Image-Based Aerodynamic Measurements
- Transfer from Aerospace to Automotive Applications

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Objective

To develop unified global high-resolution flow diagnostics tools for automotive and aerospace applications
Looking for a “Magic Camera” for Global Flow Diagnostics

Velocity
Skin friction
Surface pressure
Surface temperature/heat flux

Aeroelastic deformation
Aerodynamic loading
Species
Physics-Based Optical Flow Method  
— High-Resolution Velocity Diagnostics

- Geometrical or Perspective
- Radiometric

Optical Flow Equation

$$\frac{\partial g}{\partial t} + \nabla \cdot (g\, u) = f(x^1, x^2, g)$$
Extracting High-Resolution Velocity Fields on a Full-Scale Car Based on Smoke Visualization

Optical Flow Diagnostics: Large regions at one vector per pixel

PIV Diagnostics

Small diagnostic regions: Problem in full-scale wind tunnels
Velocity Vectors Extracted by Using Optical Flow Method
Jupiter’s Great Red Spot Observed by NASA’s Spacecraft

NASA Galileo 1996 Images

t = 0 s

t = 4320 s
Global Flow Structures of the GRS

- **High-speed, near-elliptical, anti-cyclonical collar**
- **Low-speed inner region**

**Velocity Vectors**
(resolution reduced by 4)
Cyclonic Motion & Outward Spiraling Source Node

Topological Constraint:

\[ \#N - \#S = 1 \]

Consequence:
At least one long-lived node necessary for the GRS
Global Skin Friction Diagnostics
Based on Surface Flow Visualizations

- **Global luminescent oil-film (GLOF) visualization**
- **Surface heat transfer visualization with temperature sensitive paint (TSP)**
- **Surface mass transfer visualization with pressure sensitive paint (PSP)**
Highly Complex, Separated Flow over Car — Main Source of Pressure Drag

Global Skin Friction Diagnostics is the key to understand the physics of complex separated flow around car.
Low-Aspect-Ratio Wing
The Upper Surface at AoA = 18 deg
(Sudesh Woodiga)

Typical Luminescent Oil Image  
Skin Friction Vectors
Low-Aspect-Ratio Wing

Topological Analysis Based on the Poincare-Bendixson Index Formula

\[ \# N - \# S = 1 + \left( \# Z^+ - \# Z^- \right) / 2 = -1 \]
65° Delta Wing

Typical Luminescent Oil Image

Skin Friction Lines

Secondary separation line

Reattachment line

AoA = 13 deg (Re_c = 300,000)
Reconstructed Skin Friction Field on Surface of the Wing-Body Junction for AoA = 6 deg

$\# N = 6$

$\# S = 6$

$\# N - \# S = 0$
Pressure and Temperature Sensitive Paints
— Global Pressure and Heat Transfer Diagnostics

PSP and TSP are molecule sensors with extremely high spatial resolution.

Oxygen & Thermal Quenching:
Pressure Coefficient Distributions on the FAVOR Model at AoA = 10° & Mach 0.8

(From Marvin Sellers of Arnold Engineering Development Center)
PSP Measurements on a Car Model (Engler et al. 2001)
Global Diagnostics of Aeroelastic Deformation and Aerodynamic Loading

High-Speed Videogrammetry
Dynamic Aeroelastic Deformation and Aerodynamic Loading of a Rectangular Plate in Flow

(From Roy, Britcher & Liu (2005))
Thin Wing Vibration Control - *Biologically-Inspired Concept*

(Advanced Design Wind Tunnel at WMU)
Time-Dependent Wing Surface at AoA = 8 deg at 13 m/s
Reconstructed from 6 Eigen Modes

Baseline Wing  
Wing with Fins

Maximum, Median and Minimum Amplitudes
Amplitude of 1\textsuperscript{st} Torsion Mode at AoA = 8 deg at 13 m/s
Ensemble-Averaged Velocity Fields Obtained by Optical Flow Method at AoA = 8 deg at 13 m/s

**Velocity Magnitude**

Normalized Velocity Magnitude - Baseline

Normalized Velocity Magnitude - Fins

**Velocity Variation**

Normalized Velocity Variation - Baseline

Normalized Velocity Variation - Fins
Aeroelastic Deformation Measurements of Rotor Blades at NASA Ames 40-by-80-Ft Wind Tunnel (the largest wind tunnel in the world)
“Magic Camera”

Velocity
Skin friction
Surface pressure
Surface temperature/heat flux

Aeroelastic deformation
Aerodynamic loading
Species
Toward Unified Image-Based Measurements — Integrated Camera System

- Velocity field
- Skin friction field
- Surface pressure field
- Surface temperature/heat flux field
- Species field

Optical Flow Method & Luminescence Measurements

Videogrammetry

- Aeroelastic deformation field
- Aerodynamic loading
Equipment Required in Full-Scale Wind Tunnels

- **Global Velocity Diagnostics:**
  - high-speed cameras, smoke generator, lasers, lights

- **Global Skin Friction Diagnostics:**
  - industrial cameras, oil, lights

- **PSP & TSP:**
  - scientific-grade cameras, paints, LED UV lights

- **Global Deformation and Loading Diagnostics:**
  - high-speed cameras, lights, calibration rig
Conclusions
Implementation in Full-Scale Wind Tunnels

- **Global Velocity Diagnostics:**
  Ready (optical flow algorithms & equipment)

- **Global Skin Friction Diagnostics:**
  Ready (algorithms & equipment)

- **PSP & TSP:**
  Need a lot of work for PSP, ready for TSP

- **Global Deformation and Loading Diagnostics:**
  Ready (algorithms & equipment)
Pressure and Temperature Sensitive Paints


Global Skin Friction Diagnostics


Optical Flow Method


Photogrammetry

References

Aerodynamics and Fluid Mechanics