Measurement and Scaling of Trailing-Edge Noise*

*rather an extensive look at the scaling of the related source quantities

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13th CEAS-ASC Workshop and 4th Workshop of X^3-Noise,
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Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Background

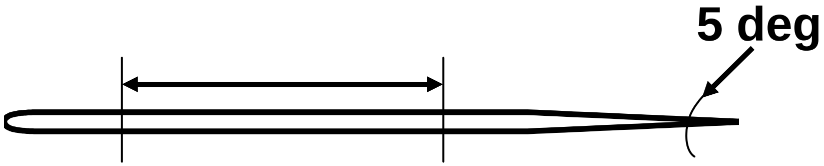
Primary goals

- Set-up of an experimental database which is suitable for parametric trailing-edge (TE) noise source studies and for CAA validation
- Improve DLR’s TE noise measurement and prediction methods
  - With reference to the upcoming “Workshop on Benchmark Problems for Airframe Noise Computations-I” to be held on June 10-11, 2010

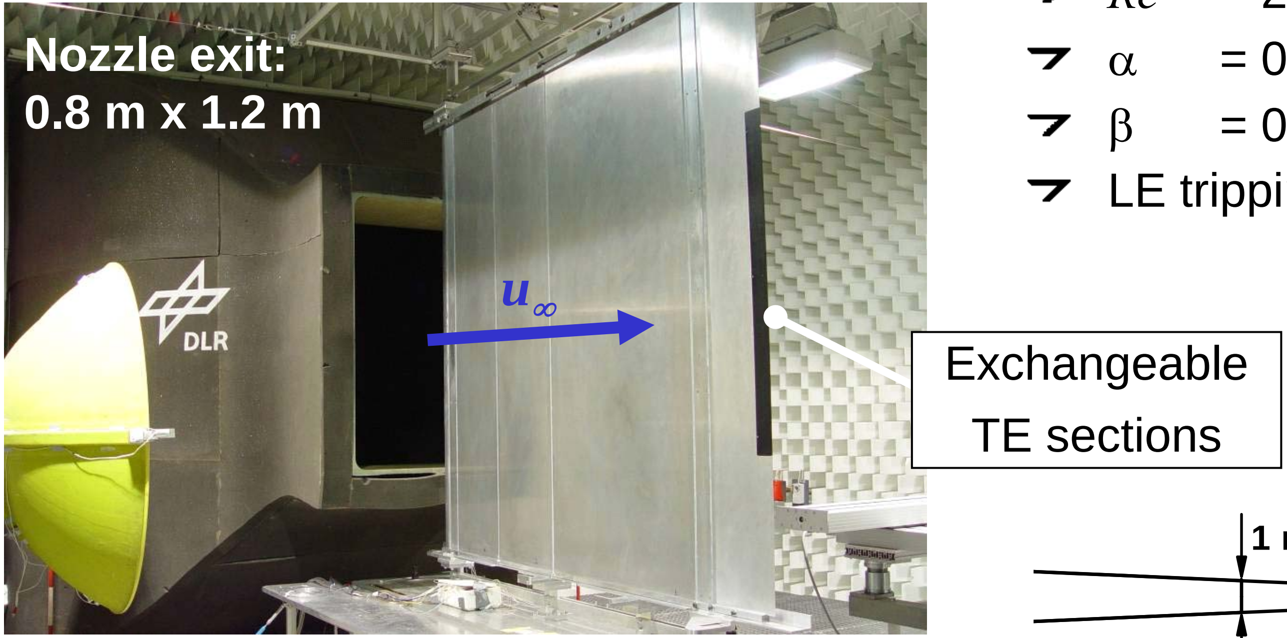
Approach

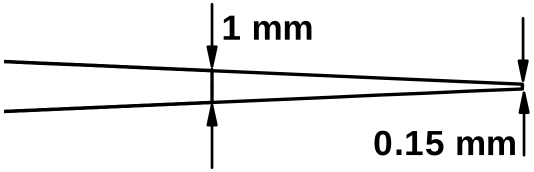
- Definition of a simple generic test setup in the Acoustic Wind-Tunnel Braunschweig (AWB) with a reduced set of parameters, including realistic (HLD) Reynolds numbers
- Comparison with theoretical approaches and with other available test data to provide
  - Validation of the chosen measurement data corrections
  - Estimates of systematic uncertainty contributions

Generic Test Setup - Acoustic Wind-Tunnel Braunschweig (AWB)



- l_c = 0.8–2.0 m
- u_∞ = 40–60 m/s
- Re = 2.1 Mio–7.9 Mio
- α = 0 deg
- β = 0 deg
- LE tripping





Trailing-Edge Noise Data Assessment

- Measurement of related scaling parameters in the source region
- Measurement of the farfield TE noise; estimation of absolute levels

Brooks & Hodgson (1981):

$$S(\varpi) = \frac{M_V b \delta_{x_3}}{2\pi^2 r^2 (1 - M_V)} S_0(\varpi) \qquad \beta = 0, \quad \theta = \varphi = 0$$

TBL mean velocity profiles and integral scales

Unsteady surface pressure point and cross spectra

Farfield TE noise spectra (re. unit distance and span)

Trailing-Edge Noise Data Assessment

- Estimation of the surface pressure spectrum from TBL data

Chase (1987):

$$P_0(\mathbf{k},\varpi) = \frac{\rho_\infty^2 u_\tau^3}{\left[k_+^2 + (b_0\delta)^{-2}\right]^{5/2}} \left\{ \left[b_4 \frac{|k^2 - \varpi^2 / c_\infty^2|}{k^2} + b_5 \frac{k^2}{|k^2 - \varpi^2 / c_\infty^2|} + 1 .. \right.\right.$$

$$\left.\left. .... - b_4 - b_5 \right] b_2 k^2 \left[\frac{k_+^2 + (b_0\delta)^{-2}}{k^2 + (b_0\delta)^{-2}} \right] + b_3 k_1^2 \frac{k^2}{|k^2 - \varpi^2 / c_\infty^2|} \right\}$$

$$k = \sqrt{k_1^2 + k_3^2} \qquad k_+^2 = \frac{\left(\varpi - V k_1\right)^2}{\left(b_1 u_\tau\right)^2} + k^2$$

Goody (2004), based on Howe (2000):

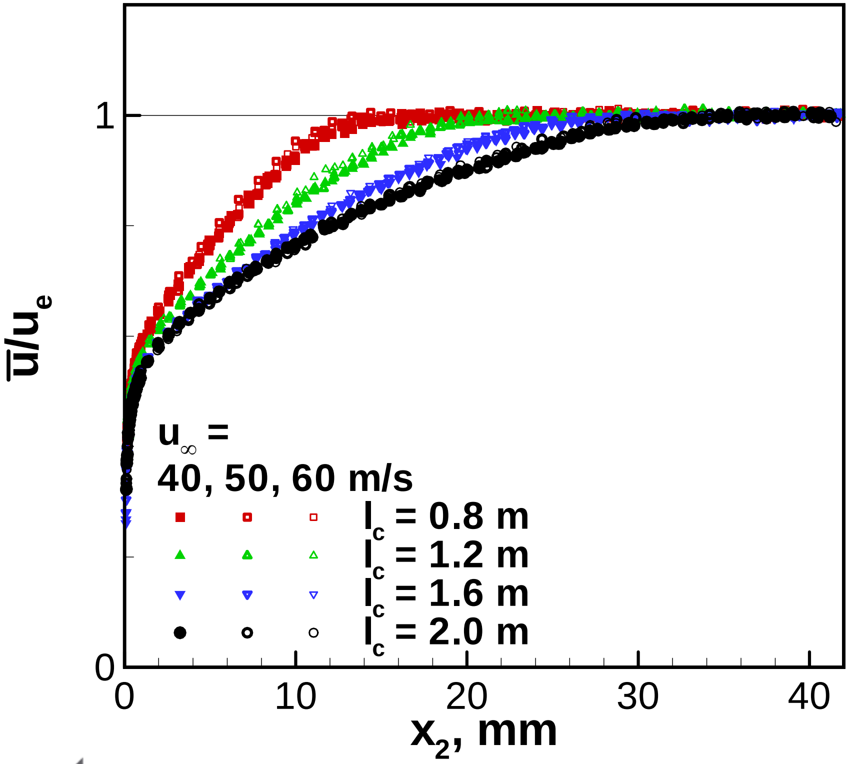
$$\frac{S_0(\varpi)(u_e/\delta)}{\tau_w^2} \approx \frac{3\left(\varpi\delta/u_e\right)^2}{\left[\left(\varpi\delta/u_e\right)^{0.75} + 0.5\right]^{3.7} + \left[1.1 R_t^{-0.57}\left(\varpi\delta/u_e\right)\right]^7}$$

$$R_t = (\delta/u_e)/(\nu_\infty/u_\tau^2)$$

- TBL thickness δ, wall friction velocity $u_\tau = (\tau_W/\rho_\infty)^{0.5}$, TBL edge velocity u_e

Part I – Measured TBL Mean Velocity Profiles

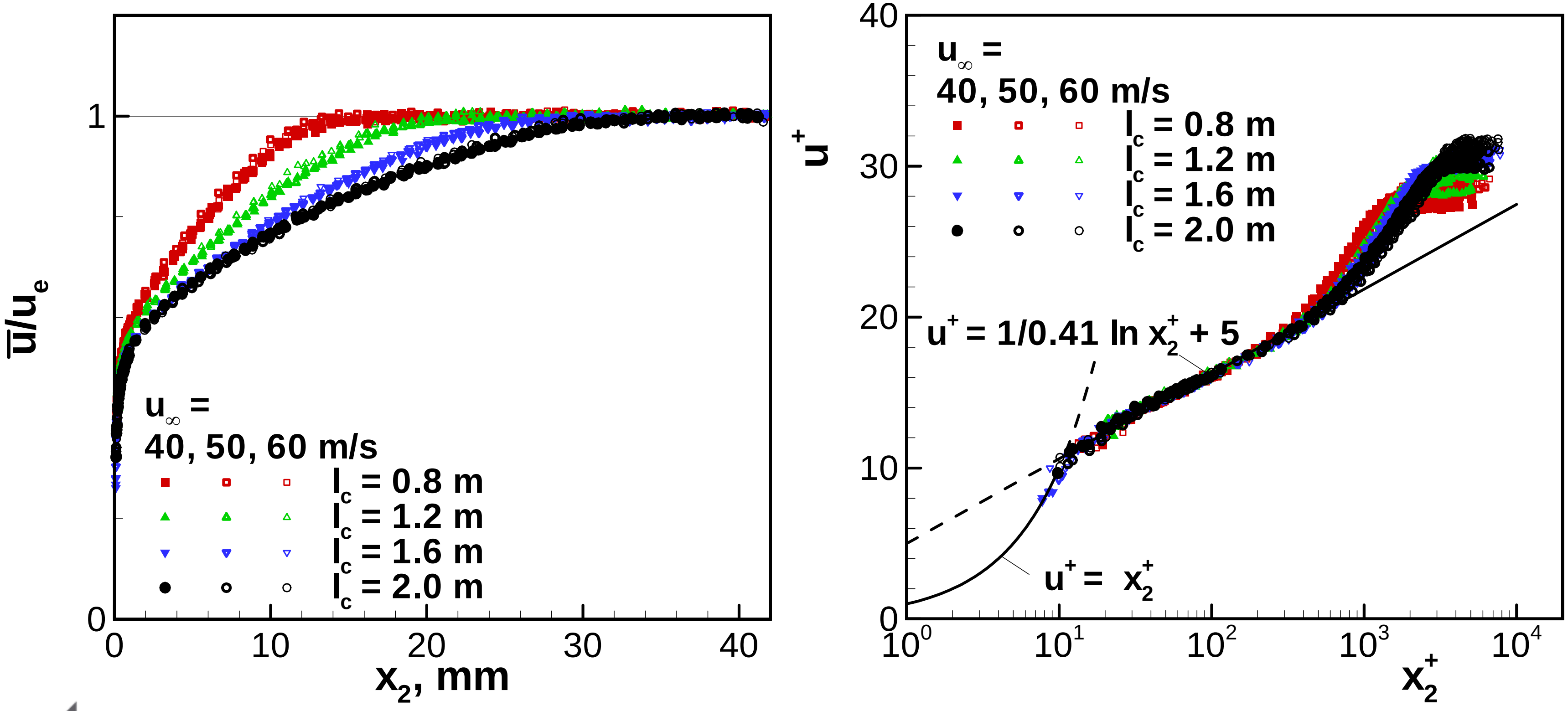
- Hot-wire (CTA) measurement results
- u_e/u_∞ = 0.98 ± 0.02 (40:1)



Part I – Measured TBL Mean Velocity Profiles

- Scaling based on inner scale, ν_∞/u_τ

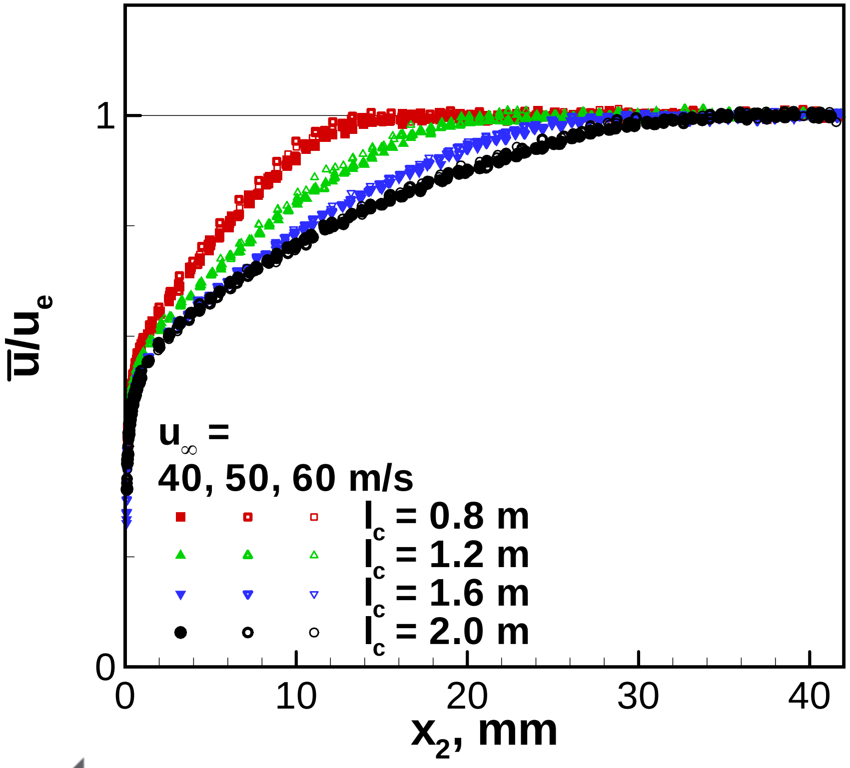
$$u^+ = \frac{\bar{u}}{u_\tau} = f(x_2^+); \quad x_2^+ = \frac{x_2 u_\tau}{\nu_\infty}$$

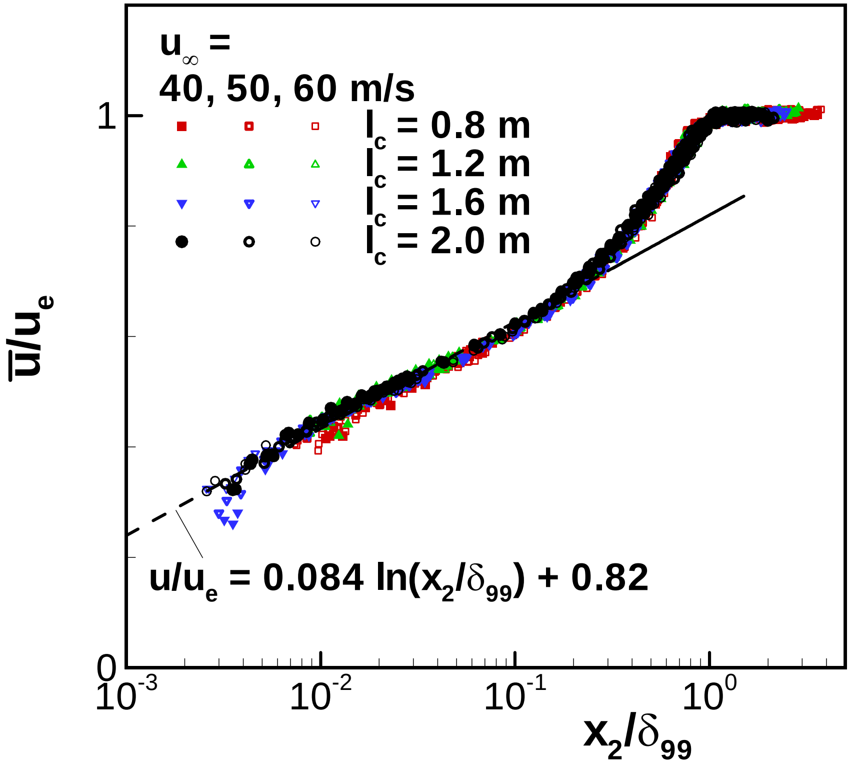


Part I – Measured TBL Mean Velocity Profiles

- Scaling based on outer scale, $\delta \approx \delta_{99}$

$$\frac{u_e - \overline{u}}{u_\tau} = F(x_2^*); \qquad x_2^* = \frac{x_2}{\delta}$$

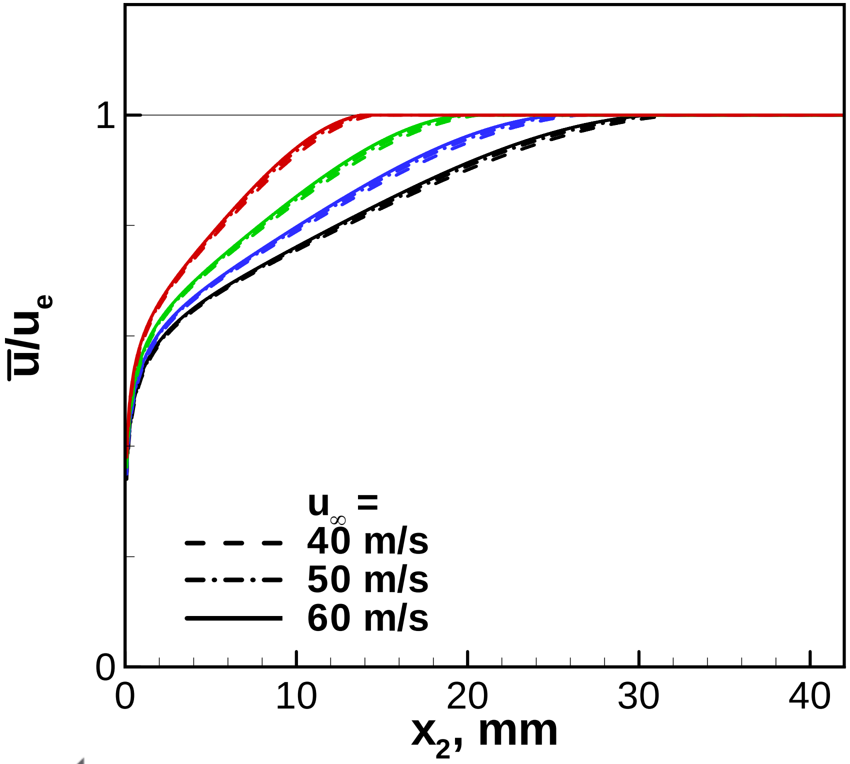




Part I – Derived Parameters

- Reconstruction of the velocity profiles, Coles' (1956) Law of the Wake

$$u^+ = \frac{1}{\kappa}\ln(x_2^+) + B + 0.5\left[1+\sin\frac{\pi}{2}\left(2\frac{x_2}{\delta}-1\right)\right]\left[\frac{u_e}{u_\tau} - \frac{1}{\kappa}\ln(\delta^+) - B\right]; \quad \delta^+ = \delta u_\tau / \nu_\infty$$



- δ_{99}
- δ_1, δ_2, H_{12}
- u_τ, τ_w

- These are used in the following for the scaling of unsteady surface pressure and TE noise data.

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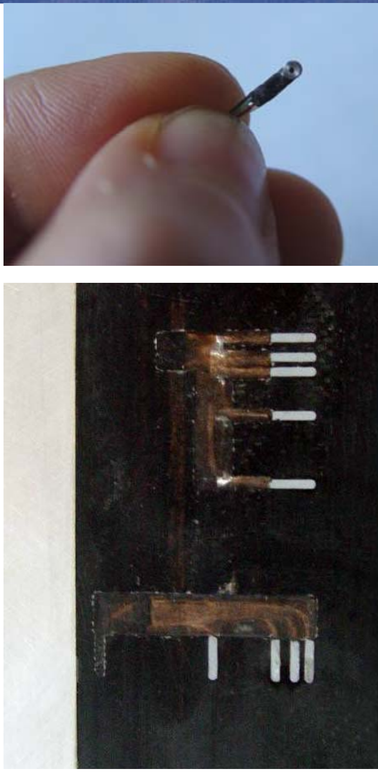
Part II – Unsteady Surface Pressure Data

- Point PSD close to the TE
- Streamwise and spanwise coherence decay
- Streamwise and spanwise coherence lengths
- Convection velocities

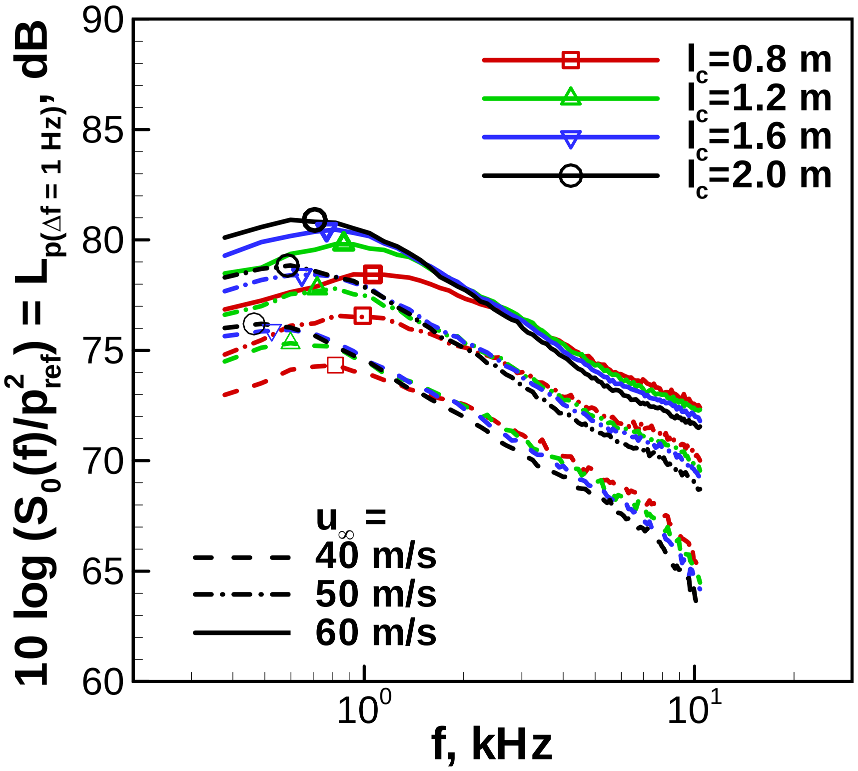


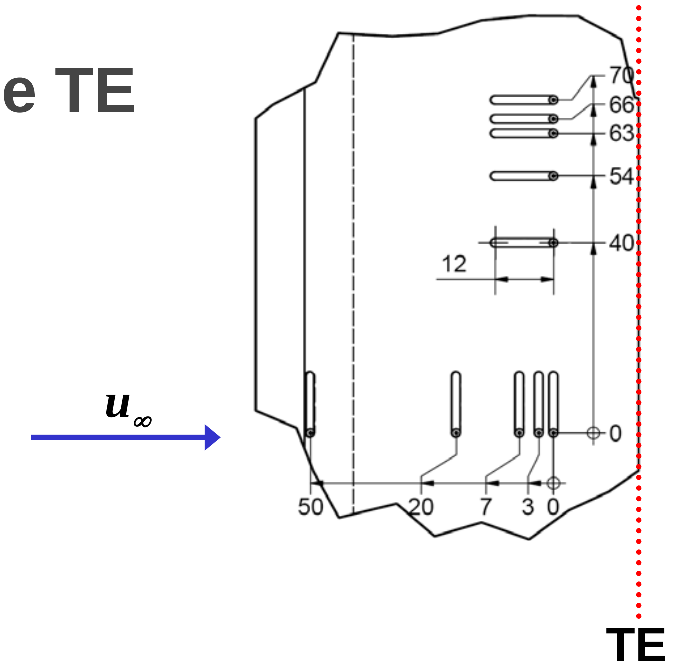
TBL mean velocity profiles and integral scales

Unsteady surface pressure point and cross spectra

Farfield TE noise spectra (re. unit distance and span)

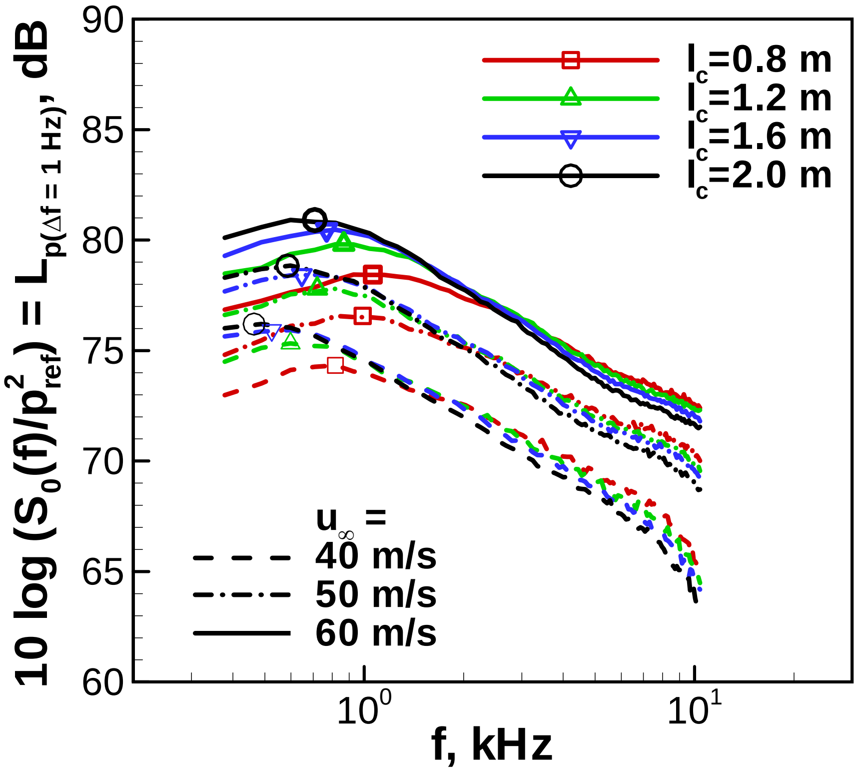
Part II – Point PSDs close to the TE

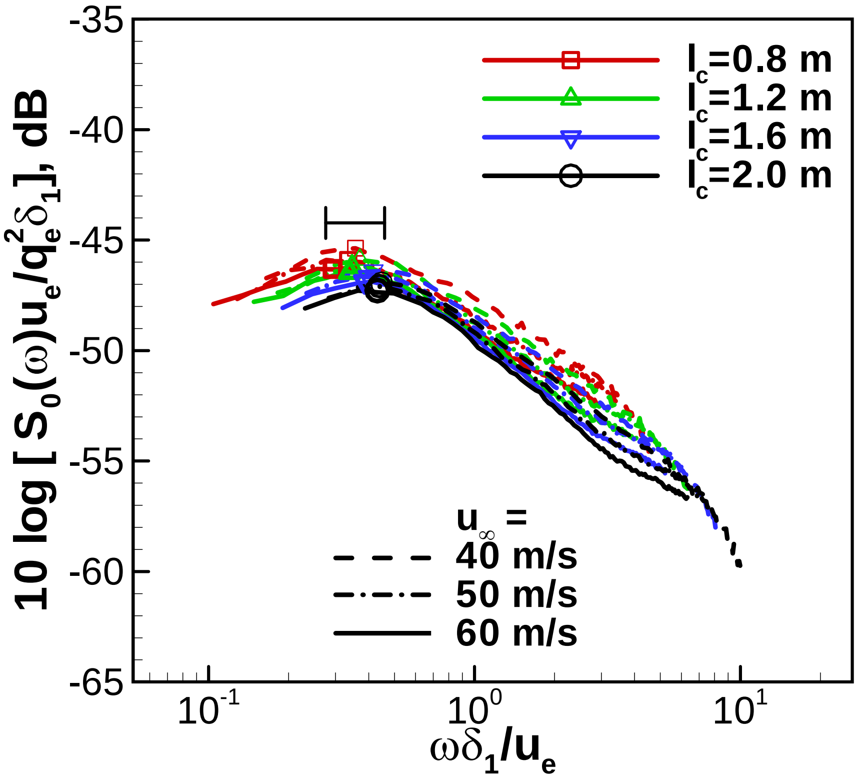




Part II – Point PSDs close to the TE

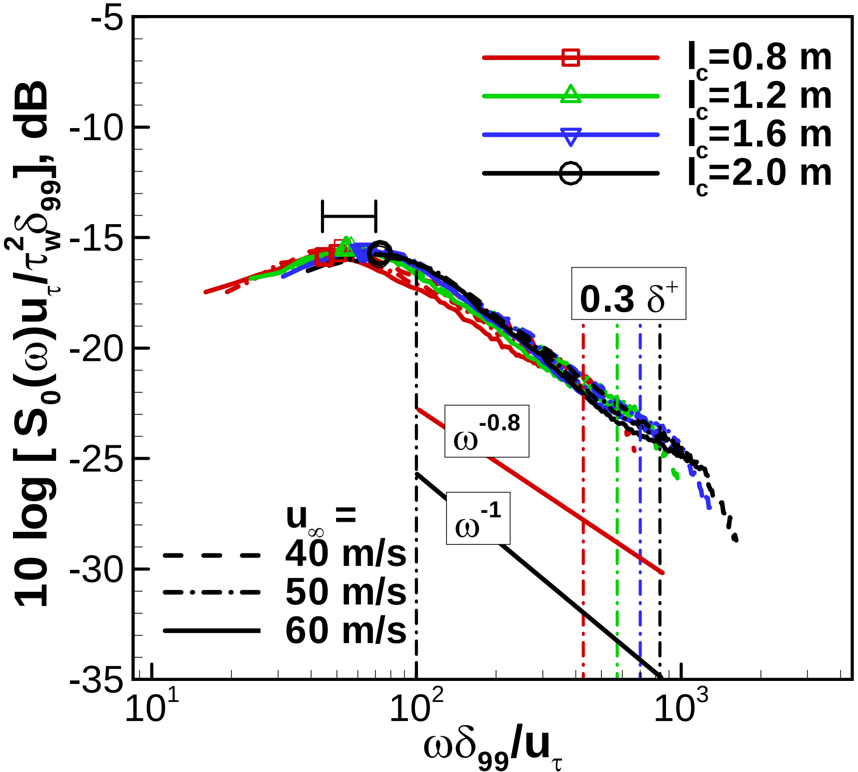
- Scaling based on outer scales:
  - Pressure scale: $q_e = \frac{1}{2}\rho_\infty u_e^2$
  - Time scale: δ_1/u_e or δ_{99}/u_e

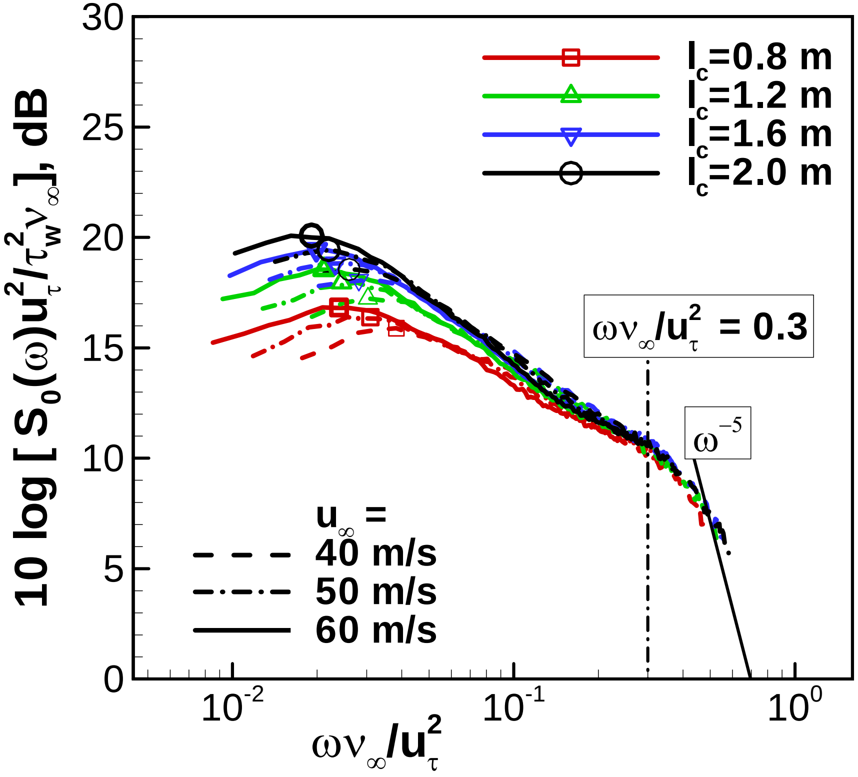




Part II – Point PSDs close to the TE

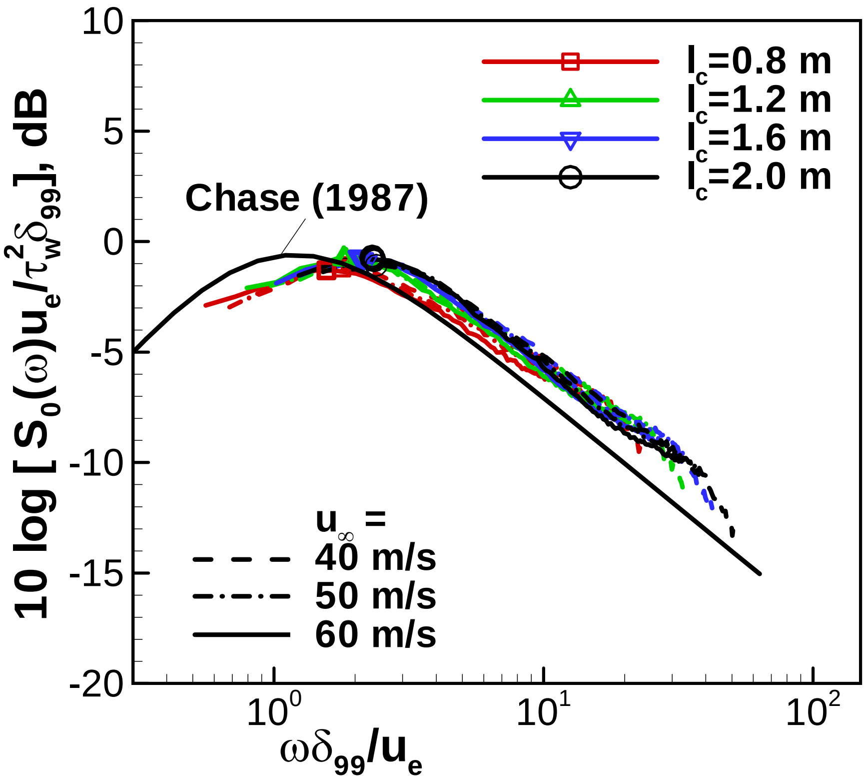
- Scaling based on “mixed” scales
  - Pressure scale: $\tau_w = \rho_\infty u_\tau^2$
  - Time scale: $\delta_1/u_\tau,\ \delta_{99}/u_\tau,\ \delta_1/u_e,\ \delta_{99}/u_e$
- Scaling based on inner scales
  - Pressure scale: τ_w
  - Time scale: ν_∞/u_τ^2





Part II – Current Prediction Models for point PSDs

- Chase (1987) model:



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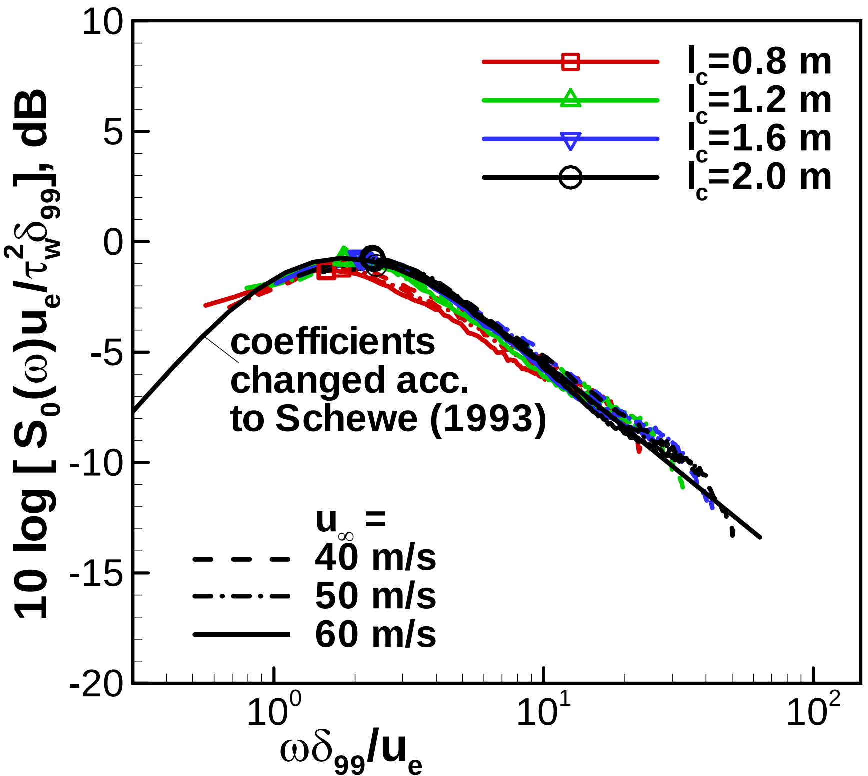
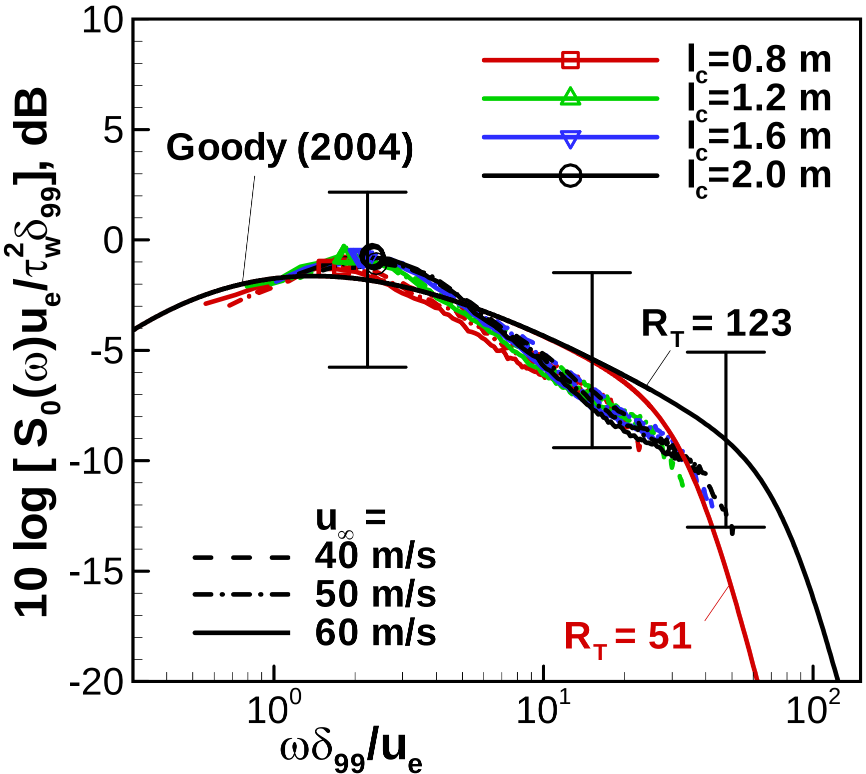


- Empirical factors need a more detailed experimental assessment

Part II – Current Prediction Models for point PSDs

- Goody (2004) model



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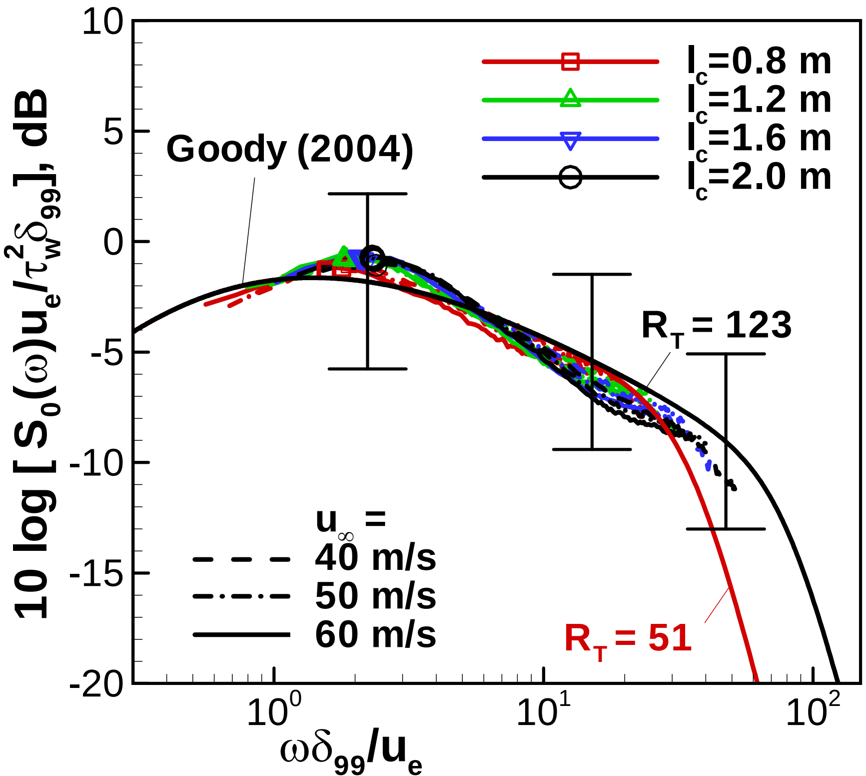
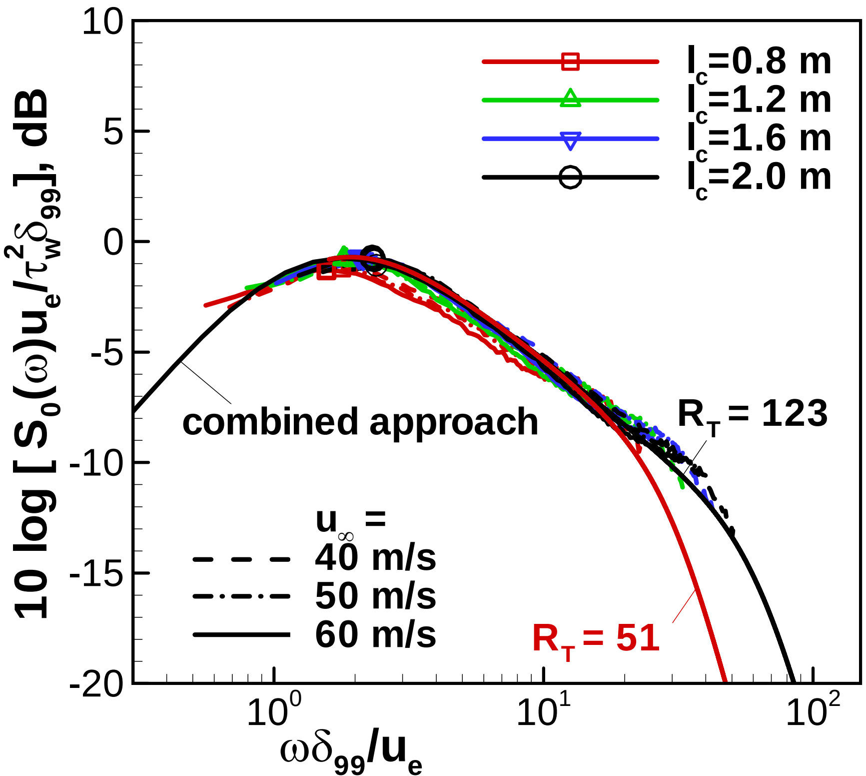


- High frequency data corrections have to be taken with care!
- Existing deviations are due to application of high-frequency data corrections which seem to overvalue actual levels

Part II – Current Prediction Models for point PSDs

- Goody (2004) model

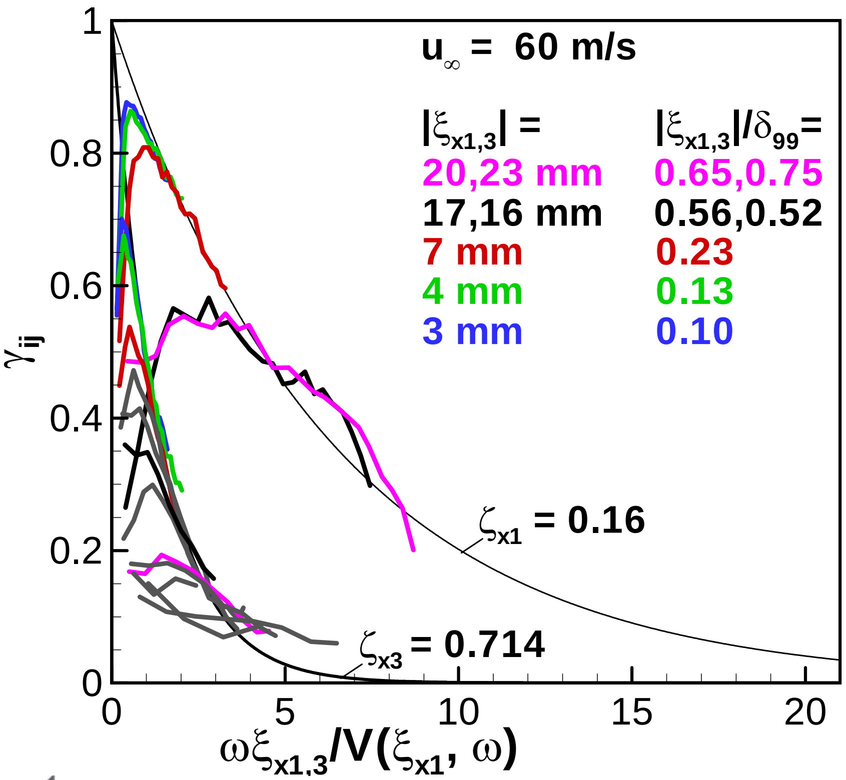


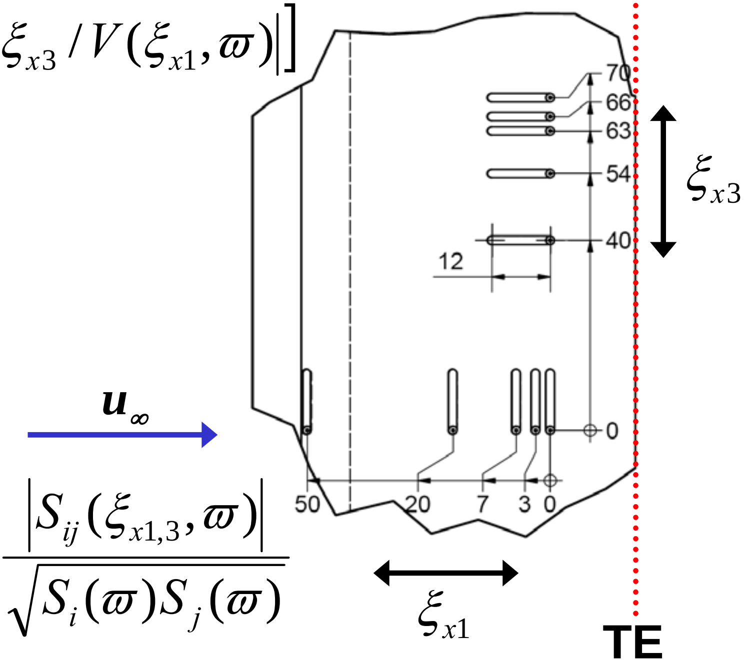
- High frequency data corrections have to be taken with care!
- Existing deviations are due to application of high-frequency data corrections which seem to overvalue actual levels
- A combination of both models might apply.

Currently restricted to 2-m-plate only!

Part II – Coherence Decay and Coherence Lengths

- Corcos' (1963) similarity approach:
  - Streamwise $\gamma_{ij}(\xi_{x1},\varpi)=\exp\left[-\zeta_{x1}\left|\omega\xi_{x1}/V(\xi_{x1},\varpi)\right|\right]$
  - Spanwise $\gamma_{ij}(\xi_{x3},\varpi)=\exp\left[-\zeta_{x3}\left|\omega\xi_{x3}/V(\xi_{x1},\varpi)\right|\right]$





$$\gamma_{ij}=\frac{\left|S_{ij}(\xi_{x1,3},\varpi)\right|}{\sqrt{S_i(\varpi)S_j(\varpi)}}$$

$$\psi_{ij}(\xi_{x1},\varpi)=\omega\xi_{x1}/V(\xi_{x1},\varpi)=k_v\xi_{x1}$$

$$k_v=\varpi/V(\xi_{x1},\varpi)$$

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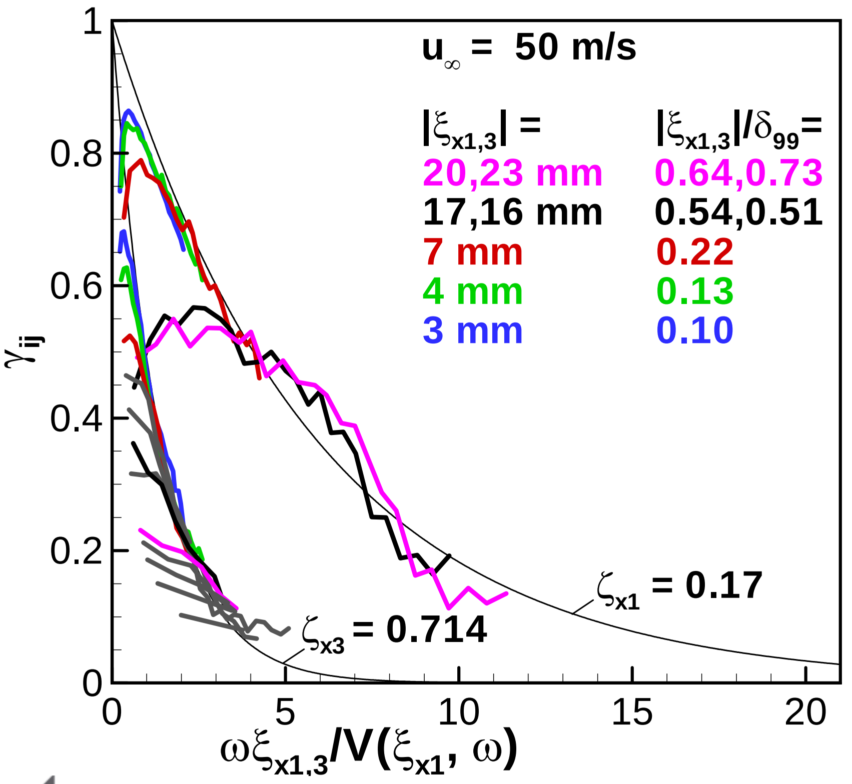

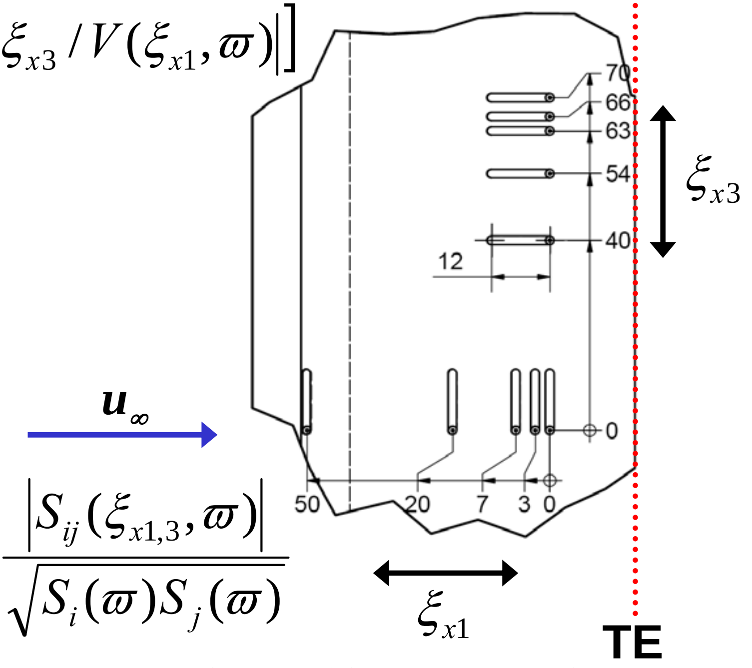

$$\gamma_{ij} = \frac{\left|S_{ij}(\xi_{x1,3},\varpi)\right|}{\sqrt{S_i(\varpi)S_j(\varpi)}}$$

$$\psi_{ij}(\xi_{x1},\varpi) = \omega\xi_{x1}/V(\xi_{x1},\varpi) = k_v\xi_{x1}$$

$$k_v = \varpi/V(\xi_{x1},\varpi)$$

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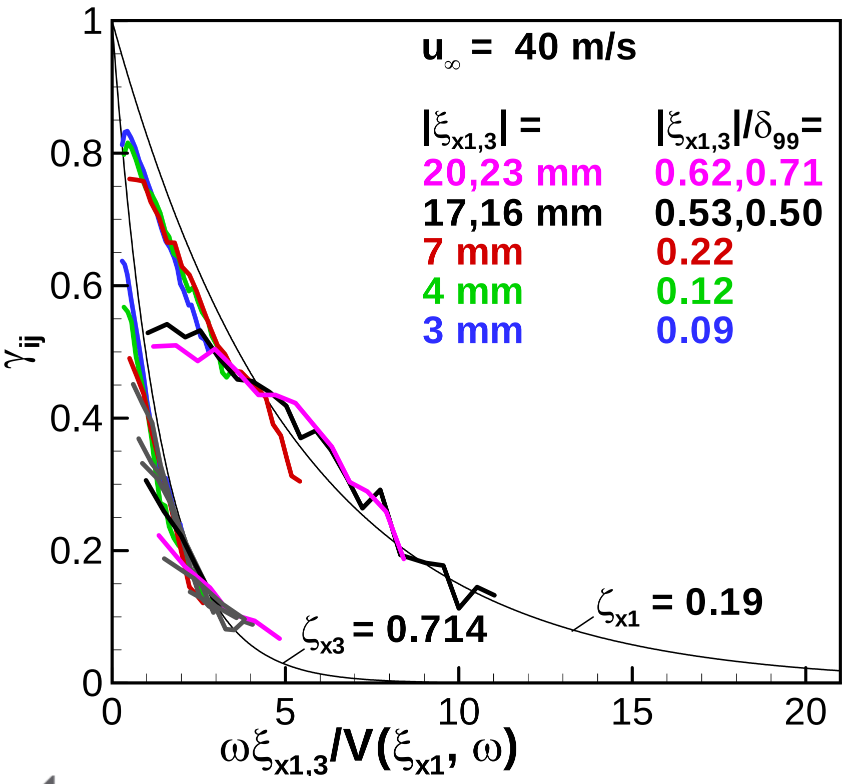
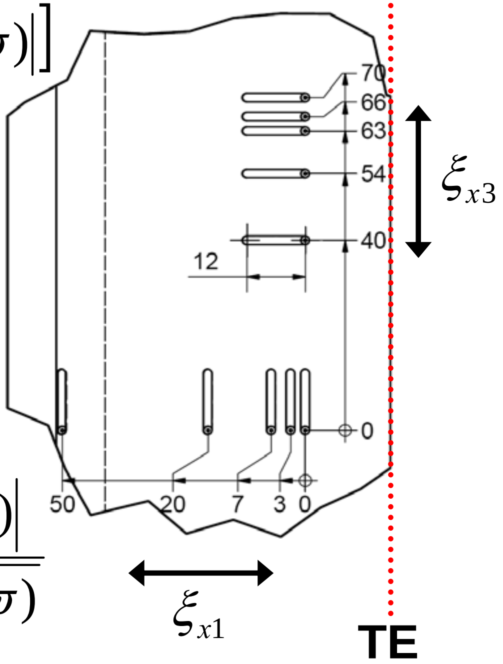




$$\gamma_{ij} = \frac{\left|S_{ij}(\xi_{x1,3},\varpi)\right|}{\sqrt{S_i(\varpi)S_j(\varpi)}}$$

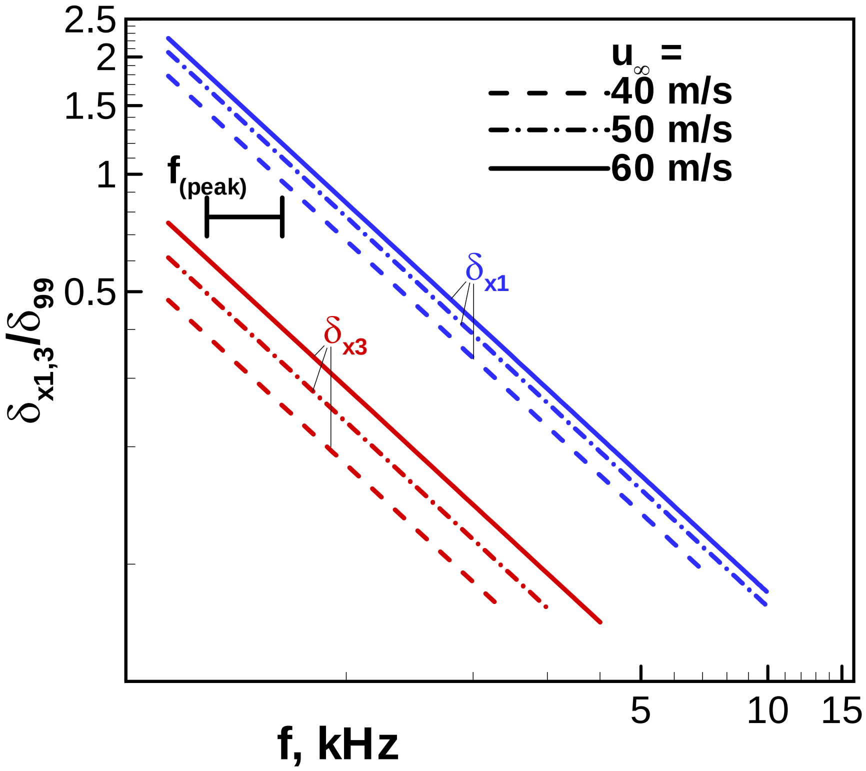
$$\psi_{ij}(\xi_{x1},\varpi) = \omega\xi_{x1}/V(\xi_{x1},\varpi) = k_v\xi_{x1}$$

$$k_v = \varpi / V(\xi_{x1},\varpi)$$

Currently restricted to 2-m-plate only!

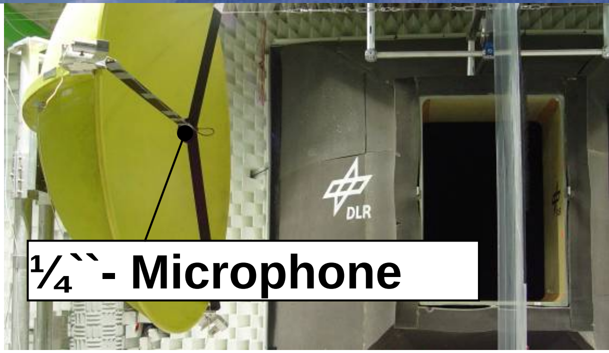
Part II – Coherence Decay and Coherence Lengths

- Assuming a constant $V \approx 0.65\, u_\infty$
  - Streamwise $\delta_{x1} = 1/\zeta_{x1} k_v = V/\zeta_{x1}\varpi$
  - Spanwise $\delta_{x3} = 1/\zeta_{x3} k_v = V/\zeta_{x3}\varpi$



Part III – Farfield TE Noise Data

- Absolute 1/3-octave band SPL re 1m span and 1m observer distance



Brooks & Hodgson (1981):

$$S(\varpi) = \frac{M_V b \delta_{x_3}}{2\pi^2 r^2 (1 - M_V)} S_0(\varpi)$$

$$\beta = 0$$

$$\theta = \varphi = 0$$

TBL mean velocity profiles and integral scales

Unsteady surface pressure point and cross spectra

Farfield TE noise spectra (re. unit distance and span)

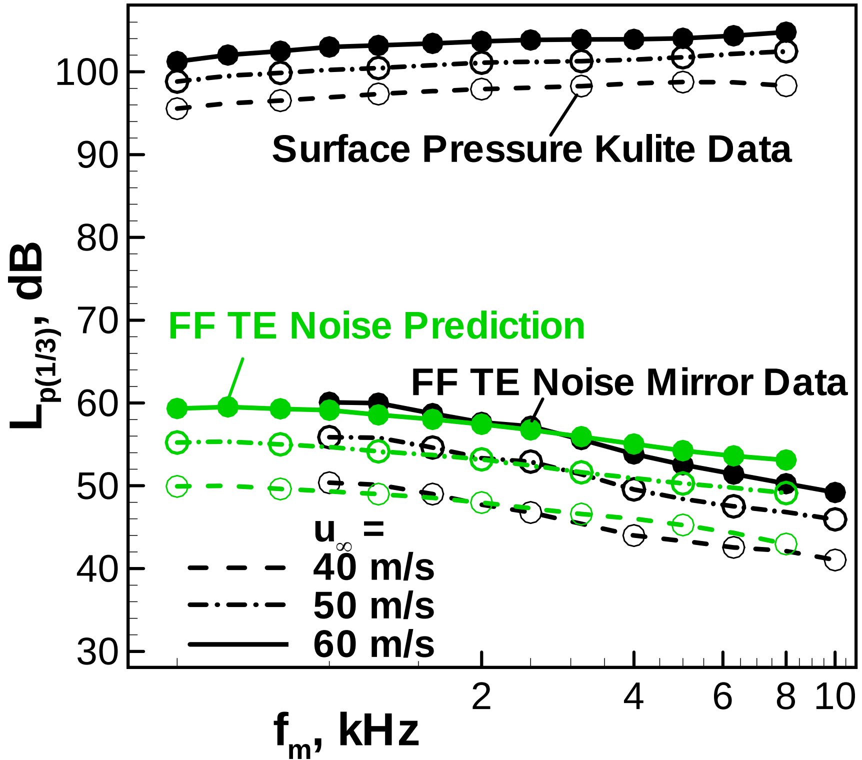
Currently restricted to 2-m-plate only!

Part III – Farfield TE Noise Data

- Prediction from the surface pressure data, assuming constant $V \approx 0.65\, u_\infty$

Brooks & Hodgson (1981):

$$S(\varpi) = \frac{M_V b \delta_{x_3}}{2\pi^2 r^2 (1 - M_V)} S_0(\varpi) \qquad \beta = 0 \qquad \theta = \varphi = 0$$

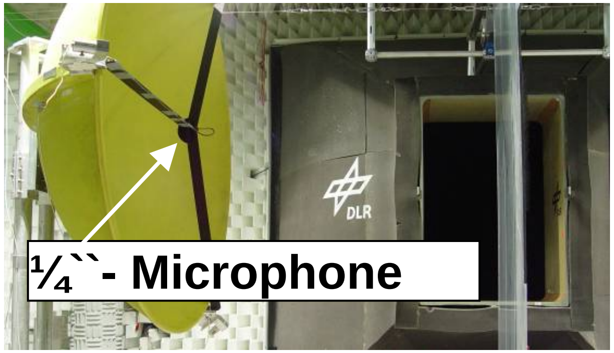


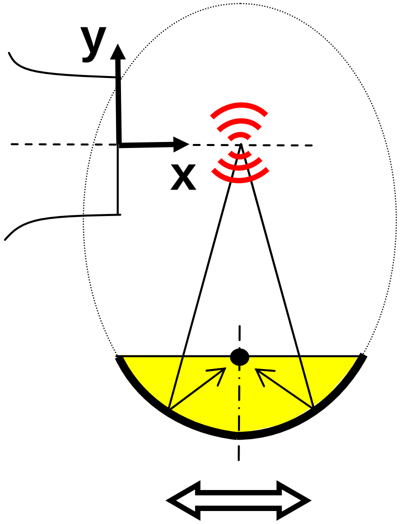
- Estimation of absolute levels (re 1m span and 1m observer distance) requires extensive data corrections, as shown in the following…

Part III – Elliptic Mirror Setup

- Elliptic mirror specifics:
  - Focal distance: 1.15 m
  - Reflector diameter D = 1.4 m
  - Resolution width ≈ λ
  - Aperture: 63 deg

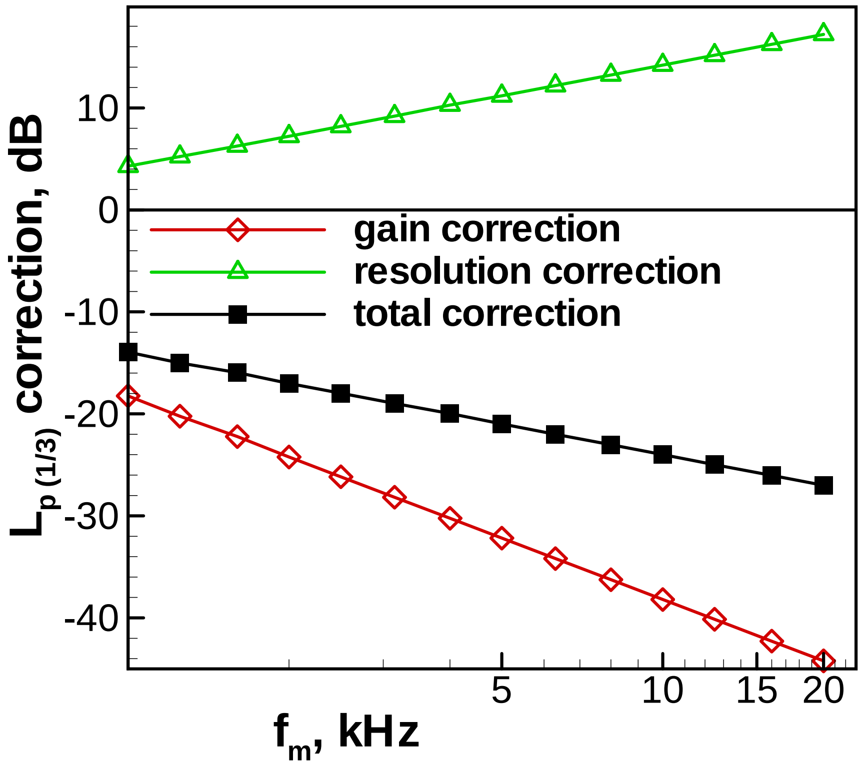
- Data correction for:
  - Background noise (S/N ≥ 3 dB)
  - Sound wave convection
  - Frequency response function (gain, resolution)
  - Shear layer refraction/scattering


¼``- Microphone



Part III – Elliptic Mirror Setup

- Correction for frequency response (Schlinker, 1977)



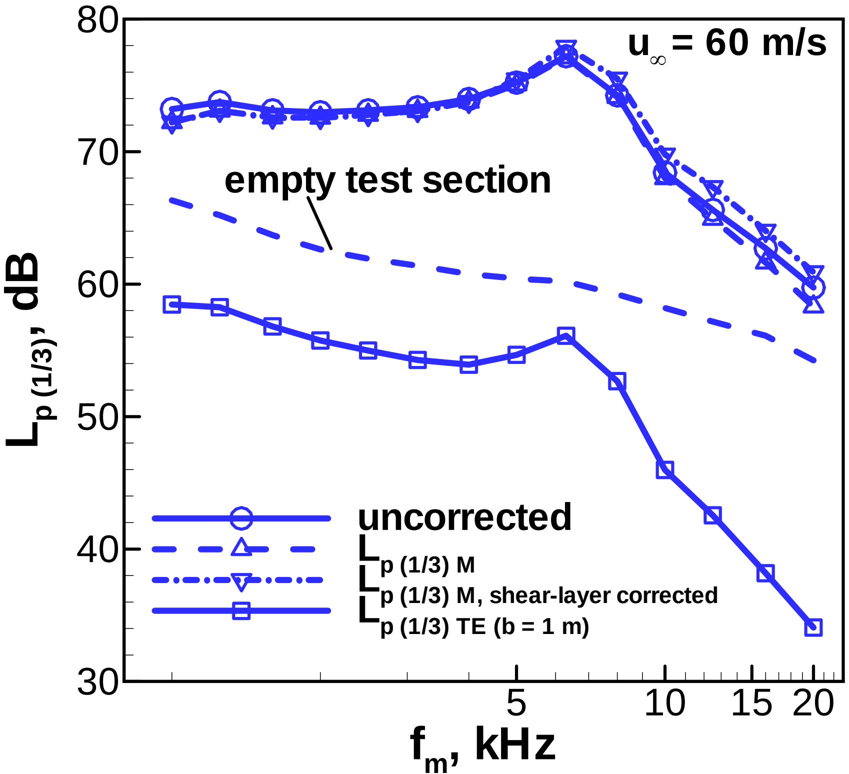
$$\langle p^2 \rangle = \frac{\langle p_M^2 \rangle}{G} \frac{b}{\int_{-b/2}^{+b/2} H(\eta)\,dx_3}$$

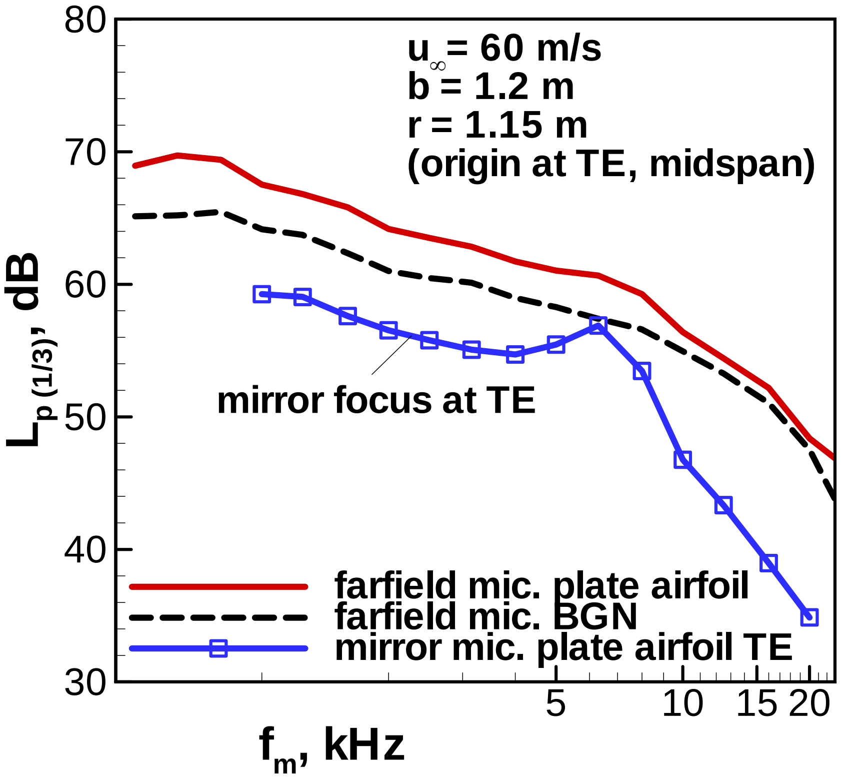
$$H(\eta) = \left[\frac{2 J_1(\eta)}{\eta} \right]^2$$

$$\eta = \frac{\pi\, D\, f\, x_3}{c_\infty\, R_D}$$

Part III – Effect of Data Corrections

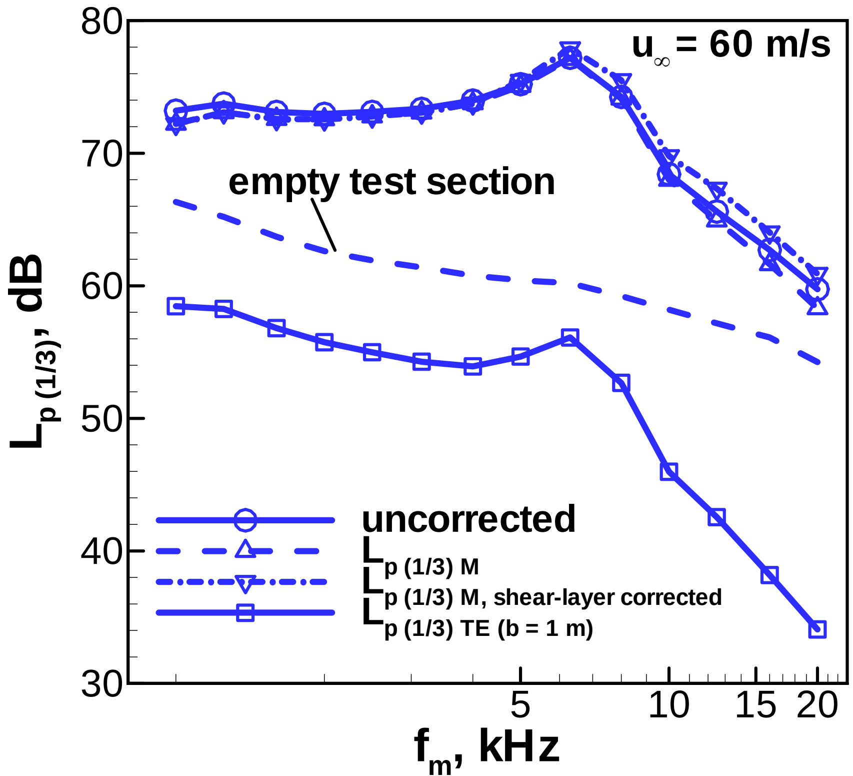
- 1.6-m plate model with blunt TE (h = 1 mm)
- Focusing measurement techniques must be used because TE noise is buried by the tunnel self-noise!

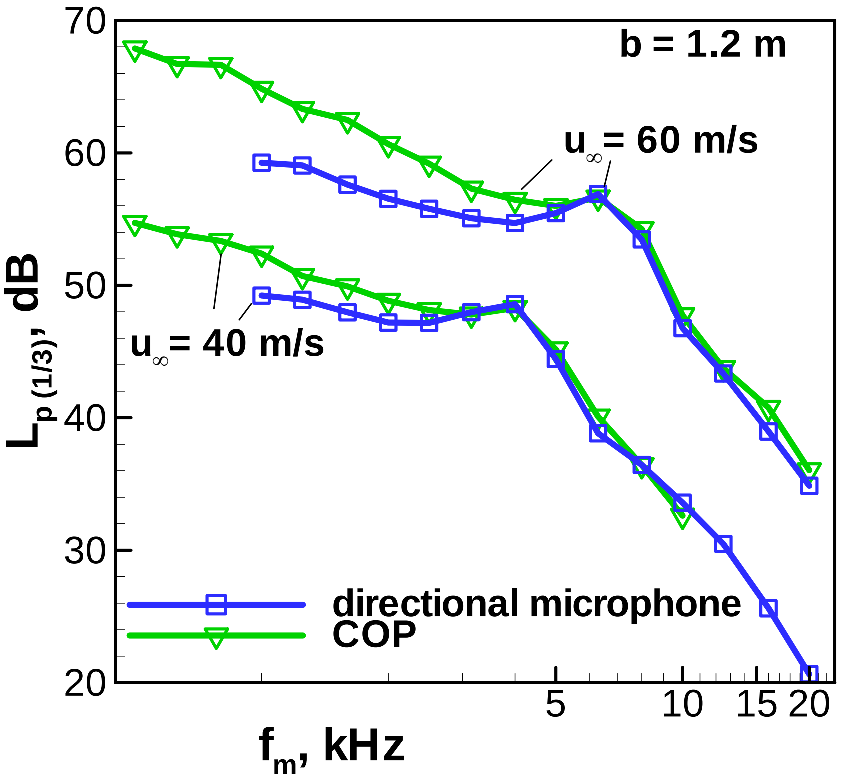




Part III – Effect of Data Corrections

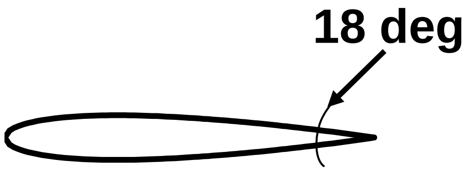
- 1.6-m plate model with blunt TE (h = 1 mm)
- Focusing measurement techniques must be used because TE noise is buried by the tunnel self-noise!
- “Validation” of the procedure by alternative measurement techniques: COP

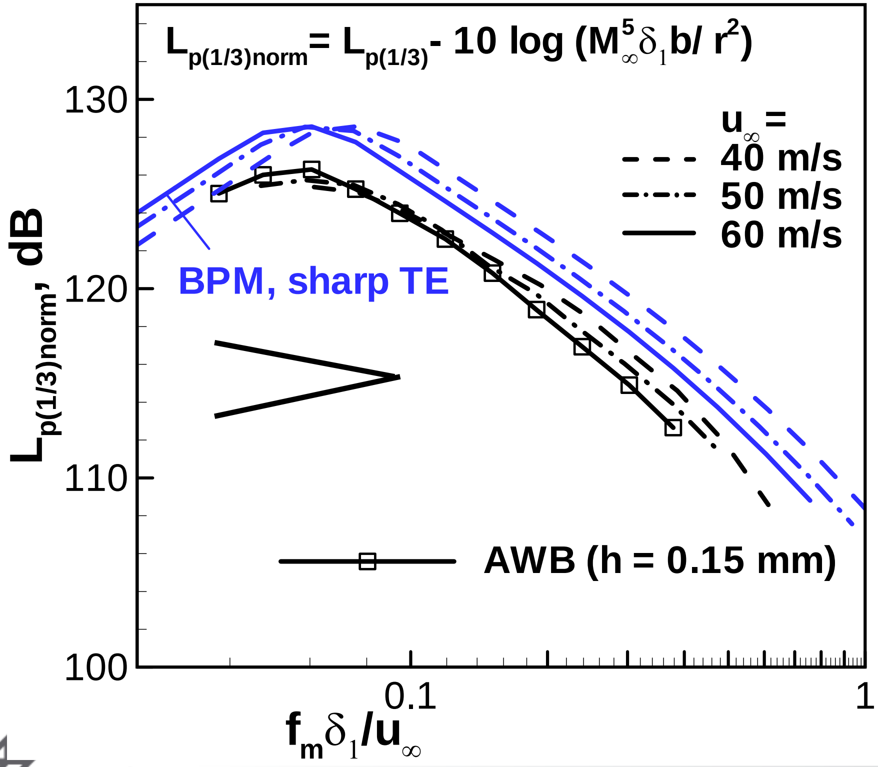




Part III – Comparisons with Published TE Noise Data

- NACA0012 data by Brooks et al. (1986): COP → semi-empirical prediction method (BPM, NAFNoise)

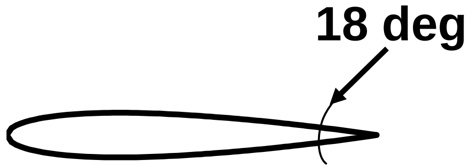


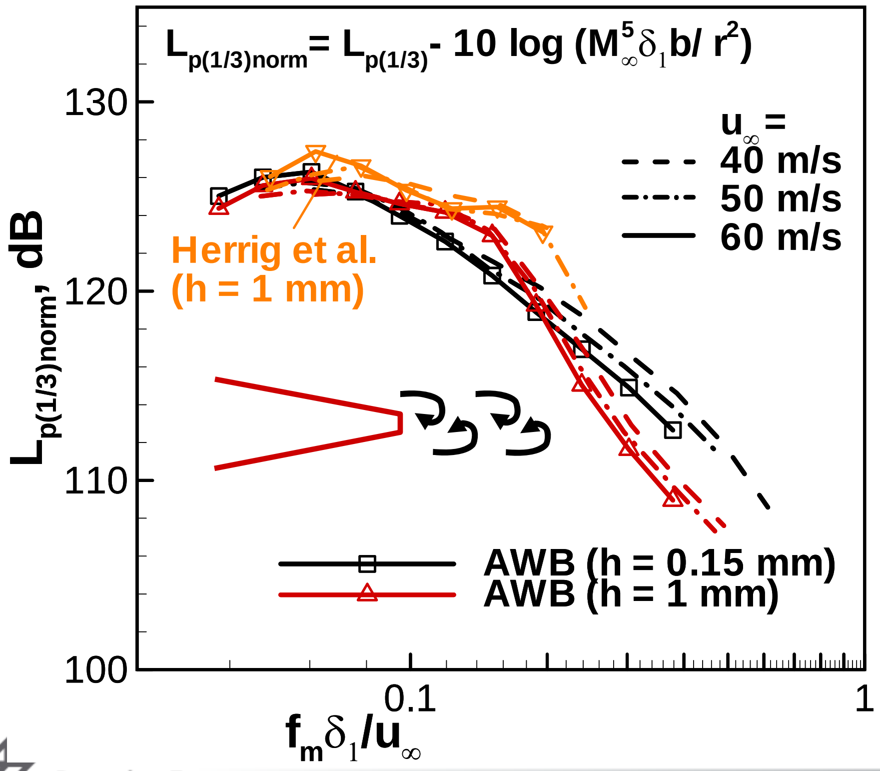


0.4-m 2D-”NACA0012” with varying TE thickness

Part III – Comparisons with Published TE Noise Data

- NACA0012 data by Herrig et al.(2008): CPV





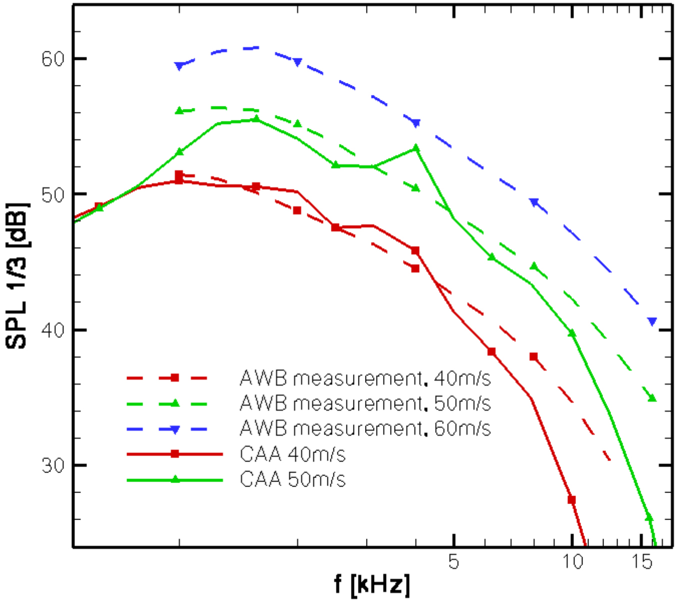

0.4-m 2D-"NACA0012"
with varying TE thickness

Conclusions

- Presentation of a parametric plate model TE noise data set which (with the limitation to nonzero angles-of-attack and $\theta = \phi = \pi/2$) could help to validate current CAA approaches, maximum Re of 7.9 Mio
- Excellent agreement of the plate model data set with theoretical models
- Fair agreement with published data sets as derived at comparable but not identical test conditions (e.g. zero-pressure gradient surface pressure data covered by the Goody model), estimation of absolute TE noise levels was cross-checked by comparisons of additional NACA0012 measurement results with available NACA0012 data
- Literature review: Considerable uncertainty with regard to the measurement of farfield TE noise and its related source quantities prevails even for very simple generic test configurations
- Need of benchmarks for TE noise measurement (with major focus on the necessary frequency response corrections and facility-related effects) to provide the necessary data quality for CAA validation

Outlook

- Conduct RANS/CAA based predictions (PIANO-RPM) for the presented plate model experiment
  - respective RANS/CAA based predictions for a NACA0012, (published in Ewert et al., AIAA 2009-3269) were promising



Outlook

- Conduct RANS/CAA based predictions (PIANO-RPM) for the presented plate model experiment
  - respective RANS/CAA based predictions for a NACA0012, (published in Ewert et al., AIAA 2009-3269) were promising
- Detailed comparison of directional microphone data with corresponding microphone array data
  - NACA0012 data available, but not yet analysed
- Numerical simulation of the mirror system transfer function (including shear-layer effects)
- Still open questions: determination of the various empirical coefficients in existing surface pressure models, estimation of $V(\xi_{x1},\varpi)$ based on mean TBL velocity profiles

- See you in June 10-11, 2010 at the “Workshop on Benchmark Problems for Airframe Noise Computations-I”?

Thank you for your attention!

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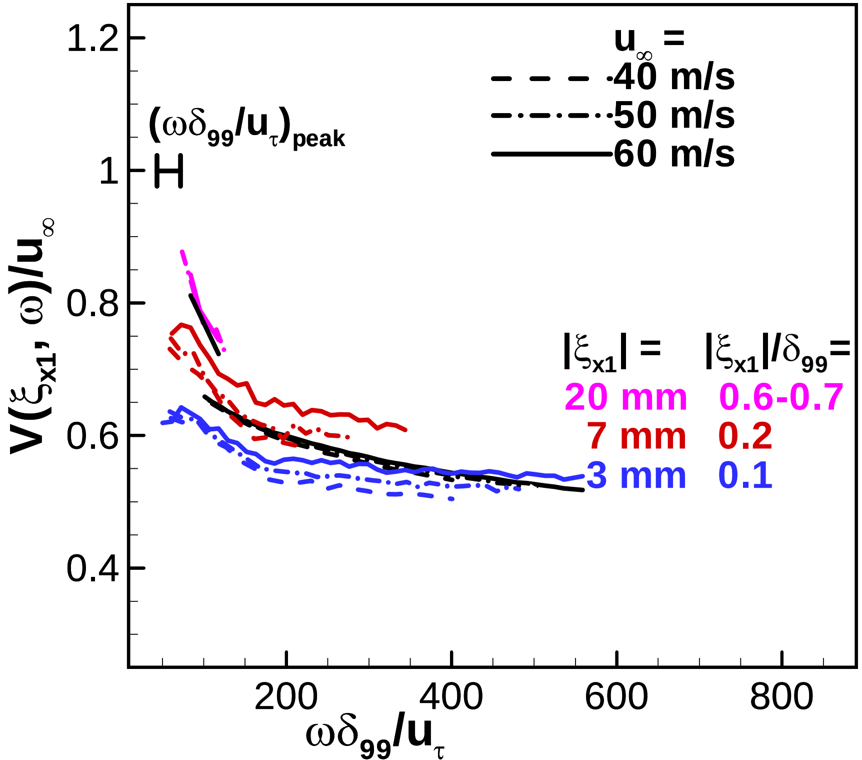
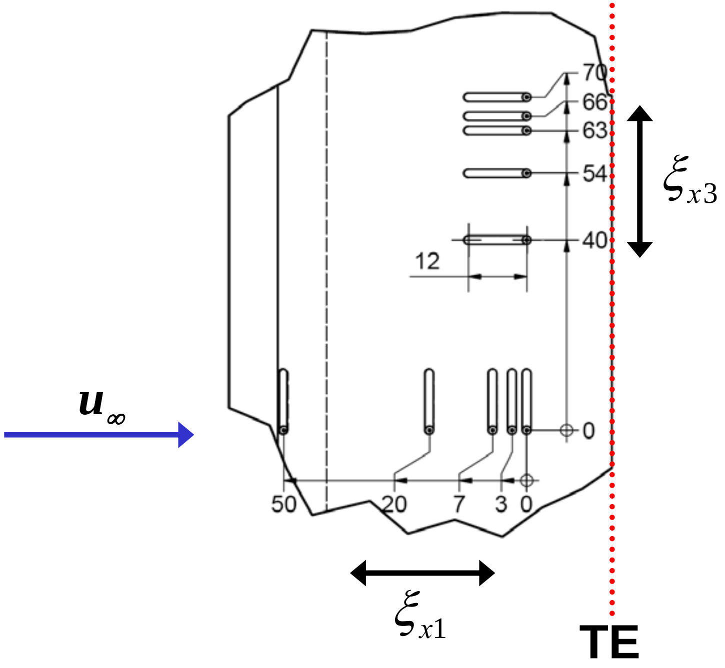
Appendix

Currently restricted to 2-m-plate only!

Part II – Convection velocity

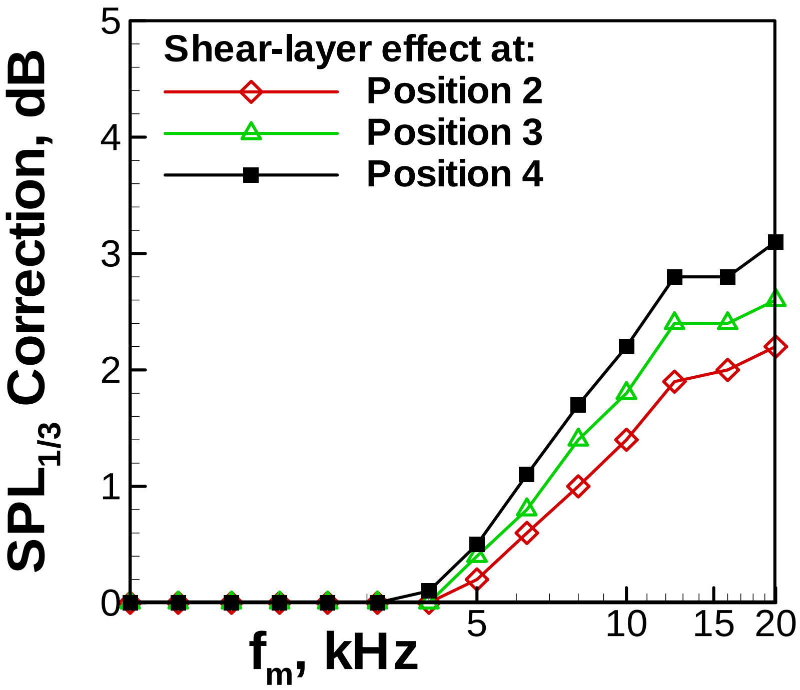
$$\psi_{ij}(\xi_{x1},\varpi) = \omega\xi_{x1}/V(\xi_{x1},\varpi) = k_v\xi_{x1} \qquad k_v = \varpi/V(\xi_{x1},\varpi)$$

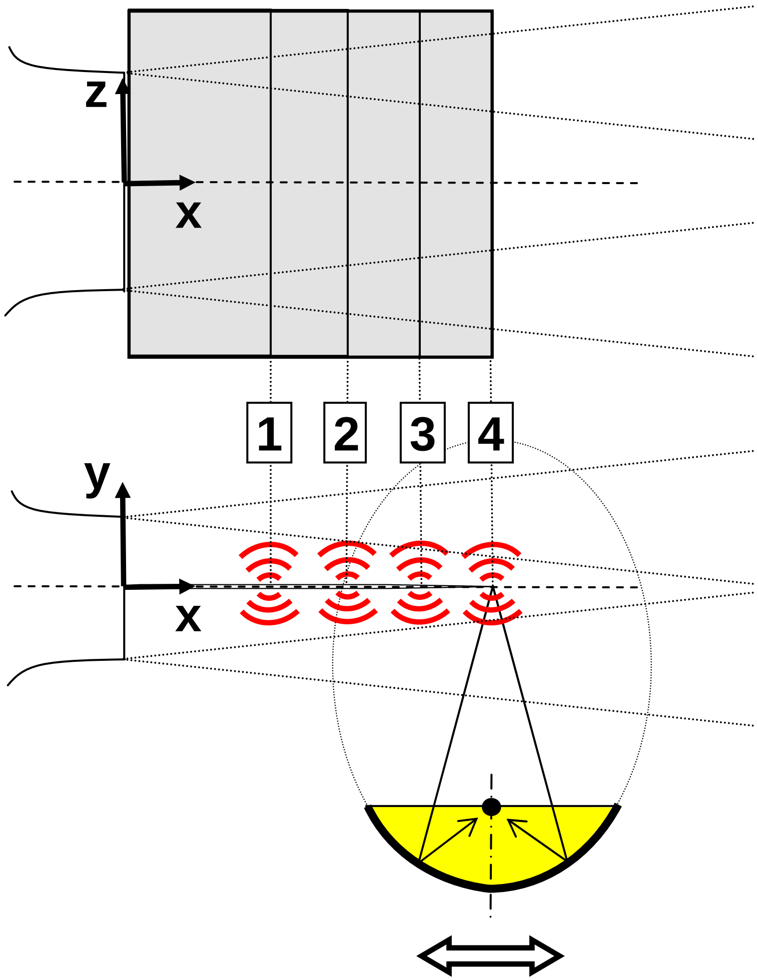




Part III – Elliptic Mirror Setup

- Shear-layer correction from comparative measurements at different x-positions, re Position 1





Part III – Elliptic Mirror Setup

- Measured “point source” frequency response function (Dobrzynski et al.,1998)