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A TWO-DIMENSIONAL INTERNAL BALLISTICS MODEL FOR MODULAR SOLID PROPELLANT CHARGES

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Many modern artillery charges are modular with granular propellant encased in combustible cases. These cases influence the ignition process because they constrain the flow of ignitor and combustion gases. In this paper the further development of a two-dimensional Internal Ballistics model to handle combustible cases is presented. Gas pressure and elastic stresses cause movement of the cases. Ignition and combustion of the cases are modelled. They are considered to be impermeable until a rupture criterion is reached. Post-rupture behaviour is described by an interim model because of inherent uncertainties. The numerical model is still under development and must also be validated.

INTRODUCTION

Numerical models for the simulation of the IB (Internal Ballistics) of guns cover a wide spectrum in terms of level of sophistication. The simplest model is called the lumped parameter or thermodynamic model. This zero-dimensional model is widely used for the prediction of global parameters like peak pressure and exit velocity.

The next level in terms of increasing sophistication is the 1D (one-dimensional) model ([1], [2] & [3]). These models numerically solve variables like pressure and velocity as a function of the axial coordinate and time. They can be used for the prediction of global parameters or, alternatively, as diagnostic “tools”, where the aim is to understand the processes taking place within the combustion chamber (for example ignition stimuli leading to the occurrence of axial pressure waves).

A two-dimensional (2D) model is needed to study flame front propagation in the axial and radial directions. A 2D (or 3D) model is also needed when parallel axial flows with different velocities occur. Secondary gas flows can take place inside a center-tube or through an annular space on the outside of the charge. The number of dimensions is not the only factor that determines the applicability of a model. Modern artillery charges are often modular with the propellant in each module encased in a combustible cartridge case. Such a charge configuration can have a large influence on the ignition process, because the flow of gas is constrained by the walls of the modules. Gas flow can take place

along the center-tube, in the volume between two modules, and also between the outside of a module and the inside of the combustion chamber. If a combustible case ruptures, then additional gas flow paths will be created. It is clear that a 2D IB program also needs the capability to model combustible cases to enable it to be used as a diagnostic tool applicable to most modern artillery charges.

The author developed a basic 2D IB model ([4]). A new 2D IB program was created by adding a reactive second phase to the commercial CFD (Computational Fluid Dynamics) code FLO++ ([5]). Other examples of 2D codes are NOVA and NGEN ([6], [7]). In this paper the IB version of FLO++ will be discussed briefly, followed by the extensions needed to model combustible cases.

OVERVIEW OF FLO++ 2D IB PROGRAM

FLO++ uses the so-called Control Volume method for spatial differencing ([8]), together with fully implicit time differencing. A 3D stationary or moving Eulerian grid or mesh is standard, but for IB a 2D axi-symmetric formulation is used. The ideal gas equation-of-state in FLO++ was replaced with the Abel-Nobel equation-of-state (which adds a co-volume term) to accurately predict the pressures attained in guns. For IB options specifying the unsteady flow of a compressible gas must be selected.

The propellant gas and the solid propellant are treated as two distinct phases. The latter is depicted in an Eulerian manner, which means that a common grid is used. The distribution of the solid is defined by means of a solid volume fraction in every cell (= 1 – gas porosity). The solid fraction in a particular cell will change as a function of time because of combustion and the movement of the grid and the propellant. The basic premise for the integration of the solid phase is that its conservation equations are solved **explicitly** before the start of the calculational cycle for the gas phase. This is possible because the propellant is considered to be incompressible.

The conservation equations for the gas phase need some modifications to account for the volume occupied by the solid phase. New terms appear that reflect inter-phase effects like heat transfer, drag and combustion. These terms are calculated by means of empirical correlations. The gas pressure gradient now accelerates both phases, and this is reflected in their momentum and energy equations. An intergranular stress will exist in the solid if a critical solid fraction is exceeded. The convection part of the continuity equation of the solid must be handled with care. A discretization scheme based on upwind differencing will lead to excessive numerical diffusion (smearing) at the edge of the region occupied by the propellant. For IB some smearing is advantageous, because a sharp propellant boundary can cause numerical problems, but the smearing should be limited and not increase with time. A successful algorithm was developed ([4]). The ignition chain itself is not modelled at present. Instead igniter gas can be released as a prescribed function of position and time.

A BASIC NUMERICAL MODEL FOR HANDLING COMBUSTIBLE CASES

In a paper presented at the 18th International Symposium on Ballistics ([6]) the IB program NGEN, which is under development at the US Army Research Laboratory, was used to simulate granular and modular charges. NGEN initially views the combustible cases as rigid and impermeable. The 2D version of NGEN was used, which combined with the rigid prescription, only allows the axial movement of a propellant module. If a significant pressure differential is reached, then the case becomes permeable. A section of the case is allowed to break or burst when a fixed time interval has elapsed since it became permeable.

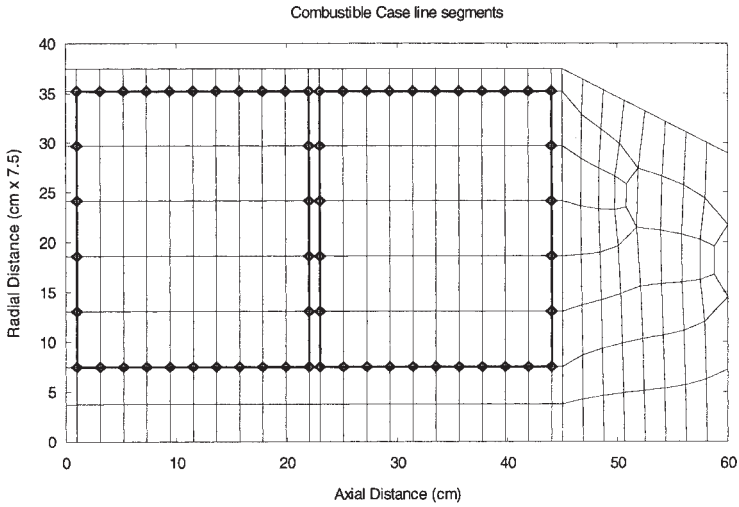
The present approach, somewhat different to that of NGEN, is based on flexible module walls that can move under the influence of gas pressures as well as elastic stresses. The case is initially impermeable and breaks or ruptures when it reaches a rupture criterion. Following rupture, gas and propellant can flow through the opening.

The first stage of the development of a numerical method was to incorporate a basic model for combustible cases in FLO++. For the basic model ignition, combustion, material strength and rupture is ignored, and the material remains impermeable. The combustible case material is considered to be incompressible, but the volume occupied by it is taken into account.

It seems logical to represent the physical position of combustible cases by means of line segments, because only a 2D representation is needed. Such line segments are joined at vertices, which can be moved to represent the movement of the combustible case. Line segments independent of the gas grid will lead to cells containing gas from both the inside **and** outside of a combustible case. There will then be no pressure differential to accelerate the case (a cell can only have a single pressure). It would also be impossible to enforce the condition that the combustible case is impermeable.

The solution is to define an initial grid in which the line segments coincide with cell interfaces. The inside and outside of a part of a combustible case are then adjacent to different cells, which can have different pressures. The impermeability condition can be enforced by not allowing gas flow through a face coincident with a line segment. FLO++ can handle the moving grid caused by the movement of line segments, but the remainder of the grid must be moved in a sympathetic fashion to avoid large cells or cells with negative volumes. Even then problems with a distorted grid can occur.

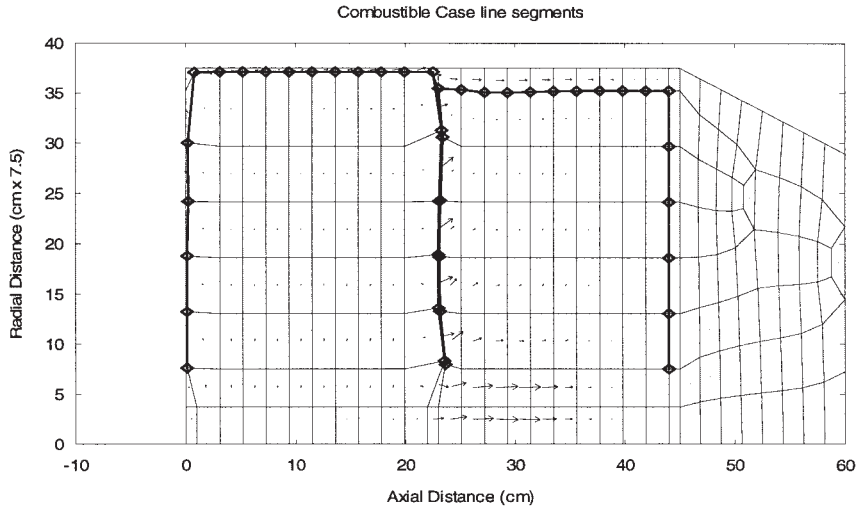
In the figure below the grid above the centerline is shown for a combustion chamber with two combustible cases or modules. The module walls, represented by line segments that coincide with selected faces, are shown with thick lines. The vertices connecting these segments are identified with diamonds. An unstructured grid is used in the conical section to facilitate the transition from 8 to 4 cells.



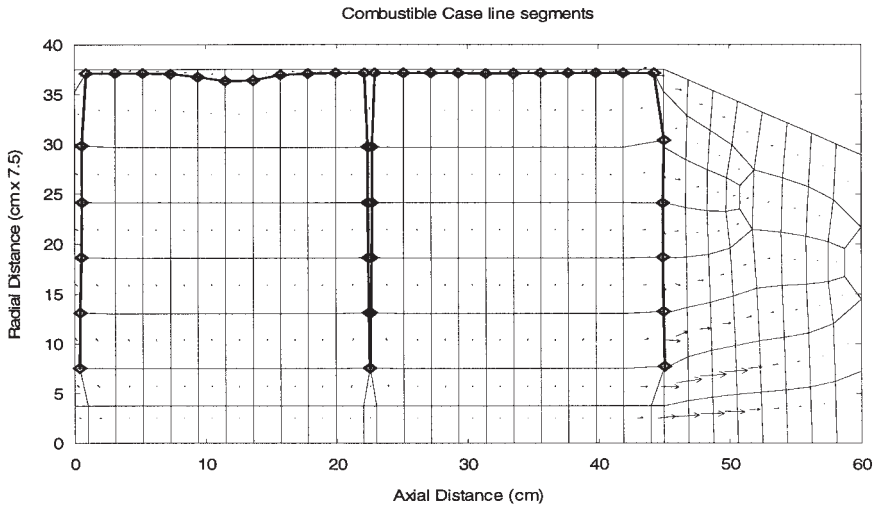
For faces coinciding with line segments, different pressures are allowed on either side instead of the normal continuous description. The momentum transferred from the gas to a line segment, in a direction perpendicular to the face area, is proportional to the pressure differential and the face area. Axial and radial velocity increments of the vertices that define the line segments can be deduced from the momentum increments of the adjoining segments. Face pressures are interpolated between adjacent cell centers using the assumption that the acceleration of the gas in the two adjacent subcells and the line segment is the same in the direction between cell centers. The calculation of new velocities and positions of vertices defining line segments is done explicitly before the start of the calculational cycle for the gas phase.

Boundary conditions must be implemented for vertices defining the line segments. The combustible case, as represented by these vertices, may not cross the centre-line, breech, combustion chamber/barrel inner radius or the base of the projectile. Contact between adjacent modules must also be accommodated. These vertices are stopped just short of a boundary they may not cross, which results in very thin cells. Such cells fortunately do not pose a problem for an implicit method.

For the first example the geometry shown above was chosen. To obtain ignition of the propellant while still retaining an inert, impermeable material description for the combustible cases, the inner walls of the two modules were removed. Igniter gas was released along the centre-line of the left module. The gas grid, combustible cases and velocity vectors are shown below. At the stage of the calculation shown in this figure, the propellant in the left module has been ignited. The pressure of the igniter and combustion gas causes the walls to expand. Contact has been made with the breech, the inner radius of the combustion chamber and the second module. It seems as if all these boundary conditions function satisfactory.

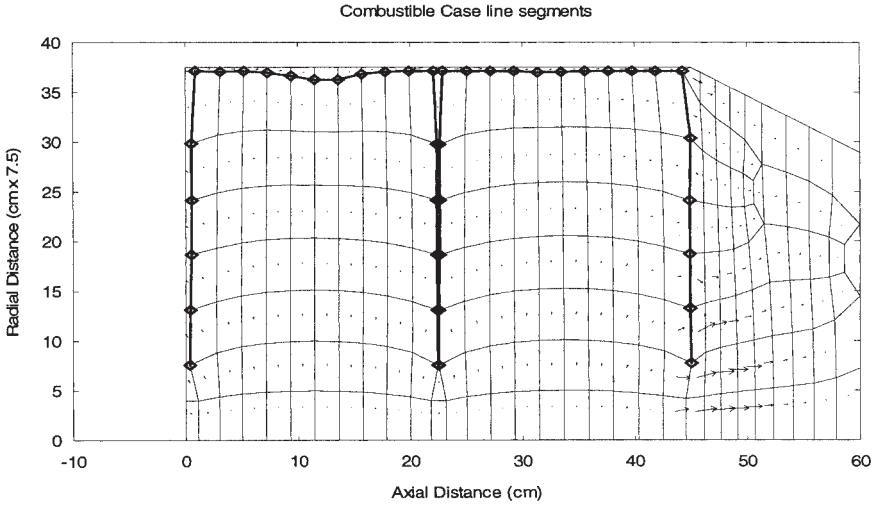


The same initial configuration was used for the next example, but igniter gas was released inside **both** modules. Only vertices defining line segments were moved. The grid and velocity vectors are depicted in the figure below. The calculation could not be continued beyond the stage shown, due to zero/negative cell volumes occurring next to the second module. An algorithm for the sympathetic movement of vertices not defining line segments is obviously needed.

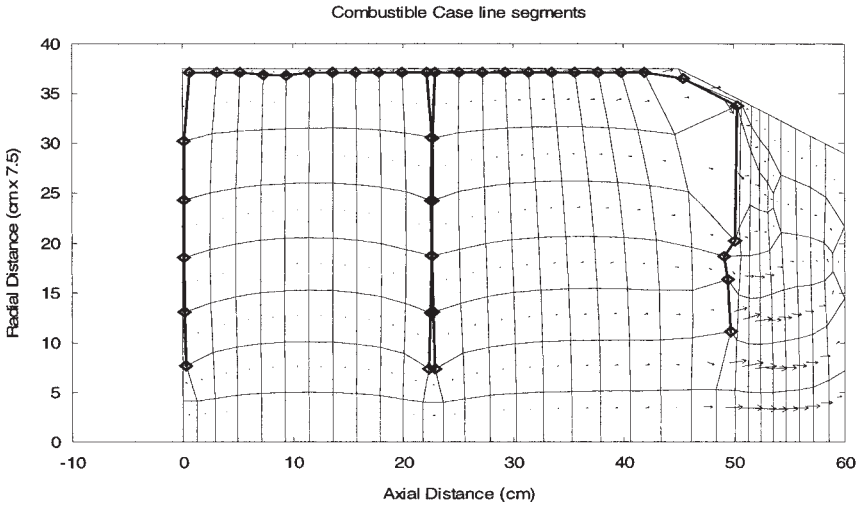


A basic algorithm for moving these vertices is to reposition them at the average position of their direct neighbours. Several iteration cycles are needed. Vertices on the outer boundaries must obviously remain on these boundaries. The result for this simple scheme,

after the same elapsed time, is shown below. The gas grid in the conical section moved in response to the movement of the front wall of the second module. Cells with a very small or negative volume in the previous figure are now of a normal size.



In response to grid problems encountered as different calculations were run for longer times, the grid movement algorithm was continually refined. The end result is an algorithm were the position of a vertex (not defining a line segment) is calculated as a weighted average of the positions of its direct and indirect neighbours. The weights are modified when problems like small interior angles or short cell sides occur.

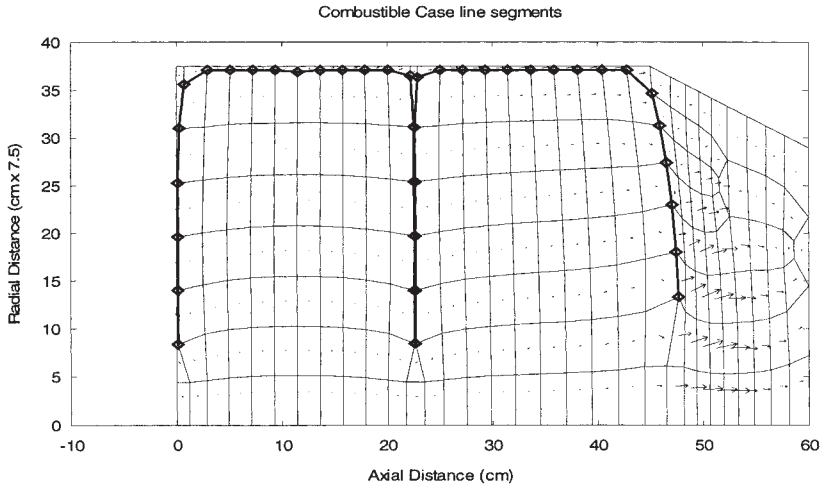


The previous problem was repeated for a much longer period of time and the improved mesh movement algorithm was used. The result appears above. The movement of front wall of the second module appears to be unstable, with one very large face and several small faces. This instability can be attributed to the lack of material strength as well as a rupture mechanism in the present model. The algorithm for sympathetic movement appears to function satisfactory.

MATERIAL STRENGTH, RUPTURE, IGNITION AND COMBUSTION

Material strength was added to the basic model. This reflects the resistance the combustible case offers to compression, elongation and bending. An elastic material model is assumed. The stresses as well as the resulting velocity increments of vertices defining line segments are calculated explicitly before the start of the calculational cycle for the gas.

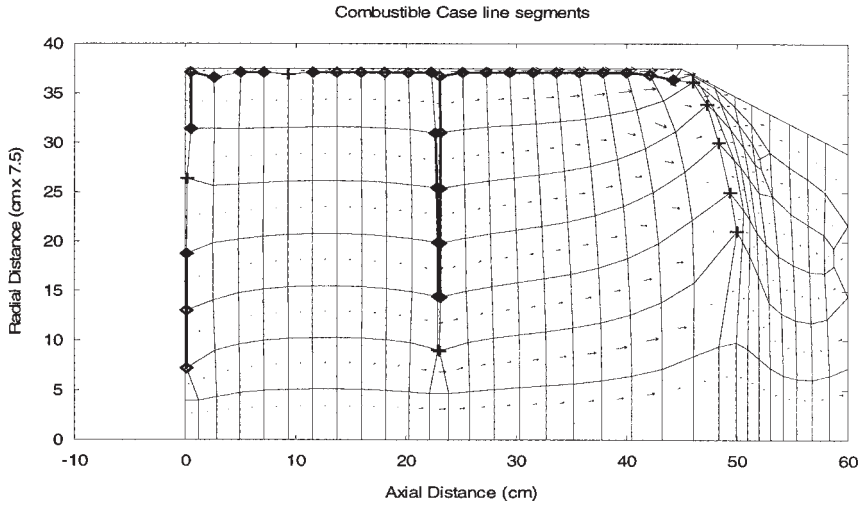
The previous calculation was repeated, but with material strength taken into account. The elapsed time was the same. The result appears below. The forward movement of the front wall of the second module is considerably less than before because the effect of the gas pressure inside the module is now partially counteracted by the elastic stresses. There is no sign of the previous instability.



A rupture criterion was the next extension to the model. Due to a lack of data it was decided to use a very simple rupture criterion based on the fractional area enlargement of a face defining a line segment. The modelling of post-rupture behaviour is inherently difficult and uncertain. The rupture phenomena is three-dimensional but the model is only two-dimensional and with line segments of a finite size. By the time rupture takes place the combustible cases have probably already played their role during the ignition process of the propellant. The exact details of what subsequently happens to the combustible cases should not have a too large influence on the rest of the IB simulation. An interim post-rupture model used in this study is described below.

After rupture a non-zero mass flux for gas and propellant across a face will be allowed. The pressure interpolation scheme for such a face is changed so that the gas experiences a greater acceleration than the solid. The resulting flow of gas is still smaller than it would have been with no solid present. This is to reflect the fact that the fragments of the combustible case will still impede the flow of gas (and propellant) to a certain degree, depending on their orientation with respect to that flow. When a baffle face ruptures, the local material strength is reduced to a small fraction of its previous value. The reasoning is that, depending on the direction in which the material cracks or shears, some strength to resist elongation and bending will remain. It was further found to be advantageous for numerical reasons to spread the reduction in material strength over a short period of time.

There are therefore several adjustable parameters in the tentative model for rupture and post-rupture behaviour. Presently, in the absence of experimental data, these factors are adjusted to yield results that appear realistic. The previous calculation was repeated, but with the rupture and post-rupture models active. The result appears below. Ruptured line segments are shown with thin instead of thick lines and the vertices with plus signs instead of diamonds. The front wall of the second module has completely ruptured, as well as some other line segments.



The numerical model was further extended by introducing ignition and combustion of the combustible cases. This is done in a way very similar to that of the propellant and will not be detailled.

When most of the main charge is burning and most of the combustible case line segments have ruptured, then the combustible cases acts mainly as a secondary propellant and has a very small effect on the gasflow. The fact that the positions of the combustible cases influence the grid can prevent some calculations from reaching projectile exit. A solution is to selectively convert combustible case line segments to propellant (with properties differing from the main charge), which is deposited in the adjoining cells. A specific line segment will be converted if it has ruptured and there is only a small gas pressure difference across it. These conversions will progressively free the gas grid and facilitate the

calculation. Calculations were done where all the combustible case material was converted and the calculation could proceed until the projectile left the barrel.

CONCLUSION

This paper presents the further development of an existing 2D IB model to handle the simulation of combustible cases. The model is still under development (using a tentative model for post-rupture behaviour) and must be validated with experimental data. The model has the potential to become a useful diagnostic tool because of the ability to accommodate some of the geometrical complexities of modular artillery charges.

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