Array measurements in wind tunnels with open test sections

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Outline

- motivation
- experimental setup
- investigations: sound propagation through shear layers:
  a) frequency broadening
  b) phase fluctuations
  c) velocity of turbulent structures
  d) generic model
- summary

1. Motivation

The microphone – array – technique in the aero acoustics:

measurements in open - jet wind - tunnels

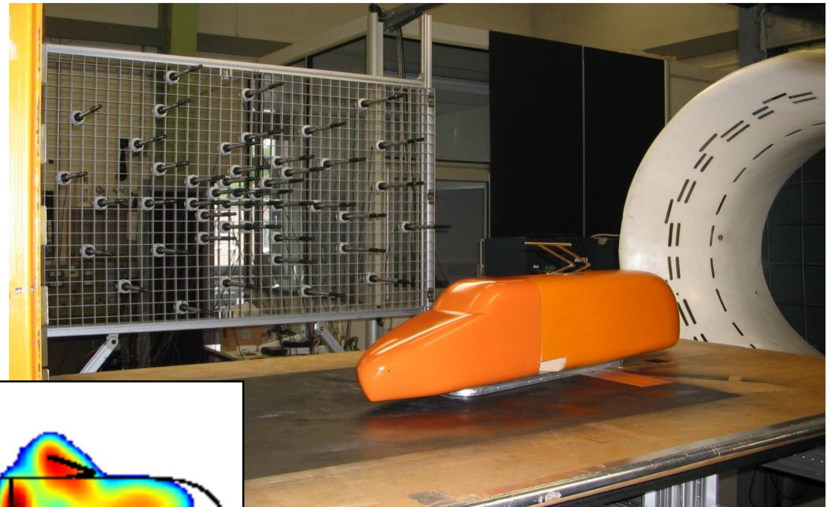
- sound source inside the flow, microphone array outside the flow: sound has to propagate through the wind - tunnel shear - layer

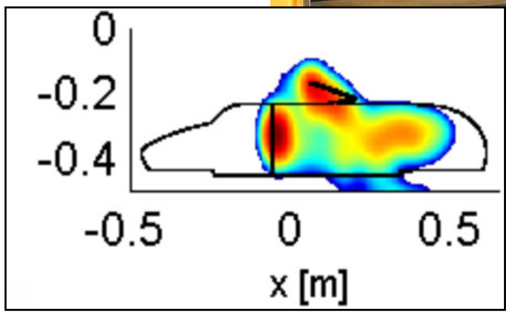
steady interactions:

- refraction in a inhomogeneous mean flow field

unsteady interactions:

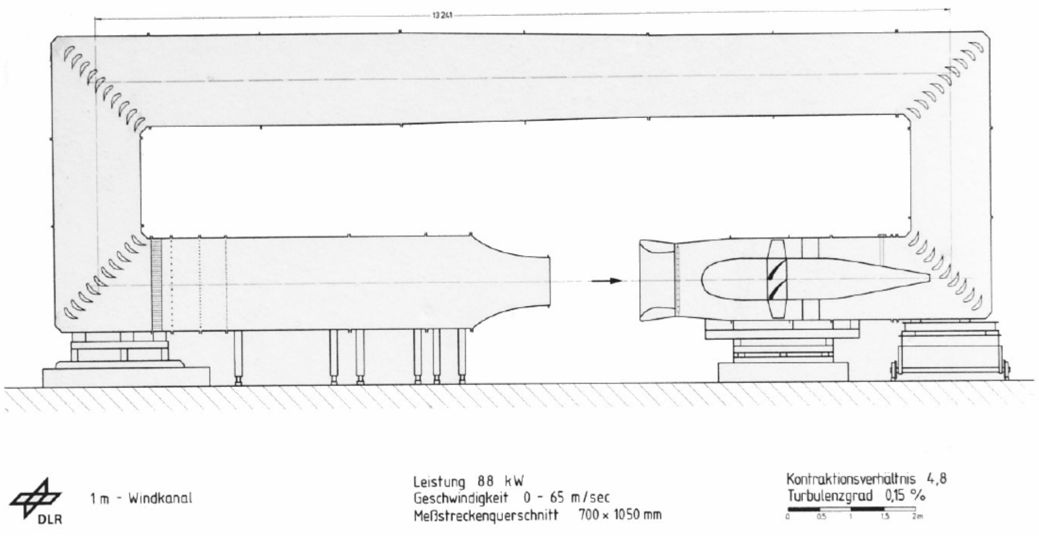
- frequency broadening
- phase fluctuations

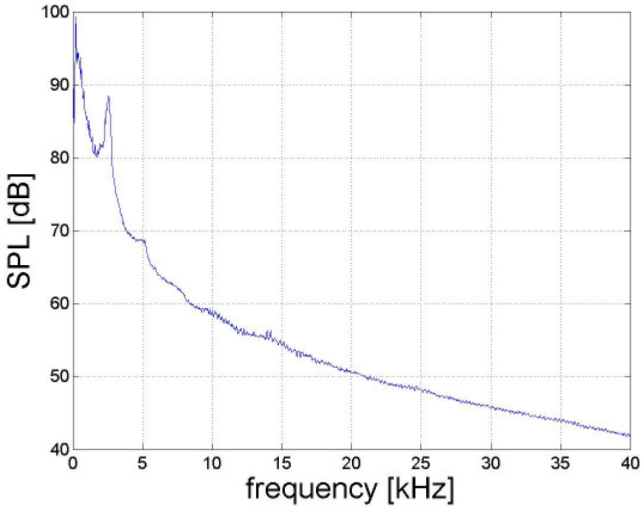




2. Experimental setup

1M wind tunnel, DLR Göttingen (‘1MG’)

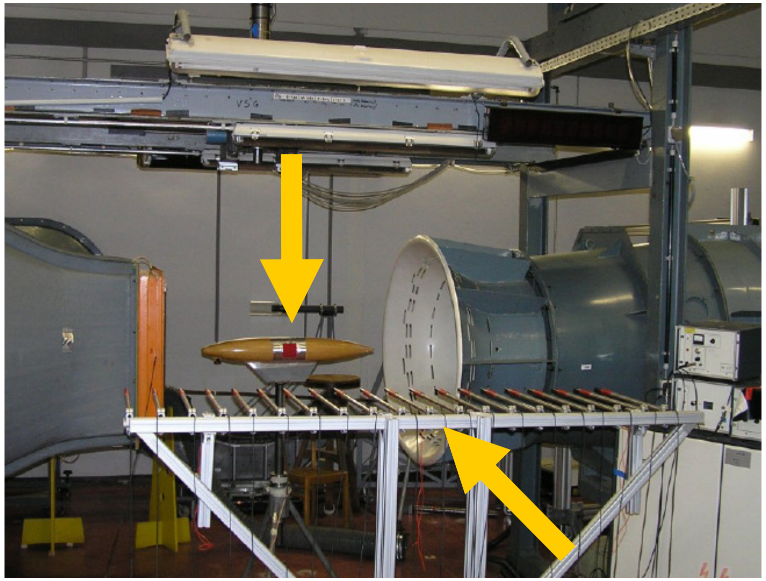


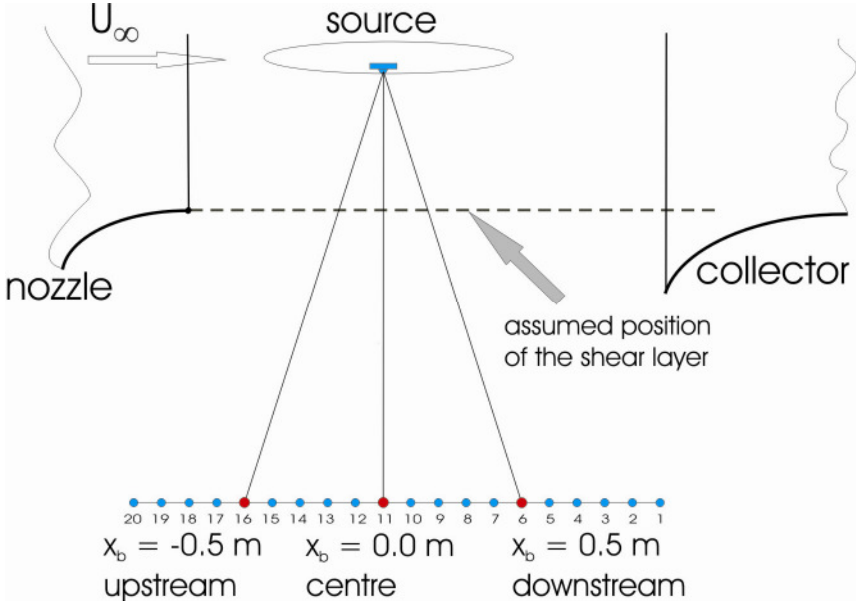


- U_∞ = 0 - 65 m/s, closed circuit, open test section
- noise, especially at lower frequencies, **not** acoustically optimized

2. Experimental setup

Sound source and microphone line – array in the 1MG



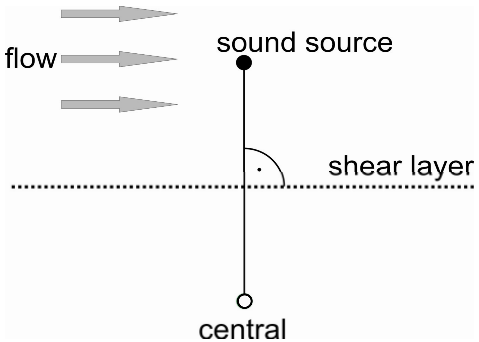


- foreground: line – array
- inside the test section: sound source, standard hi-fi tweeter, supplied with sine and/or white noise

- the red marked microphones are considered for the first investigations

3. Frequency broadening

Influence of the wind tunnel shear layer on a tone

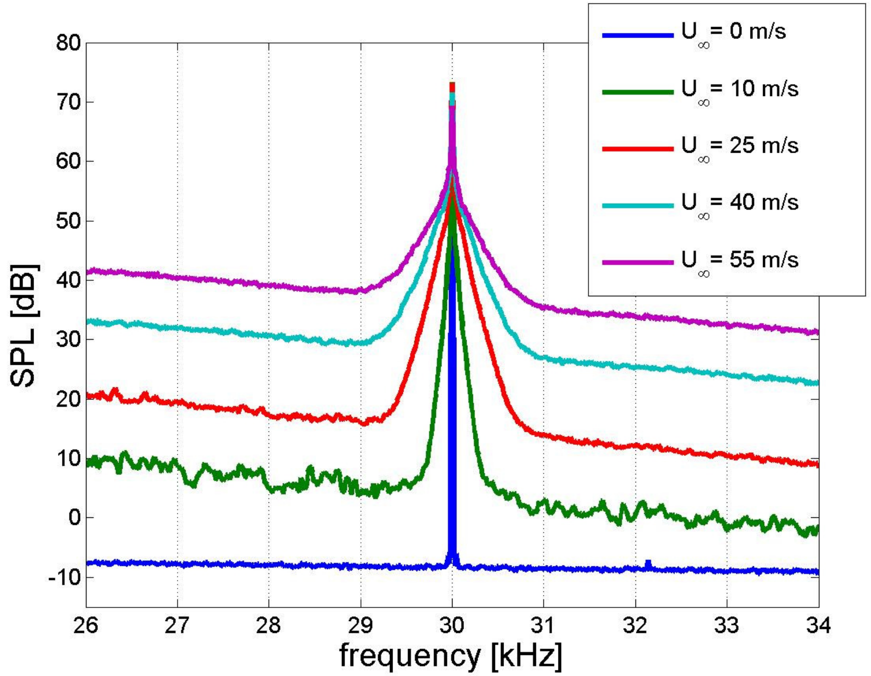


- sound source: f_{test} = 30 kHz
- microphone, central located:

  sound propagates perpendicularly
- different flow velocities U_∞

result:

- symmetric peak broadening
- SPL of the peak decreases with velocity
- (as expected, higher ambient noise level)



3. Frequency broadening

Influence of the wind tunnel shear layer on a tone

explanation:

- interaction with structures → act as sources
- due to turbulence irregularly moving sources
- irregularly fluctuating Doppler shift: Doppler broadening: well known!

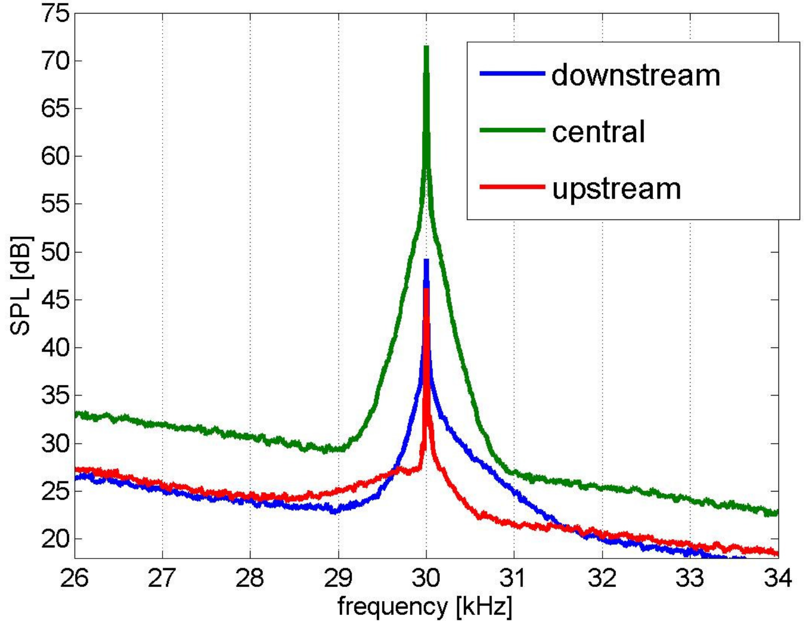
(see Ross 1981, AIAA 80-0984R)

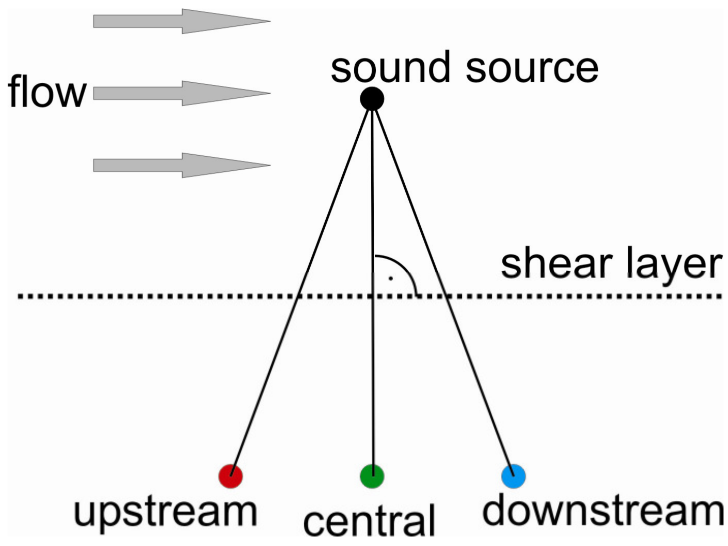
3. Frequency broadening

Influence of the wind tunnel shear layer on a tone

three different positions of the observer: $U_\infty = 40$ m/s:

- asymmetric broadening for non - perpendicularly propagation
- observer upstream (-): peak skewed to lower frequencies
- observer downstream (-): skewed to higher frequencies





3. Frequency broadening

Influence of the wind tunnel shear layer on a tone

asymmetric broadening:

- irregular movement (symmetric broadening) superimposed with:
  - component toward the observer (microphone downstream)
  - component away from the observer (microphone upstream)

assumption:

- structures inside the shear layer which influence sound propagation
- <u>these structures move downstream</u>

→ motivation for the next investigations: learn more about these structures: consideration of the phase

4. Phase fluctuations

of a wave which propagates through a shear layer

- phase fluctuations between source signal and observer signal:
  - due to acceleration or deceleration of the wave by the shear layer
- decreases correlations between array microphone signals:

  → SNR of beamformer output is reduced

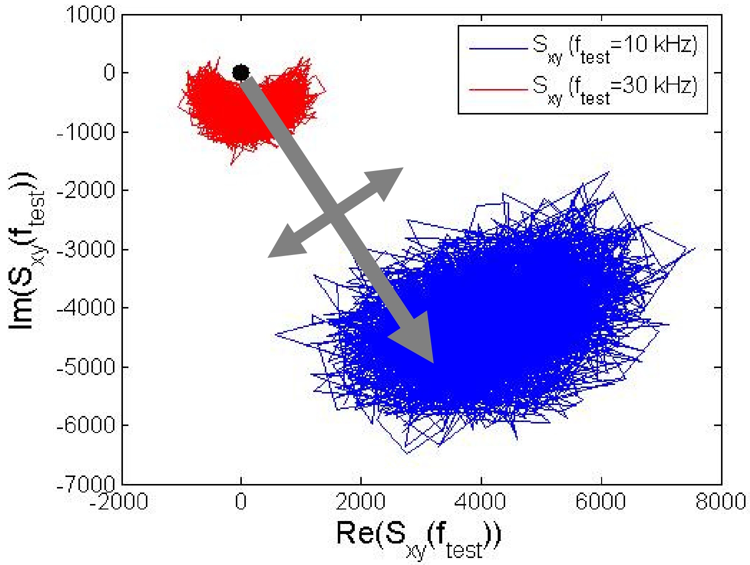
experimental setup:

- standard setup
- tone with f_{test} = 15 or 30 kHz, emitted by source inside the flow
- recorded signals:
  - central microphone
  - electrical signal from the signal generator, simultaneously
- flow velocities: U_∞ = 10, 25, 40 and 55 m/s

4. Phase fluctuations

of a wave which propagates through a shear layer: calculation

computing $\phi'(t)$:



<u>step 1</u>:

- spectral cross density between microphone signal and electrical signal from the signal generator

$$S_{xy}(f) = F\{y(t)\} \cdot [F\{x(t)\}]^*.$$

- window-wise, narrow windows
- considering a single Fourier coefficient that corresponds to f_{test}: time series

→ phase and amplitude fluctuate

parameters:

- f_{test} = 10 kHz and f_{test} = 30 kHz, signal of the source
- windows: 50% overlap, Hanning – weighted, size: 1024 samples
- Mean over time interval: 10ms @ f_s=102.4 kHz,

→artificial sampling frequency $f_{sampling,Fourier}$ =200 Hz

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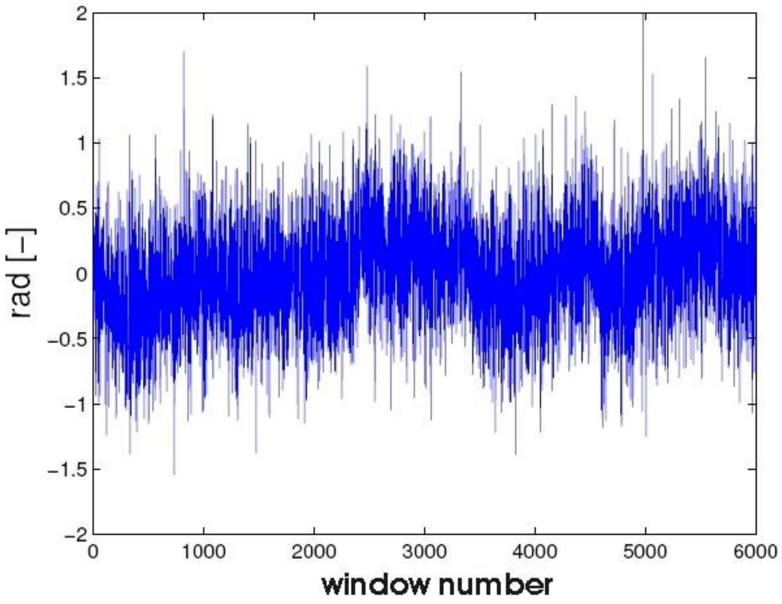
4. Phase fluctuations

of a wave which propagates through a shear layer: calculation

step 2: using expression $\phi = \arctan\left(\frac{\mathrm{Re}\left(S_{xy}\left(f_{test}\right)\right)}{\mathrm{Im}\left(S_{xy}\left(f_{test}\right)\right)}\right)$ one obtains the phase

step 3: only the fluctuations are interesting : $\phi' = \phi - \overline{\phi}$



6000 windows ≡ 30 sec measuring duration @ artificial sampling rate: $f_{sampling,Fourier}$ = 200 Hz

4. Phase fluctuations

of a wave which propagates through a shear layer: calculation

- Frequency spectra of $\phi'(t)$, from measurements with f_{test} = 15 kHz and f_{test} = 30 kHz

results:

- distinct frequency spectra
- peak is flow velocity dependent → Strouhal number:

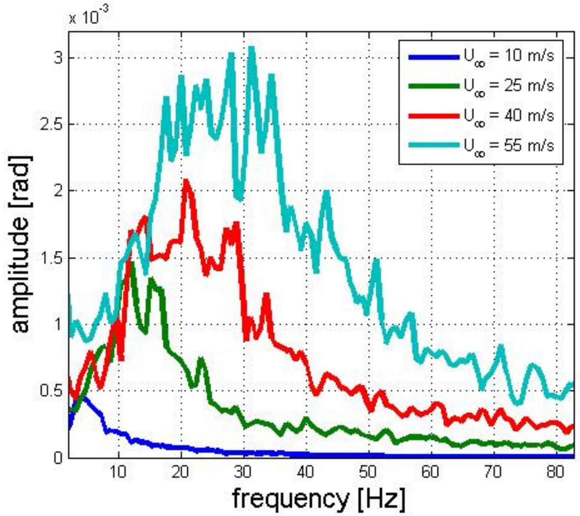
$$Sr = \frac{f\ l}{U_\infty}$$

low frequencies → large scale structures

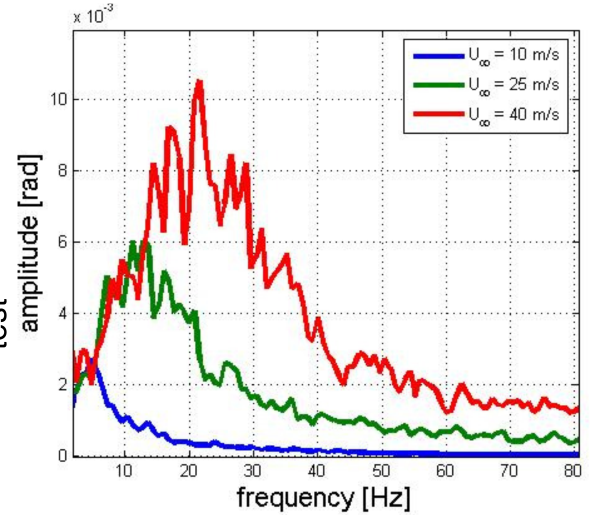
(Sr with characteristic length diameter of the nozzle)

- peak position is not influenced by f_{test}

f_{test} = 15 kHz



f_{test} = 30 kHz

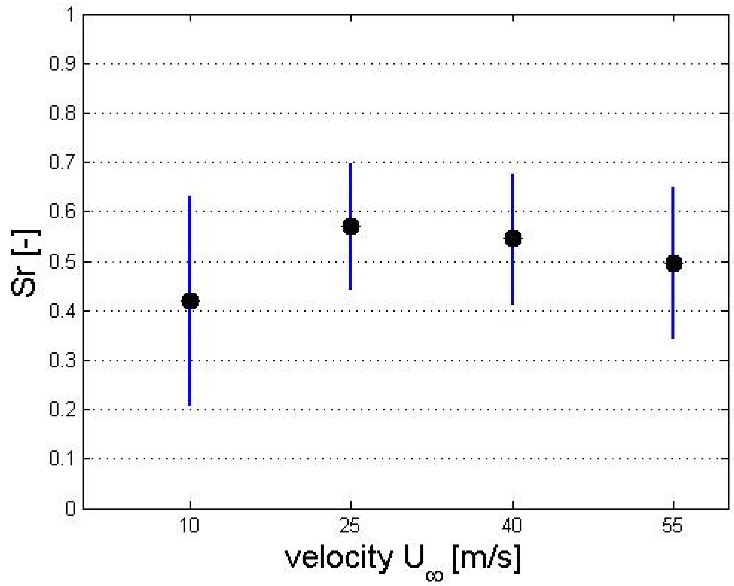


4. Phase fluctuations

of a wave which propagates through a shear layer: calculation

- Strouhal number constant around mean value $Sr \approx 0.48$

  → linear dependency between velocity and frequency

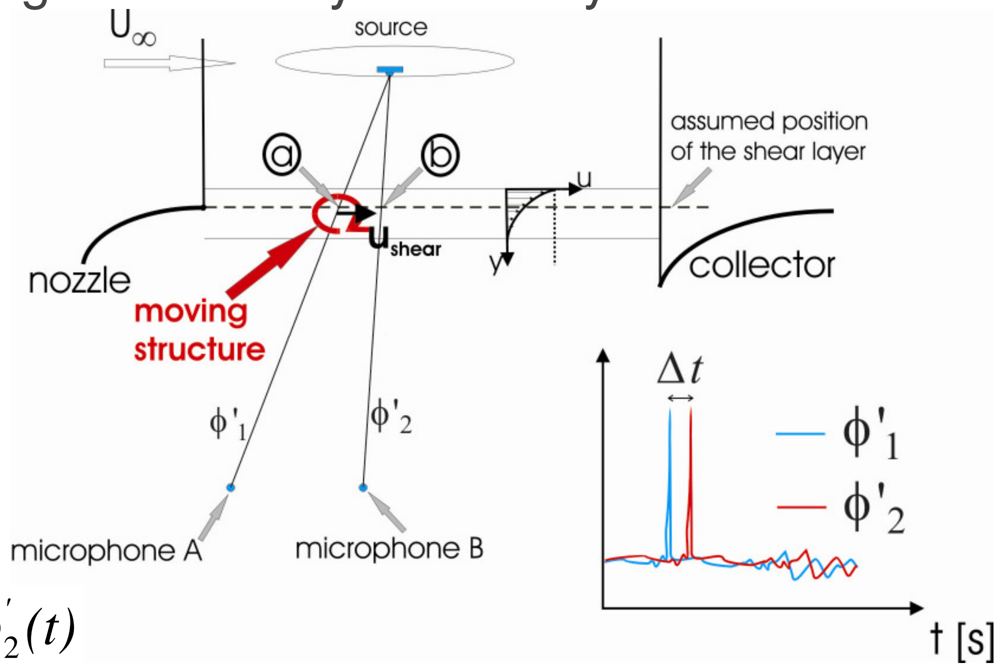


annotation concerning phase fluctuations:

- measurable = compensatable?
- 'guide star method': Ehrenfried et al. AIAA 2005-2962

4. Phase fluctuations

of a wave which propagates through a shear layer: velocity of structures



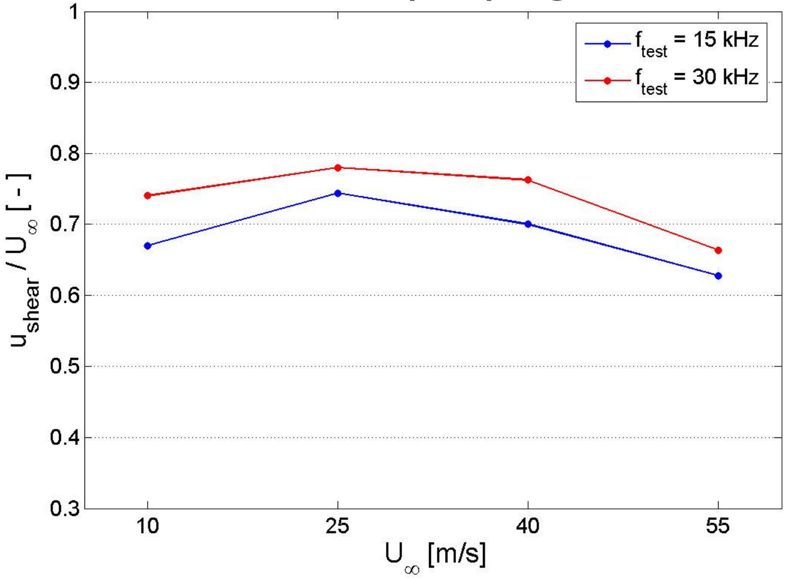
downstream moving structures:
→ asymmetric broadening

velocity measurement:

- source emits tone
- calculating time series: $\varphi_1'(t)$ and $\varphi_2'(t)$
- moving structure influences phases one after another
- cross correlation function computes time shift Δt
- one obtains the mean velocity of structures

4. Phase fluctuations

of a wave which propagates through a shear layer: velocity of structures



- ratio u_{shear} / U_∞ nearly constant
- u_{shear} between 62% and 78% of U_∞
- u_{shear} depends on f_{test}

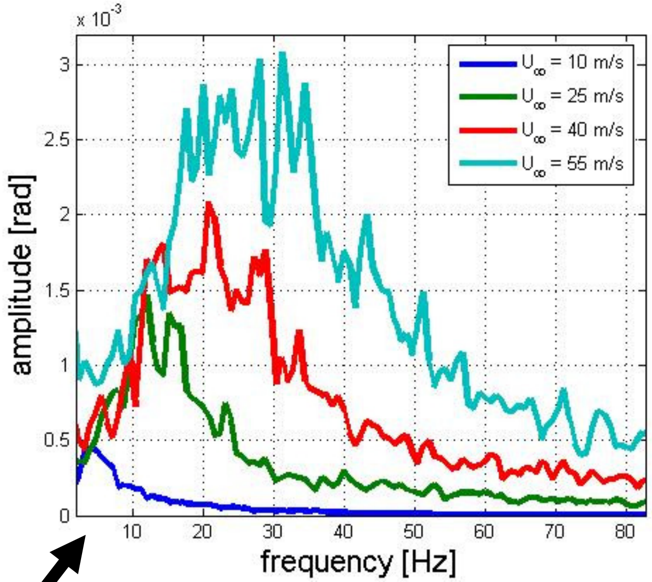
- assume: ensemble of structures with different velocities inside the shear layer
- frequency dependence:
  - strong interaction: structure size ≥ wavelength
  - weak interaction: wavelength >> structure size

→ smaller structures travel faster than larger ones

5. Model of the sound propagation

using phase modulation

$$u'(x_s, f, t) = \hat{u}_r \cdot \exp\left[i \left(2\pi f t + \varepsilon \cdot \cos\left(2\pi \tilde{f} t - \frac{2\pi \tilde{f}}{u_{shear}} x \right) \right) \right]$$



basic ideas:

- monopole source
- infinitesimal thin shear layer
- no flow
- shear layer induces phase modulation:

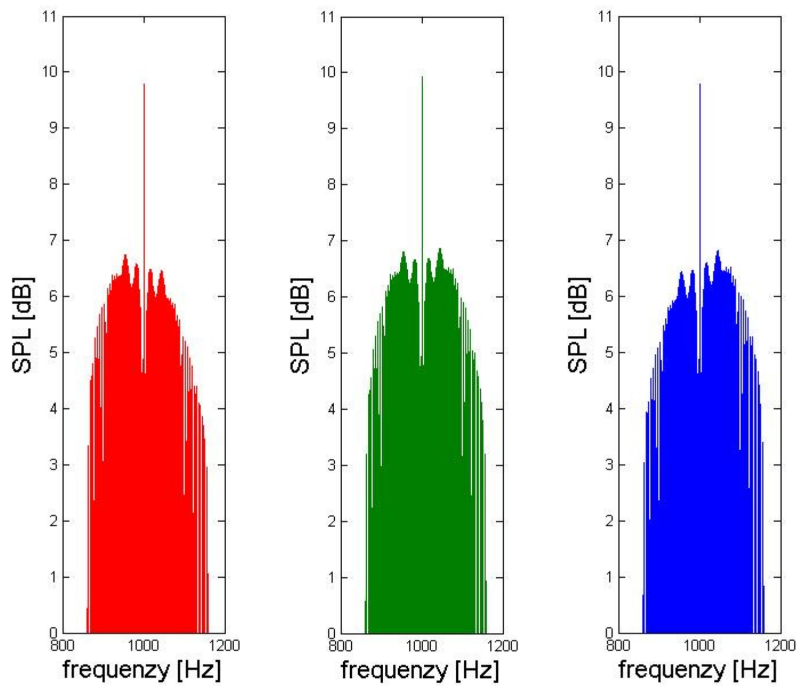
  frequency of modulation $\tilde{f}$ = frequency distribution of $\phi'(t)$
- u_{shear} = downstream velocity of phase disturbance
- using Kirchhoff – Helmholtz – integral to compute sound field in front the shear layer

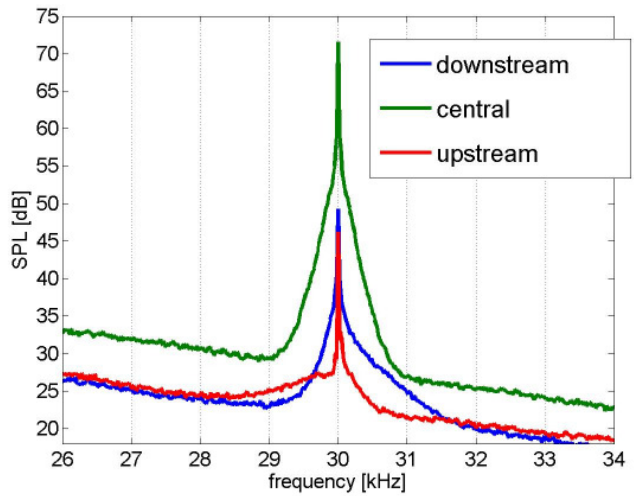
5. Model of the sound propagation

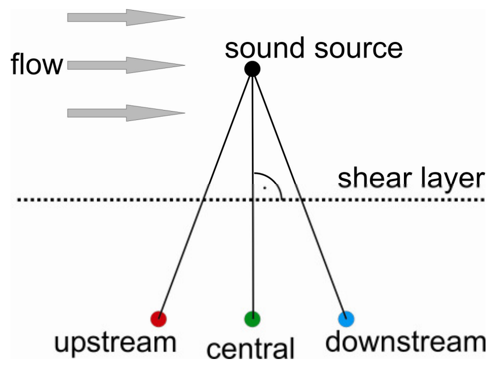
using phase modulation

test case with f_{test} = 1000Hz:

- simple model able to predict tendencies of symmetric and asymmetric broadening







6. Summary

- questions concerning array measurements in open jet wind tunnels
- an experimental setup (line array and sound source) was developed which allows investigations concerning sound propagation through a shear layer
- broadening: dependence on flow velocity and especially position of the observer: important for narrow – band analysis
- assumption of structures that influence phase, moving downstream
- computing spectra of these phase fluctuations: maxima are velocity dependent: found a Strouhal number of $Sr = 0.48$
- estimation of the velocity of these structures in the shear layer: between 62% and 78% of U_∞
- finally, development of an simple model that is able to reproduce tendencies of the symmetric and asymmetric broadening

Thank you for your attention!