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Geometric design consideration for controlled fragmentation of metallic shells

A.W. Pike [a,b], Q.H. Zuo [a,*]

[a] Department of Mechanical and Aerospace Engineering, The University of Alabama in Huntsville, Huntsville, AL 35899, USA
[b] US Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC), Redstone Arsenal, AL 35898, USA

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ABSTRACT

Geometric designs for the controlled fragmentation of metal cylindrical shells have been considered via CTH hydrocode simulations. Fragmentation is controlled by engineering notches on the interior of the shells. Design parameters considered include the shell radius, thickness, and the depth and spacing of interior notches. A large number of shell designs were analyzed and their effectiveness on the controlled fragmentation categorized. The best overall controlled fragmentation designs exhibit full and complete fragment breakup as prescribed along the system of interior notches without any of the individual fragments naturally fragmenting throughout their thicknesses. For the combination of the Composition C-4 explosive and the 4340 steel, the best performing designs were shown to commonly possess the following characteristics: (1) they each have notch or groove depths greater than half of the shell thickness, (2) they each have notch or groove spacing within a range that is approximately the same as the shell thickness, and (3) they each have shell thicknesses many times smaller than the shell radius.

1. Introduction

The explosive fragmentation of metal cylinders is of particular interest to weapons system designers as they seek to understand the physics of fragmentation and better harness its power. Effectiveness of a weapon system is directly related to the amount of energy and mass that can be deposited onto a target. Whereas blast energy alone dissipates considerably in proportion to the distance from detonation, the casing material absorbs kinetic energy, fragments, and propels those fragments over a greater distance to a target (Held [1]). Cylinders are often used because of their ease of manufacture and loading with explosive fills, the development of rifled gun tubes, aerodynamic qualities, and ease of integration into missile or rocket airframes (Kennedy [2]). Fragmentation effects are now incorporated to some extent into nearly all types of weapons ranging from hand grenades and artillery shells to rockets and missiles (Beetle and Schwartz [3], Lloyd [4]). Although the study of this topic was originally rooted in the experimental and statistical realms, fragmentation can now be approached from the theoretical and computational perspectives thanks to research performed and technological advances made within the last century.

The design of a weapon must meet the performance requirements while being constrained in terms of weight, physical dimensions, and integration into a missile airframe. Cost is always an important design consideration but is mentioned only briefly and qualitatively in this paper. The velocity of the fragments produced also contributes to overall effectiveness, however, that depends highly on the choice of explosive and materials and that is not the focus of this effort. Also a factor considered in design but not addressed to a great extent within this study is manufacturability. The primary attention is placed on efficient use of mass and the geometric design considerations that affect the fragmentation characteristics.

Given a fixed amount of fragmenting mass available from a cylindrical shell, the designer must find a balance between having fragments of sufficient size to be damaging to a specified target and generating enough fragments to have sufficiently high probability of hit (P_{Hit}) against the target. Average fragment mass and the number of fragments are, by definition, inversely proportional quantities (Mott [5,6]). Both fragment mass and quantity can be predicted and accounted for in designing for the best possible weapon effectiveness against a target.

Sufficient performance can sometimes be achieved by allowing the cylindrical shell to fragment naturally. Natural fragmentation was well described by Mott and later by others as having a fragment mass and number distribution that now bears his name. Simply stated, the Mott distribution generally predicts a small

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[*] Corresponding author. Tel.: +1 256 824 6893; fax: +1 256 824 6758.
E-mail address: zuo@eng.uah.edu (Q.H. Zuo).

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number of large fragments and a large number of small fragments. Sometimes the naturally fragmenting design produces an adequate number of fragments large enough to be effective against a particular target. If that is the situation, it likely then represents the cheapest and easiest design to manufacture. However, there is typically a threshold below which fragments of a certain mass are ineffective against the desired target for any range of velocities. If this threshold is high enough within the natural fragmentation distribution of the design it can lead to a substantial decrease in P_{Hit} of effective fragments on the target. This can correspond to a considerable amount of available fragmenting mass that is wasted and could possibly be converted into more effective fragments.

In the case of ineffective fragment masses and numbers the designer needs to prescribe the breakup, thus controlling the fragmentation distribution to achieve the desired level of performance. There are various methods available to the designer for attaining a fragment distribution of sufficient mass and number to increase effectiveness against a given target. Several of these are discussed in the paper, but the focus of this research is on the use of a series of internal grooves or notches that act as stress raisers. When the design is explosively detonated, these stress raisers form points of failure within the cylindrical shell that then lead to a more optimized fragment distribution (Lloyd [4]). Extremely small fragments cannot be eliminated completely but can be reduced in favor of the more effective fragments.

The purpose of this research is to evaluate the geometric designs for controlled fragmentation of metal shells using internal notches (grooves). Specifically examined is the relationship of the overall shell dimensions, notch spacing, and notch depth and whether natural or controlled fragmentation prevails in a given design. The premise is that for a shell design of a given thickness there are some upper and lower limits on both the spacing and depth of the notching beyond which the controlled fragmentation ceases to be effective and natural fragmentation begins. That is, if the grooves are too close together the entire shell may simply naturally fragment and result in multiples of the desired fragments remaining intact. Similar results may occur if they are not deep enough in the shell thickness. It is as if the grooves have little or no effect at all. Likewise, if the grooves are spaced too far apart the desired fragment may naturally fragment within itself and lead to insufficient individual fragment masses. This groove still has some effect, but the design is not fully optimized to yield the desired fragmentation distribution.

The paper proceeds as follows. A review of fundamentals of natural and controlled fragmentations and Mott's theory of statistical fragment distribution is given in Section 2. A brief description of the CTH hydrocode was first given in Section 3, followed by numerical analysis of controlled fragmentation problem of interest and numerical results. The paper ends in Section 4 with a summary and some conclusions reached in this study and recommendations for further study.

2. Natural and controlled fragmentations

The goal in designing the fragmentation of a metallic cylinder is to generate fragments which have sufficient mass, velocity, and spatial distribution to be effective against a specified target. A desired fragmentation may be achieved naturally or through the use of specific design features. Various design parameters exist which contribute to the fragmentation characterization and thus to the effectiveness. These include the cylinder dimensions—length, diameter, thickness—as well as properties such as molecular grain size, toughness, brittleness or ductility, explosive fill, and confinement (Lloyd [4]). The processes of both fragmentation methods are discussed in this section.

2.1. *Natural fragmentation*

The cylindrical shell subjected to natural fragmentation is simply absent of any design features intended to alter the fragment distribution resulting from detonation of the high-explosive contained within the case. The primary design choices involved are overall dimensions of the shell, shell material, and explosive. Essentially, this method includes no extra manufacturing or materials processing steps beyond that which is required to produce the metal cylinder and fill it with explosive.

Lloyd [4] describes the basic process of natural fragmentation in four steps. Upon detonation of the explosive the internal pressure builds and the case begins to expand. After continued reaction of the explosive and expansion of the gaseous products the shell material develops fractures on its outer surface in a matter of microseconds. These fractures then grow towards the inner surface of the casing and begin to allow the gaseous products from the detonation to escape. Finally, as the fracture process completes, fragments are liberated and ejected from the gas cloud. The entire event takes on the order of tens of microseconds to occur.

In the early days of the study of this subject, it was common to simply build and explosively test a shell casing design to determine its fragmentation distribution. While testing is still important, a strict trial-and-error design approach can be both costly and time consuming. It became increasingly necessary to be able to predict the resulting fragment distribution for a shell design to determine its sufficiency.

2.1.1. *Mott's theory of statistical fragment distribution*

The beginning work to develop a model for natural fragmentation was the theoretical predictions of Mott [5,6]. His contributions form the basis for this entire field. His assumptions correspond to Lloyd's description of the process discussed previously. The fragmentation itself is described as “the tearing apart of a rapidly expanding tube when the material of the tube reaches the limit of its ductility” [6]. The event was considered instantaneous as the time of the event is much smaller than a characteristic time based on the strain rate in the material. Mott proposed that the average fragment size depended on the scatter in values for the reduction in area at which tensile failure occurs—effectively the strain at failure. He derived a characteristic fragment length, x_0, based on the scatter in the strain at fracture of the material, γ

$$x_0 = \sqrt{\frac{2\sigma_y}{\rho\gamma}\frac{1}{\dot{\varepsilon}}} \tag{1}$$

where σ_y is the flow (yield) stress of the case material (material was idealized as perfectly plastic with a constant flow stress), ρ is the density of the case, and $\dot{\varepsilon} = v/r$, with v and r being, respectively, the radial velocity and the radius of the case at fracture, is the strain rate (in the hoop direction). According to Mott [6], the majority of fragment lengths occur in the range of x_0–$2x_0$, with an average of about $1.5x_0$.

There was a need to relate the mass of the fragments to the length. Mott and Linfoot [5] examined what fragmentation data was available to them and found a substantial number of fragments retained original surfaces from both the outside and inside of the shell casing. These are sometimes termed “platelet” fragments in modern context. They concluded that the length parameter was proportional to the square root of the mass for these type fragments and developed the fragment probability density distribution

$$f(m) = \frac{1}{2\mu}\left(\frac{m}{\mu}\right)^{-1/2} e^{-(m/\mu)^{1/2}}. \tag{2}$$