Optical Sensors for Measurements of Pressure, Temperature, and Skin Friction

One picture is worth a million pressure taps.

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Outline

• History of Pressure Sensitive Paint
• Temperature Sensitive Paint
  – Basic photo-physics and system
  – Boundary Layer Transition & Heat Transfer
• Pressure Sensitive Paint
  – Basic photo-physics and system
  – Radiometric Systems and Results
  – Sources of Error > why we use lifetime and binary systems
  – Lifetime PSP System and Results
  – Binary PSP Development
  – Binary PSP System and Results
• Experimental design for successful PSP measurements
• Model Deformation Measurements and PSP
  – Stereo Photogrammetry
  – Results
• Surface Stress Sensitive Film
  – Theory of Operation
  – Data acquisition Systems
  – Basic Results
  – Finite Element Model
  – Quantitative Skin Friction Measurements
  – Very Low Speed Pressure Measurements
  – Unsteady Pressure Measurements
  – Skin friction in water tunnels
  – Pressure in water tunnels
Short History of Pressure Sensitive Paint

- Russian Hydrodynamics Institute
  - First demonstration of PSP
- Optrod (TsAGI team)
  - Recognized illumination errors
  - First development of Pyrene based Binary PSP
  - Similar paints/system later developed by DLR & ONERA
- NASA AMES
  - United States PSP development
  - Photogrammetry / Resection
- University of Washington
  - PtTFPP in FIB binder
- Boeing/McDonald Douglas
  - Ruthenium in RTV paint
  - Focus on tunnel productivity
- Air Force / ISSI / NASA / BAE
  - Illumination errors
  - 2 gate lifetime PSP systems
- ISSI
  - High power LED for illumination
  - LED’s for lifetime illumination
  - Temperature compensating binary PSP
  - Focus on low speed, velocity 20 to 60 m/s
- Purdue University / Optrod
  - Fast PSP, kHz response
- Purdue University / NAL
  - Cryogenic TSP
  - Cryogenic PSP
Temperature and Pressure Sensitive Paint

- Optical instruments for surface measurements
  - minimal impact on model construction and flow field
  - continuous distribution of pressure or temperature
  - high spatial resolution (data at every pixel)
- Provides unique measurement capability
  - instrument thin sections
    - trailing edge of airfoils
    - MAV wings and control surfaces
  - instrument moving parts
    - compressor and turbine blades in research facilities
    - airfoil in flight
Temperature-Sensitive Paint

- Composed of:
  - Luminescent Molecule
  - Polymer Binder

- Photo-physical Process
  - absorb a photon
  - transition to excited state
  - competing relaxation paths

- Thermal quenching

- Intensity function of Temperature

\[
\frac{I}{I_{\text{ref}}} = 9.75 \left( \frac{T}{T_{\text{ref}}} \right)^2 - 25.5 \left( \frac{T}{T_{\text{ref}}} \right) + 16.7
\]

\[
T_{\text{ref}} = 298 \text{ K}
\]
Experimental Setup for TSP

- Note non-uniform
  - paint thickness
  - dye distribution
  - illumination
- Ratio Wind-off/Wind-on
  - illumination
  - paint thickness
  - dye distribution
  - removed
- Thermocouple at each pixel

LED Array

CCD Camera

long pass filter

excitation

phosphorescence

dye

polymer

binder

Model
Boundary Layer Transition Detection Using TSP

Cryogenic DLR
Boundary Layer Transition

- Mach 6 Ludwig Tube
  - 5° cone
  - transition bump
- Transition
  - good flow vis.
- Need heat flux
- Improved system
  - dual layer TSP

Schneider, Sullivan, Liu, & ISSI
Experimental Method for Heat Transfer

- LM-2 LED array 470 nm
- PixelVision SpectraVideo
- Filter
- Computer
- Jet
- Aluminum plate
- Mylar
- Heat source
Heat Transfer Model

\[ h = \frac{k}{L} \left( \frac{T_w - T_s}{T_s - T_{aw}} \right) \]

\[ q = h \left( T_s - T_{aw} \right) \]

\[ T_{aw} = T_\infty + r \frac{U_\infty^2}{2 C_P} \]

\[ q = k \frac{T_s - T_w}{L} \]

- Mylar with thermal conductivity \( k \)
- thickness \( L \)
- aluminum plate
- temperature-sensitive paint at surface temperature \( T_s \)
- recovery factor
- temperature \( T_w \)
Adiabatic Wall Temperature

\[ q = k \frac{(T_w - T_s)}{L} \]

\[ T_s = T_w - \frac{q L}{k} \]

\[ T_{aw} = T_\infty + r \frac{U_\infty^2}{2 c_p} \]

Process
- Control \( q \) with heating
- Measure \( T_s \) with TSP
- Plot \( T_s \) vs \( q \)
- Linear curve fit
- Extrapolate to \( q = 0 \)
- Repeat at each point
Adiabatic Wall Temperature

$\alpha = 9^\circ$ $H/D = 4.1$ $\Phi = 2.69$

$\alpha = 18^\circ$ $H/D = 4.7$ $\Phi = 2.08$

$T_{avg} = 296.0$ K
$T_{sec} = 289.9$ K (turb.)
$T_{rec} = 287.1$ K (lam.)

$T_{avg} = 296.0$ K
$T_{sec} = 288.0$ K (turb.)
$T_{rec} = 284.4$ K (lam.)

Temperature ranges:

$285$ K to $300$ K

$284$ K to $298$ K
Heat Transfer Coefficient

\( \alpha = 9^\circ \) \( \frac{H}{D} = 4.1 \) \( \Phi = 2.08 \)

\( \alpha = 9^\circ \) \( \frac{H}{D} = 4.1 \) \( \Phi = 2.69 \)

\( \alpha = 18^\circ \) \( \frac{H}{D} = 4.7 \) \( \Phi = 2.08 \)

\( \alpha = 18^\circ \) \( \frac{H}{D} = 4.7 \) \( \Phi = 2.69 \)
Pressure-Sensitive Paint

- Composed of:
  - Luminescent Molecule
  - Polymer Binder

- Photo-physical Process
  - absorb a photon
  - transition to excited state
  - conversion to triplet state

- Competing relaxation paths
  - Phosphorescence
  - Oxygen quenching

- Paint luminescent intensity is a function of partial pressure of Oxygen
Experimental Setup for PSP

- Note non-uniform
  - paint thickness
  - dye distribution
  - illumination

- Ratio Wind-off/Wind-on
  - illumination
  - paint thickness
  - dye distribution
  - removed

- Pressure tap at each pixel

LED Array → long pass filter → CCD Camera → excitation → phosphorescence

polymer binder

Model

Dye

Oxygen
Wind-Off Intensity Distribution
Sample data of impinging jet

Jet15_BG.tif  Jet15_WindOff.tif  Jet15_WindOn.tif
Processed PSP Image

- Remove background
  - Wind-off – Background
  - Wind-on – Background
- Ratio
  - Wind-on / Wind-off
- Filter
  - Low Pass
- Apply Calibration
Sensitivity to pressure
- 5% per [psi]

Sensitivity to temperature
- 0.5% per [K]

Ideal paint
- temperature sensitivity independent of pressure

Platinum tetra(pentafluorophenyl)porphine in Fluoro/Isopropyl/Butyl

\[ P_{\text{ref}} = 14.7 \text{ psia} \ (101.3 \text{ kPa}) \]

\[ T_{\text{ref}} = 25^\circ C \]
Pressure Measurements Using Pressure Sensitive Paint
Experiments in Fluids 40:697-707

Sonic under-expanded jet complex pressure variations very difficult to tap
High spatial resolution pressures at a variety of conditions

Pressure distribution along centerline location of maximum pressure easily identified
Compressor Blade in CRF
Improved Pressure Sensitive Paint

• **Errors in PSP measurements**
  – Illumination (model movement & lamp stability)
  – Temperature
  – Calibration, Photo-degradation, & Sedimentation
  – Spectral content of excitation, Filter leakage

• **Determine sensitivity coefficients**
  – Magnitude of error for each factor

• **Identify major sources of error**
  – Illumination
    • model movement between wind-off and wind-on
    • lamp stability between wind-off and wind-on
  – Temperature
    • temperature change between wind-off and wind-on
Illumination Error from Model Movement

Cylinder in cross flow
Mach number = 0.2
Tunnel dynamic P ~ 0.31 psi
Cp > +/-1.5 ??

paint sensitivity ~ 4% /psi
ΔP ~ 0.3 psi
signal change < 2%
1% resolution requires signal change to < 0.02%
small error in illumination
Illumination Errors

- Model movement/deformation
  - Sting mounted model shifts
  - Structural bending, twisting
  - Wind-on – Wind-off
- Lamp stability
  - LED’s >> not an issue
- Lifetime >> take all data at wind-on condition
  - Effective for flow > Mach 0.5
  - Near real-time results, production tunnels
- Binary >> add a reference dye
  - Effective or flow > 20-m/s
  - more data processing, better accuracy
Two-Gate Lifetime Approach

- Phosphorescence
  - decay is $\sim$ exponential
- $t_o/t$ is a function of
  - oxygen concentration
  - polymer properties

$I(t)$ illumination from LED lamp
$L(t)$ luminescence

10-µs \hspace{300µs} \sim 100-µs
- Take all data at wind-on
  - minimize model movement
- Gate 1 sensitive to:
  - illumination, paint thickness, dye conc.
- Gate 2 sensitive to:
  - illumination, paint thickness, dye conc.
  - pressure
- Ratio
  \[ S = \frac{G_2}{G_1} \]  
  \[ G_2 = \int_{t_3}^{t_4} L(t) \, dt \]  
  \[ G_1 = \int_{t_1}^{t_2} L(t) \, dt \]
• Temperature sensitivity
  – 0.5% per K
Lifetime Data Processing

- Data processing identical to Radiometric
- All data acquired at Wind-on
  - eliminate model movement
  - simple image processing
- Near real-time data presentation
Example of Lifetime Data Processing
Transverse Jet Injection for Flow Control

- TGF at Mach 3
- Blowing
  - perpendicular
  - 45 degrees
- Lifetime PSP
  - spatial resolution
  - structure of flow near jets

• Jon Tinapple & ISSI
Production testing using Lifetime PSP

Lifetime based PSP data in a 7-foot transonic wind tunnel

Mach 0.7
5° Angle of Attack

Comparison of PSP and pressure taps
$\Delta C_p \sim 0.03$

ISSI with David Hurst

Aircraft Research Association
Bedford England
Lockheed F16
US Air Force
Arnold Engineering Development Center

Lifetime based PSP in 16 foot transonic wind tunnel

\[ M = 0.9, \quad \alpha = 21.7^\circ \]

Painted Model
Integrated System at AEDC 16T

- 44 LM4X LED lamps >> ~ 12-W per lamp
- 8 cameras >> full view of the model

Acquire Gate 1 → Subtract Gate 1 Background → Identify Resection Markers
Acquire Gate 2 → Subtract Gate 2 Background

Map all camera images onto Mesh → Divide Gate 2 by Gate 1 → Apply Low Pass Filter → Apply Calibration → Identify Pressure Taps Read Pressure File → Apply in-situ correction

this is very hard to do real time it requires that the program “anticipate” the location of the markers.

the tunnel pressure system must transmit the data to the PSP system.
Compressors, Turbines, Rotating Machine

Pressure on a turbine blade in a research facility using PSP
Lifetime PSP System

- Pulsed LED lamps
- CCD camera with on chip integration
- All data at Wind-on condition
  - minimize illumination errors
- Near real-time data reduction
  - integration of system into tunnel possible
- Effective for flow speeds > Mach 0.5
- Does not deal with temperature
Temperature Errors

• Temperature variation on model caused by:
  – model construction
    • metal ⇒ isothermal
    • plastic ⇒ adiabatic
  – wind tunnel
    • operating point
    • recovery temperature

• Signal change
  – temperature?
  – pressure?
Example of Temperature Induced Error

\[ \Delta T \approx 0.6 \text{ psi error} \]

PSP pressure \(\sim 3\%\) per psi
Temperature \(\sim 1\%\) per K

\(5\text{K} \Delta T \sim 0.6\) psi error

\(\sim 5\)K temperature drop downstream of impingement results in "false" low pressure
Binary Pressure-Sensitive Paint

- oxygen
- ref. probe \( f_R = F_R(P,T)n_R I \)
- signal probe \( f_S = F_S(P,T)n_S I \)

- Fluorescence from probe
  - linear function of illumination
  - 2X illumination = 2X fluorescence

- Add a reference probe
  - spectral isolation
  - signal = red
  - reference = green

- Ratio
  - signal / reference
  - eliminate illumination error

\[
R(P,T,n_S,n_R) = \frac{F_S(P,T)n_S I}{F_R(P,T)n_R I}
\]
Emission Spectra of Binary PSP

Emission Spectra of BF405

- LM2X-400 Excitation
- BF405 Emission

Pressure Signal
Schott Glass Filter
RG645

Reference Signal
Bandpass Filter
550-nm +/- 40-nm

Normalized intensity

Wavelength (nm)

Normalized intensity
Binary PSP System
Ratio of Signal to Reference

Ratio of Signal/Reference
Min = 0.84
Max = 1.09

Ratio should be = 1.0 ??
Non-uniform Probe Distribution

- Oxygen
- Ref. probe: $f_R = F_R(P,T) n_R I$
- Signal probe: $f_S = F_S(P,T) n_S I$

Must deposit probes evenly
- Solubility of probes non-uniform

Probe distribution is static
- Wind-off ratio
- Wind-on ratio

Wind-off Ratio / Wind-on Ratio
- Eliminate probe distribution
- Only need 1 wind-off
- Improved tunnel productivity

$$L(P,T) = \frac{r_0(P_0, T_0)^{\frac{N_S}{N_R}}}{r(P,T)^{\frac{N_S}{N_R}}} = \frac{r_0(P_0, T_0)}{r(P,T)}$$
Wind-off Ratio / Wind-on Ratio

Wind off Ratio / Wind on Ratio
\( \alpha = 10 \) degrees
Mach = 0.2
Cylinder in Cross Flow with Binary

Tunnel dynamic P ~ 0.31 psi
Results more reasonable
Cp ~ -1 on side and 1 on front

V = 60 m/s
Temperature Compensation

• Ideal PSP
  – Slope of transducer constant at each Temperature
  – sensitive to relative temperature, not absolute
Why is Ideal Paint Important

• Use calibration curve at the wrong temperature
  – Start with I/Io data
  – Convert to pressure using PSP calibration at 25 C
  – Surface is really at 35 C
  – Plot PSP –versus- real result
PtTFPP/Fib for Temperature Compensation

- PtTFPP/FIB
  - Temperature sensitivity
  - small
  - constant with pressure
  - linear
Temperature Compensation

• Start with Binary PSP

\[ L(P, T) = \frac{F_1(P_0, T_0)}{F_2(P, T)} \]

• PtTFPP/FIB
  – linear with T \( F_1 = f(P) aT \)
  – select reference dye
    • linear with T \( F_2 = f(P) bT \)

• Find a reference dye with \( b \sim a \)

• Never measure temperature directly
  – sensitive to relative temperature, not absolute
  – system compensates for T
Binary FIB Paint

Pressure-Sensitive Paint Calibration

- **Temperature sensitivity**
  - ~25 times less than FIB
- **Uncertainty**
  - 50 Pa/K

UniFIB & Binary Fib calibrated over same temperature and pressure range

Platinum tetra(pentafluorophenyl)porphine in Fluoro/Isopropyl/Butyl

P_{ref} = 14.7 psia (101.3 kPa)
T_{ref} = 25°C
PSP for Automotive Aerodynamics Testing

$$V = 50 \text{ m/s}$$
$$\text{Yaw} = 5^\circ$$

Binary Pressure Sensitive Paint

Relative Pressure
kPa
PSP on MicroX in SARL

- High resolution pressure data
- Thin, removable tail section
- Multi-vortex structure?

Alyson Turri & ISSI
PSP at Low Speeds Using Binary Paint

Tunnel $V = 60$ m/s
Dynamic $P = 0.31$ psi

<table>
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<th>#</th>
<th>Tap</th>
<th>PSP</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>13.75</td>
<td>13.74</td>
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<tr>
<td>2</td>
<td>13.60</td>
<td>13.62</td>
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<tr>
<td>3</td>
<td>13.95</td>
<td>13.96</td>
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<tr>
<td>4</td>
<td>13.76</td>
<td>13.75</td>
</tr>
<tr>
<td>5</td>
<td>13.75</td>
<td>13.73</td>
</tr>
<tr>
<td>6</td>
<td>13.93</td>
<td>13.92</td>
</tr>
</tbody>
</table>
PSP on Fighter Model Tail at $\alpha=30^\circ$

Clean

ISSI and EADS

Brake

20 m/s

30 m/s

Pa

98400

98100

97800

97500

97200

96900

96600

96300

96000

95700

95400

95100
Binary PSP System

- LED lamps
- CCD camera with on chip electronic shutter
- Filter switch or 2 cameras
- Wind-off and Wind-on data
  - minimize illumination and temperature errors
- Near real-time data reduction more complex
  - integration of system into tunnel is possible
- Effective for flow speeds > 25-m/s
Experimental Design for PSP

- PSP proven and deployed in transonic tunnels
  - Quantitative results, production level systems
  - Binary or Lifetime based systems
- Extended PSP use to low speed tunnels
  - A lot more tunnels (Mach# < 0.2)
- Is there a “best” PSP system for low speed?
  - Radiometric
  - Binary
  - Lifetime
- Best system is a well designed experiment
  - Review ISSI’s experience with low speed PSP measurements using these systems
Radiometric

- Simple acquisition and processing
  - Wind-off Wind-on ratio
  - Good cameras, stable illumination sources
- Potential Errors
  - Deformation or displacement of the model
  - Temperature
  - Sedimentation or Photo-degradation
- Stiff, isothermal materials (metal)
- Careful experimental procedures
Very Low Speed (17-m/s) PSP
Results from AIAA 2004-878 (James Bell)

- Turn on tunnel and lamps, run for ~ 4 hours
- Acquire wind-on images
- Immediately turn off tunnel and acquire wind-off
Radiometric Binary

• Simple acquisition and processing
  – Still use Wind-off & Wind-on ratio
  – Isolate signal & reference probe with spectral filter
  – Same cameras and illumination sources
  – Add a filter switch

• Potential Errors
  – Image alignment
  – Photo-degradation

• Stiff, isothermal materials (metal)
• Careful experimental procedures
Very Low Speed (17-m/s) PSP
Results from AIAA 2004-878 (James Bell)

- Random noise is increased
  - More images (4) than Radiometric case (2)
  - Data acquired in 200-seconds –vs- 4 hours
- Span-wise variation is less evident
Lifetime

• Simple acquisition and processing
  – Wind-on two gate ratio
  – Camera technology has improved dramatically
  – Stable illumination sources

• Potential Errors
  – Temperature
  – Wind-off lifetime variation
  – Wind-off required for low speed
Wind-off Noise

- **Gate 1 / Gate 2**
  - Variation up to 25%
- **TFPP lifetime \( \sim 10\text{-ns} \)**
  - Signal is in gate 1
- **PtTFPP lifetime \( \sim 10\text{-\mu s} \)**
  - Signal is in gate 1 and gate 2
- **Add a bit of TFPP to UniFIB**
  - Source of Wind-off noise is residual TFPP
  - Not optimum for low speed
Experimental Design Conclusions

• No silver bullet
  – Lower limit of ~ 0.1-psi (700-Pa) dynamic range
  – Radiometric
    • Model displacement/deformation & temperature
  – Lifetime
    • Temperature
  – Binary
    • Image alignment

• Careful design of the experiment!!
  – Rigid mounts and model
  – Isothermal surface
Model Deformation Measurements

- Stereo view of the model
- Markers with known positions
  - pressure taps or resection markers
- Photogrammetry (Stereo PIV)
  - wind-on marker positions on bitmap
  - reconstruct physical location of each marker
  - yields 3 components of deformation
- PSP & Stereo Photogrammetry System
  - minimal impact on test
  - increase value ⇒ pressure and geometry
Stereo Photogrammetry System

- **Calibration**
  - wind-off markers
  - need a 3D field
- **Dynamic range**
  - camera depth of field
- **Accuracy (Stereo PIV)**
  - $\sim 1/10$ pixel in plane
  - $\sim 1$ pixel out of plane
- **Response time**
  - Limited by camera
Model Deformation

• Root to Tip deformation
  - $\Delta d \sim 0.4$ in
• Bulk displacement
  - $\Delta \sim 1.0$ in

$M = 0.4$
$\alpha = 20^\circ$

• Improve spatial resolution
  - more markers
  - non-uniform paint
• Improve frequency response
  - faster camera (limited)
Model Deformation for CFD Validation

Model Design

Numerical Prediction

Build Model

Experimental Data

Compare CFD & EFD

Validate Numerical Code

Rapid Prototype

Pressure, Velocity, Skin Friction, Geometry

AIAA-0035
AIAA-0440
AIAA-1028
Skin Friction and Pressure Measurements with Elastic Films
Background

• Surface Stress Sensitive Film (S3F) ~2003
  – elastic film that deforms under physical loads
  – monitor the deformations
    • digital image, capacitance gauge, etc.
  – convert deformations to loads using FEA model
    • known thickness and shear modulus, obeys Hooke’s law

• Advantages
  – responds directly to skin friction
  – responds to pressure gradients
  – develop as 2D point sensor or image based system
  – should operate in any fluid > water tunnels
Response to Tangential Forces

When a tangential load is applied to the film, the film will deform elastically under the load but will not compress or yield.

Surface markers displace under the load as the film shears.

Tangential Force $F_T$  Thickness $h$

Displacement $D_X$  Shear Modulus $G$

The displacement is a function of the applied force, the thickness of the film, and the shear module of the film.
Response to Normal Forces

When a normal load is applied to the film, the film will again deform elastically but will not compress or yield.

The thickness is a function of the applied force, the initial thickness, and the shear module of the film.

S3F is a gradient sensor, not an absolute pressure sensor.
System for measuring thickness & displacement using a single camera > just like PSP system

- Place polymer film on model
  - fluorescent dye
  - surface markers
- Illuminate surface
  - LED array
- Image surface
  - wind-off & wind-on images
  - surface marker pattern
    - tangential deformation
  - fluorescent dye
    - film thickness
Static Calibration of S3F

\[ \mu = \frac{\Delta F \times h}{S \times \Delta X} \]

\( \Delta F \) - tangential force increment = \( mg \sin(\alpha) \)

\( \Delta X \) - tangential displacement

\( S \) - contact area

\( h \) - film thickness = 1.7-mm

\( \mu \) - Shear Module = 117-Pa
Measuring film thickness

The film is lightly doped with a fluorescent dye and exposed to an illumination source to excite the dye.

An image of the film fluorescence is recorded at an unloaded condition (wind-off) and a second image is recorded at the loaded condition (wind-on).

The fluorescence of the film is a linear function of the film thickness so a ratio of the wind-off to wind-on image is an effective measurement of the film thickness.
Measuring tangential displacement

Small markers are randomly applied to the film surface

Again, an image of the film is recorded at an unloaded condition (wind-off) and a second image is recorded at the loaded condition (wind-on)

The tangential displacement of the film surface is determined using a cross-correlation
Comparison of PSP and S3F for Low Speed Pressure Measurements

S3F can be tuned to detect very small pressure gradients. Effective at very low speeds.

AOA = 10°
V = 13 m/s
Supersonic application of S3F

Görtler Vortices in Reattaching Shear Flow

7° Shock Generator
No discharge
Hypersonic Application of S3F

plasma off
plasma on

anode & cathode
S3F cavity

note cross flow

shock generator

Top view
Side view
Mach 5 Shock Boundary Layer
Strut End-wall Flow in Water

ISSI & A. Fontaine (Penn State)

Saddle Point

Stagnation Point
2D FEA Model

\( x = X/h \)

\( \mathbf{R}(x) = (R_x, R_y) \) is the elastic reaction of the film to an arbitrary load \( \mathbf{L}(x) = (L_x, L_y) \)

\[ \mathbf{R}(x) = \int \mathbf{g}(x - x') \mathbf{L}(x') \, dx' \]

\( g(x) \) is the response matrix that describes the film's response to the normal and tangential loads

\[ g(x) = \frac{1}{\mu} \begin{pmatrix} \delta_{xx}(x, \nu) & \delta_{xy}(x, \nu) \\ \delta_{yx}(x, \nu) & \delta_{yy}(x, \nu) \end{pmatrix} \]
2D FEA Model

\[ R_{xj} = \frac{\Delta x}{\mu} \sum_{k=0}^{N} T_k \delta_{xx} (x_j - x_k) + P_k \delta_{yx} (x_j - x_k) \]

\[ R_{yj} = \frac{\Delta x}{\mu} \sum_{k=0}^{N} T_k \delta_{xy} (x_j - x_k) + P_k \delta_{yy} (x_j - x_k) \]
FEA model for $\nu = 0.499$

for forces acting over an area 5X the film thickness, the response to skin friction is $\sim 100X$ the response to pressure gradients.

spatial frequency of applied force $x/h$

response amplitude

normal
tangential
cross-talk
Simple FEA model for $n = 0.5$

- Poisson ratio $= 0.5$ (incompressible)
  - special case, result can be written in terms of
    - tangential force ($F_x$)
    - pressure gradient ($\frac{dP}{dx}$)
    - film thickness ($h$)
    - film shear modulus ($\mu$)
    - reaction forces ($R_x, R_y$)

**tangential response**

\[
R_x = \frac{1}{\mu} \left( h F_x - \frac{h^2}{2} \frac{\partial P}{\partial x} \right)
\]

**normal response**

\[
R_y = \frac{1}{\mu} \left( \frac{h^3}{3} \frac{\partial^2 P}{\partial x^2} - \frac{h^2}{2} \frac{\partial F_x}{\partial x} \right)
\]
Physical Quantities

• Film thickness
  – capacitance gauge
  – luminescent signal from film

• Film Shear Modulus
  – static based on displacement to applied force
    • response function \( \frac{h}{\mu} \)
  – dynamic based on excitation of tangential mode

• Tangential displacement
  – PIV, holography

• Normal displacement (thickness)
  – Stereo PIV
  – luminescent signal (relative thickness)
Film Thickness

- Ultrasonic thickness gauge
  - range 25-µm to 1500-µm, accuracy 1-µm + 1% of reading
  - 1.1% - 5% error

- Interferometer
  - accuracy ~ $\lambda/10$, error estimate ~ 0.1%
  - index of refraction probably major error in this

- Luminescent coating (used during test)
  - relative thickness
  - uncertainty ~ 0.01% film thickness
  - error based on experience, dominated by camera noise

- Conservative estimate of error is up to 5%
  - 2% for a 100-µm film
Shear Modulus

• Static system
  – place a small weight on the film
  – apply a known load
  – monitor the displacement
  – plot displacement versus applied force
    • slope is shear modulus

• Errors
  – mass of weight * angle of rotation (applied force)
  – relative displacement
  – need relative not absolute numbers
    • slope of curve is linear
Static Calibration of S3F

\[ \mu = \frac{\Delta F \times h}{S \times \Delta X} \]

- \( \Delta F \) - tangential force increment = \( mg \sin(\alpha) \)
- \( \Delta X \) - tangential displacement
- \( S \) - contact area
- \( h \) - film thickness = 1.7-mm
- \( \mu \) - Shear Module = 117-Pa

\[ F = mg \sin(\alpha) \]
Shear Modulus

• Looking for slope, plot $\Delta F$ vs $\Delta x$

  $F = m \cdot g \cdot \sin(\alpha)$

  – 1 degree error in $\Delta \alpha \sim 1.7$

• Relative displacement

  – cross-correlation with optical flow
    • displacement accurate to up to 1/500 pixel

  – PCO.1600
    • 7.4-µm per pixel, 1/100 pixel resolution  >> 75-nm
    • diffraction limit is closer to 300-nm

  – Film thickness ~ 100-µm
    • displacement ~ film thickness
    • error ~ 0.3%

• Applied force dominant error ~ 2%
Dynamic Calibration of S3F

\[ \omega_0 = \sqrt{\frac{(2.5 \, \mu)}{(\rho \, h^2)}} \]

- \mu - Shear Module
- \rho - film density
- h - film thickness
- \omega_0 - first tangential mode

Amplitude

Electro-magnet

F = C \sin(\omega t)

mass

Film

amplitude

\[ \frac{\omega}{\omega_0} \]
Tangential Film Reaction

• Relative displacement, $\Delta x$
  – cross-correlation with optical flow
    • displacement accurate to up to 1/500 pixel
  – PCO.1600
    • 7.4-μm per pixel, 1/100 pixel resolution $\gg$ 75-nm
    • diffraction limit is closer to 300-nm
  – Film thickness $\sim$ 100-μm
    • displacement $\sim$ 1/10 film thickness

• Tangential error $\sim$ 3%
Normal Film Reaction

• Relative displacement, $\Delta y$

• Luminescent coating
  – relative accuracy $\sim 0.01\%$ film thickness (need to average)
  – error based on experience, dominated by camera noise
  – PCO.1600
    • full well is 40,000 photons, 0.7% noise
    • low pass filter can easily drop to 0.1%
  – This is relative thickness
  – absolute is still $\sim 2\% +$ noise

• Normal error $\sim 2\%$
Simple FEA model for $\nu = 0.5$

- **Unknown quantity**
  - tangential force ($F_x$)
  - pressure gradient ($dP/dx$)

- **Measured quantity**
  - film thickness ($h$) error estimate $\sim 2\%$
  - film shear modulus ($\mu$) error estimate $\sim 2\%$
  - reaction forces ($R_x, R_y$) error estimate $\sim 3\%$

\[
\frac{\mu R_x}{h} = F_x - \frac{h}{2} \frac{\partial P}{\partial x}
\]
\[
\frac{\mu R_y}{h^2} = \frac{h}{3} \frac{\partial^2 P}{\partial x^2} - \frac{1}{2} \frac{\partial F_x}{\partial x}
\]
Zero pressure gradient boundary layer

• Error in tangential response
  – $\Delta F_x = \Delta \mu + \Delta R_x + \Delta h$
  – $7\% = 2\% + 2\% + 3\%$

• Error in normal response
  – $\Delta (dF_x/dx) = \Delta \mu + \Delta R_y + 2\Delta h$
  – $8\% = 2\% + 2\% + 2*2\%$

\[ F_x = \frac{\mu R_x}{h} \]

\[ \frac{\partial F_x}{\partial x} = \frac{-2 R_y \mu}{h^2} \]
Fully Developed Channel

- Constant $F_x$ and linear pressure gradient

\[ R_Y = \frac{h^2}{\mu} \left( \frac{h}{3} \frac{\partial^2 P}{\partial x^2} - \frac{1}{2} \frac{\partial F_X}{\partial x} \right) = 0 \]

- Rearrange $R_X$ and substitute for pressure gradient

\[ F_X = \frac{1}{h} \left( \mu R_X + \frac{h^2}{2} \frac{(P_1 - P_2)}{L} \right) \]

$L \gg h$
Fully Developed Channel

• Simple experimental setup
• Well known analytical solution
  – Poiseuille flow
    \( C_f = \frac{24}{\text{Re}_{Dh}} \)
• Independent experimental measurement
  – pressure gradient
    \( \tau_w = -\frac{H}{2} \frac{dP}{dx} \)
Poiseuille flow

\[ C_f = \frac{24}{\text{Re}_{Dh}} \]

pressure gradient

\[ \tau_w = -\frac{H \, dP}{2 \, dx} \]
S3F Skin Friction (Pa)

Poiseuille Skin Friction (Pa)

h=0.3-mm
μ=3035-Pa
H=0.75-mm

Rx ~ 4.7-μm
ΔRx ~ 0.3-μm
error est. ~ 6%

h=0.8-mm
μ=312-Pa
H=0.8-mm
Box – S3F data
O’s – pressure port data
brown line – “24/Re” model

Flow is Laminar

$C_f$ as function of Reynolds number

$C_f$ vs Reynolds Number

S3F and pressure gradient data agree to better than 3% full scale

$h=0.8$-mm
$\mu=312$-Pa
$H=0.8$-mm

$h=0.3$-mm
$\mu=3035$-Pa
$H=0.75$-mm
Inclined Jet Impingement
maximum surface pressure 40-Pa

Pressure taps
S3F Pressure
S3F Shear
Along line

Normal Deformation Field
X-component of Shear Deformations
Laminar Separation on NACA-0012
V = 10-m/s > Very Low Speed

Normal Deformation Field

Deformations in Section A-A

S3F - Pressure Taps.
V = 10m/s
wind-off

wind-on

vortex

image ratio

vortex

normal deformation represents a pressure gradient

tangential deformation represents skin friction
Building Research Model

Viewing Direction

Flow $V = 6-12 \text{ m/s}$

Normal Deformations

Shear Deformations $U_x$

Shear Deformations, $U_y$

Normal Deformations
Unsteady Pressure, $V = 6 \text{ m/s}$

- Flapping Vortex
- Exposure = 25-ms
- 15 FPS
- Film response
- Time $\sim 300 \text{ Hz}$
- Pressure variations
- $\sim 50 \text{ Pa}$

Flow
High Reynolds Number Flow

• Turbulent boundary layer

• Penn State University 12-inch water tunnel
  – well documented flow with good optical access
  – skin friction measured with
    • drag balance
    • 2D-LDV velocity profile
  – Reynolds number up to 11-million
  – Velocity up to 20-m/s
  – skin friction up to 500-Pa
    • traditional S3F ~ 500-Pa, water S3F ~ 30,000-Pa
Sensor is designed as a Plug. Plug is mounted flush with the tunnel wall.

Side view of the sensor plug

2D point gauge tunnel installation

3 inch hole for Plug

Acrylic tunnel window

Plug

Film

S3F

Objective Lens

Window

LED

CCD (CMOS) matrix
S3F Displacement -vs- Velocity for Sensor 1 & 4

scale 6.394 μm per pixel
Sensor 1 shear modulus = 13.78-kPa
Sensor 4 shear modulus = 140.4-kPa
Skin Friction Comparison for Sensor 1 & 4

a-priori calibration
$\Delta x \cdot F(\mu, h, R) \gg$ from FEA model

RMS Deviation = 12.4-Pa
$\sim 5\%$ of the full scale value

RMS Deviation = 48-Pa
$\sim 10\%$ of the full scale value
compare smooth wall drag balance to S3F a-priori result

"perfect" result

\[ y = mx + b \]

\[ m = 1.0, b = 0 \]
Skin Friction Comparison for Sensor 4

Linear Curve Fit $y = mx + b$
$m = 1.03, b = 42.4$

offset likely a bias
error in displacement

---

Drag Balance Skin Friction [Pa]
S3F Skin Friction [Pa]

- △ a priori calibration
- ○ in situ correction
- --- Drag Balance

---

0 100 200 300 400 500
0 100 200 300 400
Measurements repeatable to better than 2% full scale

All data based on a priori calibration of 140.4 Pa/μm
Projection Moire Style Detection

Write lines above and below S3F, use photo-resist

Line spacing ~ 200 lines/mm, use inference pattern from laser
Projection Moire Style Detection

As upper lines distort with S3F line pattern is modified
Result is sum and difference frequencies

- Difference frequency appears as fringe pattern
- System is AC-coupled
  - fringe frequency is measure of tangential displacement of the top of the film relative to the bottom
- Reference channel moves with the model
  - no wind-off needed
Holographic Detection

- Surface particles
- Laser
- S3F
- Holographic Film
- Model

Exposure and fix film

“Image” of undistorted particles is fixed. This is the wind-off image fixed to the model.
Holographic Detection

- Mono-chromatic source, i.e. LED’s
- Interference pattern from “particles”
- Camera image
- Distorted surface particles
- “Image” of undistorted surface particles
- Fringe spacing and orientation indicates magnitude and direction of skin friction
Holographic Detection

• Advantages
  – Reference channel on model
    • no wind-off, image registration, etc.
  – AC detection, i.e. fringe spacing
  – 2 components of skin friction
  – high resolution of tangential reaction

• Disadvantages
  – Small field of view
    • point gauge, or scanned line
  – Exposure of holographic film
Conclusions

• Temperature Sensitive Paint
  – Boundary layer transition and heat flux in hypersonic flows
  – Heat transfer and adiabatic wall temperature on compressible jets

• Pressure Sensitive Paint
  – Lifetime systems for flow over Mach 0.5
  – Binary systems for temperature compensation
  – Binary systems for flow down to 20-m/s

• Surface Stress Sensitive Film
  – Compatible with PSP data acquisition hardware
  – Sensitive to 2 components of skin friction
  – Operate in a wind or water tunnels
  – Tunable sensitivity, control shear modulus and thickness
  – Validated using fully developed channel and turbulent boundary layer
  – Resolve pressure differences as low as 2-Pa
  – Unsteady measurements of pressure up to several kHz
Future Developments

• Brighter LED’s
  – More light = more photons = better S/N
    • LM4 ~ 1.2-W (no longer in production)
    • LM2X ~ 3-W (in production)
    • LM2XX ~ 25-W (in production Sept. 2008)

• New 2-color PSP
  – Use color version of cooled scientific camera
    • Red pixels > pressure channel
    • Green pixels > reference channel
  – All data in 1 picture = faster data acquisition
  – Better image alignment = better S/N

• Surface Stress Sensitive Film
  – Skin friction with better than 10% experimental uncertainty
  – Very low speed pressure measurements
  – Unsteady pressure measurements