# Database Driven 6-DOF Trajectory Simulation for Debris Transport Analysis

May 18, 2007

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## ABSTRACT

Debris mitigation and risk assessment have been carried out by NASA and its contractors supporting Space Shuttle Return-To-Flight (RTF). As a part of this assessment, analysis of transport potential for debris that may be liberated from the vehicle or from pad facilities prior to tower clear (Lift-Off Debris) is being performed by MSFC. This class of debris includes plume driven and wind driven sources for which lift as well as drag are critical for the determination of the debris trajectory.

As a result, NASA MSFC has a need for a debris transport or trajectory simulation that supports the computation of lift effect in addition to drag without the computational expense of fully coupled CFD with 6-DOF. A database driven 6-DOF simulation that uses aerodynamic force and moment coefficients for the debris shape that are interpolated from a database has been developed to meet this need. The design, implementation, and verification of the database driven six degree of freedom (6-DOF) simulation addition to the Lift-Off Debris Transport Analysis (LODTA) software are discussed in this paper.

## 1. INTRODUCTION

### 1.1 History and Motivation

As a part of the Return-To-Flight (RTF) effort, the Space Shuttle Program undertook the effort of identification, control and residual risk assessment for every possible source of debris that could be liberated during Lift-Off and Ascent of the Space Shuttle Vehicle (SSV). NASA/MSFC was tasked to analyze the potential debris transport during the Lift-Off portion of the flight regime. The Lift-Off timeframe begins with the start of tanking and ends when the vehicle clears the tower and falling debris from the fixed service structure (FSS) can no longer have a transport path to the SSV. Lift-Off Debris Transport Analysis (DTA) solutions were obtained using NASA's OVERFLOW code. These results, referred to as Cycle-1, have been reported previously [TFAWS] and provided an effective screening of the potential debris sources, highlighting sources that posed a potential threat to the SSV. In addition, these results provided insight into the critical shortcomings of the Cycle-1 conceptual and computational models to address the Lift-Off debris risk.

It was clear that the Cycle-2 model had to include significant reductions in uncertainty in both the CFD and DTA aspects of the simulations to address the Lift-Off debris risk in a meaningful way. The Cycle-2 Lift-Off CFD Model, implemented using the unstructured grid CFD code Loci-CHEM, addresses shortcomings in the Cycle-1 CFD through incorporation of higher fidelity facility geometry and realistic plume gas using a three-tiered modelling approach [JANNAF]. In addition to implementation of capabilities required to realize the CFD Model improvements, the Cycle-2 DTA tool included development of an experimentally validated rebound model and a "database-driven 6-DOF" capability for calculation of debris trajectories including lift forces in addition to drag forces. This paper details the design, implementation and verification of the database-driven 6-DOF capability.

The purpose of the addition of the 6-DOF is to model the lift effect on the debris trajectory. The lift results in cross range motion of the debris away from a nominal 3-DOF trajectory. For

LODTA the modelling of debris rebound off of the Mobile Launch Platform (MLP) and interactions with plumes that change the direction of the trajectory make probabilistic computations more difficult. The database driven 6-DOF can be used to generate Monte Carlo sets of trajectories that may be used for creating cross range envelopes, impact distributions, and event probabilities.

### 1.2 Limitations of Uncoupled CFD and 6-DOF

The effect of flow variation across the debris surface that would occur at flow features such as plume edges and shocks is not modelled. The shift in center of pressure on the debris at these areas of high flow velocity gradient could produce large moments. Non static aerodynamic effects such as damping moment would need to be computed by analytic approximations, from CFD coupled with 6-DOF (eg CART3D or FASTRAN), or empirical data to improve accuracy of the simulation. Some more complex transient effects and coupling may not be modelled at all. The effect of the debris on the flow field is not modelled but may be assumed as minor for smaller sizes of debris.

## 2. 6-DOF SIMULATION MODEL AND INTEGRATION

### 2.1 Simulation Architecture

A 6-DOF module has been added as an option to an existing 3-DOF model within an existing debris trajectory simulation application. The software originated as a CFD solution post-processing tool. The debris trajectory simulation propagates the debris through a flow field. The flow field may be either a structured grid in Plot3D format or an unstructured grid. The grid and solution files are loaded at the start. The application supports running multiple trajectories in series with the debris properties and initial conditions read from a single input file. Aerodynamic force and moment coefficients for the debris are loaded from a database file at the start of the first trajectory simulation of the set.

### 2.2 6-DOF Model

The 6-DOF model is for a rigid body with 3 axis Newtonian equations for translation and 3 axis Euler rotational equations. The debris body axis forces and moments are computed based on an aerodynamic coefficient database that is created separately for each cardinal debris shape. The aerodynamic coefficients include 3 static debris body axis forces and 3 static moments about the respective body axis. The addition of damping moment components for each axis is planned. The relative fluid incidence and state are determined at the center of mass of the debris. A routine searches for the cell containing the debris position and interpolates the gas properties for that position. The debris orientation and Mach number relative to the local static flow field are used in table lookups to obtain the aerodynamic force and moment coefficient database tables. Dynamic lift effects (lift due to rate of rotation) and damping moments (aerodynamic moment due to rate of rotation) are not presently modelled.

### 2.3 Implementation of the Equations of Motion and Integration

The integration is accomplished via a Runge Kutta fourth order method. An adaptive time step option is normally used. It adjusts the integration time step both to keep the integration error of each state below a threshold and to provide one or more steps per grid cell.

The equations of motion are implemented within a state derivatives computation routine that is called by the Runge Kutta integration routine several times in each integration step. The state derivatives routine calls the grid search and interpolation routines to determine the gas properties at the current position within the flow field. The state dependent parameters such as the transformation matrix between the inertial axis and the debris body axis, air velocity, Mach number, angle of attack, and sideslip are then computed. The aerodynamic force coefficients and moment coefficients are determined by table lookup and interpolation as a function of angle-of-attack, sideslip, and Mach number. The debris acceleration relative to the grid is computed after transforming the aerodynamic forces on the debris into the grid coordinate system. The net relative acceleration to the grid is then computed for output as part of the state derivatives. The total moment is computed from aerodynamic moment coefficients and an additional term to support an offset between the debris center of mass and aerodynamic reference point. The rotational acceleration is computed using Euler equations for rotation. Only the diagonal terms $I_x$, $I_y$, and $I_z$ are used from the moment of inertia tensor. The orientation state of the debris is maintained as a quaternion. This is done to readily support tumbling motion. The quaternion rates are computed for output as part of the state derivatives.

The traditional Euler angles for yaw, pitch, and roll are computed as dependent parameters. They are used for debris trajectory output only as a more intuitive and traditional expression of orientation. They are also used as input of the initial debris orientation for the same reason.

### 2.4 CFD Flow Field

Both structured and unstructured grid support are available. Structured Grids in Plot3D format and associated solution files are supported. Unstructured grids in a Loci-Chem CFD native grid and solution file format are supported. Grid search and local gas property interpolation functions are accessed through a common interface. Wall or surface distance and normal vector are also computed at the debris position for use by the rebound models.

### 2.5 Rebound Models

Rebound model does not consider orientation of the debris. It only models the change in velocity and position that occurs at rebound. The functionality is the same for both 3-DOF and 6-DOF modes of operation. Two models are present. There is a simple generic rebound model that uses the coefficient of restitution (CR) from an input file. The rebound model sets the normal component of rebound velocity as the product of the CR and the normal component of impact velocity. There is an optional rebound model that is tailored for an alloy steel sphere rebound from a steel plate. It computes its own coefficient of restitution based on empirical models of both experimental and computational data.

## 3. AERODYNAMIC COEFFICIENT DATABASE

### 3.1 Computation of Aerodynamic Forces and Moments

The Loci-Chem CFD code is used to compute aerodynamic forces and moments, but the process can be adapted to any CFD code. A Perl script is used to extract forces and moments from many output files and place them into a single text file. Tailoring of the script can readily be done to get the forces and moments into the necessary coordinate conventions and units. The symmetry in the debris shape determines the range of angle of attack and side slip to generate the sufficient data for the coefficient tables. For shapes of revolution a sweep of angle of attack in one plane is sufficient. Fewer CFD runs are needed with a shape of revolution. For planer symmetric objects, such as a box, CFD runs are done in one octant consisting of a grid defined by angle of attack from 0 to 90 degrees and side slip from 0 to 90 degrees. This set will need to be repeated at multiple Mach numbers. For LODTA purposes, a set of values from a Mach near zero to 3.0 should be sufficient. A 3 dimensional grid of 1000 runs may provide a minimal data set for a typical planer symmetric object.

### 3.2 Computation of Aerodynamic Coefficient Tables

The aerodynamic force and moment are expected to be in the necessary order, axis convention, and units at this point. The forces and moments are converted to coefficients using a Matlab or Octave script to perform conversions, transformations, and write the data to the table file. The script may be readily tailored for a given shape. For a shape of revolution, such as a cylinder, the CFD data is expected to be in one plane using an angle of attack sweep relative to the shape's axis of revolution. The script is used to convert the data into a full table.
For plane symmetric shapes, like boxes and plates, the CFD data is generated in one octant (alpha 0 to 90, beta 0 to 90) and then transformed with the appropriate sign changes for each octant to create a full table.

### 3.3 Table Lookup and Interpolation of Coefficients

The coefficient tables for a single shape are in a formatted text file. The tables are loaded at initialization, and only one set of coefficients or one debris shape is supported in a run directory. The coefficient tables are represented as 3D matrices with the same alpha, beta, and mach ordinates shared by all coefficient tables within the file. The coefficients are interpolated currently with tri-linear interpolation as a function of angle of attack, side-slip, and Mach. The range of these values in the table is expected to cover the full range to be encountered in the debris trajectory.

## 4. VERIFICATION AND VALIDATION

### 4.1 Verification of Translational Motion.

An existing 3-DOF Debris verification case for checking translational motion was reused for 6-DOF verification. It uses a 1-DOF analytic solution for a particle with constant specified drag coefficient for comparison. The 6-DOF body axis aerodynamic coefficient tables for a sphere were created using transformation of the specified drag coefficient to a full table of body axis aerodynamic force coefficients. The trajectory position and velocity was then compared. Also, tests were done with all aerodynamic coefficients set to zero to check both constant velocity and constant acceleration cases against analytic predictions.

### 4.2 Verification of Rotational Transformations.

For the sphere, if no static or dynamic moments are present, the trajectory should be insensitive to the rotation of sphere shaped debris. Any error in the rotational transformations between the debris body axis and the inertial axis would ultimately affect the trajectory matching against the analytic predictions. Multiple trajectories were run with arbitrary initial rotation rate and compared to analytic predictions or 3-DOF trajectories. The trajectories match subject to tolerances that are dependent on expected numerical error in the interpolation of coefficients.

### 4.3 Verification of Rotational Motion.

The rotational motion of a sphere supports deterministic analytic computations of the attitude motion resulting from an arbitrary initial rotational rate. Analytic predictions of the motion from a constant applied moment are also checked by a test version of the code to support a user specified moment. The motion of non spherical shapes results in some gyroscopic coupling effects. Analytic prediction of rotational motion of a cylinder or other axis-symmetric shapes with zero external moment is possible. A test was done to compare the 6-DOF results to analytic prediction for a cylinder.

### 4.4 Verification by Parameter Estimation

Further verification of the 6-DOF EOM was done by aerodynamic coefficient estimation for a cylinder from the trajectory output. The 6-DOF output trajectory (velocity, attitude, and rotation rate vectors) were post-processed with an estimation tool that computes estimated total angle of attack, normal force coefficient, axial force coefficient and moment coefficient in a 2-D plane through the axis of symmetry. Results from a set of 6-DOF trajectories show a successful comparison of estimated coefficients to those taken directly from the aerodynamic coefficient tables.

### 4.5 Validation Methods

The basic equations used in the 6-DOF are widely used and have a history of validation. The validation of this 6-DOF would apply mostly to the testing of the aerodynamic model which includes the static aerodynamic coefficients and the planned addition of damping moment terms. The validation has not been performed yet for this 6-DOF. Validation work is planned at this point to use the same test data set used for a CART3D coupled 6-DOF validation of debris trajectories (ref. AIAA2006_0662). Comparisons of the database driven 6-DOF results are expected to be done against both the NASA Ames aero-ballistic experiment test data and the CART3D coupled 6-DOF. Additional aerodynamic database validation work may be done by comparing drag coefficient as a function of Mach number to experimental data for certain shapes such as the cube and cylinder.

## 5. RESULTS

### 5.1 Oscillation, Spinning, Tumbling Debris and Resulting Lift Effects

Illustrations of several types of rotational motion to include oscillation and tumbling debris are planned. The effect of the lift transients on cross range motion of the debris will be illustrated.

### 5.2 Variation of 6-DOF Trajectories Relative to 3-DOF Reference Trajectory

Illustrations will be presented of sets of trajectories from a single release point at a different initial attitude and rotation rate for each trajectory. The resulting dispersion of trajectories in cross range will be shown for various debris types.

### 5.3 Variation of 6-DOF Trajectories Encountering Plume

Illustrations will be presented of sets of trajectories from a single release point at different initial attitude and rotation rate for each trajectory. The nominal trajectory will encounter a rocket plume. The 6-DOF debris trajectories will have a transient response to the encounter with the plume that is a function of the attitude of the debris. The resulting dispersion of trajectories in cross range will be shown for various debris types.

### 5.4 Application to Lift-off Debris Transport Analysis

Illustrations will be presented of sets of complex LODTA trajectories with both plume interaction and rebounds. Examples of particles unique to 6-DOF results may be isolated to show the importance of lift effects and the resulting cross range motion. Even slight variations in trajectory may lead to larger trajectory distributions because of the chaotic possibilities added by rebound from complex surfaces.

## 6. SUMMARY

The 6-DOF using aerodynamic coefficients from a database meets the need for lift effects efficiently. The 6-DOF equations with orientation via quaternion are widely used and are a robust solution to support tumbling motion. The process of computing and using aerodynamic coefficient tables for fully tumbling debris shapes has been described and may be applied to a larger array of simulations. The verification of 6-DOF EOM is straight forward. Validation is planned to build confidence in the quality of the 6-DOF implementation and the aerodynamic coefficient database. The 6-DOF trajectories will be useful in expanding on the trajectory possibilities that result for lift-off DTA and potentially seeing things not seen with the 3-DOF trajectory sets.