Large Scale Motion in a Dual Stream Jet

Ulf Michel, Felix Kramer, Charles Mockett
CFD Software E+F GmbH , Berlin

Fourth International Workshop
"Computational Experiment in Aeroacoustics"
September 21-24, 2016
Svetlogorsk, Russia

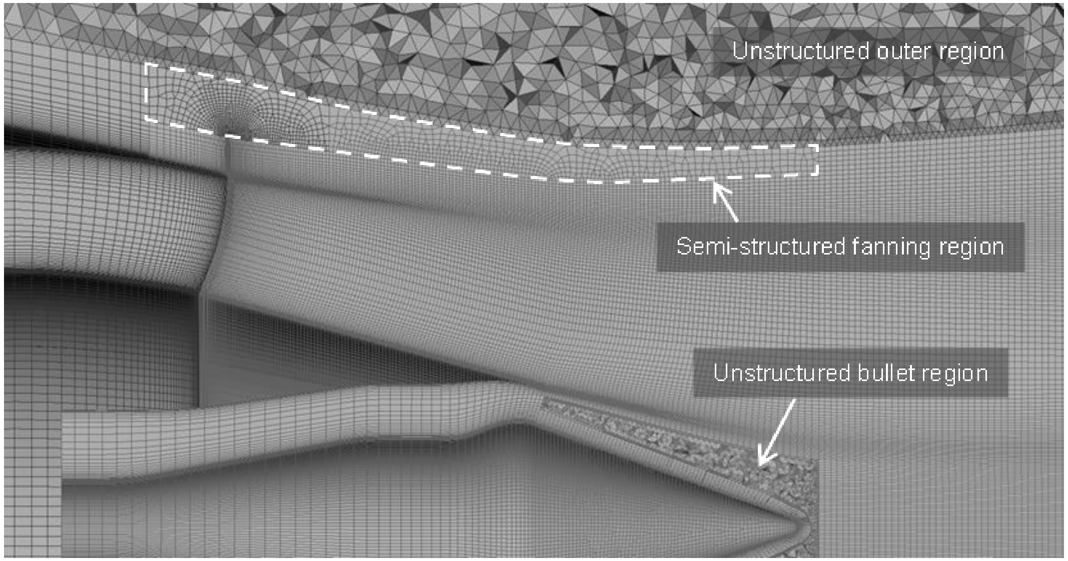
Simulation of a dual stream jet

Computational Experiment on the noise sources in a dual stream jet

- Hybrid RANS-LES (DES) with recent developments concerning treatment of grey area problem (Mockett et al 2016)
- Simulation performed with a time step corresponding to a sampling Strouhal number $f_s D_e / U_e = 1035$.
- All source-relevant flow quantities stored every 32nd time step for later source analysis. Maximum Strouhal number of analysis = 16.
- Simulation was run over 186 convective time units D_e/U_e.
- Data stored on 4 TB hard drive for later source analysis

Grid

- The grid consists of around 28.5 million cells, with 160 cells applied in the azimuthal direction
- Hybrid structured-unstructured grid. Structured meshing inside the jet plume region coupled with unstructured meshing elsewhere



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

Sources of jet noise

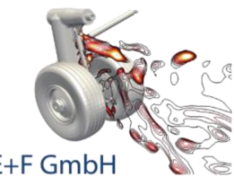
- Convective Lighthill equation to account for the flight stream

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

- Source

$$q=\frac{\partial^2}{\partial x_i \partial x_j}(\rho u_i u_j-\tau_{ij})-\left(\frac{\partial}{\partial t}+U_i\frac{\partial}{\partial x_i}\right)^2\left(\rho-\frac{p}{a_0^2}\right) \qquad u_i=v_i-U_i$$

- **Quadrupole** radiation to acoustic far field requires storage of three velocities u_i.
- **Dipole** radiation to acoustic far field requires storage of three density gradients
- Pressure stored in addition



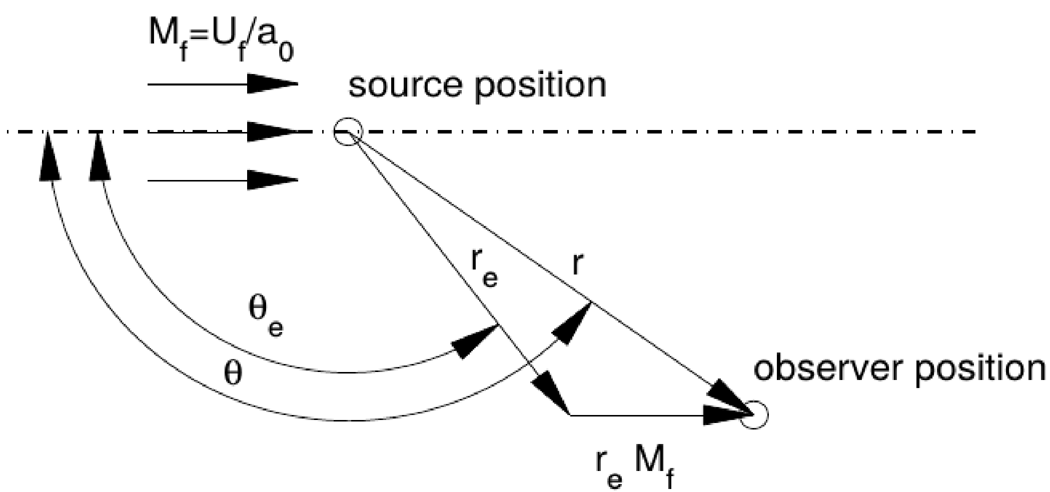
Pressure as source variable

- Solution of convective Lighthill equation for an unbounded field

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

Doppler factor
$D_f = 1 - M_f \cos\theta_e$

- **Valid everywhere, including the source region**
- Integral finite for $r_e \rightarrow 0$ ($x_i \rightarrow y_i$)
- p' describes influence of q in vicinity of source position y_i.



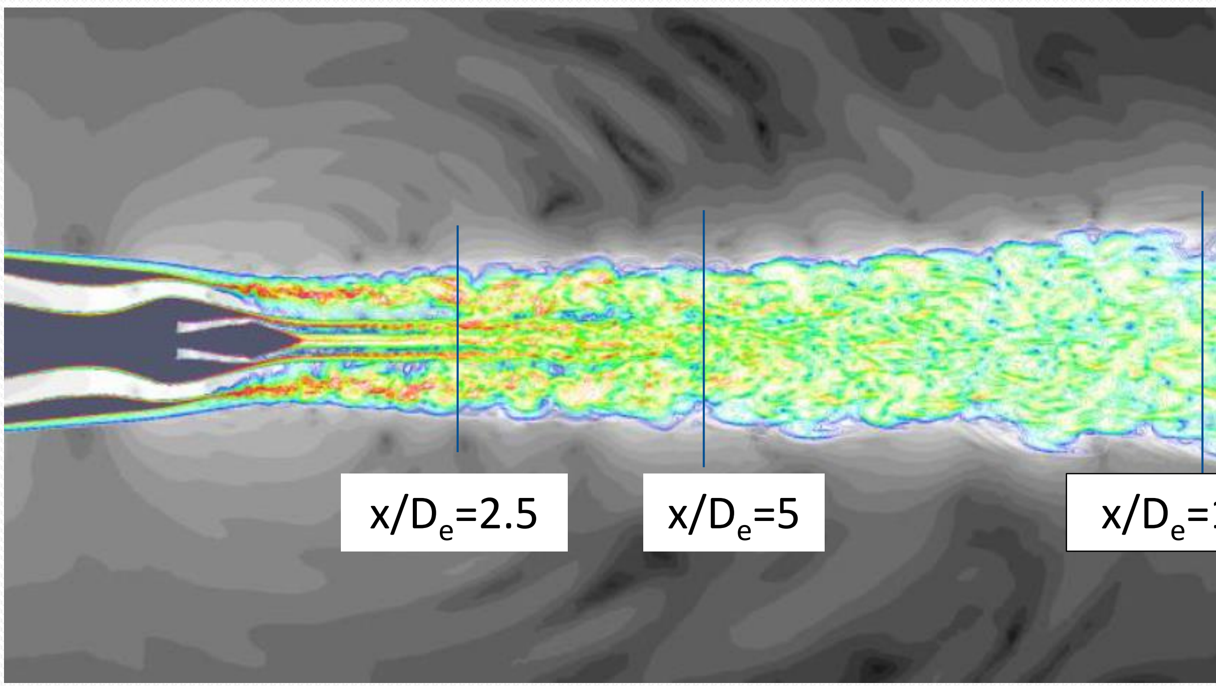
r_e is emission distance

θ_e is emission angle

CFD Software E+F GmbH

Unsteady pressure in jet

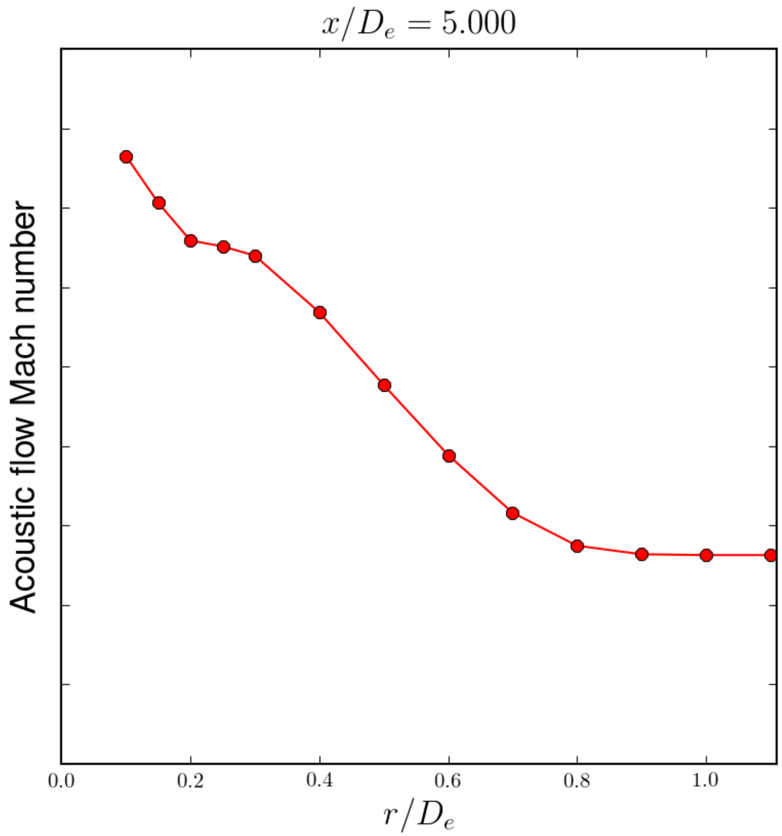
Unsteady pressure is related to sources
Pressure field studied at x/D_e = 2.5, 5, 10, 20

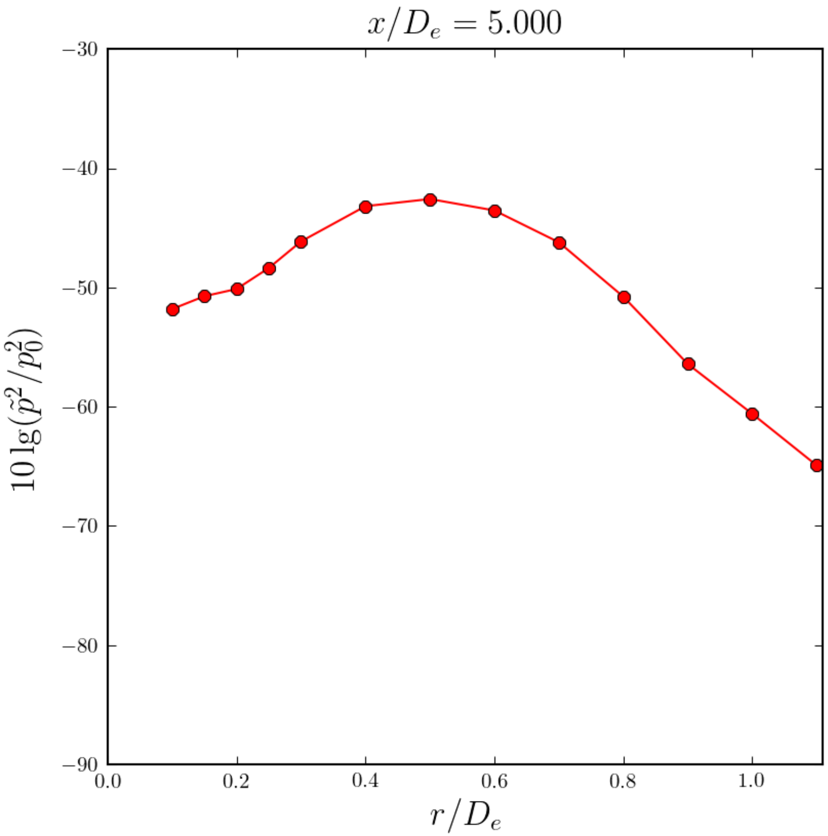


→ x/D_e=20

Snapshot of simulation with locations of source analysis

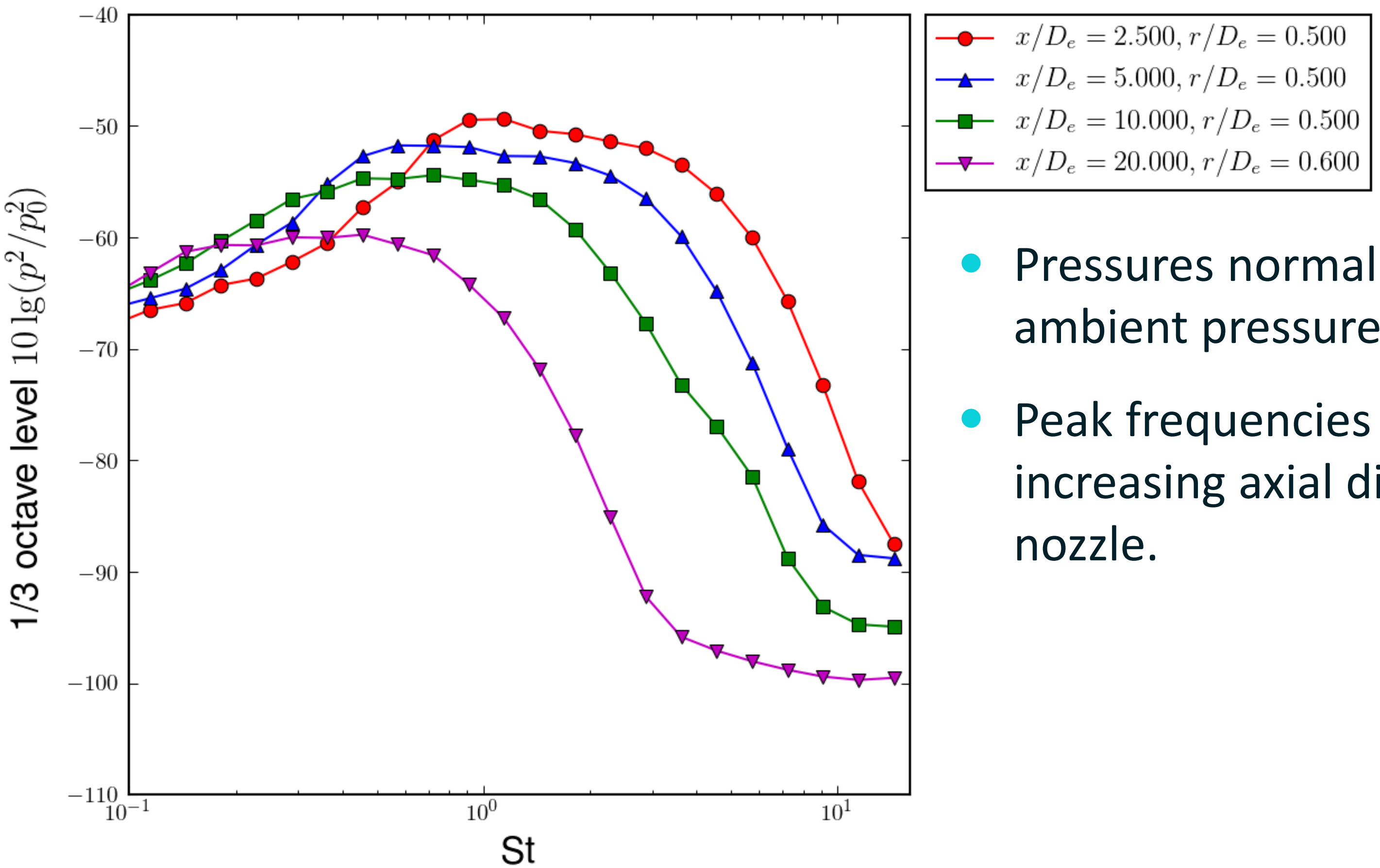
Mean velocity and mean square pressure x/D_e=5





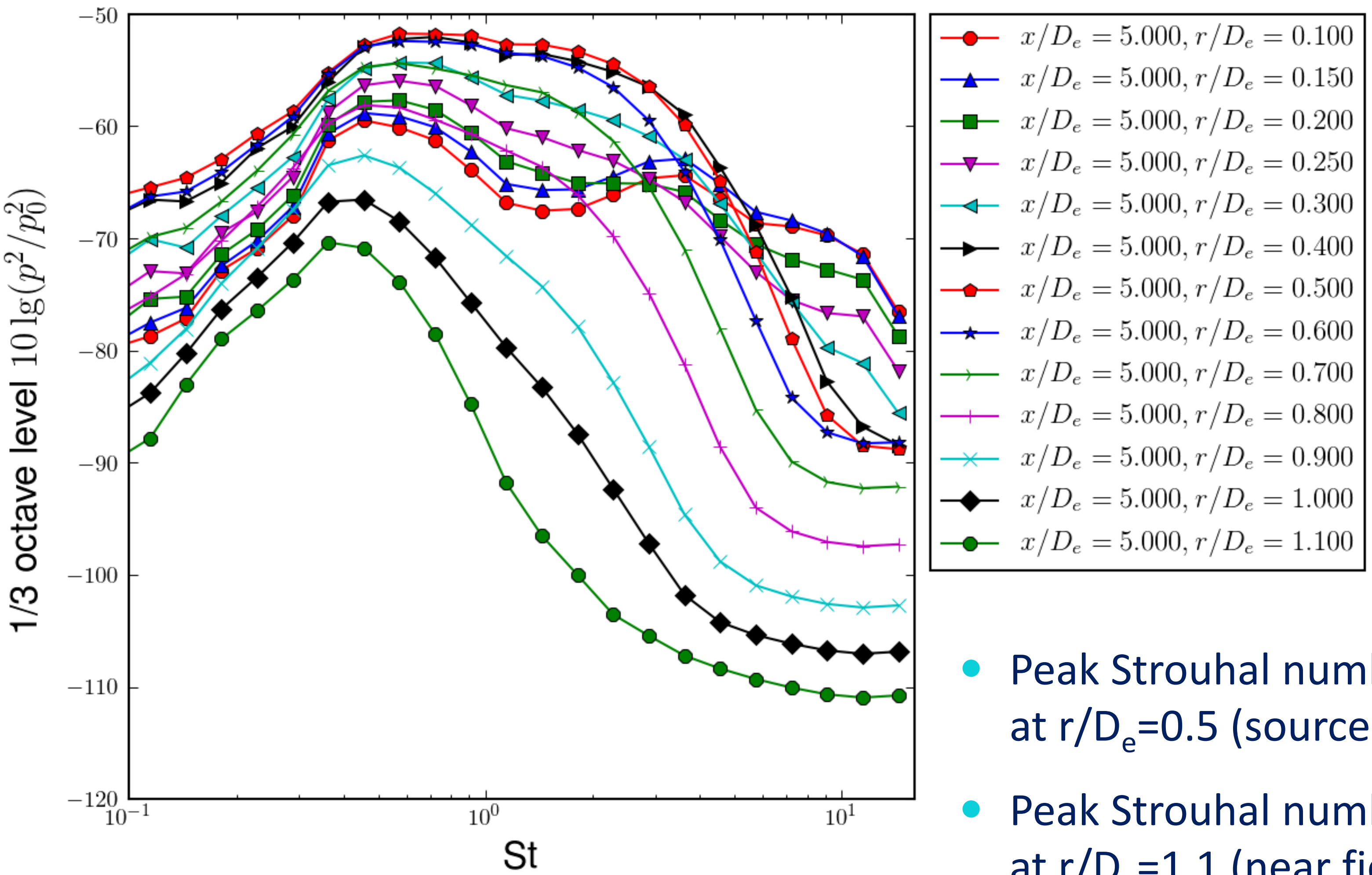
- Pressure fluctuations largest where radial velocity gradient largest
- Valid for all axial positions in jet

One-third octave band spectra for various x/D_e



- Pressures normalized with the ambient pressure p_0.
- Peak frequencies get smaller with increasing axial distance from the nozzle.

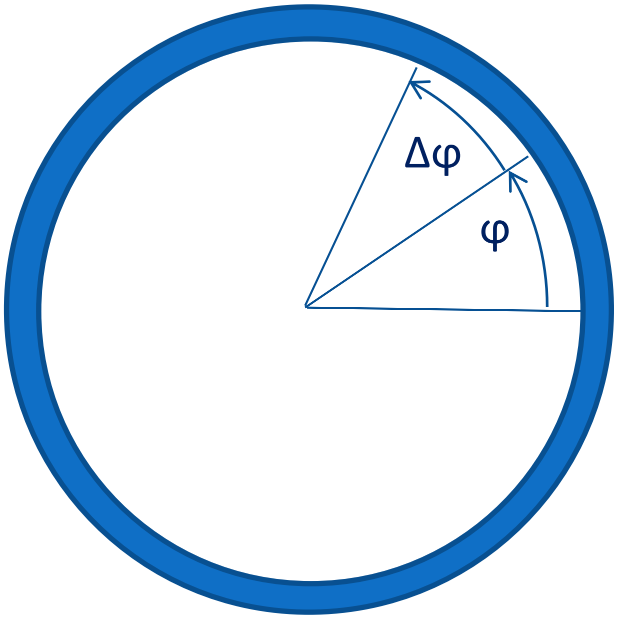
One-third octave band spectra for x/D_e=5



- Peak Strouhal number St=0.7 in at r/D_e=0.5 (source field)
- Peak Strouhal number St=0.4 at r/D_e=1.1 (near field)

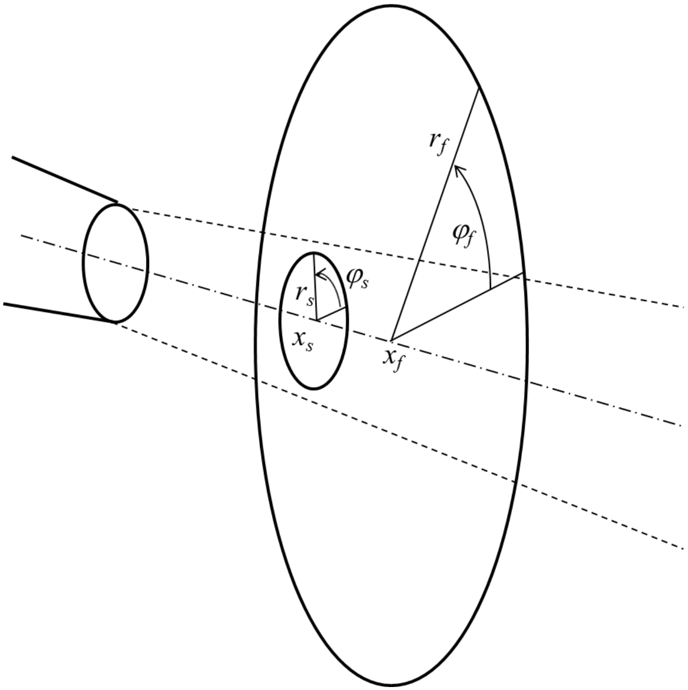
Identification of large scale structures

- Large scales can be studied with two-point cross-spectra
- Ring source element for azimuthal source separation.



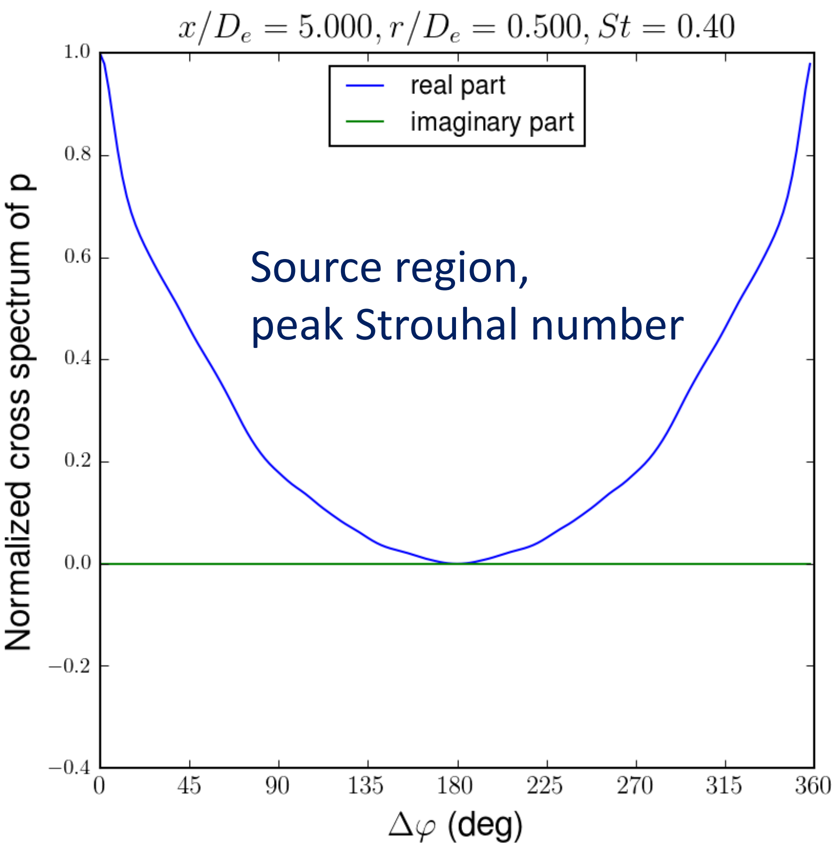
- Cross spectrum only function of frequency and azimuthal angle difference $|\Delta\varphi|$
- Cross spectra as function of $|\Delta\varphi|$ can be decomposed into Fourier series

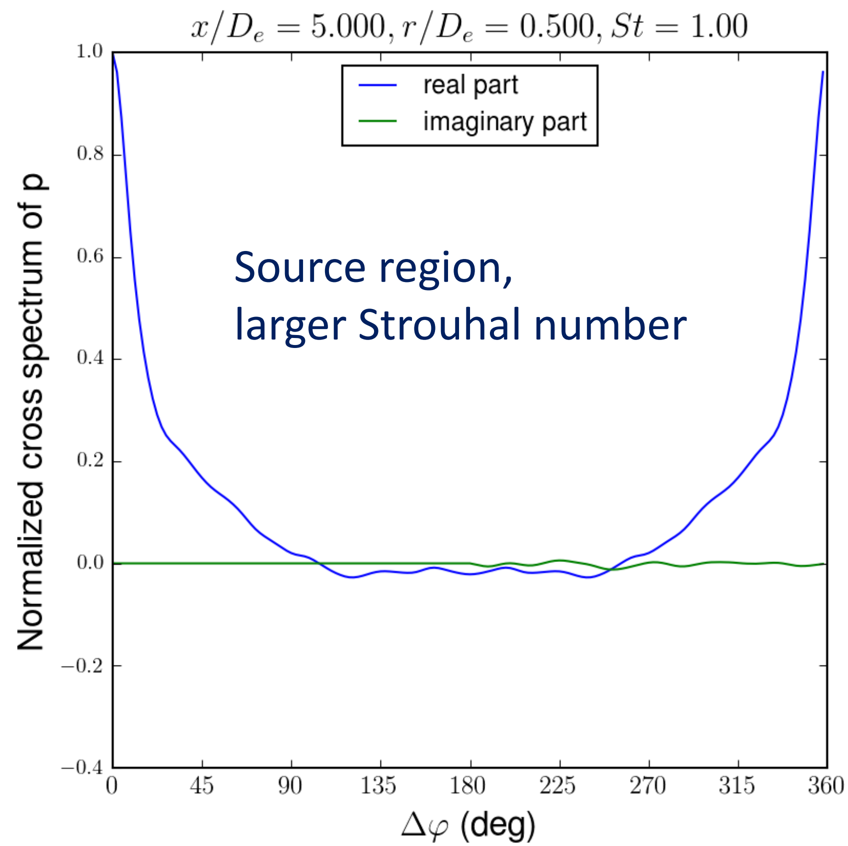
Azimuthal components of unsteady flow and sound fields



- Decomposition into azimuthal components *m* possible for any flow variable, including *q* or *p*
- Each far-field *m* is caused by the same *m* of sources in flow field (Michalke 1972)
- Pressure field inside jet dominated by low-order *m* (Experiments Armstrong et al 1977)
- Far field dominated by low-order *m* (Experiments Maestrello 1977)
- Results of computational experiment are now shown

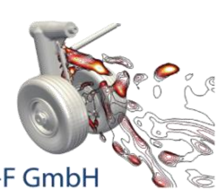
Cross spectra of pressure on a ring



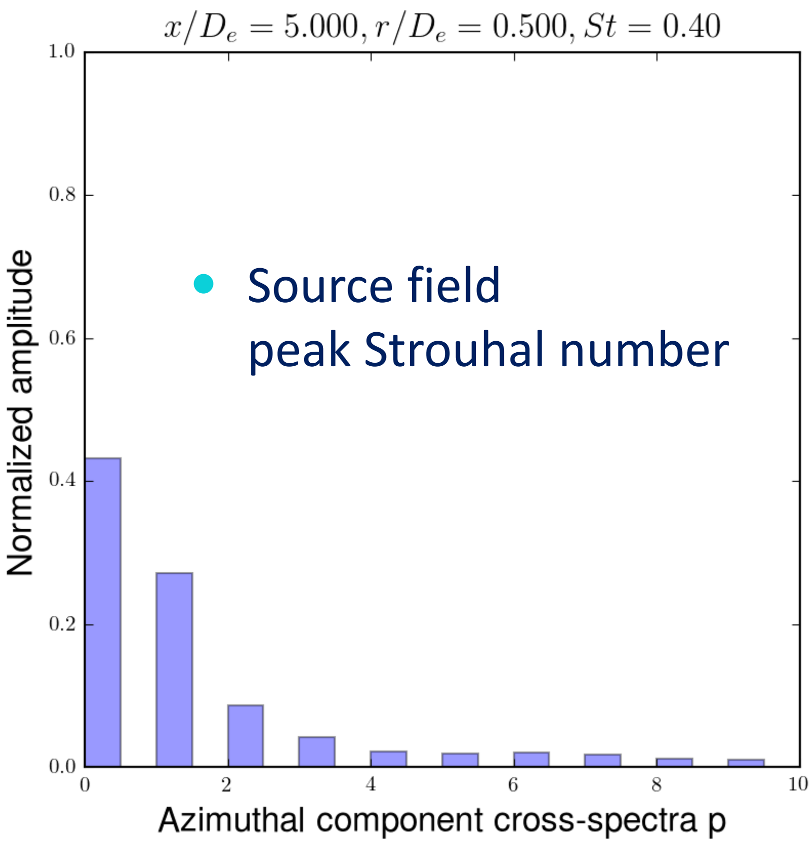


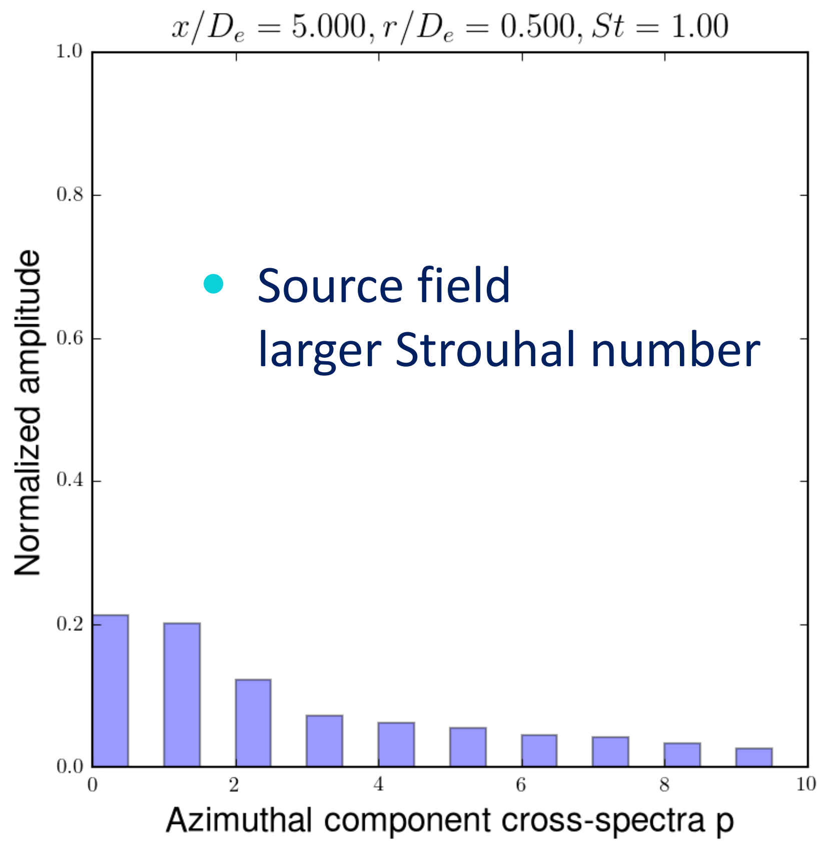
- Peak Strouhal number in middle of shear layer
- Gradual decrease of real part

- Higher Strouhal number in middle of shear layer
- Rapid decrease of real part

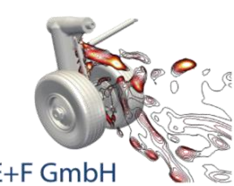


Decomposition into azimuthal Fourier components

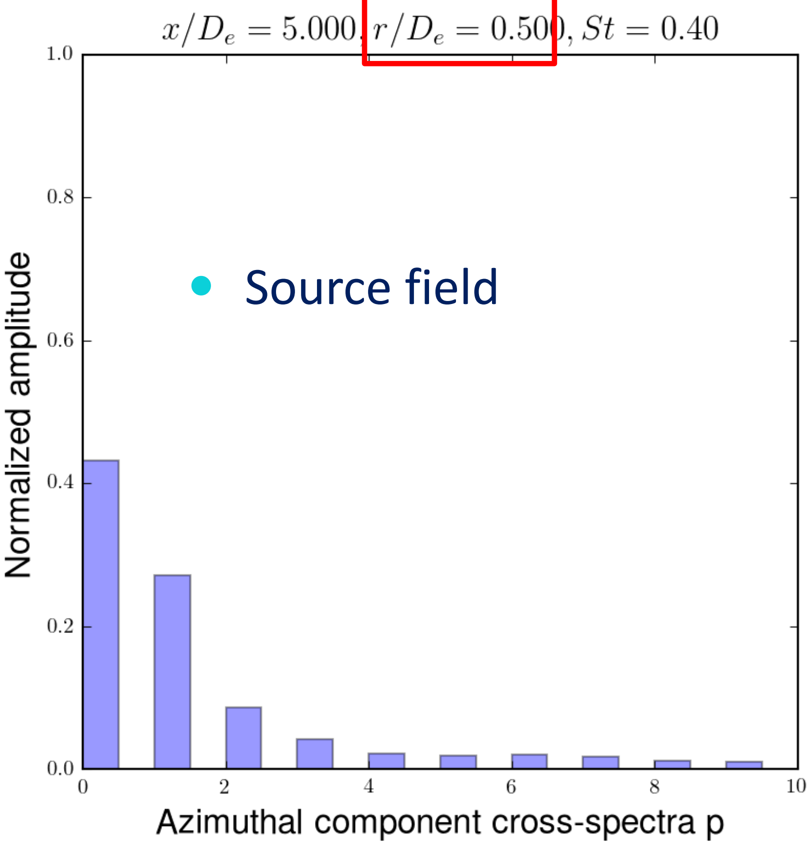


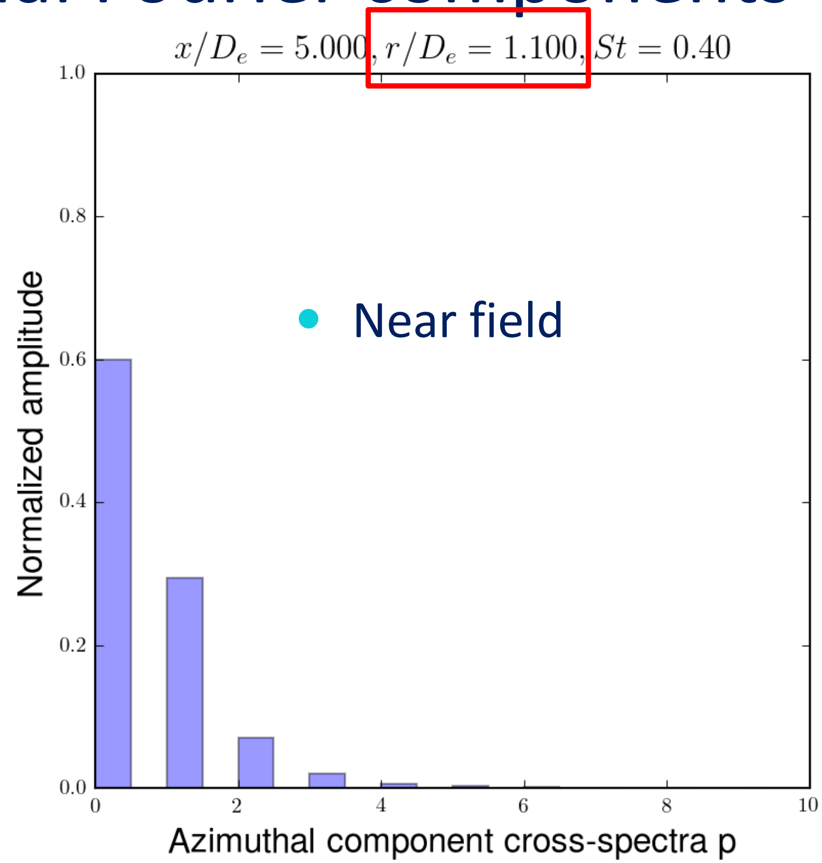


- m=0 and m=1 components dominate source field
- Amplitude decay faster for higher Strouhal number, less efficient radiation
- Pressure fluctuations for both St almost identical



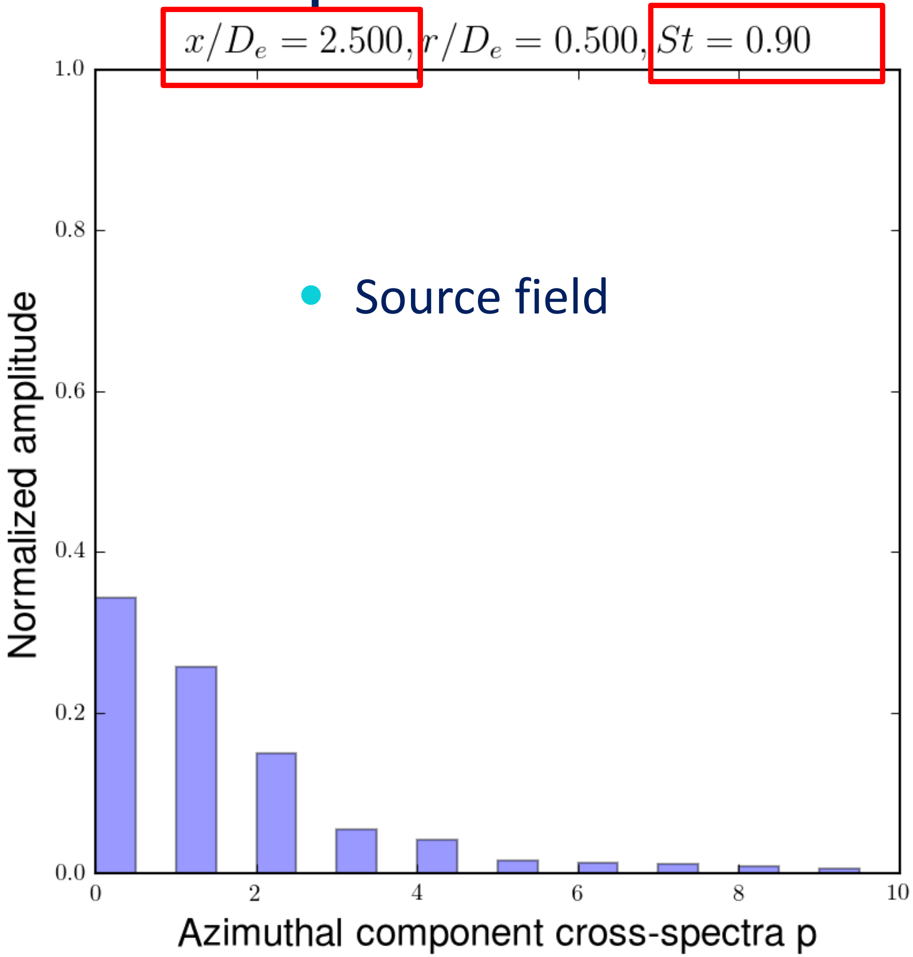
Decomposition into azimuthal Fourier components

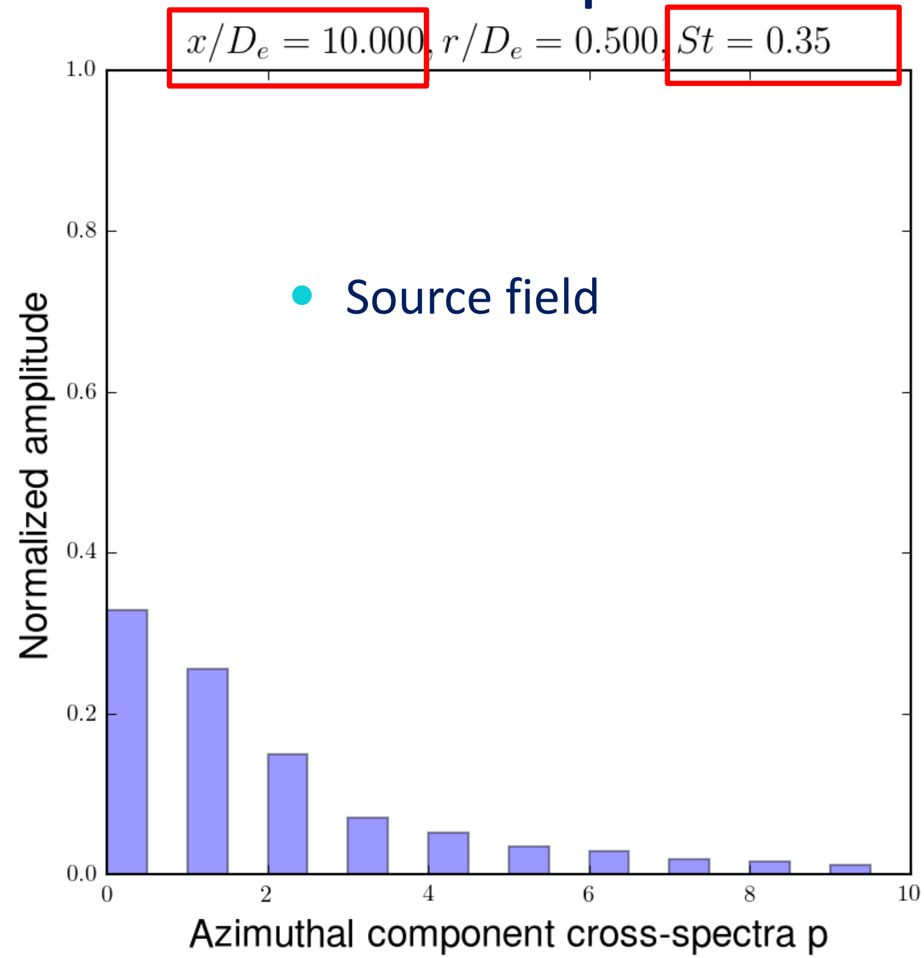




- Low order *m* are larger in near field than in source field because of lower radiation efficiency

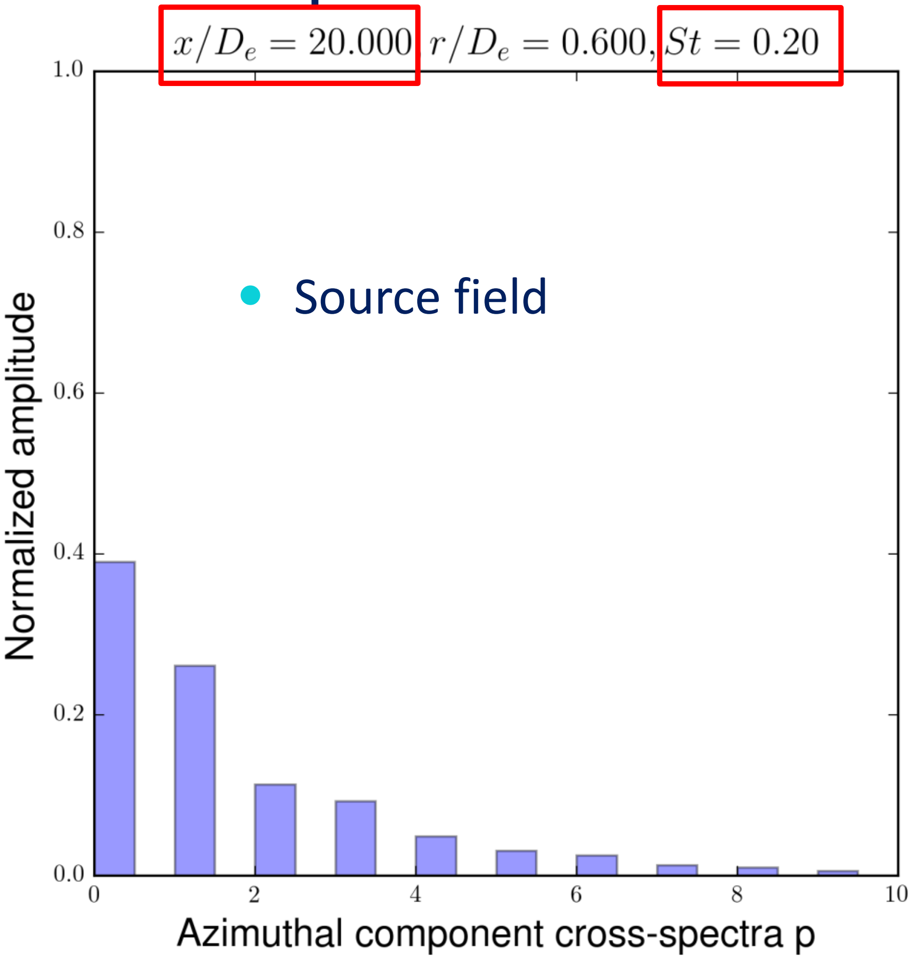
Decomposition into azimuthal Fourier components

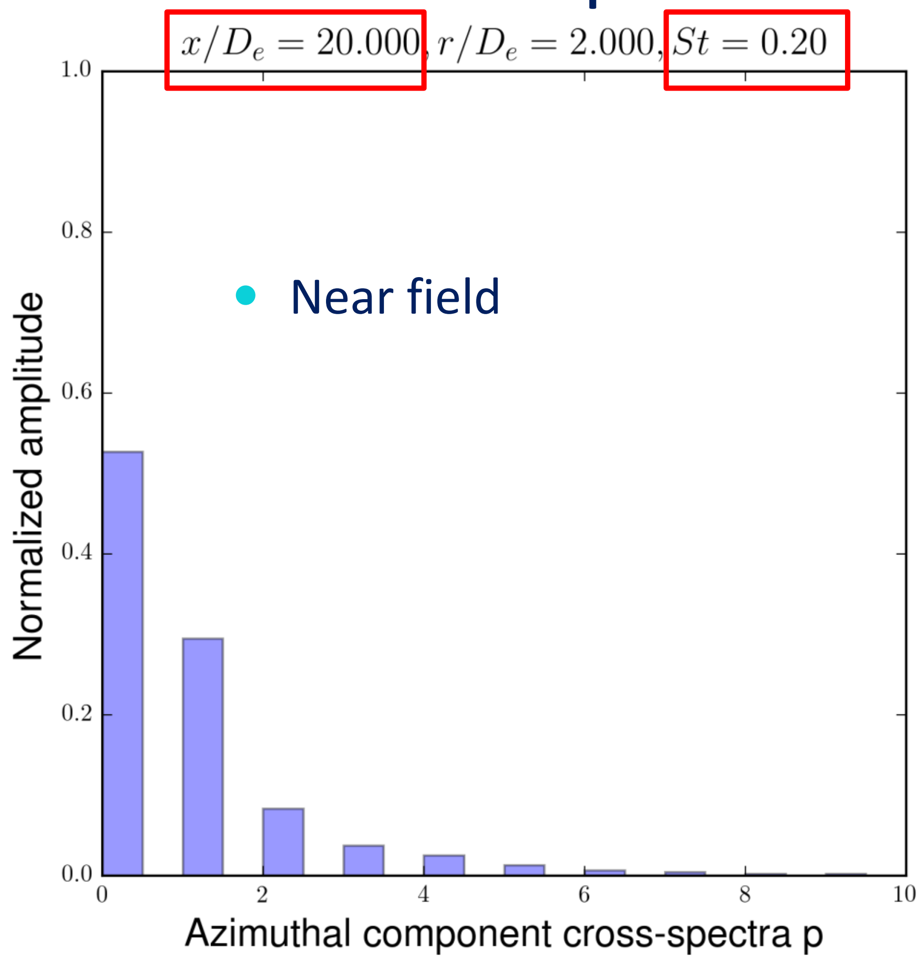




m=0, 1, and 2 components dominate source field at x/D_e=2.5 and x/D_e=10, levels almost identical

Decomposition into azimuthal Fourier components

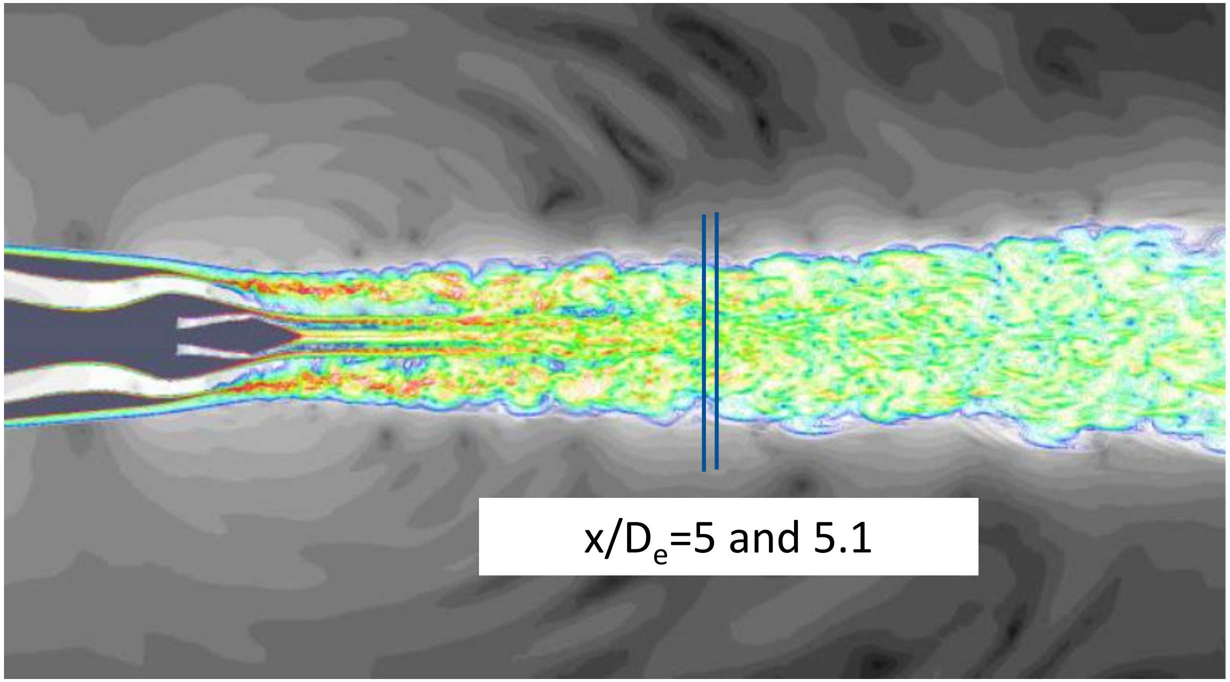




m = 0 and 1 components dominate source field and near field at x/D_e=20

Phase speeds

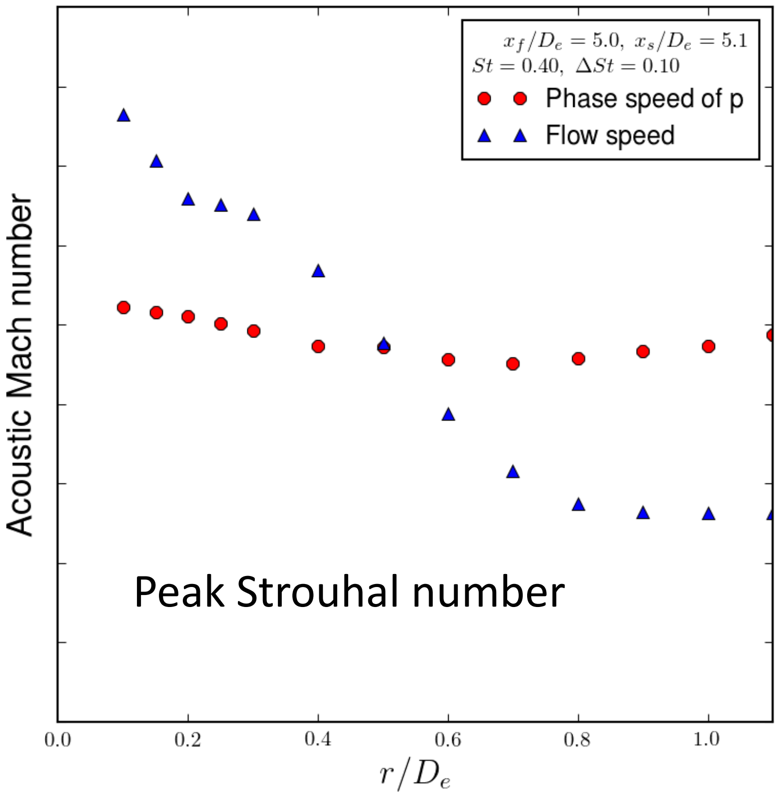
Cross-spectral density between two axial positions
Results shown for $x_1/D_e = 5.0$ and $x_2/D_e = 5.1$

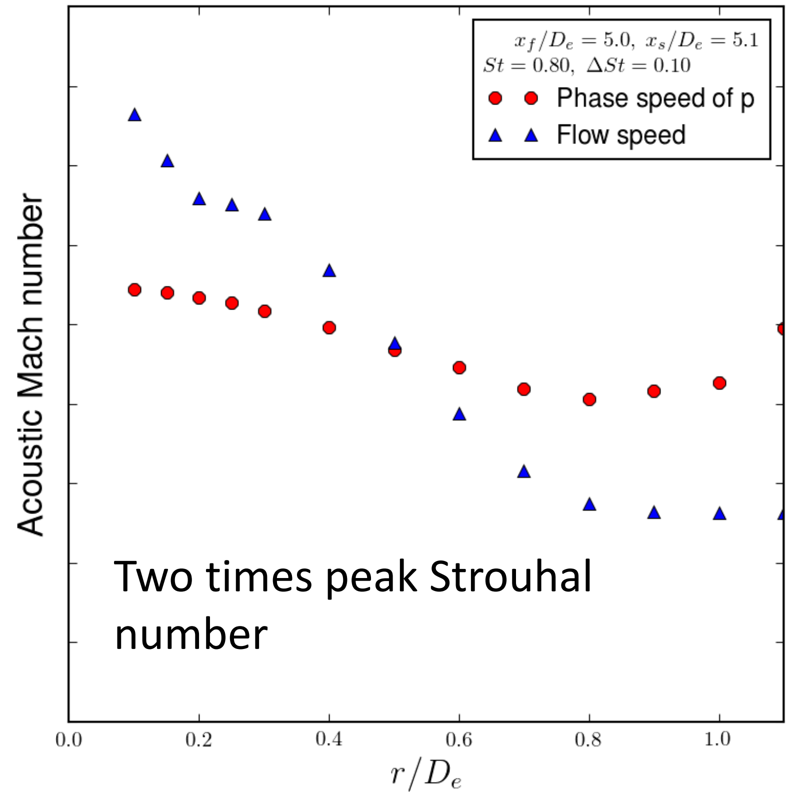


Snapshot of simulation with location of phase speed analysis

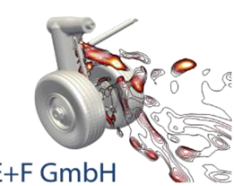
→

Phase speeds x/D_e=5





- Phase speed almost independent of radius
- Even in near field outside jet
- Result similar for all other axial positions
- Pressure fluctuations dominated by the influence of wave-like fluctuations related to the instability of the jet shear layer.



Conclusions

- Jet noise sources dominated by contribution of low-order azimuthal modes
- Noise sources are results of wave-like motion
- 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 and likely even less to the far-field radiation
- The noise sources are concentrated at the radial location with the steepest radial velocity gradient.
- A cylindrical jet noise source model is likely sufficient
- “Small scale stuff” in source region is ineffective radiator
- “Small scale stuff” may even mask large scale motion

Conclusions 2

- Moving eddy model for jet noise sources is completely wrong.
- In the critical layer (phase speed = flow speed) the frequency of a moving eddy would be zero.
- Lighthill (1954) and Ffowcs-Williams (1963) erred in this respect.
- Michalke (1972) was right when he introduced the wave model for jet turbulence.

Acknowledgement

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

References

- A. Michalke (1972): An expansion scheme for the noise from circular jets. Z.Flugwiss. 6, 229-237
- L. Maestrello (1977): Statistical properties of the sound and source fields of an axisymmetric jet. AIAA-1977-1267
- R. R. Armstrong, A. Michalke, H. V. Fuchs (1977): Coherent Structures in Jet Turbulence and Noise . AIAA Journal 15, 1011-1017
- U. Michel (2009): The role of source interference in Jet Noise. AIAA-2009-3377
- C. Mockett, M. Fuchs, F. Kramer, U. Michel, F. Thiele, M. Steger (2016): Turbulence Modelling and Meshing Developments for the Prediction of Jet Noise Installation Effects