One-Dimensional Analysis of a Sleeved-Piston Gas Gun

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Introduction

GUNS which use compressed gas as a driver are used frequently to propel models of projectiles and flight vehicles in a ballistic range. Information pertaining to gun performance is an essential ingredient in the design of ballistic tests and the analysis of test results. The purpose of this Note is to describe a one-dimensional performance analysis method as applied to an unusual sleeved-piston compressed gas gun.

A one-dimensional, unsteady, adiabatic flow of a single ideal gas is assumed. In some parts of the analysis the condition of isentropy is also employed. In addition, 1) slots and gaps are modeled as converging nozzles, 2) moving parts of the gun are assumed to be frictionless, and 3) all seals are considered to be leakproof.

Gas Gun Operation

A schematic diagram of the subject gas gun is shown in Fig. 1. This gun is used in the ballistic ranges at the U.S. Air Force Armament Testing Laboratory at Eglin, Florida. The unique sleeved-piston firing mechanism offers special difficulties in the application of the one-dimensional method because of the complexity of the flow through the piston slots.

The gun is charged with high-pressure gas through the charging port (1) and one-way valve (2). The firing cycle is initiated with the opening of the fast-acting dump valve (3). When the pressure in the discharge chamber (4) drops to a certain level the motion of the sleeved piston (5) is initiated. The barrel seal (6) is broken and the piston slots (7) are vented to the barrel chamber (8). High-pressure gas flows from the main chamber (9), through the piston slots, and into the barrel chamber behind the sabot (10). The impulsive charge of high-pressure gas in the barrel chamber propels the sabot and test model down the barrel (12). The essential firing cycle is terminated by full travel of the piston to the right, although piston rebound, particularly at high charging pressures, is common.

Mathematical Model of Gun Operation

The operation of the gun is modeled in static and dynamic phases. The sleeved piston, which is the only moving part of the firing mechanism, remains at rest after the dump valve is opened until sufficient pressure differential is created to initiate motion. The flow from the discharge chamber is assumed to be isentropic, and the flow through the discharge hose and dump valve is represented as a Fanno flow. From conservation of mass the discharge chamber pressure can be given by

$$P_D(t) = P_i\left[1 + \frac{\gamma-1}{2}\left(\frac{2}{\gamma+1}\right)^{[\gamma+1/2(\gamma-1)]}\left(\frac{\epsilon A_e a_i}{\forall_D}\right)t\right]^{(-2\gamma/\gamma-1)} \tag{1}$$

where $\epsilon = \dot{m}_f^*/\dot{m}_e^*$ is the ratio of the choked mass flow rate with resistance to the ideal choked mass flow rate, A_e the exit area, $\forall_D$ the chamber volume, and a_i the initial sound speed. The corresponding time required after firing to initiate piston motion is given by

$$\tau = \left(\frac{2}{\gamma-1}\right)\left(\frac{\gamma+1}{2}\right)^{[\gamma+1/2(\gamma-1)]}\left\{\left[(1-\alpha^2) + \left(\frac{D'}{D_p}\right)^2\frac{P_a}{P_i}\right]^{(1-\gamma/2\gamma)} - 1\right\}\frac{\forall_D}{\epsilon A_e a_i}\Bigg) \tag{2}$$

where $\alpha = D/D_p$, the ratio of the sleeve to piston diameters.

The remainder of the firing cycle constitutes the dynamic phase of gun operation. The dynamic equations of motion of the piston and sabot can be determined from the forces imposed by the various chamber pressures as pictured in Fig. 2. These equations can be written:

For the piston,

$$\frac{\mathrm{d}\dot{x}_p}{\mathrm{d}t} = \frac{1}{m_p}\{A_p[P_M(1-\alpha^2) + P_B\alpha^2 - P_D] - F_{RP}\}$$

For the sabot,

$$\frac{\mathrm{d}\dot{x}_s}{\mathrm{d}t} = \frac{1}{m_s}[(P_B - P_F)A_s - F_{RS}] \tag{4}$$

where the sabot nose pressure, P_F, is computed by neglecting the precursor flowfield and assuming a simple isentropic compression.

The time variation of pressure in each of the chambers of the gun during the dynamic phase of operation is determined by application of mass conservation principles. In each case the apertures between connecting chambers are modeled as converging nozzles with isentropic flow. In addition, the barrel chamber volume and the flow area between main and barrel chambers are both functions of time since they depend on the sabot and piston positions, respectively. The equations for the pressure variations can be written as follows.

For the discharge chamber,

$$\frac{\mathrm{d}P_D}{\mathrm{d}t} = \frac{P_D}{\ell - x_p}\left[\gamma\dot{x}_p - \left(\frac{\epsilon\dot{m}_e a_i^2}{A_p}\right)\left(\frac{P_i^{1-\gamma}}{P_D}\right)^{1/\gamma}\right] \quad \text{when } x_p < \ell_c \tag{5}$$

$$= \frac{\gamma\dot{x}_p}{\ell - x_p}P_D \quad \text{when } x_p \geq \ell_c \tag{6}$$

For the main chamber,

$$\frac{\mathrm{d}P_M}{\mathrm{d}t} = \frac{-\dot{m}_M a_i^2}{\forall_M}\left(\frac{P_M}{P_i}\right)^{(\gamma-1/\gamma)} \tag{7}$$

where, for choked slots, the mass rate is

$$\dot{m}_M = \gamma\left(\frac{2}{\gamma+1}\right)^{[\gamma+1/2(\gamma-1)]}\left[\frac{A_p(x_p)}{a_i}\right]P_m^{(\gamma+1/2\gamma)}P_i^{(\gamma-1/2\gamma)} \tag{8}$$

and, for unchoked slots, the mass rate is

$$\dot{m}_M = \frac{A_p(x_p)(P_a^{1-\gamma}P_B)^{1/\gamma}}{RT_a}\frac{2}{\gamma-1}\left[a_i^2\left(\frac{P_M}{P_i}\right)^{(\gamma-1/\gamma)} - a_a^2\left(\frac{P_B}{P_a}\right)^{(\gamma-1/\gamma)}\right] \tag{9}$$

For the barrel chamber,

$$\frac{\mathrm{d}P_B}{\mathrm{d}t} = \frac{P_B}{(D^2x_s + \ell_0 D'^2 + D^2x_p)}\left[\frac{4\dot{m}_B a_a^2}{\pi}\left(\frac{P_a^{1-\gamma}}{P_B}\right)^{1/\gamma} + \gamma(D^2\dot{x}_s + D_p^2\dot{x}_p)\right] \tag{10}$$

where $\dot{m}_B = -\dot{m}_M$.

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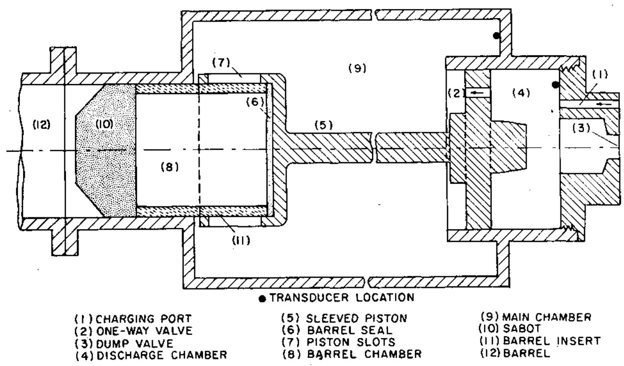

Fig. 1 Schematic of sleeved-piston gas gun.

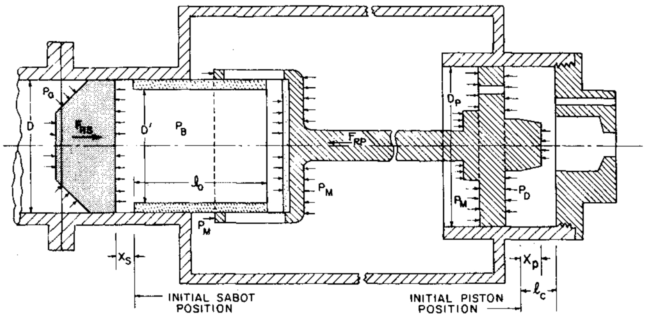

Fig. 2 Gun geometric relationships.

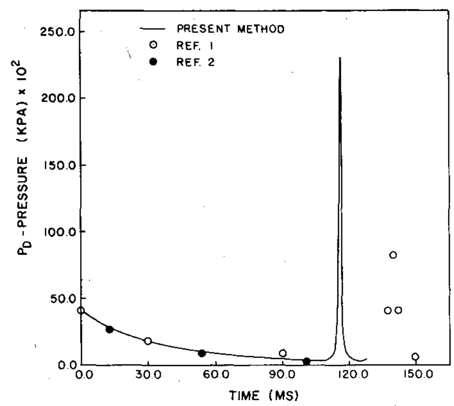

Fig. 3 Discharge chamber pressure history.

Equations (3-10), which are the governing equations for the dynamic and gasdynamic motions of the gun, can be written as a set of seven nonlinear, ordinary differential equations by defining the second-order derivatives in Eqs. (3) and (4), respectively, as $\dot{x}_p = u$ and $\dot{x}_s = w$. Initially the piston and sabot are at rest. The barrel chamber pressure is atmospheric, the main chamber pressure is the charge pressure, and the discharge chamber pressure is given by Eq. (1) evaluated at time t. The equations of motion are integrated from these initial conditions using a fourth-order Runge-Kutta scheme.

Results

Experimental pressure histories for the sleeved-piston gas gun were determined by West[1] with transducers mounted in the discharge and main chambers in the locations indicated in Fig. 1. Additional data in a simulated discharge chamber were acquired by Pakarat.[2]

A typical pressure correlation is shown in the discharge chamber pressure history of Fig. 3. The spike near the end of the firing cycle is caused by piston rebound after the initial discharge. The displacement of this spike from the experimental data can be attributed to model deficiencies imposed by the assumptions of isentropic nozzle flow and frictionless piston motion.

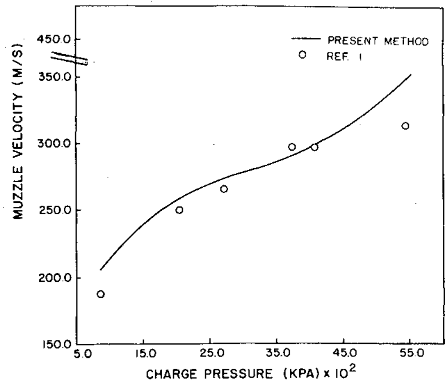

Fig. 4 Sleeved-piston gas gun performance.

Calculations at various charge pressures were performed to provide an indication of gun performance. These results, shown in Fig. 4, compare favorably with experimental data for low to moderate charge pressures. The deviation at high charge pressures can be attributed to increased sabot friction and distortion.

Conclusions

A one-dimensional analytical model has been developed to evaluate the performance of a sleeved-piston gas gun. The model has been shown to predict projectile muzzle velocity for a range of charge pressures with acceptable accuracy. The model also provides detailed information on internal kinematics and pressures during the gun firing cycle.

Acknowledgment

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References

[1] West, K.O., Unpublished Experimental Data for a Sleeved-Piston Gas Gun, U.S. Air Force Armament Testing Laboratory, Eglin, Fla., 1979.

[2] Pakarat, A., "Pressure Variation in a Gas Gun Chamber," MS Thesis, Louisiana State University, Baton Rouge, La., Dec. 1980.

Errata

Predictive Surveillance Technique for Air-Launched Rocket Motors

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EIGHT paragraphs of this article were inadvertently transposed in printing. Paragraph 4, page 162, concluding, "...applicability of the concept," ends the Introduction section and should be directly followed by the section on page 163 headed "Technical Approach." The intervening text should be inserted on page 164 following the paragraph concluding, "... batch-to-batch differences..."

Equation (4) should have been correctly printed as follows:

$$\frac{N_m}{\bar{N}} = \left[-\ln\left(1 - \frac{m}{n+1}\right) \right]^{1/\alpha} \Big/ \Gamma\left(1 + \frac{1}{\alpha}\right)$$

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