4D-PIV advances to visualize sound generation by air flows

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Aero-acoustics
Investigation approaches, from lab scale detail to full scale systems

Phased microphone array field measurements (Sijtsma, DLR)

Phased microphone array in large wind tunnel (DNW)

Direct numerical simulation of a transitional jet (Freund et al. 2000)

Jet noise prediction based on PIV and acoustic analogy (Schram, 2003, VKI)

Direct numerical simulation of trailing edge noise (DLR)

Rod-airfoil noise prediction based on time-resolved PIV and Curle’s acoustic analogy (Lorenzoni et al, 2008, TU Delft)
Aeroacoustics research approaches

Sound in the *far-field* by phase-microphones array
  (field tests and large-anechoic wind tunnels)

Phenomenological research by Computational aero-acoustics (CAA)
  - DNS, LES (direct approaches)
  - DNS+LEE, LES+BEM, RANS+SNGR (hybrid approaches)

Surface pressure sensors and acoustic analogies
  e.g. Pressure transducers and Curle analogy

Experimental noise-source identification by PIV
  statistical techniques (spatio-temporal velocity correlations)
  time-resolved analysis (velocity or derived pressure spectra)
## Use of PIV in aeroacoustics

An incomplete list of milestones

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<td>Two-point time-delayed velocity correlation tensor</td>
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<td>[Schroeder, 2004]</td>
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<td>[Haigermoser, 2009]</td>
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PIV and acoustic analogies
Quantitative source visualization for noise prediction

In the use of analogies, the acoustic pressure \( p' \) is expressed as integral of the fluid dynamic properties in the source region:

\[
p'(x, t) = \frac{x_i x_j}{4\pi c_0^2 |x|^2} \frac{\partial^2}{\partial t^2} \int \rho_0 v_i v_j \left(y, t - \frac{r}{c_0}\right) \frac{dy^2}{r}
\]

**Lighthill analogy** (low Mach, far-field), e.g. Jet noise

\[
p'(x, t) = \frac{x_i x_j}{4\pi c_0^2 |x|^2} \frac{\partial^2}{\partial t^2} \int_{V_y} \frac{\rho_0 v_i v_j}{r} \bigg|_{t=t_e} dV + \]
\[
- \frac{x_j}{4\pi c_0 |x|} \frac{\partial}{\partial t} \int_{\partial V_y} \frac{P_{ij}}{r} \bigg|_{t=t_e} n_i dS,
\]

**Curle analogy** (low Mach, far-field), e.g. Airframe noise

\[
p'(x, t) = -\frac{x_j}{4\pi c_0 |x|^2} \frac{\partial F_j(t_e)}{\partial t}
\]

**Gutin’s principle** (dipolar term for compact rigid body)

TUDelft
Vortex-structure interaction noise
Acoustic source determination by time-resolved measurements

High-speed PIV and acoustic experiments (KAT-NLR)

Illumination and imaging

Data reduction

2C TR-PIV: \( V(x,y,t) \)
(2000x1000 pixels@2700Hz)

Planar Pressure Imaging (PPI): \( P(x,y,t) \rightarrow \) on airfoil surf

Curle’s analogy:
\( p'(x,y,t) \) (far field)

Acoustic array and far-field microphones
Planar Pressure Imaging (PPI)  
From time-resolved velocity field to the pressure spatial distribution

- **Pressure gradient** derived from experimental velocity data using definition of material derivative [Liu & Katz, 2006]:

\[
\nabla^2 p = -\rho \left( \frac{D\vec{U}}{Dt} - \nu \nabla^2 \vec{U} \right)
\]

- **2D Poisson equation** for the pressure

\[
\nabla^2 p = -\rho \left( \frac{\partial Du}{\partial x} \frac{1}{Dt} + \frac{\partial Dv}{\partial y} \frac{1}{Dt} \right)
\]

- **Incompressible** and **inviscid** flow assumptions. Pressure solver [de Kat et al. 2008]. Neumann conditions at body surface. Dirichlet conditions in potential-flow region (e.g. free-stream).
Planar and surface pressure distribution

Surface pressure fluctuations due to vortex interaction with airfoil LE

Planar pressure distribution (w.r.t. $p_\infty$)

r.m.s. of pressure fluctuations along airfoil surface

Assessment of PPI w.r.t. Direct surface pressure measurement (de Kat et al. 2008)
Predicted vs. measured noise
Surface pressure fluctuations due to vortex interaction with airfoil LE

- C.L. (coherence length): percentage of airfoil span emitting in phase
- Main peak at the rod-shedding frequency
- Peak noise and narrow band level (200-500 Hz) well resolved
- Higher numerical robustness of Gutin’s approach (no surface pressure needed)
- Decay in the high frequency range not well captured (no scale dependence in the span-wise model, measurement noise)
Emission directivity

Surface pressure fluctuations due to vortex interaction with airfoil LE

- Maximum emission perpendicular to airfoil chord
- Emission 20% reduction in streamwise direction
Extension to 3D flow problems

Vortex-based definitions of acoustic source

Tomographic PIV measurement

Direct Numerical Simulation

Laminar flow at $Re = 360$

Turbulent regime ($Re = 5540$)

Laminar flow around a cylinder: $Re = 360$
Fluid: water, diameter = 12 mm, $V = 30$ mm/s
Velocity vector fields from Tomographic PIV
Frame rate = 7 Hz
$t = 143$ [ms]

Turbulent flow around a cylinder: $Re = 5540$
Fluid: water, diameter = 12 mm, $V = 0.04$ m/s
Velocity vector fields from Tomographic PIV
Frame rate = 7 Hz
$t = 143$ [ms]
3D PIV by tomography

Elsinga et al. 2005 *

Computerized Axial Tomography (CAT)

Tomograpic PIV

2d slice (tomas)

particles in 3D space

* Collaboration TU Delft – LaVision GmbH
Tomographic PIV

Working principle: MART reconstruction and 3D cross-correlation

- Image to object 3D mapping function + Self calibration (Wieneke, 2008)
- Iterative volume reconstruction (Multiplicative Algebraic Reconstruction Technique, MART)
- 3D Cross-correlation (Volume Deformation Iterative MultiGrid, VODIM)

Digital images

A

B

C

D

3D intensity field

3D velocity field
Transitional Jets
4D-measurements by time-resolved tomographic PIV

Jet:
Nozzle exit diameter: 10 mm
Exit velocity: 0.1 – 2.5 m/s
Re: 1,500 – 25,000
Simulation domain: up to 60 diameters

Measurement equipment:
Quantronix Darwin-Duo: 2x25 mJ @1kHz
4xPhotron SA1: 1024x1024@5.4kHz
Latex particles: $C \sim 0.8$ part/mm$^3$

Data analysis:
LaVision DaVis7.4
Meas. domain (cylindrical): 2x2x5 $D^2$
Box size: 1.5x1.5x1.5 mm$^3$
Time resolution: ~20 samples/cycle
Transitional Jets
4D-measurements by time-resolved tomographic PIV

Powell analogy

\[ p'(x,t) = \int_{V_s} \rho_0 \left( \omega \times V \right) \nabla G \, dy^3 \]

- Far field acoustic prediction
- Comparison with incompressible DNS
- Acoustic measurements in air jet under similarity conditions
Conclusions

Time resolved PIV enabling planar pressure field imaging (PPI)
  PIV used with Curle’s analogy for the prediction of rod-airfoil acoustics

Introduction of tomographic PIV for the 3D complex flows
  3D vorticity patterns of transitional and turbulent flows

Time-resolved tomo-PIV for acoustic source analysis
  Jet noise prediction by means of 4D-PIV and Powell’s analogy

Congratulations to DLR successful 25 years in PIV

...and best wishes for the next 25!!!