Microphone-Array Measurements in Wind Tunnels: Challenges and Limitations

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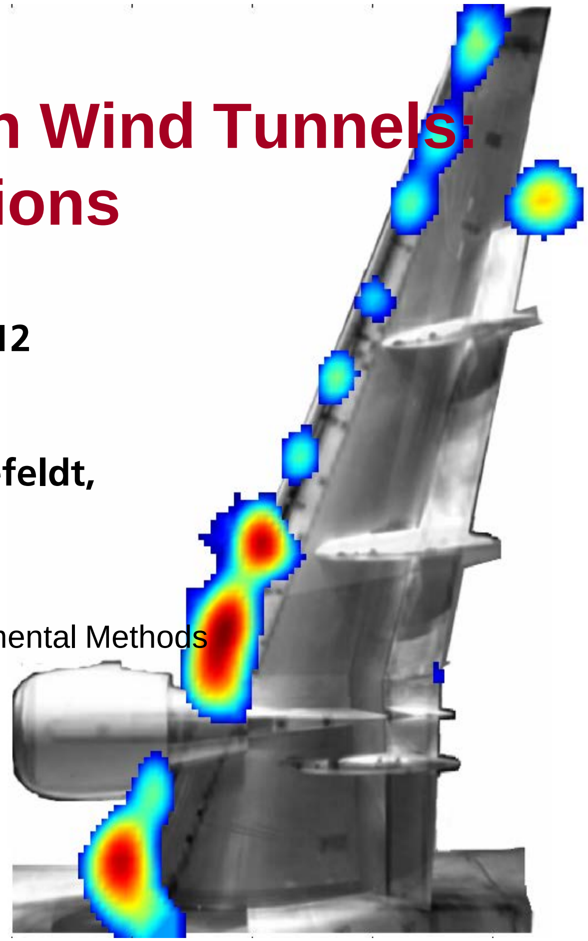

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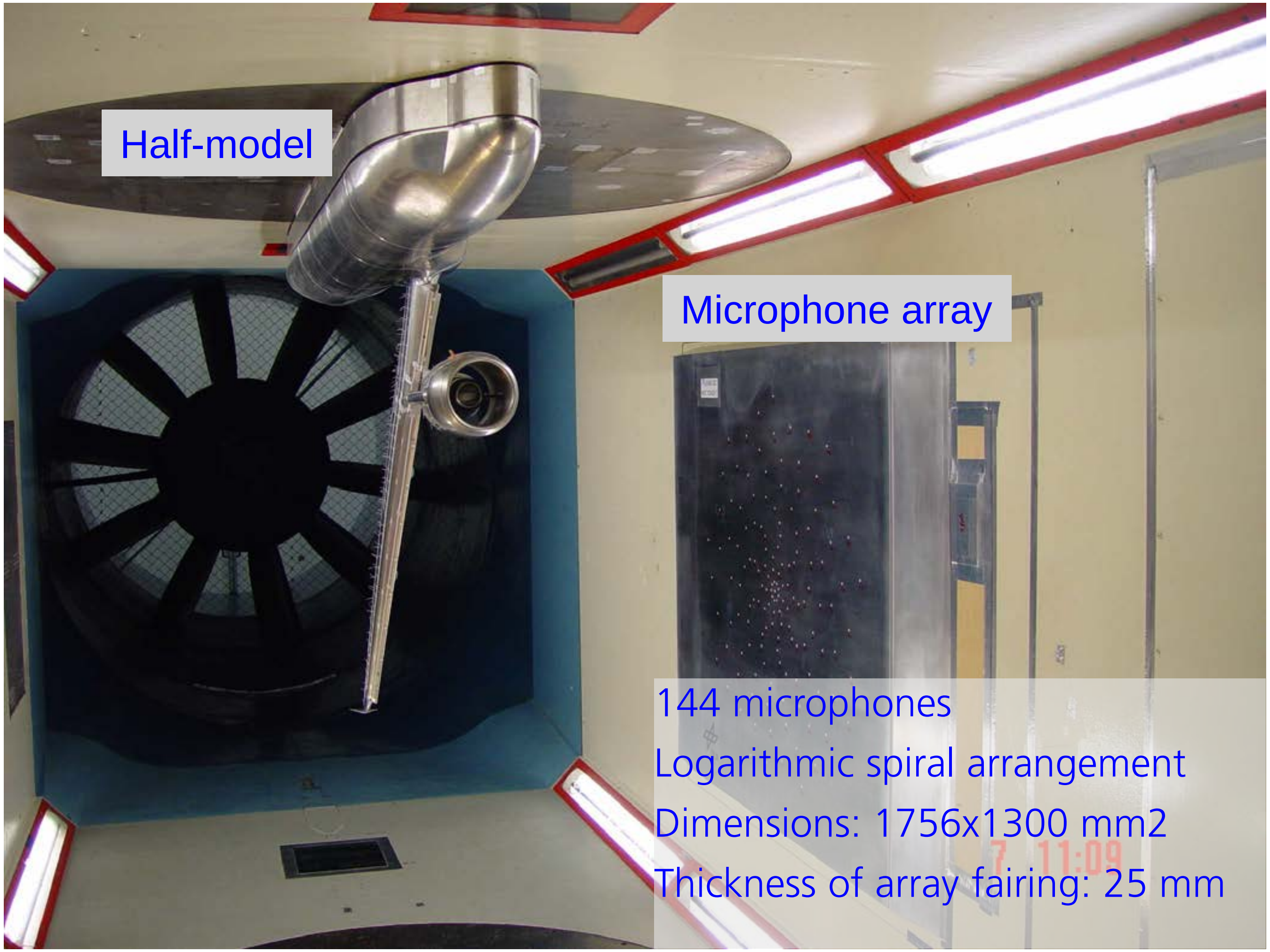
Outline

- Status quo of microphone array measurements in closed and open test section wind tunnels
  - Typical setup of industrial wind tunnel measurements
  - Application in ground transportation
  - Summary and conclusions
- Challenges and limitations, open issues
- Two examples:
  - Re-number effects → Measurements in cryogenic wind tunnels
  - Comparability → Measurements in different test facilities
- Conclusion

Measurement in industrial closed test section WT

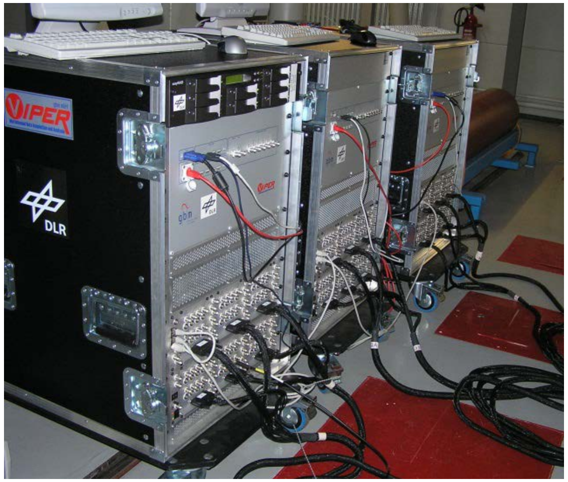
Measurement setup

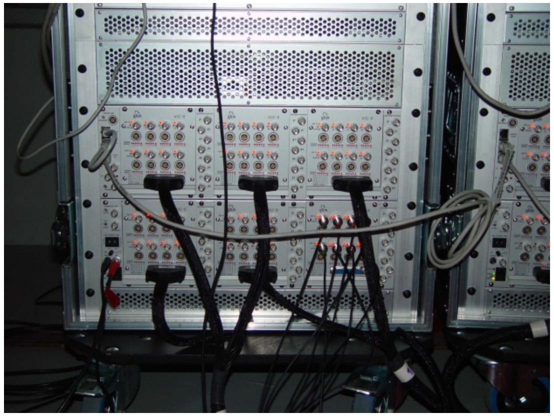


Measurement in industrial closed test section WT

Measurement setup

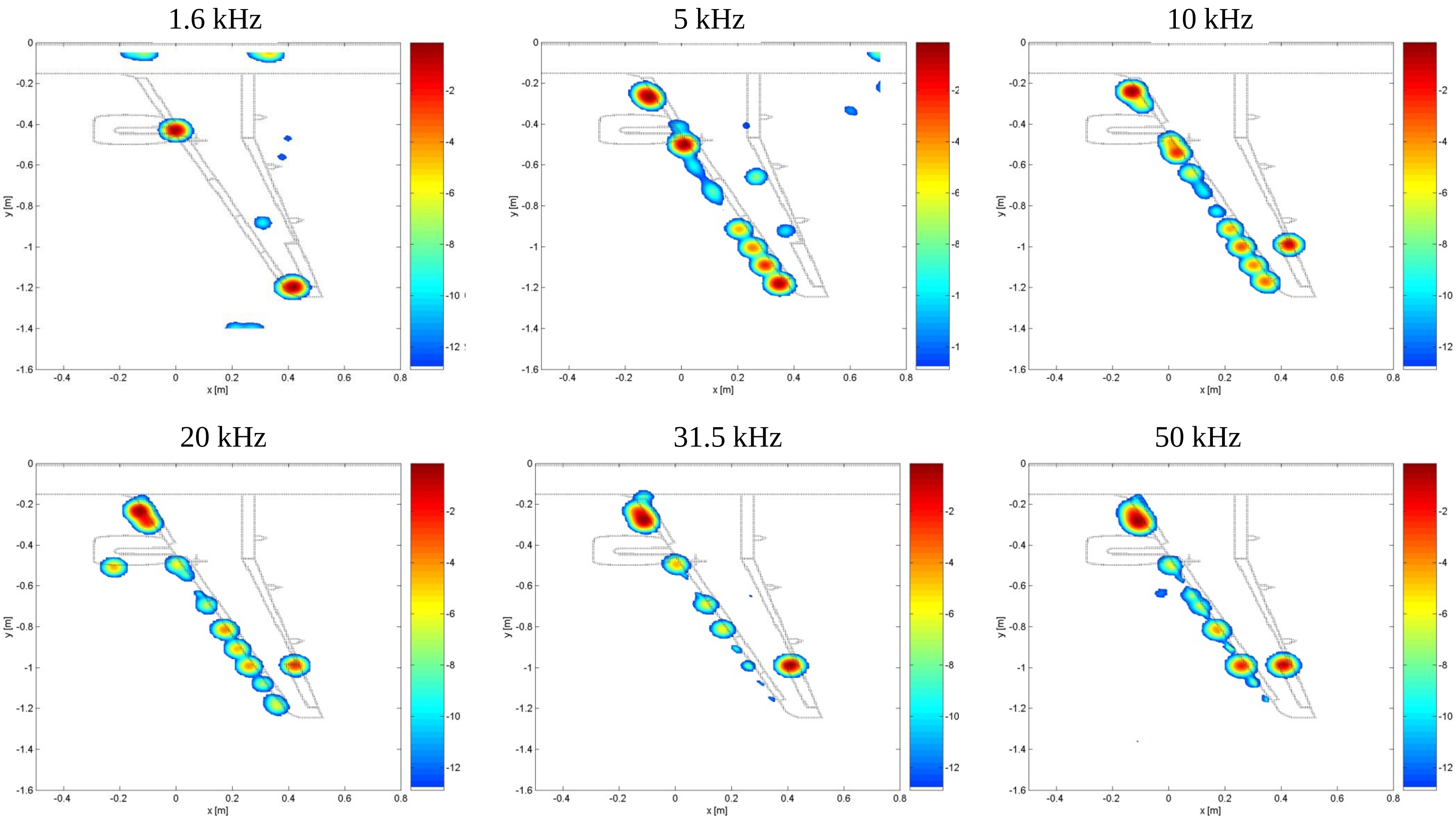
- **Frequency range:** **$f_{s,max}$ = 250 kHz**
- **Number of channels:** **7 x 48 = 336 at DLR**
- AD conversion: 16-bit sigma/delta
- Filters: Several high-pass and low-pass filters
- **Gain factor:** **0.5 to 500000**
- Dynamic range: ≥ 80 dB
- **High pass filter:** **500 Hz or 6 kHz (A weighting)**





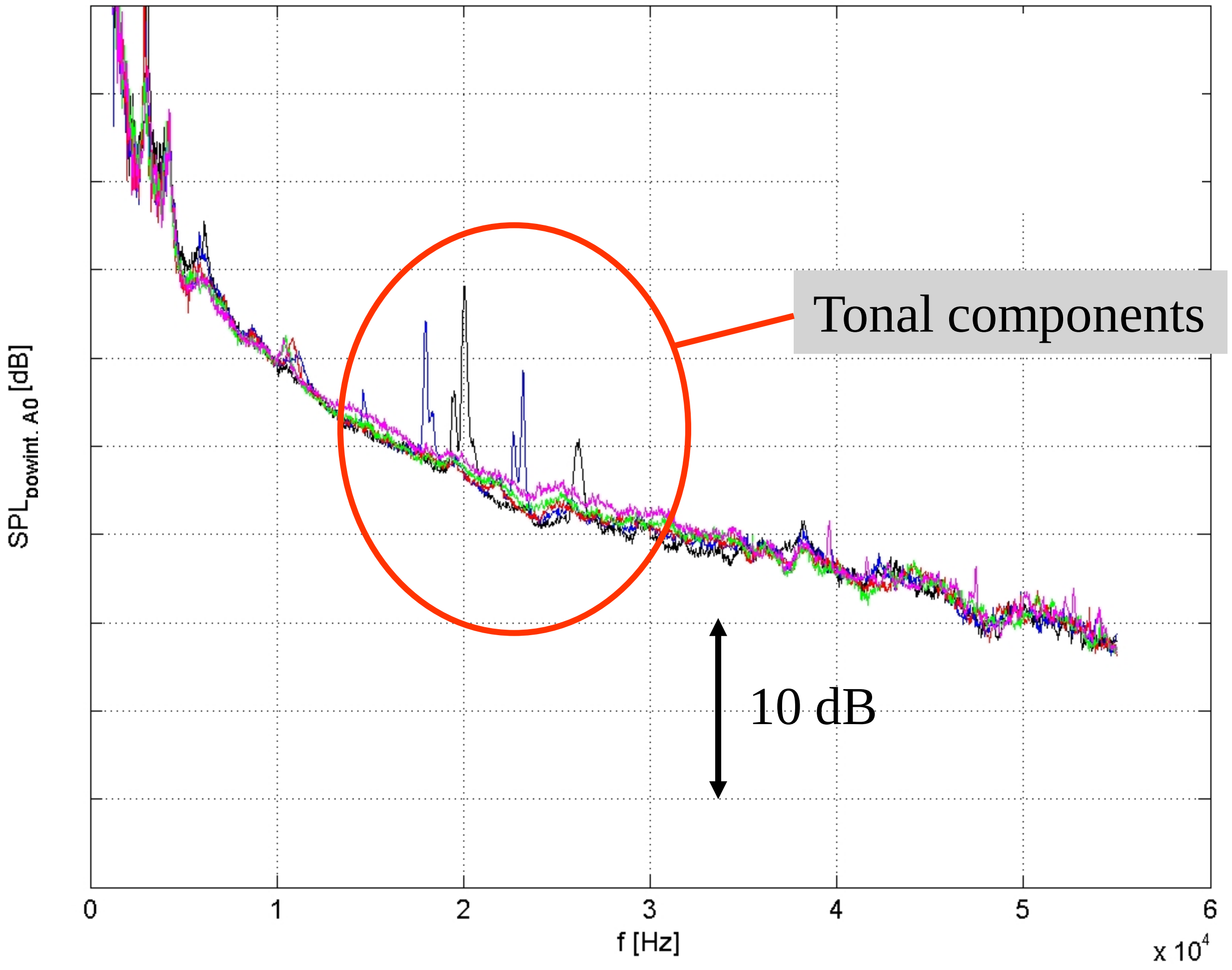
Measurement in industrial closed test section WT

Results, Source maps



Measurement in industrial closed test section WT

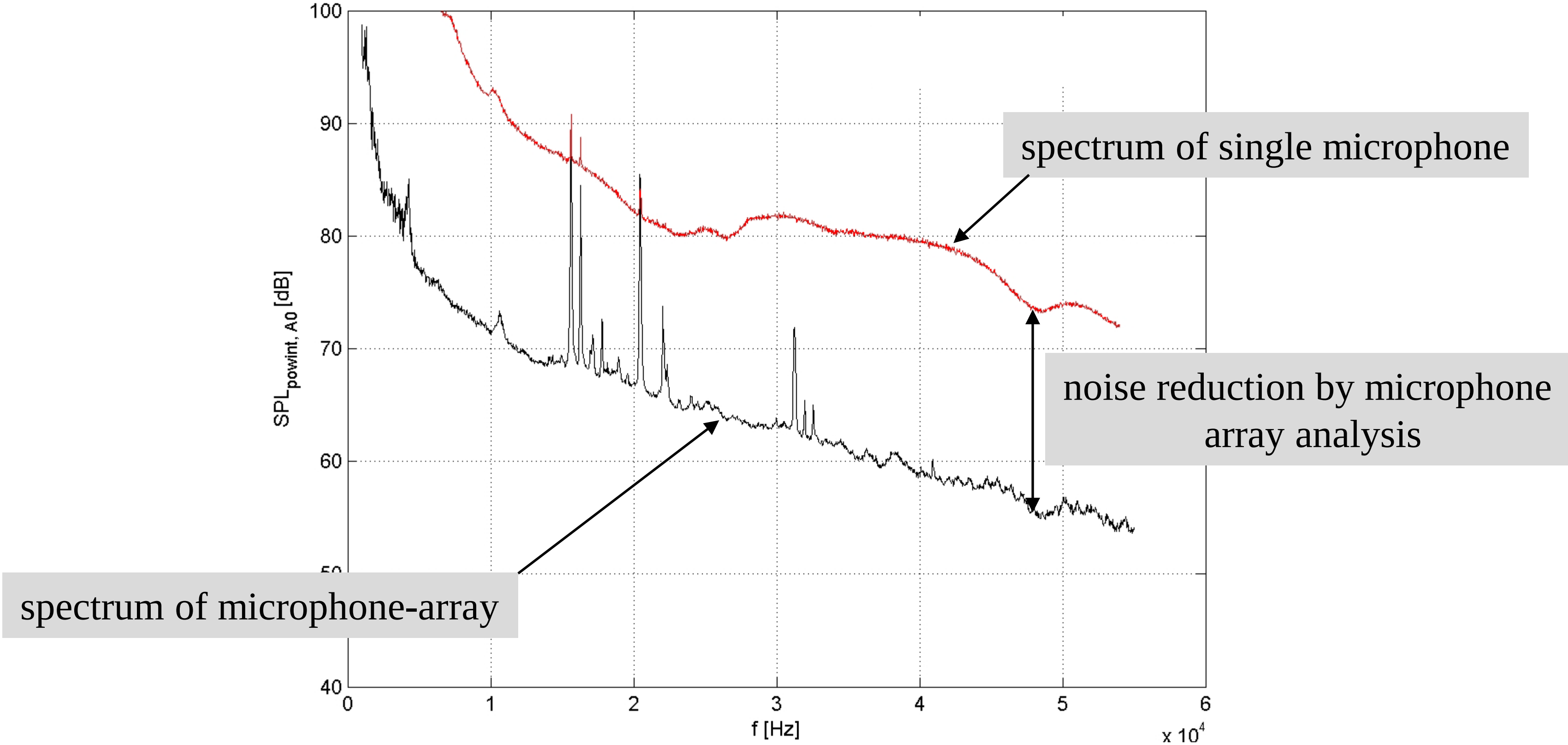
Results, SPL for variation of angle of attack



Measurement in industrial closed test section WT

Noise in closed test section measurements

- SPL of single microphone vs. SPL calculated from microphone array
- Reduction of noise by 21 dB (144 times)



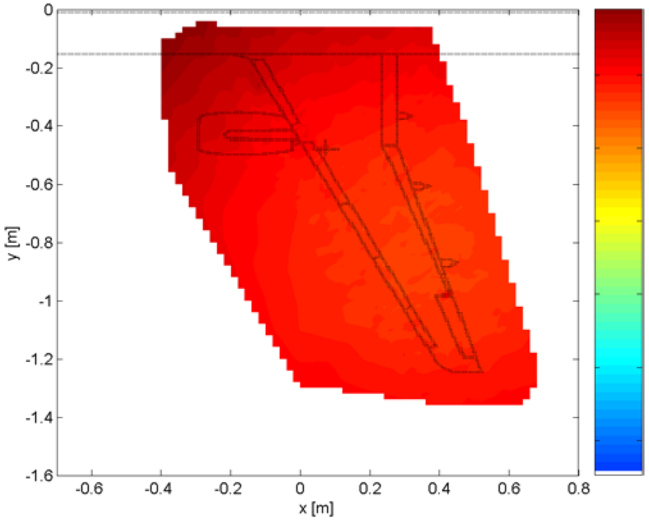
Measurement in industrial closed test section WT

Reduction of high frequency random pressure fluctuations

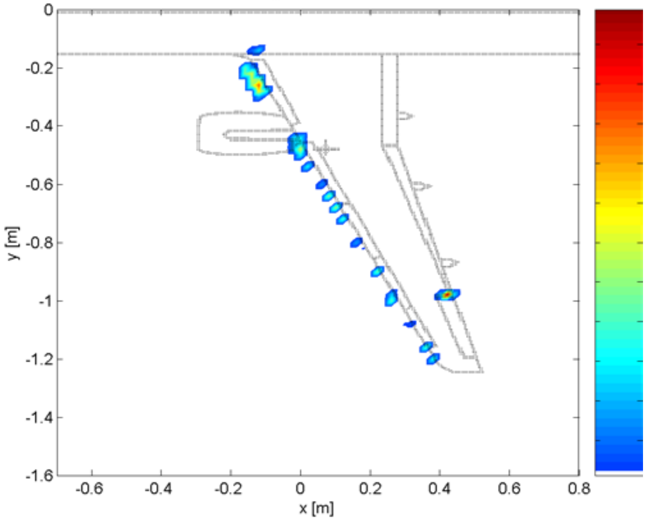
- Turbulent boundary layer of a wall in a closed test section
- Reduction of noise from turbulent boundary-layer (TBL) pressure fluctuations → diagonal removal (DR)

40000 Hz

without DR



with DR

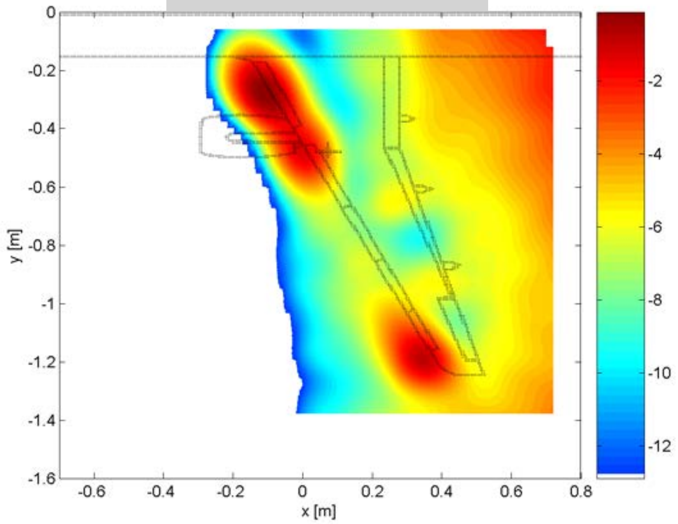


Measurement in industrial closed test section WT
Reduction of low frequency background noise

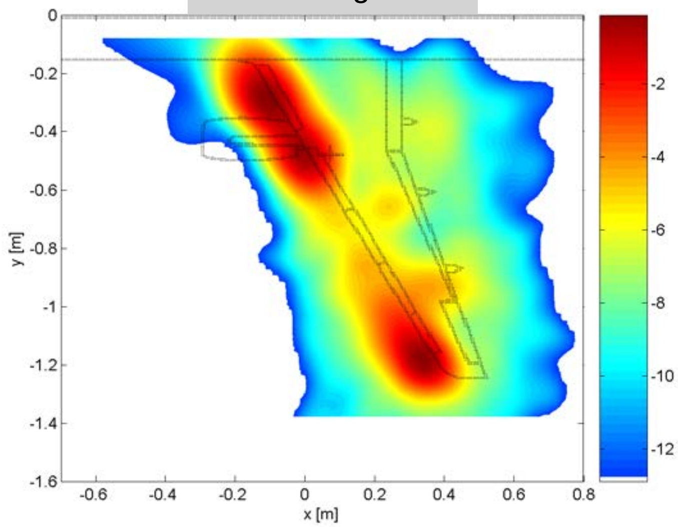
- Closed test section: background noise in low frequencies
- Upstream propagating waves (acoustically hard side-walls)
- Waves cause artifacts in source maps
- Reduction by 6 dB with BiClean algorithm
- Subtracting of Low frequency background noise (noise = plane wave)

3150 Hz

Standard evaluation



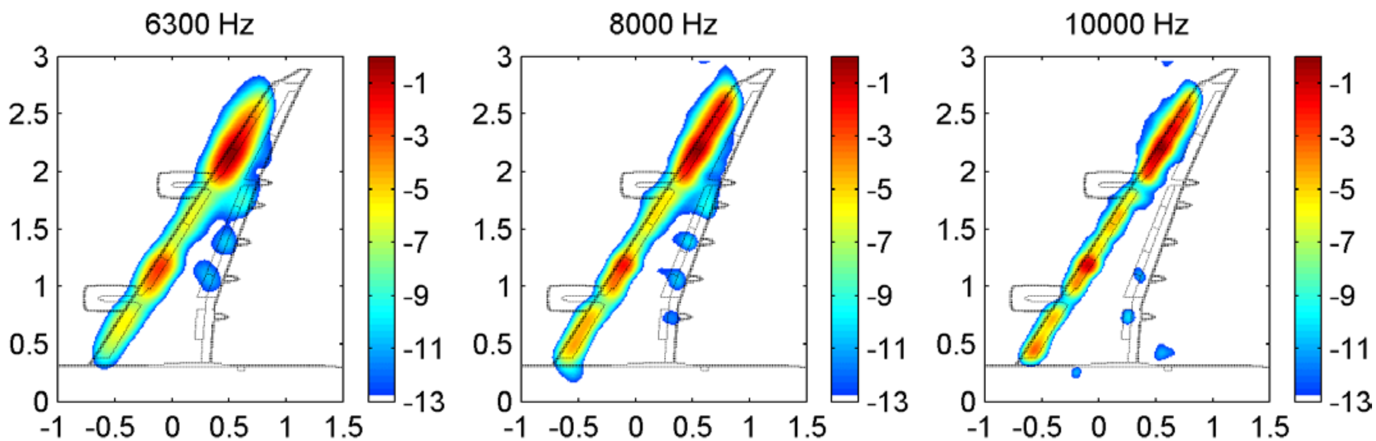
BiClean algorithm



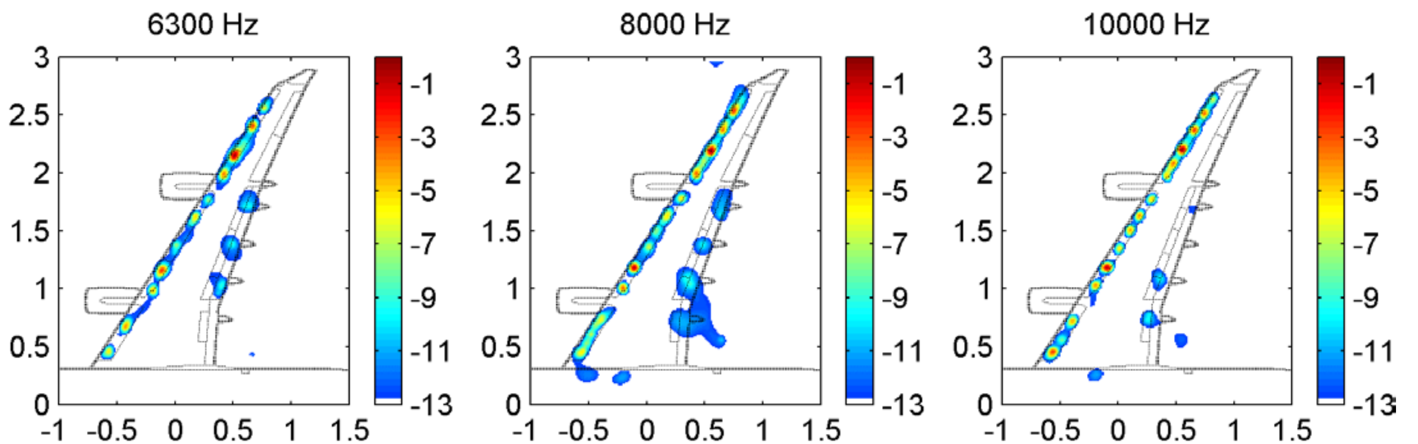
Measurement in industrial closed test section WT

Improved spatial resolution by deconvolution – Embedded DAMAS, CLEAN-SC

Conventional beamforming:



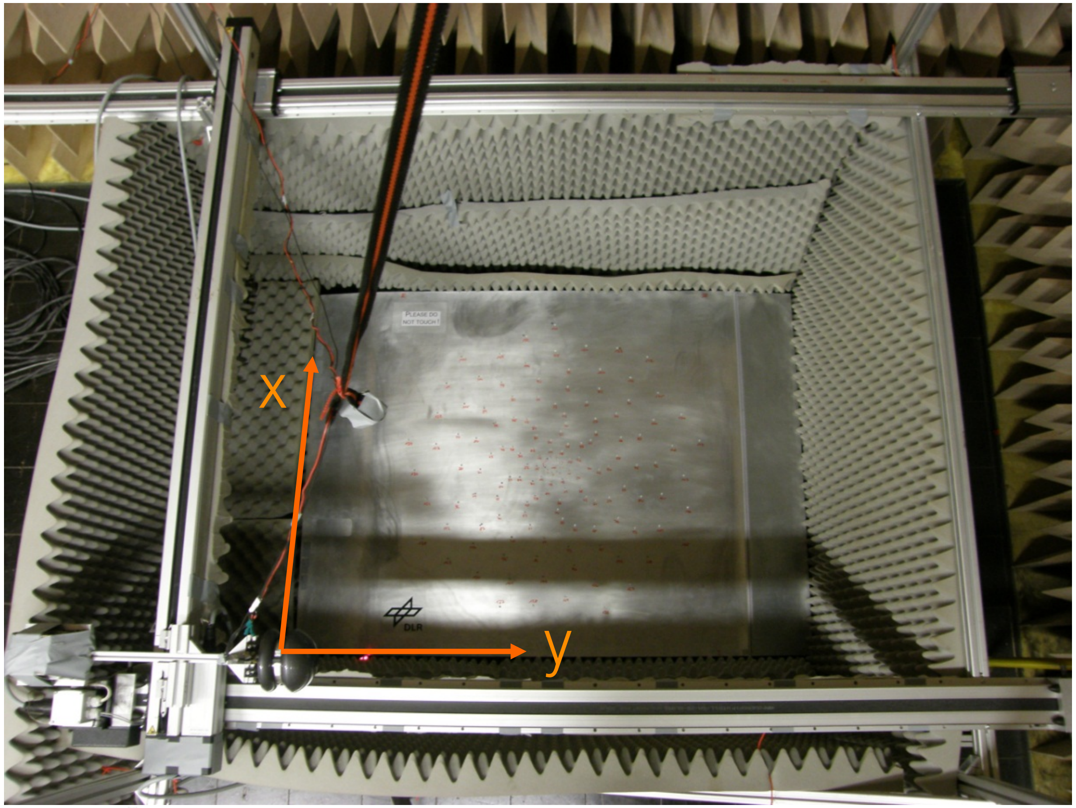
Deconvolution:



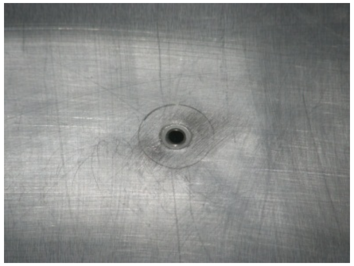
Measurement in industrial closed test section WT

Sensor calibration

- Comparison with a reference microphone
- Traversable speaker for exact positioning in top of every microphone



- reference 1: pressure-field microphone mounted in plate

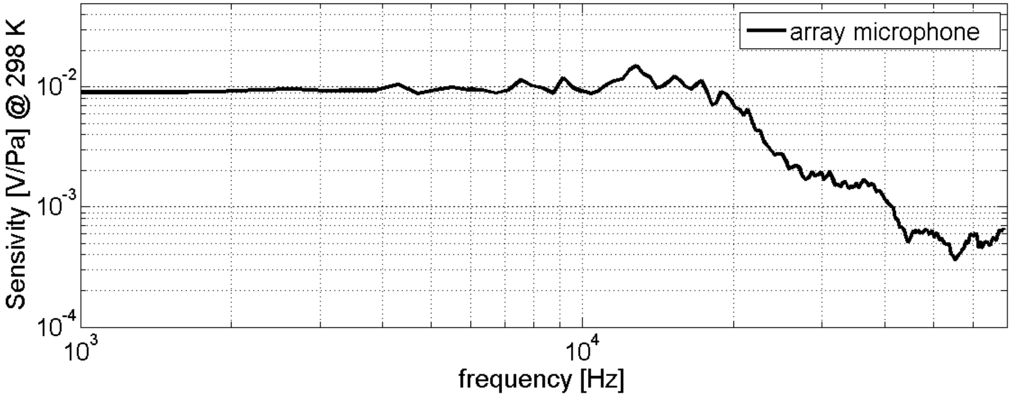


- reference 2: free-field microphone mounted in foam

Measurement in industrial closed test section WT
Sensor calibration

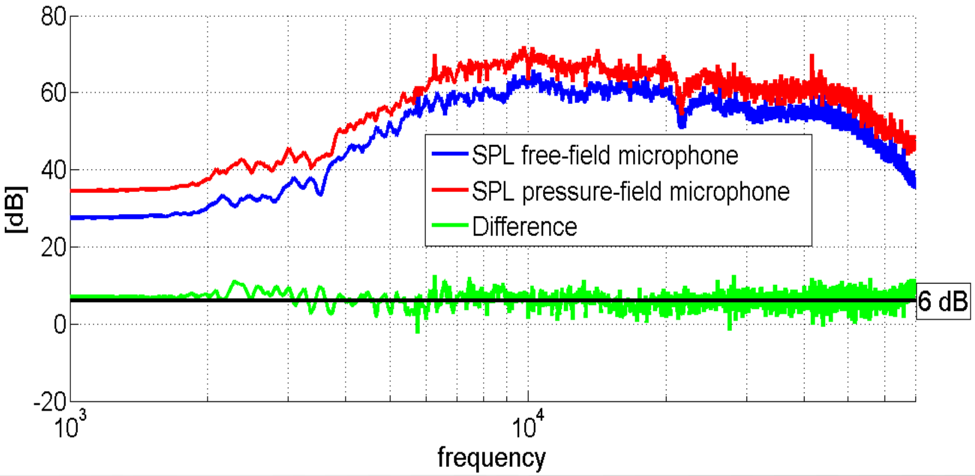
Array-microphone sen. (example)

- ≈ flat response:
  1 kHz < f < 20 kHz



Comparison of references

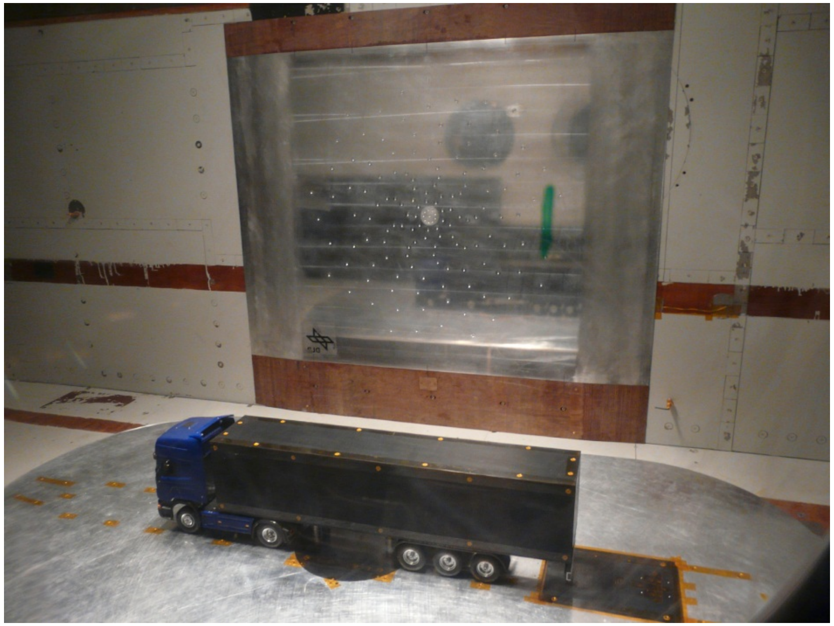
- ≈ 6 dB difference at
  overall frequency range

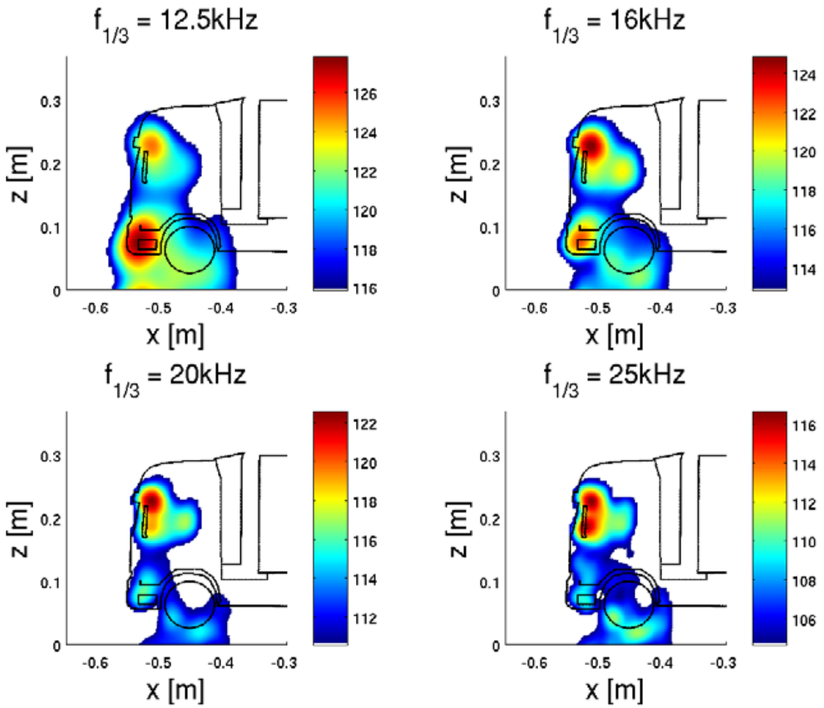


Measurement in industrial closed test section WT

Truck model in DNW-KKK @ ambient temperature

- Truck model in DNW-KKK
- Test parameters: Ma = 0.253, T = 290.3K
- Re = 1×10^6 (w.r.t. width of the truck)
- SPL [dB] with 12 dB Dynamic

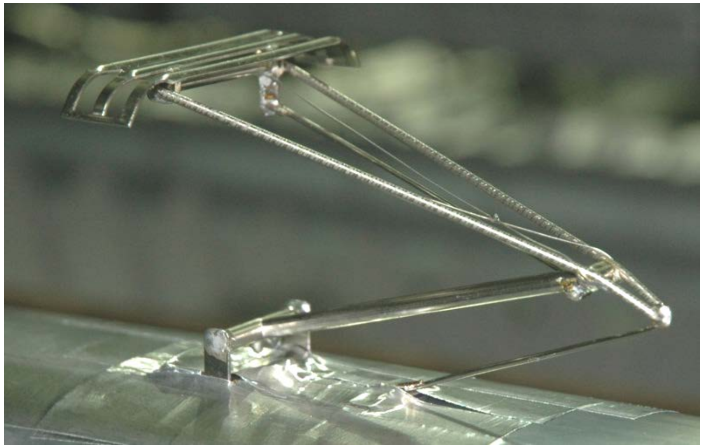


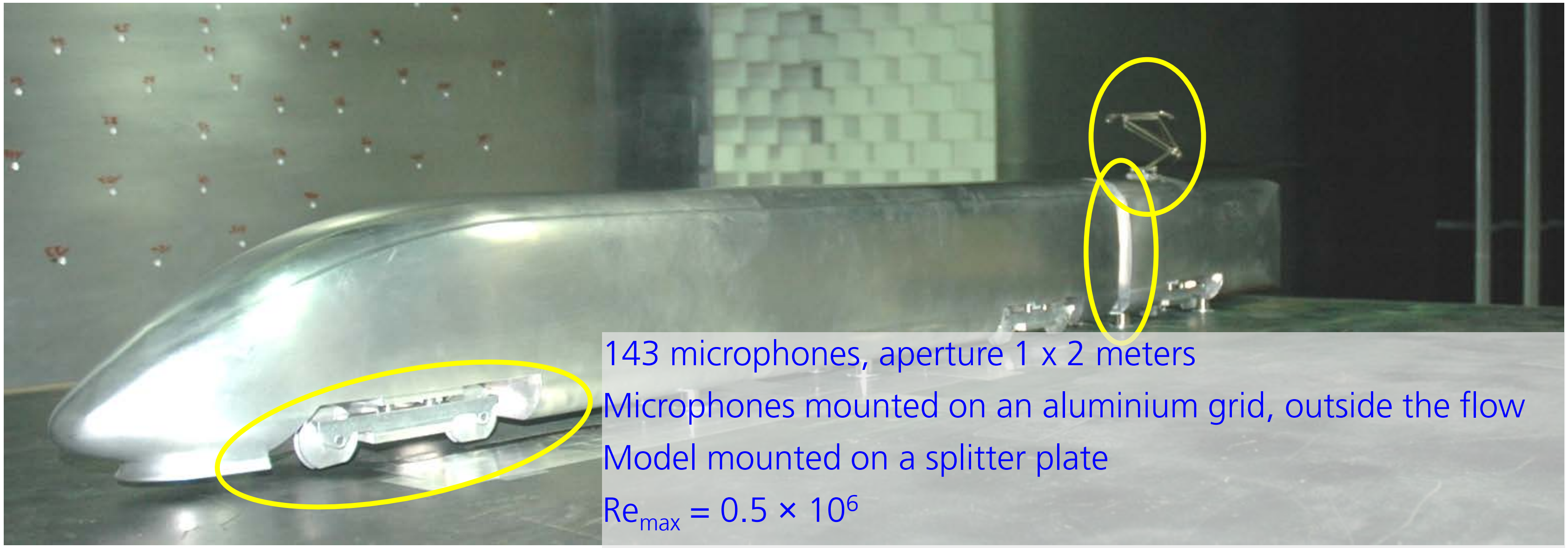


Measurement in open test section WT (AWB)

High speed train

- Measurement on ICE 3, 1:25
- Details:
  - Bogies, Pantograph, Gap between traction unit and first car



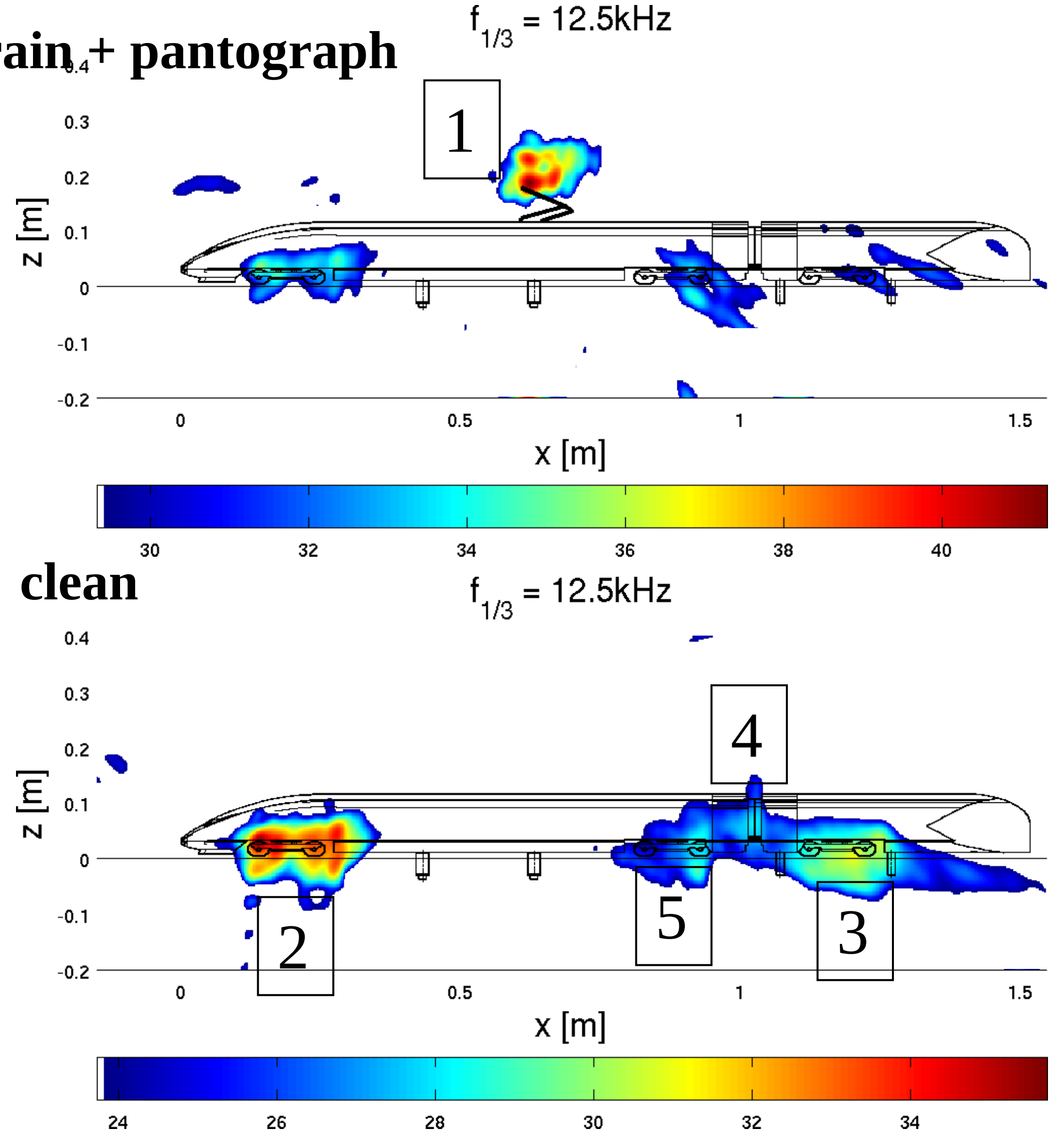


Measurement in open test section WT (AWB)

High speed train

- High-speed train in aeroacoustic wind tunnel (AWB)
- $f_{1/3} = 12.5$ kHz
- $U_\infty = 40$ m/s
- Dynamic range: 12 dB

- Main sources:
  1. Pantograph
  2. First bogie
  3. Third bogie
  4. Cavity
  5. Second bogie



Microphone array measurements in wind tunnels
Status and conclusions

- Microphone array measurements in wind tunnels
  - Source localization and quantification
  - Quantification of level differences (configuration, modification)
  - Noise source ranking
  - Frequency range:
    - 2 kHz – 63 kHz → closed test section
    - 500 Hz – 16 kHz → open test section
- DLR arrays can be installed in any closed and open test-section WT
  - Mobile system
  - Minor installation effects: Measurement in parallel to aerodynamics
- Very fast measurement techniques

Microphone array measurements in wind tunnels

Limitations → Error sources

- Real-flight Reynolds numbers are not achieved in conventional wind tunnels
- Comparability between results from different test facilities (open, closed) and between wind tunnel and full scale aircraft (train, vehicle) not guaranteed
- Airframe noise is simulated by scaled and therefore simplified wind tunnel models
- Microphones are exposed to pressure fluctuations originating from turbulent boundary layer → near field noise
- Different type of sound sources (monopole, dipole…, coherent) results in different results
- Wind tunnel background noise leads to a limited measurement range → low signal-to-noise-ratio
- Reliability and accuracy of data analysis

Microphone array measurements in wind tunnels

Challenges → Open issues in MA wind-tunnel measurements

- Assess Re-number dependency of aeroacoustic sources
- Investigate comparability of test results from different facilities:
  - Open closed test section
  - Scaled models
  - Real aircraft/train/…

  } Dedicated experiments
- Systematic investigation on optimal mounting of microphones (Recessed, Kevlar, flush mounted)
- Absolute level of resulting spectra (diagonal removal, deconvolution)
- Consider the directivity of sound sources (not only in the transfer function!)
- Coherent sound sources: Determine the coherence lengths of typical aeroacoustic sound sources (implication on microphone array results)
- Wind tunnel modifications
- Assess data analysis software

Microphone array measurements in wind tunnels

Open issues in MA wind-tunnel measurements: three examples

- Assessment Re-number effect on aeroacoustic source radiation:
  - Measurements setup: Array measurements in cryogenic flows
  - Results
- Investigate comparability of test results from different facilities: open/closed test section
  - Measurements with a reference loudspeaker
  - Measurements with an airframe noise model
- Note on data analysis: EWA Benchmark test to evaluate data analysis software

Microphone-Arrays in cryogenic environment

Motivation: Assess Re-number dependency

- Common practice: Acoustic measurement on small-scale models …

real-flight conditions

scaled model in wind tunnel

- Conventional wind tunnel: real-flight Reynolds numbers not achieved
  → cryogenic and/or pressurized wind tunnel
- Objective:
  - Provide cryogenic acoustic measurement technique for industrial applications
  - Investigate Re number effects on aeroacoustic measurements

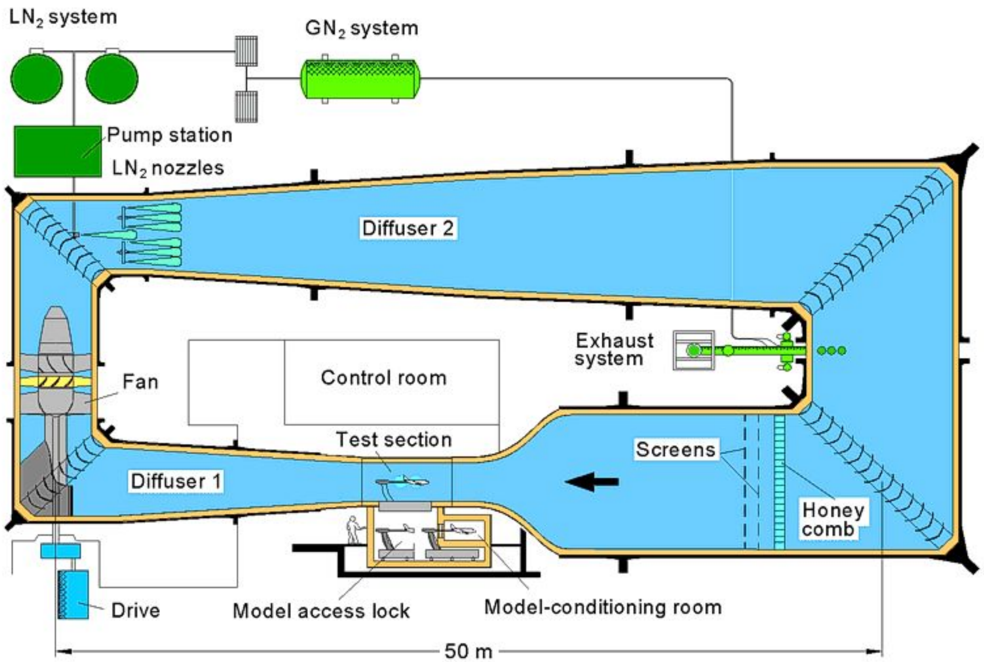
Microphone-Array for cryogenic flows

Wind tunnel: KKK, Cryogenic wind tunnel cologne

- Cryogenic wind tunnel located at the DLR's Cologne Site (from DNW) "Göttingen type wind tunnel"

- Closed test section 2.4 m x 2.4 m
- Operational range:

300 K > T > 100 K
0.1 < Ma < 0.38
$Re_{0.1\sqrt{S}} \leq 9.5 \cdot 10^6$

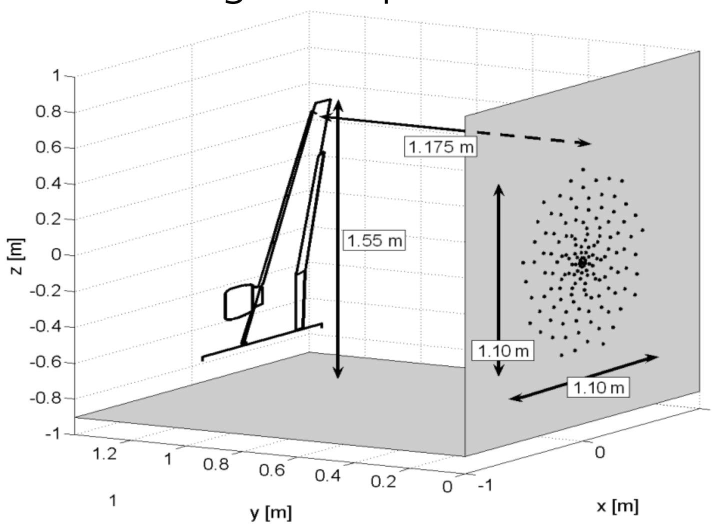


Microphone-Array for cryogenic flows

Measurement Setup @ KKK

Microphone array

- 144 microphones
- Arranged in spiral arms



Parameter

- Ma number: 0,125 – 0,25
- Temperature: 300 K – 100 K
- $Re_c = 1 \cdot 10^6 - 9 \cdot 10^6$

DO–728 half model

- Scale: 1 : 9.24
- ½ - spanwidth: 1.44 m
- Chord length: 0.338 m

DO-728 half model in landing configuration

Microphone-Array for cryogenic flows

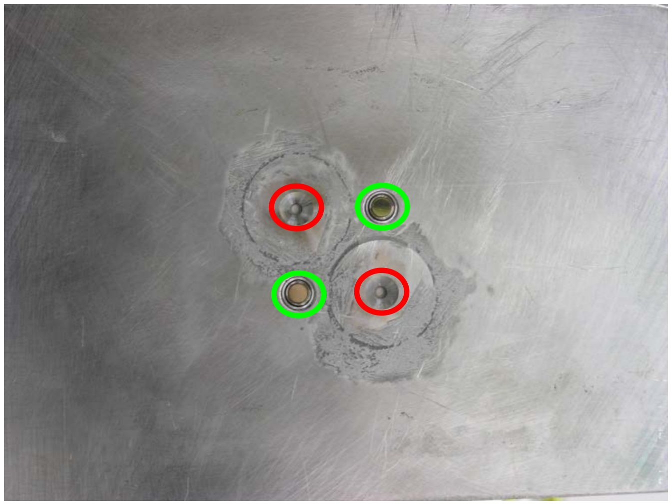
Setup – considerations due to cryogenic environment

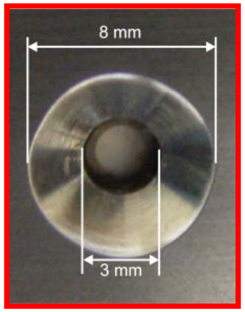
- Appropriate electronic components
- Durability and reliability of sensors and electronic equipment verified in previous study[1]
- Contraction at lower temperatures
  (L = 1 m $dL_{290K-100K} \approx -3.7$ mm)
  - Array fairing movably mounted
  - Rigidly fixed at bottom center
- Data analysis:
  - Temperature, pressure, nitrogen gas etc.

[1] T. Ahlefeldt and L. Koop, AIAA-2009-3185

Microphone-Array for cryogenic flows

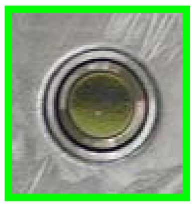
Sensor Calibration – Temperature



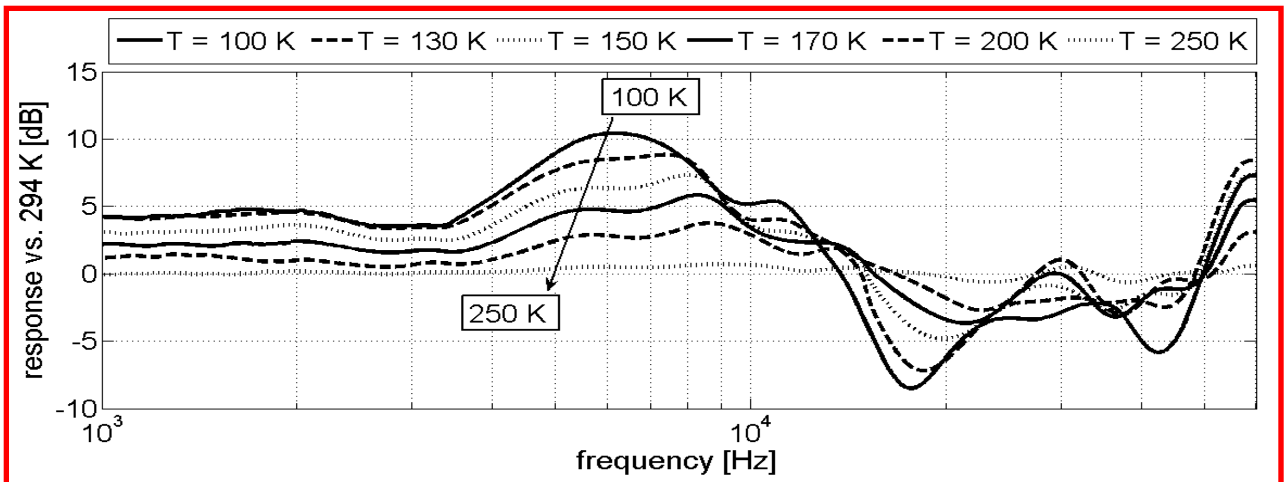


- Electret *cryo* microphone capsule -recessed behind a cone-

versus



- Bruel&Kjær ¼ -inch microphones for use in cryogenic environment -flush mounted-



- Average of the obtained transfer functions
- Large deviations:
  - high frequencies
  - low temperatures

Microphone-Array

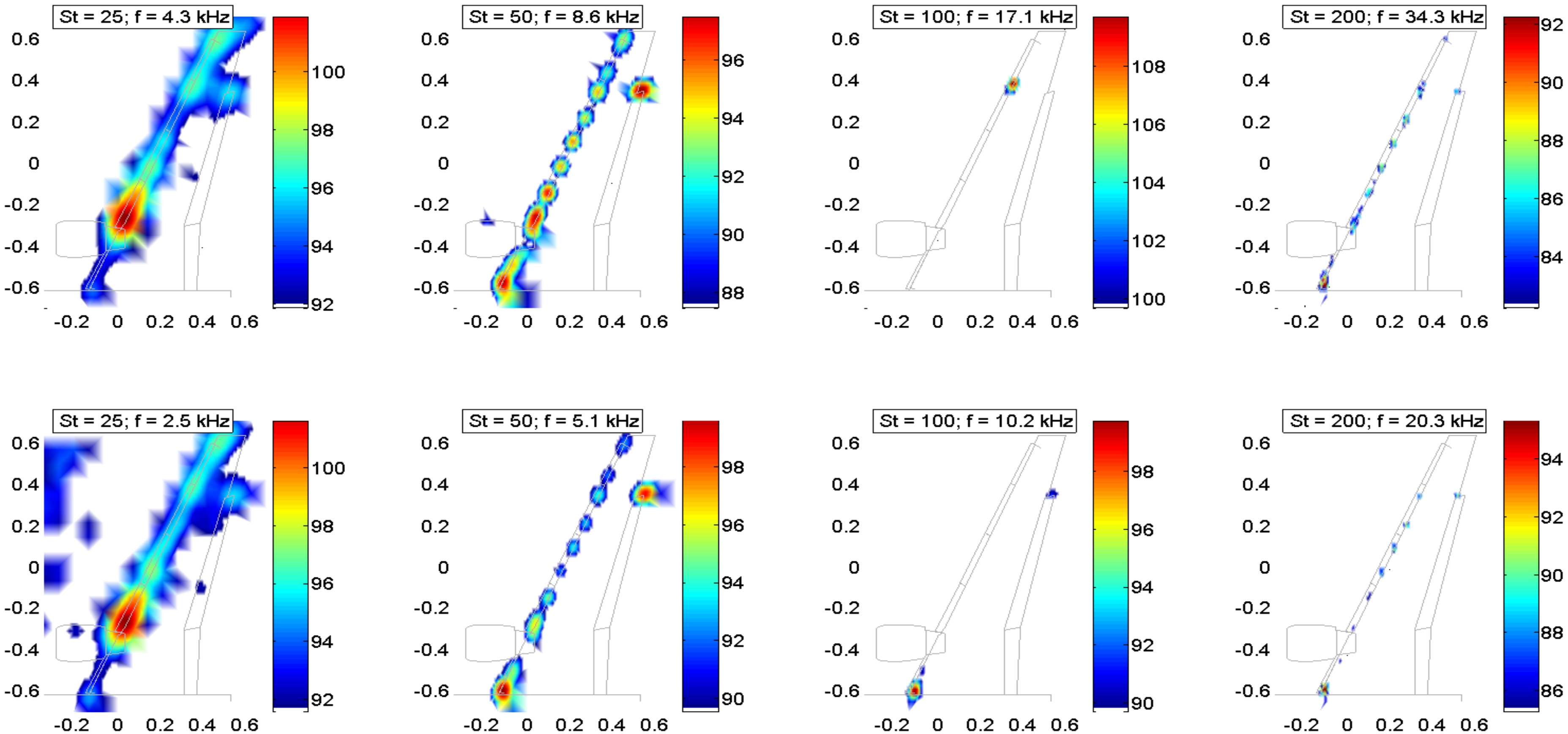
Results

T = 290 K | Re = $2.00 \cdot 10^6$ | f = 51.4 kHz

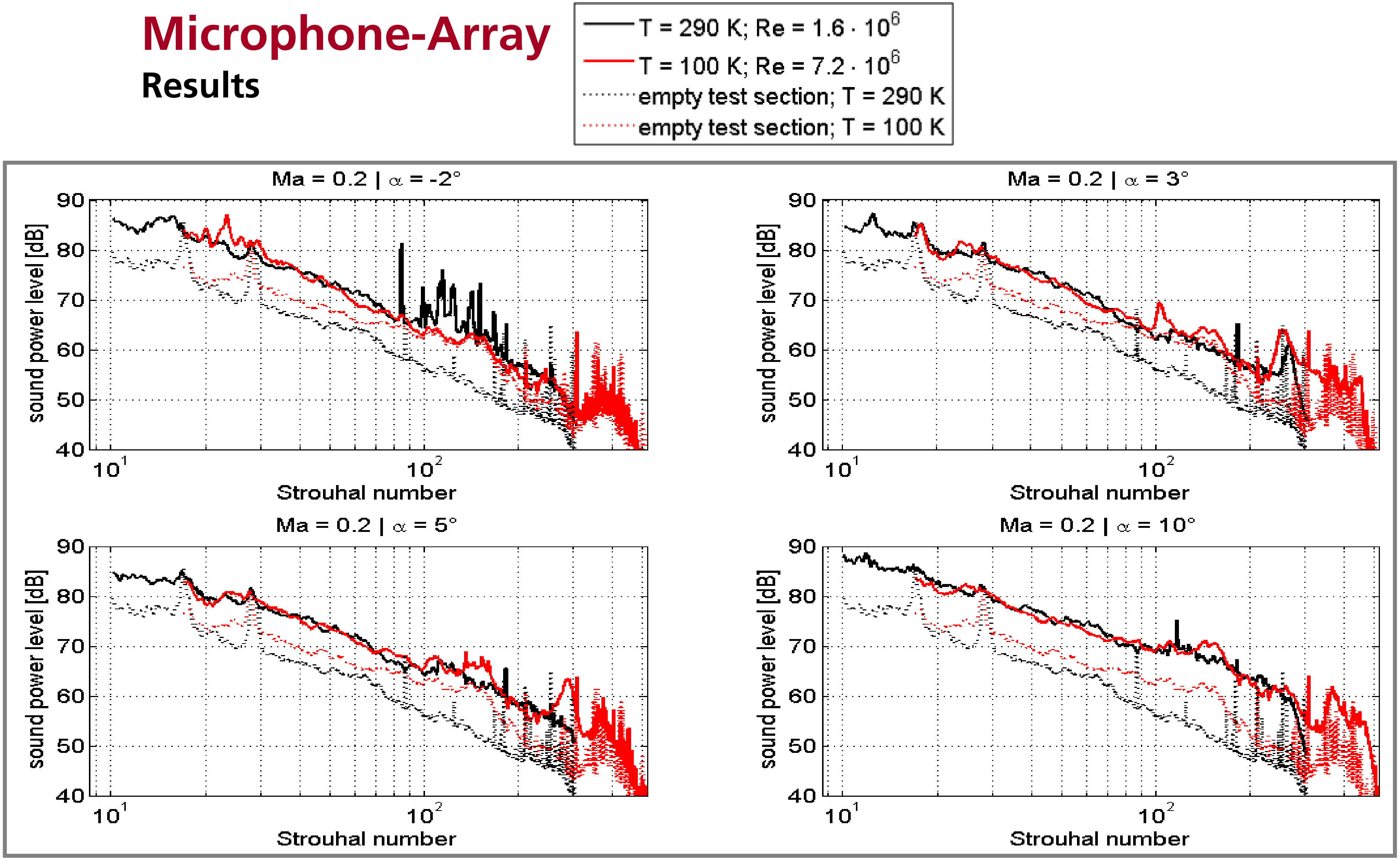
vs.

T = 100 K | Re = $9.01 \cdot 10^6$ | f = 30.5 kHz

St = 300
Ma = 0.175
α = 7°

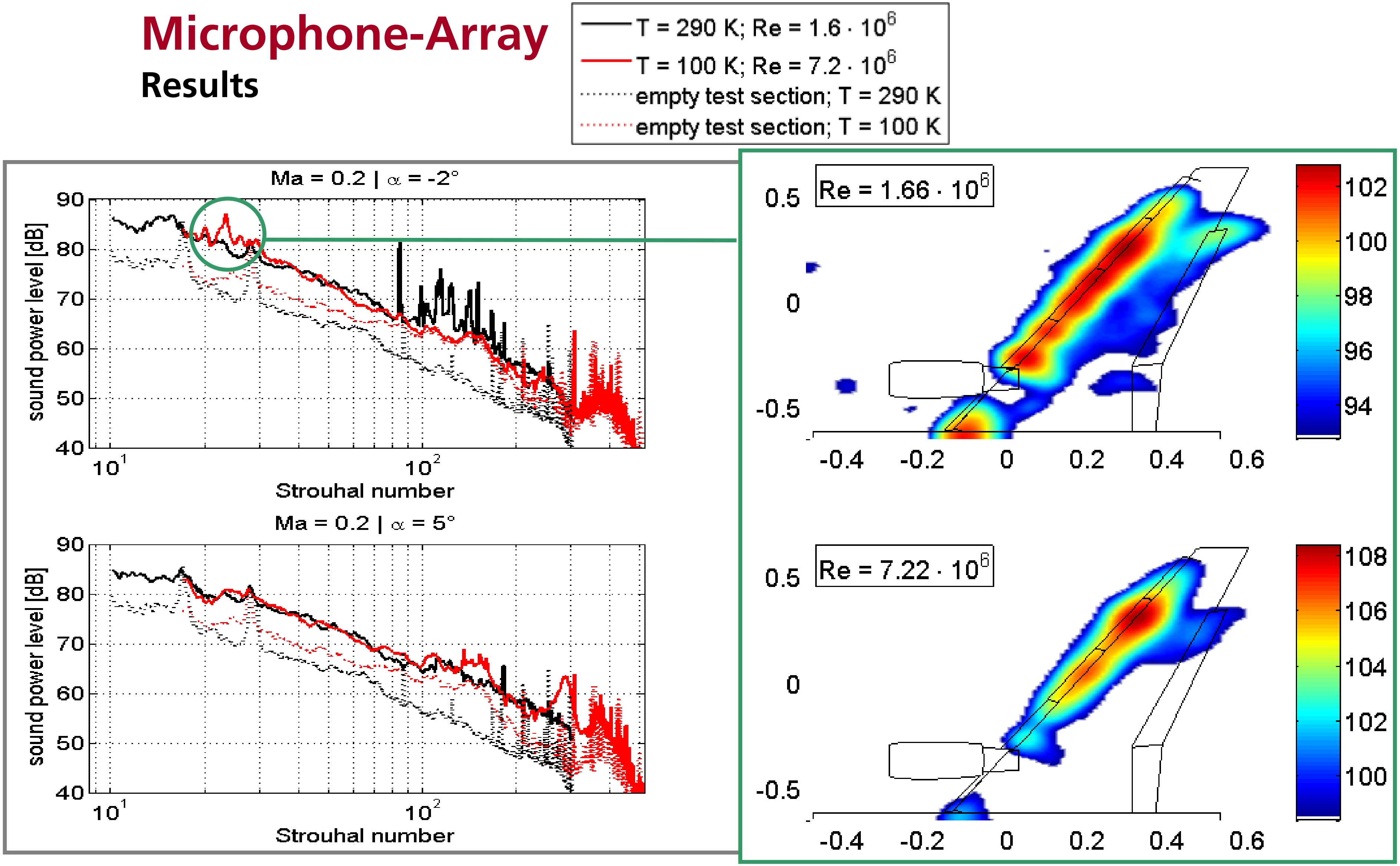


Microphone-Array
Results

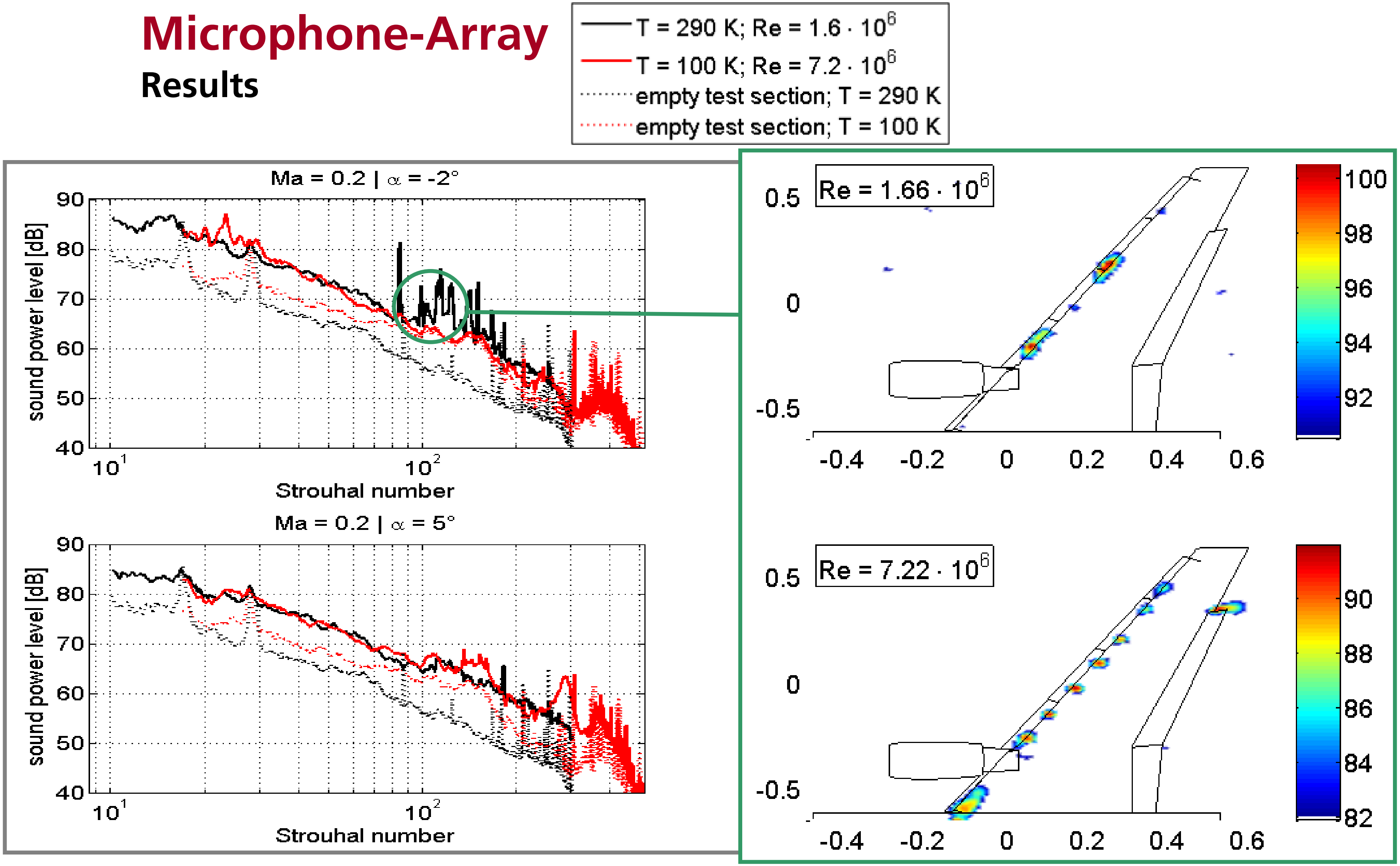


Microphone-Array

Results

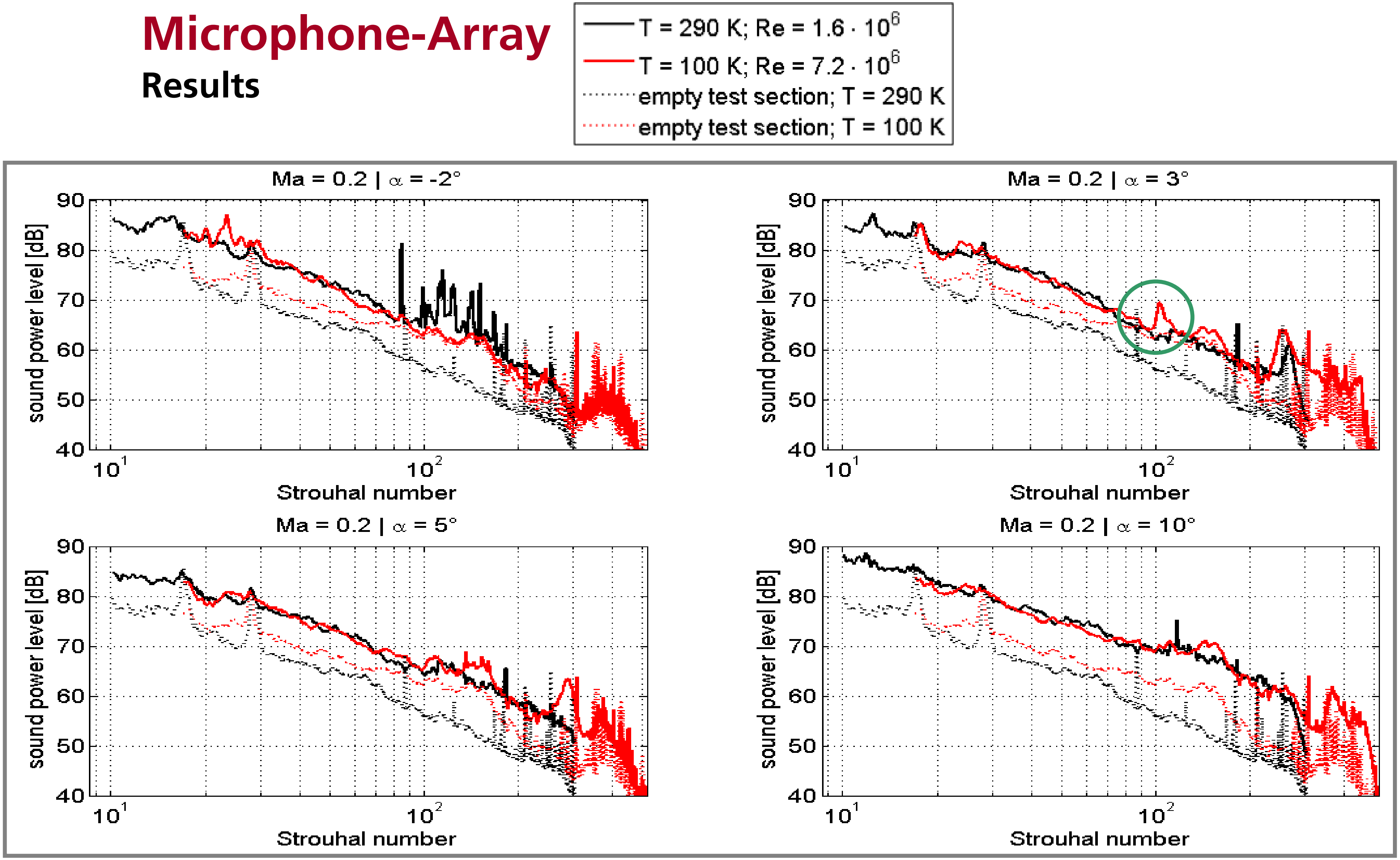


Microphone-Array
Results



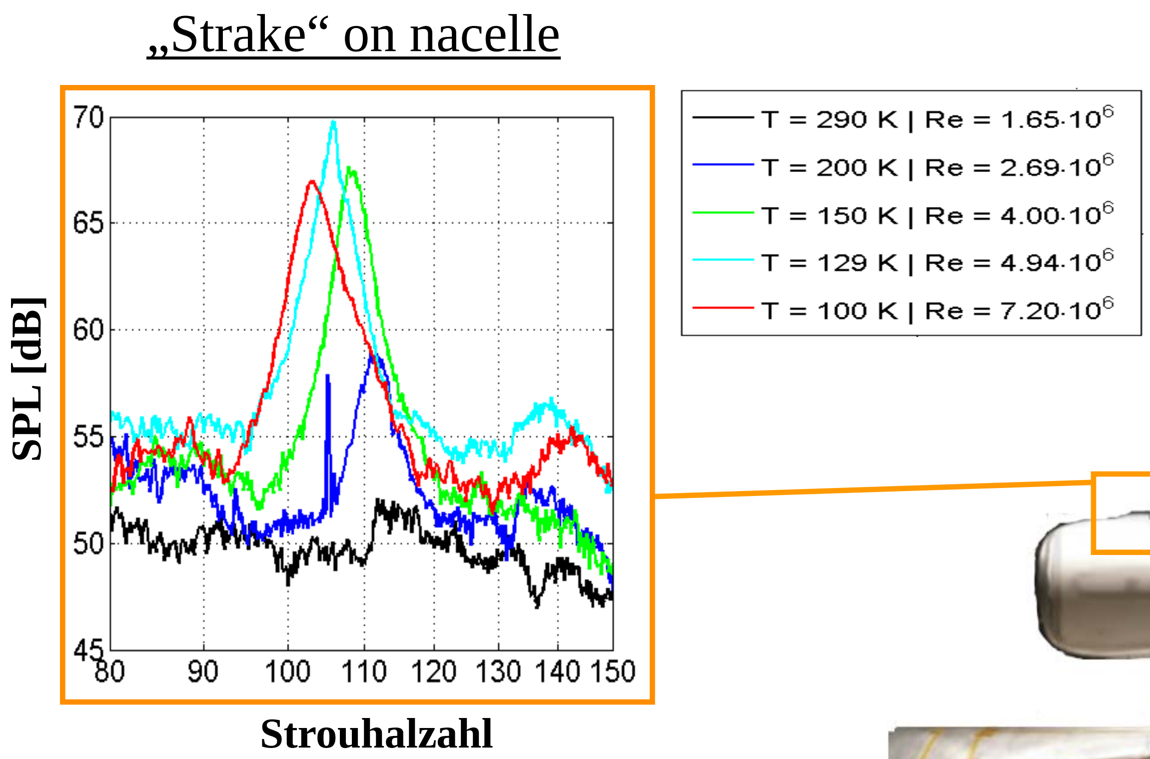
Microphone-Array

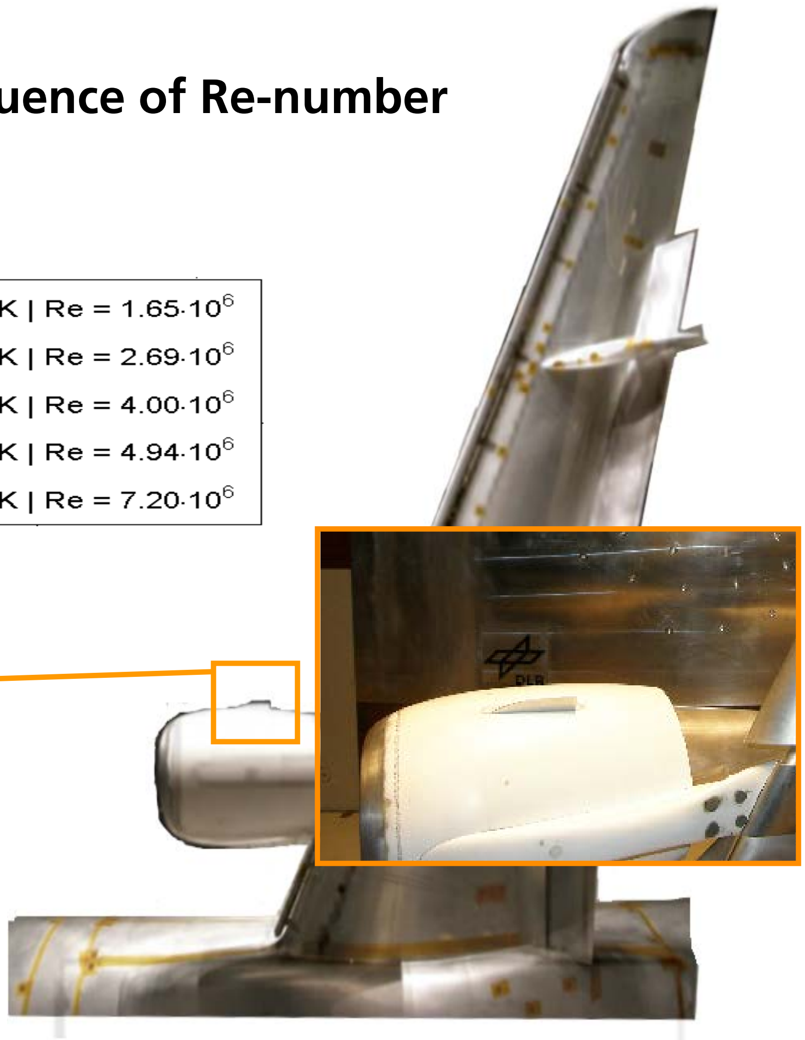
Results



Microphone-Array

@ cryogenic condition (DNW-KKK): Influence of Re-number



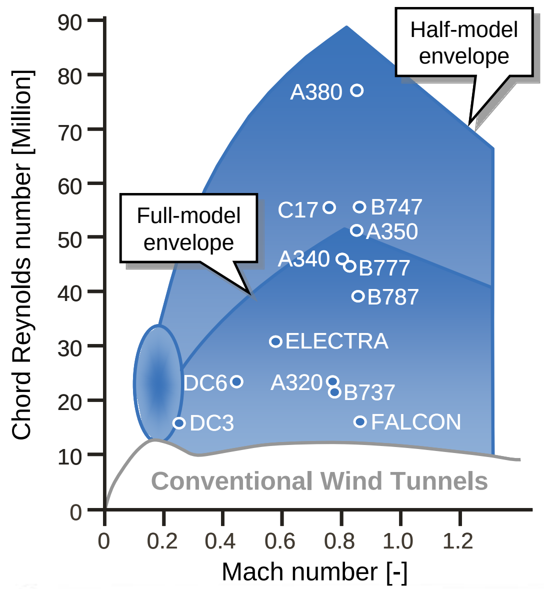


- Local sound power spectra on nacelle
- Clear effect of Re-number on radiated sound power

Microphone-Array for cryogenic flows

Future developments: Microphone array measurements in ETW

- Objective: Aeracoustic measurements at flight Re-numbers
- European Transonic Wind Tunnel (ETW) in Cologne
- Measurements at cryogenic conditions and **total pressure of 4.5 bar**
- National research project
- Partner: ETW, DLR, TU Berlin



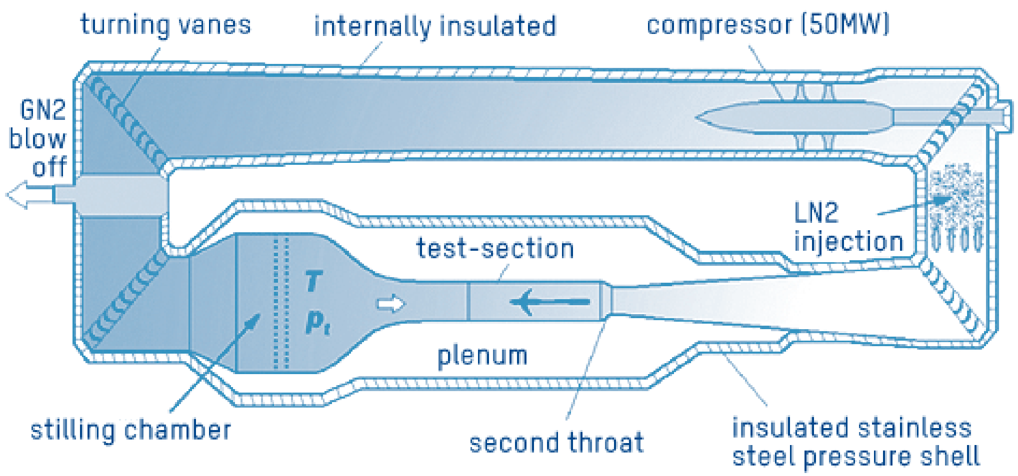
Microphone-Array for cryogenic flows

Future developments: Microphone array measurements in ETW

- ETW specifications:
  - Mach number: 0.15 - 1.35
  - Total pressure: 1.15 bar - 4.5 bar
  - Temperature: 110 K - 313 K

Max. Re-number: 50 million *full-span models*

Max. Re-number: 90 million *semi-span model*



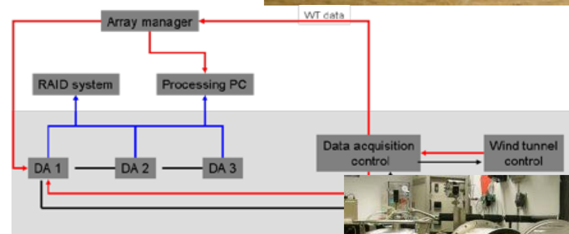
- Wind tunnel requirements:
  - Non intrusiveness
  - Full reliability over the complete tunnel operating range
  - Remotely controlled operation
  - Not affecting the flow-field near the model

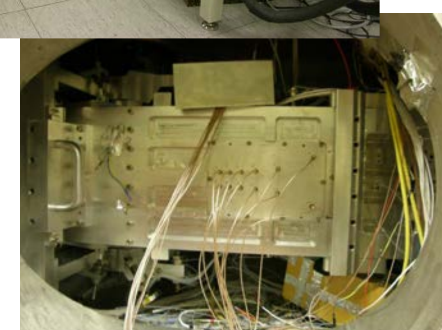
Microphone-Array for cryogenic/pressurized flows

Microphone array measurements in ETW: Main issues

Approach:

- Concepts of sensors and electronic components
- Cabling
- Remotely controlled data acquisition
- Calibration of sensors in cryogenic and pressurized environment
- Pretests under real conditions PETW
- Demonstration test in ETW





Microphone-Array for cryogenic/pressurized flows

First demonstration at ETW

December 2011:

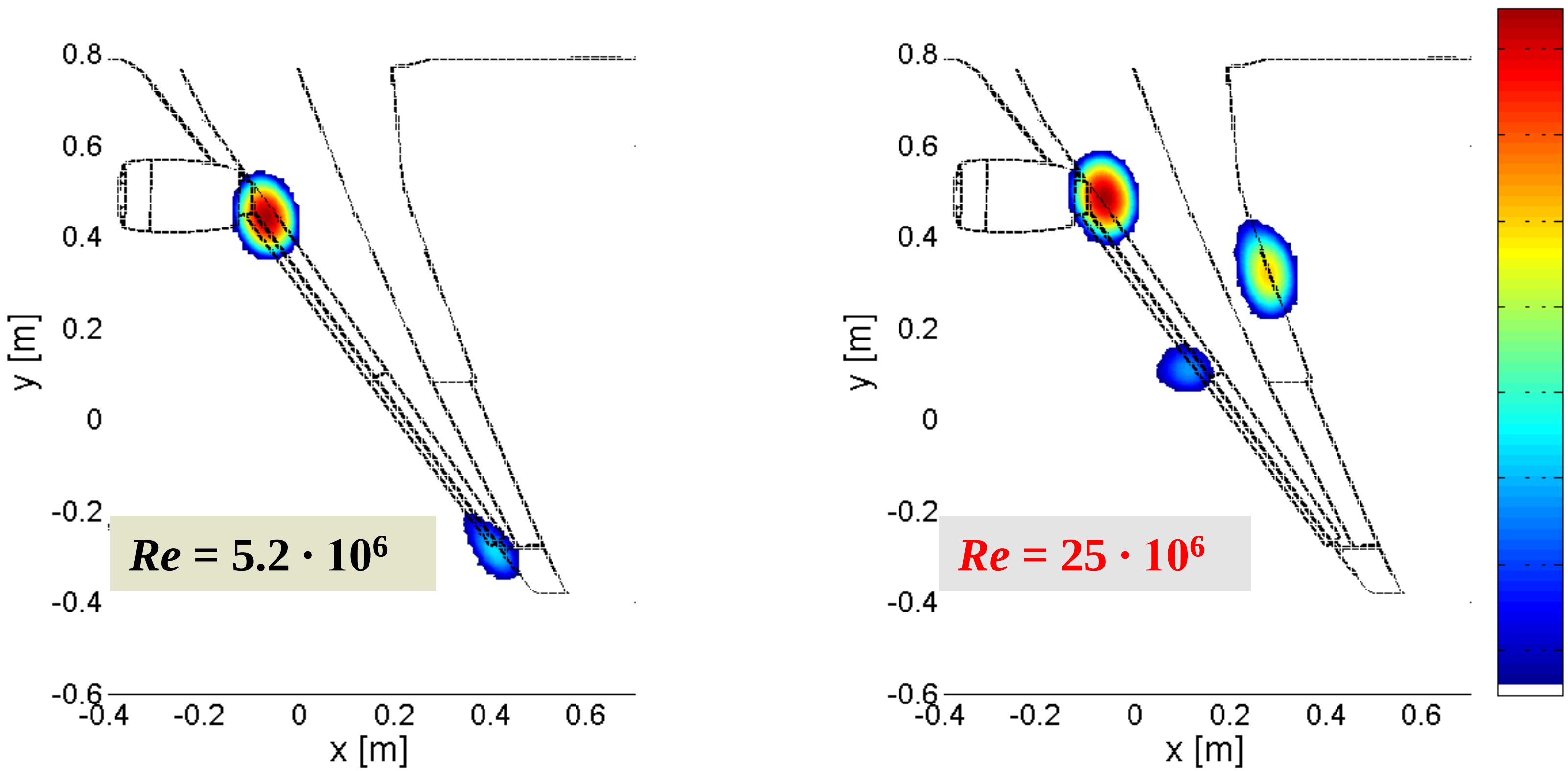
- Test array with 14 sensors
- Measurements on a R&T scaled half-model in high-lift configuration

Microphone-Array for cryogenic/pressurized flows

First demonstration at ETW

$\alpha = 5°$
$M = 0.2$

p_{total} = 187 kPa | T = 272 K	p_{total} = 397 kPa | T = 115 K
St = 350 | f = 60.8 kHz	St = 350 | f = 40.4 kHz



Microphone-Array for cryogenic flows
Summary

- **First successful application** of microphone arrays **in cryogenic and pressurized environment**
  - Re-number variation at constant Ma-number
  - Gives us the possibility to investigate Re-number effects in aeroacoustic measurements
- **Clear effect of Re-number** on radiated sound power
  - Depends on: Ma-number, model configuration, source mechanism
  - Definition of acoustic **Re-number corrections** between WT-models and real flight condition **very challenging**

Microphone-Arrays in different test facilities

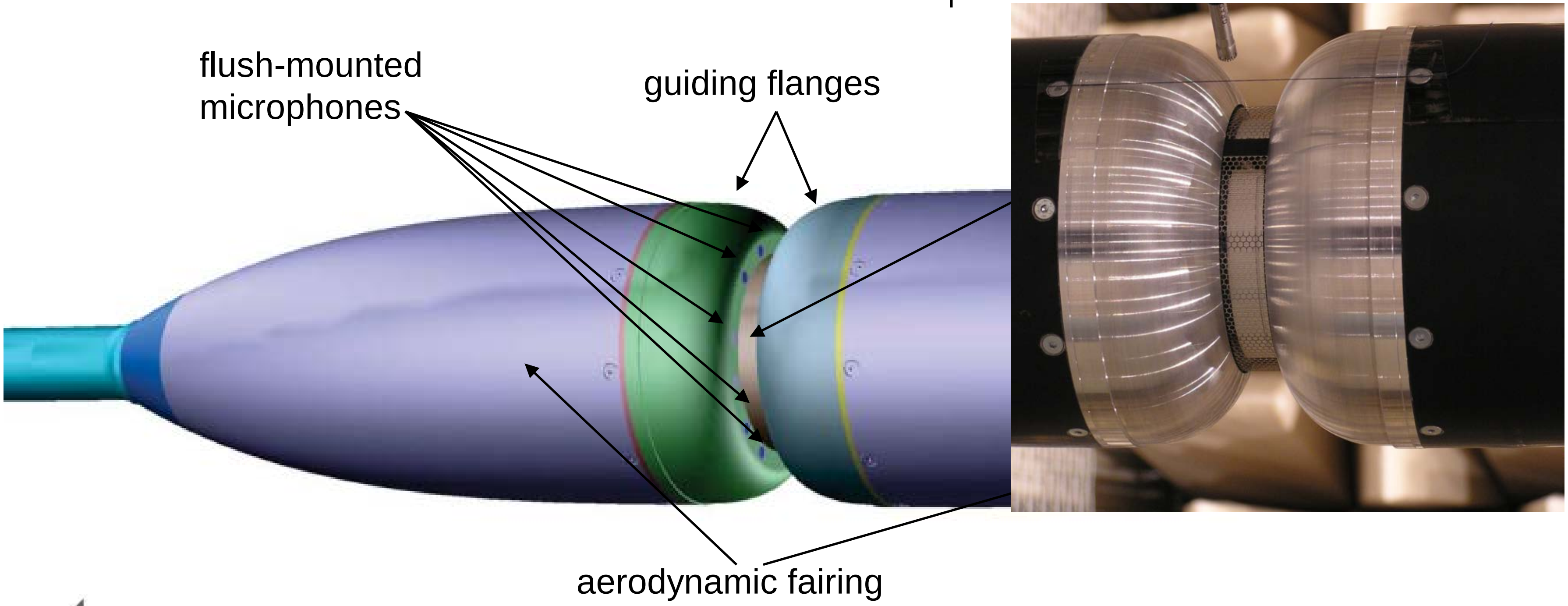
Motivation

- Comparability between results from different test facilities (open, closed) and between wind tunnel and full scale aircraft (train, vehicle) not guaranteed
- Question: How far is it possible to compare beamforming results from different wind tunnels?
- Dedicated experiments: Similar experimental setup and aeroacoustic sound generation
    1. Measurements with a reference loudspeaker
    2. Measurements with an airframe noise model designed specifically for this purpose

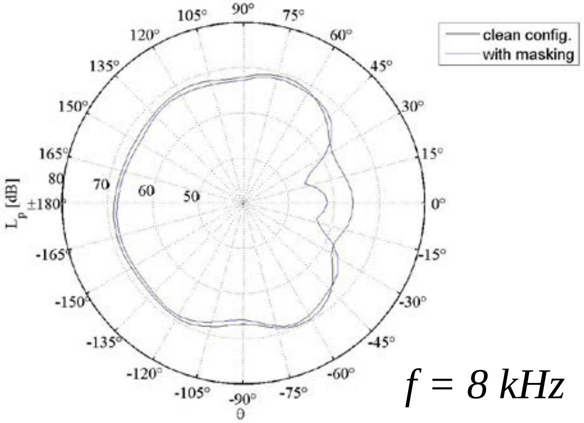
Comparison measurements

DLR reference source – Design

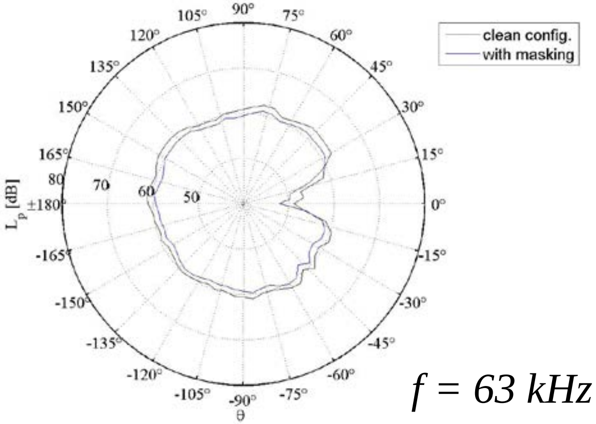
- Electro dynamic ribbon loudspeaker: defined signal, repeatable
- Large frequency range (up to 65 kHz)
- Two guiding flanges serve as an impedance adjustment
- Ribbon diameter: 90mm; height 15 mm
- Omnidirectional sound radiation in centre plane



Comparison measurements
DLR reference source – Design and directivity



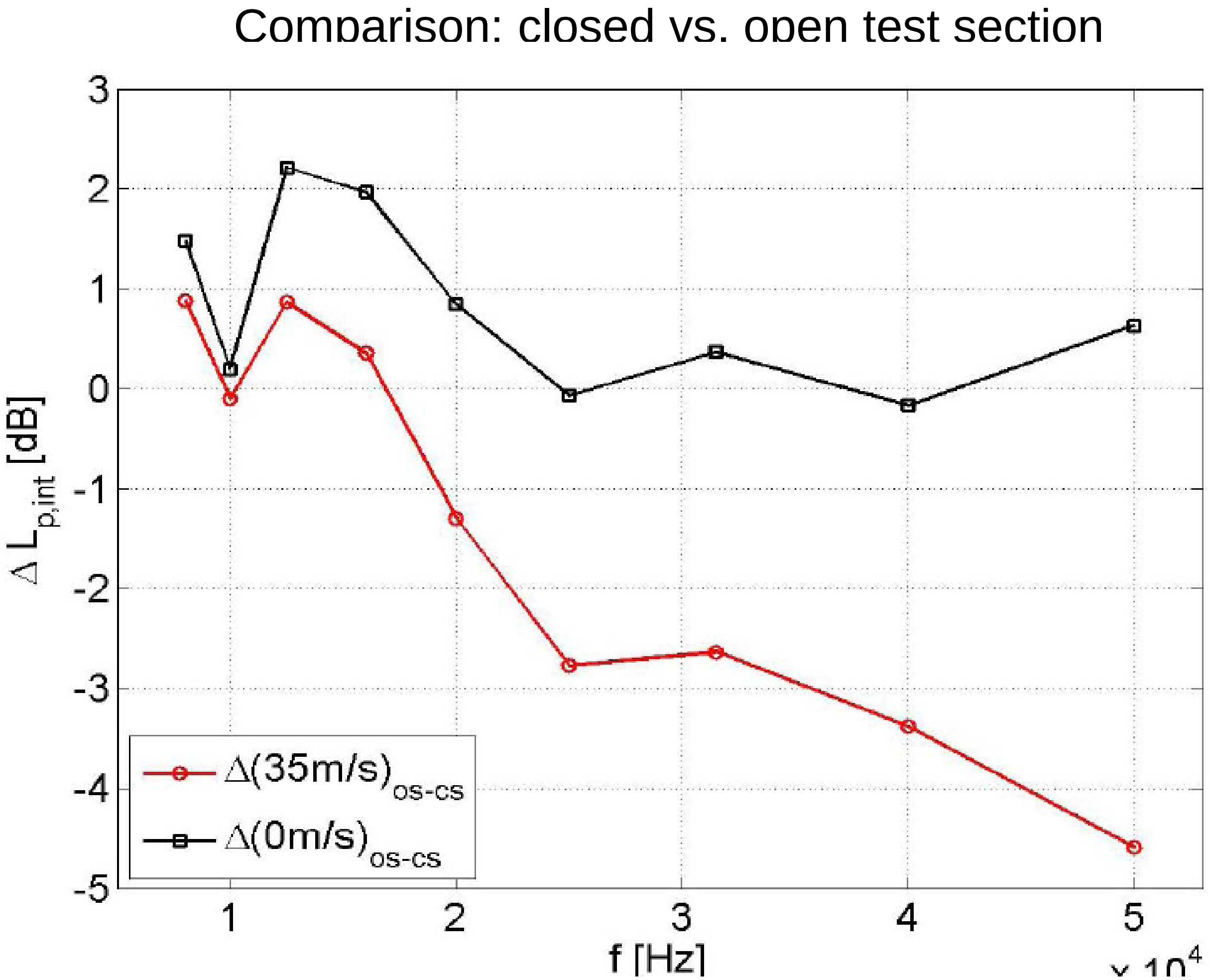
f = 8 kHz



f = 63 kHz

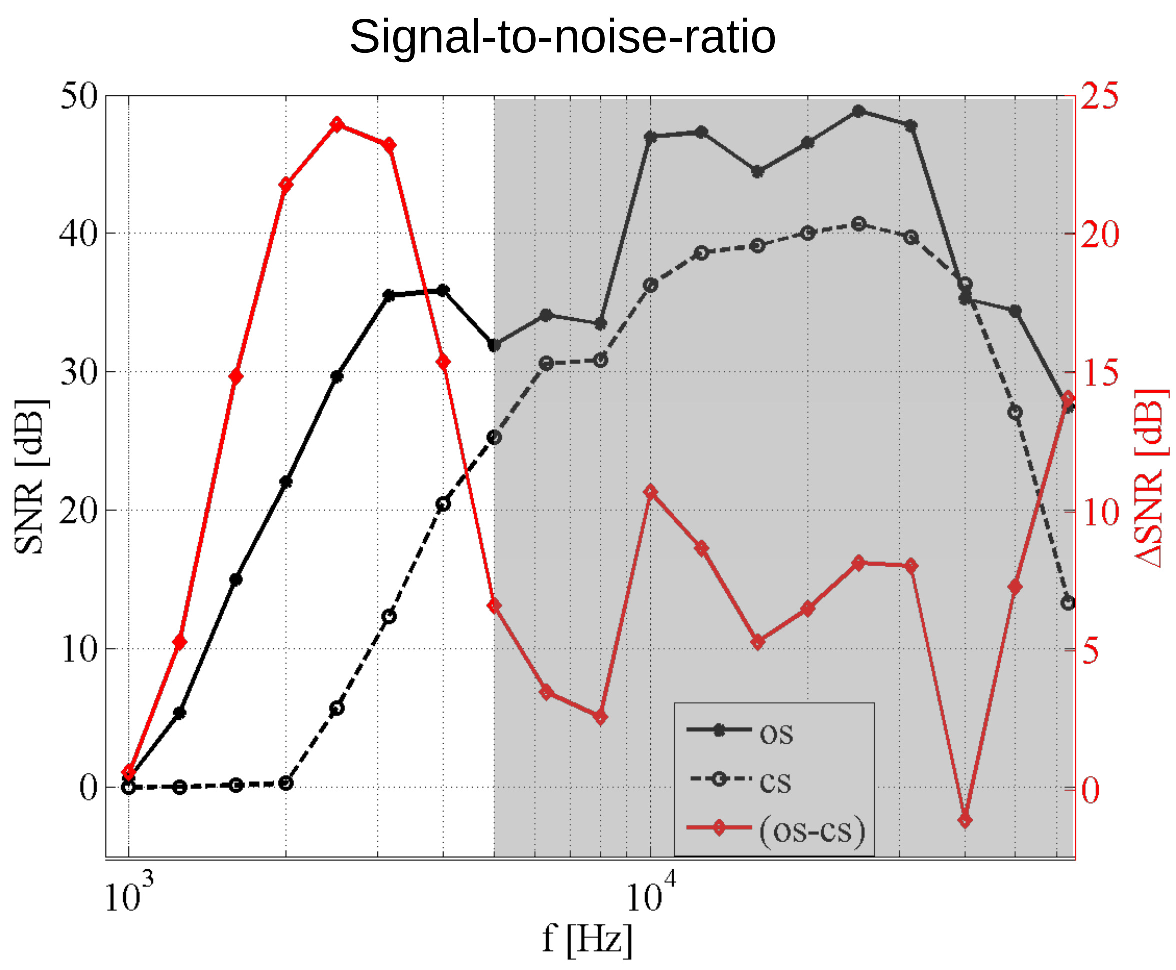
Comparison measurements

DLR reference source – integrated spectra



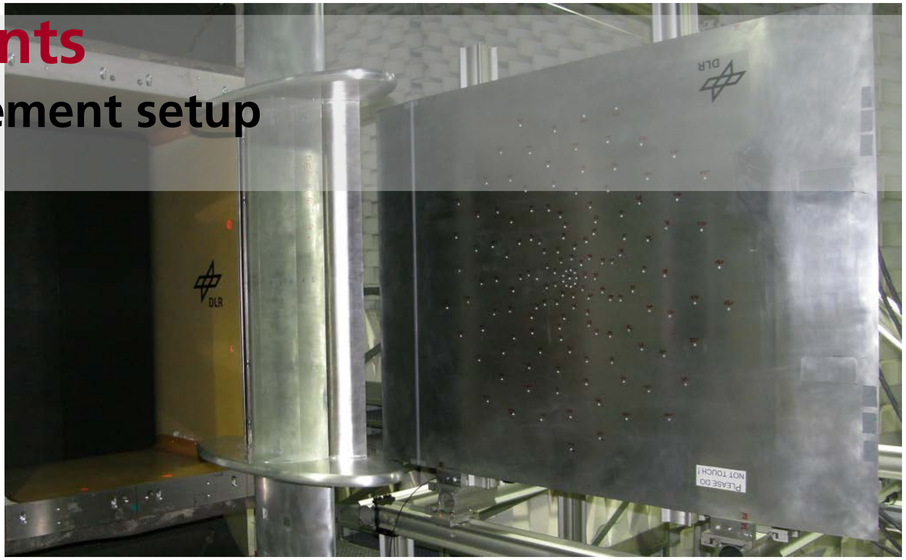
Comparison measurements

DLR reference source – Signal-to-Noise-Ratio

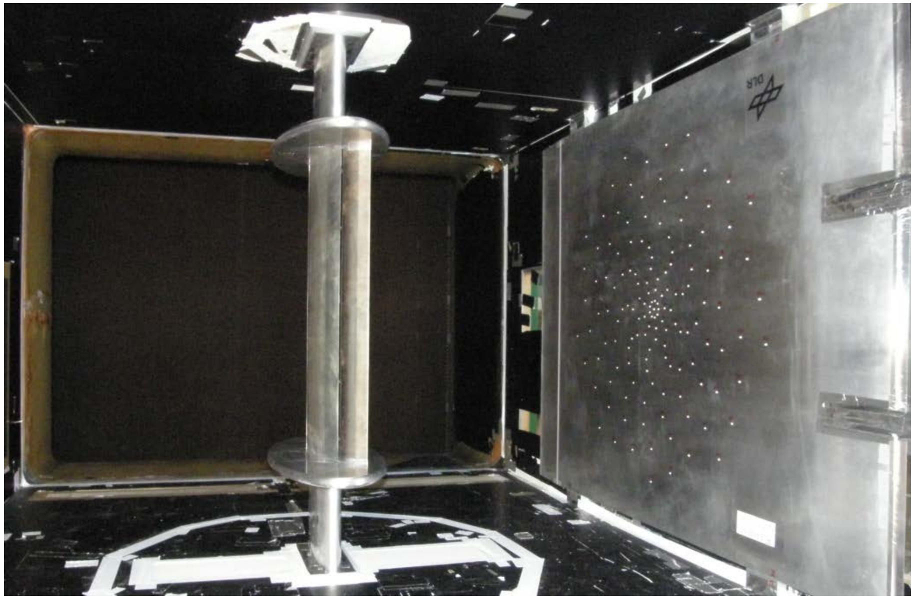


Comparison measurements
Airframe noise source – measurement setup

- Aeroacoustic wind tunnel Braunschweig (AWB)
- Closed circuit wind tunnel, open test section with anechoic room
- Nozzle exit: 1.2 m x 0.8 m

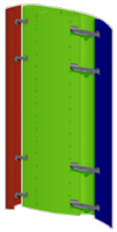


- Wind tunnel at Technical University Berlin
- Closed circuit wind tunnel, closed test section
- Test section dimensions: 1.4 m height, 2.0 m width
- Wind speed up to 35 m/s

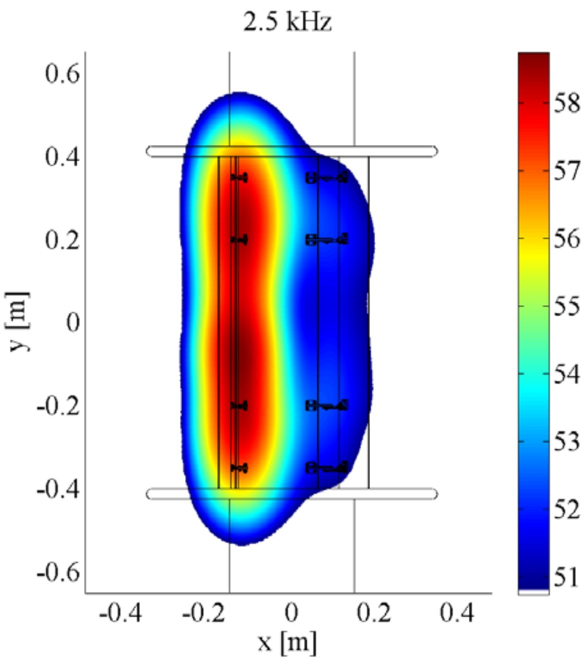


Comparison measurements

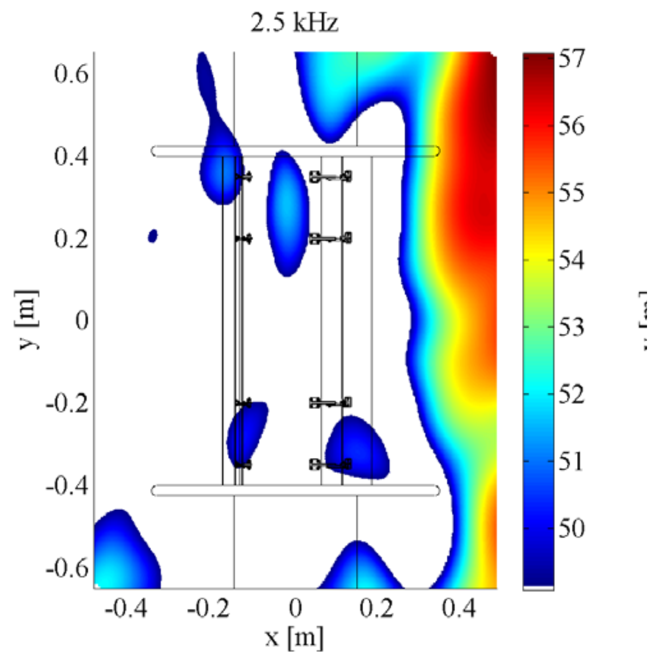
Airframe noise source – source maps



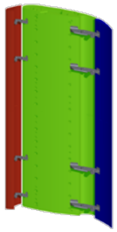
$\alpha_{os} = 12°$



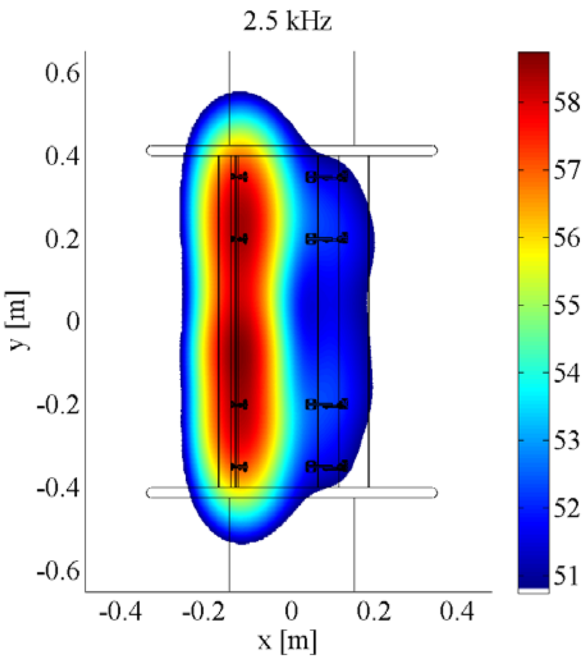
$\alpha_{cs} = 12°$



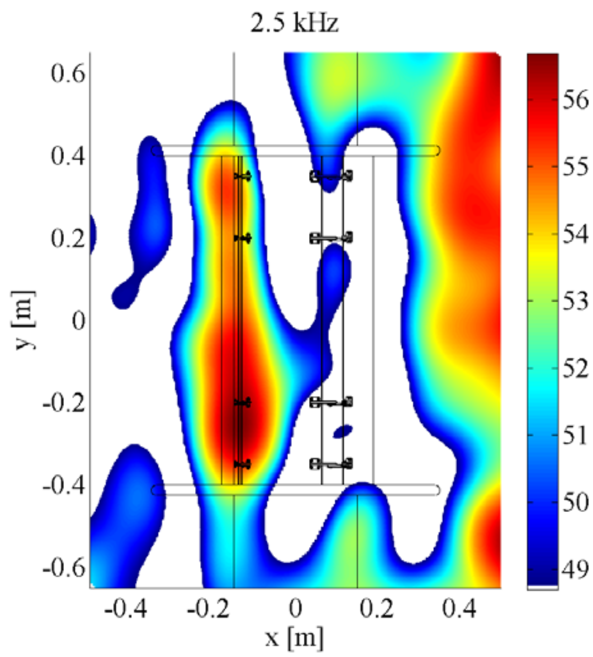
Comparison measurements
Airframe noise source – source maps



$\alpha_{os} = 12°$

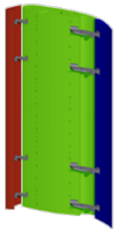


$\alpha_{cs} = 5.5°$

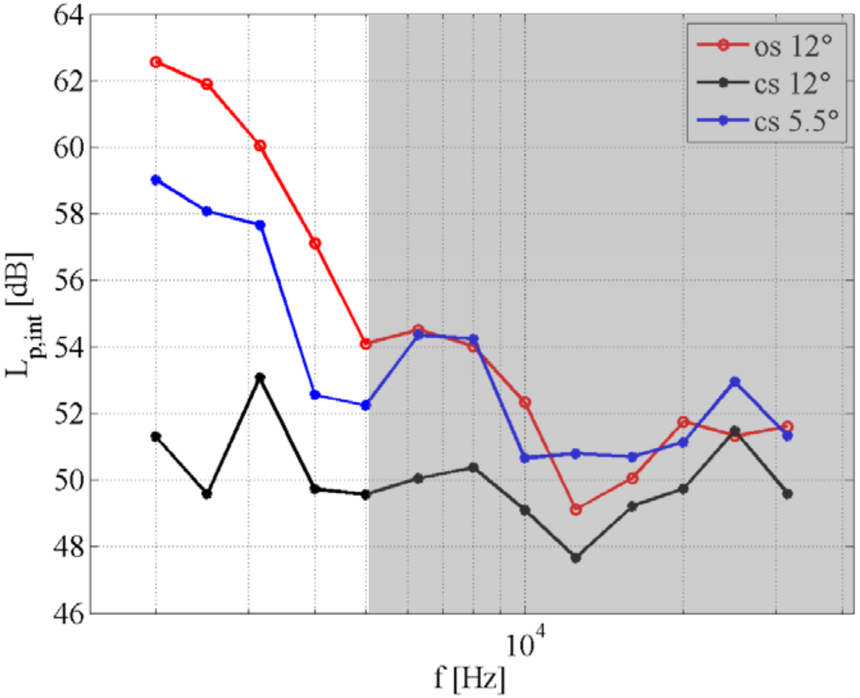


Comparison measurements

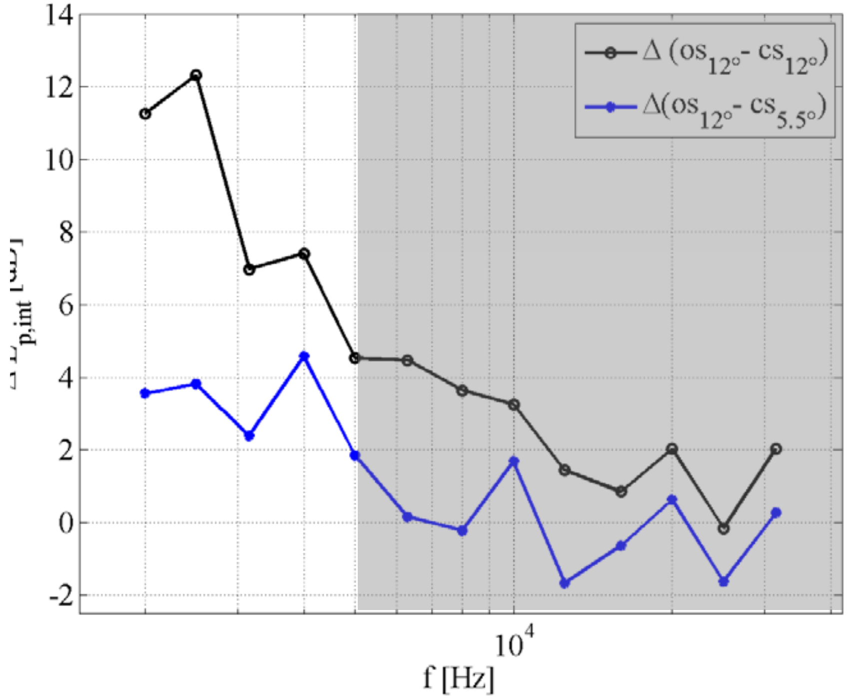
Airframe noise source – integrated spectra



Integrated spectra: open/closed section



Integrated spectra: L_{open} - L_{closed}



Comparison measurements

Summary

- DLR reference source provides:
  - Known sound field in a large frequency range (up to 70 kHz)
  - Repeatable results with known amplitude and phase
  - Independent of flow condition
  - **Signal-to-noise-ratio and comparative measurements**
  - **Assessment of wind tunnel with respect to aeroacoustic measurements**
- Comparisons shows:
  - Level differences open/closed in the range ± 2dB;
  - Low frequency range: larger deviations in CS (reverberant field)
  - Higher frequency range: larger deviations in OS (coherence loss)
  - **Signal-to-noise-ratio higher in OP than in CS**
  - **Limited frequency range in OS**
  - **Accuracy depends on aerodynamic setup**
  - **Measurements have to planned and analysed by experts**

Microphone array measurements in wind tunnels
Summary

- General:
  - State-of-the-art microphone array measurements in closed and open test section at DLR
  - Accurate and reliable source localization
  - Mobile measurement systems
  - Fast measurement technique with minor installation effects
- High Re-number measurements:
  - First successful application of microphone arrays in cryogenic and pressurized WT
  - Clear influence of Re-number on aeroacoustic source strength
  - Definition of acoustic Reynolds corrections between WT-models and real flight condition very challenging
- Comparability between wind tunnels (and to real flight):
  - Challenge: Accuracy depends on aerodynamic setup → Measurements have to planned and analysed by experts

Microphone array measurements in wind tunnels

Challenges → Open issues in MA wind-tunnel measurements

- Assess Re-number dependency of aeroacoustic sources
- Investigate comparability of test results from different facilities:
  - Open closed test section
  - Scaled models
  - Real aircraft/train/…

  } Dedicated experiments
- Systematic investigation on optimal mounting of microphones (Recessed, Kevlar, flush mounted)
- Absolute level of resulting spectra (diagonal removal, deconvolution)
- Consider the directivity of sound sources (not only in the transfer function!)
- Coherent sound sources: Determine the coherence lengths of typical aeroacoustic sound sources (implication on microphone array results)
- Wind tunnel modifications

Future progress in microphone array (wind tunnel) measurements can only be achieved by physical understanding and hardware oriented activities!