On the dominating influence of the large-scale motion in a jet on its pressure near field and the acoustic far field

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Fifth International Workshop

"Computational Experiment in Aeroacoustics"

September 18-22, 2018

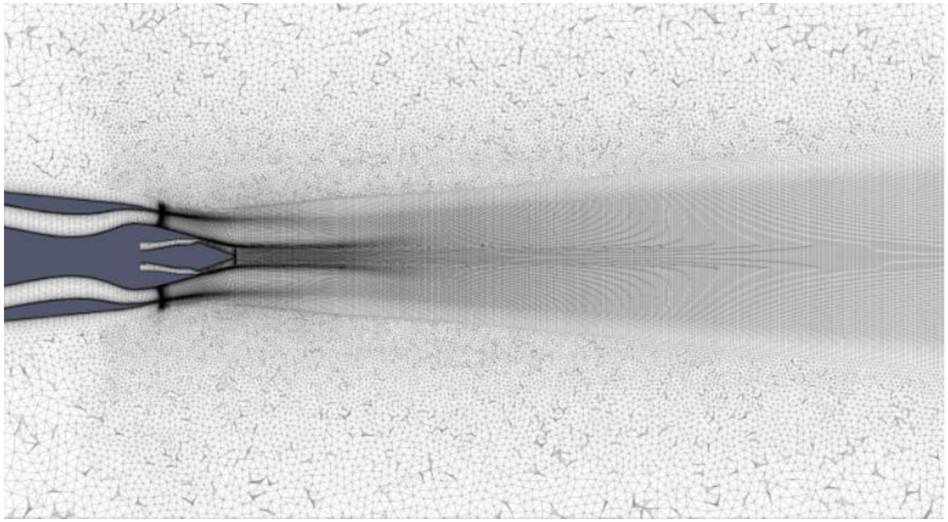
Svetlogorsk, Russia

CFD Software E+F GmbH

Noise sources in a dual-stream jet

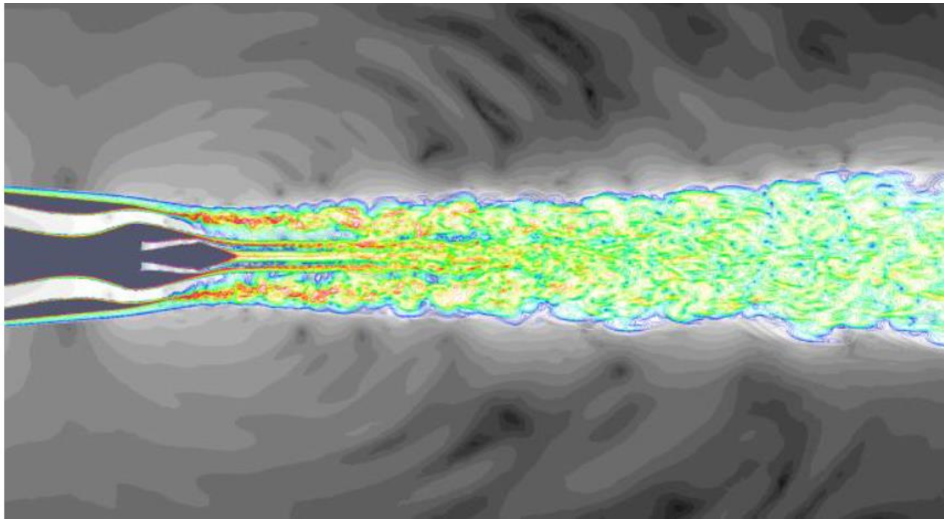
Computational experiment

First results already reported at CEAA 2016



Hybrid structured/unstructured mesh
25.6 million cells

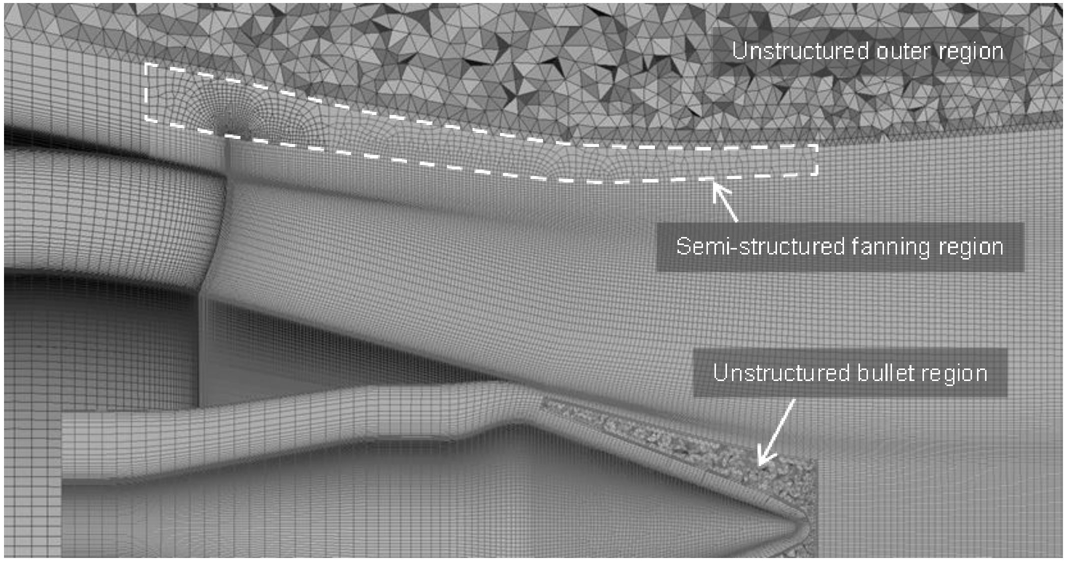
Mockett et al. (2016)



Vorticity (colour)
Vorticity border (blue)
time derivative of pressure (grey)

Grid

- Hybrid structured-unstructured grid. Structured meshing inside the jet plume coupled with unstructured meshing elsewhere. (Objective: to simplify gridding of 3D wing to be added later)
- Hybrid RANS-LES (DES) with recent developments concerning treatment of grey area problem (σ-DDES+$\widetilde{\Delta}_{\omega}$, Mockett et al 2016).
- The grid consists of around 26.5 million cells, with 160 cells applied in the azimuthal direction



Detail of grid in vicinity of nozzle (Mockett et al. 2016)

Grid software ANSA (Beta CAE)

Simulation of flow in a dual-stream jet

- Simulation performed with a time step corresponding to a sampling Strouhal number $f_s D_e / U_e$ = 1035.
  D_e is area-equivalent single-stream nozzle,
  U_e is mass-flow equivalent single-stream velocity
- All flow quantities relevant for sound sources (velocity, pressure, density) stored every 32nd time step for later source analysis. Maximum Strouhal number of analysis = 16.
- 6000 time steps stored (4 TByte data)
- Equivalent to 186 convective time units, 186 $\mathrm{D_e/U_e}$ = 0.144 s
  (1/10$^{\text{th}}$ model scale, equivalent to 1.4 seconds full scale)
- Pressure fluctuations analysed in the following

Pressure fluctuations and source of jet noise

- Convective Lighthill equation accounts for flight stream U_i

$$\frac{1}{a_0^2}\left(\frac{\partial}{\partial t}+U_i\frac{\partial}{\partial x_i}\right)^2 p-\frac{\partial^2 p}{\partial x_i^2}=q$$

q is source of sound

- Solution of convective Lighthill equation for an unbounded field (Michalke & Michel 1979)

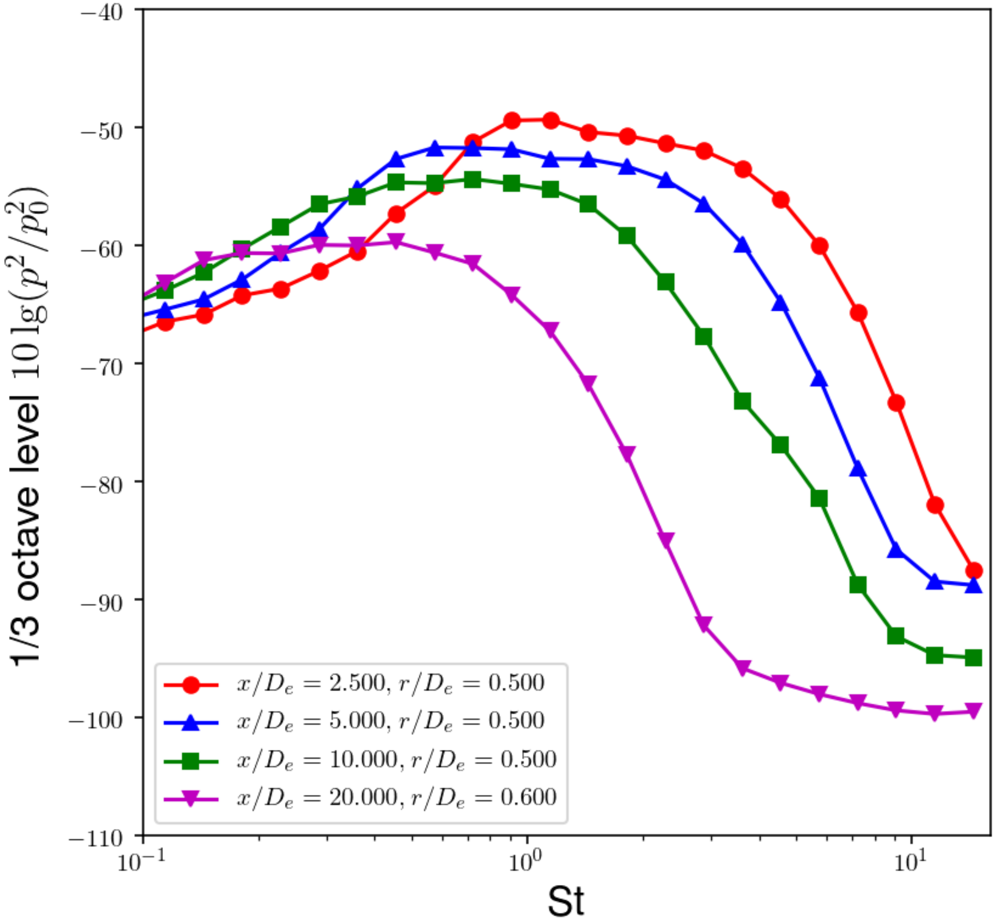
$$p'(x_i,t)=\frac{1}{4\pi}\int\limits_V \frac{q(x_i,y_i,t_r)}{r_e D_f}\mathrm{d}V(y_i)$$

$1/(r_e\, D_f)$ is free-space Green function of convective wave equation,
Wave-normal distance r_e ,
Doppler factor $D_f = 1 - M_f \cos\theta_e$
Flight Mach number M_f ,

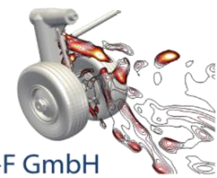
- **Valid everywhere, including the source region**
- Integral finite even for x_i inside source region y_i, wave-normal distance $r_e \to 0$
- x_i in source region: $p'(y_i)$ describes influence of q in vicinity of source position y_i.
- p' may be used to describe source quantity q as long as x_i is in source region

One-third octave spectra for various x/D_e

- Pressures inside jet normalized with the ambient pressure p_0.

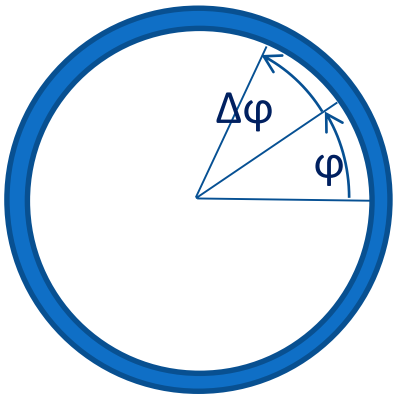


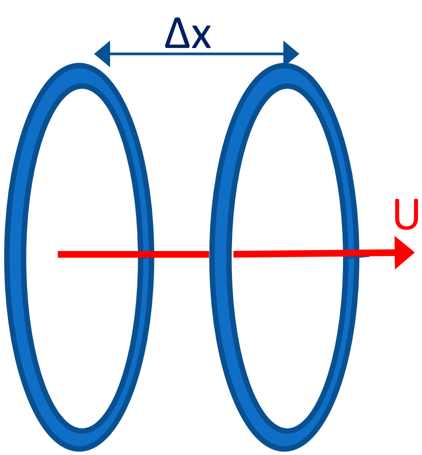
- Position with steepest radial mean velocity gradient chosen
- Pressure fluctuations are largest there
- Peak frequencies get smaller with increasing axial distance from the nozzle.
- Spectral peak level extends over rather wide frequency range of several octaves



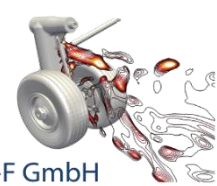
Identification of large scale structures

- Large structures can be studied with two-point cross-spectra

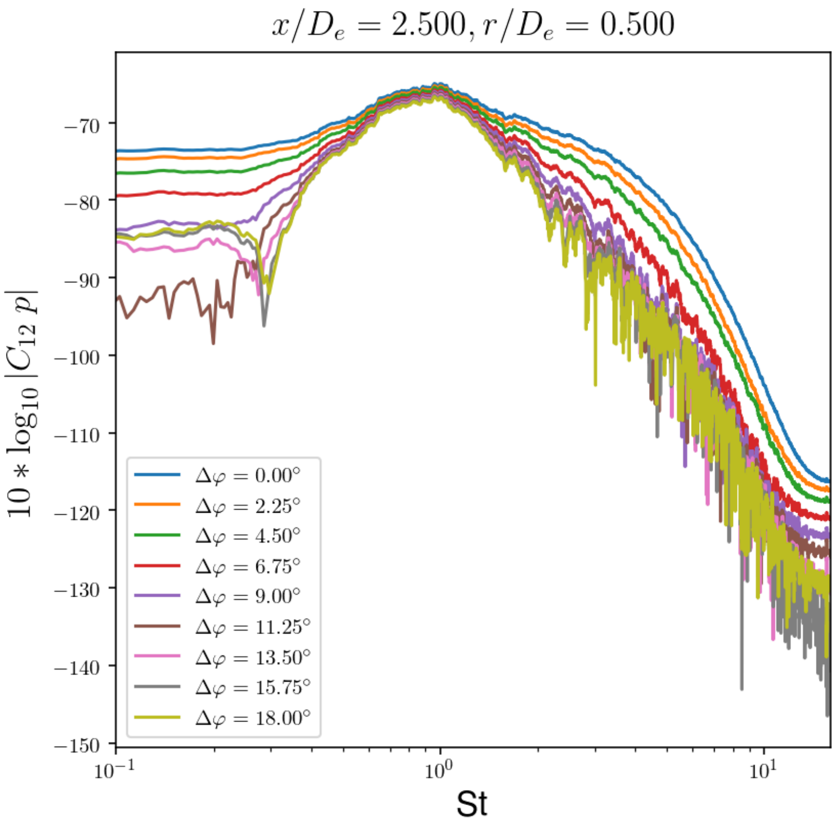


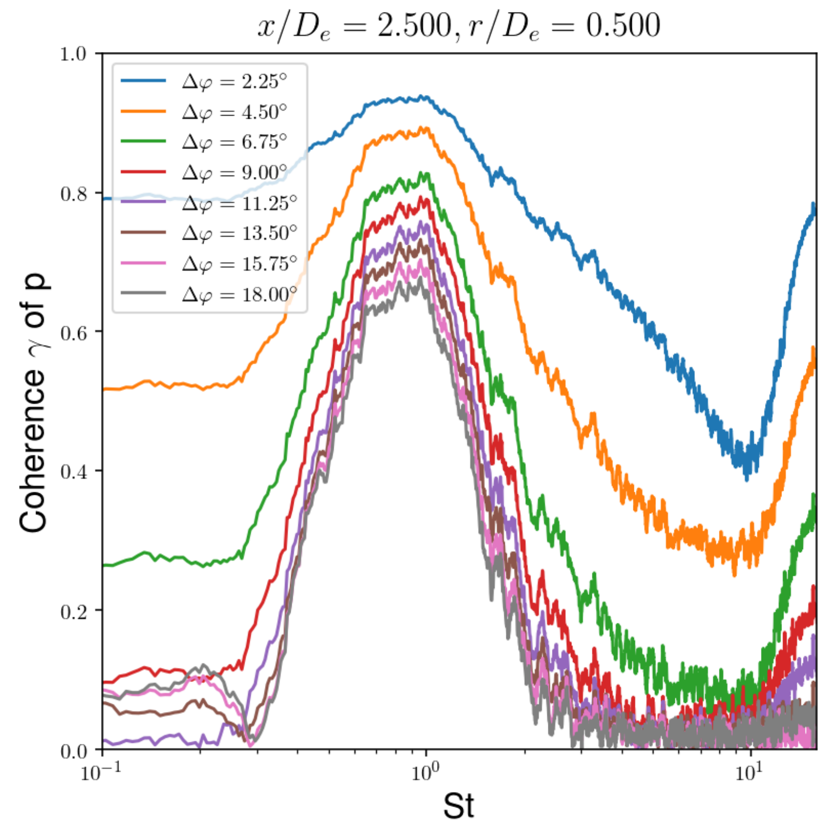


- Statistical stability limited by short time series of simulation
- Increase of statistical stability by exploiting symmetry conditions
- Mean flow axisymmetric, only function of radius r
- Turbulent flow of axisymmetric unexcited jet is stationary random
- Power spectrum independent of azimuthal position φ
- Cross spectra between two rings function of |Δφ| and Δx
- Cross spectra periodic in 2 π, can be decomposed into Fourier series
- Statistical stability increased by
  - Considering that mean squares are independent of azimuthal angle,
  - cross-spectra depend on |Δφ| only
  - Using rather large frequency bandwidth (ΔSt=0.1) averaging over 19 (out of 3001) frequency bins

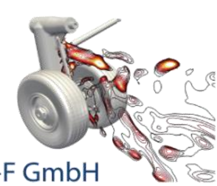


Azimuthal probe separation, x/D_e=2.5

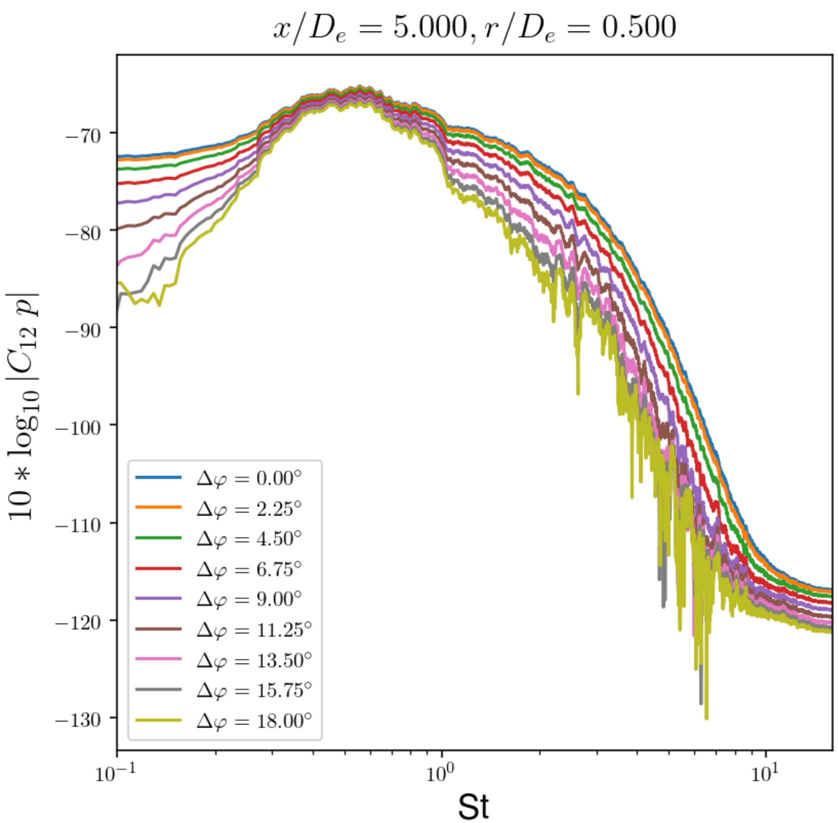


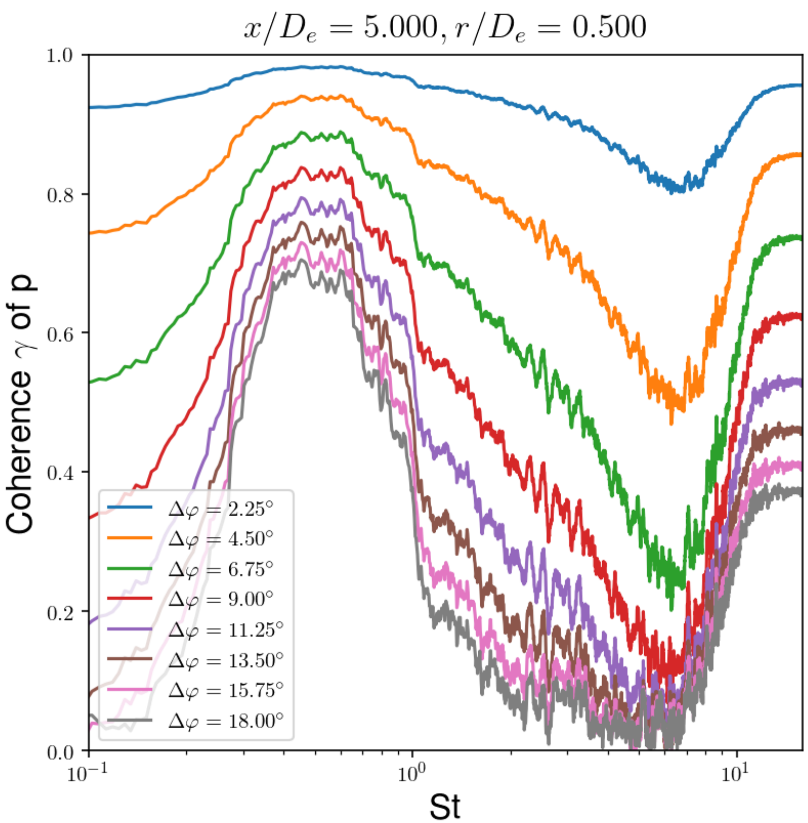


- Coherence decays rapidly with increasing Δφ for off-peak frequencies
- Radiation efficiency decays correspondingly
- Radiation dominated by a narrow frequency band around St=1.0
- Only few azimuthal Fourier components required near peak frequency

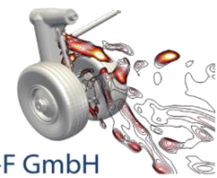


Azimuthal probe separation, x/D_e=5





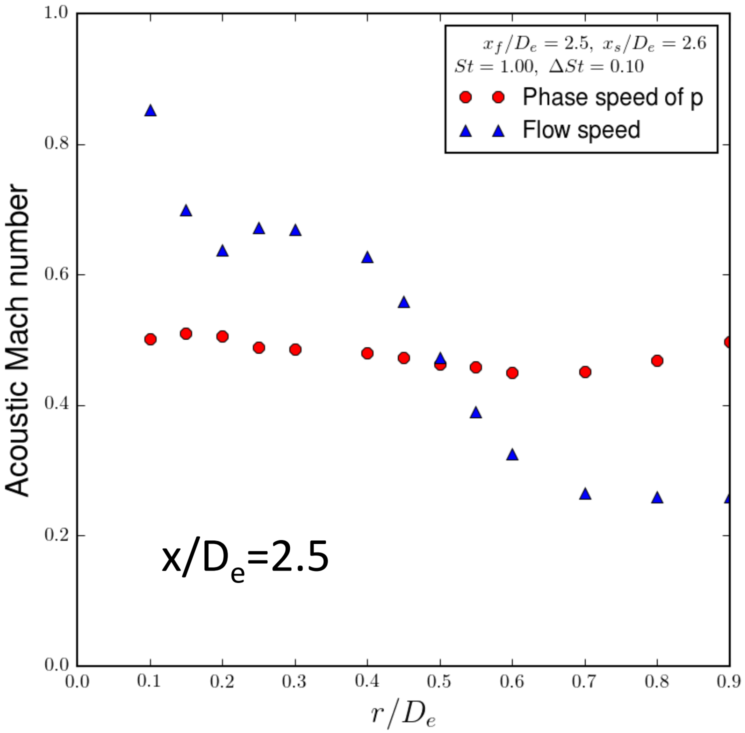
- Situation for x/D_e=5 similar to x/D_e=2.5
- Peak Strouhal number reduced to St=0.6
- Decay with increasing Δφ less steep than at x/D_e=2.5 but still strong

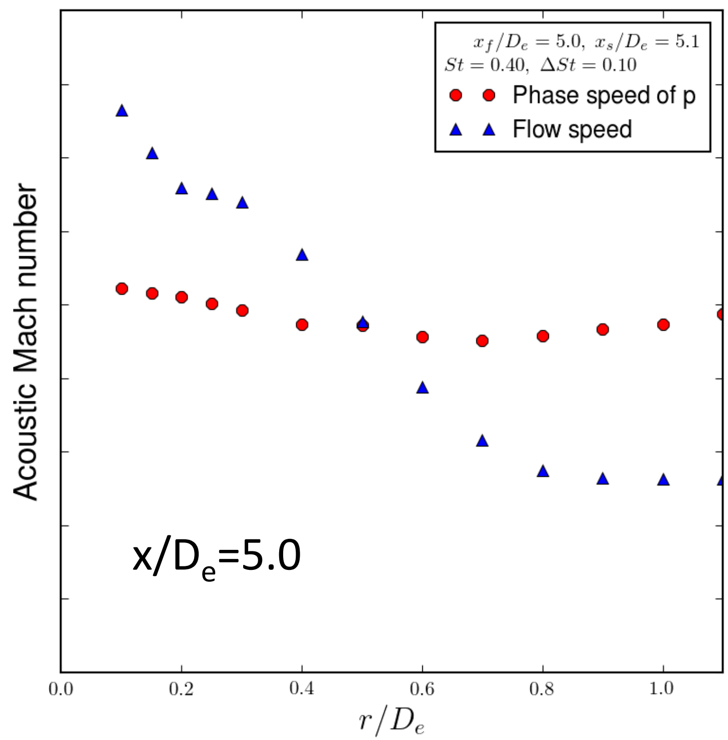


Conclusion on azimuthal decay

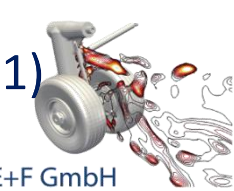
- Pressure fluctuation in source region peak for specific Strouhal number
- Only a few azimuthal components for frequencies in peak region.
  High sound radiation efficiency of these components
- Many azimuthal components for frequencies in off-peak region.
  Low radiation efficiencies of these components.
- Filtering effect of radiation efficiency:
  Contribution of each axial station to far field peaks even more than in source region

Axial phase speeds

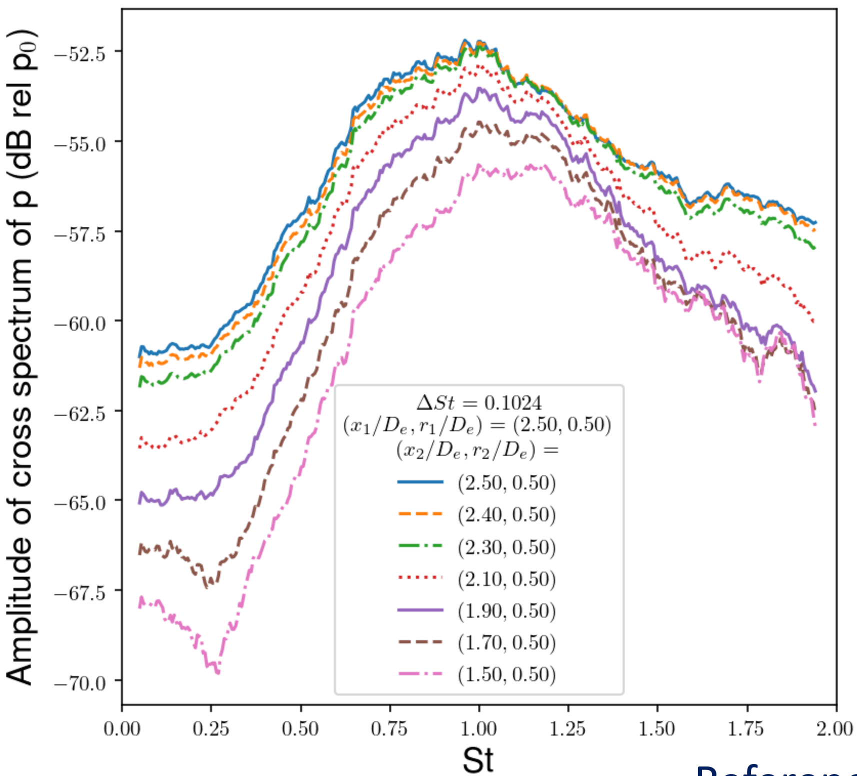


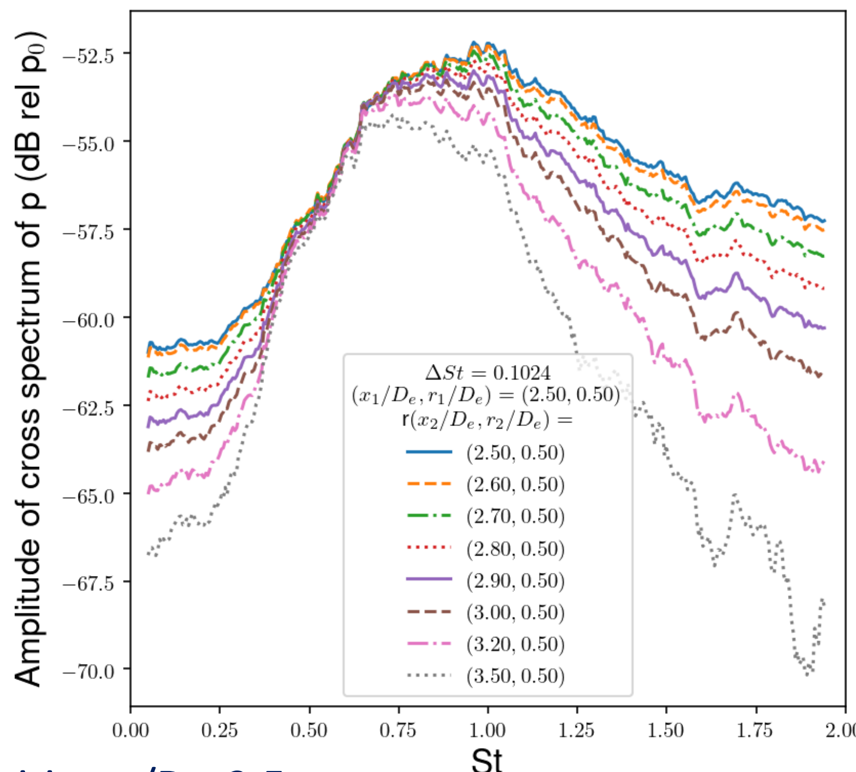


- Axial phase speed almost independent of radius
- Even in near field outside jet
- Result similar for all other axial positions
- Proof that pressure fluctuations dominated by the influence of wave-like fluctuations, related to the instability of the jet shear layer. (Michalke 1971)



Influence of axial probe separation Δx on cross-spectral density



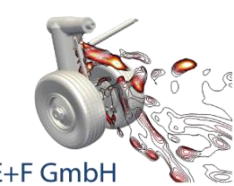


Reference position x/D_e=2.5

Second position upstream

Second position downstream

- Amplitudes of cross spectra peak in narrow frequency band like for azimuthally separated probes



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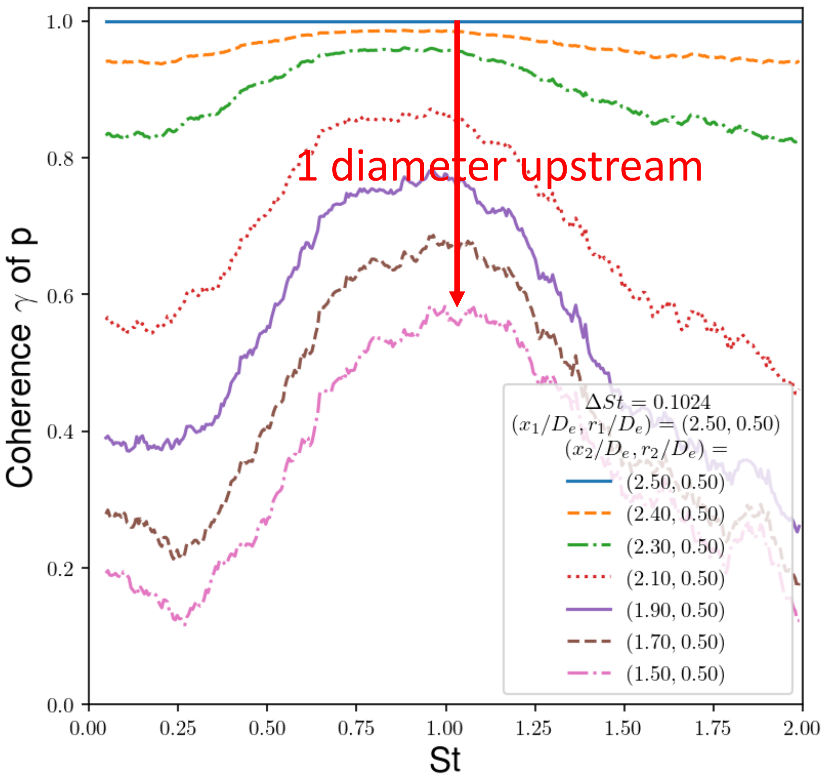
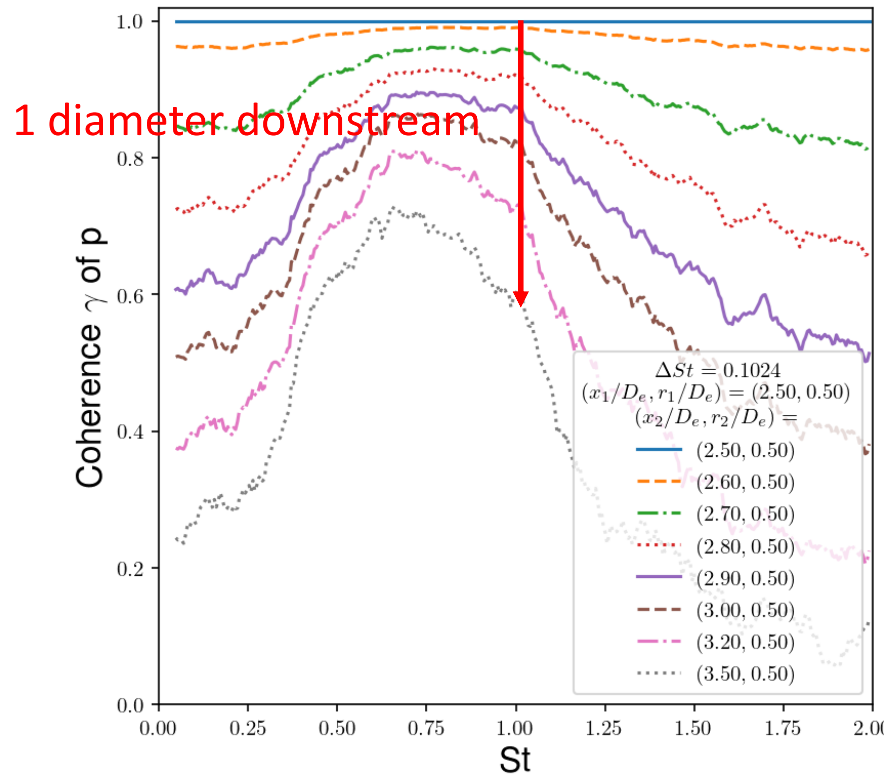
Influence of Δx on coherence, x/D_e=2.5



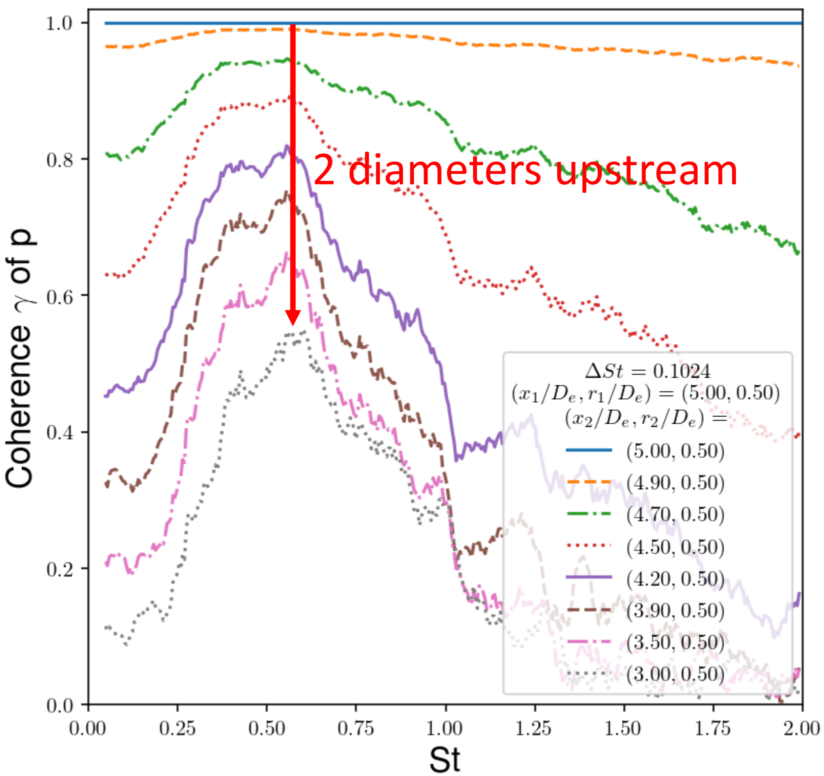
Upstream direction



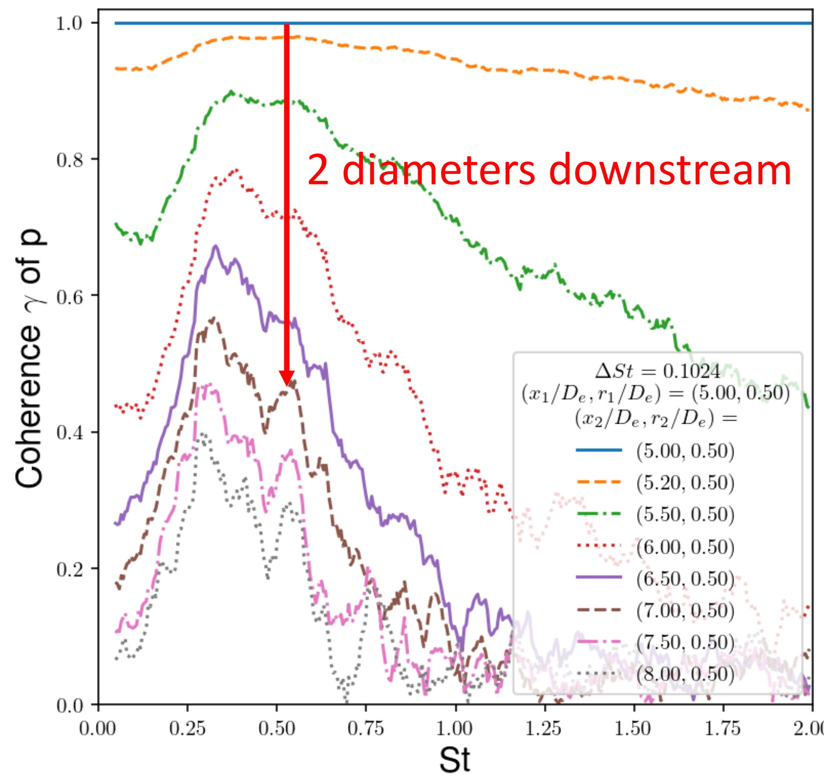
Downstream direction

- Coherence decays slowly in range of peak frequencies, which are controlled by instability waves
- Coherence decays rapidly for higher and lower frequencies
- Axial length scale very large for peak frequency, L/D ≈ 2

Influence of Δx on coherence, x/D_e=5



Upstream direction



Downstream direction

- Situation similar for x/D_e=5.0
- Length scale even larger L/D≈4
- Length scale important for source interference and rear arc amplification of jet noise (Michel 2009)

Conclusions

- Small decay of coherence for axially separated positions proof that jet noise sources are result of a wave-like motion
- Wave-like motion is caused by growth and decay of instability waves
- High frequencies caused by wave-like motion close to nozzle
- Low frequencies caused by wave-like motion further downstream
- Only a few azimuthal components contribute to the near-field radiation
- Even less azimuthal components contribute to the far-field radiation due to the decreasing radiation efficiency of higher order components (Michalke 1972)
- The noise sources are concentrated at the radial location with the steepest radial velocity gradient.
- A cylindrical jet noise source model based on instability waves is sufficient (proposed by Michel 2009)

Conclusions, ctd

Wave-like motion in jets has consequences:

- RANS simulations erroneous because it is assumed that flow quantities propagate with local flow velocity.
- A relevant part of the flow quantities propagates with phase velocity of the locally most unstable instability wave.
- Length scale of pressure waves has nothing to do with k or ε.
- Rear arc amplification is caused by source interference and not by “eddy motion” (Michel 2009)
- “Small scale stuff” in source region is ineffective radiator.
- Moving eddy model for jet noise sources (Lighthill 1954, Ffowcs-Williams 1963) is incorrect, because eddy moving with the phase speed of the disturbances would have frequency zero in a moving eddy coordinate system. (Source would move with the wave crest.)

Acknowledgement

The work was performed in the EU-funded project “JERONIMO” (ACP2-GA-2012-314692-JERONIMO).

References

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