Acta Astronautica 114 (2015) 34–53

Contents lists available at ScienceDirect

Acta Astronautica

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

Eddy currents applied to de-tumbling of space debris: Analysis and validation of approximate proposed methods[☆]

Natalia Ortiz Gómez[*], Scott J.I. Walker

Southampton University, Highfield SO17 1BJ, United Kingdom

ARTICLE INFO

Article history:
Received 19 October 2014
Received in revised form
23 March 2015
Accepted 16 April 2015
Available online 28 April 2015

Keywords:
Active debris removal
Earth's magnetic field
Eddy currents
Tumbling

ABSTRACT

The space debris population has greatly increased over the last few decades. Active debris removal (ADR) methods may become necessary to remove those objects in orbit that pose the biggest collision risk. Those ADR methods that require contact with the target show complications if the target is rotating at high speeds. Observed rotations can be higher than 60 deg/s combined with precession and nutation motions. 'Natural' rotational damping in upper stages has been observed for some space debris objects. This phenomenon occurs due to the eddy currents induced by the Earth's magnetic field in the predominantly conductive materials of these man made rotating objects. Existing solutions for the analysis of eddy currents require time-consuming finite element models to solve a Poisson equation throughout the volume. The first part of this paper presents a new method to compute the eddy current torque based on the computation of a new tensor called the 'Magnetic Tensor'. The general theory to compute this tensor by Finite Element Method is given as well as a particular frame model. This last model enables an explicit formula to be determined to evaluate the magnetic tensor. Analytical solutions for the spherical shell, the open cylinder and flat plates are given for the magnetic tensor and the eddy current torque model is validated with existing published work. The second part of the paper presents an active de-tumbling method for space debris objects based on eddy currents. The braking method that is proposed has the advantage of avoiding any kind of mechanical contact with the target. The space debris object is subjected to an enhanced magnetic field created from a chaser spacecraft which has one or more deployable structures with an electromagnetic coil at its end. The braking time and the possible orientation change in the rotation axis is analysed for a metallic spherical shell considering different ratios of conductive versus non-conductive material. The paper finalises with a case study based on the de-tumbling of an Ariane-4 Upper Stage H10 under the effect of the gravity gradient and a preliminary analysis of the non-uniformity of the magnetic field is presented.

1. Introduction

The total number of tracked objects in Earth orbit above 10 cm in size exceeds 21,000 [1]. Particles between 1 and 10 cm in size are estimated to be 500,000 and particles smaller than 1 cm are estimated to be above 100 million [1]. At present, every new Earth mission needs to allocate a certain amount of propellant for collision avoidance manoeuvres and these manoeuvres have become more frequent over the years [2]. In addition, the average estimated collision rate per year in mid-2013 was 0.24 (that is, 1 collision every 5 years) [3]. In the coming years, Active Debris Removal (ADR) methods may become necessary to remove those objects in orbit that pose the biggest risk.

Current active debris removal methods can be divided into contact and contactless methods for complete removal [4,5]. Non-contact methods have some advantages with

---

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

[*] Corresponding author.

E-mail addresses: N.Ortiz-Gomez@soton.ac.uk (N. Ortiz Gómez), sjiw@soton.ac.uk (S.J.I. Walker).

http://dx.doi.org/10.1016/j.actaastro.2015.04.012

respect to contact methods because all problems related to the grabbing of a non-cooperative target are avoided. However, contactless methods lead to an uncontrolled re-entry which is only adequate for de-orbiting small targets which will disintegrate in the atmosphere or for re-orbiting them to a graveyard orbit.

The controlled re-entry of large objects requires the use of chemical propulsion for the de-orbiting phase. This can be achieved with contact ADR methods which grab the space debris object by means of a rigid or flexible capture system and de-orbit the combined system in a controlled way. Examples of proposed rigid capture systems are tentacles or a robotic arm. Examples of flexible capture systems are a net, harpoon or clamp. All these methods have applicability limitations depending on the rotational motion of the target. For instance, the maximum rotational speed that can be stopped by current robotic arms is around 4–5 deg/s [6].

However, even if the target is rotating at a lower speed, it may be difficult to achieve zero relative angular velocity between the chaser and the target if the non-cooperative object has a complex motion, such as a rotation about all three axes. This aspect is not well tackled in the literature as the capture process is usually analysed for targets that are rotating about 1 axis.

Dealing with tumbling objects using flexible capture systems is still an open point. In the case of a harpoon or a net, there exists the risk of an entanglement between the tether and the target if the rotational motion of the target is not stabilised. Some papers claim that once the target is captured, the tension achieved on the tether with impulsive thrusts during the de-orbiting phase will help to control the rotational motion of the target [7,8].

Due to the limitations of the proposed contact ADR methods, a de-tumbling phase prior to the grabbing phase may be needed.

The present paper focuses on the analysis of a contactless de-tumbling method based on eddy currents which was first proposed by Kadaba [9]. Little work has been carried out afterwards on this idea [10] and this paper deepens on the mathematical models that drive this phenomenon as well as some aspects of the mission design. The main objective of the present work is to provide with the necessary mathematical expressions to analyse the orbital and rotational dynamics of the chaser–target system (forces and torques) due to the eddy current phenomenon, in an approximate but direct way. The paper is organised as follows. Section 3 presents a deep analysis on the mathematical models of the eddy currents phenomenon. The major contribution of this paper is the introduction of a new tensor called the ‘Magnetic Tensor’ which provides us with a direct formula to evaluate the torque induced by the eddy currents when the magnetic field is homogeneous and constant. This way, it is possible to avoid solving the Poisson equation with Neumann conditions, for any type of conductive solid, in each time step of the integration of Euler equations. Section 3.3 includes a method to evaluate this tensor based on a generic Finite Element Method and Section 3.3.1 is particularised for a specific F.E.M. (frame model) which leads to a direct formula to evaluate this tensor. In addition, analytical solutions of this tensor are presented and compared with existing solutions for the eddy current torque [11,12] (Section 3.4).

The second part of the paper presents a preliminary analysis of an active contactless de-tumbling method based on eddy currents (Section 4). The process will be done actively with a chaser spacecraft which has one or more magnetic coils. Sections 4.3 and 4.4 analyse the characteristic time of decay of the process for different percentages of conductive material and the orientation change in the rotation axis under the assumption of a constant (no time variation) and homogeneous magnetic field. Section 4.5 presents a case study based on the Ariane 4 Upper Stage under the same assumption. Finally, Section 4.6 explains the main consequences of having a spatial gradient on the magnetic field which result in an efficiency penalty in the method and the appearance of net forces between the chaser and the target object.

2. Nomenclature

The nomenclature used in this paper can be found in Table 1.

3. Eddy currents analysis

The rotational dynamics of a rigid body can be studied using Euler equations [13]. The advantage of these equations is that they are expressed in a fixed frame to the rigid body (body reference frame) and therefore, the inertia tensor is constant in this reference frame. The body reference frame used in this paper has its origin at the centre of gravity (COG) of the target and its axes go along the principal inertia axes

Table 1
Nomenclature.

Symbol	Quantity	Unit
A	Area	m^2
$\vec{B}$	Magnetic field vector	T
E	Energy	J
$\vec{E}$	Electric field vector	$V\,m^{-1}$
e	Thickness	m
f	Force	N
I	Inertia tensor	$kg\,m^2$
J	Electric intensity	A
$\vec{j}$	Electric current density vector	$A\,m^{-2}$
K	Stiffness matrix	$N\,V^{-1}$
L	Length	m
M	Magnetic Tensor	$S\,m^4$
$\vec{m}$	Magnetic moment	$A\,m^2$
R	Radius	m
$\vec{T}$	Torque	N m
ϵ	Electric permittivity	$F\,m^{-1}$
ε	Electromotive force	V
Λ	Jacobian matrix	$T\,m^{-1}$
μ	Magnetic permeability	$H\,m^{-1}$
$\vec{\omega}$	Angular velocity vector	$rad\,s^{-1}$
ϕ	Electric potential	V
ψ	Potential	V
φ	Magnetic flux	V s
σ	Conductivity	$S\,m^{-1}$
τ	Characteristic time	s