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Self-docking analysis and velocity-aimed control for spacecraft electromagnetic docking

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Abstract

As a novel and potential supporting technology for on-orbit operation missions, spacecraft electromagnetic docking has not only distinct visible advantages, but also several intrinsic unconspicuous capabilities, such as the self-docking capability which could be exploited to alleviate the burden of the docking controller. Based on theoretical derivation and comparison with the near-field model and numerical simulation, the feasibility of utilizing the far-field electromagnetic force/torque model to spacecraft electromagnetic docking characteristics analysis is firstly verified. Then, the self-docking capability is studied with self-alignment and self-attraction analysis, and the necessary condition for the former and the sufficient condition for the latter are derived. Finally, a velocity-aimed electromagnetic docking control approach based on the self-docking capability and the conservation laws is put forward and verified by numerical simulations.

Keywords: Electromagnetic docking; Self-alignment; Self-attraction; Velocity-aimed control; Conservation laws

1. Introduction

Spacecraft electromagnetic docking is a novel technology that applies inter-craft electromagnetic force/torque produced by the interaction between two controllable electromagnetic fields to controlling the relative motion between the Target (noted as ‘T’) and the Chaser (noted as ‘C’) spacecraft (Zhang et al., 2012, 2013). Electromagnetic docking has distinct advantages of no propellant consumption and plume contamination, having continuous, reversible, synchronous and non-contacting control capability, thus ensuring a broad prospect of application in on-orbit operation missions. However, along with these advantages are its complex dynamics, such as strongly nonlinear, coupled and uncertain dynamics, and the corresponding robust control requirement. Actually, similar to other researches which exploit the intrinsic properties of control plant, such as scramjet engine making use of the air to reduce oxidant consumption, deep-space spacecraft utilizing the gravitational force difference to turn around and low-orbit spacecraft exploiting the Earth’s gravitational force to form certain orbits, the self-docking capability of electromagnetic docking technology, behaving as relative attitude self-alignment and relative distance self-attraction, could be exploited to alleviate the burden of the docking controller. This self-docking capability has been studied and several conditions for magnetic moments are given (Zhang et al., 2011), but this study is preliminary and does not consider the feasibility of the far-field electromagnetic force/torque models. In addition, Hussein and Huang explores the relative equilibrium and the corresponding static configurations of spacecraft electromagnetic formation flight (Hussein and Bloch, 2008; Huang

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et al., 2014a, 2014b), which could be referred for analyzing electromagnetic docking dynamics. As to the controller design for spacecraft electromagnetic docking and formation flight, several methods of robust H_∞, adaptive control and LQR are applied and validated, yet these controllers fail to consider the intrinsic characteristics of self-docking and relative equilibrium (Ahsun et al., 2006; Ahsun and Miller, 2007; Ahsun et al., 2008, 2010; Zhang et al., 2013). If the self-docking and relative equilibrium capabilities could be thoroughly and theoretically exploited, the relative motion of the docking spacecraft pair could be better designed and the possibility of soft-docking could be actualized.

However, this self-docking operation generates high contact velocity which may be unacceptable to spacecraft docking, hence the need of active velocity control. The actuated electromagnetic force/torque belongs to internal and conservative actuation as to these docking spacecraft, therefore the total linear momentum, angular momentum, mechanical energy and motion of center of mass of the spacecraft electromagnetic docking system are conserved (Kim and Schaub, 2006; Norman and Peck, 2011), limiting the relative motion states of the docking spacecraft pair at different times. Given the final soft-docking states, seven constants (three for total linear momentum conservation, three for total angular momentum conservation and one for total mechanical energy conservation) are got which constrain other relative motion states at previous time. Therefore, to satisfy the soft-docking requirements, a velocity-aimed control approach based on these conservation laws could be properly designed, which intrinsically meets the soft-docking requirements and enjoys simple controller parameters tuning and better robust capability.

This paper concentrates on the self-docking capability analysis and the velocity-aimed control approach for spacecraft electromagnetic docking. In Section 2, the feasibility of the far-field electromagnetic force/torque models for spacecraft docking characteristics analysis is verified by theoretical derivation and comparison with the near-field model as well as numerical simulations. Several potential applications of the far-field model are put forward. In Section 3, the self-docking capability is studied by analyzing self-alignment and self-attraction characteristics, and the necessary condition for the former and the sufficient condition for the latter are derived. In Section 4, a velocity-aimed electromagnetic docking control approach based on the conservation laws is proposed and verified by simulations.

2. Feasibility analysis of the far-field model

Presently, three kind of electromagnetic force/torque models are generally applied: far-field model, near-field model and nearest-field model (Buck and Miller, 2013). The far-field model takes the electromagnetic coils as magnetic dipoles and calculates the corresponding electromagnetic force/torque, thus widely applied in dynamics analysis and controller design (Sakaguchi, 2007; Gardner, 2008). However, when the relative distance between electromagnetic coils is smaller than a certain value which is determined by the geometries of electromagnetic coils, the relative model error is larger than 10% and nonlinearly increases as the relative distance decreases. Therefore, a high-precision electromagnetic force/torque model is needed and has been presented, which is the near-field model and seen as the actuation between electromagnetic coils with only a loop. And then, if the precision of the near-field model does still not suffice, a nearest-field model with full electromagnetic structure consideration is put forward, which is seen as an actuation between electromagnetic coils with *N*-loop.

In this section, the feasibility of the far-field model for spacecraft docking characteristics analysis is verified and several potential applications are put forward.

2.1. Comparison between the far-field model and near-field model

Based on the geometrical configuration of the two magnetic coils in Fig. 1, the theoretical derivation flow charts for the near-field and far-field electromagnetic force/torque models of coil 2 actuated by coil 1 are depicted as Figs. 2 and 3, where the arrowheads show the derivation procedure, and the subscripts 1 and 2 represent coil 1 and coil 2, respectively. In Fig. 1, o, ρ, i and dl are the center, the radius, the current and the current segment of the coil, and $(\boldsymbol{d}, \boldsymbol{r}, \boldsymbol{s})$ are the distances from o_1 to o_2, dl_1 to dl_2 and o_1 to dl_2. In Figs. 2 and 3, $(\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{F}, \boldsymbol{\tau})$ are the magnetic vector potential, field, force and torque, $J(\cdot)$ the current density and μ_0 the permeability of free space.

The comparative analysis of the derivation procedures of the near-field model and far-field model, as well as several uncertainty characteristics of the latter could be got as follows.

(1) Because the far-field model is derived by assuming $1/|\boldsymbol{s}-\boldsymbol{\rho}| = 1/s + \boldsymbol{s}\cdot\boldsymbol{\rho}/s^3 + \text{H.O.T}$, two characteristics of the far-field model are obtained: the unmodeled part H.O.T has the same posterior derivation procedure as that

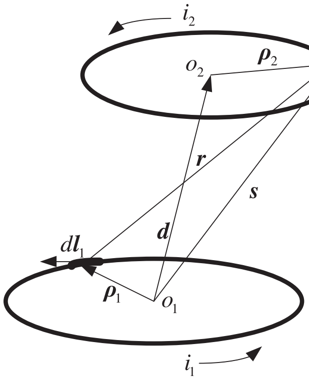

Fig. 1. Geometrical configuration and corresponding parameters of two magnetic coils.