Aerodynamic Coefficient Modelling of Cylindrical Space Debris Analogues During Atmospheric Entry

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ABSTRACT

In the study of atmospheric entry, defunct satellites are often modelled using what is known as the "object-oriented" approach. This type of analysis involves constructing a numerical analogue of a re-entering spacecraft using geometric primitives to represent its constituent components. Shapes such as cuboids, cylinders, cones, and spheres may be used to represent the likes of electronics enclosures, reaction wheels, fuel tanks, antennae, etc., affording this type of modelling a high degree of versatility.

During a typical analysis of this type, a full model of the re-entering spacecraft is constructed using the geometric primitives described above, and its trajectory propagated through the Earth's atmosphere using 6 DOF (degree of freedom) dynamics. At either a pre-defined altitude or as the result of a transient heat transfer calculation, the breakup of the spacecraft model is simulated. From this point onwards in the simulation, the geometric primitives representing the internal components are modelled individually, their trajectories allowing the calculation of thermal loads and touchdown coordinates (provided of course that they do not burn up during their transit through the atmosphere).

A major drawback of this method as it is currently employed, however, lies in the calculation of the debris analogues' aerodynamic properties. As is mentioned above, the full model of a spacecraft is usually simulated using 6 DOF dynamics, with the relevant aerodynamic derivatives being provided by hypersonic panel methods. Once the breakup event is simulated, however, the individual components are typically assessed aerodynamically using tumble-averaged correlations in order to ensure computational efficiency. Such correlations are a large potential source of uncertainty in debris re-entry calculations, and as such limit the potential accuracy of these otherwise extremely efficient numerical methods.

In order to improve the accuracy of object-oriented debris re-entry codes, a series of new aerodynamic databases have been generated using a type of machine learning known as GPR (Gaussian Process Regression) modelling. These databases, which are currently implemented for a generic cylinder of unit aspect ratio, i.e. L/D = 1, utilise 3 dimensional covariance functions (kernels) to correlate freestream Mach and Knudsen numbers, and the angle of incidence of the cylinder. Each model is trained on a single aerodynamic coefficient, with input data being generated using a hypersonic panel method analysis code called RAC (Re-entry Aerothermal Calculator). Once trained, GPR models are extremely computationally efficient, allowing them to feasibly replace tumble-averaged correlations in future debris re-entry codes.

Description of the models' construction and the underlying theory of GPR methods are presented, followed by a summary of the simulations performed using RAC. The GPR models are then tested using a random set of input variables which are also used as input data for further RAC simulations. Next, these two sets of data are compared in order to ascertain the accuracy of the GPR models' predictions compared to RAC. Finally, the execution times and computational resource usage of the two methods are profiled. Hence, the ability of such GPR models to potentially improve future debris re-entry calculations is assessed.