Computer methods in applied mechanics and engineering

Comput. Methods Appl. Mech. Engrg. 190 (2001) 5495–5503

www.elsevier.com/locate/cma

Sensitivity analysis of bare-wire space tether systems

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Received 26 June 2000

Abstract

Hypergeometric series solutions are presented for the electrodynamic response of bare-wire tether systems, and are used to generate closed-form expressions for the sensitivity coefficients in the generator configuration. For the thruster configuration, the governing equations are in the form of three simultaneous differential equations, which do not allow closed-form solutions for the sensitivity coefficients to be generated, and therefore numerical solutions for the sensitivity coefficients are presented. © 2001 Elsevier Science B.V. All rights reserved.

1. Introduction

The concept of the bare-wire electrodynamic tether was first introduced by Sanmartín et al. [1,2] as a more efficient alternative to insulated electrodynamic tethers [3–6]. Insulated tethers had flown on several NASA missions, including the Tethered Satellite System (TSS) missions [5] and the Plasma Motor Generator (PMG) mission [6], but their electron capturing ability was limited to collection at specially designed end contactors. The planned NASA Propulsive Small Expendable Deployer System (ProSEDS) mission [7,8] will be the first NASA mission to evaluate the performance of a bare-wire tether system collecting electrons along much of the bare-wire section.

Bare-wire tether systems operate in either a generator or a thruster configuration, as depicted in Fig. 1. In both configurations, an electric potential is induced along the tether due to its motion through earth's (or any other planet's) magnetic field. The subsequent positive potential bias of the tether relative to the space plasma allows the bare-wire portion of the tether to collect and transport electrons, creating a current flow in the tether. This electron transport terminates at the cathode end of the tether, where the electrons are emitted and returned to the plasma.

The intended use of the induced current flow differentiates the generator configuration from the thruster configuration. In the generator configuration, the tether is upwardly deployed from the cathode and the current flow charges an on-board battery. When this tether is incorporated into an orbiting body, such as a satellite system or a space station, the charged battery can be used to continuously power the orbiting body's electrical needs, although at the cost of a Lorentz drag force which tends to de-orbit the body. In the thruster configuration, the tether is downwardly deployed and a battery compensates for voltage losses due to the tether's resistivity, insuring that the bare-wire portion is positively biased relative to the space plasma. The interaction of the current flow with earth's magnetic field produces a Lorentz force which tends to boost the attached orbiting body, at the cost of depleting the battery's stored electrical power.

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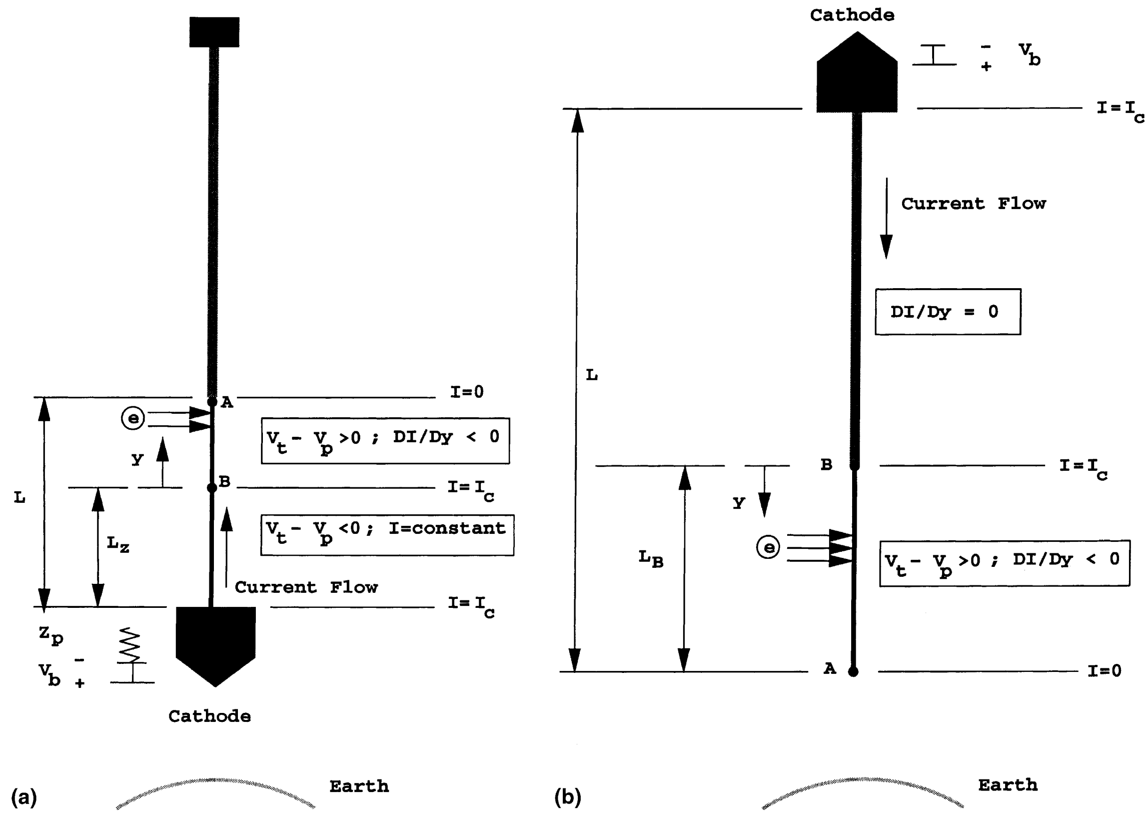

Fig. 1. Generator and thruster configurations of the electrodynamic bare-wire tether: (a) generator; (b) thruster.

The goal of this study is to present sensitivity coefficients for both the generator and thruster configurations of the bare-wire tether system. These coefficients measure the sensitivity of the system to small changes in material and environmental parameters. The chosen generator configuration of Fig. 1 follows from the configuration of the ProSEDS mission, and differs from the original configuration proposed by Sanmartín et al. [1] by the modified location selected for the bare-wire section. The thruster configuration in Fig. 1 is identical to that used in [1].

2. Mathematical formulation

The dimensionless equations governing the operation of generator and thruster configured bare-wire tethers were first developed by Sanmartín et al. [1]. The resulting expressions are given in Section 2.1, and a detailed derivation for the generator configuration is presented in Appendix A. The development of the thruster configuration follows closely to that of the generator configuration, and is not presented in detail. A hypergeometric series solution to one of the governing equations is presented herein, which enables the development of closed-form expressions for the sensitivity coefficients in the generator configuration, and more efficient numerical evaluation of the sensitivity coefficients in the thruster configuration.

2.1. Governing dimensionless equations

2.1.1. Generator configuration

The dimensionless form of the circuit equation for the generator configuration is given by

$$i_c - 1 + \frac{\sigma V_b}{J_*(L - L_* \xi_A)} + \frac{\sigma A_t i_c Z_p}{(L - L_* \xi_A)} = 0, \tag{1}$$