S.I. Jackson.
"The Detonation Cylinder Test: Determination of Full Wall Velocity and Shape from a Single Velocimetry Probe with an Arbitrary Angle."
In AIP Conference Proceedings, volume 1793, p. 050017 (AIP Publishing, 2017)

The Detonation Cylinder Test: Determination of Full Wall Velocity and Shape from a Single Velocimetry Probe with an Arbitrary Angle

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Abstract. Laser velocimetry probes are used for measuring wall velocity in cylinder test expansion experiments. Previously, a method was developed to determine the full wall velocity, angle and case shape from a single probe aligned with the initial cylinder wall normal (S.I. Jackson, Proc. Combust. Inst., Vol. 35, 2015, pg.1997-2004). However, probes are often positioned at arbitrary (non-normal) angles to optimize light return from the cylinder surface. This work extends the prior method to accommodate arbitrary probe angles and allows solution of the full cylinder wall motion and shape from a single probe, using only the assumption of steady flow in the shock frame. When used in conjunction with the prior method, it can also be used to approximate the detonation product isentrope analytically from a single velocimetry probe at any angle.

INTRODUCTION

The detonation cylinder expansion test is a standard explosive performance test utilized to measure the product expansion energy and isentrope associated with detonation products. The test consists of a tube of metal confining a condensed-phase explosive. Detonation of the explosive results in high pressure products that accelerate and expand the metal wall (Figure 1). The velocity of the wall at standard locations can be used to infer the Gurney energy [1, 2], while a combination of the wall position and acceleration history yields the isentrope of the detonation products [3, 4, 5]. Computational fluid dynamics (CFD) simulations can also be used, in an iterative fashion, to reconstruct the product isentrope. Regardless of the reduction method, accurate wall position and velocimetry measurements are critical for accurate product state determination.

The cylinder expansion test concept was imagined before adequate experimental diagnostics existed to record the rapid wall motion associated with the wall [3]. For many decades, the streak camera diagnostic was combined with backlighting to record the wall expansion position versus time along a radial line [3, 1, 4]. These data were then once or twice differentiated to compute Gurney energies [1] or product isentropes [4]. However, the streak camera measurement technique does not yield sufficient resolution to accurately resolve the compressible ringing motion of the wall, which for most combinations of ideal explosives and standard copper confinement, can persist for wall pressures as low as 1 GPa [5]. Models that do not capture this compressible motion will generally underestimate the product pressure in this compressible region [4].

Recent improvements in high-speed velocimetry diagnostics [6] allowed direct measurement of the wall velocity with a laser velocimetry probe with sufficient resolution to capture the oscillatory ringing associated with compressible cylinder wall motion [5, 2]. These probes emit collimated beams of light that are recollected by the same probes after reflection from a target. Target motion normal to the probe will Doppler shift the wavelength of reflected light, allowing direct measurement of the wall velocity component *in the normal probe direction*. [6, 7, 8]. Jackson [2] developed an analytical reduction methodology that was able to (a) exactly reconstruct the two-dimensional cylinder

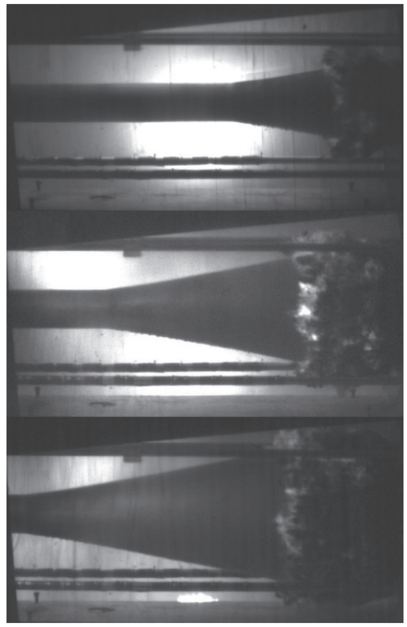

FIGURE 1. Snapshots of a cylinder expansion test from Ref. 2 taken 17.5 μs apart. Detonation propagation is to the left.

wall motion and shape from a *single* velocimetry probe oriented normal to the initial cylinder wall and (b) accurately approximate the product isentrope in the compressible regime from compressible wall ringing in a rational fashion with an impedance matching technique. This work [2] yielded an accuracy improvement over prior methods that assumed quasi-one-dimensional and incompressible wall motion [3, 1, 4]. A key component of the model [2] was the inclusion of a term to properly account for the increase of the wall radius at the measurement station due to translation of the cylinder wall in a direction normal to the probe. Heterodyne-interferometry probes do not measure this normal motion; streak diagnostics do. Jackson [2] showed that not accounting for it would incur a 2-3% error in velocity magnitude for a cylinder test with an ideal explosive; the error magnitude generally increases for explosives with slower detonation velocities but high product energies. Full reconstruction of the cylinder motion and subsequent product isentrope determination continues to generate interest from other researchers [9, 10, 11, 12].

One remaining issue is that many experimental researchers field cylinder tests with probes at a non-normal angle. This is done in order to increase the power of the collected probe light that is reflected from the cylinder wall at the later stages of wall expansion, when the wall has angled towards the detonation propagation direction. In this manuscript, the prior method [2] is extended to accommodate velocimetry probes at such non-normal angles. This is done by first showing how to algebraically solve for the total wall motion and wall angle with a single velocimetry probe by assuming *only* that the cylinder motion is steady in the frame of the detonation. This result is then integrated along the probe observation line, taking into account the non-measurable radial increase term associated with wall motion normal to the probe. Finally, angled probe data is transformed to normal probe data, which can be used to yield the exact cylinder shape and approximate product equation of state [2]. In that this approach only requires a *single* probe and a rational algebraic approach, it can be considered more straightforward and computational efficient than other strategies [9, 11] that require a combination of multiple probes to be fielded on each test, iterative solution methods, or CFD modeling to back out the full case motion.

FULL WALL VELOCITY AND ANGLE FROM A SINGLE ANGLED PROBE

For the purposes of this technique, we assume that a single PDV probe is used to measure the wall motion. The probe is fixed at an angle ϕ relative to the initial cylinder wall normal as shown in Figure 2. Passage of the detonation front by the probe observation point on the wall results in acceleration of the wall. During this motion, the wall normal will turn downstream towards the detonation propagation direction (Figure 1). Wall acceleration will always be normal to the wall. Generally, this acceleration starts at a high value, after which it monotonically decreases in time. Eventually, the cylinder wall will asymptote to a constant wall angle and terminal velocity. An example of the wall angle and velocity evolution during a cylinder test is discussed in Jackson [5].

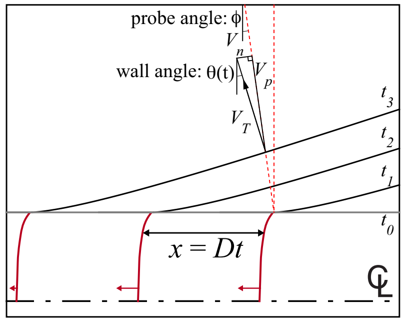

FIGURE 2. A schematic of the steady cylinder motion at three different times.

The PDV probe records this motion. The measured probe velocity V_p is related to the total probe velocity V_T by

$$V_p = V_T \cos(\phi - \theta) \tag{1}$$

where ϕ and θ are the probe and wall normal angles, respectively, relative to the initial wall position normal. In general, the probe is not aligned with the changing wall normal and does not measure the total wall velocity. Thus, an additional transverse velocity wall component V_n exists that is not measured by the probe

$$V_n = V_T \sin(\phi - \theta)\ . \tag{2}$$

The total velocity is the combination of the two normal components. With respect to V_p and V_n, it is

$$V_T^2 = V_p^2 + V_n^2\,, \tag{3}$$

while it is

$$V_T^2 = v^2 + u^2 \tag{4}$$

where v and u are radial and axial wall velocity components as used in Jackson [5].

Usually, the probe angle ϕ is measured during cylinder test assembly, while the detonation velocity D and $V_p(t)$ are recorded during the test. It is possible to solve for the remaining parameters u, v, and θ algebraically using a system of three equations. The first equation is obtained from the combination of equations 1 and 4,

$$V_p = \sqrt{v^2 + u^2}\cos(\phi - \theta)\ . \tag{5}$$

The second and third equations come from considering the differential motion

$$\tan\theta = v/(D + u) \tag{6}$$

and instantaneous motion

$$\tan\theta = -\frac{du}{dv} \tag{7}$$

of a wall element, as discussed in Jackson [5]. Note that Equation 7 above corrects the physically inaccurate assumption that $\tan\theta = -u/v$ in Jackson [5], which assumed that wall material velocity vector is always normal to the wall surface in the shock-fixed frame. As the product pressure acts normal to the cylinder interior, it is more physically realistic to assume that the acceleration vector is, at all times, normal to the wall surface as shown in Equation 7. Equation 7 can be integrated by equating it with Equation 6 to eliminate $\tan\theta$. The result can then be explicitly solved for u. Choosing the physically plausible solution branch yields

$$u = -D + \sqrt{D^2 - v^2} \tag{8}$$

This result should be used in place of Equation 1 in Jackson [5].

Thus, Equation 5, 6, and 8 can be simultaneously solved for u, v, and θ with ϕ, D, and $V_p(t)$ as known. In practice, this solution must be performed for each discrete $V_p(t)$ point. Application of this simultaneous solution to typical probe record lengths does not take more than a few minutes on a personal computer. That said, it is worth considering that orienting the probe normally reduces this equation set to only Equation 8, such that a simultaneous solution method is not required.

SOLVING FOR CASE SHAPE FROM A SINGLE ANGLED PROBE

Determination of the total velocity and wall angle trajectory in time enables integration of the case shape. As with a normal probe [5], the wall motion normal to the probe must be accounted for in this integration; transverse motion of an angled plate (relative to the probe line) will alter the cylinder wall's distance from the probe in a way that cannot be measured via Doppler interferometry [7, 8]. Novel combinations of optical ranging and interferometry are being developed to recover this distance variation [13]. However, it is more efficient to analytically anticipate and correct for this motion when the experimental geometry is steady in shock frame.

Using a discrete approach consistent with the discrete probe data $V_p(t)$, it can be shown that, at any given instant, the total wall motion towards the probe can be decomposed into two components

$$\Delta L = \Delta L_p + \Delta L_n \,. \tag{9}$$

The first term is simply the distance travelled by the measured velocity V_p

$$\Delta L_p = V_p \Delta t \,. \tag{10}$$

The second is the wall motion towards the probe resulting from a combination of the transverse velocity and wall angle

$$\begin{aligned} \Delta L_n &= V_n \tan(\phi - \theta)\,\Delta t & (11)\\ &= V_T \sin(\phi - \theta)\tan(\phi - \theta)\,\Delta t & (12)\\ &= V_p \tan^2(\phi - \theta)\,\Delta t \,. & (13) \end{aligned}$$

The full wall motion towards the probe at timestep j is thus

$$L_j(t_j) = \sum_{i=1}^{j} \Delta L_i \Delta t_i \,. \tag{14}$$

where $t_j = \sum_{i=1}^{j} \Delta t_i$. Finally, the motion towards the probe can be translated into the radial and axial motion components that would be recovered by a normally oriented probe. The radial and axial motion components along the probe line are,

$$r(t) = L(t)\cos(\phi) \tag{15}$$

and

$$x(t) = -L(t)\sin(\phi) \,, \tag{16}$$

respectively. As the cylinder wall motion is steady, it appears to translate upstream at the detonation velocity D in the lab frame, as shown in Figure 1 and Figure 2. Thus, the angled probe data can be transformed to data that would have been measured by a normal probe by simply modifying the angled probe timebase to account for the time associated with this steady translation. The time correction $-x/D$ is required to align the above values of r and x with those that would be measured by a normal probe at time t_{corr},

$$t_{corr} = t + \frac{x(t)}{D} \,. \tag{17}$$

Translation of the data to other non-normal probe angles can be accomplished in similar fashion. Parameters $r(t)$ and $x(t)$ can then be plotted parametrically to generate the full case shape or used with Reference [5] to generate an approximate detonation product isentrope.

CONCLUSIONS

A method has been presented to reconstruct the full cylinder wall motion and case shape from the detonation cylinder expansion test. This technique requires only data from a single velocimetry probe at an arbitrary angle and extends the earlier work of Jackson [5], which was limited to normally oriented probes. The transformation of the angled probe motion to that of a normally oriented probe allows application of our previous approach [5] to determine an approximate detonation product isentrope.

ACKNOWLEDGMENTS

This work was supported by the Department of Energy via Campaign 2 "Dynamic Material Properties."

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