A NOTE ON EXPLOSIVES WITH MODIFIED TRUMPET LINERS

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ABSTRACT

The jet formation by explosives with modified trumpet liners has been explained by a simple extension of the non-steady state hydrodynamic theory of jet formation by lined conical cavities. It has been shown that the modified trumpet liners give a greater depth of penetration than a conical liner of the same calibre and height.

The basic theory of jet formation by explosives with lined wedge-shaped or conical cavities was developed by Birkhoff *et al.* (1948) and a simple extension of the theory was presented by Pugh *et al.* (1952) and Eichelberger (1955). Singh (1956) explained the jet formation by lined trumpet cavities. The walls of the trumpet liner were assumed to have a fixed radius of curvature having the centre either in the plane through the apex and parallel to the base of the liner or in the plane of the base of the liner; and such a trumpet liner was found to be inferior in performance to a conical one of the same calibre and height. The present paper describes a modified trumpet liner which gives a greater depth of penetration than a conical one of the same calibre and height.

Text-fig. 1 shows the section of a modified trumpet liner, which is a combination of conical and trumpet liners, having D as the calibre, h the height and a the radius of the flat top. The portions of the liner from A to K and from L to B are conical and the portion from K to L is trumpet in shape. The conical parts AK and LB have apex angles of $2\theta_1$ and $2\theta_2$ respectively. For simplicity in specifications, the trumpet portion of the liner (i.e. from K to L) is assumed to be an arc of a circle of radius R with its centre in the plane of the flat top of the liner. The radius R is given by

$$R = \tfrac{1}{2}\left(\frac{D}{2} - a\right) \operatorname{cosec}^2\alpha \quad \ldots \quad (1)$$

where $\alpha = \tan^{-1}\left[\left(\frac{D}{2} - a\right)\Big/ h\right]$. The positions of K and L which mark the boundaries of the trumpet part are fixed such that the radii OK and OL make angles θ_1 and θ_2 with the radius OA respectively. With this choice, it is clear that KA and LB will be tangential to the circular arc KL.

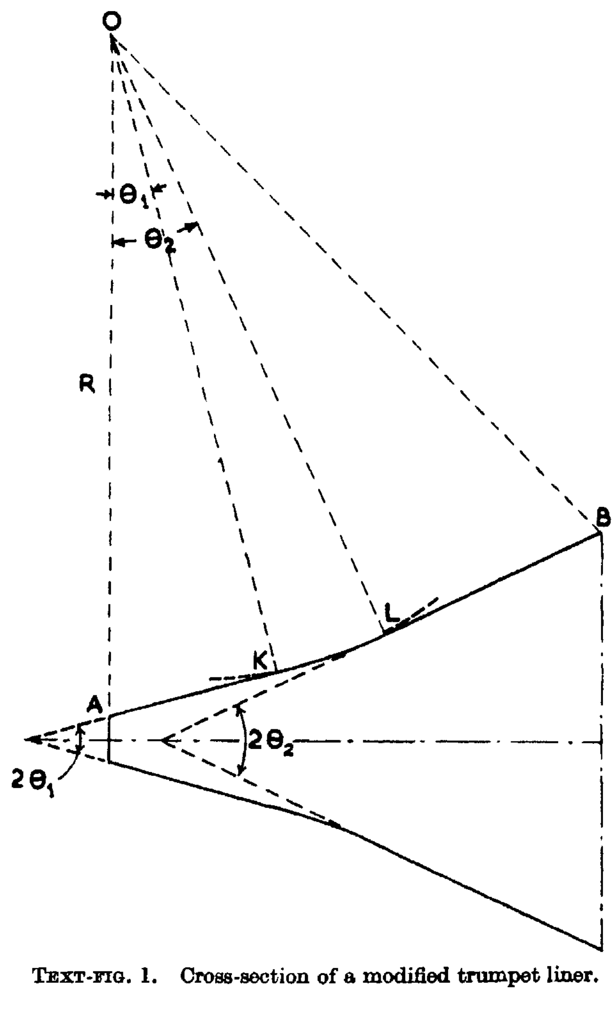
Let us consider the trumpet liner to be divided into small elements and let θ be the angle which an element makes with the axis of propagation of detonation. The angle θ for all the elements in the segments AK and LB are θ_1 and θ_2 respectively, and θ varies from θ_1 to θ_2 in the segment KL. The individual zonal elements are considered independent of one another and all the relations are derived by applying the laws of conservation of mass, momentum, energy and Bernoulli's theorem to individual zonal elements. The arguments given in the earlier paper (Pugh *et al.*, 1952) are then valid and it can be shown that

$$\sin \delta = V_0 \cos \theta / 2U_d \text{ (Taylor's relation)} \quad \ldots \quad (2)$$

$$V_j = V_0 \operatorname{cosec} \frac{\beta}{2} \cos \left(\theta + \delta - \frac{\beta}{2}\right) \quad \ldots \quad (3)$$

$$dm_s/dm = \cos^2 \frac{\beta}{2} \quad \ldots \quad (4)$$

$$dm_j/dm = \sin^2 \frac{\beta}{2} \quad \ldots \quad (5)$$



TEXT-FIG. 1. Cross-section of a modified trumpet liner.

where δ is the angle between the direction an element of the liner travels after being struck by the detonation wave and the normal to the liner surface, V_0 the velocity at which the liner element travels towards the axis, U_d the detonation rate of the explosive, V_j the velocity of the jet element formed, β the angle between the collapsing liner wall and the axis, m_s the mass of the slug, m_j the mass of the jet, and m the mass of the liner. The masses dm_s, dm_j and dm are each functions of x, where x is the length measured from the flat top along the axis to the plane of the zonal element; i.e. dm is the mass of the element of liner included between two planes perpendicular to the axis at x and $x+dx$. β is a variable and is given as a function of x for the segments AK and LB by a more complex formula

$$\tan\beta = \frac{\sin(\theta+2\delta)-(a\cos\theta+x\sin\theta)(1-\tan A\tan\delta)\,V_0'/V_0}{\cos(\theta+2\delta)+(a\cos\theta+x\sin\theta)(\tan A+\tan\delta)\,V_0'/V_0} \quad .. \quad (6)$$

where $V_0' = \partial V_0/\partial x$ and $A = \theta+\delta$. β for the segment KL is given as follows

$$\tan\beta = \frac{\sin(\theta+2\delta)-(1-\cos\theta+a/R)(V_0'/V_0-A'\tan A)}{\cos(\theta+2\delta)+(1-\cos\theta+a/R)(V_0'\tan A/V_0+A')} \quad .. \quad (7)$$

$$\text{where } V_0' = \frac{\partial V_0}{\partial\theta} = R\cos\theta\frac{\partial V_0}{\partial x}$$

$$A' = \frac{\partial A}{\partial\theta} = 1+\frac{V_0'\cos\theta - V_0\sin\theta}{2U_d\cos\delta}$$

$$\text{and } x = R\sin\theta$$

Pugh *et al.* (1952) have shown that the collapse velocities decrease continuously from the apex to the base since near the base the belt of explosive surrounding the liner is much thinner and the masses of the liner elements are much greater than near the apex. Recently Singh (1955) suggested a relation between the collapse velocity of a metal plate and the angle, θ, which the plate subtends with the axis of propagation of detonation and is as follows

$$V_0 = \tfrac{1}{4}U_d(1+\sin\theta) \quad .. \quad .. \quad .. \quad .. \quad (8)$$

This suggests that the collapse velocity is a function not only of U_d and θ but also of dm and dE the masses of the elements of liner and explosive respectively between two planes perpendicular to the axis at x and $x+dx$. We may therefore write

$$V_0 = f(\theta, U_d, dm, dE). \quad .. \quad .. \quad .. \quad .. \quad (9)$$

By dimensional analysis, it follows that this relation must have the form

$$\frac{V_0}{U_d} = f\left(\theta, \frac{dm}{dE}\right). \quad .. \quad .. \quad .. \quad .. \quad (10)$$

However, since the θ dependence must have the form (8), which is found to be correct for the known experimental data, so that $dE\to\infty$ for each element. We must stipulate that

$$f\left(\theta, \frac{dm}{dE}\right) \to \tfrac{1}{4}(1+\sin\theta) \text{ when } \frac{dm}{dE}\to 0. \quad .. \quad .. \quad (11)$$

In accordance with this requirement we may therefore write

$$\frac{V_0}{U_d} = \frac{\tfrac{1}{4}(1+\sin\theta)}{\phi\left(\frac{dm}{dE}\right)} \quad .. \quad .. \quad .. \quad .. \quad (12)$$

where

$$\phi(o) = 1. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (13)$$

There seems to be no way of theoretically predicting the form of the function ϕ. In general we may express ϕ in the form of a series

$$\phi\left(\frac{dm}{dE}\right) = a_0+a_1\left(\frac{dm}{dE}\right)+a_2\left(\frac{dm}{dE}\right)^2+\dots \quad .. \quad .. \quad (14)$$

By condition (13), $$a_0 = 1. \quad .. \quad .. \quad .. \quad .. \quad .. \quad (15)$$

In the absence of a theoretical expression for ϕ, the only feasible method for determining the form of this function seems to be to fit an expression of the type (14) to the available experimental values of $\frac{1}{4} U_d(1+\sin\theta)/V_0$. The data chosen relate to the standard $M9A1$ steel liner in the standard C.I.T. laboratory charge and take Eichelberger's (1955) published values of V_0, β and V_j as a function of x. With these data, a polynomial of the fourth degree in dm/dE was found, by a least-squares fitting, to give a leading coefficient a_0 approximately equal to 1. The resulting expression for V_0 is

$$V_0 = \frac{\frac{1}{4} U_d(1+\sin\theta)}{1{\cdot}03-0{\cdot}786\left(\frac{dm}{dE}\right)+6{\cdot}217\left(\frac{dm}{dE}\right)^2-7{\cdot}79\left(\frac{dm}{dE}\right)^3+3{\cdot}775\left(\frac{dm}{dE}\right)^4} \quad .. \quad (16)$$

where $$dm = \pi\, dx \tan\theta d_1 \sec\theta\rho(2x+2a\cot\theta+dx-d_1\operatorname{cosec}\theta),$$

$$dE = \pi\, dx\, \rho_E\left[\frac{D^2}{4}-\tan^2\theta\left\{(x+a\cot\theta)^2+dx\left(x+a\cot\theta+\frac{1}{3}dx\right)\right\}\right]$$

and d_1 is the thickness of the metal liner, and ρ and ρ_E are the densities of the liner metal and the explosive respectively. For numerical evaluation, we take a steel modified trumpet liner having the calibre, height and radius of the flat top to be the same as that of the standard $M9A1$ steel liner, and θ_1 and θ_2 to be 15° and 25° respectively, and wall thickness to be 0·037 in. ρ and ρ_E are taken as 7·8 gm. cm.$^{-3}$ and 1·66 gm. cm.$^{-3}$ respectively. As a first approximation, we assume that V_0 for different elements of the modified liner is given by eq. (16), β is given by eq. (6) or eq. (7) and V_j and δ are given by eqs. (3) and (2) respectively. Knowing the collapse parameters (V_0, β and V_j as a function of x) of the modified trumpet liner, the depth of penetration can be evaluated (Singh, 1957). The calculated depth of penetration indicates that the modified trumpet liner is superior in performance ($\sim$ 7 per cent) to the conical liner. By static firings of shaped charges having the conical and the modified trumpet liners, we have shown that the modified trumpet liner gives a greater depth of penetration than the conical liner, especially at low standoffs. The superiority of modified trumpet liners to conical ones have been further confirmed by static firings of shaped charges of bigger calibres.

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