HYBRID CFD ENGINEERING MODEL OF PLUME INDUCED EROSION AND CRATER FORMATION DURING DESCENT OF LUNAR LANDERS

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ABSTRACT

With rapidly increased worldwide interest in landing on the moon, the issue of Plume Surface Interactions (PSI) is gaining attention. Hazards posed by lander plume induced dust and debris, as well as landing site deformation can be mitigated when better understood through predictive simulations. As simulation enabling computational power continues to increase, hybrid Computational Fluid Dynamics (CFD)/Engineering models provide the immediate ability to conduct parametric/trade studies driving design decisions for landers. Reduced order erosion engineering models apply correlations of the surface erosion rate to the plume induced surface forces with the correlations anchored to flight observations from Apollo LM landings. The MSFC propulsion fluid dynamics branch has developed such a hybrid model for predicting the plume induced viscous erosive regression of the Lunar surface beneath a landing vehicle. The (Descent Interpolated Gas Granular Erosion Model) DIGGEM was originally implemented as a post processing tool to calculate induced erosion rates through vehicle descent using CFD solutions of the vehicle plume at several fixed altitudes. This capability has since been advanced in the Loci/Chem-DIGGEM model to allow transient, moving vehicle, fully coupled viscous erosion modeling of vehicle descent PSI. This model has recently been used to make preflight predictions of the erosive regression of the ground beneath a Commercial Lunar Payload Services (CLPS) vehicle in support of measurements to be made by the Stereo Cameras for Lunar Plume Surface Studies (SCALPSS) instrument.

INTRODUCTION

As a vehicle descends using propulsive deceleration, the impingement of the rocket exhaust plume on the granular ground surface results in complex interactions that pose risks to the lander and surrounding assets. These PSI risks can include visual obscuration of the landing site, debris impacts to the vehicle or other existing assets, and deformation of the landing terrain that may result in excessive vehicle tilt. Some of these risks were identified and observed as early as the Apollo landings. Audio recordings of astronaut descriptions and video footage of landings indicate significant obscuration once the regolith is disturbed by the engine plume and can be seen in Figure 1. The Apollo 12 Lunar Module landed 160m away from the Surveyor III craft, sandblasting it with PSI debris, the effects of which were visible on samples returned to Earth.

The ER42 propulsion fluid dynamics branch as NASA Marshall Space Flight Center has developed a suite of tools for predicting PSI effects with various levels of fidelity. A two-phase CFD tool built on the Loci framework[1], Gas Granular Flow Solver[2] (GGFS) is a high-fidelity tool capable of directly simulating much of the complex soil particle phase physics relevant to PSI, including ejecta sheet formation, regolith bed fluidization, and crater formation. However, computational costs still prevent production use of this tool for parametric studies of vehicle and landing trajectory design. To fill this gap in capability and allow fast turnaround simulations of multiple lander trajectories and configurations, several hybrid CFD/Engineering models have been developed. One such tool, Loci/CHEM-DIGGEM, uses CFD to simulate the plume gas flow field, and an engineering model to approximate the effects on the regolith surface by making simplifying assumptions about the nature of the interactions. The model also makes use of a time-compression technique to further reduce the required computational time to allow production level simulations. Details of the Loci/CHEM/DIGGEM model and the time compression approach are included in the following section, followed by a presentation of preflight cratering predictions for the Nova-C lander made using this model.

Figure 1: Frames from video footage of Apollo 15 landing showing difference between clear view of ground (left) and view obscured by PSI effects (right)

MODEL DESCRIPTION

LOCI-CHEM/DIGGEM MODEL

The Descent Interpolated Gas Granular Erosion Model[3] (DIGGEM) was originally developed as a one-way coupled post-processing application to predict time-varying crater depth on the Lunar surface beneath a descending vehicle using propulsive deceleration. The model assumes that the erosion regime is limited to viscous shear erosion such that a functional relationship between plume induced shear stress on the ground and eroded regolith mass flux can be established. For the viscous erosion regime, the liberation of particles from the granular surface requires applying a shear stress sufficient to overcome the other forces (gravity and cohesion) holding the particle in place. The relationship between the mass flux of particles leaving the surface and the excess shear stress can be written as:

$$\dot{m}(x,y,t) = C(\tau(x,y,t) - \tau_{threshold})^n \tag{1}$$

where $\dot{m}$ is the locally eroded mass flux, τ is the local shear stress on the ground, and C, n, and $\tau_{threshol}$ are model parameters which must be calibrated using available data. The model parameters were determined by comparing CFD predicted shear stress for the Apollo 12 LM at several fixed altitudes to observationally calculated erosion mass flow rates from an analysis of Apollo 12 landing footage by Lane and Metzger[4]. To predict crater formation for a lander, DIGGEM would use an interpolation algorithm applied as a post-processing step to the results of several CFD simulations to calculate the time dependent shear stress on the flat, solid ground. Equation 1 was used after the interpolation algorithm to calculate the resulting mass removal rate in the affected regions, and ultimately the accumulated excavated crater volume.

While the use of this engineering model allowed for relatively quick turnaround times for predicting crater growth beneath a vehicle, it suffered from some notable limitations in its one-way coupled implementation. The CFD solutions could not account for the changing terrain shape due to crater growth, thereby limiting application to cases which are loosely coupled (very shallow craters). Also, the process requires separate pseudo-steady CFD solutions of the vehicle at several fixed altitudes as inputs. Because the shear stress for altitudes between those which are simulated must be interpolated, and it is not always clear which altitudes will need to be simulated to capture important plume impingement features, the solution quality could be highly dependent on which altitudes were chosen for simulation. To overcome these limitations, the DIGGEM model has been directly integrated into the

Loci/CHEM tool to allow fully two-way coupled simulations of a moving vehicle through the final portion of descent where significant erosion occurs.

Loci/CHEM includes two capabilities which allow this implementation of the DIGGEM model. The first is a moving body overset mesh capability (componentMotion), which allows one mesh for the background and the Lunar surface and a separate mesh surrounding the vehicle. Relative motion between the vehicle mesh and the background mesh can be prescribed such that the vehicle position in time throughout the simulation can be made to match an expected/known trajectory. The second capability is a module (gridMotion), which allows the mesh to be deformed by altering the location of surface nodes and then smoothly displacing volume elements in the region surrounding the deformed surface. The DIGGEM model was implemented by creating an additional module (surfaceErosionFlux), which uses the instantaneous shear stress on the surface mesh to determine the required local displacement of the surface at each timestep. This displacement is calculated using the relationship from the DIGGEM model:

$$d = -[C(\tau - \tau_{threshold})^n/\rho]dt \tag{2}$$

where d is the distance that the surface at a given location should be displaced in the normal direction, ρ is the regolith density, and dt is the simulation timestep size. Note the negative sign in the equation for displacement, since the displacement is in the direction into the solid surface to represent a loss of surface material at that location. The calculation of the surface motion and flow field (and shear stress) calculation occurs at each timestep, allowing for tight coupling of the simulation.

TIME COMPRESSION APPROACH

The timescales involved in simulating the flow of rocket engine exhaust plumes are quite different from those involved in the descent of a landing vehicle, or the regression of the Lunar surface under viscous erosion effects. Fluctuations in plume flow take place in microseconds, and gas velocities are in kilometers per second. The vehicle final descent takes several seconds at speeds around 1 meter per second, and Lunar surface regression velocity is on the order of centimeters per second at maximum. This presents a difficulty for the fully coupled simulations. Maintaining a time step of 1 or 10 microseconds to accurately model the plume flow, for a duration of 10s of seconds to capture a landing sequence, would require millions of simulation timesteps. This would require computational time in excess of a year even when using thousands of processors simultaneously. Because the timescales are separated by several orders of magnitude, it is possible to compress some of the timescales without drastically altering the nature of the interactions in the simulation. The Lunar surface does not need to respond to each and every short-term fluctuation in the plume, because it is the average effect over longer durations that matters. Similarly, in the time that it takes the vehicle to move considerably closer to the ground, the plume has undergone thousands of fluctuations and can be seen to respond almost instantaneously to changes in the vehicle position.

A very good approximation to the solution to the problem of viscous erosion crater formation may be obtained by compressing many fluid field solution steps into a single vehicle motion or ground deformation step. In the coupled Loci/CHEM-DIGGEM tool, this is done by artificially increasing the rates of vehicle motion and eroding surface regression by a factor of 100. This allows an entire descent trajectory to be simulated using only tens of thousands of fluid solver timesteps. Exact implementation is achieved by multiplying the constant C in the erosion/ shear stress calculation by 100, and multiplying the times at which vehicle location is specified in the component motion file by 100. An additional step is made to correct some of the error introduced when using this method. When the vehicle speed is increased to hundreds of meters per second, an accompanying error in the applied engine exhaust velocity occurs. When the engine exhaust velocity is 3000 m/s and the actual vehicle velocity is 3 m/s (increased to 300 m/s for time compression), the error in exhaust velocity is 10% because the apparent velocity of the gas in the simulation is the sum of the 3000 m/s applied at the engine outlet and the 300 m/s motion of the engine outlet itself. The correction is made by subtracting the excess vehicle velocity (in this case 297 m/s) from the gas velocity applied at the engine outlet boundary.

A sensitivity study of the effects of various degrees of time compression was carried out to verify the appropriateness of this approximation on the prediction of crater depth over time. Factors of 1 (no compression), 10, 100, and 1000 were used in a simplified axisymmetric case for 5 s of simulated physical time (to allow the simulation without time compression to complete in a reasonable amount of computational wall-time). The results are shown in Figure 2. The solutions for compression factors up to 100 are very close to the solution for the uncompressed approach. At a factor of 1000, the differences become noticeable, and qualitative features are no longer captured correctly.

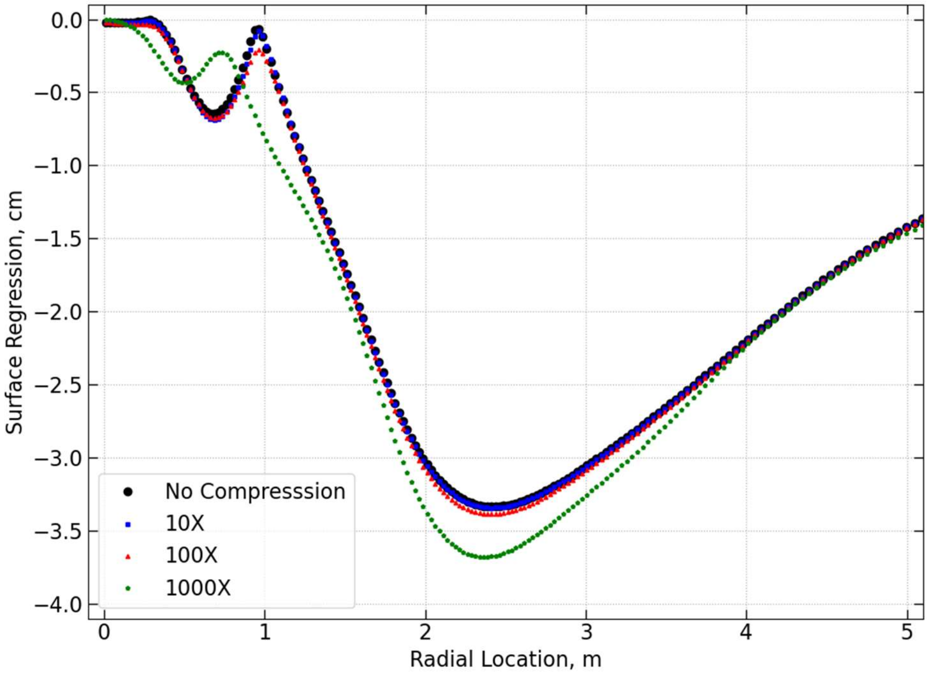

Figure 2: Comparison of time compression factor effect on crater shape after 5 seconds of plume impingement

APPLICATION TO INTUITIVE MACHINES NOVA-C LANDER

The Loci/CHEM-DIGGEM model is being applied in a synergistic way to simulate PSI crater formation for Commercial Lunar Payload Services (CLPS) vehicle landings. Multiple CLPS landers will be fitted with instrumentation systems to gather data regarding PSI effects. The Stereo Cameras for Lunar Plume Surface Studies (SCALPSS) instrument will be used to capture three-dimensional crater formation data. Loci/CHEM-DIGGEM predictions are being used to inform SCALPSS camera requirements and placement. The data collected by the instrument will then be used to update the calibration of Loci/CHEM-DIGGEM model parameters.

The first CLPS landing that will include SCALPSS is the CLPS-2 mission to be flown by the Intuitive Machines Nova-C lander. Loci/CHEM-DIGGEM has been used to make preflight predictions of crater formation beneath this lander using the fully 2-way coupled, moving body, time compression approach described above. The Nova-C spacecraft has a single central engine for landing, like the Apollo LM, however, the Nova-C spacecraft’s mass and thrust are much lower, and the engine uses different propellants. This shows the benefit of the hybrid CFD engineering model, which was calibrated using Apollo data, but can still be used to simulate a different vehicle because the flow properties responsible for PSI can be simulated for any plume composition. The naive expectation might be for shallower cratering than Apollo due to the lower thrust level, but for the viscous erosion regime, the local mass flux is expected to depend on the local shear stress rather than total thrust. In fact, the higher total pressure of the Nova-C engine has the potential for greater impingement pressure and shear stress than Apollo, and it may form a deeper crater.

The simulated portion of the vehicle descent trajectory begins at an altitude of approximately 36 m above the Lunar surface. The vehicle thrust and velocity are varied throughout the descent to match the planned propulsion system operation as provided by Intuitive Machines. Initially, the engine thrust is near maximum as the vehicle is decelerated, but for the final portion of the descent the engine is deeply throttled to maintain a nearly constant vehicle velocity. The changing thrust levels and vehicle velocity necessitate applying a variable correcting adjustment to the engine exhaust profile as described when using time compression. Results of the simulation are depicted in Figure 3. At the start of the simulation a large plume expands beneath the vehicle to very high Mach number. Due to the low density of the plume far from the vehicle, there is very little interaction with the ground and the erosion rate is slow. As the vehicle descends to 17m, an annular crater begins to grow, but is still very shallow. At very low altitudes the plume interactions with the ground strengthen significantly and the plume shape is altered. The crater depth below 5m altitude should be visibly detectable by SCALPSS, but the high density hot gas in the simulation starts to obscure the view of the ground. High density gas has the capability of entraining a large mass of ejecta which may similarly obscure SCALPSS view of the crater. When the vehicle touches down, the plume has altered drastically as the flow interacts with the vehicle legs. The final crater depth is predicted to be about 4.5 cm.

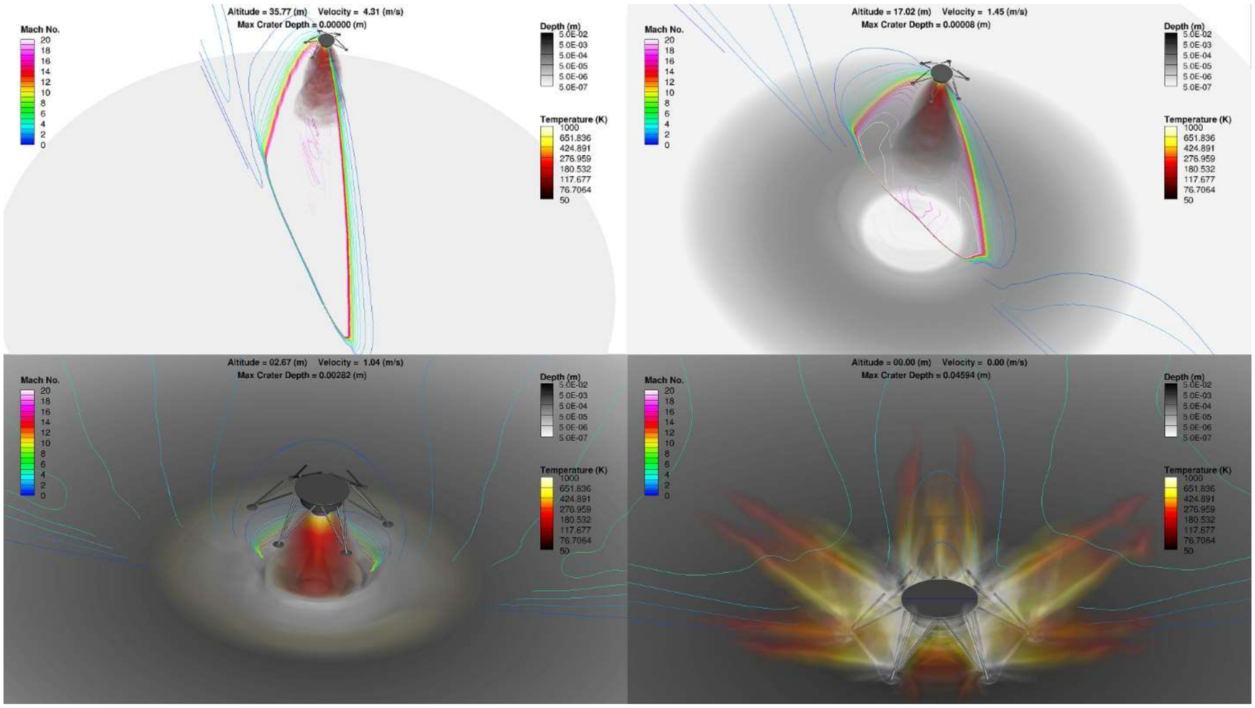

Figure 3: Simulation results for Nova-C descent. A) initial altitude of 35.77m with no erosion yet. B) altitude of 17 m with annular crater beginning to form. C) 2.67m altitude with crater almost 3 mm deep with high density plume gas covering ground. D) Vehicle has touched down in its own crater and plume is deflected around legs.

The simulation took approximately 1 week to complete using 4000 processors. The simulated time for the final 36 meters of descent was approximately 23 seconds, and the time step used was 10 microseconds, resulting in 23,000 timesteps needed for completion. Without the time compression technique, this simulation would have required 2.3 million timesteps, and nearly 2 years of constant computation. These preflight predictions will be validated against SCALPSS data as it becomes available. The Loci/CHEM-DIGGEM tool is currently being used to predict crater formation for other CLPS vehicles, as well as Human Landing System (HLS) vehicles which are much larger than Apollo.

SUMMARY AND CONCLUSIONS

Risks posed by PSI phenomena amid recent development of several new Lunar landers has created renewed interest in understanding and quantifying these effects. The fluid dynamics branch at

MSFC has a cascade of tools available for computationally predicting PSI effects, including the hybrid CFD/engineering model Loci-CHEM DIGGEM. The Loci/CHEM-DIGGEM tool allows simulations of viscous erosion crater formation beneath Lunar descent vehicles to be completed with approximately 1 week of computation time. The tool has been calibrated using available data from Apollo but can benefit from updated data including measurements specifically designed to detect crater formation by SCALPSS. While awaiting SCALPSS data, Loci/CHEM-DIGGEM is being used to make preflight predictions of cratering for CLPS and HLS vehicles.

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