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The Application of Perturbation Method in Low-thrust Orbit Optimization† ⋆

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Abstract For the multi-target and multi-mission explorations of near-Earth asteroids in the solar system, how to select the reachable targets from a large amount of asteroids is still an unsolved problem in the low-thrust orbit design. Here we explore the orbit transfer problem of a low-thrust spacecraft in the interplanetary space. Adopting the idea of the perturbation theory of traditional celestial mechanics and taking the low-thrust as a perturbation, in the sense of fist-order approximation, we have derived the necessary condition for the successful transfer of two Kepler orbits in the given time under the action of low-thrust. In formulation, this condition is a simple combination of several orbital elements between the initial and terminal orbits, with a small amount of calculations, it can be used to rapidly reject the unreachable asteroids for the given transfer time and low thrust, and the numerical results have confirmed the feasibility of this condition for the near-Earth asteroid explorations.

Key words celestial mechanics: perturbation theory—celestial mechanics: orbit dynamics—planets and satellites: deep space exploration—asteroids: general—methods: analytical

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1. INTRODUCTION

Asteroids are the remnants during the formation of the solar system, and they have preserved much important information about the origin of the solar system. Therefore, the study on the material composition, internal structure, orbit distribution, formation and evolution of asteroids has an important scientific significance for understanding the formation of the solar system and even the origin of the life on the Earth[1−2]. Particularly, as a kind of potential threat to the Earth, the study on the near-Earth asteroids has a very realistic meaning for the safety of the Earth life. However, because of the small size of most asteroids and the limited aperture size of telescopes, it is very difficult to study their shapes and morphologies in detail. So to make the deep space explorations by launching spacecrafts is the best way to study the asteroids.

In the past few decades, most deep-space exploration missions employed the large-thrust chemical propulsion to send the spacecrafts to the target planets. In comparison, because of its high specific impulse (dozens of times of chemical propulsion), the ion-electric propulsion may greatly increase the payload weight in deep-space exploration missions. NASA's Deep Space 1 mission in 1998 testified the feasibility of high specific impulse electric propulsion in the deep space exploration, and also made the low-thrust transfer orbit design become a hot point of public attention[3]. After that, the Smart-1 of ESA, the Hayabusa of JAXA and the Dawn of NASA have proved that the electric propulsion can really be applied to deep-space exploration missions. And in the previous domestic and international orbit design competitions, the application of continuous electric propulsion in the orbit design of multi-target multi-task asteroid explorations is also the main subject to discuss[4−7].

Generally, the electric propulsion engines have a high specific impulse but a low thrust, therefore they are also named the low-thrust engines (for example, the total thrust of the four electric thrusters on the Japanese asteroid probe Hayabusa is only 0.032 N[8]), the corresponding orbit design problem is different from that of traditional chemical propulsion. The low-thrust orbit optimization is generally divided into the global optimization and local optimization two parts. The global optimization is mainly used to determine the exploration sequence and mode under given constraints, as well as the node times and node velocities, including mainly the splicing method of conic sections and the nominal orbit method. The local optimization is used to covert the preliminary orbit given by the global optimization into the low-thrust orbit that satisfies the constraints, including mainly the direct, indirect and hybrid methods[4]. Viewing from the current research progress, the low-thrust local optimization methods have become mature, while the global optimization methods still have many problems to solve[9].

Among the global optimization methods, the conic splicing method is simple, effective, and widely used in the previous orbit design competitions[4−7,10−11]. The basic idea of the conic splicing method is to divide the whole mission orbit into several segments, each segment is approximated with a two-body Kepler orbit, and the velocity increment between the both