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Coupled Rock Motion and Gas Flow Modeling in Blasting *

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Abstract

The spherical element computer code DMC (Distinct Motion Code) used to model rock motion resulting from blasting has been enhanced to allow routine computer simulations of bench blasting. The enhancements required for bench blast simulation include: 1) modifying the gas flow portion of DMC, 2) adding a new explosive gas equation of state capability, 3) modifying the porosity calculation, and 4) accounting for blastwell spacing parallel to the face.

A parametric study performed with DMC shows logical variation of the face velocity as burden, spacing, blastwell diameter and explosive type are varied. These additions represent a significant advance in the capability of DMC which will not only aid in understanding the physics involved in blasting but will also become a blast design tool.

Introduction

Detonation of the explosive in a blastwell results in a transient stress wave that fragments the rock, and a high pressure, high temperature gas pocket that expands pushing the rock in front of it. Events that occur during a blast have been difficult to understand because the short time scale and the severe environment makes measurements difficult. Numerical modeling can contribute greatly to an understanding of the physics involved in the blasting process and can also contribute to the blast design. This paper will describe the latest enhancements to the blast modeling code DMC (Distinct Motion Code) [Taylor and Preece, 1989] and will demonstrate the ability of DMC to model gas flow and rock motion in a bench blasting environment.

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DMC has been used previously to model rock motion associated with blasting in a cratering environment [Preece and Taylor, 1990] and in confined volume blasting associated with in-situ oil shale retorting [Preece, 1990 a&b]. These applications of DMC treated the explosive loading as force versus time functions on specific spheres which were adjusted to obtain correct face velocities. It was recognized that a great need in explosives modeling was the coupling of an ability to simulate gas flow with the rock motion simulation capability of DMC. This was accomplished by executing a finite difference code that computes gas flow through a porous media [Baer and Gross, 1989] in conjunction with DMC. The marriage of these two capabilities has been documented by Preece and Knudsen, 1991.

These calculations do not treat the fragmentation of the material by the explosive and thus would not be capable of predicting behavior such as backbreak or fragment size. At the beginning of the rock motion calculations performed here, the material is assumed to be already fragmented.

The capabilities that have been added recently to DMC and which will be documented in this paper include: 1) addition of a new equation of state for the explosive gases, 2) modeling of gas flow and sphere loading in a bench environment, 3) porosity calculation in a bench environment, and 4) adapting a 2-D calculation to include the effects of spacing parallel to the face in a bench environment.

Equation of State

DMC has utilized the JWL (Jones, Wilkins, Lee) equation of state [Lee et al, 1973] to describe the pressure-volume relationship of the explosive gases. A new equation of state, (EOS) in addition to JWL, has been added to DMC. It is called the ICI equation of state [Kirby and Leiper, 1985] because it is used by the ICI Explosives Group Technical Centers for modeling ideal and non-ideal detonations. The ICI equation of state has the following form

$$E = \frac{P}{\rho\,(g-1)} \qquad (1)$$

$$g = g_0 + g_1\rho + g_2\rho^2 \qquad (2)$$

where P = pressure, ρ = density, E = specific internal energy and g_0, g_1 and g_2 are constants for a particular explosive and g is a function of those constants. An advantage of this EOS is that at low pressures it exhibits the behavior of an ideal gas. As the density approaches zero, g approaches g_0, which is the ideal gas γ. Thus at low densities the explosive gas behaves as an ideal gas.

The data available for a particular explosive usually includes the equilibrium pressure and detonation velocity as a function of borehole diameter. These data are calculated using the CPEX non-ideal detonation computer model. The steps required to implement this EOS are: 1) use the equilibrium pressure and the material properties to calculate the borehole expansion upon detonation, 2) use the undetonated explosive density and the calculated borehole expansion to calculate the density of the explosive immediately after detonation, and 3) use Equation (1) with the gas density immediately after detonation and the equilibrium pressure to calculate the equilibrium energy. Thus the initial conditions for the gas flow calculation are the equilibrium pressure, equilibrium density and equilibrium energy.

The advantage of incorporating this equation of state is that parameters are available in this form for many different explosives. Costly time-consuming conversions to JWL parameters are thus avoided. This

makes it possible to study the influence of different explosive types on rock motion.

Gas Flow in a Bench Environment

The gas flow calculation assumes the rock is a porous media and computes the gas flow through the porous field taking all the significant properties of the gas into account including: gas viscosity, specific heat, Prandtl number, and thermal conductivity. The properties of the rock that are utilized in the gas flow calculation includes the temperature, initial porosity, specific heat and particle size. The particle size is the size of the close-packed spheres assumed to represent the matrix of the rock. It is used to set rock mass permeability and does not necessarily correspond to the sphere size chosen for the calculation.

A blastwell from a typical bench blast has a very large aspect ratio which makes it difficult to model the gas flow from the entire blastwell. This difficulty has been overcome by setting the gas flow calculation grid to be a perpendicular slice through the center of the blastwell as shown in Figure 1. This greatly reduces the number of gas computation cells which makes the calculation tractable on a SUN SPARCstation 2 computer workstation. The explosive column is defined as a line with two endpoints. The perpendicular distance from each sphere to the line defining the explosive column is calculated and used on the gas computation grid to determine the gas computation cell that corresponds to the sphere. The pressure gradient and gas velocities associated with that cell are then used to calculate the gas loading of the sphere. Two mechanisms for transferring momentum from the gas to the spheres have been used, viscous drag and pressure gradient [Preece and Knudsen,1991].

An advantage of performing the gas computation on a thin grid at the explosive column mid-height is that this method can easily be adapted to multiple rows with delays and also to decked explosives where different explosives exist in the same column.

Porosity Calculation

An essential element of gas flow modeling in blasting is accurate treatment of porosity increases adjacent to the blastwell as the material is pushed in front of the expanding gas pocket. A method previously documented [Preece, 1990a] for calculating the porosity of the gas grid at each time step based on the location of the spheres employed a boxing scheme. The box size was chosen to be approximately five times the sphere size and the porosity was calculated as the ratio of the area enclosed by spheres in the box with the area of the box. A problem with this method is that it smeared large porosity increases in small areas over the entire porosity calculation box. So even though a gap might open up next to the explosive, the box associated with that region would see only a slight increase in porosity.

This difficulty has been remedied in the bench environment by choosing a tracer sphere next to the explosive and using the motion of the tracer sphere to determine the porosity. This method is shown in Figure 2 where the porosity defined by the tracer sphere is given by the following set of equations.

$$w = \frac{tx}{dx} \tag{3}$$

$$S = -\frac{w}{Ndx} \tag{4}$$

$$D = dx(i - imx + 1) \tag{5}$$

$$\Phi_{i,j} = w + SD + \Phi_m \quad \Big| \quad \begin{matrix} i = imx + 1, N \\ j = 1, ny \end{matrix} \tag{6}$$

$$\Phi_{i,j} = max(\Phi_{i,j}, 1.0) \tag{7}$$

Where $\Phi_{i,j}$ = porosity in cell i, j , tx = tracer sphere displacement perpendicular to blastwell, dx = gas cell size, N = number of gas cells over which $\Phi_{i,j}$ linearly decreases to 0.0, D = distance of grid cell i, j from blastwell, Φ_m = initial matrix porosity, $imx = i$ grid location of the edge of the blastwell, and ny = number of cells in vertical direction. It is assumed that the porosity of the gas computation grid decreases linearly over ten grid cells (N = 10). To assume that the porosity decreases with distance in some manner is logical though the characteristics of this decrease and the length of the influence are subjects for further research and debate.

Blastwell Spacing Parallel to Bench Face

Any 2-D computer modeling technique inherently has difficulty treating the third dimension which is parallel to the bench face in most applications. An approximation that has been applied here is to treat the circular elements used in a bench blast calculation as cylindrical rods whose length is equal to the spacing between blastwells. The spacing of a row of blastwells is used to determine the length of the cylindrical rods that lay between that blastwell and the next row of blastwells toward the face. The mass and rotational moment of inertia of the elements are calculated based on cylindrical rods instead of spheres. This allows some influence from the spacing in the third dimension since the mass of material to be moved by each explosive charge is taken into consideration.

Example Problem

Figure 3 shows an example bench blast consisting of a single row of blastwells. Table 1 shows the various parameters associated with this bench blast calculation. The top row is the baseline calculation with the other rows having one parameter different from the baseline calculation to see its effect. The material is a Dolomite with a specific gravity of 2.65, a Youngs' Modulus of 40.0 Gpa, and a Poissons' Ratio of 0.28. Figure 4 shows the spherical element model of the baseline calculation 100 ms after detonation. The arrows on the spheres represent the velocities of the spheres. At this point in time the face velocities are approximately 7.6 m/s. The blastwell is not shown explicitly in Figure 4 but it is evident from the split between the spheres. Figures 5 and 6 show the motion of the material at 500 ms and at 6.0 s, when motion has stopped and the muck pile has been formed. Observed bench blast behavior, such as vertical lift of the

material due to dilation and bulging of the face at mid-height is evident in this calculation. This calculation required 12465 CPU seconds (3.5 hours) to complete on a SUN SPARCstation 2 workstation.

Figure 7 shows the instantaneous impulses imparted to the spheres by the gas as a function of time and indicates that the influence of the gas in this bench geometry is totally over by approximately 100 ms. Due to the asymptotic nature of the curve it is evident that most of impulse has been imparted by approximately 50 ms. This implies that the energy used to produce motion of the particles is expended in a very short period of time and that subsequent rock motion is ballistic in nature.

The tabulation of the face velocities as a function of parameter changes is shown in Table 1. The face velocity changes with each parameter change are logical. Face velocity reductions result from decreasing the blastwell diameter as well a increasing the spacing and burden. Face velocity increases result from decreases in burden or spacing and from using a Heavy ANFO explosive that has a higher proportion of emulsion and thus a higher initial density and detonation velocity.

Conclusions

The spherical element computer program DMC has been enhanced to perform coupled gas flow and rock motion simulations in a bench blasting environment. The ICI equation of state for the explosive gases has been added to the program which will allow modeling of many different explosives including those that exhibit non-ideal detonation behavior. Effective use of the program required development of a reduced gas grid technique, a new porosity computation scheme and a method to include the effects of blastwell spacing.

A parameter study using these techniques showed logical variations of face velocities with variations of blastwell diameter, spacing, burden and explosive type. Even though a powerful computational ability has been developed this technique still requires validation and fine tuning using field data from bench blasts.

This paper shows the results from a single row bench blast, however, the program will soon be modified to incorporate multiple rows with delays and also decked explosives in the same column. The enhancements discussed here will make numerical modeling of bench blasting a useful tool for designing bench blasts.

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Table 1:

Explosive	Blastwell Dia. (mm)	Burden (m)	Spacing (m)	Face Velocity (m/s)	% Difference From Baseline
Heavy ANFO 70/30*	310	4	5	7.6	0%
"	168	"	"	5.4	-29%
"	310	"	6	5.9	-22%
"	"	"	4	9.4	+24%
"	"	3	5	8.5	+12%
"	"	5	"	4.6	-40%
Heavy ANFO 50/50*	"	4	5	9.4	+24%
"	"	5	"	5.9	-22%

* mixture ratio - ANFO to Emulsion

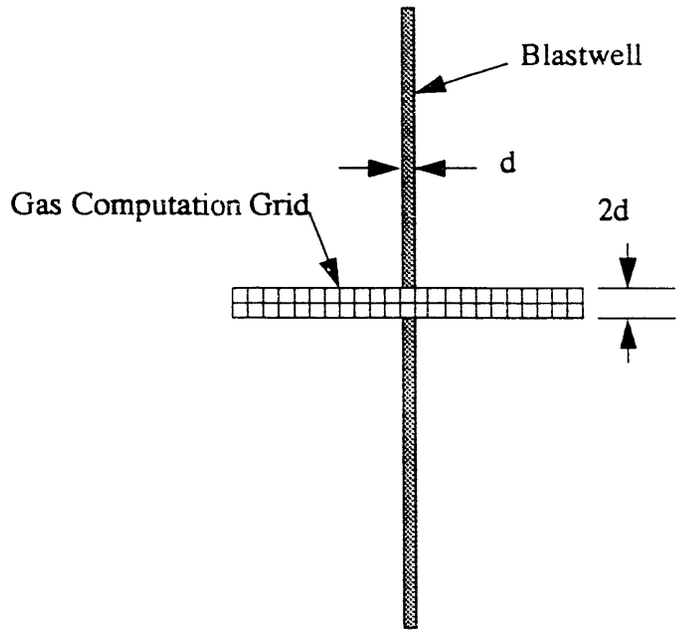

Figure 1: Blastwell and Gas Computation Grid

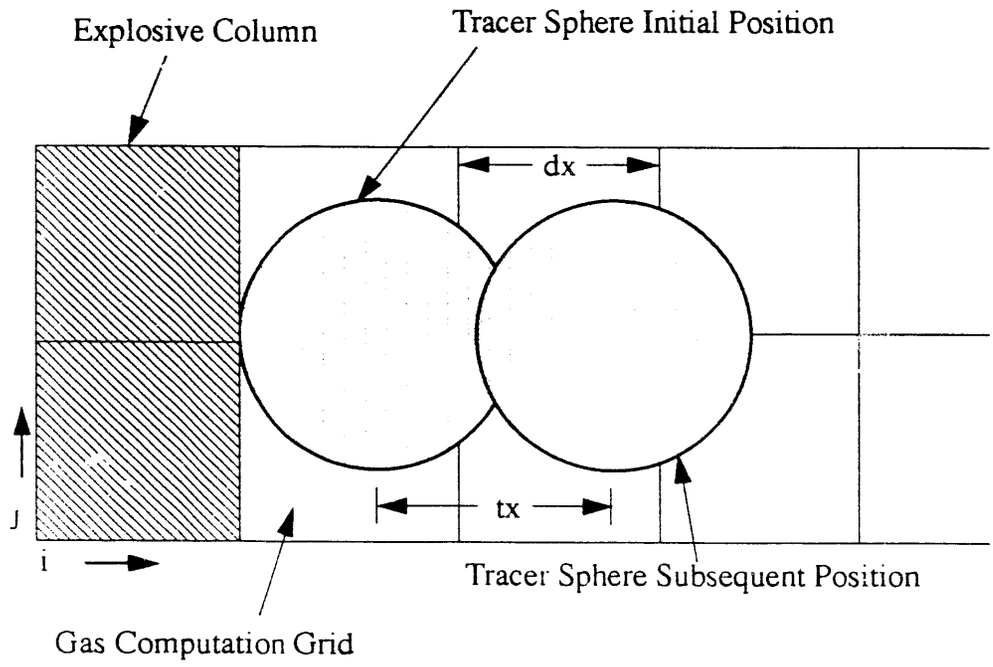

Figure 2: Porosity Calculation Using Tracer Spheres

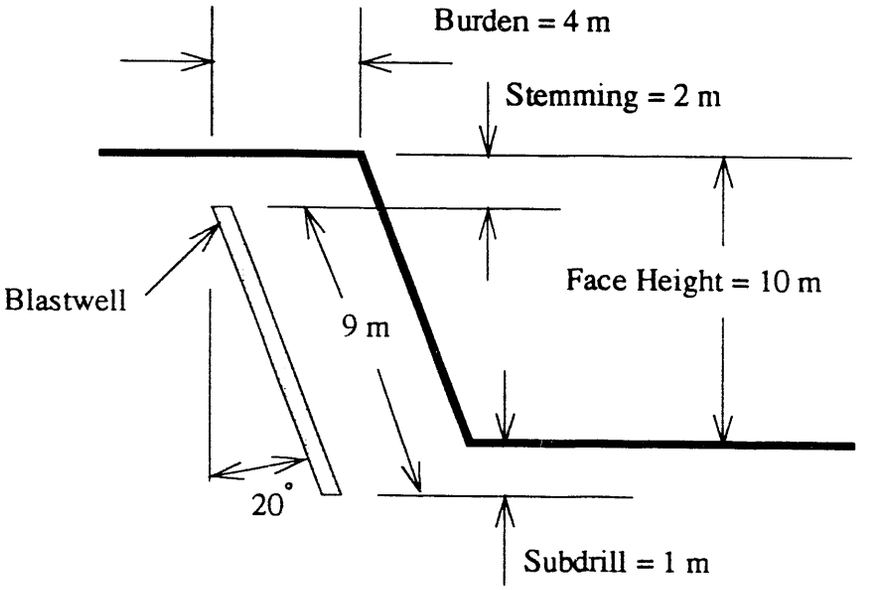

Figure 3: Single Row Bench Blast

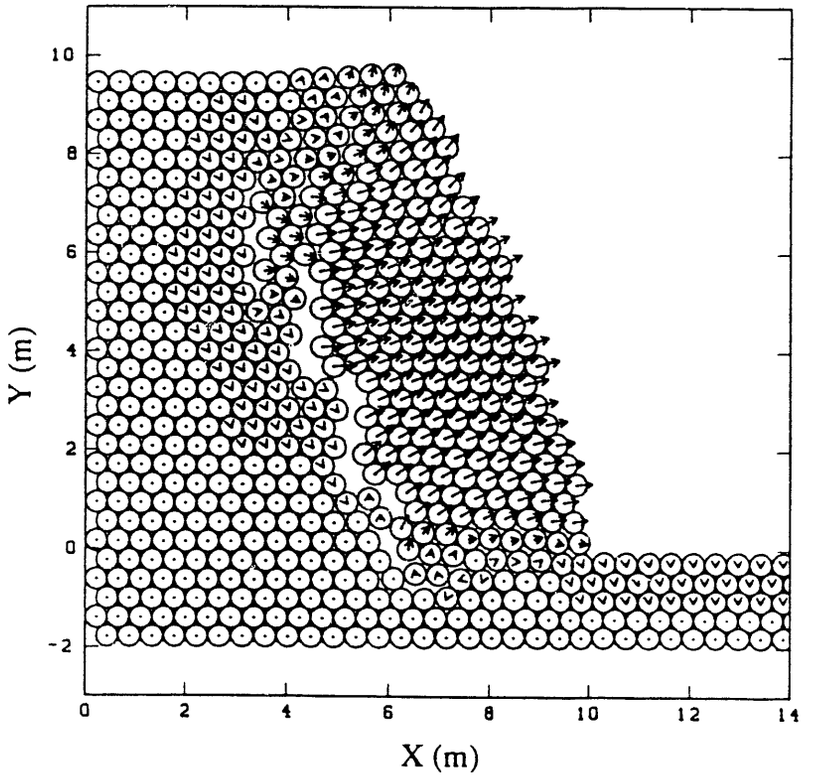

Figure 4: Bench Blast Simulation at 100 ms Showing Initial Velocities.

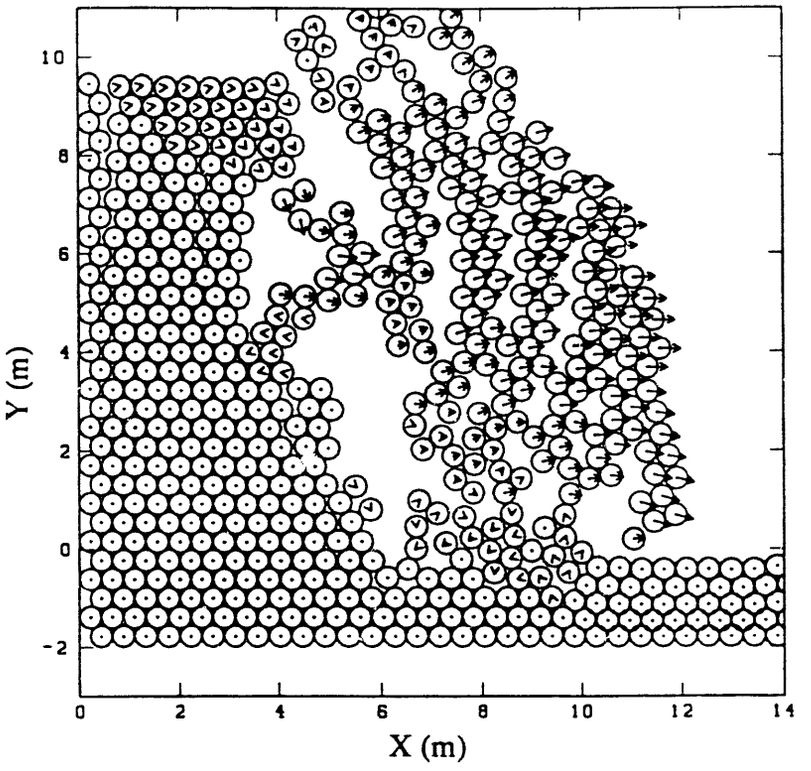

Figure 5: Bench Blast Simulation at 500 ms

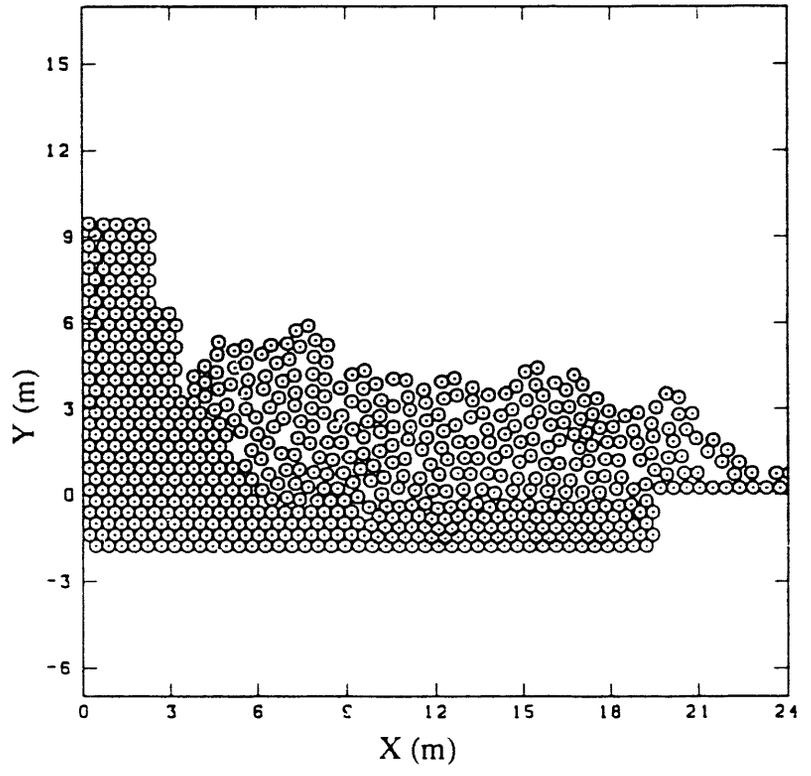

Figure 6: Bench Blast Simulation at 6.0 s

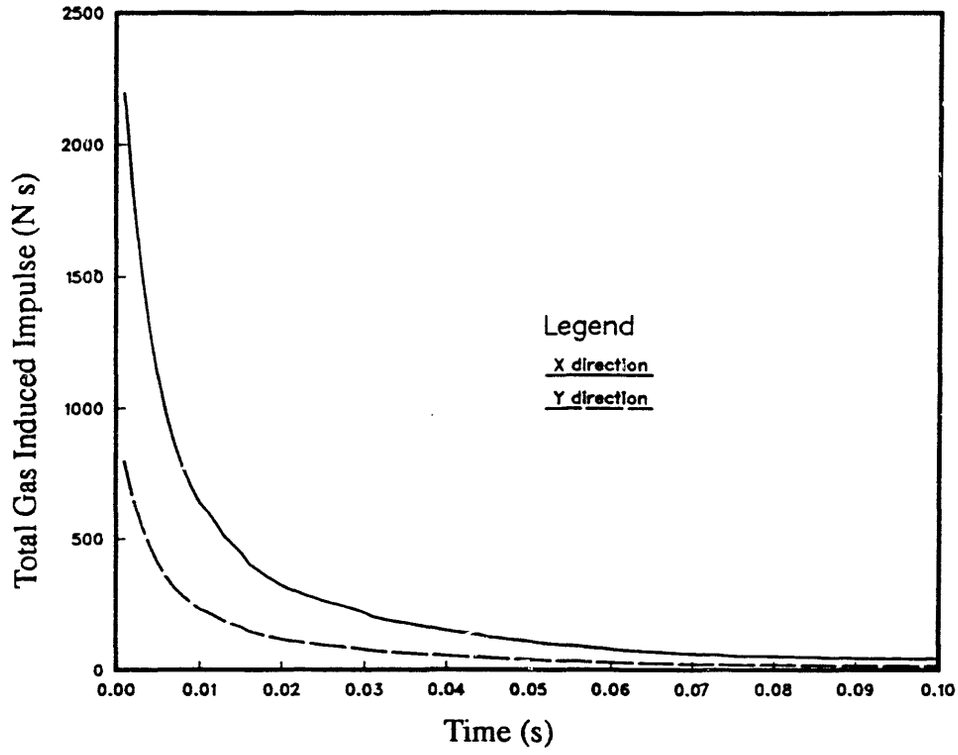

Figure 7: Total Gas Induced Impulse Versus Time

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