Data Processing Tools for Dynamic Pressure-Sensitive Paint

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f = 281.2 Hz

f = 668.0 Hz

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Greg Elliott
Standard PSP in Production Wind Tunnels

Mach 0.7
5° Angle of Attack
Binary PSP

PSP Systems in operation at AEDC, ARA, DNW, JAXA, etc.

2008
Innovative Scientific Solutions
Dayton Ohio

Aircraft Research Association
Bedford England

Binary PSP

Lifetime PSP
Frequency Response of PSP

• Traditional PSP has a slow response time
  – Works well during steady testing
  – Does not respond to unsteady pressure fluctuations

• Response time is governed by gas diffusion in the paint binder:
  \[
  \frac{\partial [O_2]}{\partial t} = D_m \frac{\partial^2 [O_2]}{\partial z^2}
  \]
  \[
  \tau \propto h^2 / D_m
  \]
  – Decrease paint layer thickness \((h^2)\)
    – Thin paint limits Signal-to-Noise
  – Increase gas diffusivity within the paint binder \((D_m)\)
    – Open system is fully quenched at low pressure, limits Signal-to-Noise
Porous PSP for Fast Response

Fast PSP has open pores that increase surface area. Active probe sits on the surface and Oxygen has direct access to the probe.

Regular PSP requires that the Oxygen diffuse through the binder to the active probe. The diffusion process is much slower.

- **Anodized Aluminum**
  - 100+ kHz
  - High temperature sensitivity
  - Application not always practical
  - Quenched at low static pressure

- **PtTFPP-PP**
  - ~20 kHz response
  - High temperature sensitivity
  - Spray on surface with airbrush
  - Operation to 2+ atm.

- **Turbo-Fib**
  - ~2 kHz response
  - Lower temperature sensitivity
  - Spray on surface with airbrush
  - Operation to 1+ atm.
How Intrusive is PSP?

No PSP or Kulite

Taps & Kulite

Jim Gregory ~ 2010

Apply fast PSP to laminar flow airfoil to study fast PSP impact on laminar flow

Surface finish of Fast PSP is smooth, does not trip boundary layer. Does better than traditional taps, or fast transducer.

Everything is intrusive. PSP is no worse than a pressure tap. (might be better)

IR on a natural laminar flow airfoil

\[ \alpha = -6^\circ \]

\[ M = 0.28 \]

\[ \text{Re}_c = 1.8 \text{ million} \]

Fast PSP does not transition the flow

Fast PSP, Taps, & Kulite

Kulite

Taps

Kulite

Taps
Fast Paint Calibrations

• Porous Polymer
  – ~20-kHz Response
  – 1% - kPa

• Turbo-Fib
  – ~2-kHz Response
  – 1% - kPa
  – Low Temp. Sens.

• Which is the “best” choice

~ 20X temperature sensitivity

Platinum tetra(pentafluorophenyl)porphine in Porous Polymer

P̂_ref = 14.7 psia (101.3 kPa)
T̂_ref = 25°C
A Few Keys to Fast PSP Data Processing

• Recognize where PSP errors originate
  – Model motion, illumination, temperature, sedimentation, photodegradation
  – Low frequency content >> Wind-off to Wind-on
  – Separate mean and rms data, process independently

• AC couple the measurement
  – Average wind-on is the wind-off
  – Thermal gradients built in to the running wind-off
  – Minimal motion, temperature variation, etc.
  – Ratio and multiply by slope of PSP

• Fast PSP acquired in 2 sec.
  – Only concerned with errors that occur on this time scale
Ideal PSP for Pressure Fluctuations

Ideal Plot of Fast FIB Pressure-Sensitive Paint

- Ideal PSP Plot
- Normalize each isotherm at reference pressure
- PSP slope at each temperature

Ideal Plot of PtTFPP-PP Pressure-Sensitive Paint

- Temperature sensitivity is not important for unsteady data

Ideal PSP for AC coupled processing
- average wind-on is wind-off
- temperature gradients are not relevant
- local slope of calibration curve is key

Ideal PSP with linear calibration preferred
Fast Radiometric System

- Fast Cameras
  - Faster with better QE
- LED
  - >1,000X brighter
- Data processing
  - PC technology

**Excitation/Illumination**

<table>
<thead>
<tr>
<th>LED</th>
<th>LED</th>
</tr>
</thead>
</table>

Camera

**Long-pass filter isolates excitation from PSP emission**

**Normalization of intensity**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Normalized intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>0.2</td>
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<tr>
<td>500</td>
<td>0.4</td>
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<tr>
<td>600</td>
<td>0.6</td>
</tr>
<tr>
<td>700</td>
<td>0.8</td>
</tr>
<tr>
<td>800</td>
<td>1</td>
</tr>
</tbody>
</table>

**PSP Emission**

- Oxygen permeable binder with fluorescent dye
- Oxygen quenches dye emission
- PSP emission decreases with increasing $O_2$ pressure

**Detail of PSP/Model surface**

NACA0012 model with PSP coating

Paint thickness $\sim 50 \mu m$

Roughness $< 10 \mu m$
Single-Shot Lifetime System

- Lifetime PSP on rotating surfaces
- Demonstrated in 2000
  - Crafton and Carter
  - Kodak ES4, DCR4
- Frame Transfer Camera
  - Faster shift, better QE
- Fire-on-demand laser
  - Smaller, more power
- NASA Rotorcraft
Radiometric Fast PSP Data Processing

• Fast PSP data set is extremely large
  – Multiple Megapixel cameras with 5000-200,000 frames
  – Get the data off of the cameras and store it
  – Acquire for 2 sec. download for 15 min.

• Data processing
  – Conversion to pressure is linear algebra
    • +, -, *, / a 3D matrix, map data to mesh
  – GPU not terribly effective
    • not compute bound, data transfer is the issue
  – Get a workstation
    • lots of processors and lots of ram (64 Gig minimum)

Marvin can do it faster

Takes longer to load image than to process
Fast PSP Demonstration

Transverse Jet Injected into a Supersonic crossflow (2009)
AFRL, Carter, Gruber

Lots of fast pressure taps. Sampled simultaneously.
Spatial resolution of mm or better.
Fast PSP Data Analysis

• What can you do with Fast PSP data
  – Anything you can do with traditional fast transducer, you just have a lot more of them, and they were sampled simultaneously
  – Fluctuating pressure, Power spectra, Correlation coefficients, Coherence, Proper Orthogonal Decomposition, Dynamic Mode Decomposition, etc.

• Quick and dirty analysis on bitmap
  – Quickly identify key temporal and spatial frequencies

• Map to mesh to control data size
  – Usually around 100,000 data points per camera
Pressure Fluctuations, Virtual Taps

Stagnation
Bow shock
Behind jet

Jet Pressure 703 kPa

SPL (dB)
1024 x 1024
5000 images
6 Gig, thought that was a lot

7 kHz

Virtual taps

4.76 mm 90° Nozzle
Correlation Coefficients

- Correlation Coefficient
  - select control point
  - compute correlation coefficient at every other point in flow
  - 100,000 simultaneously sampled points
  - 100,000 correlation maps?

- Weak pressure fluctuation behind jet
- Strong influence on major flow features
- Stagnation zone of minor importance to flow dynamics
Power Spectra Maps

Rossiter Tones in Supersonic Cavity TGF at AFRL Schmit, Grove (2012)

30,000 images, Map to mesh (2-mm resolution). Extract data at each pixel and compute spectra. Reconstruct map at each frequency.

Maps here show amplitude of pressure fluctuations at Rossiter frequencies identified by taps.
Taps –vs- PSP

- PSP frequency peaks
  - near perfect agreement with taps

- PSP amplitude
  - reasonably close
  - > 4 dB in SPL

- No in-situ correction

- Past fast PSP data
  - frequency > excellent
  - amplitude > good

Traditional PSP
100 Pa error after in-situ correction is very good
1 Pa never happens
Evaluation of Flow Control Devices

Fast PSP data on ceiling of cavity with several passive flow control devices.

Note asymmetric tone evident with Flatspoiler. Hard to identify with 7 taps along centerline.

Easy to identify effective flow control devices with full map.
Noise Floor of Fast PSP

Maximum difference
Tap –vs- PSP ~ 8 Pa

Noise Floor ~ 107 dB
~ 4.5 Pa
Pretty close to theoretical calculation

Acquiring 62,000 images in 2.5 seconds, 8X8 pixel filter

Images at full well (20000 photons), noise ~ 88 Pa

Compute spectra using 256 points (20 Hz bins) 50% overlap

Averaging ~ 484 spectra
Theoretical noise floor ~ 4 Pa
Transition Fast PSP to Large Tunnel

AF RIF Program
ISSI, Marvin Sellers, Wim Ruyten, Ming Chang
June 2014

Cavity Acoustics in AEDC 16T

Mach 0.9, alpha 5 deg.
Mach 0.9, alpha 0 deg.
Mach 0.9, alpha -2 deg.
Taps –vs- PSP in 16T

- Frequency peaks
  - near perfect agreement with taps
- PSP amplitude
  - reasonably close
- No in-situ corrections applied
Proper Orthogonal Decomposition

- Extract relevant flow structures
- Suggested by Gregory
  - demonstrated by Sellers

\[ p(x, t) = \sum a_n(t) \phi_n(x) \text{ represent flow} \]

\[
 u^i = \begin{bmatrix}
 u_1^i \\
 u_2^i \\
 u_3^i \\
 \vdots \\
 u_M^i
\end{bmatrix}
\]

extract pressure at grid point \( m \), time step \( i \) to form \( u^i \)

\[
 U = \begin{bmatrix}
 u^1 \\
 u^2 \\
 u^3 \\
 \vdots \\
 u^N
\end{bmatrix}
\]

\[
 \tilde{C} = U^T U \text{ correlation matrix}
\]

\[
 CA^i = \lambda^i A^i \text{ eigenvalue problem}
\]

eigenvalue solution to compute POD modes

\[
 \phi^i = \frac{\sum_{n=1}^{N} A^i u^n}{\sqrt{\sum_{n=1}^{N} A^i u^n}} \quad i = 1, \ldots, N
\]

compute \( a_n \) to reconstruct pressure field with selected modes

\[
 a_n(t) = \text{diag}\left(\sqrt{\lambda_n}\right) A_n^T
\]
Transverse Mode in Cavity

- Compute POD modes using ~ 5000 images
- 95% energy in modes 1-50
  - large pressure structures contain most of the energy
- First several modes resemble cavity tones

Not pure tones, kinetic energy.
Modes contain multiple frequencies
POD for Data Analysis

- Modes 7 – 11
  - substantial asymmetry
  - Mixed with tones
- Feature not evident in Baseline spectral data
- Asymmetry evident
  - Flatspoiler Tone 2
- Model misalignment?
- Never see without POD
  - Not evident in DMD
Coherence

• Coherence
  \[ \gamma(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f) G_{yy}(f)} \]
  Spatial scale of pressure fluctuations

• Select a specific pixel
  – Compute coherence to each other pixel in flow
  – 100,000 pixels > 100,000 coherence maps

• Spatial scale of unsteady pressure fluctuations
  – How many unsteady pressure taps are needed
    • More kulites?
  – What kind of low-pass filtering can be applied
    • Improve noise floor
Launch Vehicle Buffet Test

- 216 Kulites
- Dynamic balance
- 4 camera Fast PSP
- Compare integrated fast PSP, virtual tap PSP, Kulites
- Discrete data overpredicts unsteady loads
- Assumed coherence is 0.5
- Coherence maps
  - Each tap
- Coherence $<< 0.5$
  - Need more taps
Dynamic Mode Decomposition

- Similar to POD with focus on frequency rather than kinetic energy

\[ V_1^N = \left[ v_1, Av_1, A^2v_1, \ldots, A^{N-1}v_N \right] \]

represent flow with linear growth

\[ \tilde{S} = U^H AU \]

eigenvalue solution to compute modes. \( U \) is POD basis

\[ V^i = \begin{bmatrix} v_1^i \\ v_2^i \\ v_3^i \\ \vdots \\ v_M^i \end{bmatrix} \]

extract pressure at grid point \( m \), time step \( i \) to form \( v^i \)

\[ V = \begin{bmatrix} v_1 & v_2 & v_3 & \cdots & v_N \end{bmatrix} \]

Select \( S \) to minimize residual

\[ AV_1^{N-1} = V_2^N = V_1^{N-1}S + re_{N-1}^T \]

Modes are eigenvalues of \( S \), complex part is frequency of mode

\[ \Phi_j = Uy_j \quad \omega_j = \log(\lambda_j)/\Delta t \]

reconstruct pressure field using (or excluding) specific frequencies
Spectral Peaks –vs- DMD Peaks

Energy Spectra

- Peaks
- Tone 1
- Tone 2
- Tone 3
- Tone 4
- Tone 5
- Tone 6

1024 images

Mach 1.5 Baseline Tap Data

- 1194 Hz
- 2658 Hz
- 3429 Hz
- 4161 Hz

3000 images
DMD/POD Camera Noise Filter

- POD used to isolate structure
- DMD used to isolate frequency

Mixing experiment using fast PSP
Data acquisition at 40 kHz

- Spectra computed using ~ 32,000 images
- Fast camera pattern noise at distinct frequencies
- Remove noise from data
  - POD
  - DMD

Mixing peak just visible in upstream data

Camera Noise

Mixing peak
Camera Noise Spectra

- Focus on upstream ROI
- Cannot show downstream
- Fundamental and 2 harmonics
- Common to see noise structures in fast CMOS camera
Camera Noise POD

- Reconstruct and remove?
- POD modes using 1024 images

- Structures present in POD modes
- Difficult to ID in spectra
POD Reconstruction

- Reconstruct each mode and compute spectra
- POD modes contain multiple frequencies
- POD good for pattern noise, not frequency
Camera Noise DMD

- DMD modes using 1024 images

- Noise structures present in DMD modes
DMD Reconstructed

- Camera noise peaks clear in Energy Spectrum
- Downstream mixing peak is also evident
  - Barely visible is spectra (32,000 images)
Practical Demonstration

Acoustic box with 2 speakers

- POD
- DMD
- Camera Noise streaks
Conclusions and Future Work

• Fast PSP provides high spatial resolution pressure maps
  – frequency content excellent, amplitude data good
  – operation demonstrated in small and large wind tunnels

• Cross-correlation, Coherence, and Spectral maps
  – identify flow scales, frequency content, and relationships

• POD and DMD analysis
  – Identify structures with significant kinetic energy (POD)
  – Identify specific frequency content in the flow
  – Can operate as a filter to remove noise or flow features

• Data mining tools
  – Identify key flow features, noise sources quickly and automatically

• Fast Binary PSP for mean and unsteady in single run
  – Development complete, testing underway