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ScienceDirect

Advances in Space Research 54 (2014) 1590–1607

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Modeling satellite drag coefficients with response surfaces

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Received 20 December 2013; received in revised form 18 June 2014; accepted 20 June 2014
Available online 30 June 2014

Abstract

Satellite drag coefficients are a major source of uncertainty in predicting the drag force on satellites in low Earth orbit. Among other things, accurately predicting the orbit requires detailed knowledge of the satellite drag coefficient. Computational methods are an important tool in computing the drag coefficient but are too intensive for real-time and predictive applications. Therefore, analytic or empirical models that can accurately predict drag coefficients are desired. This work uses response surfaces to model drag coefficients. The response surface methodology is validated by developing a response surface model for the drag coefficient of a sphere where the closed-form solution is known. The response surface model performs well in predicting the drag coefficient of a sphere with a root mean square percentage error less than 0.3% over the entire parameter space. For more complex geometries, such as the GRACE satellite, the Hubble Space Telescope, and the International Space Station, the model errors are only slightly larger at about 0.9%, 0.6%, and 1.0%, respectively.
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Keywords: GRACE; Drag modeling; Response surface; ISS; Hubble Space Telescope; Satellite drag modeling

1. Introduction

The Committee for the Assessment of the U.S. Air Force's Astrodynamics Standards established by the National Research Council (NRC) recently released a report highlighting the issues with current algorithms, models, and operational standards of the Air Force Space Command (AFSPC). The report cites atmospheric drag as the largest source of uncertainty for low-perigee objects due to inaccurate knowledge of atmospheric density and improper modeling of the interaction between the atmosphere and the object (Aeronautics and Space Engineering Board, 2012). The theoretical drag model is given by

$$\vec{a}_{drag} = \frac{1}{2}\rho\frac{C_D A}{m}v_{rel}^2\frac{\vec{v}_{rel}}{|\vec{v}_{rel}|} \quad (1)$$

where $\vec{a}_{drag}$ is the drag acceleration, ρ is the atmospheric mass density, C_D is the drag coefficient, A is the cross-sectional area, m is the satellite mass, and $\vec{v}_{rel}$ is the bulk velocity of the atmospheric gas particles relative to the satellite.

Accurate satellite drag coefficient values are important for reducing biases in densities derived from satellite drag measurements as well as explicitly reducing orbit prediction errors. Numerical simulations produce accurate drag coefficient estimates subject to uncertainties in atmospheric and gas–surface interaction (GSI) models, but are too slow for predictive conjunction assessment applications. Therefore, accurately and efficiently modeling the drag coefficient is very important. In this work, we present a technique for

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http://dx.doi.org/10.1016/j.asr.2014.06.033
0273-1177/Published by Elsevier Ltd. on behalf of COSPAR.

modeling drag coefficients with response surfaces that replicates numerical simulations. The response surface models (RSMs) can be evaluated quickly while maintaining a high degree of accuracy. Current work uses the state-of-the-art atmospheric and GSI models (Walker et al., in press-a,b).

In the realm of spacecraft dynamics and orbit determination, the drag coefficient is defined in three distinct ways: (i) a fixed drag coefficient, (ii) a fitted drag coefficient, and (iii) a physical drag coefficient. Fitted drag coefficients are estimated as part of an orbit determination process and fixed drag coefficients simply use a constant value for the drag coefficient. A drag coefficient value of 2.2 is an approximation for the physical drag coefficient of satellites with compact shapes and has been commonly used in the past. Errors from the use of fixed drag coefficients arise because of the application of the value of 2.2 derived for compact satellites to satellites with complex geometries or geometries with high aspect ratios such as a rocket bodies (Jacchia, 1963; Slowey, 1964; Cook, 1965). For high aspect ratio objects, shear can drastically increase the drag coefficient. Meanwhile, multiple reflections for complex geometries can also lead to divergence from the commonly used value of 2.2. The drag coefficient also changes with altitude and solar conditions since the atmospheric properties that affect the drag coefficient are heavily dependent on the solar flux and geomagnetic conditions (Moe et al., 1998). Fitted drag coefficients are specific to the atmospheric model used and therefore carry along the limitations of the atmospheric model and also frequently absorb other model errors. In addition, fitted drag coefficients are also dependent on the mass and cross-sectional area of the object used in the drag model. Physical drag coefficients are determined by the energy and momentum exchange of freestream atmospheric particles with the spacecraft surface (Schaaf and Chambre, 1961). Throughout this work, the term drag coefficients will refer to physical drag coefficients, unless stated otherwise.

The drag coefficient, characterized by the interaction between the atmosphere and the object, is an independent source of error whereas the errors in atmospheric mass density often stem from the use of fixed and/or fitted drag coefficients in its derivation from orbital drag measurements. Accurately deriving densities from drag measurements requires, in addition to accurate and high temporal resolution data (as in the case of an accelerometer), accurate modeling of the drag coefficient along the orbit. In addition, if the fixed drag coefficient is significantly different than the true physical drag coefficient, or if the conditions (in terms of dynamic model error) for which the fitted drag coefficient is estimated do not apply to the conditions for the orbit prediction, the use of fixed and/or fitted drag coefficients can by itself induce large orbit prediction errors.

Closed-form solutions for the drag coefficients of satellites with simple convex geometries like a sphere, cylinder, and cube in free molecular flow (FMF) were developed early in the Space Age (Schaaf and Chambre, 1961; Sentman, 1961), however, most satellites have complex shapes with concave geometries and require numerical modeling of the drag coefficient. The need for numerical modeling arises from multiple surface reflections and flow shadowing that changes the incident velocity distribution that is assumed to be Maxwellian for the analytic solutions. The drag coefficient in FMF is a function of the atmospheric translational temperature, T_∞, surface temperature, T_w, spacecraft relative velocity, v_{rel}, chemical composition of the atmosphere, GSI model (Walker et al., in press-a), as well as the mass, geometry, and orientation of the object.

A comparison of drag coefficients computed with the Direct Simulation Monte Carlo (DSMC) method using the diffuse reflection with incomplete accommodation (DRIA) and the quasi-specular Cercignani–Lampis–Lord (CLL) GSI models shows the highly sensitive nature of drag coefficients to GSIs (Mehta et al., 2014). The present work uses the CLL GSI model because it is able to reproduce the quasi-specular reflection observed in molecular beam experiments (Cercignani and Lampis, 1971). The CLL model uses the normal energy accommodation coefficient, α_n, and the tangential momentum accommodation coefficient, σ_t, to describe the exchange of energy and momentum between the gas and surface (Lord, 1991). The value of σ_t is assumed to be unity for free molecular flows (Walker et al., in press-a). An empirical model linking σ_n and α_n was recently developed for use with the CLL GSI model (Walker et al., in press-a). Drag coefficients computed using the DRIA and CLL GSI models are within 2–3% of each other at altitudes up to ~500 km (Mehta et al., 2014; Walker et al., in press-a).

A technique for creating parameterized drag coefficient models for satellites with complex geometries was recently developed (Mehta et al., 2013). The technique was applied to the Gravity Recovery and Climate Experiment (GRACE) satellite (Tapley et al., 2004) by developing parameterized relations between drag coefficient and sensitive input parameters based on a local sensitivity analysis. The model was developed for use with the DRIA GSI model (Mehta et al., 2013).

This work presents and validates a state-of-the-art technique for modeling drag coefficients with a response surface. The developed model takes into account all the relevant parameters that affect the drag coefficient and uses the CLL GSI model. The technique is validated using a sphere (simple geometry), where the closed-form solution is known, and then extended and applied to the more complex cases of the GRACE satellite, a simplified model of the Hubble Space Telescope (HST) with articulating solar panels, and the International Space Station (ISS).

The GRACE mission uses two identical satellites, GRACE-A and GRACE-B. The two satellites GRACE-A and GRACE-B are separated by an along track distance of approximately 200 km. The leading satellite is flipped 180 degrees about the sideslip axis in order to maintain communication with the trailing satellite. The use of the