BALLISTIC EFFECTS OF BORE RESISTANCE

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1. Introduction

Corner (1949) made a valuable contribution to the important Internal Ballistics problems of bore resistance, when he gave his 'weighing-factor' method of discussing the ballistic effects of bore resistance and illustrated it by using it for determining the disturbance in the muzzle velocity caused by a concentrated bore resistance as well as by long stretches of bore resistance. Recently Tawakley (1956) extended Corner's method for a single charge to a composite charge consisting of two component charges with form-functions in the standard quadratic form $z = (1-f)(1+\theta f)$. However, the ballistic effects of bore resistance were not explicitly deduced either by Corner or by Tawakley; their results having been expressed in terms of mathematical formulae, which, in their treatments, are not always very simple.

In the present paper, we extend Corner's method to apply to a charge with the general form-function $z = \phi(f)$ and obtain some interesting and useful general results about the effects of bore resistance on:

(i) the magnitude of the maximum pressure;
(ii) shot-travel till the instant of maximum pressure:
(iii) fraction of the charge burnt till this instant;
(iv) velocity at this instant;
(v) shot-travel till the instant of all-burnt;
(vi) pressure at all-burnt;
(vii) time till all-burnt;
(viii) velocity at all-burnt;
(ix) muzzle velocity.

The results are obtained under certain assumptions which are shown to be quite plausible and likely to hold in all cases of practical importance.

2. The Fundamental Equations and their Integrations:

The basic equations, with bore resistance, are:

$$FCz = Ap(x+l)\,\frac{W_1+\frac{1}{3}C}{W_1+\frac{1}{2}C}+\tfrac{1}{2}(\bar{\gamma}-1)(W_1+\tfrac{1}{3}C)v^2+Ap_0\Delta x \quad .. \quad (1)$$

$$(W_1+\tfrac{1}{3}C)\,\frac{dv}{dt} = Ap \quad .. \quad .. \quad .. \quad .. \quad (2)$$

$$D\,\frac{df}{dt} = -\beta p \quad .. \quad .. \quad .. \quad .. \quad (3)$$

$$z = \phi(f) \quad .. \quad .. \quad .. \quad .. \quad (4)$$

Before bore resistance acts, the above equations hold with $AP_0\Delta x$ absent from (1). If V_0 and V_1 denote velocities just before and after the action of resistance, we have

$$\tfrac{1}{2}(W_1+\tfrac{1}{3}C)V_1^2 = \tfrac{1}{2}(W_1+\tfrac{1}{3}C)V_0^2-AP_0\Delta x \qquad (5)$$

Now we make the substitutions

$$\xi = 1+\frac{x}{l} \qquad (6)$$

$$\eta = \frac{AD}{FC\beta}\,\frac{W_1+\frac{1}{3}C}{W_1+\frac{1}{2}C}\,v \qquad (7)$$

$$\zeta = \frac{Al}{FC}\,\frac{W_1+\frac{1}{3}C}{W_1+\frac{1}{2}C}\,p \qquad (8)$$

$$M = \frac{A^2D^2}{W_1FC\beta^2}\,\frac{1+\dfrac{C}{3W_1}}{\left(1+\dfrac{C}{2W_1}\right)} \qquad (9)$$

$$R = \frac{AP_0\Delta x}{FC} \qquad (10)$$

so that ξ, η, ζ are dimensionless variables corresponding to shot-travel, velocity and pressure respectively, M is the dimensionless central ballistic parameter, and R is a dimensionless constant corresponding to the bore resistance.

Integrating and keeping only the first order terms, as in Corner (1949) we get

$$z = \zeta\xi+\tfrac{1}{2}(\bar{\gamma}-1)\frac{\eta^2}{M}+(\bar{\gamma}-1)R \qquad (11)$$

$$\eta = M(1-f)-\frac{R}{1-f_0} \qquad (12)$$

$$\int_1^{\xi}\frac{d\xi}{\xi} = -M\int_1^{f}\frac{df}{Z}+\frac{R}{1-f_0}\left[\int_{f_0}^{f}\frac{df}{Z(1-f)}+M(\bar{\gamma}-1)\int_{f_0}^{f}\frac{(f_0-f)df}{Z^2(1-f)}\right] \qquad (13)$$

where f_0 is the value of f at the instant when the bore resistance acts and

$$Z(1-f) = \phi(f)-\tfrac{1}{2}(\bar{\gamma}-1)M(1-f)^2 \qquad (14)$$

From (11) and (12)

$$z = \zeta\xi+\tfrac{1}{2}(\bar{\gamma}-1)M(1-f)^2-\frac{(\bar{\gamma}-1)R(f_0-f)}{1-f_0} \qquad (15)$$

From (13)

$$\log\xi = -[\Phi(f)-\Phi(1)]+R[\Psi(f)-\Psi(f_0)], \qquad (16)$$

where

$$\Phi(f) = M\int_{f_0}^{f}\frac{1}{Z}\,df \qquad (17)$$

$$\Psi(f) = \frac{1}{1-f_0}\left\{\int_k^f\frac{df}{Z(1-f)}+M(\bar{\gamma}-1)\int_k^f\frac{(f_0-f)\,df}{Z^2(1-f)}\right\}, \qquad (18)$$

where k is a suitable constant less than unity.

After all-burnt $z = 1$, and we have

$$d(\zeta\,\xi^{\bar\gamma}) = 0$$

$$\therefore\quad \zeta\,\xi^{\bar\gamma} = \zeta\quad \xi^{\bar\gamma}_{\bar 2} \qquad \ldots \qquad (19)$$

where the suffix $\bar 2$ corresponds to the position at all-burnt.

From (11), we get for motion after all-burnt.

$$\eta^2 = \frac{2M}{\bar\gamma - 1}\,[1 - \zeta\,\xi - (\bar\gamma - 1)R]. \qquad \ldots \qquad (20)$$

Therefore if suffix $\bar 3$ corresponds to the muzzle

$$\eta^2_{\bar 3} = \frac{2M}{\bar\gamma - 1}\left[1 - \frac{\zeta_{\bar 2}\,\xi^{\bar\gamma}_{\bar 2}}{\xi^{\bar\gamma - 1}_{\bar 3}}\right] - 2MR. \qquad \ldots \qquad (21)$$

But at all-burnt (15) gives

$$1 = \zeta_{\bar 2}\,\xi_{\bar 2} + \tfrac{1}{2}(\bar\gamma - 1)M - \frac{(\bar\gamma - 1)Rf_0}{1 - f_0}$$

$$\therefore\quad \eta^2_{\bar 3} = \frac{2M}{\bar\gamma - 1}\left\{1 - \left(1 - \tfrac{1}{2}(\bar\gamma - 1)M + \frac{(\bar\gamma - 1)Rf_0}{1 - f_0}\right)\left(\frac{\xi_{\bar 2}}{\xi_{\bar 3}}\right)^{\bar\gamma - 1}\right\} - 2MR. \qquad (22)$$

Again from (15)

$$\zeta = \frac{\phi(f) - \tfrac{1}{2}(\bar\gamma - 1)M(1 - f)^2 + \dfrac{(\bar\gamma - 1)R(f_0 - f)}{1 - f}}{\xi} \qquad \ldots \qquad (23)$$

Therefore pressure would be maximum when

$$\frac{\phi'(f) + (\bar\gamma - 1)M(1 - f) - \dfrac{(\bar\gamma - 1)R}{1 - f_0}}{Z(1 - f) + \dfrac{(\bar\gamma - 1)R(f_0 - f)}{1 - f_0}} + \frac{M}{Z} - \frac{R}{1 - f_0}\times$$

$$\times\left\{\frac{1}{Z(1 - f)} + M(\bar\gamma - 1)\,\frac{f_0 - f}{Z^2(1 - f)}\right\} = 0 \qquad \ldots \qquad (24)$$

Let $f_{\bar m}$ be the solution of (24). Substituting $f_{\bar m}$ for f in (23) and using (16), we get the value of the maximum pressure.

3. Ballistic Effects of Bore Resistance

3.1. *Assumptions made:*

From (14) and (15)

$$Z(1 - f) = \zeta\,\xi - \frac{(\bar\gamma - 1)R(f_0 - f)}{1 - f_0} \qquad \ldots \qquad (25)$$

When $R = 0$, (25) shows that Z is always positive. The same conclusion follows from (13), as when $R = 0$, it gives

$$\frac{d\xi}{df} = -\frac{M\xi}{Z},$$

and since ζ increases as f decreases, Z must be always positive. When R is not necessarily zero (14) gives

$$Z(1-f) = [\phi(f)-(1-f)^2]+(1-f)^2[1-\tfrac{1}{2}(\bar{\gamma}-1)M] \quad .. \quad .. \quad (26)$$

In all problems of practical interest, $\bar{\gamma}-1$ has a value in the neighbourhood of ·3 and M lies between 1 and 5. For this range

$$1-\tfrac{1}{2}(\bar{\gamma}-1)M > 0 \quad .. \quad .. \quad .. \quad .. \quad (27)$$

Next we examine the sign of $\phi(f)-(1-f)^2$ for the standard quadratic form-function. In this case

$$\phi(f)-(1-f)^2 = (1-f)(1+\theta)f$$

and as $1+\theta \geqslant 0$, we have

$$\phi(f)-(1-f)^2 \geqslant 0 \quad .. \quad .. \quad .. \quad .. \quad (28)$$

For the cubic form-function

$$z = (1-f)(1+\theta f+\psi f^2), \quad .. \quad .. \quad .. \quad .. \quad (29)$$

we have

$$Z(1-f) = [1-\tfrac{1}{2}(\bar{\gamma}-1)M][1-f]+f[1+\theta+\psi]-f\psi(1-f) \quad .. \quad (30a)$$

$$= [1-\tfrac{1}{2}(\bar{\gamma}-1)M][1-f]+f(1+\theta)+\psi f^2 \quad .. \quad .. \quad .. \quad (30b)$$

We also know that if (29) is to represent a possible form-function

$$1+\theta+\psi > 0 \quad .. \quad .. \quad .. \quad .. \quad (31)$$

Now

(i) if $\psi \leqslant 0$, (27), (30a) and (31) show that $Z > 0$,

(ii) if $\psi > 0$ and $\theta \geqslant -1$, (27) and (30b) show that $Z > 0$,

(iii) if $\psi > 0$, $\theta < -1$, $1+\theta+\psi \geqslant 0$, Z may be negative.

The last case, however, is not satisfied, by any known geometrical form used in guns, and thus is of no practical interest.

Actually for all the form-functions used in practice, (28) is always satisfied.

In all our further discussions, we shall be making the assumptions

$$1-\tfrac{1}{2}(\bar{\gamma}-1)M > 0$$

$$\phi(f) \geqslant (1-f)^2 \text{ for } 0 \leqslant f \leqslant 1.$$

We have seen that both these assumptions are satisfied in all cases of practical interest.

Subject to these assumptions, (26) shows that Z is always a positive function of f.

That Z should be positive throughout is also seen from the integrals in (13). When $f = f_0$, (25) shows that Z is positive, and when $f = 0$, (26) shows (subject to assumptions (27) and (28)) that Z is again positive. If Z becomes negative anywhere between f_0 and 0, it has to vanish somewhere in this range and, in that case, the integrals on the R.H.S. of (13) would become divergent.

3.2. *Shot-travel for any given f :*

Let ΔX denote the change in any variable X on account of bore resistance, then from (13) and (16)

$$\Delta (\log \xi) = \frac{R}{1-f_0} \left\{ \int_{f_0}^{f} \frac{df}{Z(1-f)} + M(\bar{\gamma}-1) \int_{f_0}^{f} \frac{(f_0-f)df}{Z^2(1-f)} \right\} \quad .. \quad (32a)$$

$$= R\{\Psi(f)-\Psi(f_0)\} \quad .. \quad .. \quad .. \quad .. \quad .. \quad (32b)$$

Since Z is positive throughout the range f_0 to f, (32a) shows that Δ (log ξ) is negative. Thus we state

(i) *For any given f or z, the effect of bore resistance is to decrease the shot-travel.*

(ii) *Conversely, for any given shot-travel, a greater fraction of the charge would be burnt on account of bore resistance.*

Again from (13)

$$\frac{1}{\xi}\frac{d\xi}{dz} = \frac{1}{\phi'(f)} \left\{ -\frac{M}{Z} + \frac{R}{1-f_0} \left[\frac{1}{Z(1-f)} + \frac{M(\bar{\gamma}-1)(f_0-f)}{Z^2(1-f)} \right] \right\} \quad .. \quad (33)$$

$$\therefore \Delta \left(\frac{d}{dz} \log \xi \right) = \frac{1}{\phi'(f)} \frac{R}{1-f_0} \left\{ \frac{Z+M(\bar{\gamma}-1)(f_0-f)}{Z^2(1-f)} \right\} \quad .. \quad .. \quad (34)$$

Since $\phi'(f)$ is negative, (34) shows that

(iii) *The effect of bore resistance is to decrease the slope of the $\xi - z$ curve.*

The above three results are illustrated in Fig. 1, where the dotted curve gives the $\xi - z$ curve with bore resistance at point where $z = z_0$

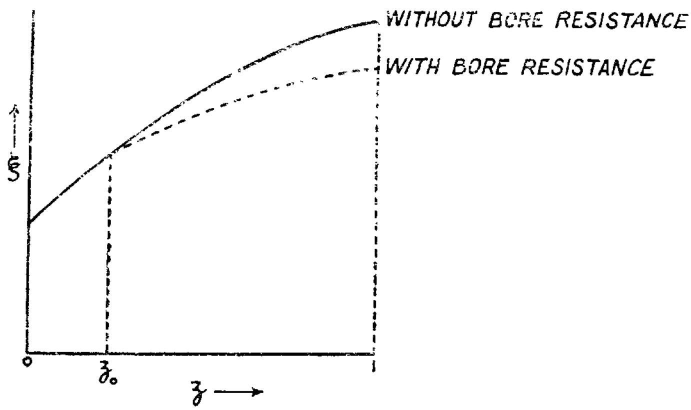

FIG. 1

3.3. *Pressure for any given f :*

From (5), we have at any time

$$\zeta = \frac{\phi(f) - \frac{1}{2}(\bar{\gamma}-1)M(1-f)^2 + (\bar{\gamma}-1)R\,\dfrac{f_0-f}{1-f_0}}{\xi} \quad .. \quad .. \quad (35)$$

$$\therefore \quad \Delta(\log \zeta) = \frac{(\bar{\gamma}-1)R\dfrac{f_0-f}{1-f_0}}{Z(1-f)} - \frac{\Delta \xi}{\xi}$$

$$= \frac{(\bar{\gamma}-1)R(f_0-f)}{(1-f_0)Z(1-f)} - R[\Psi(f)-\Psi(f_0)] \quad .. \quad .. \quad .. \quad (36)$$

Since $\Delta\xi/\xi$ is negative, it follows from (36) that $\Delta\zeta/\zeta$ is positive. Thus we have

(iv) *For any given f, the pressure is greater on account of bore resistance.*

(v) *Conversely for any given pressure, a smaller fraction of the charge would be burnt on account of bore resistance.*

The results are illustrated in Fig. 2.

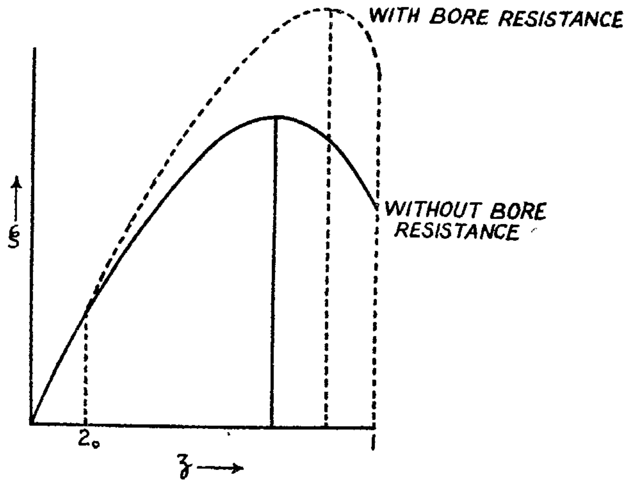

FIG. 2

3.4. *Velocity for any given f:*

From (12), it follows that

(vi) *For any given f or z, the velocity is decreased by bore resistance.*

The result is illustrated in Fig. 3.

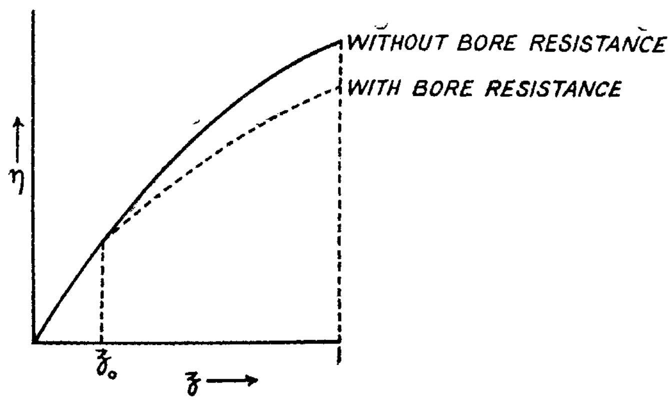

FIG. 3

3.5. *Maximum pressure:*

From (24), neglecting squares and higher powers of R, we find that maximum pressure occurs when

$$\phi'(f)+(\bar{\gamma}-1)M(1-f)+M(1-f)$$
$$+\frac{R}{1-f_0}\left\{-(\bar{\gamma}-1)-(\bar{\gamma}-1)\frac{f_0-f}{Z(1-f)}[\phi'(f)+(\bar{\gamma}-1)M(1-f)]\right.$$
$$\left.-1-\frac{M(\bar{\gamma}-1)(f_0-f)}{Z}\right\}=0. \quad \ldots \quad (37)$$

If $R = 0$, maximum pressure occurs when $f = f_{\bar{m}}$, where

$$\phi'(f_{\bar{m}})+\bar{\gamma}M(1-f_{\bar{m}}) = 0 \quad \ldots \quad (38)$$

When $R \neq 0$, let maximum pressure occur when

$$f = f_{\bar{m}}+AR \quad \ldots \quad (39)$$

Substituting in (37) and simplifying, we get

$$A = \frac{\bar{\gamma}}{(1-f_0)(\phi''(f_{\bar{m}})-\bar{\gamma}M)} \quad \ldots \quad (40)$$

Now for the quadratic form-function

$$\phi''(f_{\bar{m}})-\bar{\gamma}M = -2\theta-\bar{\gamma}M$$

and is thus negative for all degressive, constant-burning and moderately progressive burning surfaces.

Similarly for the cubic form-function (29)

$$\phi''(f_{\bar{m}})-\bar{\gamma}M = -2[(\theta-\psi)+3\psi f_{\bar{m}}]-\gamma\bar{M}$$

For almost all forms used in practice (tube, cord, ribbon, square flake, sphere, cube) $\psi > 0$, $\theta \geqslant \psi$ and thus the R.H.S. is negative. Thus for all cases of practical importance, we are justified in assuming

$$\phi''(f_{\bar{m}})-\bar{\gamma}M < 0 \quad \ldots \quad (41)$$

With this assumption A is negative, and we can state

(vii) *The effect of bore resistance is that the maximum pressure occurs when a greater fraction of the charge has been burnt.*

Combining the results of (iv) and (vii), we get

(viii) *The effect of bore resistance is to increase the maximum pressure.*

Results (vii) and (viii) are illustrated in Fig. 2.

Now the shot-travel till the instant of maximum pressure is given by

(i) $\log \xi_{\bar{m}} = -[\Phi(f_{\bar{m}})-\Phi(1)]$ without bore resistance

and by (ii)

$$\log \xi'_{\bar{m}} = -[\Phi(f_{\bar{m}}+AR)-\Phi(1)] + R[\Psi(f_{\bar{m}})-\Psi(f_0)] \quad \text{with bore resistance}$$

$$\therefore \quad \Delta\left[\log \xi_{\bar{m}}\right] = -AR\Phi'(f_{\bar{m}})+R[\Psi(f_{\bar{m}})-\Psi(f_0)]$$

$$= -\frac{ARM}{Z_{\bar{m}}}+\frac{R}{1-f_0}\left\{\int_{f_0}^{f_{\bar{m}}}\frac{df}{Z(1-f)}+M(\bar{\gamma}-1)\int_{f_0}^{f_{\bar{m}}}\frac{(f_0-f)df}{Z^2(1-f)}\right\} \quad .. \quad (42a)$$

$$= \frac{R}{1-f_0}\left\{\frac{\bar{\gamma}M}{Z_{\bar{m}}[-\phi''(f_{\bar{m}})+\bar{\gamma}M]}+\right.$$

$$\left. +\int_{f_0}^{f_{\bar{m}}}\frac{df}{Z(1-f)}+M(\bar{\gamma}-1)\int_{f_0}^{f_{\bar{m}}}\frac{(f_0-f)df}{Z^2(1-f)}\right\} \quad .. \quad (42b)$$

On the R.H.S. of (42*b*), the first term is positive and the second and third terms are negative. Thus

(ix) *The shot-travel till the instant of maximum pressure increases or decreases according as*

$$\left\{\frac{\bar{\gamma}M}{Z_{\bar{m}}[\bar{\gamma}M-\phi''(f_{\bar{m}})]}+\int_{f_0}^{f_{\bar{m}}}\frac{df}{Z(1-f)}+(\bar{\gamma}-1)M\int_{f_0}^{f_{\bar{m}}}\frac{df(f_0-f)}{Z^2(1-f)}\right\} \gtrless 0 \quad .. \quad (43)$$

Also from (36), for increment in maximum pressure, we have

$$\Delta\left[\log \zeta_{\bar{m}}\right]$$

$$= R\left\{\frac{(\bar{\gamma}-1)(f_0-f_{\bar{m}})}{(1-f_0)[\phi(f_{\bar{m}})-\frac{1}{2}(\bar{\gamma}-1)M(1-f_{\bar{m}})^2]-[\Psi(f_{\bar{m}})-\Psi(f_0)]}\right\} \quad .. \quad (44)$$

3.6. *All-burnt position :*

The position corresponds to $z = 1$ or $f = 0$ and for this we deduce from results (i), (iv) and (vi)

(x) *The shot-travel till all-burnt is decreased by bore resistance or the effect of bore resistance is to make the all-burnt position occur earlier in the gun.*

(xi) *The pressure at all-burnt is increased by bore resistance.*

(xii) *The velocity at all-burnt is decreased by bore resistance.*

Again from (3)

$$\int_{t_0}^{t} dt = -\frac{D}{\beta}\int_{f_0}^{f}\frac{df}{p} \quad .. \quad .. \quad .. \quad .. \quad (45)$$

Since the effect of bore resistance is to increase p as a function f, (45) shows that for any given f, the time is decreased. Thus

(xiii) *For any given f or z, the time is decreased by bore resistance.*

(xiv) *Conversely at any given time t, the greater fraction of the charge has been burnt till that time.*

(xv) *In particular the all-burnt position occurs earlier in time.*

Combining the results of (iv) and (xiv)

(xvi) *At any given t, the pressure is greater on account of bore resistance.*

The results are illustrated in Figs. 4 and 5.

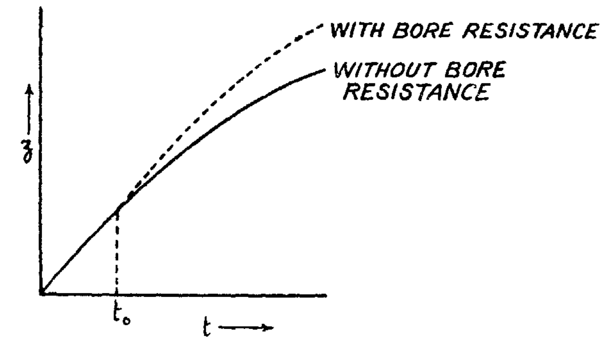

FIG. 4

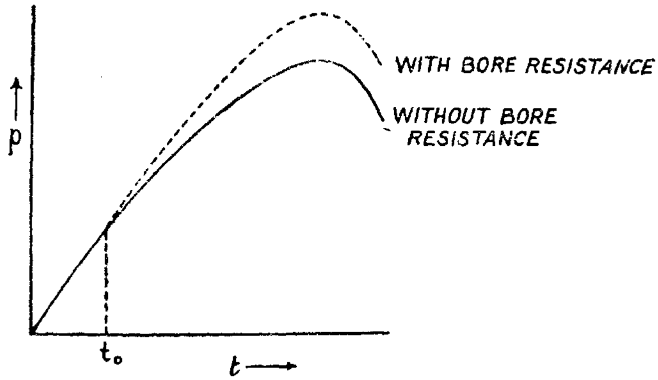

FIG. 5

3.7. *Muzzle velocity :*

From (23)

$$\Delta\,(\eta_3^2) = -\frac{2MRf_0}{1-f_0}\left(\frac{\xi_{\bar{2}}}{\xi_{\bar{3}}}\right)^{\bar{\gamma}-1} - 2MR$$

$$-2M(1-\tfrac{1}{2}(\bar{\gamma}-1)M)\left(\frac{\xi_{\bar{2}}}{\xi_{\bar{3}}}\right)^{\bar{\gamma}-1} R[\Psi(0)-\Psi(f_0)]$$

$$= -2MR\left\{1+\frac{f_0}{1-f_0}\left(\frac{\xi_{\bar{2}}}{\xi_{\bar{3}}}\right)^{\bar{\gamma}-1}\right.$$

$$\left.-(1-\tfrac{1}{2}(\bar{\gamma}-1)M)\left(\frac{\xi_{\bar{2}}}{\xi_{\bar{3}}}\right)^{\bar{\gamma}-1}[\Psi(f_0)-\Psi(0)]\right\} \quad \ldots \quad \ldots \quad (46)$$

Here $\xi_{\bar{2}}$ is the undisturbed value corresponding to shot-travel till all-burnt.

Since $\Psi(f_0)-\Psi(0)$ is positive, the muzzle velocity may increase or decrease. Physically speaking, the muzzle velocity decreases on account of the fact that the velocity at burnt is smaller and increases as the all-burnt position occurs earlier. The relative importance of these factors is given by the first two terms and the third term respectively on the R.H.S. of (46).

3.8 *Particular case of a quadratic form-function*

If

$$z = (1-f)(1+\theta f),$$

then

$$Z = 1-\tfrac{1}{2}(\bar{\gamma}-1)M+\theta_1 f, \quad \ldots \quad (47)$$

where

$$\theta_1 = \theta+\tfrac{1}{2}(\bar{\gamma}-1)M \quad \ldots \quad (48)$$

and

$$\Phi(f) = \frac{M}{\theta_1}\log\{1-\tfrac{1}{2}(\bar{\gamma}-1)M+\theta_1 f\}, \quad [\theta_1 \neq 0] \quad \ldots \quad (49a)$$

$$= \frac{M}{1-\tfrac{1}{2}(\bar{\gamma}-1)M}f, \quad [\theta_1 = 0] \quad \ldots \quad (49b)$$

and

$$\Psi(f) = \frac{1}{(1-f_0)(1+\theta)^2}\left\{(1+\theta)-(\bar{\gamma}-1)M(1-f_0)\log\frac{Z}{1-f} - \frac{[(1+\theta)-\theta_1(1-f_0)]}{\theta_1}(1+\theta)\frac{1}{Z}M(\bar{\gamma}-1)\right\}_k^f, \quad [\theta_1 \neq 0] \quad \ldots \quad (50a)$$

and

$$\Psi(f) = \frac{1}{(1-f_0)[1+\tfrac{1}{2}(\bar{\gamma}-1)M]^2}\left\{M(\bar{\gamma}-1)f+\log(1-f)[M(\bar{\gamma}-1)(1-f_0)- -1-\tfrac{1}{2}(\bar{\gamma}-1)M]\right\}_k^f, \quad [\theta_1 = 0] \quad \ldots \quad (50b)$$

For the cubic form-function

$$Z = (1-\tfrac{1}{2}(\bar{\gamma}-1)M)+f\theta_1+\psi f^2 \quad \ldots \quad (51)$$

and the definite integrals in (13) can easily be integrated in finite terms.

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Abstract

Corner's first-order weighing-factor method of discussing bore resistance has been generalised to the case when the component charges may have general form-functions and from these some general results about ballistic effects of bore resistance on maximum pressure, all-burnt position and muzzle velocity have been obtained under assumptions which are shown to be extremely plausible.

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