Mission Analysis for High Specific Impulse Deep Space Exploration

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Abstract

This paper describes trajectory calculations for high specific impulse engines. Specific impulses on the order of 10,000 to 100,000 sec are predicted in a variety of fusion powered propulsion systems. This paper and its companion paper seek to build on analyses in the literature to yield an analytical routine for determining time of flight and payload fraction to a predetermined destination. The companion paper will compare the results of this analysis to the trajectories determined by several trajectory codes. The major parameters that affect time of flight and payload fraction will be identified and their sensitivities quantified. A review of existing fusion propulsion concepts and their capabilities will also be tabulated.

Introduction

There are several fusion propulsion concepts currently proposed in the literature. Most of these concepts are being actively pursued at research centers around the world. These propulsion concepts are nearly always identified for deep space missions, that is missions to the outer planets and to interstellar space. The merits of these concepts are quantified in terms of the potentially attainable Specific Impulse, Lawson number, which is the product of the confinement time and plasma density confined, and the energy return, Q, which is the ratio of energy out to energy input. This work quantifies the possibilities of these propulsion concepts in terms of vehicle design criteria for deep space vehicles, i.e. time of flight or trip time for the vehicle and the ratio of the payload mass delivered to the final destination to the initial mass of the vehicle.

This paper also identifies the optimum conditions for time of flight and payload mass ratio using analytical techniques. Achieving these optimum conditions can sometimes even exceed the capabilities of proposed fusion systems so sensitivities to non-optimum conditions are also quantified. These sensitivities illustrate that specific impulse is not the only important variable in interplanetary performance. These calculations are compared to those reviewed in the literature. Finally the underlying assumptions and the extent of applicability of these equations is determined.

Background

Propulsion Concepts Considered

There are several fusion propulsion concepts currently on the drawing board. A partial list of these concepts and their documented predicted performance is listed in table 1. Any attempt to compare these concepts would be futile since none have come to fruition. Each has their own advantages and disadvantages for attaining confinement and sustainable fusion reactions. Some sacrifice performance for the promise of shorter development time to achieve fusion. This paper attempts to determine the trade of the critical trajectory variables to make these concepts most useful for interplanetary flight.

Other concepts are also listed in Table 1. The Laser Augmented Plasma Propulsion System (LAPPS), first proposed by Kammash et al.[1] exists on the high end of the specific impulse spectrum. Conversely, existing and near term nuclear electric propulsion concepts populate the lower end of the specific impulse spectrum. These concepts are included to round out the range of specific impulses used in continuous thrust systems. Note that propulsion systems that use external energy for propulsion, such as the various solar, laser and magnetic sails are not included due to their extremely low thrust, thrust as a function of distance to the sun or laser, and radial thrust profiles makes the underlying assumptions for these calculations untenable.

Previous analytical trajectory work

A review of the literature reveals several attempts to address high specific impulse constant thrust trajectories. Williams[2] discussed several papers and works by Cole[3],

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Moeckel[4] and Shepherd[5] as genesis of his work. This paper builds on the efforts of both Shepherd and Williams in high specific impulse - high thrust calculations.

The Shepherd -Williams equations calculate time of flight as a function of specific impulse, distance and specific power. The equation for payload ratio is derived and differentiated to find the optimum relationship between payload ratio and specific power. The resulting equation is then included in the derivation of time of flight. The use of an optimum payload ratio implies a limitation of the range of specific powers. This limitation can drive the required specific power to untenable values, even for the most advanced fusion concepts. Williams also developed two-burn rendezvous and four-burn round trip calculations assuming coast time

There is some disagreement on the need for coast time in optimum interplanetary trajectories. Irving and Blum[6] calculate that no coast time should be included in the trajectory. However, Moeckel[7] states that a coast time of 1/3 the total trip time should be included for an optimum trajectory. Their calculations are compared and contrasted below.

Calculations

Using the calculations made by Shepherd, Williams, Moeckel and Irving/Blum as a starting point this work derives time of flight and payload ratio as a function of distance, specific impulse, power ratio, and ratio of total power to initial mass. Optimum points are also determined separately but are not included in time of flight calculations in order to allow for non-optimum operation at more realistic specific impulse-specific power combinations. These calculations are compared to results from widely used interplanetary trajectory codes in a companion paper.[8]

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[3] Cole, D. M., "Minimum Time Interplanetary Orbits", *Journal of Astronautical Sciences*, 1959, pp 31-38.

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[5] Shepherd, *Aerospace Propulsion*, American Elsevier Publications, NY, 1972.

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[8] Adams, R. B., Polsgrove, T. T., "Mission Analysis for High Specific Impulse Deep Space Exploration", Submitted to AIAA 33rd Plasmadynamics and Lasers Conference, 20-23 May 2002.