Material Science & Engineering Journal

Research Article
Published: 30 Oct, 2017

Novel Computer Simulations Addressing the Impact Risks in Space from Orbiting Debris

Martin O Steinhauser[1,2]*

[1]*Fraunhofer Institute for High-Speed Dynamics, Germany*

[2]*Department of Chemistry, University of Basel, Switzerland*

Abstract

Since the launch of Sputnik I on October 4, 1957, which marks the beginning of space age almost exactly 60 years ago at the time of writing this article, human space activities have created an orbital debris environment that poses increasing impact risks to existing space systems such as satellites, manned space flight and robotic missions. In this editorial, I intend to briefly discuss novel mesh-free computer simulation methods that constitute a first crucial step towards evaluating the actual risks of impact in the orbital debris environment by implementing a physical-based model that allows for simulating realistic Hyper Velocity Impact (HVI) scenarios. The proposed simulation scheme is based on the Discrete Element Method (DEM) which has so far only been applied in the low velocity regime and thus constitutes the first application of this method to the simulation of impact events at hypervelocity speed beyond ~6 km/s. A quantitative computational analysis of debris clouds generated from HVI and a comprehensive parameter study of the proposed model are presented. Good agreement is found with corresponding HVI experiments at comparable striking velocities on a laboratory length scale when the impact conditions create shock pressures in the target and impact or many times greater than the material strength. The ultimate objective of this research work is to eventually apply the DEM for the complex simulation of spacecraft fragmentations resulting from collisions of space debris with spacecraft structures such as satellites.

Introduction

Space junk represents a growing threat to commercialization and other activities in space. Currently more than 9,000 man-made objects including breakup fragments with a combined mass exceeding 5 million kg are orbiting the Earth. Hence, there has been an ever-growing risk of active satellites being hit by space debris in the low earth orbit [1-4]. In order to assess the risk of future collision events, it is important to be able to predict the impact dynamics of the resulting debris cloud when space debris traveling with hypervelocity speed strikes a satellite structure. The study of hypervelocity impact problems is not only of interest in fundamental shock wave physics research but also of great interest for many optimization processes in engineering applications, such as spacecraft shield design [5]. The term hypervelocity generally refers to velocities so high that the strength of materials upon impact plays only a minor role and the material ceases to behave as a rigid solid, but more like a fluid [6]. Using the conservation of mass, momentum, and energy, one can make a simplified analysis by neglecting material strength, often referred to as a hydrodynamic model. The velocities at which materials start to behave like a fluid vary widely depending on the material's shock impedances and can be anywhere between 2 km/s to 10 km/s [7]. For example, for aluminum, steel and quartz the hypervelocity phenomenon emerges with impact speeds of 5 km/s to 6 km/s [8].

Numerical simulations of hypervelocity impact are needed when the size and velocity of the colliding objects are not easily accessible in ground experiments. Particularly, the characterization of spacecraft collisions with larger space debris objects in the relevant velocity regime is a demanding task for computational modeling. Nevertheless, the complex interactions of impact generated eject a clouds strongly affect the generation and distribution of fragments in orbit. The current debris population in the Low Earth Orbit (LEO) region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future. Even without new launches, collisions will continue to occur in the LEO environment over the next decades, primarily driven by the high collision activities in the region between 900 km and 1,000 km altitudes, and will force the debris population to increase. Semi-empirical models to

OPEN ACCESS

Correspondence:
Martin O. Steinhauser, Department of Chemistry, University of Basel, Klingelbergstrasse 80, CH-4056 Basel, Switzerland, Tel: +497612714424; Fax: +49 761 2714 1424;
E-mail: martin.steinhauser@unibas.ch

Received Date: *25 Sep 2017*
Accepted Date*: 24 Oct 2017*
Published Date*: 30 Oct 2017*

Citation:
Steinhauser MO. Novel Computer Simulations Addressing the Impact Risks in Space from Orbiting Debris. Mater Sci Eng J. 2017; 1(1): 1005.

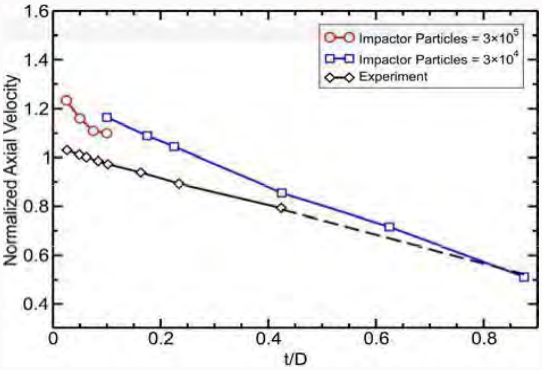

Figure 1: Debris cloud axial expansion velocity with v_0=6.5 km/s at different *t/D* ratios. The simulation results are compared to experiments [10].

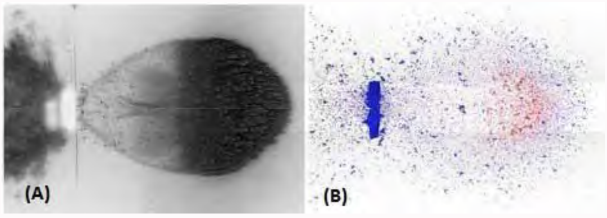

Figure 2: Simulations with large *t/D* ratios match the experiment closely with complete fragmentation of the impactor and a similar cloud shape. A) High-speed photograph of experiment, B) 3D simulation shown with v_0=6.7 km/s and *t/D*=0.425.

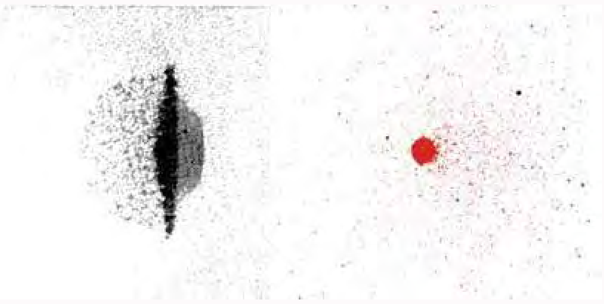

Figure 3: The shape of the debris cloud is highly affected by the *t/D* ratio. Left: High-speed photograph of experiment [10]; Right: 3D simulation shown with v_0=6.7 km/s and *t/D*=0.05.

describe the debris distribution like the NASA break-up model are based on only a few model scale laboratory tests [9]. Hence, there is a need for the development of new computational methods for simulating fragmentation upon impact, which also requires enhanced experimental methods to investigate HVI failure of materials in the laboratory. Experimental data is needed to validate computational models in generic test cases.

In this editorial, I shortly discuss new sophisticated mesh-free, particle-based computer simulations based on the Discrete Element Method (DEM) which was originally developed in the area of geophysics for the simulation of hard rock. The discussed computational method bears the potential of time-efficient parallelizable simulation of very complex phenomena without any of the typical problems occurring in mesh-based methods such as the finite element method when it comes to large distortions or even fracture of solids. In the model, energy-conserving simulations of HVI scenarios are considered that map the experimental setup where a sphere strikes a thin plate at hypervelocity. The physical model works particularly well in the velocity range where the local stresses caused by impact shock waves markedly exceed the ultimate material strength.

Discussion

Numerous HVI simulations at a variety of different impact velocities and different ratios *t/D* of plate thickness t and diameter D of the impacting sphere are performed and compared with experiments. The true challenge here is the very limited quantifiable data that have been obtained from HVI experiments in the past. The short time scale which is in the range of several microseconds and limited instrumentation mean that often high-speed photographs are the only data available from the experiments. This fact restricts quantitative comparison between numerical models and experiments. One of the observables extractable from experimental photographs is the debris cloud's expansion velocity. Normalizing the expansion velocities with the impact velocity, v_a/v_0 allows for comparing cloud characteristics at different striking velocities. In Figure 1, a comparison of the calculated debris cloud's axial expansion velocity with experimental values performed by Piekutowski [10] at striking velocity of 6.7 km/s and for different *t/D* ratios is presented. The diameter of the impacting sphere is 9.53 mm both, in the simulation and experiment. At larger *t/D* ratios, the simulation model has to be rescaled to avoid simulating an excessive number of particles as the plate thickness increases. The dashed line represents linearly extrapolated experimental data. The simulation data exhibit a slight overestimation of the expansion velocities, but the overall decreasing trend is captured in correspondence with experimental data. The decreasing trend is due to the increase in thickness of the target plate at higher *t/D* ratios. Since the sphere's size remains constant, a thicker plate requires more momentum to be transferred from the impact or particles to the plate particles. This increases the total mass in the debris cloud, while reducing its velocity.

The overestimation of expansion velocities in the proposed simple material model results from the lack of a dissipative energy term. The propagation of a shock wave through a material is a highly transient process that produces entropy, i.e. some of the kinetic energy is converted into heat and the material exhibits a sudden jump in thermodynamic variables such as pressure, energy, and density. This jump between two points on the Hugoniot curve takes place along the Rayleigh line as a non-isentropic process. The rarefaction waves that bring the material back to ambient condition occur on an isentropic path. The difference in entropy gained in the process is therefore converted into heat which is absorbed by the material. If the shock pressure is high enough, melting or vaporization will occur. Without any dissipative effects accounting for heating and melting, all of the energy from the propagating shock wave, except what is lost within the broken bonds, is recovered and transformed into kinetic and potential energy. This result in too much kinetic energy assigned to certain particles, leading to an overestimation of the cloud expansion velocity. A secondary effect of the lack of energy dissipation is a more diffuse boundary in the simulation debris cloud caused by a larger variance of particle velocities compared to the experiment. Here, the creation of entropy through heating and melting limits the particle velocities and results in a sharper cloud boundary, as displayed in Figure 2.

Albeit the expansion velocities of the debris cloud provide useful and easily quantifiable information, they do not account for the shape and degree of fragmentation of the cloud. The problem with

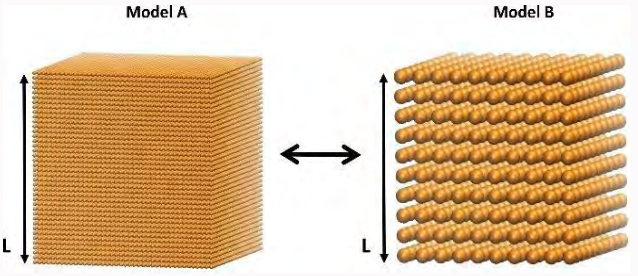

Figure 4: The model particles are initiated into a regular cubic lattice. The model's properties are independent of number of particles.

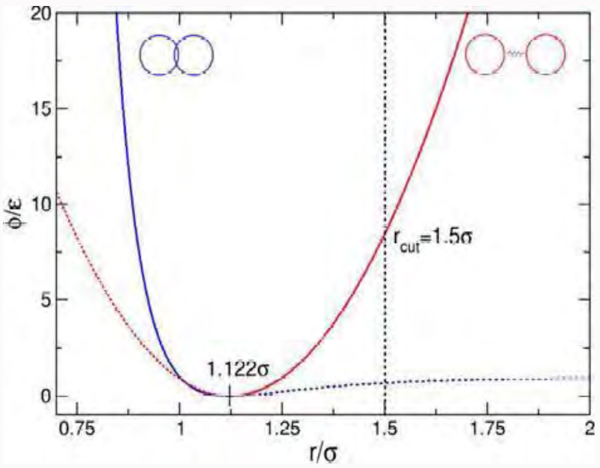

Figure 5: Repulsive (solid blue line) and cohesive (solid red line) potentials used in the model. The combined blue and red solid lines govern the forces acting on each particle pair; the dotted lines are excluded.

experiments is that they do not generally allow for a straightforward quantitative analysis of the distribution of fragments in the cloud. Hence, such an analysis is usually based on visual inspection which is demonstrated in Figures 2 and 3 for two different *t/D* ratios.

Similarities in debris cloud shape and fragmentation level can be seen in Figure 2, but strong differences in shape and fragmentation occur at the low *t/D* ratio range in Figure 3. Here, the well-defined front end (left side of debris cloud) as seen in the experiment is missing in the simulation. In addition, the large central fragment in the simulation did not fracture into a distinctive debris bubble behind the dense cloud center (right side of debris cloud) as seen in the experiment.

The lack of a well-defined front end structure is due to the absence of dissipative mechanisms in the model to account for heating and melting as previously explained. The failure to form a distinctive debris bubble at the rear of the cloud results from the model's limitation when the shock pressures are too low. The amplitude of a shock wave in HVI is dependent on the impact velocity and the combined geometry of target and impactor.

Simulation model

I propose a very simple mesh-free, i.e., particle-based model with three free parameters using two cohesive and repulsive potentials. In developing the model, I postulate that the extremely high pressures experienced by the material under HVI relegate its material strength to a minor role. This is equivalent to assuming that the material under impact behaves like a viscous fluid instead of a rigid solid, hence allowing a simplified approach.

The model's parameters are determined by comparing the simulation results to experimental data taken from literature and performed at the Fraunhofer Ernst-Mach-Institute's hypervelocity testing facility. When evaluating the model's suitability, one finds good correspondence between simulation and experiment when the impact conditions lead to strong shock waves propagating through the material, but poor results when the impact velocity or geometry hinders strong shocks from forming.

Initial setup

The particles are initiated into a regular cubic lattice structure, as presented in Figure 4. Each particle has two properties: mass *mi*, and a length scale, diameter σ_i, according to the system's geometry. In the simulations presented here, monodisperse configurations of particles are used, i.e., all length scales and masses are the same for all particles. To form larger solids, many particles are connected bonds, modeled as spring potentials. A random velocity taken from an equilibrium Boltzmann-distribution is applied to each particle at the beginning. By disrupting the perfect alignments of the initial setup this random velocity ensures that the load transfer path is distributed through the material.

Methods

Newton’s second law in Equation (1) is used to evaluate the accelerations acting on each particle at every time step during the simulation and, thus, governs the dynamics of the particles,

$$-\nabla_{r_i}\Phi tot = F_i = m\ddot{r}_i \qquad (1)$$

with Φtot being the interaction potential, i.e., the sum of all potentials acting on each particle *i* introduced in Equations (2) to (5). The accelerations can then be integrated to yield velocities and positions. The forces acting on each particle are defined via the pair potentials of Equation (3) and (4). ***Fi*** comprises the force acting on the *i*-th particle due to the interaction potentials and m_i is the mass of one particle. Interactions are generally classified as contact or bonded interactions. Bonded interactions correspond to the pair wise interactions of particles connected by a spring. Contact interactions are those pair wise interactions experienced by particles whose centers are less than two radii away from each other. The standard Lennard-Jones Potential is used as a physical basis for the non-bonded interactions.

$$\Phi_{rep}^{LJ}(r_{ij}) = \varepsilon\left\{\left(\frac{\sigma}{r_{ij}}\right)^{12} - \left(\frac{\sigma}{r_{ij}}\right)^{6}\right\} \qquad (2)$$

In Materials Science, this simple potential is used as standard in Molecular Dynamics simulations of soft spheres [11-13], where σ is the diameter of each simulation particle and ε is a pre-factor which has units of energy. The spheres are allowed to interpenetrate each other to a small extent (soft spheres), but quickly experience a strong repulsive force. In the presented model, the Lennard-Jones potential of Equation (2) is modified slightly to refine the description of the physics of particle interactions: A cutoff distance, set to the potential minimum, is defined to remove the attractive component. Beyond this distance, the cutoff distance, see Figure 5, the potential is defined to be zero. Shortening the potential's range also provides the benefit of reducing the computational time because each particle interacts with fewer neighboring particles which reduces the complexity of the interaction search algorithm. Additionally, the potential is shifted upwards by the factor ε to ensure smooth continuity with the spring potential such that:

$$\Phi_{rep}(r_{ij}) = \begin{cases} \varepsilon\left\{\left(\frac{\sigma}{r_{ij}}\right)^{12} - \left(\frac{\sigma}{r_{ij}}\right)^{6} + 1\right\} \\ 0 \end{cases} \qquad (3)$$

Neighboring particles are linked together to form a crystalline lattice structure. The bonded particle pairs experience both cohesive and repulsive forces. A quadratic spring potential according to Equation (4) is used for the cohesive component, and the potential of Equation (3) for the repulsive component. Parameter κ is in essence the spring constant and has units of energy divided by units of length squared.

$$\Phi_{coh}(r_{ij}) = \begin{cases} \frac{1}{2}k(r_{ij} - r_{eq})^2 \\ 0 \end{cases} \qquad (4)$$

The three free parameters of our model, ε, κ, and r_{cut} (Figure 5), are empirically fit by comparing the simulation results directly to experiments performed with aluminum spheres impacting aluminum plates at striking velocity v_0=6.5 km/s and a ratio of plate thickness to projectile length t/D=0.41. Figure 6 shows a high-speed image of the experiment with the image's intensity inverted to allow for better viewing. Due to the challenges in performing HVI experiments, multiple experiments with the exact same parameters are usually unavailable. The experiment shown in Figure 6 is taken from a series of experiments studying the scalability of HVI, all of which have the same cloud expansion properties. This provides some degree of confidence that the values measured from this single experiment are representative of HVI phenomena and therefore valid for fitting the model's parameters.

In a study currently underway, the here presented simple model is extended to account for dissipative effects such as heating and melting. It is planned to investigate more complex and comprehensive models that will lead to accurate simulations at low shock pressures. The model is also currently expanded to cover more complex impact geometries such as Whipple shields (with an example from initial simulations shown in Figure 7 used for spacecraft shielding and to different impactor geometries such as cylinders. It is planned to analyze the debris cloud resulting from such impacts with respect to fragment size, kinetic energy, cloud shape, and expansion velocity.

Conclusion

In this editorial, I explored the suitability of simulating impacts at velocities beyond 6 km/s with the DEM. I propose a very simple physical model of a solid with three free parameters using a cohesive and repulsive potential. The model is based on the hypothesis that the extremely high pressures experienced by any material under HVI conditions assign its material strength a minor role. In essence, it can be assumed that the material under HVI impact behaves like a viscous fluid instead of a rigid, crystalline solid with shear resistance, hence allowing this simplified modeling approach. The model's parameters are determined by comparing the simulation results to experimental data taken from literature and from specific experiments done at the hypervelocity testing facility of Fraunhofer EMI in Freiburg, Germany. Good agreement between simulations and experiment is obtained for the case of very strong shock waves propagating through the material, but poor agreement is observed when the impact velocity or geometry prevents strong shocks from forming.

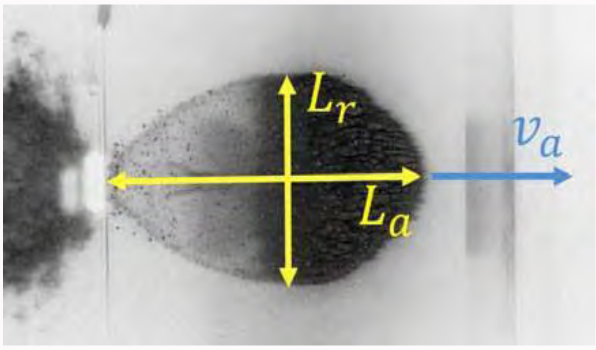

Figure 6: Experimental high-speed photograph of the debris cloud showing the cloud's length ratio *R=La/Lr*, and axial expansion velocity *va,* which are used for a quantitative comparison with simulation results.

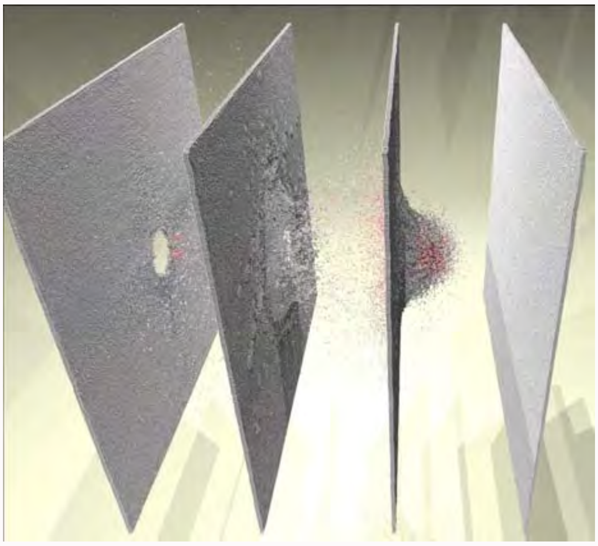

Figure 7: Computer simulation of HVI in a more complex geometry, based on a multilayer of planes.

The overall objective of the described research is to make a sophisticated approach available for the simulation of hypervelocity fragmentations of complex spacecraft.

Acknowledgment

The author acknowledges support from E. Watson in the computer coding of the physical model as a new feature in the author's software-suite MD-CUBE and in the analysis and visualization of generated simulation data. The author also acknowledges financial support from the German Federal Ministry for Economic Affairs and Energy under grant no. 50 LZ 1502.

References

1. Steinhauser MO, Grass K, Strassburger E, Blumen A. Impact failure of granular materials – Non-equilibrium multiscale simulations and high-speed experiments. Int J Plasticity. 2017;25:161-82.
2. Wegener P, Bendisch J, Krag H, Oswald M, Stabroth S. Population evolution in the GEO vicinity. Space Res. 2003;34:1171-6.
3. Liou JC, Johnson NL. Planetary science. Risks in space from orbiting debris. Science. 2006;311:340-1.
4. Liou JC. Collision activities in the future orbital debris environment. Adv Space Res. 2006;38:2102-6.
5. Liu P, Liu Y, Zhang X. Improved shielding structure with double honeycomb cores for hypervelocity impact. Mech Res Commun. 2015;69:34-9.
6. Kinslow R. High-velocity impact phenomena academic. New York; 1970.

7. Zukas J, Nicholas T, Swift H. Impact Dynamics. New York: John Wiley & Sons, USA; 1982.

8. Zhang X, Guanghui J, Huang H. Fragment identification and statistics method of hypervelocity impact SPH simulation. Chin J Aeronaut. 2011;24:18-24.

9. Johnson NL. NASA's new breakup model of EVOLVE 4.0. Adv Space Res. 2001;28(9):1377-84.

10. Piekutowski AJ. Formation and description of debris clouds produced by hypervelocity impact. National Aeronautics and Space Administration, Marshall Space Flight Center; 1996.

11. Jones JE. On the determination of molecular fields. I. From the variation of the viscosity of a gas with temperature. In Proceedings of the Royal Society of London A: Mathematical. Phys Eng Sci. 1924;106:441-62.

12. Steinhauser MO. Computer simulation in physics and engineering, 1st ed. deGruyter: Berlin, Germany; 2013.

13. Steinhauser MO. Computational multiscale modeling of fluids and solids. 2nd ed. Berlin/Heidelberg: Springer, Germany; 2017.