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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Angular Motion Effects on Kinetic Energy Projectile Performance

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Nomenclature

A	= rod cross-sectional area
C_D	= drag coefficient
D, L	= rod diameter, length
m	= rod mass
P, P_0	= penetration depth with, without yaw
R_m	= target tensile strength
V, V_m	= flight, muzzle velocity
x	= downrange distance
θ	= target obliquity angle
λ, ω	= aerodynamic damping, yaw period
ξ	= complex yaw angle, $\beta + i\alpha$
ρ, ρ_p, ρ_t	= air, penetrator, target density

Introduction

DURING development, kinetic energy projectile perforation of a set of real and conceptual targets out to a given range is of primary concern. Free-flight characteristics that influence perforation are drag, angular motion, and bending or flexing. Because perforation is directly related to kinetic energy,[1,2] the decrease in velocity associated with aerodynamic drag reduces effectiveness as the round moves downrange. Efficient penetrators are typically very long slender rods with an aspect ratio greater than 20. Maximum performance is attained when the velocity vector of the round is oriented along the axis of the rod, i.e., zero yaw and zero bending. The present Note makes use of available, empirically based relations[2,3] to describe the perforation behavior of kinetic energy projectiles influenced by drag and angular motion. The case of flexing rods[4,5] is not treated because perforation data are not available for this case. Impact into both normal and oblique incidence rolled homogeneous armor (RHA) targets is considered. Whereas modern armors employ oblique plates, spaced plates, compound armors, explosive reactive armor, and more to avoid the mass penalty of steel, RHA remains a basic measure of penetrator performance and is, for this reason, adopted here.

Normal Incidence

For tungsten alloy long rods, Lanz and Odermatt[2] give an expression for perforation based on a fit to an extensive database:

$$\frac{P_0}{L} = (\cos\theta)^{0.745}\left(\frac{\rho_p}{\rho_t}\right)^{\frac{1}{2}}\exp\left(\frac{-25.9R_m}{\rho_p V^2}\right) \tag{1}$$

The ratio P_0/L increases monotonically from near zero at 500 m/s to a value of about 1.2 at 2500 m/s. The database does not extend beyond this velocity. Because the projectile decelerates under the action of aerodynamic drag, perforation degrades as it moves downrange. Velocity decay at zero yaw can be approximated as

$$\frac{dV}{dx} = -\frac{\rho V_m A C_D}{2m} \tag{2}$$

Simply integrating Eq. (2) and substituting into Eq. (1) provides an expression for perforation as a function of range.

The effect of yaw is treated by Bjerke et al.,[3] who provide a fit to impact data for tungsten alloy rods with an aspect ratio of 30 into RHA:

$$\frac{P}{P_0} = \cos\left(\frac{11.46\xi}{\xi_{\text{crit}}}\right) \tag{3}$$

where ξ_{crit} is the critical yaw at which the rear of the rod just touches the edge of the penetration channel as it passes into the armor. The free-flight angular motion of fin-stabilized projectiles has been measured with high accuracy in ballistic ranges but for developmental designs is typically measured outdoors using yaw cards. In this case, it is fitted to the equation of a damped sinusoid[6]:

$$\xi = \xi_1 e^{-\lambda x/D}\sin(\omega x/D) \tag{4}$$

Use of Eqs. (1–4) permits estimation of the perforation of a yawing rod as it moves downrange. This Note takes as a sample case an $L/D = 30$, $D = 6.5$ mm, tungsten alloy rod launched at 1500 m/s and with an initial yaw rate sufficient to generate a first maximum of yaw of 5 deg. Estimated thickness of normal obliquity RHA perforated is plotted vs range in Fig. 1. Near the weapon, perforation is seriously degraded as yaw builds up toward successive maxima. As the projectile moves downrange, yaw damps and ceases to influence perforation after roughly 0.3 km. However, the perforation continues to decay as the velocity drops due to aerodynamic drag.

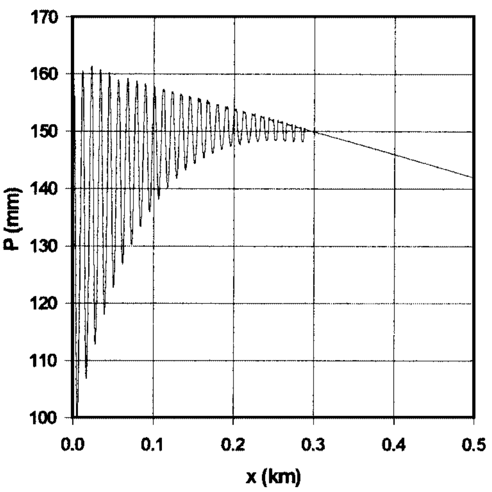

Fig. 1 Perforation at normal incidence.

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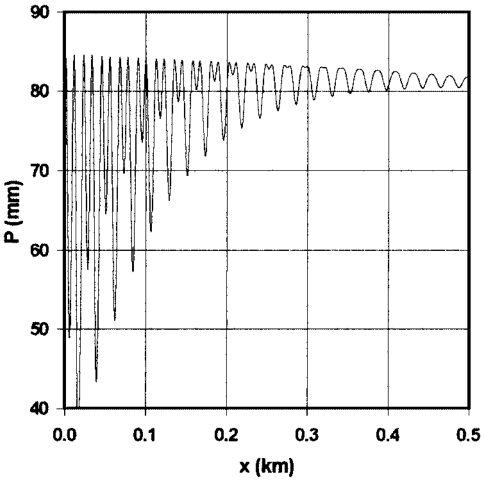

Fig. 2 Perforation into oblique plate.

Oblique Target

In actual usage, normal incidence targets are rarely encountered. Tank frontal armors are highly sloped, and engagements occur at arbitrary angles between combatants. Roecker and Grabarek[7] present data for penetration of yawed tungsten alloy rods into semi-infinite RHA targets at obliquities of 60, 65, and 70 deg. Data are given only in the pitch plane, i.e., the plane containing the surface normal of the plate and the velocity vector of the rod. Examination shows that it is difficult to ascertain a meaningful difference between the data at various obliquities. For this reason, the data are grouped into a single set and fit to the relation

$$P/P_0 = \cos(12.59\alpha - 7.81) \tag{5}$$

To treat combined pitch and yaw, it is necessary to make some assumptions that are not supported by the available data set. It will be assumed that the degradation of perforation due to yaw alone into the oblique plate can be represented by Eq. (3), with P_0 given by Eq. (1). It will further be assumed that the pitch and yaw effects can be separated using the following relation:

$$\frac{P}{P_0} = \cos(12.59\alpha - 7.81)\cos\left(\frac{11.46\beta}{\beta_{\text{crit}}}\right) \tag{6}$$

Whereas this expression cannot be proven to be valid for the oblique plate, this type of separation can be shown to be a reasonable approximation in the case of normal incidence impact if the total yaw is less than 5 deg. Equations (1), (2), and (4–6) permit the calculation of perforation vs range for combined pitching and yawing motion. With the plane of angular motion oriented 45 deg (equal pitch and yaw) from the vertical, the thickness of $\theta = 65$ deg oblique RHA perforated is plotted in Fig. 2. The plot clearly shows the influence of the pitch plane perforation asymmetry, Eq. (5). As the round moves downrange, the perforation is more severely degraded by the adverse pitch states. The reason that the values of P are so much lower in this case is that Eq. (1) gives the thickness of plate perforated, not the line-of-sight perforation.

Conclusions

A method to estimate the effects of free-flight drag and angular motion on perforation is presented. Both normal and oblique impacts are treated. Predictions show that, at discrete ranges, penetrator performance is significantly degraded by angular motion. As range increases, yaw damps, and deceleration due to aerodynamic drag dominates.

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Numerical Study of Hypersonic Rarefied-Gas Flows About a Torus

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Nomenclature

A	= torus base area, $4\pi RH$, m^2
C_f	= local skin-friction coefficient, $\tau_w/q_\infty A$
C_p	= local pressure coefficient, $(p_w - p_\infty)/q_\infty A$
C_x	= drag coefficient
H	= distance between the axis of symmetry and the torus disk center, m
$Kn_{\infty,R}$	= Knudsen number
M	= Mach number
p	= pressure, N/m^2
q_∞	= dynamic pressure, $0.5\rho_\infty u_\infty^2$, N/m^2
R	= radius of a torus disk, 0.1 m
τ_w	= viscous stress at the torus surface, N/m^2

Subscripts

R	= torus disk radius as a length-scale parameter
w	= wall condition
∞	= freestream parameter

Introduction

NUMERICAL and experimental studies of the aerothermodynamics of simple-shape bodies have provided valuable information related to physics of hypersonic flows about spacecraft elements and testing devices.[1–5] Numerous results had been found in the cases of plates, wedges, cones, disks, spheres, and cylinders.[1–7]

In the present study, the hypersonic rarefied-gas flow about a torus has been studied. The flow pattern has not been yet discussed in the research literature. Several features of the flow are unique.

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