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Optimization of Wall Velocity Measurements Using Photonic Doppler Velocimetry (PDV)*)

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Abstract: The paper describes the measurement of cylindrical charge wall velocity profiles at various angles to the surface normal. The wall velocities were measured using simple zero generation photonic Doppler velocimetry (PDV). The detonation velocity was measured simultaneously using fiber optic probes coupled with a digital chronometer. The PDV probe angles were set in the range of -2° to 17° to the surface normal. Powdered pentaerythritol tetranitrate (PETN) and the PETN-based plastic-bonded explosive Semtex 1A were selected as the explosive materials in order to ensure reliable detonation under the measurement conditions. The explosive charges were confined in thin-walled aluminum tubes with an internal diameter of 16 mm and wall thickness of 2 mm. The results can be useful for the characterization of charge expansion phenomena and also for the optimization of cylinder test measurements using PDV. Gurney constants were determined for both explosives.

Keywords: bare fiber probe, Gurney constant, pentaerythritol tetranitrate, photonic Doppler velocimetry, Semtex

1 Introduction

The wall velocity of an explosive charge can be measured discontinuously by electrical contact pins or viewed directly using a high-speed streak camera [1]. These methods suffer from lack of resolution and can hardly be used to measure

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the initial stages of expansion. Continuous measurement of radial expansion of the charge casing can be accomplished with a Velocity Interferometer System for Any Reflector (VISAR) [2] or a Fabry-Perot interferometer [3]. Nowadays, the photonic Doppler velocimetry (PDV) technique has proved to be a useful alternative to VISAR [4]. Compared to VISAR, it provides simpler operation and less service demands at much lower overall cost. The cost of consumable items can be further reduced by using bare fiber probes [5].

The terminal wall velocity (v) is the peak velocity the charge casing acquires before it ruptures. As it is not easy to measure the velocity at this moment, the velocities at the relative volume expansions of $V/V_0 \approx 2$ and $V/V_0 \approx 7$ (or 6 mm and 19 mm wall displacements for the standard 1 inch cylinder test) are usually reported in the literature [6-8]. The latter is sometimes assumed to be the terminal velocity in the case of the standard copper cylinder test [1]. The ability of an explosive to accelerate the surrounding medium can be also expressed using the Gurney constant (G). This can be calculated using the terminal wall velocity and the charge geometry parameters (the casing mass M and the charge mass C) via the Gurney equation for a cylindrical charge [9]:

$$\frac{v}{G} = \left(\frac{M}{C} + \frac{1}{2} \right)^{-1/2} \tag{1}$$

PDV captures the wall velocity component in the direction of the probe, which allows measurement of the wall velocity in a desired position and angle to the wall. According to [10], a velocity vector of the expanding cylindrical charge casing can be calculated by decomposing the PDV wall velocity profile. The recommended probe angle to the surface normal should be somewhat less than half the angle of the tube expansion, as this should correspond to a real material flow velocity.

2 Experimental

2.1 Materials

Powdered pentaerythritol tetranitrate (PETN), designated NS, and PETN-based plastic-bonded explosive Semtex 1A (S1A) were used in this study, both supplied by the Explosia company. The flour-like NS powder had particle size under 0.2 mm [11]. The S1A consists of multimodal particle sized PETN (83%) and a plasticized polymer matrix (17%). Aluminum tubes were filled with the NS by tapping. The S1A was hand packed in such a way that there were no cavities. The density was then calculated using the charge weight and the tube dimensions. The charges were initiated using standard electric detonators.

Commercial grade tubes made of wrought aluminum alloy AW-6060 were used as the charge casing. Besides aluminum, the alloy also contains silicon, iron, magnesium and trace amounts of a few other elements, according to European standard EN 573-3. The internal diameter of the tubes was in all cases 16 mm, the wall thickness was 2 mm and the tube length 200 mm.

2.2 Measurement arrangement

The measurements of the wall velocities were performed using a single channel basic PDV with a reference signal taken from the probe back reflection [12]. The measurement arrangement consisted of a laser emitter, a circulator, a detector and an oscilloscope (4 GHz, 25 $GS \cdot s^{-1}$). The laser module operated at 1550 nm and was limited in its power output to 40 mW. The real power output used for testing was 36 mW at the laser, which corresponded to 22 mW at the probe tip. Losses were caused by attenuation in cables, connections and in the circulator. Bare fiber probes were fixed in a drilled aluminum block at a position of about 140 mm from the tube edge. Side view photographs were taken before each shot in order to determine the actual probe angle (α) and the probe to charge distance (d).

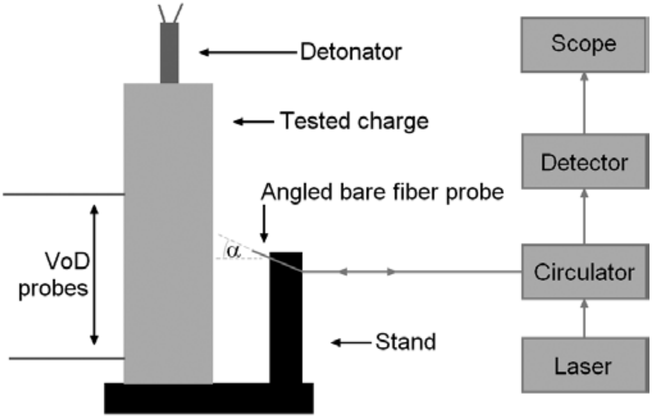

Figure 1. Scheme of the measurement arrangement.

The detonation velocity (D) was measured simultaneously as evidence that the detonation had proceeded properly. Plastic fiber optic probes coupled with an electronic chronometer operating at 50 MHz were used for the measurements.

The probes were introduced into the explosive charge through holes drilled in the casing at about 20 and 140 mm distance from the charge end. The probe tips were covered with aluminum tape in order to shield light preceding the reaction front and thus ensuring activation only by the passing shock wave. The scheme of the whole measurement arrangement is shown in Figure 1.

3 Results and Discussion

The scope records from the PDV probes were evaluated using short-time Fourier transform (STFT) in MATLAB based software to obtain the velocity *vs*. time curves. Typical raw wall velocity profiles obtained by the STFT for the probe angle close to 0° (charge Nos. 01 and 11) are shown in Figure 2. It can be seen, that only the latter part of the record is well resolved as the wall is approaching the fiber probe. The very beginning is somewhat resolved on the NS record but not resolved on the S1A record.

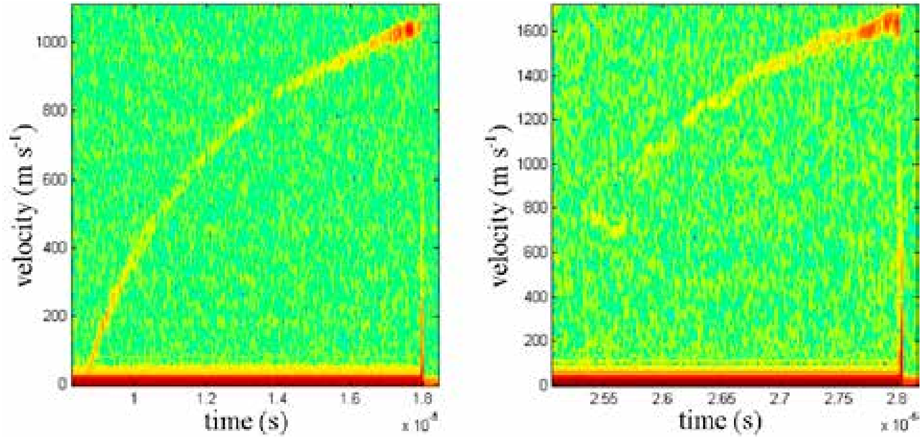

Figure 2. Examples of records obtained by STFT at low probe angle; NS charge No. 01 (left), S1A charge No. 11 (right).

Typical raw wall velocity profiles for a medium angle probe (charge Nos. 06 and 13) are shown in Figure 3. It can be seen that the profiles are uniform except at the very beginning. Such signals can be easily processed. The same quality raw profiles were obtained for charge Nos. 03, 04 and 05.

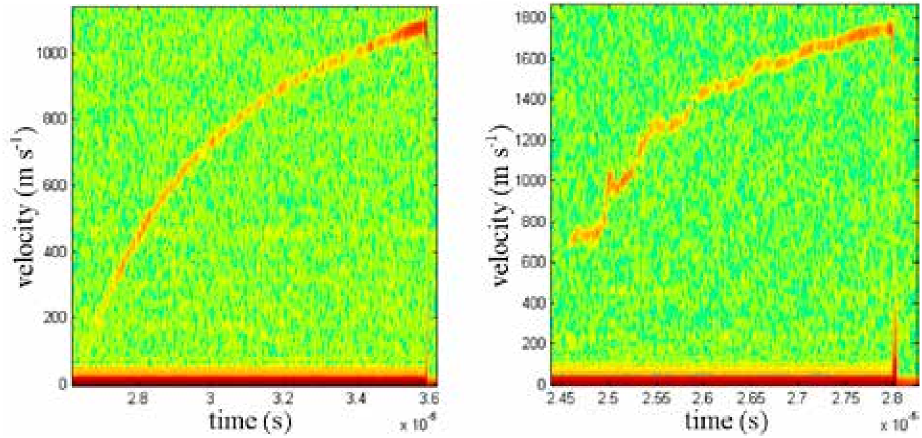

Figure 3. Examples of records obtained by STFT at medium probe angle; NS charge No. 06 (left), S1A charge No. 13 (right).

The raw wall velocity profile shown in Figure 4 (left) is interesting due to the second velocity trace, which is visible at the end of the record. This trace is caused by multiple reflection of the laser beam between the probe tip and the cylinder wall. This effect can only be registered when the probe tip and the target surface are parallel, *i.e.* the probe angle in this case was equal to the charge casing expansion angle. Both profiles in Figure 4 are not resolved in the first third.

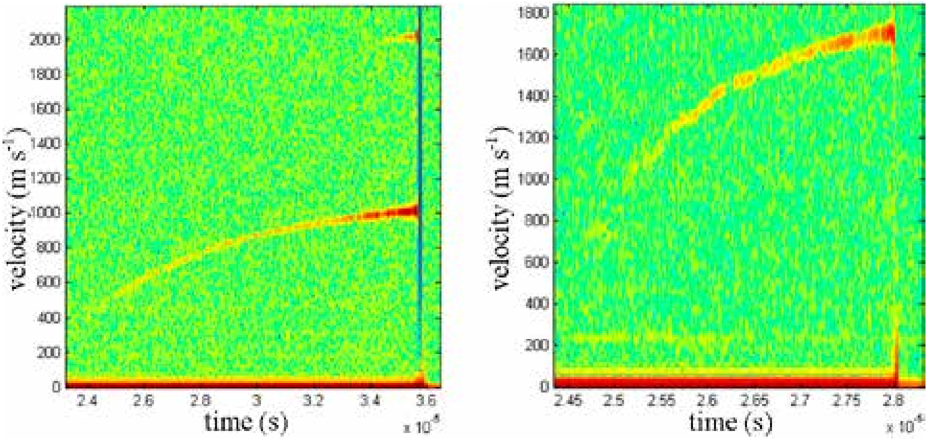

Figure 4. Examples of records obtained by STFT at high probe angle; NS charge No. 09 (left), S1A charge No. 15 (right).

The wall velocity profiles of NS and S1A charges are shown in Figure 5. Wall velocity profiles obtained with low angled probes are noisy, which complicates further processing. It can be seen that there is a slight difference between profiles obtained with less-angled probes (charge Nos. 06 and 07) compared to more-angled probes (charge Nos. 07, 08, 09 and 10). However, there is either no general trend or it is hidden in the measurement uncertainty. The wall velocity profiles of S1A charges at longer probe to target distances are shown in Figure 6. The only record which is fully resolved is that taken at 7.2° probe angle, whereas the others are too noisy at the beginning.

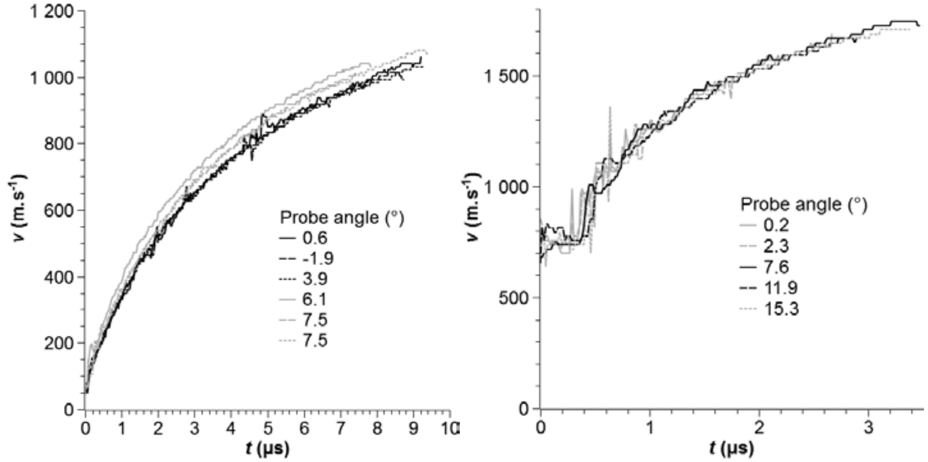

Figure 5. Wall velocity profiles of NS (left) and S1A (right) charges.

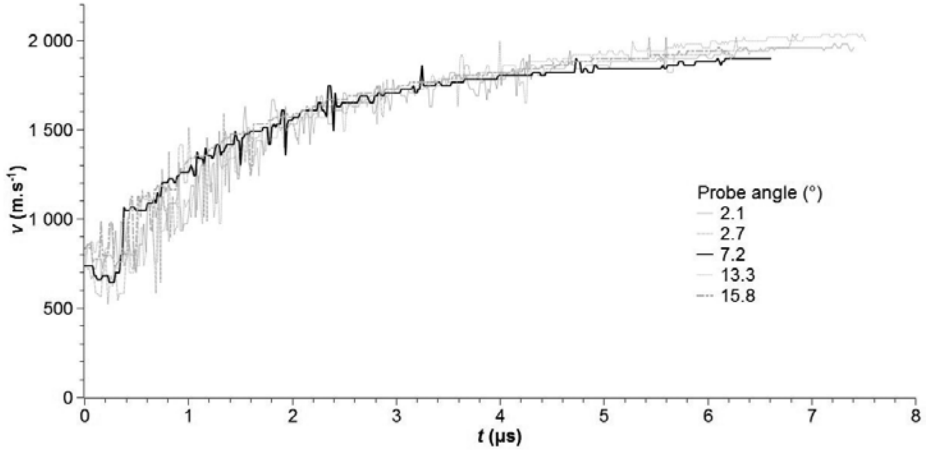

Figure 6. Wall velocity profiles of S1A charges at longer probe to target distances.

It can be clearly seen that angled probes should be preferred to perpendicular probes because of better signal quality. The same conclusion has recently been published in the Los Alamos National Laboratory Report [13].

The key parameters of all of the tested samples are summarized in Tables 2 and 3. The average detonation velocities of NS and S1A were 3860 ± 92 $m \cdot s^{-1}$ and 7315 ± 104 $m \cdot s^{-1}$, respectively, corresponding to an acceptable error of about 2%. The measured values are also consistent with literature data at similar densities [14]. Our previous measurements on NS, at a charge diameter of 10 mm under the same aluminum confinement, gave a detonation velocity of 3820 ± 80 $m \cdot s^{-1}$.

Table 1. Summary of the wall velocity measurements of NS charges

No.	α [°]	d [mm]	ρ [$g \cdot cm^{-3}$]	D [$m \cdot s^{-1}$]	v(2) [$m \cdot s^{-1}$]	v(7) [$m \cdot s^{-1}$]	M/C	G [$m \cdot s^{-1}$]
01	0.6	6.7	0.55	3900	851	1126	2.589	1979
02	-1.9	5.9	0.55	n/a	833	1115	2.589	1960
03	3.9	7.4	0.56	n/a	833	1105	2.577	1939
04	6.1	5.6	0.56	4020	880	1151	2.577	2019
05	7.5	5.1	0.57	n/a	870	1140	2.499	1974
06	7.5	6.8	0.56	3850	861	1150	2.577	2018
07	11.1	12.2	0.55	3850	n/a	1182	2.589	2078
08	12.0	9.7	0.56	3810	n/a	1108	2.577	1944
09	14.5	9.7	0.54	3690	n/a	1039	2.636	1841
10	17.4	10.3	0.57	3890	n/a	1160	2.521	2017

Table 2. Summary of the wall velocity measurements of S1A charges

No.	α [°]	d [mm]	ρ [$g \cdot cm^{-3}$]	D [$m \cdot s^{-1}$]	v_2 [$m \cdot s^{-1}$]	v_7 [$m \cdot s^{-1}$]	M/C	G [$m \cdot s^{-1}$]
11	0.2	3.5	1.41	7386	1590	n/a	1.047	n/a
12	2.3	3.6	1.41	7299	1590	n/a	1.055	n/a
13	7.6	4.5	1.42	7356	1590	n/a	1.048	n/a
14	11.9	3.6	1.41	7327	1590	n/a	1.047	n/a
15	15.3	4.3	1.41	7289	1590	n/a	1.045	n/a
16	2.1	11.8	1.43	7496	n/a	1967	1.038	2439
17	2.7	10.5	1.42	7128	n/a	1968	1.041	2444
18	7.2	10.2	1.42	7335	1633	1893	1.041	2350
19	13.3	11.7	1.42	7386	n/a	2028	1.041	2517
20	15.8	9.5	1.42	7150	1628	1958	1.039	2429

The wall velocity values v_2, corresponding to $V/V_0 = 2$ volume expansion, were read off directly from the velocity profiles. The wall velocity values v_7, for $V/V_0 = 7$, were obtained by slight extrapolation of the available wall velocity profiles using SciDavis software. The extrapolation was performed with first order exponential decay curves, starting at $t = 1$ μs, in such a way that the integral of the resulting wall velocity profile (distance travelled) was equal to the wall displacement corresponding to $V/V_0 = 7$ (12 mm). The values of v_7 were then used for calculation of the Gurney constants using Equation (1), although they are not the true terminal velocities and the results may thus be slightly underestimated. Average values of $G = 1977 \pm 61$ m·s^{-1} and $G = 2436 \pm 53$ m·s^{-1} were found for the NS and S1A charges, respectively. In the case of S1A, only the data obtained from charges 16-20 were averaged. The short length of wall velocity profile for charges 11-15 makes the extrapolation unreliable.

4 Conclusions

The effect of intentional misalignment of the bare fiber PDV probe on the resulting wall velocity profiles was examined for high explosive charges confined in aluminum tubes. There were no systematic differences between the terminal velocities obtained using angled probes compared to those using perpendicular probes. However, use of angled probes should be preferred because it leads to better signal quality. The best signals were obtained at probe angles in the range of 4-8°. Bare fiber probes were able to provide records of sufficient quality at distances of more than 10 mm from the target. Gurney constants for low density powdered PETN and Semtex 1A plastic-bonded explosive were determined.

Acknowledgements
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