Acta Astronautica 119 (2016) 34–47

Contents lists available at ScienceDirect

Acta Astronautica

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

A study on simultaneous design of a Hall Effect Thruster and its low-thrust trajectory

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ARTICLE INFO

Article history:
Received 18 October 2014
Received in revised form
30 April 2015
Accepted 1 November 2015
Available online 10 November 2015

Keywords:
Hall Effect Thruster
Low-thrust trajectory
Simultaneous design environmen

ABSTRACT

Space missions involving Hall Effect Thrusters are more and more common, and designs of both Hall Effect Thrusters and low-thrust trajectories require more elaborated process to meet the on-going mission demands. The design of a new Hall Effect Thruster can be improved by considering mission goals for high-demand missions rather than by relying on the current empirical and experimental design process. Moreover, the optimization of low-thrust trajectories involving the Hall Effect Thrusters can also be improved by incorporating the physics of the Hall Effect Thrusters rather than using a simplified model of the given thruster or incorporating the limited existing thruster characteristics. In order to accomplish these two objectives, a simultaneous design environment of the Hall Effect Thruster and its associated low-thrust trajectory is developed. By linking these two disciplines through a direct embedding of the Hall thruster analysis module within the low-thrust optimal control problem, we show that a new Hall Effect Thruster and the associated low-thrust trajectory can be designed simultaneously. As a starting example applying this coupled strategy, a plausible, high-demand mission scenario is attempted with highly simplified assumptions on trajectory optimization, which is the final stage of a geostationary transfer orbit that takes place entirely outside the Van Allen radiation belts.

1. Introduction

Hall Effect Thrusters (HETs) are now commonly flown in space missions. One of the most famous HETs is the SPT-100 (1.35 kW class thruster), which has been well proven for actual space missions [1]. Typically, HETs have been used for North South Station Keeping (NSSK) purposes, but recent applications have been extended to orbit transfer missions. The PPS®-1350 HET, which belongs to the same power class as the SPT-100 HET, is a good example because it was used as a primary propulsion system of the SMART-1 mission, although it was originally developed for the implementation of NSSK for geostationary Earth orbit (GEO) satellites [2]. In addition, Lockheed Martin Space Systems Company and General Dynamics Space Propulsion Systems developed a 4.5 kW HET propulsion system for applications on GEO satellites. This HET was designed to perform on-orbit station-keeping, repositioning maneuvers, and geosynchronous transfers [3].

Classically, the design of an HET and the design of the trajectory in a mission including this HET are performed independently in two steps (see Fig. 1 left). First, the design of an HET is carried out, mostly through an empirical and experimental process [4,5]. The typical preliminary design step for a new HET is to narrow down the design space based on approximated scaling laws established from historical data. This empirical process

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http://dx.doi.org/10.1016/j.actaastro.2015.11.002
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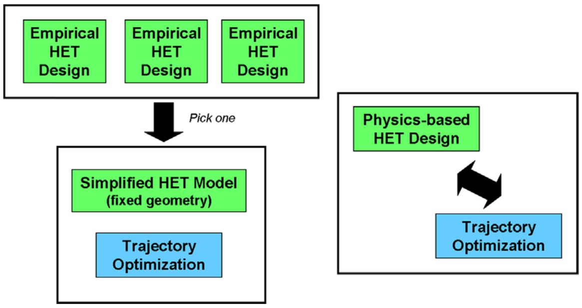

Fig. 1. Traditional design methodology (left). Proposed simultaneous design methodology (right).

usually determines a large number of design parameters in the early design stage. An experimental trial-and-error approach is then applied to obtain an effective HET. Thus, in order to improve the current HET design process, the underlying physical details of HETs, which are often complicated and nonlinear, need to be incorporated in this preliminary design process so that a more reliable physics-based approach can be infused in the early stage of HET design.

Secondly, for a given space mission, an HET is chosen among the catalog of existing thrusters. The optimization of the low-thrust trajectory of the mission is then performed with respect to propellant mass or other parameters of interest. This aspect presents a difficult challenge to space mission trajectory designers since low-thrust optimization problems are also highly nonlinear and typically involve large dimensions. A variety of methods has been proposed to tackle these challenging types of problems [6]. However, due to the level of difficulty in obtaining a solution, most methods assume ideal electric engines, which have constant efficiency and constant or linear variation of specific impulse with power, although several researchers have accounted for the variable specific impulse or efficiency to investigate the effects on the low-thrust trajectory optimization [7,8]. There also is a demonstration in the literature of applying actual but limited thruster performance envelopes to the trajectory optimization [9]. Thus, there is a need to consider a more reliable and advanced physics-based modeling of performance of electric thrusters in the preliminary stage of low-thrust trajectory optimization [10].

To develop the simultaneous design environment of both a HET and its associated low-thrust trajectory, we present in this paper a new multidisciplinary approach where the HET design is performed along with the low-thrust trajectory design of its intended nominal mission. At a time when the space agencies are being curtailed under tight budgets, it is crucial that the next investments in HET electric propulsion address near and mid-term mission needs. Custom-design HETs would be particularly suitable in the context of highly repetitive missions, such as transfers to GEO. In that context, mission planning stands to benefit from a unified system design where both HET propulsion design and low-thrust optimization are performed simultaneously under the same framework (see Fig. 1, right). Indeed, the characteristics and dimensioning of the HET directly impacts the associated low-thrust trajectories, which has an indirect feedback effect on the mission performances. Thus, the current philosophy is to provide a more optimal designed HET with trajectory and mission considerations rather than one separately designed based on the power class or empirical approach.

Two primary components are necessary to implement systematically this approach. The first building block of our approach is a fast and accurate HET modeling tool. The HET modeling should be considered with minimal simplifications in the trajectory optimization process. An appropriate tool for this purpose has therefore been developed using a new analysis method [11]. The method uses a 1-D fluid description and is quite suitable for the current purpose, which is briefly explained in the next section. One obstacle of this method for the current purpose is the electron anomalous cross field transport, which has not been fully understood on physical basis [12,13]. No numerical method currently exists to resolve it. In order to compensate for the difference between the calculated electron cross field diffusion and the observed one, the typical approach is to add an artificial collision frequency with artificial coefficients based on the electron cyclotron frequency [14–16]. Our approach is to treat these artificial coefficients as design variables with appropriate ranges based on the previous literature and experimental observations for existing HETs (see Appendix for more details). As a result, their designed values from the simultaneous design are arbitrary. The resultant HET design and associated optimized trajectory will not be exact either. Although the designed values of artificial coefficients are arbitrary, the values of other design variables (especially the thruster geometry) are obtained from the current coupled optimization strategy. However, the designed values of the artificial coefficients are physically meaningless in that there is a risk that the designed HET might be not physically working to fly through the optimized trajectory. In order to prevent this situation, a probabilistic approach such as Monte Carlo simulation for their ranges is used and the effects of their variation on the simultaneously optimized results are investigated. Thus, the merit of this work is that the large uncertain design space could be narrowed down despite of this obstacle. This is actually a great advantage in view of making an informed decision for designing a more optimal HET.

Although the current HET modeling is 1-D description, this analysis is computationally intensive in view of design process. To speed up the HET modeling, we therefore use surrogate models. The resulting tool is expected to provide more reliable and realistic results in the early conceptual design phase by narrowing down a large and uncertain design space.

The second essential component is an innovative multidisciplinary optimization framework for simultaneous HET and trajectory design. Within a recently-developed unified optimization framework, the performance of real HETs from the physics-based tool can be incorporated in the preliminary low-thrust trajectory optimization process. Thus, the distinct feature of the current approach is that the thruster geometry can also be designed in the unified optimization framework.