MUSAF II colloquium
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Simulation of Airframe Noise using a two-step DES/FWH approach

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Work of the

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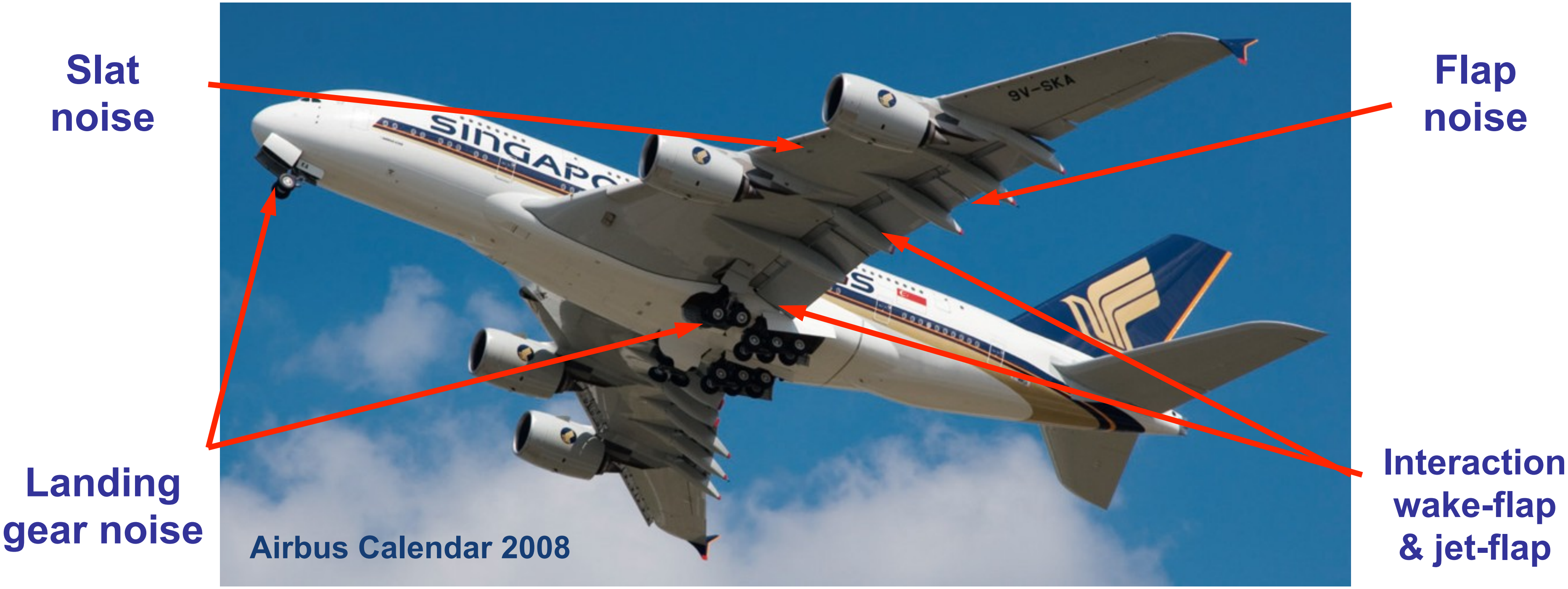
Outline

- Introduction
  - Airframe noise (AFN)
  - Two-step DES/FWH approach
- Application to selected AFN test cases
  - Two struts (square cylinders)
  - Tandem cylinder (circular)
  - Rudimentary landing gear
- Conclusion

Airframe Noise (AFN)

- AFN is an important issue for communities and aircraft manufacturers
  - During landing approach engines operate at reduced power (less noise from engines)
  - Large areas near airports affected due to shallow approach angle (safety requirement)

- AFN sources of a turbofan aircraft (Michel 2010)



Airframe Noise (AFN)

- AFN mainly generated by turbulent interactions between large scale separated flows and downstream surfaces and edges.
  - Slats (Interaction of slat cove unsteadiness with slat trailing edge)
  - Flaps (Interaction of flow unsteadiness with flap side and trailing edges)
  - **Landing gear** (Interaction of wake with gear surface and ceiling)

- High Reynolds numbers > 10^5
  - Turbulent flow with separation
  - Wide range of active scales, full resolution with DNS or LES impossible
  - Partial resolution of turbulence needed to capture broadband noise sources

- Low Mach numbers < 0.3
  - Large disparity between hydrodynamic and acoustic scales
  - Same frequency but large differences in size, strength and speed
  - Split problem into source simulation (step 1) and wave propagation (step 2)

Two-step DES/FWH approach (step-1)

- Nearfield simulation with pressure based solution method
  - Naturally efficient at low Mach number (no preconditioning required)
  - Time-implicit finite-volume discretisation (no time step limitation)
  - 2nd order accurate in both time and space
  - Reynolds-averaged/filtered Navier Stokes equations
  - Iterative solution via compressible SIMPLE algorithm

- Hybrid RANS – LES turbulence treatment: **D**etached **E**ddy **S**imulation

- DES is an efficient way to simulate separated flows
  - RANS adequate and much cheaper than LES in boundary layers.
  - LES describes large scale separated flow better than RANS.
  - **DES** = RANS in attached boundary layers + LES in separated flow regions.
  - Dominant sound sources resolved with energetic part of energy spectrum.
  - Improved DES formulations extend application range to wall-modelled LES.

Two-step DES/FWH approach (step-1)

- DES provides access to AFN prediction at minimal computational cost

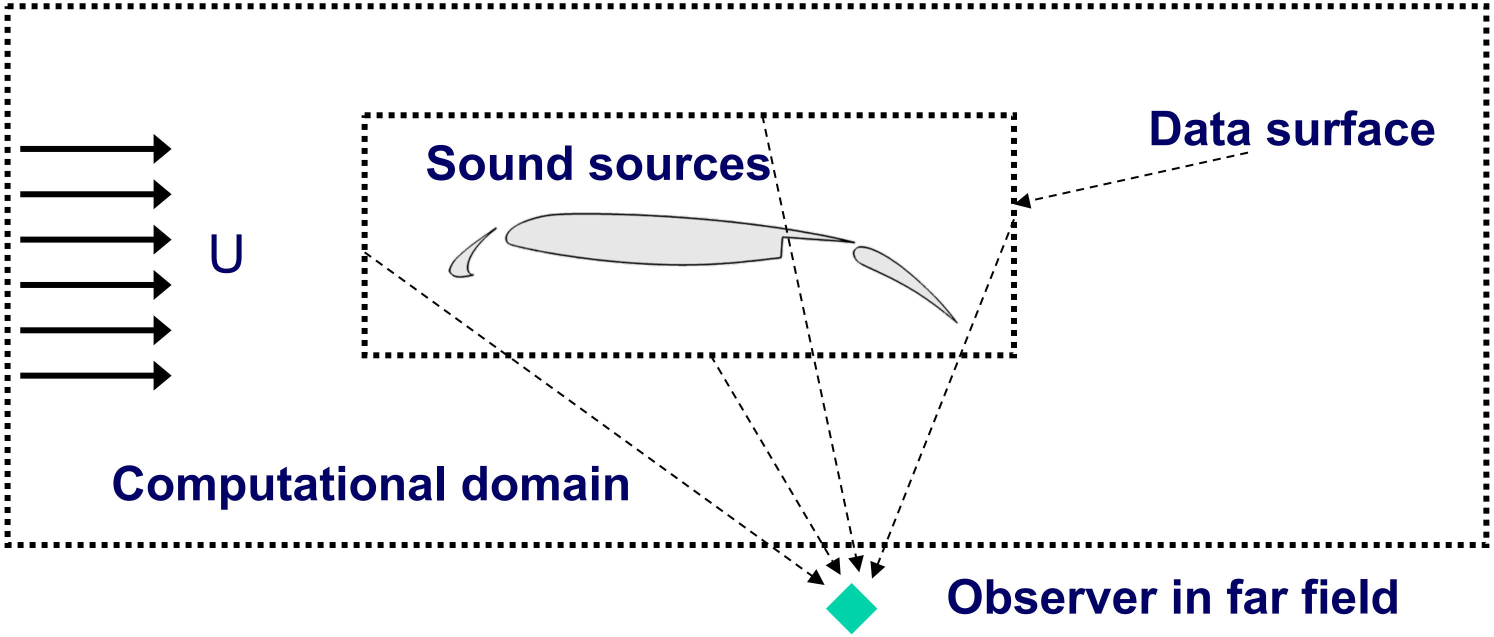
- Three variants of DES for nearfield simulation:
  - **DES97**: *Original version:* assumes that wall-tangential grid is coarse enough to avoid LES-mode entering boundary layer (no longer used)
  - **DDES**: *Delayed DES:* Boundary layers protected from LES intrusion, finer grids for higher frequencies possible
  - **IDDES**: *Improved DDES:* LES allowed to penetrate into outer part of boundary layers, partial resolution of boundary layer turbulence

  See
  - *Diss. Mockett*
    http://opus.kobv.de/tuberlin/volltexte/2009/2326/pdf/2160_mockett_charles.pdf
  - *Spalart, Annual Review of Fluid Mechanics, 41: 181-202 (2009)*

- Storage of unsteady flowfield variables on control surfaces for step-2...

Two-step DES/FWH approach (step-2)

- 3D unsteady flow field is simulated within a domain containing the aerodynamic sound sources.



- Sound emission to any observer position is computed with the acoustic analogy by solving the **F**fowcs-**W**illiams **H**awkings integral, either over
  - **solid** body surface (volume sources neglected) or
  - **permeable** data surface (volume sources outside data surface neglected)

Solid/permeable FWH (step-2)

- Low Mach number has implications on AFN generation
  - *Weak* role of quadrupole noise sources: $p'_Q/p_\infty = O(M^4)$
  - *Mainly* loading noise (surface dipoles): $p'_D/p_\infty = O(M^3)$
- Solid surface based FWH integration
  - accurate representation of unsteady surface pressures is key
  - may well be sufficient for AFN predictions at low Mach numbers
- Permeable surface based FWH integration
  + \+ Allows to include inner quadrupole noise sources
  + \+ Allows to account for inhomogeneous mean flow effects
  + – Requires sufficient resolution of wave propagation up to the surface
  + – *May also lead to inclusion of spurious noise sources*
    - ➢ *Passing of vortical disturbances over downstream end of FWH surface*
    - ➢ *Artificial noise due to approximation errors (poorly resolved energetic structures)*

Application to selected AFN testcases

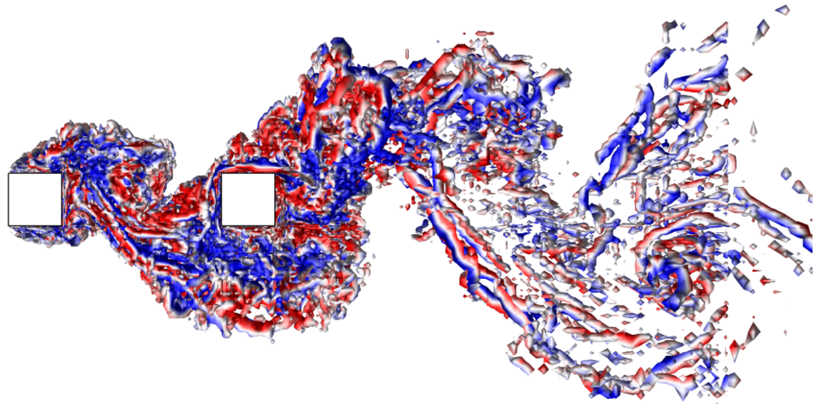
- Focus on landing gear area
- LG is one of the most significant AFN contributors
- Complex geometry with strong interaction between components
- Numerous struts (both edged and rounded)
- Truck and wheels

- Work from SEVENTH FRAMEWORK PROGRAMME projects

VALIANT + ATAAC

Two-struts test case

1

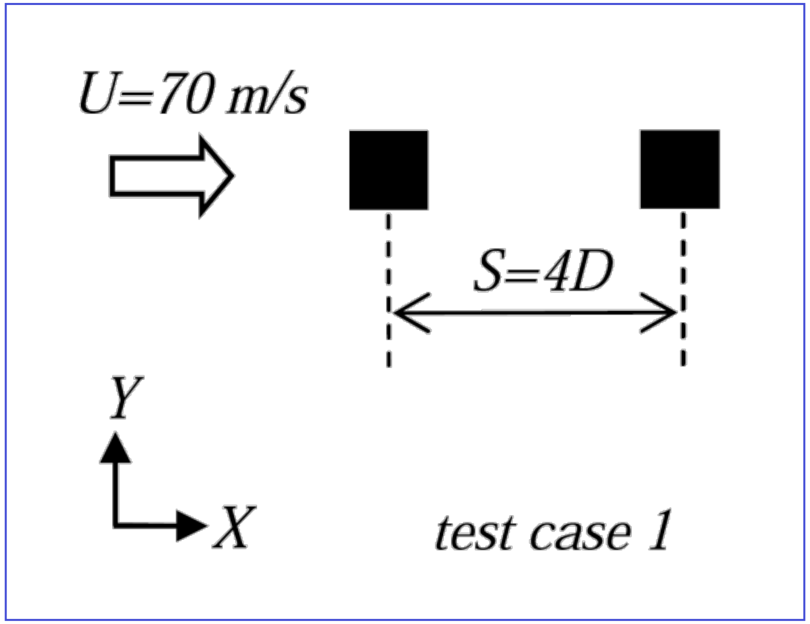


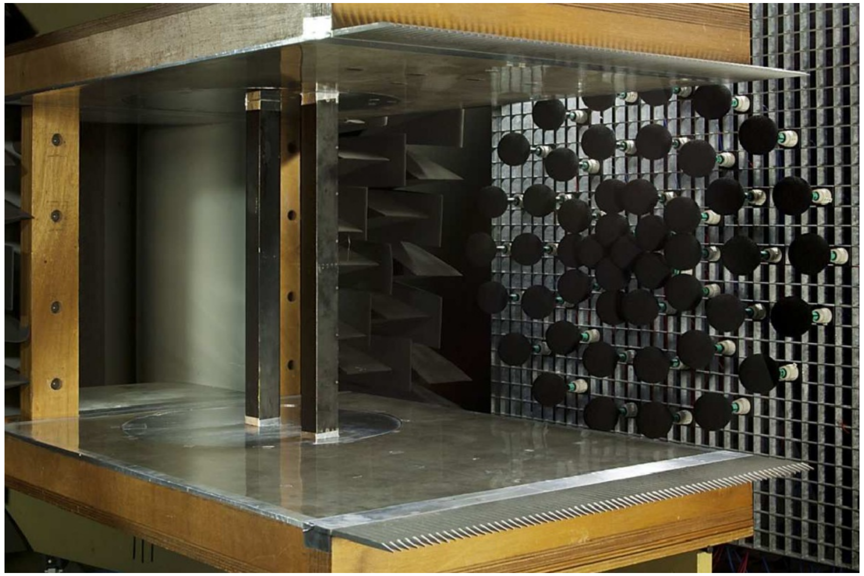
T. Knacke and F. Thiele: „*Prediction of broadband noise from two square cylinders in tandem arrangement using a combined DDES/FWH approach*“, In: TI 2012, 3rd international conference on turbulence and interactions. 11th – 14th June, 2012, La Saline-Le-Bains, Reunion Island.

Two-struts test case

- Representative of real landing gear noise mechanisms and simple
- Two square cylinders in tandem arrangement immersed in uniform flow
- Strut width D=4 cm, center to center distance S=4D,
- **Re_D = 182 000**
- **Ma = 0.2**

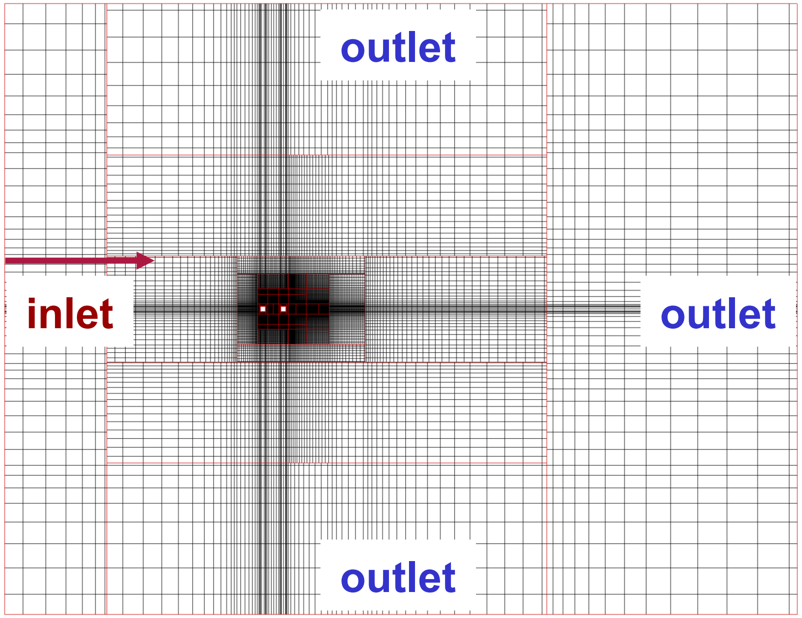
experimental data provided by NLR &



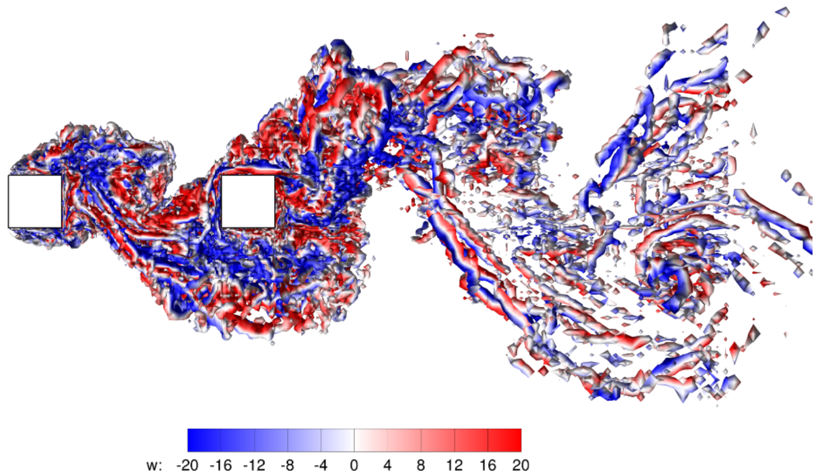


Mesh and Setup

- 8.7 mio cells for 3D span
- Max. 96 cells and periodic BC into homogeneous spanwise direction
- NRBC (Bogey & Bailly type) at inlet and outlet
- **DDES** based on SALSA 1-eq. turbulence model



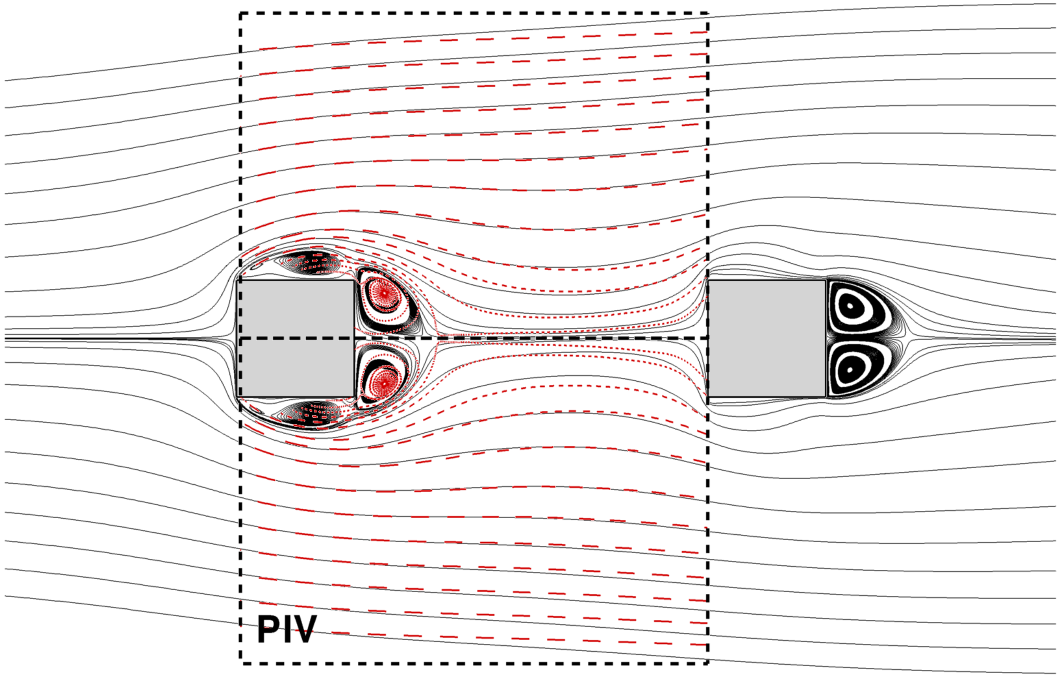
only every 2nd cell is shown



Resolved vortical structures
(λ_2 isosurface coloured with w-velocity)

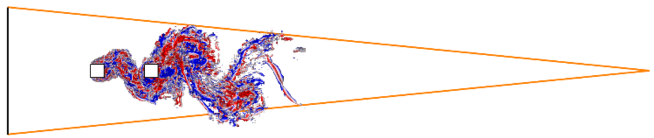
Time averaged flow (streamlines)

- DDES results averaged over time and span after 60 000 timesteps
- $\Delta t = 0.0175 \cdot D/u \rightarrow$ CFL < 1 within focus region
- Evaluated time corresponds to 210 flow passes over configuration
- Flow field symmetry indicates sufficiently large statistical sample

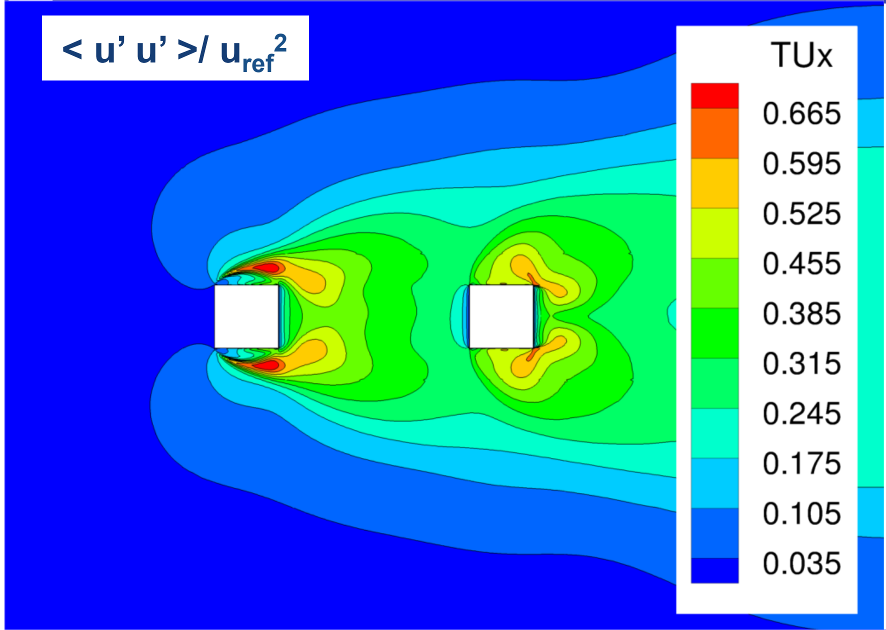


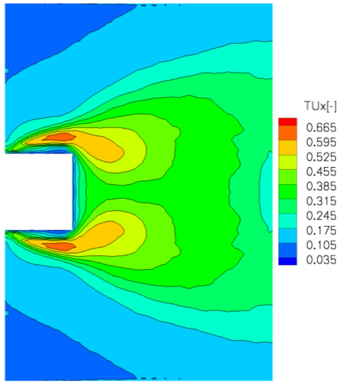
(PIV data mirrored at symmetry plane)

- Geometrically induced flow separation at the 1st strut sharp leading edges
- Recirculation regions above and below the 1st strut and in both struts wakes
- Agreement between PIV (red, dashed) and DDES (black) is very good
- Deviations restrained to outer flow regions (these may be due to the limited extent of wind-tunnel jet potential core)

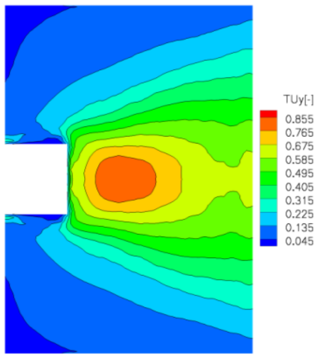


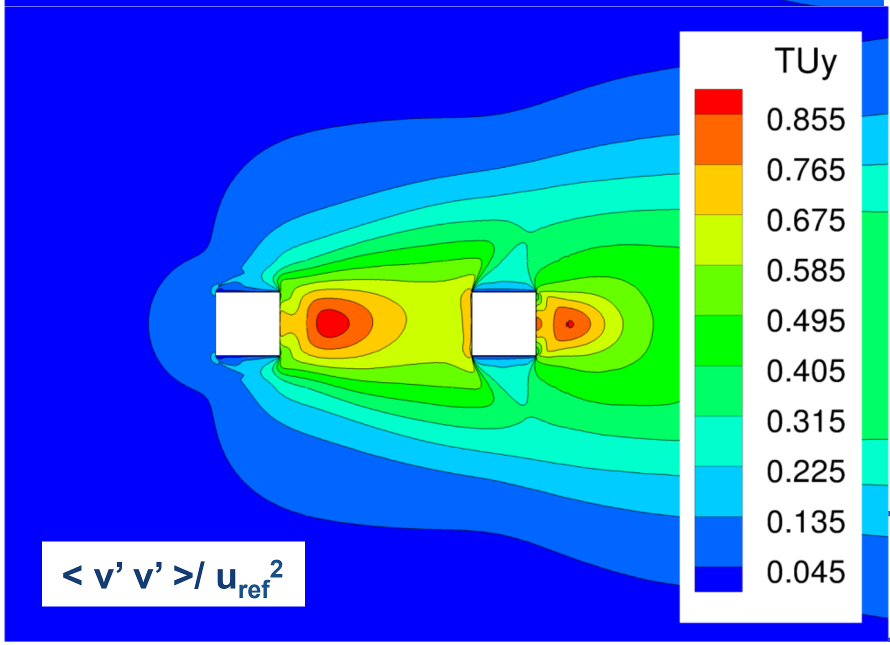
Time averaged flow (fluctuations)





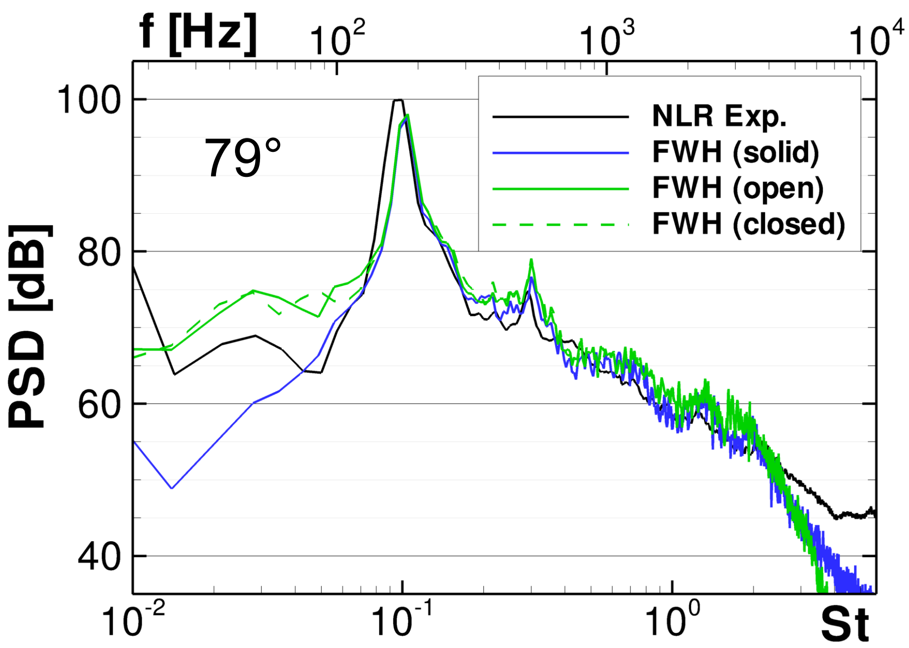
PIV

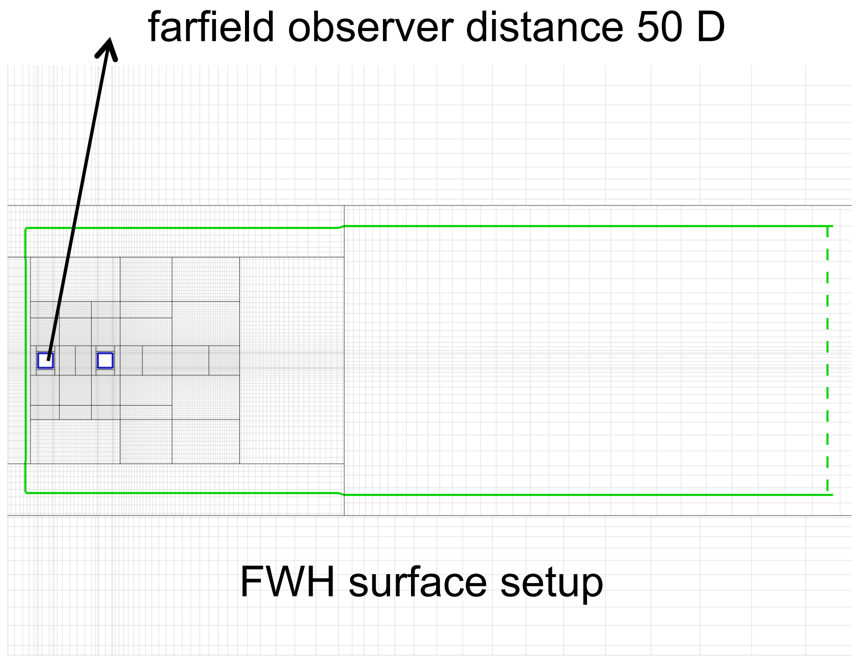




- Qualitative agreement very good
- Some differences in peak intensities
- Could be due to differing resolution of LES/PIV
- Vertical velocity fluctuations stronger then horizontal fluct.
- Almost 90% of the freestream velocity^2 reached in strut 1 wake

Farfield pressure spectra

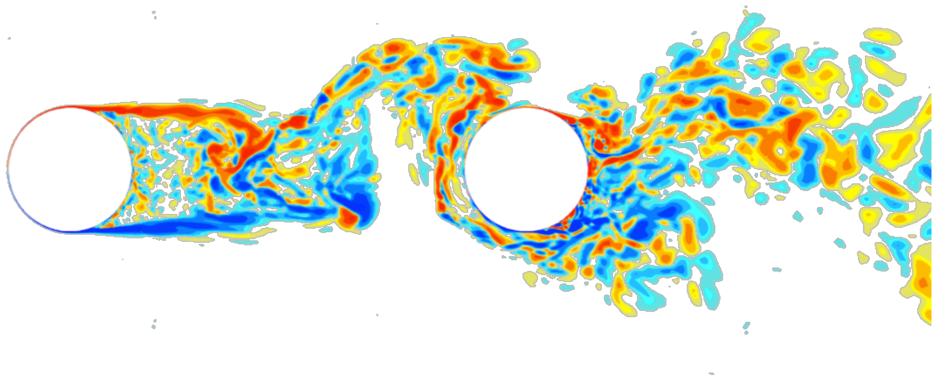




- PSD levels corrected for shear layer refraction and differing spanwise extent
- Very good agreement between FWH and measured farfield noise (0.06 < St < 3)
- Peak underestimated due to span-correction assuming uncorrelated sources
- Solid FWH and open/closed permeable FWH integration results are very similar (in agreement with low Mach number aeroacoustic theory)

Tandem cylinder test case

2

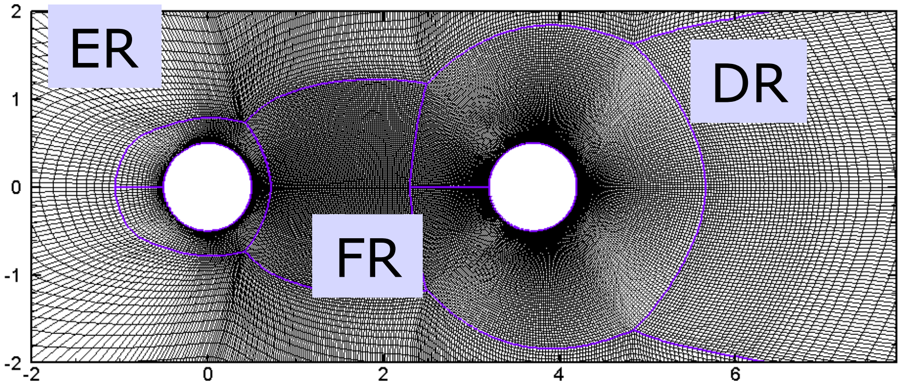


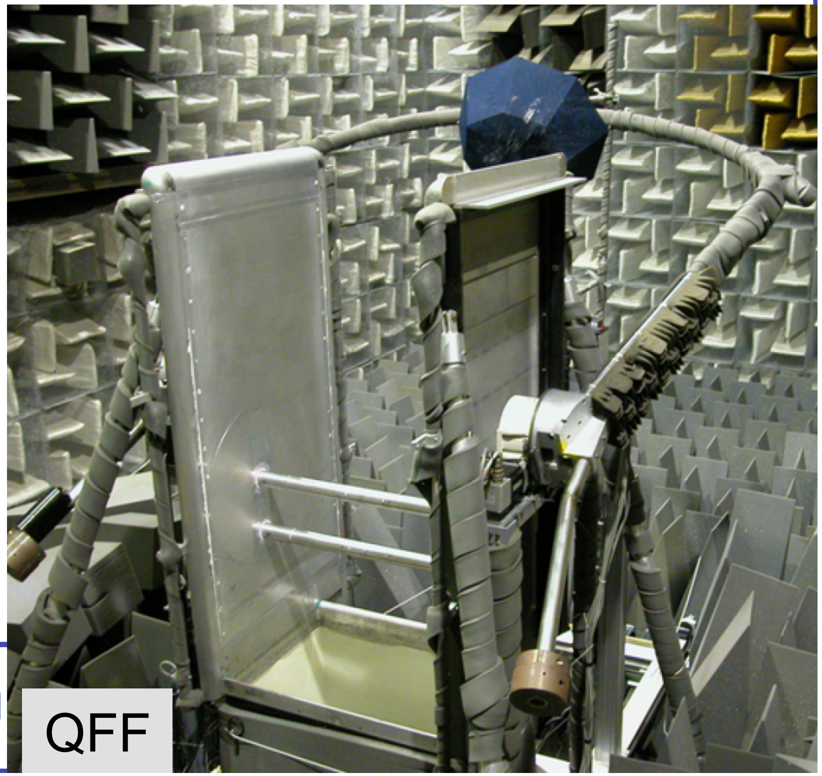
B. Greschner, D. Eschricht, C. Mockett and F. Thiele: „*Turbulence modelling effects on Tandem Cylinder Interaction Flow and Analysis of Installation effects on broadband noise using Chimera Technique*“, AIAA Paper 2012-3033.

Tandem cylinder test case

- Representative of real landing gear noise mechanisms and simple
- Two circular cylinders in tandem arrangement immersed in WT-jet flow
- Strut width D=5.715 cm, spacing S=3.7D
- **Re_D = 166 000**
- **Ma = 0.1285**
- mandatory core mesh: 9.5 mio cells
- extended with Chimera mesh for WT-jet
- spanwise extent 3D

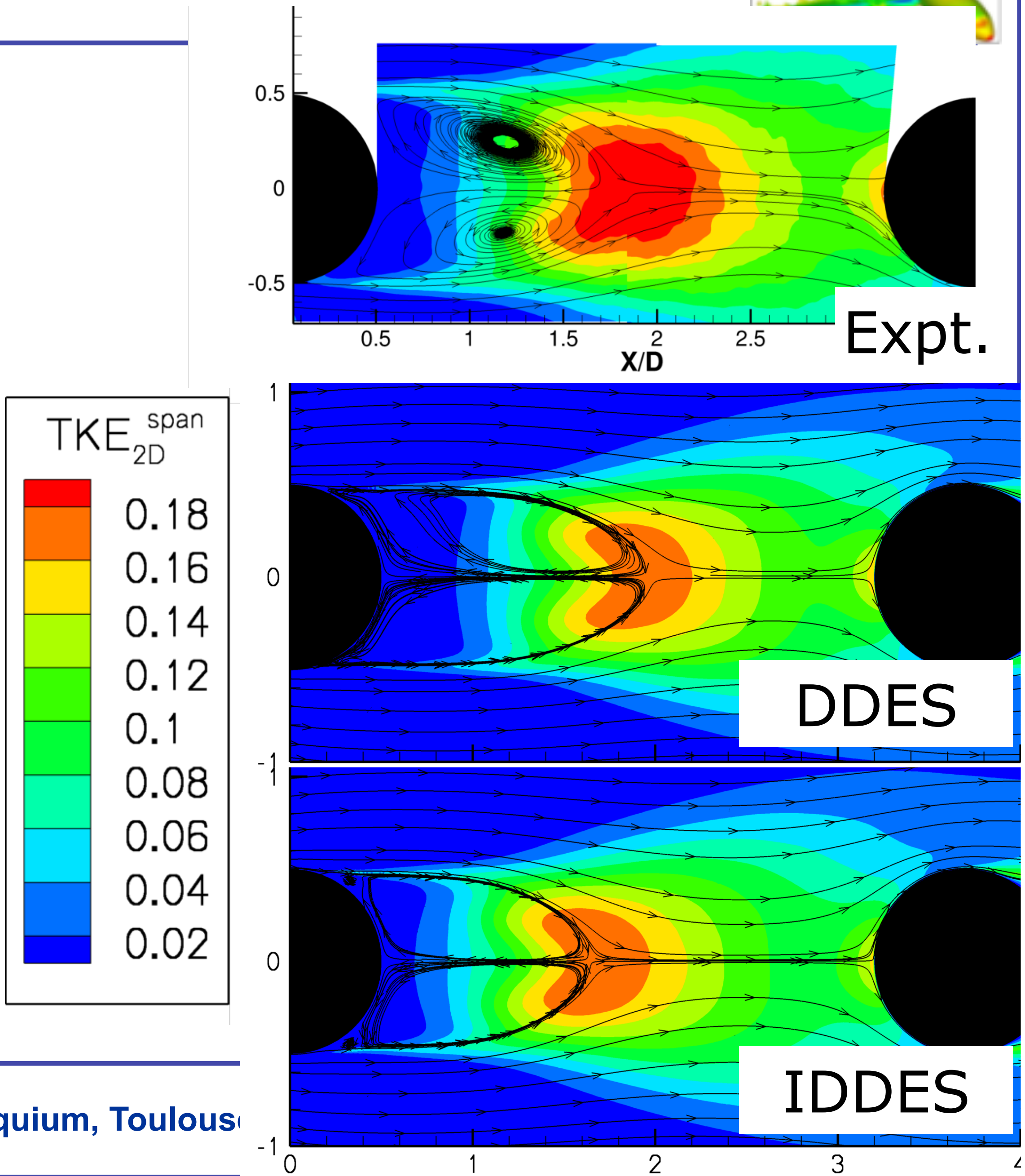
exp. data provided by NASA





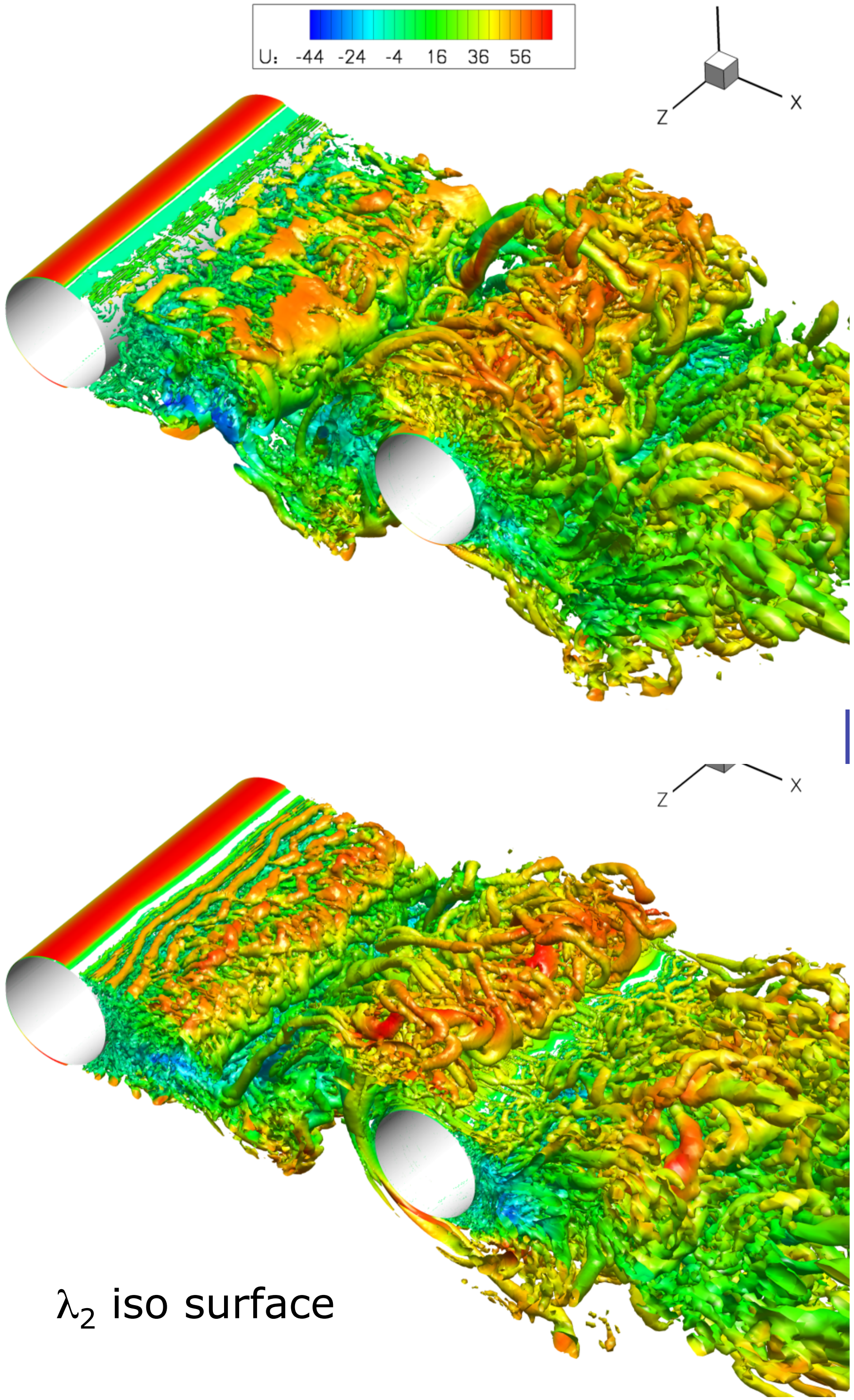
Time-averaged flow (fluctuations)

- Statistics over at least 300 CTU (D/u_∞)
- $\Delta t = 0.01 \cdot D/u_\infty$
- Recirculation lengths:
  - Exp: 1.66 D
  - DDES: 1.96 D
  - IDDES: 1.64 D
- Switch from DDES to IDDES improves agreement with exp. data



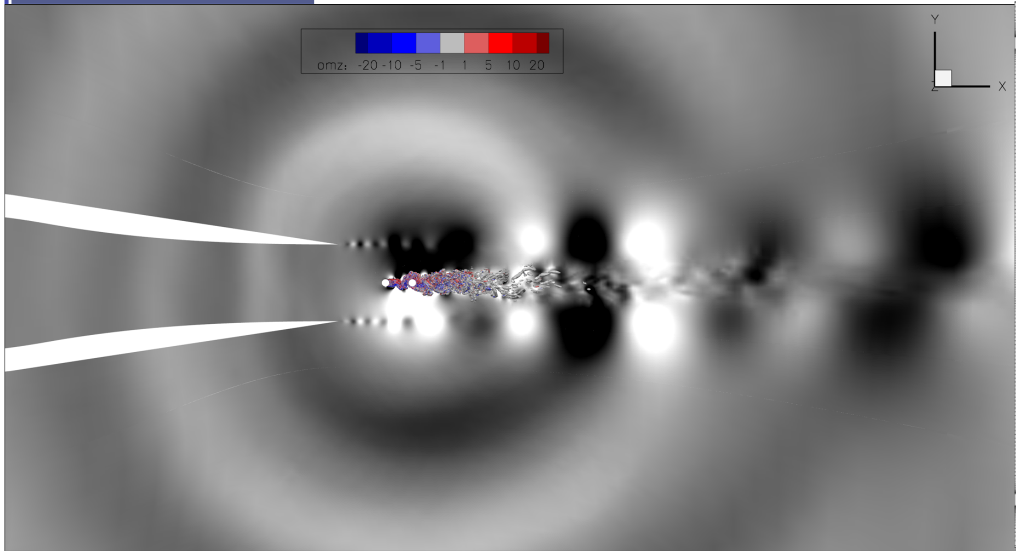
Snapshots

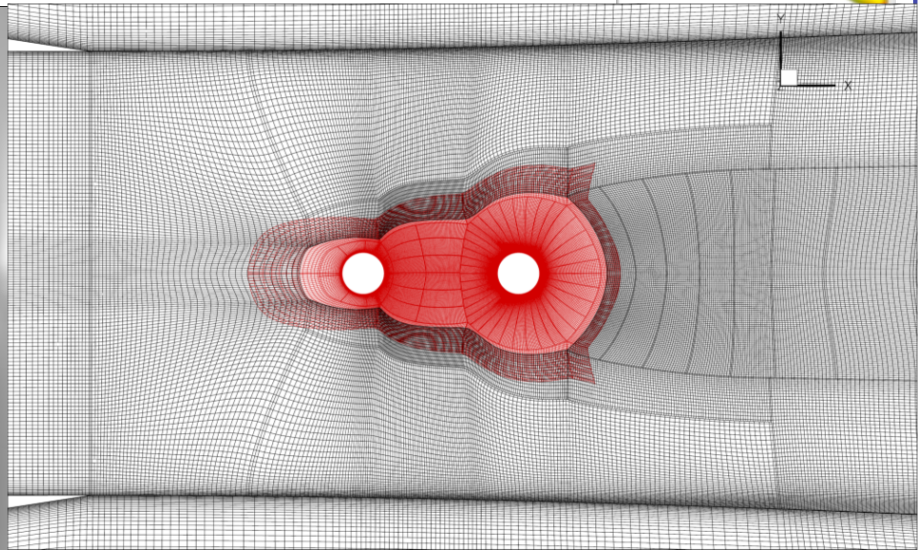
- Modelled viscosity transported from RANS boundary layer into free shear layer delays the transition to resolved turbulence
- Typical „grey area“ problem of RANS/LES hybrids
- IDDES: Earlier activation of LES mode → rapid reduction of modelled viscosity behind separation
- Instant formation of resolved vortical structures in IDDES mode

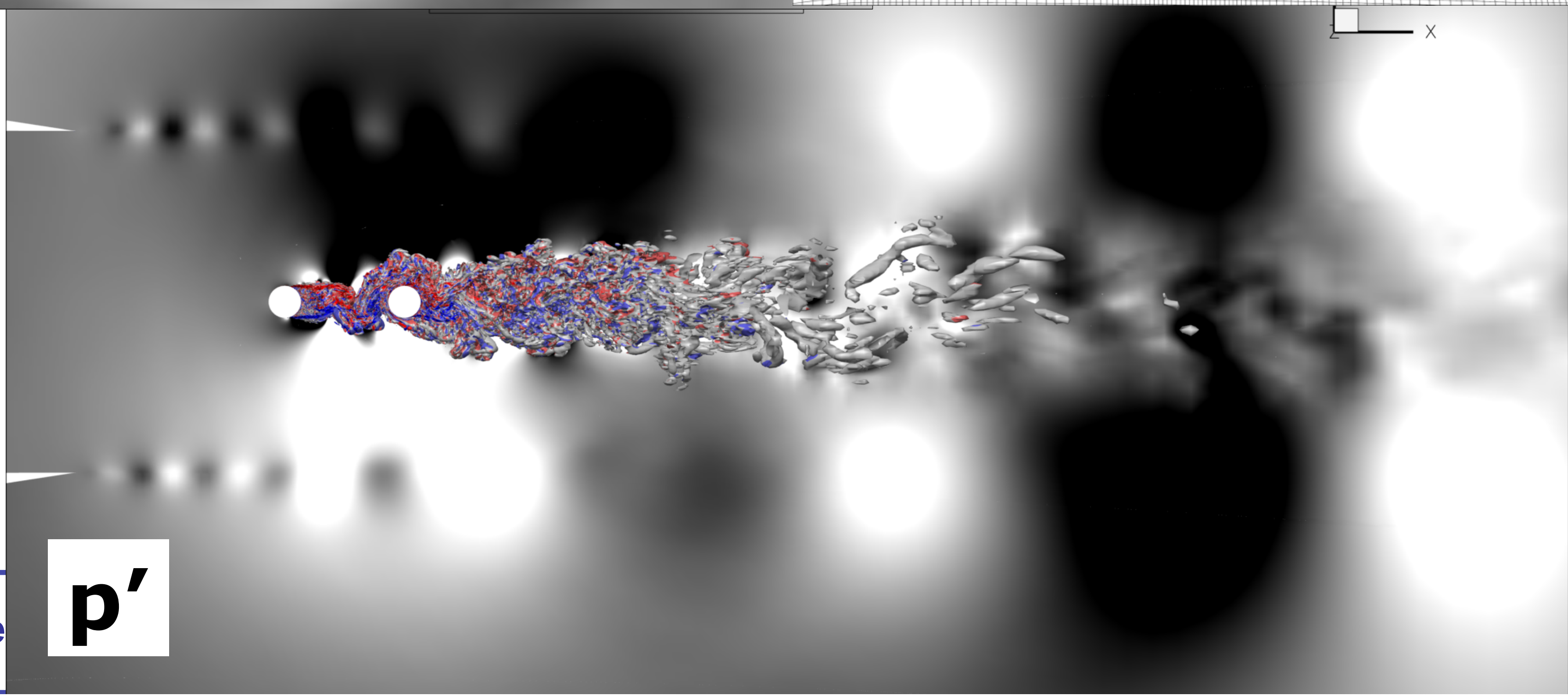


λ_2 iso surface

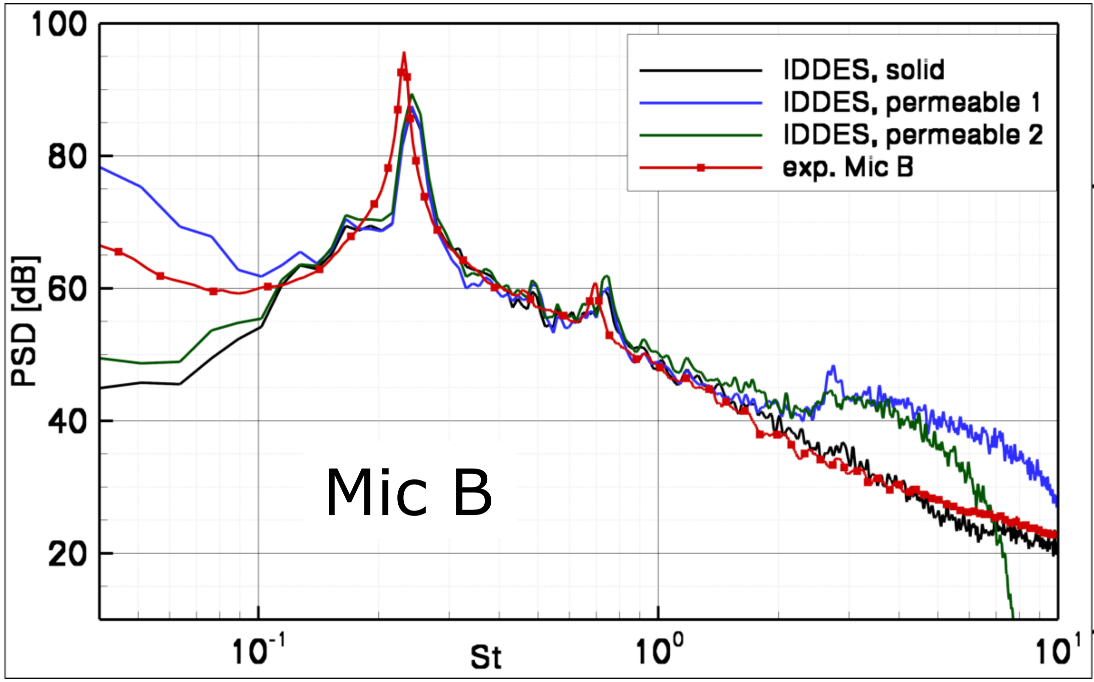
Snapshot from compressible IDDES

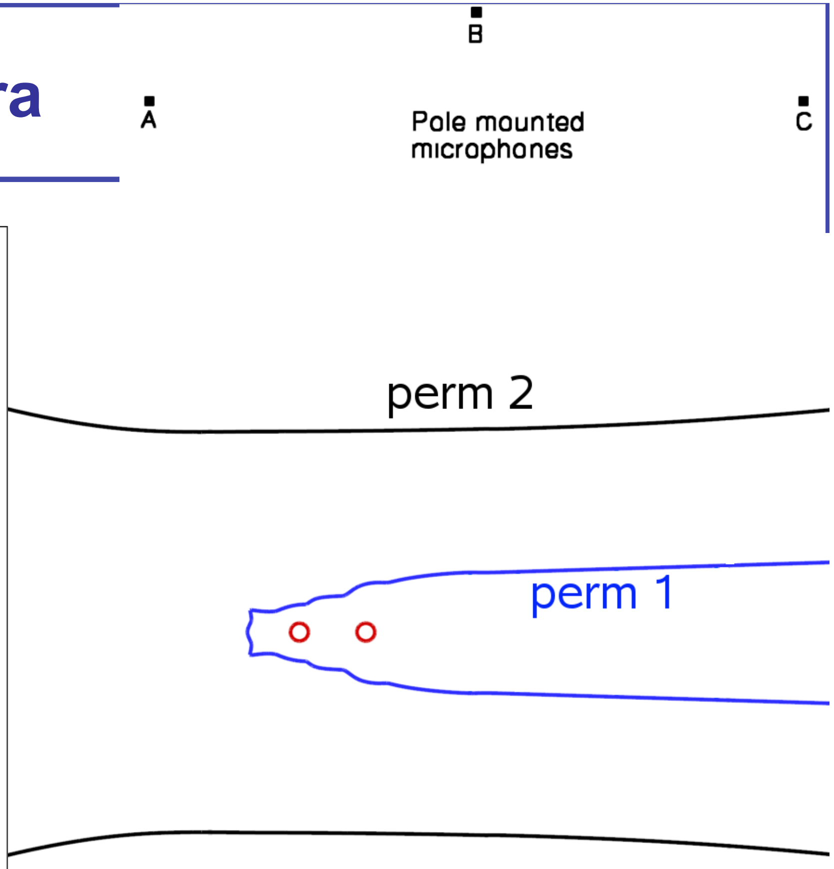






Farfield pressure spectra

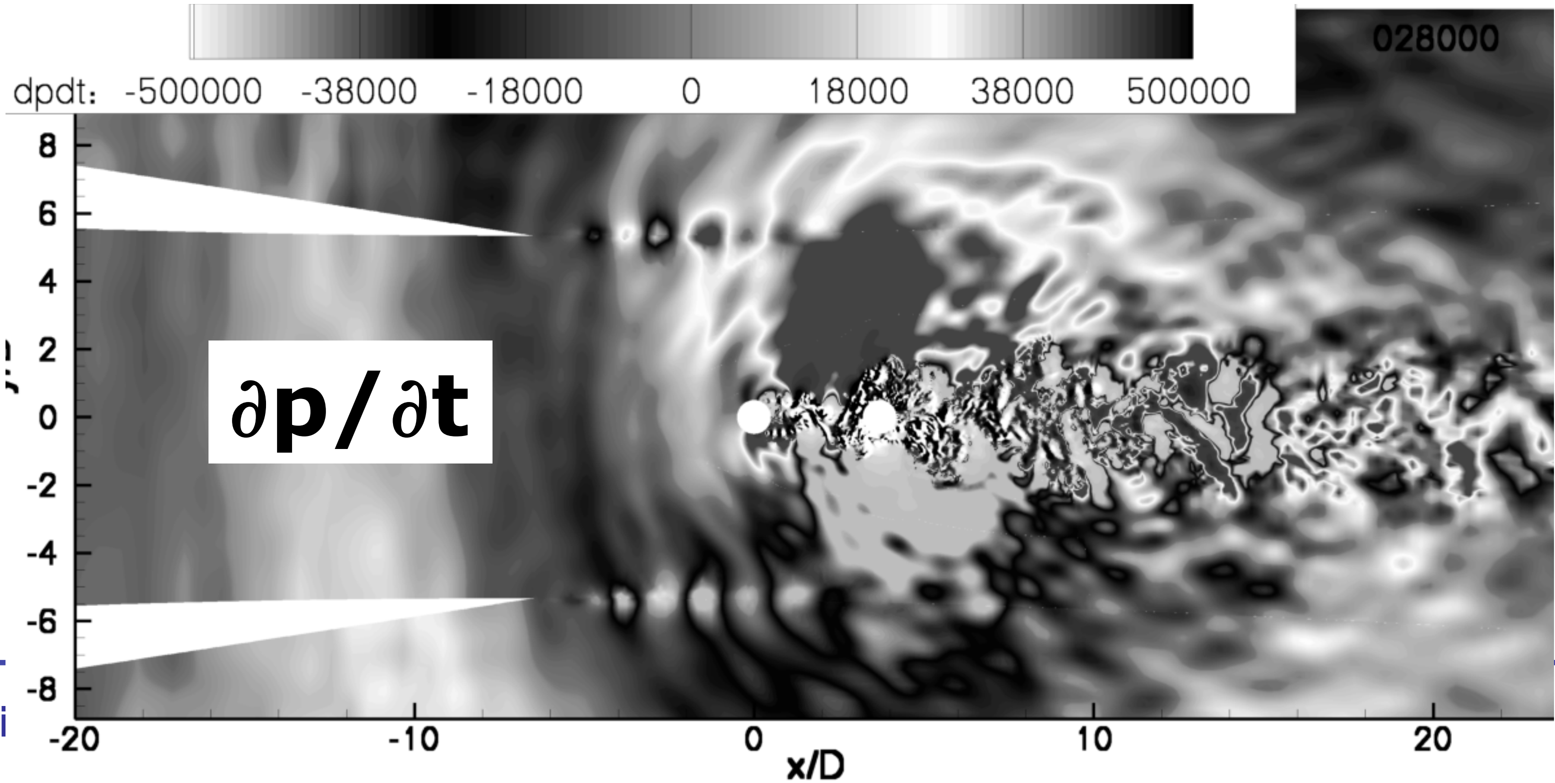




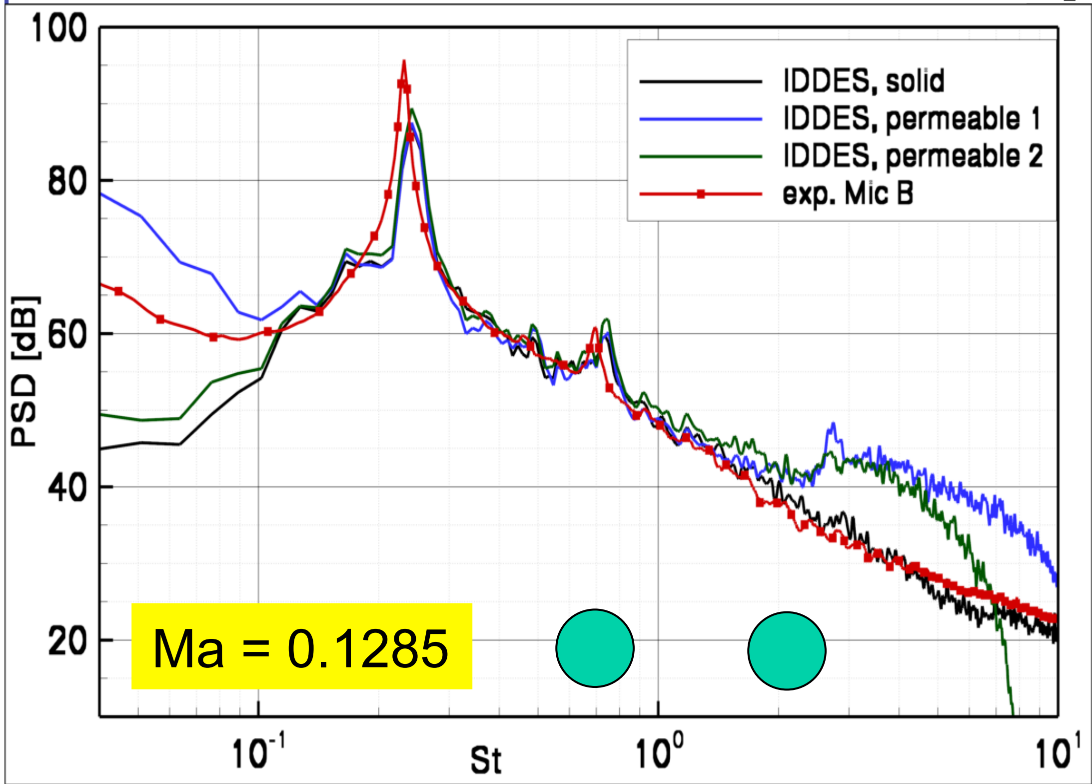
- PSD levels corrected for differing spanwise extent (3D → 16D, +8dB broadband)
- Very good agreement between solid FWH and exp. results (0.1 < St < 10)
- Peak underestimated due to span-correction assuming uncorrelated sources
- Solid and permeable integration results differ by ~ 10 dB in high-frequency range (**not** expected from low Mach number aeroacoustic theory) → spurious noise

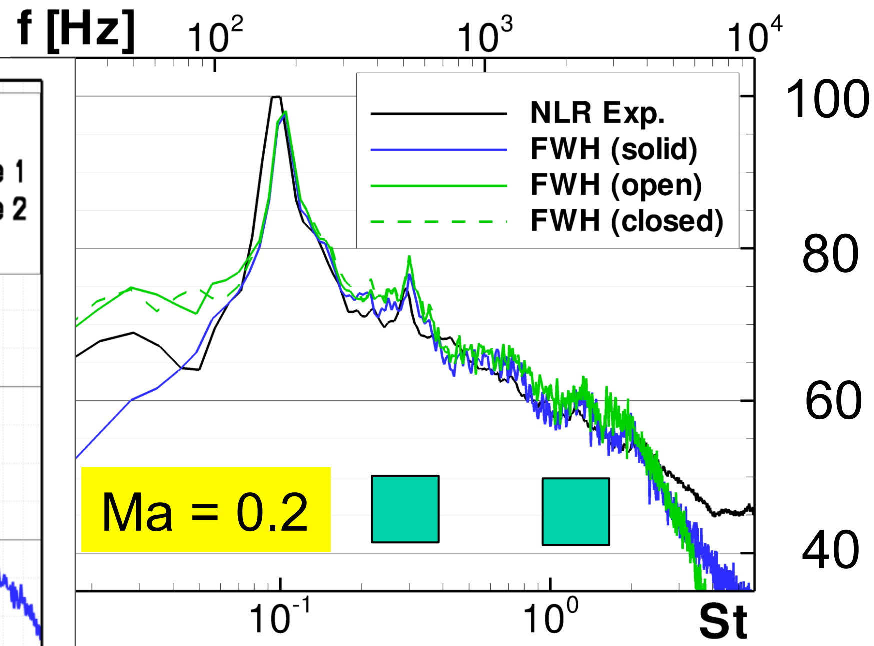
Spurious high-frequency noise

- Spurious noise at high-frequencies stems from wake region (x=10D to 20D)
- Unexpected behaviour
- Mach number very low
- Absolute PSD levels for St = 5 to 10 around 30 dB → p'_{rms}= 0.0006 Pa
- >100 dB below hydrodynamic fluctuations → numerics
- Energetic vortical structures become poorly resolved /deformed in wake region



Comparison TC + 2S cases

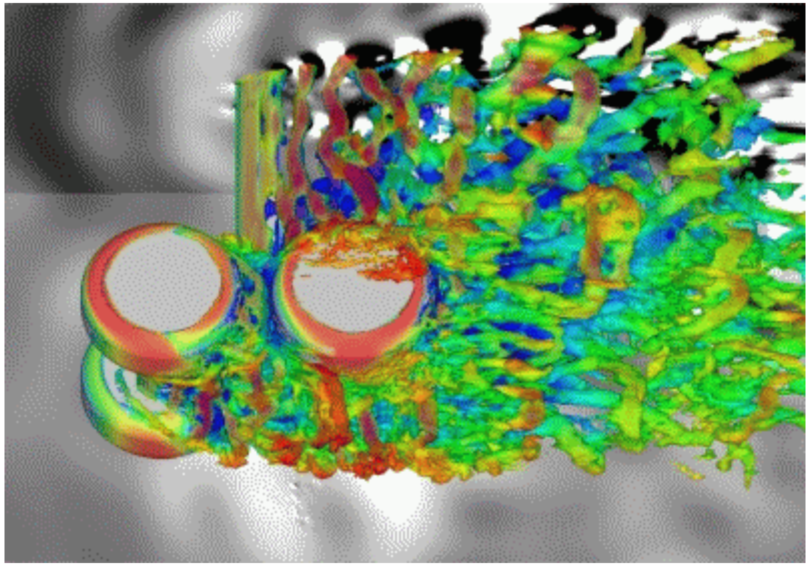




- Spurious „numerical“ noise level in Tandem Cylinder case around 40 dB
- Probably masked by physical noise in Two Struts test case
- Solid wall based FWH results more reliable at very low Mach numbers

Rudimentary landing gear

3



L. Wang, C. Mockett, T. Knacke and F. Thiele: „*Detached-Eddy Simulation of Landing-Gear noise*“, AIAA paper 2013-2069.

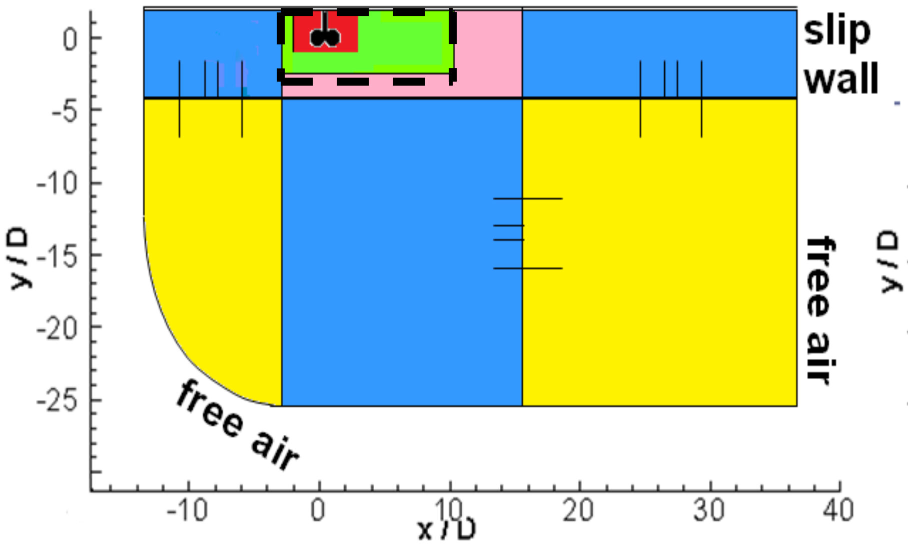
RLG test case

- Rudimentary Landing Gear (RLG)
  - “Stepping stone" test case of the EU project ATAAC (2008-2012)
  - Studied numerically and experimentally by 10 groups.
- 4 wheels but moderate geometric complexity, immersed in uniform flow
- wheel diameter D=40.64 cm
- **Re_D = 1 x 10^6 and 2 x 10^6**
- **Ma = 0.115 and Ma = 0.23**
- **IDDES based on SA-model**
- **Carefully designed mesh**
  - **37 mio cells (for aero-acoustics)**
- **Sampling time at least 31 CTU**

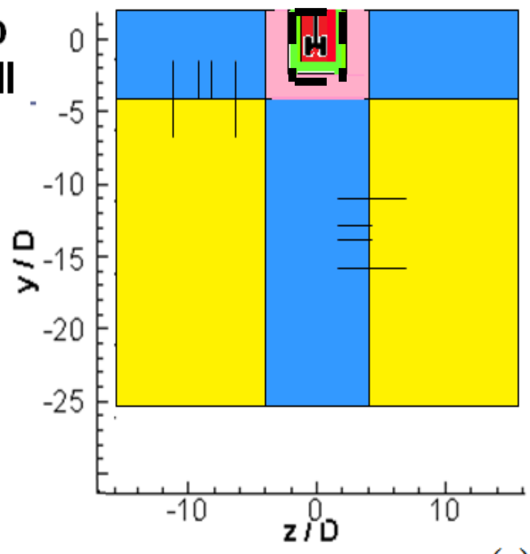
exp. data provided by NAL, Bangalore & University of Florida

Oil-flow visualization (Spalart & Mejia, 2011)

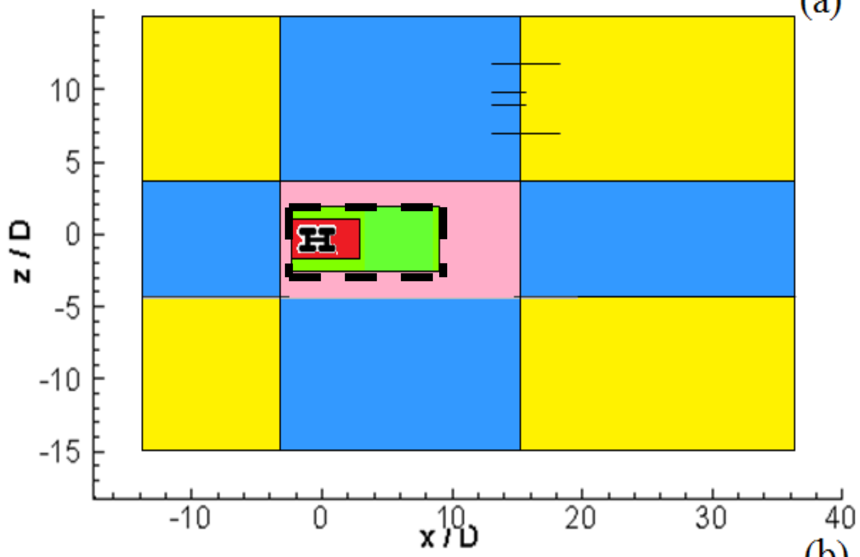
Mesh for aero-acoustic nearfield sim.



(a)



(c)



(b)

	FINE	MEDIUM
red	1-1.01	1-1.02
green	1.02	1.03
pink	1.03	1.05
blue / yellow	1.05/H	1.05

stretching rate in different regions

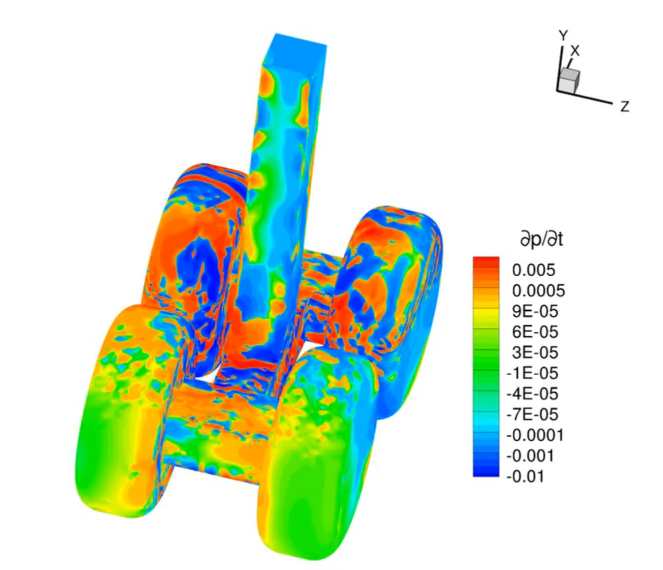
permeable FWH data surfaces

Δ_{max} =0.02 D up to FWH surfaces

Non-reflecting B.C. (Bogey & Bailly 2002)

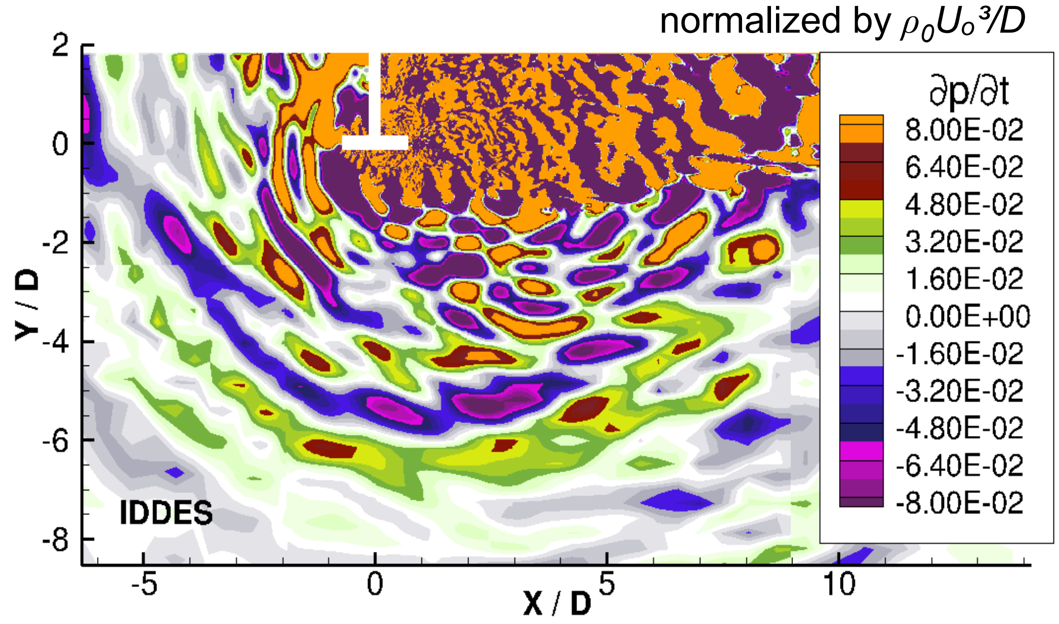
Resolved pressure fluctuations (M=0.115)

on RLG surface



in symmetry plane

normalized by $\rho_0 U_0^3/D$

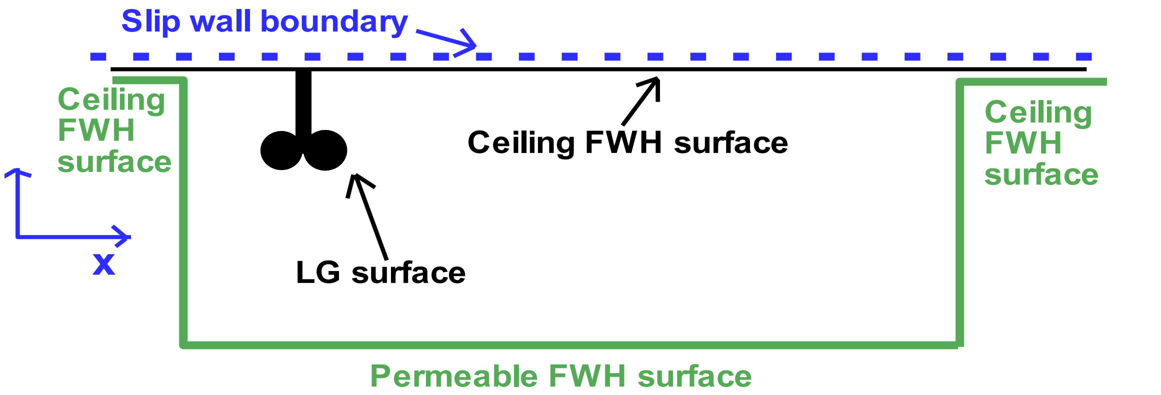


- Intensive turbulent regions exist on the rear wheels due to the impingement of the separated flow from the front wheels.
- Downward-directed wavelength ~1.5 D (changes to ~ 0.75 D for M = 0.23)
- No visible reflections from domain boundaries

Setup of FWH surfaces

"ceiling" approach:
- SC (LG+Ceiling)
- PC (Permeable+Ceiling)

"mirror" approach:
- SM (Solid Mirror)
- PM (Permeable Mirror)

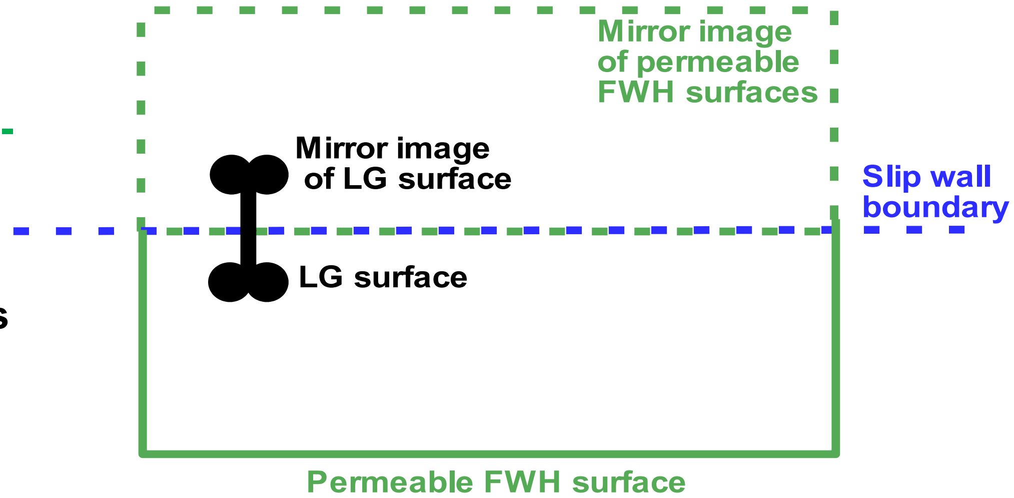


- FWH equation:

$$p'(\mathbf{x},t) = A(\mathbf{x},M_r)\frac{\partial^2}{\partial t^2}\int_V \overline{\overline{\mathbf{T}}}dV \quad \text{Quadru-poles}$$

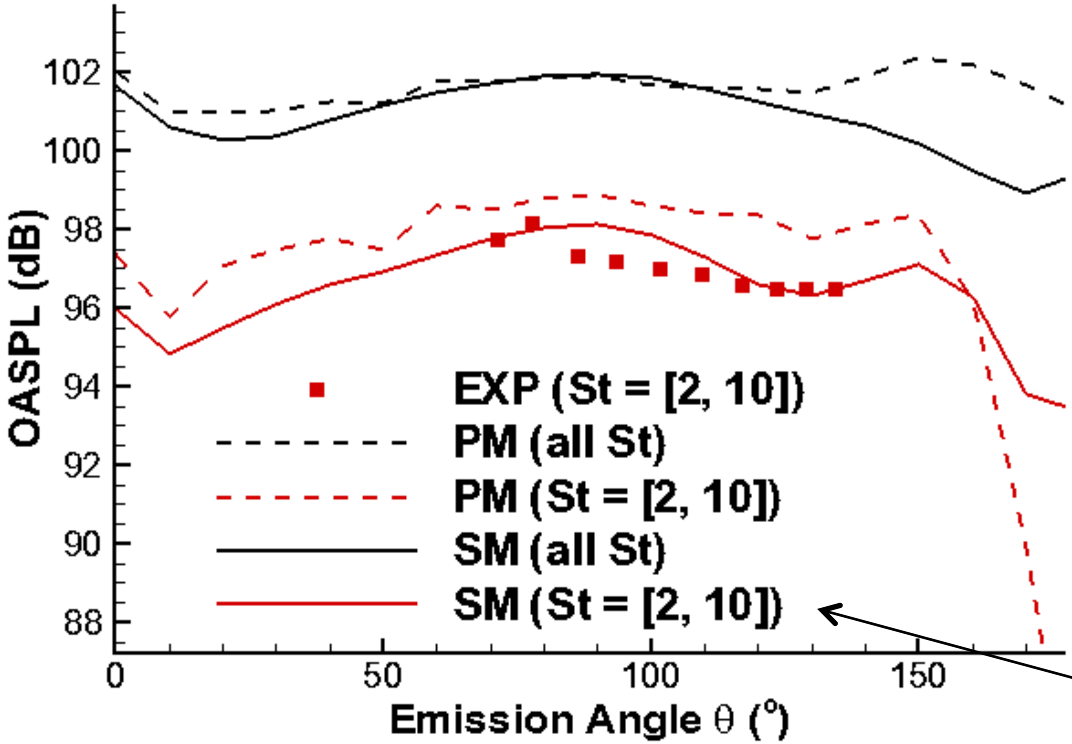
$$+B(\mathbf{x},M_r)\frac{\partial}{\partial t}\int_\Sigma F(p',\rho,\mathbf{u}')d\Sigma \quad \text{Dipoles}$$

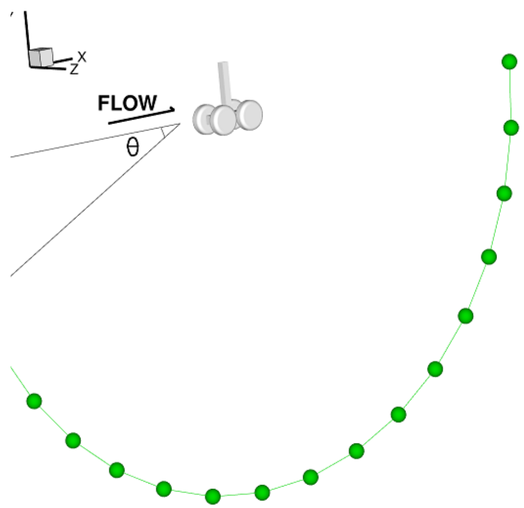
$$+C(\mathbf{x},M_r)\frac{\partial}{\partial t}\int_\Sigma G(\rho,\rho',u_n)d\Sigma$$



Farfield noise directivity M = 0.115

- Very satisfactory agreement in OASPL with exp. data (< 2 dB, all θ)
- Among best agreement seen at BANC-II workshop (others > 5 dB)
- Deviation between SM & PM in downstream direction due to open FWH
- PM spectrum contains more energy than SM case at low frequencies

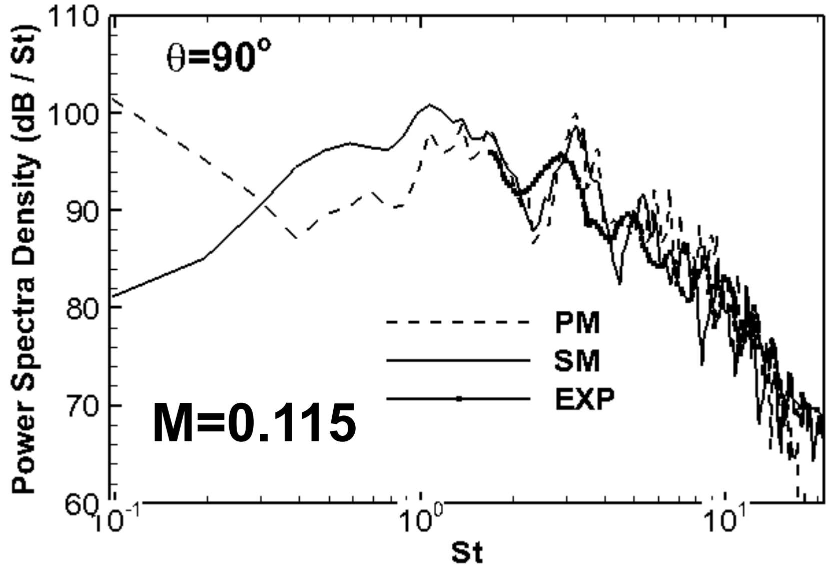


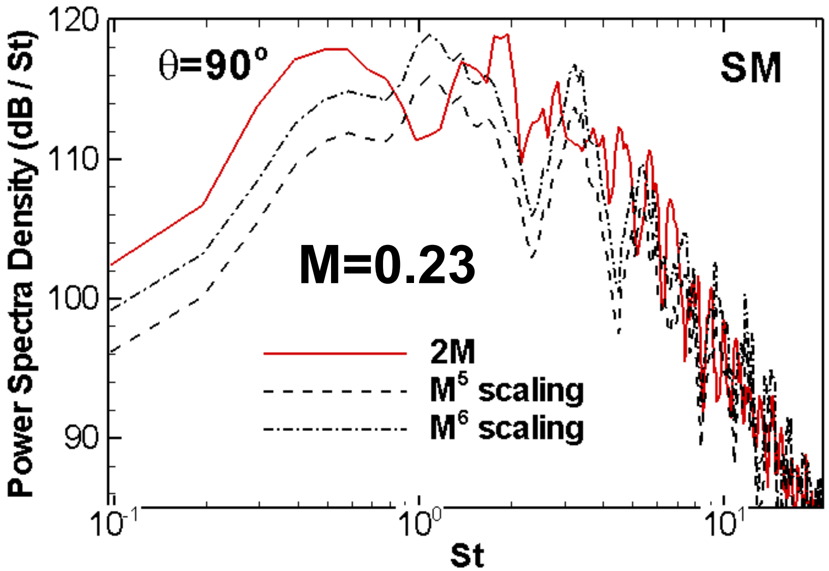


PSD integrated from St = 2 to 10

Farfield noise spectra

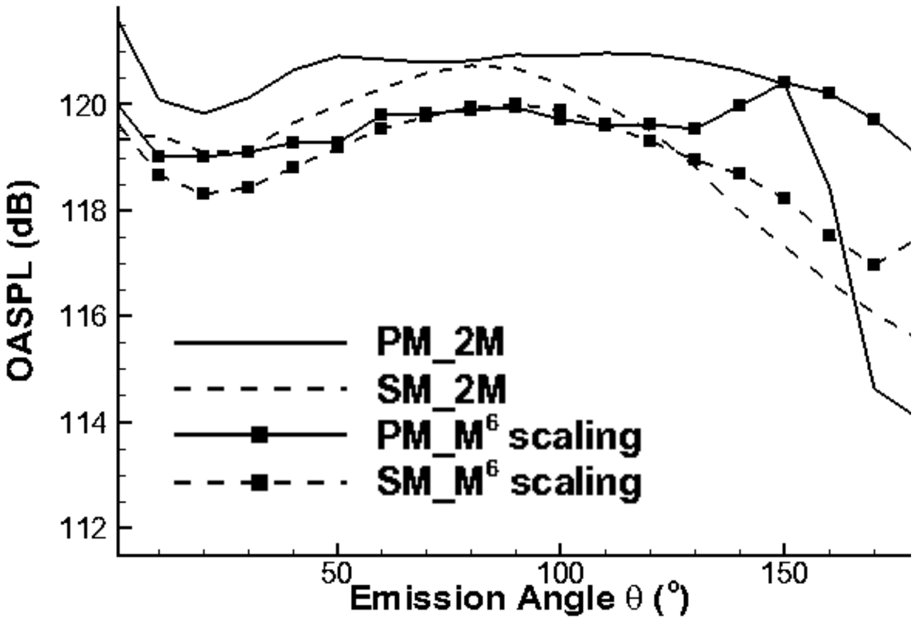
- Good agreement above St = 1 between PM and SM approaches and with experimental data as well
- Deviation between PM & SM at very low frequencies due to open-ended FWH surfaces (Shur et al. 2006)
- Agreement between PM & SM results indicates
  - Low levels of quadrupole noise
  - Low levels of spurious high-frequency noise
- Peaks and valleys due to interference with wave reflections from the ceiling
- Re-scaled results M=0.115 → M=0.23 agree well with higher Mach number sim.

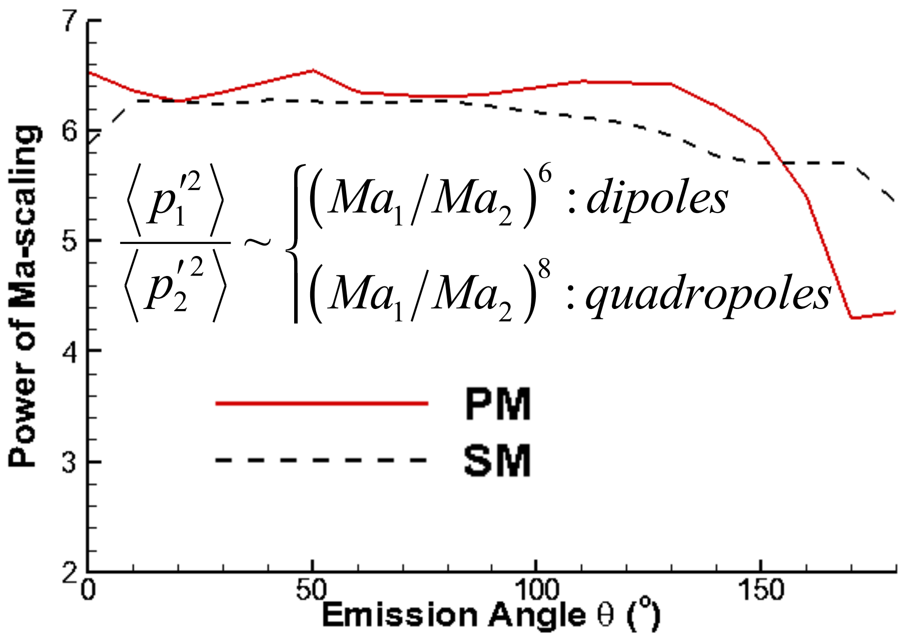




Farfield noise Mach number scaling

- „2M“ → Ma = 0.23 results agree well with re-scaled M = 0.115 results
- M^6 scaling: M = 0.115 OASPL re-scaled assuming M^6 energy scaling
- Actual exponent is about 6.2 to 6.4
- The **dipoles** surpass the **quadrupoles** in acoustic power





$$\frac{\langle p_1'^2 \rangle}{\langle p_2'^2 \rangle} \sim \begin{cases} (Ma_1/Ma_2)^6 : dipoles \\ (Ma_1/Ma_2)^8 : quadropoles \end{cases}$$

Conclusions

- Two-step DES/FWH procedure based on pressure-based solution method very well suited for the prediction of AFN in the high-Re / low-Ma regime
- Good agreement between experimental data and surface pressure based FWH predictions indicates low levels of quadrupole noise
  - Observable in two struts, tandem cylinder and RLG test cases
  - In compliance with low Mach number aeroacoustic theory
- Approximation errors may introduce spurious high-frequency noise sources
  - Spurious volume sources may contaminate permeable surface FWH results
  - Numerical error often masked by physical noise sources
  - Mesh quality important not only in DES „focus region“ but also in „departure region“
  - Need for „quiet“ numerical schemes in nearfield simulation method

    see e.g.

    - T. Knacke: *„Potential effects of Rhie & Chow type interpolations in airframe noise simulations“*, In: Schram, C.; VKI lecture notes on Accurate and Efficient Aeroacoustic Prediction Approaches for Airframe Noise, March 25-28, 2013
- Coupling of DES & solid FWH recommended for AFN prediction at low Ma numbers

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