Frontal and tilted PDV probes for measuring velocity history of laser-shock induced calibrated particles.

G Prudhomme$^{1,2}$, P Mercier$^1$, L Berthe$^2$, J Bénier$^1$ and P-A Frugier$^1$

$^1$CEA, DAM, DIF, F-91297 ARPAJON CEDEX
$^2$PIMM, Arts et Métiers ParisTech, 153 bd de l’Hôpital, F-75013 Paris

E-mail: gabriel.prudhomme@cea.fr

Abstract. Photonic Doppler Velocimetry (PDV, also known as LDV or HetV) is a remarkable tool for measuring the different velocities of many objects simultaneously, including tiny individual reflectors such as particles ejected by the rear face of a metallic plate damaged by a shock. This paper presents simplified experiments in which calibrated particles are accelerated and observed with PDV. They were shock-loaded using a pulsed laser (0.7 J, 10 ns, 532 nm) resulting in an acceleration up to 100 m/s. Various experiments have been performed to study the influence of different particle parameters: the material (Cu, Al), the size (10 to 200 micrometers) and the shape (sphere or rods). We recorded the back-reflected light with both orthogonal and tilted probes, and present the corresponding PDV spectrograms displaying cloud velocities as well as velocity tracks due to single particles. All of them decelerate within the ambient gas, while some rods also rotate. By applying simple models of deceleration and rotation, we try to retrieve their sizes or to evaluate their initial velocities. In addition, the tilted probes could be used to infer information on the global shape of the moving particle clouds.

1. Introduction
In shock experiments (with high power laser, gun or high explosive), the rear face of a shock-loaded plate is usually damaged. It is the result of different causes such as micro-jetting, spalling or melting [1] leading to the ejection of a cloud of particles. The size and the velocity of these particles are respectively distributed in the 0.5 to 20 µm and in the 1 to a few km/s ranges.

For the last thirty years, several laboratories have been trying to investigate these particle clouds by using different techniques such as velocimetry [2], radiography [3–5], protonography [6,7], holography [8,9], Mie-scattering [10] or post mortem analysis [11,12].

Photonic Doppler Velocimetry (PDV) designed at 1.55 µm by T. Strand [13] was the first tool really able to measure simultaneously the different velocities of many particles versus time [14, 15]. In a first time, our aim is just to try, with PDV, to characterize the cloud of flying particles, without taking into account their creation mechanisms. Nevertheless, the characterization of such particles, especially in gasses, still remains difficult due to various size and velocity distributions, partial cloud probing and different physical phenomena (fragmentation, ablation and shock wave in gas).

To start this study, we decided to simplify the setup with non-destructive and quick-assembly experiments in order to more easily understand the influence of certain parameters before working on more complicated and usual devices (such as HE on metallic plates). Thus, we chose to work in ambient air and to deposit a layer of calibrated metallic particles (Cu or Al).
on the rear face of a thin aluminum plate; its front face is irradiated by a pulsed Yag laser and particles are accelerated up to few tens of m/s. Three PDV probes, adjusted along different directions, aim at the powder deposited on this plate. Notice that the laser-induced shock in the target plate is not sustained (only a few ns) and not plane, but these constraints do not prevent particles from accelerating.

About 50 experiments were performed in the Arts et Métiers ParisTech-PIMM laboratory in July 2012; we present the results obtained with 3 of them: shots #24, #27 with calibrated spherical copper particles and shot #53 with aluminum rods. The nine first shots were performed without powder; we never observed any particle cloud but either the oscillation of the aluminum plate rear face or a flying spall. Consequently the aluminum plate does not generate other particles which could contaminate the studied cloud. Three typical behaviors are reported: the slowing-down of the shock-accelerated particles, the particle rotation and the rebuilding of the cloud.

2. The experimentation

2.1. The setup

Its design is axi-symmetrical. From the bottom to the top, there are three parts:

- **The laser source**: it is a Yag laser delivering a single 0.7 J pulse at 532 nm, during 10 ns. It is focused on the target front face with a Gaussian-like spot laser (diameter is approximately 1.4 mm). All these features were assumed to be the same over the shot program.

- **The target**: set horizontally, it is an aluminum plate (100 µm in thickness, 15x15 mm² in size) covered with an adhesive tape on its front face to better confine the pressure induced by the laser. This plate is stamped in its middle (5-mm diameter) to receive and maintain particles on its rear face; we change it for each shot. The program is built according to different parameters: particle material (copper and aluminum), particle diameter (1 µm to 10 µm) or length (200 µm), powder layer thickness (5 µm to 15 µm for spheres). The plate is weighted before and after this manipulation to determine the amount of powder (7 to 22 mg depending on the experiment). The irradiance on the aluminum plate front face is about 4.5 GW/cm² and the induced pressure is about 2 GPa (determined with the aluminum EOS and the measured free-surface velocity).

- **The diagnostics**: three PDV probes are oriented toward the target (Figure 1). The first one is vertical, perpendicular to the target and its axis is quasi-common with the setup symmetry axis. The two other probes cut this axis 7 mm above the target with an angle of 15°. For several experiments, a post-mortem analysis is done with recovered particles stopped by the protective PDV window.

2.2. Recording and the Fourier analysis

The PDV signals were recorded on an Agilent digitizer. Its bandwidth is 12 GHz and its fastest sampling rate is 40 GS/s. For our experiments, we decreased it to 2 GS/s (i.e. 775 m/s for the speed limit). The total useful recording time is 1000 µs. Our diagnostic chain is equipped with two frequency-shifted lasers inducing a baseline on the spectrogram (velocities are thus increased positively).

We apply a Short Time Fourier Transform with a 2.5-µs Hamming window, a 0.5-µs step and a 10-µs zero-padding width. The velocity sampling is therefore equal to 0.062 m/s.
Figure 1. Experimental setup: the main laser in the bottom, the target with particles in the middle and the 3 PDV probes over.

3. Results with the frontal PDV probe

3.1. Deceleration in air

On the spectrogram of several shots, after a granular area (first 50 µs), we observe single ‘velocity’ tracks which could correspond to single particles slowing-down in air. It is the case for shot #24 (Figure 2) with spherical copper particles (manufacturer data: median diameter 10 µm, standard deviation 2.6 µm). Each track lasts around 200 µs; it could correspond to the travel duration of the particle through the PDV laser beam and demonstrates that the particle trajectory and the frontal PDV axis do not have exactly the same direction. Thus, with a 500-µm diameter beam and a 50 m/s average velocity, the length of the lighted track part is about 10 mm (200 µs x 50 µm/µs) and the angle between those 2 axes is less than 3°, which is not that much away; it could be due to either a light angular adjustment defect or a light shift between the center of the Yag laser impact and the frontal PDV probe axis.

We applied an analytical model of deceleration on these individual tracks with several simplifying hypotheses.

- Particles are (quasi) spherical (confirmed by observation with a microscope),
- Particles are independent (no interaction occurs between them, like encounters or by induced individual air shocks),
- All velocity axes are nearly perpendicular to the static target surface,
- All particles start moving at the same time (actually within less than 1 µs),
- There is no shockwave in air,
- There is no fragmentation or ablation of the particles.

In the equation of motion, the drag force depends on the $C_D$ drag coefficient (which is bound to the Reynolds number $Re$) [16] and on the volumic mass $\rho_{\text{gas}}$ ($=\rho_{\text{air}}$ in our case):

$$ m \frac{dv}{dt} = -\frac{1}{2} C_D \cdot A \cdot \rho_{\text{gas}} (v - u_{\text{gas}}) |v - u_{\text{gas}}| \quad \text{and} \quad Re = \frac{\rho_{\text{gas}} |v - u_{\text{gas}}| d}{\mu_{\text{gas}}} \quad (1) $$

$$ C_D = \begin{cases} \frac{24}{Re} + \frac{4}{Re^{1/2}} & \text{if } Re \leq 1000 \\ 0.424 & \text{if } Re > 1000 \end{cases} \quad (2) $$

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$m$ is the particle mass, $\rho_{\text{metal}}$ its volumic mass, $d$ its diameter, $A$ its right section ($\pi d^2 / 4$), $v$ its velocity, $u_{\text{gas}}$ the gas velocity (assumed to be null here because we do not take into account the air shock wave) and $\mu_{\text{gas}}$ its dynamic viscosity. Given the low measured velocities (less than 100 m/s) and the small particle diameters, the Reynolds number reasonably remains lower than 1000, and the corresponding analytical solution is given by:

$$v(t) = \left[(v_0 - 2/3) + C \exp \left(\frac{2}{3} B (t - t_1)\right) - C\right]^{-3/2}$$

(3)

with $B = 18 \frac{\mu_{\text{gas}}}{\rho_{\text{metal}} d^2}$ and $C = \frac{\rho_{\text{gas}}}{6} \left(\frac{d}{\mu_{\text{gas}}}\right)^{2/3}$

(4)

To fit the experimental tracks, we have to deal with a non-linear optimization problem which determines, for each particle, $d$ and $v_0$, its initial velocity. Figure 3 shows results corresponding to the 9 particles of shot #24. Their initial velocities are distributed in the 50 to 80 m/s range and their diameters are close to the manufacturer value (10 µm). Only one presents a different size (20 µm); we can suppose it is composed of a cluster of 2 associated basic particles. The estimated diameter and initial velocity uncertainties ($\sigma$) are respectively 0.1 µm and 0.5 m/s. These average uncertainties are calculated thanks to the fitting process sensitivity, the model being determined. They strongly depend on the track length, on the initial velocity and on the particle diameter. Globally there is a good agreement with the manufacturer data (Figure 3). In addition we measure the recovered particles with a microscope; all of them appear to have the same geometrical properties than those initially deposited: copper spheres with the same diameter distribution. Apparently, they were not modified by the experiment (no fragmentation, no melting).

3.2. Particle rotation

Several shots were performed with aluminum rods whose size distribution (manufacturer data) was in the 150 to 200 µm range. It was confirmed by a microscopic observation, with a 5 to 10 shape ratio (length/width). Four spectrograms present new sinusoidal tracks (Figure 4). We make the assumption it is related to the rod rotation (Figure 5) and we think we follow the motion of its scattering ends.

When the shock breaks out, the rotation axes of the accelerated rod-shaped particles can be distributed in all directions, between two extreme cases (with different level of rotation...
Figure 4. Shot #53. Track of an aluminum rod rotating while slowing-down. It seems to be due to its end which better scatters the light than the other parts. The measured time and velocity data would involve a rod length of about 230 µm.

velocities): those moving toward the PDV probe as a propeller rotating around the PDV probe axis and which cannot create this observed sinusoidal track unlike those with a rotation axis perpendicular to the PDV probe axis. Considering shot #53 track, we found a 205 µs rotation period T and a 7 m/s double velocity amplitude variation 2·v_a. These data lead to a 30,650 rad/s rotation velocity ω and therefore to a 230 µm rod length L (2·v_a = L·ω) which is in a good agreement with the measurements made with the microscope. As we measure a projected velocity and as we do not know the angle between the rod axis of rotation and the PDV probe axis, this value would determine a size lower boundary.

4. Results with the frontal PDV probe: particle cloud reconstruction

Thanks to the orientation of the PDV probe axes (15° from the target axis and crossing it 7 mm above its rear face, as shown on the sketch in figure 6 right side), the cloud can be scanned while it moves. Depending on its thickness (or its mass), the PDV beam is more or less able to penetrate it. We present the spectrogram of shot #27 dealing with 10-µm-diameter copper particles (Figure 6) and revealing the cloud structure: at t_1, the cloud (which is close to an

Figure 6. Shot #27 spectrogram showing the dynamical structure of the cloud. On the upper right side, the sketch of the cloud probing.

Figure 7. Particle cloud reconstruction at 2 different times (deceleration model taken into account).
axi-symmetrical shape bell-like layer) is tangent to the beam (80 m/s). At \( t_2 \) the beam crosses the top of the cloud (maximum velocity, 110 m/s). Then two particle families, slowing down, appear: the right side, well visible because spatially observed first by the probe and at higher velocity because close to the top. For the left side, it is the opposite: less light (due to the right side absorption and scattering) and at lower velocity because further on the bell-like cloud wing. Between these two branches, we guess that there is a volume with no particles. By applying the previous decelerating model, we can re-built (Figure 7) the cloud shape at different times (of course, a dissymmetry due to the right side extinction remains). Thus, 50 \( \mu \)m after the break out, the cloud is 8 mm in height and about 6 mm in width.

5. Conclusion

We demonstrated the capability for a laser shock-induced target to accelerate calibrated particles (1 to 200 \( \mu \)m, copper or aluminum) deposited on its rear face, up to 100 m/s. With the frontal PDV probe, we observe for certain shots with spherical particles, single slowing-down tracks on the spectrogram; we suppose they are due to single particles decelerating in ambient air. By applying a simple drag force model, we infer initial velocities and diameters which are in a good agreement with the manufacturer distribution. Some tests performed with aluminum rods (200 \( \mu \)m in length) displayed sinusoidal tracks; they seem to sign the rotation of the rod end. From both rotation velocity and velocity amplitude variations, we derive a rod length which is similar to the length measured with a microscope prior the shot. With a tilted PDV probe, we discover that it was possible to scan the cloud (if not too absorbing) and to rebuild its shape as a function of time. These different results emphasize the capability of PDV diagnostic to probe a cloud of particles and deliver different quantitative informations.

We continue to explore this subject with the Yag laser and calibrated particles: thus we plan to combine different distributions. A little vessel has been also designed to set the target and their particles either in the vacuum or in a gas at different pressures. The next step is the use of high explosives: the first shots have already been performed with calibrated particles deposited on ‘non-ejecting’ plates [17] and we plan to continue with real cloud directly provided by the damaged rear face of metallic plates.

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