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Progress in Modeling Pressure Oscillations in Regenerative Liquid Propellant Guns

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Regenerative liquid-propellant guns (RLPG) have been studied for many years. Liquid propellant is injected through a piston or pistons into a combustion chamber as the gun is firing. The propellant combusts and pushes the projectile down the tube. The chamber pressure also pushes the piston(s), controlling the propellant injection. RLPG gun firings almost always show large high-frequency pressure oscillations. To study this phenomenon, a two-dimensional axisymmetric fluid-dynamics model of the combustion chamber/gun tube of an RLPG has been developed. High-frequency oscillations are generated naturally by the code. Recently, the code has been extended to three dimensions. The major difficulty in the simulations has been modeling the jet breakup and combustion. A number of different approximations to the jet breakup have been implemented. The most useful approximation has been to assume that most of the propellant is in an intact core. Comparisons have been made between the model and gun firings, leading to methods for reducing the pressure oscillations.

Introduction

A DIAGRAM of the U.S. Army Research Laboratory (ARL) 30-mm Concept VIC (6-C) regenerative liquid-propellant guns (RLPG) is shown in Fig. 1. The monopropellant in the liquid reservoir is prepressurized and located between the control piston and the injection piston. An external solid- or liquid-propellant igniter venting into the combustion chamber initiates the ballistic cycle. The chamber pressure forces both the control and injection pistons rearward. Liquid propellant is then injected from the liquid reservoir through the annulus between the pistons into the combustion chamber where it burns. Because of the area differential of the injection piston, the reservoir pressure will remain greater than the chamber pressure throughout the firing cycle. The motion of the control piston depends on the damper assembly. The injection piston follows the control piston. If the injection piston lags the control piston, the annular injection area will increase, and more liquid will be injected into the chamber. The reservoir pressure will then drop and the piston will accelerate. Similarly, if the injection piston moves too close to the control piston, the injection area will close down. The reservoir pressure will then increase and the injection piston will be decelerated. The hot gas flows into the gun tube, accelerating the projectile. There is a large area change from the chamber to the tube.

Jet breakup and combustion is a very complicated phenomenon. Some of the injected liquid will be in an intact core. The length of this core depends, in part, on the gas density and the turbulence generated in the injector. Liquid will be stripped from the core by aerodynamic forces (primary breakup), and then further break up into droplets (secondary breakup).[1] Because of the pressure and temperature in the chamber, the droplets heat and then combust. The gas-generation rate depends on the local conditions. Almost all experimental work to measure quantities such as core length and droplet sizes has been for round jets at low pressures and low flow rates compared with the conditions in the RLPG. Because of the complexity of the phenomena and lack of information about annular jets at gun conditions, simplifying assumptions must be made in the numerical simulations.

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Gun firings have been successfully simulated using a lumped parameter code RLPGUN.[2–5] The injected liquid is assumed to instantaneously break up into droplets and instantaneously ignite. The droplet diameter is obtained from a theoretical formulation[6]:

$$d = 5.1426 v^{-\frac{4}{3}} D^{\frac{1}{6}} \sigma_L^{\frac{1}{2}} \mu_L^{\frac{1}{3}} \rho_L^{-\frac{1}{6}} \rho_G^{-\frac{2}{3}}$$

where d is the droplet diameter (cm), v is the relative velocity between the liquid and gas (cm/s), D is the diameter of the injector (cm), σ_L is the surface tension of the liquid (dynes/cm = g/s^2), μ_L is the liquid dynamic viscosity (P = g/cm s), ρ_L is the liquid density (g/cm^3), and ρ_G is the gas density (g/cm^3). The injection velocity is used as the relative velocity (assume that the gas in the chamber is stagnant). However, it has been found necessary to multiply the droplet diameter obtained by 30 to obtain the proper pressure rise rate. This has been hypothesized as being due to coalescence in the very dense spray. Using this correlation, good agreement with data has been obtained for a wide variety of RLPG firings.

Essentially, all firings of RLPGs show high-frequency, high-magnitude pressure oscillations. Pressure oscillations are driven by the energy released by the combustion process. Essentially all of the combustion occurs in the chamber (based on analysis of experimental data). Pressure waves then move down the gun tube. These pressure waves may have an undesirable effect on the projectile and on the injection process.

To better understand and reduce pressure oscillations, a two-dimensional/three-dimensional model named Liquid Propellant Oscillations (LPOSC) has been written for the combustion chamber and gun tube of an RLPG.[7–9] The output from the lumped-parameter gun code is used as input for the two-dimensional code. The piston motions, liquid-propellant injection rate, and injected droplet size are all obtained from a lumped parameter code simulation. In addition, an igniter model is required. The igniter model causes hot gas to be injected through an annulus in the right-hand wall of the chamber at a specified rate at the start of the integration. Because of a lack of information about spray behavior under gun conditions, the very simple breakup model from the lumped parameter code has also been used in LPOSC.

Pressure waves are generated naturally by the model. As the liquid is injected it starts to combust. Inertial confinement causes a small local pressure increase. This pressure wave leaves the neighborhood of the injector. The rate of gas generation at the injector decreases because of the pressure dependence of the burning rate and the combustion of much of the propellant. The small pressure wave reflects from the walls and returns to the injector. Accumulated liquid now burns more rapidly, increasing the local pressure. After several iterations the pressure waves become very large.

The experimental data suggest a limited regime for the jet breakup and combustion model. If the injected droplets are too large, the mean pressure rise is too slow. Experimental data indicate that the liquid burns very rapidly after being injected, and the mean pressure rise is primarily determined by the injection rate. On the other hand, if the injected droplets are too small, pressure oscillations will not be established. The liquid will burn rapidly with little dependence on the local pressure, and there is not enough liquid accumulation to enhance the pressure waves. Normally LPOSC is implemented assuming a minimum injected droplet diameter. Values from 50 to 200 μm can be used and still obtain the proper mean pressure rise and large oscillations. Best results are obtained with values between 100 and 150 μm.

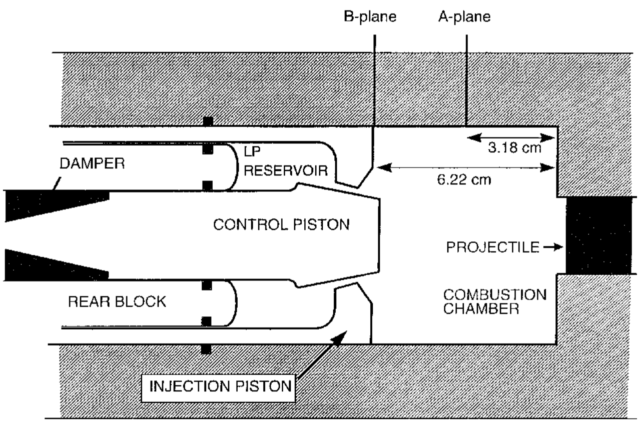

Fig. 1 Diagram of the ARL 30-mm Concept VIC RLPG.

In general, the model results are in reasonable agreement with experimental data from 30- and 155-mm guns. However, there are more complicated cases that the model does not represent well. One such case is flow dispersers.[10] Flow dispersers are extensions of the inner piston nose, which are designed to more efficiently disperse and break up the liquid jet. The experimental data for guns fired with flow dispersers indicate a large reduction in pressure oscillations, whereas the standard model shows only a small effect.

Numerical Procedure

Figure 2 shows the grid for a 30-mm simulation. The grid is generated by a separate program. The user specifies the boundary of the chamber. Each section of the boundary is either a straight line or a section of a circle. The user also specifies how many grid points are on each section and the ratio of grid points in the axial direction to grid points in the radial direction. The code then generates the boundary points and connects them with straight lines to get the interior points. The grid is composed of general quadrilaterals. The triangular sections near the boundary are considered degenerate quadrilaterals with coincidental vertices.

The grid covers the combustion chamber from the centerline to the wall. The gun tube grid is to the right (not shown). At the left are the outlines of the injection piston (Fig. 2a) and control piston (Fig. 2b).

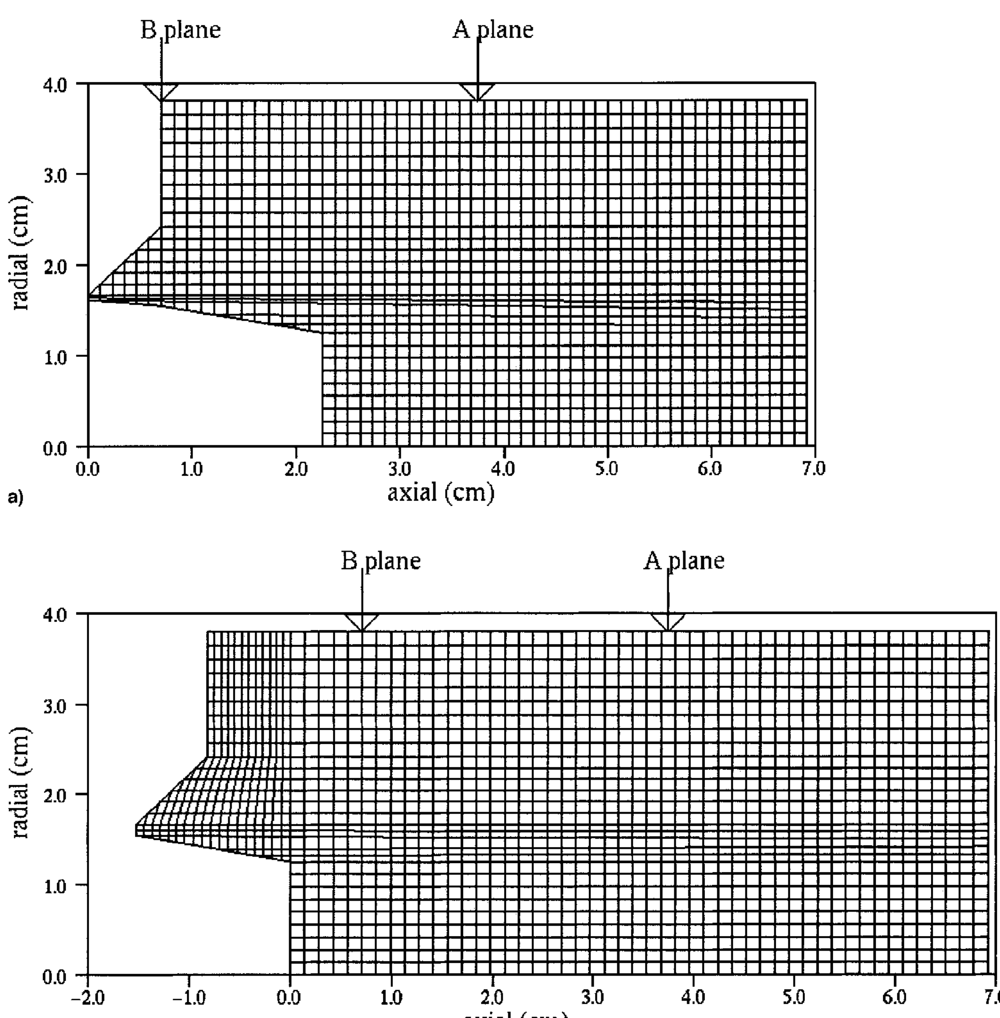

Fig. 2 Grid for the 30-mm small charge gun firing, round 161: a) initial grid and b) grid near maximum piston separation.

Initially, the pistons have a small gap between them. As the pistons separate, the grid points on the injection piston (outer piston) move as a unit at the injection piston velocity. The axial velocity of the points on the control piston (inner piston) vary between the control piston velocity at the right and the injection piston velocity at the left. The radial velocity is chosen so that the points move along the surface of the piston. Points on the outer wall above the control piston are uniformly compressed. Points to the right of the control piston are stretched uniformly, and new grid points are added as necessary.

The grid divides the combustion chamber into annular control volumes. The scalar quantities (pressure, temperature, and densities) are assumed to be uniform within a control volume. The axial and radial velocities are defined on the vertices of the control volumes. The position of the vertices may be arbitrarily specified as a function of time. This type of mesh is called an arbitrary Lagrangian–Eulerian mesh[11–13] and is useful for representing moving boundaries. The governing Navier–Stokes equations are cast in integral form. The procedure is inherently conservative. Turbulent transport processes are described by a k-ε turbulence model.[14,15] Boundary-layer theory (law of the wall) is used to set the boundary conditions.[16]

A control volume can contain both gas and liquid. A Noble–Abel equation of state is used to describe the gas. The liquid must be considered compressible under gun conditions. The density of the liquid depends only on the pressure (temperature effects are ignored). The pressure is assumed to be the same for both the gas and the liquid. The liquid is assumed to be in the form of drops. All of the drops in a control volume are the same size, considered to be the Sauter mean diameter of the actual distribution. The liquid combusts according to a pressure-dependent burn rate.

The gun tube is considered to be a cylinder with a projectile for the right-hand wall. The projectile acceleration depends on the average pressure on its base. The grid in the tube is attached to the base and stretches uniformly as the projectile moves. New grid points are added axially as the tube volume increases. The gun tube can be either two dimensional or one dimensional. Because almost all of the combustion occurs in the chamber, the results are practically identical. Therefore, the one-dimensional gun tube model is generally used.

Because of the requirement of tracking pressure waves, the code is explicit. Small time steps must be taken to accurately follow the large pressure waves. With an implicit method, larger time steps could be taken, but the solution accuracy would be unacceptable. The limiting factor is accuracy, not stability.

Grid-refinement studies have been done, and the code converges to basically the same solution if a finer grid is used.

Intact Core

Various other assumptions for the jet breakup were implemented and tested in the model.[17] The most useful new assumption is that most of the liquid is in an intact core. It is known that at least some of the liquid will be an intact core rather than in the form of droplets.

The length of a jet intact core for a circular pressure atomized jet can be approximated by

$$L/d = c\sqrt{\rho_L/\rho_G}$$

where L is the length of the intact core, d is the diameter of the orifice, ρ_L is the liquid density, ρ_G is the gas density, and C is a constant between 7 and 16 (Ref. 1). Almost all work on jet breakup has been performed for $\rho_L/\rho_G > 500$. In the gun, this ratio is close to 10 near peak pressures. This formula was implemented in the code, in which ρ_L is the density of the injected liquid, ρ_G is the average gas density in the combustion chamber, and d is the hydraulic diameter of the annulus. The incoming liquid is assumed to break up into droplets using the Wolfe and Andersen correlation,[6] but without a multiplying factor. A minimum droplet diameter of 10 μm is used. To model the core, combustion is set to zero. When liquid leaves the core, it is assumed to instantaneously break up into droplets and begin burning. The gas and liquid velocities instantaneously equilibrate. For the small droplets now used, these are reasonable assumptions. The model is now simple enough to be tractable.

At first, the intact core was assumed to be directly in front of the injector. It proved impossible to obtain satisfactory results. However, an alternative approach was tried, based on recent experimental data.[18] In the experiment, liquid propellant was injected through an annulus into relatively high-pressure gas, and the core was studied using flash x rays. The core very quickly collapsed toward the centerline.

Based on these results, the core is assumed to extend radially from the top of the injector to the top of the control piston. The area under the injector may not be entirely intact core, but may also include a dense spray region. The assumption is that hot gas cannot get under the core and above the control piston and ignite the spray. The value of the constant is chosen to obtain approximately the correct mean pressure rise.

30-Millimeter Simulation

This version of the code was run for round 161 of the ARL 30-mm gun. This was a small charge (91 cm^3) firing.[19] Several pressure ports are located in the A plane (near the tube) and in the B plane (nearer the pistons). Most ports are the standard recessed, grease-packed, two-diameter ports. The A90 (90 deg from the top of the gun) and B30 (30 deg from the top of the gun) gauge locations are flush-mounted ports, which are expected to record oscillations more accurately. However, the flush-mounted ports record the mean pressure too low, because of thermal drift of the exposed gauges.[20] This shot was one of a small number with a flush-mounted pressure gauge in the center of the control piston face.

The constant C was set equal to 3.0. The results at the A and B planes are shown in Figs. 3 and 4, respectively. The oscillations are somewhat low in magnitude at the B plane. However, the magnitude of the oscillations at the centerline from the model compares favorably to the data (see Fig. 5).

The Fourier transforms are shown in Figs. 6–8. The code does generate about the correct frequency, a first radial mode for the chamber. The magnitude is much too low at the B plane. However, it is about correct at the A plane and the centerline. These model parameters were the first time that the code generated a large oscillation near 19 kHz at the centerline.

Analysis of the model shows some combustion on top of the core. There is a substantial amount of combustion at the end of the core. There is also much combustion under the core, past the end of the control piston. This generates the first radial mode for the cylinder. If the core is made shorter, the strong 19-kHz signal is not generated.

The model shows larger oscillations at the A plane, whereas the data show larger oscillations at the B plane. In the model, a longitudinal mode is set up at the top of the chamber, as well as the primary radial mode. This wave reinforces at the A plane and interferes at

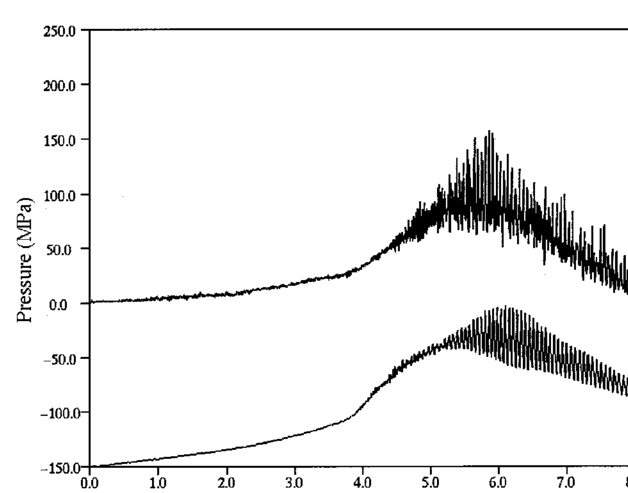

Fig. 3 Round 161, A90 gauge (top) and intact core model, $C = 3$ (bottom).

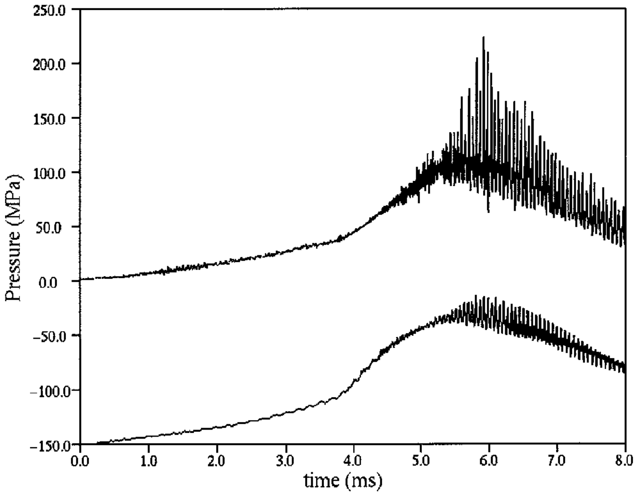

Fig. 4 Round 161, B30 gauge (top) and intact core model, C = 3 (bottom).

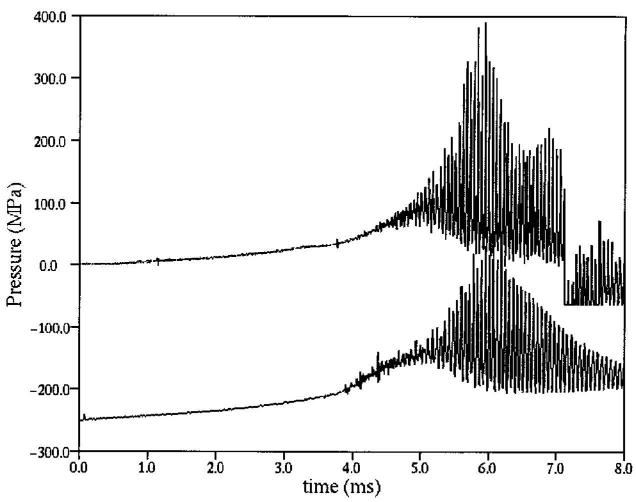

Fig. 5 Round 161. Control piston gauge (top) and intact core model, C = 3 (bottom).

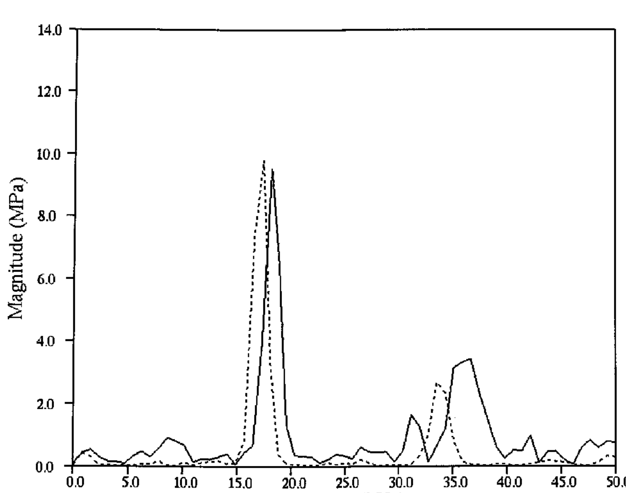

Fig. 6 Round 161. Fast Fourier transform, 5.5–6.5 ms: ——, A90 gauge; and · · · ·, intact core model, C = 3.

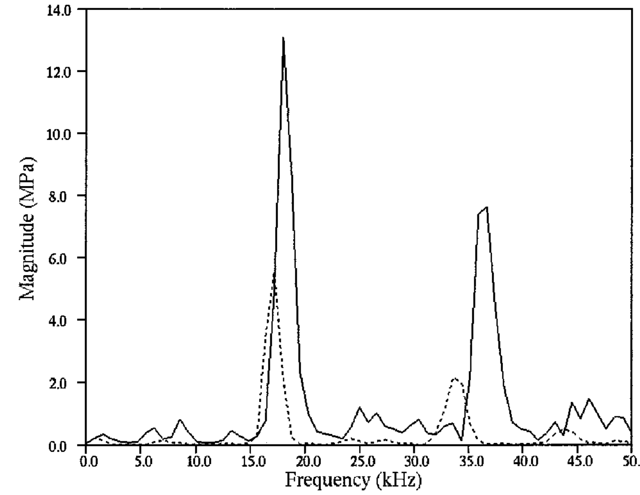

Fig. 7 Round 161. Fast Fourier transform, 5.5–6.5 ms: ——, B30 gauge; and · · · ·, intact core model, C = 3.

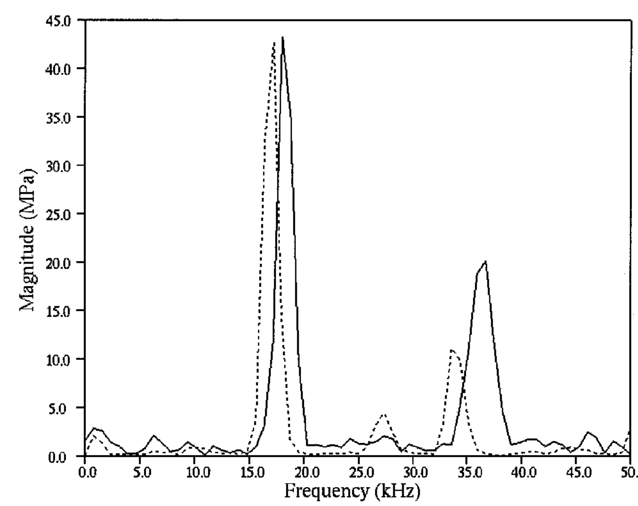

Fig. 8 Round 161. Fast Fourier transform, 5.5–6.5 ms: ——, piston gauge; and · · · ·, intact core model, C = 3.

the B plane. A number of other parameters were tried in the model, without changing this fundamental pattern. The model is apparently too simplified to obtain the precise chamber behavior.

Flow Dispersers

Impressive reductions in pressure oscillations have been obtained in the 30-mm RLPG using flow splitters or dispersers. The most effective designs have been nonaxisymmetric. The model was extended to three dimensions partly to study flow dispersers.

Baseline shots were fired before the shots with the flow dispersers. While the baseline conditions were very similar to round 161, discussed earlier, the results were slightly different. Figures 9 and 10 show the Fourier transforms of the data at the A90 and B30 gauges, respectively. At the B plane, the strongest signal is 24 kHz (first radial for the annulus). At the A plane, the strongest signal is 19 kHz (first radial for the cylinder). The intact core model was run with the multiplying constant $C = 3$ and 1. With the longer core, the results were similar to the previous case. The strongest signal was at 17 kHz, with the oscillations larger at the A plane than at the B plane. With the shorter core, the strongest signal was at 24 kHz, with the oscillations larger at the B plane than at the A plane. It proved impossible to generate both modes at once in the model. This is most likely because of the simplification of the jet breakup and combustion processes.

A number of flow dispersers were tested in the 30-mm gun, including three axisymmetric concepts. While these splitters were

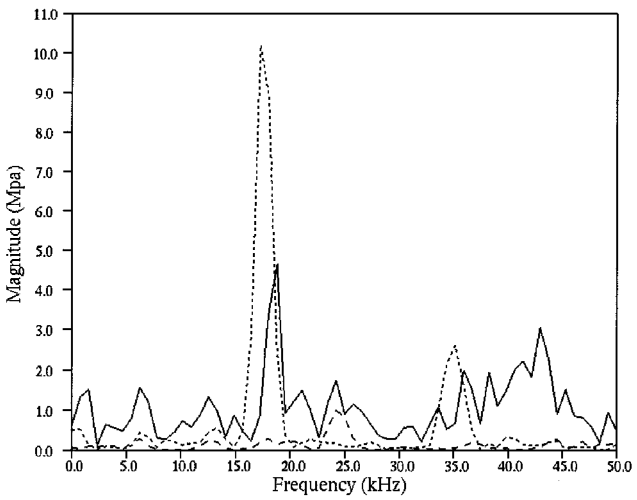

Fig. 9 Round 119. Fast Fourier transform, 5.5–6.5 ms: ——, A90 gauge (line); · · · · ; intact core model, C = 3; and - - -, C = 1.

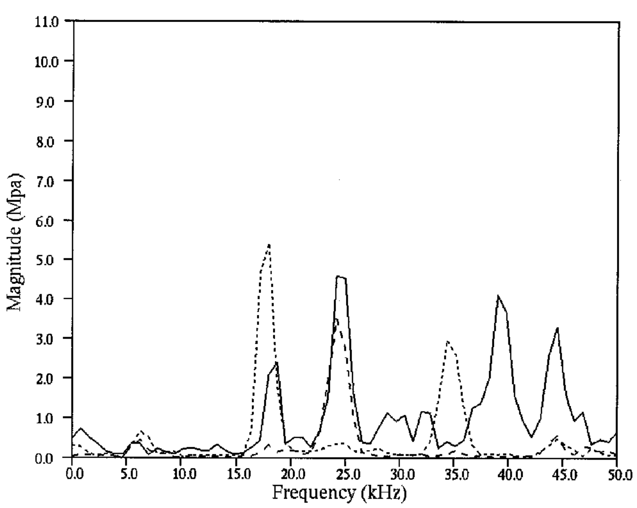

Fig. 10 Round 119. Fast Fourier transform, 5.5–6.5 ms: ——, B30 gauge; · · · · ; intact core model C = 3; and - - -, C = 1.

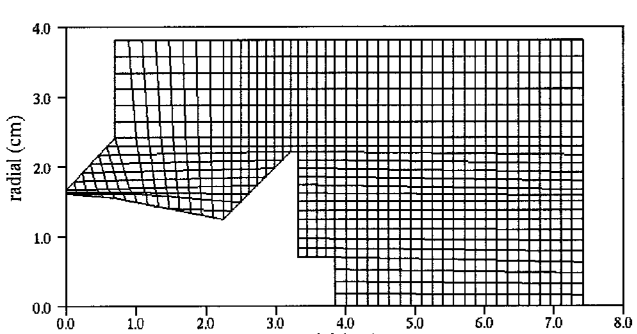

Fig. 11 Axisymmetric 45-deg conical disperser. Initial 50 × 24 grid.

less successful in reducing oscillations, they did have a major effect on the excited frequencies. These tests were completed before the flush-mounted ports were put into the 30-mm gun.

A 45-deg conical disperser was modeled first as a two-dimensional calculation. The initial grid for the calculation is shown in Fig. 11. The splitter was attached to the control piston with a hex bolt, which is approximated as a circular obstruction.

In Figs. 12 and 13, the Fourier transforms are shown. The disperser eliminates the usual 18- and 23-kHz signals. However, new

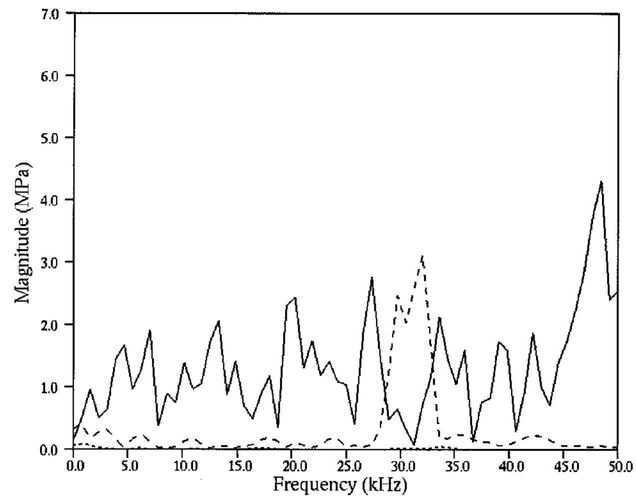

Fig. 12 Round 43, axisymmetric flow disperser. Fast Fourier transform, 5.0–6.0 ms: ——, A120 gauge; · · · · ; intact core model, C = 3; and - - -, C = 2.

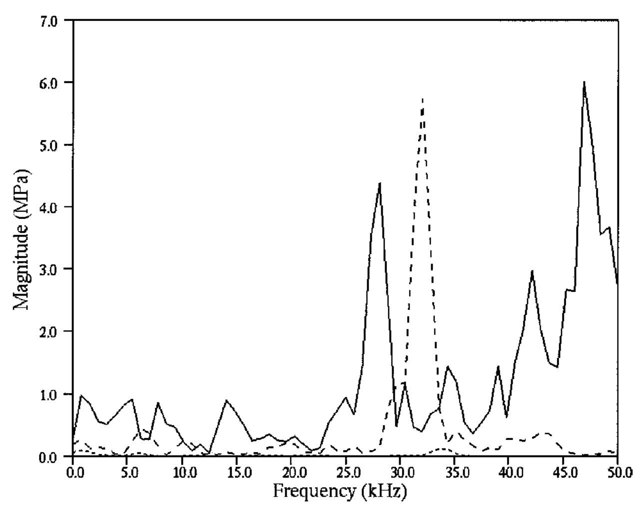

Fig. 13 Round 43, axisymmetric flow disperser. Fast Fourier transform, 5.0–6.0 ms: ——, B240 gauge; · · · · ; intact core model, C = 3; and - - -, C = 2.

frequencies are excited. The most prominent is at 28 kHz. The large frequency near 50 kHz may be an artifact of the two-diameter port.

Using $C = 3$ in the intact core model, the oscillations are basically nonexistent. With this value, the length of the core is greater than the distance from the injector to the disperser, so that all of the combustion takes place above the core. With $C = 2$, the jet does end before the splitter. It is reasonable to assume that the splitter will affect the length of the core as it interacts with the jet and the surrounding gas flow. The model also eliminates the usual modes and generates a new mode at 32 kHz.

This new mode is longitudinal, with pressure waves bouncing between the injector and the disperser. The difference in frequency compared with the data may be due to errors in computing the sound speed in the two-phase mixture, which is sensitive to the exact distribution of gas and liquid. The previous droplet model gives similar results. As long as the combustion is between the injector and the splitter, the primary mode set up is longitudinal. This is the likely occurrence in the experiment.

The most effective flow disperser in the 30-mm gun was the 45-deg daisywheel. This splitter has eight three-sided blades designed to deflect the flow from the regenerative injector region. The model takes advantage of the symmetry and only represents one of the blades. Figure 14 shows part of the initial 50 × 24 × 22 grid.

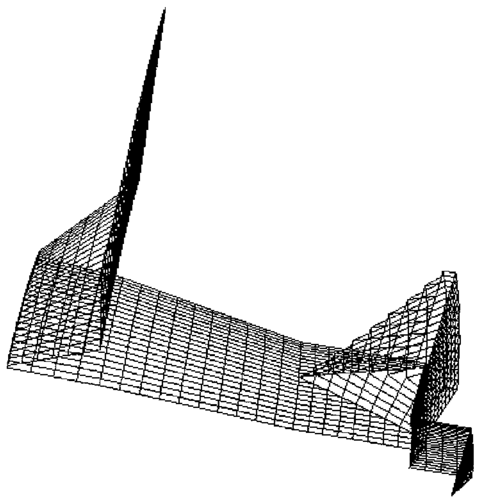

Fig. 14 Round 122, 45-deg daisywheel disperser. Initial 50 × 24 × 22 grid.

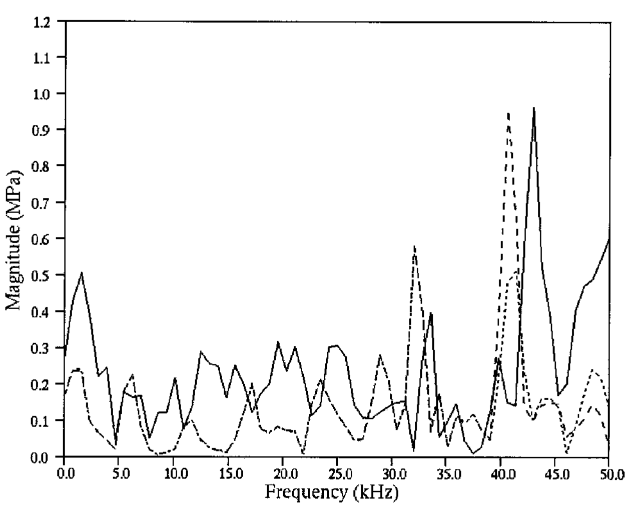

Fig. 15 Round 122, flow disperser. Fast Fourier transform, 5.0–6.0 ms: ——, A90 gauge; intact core model, C = 3; · · · ·, A30; and - - -, A90.

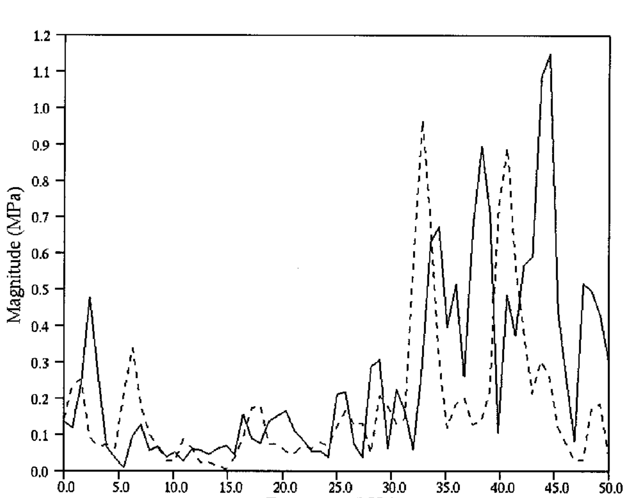

Fig. 16 Round 122, flow disperser. Fast Fourier transform, 5.5–6.5 ms: ——, B30 gauge; and · · · ·, intact core model, C = 3.

The orientation of the disperser in the gun was not recorded; so arbitrarily, the low point between blades was located at 0 deg. The simulation required about a week of CPU time on a Silicon Graphics Power Challenge Array.

The intact core model was run with $C = 3$. The Fourier transforms are shown in Figs. 15 and 16 (note the change in the y-axis magnitude scale). The model now accurately simulates the drastic reduction in the magnitude of the oscillations. In the data, the largest remaining frequency was at 43 kHz. The model comes close to this with a relatively large 41-kHz frequency. Animation of the simulation results reveals an apparent three-dimensional mode, with pressure waves bouncing at an angle between the blades of the disperser and the injection piston. Much of the combustion takes place between the blades of the piston. The 41-kHz signal is stronger at some locations than at others (see Fig. 15). Because the orientation of the disperser in the gun is not known, the tangential pattern in the model cannot be compared with the data.

Runs were made with a longer control piston, without disperser blades. A smaller reduction in the pressure oscillations was observed compared with the baseline. Some of the reduction in pressure oscillations may be because hot gas can no longer get under the core at the end of the control piston.

155-Millimeter Guns

Flow dispersers were also incorporated in a 155-mm gun. The dispersers did not extend as far up radially as in the 30-mm gun. A 45-deg daisywheel disperser worked well for a 4-1 charge. Unfortunately, the simulation indicated that the flow disperser has very little effect on the oscillations. Most of the combustion takes place above the disperser. It is possible that the model does not resolve the motion of the core properly and that the combustion takes place closer to the splitter.

For a 7.1-l charge, the splitter in the experiment had very little effect. However, a modified splitter that was set another 1.2 cm back from the injector proved effective. This suggests a critical distance for a splitter to work effectively. It is postulated that if the disperser is too close to the injector, the core combusts past the disperser, still generating large oscillations. Further research is needed on 155-mm guns.

Conclusions

A two-dimensional/three-dimensional code has been developed to model pressure oscillations in regenerative liquid-propellant guns. A number of options for the jet breakup have been implemented. The best agreement with data is obtained by assuming that most of the injected liquid is in the form of an intact core. This accurately reproduces the baseline 30-mm firings, the shots with pressure measured on the control piston, and the flow disperser shots. Unfortunately, the new model is not as accurate for 155-mm gun firings.

Based on the modeling, the following conclusions can be made. Most of the injected liquid is in the intact core or in a very dense noncombusting spray. When the liquid breaks up, it rapidly forms small droplets that quickly ignite and burn. To make the problem tractable, the jet breakup and combustion must be simplified and the grid must be relatively coarse.

The model indicates that pressure oscillations can be reduced in three ways:

1) Prevent the oscillations from increasing in size by reducing the amount of liquid in the chamber.

2) Dampen the oscillations faster than they grow in magnitude.

3) Break up the dominant radial modes in the chamber.

A faster-burning liquid propellant has been developed and tested, with ambiguous results.[21] There has also been some success with chamber liners that damp the pressure waves at the walls of the chamber.[22] The most practical method tested so far has been flow dispersers.

The model suggests that flow dispersers in the 30-mm gun reduce oscillations not by physically breaking up the jet (method 1), as originally proposed, but by interfering with the radial pressure waves (method 3). The combustion is located between the blades of the disperser, which act as baffles. This implies that if a disperser is to be effective for a range of charge sizes, the blades must be made longer. However, this conclusion is only tentative, and further research on jet breakup and data from the 155-mm gun are needed.

Acknowledgment

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