Photonic Displacement Interferometer

Thermomechanical Shock (TMS)
and
Early Thermostructural Response (TSR)
Measurement Applications

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Introduction

- Laser interferometry use in thermomechanical response measurements goes back to 1968 (Ref 1)
- Surface displacement in e–beam experiments to measure Gruneisen parameter in 1970 (Refs 2-4)
- Development of Photonic Doppler Velocimeter (PDV) – 2004 (Ref 5)
- Adaptation of PDV as a displacement interferometer
- Examples from disks and cantilevered beams
- Issues concerning thin specimens
- Radiation Source Fluence Measurements – ‘Z’
- Observation of material change

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Fiber Optic Interferometer Probe

Pulsed Radiation

Photonic Displacement Interferometer

- Optical path length difference between light reflected by sample and probe results in an interference phase angle when recombined (arbitrary $\phi_0$)
- Displacement of sample surface causes phase angle to evolve
- Recorded intensity $I = A + B\cos(4\pi x/\lambda + \phi_0)$, $A, B$ approximately constant
- One ‘fringe’ ($\Delta\phi = 2\pi$) equivalent to 0.775 micron ($\lambda/2$) displacement
- Positive or negative, nonuniform motion – displacement vs time accurate
For our studies, velocities are nonuniform and small (peak values as small as a few m/s)
Peak displacements: fraction of one micron to several microns
Required VISAR delays ($\tau$) for ‘one-fringe’ precision are impractical (532 nm air delay)
Validity of FT for extracting velocity unclear – nonuniform motion, reversals in velocity
Attributes

- Immune to electromagnetic noise
- Non contact/no bond joints to transducer:
  - Multiple shots on sample, material change/damage
- Sample surface preparation: little to none (aided by IR wavelength)
- Probe spot size: > 35 microns (depends on surface quality)
  - Enhances/extends validity of 1-D analysis

Present system:
- 4 channel utilizing 300 mW total power (2W, 1550 nm Erbium-fiber laser)
- DC – 3.5 GHz detectors
- 8 channel, 2 Gs/sec, 500 MHz BW, 1 Mpoints/channel (≥ 4 msec) recording
SPHINX accelerator configured for electron beam mode (a TSR disc experiment is shown). Typical spectrum and time history is shown from shot 19826.
- ~ 2 MeV end-point
- ~ 9 ns FWHM
Filtered (32 mil Al & 5 mil Ti) dose-depth profiles are shown for Al 6061, Al 7075, SS304L & Cu.
Noise Immunity
‘Typical’ Signal Quality

4340 steel, 3 mm (totally stopping) in SPHINX E beam
Sanded, machined surface

SX25070 Steel

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Fringe Analysis

\[ I = A + B \cos \left( \frac{4\pi x}{\lambda} + \phi_0 \right) \]

Normalize and offset: \[ S = \frac{(I-A)}{B} = \cos \left( \frac{4\pi x}{\lambda} + \phi_0 \right) \]

\[ x = \left( \frac{\lambda}{4\pi} \right) \cdot \left( \cos^{-1} S - \phi_0 \right) \]

Reversals not always obvious – makes automation difficult without quadrature recording. Analysis routine is under development.
Uncertainty

½ Fringe = ¼ wavelength ~ 0.38 µm  
**Rule-of-thumb:** Resolve 0.02 – 0.05 fringe

Total phase (displacement) accumulates (+/-), but uncertainty resets every ½ fringe

Uncertainty is inherently << 1/4 fringe, but $\phi_0$ and reversals near intensity extrema increase it

Constancy of interference contrast determines phase resolution uncertainty

Affected by surface quality, large displacements, recognition of superposed motions

Quadrature recording will reduce these contributors

Displacement ~ (N + n) fringes, Fractional uncertainty = $\delta n/(N+n)$
Three successive shots on SPHINX, monitoring rear surface

Center channels on disk (range thick)

1 inch aperture on a 1 ¾ inch disk

Captures information for obtaining deposition profile, fluence diagnostic

Probe spot size ~ 50 microns enhances validity of 1-D analysis for nonuniform e-beam profiles

Peak velocity ~ 7.5 m/sec would require VISAR delay of 35 nsec for ‘one-fringe’ accuracy of peak (532 nm).

Evident that TSR begins before first TMS response is complete (rear surface)

Clean TSR measurement within loading region from $t = 0$. 
VISAR Comparison

Simulated VISAR results for measured displacement data: 
\[ v \approx \frac{(S(t) - S(t-\tau))}{\tau} \]

532 nm air delay of > 30 ns required for ‘one-fringe’ precision of peak velocity
1550 nm delay of ~ 100 ns or greater required for 1550 nm

Long delays lead to large distortion – displacement analysis during ‘\( \tau \)’ required anyway
Three channels on single shot

Range thick sample, 25.4 mm aperture

Response is not radially symmetric about center

TMS response provides loading information across ‘structure,’ input for response modeling

TMS/TSR response for code/model V&V when combined with other diagnostics

Reversals can occur at intensity extrema

Superimposed motions mask symmetries that help identify reversals

Quadrature (2 ch) recording makes reversals unambiguous

Requirement for routine analysis of records > ~ 10 microseconds
Design Details of TSR Cantilever Beam Experiment – SPHINX e-beam

Exposure Area (Dia. = 25.4 mm)

L = 62 mm

w = 12.7 mm

L/10
L/2
F1/F2
TC1
TC2

V1
V2
V3

L_tot = 74.68 mm

OD = 8 mm

20 mm

Fused silica window shields probes

ozOptics Pigtail Focuser Type: LPF-04

WD = 28 mm

Incident fluence was 3 cal/cm²

Courtesy ITT-AES
Cantilevered beam is thin ($\rho t \approx 0.4 \text{ g/cm}^2$)

Jump in Ch 2 displacement is substantial and positive in this example

Increase in optical intensity in channel 2 at beam time indicates radiation-induced darkening is not only likely effect occurring

Because material is thin, material response to deposition at probed surface should begin instantaneously, complicating interpretation—what is real motion, what is other optical effects?
Considerations for Thin Samples

\[ OPL = L_1 + \int n(x,t)dx + L_o - \int u_1(t)dt - \int u_2(t)dt + \int n(x,t)dx \]

In addition, any phase change on reflection from sample due to currents, excitations.
Thermoelastic Calorimetry Application

X-ray or e-beam fluence, or source 
X-ray yield may be obtained using:

- Source spectrum and flux history 
- Rad transport 
- Absorber model \((\Gamma, c_0, \nu, Y, \ldots)\) 
  - elastic behavior best. Material choice

Potentially cheaper, faster result than from quartz TEC gauges, immune to pulsed power noise environment
PRS Fluence Measurement – ‘Z’

**Z1594**  SS wire array
2 mm Al 6061 – T6 absorber
2 probes agree to +/- 1.1% in peak displacement
~ 4 % uncertainty individual channel
53.6 kJ yield, 2 ns pulse

**Yields (kJ)**

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<td>Z1594</td>
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<td>Z1596</td>
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**Z1596**  SS wire array
2 mm Al 6061 – T6 absorber
25 kJ model scaled to 21.9 kJ total x-ray yield
Low yield, ‘long’ pulse (4.4 ns)
Measurements of material response to pulsed radiation using bonded transducers preclude observing (efficiently) changes in response behavior or material modification – is a change in observed response due to degradation or failure of the bond?

- Non-contact measurement of material response in a radiation source capable of repetitive pulsing (without refurbishment) allows observation of the material modification resulting from exposure.

- This capability allows observational assessment of material or component survivability in pulsed radiation environments.
Material Evolution

Poled PZT ceramic, rough ground surface

Repetitive shots on sample indicates material capability to withstand pulsed radiation deposition

Incipient spall signature on 15th shot
Structure, dynamics of damage can be analyzed from record

Fluence sufficient to heat into paraelectric phase on part of deposition profile
Gruneisen of depoled material much smaller in FE2 phase than for poled material
Material Evolution, PZT

Repetitive shots on sample indicates material capability to withstand pulsed radiation deposition.

Incipient spall signature on 15th shot. Structure, dynamics of damage can be analyzed from record.
Summary

Very simple interferometer system for multipoint surface displacement measurements

Noise immunity in pulsed power environment is enormous advantage

Non contact, optical technique allows for monitoring changes in material or structural response due to radiation deposition – ‘damage’ thresholds

1-D measurements of material response possible in small diameter drive sources

Early TSR results will provide interesting data for model comparison – quadrature recording required for reliable, unambiguous fringe unwrap—

In-line phase shifter being investigated
Laser frequency stability a question
References


