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On the simulation of tether-nets for space debris capture with Vortex Dynamics

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ABSTRACT

Tether-nets are one of the more promising methods for the active removal of space debris. The aim of this paper is to study the dynamics of this type of systems in space, which is still not well-known and the simulation of which has multiple outstanding issues. In particular, the focus is on the deployment and capture phases of a net-based active debris removal mission, and on the effect of including the bending stiffness of the net threads on the dynamical characteristics of the net and on the computational efficiency. Lumped-parameter modeling of the net in Vortex Dynamics, without bending stiffness representation, is introduced first and validated then, against results obtained with an equivalent model in Matlab, using numerical simulations of the deployment phase. A model able to reproduce the bending stiffness of the net in Vortex Dynamics is proposed, and the outcome of a net deployment simulation is compared to the results of simulation without bending stiffness. A simulation of net-based capture of a derelict spacecraft is analyzed from the point of view of evaluating the effect of modeling the bending stiffness. From comparison of simulations with and without bending stiffness representation, it is found that bending stiffness has a significant influence both on the simulation results and on the computation time. When bending stiffness is included, the net is more resistant to the changes in its shape caused both by the motion of the corner masses (during deployment) and by the contact with the debris (during capture).

1. Introduction

A promising method for containing the growth of space debris, which jeopardizes operation of spacecraft, is the Active Debris Removal (ADR) of large and massive derelict objects. An ADR technique that has been receiving some attention is to use a tethered net (tether-net for short) deployed from a servicing spacecraft, to capture and contain the debris [1]. This type of device is designed to be flung towards the target debris by accelerating corner masses, and to entangle the debris, providing a link for tugging it to a disposal orbit. Since the behavior of tether-nets in space is unknown to date, numerical simulation is needed to gain understanding of deployment and capture dynamics. Interest in net-based ADR is relatively recent, and the numerical simulation of this type of systems and their contact with debris is still an open problem.

Simulation of tether-net dynamics in space has multiple outstanding issues. First, to date, there is no agreement on the importance of modeling the bending stiffness of the threads. Moreover, modeling of snap loads in the net during the deployment is difficult and computationally expensive. Finally, contact between the net and the debris must be modeled accurately in the capture phase simulation in order to have reliable predictions of the success (or failure) of the capture: this remains a challenging and computationally intensive problem. The aim of this paper is to explain the modeling of a net in Vortex Dynamics[1] and to examine the effect of bending stiffness on tether-net dynamics.

Vortex Dynamics is a powerful multibody dynamics simulation platform designed for real-time simulation of complex systems, which also provides graphical visualization; with its capabilities, the importance of bending stiffness on net response is investigated, and the additional computational cost associated with modeling of bending stiffness is assessed.

Section 2 of this paper describes the state-of-the-art in the simulation of tether-nets for ADR in space and collects information on the current perception of the importance of bending stiffness. Section 3

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[1] Vortex Dynamics is a commercial multibody dynamics simulation software marketed by CM Labs Simulations Inc. www.cm-labs.com/market/robotics/products/vortex-dynamics-software.

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presents the modeling of the net under study: the lumped-parameter model implemented in Vortex Dynamics is introduced; the modeling of bending stiffness is also explained and validated. The validation of the lumped-parameter model without bending stiffness and the results of deployment simulations with and without bending stiffness representation are presented in Section 4; capture simulations are addressed in Section 5. Section 6 concludes the work with a summary of the findings and with suggestions on future work.

2. State-of-the-art

Multiple works on net-based devices for ADR of defunct spacecraft have stemmed from the ESA's interest in deorbiting Envisat. ROGER preliminary study by Astrium was the pioneer study on tether-net systems to capture and dispose of large space debris [1]. With the objective of determining the feasibility of net-based capture, a few simulators have been implemented. Preliminary simulations of capture were executed at the ESA with the 3D modeling environment Blender, and Bullet Physics engine; the net was modeled with a series of interconnected Kelvin–Voigt elements [2]. This work was recently combined with the research performed by Benvenuto et al., with the participation of some European industries: the developed simulator is based on the lumped-parameter approach, and validation of the model by means of experiments is envisaged [3]. Previous work by Botta et al. addressed the modeling and simulation of a net and of contact dynamics, using a lumped-parameter approach and the continuous compliant contact dynamics formulation [4]. Another lumped-parameter-based simulator was developed by Liu et al. to study casting and deployment performance of flexible nets in space [5]. A different modeling approach was chosen by Golebiowski et al., who represented the threads of the net with Cosserat rods [6].

Among the aforementioned simulators for the dynamics of tether-nets in space, the majority take a lumped-parameter approach in which bending stiffness of the threads is not accounted for. The reason why this choice is so common is that this type of model is expected to provide a good compromise between accuracy and computational efficiency. Researchers have argued that this type of model proved sufficient for fishing nets; however, few comments on the role of bending stiffness were found in the literature related to underwater nets. Lee et al. affirmed that the results of their simulation with lumped-parameter models and of experiments matched well in a qualitative comparison of the shape of the net and a quantitative comparison of some geometrical properties of the net (e.g., depth of net center, width and height of net mouth) [7]. With the aim of simulating fishing nets, Takagi et al. [8] also employed lumped-parameter models with no discussion of bending effect and found qualitative agreement between experimental and theoretical net shape configurations; for quantitative analysis, they compared the overall horizontal and vertical dimensions of the net, and found slightly larger values in the numerical simulations. These discrepancies were attributed to reading error and parallax in the video image and to some spring rate value [8]. LeBris and Marichal and Bessonneau and Marichal modeled the threads as rigid bars constrained by rotational joints, subdividing each thread in two in order to describe its shape [9,10]; they only accounted for tension, neglecting bending. By comparing experimental and calculated net shapes, LeBris and Marichal observed that, in still water, the effect of twine bending stiffness is not negligible on geometry, especially in the slack zones of the net. Buckham et al. addressed the dynamics of underwater tethers and affirmed that, if the motion of slack marine cables is to be simulated accurately, the effects of bending and torsional stiffness of the cable must be captured [11]. In his Ph.D. thesis, Buckham observed that when the tether is in high tension, the magnitude of the tensile forces dominates the tether dynamics, and bending and torsional effects are negligible; on the other hand, he showed that it is important to include a bending stiffness model for simulating the dynamics of slack tethers [12]. In any case, it is difficult to forecast the effect of bending on the dynamics of nets in space on the basis of studies on underwater systems: neutrally buoyant tethers are in similar conditions to tethers in space, but the presence of hydrodynamic drag, when the tether moves in the water, creates a very different external forcing conditions: for example, it is much more likely for threads subject to drag to be taut. Therefore, it is expected that in vacuum conditions, the effect of bending is going to be more significant than in underwater environment.

To the authors' knowledge, no study dedicated to evaluating the effect of bending stiffness on the dynamics of nets for ADR removal exists to date. Notwithstanding the debate about the importance of modeling bending stiffness in tether-net dynamics simulation, only a few works in this research domain have provided some remarks on the subject. Yu et al., in their work on space webs, neglected bending after commenting that it had been demonstrated that energy variation for shearing and bending is negligible with respect to energy variation for tensile force [13]. In his thesis on a tether-net simulation tool, Salvi discarded bending effects arguing that the value of bending stiffness per unit length is orders of magnitude lower than the value of axial stiffness per unit length, which makes the first irrelevant [14]. On the other hand, Golebiowski et al. used a Cosserat rod model, which enables reproducing stretching, bending and torsion behaviors; however, they did not comment on the values of bending stiffness, and on the reasons for which they expect bending dynamics to be important [6].

The intent of this paper is to contribute to the debate on the importance of including bending stiffness in the modeling of nets for ADR in space, by formalizing tools for the analysis of the effect of modeling choices, and by providing results demonstrating the effect of modeling bending stiffness for a net in zero gravity and vacuum conditions.

3. Modeling of the net and of contact dynamics

In the foreseen scenario for tether-net ADR, a net would be pulled out of a canister by weights, which are ejected towards the debris by a mechanism mounted on the servicing spacecraft. The net configuration used in the current work is square, with a square mesh, and 4 weights for ejection. An illustration of the net geometry is provided in Fig. 1 for $N_s=6$, where N_s is the number of nodes on a side of the net. In the following, the phrase *corner mass* will refer to nodes such as 37, 38, 39, 40 in Fig. 1, while the phrase *corner thread* will refer to threads such as 61, 62, 63, 64 in Fig. 1.

The net geometry is represented in the software environment by numbering the nodes and threads of the net and by creating a connectivity table in an automated way. In the automated creation of the connectivity table, an internal link (thread) is added, for all $i = 1, \ldots, N_s^2$ and for all $j = i + 1, \ldots, N_s^2$, if the following conditions are verified:

$$(j = i + 1 \wedge i \bmod N_s \neq 0) \vee (j = i + N_s) \tag{1}$$

The four corner threads are appended to the table after the inner threads.

3.1. Lumped-parameter model without bending stiffness

The lumped-parameter model has been extensively used in the simulation of the dynamics of nets, because of its simplicity of implementation. In this model the physical nodes of the net are