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AERODYNAMIC INTERACTIONS OF ION THRUSTER PLUME PLASMAS IN VERY LOW EARTH ORBIT

Abstract

Very Low Earth Orbit (VLEO) is a highly appealing region for spacecraft operations, as reducing the operational altitude of remote sensing payloads improves radiometric performance and spatial resolution, whilst reducing the size, mass, power requirement and cost of instruments. VLEO, therefore, offers high-performing and economical spacecraft platforms, but mission lifetime is limited owing to high drag within the thermosphere. Understanding aerodynamic interactions of ion thruster plumes with the spacecraft is vital in assessing the practicality of Electric Propulsion (EP) to provide continuous drag compensation and the feasibility of Air-Breathing Electric Propulsion (ABEP) systems. Quasi-neutral "Direct Simulation Monte-Carlo" – "Particle-in-Cell" simulations, involving interactions of ion thruster plumes with rarefied ambient thermosphere/ionosphere, are presented for steady drag-compensating thruster firings in orbits of 160-250km. The "variable hard sphere method" was used to calculate elastic cross sections for Xe-thermosphere momentum collisions and analytical approaches are used to infer Xe^+-thermosphere charge-exchange cross sections, allowing for detailed analysis of direct nonequilibrium collisional and indirect charged-aerodynamic mechanisms. The thrust required was modelled with a range of mass flow rates, exhaust velocities and ionisation efficiencies, to understand the aerodynamic impact of varying thruster operating conditions. It was seen that thermosphere collisions with charge-exchange Xe^+ backflow increased ambient number density toward the trailing-edge of spacecraft surfaces parallel with the freestream, increasing effective free-molecular shear stress. This effect reduces at lower altitudes and charge-exchange fluxes decrease linearly with greater thermospheric density, as the freestream can more easily penetrate the plume. For the typical operating conditions of a T5(UK-10) gridded ion engine, increase in drag was seen to be 6.64% at 160km to 6.89% at 250km greater than that in absence of the thruster. This drag increase grows with increase in charge-exchange ion production rate, a function of thruster operating conditions, thus greater exhaust velocities yield more efficient drag compensation, particularly at higher altitudes. Surrogate-model shape optimisation of the spacecraft boat-tail was conducted to minimise drag. Calculations have shown that the optimum tail geometry was given by the trade between a decreasing taper, to shade aft surfaces with the fore-body, and increasing taper, to shade the surfaces from charge-exchange backflow. The drag of an ion thruster propelled spacecraft is a closed-loop function of the very thruster exhaust properties, and thus, VLEO drag models for drag-compensating or ABEP systems are not complete without the inclusion of EP plume interactions.