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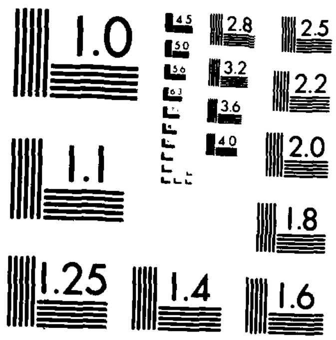

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TECHNICAL REPORT ARCCB-TR-87028

TRAVELLING WAVE RESONANCE IN GUN TUBES

T. E. SIMKINS

OCTOBER 1987

US ARMY ARMAMENT RESEARCH, DEVELOPMENT
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Moving Pressure

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experimental and analytical studies have verified the existence of high amplitude dynamic strains in large caliber gun tubes. These strains have been observed to travel with the projectile as axially symmetric waves and are large enough to exceed the yield stress of the gun tube material and become even larger as the wave reflects from the muzzle. The possibility for such waves in cylinders has been known since 1964 and physical evidence for their existence in gun tubes was first reported in 1978 and in 1986 by the

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20. ABSTRACT (CONT'D)

author. These waves not only create strains higher than those for which the gun tube is designed, but are capable through coupling of producing beam-like motions affecting projectile launch conditions. Muzzle motions affecting round accuracy have long been suspect and their spurious character has evaded the most arduous attempts to predict them.

The existence of large amplitude dynamic strains in gun tubes implies a projectile environment more hostile than previously supposed. Designers of projectile casings, warheads, fuzes, etc., should be interested in these ramifications as should those concerned with projectile/tube friction and wear.

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INTRODUCTION

The work presented herein was motivated by a series of unusual strain data collected during a series of test firings of a 120-mm gun tube at Aberdeen Proving Ground (APG) during the latter part of 1985. During these tests, circumferential strains exceeding three times those predicted by the customary Lame´ design formula (ref 1) were recorded from the outer surface of this tube a few feet from the muzzle. The strain data was unusual in that a very sudden strain 'spike' was recorded as the projectile passed the gage location (see Figure 1). Initially it was thought that this spike might be due to faulty gage bonds, electrical interference, etc. Subsequent verification of the data, however, resulted from additional measurements in which displacement eddy probes located close to the strain gages showed surface displacements in very good agreement with those predicted by the strain gages. The 'spike' was real.

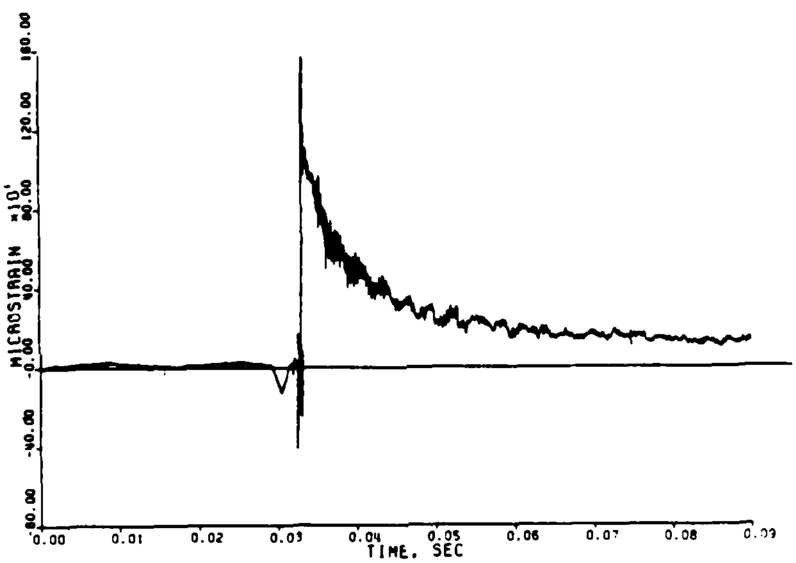


Figure 1. Typical Strain Record.

References are listed at the end of this report.

As more data was accumulated, analysis showed a strong dependency of the strain magnitudes on projectile velocity (see Figure 2), and it was this feature more than any other which guided the research reported herein.

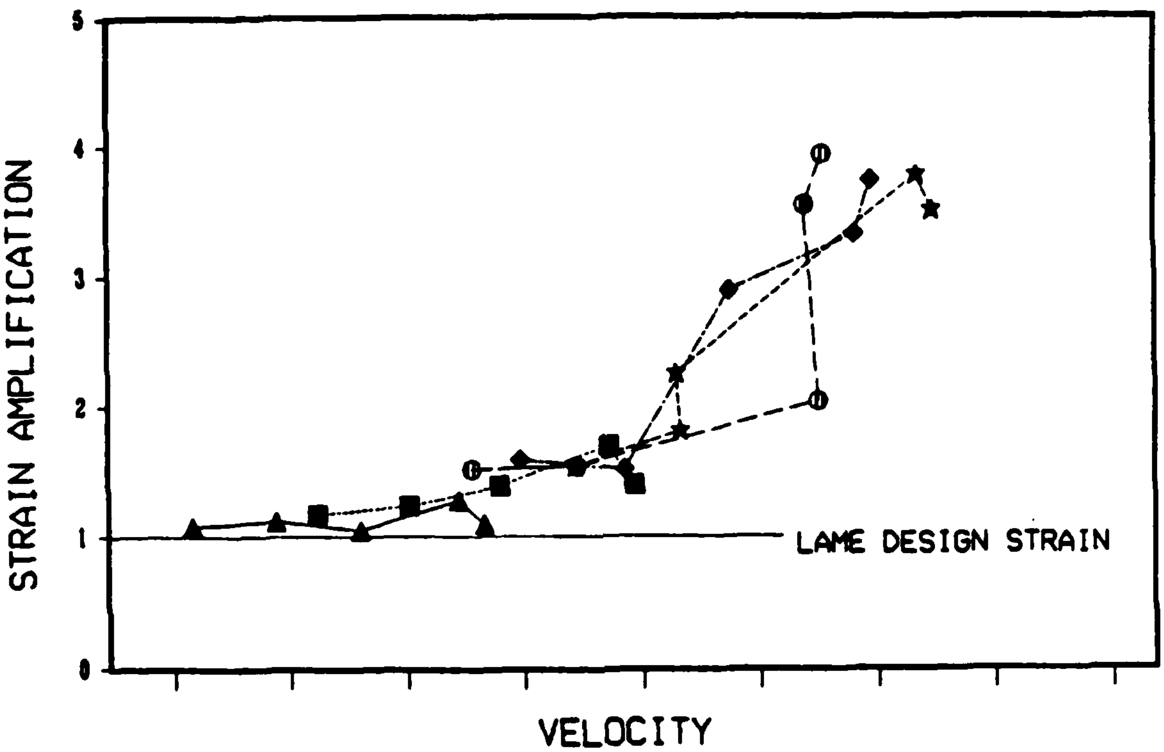
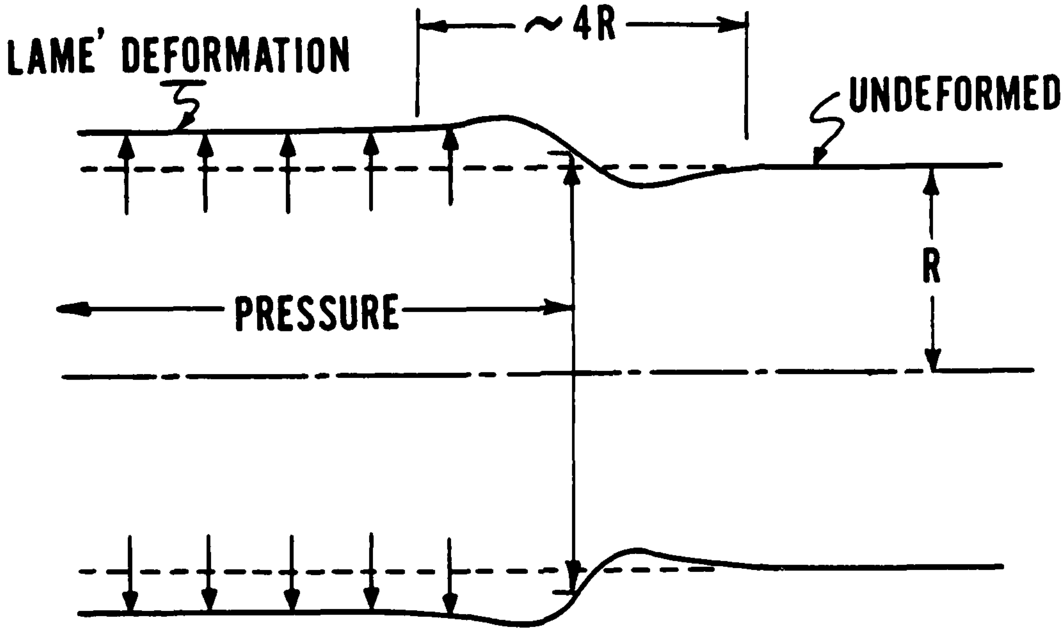


Figure 2. Strain Dependence on Projectile Velocity.

HYPOTHESIS

The key idea to be explored was that there may be a limit as to how fast the tube deformation - in the immediate vicinity of the projectile - could be made to travel before some sort of a wave would develop. An exaggerated view of this deformation when the projectile velocity is low is shown in Figure 3.



DEFORMATION OF BORE SURFACE
(STATIC)

Figure 3

Under these 'quasi-static conditions', the deviation from the Lame´ predicted deformation is less than three percent. A search of the literature showed that this idea had received attention at least thirty years ago, although not with application to gun tubes. According to the literature (refs 2-5), there is indeed a critical projectile speed at which one can anticipate a resonance phenomenon accompanied by very high strain levels within the tube wall.

VERIFICATION

Calculations based on much simplified thin-walled shell equations showed that the strain data of Figure 1 was much too compressed in the time scale to ascertain even a qualitative resemblance to the strain versus time predicted by the 'critical velocity' theory. In April 1986, new test firings were therefore conducted for the purpose of gaining more detail to the tube response at the instant of projectile passage. The results showed the 'spike' not to be a spike at all - but a high amplitude, high frequency (approximately 15 khz) strain very close to that predicted by the 'critical velocity' theory, which by this time had been considerably refined and quantified for the 120-mm gun tube application. Two strain gages and eddy probes mounted on diametrically opposite sides of the tube gave the same measured values, attesting to the perfect axial symmetry of the phenomenon. A comparison of the predicted strains with these measured values appears in Figure 4.

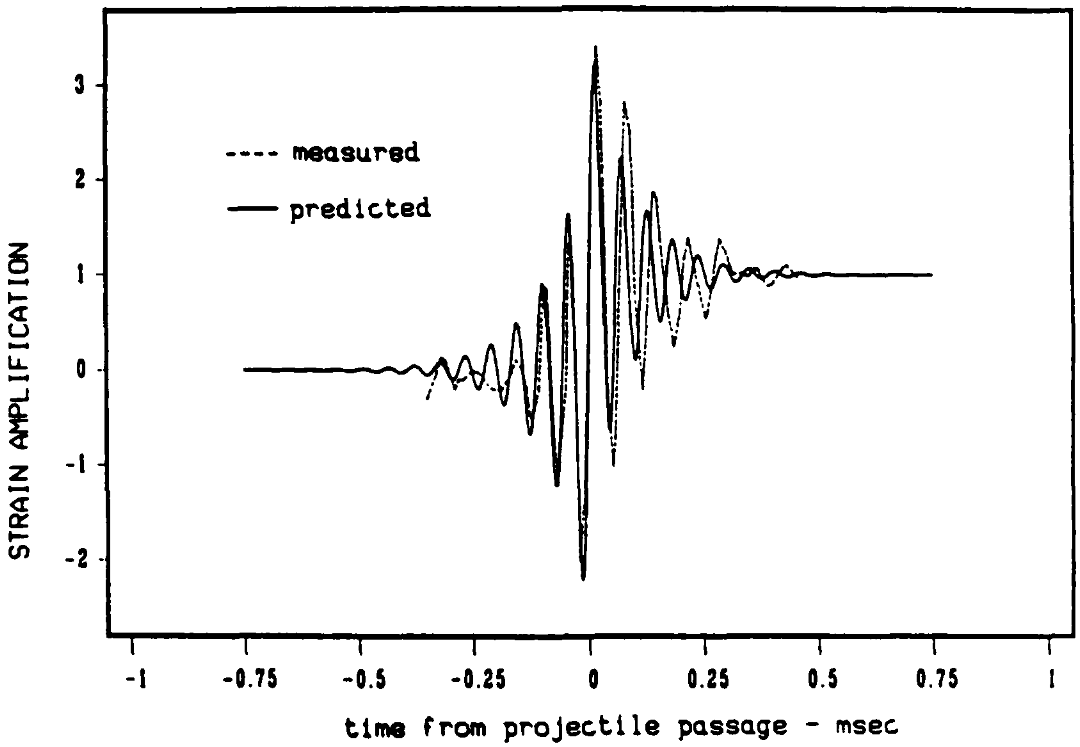


Figure 4. Verification of the Critical Velocity Theory.

The work herein attempts to give an overview of the mathematical physics involved in the 'critical velocity' theory of axial symmetric tube deformation and explores the implications this theory holds for nonaxisymmetric motions of the tube. A special case of these are the beam-like motions which influence the launch angle of the projectile at shot exit, a subject which has occupied the forefront of gun dynamics during the past decade (refs 6-9).

THE ESSENTIALS OF THE CRITICAL VELOCITY THEORY

In Figure 3 the tube is imagined to be infinitely long, of uniform cross section, and subjected to an axisymmetric pressure step moving at constant velocity. The simplest equation containing the essential physics of the situation is (ref 2)

$$D\frac{\partial^4 w}{\partial x^4} + \frac{Ehw}{R^2} + m\frac{\partial^2 w}{\partial t^2} = Q(1-H(x-vt)) \qquad (1)$$

where Q is a constant and represents the magnitude of the moving pressure and H is the Heaviside step function:

$$H(x-vt) = 0 \quad x < vt$$
$$= 1 \quad x > vt$$

In this equation, w is the radial displacement of the median surface of the cylindrical shell located at a distance x along, and R from, the central axis; h is the shell thickness and is assumed to be small compared to R; $m = \rho h$ where ρ is the mass density of the shell material; $D = Eh^3/12(1-\nu^2)$; E is Young's modulus of elasticity; ν is Poisson's ratio; and v is the velocity of the moving pressure, assumed to be finite and constant. Equation (1) is equivalent to the equation governing the motion of a Bernoulli-Euler beam on an elastic foundation, and accordingly, the effects of shear deformation and rotatory inertia are neglected.

Conventionally, steady-state solutions are sought to this equation under the conditions that the displacement remain bounded at $x = \pm\infty$ and that the stresses and displacements be continuous at the location of the pressure front, $x = vt$. In particular, these solutions have the form $w = Ae^{ik(x-vt)}$ and are steady when seen by an observer moving with the pressure front at $x = vt$. k is the wave number and, in general, is complex. Only when k is real does the assumed form of the solution represent a wave. To find what waves can exist naturally in the cylinder, one sets $Q = 0$, and substituting the assumed solution into Eq. (1), it is seen that real waves are possible for those values of k which are the real roots of the equation

$$k^4\gamma^4 - 2\lambda k^2\gamma^2 + 1 = 0 \qquad (2)$$

where

$$\gamma^4 = Eh/R^2D$$

$$2\lambda = mv^2\sqrt{\frac{R^2}{EhD}}$$

and v is the phase velocity (real). A plot of these wave numbers versus phase velocity is called a dispersion curve and is shown in Figure 5 ($C_c = \sqrt{E/\rho}$). This plot shows that waves of low wave number (long waves) travel with phase velocities which decrease with wave number, while waves with high wave numbers (short waves) have phase velocities which increase with wave number. This happens because of two competing restoring forces contained within the model. The tube can deform as a cylindrical membrane in which case the second term of Eq. (1) dominates the behavior, or it can deform as a beam in which case the first term dominates. The fact that these two mechanisms compete to produce a minimum in the dispersion curve of Figure 5, is the important part of the critical velocity theory.

Phase and Group Velocities vs. Wave Number

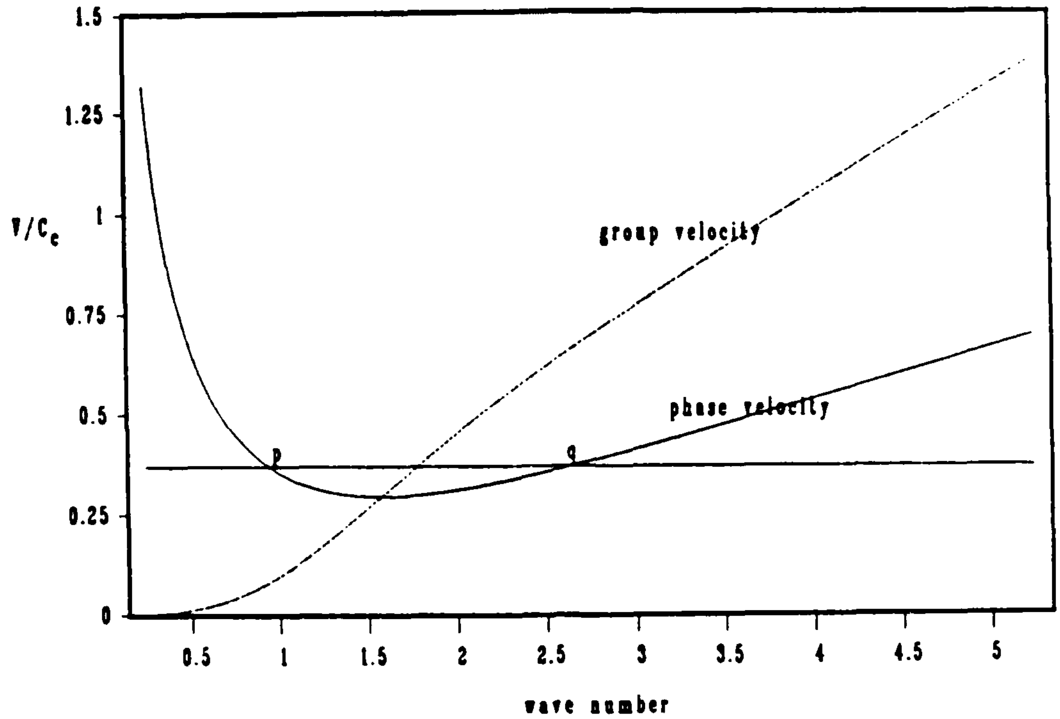


Figure 5

For the purpose of discussion, it can be considered axiomatic that if waves are to be generated by a moving axisymmetric pressure Q, the phase velocity of these waves will be the velocity of the moving load. That is, the load must be in phase with the wave(s) it creates. With this in mind, Figure 5 shows that such waves are possible provided the load velocity equals or exceeds the minimum possible value. Let us assume for the moment that the load velocity (the projectile velocity) somewhat exceeds this minimum. Figure 5 shows that under these circumstances two waves can exist with this phase velocity. In this case, the solution for the midwall displacement w is

$$w/C = \frac{-b^2}{b^2-a^2} \cos a(x-vt) + 1 \quad ; \quad x \leq vt$$

and

$$w/C = \frac{-a^2}{b^2-a^2} \cos b(x-vt) \quad ; \quad x \geq vt \tag{3}$$

where

$$a = \sqrt{\frac{1+\lambda}{2}} - \sqrt{\frac{\lambda-1}{2}} \quad , \quad b = \sqrt{\frac{1+\lambda}{2}} + \sqrt{\frac{\lambda-1}{2}}$$

and $C = QR^2/Eh$ approximates the Lame´ displacement. Note that for $\lambda >> 1$, the solution for $x \leqslant vt$ approaches 2C, twice the Lame´ displacement.

Now, physically we know that the energy contained in these two waves must radiate away, not toward, the source of the disturbance, namely the pressure front. Further, it is known that energy travels not at the phase velocity, but at another velocity called the 'group velocity'. The group velocity is related to the phase velocity as follows:

$$V_g = kdv(k)/dk + v(k)$$

where v(k) is the phase velocity curve of Figure 5.

It can easily be seen that should dv/dk ever vanish, the group velocity and phase velocity would be equal and that energy could then not radiate away from the pressure front, but would continually build the deformation in the neighborhood of the front as time progressed, i.e., resonance would result. Thus, the minimum phase velocity of Figure 5 is indeed a 'critical velocity' and it is the near attainment of this velocity which caused the high strains in the 120-mm gun tube.

If the velocity of the moving pressure is less than the minimum possible for wave formation, the wave number k is complex and the solution to Eq. (1) has the form of a damped harmonic:

$$w/C = \frac{e^{d(x-vt)}}{2}\left(-\cos c(x-vt) + \frac{d^2-c^2}{2cd} \sin c(x-vt)\right) + 1 \qquad x \leqslant vt$$

and

$$w = \frac{e^{-d(x-vt)}}{2}\left(\cos c(x-vt) + \frac{d^2-c^2}{2cd} \sin c(x-vt)\right) \qquad x \geqslant vt \qquad (4)$$

where

$$c = \sqrt{\frac{\lambda+1}{2}}, \quad \text{and } d = \sqrt{\frac{1-\lambda}{2}}$$

From the standpoint of gun tube design, it is important to be able to predict critical velocities as accurately as possible and to be able to predict results for different wall thicknesses. It is also of interest to accurately predict the steady-state deformation at any velocity of the pressure front. Thus, it is necessary to use a model which is not restricted to cylinders of thin wall thickness. Equations of motion representing such a model have been derived by Mirsky and Herrmann (ref 10) and are considerably more complicated than Eq. (1). They are used to obtain the results which follow in much the same way as discussed previously. (Tang (ref 3) has solved this moving pressure problem using the three shell equations of Lin and Morgan (ref 11). The set of four equations derived by Mirsky and Herrmann is reportedly better for thick-walled cylinders, however.)

Although transient effects, boundary reflections, nonuniformity of wall thickness, and variable pressure (projectile) velocity are ignored, steady-state calculations for thick-walled cylinders nevertheless produce results in remarkable agreement with measured values when the projectile velocity is close to critical (see Figure 4). (The assumption of constant projectile velocity is justified in the forward regions of many gun tubes where the projectile velocity/travel curve is relatively flat.)

The best prediction of critical velocity can be obtained using the exact equations of three-dimensional elasticity as opposed to the approximate shell equation (Eq. (1)) used thus far. The relevant equations are (ref 12)

$$
\begin{aligned}
f(K) = [&K_{10}(\beta)K_{01}(\gamma) + K_{01}(\beta)K_{10}(\gamma) \\
&+ (8/\pi^2\beta\gamma ab) + FK_{11}(\gamma)K_{00}(\beta) \\
&+ (1/F)K_{11}(\beta)K_{00}(\gamma)] \\
&+ [(1+\bar{B})^2/F\gamma^2 ab]K_{11}(\beta)K_{11}(\gamma) \\
&- [(1+\bar{B})/\gamma ab][aK_{11}(\gamma)K_{10}(\beta) \\
&+ bK_{11}(\gamma)K_{01}(\beta)] \\
&- [(1+\bar{B})/F\gamma ab][aK_{11}(\beta)K_{10}(\gamma) \\
&+ bK_{11}(\beta)K_{01}(\gamma)] = 0
\end{aligned}
\tag{5}
$$

where

$$K_{mn}(z) = J_m(zb)Y_n(za) - J_n(za)Y_m(zb)$$

$$\beta^2 = \alpha^2\left(\frac{V^2}{C_c^2} - 1\right)$$

$$\gamma^2 = \alpha^2\left(\frac{V^2}{C_s^2} - 1\right)$$

$$\bar{B} = \frac{V^2}{2C_s^2} - 1$$

$$F = \frac{\alpha^2\bar{B}^2}{\beta\gamma}$$

$$C_c^2 = (\bar{\lambda}+2\mu)/\rho$$

$$C_s^2 = \mu/\rho$$

α = wave number

a = the inner radii of the cylinder

b = the outer radii of the cylinder

$J_m(z)$ = Bessel functions of the first kind

$Y_m(z)$ = Bessel functions of the second kind

$\bar{\lambda}$ = Lame´ elastic constants

Equation (5) is now the dispersion relation in place of Eq. (2) and the corresponding dispersion curve for the 120-mm gun tube is shown in Figure 6. It is interesting to note that the critical velocity, as determined from Eq. (5), is only about eight percent lower than that predicted by the much simplified dispersion relation (Eq. (2)).

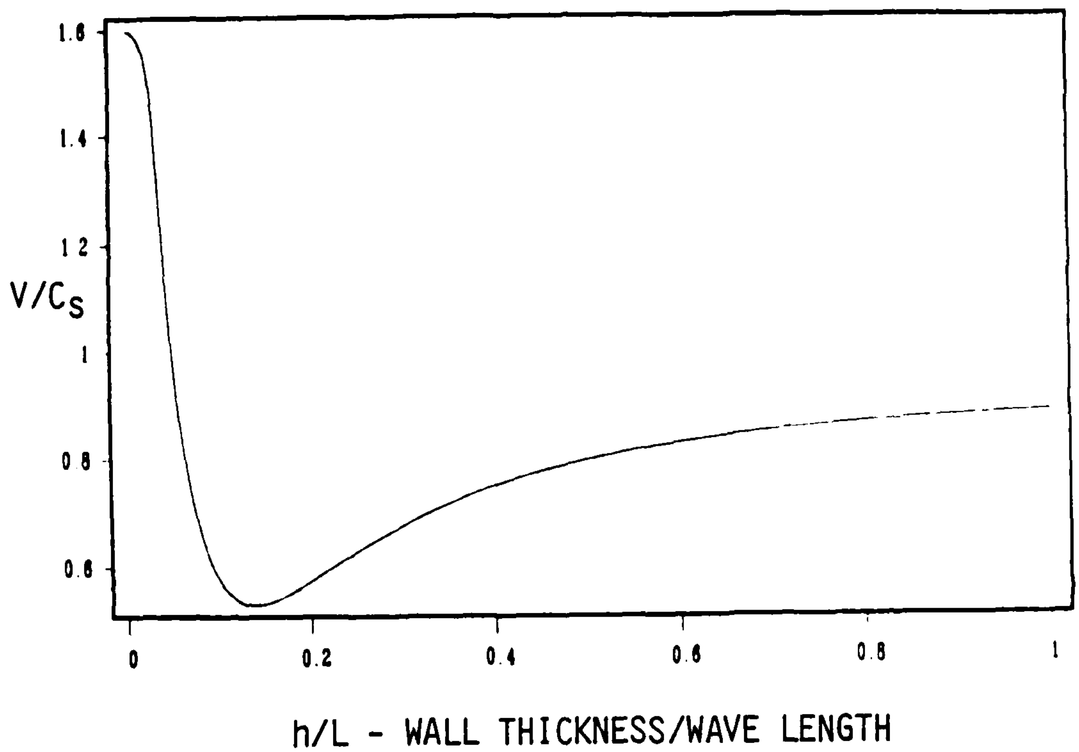


Figure 6. Dispersion Curve - 3-D Elasticity.

A complete account of the steady-state calculations can be found in a technical report (ref 13) by the author. Pertinent results are shown in Figure 7 - an amplification curve comparing the dynamic strains with those computed by the 'static' Lamé formulation, and in Figure 8 - a curve showing the variation of critical velocity with tube wall thickness.

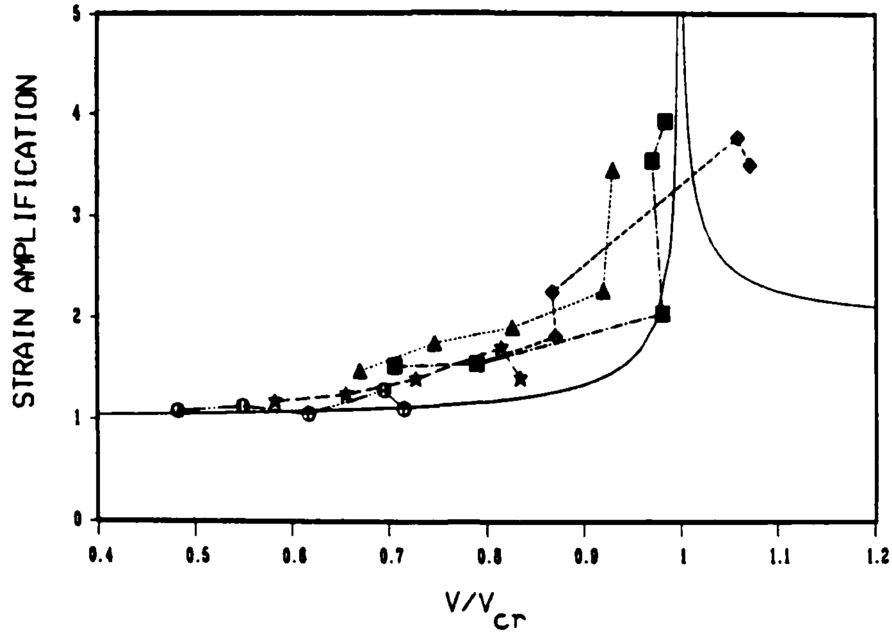


Figure 7. Predicted and Measured Strains.

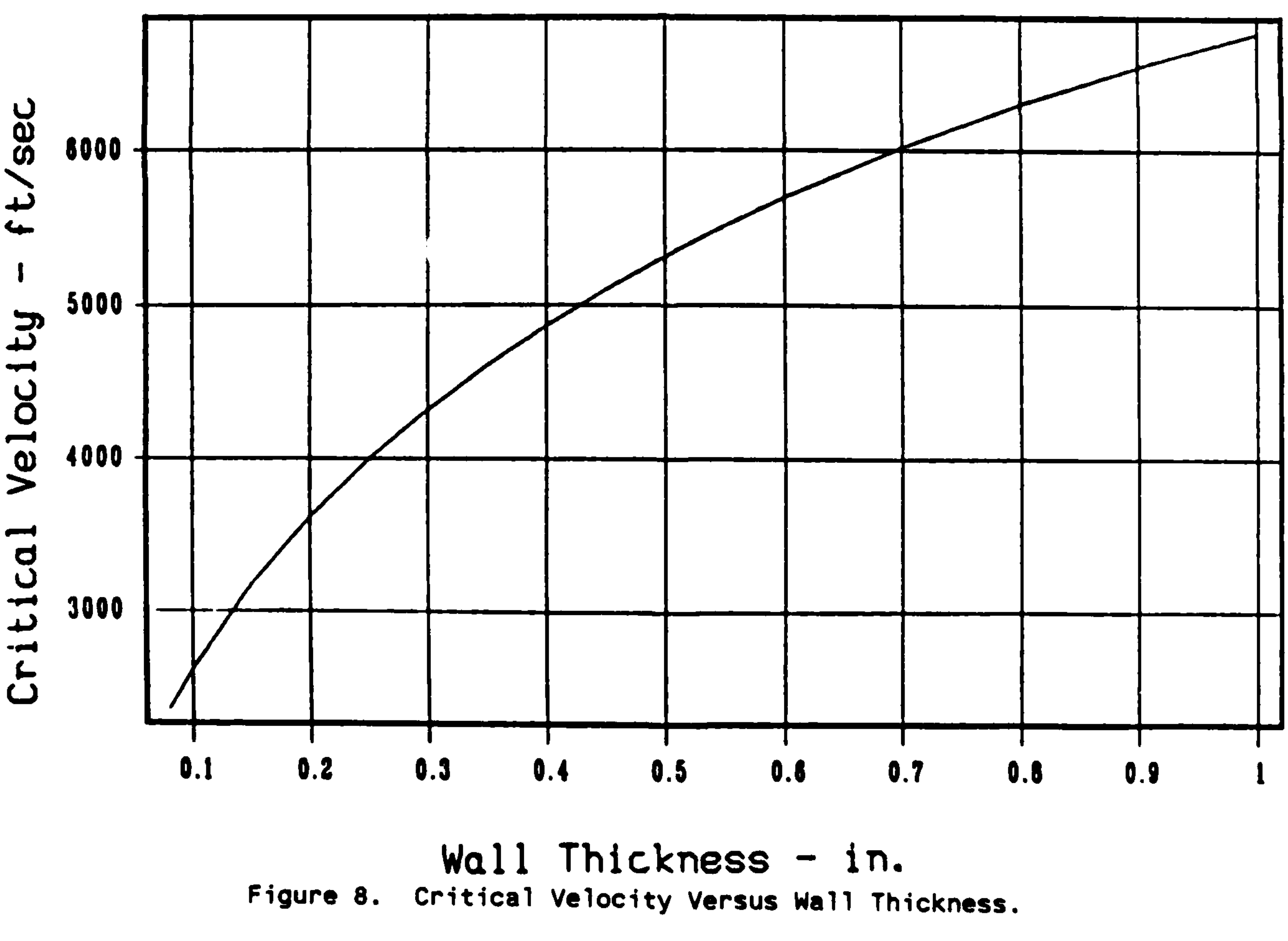


Figure 8. Critical Velocity Versus Wall Thickness.

NON-AXISYMMETRIC MOTIONS - IMPLICATIONS OF THE CRITICAL VELOCITY THEORY

Mirsky and Herrmann (ref 14) have also derived a set of five equations which govern both axisymmetric and nonaxisymmetric motions of a uniform hollow cylinder. Gazis (ref 15) has gone a step further, accomplishing the same end using the more accurate three-dimensional equations. Briefly, solutions for the radial displacements at midwall are sought of the form

$$Ae^{ik(x-vt)}\cos n\theta \text{ or } Ae^{ik(x-vt)}\sin n\theta \qquad (6)$$

where $n = 0,1,2,\ldots$ and x and θ are the coordinates of any midwall material point. The cases of interest to gun dynamics are

$n = 0$, axisymmetric motions

$n = 1$, the deformation is beam-like (the top and bottom of the tube move equal amounts in the same direction so that the bore axis is displaced). The dispersion curve is shown in Figure 9.

$n = 2$, the bore axis is not displaced and the tube assumes a shape somewhat of an ellipse. The dispersion curve for this case is shown in Figure 10.

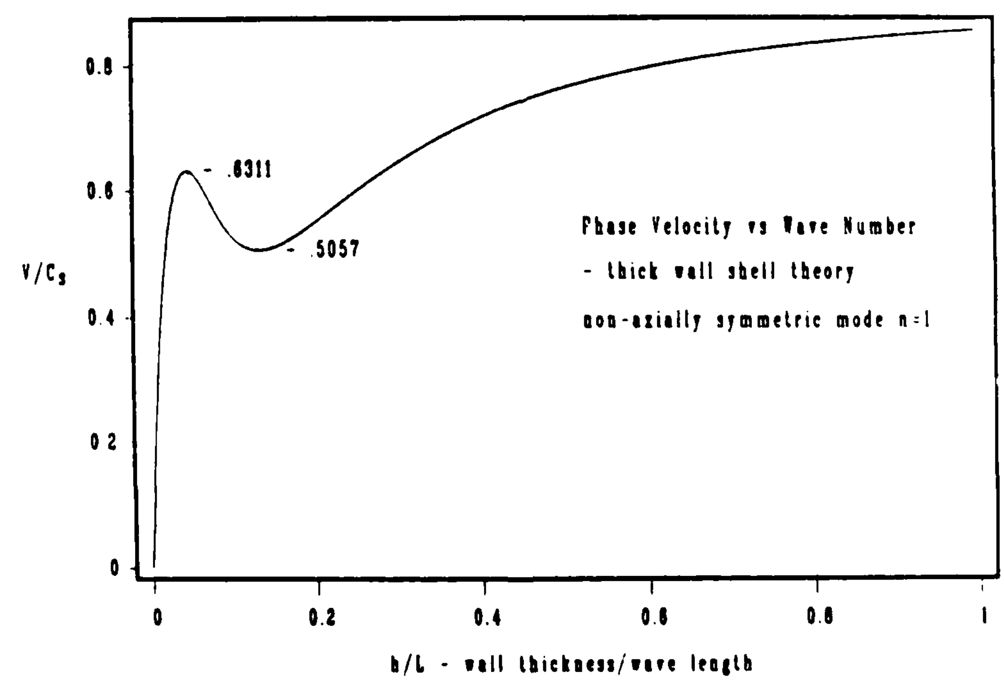


Figure 9

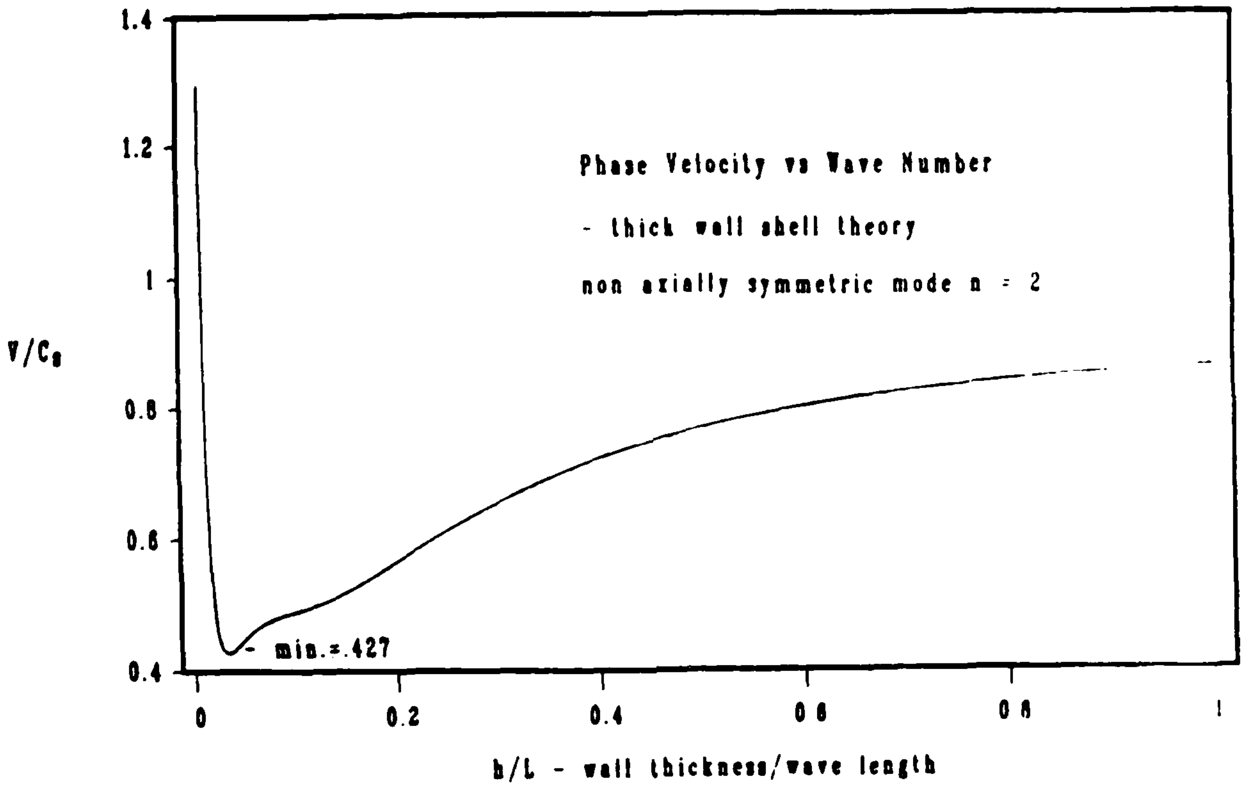


Figure 10

Recalling the importance of extreme values of the dispersion relation, i.e., dv(k)/dk = 0, the dispersion curves for the cases n = 1 and n = 2 are of some interest. The curve for n = 1 shows two possible critical velocities, one which is probably above the range of current ammunition for conventional cannon, but certainly of interest in more exotic weaponry such as electromagnetic cannon. The lower critical velocity is probably attainable in some conventional weapons. However, work in progress seems to indicate that the resonant band associated with this minimum is extremely narrow, most of the energy flowing into the longer wave having the same phase velocity. (The term 'resonant band' is defined here as the range of projectile velocity near a critical value which will cause appreciable strain and displacement amplification.) The width of the resonant band at the higher critical velocity seems to be much greater - more closely resembling the n = 0 case - leading to the speculation that energy tends to flow in the longer wave lengths. When n = 2, a critical value even lower than that for n = 0 is predicted.

In order to excite one or more of the many natural waves possible in a uniform cylinder, it is not only necessary that the load travel at the phase velocity of some possible wave, but the load must be distributed in such a way as to encourage the deformed shape (i.e., the load distribution must contain some modal content). Thus, an axisymmetric wave requires an axisymmetric component of pressure for its excitation. Similarly, the beam-like wave requires that some of the pressure be distributed asymmetrically about the bore axis, etc. In gun tubes, however, the ballistic pressure load is strictly axisymmetric and it may seem at first that nonaxisymmetric motions will not be excited. However, only uniform cylinders have been considered thus far, and if the real nonuniformities of gun tubes are considered, energy may flow to these modes by coupling. This prospect seems particularly feasible for the beam-like modes (n = 1) because beam displacements of significant magnitudes do not require a great deal of energy at the longer wave lengths. Thus, if even a little energy is transferred from axially symmetric motion to n = 1 motion, significant motion of the tube access may occur. Analysis is presently underway to quantify these effects in gun tubes.

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