Modelling hypervelocity impact in DYNA3D

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Abstract

This paper presents part of the work on development of tools and modelling techniques for simulation of hypervelocity impact on spacecraft structures using the Lawrence Livermore DYNA3D code. Calculations were performed to evaluate the current capability of DYNA3D to model hypervelocity impact on multiple plate structures. These have shown that improvements need to be made to DYNA3D before it can be used to produce reliable and accurate results. Two important areas that require improvement are the contact algorithm and the equation of state.

Impacts with relative velocities of up to 15 kms\(^{-1}\) generate pressures of several Mbar. Existing DYNA equations of state (EOS) are not accurate at these high pressures and a new EOS was needed, hence the SESAME equation of state library was selected. This is a tabulated equation of state which covers the range of densities and pressures of interest. The SESAME EOS has been implemented into DYNA3D, and tested.

The element erosion contact algorithm in DYNA was used to model bumper shield perforation. The existing erosion algorithm was found to interfere with the formation of shock waves in both bodies. A new erosion criterion solved this problem and gave significantly more accurate results. Additional modification is needed to allow accurate modelling of impact on multi-plate structures.

1 Introduction

Spacecraft structures can be seriously damaged by a hypervelocity impact with even small particles. In recent years the threat from such impacts has been augmented by the proliferation of orbital debris. Spacecraft shielding designs to
counter this threat are usually based on empirical formulae derived from laboratory tests. Laboratory facilities for hypervelocity impact testing are expensive, and can not fully test shielding designs due to launcher limits on maximum projectile mass and velocity. Computer simulation offers a useful complement for both shield design and in evaluating possible impact damage.

The greatest threat from debris occurs in Low Earth Orbit, often taken as being below 2000 km altitude (Kessler\(^1\)). The average impact velocity between a spacecraft in Low Earth Orbit and orbital debris ranges from 10 kms\(^{-1}\) to 13 kms\(^{-1}\), depending on the orbital inclination of the spacecraft\(^1\). The maximum impact velocity is approximately 15 kms\(^{-1}\). When solids collide at these velocities shock waves are generated in both bodies, behind the shock waves pressures of up to several megabars are generated. At these impact velocities the shock waves are strong enough to melt or vapourise the material they pass through.

Several shielding designs have been developed to provide a degree of protection against hypervelocity impacts. The simplest of these is the single bumper shield, which places a single sacrificial plate around the body to be protected. The plate is intended to break up the incoming particle. The resulting debris cloud, consisting of material from both the particle and the shield, expands and spreads the impact loading over a larger area of the rear wall, reducing the likelihood of rear wall perforation.

2 Capability of DYNA3D

2.1 Hypervelocity impact modelling

To evaluate the capability of Lawrence Livermore DYNA3D (Whirley\(^2\)) for modelling hypervelocity impact we attempted to model a particular case. The case chosen was normal impact of a spherical aluminium projectile on an aluminium bumper shield at 8 kms\(^{-1}\). It was chosen as there are published experimental and computational results (Frey\(^3\)). The projectile diameter is 4.0 mm and the bumper plate is 0.8 mm thick. From experiment the final hole diameter in the plate should be 7.8 mm.

Modelling normal impact allows a smaller computational model to be used as the problem is axisymmetric, in the present case a quarter model was used. The material behaviour was modelled using the Steinberg-Guinan (Steinberg\(^4\)) constitutive model and a Gruneisen\(^2\) equation of state. The Steinberg-Guinan model is designed to model problems with strain rates above \(10^5\) s\(^{-1}\) (Steinberg\(^4\)). An element erosion contact algorithm was used, as without an eroding contact surface large element deformations cause the calculation to stop. Using element erosion the projectile perforates the plate, and material from both plate and projectile travels away from the plate (Figure 1).

In a calculation where element erosion was not used the expected wave behaviour can be seen (Figure 2). Shock waves propagate through projectile
and plate, and where the shock wave has reached the free surface at the rear of the plate an expansion wave is formed. In a calculation where erosion was used (Figure 3) the shock waves are much less defined and the expansion wave cannot be clearly seen. In addition the maximum pressure observed during the calculation, 0.75 Mbar, is significantly less than the expected value of 1.2 Mbar (Frey3). The cause of this problem appears to be that when an element erodes, the node on the new contact surface is initially out of contact. This can be seen in Figure 3, where there is a clear gap between the projectile and the plate. As a consequence expansion waves are formed that would not be present in real life. The lack of a strong shock wave in the shield resulted in the final hole diameter being too small. The final hole diameter is approximately the same as the original particle diameter of 4 mm, rather than the 7.8 mm expected from experiment.

Three areas were identified that have a major effect on the accuracy of a hypervelocity impact simulation:

- Shock wave modelling
- Equation of state
- Contact algorithm

2.2 Shock wave modelling and equation of state

Shock waves are very important in hypervelocity impact, they dominate the behaviour of both the projectile and shield. DYNA uses an artificial bulk viscosity method to spread the shock wave over several elements, eliminating any shock discontinuities. Using the DYNA default values for the bulk viscosity coefficients, we have found that the shock front is spread across approximately three elements. As DYNA does not have adaptive meshing a fine mesh is necessary for adequate modelling of shock wave propagation, in a 3D code this can lead to a very large model. A sensitivity study will be necessary to determine the mesh size for adequate shock wave modelling.

For accurate results the material behaviour must be modelled correctly. The most important part of the material model during the initial stages of impact is the equation of state (EOS). The EOS used must be valid over the whole range of conditions encountered during the calculation. An aluminium on aluminium impact at 15 kms\(^{-1}\) produces a maximum pressure of 3-4 Mbar. The state of the material after the shock and expansion waves is important in determining the form of the debris cloud. The Gruneisen EOS gives poor results for multiply shocked material and material in the vapour region (Asay5). Both conditions can occur during impact on multi-plate structures.

A suitable tabulated EOS, generated from physics models, is accurate over the necessary range of conditions. The SESAME EOS library (Lyon6) contains tabulated data for many materials, and for the whole high pressure range of interest.
2.3 Contact algorithm

An element erosion algorithm needs to be used to model the perforation of the plate. The element erosion criterion in DYNA is based on the element effective plastic strain. In our calculations this criterion did not prove suitable for modelling hypervelocity impact.

The Steinberg-Guinan constitutive model allows the material in an element to melt, this usually happens when a strong shock wave passes through the element. When an element melts the yield stress and shear modulus are set to zero, so the material in the element behaves like a fluid. As a consequence of a zero shear modulus the effective plastic strain becomes very large, this means a melted element will immediately erode. This caused elements to erode too quickly after contact was established, leaving a large void between the plate and projectile which interfered with the formation of a strong shock wave. This void would not occur during a real impact.

When an element erodes it is deleted from the calculation, it is assumed that the material will no longer contribute to the physics of the problem. This assumption is not appropriate when modelling impact on a multi-plate structure, where the impact with the first plate breaks up the projectile and material from the first plate and projectile form a debris cloud that impacts on the subsequent plate. Deleting material from the calculation does not allow this subsequent impact to be accurately modelled. A promising solution to this problem appears to be the use of a gridless Lagrangian technique, such as Smoothed Particle Hydrodynamics (Stellingwerf).

3 Implementation and Validation of the SESAME EOS

In DYNA the equation of state is used to calculate the element pressure from the element density and internal energy. SESAME is a tabulated equation of state, so the pressure is calculated by finding the nearest points in the table and interpolating between them.

3.1 Implementation

DYNA uses an equation of state to calculate the pressure \((P)\) and the density and energy derivatives of the pressure, from the element density \((\rho)\) and specific internal energy \((E)\). The pressure and the derivatives are used to calculate the element speed of sound, which is used to calculate the maximum stable element time step. The EOS is then used to calculate the new pressure for that timestep. This updated value of the pressure is used in the constitutive model.
The element speed of sound, $c$, is evaluated using \( \text{(Hallquist}^8) \)

\[
c^2 = \frac{4G}{3\rho_0} + \left. \frac{\partial P}{\partial \rho} \right|_e + \left. \frac{P V^2}{\rho_0} \frac{\partial P}{\partial \varepsilon} \right|_\rho
\]  

(1)

where $G$ is the shear modulus.

The element pressure for the new timestep is calculated at the same time as the element internal energy is updated from the previous timestep. A linear relationship between internal energy and pressure cannot be assumed with the SESAME EOS. When this relationship is not linear, a two step iteration process is used to calculate the new pressure (Hallquist\(^8\)). In this process, a trial value of the total internal energy, $e^*$, is calculated from the work done by the element stresses. Using the trial value an approximation of the pressure is calculated by the equation of state. In the case of SESAME the new value is interpolated from the tables.

The internal energy is then updated using

\[
e = e^* - \frac{1}{2} \Delta V P^*
\]  

(2)

$\Delta V$ is the change in element volume in the current time-step. The new value of the internal energy is used to calculate the final value of the pressure.

The SESAME equation of state has been linked with the Gruneisen equation of state already implemented in DYNA. The Gruneisen equation of state is used when the pressure is below approximately 0.1 Mbar, SESAME is used for the high pressure region. With the SESAME equation of state the interpolation between the closest points in the table occurs three times for each element every timestep, this takes more CPU time than evaluating the analytical expression twice per element for the Gruneisen equation of state.

### 3.2 Validation

The implemented equation of state was validated by calculation of the Hugoniot curve for aluminium from DYNA calculations. The Hugoniot curve is a material property which defines the locus of attainable shock states. From fixed initial conditions the state of material behind a plane normal shock wave will lie on the Hugoniot curve and will only change with the strength of the shock wave.

The material modelled was aluminium (SESAME material 3717). This was then compared with the curve calculated directly from the SESAME data. The Hugoniot curve calculated directly from the SESAME data shows good agreement with experimental results from Marsh\(^9\) and Mitchell\(^10\) (Figure 4).

A common method of experimentally determining Hugoniot data is to impact two flat plates of identical material. Away from the edges of the plates plane shock waves propagate into the two plates producing a state of uniaxial
strain behind them and data is recorded from behind the shock waves, each impact producing one point on the curve. To calculate Hugoniot data from DYNA a model of two flat plates was created using solid elements, one plate was given an initial velocity. Only a quarter of each plate was modelled, xz and yz symmetry planes being used. Time history data was taken for elements and nodes near the centre of the plate. Calculations were performed for impact velocities ranging from 2 kms\(^{-1}\) to 16 kms\(^{-1}\).

The Hugoniot equations (eqns 3-5) express the conservation of mass, momentum and energy across a shock wave. They relate the pressure, internal energy \((E)\), and specific volume \((V)\) or density across the shock wave in terms of the shock velocity \((u_s)\) and particle velocity due to the shock \((u_p)\). A zero subscript relates to the condition in front of the shock wave.

\[
\rho_0 u_s = \rho (u_s - u_p) \tag{3}
\]

\[
P - P_0 = \rho_0 u_p u_p \tag{4}
\]

\[
\left( E - E_0 \right) - \frac{u_p^2}{2} \rho_0 u_s = P_0 u_p \tag{5}
\]

The measurement of any pair of variables with known initial conditions, is sufficient to determine a point. The most common variables measured in experiments are the shock and particle velocities. For the DYNA calculations, particle velocity and pressure were read from the time history data. From these the shock velocity and specific volume can be calculated (eqns 6,7)

\[
u_s = \frac{(P - P_0)}{\rho_0 u_p} \tag{6}
\]

\[
V = V_0 - \frac{u_p^2}{(P - P_0)} \tag{7}
\]

The calculated Hugoniot points were compared with the Hugoniot curve calculated directly from the EOS (Figure 5) and show good agreement. The equation of state data is being used correctly within DYNA.

The SESAME equation of state should improve accuracy when modelling the propagation of the debris cloud and the impacts on subsequent plates. The improvement cannot yet be tested as our simulations have not reached this stage.
4 Improvement of erosion algorithm

Effective plastic strain is not the only criterion available to decide whether to erode an element, a criterion based on total element strain is also possible. To investigate the effectiveness of this type of criterion, DYNA was modified to include an erosion criterion based on element deformation. The erosion algorithm was further modified to work with the Johnson-Cook constitutive model (Johnson), the Johnson-Cook model is valid for the low strain rates where the Steinberg-Guinan model becomes inaccurate.

The new criterion was tested using the same case of normal impact on a thin plate. Calculations were carried out using both constitutive models, results from these calculations are shown in Table 1. These results are much improved over the results from the calculations using the effective plastic strain erosion criterion. The expected wave propagation behaviour can be seen (Figure 6), with the impact generated shock propagating through the plate and reflecting as an expansion wave off the free surface on the underside of the plate. The maximum pressure observed, 1.25 Mbar, is close to the expected value. As the calculation progresses a far more pronounced splash is formed (Figure 7) than the original calculations (Figure 1). These calculations were stopped once the simulation time reached 4 μs after impact (Figure 8), by this time the hole in the plate had finished expanding. The results show a hole diameter close to that expected from experiment (Table 1).

Table 1: Results from simulations of impact on a thin plate.

<table>
<thead>
<tr>
<th>Constitutive model</th>
<th>Hole diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steinberg-Guinan</td>
<td>7.8</td>
</tr>
<tr>
<td>Johnson-Cook</td>
<td>7.2</td>
</tr>
<tr>
<td>Johnson-Cook</td>
<td>7.5</td>
</tr>
<tr>
<td>Johnson-Cook</td>
<td>7.6</td>
</tr>
</tbody>
</table>

The results from the calculations using the Johnson-Cook constitutive model are much closer to the expected value, this is probably due to the Steinberg-Guinan model not being valid at the lower strain rates that occur in the plate after the projectile has completely penetrated.

The results also show that the final hole diameter is dependent on the magnitude on the erosion criterion, the hole diameter increases as the magnitude of the erosion criterion increases. It is not possible to increase the magnitude indefinitely. Increasing the magnitude much above 2.5 lead to the occurrence of problems that element erosion is used to prevent, such as excessive element deformation. Several more erosion criteria will be investigated to determine the criterion most suited to the modelling of hypervelocity impact.
5 Conclusion

The aim of the work is to develop the tools required for accurate modelling of hypervelocity impact in a Lagrangian Hydrocode. The Lawrence Livermore DYNA3D code has been used.

- The DYNA3D code required improvement to the equation of state and the contact/erosion algorithm to allow the calculation of reliable results.
- The SESAME tabulated equation of state has been implemented in DYNA3D to provide an equation of state valid for all the conditions that occur during impact. The implementation was validated by calculation of Hugoniot data, good agreement with experiment was seen.
- The erosion algorithm was improved by incorporating a new erosion criterion. Results from calculation using the new criterion show much better agreement with experiment.

References


Figure 1: Impact of a spherical projectile on a thin plate at 8km/s, effective plastic strain erosion criterion. Time: 0.5 μs after impact.

Figure 2: Pressure contour plot at 0.125 μs, no erosion.
Figure 3: Pressure contour plot at 0.125μs, effective plastic strain erosion criterion.

Figure 4: Graph showing SESAME 3717 Hugoniot curve and experimental data.
Figure 5: Graph showing DYNA Hugoniot points plotted with the SESAME 3717 Hugoniot curve.

Figure 6: Pressure contour plot at 0.125μs. New erosion criterion.
Figure 7: Impact of spherical projectile on a thin plate at 8 kms$^{-1}$. New erosion criterion. Time: 0.5μs after impact.

Figure 8: Impact of spherical projectile on a thin plate at 8 kms$^{-1}$. New erosion criterion. Time: 4μs after impact.