HETEROODYNE VELOCIMETRY
AND DETONICS EXPERIMENTS

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OVERVIEW

- APPARATUS CONFIGURATIONS
  - 1 or 2 lasers
  - 1 or 2 optical fibers

- HARDWARE

- SOFTWARE & PROCESSING

- EXPERIMENTS
  - Tin particles velocity
  - Laser shock driven experiments
  - Embedded fibers in nitromethane

- CONCLUSION
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- **CONCLUSION**
PDV: single setup with one optical fiber

- Single-mode laser 1.55µm, 2W
- Circulator
- Single-mode optical fiber
- Moving object
- Coupler
- Detector
  BW: 50kHz-12 GHz
- Digitizer
  BW: 8 GHz
  20 GS/s
PDV: single or two-laser setups with a single optical fiber

Single-mode laser 1.55μm, 2W

10 mW (200 μW after coupler)

400 mW

-50 dB return loss (coating, angle)

Single-mode optical fiber

F₀

F

1 to 10 μW

Moving object

Circulator

Coupler

Single-mode laser 1.55μm+ δλ, 50 mW

F₁

Detector

BW: 50kHz-12 GHz

Digitizer

BW: 12 GHz
50 GS/s
PDV: Static adjustment easier with 2 spectrally-shifted lasers
PDV setup with 2 spectrally-shifted lasers: velocity range $x2$

- 1 laser: frequency $f_0$
  
  $f_D := f_0 \left(1 + 2 \frac{V}{C}\right)$  \hspace{1cm} $\Delta f := f_D - f_0$

- 1 single solution

- Laser N°0: frequency $f_0$

- Laser N°1: frequency $f_1$

- Bandwidth is doubled

2 solutions

(only 1 is physical)

$V_{\text{real}} = V_{\text{pivot}} \pm V_{\text{measured}}$

$V_{\text{measured}} = |V_{\text{real}} - V_{\text{pivot}}|$
**PDV setup with 2 spectrally-shifted lasers: velocity solutions**

**Experimental velocities**

**Measured velocities (TFR)**

**Retrieved velocities**

\[ V_p = (F_D - F_0) \cdot \lambda / 2 \]
\[ V_m = (F_D - F_0) \cdot \lambda / 2 \]
\[ V_e = (F_D - F_0) \cdot \lambda / 2 = (F_D - F_1) \cdot \lambda / 2 + (F_1 - F_0) \cdot \lambda / 2 \]
\[ V_e = V_m + V_p \]

\[ V_m = |V_p - V_e| \]
\[ V_c = V_p \pm V_m \]
PDV setup with 2 spectrally-shifted lasers: velocity solutions with a wrong shift way

Experimental velocities  Measured velocities (TFR)  Calculated velocities

Example 3

\[ V_m = |V_p - V_e| \]

\[ V_c = V_p \pm V_m \]

Wrong solution

Right solution
FREE SURFACE VELOCITY OF Ta PLATE.  H.E. PWG

Single laser and two-laser results: Excellent agreement

Aliasing on 2-laser setup makes the signal slightly more complex
PDV with two spectrally-shifted lasers

- Bandwith x2 → velocity range x2

- Higher velocity measurement (10, 20 km/s….)

- Frequency beat is useful
  - For static level adjustments (easier for operator)
  - To measure photometry level and evolution (static/dynamic)

- No folding of negative velocity (example later)

- Processing: two possible solutions, only one is physical

\[ V_{\text{experimental}} = |V_{\text{measured}} \pm V_{\text{pivot}}| \]


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PDV: single or two-laser setups with a single optical fiber

- Single-mode laser 1.55 µm, 2W
- 400 mW
- 10 mW (200 µW after coupler)
- Single-mode optical fiber
- Circulator
- Detector BW: 50 kHz-12 GHz
- Digitizer BW: 12 GHz 50 GS/s
- Moving object
- -50 dB return loss (coating, angle)

(2%, 98%)
PDV: single or two-laser setups with two optical fibers

Single-mode laser
1.55 µm, 2W

Single-mode laser
1.55 µm + 8λ, 50 mW

400 mW

10 mW
(200 µW after coupler)

F₀

F₀

F₁

Coupler
(2%, 98%)

Detector
BW: 50kHz-12 GHz

F - F₁

Digitizer
BW: 12 GHz
50 GS/s

No coating

Moving object

1 to 10 µW

(2%, 98%)
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Subcontracted PDV cabinet

- Digitizer
  DPO 71254
  (12 GHz, 50 GS/s)
- Detector unit
- Tunable laser
- Main laser
PDV PROBES: «OZ optics» and «LIGHTPATH»

- Efficiency law: level and probing depth range
- Return loss (-40 to -60 dB)
- Size

**OZ Optics: Φ 2.5 mm**

**Lightpath: Φ 1.25 mm**

E2000 connector
**Copper cylinder experiment:**

- 2 channels setup with couplers and circulators.
- Single channel setup with couplers.
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Short Term Fourier Transform algorithm (FFT as implemented in Matlab). Mostly with 50 ns (1000-2000 pts) windowing and 10 ns step. Satisfying enough for most experiments.

\[ |S_x(\tau, \nu)|^2 = \int x(\tau)h(\tau - t)^* x(u)^* h(u - t) e^{-j2\pi \nu (\tau - u)} d\tau du \]

\[ I(t) = 1 + \cos \left( 2 \cdot \frac{2\pi}{\lambda_0} \int_0^t v(u) du \right) \]

\[ V(t) = \Delta F(t) \cdot \frac{\lambda_0}{2} \]
Uncertainties are spread over:

**Signal dependent**
- **Drift**
  - A few $10^{-4}$ m/s each
  - $Biais\left(f_i(l)\right) \approx \frac{\phi^{(3)}(lT).h^2}{80.\pi}$
  - *Difficult* to evaluate

- **Variance**
  - $Var\left(f_i(l)\right) \approx \frac{6\sigma^2 T}{4\pi^2 |A|^2 h^3}$
  - *Evaluable* through momentum algorithm (under gaussian white centered noise assumption)

**Sampling / Processing dependent**
- **Quantization**
  - $\Delta \nu = \frac{1}{2 \cdot \delta t \cdot N \cdot padding}$
  - Typically 5-15 m/s
Collaboration with a DSP team (Supelec) brought us to develop an algorithm with adaptative window. Currently under development (latest modifications allow efficient processing, even with multi-frequency contents). To be further tested and implemented.

*The size of the window is chosen such as to minimize bias and variance (chosen through an interval of confidence algorithm):*

- Thus, bias and variance are made negligible wrt quantization: in this case, zero-padding lowers down uncertainties

- Not applicable to rapid changes in velocities
- Easier Graphical User Interface for ‘daily’ processing of PDV signals

- Better visualisation

- Automatic selection of the velocity curve on the spectrogram…

- …and direct export to a .xls file

- Designed to be expandable (modules) and compilable as a standalone crossplatform application
PDV Signal Processing

Software: signal interface
PDV Signal Processing

Software: spectrogram interface – linear scaling
PDV Signal Processing

Software: spectrogram interface – Log10 scaling
PDV Signal Processing

Software: spectrogram interface – column-normalized scaling
PDV Signal Processing

Software: spectrogram interface – column-normalized and Log10 scaling
Software: interactive tracking of the velocity
Software: interactive tracking of the velocity

- The blue dots are the ones that are actually exported in the ‘.xls’ file
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GUN EXPERIMENT ON TIN : PARTICLE VELOCITY

Corrected Time-Frequency Spectrogram

V_{Tin free surface} about 1700 m/s

V_{Tin articles} 1800 to 2500 m/s

Raw Time-Frequency Spectrogram
GUN EXPERIMENT ON TIN : PARTICLE SIZE

- No vacuum (air atmospheric pressure)
- Model with only drag force: braking
- $C_d = 0.45$
- Size range: 0.4 to 5 µm
- Better model: with ablation
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LULI EXPERIMENTAL SETUP

- **Laser**
- **Protection window**
- **PDV probe**
- **Other diagnostics (VISAR or camera)**
- **Particles**
- **Al target (20 to 1000 µm)**
- **Transverse Shadowgraphy (3 cameras)**
LULI 2000 LASER : EXPERIMENTAL CHAMBER

- **LULI 2000**
  - $\lambda = 1057$ nm
  - $E = 790$ J
  - Pulse duration = 2 or 3 ns
  - Target spot diameter : 3 or 4 mm
  - Irradiance = 2 to 5 TW/cm²
  - Vacuum = $10^{-5}$ mbar
LULI PDV SHOT PROGRAM (12 ns shots, 22 fs shots)

<table>
<thead>
<tr>
<th>Shot</th>
<th>Target</th>
<th>Laser ($\lambda = 1057$ nm)</th>
<th>Target (defocus)</th>
<th>Diagnostics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material</td>
<td>Thickness</td>
<td>Pulse</td>
<td>Energy</td>
</tr>
<tr>
<td>T15 ns</td>
<td>Al</td>
<td>200 $\mu$m</td>
<td>LULI200</td>
<td>2.2 ns</td>
</tr>
<tr>
<td>T20 ns</td>
<td>Al</td>
<td>1000 $\mu$m</td>
<td>LULI200</td>
<td>3.1 ns</td>
</tr>
<tr>
<td>T19 fs</td>
<td>Al</td>
<td>20 $\mu$m</td>
<td>100TW</td>
<td>300 fs</td>
</tr>
<tr>
<td>T22 fs</td>
<td>Al</td>
<td>20 $\mu$m</td>
<td>100TW</td>
<td>300 fs</td>
</tr>
</tbody>
</table>

Single laser configuration
OZ probe, $\Phi$ 2.5 mm
SHOT T20 ns: 1 mm, 2 TW/cm², 3.1 ns $\rightarrow$ Spall created

- Break-out time
- VISAR
- Spall comes away from the Al bulk
- Flight of the spall
- Impact on the window

26 ns (70 µm thickness)
SHOT T15 ns : 200 µm, 5 TW/cm², 2.2 ns → Particles created

Flight of particles and fragments

Impact on the window

PDV raw signal

T = 250 ns

T = 500 ns

4.7 µs

Break out time

Velocity

5000 m/s

4000 m/s

3000 m/s

2000 m/s

1000 m/s

Time
SHOT T19 fs: 20 μm, 1.7 PW/cm², 300 fs → Particles cloud

Impact on window

Hyperbola: \( V = d / (t - t_{\text{break out}}) \)

Artefact: beats of two laser modes

1st particle family

2nd particle family

Break out time

PDV raw signal

T = 1 µs

T = 3 µs
PDV: Velocity sign accessible with 2 spectrally-shifted lasers.

- Two laser configuration
- Single laser configuration

Negative velocity
Folded velocity

Al target (20 to 1000 µm)
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PDV SETUP FOR EMBEDDED FIBER IN NITROMETHANE

Single-mode laser
1.55μm, 2W

Single-mode laser
1.55μm+ δλ, 50 mW

Circulator

Singlemode optical fiber

Coupler

Detector
BW : 50kHz-12 GHz

Digitizer
BW : 8 GHz
20 GS/s

Moving object

Bare fiber
PDV AND EMBEDDED FIBER IN NITROMETHANE: STEADY DETONATION

\[ V_{\text{real}} = \frac{V_{\text{pivot}} + V_{\text{measured}}}{n_{\text{silica}}} = 6270 \text{ ms}^{-1} \]
PDV AND EMBEDDED FIBER IN NITROMETHANE: NON STEADY DETONATION
HV AND EMBEDDED FIBER IN NITROMETHANE: NON STEADY DETONATION
CONCLUSION

- **Photonic Doppler Velocimetry (PDV)** is a remarkable and versatile tool with many advantages in comparison to DLI and VISAR:
  - Low cost, fully fibered setup, small probe sizes & spot
  - Good accuracy (a few m/s), good photometric dynamics (more than 26 dB)
  - Long time record (5 to 100 µs)
  - Ability to record simultaneously many velocities (with one or two solutions)
  - Large velocity range (0 – 20 km/s with 2-laser setup)
  - New PDV equipments subcontracted (12 GHz BW, 50 GS/s sampling)

- **Future**
  - We plan to improve the number of probes
  - Raw signal information (20 ps sampling) not yet completely used
  - Particles (histogram, size)
  - Embedded fibers…
2006 :
P. MERCIER, J. BENIER, A. AZZOLINA, JM. LAGRANGE, D. PARTOUCHE
"Photonic Doppler Velocimetry in shock physics experiments“

2008 :
P. MERCIER, J. BENIER, P.A. FRUGIER, G. CONTENCIN, J. VEAUX, S. LAURIOT-BASSEUIL, M. DEBRUYNE
Heterodyne velocimetry and detonics experiments.
28th International Congress on High-Speed Imaging and Photonics. Canberra, Australia. 9-14 november (2008).

2009 :
Velocity Heterodyne measurements under high power laser shock into solids

P.A. FRUGIER, P. MERCIER, J. BENIER, E. DUBREUIL, J. VEAUX
PDV and shock physics
SPIE - Optics and photonics. San Diego, USA. 2-6 august (2009).

J. BENIER, P. MERCIER, E. DUBREUIL, J. VEAUX, P.A. FRUGIER.
New Heterodyne Velocimetry and shock physics.
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