ANALYSIS OF GAS DYNAMIC WAVES IN EXPLOSIVELY ACTUATED DEVICES

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ABSTRACT

Explosively actuated devices exist in diverse applications where dependability and performance is of the utmost importance. These devices reliably and safely deliver high power in remote locations by converting chemical potential energy into useful mechanical work by means of the gas products produced from combustion. Pin pullers, valves, thrusters, and cable cutters are only a few examples of these devices that carry out critical functions such as parachute deployment, fuel/engine shutoff, and emergency jettison. Historically, assessing device performance has been largely empirical. Although these experiments are necessary to observe actual device behavior, computational modeling can be implemented to interpret the experimental results, and to assist the design process which saves both time and money.

A simplified axisymmetric device in a prefired and operational state is shown in Fig. 1 (a) and (b). The actuator stores a granular solid explosive and is separated from the expansion chamber by a port. Following ignition, the solid explosive burns producing primarily gas phase products in the actuator. The product gas further enhances the pressure-dependent combustion process thus releasing available energy. Product gas, and possibly burning explosive, flows from the actuator through the port and into the expansion chamber. Useful work is then extracted from the device as the piston is pushed by the gas pressure.

To properly assess the performance of any explosively actuated device, an understanding of the complex interplay between multiphase combustion energy release, mass and energy transport, and device geometry is required. A simplified model was recently formulated to assess the system-level response of explosively actuated valves. This model accounts for gas production due to a burning explosive within an actuator, transport of product gas from the actuator to an expansion chamber, and the insertion of an initially tapered piston into a constant area bore driven by the gas pressure within the expansion chamber. The model assumes spatially equilibrated properties within both the actuator and expansion chamber. However, estimates reveal that device operation and acoustic time scales are approximately of the same order [i.e. ~O(\mu s)] which suggest that wave interactions may significantly influence device performance. These similar time scales motivate the development of new models that consider such wave interactions within the actuator and expansion chamber. Gas dynamic modeling for explosively actuated devices is the primary focus of the presented work.

A two-phase quasi-one-dimensional computational analysis will be presented that characterizes how wave propagation occurring within and between the actuator and expansion chamber affect overall device operation and performance. The model describes important physical features of an actual device including pressure-dependent combustion of solid explosive grains to form high pressure gas product mass, convective heat transfer interactions between each phase, flow of product gas mass and possibly burning solid explosive through the variable area port, and piston motion due to high pressure gas acting on its surface. The theoretical formulation was guided by the model of Kapila, et al which is valid for fast interphase velocity and pressure equilibration rates. This model is a formal asymptotic limit if the model presented by Baer and Nunziato, and later improved by Bdzil, et al. A high-resolution numerical method is used to accurately capture strong shock waves with minimal numerical diffusion and dispersion. The governing equations are solved in generalized curvilinear coordinates which allows grid...
deformation as the piston advances through the expansion chamber. Key objectives of the analysis are to examine how 1) expansion chamber geometry, 2) port diameter, 3) explosive mass, and 4) piston mass affect unsteady wave propagation within the simplified device, piston motion, and device performance.

Preliminary predictions are shown in Figs. 2 and 3 for a simple device geometry, single phase gas, and a stationary piston. These predictions are intended to illustrate key features of the gas dynamic fields, and the influence of pressure at the boundaries. For this simulation, pressure-dependent mass, momentum, and energy fluxes were imposed at the actuator boundary, representing explosive combustion, and a reflective condition was imposed at the piston boundary.

Pressure field predictions are shown in Fig. 2; also shown in this figure is the axial variation in device radius used for this simulation. Immediately following ignition at $t = 0.5\mu s$, a shock wave emanates from the actuator boundary, located at $x = -1.5\text{mm}$, due to the imposed flux which propagates toward the device port (throat) located at $x = 0.0\text{mm}$. The incident shock is partly reflected off the converging section of the actuator and partly transmitted into the expansion chamber, as shown by the profiles corresponding to $t = 1.5$ and $t = 3.0\mu s$. Once the reflected shock reaches the actuator boundary, it causes a rapid acceleration in pressure-dependent combustion which results in a second, stronger shock wave emanating from the boundary. This sequence of events is repeated several times within the actuator before explosive combustion is complete at $t_{\text{burn}} = 11.69\mu s$. Subsequently, the actuator boundary is switched to a reflective condition causing the spatial pressure profile to approach an equilibrium state as time evolves. Shock waves are observed in the expansion chamber during the simulation which interact with each other and the piston face boundary located at $x = 6\text{mm}$.

Fig. 3 shows pressure variations with time at the inflow and piston boundaries. The unsteady pressure on the piston surface may result in irregular piston motion that is undesirable in practice.

![Figure 2: Numerically predicted pressure fields: (a) immediately following ignition and (b) near complete combustion and pressure equilibrium.](image)

![Figure 3: Numerically predicted pressure history at the boundaries.](image)

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**REFERENCES**