Broadband Trailing-Edge Noise
as a Canonical Benchmark Problem for Airframe Noise Predictions

Outcome of the BANC-III Workshop & Invitation for BANC-IV

Michaela Herr
EXTENDED UPLOAD VERSION
Institute of Aerodynamics and Flow Technology,
German Aerospace Center (DLR), Braunschweig, Germany

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michaela.herr@dlr.de
Introduction

Motivation behind BANC activity

Workshops on Benchmark Problems for Airframe Noise Computations (BANC)

- Objectives of the BANC workshops (since 2010) are
  - to provide a forum for a thorough assessment of simulation-based noise-prediction tools;
  - to identify current gaps in physical understanding, experimental databases, and prediction capability for the major sources of airframe noise;
  - to help determine best practices, and accelerate the development of benchmark quality datasets;
  - to promote future coordinated studies.

https://info.aiaa.org/tac/ASG/FDTC/ DG/BECAN_files_/
Introduction

Motivation behind BANC activity

Workshops on Benchmark Problems for Airframe Noise Computations (BANC)

- Workshop categories:
  1. Airfoil trailing edge noise (TEN)
  2. Unsteady wake interference between a pair of inline tandem cylinders
  3. Minimal 4-wheel landing gear
  4. Partially-dressed, cavity-closed nose landing gear
  5. The LAGOON Simplified Landing Gear configuration tested by Airbus and ONERA
  6. Slat Noise (DLR/ONERA Configuration)
  7. Slat Noise (modified NASA 30P30N Configuration)
  8. Acoustic Propagation Phase of Airframe Noise Prediction

new since BANC-II
Introduction

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  8. Acoustic Propagation Phase of Airframe Noise Prediction

- BANC-II-1: AIAA-2013-2123
- BANC-III-1: AIAA-2015-2847

new since BANC-II
**Test cases**

- Provide $c_p(x_1)$, $c_f(x_1)$, near-wake mean flow / turbulence profiles, surface pressure spectra $G_{pp}(f)$, FF noise $L_p(f_c)$ for CASES#1-5 ($Re = 1–1.5$ Mio.)

<table>
<thead>
<tr>
<th>Case#1</th>
<th>56 m/s 0°</th>
<th>NACA0012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case#2</td>
<td>55 m/s 4°</td>
<td></td>
</tr>
<tr>
<td>Case#3</td>
<td>53 m/s 6°</td>
<td></td>
</tr>
<tr>
<td>Case#4</td>
<td>38 m/s 0°</td>
<td></td>
</tr>
<tr>
<td>Case#5</td>
<td>60 m/s 4°</td>
<td>DU-96-180</td>
</tr>
</tbody>
</table>

**CASE#1:** single core test case for those who could not afford the full matrix

For the full problem statement with more specified definitions of

- profile coordinates (sharp TE!)
- tripping devices (TBL-TE noise!)
- TBL transition locations
- ambient conditions, etc.
- data formatting instructions including templates

please contact michaela.herr@dlr.de.
Overview on contributions

- **BANC-III-1 participants:**

  1. **PoliTo:** Andrea Iob, wavePRO, Torino, & Renzo Arina, Politecnico di Torino, Italy & Paul Batten / S. Chakravarthy, Metacomp Technologies, USA (CA)
  2. **DLR:** Roland Ewert / Christof Rautmann, German Aerospace Center
  3. **IAG:** Dimitrios Bekiropoulos / Mohammad Kamruzzaman, University of Stuttgart, Germany
  4. **DTU:** Franck Bertagnolio, DTU Wind Energy, Technical University of Denmark
## Overview on contributions

<table>
<thead>
<tr>
<th>configuration/ participant</th>
<th>PoliTo</th>
<th>DLR</th>
<th>IAG</th>
<th>DTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case#1 56 m/s 0°</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Case#2 55 m/s 4°</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Case#3 53 m/s 6°</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Case#4 38 m/s 0°</td>
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<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Case#5 60 m/s 4°</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>
Overview of methods

Contribution PoliTo: IDDES with Large Eddy STimulation (CFD++ Code, Metacomp)

Hybrid RANS/LES coupled with Large-Eddy STimulation

- LEST automatically converts RANS statistics into fluctuating turbulent velocity fields, suitable for sustaining an embedded LES

Mean Flow
- RANS
  - SA model
  - QCR terms

Near Field
- Synthetic turbulence
  - Fourier-based method
  - Implemented in CFD++

Far Field
- FWH
- Time integration
- 2D → 3D
- Span

IDDES
- Implemented in CFD++

Stochastic velocity field

cf. AIAA-2014-2764; Iob et al.
Overview of methods

Contribution DLR: CAA-code PIANO with stochastic source model FRPM*

PIANO: Perturbation Investigation of Aeroacoustic Noise

CFD RANS

\[ \vec{u}_0, \rho_0, p_0 \]

mean flow; here:

DLR code TAU with SST

\[ \vec{L}' = -\vec{\omega}_0 \times \vec{u}^t - \vec{\omega}^t \times \vec{u}_0 \]

vortex sound sources

\[ *Ewert, \text{Comp.} \& \text{Fluids (Vol. 37)} \]

cf. AIAA-2014-3298; Rautmann et al.

CAA APE

\[ p' \]

source \( \vec{L}' \)

4D-Stochastic Sound Sources FRPM*

Sound Field

Spectral analysis

www.DLR.de • Chart 9
Overview of methods

Contribution IAG: simplified theoretical prediction code Rnoise of ‘Blake-TNO’-type

**Rnoise: RANS based trailing-edge noise prediction model**

- Simplified theoretical airfoil trailing-edge far-field noise prediction model based on steady RANS: highly accurate and very fast

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**Source Modeling**

- **Poisson Equation For Wall Pressure Fluctuations**
  - Solution in Fourier Space
  - Assumption on Source Terms:
    - homogeneous & isotropic turbulence
    - neglecting turbulence-turbulence (TT) interaction terms
    - convective wave number, $k_0 \ll k$

- **Turbulence Noise Source Modelling**
  - Semi-empirical Anisotropy Scaling
  - Isotropic Turbulence Theory

- **RANS Flow Solver:**
  - DLR-FLOWer
  - Rnoise
    - Block structured FV solver
    - Different turbulence models
    - Higher order accurate & efficient

---

**Governing Eqns.**

**RANS Simulation**

$$P(k_1, k_3, \omega) = 4 \rho c \left( \frac{k_1^2}{k_1^2 + k_3^2} \right) \frac{1}{k_1} \int_0^\infty \left[ \frac{dU_1(x_2)}{dx_2} \right]^2 A_2(x_2) \phi_{22}(k_1, k_3; x_2) \langle u_2^2(x_2) \rangle \Phi_m(\omega - k_1 U_c) \exp^{-2|k_1 x_2|} dx_2$$

(Parchen, 1998)

$$S(\omega) = \frac{b}{4 \pi} \int_{-\infty}^{\infty} \frac{\omega}{c_\infty k_1} P(k_1, 0, \omega) dk_1$$

(Brooks & Hodgson, 1981)
Simplified theoretical airfoil trailing-edge far-field noise prediction model based on steady RANS: highly accurate and very fast

Rnoise: RANS based trailing-edge noise prediction model

- Overview of methods
- Contribution IAG: simplified theoretical prediction code Rnoise of ‘Blake-TNO’-type

Source Modeling
- Poisson Equation for Wall Pressure Fluctuations
- Solution in Fourier Space
  - Assumption on Source Terms:
    - homogeneous & isotropic turbulence
    - neglecting turbulence-turbulence (TT) interaction terms
    - convective wave number, \( k_0 \ll k \)
  - Pressure Spectrum \( P(k, \omega) \)
  - Propagate to Far-Field
    - Solving a diffraction problem \( S(\omega) \)

Turbulence Noise Source Modelling
- Semi-empirical Anisotropy Scaling
- Isotropic Turbulence Theory

RANS Flow Solver:
- DLR-FLOWer

- Rnoise
  - Block-structured FV solver
  - Different turbulence models
  - Higher order accurate & efficient

RANS Simulation

Airfoil Design & Verification

Wind Tunnel Exp. & Validation

www.DLR.de • Chart 11
Overview of methods
Contribution DTU: simplified theoretical prediction of ‘Blake-TNO’-type

**TEN modeling @ DTU Wind Energy**

- **Airfoil flow calculation – EllipSys2D**
  - Classical 2D incompressible RANS solver
  - $k-\omega$ SST turbulence model

- **Surface pressure calculation – Blake-TNO**
  - Using anisotropic turb. stress tensor by stretching each direction of space using stretching factors
  - Stretching factors tuned using mean pressure gradient (Bertagnolio et al., 2014)

- **Farfield noise – diffraction theory (Brooks & Hodgson, 1981)**

- **Important note concerning calculations:**
  - Trip-tapes are modeled by fixing transition and using higher intermittency factor in $Re-\theta$ transition model
Near-wake flow characteristics

IAG-LWT 2-point correlation measurements

Orientation of flow profiles position @ 100.38 % l_c
Near-wake flow characteristics CASE#1 SS

Overall comparisons

Aerodynamical data

IAG-LWT 2-point correlation measurements

Traveling probe
Waiting probe
Near-wake flow characteristics CASE#1 SS

Overall comparisons
Aerodynamical data

PoliTo: CFD++ + SA (+ QCR terms)

IAG-LWT 2-point correlation measurements
Overall comparisons
Aerodynamical data

Near-wake flow characteristics CASE#1 SS

\[ \left\langle u_3^2 \right\rangle = \frac{2}{3} \kappa_T \]
\[ \left\langle u_1^2 \right\rangle : \left\langle u_2^2 \right\rangle : \left\langle u_3^2 \right\rangle = 4 : 2 : 3 \]
Overall comparisons

Aerodynamical data

Near-wake flow characteristics CASE#1 SS

PoliTo: CFD++ + SA (+ QCR terms)
DLR: TAU + SST (4 : 2 : 1)
IAG: FLOWer + SST (+ anisotropy model)

\[ \langle u_3^2 \rangle = 2/3 k_T \]
\[ \langle u_1^2 \rangle : \langle u_2^2 \rangle : \langle u_3^2 \rangle = 4 : 2 : 3 \]
Near-wake flow characteristics CASE#1 SS

Overall comparisons
Aerodynamical data

PoliTo: CFD++ + SA (+ QCR terms)
DLR: TAU + SST (4 : 2 : 1)
IAG: FLOWer + SST (+ anisotropy model)
DTU: EllipSys2D + SST

\[
\langle u_3^2 \rangle = \frac{2}{3} k_T \\
\langle u_1^2 \rangle : \langle u_2^2 \rangle : \langle u_3^2 \rangle = 4 : 2 : 3 \\
\langle u_2^2 \rangle = 0.45 k_T
\]
Near-wake flow characteristics CASE#4 SS

Overall comparisons
Aerodynamical data

PoliTo: CFD++ + SA (+ QCR terms)
DLR: TAU + SST (4 : 2 : 1)
IAG: FLOWer + SST (+ anisotropy model)
DTU: EllipSys2D + SST

\[ \langle u_1^2 \rangle = \frac{2}{3} k_T \]
\[ \langle u_1^2 \rangle : \langle u_2^2 \rangle : \langle u_3^2 \rangle = 4 : 2 : 3 \]
\[ \langle u_2^2 \rangle = 0.45 k_T \]
Overall comparisons
Aerodynamical data

Near-wake flow characteristics CASE#2 SS

PoliTo: CFD++ + SA (+ QCR terms)
DLR: TAU + SST (4 : 2 : 1)
IAG: FLOWer + SST (+ anisotropy model)
DTU: EllipSys2D + SST

\[
\left\langle u_1^2 \right\rangle = \frac{2}{3} k_T \\
\left\langle u_1^2 \right\rangle : \left\langle u_2^2 \right\rangle : \left\langle u_3^2 \right\rangle = 4 : 2 : 3 \\
\left\langle u_2^2 \right\rangle = 0.45 k_T
\]
Overall comparisons
Aerodynamical data

Near-wake flow characteristics CASE#3 SS

PoliTo: CFD++ + SA (+ QCR terms)
DLR: TAU + SST (4 : 2 : 1)
IAG: FLOWer + SST (+ anisotropy model)
DTU: EllipSys2D + SST

\[ \left\langle u_1^2 \right\rangle = \frac{2}{3} k_I \]
\[ \left\langle u_1^2 \right\rangle : \left\langle u_2^2 \right\rangle : \left\langle u_3^2 \right\rangle = 4 : 2 : 3 \]
\[ \left\langle u_2^2 \right\rangle = 0.45 k_I \]
Overall comparisons

Aerodynamical data

Near-wake flow characteristics CASE#5 SS

No measured comparison data available!

PoliTo: CFD++ + SA (+ QCR terms)
DLR: TAU + SST (4 : 2 : 1)
IAG: FLOWer + SST (+ anisotropy model)
DTU: EllipSys2D + SST

\[
\begin{align*}
\langle u_1^2 \rangle & = 2/3 k_T \\
\langle u_1^2 \rangle : \langle u_2^2 \rangle : \langle u_3^2 \rangle & = 4 : 2 : 3 \\
\langle u_2^2 \rangle & = 0.45 k_T
\end{align*}
\]
Surface pressure data

Position @ 99 % \( l_c \)
PSDs (measurement data normalized to \( \Delta f = 1 \) Hz)
Overall comparisons
Surface pressure data

Unsteady surface pressure PSD $G_{pp}(f)$ CASES#1 & #2

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Surface pressure data

- PoliTo: IDDES-LEST
- DLR: PIANO-FRPM
- IAG: Rnoise 'Blake-TNO' derivative
- DTU: 'Blake-TNO' derivative
Overall comparisons

Surface pressure data

Unsteady surface pressure PSD $G_{pp}(f)$ CASES#3 & #5

PoliTo: IDDES-LEST
DLR: PIANO-FRPM
IAG: Rnoise ‘Blake-TNO’ derivative
DTU: ‘Blake-TNO’ derivative

No measured comparison data available!
Overall comparisons

TEN farfield noise data

elliptic mirror @ DLR AWB

b = 1 m
r = 1 m
1/3-octave band spectra

θ = 90° chord-normal view direction for noise prediction
Overall comparisons

Farfield noise data

1/3-octave band FF noise spectra $L_{p(1/3)}(f_c)$ CASES#1 & #2

- PoliTo: IDDES-LEST/FWH
- DLR: PIANO-FRPM
- IAG: Rnoise (‘Blake-TNO’ / Brooks & Hodgson)
- DTU: (‘Blake-TNO’ / Brooks & Hodgson)

**Diagram Description:***

- The diagram illustrates the 1/3-octave band FF noise spectra $L_{p(1/3)}(f_c)$ for CASES#1 & #2.
- The x-axis represents the frequency $f_c$ in kHz, ranging from 5 to 1520 kHz.
- The y-axis represents the sound pressure level $L_{p(1/3)}$ in dB, ranging from 30 to 90 dB.
- Each line corresponds to different cases:
  - **CASE#1, PoliTo** (red line)
  - **CASE#1, DLR** (green line)
  - **CASE#1, IAG** (blue line)
  - **CASE#1, DTU** (magenta line)
  - **CASE#2, DLR** (black line)
  - **CASE#2, IAG** (light blue line)
  - **CASE#2, DTU** (dark blue line)

- The data points are marked with error bars, indicating variability or uncertainty in the measurements.
Overall comparisons
Farfield noise data

1/3-octave band FF noise spectra $L_{p(1/3)}(f_c)$ CASES#3 & #5
Pressure data revisited to identify common trends; are relative effects captured by the predictions?
Overall comparisons

Effect of flow velocity on $L_{p(1/3)}(f_c)$ and $G_{pp}(f)$: CASE#1 vs. #4

Pressure data

$U_\infty = 56$ m/s
$U_\infty = 38$ m/s
Overall comparisons

Effect of flow velocity on $L_{p(1/3)}(f_c)$ and $G_{pp}(f)$: CASE#1 vs. #4

Pressure data

$U_\infty = 56 \text{ m/s}$

$U_\infty = 38 \text{ m/s}$
Effect of flow velocity on $L_{p(1/3)}(f_c)$ and $G_{pp}(f)$: CASE#1 vs. #4

Pressure data

- **Overall comparisons**

- **Effect of flow velocity on $L_{p(1/3)}(f_c)$ and $G_{pp}(f)$: CASE#1 vs. #4**

- **Pressure data**

  - **CASE#1**
  - **CASE#4**

  - **DLR simulation**
  - **IAG simulation**
  - **DTU simulation**

  - **CASE#1-PS, DLR**
  - **CASE#1-SS, DLR**
  - **CASE#4-PS, DLR**
  - **CASE#4-SS, DLR**

  - **CASE#1-PS, IAG**
  - **CASE#1-SS, IAG**
  - **CASE#4-PS, IAG**
  - **CASE#4-SS, IAG**

  - **CASE#1-PS, DTU**
  - **CASE#1-SS, DTU**
  - **CASE#4-PS, DTU**
  - **CASE#4-SS, DTU**

  - **DLR simulation**
  - **IAG simulation**
  - **DTU simulation**

  - **black/grey: measurement data**
  - **black: measurement data**
Overall comparisons

Effect of a-o-a on $L_{p(1/3)}(f_c)$: CASES#1 to #3

Pressure data
Overall comparisons

Effect of a-o-a on $G_{pp}(f)$: CASES#1 to #3

**Pressure data**

**SS**

- **Measurement data**
- **DLR simulation**
- **IAG simulation**

**PS**

- **Measurement data**
- **DLR simulation**
- **IAG simulation**

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Overall comparisons

Effect of a-o-a on $G_{pp}(f)$: CASES#1 to #3

Measurement data

DTU simulation

IAG simulation

SS

PS

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Overall comparisons

Effect of airfoil geometry on $L_{p(1/3)}(f_c)$: CASE#2 vs. CASE#5

Pressure data

Measurement data:
- Individual datasets
- Averaged comparison spectra

CASE#2
CASE#5

Measurement data:
- DLR simulation
- IAG simulation
- DTU simulation
Overall comparisons

Pressure data

TEN directivities CASE#1

1 kHz

2 kHz

5 kHz

8 kHz

10 kHz

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Overall comparisons

Pressure data

TEN directivities CASES#1 to #5

1 kHz  2 kHz  3 kHz  8 kHz  10 kHz

case #1

240  270  300  
210  180  150  

\(\theta, \text{deg}\)

normalized \(p_{\text{rms}}(\theta)\),

 case #2

240  270  300  
210  180  150  

\(\theta, \text{deg}\)

normalized \(p_{\text{rms}}(\theta)\),

 case #3

240  270  300  
210  180  150  

\(\theta, \text{deg}\)

normalized \(p_{\text{rms}}(\theta)\),

 case #4

240  270  300  
210  180  150  

\(\theta, \text{deg}\)

normalized \(p_{\text{rms}}(\theta)\),

 case #5

240  270  300  
210  180  150  

\(\theta, \text{deg}\)

normalized \(p_{\text{rms}}(\theta)\),
Conclusions

- The outcome of the BANC-III workshop category 1 has been summarized.

- Results display a high scientific quality level; FF TEN predictions are within or very close to the provided data scatter band, TEN maxima are principally well-predicted; but:
  - General trends (a-o-a, velocity scaling) are not always correctly predicted.
  - Code-specific advantages/disadvantages are observable, indicating that a methodology which comprehensively predicts all of the requested nearfield & FF quantities is not available to date.

- The category 1 workshop problem remains a challenging simulation task due to its high requirements on resolving/modeling of TBL source quantities.

- We still faced a comparatively low number of participants, these were mainly developers of faster approaches dedicated for use in an industrial context (design-to-noise), BANC-III-1 results will hopefully activate multiplied follow-on activity by anyone interested to join the community.
We hope to motivate a more representative spectrum of the TEN community to participate at BANC-IV-1 in 2016.

BANC-IV-1 will supplement the existing CASES#1–5 by additional datasets:

- **0.6-m chord NACA64-618** data provided by DTU Wind Energy; $c_p(x_1)$, flow profiles, $L_{p(1/3)}(f_c)$, $G_{pp}(f)$, spanwise correlation of $G_{pp}$; $Re = 1.43$ Mio.

<table>
<thead>
<tr>
<th>Case#6</th>
<th>45.03 m/s -0.88°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case#7</td>
<td>44.98 m/s 4.62°</td>
</tr>
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- **0.6-m chord NACA64-618** data provided by DTU Wind Energy; \( c_p(x_1) \), flow profiles, \( L_{p(1/3)}(f_c) \), \( G_{pp}(f) \), spanwise correlation of \( G_{pp} \); \( Re = 1.43 \text{ Mio} \).

The by now established BANC category 1 data base is open for use to anyone interested and will be maintained according to your feedback.

The BANC-IV-1 updated problem statement will be soon available; if you wish to be included in the distribution list please contact:

[mailto:michaela.herr@dlr.de](mailto:michaela.herr@dlr.de)

Thank you for your attention!