ON THE IDENTIFICATION OF SOLID SOUND SOURCES VIA THE FFOWCS WILLIAMS-HAWKINGS INTEGRAL

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Ffowcs-Williams Hawkings Integral Equation

$$4\pi|\mathbf{x}|(1-M_r)\,p'(\mathbf{x},t) = \frac{x_j x_l}{|\mathbf{x}|^2 c_0^2}\frac{\partial^2}{\partial t^2}\int_V \{T_{jl}\}_{ret}\, dV$$

External Volume, Quadrupoles

$$+\frac{x_j}{|\mathbf{x}|c_0}\frac{\partial}{\partial t}\int_\Sigma \{p' n_j + \rho u_j(u_n - U_n)\}_{ret}\, d\Sigma$$

Surface, Dipoles

$$+\frac{\partial}{\partial t}\int_\Sigma \{\rho_0 u_n + \rho'(u_n - U_n)\}_{ret}\, d\Sigma$$

Surface, Monopoles

- Post-processing of a turbulence-resolving simulation to far-field
  - Not the same as "finding physical sound source, e.g., quadrupoles"
- Almost all applications have only surface integrals
  - The surf … surround … de it
- The commu …
  - Partly ba …
  - Placing …
  - In most … boundary, thus violating the assumptions

This (FWH) theory is, however, a purely formal one and may need very careful interpretation in many circumstances if erroneous or ambiguous results are to be avoided (Crighton 1975)

Principal Questions Asked Today

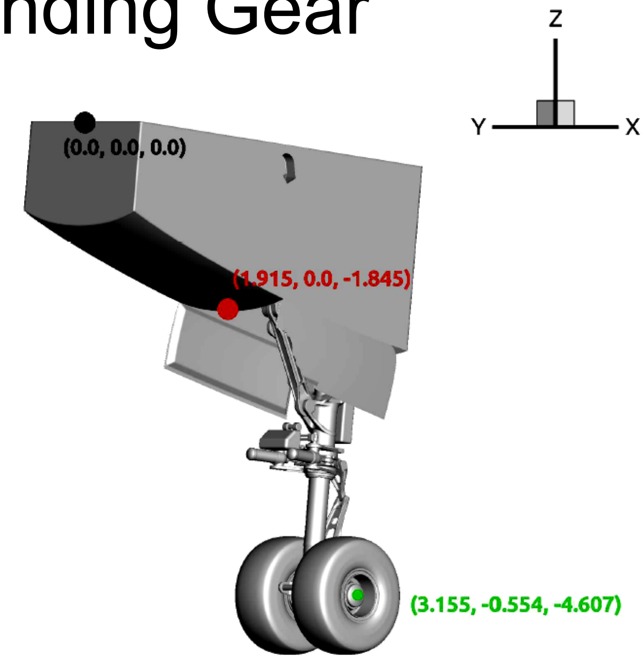
- Many ideas were already in my paper:
  - “On the precise implications of acoustic analogies for aerodynamic noise at low Mach numbers,” JSV, 2013
- Is the solid surface sufficient, for Airframe Noise?
  - Flaps, slats, sharp edges, landing gear, cavities
- Curle’s final arguments hinge on the device being compact
- Does the solid-surface integral allow us to identify the sources of sound?
  - Common approach is to separate

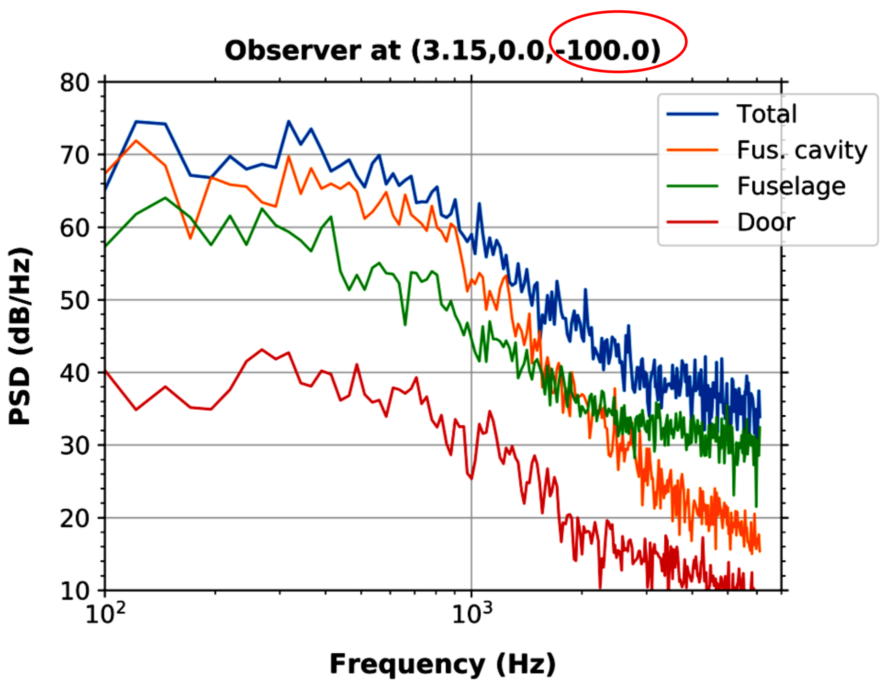
When the surface is non-compact, no general result can be drawn from the formal solution to eqn. (6.6) alone (Crighton 1975)

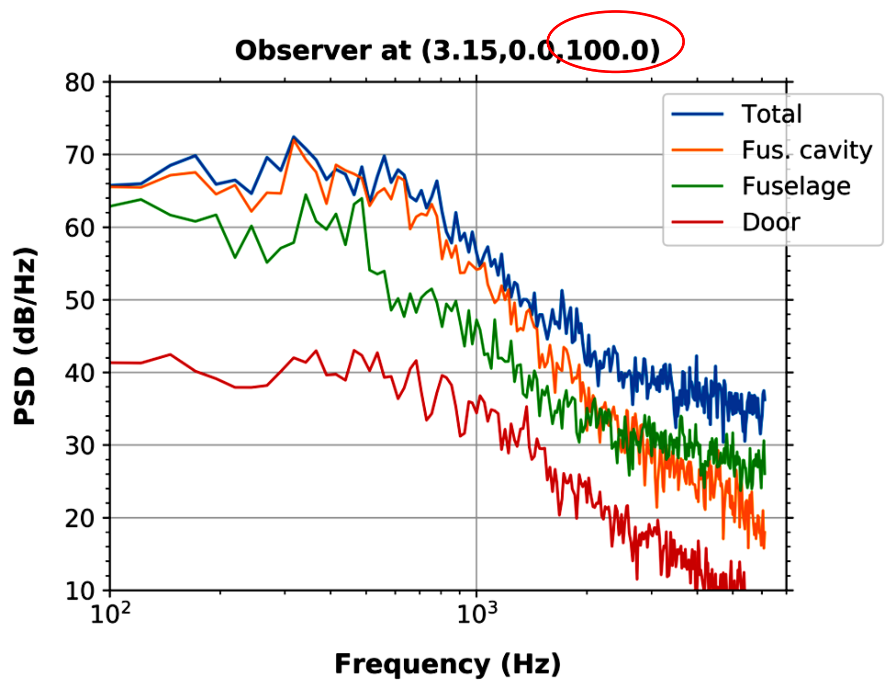
- We
  –
  - Fuselage with cavity
  - Fuselage with bluff body

Solid-Surface Results for Landing Gear

- Work of W. Wolf and T. Ricciardi
  - U. of Campinas, Brazil
  - Collaboration with Boeing (St. Louis)
- Calculated sound is almost the same for observers under the airplane, and above it
  - Seems to be a paradox







Curle's Approximations: a Gentle Reminder…

- Curle correctly showed that the dipole noise satisfies

$$\overline{p_D'^2} / p_0^2 = O(M^6) \quad \text{when M << 1 (df/dt on compact body)}$$

- Everybody "knows" from Lighthill that quadrupole noise satisfies

$$\overline{p_Q'^2} / p_0^2 = O(M^8)$$

  - Therefore, the dipole approximation is of second order in M!
  - Curle wrote this in 1955

- However, the reality is that

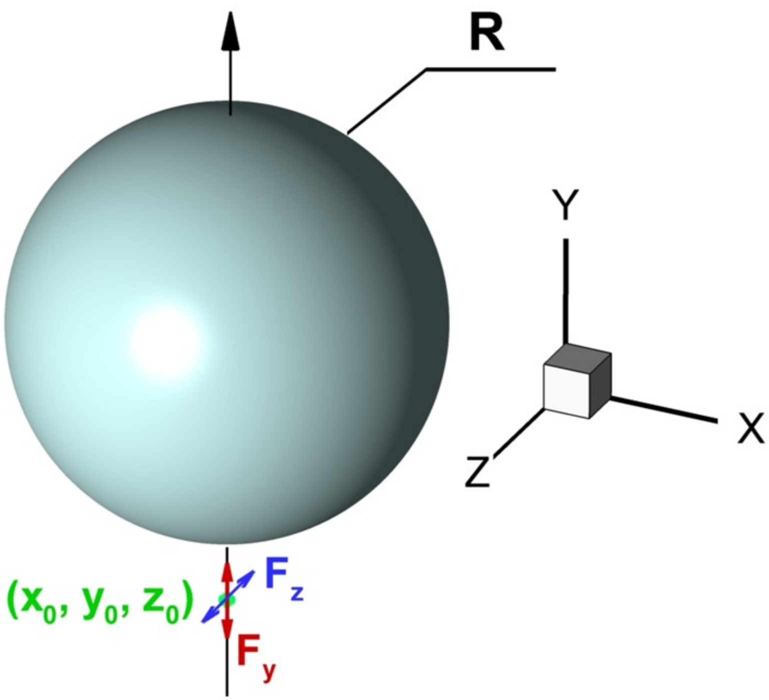
$$\frac{\overline{p'^2}}{p_0^2} = \frac{\overline{(p_D' + p_Q')^2}}{p_0^2} = \frac{\overline{p_D'^2}}{p_0^2} + \frac{2\overline{p_D' p_Q'}}{p_0^2} + \frac{\overline{p_Q'^2}}{p_0^2}$$

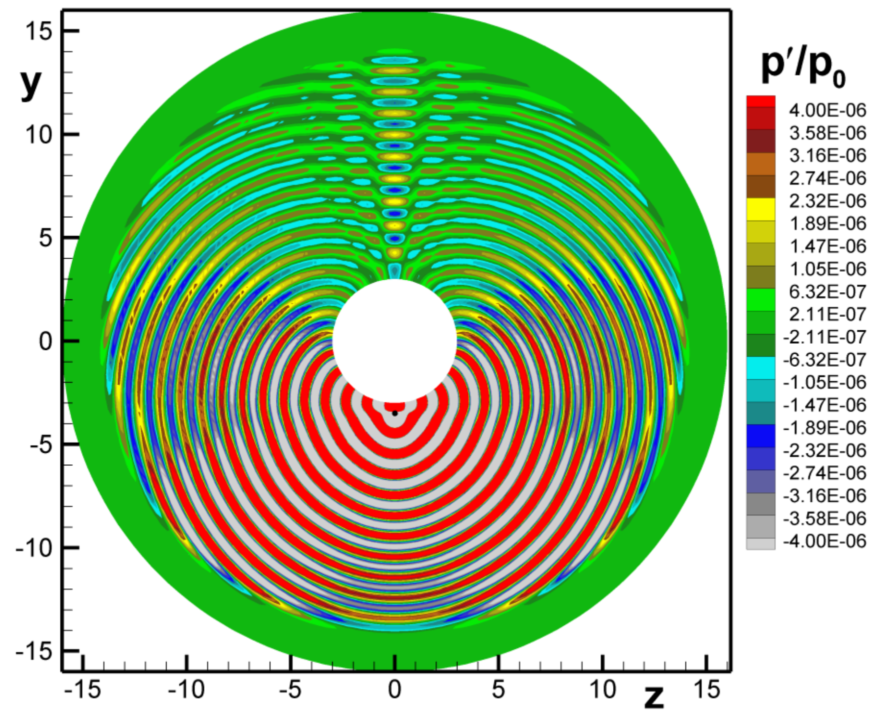
M^6 M^7 M^8 (compact sources)

- Neglecting the quadrupoles *in the presence of dipoles* is only a first-order approximation in M
- The cross-term, $O(M^7)$, may be of either sign!

Model Problem 1: Dipole Under Sphere

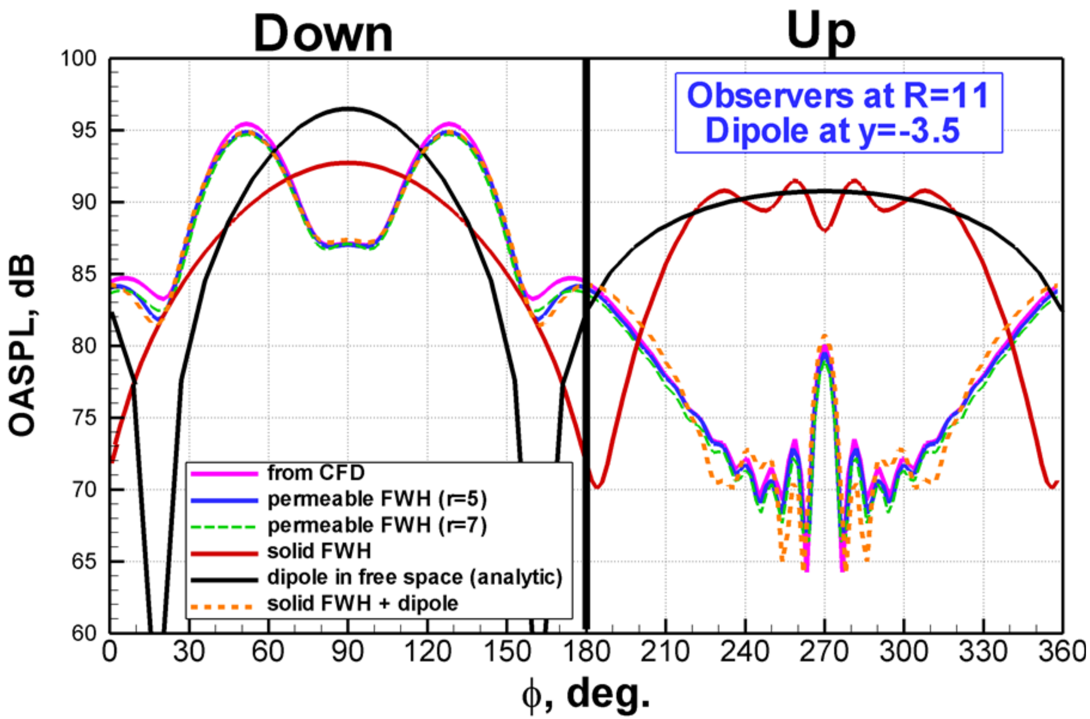
- The oscillating force could be from a wheel, with vortex shedding
- It is the “true” source of sound
  - We could apply Curle’s compact-source theory to it
- Solve this in the presence of a large solid body

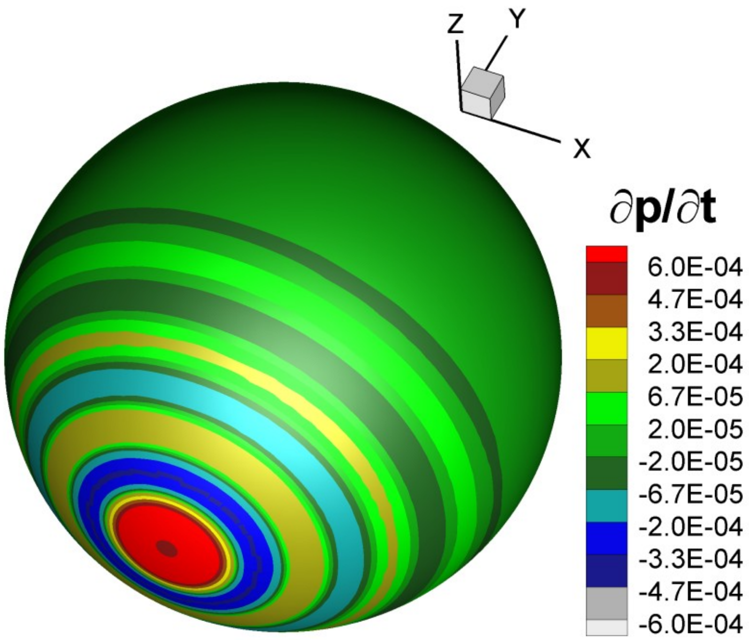




Dipole Under Sphere

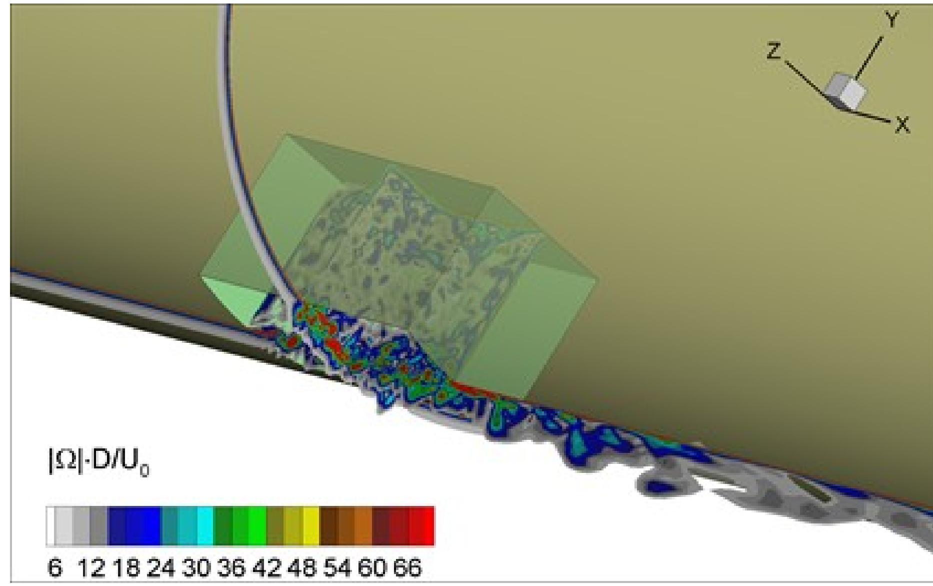
- Apply FWH three ways:
  - Dipole only
  - Dipole and sphere surface
  - Permeable surface
  - Near-field FWH utility courtesy of A. Duben and T. Kozubskaya
- True sound of simulation, permeable FWH, and full solid FWH all agree
  - Sound of dipole alone is very wrong

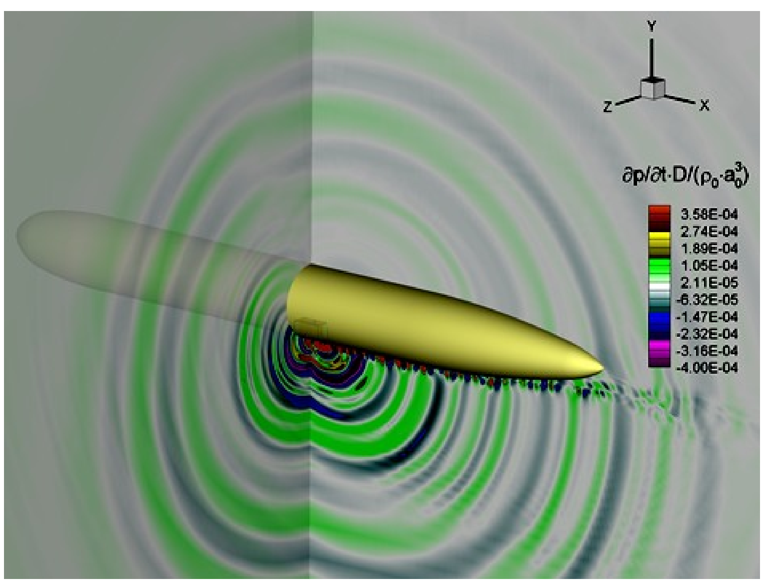


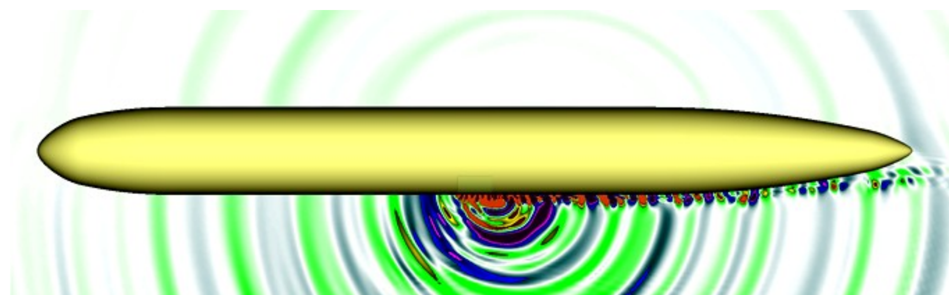


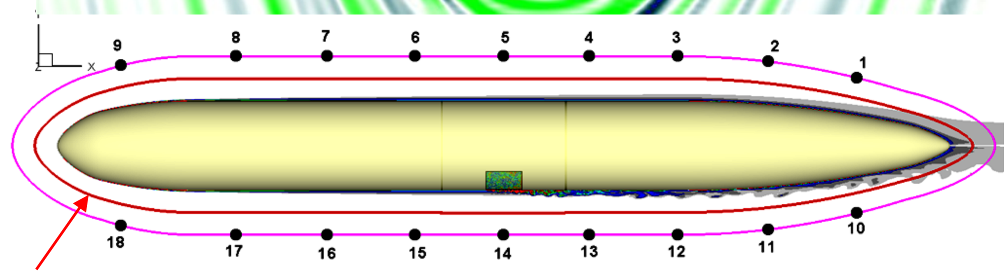
Model Problem 2: Cavity Under Fuselage

- M = 0.25; diameter Re = 10^7
- Detached-Eddy Simulation
- What is "the sound of the landing-gear cavity?"
- Apply FWH three ways:
  - Cavity only
  - All solid surfaces
  - Permeable surfaces
- Compare with true sound of the simulation





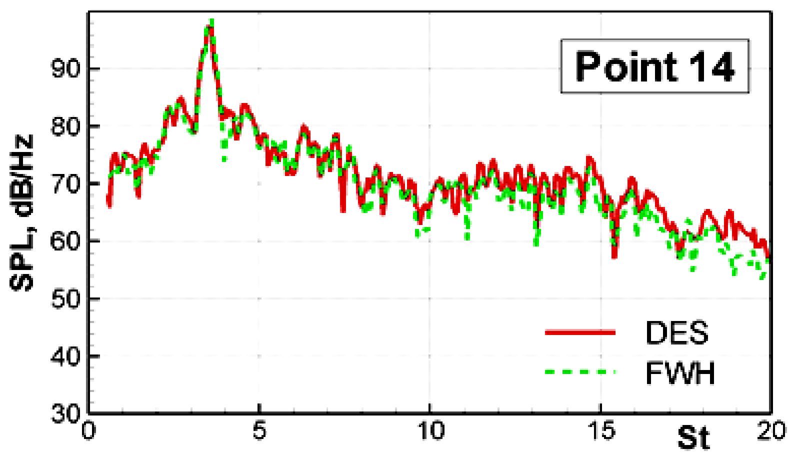


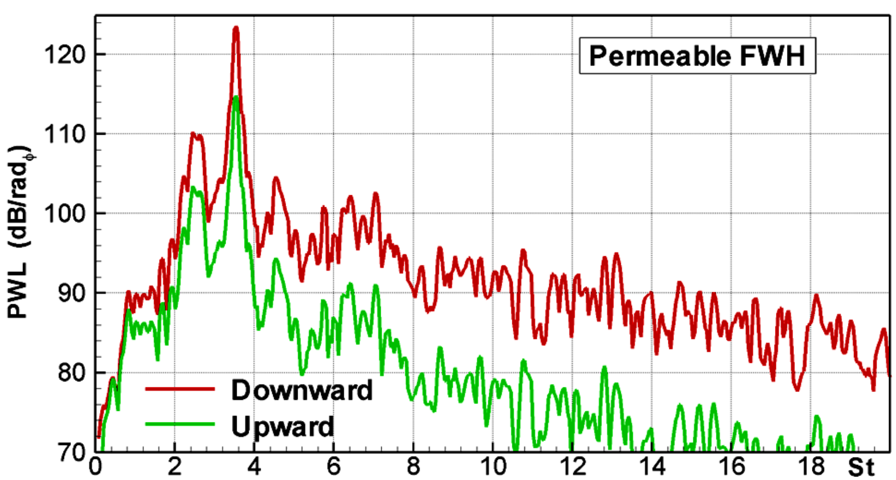


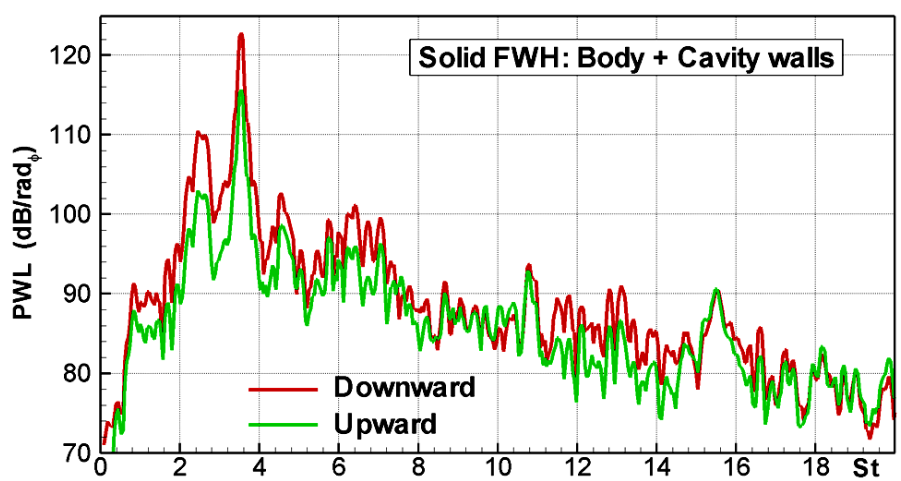
Permeable surface

Cavity Under Fuselage

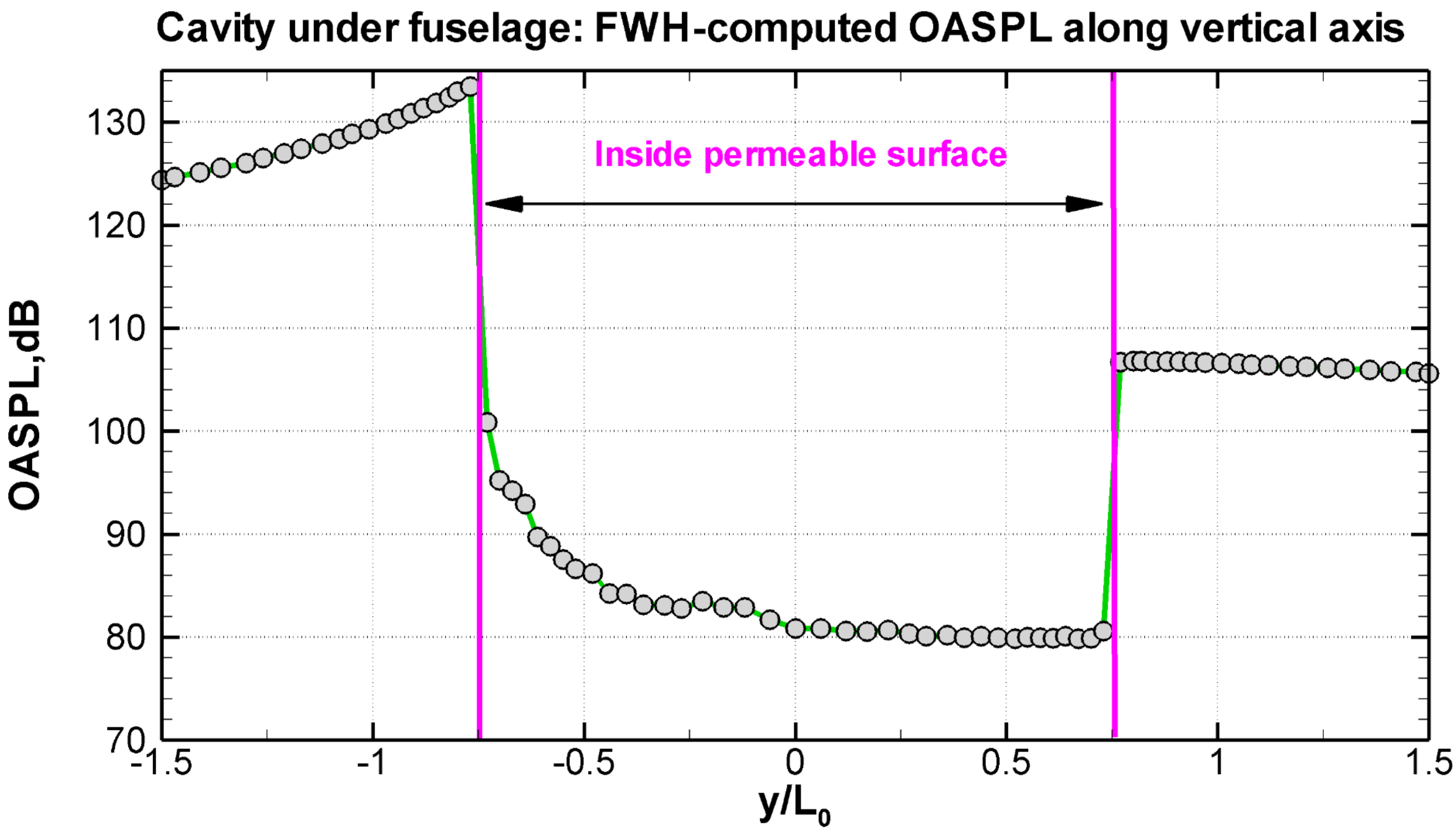
- First check FWH with permeable surface
  - Compare with true sound of simulation
    - They agree
  - Compare sound downward and upward
    - Quite different
  - Sound inside permeable surface (zero, in theory) is lower by 27dB or more
- Then look at solid-only FWH





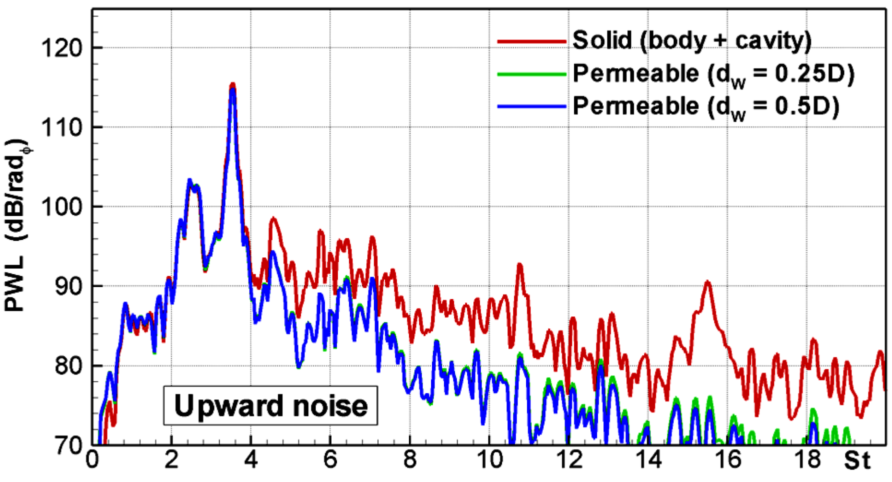


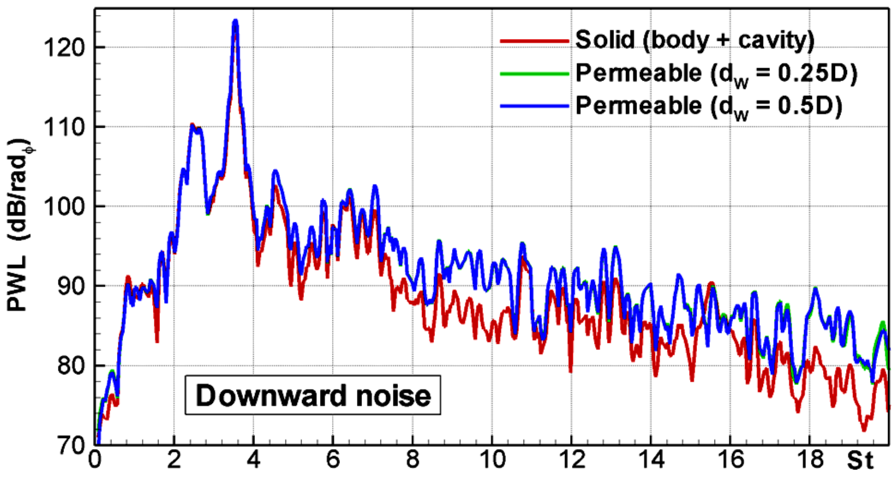
Sound Calculated Inside Permeable Surface



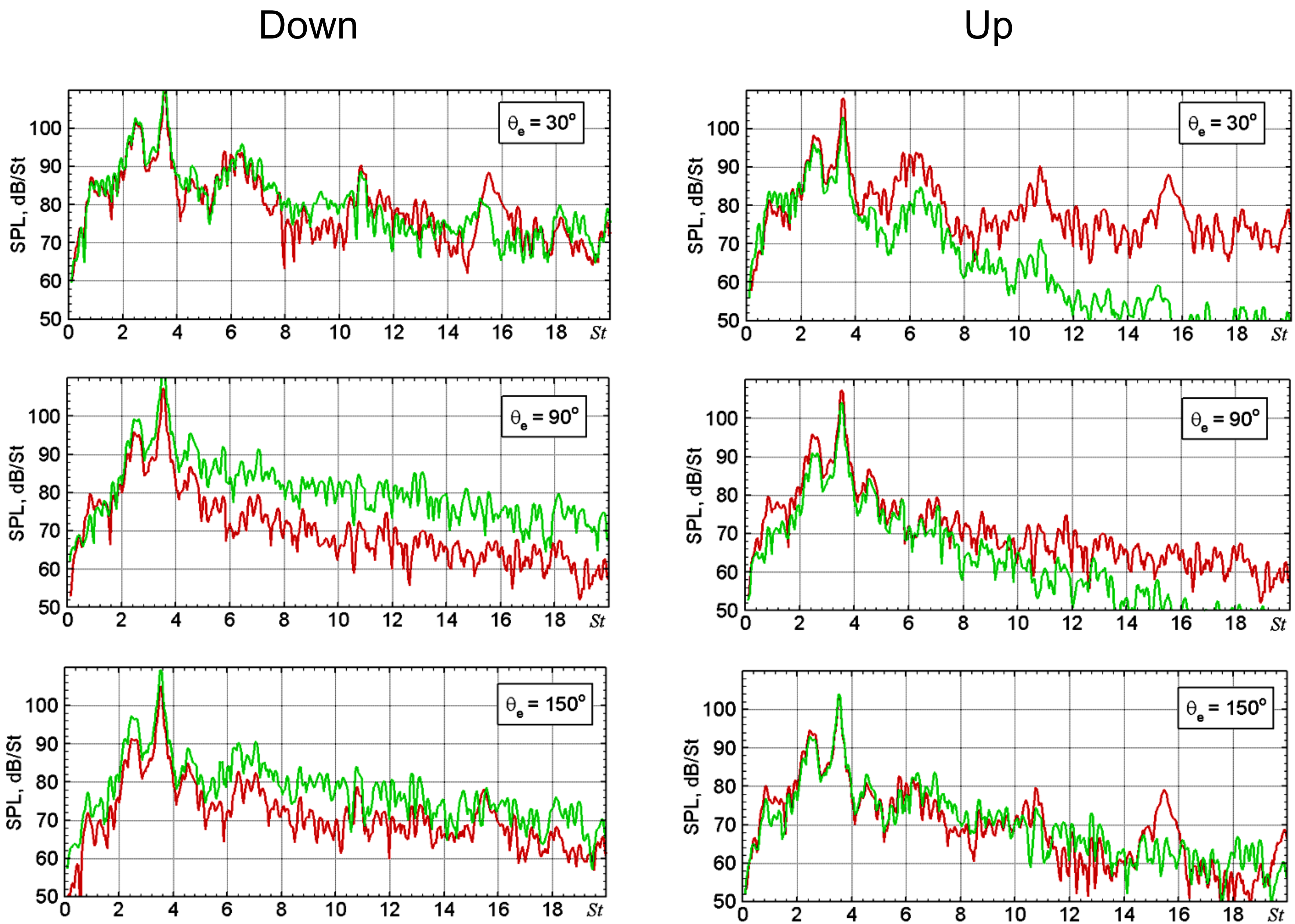
Cavity Under Fuselage

- What is the sound of the landing-gear cavity?
- Solid-only sound
  - Accurate up to St ~ 4
  - Above 4, “quadrupole effect” is strong
    - Solid-FWH sound misses some of the shielding
  - Trying to explain why effect is frequency-dependent…
    - Cannot argue that the body is compact at this St (would mean 1 << 1)



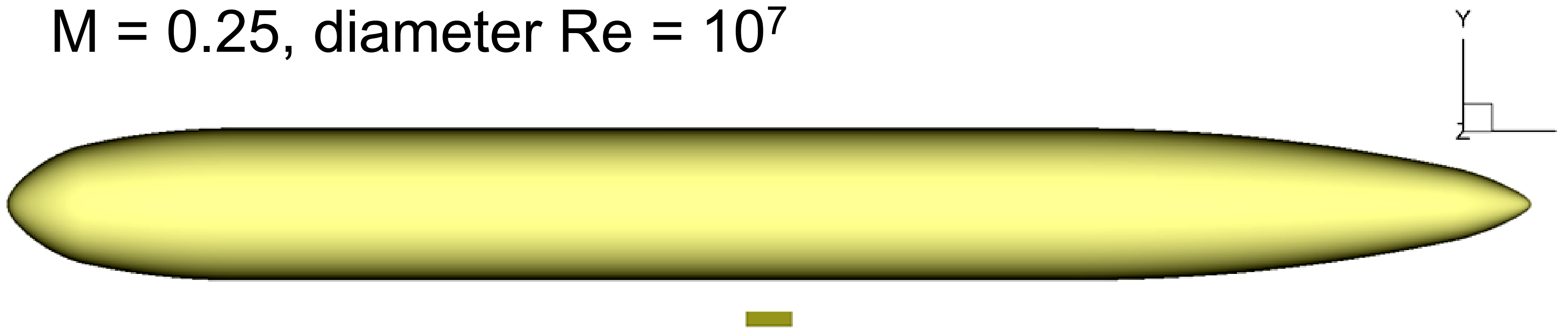


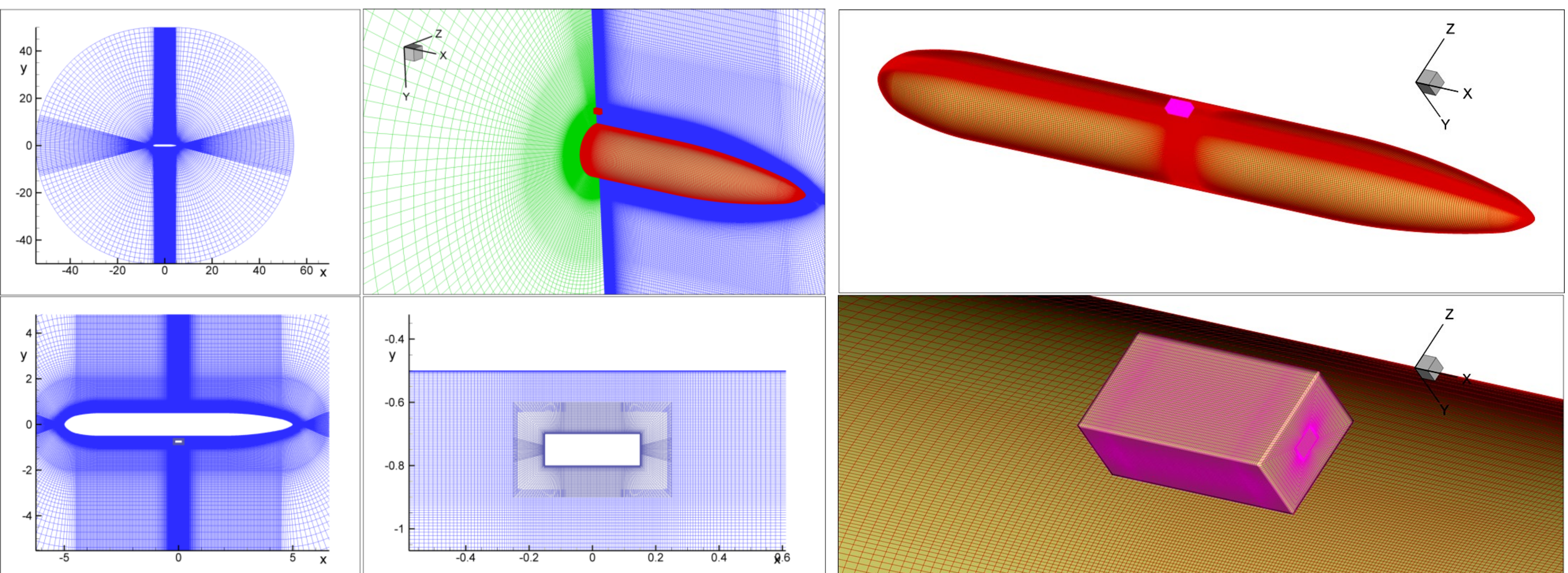
Compare Sound "Attributed to Cavity" and True Sound



Model Problem 3: Bluff Body Under Fuselage

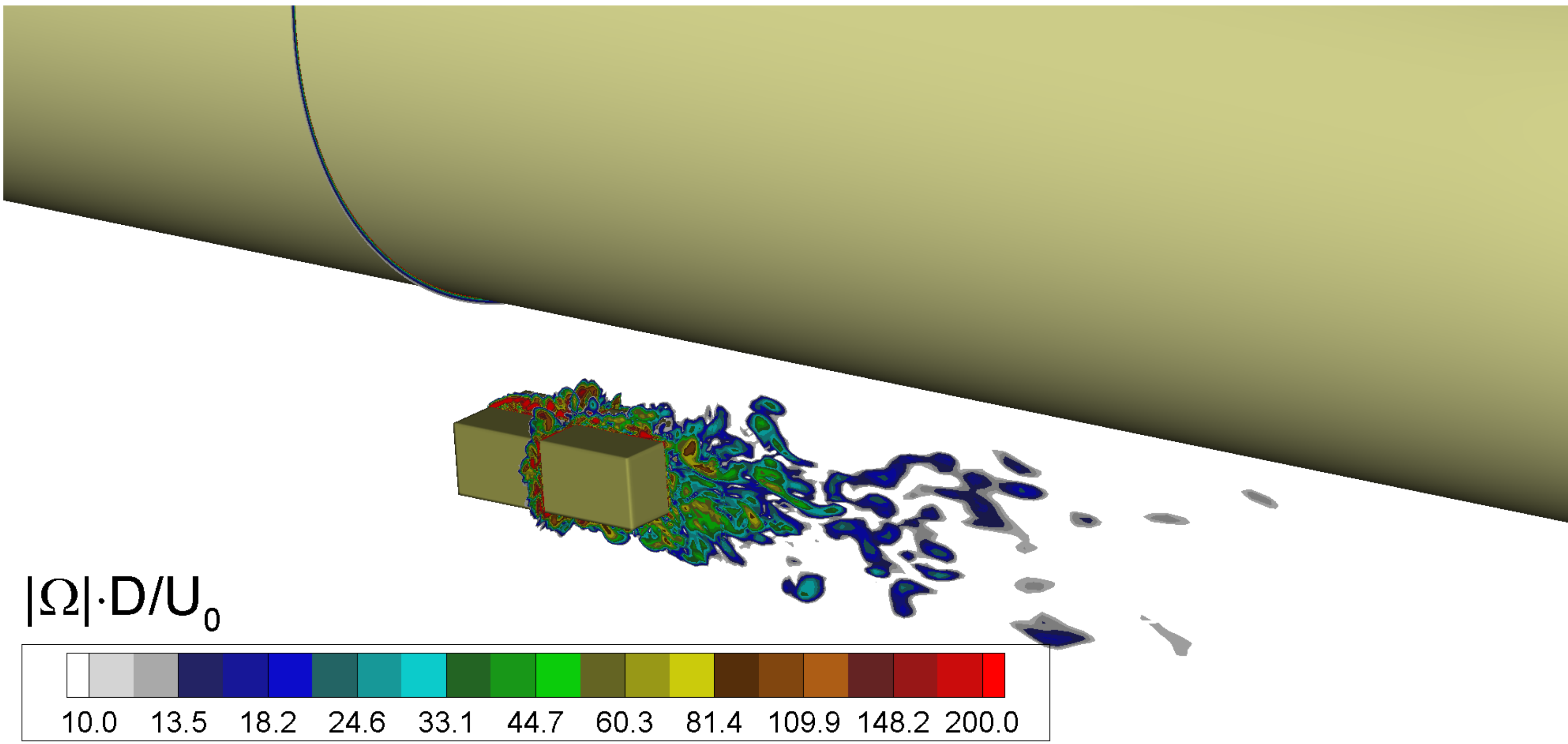
- Model for landing-gear component
- M = 0.25, diameter Re = 10^7



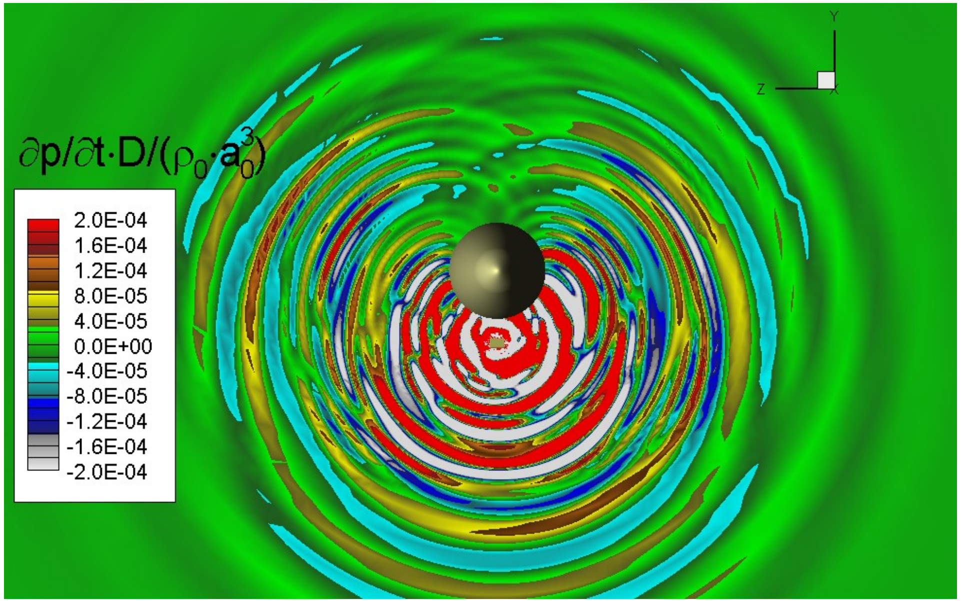


Snapshot of Vorticity

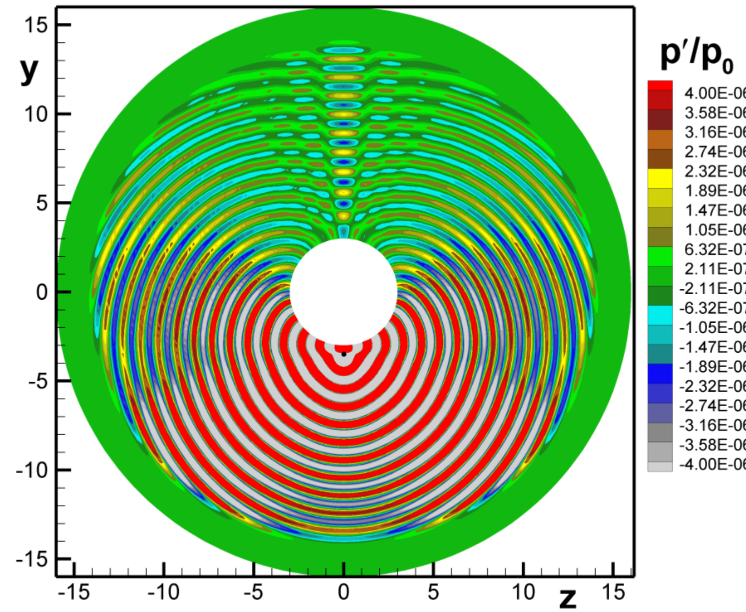
- Fuselage in URANS mode, bluff body in DES



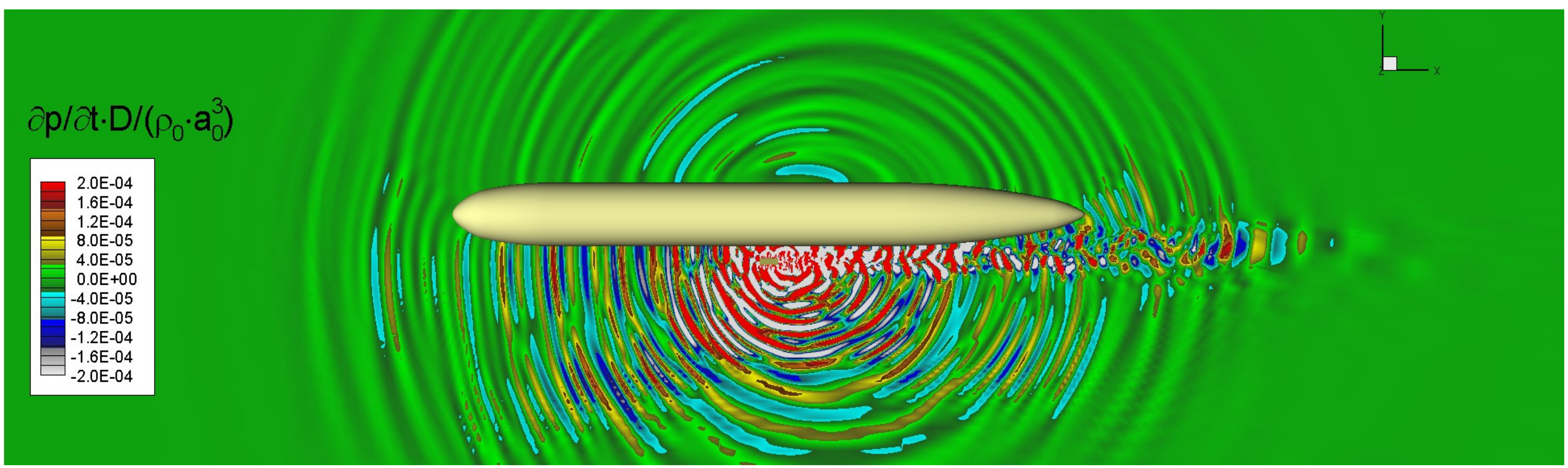
Snapshot of dp/dt



Front view of mid cross-section

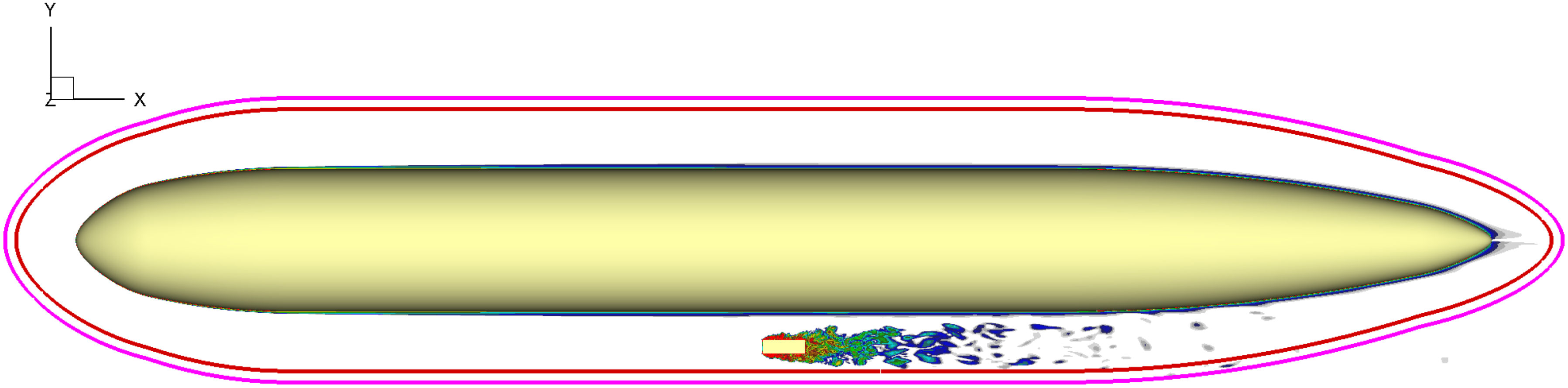


Dipole placed under sphere

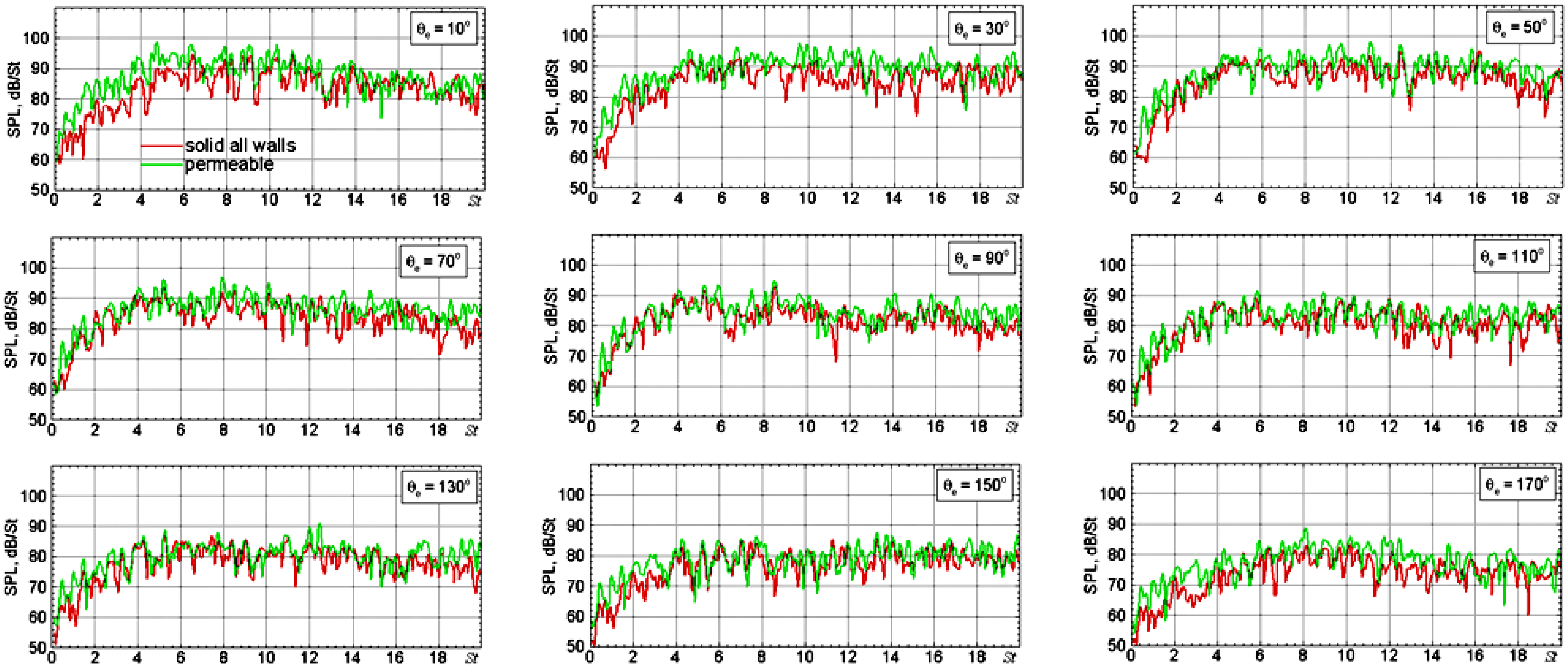


Meridian plane

Nested Permeable FWH Surfaces

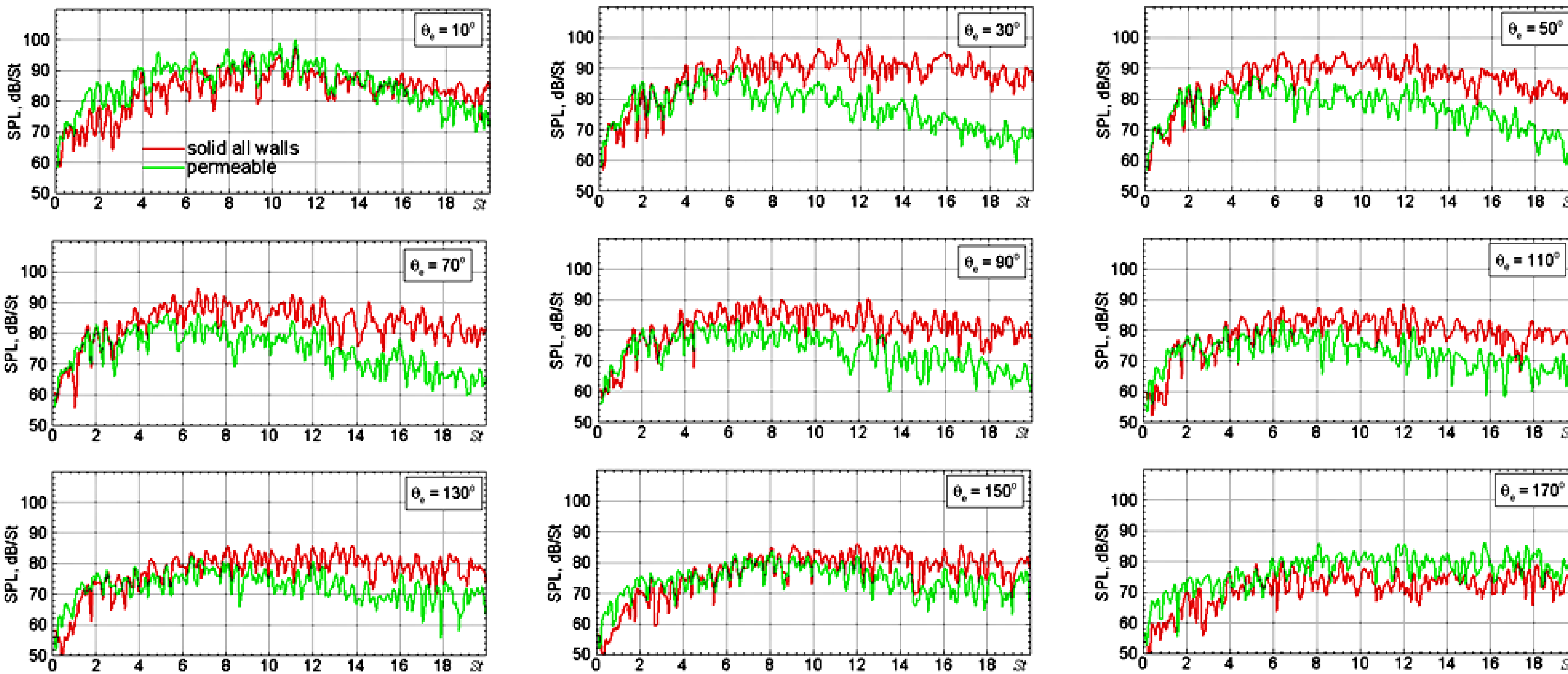


DOWN: All Solid Surfaces (Bluff Body + Fuselage)



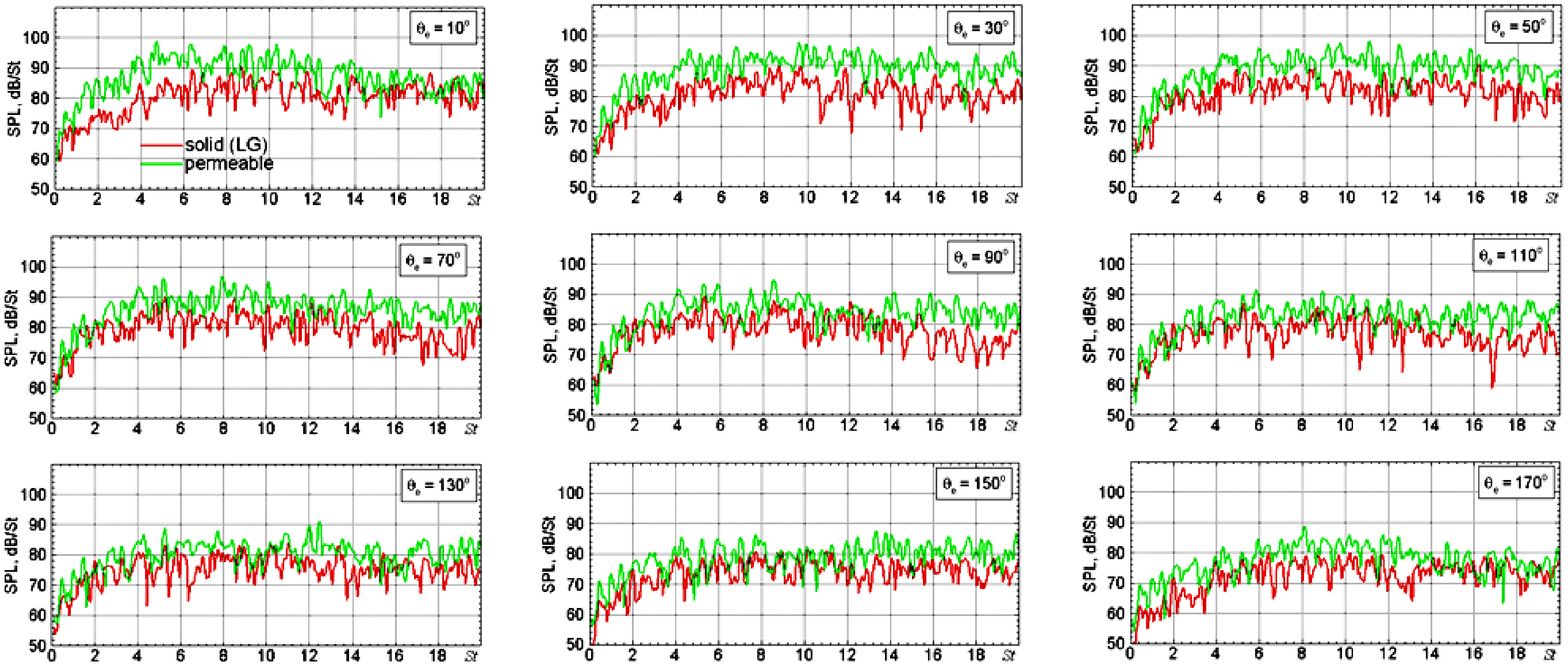
Good agreement of solid and permeable results, except for shallow angles

UP: All Solid Surfaces (Bluff Body + Fuselage)



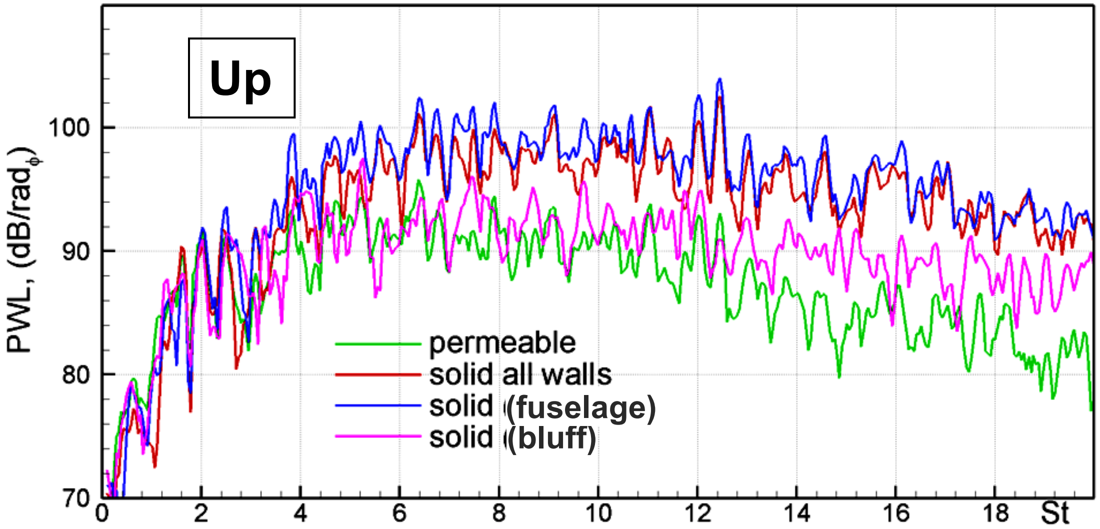
Much worse agreement: solid result is too high

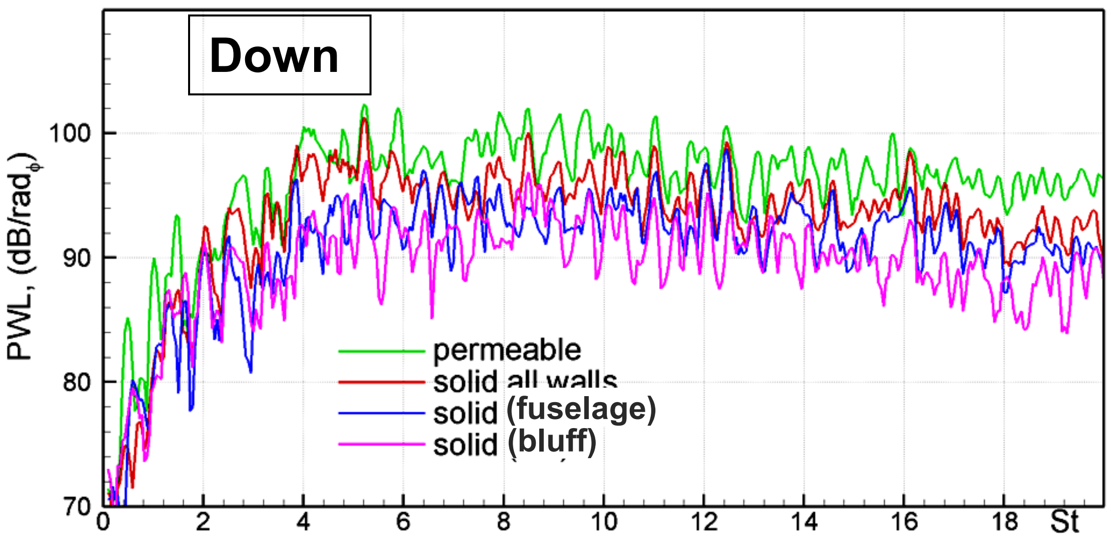
DOWN: Solid Surface, Bluff Body Only



Sound is under-predicted

Sound Power Level

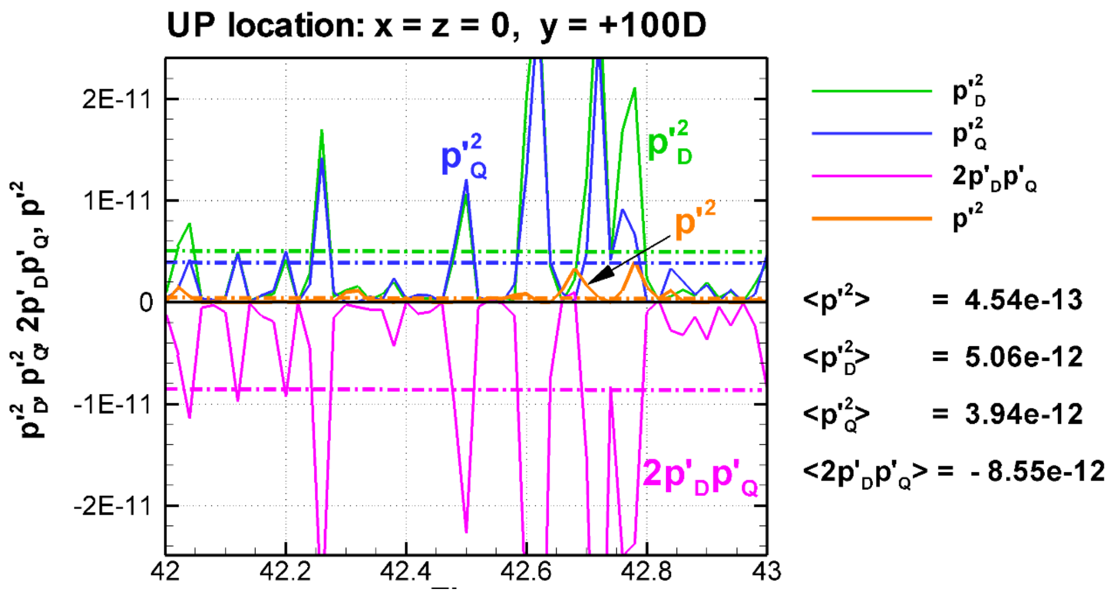




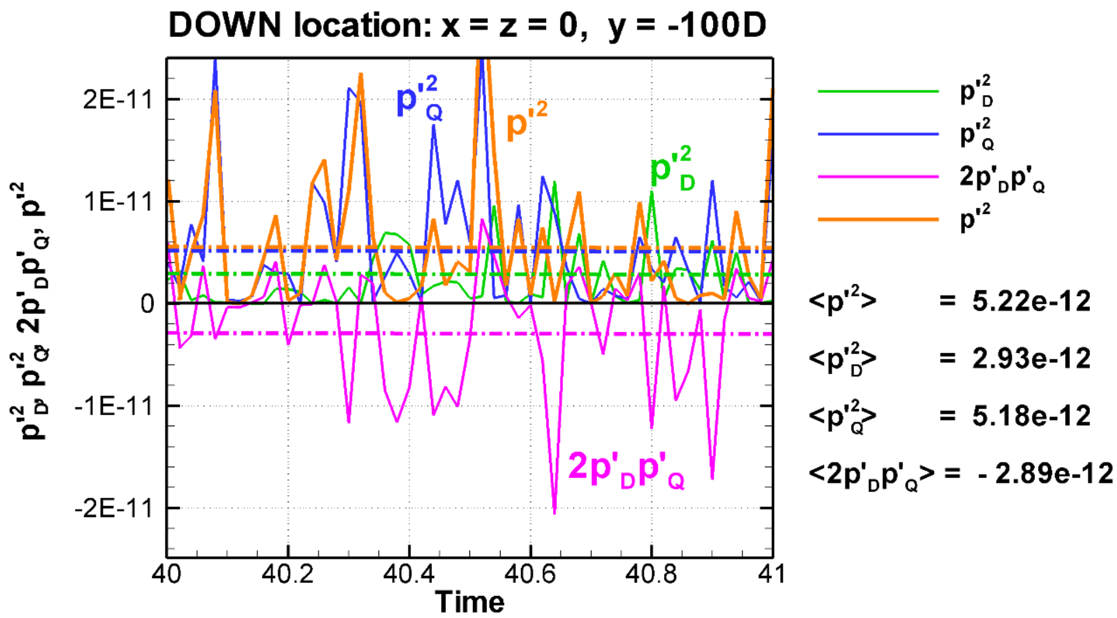
- Similar to what is observed for Fuselage with Cavity, solid FWH with all walls results in:
  - Underestimation of downward noise (up to ~5 dB)
  - Overestimation of upward noise (up to ~12 dB)
- Quadrupole effect is very selective, and can be in either direction
  - In some regions, solid and quadrupole terms essentially cancel each other!

The Three Terms in p'^{2}

- In the upwards direction, the cross-term nearly cancels the two square terms
  - p'$_D$ and p'$_Q$ have very negative correlation: coefficient = -0.96

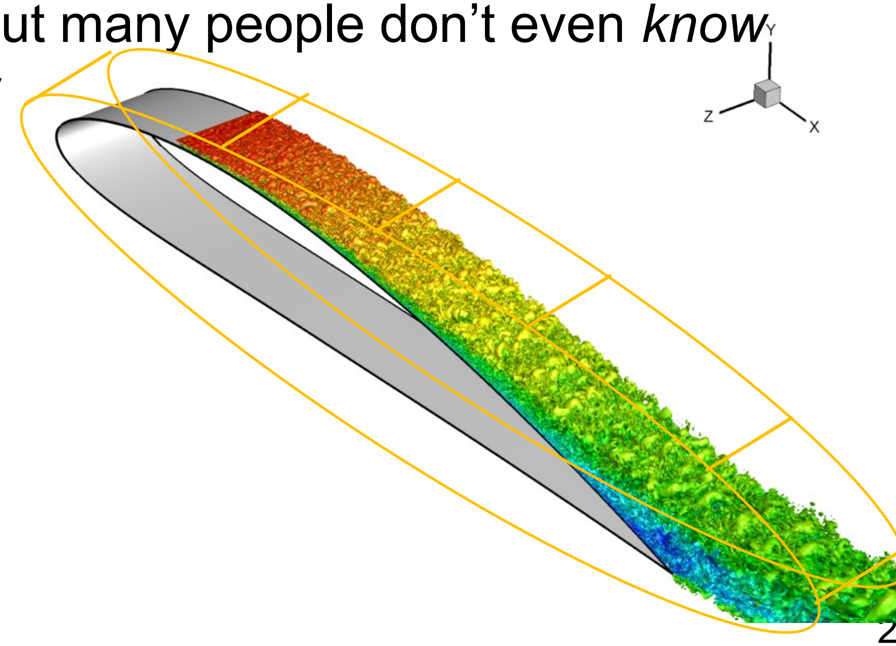


- In the downwards direction, the cross-term opposes the two square terms
  - p'$_D$ and p'$_Q$ have mostly negative correlation: coefficient = -0.37



Application of 3D FWH to Periodic Flow Fields

- Many airfoil simulations use periodic lateral boundary conditions
  - A typical period is 1/10th of the chord
- People then apply FWH to the "slice" of surface, solid or permeable (gold patches)
  - This uses the 3D Green's function as if the surface surrounded the turbulence (on all sides)
- The two "sound fields" have nothing in common
  - The pressure p' from 3D FWH decays like 1/r
  - In the real flow, p' decays like 1/√r
- There are "corrections" for length, but many people don't even *know* this is a violation of the FWH theory



- What is needed is a periodic version of FWH
  - Although this would give the "true" sound, but not a comparison with a finite-span experiment
  - Lockard has a 2D version, but not periodic

Summary

- The FWH integral is an essential part of far-field sound calculations
  - And comparisons with the simulation in the near-field are good
  - Properly closing the permeable surface is delicate
- *Grid convergence of turbulence-resolving simulations on complex geometries is not in hand*
- Too many people take the “easy” solution of including only solid surfaces
  - Often, “good” agreement is invoked, but standards are much too low
    - “a 10dB disagreement is not so bad…”
  - Quadrupoles often cannot be neglected
    - Also recall the M^7 scaling
    - Some mild “mysteries” remain in terms of physics (the St < 4 range)
  - People are even satisfied with mediocre agreement for the wall-pressure fluctuations (hydrodynamic)
    - I believe these should be seen on linear axes…
- Separating parts of the aircraft in the integral can be misleading
  - It rapidly leads to paradoxes, often related to shielding
  - There would be great technological value in identifying “dominant” source
- Future plans: varying Mach, hoping to confirm $M^6/M^7/M^8$ scaling
  - Write paper, if feedback here is good