Relative equilibrium and dynamic characteristic of spacecraft electromagnetic formation

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With the development of the spacecraft on-orbit servicing technology, the use of multiple spacecraft formation coordinated flying to implement orbit control for a particular spatial object will become a new approach of space missions. In recent years, the research on spacecraft non-contacting internal forces which include the electromagnetic force, the Coulomb force and Flux-pinned effect force provides novel insight and a technology alternative in on-line orbit control, namely the use of internal forces among different satellites to accomplish non-contacting orbit operations, thus avoiding physical connection and improving on-line orbit manipulation safety.

Electromagnetic Formation Flying (EMFF) is a novel technology that uses superconducting electromagnetic coils to provide electromagnetic forces/torques which can be used to control the relative position and attitude among different satellites in a formation. This concept could effectively solve the problem of propellant consumption and plume contamination caused by conventional propellant approaches such as thrusters, and offer non-contacting continuous reversible and synchronous controllability. With the development of coordinated spacecraft formation technology, the EMFF technology increasingly turns into a research hotspot. In this field, abundant researches have been carried out home and abroad. Nevertheless, it is a challenge to investigate the dynamics and control of Electromagnetic Formation Flying because of the characteristics of electromagnetic internal force/ internal moment and the high nonlinearity/coupling of the dynamic equation. A lot of problems still remain to be solved. Thus, the fundamental dynamics research on static electromagnetic formation flying has great significance.

The electromagnetic formation flying is subordinate to multi-spacecraft coordinated flying which involves complicated and correlative motions. These motions can be decomposed into two parts，one is the group motion of the formation flying itself and the other is the relative motion among member spacecraft of the electromagnetic formation system. Therefore, in order to describe the dynamic characteristics of the formation itself and the relationship among each satellite of electromagnetic formation system clearly, the method of analytical mechanics is used

to this research. The traditional dynamics and kinematics models of spatial formation flying systems are based on the vector mechanics which is limited by multiple factors, including model precision and nonlinear equation solution. Different from the vector mechanics, the analytical mechanics investigates the problem via the system energy which includes kinetic energy and potential energy. The analytical mechanics variation principle proceeds from the point of analytical mathematics and the energy view to study the dynamics problem. Typical methods of analytical mechanics include: Lagrange mechanics system, Hamilton mechanics system and Gibbs-Appell methods.

This paper mainly concentrates on the dynamics problems of spacecraft electromagnetic formation flight, and investigates the Hamilton 6-DOF model, relative equilibrium analysis and dynamic characteristic analysis of the electromagnetic formation etc. First, the relative equilibrium for the vector mechanics model is analyzed and the necessary conditions for a circularly restricted static electromagnetic formation are derived. Second, the 6-DOF coupled nonlinear dynamic models by Hamiltonian method for the multi-spacecraft electromagnetic formation are obtained without earth perturbation. Then, the equilibrium solution and the magnetic dipole scheme of the given static formation are gained. Finally, based on the equilibrium conditions, the characteristics of stability and controllability of the equilibrium solution are investigated.

In conclusion, the study on Electromagnetic Formation Flying is multi-faceted, yet the static electromagnetic formation dynamics research is fundamental and potentially prospective. On the basis of the established dynamic model, this article considers the necessary conditions for static equilibrium formation to give the equilibrium solution, and conducts stability analysis of the electromagnetic formation system and magnetic dipole configuration. All of these explorations are grounded on both theoretical analysis and numerical simulation, providing a foundation for future studies on electromagnetic formation flight technology.

Key words: Electromagnetic Formation Flying; relative equilibrium; Hamilton dynamic model; dynamics characteristic

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