MODELING FRAGMENTATION PERFORMANCE OF NATURAL AND CONTROLLED FRAGMENTATION MUNITIONS

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The developed model links high-strain high-strain-rate continuum hydrocode analyses with a series of fragmentation modeling routines enabling accurate simulation of performance of natural and controlled fragmentation munitions without costly arena fragmentation tests. An additional input to the fragmentation modeling routines requires knowledge of global fragment distribution parameters, which is a function of the fragmenting shell types, materials, and fabrication techniques employed. Assuming that effect of the air resistance on the trajectory of fragments is negligible, the developed model enables prediction of crucial spatial characteristics of explosive fragmenting munitions including the number and fragment mass distribution, and the average fragment velocities. The developed model makes possible an accurate and reliable assessment of the lethality of fragmentation munitions without costly arena fragmentation tests, offering the warhead designers and fragmentation munition developers more ammunition performance information for less money spent. The developed model has been shown to accurately reproduce the available experimental data.

INRODUCTION

The function of any explosive fragmentation ammunition is the elimination or incapacitation of the intended personnel, aerial, or ground materiel targets. The probability of accomplishing this mission depends on the characteristics of the weapon system, the fragmentation parameters of the warhead, and the “hardness” or resistance of the assaulted target. Accordingly, for a given choice of the weapon and the target, the overall effectiveness or “lethality” of the explosive fragmentation ammunition is a function of fragmentation characteristics of the warhead including the number, mass, and shapes of fragments, the velocity of fragments, and the spatial fragment mass distribution. Once the fragmentation characteristics of the munition are determined, the fragmentation warhead lethality can be conveniently assessed in terms of two-dimensional areal plots of the probability of target incapacitation P_i, or in terms of a single lethality parameter, the lethal area, A_L. Customarily, all warhead fragmentation data including the fragment velocities and spatial and mass fragment distributions required for computing P_i and A_L are obtained from fragmentation arena tests.

In a typical arena fragmentation test a warhead is detonated within an enclosed structure half of which consists of "witness panels" for determining fragment velocities and half of "collection panels" for catching and examining the fragments. For statistical stability, a minimum of two or three tests is required, and the resulting fragmentation and velocity data are averaged and consolidated into a single JMEM (Joint Munitions Effectiveness Manual [1]) format data file. This data commonly referred to as a "Z-data" file, can be used in a number of analytical codes to estimate the probability of incapacitation P_i relative to the point of warhead burst and, consequently, the lethal area, A_L. In the PAFRAG (Picatinny Arsenal Fragmentation) modeling and experimentation approach presented in this work, the assessment of the ammunition lethality is performed without costly fragmentation arena tests, offering the warhead designers more ammunition performance information for less money spent. The methodology is based on three-dimensional axial symmetric high-strain high-strain-rate continuum analyses linked with a phenomenological fragmentation model calibrated through a series of experiments including flash radiography, high speed photography, and sawdust fragment recovery.

In fragmentation arena tests, the ammunition fragmentation characteristics are assessed as functions of polar angles Θ identifying angular positions of fragment-catching witness panels and velocity-measuring screens. In PAFRAG code analyses, positions of these devices are irrelevant, and the fragmentation characteristics are assessed in reference to the fragment trajectory angles Θ' calculated from the CALE code cell velocities at the time of the shell break-up. Once the shell breaks up and fragments are formed, fragment velocities may change with time due to a number of reasons, including the air drug and the rigid body motion induced at the time of the shell break up. Assuming that the fragment trajectory angles Θ do not change with time (that is the rigid body motion and the lateral drift of fragments due to air resistance is relatively small) and that the definitions of angles Θ and Θ' are approximately identical, the PAFRAG model enables prediction of crucial characteristics of explosive fragmenting munitions including the number of fragments, the fragment size distribution, and the average fragment velocities.

THE PAFRAG FRAGMENTATION MODEL

Similarly to the fragmentation arena test fragment sampling assumptions, the PAFRAG fragmentation model assumes that for any point within a fixed Θ-angle zone the fragment number distribution $N_j(m)$ is uniform and independent of the altitude and the azimuth angles Θ and ϕ, respectively. Hence, the total fragment number distribution is given by

$$N(m) = \sum_{j}^{L} N_j(m) \tag{1}$$

In equation (1) m is the fragment mass, L is the number of altitudinal Θ-angle zones, $0 \le \Theta \le \pi$, and $N_j(m)$ is the fragment number distribution function for the j-th zone. For convenience, all Θ-zones are assumed to have the same altitudinal lengths of $\Delta\Theta = \pi/(L-1)$, except for the first and the last "half-length" zones with lengths of ½ΔΘ. In the U.S.A. fragmentation ammunition arena testing practice [1], the number altitudinal zones is usually L=37, resulting in uniform Θ-angle resolution of ΔΘ=5°. Accordingly, the Θ-zones are identified by the middle of the altitudinal zone angles Θ_j given by the following series

$$\Theta_j = \begin{cases} \frac{1}{4}\Delta\Theta & j = 1 \\ \Delta\Theta(j-1) & 2 \le j \le L-1 \\ \pi - \frac{1}{4}\Delta\Theta & j = L \end{cases} \tag{2}$$

In the case of traditional fragmentation arena testing, all individual fragment number distribution functions $N_j(m)$ for all polar Θ-zones are determined directly from the test data. The main drawback of this approach is the extremely high testing costs limiting the fragmentation arena testing to final ammunition fragmentation characterization. Alternatively, the PAFRAG modeling and experimentation is a relatively low-cost procedure enabling accurate assessment of the fragmenting munition performance at the research, design, and development phases. In the PAFRAG approach the individual Θ-zone fragment number distribution functions $N_j(m)$ are computed analytically from the bulk sawdust or water tank fragment recovery test data, $N(m)$. Mathematically, the PAFRAG fragmentation modeling is a solution of the inverse problem of equation (1), *i.e.* determining a series of individual $N_j(m)$'s for given $N(m)$.

Since with PAFRAG approach, the $N(m)$ function is assessed based on approximately 98-99% fragment recovery data, the accuracy of PAFRAG predictions is high.

The PAFRAG-MOTT model

For a large part the PAFRAG-MOTT fragmentation model is based on the Mott's theory of break-up of cylindrical "ring-bombs" [2-3], in which the average length of the resulting circumferential fragments is a function of the radius and velocity of the ring at the moment of break-up, and the mechanical properties of the metal. Accordingly, in the PAFRAG-MOTT model the "random variations" in fragment sizes of natural fragmentation warheads are accounted through the following fragment distribution relationship

$$N_j(m) = N_{0j} e^{-\left(m / \mu_j \right)^{1/2}} \tag{3}$$

In eq. (3) N_{0j} and μ_j represent number of fragments and one half of the average fragment mass in the j-th Θ-zone, respectively, computed from the CALE-code generated data.

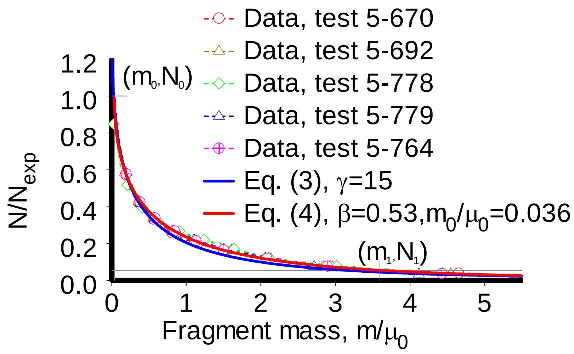

Figure 1. PAFRAG-MOTT and PAFRAG-WBL model curves fitted to the sawdust recovery data of a natural fragmentation warhead shown in the photograph.

The PAFRAG-WBL model

The mathematical form of the PAFRAG-WBL fragmentation model is based on the Weibull distribution statistics and defined as

$$N_j(m) = \frac{m_j}{\mu_0} e^{-\left(\frac{m}{\mu_1}\right)^{\beta}} \tag{4}$$

The mathematical form of eq. (4) is a more general case of Mott and Linfoot fragment distribution models [3] having an arbitrary exponent β. In PAFRAG modeling the exponent β can be determined from fitting eq. (4) to sawdust fragment distribution data on the interval $[(m_0, N_0), (m_1, N_1)]$. Parameters μ_0 and μ_1 are given by the following relationships

$$\mu_0 = \frac{\sum_j^L m_j}{N_0} \tag{5}$$

$$\mu_0 = \frac{m_1 - m_0}{\ln^{1/\beta}\left(\frac{N_0}{N_1}\right)} \tag{6}$$

Figure 1 presents an example of PAFRAG-MOTT, eq. (3), and PAFRAG-WBL, eq. (4), models applied to a typical natural cumulative fragment mass distribution $N(m)$ resulting from fragmentation warhead shown in the photograph.

The PAFRAG-FGS2 model

Similar to PAFRAG-MOTT and PAFRAG-WBL models, the PAFRAG-FGS2 model is based on the assumption that for a given explosive and fragmenting shell type and shape, the resulting number of fragments distribution function is an extensive property of the fragmenting shell; that is the number of fragments distribution function per unit mass of the shell is the same through the entire shell. Hence, the $N_j(m)$ function for the j-th Θ-zone is given by

$$N_j(m) = \frac{m_j}{\sum_j^L m_j} N(m) \tag{7}$$

where m_j is computed from the CALE-code generated data and $N(m)$ is obtained from the bulk fragment recovery test data. The mathematical form of the PAFRAG-FGS2 model is based on Ferguson's parametric cubic curve representation [4]. Given that for all zones j, $m_j(\xi) \equiv m(\xi)$, applying equation (7), the PAFRAG-FGS2 relationship for $N_j(m)$ is defined in parametric form as

$$\begin{bmatrix} N_{jk}(\xi_k) \\ m(\xi_k) \end{bmatrix} = \begin{bmatrix} \dfrac{m_j}{\sum_j^L m_j}(a_{N0k} + a_{N1k}\xi_k + a_{N2k}\xi_k^2 + a_{N3k}\xi_k^3) \\ a_{m0k} + a_{m1k}\xi_k + a_{m2k}\xi_k^2 + a_{m3k}\xi_k^3 \end{bmatrix} \tag{8}$$

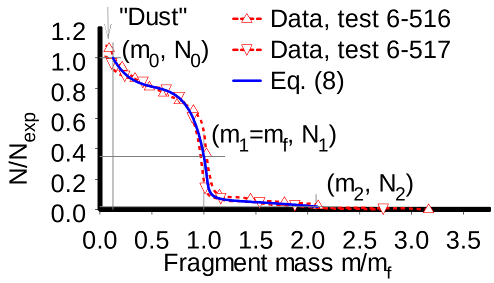

Figure 2. PAFRAG-FGS2 model curve fitted to the sawdust recovery data of a controlled fragmentation shell shown in the photograph.

In equation (8) ξ_k is a non-dimensional parameter, $0 \le \xi_k \le 1$, k is the curve index, k=0,1, and sixteen coefficients a_N's and a_m's are obtained by fitting two curve segments k=0 and k=1 with conditions of curve and tangent continuity at the adjacent ends.

Figure 2 shows a typical $N(m)$ data resulting from a representative controlled fragmentation warhead with a characteristic "jump" at the preferred fragment size m_f.

PAFRAG model prediction results

Assessment of the accuracy of the PAFRAG model predictions presented in this work was accomplished using a representative controlled fragmentation shaped charge warhead shown in figures 2 and 3. The high-strain high-strain-rate continuum modeling of the warhead was performed with an Arbitrary Lagrangian-Eulerian computer program CALE [5]. As illustrated in the figure 3, the dilation of the fragmenting steel shell is accompanied by the implosion of the copper shaped charge liner producing a high-speed metal jet moving along the charge's axis of symmetry z. As shown in the figure, upon initiation of the high explosive charge, rapid expansion of high-pressure high-velocity detonation products results in high-strain high-strain-rate dilation of the steel shell, which eventually ruptures generating a "spray" of high-velocity steel fragments moving with trajectories at angles Θ with z-axis.

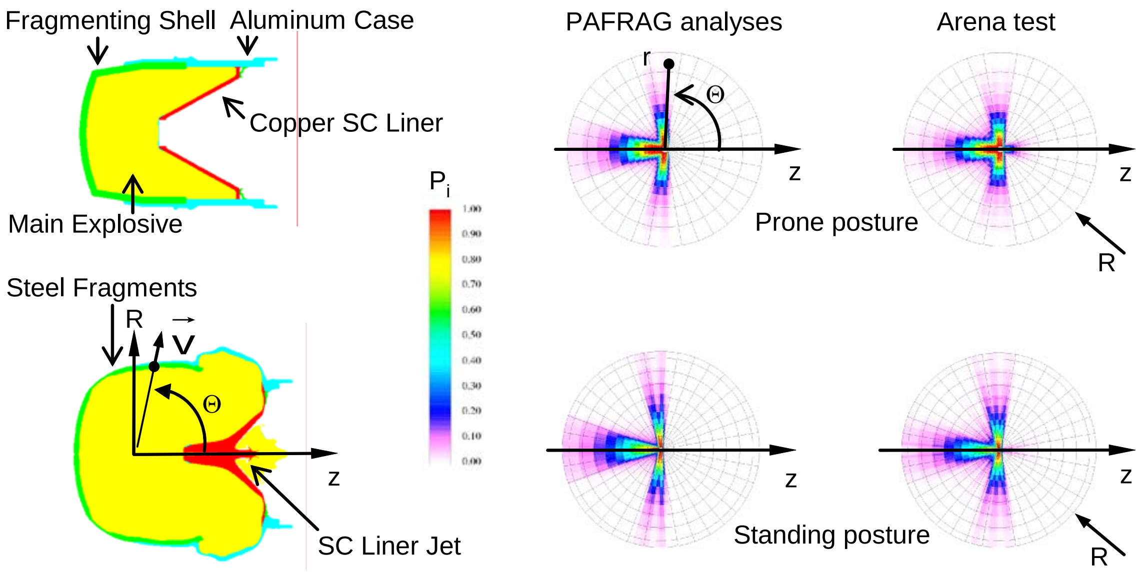

Figure 3. CALE-PAFRAG modeling and ALGRID lethality area plots a fragmentation warhead fired against standing and prone personnel protected by body armors and helmets. An agreement between P_i plots calculated from the CALE PAFRAG model prediction and that from the fragmentation arena test data is very good.

The fundamental assumption of fragmentation analyses presented in this work was that the fragmentation occurs simultaneously throughout the entire body of the shell. Accordingly, at approximately 3 volume expansions, the fragmenting steel shell was assumed completely fractured, and the CALE-code cell flow field data was passed to the PAFRAG-FGS2 fragmentation model. Parameters of the model were determined by fitting eq. (8) with the $N(m)$ data given in figure 2. Upon completion of the PAFRAG analyses, the resulting Z-data together with the Z-data from independent conventional fragmentation arena tests had been submitted for lethality analyses with ALGRID [6, 7] computer program.

Figure 3 presents a series of ALGRID areal lethality plots of the probabilities of incapacitation P_i computed from the Z-data from the CALE-PAFRAG analyses and that from the conventional fragmentation arena tests. Lethality plots shown in the figure were computed from the static Z-data by taking into account a number of the ammunition/gun system air-ballistic parameters including possible projectiles' ranges, heights, velocities, and altitude angles at burst. Combining the static fragment mass and velocity distribution data with the projectile's dynamic air-ballistic data, ALGRID computes the probabilities of incapacitation P_i as functions of polar angles Θ and distances from the projection of the warhead burst on the ground to possible target positions *r*. ALGRID target algorithm is using a complex six-part representation of individual personnel targets and is capable of a detailed account of possible battlefield scenarios with various levels of resistance or "hardness".

As shown in the figure, taking into account the projectile's terminal velocity at burst, the majority of the fragment spray is projected in the areas of approximately 180°≥Θ≥160° and 110°≥Θ ≥90°. Since the expanding fragmenting shell breaks relatively early at the end corner, the shell does not project fragments in the relatively large area of 160°≥Θ ≥110° making the considered warhead design relatively ineffective. As shown in the figure, agreement between P_i plots calculated from the PAFRAG-FGS2 model prediction and from the fragmentation arena test data is very good.

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