the recent literature data.

2. E-sail modelling strategies

The major challenge in a FE analysis of an E-sail is the achievement of a numerical convergence due to the very small bending stiffness and the highly non-linear behaviour of the tethers. In particular, the tether slenderness causes the beam elements to have a hill-conditioned stiffness matrix, which, in turn, results in numerical convergence difficulties. In this paper, the modelling technique based on substructures is used to deal with such a problem, and a sensitivity study on the type of elements and their number is also performed.

The substructure approach within ABAQUS 6.14 [20] is able to manage models composed of a large number of nominally identical components, even in the presence of remarkable geometrical non-linearities. In particular, the repetitive structural unit is preliminarily modelled as a stand-alone component, but it is analyzed with its own role in the assembled structure, that is, by implementing its nature as a substructure. Then, the single unit is repeatedly inserted into the complete structural model, in which all the connections between the different components are defined, along with the external boundary conditions. The loads acting on the repetitive units, already defined at a substructure level, are recalled at the assembly level with a specific magnitude for each component, in order to account for the potential non-uniformity of the external forces. The communication between substructure and assembly level takes place via a sub-set of nodes, referred to as retained nodes. Only the retained nodes of the substructure actively participate at an assembly level, while the degrees of freedom of the remaining nodes are merely internal. The displacements that the retained nodes undergo at assembly level are then used as inputs at the substructure level to accurately calculate the stress-strain field of all the internal nodes.

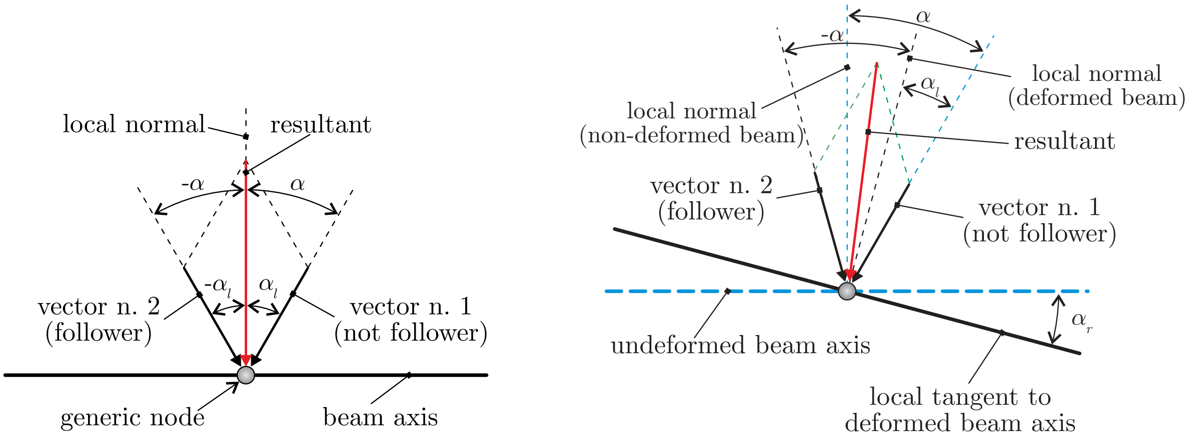
The effectiveness of such a technique consists not only in a complete automatization of the analysis process of models with high redundancy of subcomponents, but also in the possibility of overcoming convergence problems with a suitable choice of the retained nodes. According to the sub-structuring philosophy, the retained nodes must be those strictly necessary to correctly describe the displacements induced by the external loads. As a result, the more curvature changes are expected in the deflection, the more retained nodes are needed. Furthermore, for a same retained node-set, the accuracy of the displacement field prediction depends on the selected type of elements and on the order of its shape functions. Conversely, the number, type, and order of the internal elements exert a strong influence on the evaluated stress-strain field. The substructure modelling technique is applied to the E-sail case in such a way that each tether is modelled as a substructure. To predict its deflected shape in the assembled structure, beside the two mandatory end-nodes, at least other three retained nodes are defined, by thickening them near the free end. The centrifugal pre-tensioning load is induced at a substructure level, to provide each tether with the stiffness necessary to resist to the solar wind, whose action is triggered at an assembly level.

Three different types of beam elements (all within the ABAQUS 6.14 element library [20]) are tested to model the tethers. The Euler-Bernoulli beam element (with cubic shape functions) is used for its efficiency in managing the non-linearity of the large rotations induced by the bending effect in very slender beams. Unfortunately, the Euler-Bernoulli beam exhibits convergence difficulties in strongly non-linear problems because it is based on the assumption of very small axial strains. Indeed, the Euler-Bernoulli beam totally neglects the beam shear flexibility and, therefore, it is not compatible with "follower" loads. These problems can be overcome by using the shear-flexible (largely extensible) beam elements, especially in their quadratic formulation. These elements, sometimes not properly associated with the Timoshenko model, are effective also for slender beams because they are able to correctly simulate the so-called non-linear stress stiffening, that is, a phenomenon for which the variation of the shear strain along the beam axis introduces a constraint to bending rotations. A hybrid beam element is also tested, which resumes the properties of the two previous models by optimizing them to the case of extremely slender beams subjected to multi-axial loads. The numerical high performance of these elements is obtained by treating both the axial and the shear force as independent unknowns. A very refined mesh is adopted for each type of beam element, with an average size of 25 m for tethers whose length ranges between 4 and 15 km. The total number of elements varies consequently from 160 to 600, while the number of nodes is exactly doubled, due to the quadratic formulation of the elements. According to our sensitivity studies, a much coarser mesh does not allow a numerical convergence or, at least, compromises its efficiency, while an intermediate number of nodes and elements does not capture correctly the curvature of the deflected shape of the tethers and does not reproduce accurately the distributed nature of the solar wind action. A larger number of elements does not significantly improve the numerical results, while it considerably increases the simulation times. Finally, no fictitious source of numerical stabilisation is used in the simulations.

3. Details of FE models

The FE analysis of a single tether is composed of two steps: the first one (static-linear type) is related to the centrifugal pre-tensioning, while in the second one (substructure type) the solar wind action is set up by assuming a given value of sail pitch angle α and a load acting in the plane containing the beam and the spacecraft spin axis.

During the first pre-tensioning step, the generic tether is modelled as a beam of circular section, with a radius equivalent to a Heytether configuration [22]. The beam has a concentrated tip mass, and is subjected to a distributed axial load of type `ROTATIONAL BODY FORCE` [20]. The retained node-set is defined in the second substructure step, and the solar wind action is simulated as a series of nodal forces, whose resultant is always aligned with the local normal to the beam axis. In particular, the nodal force magnitude is proportional to the angle α_l between the local normal to the beam axis and the solar wind direction [23]. Note that α_l coincides with the angle between the beam axis and the Sun-spacecraft line; see Fig. 2.



(a) Case of non-elastic tether.

(b) Case of elastic tether.

Figure 2: Nodal force decomposition to simulate the solar wind action in the substructure reference model.

A large number of nodes is used to describe the distributed nature of the load, whose magnitude and direction are modelled by decomposing each nodal force as the sum of two vectors. Those vectors have the same magnitude, which is equal to half that induced by the solar wind pressure, and a symmetric direction with respect to the local normal to the beam axis. The angle between the direction of the first vector and the local normal to the beam axis coincides with the pitch angle α, whereas the direction of the second vector (referred to as "follower") has a negative incidence angle (i.e., $-\alpha$); see Fig. 2(a). The tether flexibility induces its normal to rotate of an angle equal to α_r (see Fig. 2(b)), so that the local pitch angle reduces to $\alpha_l = \alpha - \alpha_r$. The two vectors are then summed with the constraint that only the follower rotates.

Accordingly, the resultant force is closer to the local normal to the beam axis, while its magnitude roughly scales as the cosine of the pitch angle; see Fig. 2. The above-described loading conditions, although affected by some error, avoid the non-conservative results produced by a non-elastic tether.

The whole E-sail model consists of a single step of static-non-linear type. With reference to the scheme in Fig. 3, the structure assembly is obtained by inserting the tethers starting from the right-hand side of the horizontal axis and proceeding counterclockwise. All the tethers are connected both to the spacecraft

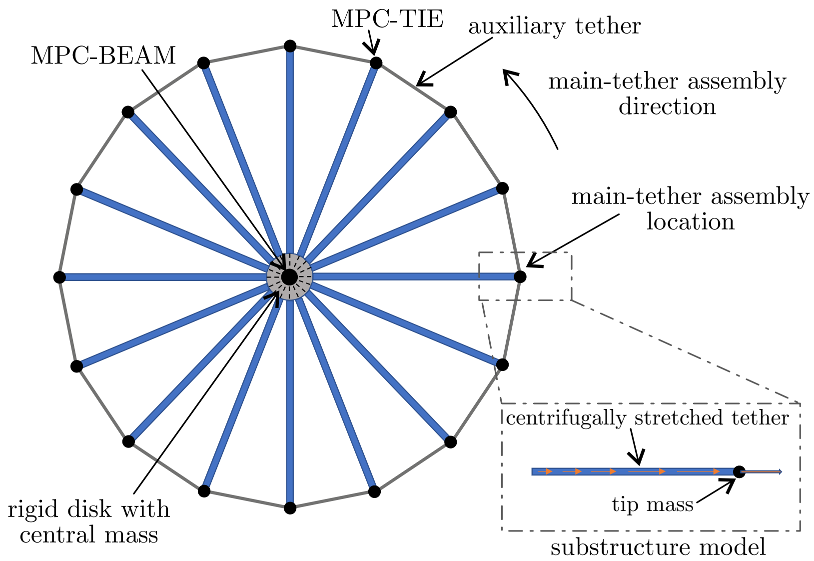


Figure 3: Assembly procedure of the E-sail model.

main body (modelled as a rigid disk) by means of Multi-Point Constraints (MPC) of type `MPC-BEAM`, and to a stabilising auxiliary tether [23] (modelled as a polygonal truss) by means of MPC of type `MPC-TIE`. In particular, the `MPC-BEAM` refers to a rigid beam connection used to constrain both the displacement and rotation of the tether slave node to that of the disk control node. On the other hand, the `MPC-TIE` makes all active degrees of freedom identical at slave and control nodes. The central disk, due to its rigid nature, has a single control point (placed at its centre), which is connected to the main tether slave nodes on the perimeter.

Many control points of the auxiliary tether, modelled as a deformable body, are connected to coincident slave nodes of the main tether. The central node of the rigid disk, in accordance with the static nature of the analysis, is fixed in the inertial space. The tethers are imported as substructures in the stress-strain state calculated at the end of the centrifugal pre-tensioning step. The solar wind action, instead, must be recalled in the assembly model and updated for each tether. The three spatial components are multiplied by suitable correction factors, to account for the actual angle between the tether axis and the plane defined by the solar wind direction and the sail spin axis. The correction factors are represented by the cosine directors of the axis of the generic tether with respect to the reference axis, relevant to the horizontal tether on the right; see Fig. 3.

4. Numerical code architecture

The E-sail modelling phases, as well as the elaboration of the results, are merged in a numerical code by means of inter-connected scripts in Python language, as schematically illustrated in Fig. 4.

Three scripts execute the pre-processing activities by creating the FE models in cascade. A first script, which runs independent of ABAQUS 6.14 software [20], generates all the input data necessary for the following phases. In particular, using the approach discussed in Ref. [21], an implementation of the E-sail mass budget model provides all the geometrical, inertial, and loading information for a generic E-sail-based

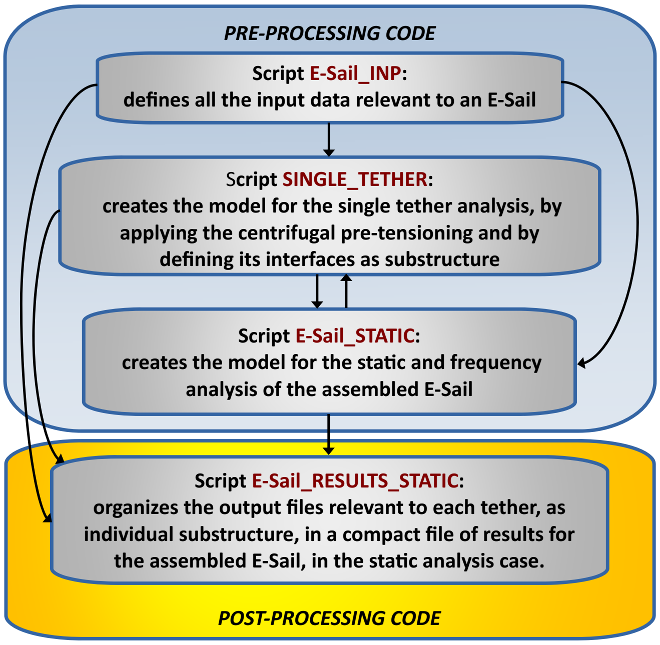


Figure 4: Conceptual scheme of the numerical code.

spacecraft configuration with a given characteristic acceleration a_c and payload mass m_{pay}. The second script reads the input data and, interacting with ABAQUS 6.14 software, creates the FE model of each single tether as a substructure, which is then used as an input file to the solver. The third script, by pointing at both the input and output files of each single tether model, creates the FE models of the complete E-sail, and submits the static analysis to the solver. The resulting output files are then re-organised in an assembled structure by means of a dedicated Python script.

5. Results and comparison with analytical predictions

The proposed procedure has been validated by considering a Sun-facing sail at a solar distance of 1 au. In particular, using the mass-budget model described in Ref. [21], this study analyzes three typical E-sail arrangements that correspond to three different values of both characteristic acceleration and spacecraft mass. The three E-sail configurations are summarized in Tab. 1, where N, L, m_{tot}, m_t, and ω are the number of tethers, the length of each tether, the total spacecraft mass, the total tip mass, and the sail spin rate, respectively. The last parameter reported in the table is the ratio of the solar wind resultant force (F_{sw}) to the centrifugal force (F_c) acting on a single tether. The centrifugal force is always chosen as the maximum admissible value for the tether, while the resultant force due to the solar wind varies according to the required characteristic acceleration and spacecraft mass.

E-sail conf.	a_c [mm/s^2]	m_{pay} [kg]	N	L [km]	m_{tot} [kg]	m_t [kg]	ω [rad/s]	$\frac{F_{sw}}{F_c}$ [N/N]
①	1	100	44	15.3	391	0.862	0.00294	0.00886/0.12573
②	1	300	86	20	996	0.8235	0.00259	0.01158/0.12573
③	0.1	100	12	4.02	280	0.858	0.0059	0.00233/0.12573

Table 1: E-sail configuration data.

The deflected shape of the (single) generic tether for configurations ① and ② is shown in Fig. 5, whereas Fig. 6 shows the out-of-plane displacement field of the complete E-sail in the configuration ②. Note that Figs. 5 and 6 illustrate how the tether portion near the spacecraft describes actually a cone, while the tip tends to flatten due to the stiffening induced by the centrifugal force. In Fig. 5, the tangent relevant to the

F_{sw}/F_c ratio is reported for both the analyzed configurations, thus enabling a direct comparison of the cone angle near the spacecraft main body as predicted by the FEM with that of a straight (rigid) tether. It is clear that the reference tangent is able to accurately describe the cone angle in the neighbourhood of the spacecraft.

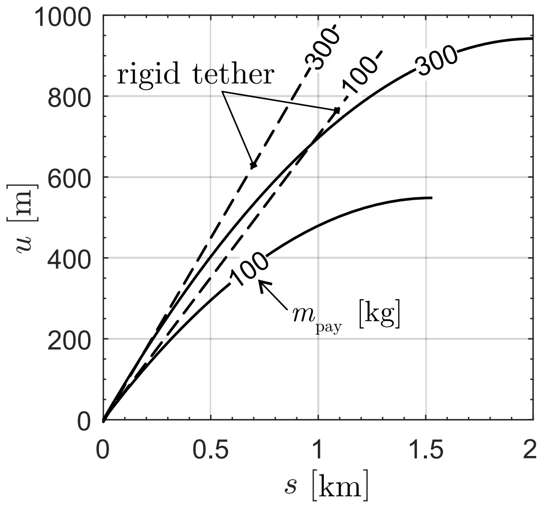


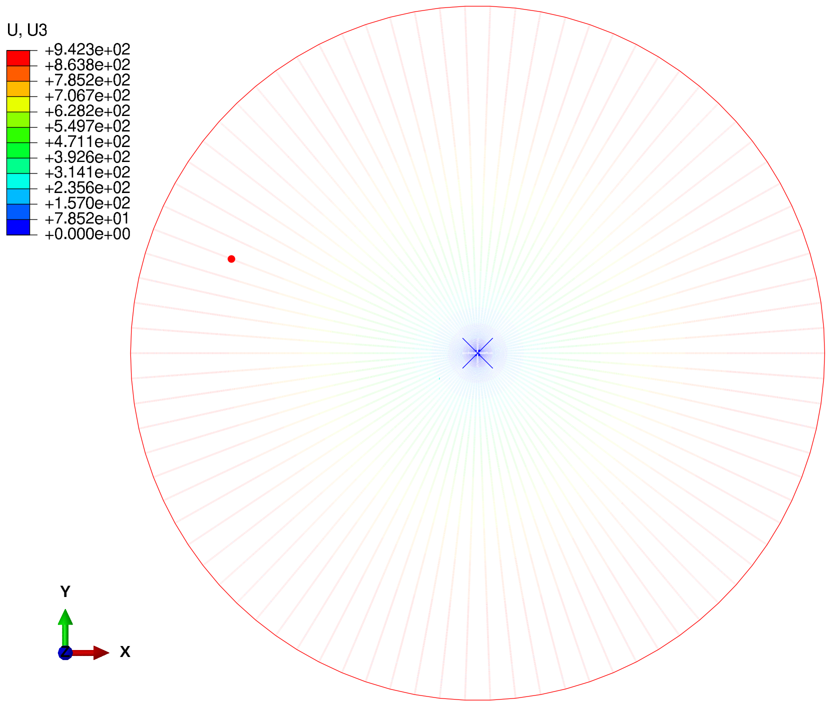
Figure 5: Single tether deflection when $a_c = 1\,\mathrm{mm/s^2}$ and $m_{\text{pay}} = \{100,\, 300\}$ kg.

The E-sail configuration ③ is characterized by $a_c = 0.1\,\mathrm{mm/s^2}$ and $m_{\text{pay}} = 100\,\mathrm{kg}$. The (relatively) smaller size and the consequent smaller computational effort, make this configuration a good case-study to perform sensitivity analysis to obtain comparisons with analytical models. In particular, the influence of the beam element type used to model the tethers is tested both in terms of result accuracy and numerical convergence performance. The tether deflection is reported in Fig. 7 for the Euler-Bernoulli beam (element B33), the shear-flexible beam (element B32), and the hybrid beam (element B32H). Note that he Euler-Bernoulli beam shows an inadequate behaviour. Indeed, the serious convergence problems affect the result reliability, whose non-conservativeness could be of misleading numerical nature. The shear-flexible beam provides the same results as the hybrid model, but with slower convergence rates.

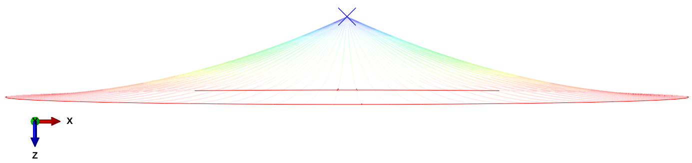
Using the data of this last (③) configuration, it is interesting to compare the tether deflections predicted numerically with those recently obtained in analytical form by Bassetto et al. [14], who proposed a mathematical model based on the solution of an integral equation similar to that of a catenary. Note that the model of Ref. [14] does not include the auxiliary tether, nor accounts for the presence of masses at the tether tips. Therefore, the comparability conditions have been restored by removing the missing components in the analytical approach from the FE model and by correspondingly increasing the spacecraft angular velocity. The resulting comparison between the numerical and analytical predictions of the tether deflection is shown in Fig. 8. The two curves in Fig. 8 have a similar shape, even though the analytical model of Ref. [14] estimates a tether stiffness greater than that estimated by the numerical one. The latter yields a larger aperture of the cone near the spacecraft and a consequent lower tip deflection. A comparison with the tangent relevant to the F_{sw}/F_c ratio shows that the cone angle near the spacecraft main body as predicted by the FEM is again very similar to that of a straight (rigid) tether.

6. Conclusions

The numerical code developed to perform static structural analyses of an E-sail has proved to be an effective tool to find a realistic deflection pattern of the tethers. The strong non-linearity of the structural response has been faced by implementing the substructure modelling technique with a suitable selection of the retained nodes, as well as by optimizing the number and the type of elements. To overcome the difficulty of connecting components with remarkably different stiffness, the peculiar properties of different types of Multi-Point Constraints have been exploited. The coordination of the Finite Element pre- and post-processing activities in Python scripts guarantees a good level of automatization of the analysis process.



(a) In plan view.



(b) Side view.

Figure 6: Out-of-plane displacements of an E-sail with configuration ②.

The comparison of the calculated tether deflection with the analytical predictions shows a good agreement in terms of tether shape. In both cases, the tether portion near the spacecraft describes a cone, while the tips tend to flatten due to the stiffening induced by the centrifugal force. The analytical model, which only accounts for the axial flexibility of tethers, is anyway intrinsically stiffer than the Finite Element model. The know-how acquired by setting-up a static analysis is a fundamental step for developing more realistic dynamical models, also in the presence of an E-sail attitude different from a simple Sun-facing condition. These new models are currently under investigation.

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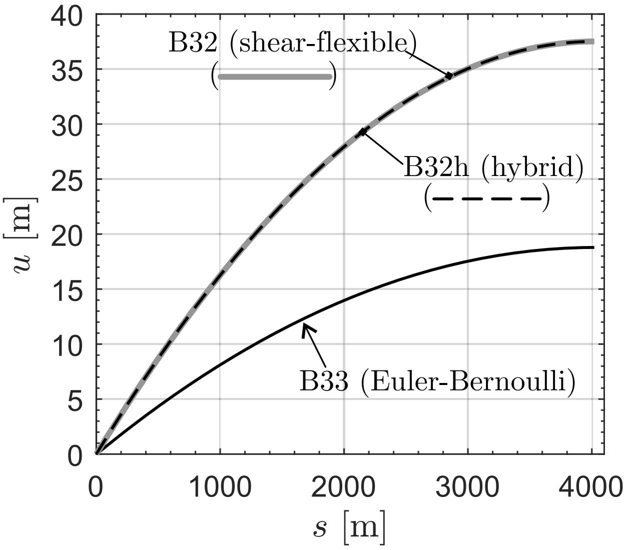

Figure 7: Tether deflection of an E-sail with configuration ③: comparison between different beam elements.

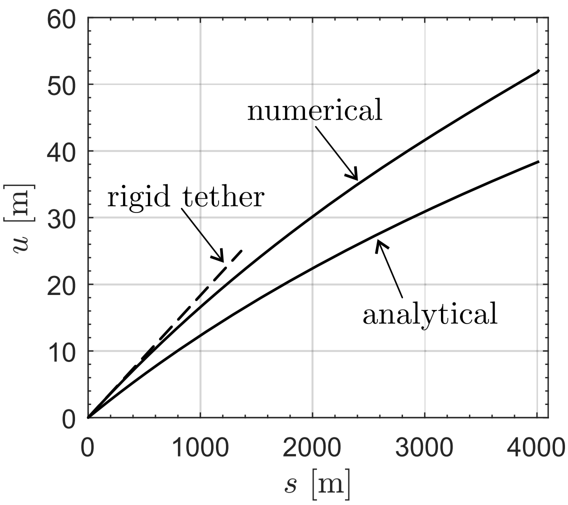

Figure 8: Tether deflection of an E-sail with configuration ③: comparison between analytical and numerical results.

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