Unsteady Pressure-Sensitive Paint Techniques for Dynamic Wind-Tunnel Testing

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Visit to University of Washington in 1995

Prof. Martin Gouterman

Astronaut Janet L. Kavandi -mission specialist

Dr. Kavandi served as a mission specialist on STS-91 (June 2-12, 1998), STS-99 (February 11-22, 2000) and STS-104/ISS Assembly Flight 7A (July 12-24, 2001).

Dr. Kavandi currently serves as Director, Flight Crew Operations, NASA Johnson Space Center.

In 1986, while still working for Boeing, she was accepted into graduate school at the University of Washington, where she began working toward her doctorate in analytical chemistry. She has obtained Doctorate in Analytical Chemistry from the University of Washington - Seattle in 1990.

Her doctoral dissertation involved the development of a pressure-indicating coating that uses oxygen quenching of porphyrin photoluminescence to provide continuous surface pressure maps of aerodynamic test models in wind tunnels. Her work on pressure indicating paints has resulted in two patents.
Pressure- and Temperature-Sensitive Paints

- **Pressure-Sensitive Paint** [PSP]
- **Temperature-Sensitive Paint** [TSP]

![Diagram of molecular sensors](image)

Example of molecular sensors (metal complex compound)

**Principle of measurement**
- Oxygen quenching → PSP
- Thermal quenching → TSP

**Demo of PSP Response**: Oxygen quenching

UV illumination

\[
\frac{I_0}{I} = 1 + k_q \tau_0 [O_2]
\]

Stern-Volmer Relationship

O₂ → N₂

PSP: Platinum Porphyrine + TLC Plate
Pressure Sensitive Paint (1st Generation)

Washington Univ. (USA)

Sensor: Platinum Octaethylporphyrin (PtOEP)
Binder: Polydimethylsiloxyan (PDMS)

Pressure

Absorption/emission spectra

380nm

650nm

PSP Calibration
Stern-Volmer Equation

PSP/TSP measurement system (imaging)

- Excitation: Xe arc, LED
- Emission: CCD camera

PC with digitizing board

Imaging Method
**Processing of PSP images**

Wind-off image $I_{ref}$  
Wind-on image $I$

Image registration  
T correction

$I_{ref} / I$ (ratioing)  
Pressure

**Image registration**

Pressure map (pseudo color)

\[
\frac{I(P_{ref},T)}{I(P,T)} = A(T) + B(T) \cdot \frac{P}{P_{ref}}
\]

**Application of PSP Technique to a Domestic Civil Aircraft Development**

**JAXA PSP systems** applied to develop MRJ
Both high-speed (transonic) and low-speed
* Estimate load on the main wings
* Validate aerodynamic model

MITSUBISHI REGIONAL JET (MRJ)

Experimental Results@TWT1 (M=0.8, AoA=4deg)

K. Mitsuo, et al.
Flow around Shuttle Cock (U = 30 m/s)

Collaboration with Akita Univ.

Model Painted with PSP

Application to Sport Aerodynamics

Surface Pressure Distribution over World Cup Soccer Balls (2012)

Prof. Seo (Yamagata Univ.)

smooth

2004

2010
Karman vortex cause undesirable periodic forcing during the high winds. It is important for engineers to account for the possible effects of vortex shedding when designing a wide range of structures (tall building, bridge, chimney, etc).

Tacoma Narrows Bridge collapse (Nov., 7, 1940)

**Fast-responding PSP**

**Requirements for fast PSP**

- Fast response time
- High luminescent intensity

**Diffusion Theory**

Time constant: \( \tau \propto \frac{h^2}{D_m} \)

(ex) silicone polymer (Poly(DMS))

\[ D_m = O(10^{-10})m^2/sec \]

\[ h=10\mu m \rightarrow \tau = O(1)sec \]

Faster response \( \rightarrow \) thinner \( \rightarrow \) lower intensity and SNR

A key is “Porous Binder”
Porous materials for fast-response PSP

- Silica-gel thin-layer chromatography plate (TLC-PSP)
- Anodized-aluminum (AA-PSP)
- Polymer/ceramic (PC-PSP)
- Ultra fine ceramic powder

Frequency characteristics of PC-PSP

PtTFPP, T=20°C, P=100 kPa

- The amplitude attenuation starts at about 1 kHz and it reaches -3 dB at the frequency of 3.8 kHz.
- The phase delay increases in the frequency range over 1 kHz.
- Frequency response of PC-PSP is that of 1st order system of which time constant is determined by luminescent lifetime of sensor molecules
Conditional Image Averaging (1)


- Time-series PSP images are acquired with a CMOS high-speed camera under continuous excitation.
- Acquisition timing of every camera image and reference signal (phase information) are measured simultaneously.
- After image acquisition, PSP images are sorted by phases of filtered reference signal (ex. BP, POD) and averaged.
- This technique yields a series of high-SNR instantaneous pressure images.

Application to flow around square cylinder

- 3-D Square Cylinder
  - Height $H = 100$ mm
  - Width $W = 40$ mm
  - Length $L = 40$ mm
  - One high-frequency pressure transducer is provided on the center point of the side surface

- Experimental condition
  - Free-stream velocity : $50$ m/s ($Re=1.4\times10^5$)
  - Incidence angle : 0 degree

- Pressure variation on lateral side surface

![Image of experimental setup and data](image-url)
The pressure variations on the side surface were successfully visualized.
- High fluctuating-pressure regions appear at the bottom rear part.
- The PSP data are in good agreement with the pressure transducer data.
Application of conditional image sampling

2D unsteady pressure distribution on a ground plane (V=50m/sec)

The peak frequency is 150 Hz and the pressure amplitude is on the order of several hundred Pa.

Next-Generation Dynamic Wind-Tunnel Testing – Tohoku University, Japan

“Hybrid Flight Simulator”
Application to Dynamic Wind-Tunnel Testing

Oscillated Delta Wing (Phase-lock Method + Binary PSP)

1-DoF Roll Oscillation

\( f = 1 \text{ Hz}, \Delta\phi = \pm 30 \text{ deg} \)

- Relative Intensity
- Wave length [nm]
- Pressure Sensor
- Bi-PSP uncorr.
- Bi-PSP corr.

**Without correction**

- \( U = 30 \text{ m/s} \)
- AoA = 35 deg.

**With correction**

- \( \phi = 0 \text{ deg} \)
- \( \phi = 25 \text{ deg} \)

**Time History of \( C_p \)**

at \( x/c = 0.5 \) on Right Wing
The failure occurred during a flight on the Hawaiian island of Kauai on June 26, 2003.

The National Aeronautics and Space Administration (NASA) released on September 3rd its final report on the crash of Helios, a solar-powered "flying wing" that suffered structural failure and fell into the Pacific Ocean during a long-duration test flight last summer. A review of the flight data concluded that atmospheric turbulence caused the plane's wing tips to bend upward abnormally and then caused the entire wing to oscillate. The growing oscillations caused the Helios to gain speed until it suffered a structural failure. The accident investigation board determined that the mishap resulted from the inability to predict, using available analysis methods, the aircraft's increased sensitivity to turbulence following modifications to allow long-duration flights. Specifically, the addition of a hydrogen-air fuel cell pod and two hydrogen storage tanks placed significant loads along the length of the flying wing, reducing the safety margins for the aircraft. See the press release from the NASA Dryden Flight Research Center or go directly to the full report.