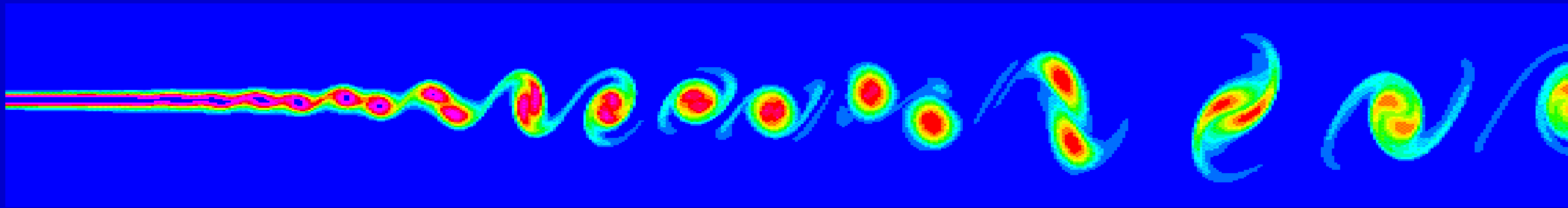

AERO-ACOUSTICS AT LMS INTERNATIONAL

Overview : May 2002

Colin McCulloch

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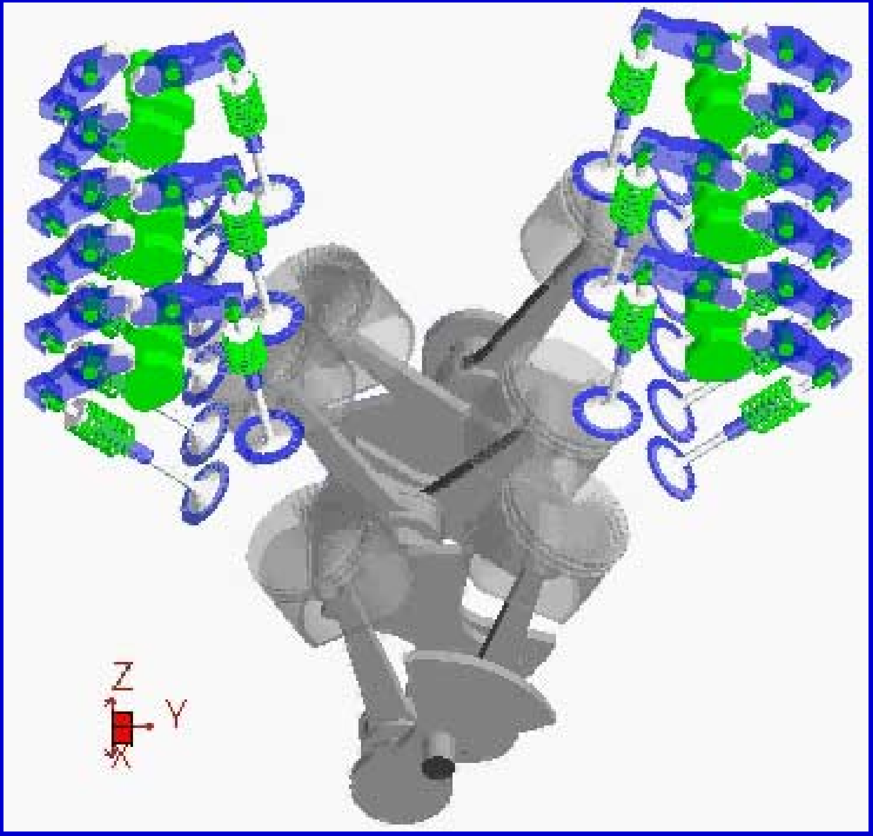
But first… a digression…

- Structural dynamics
  - MBS + FEA => Strong coupling!
- Vibro-acoustics
  - Weak coupling
  - "Standard stuff"
- Classic applications
  - Engine acoustic radiation prediction
  - …

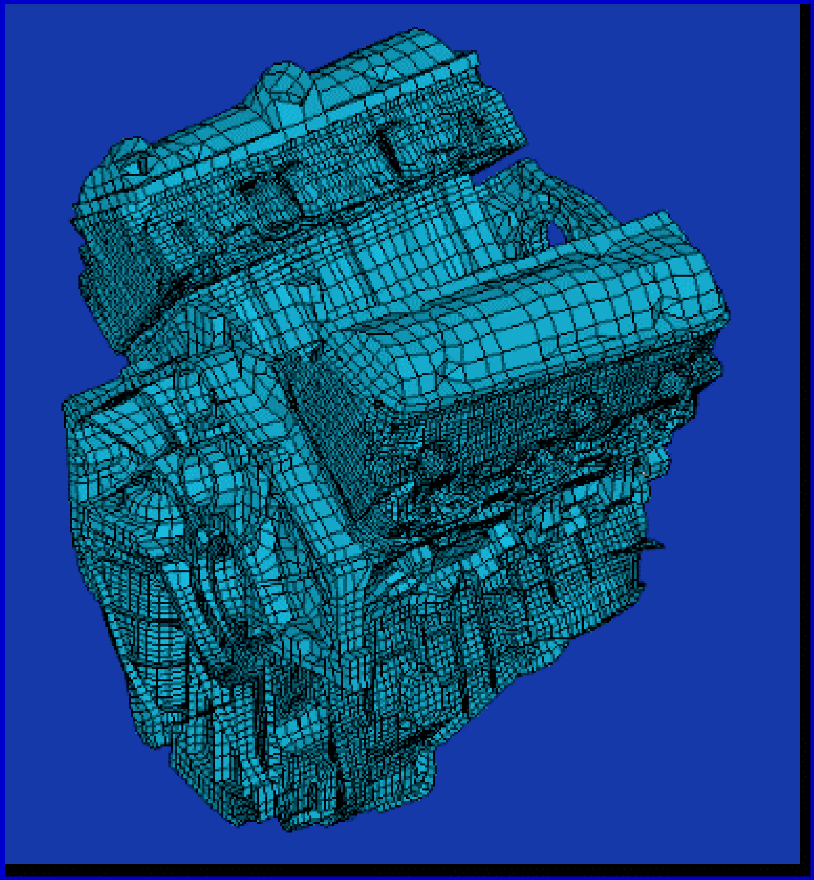
Engine Dynamics

Air-borne and Structure-borne noise come from this...



Engine Internal Dynamics and Structural Modes

Modes in time domain model => MPFs



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Engine Acoustic Radiation

We

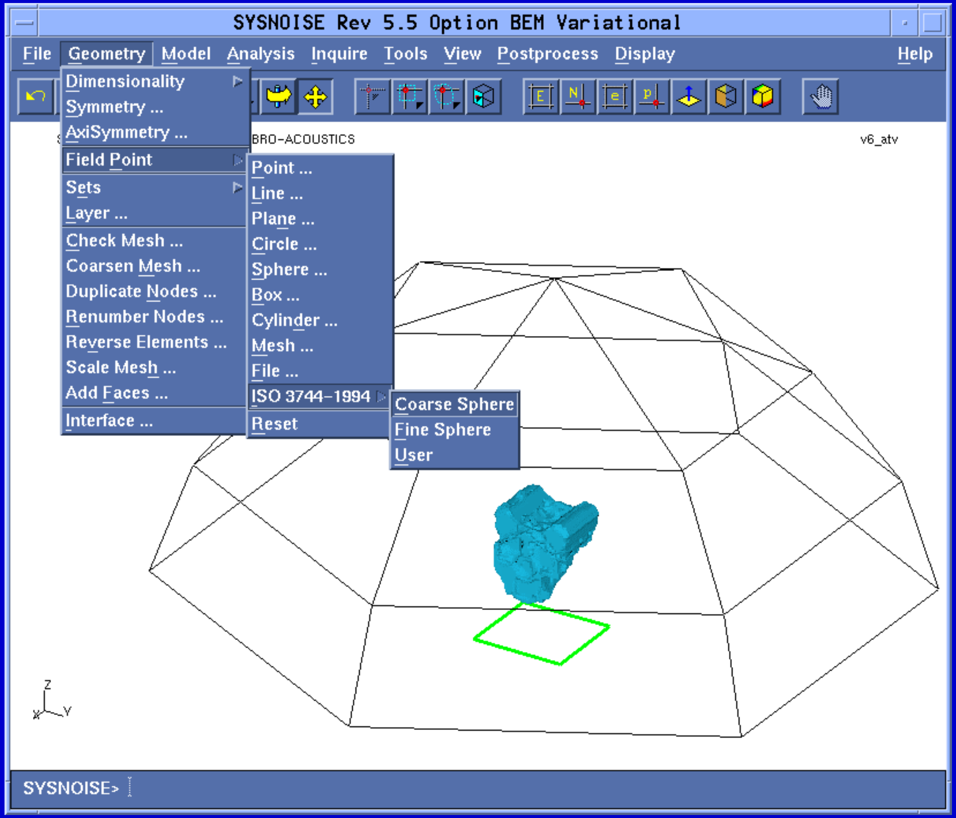
measure…

and model the

measurement

set-up

(ISO3744)



BEM : Modal Acoustic Transfer Vectors

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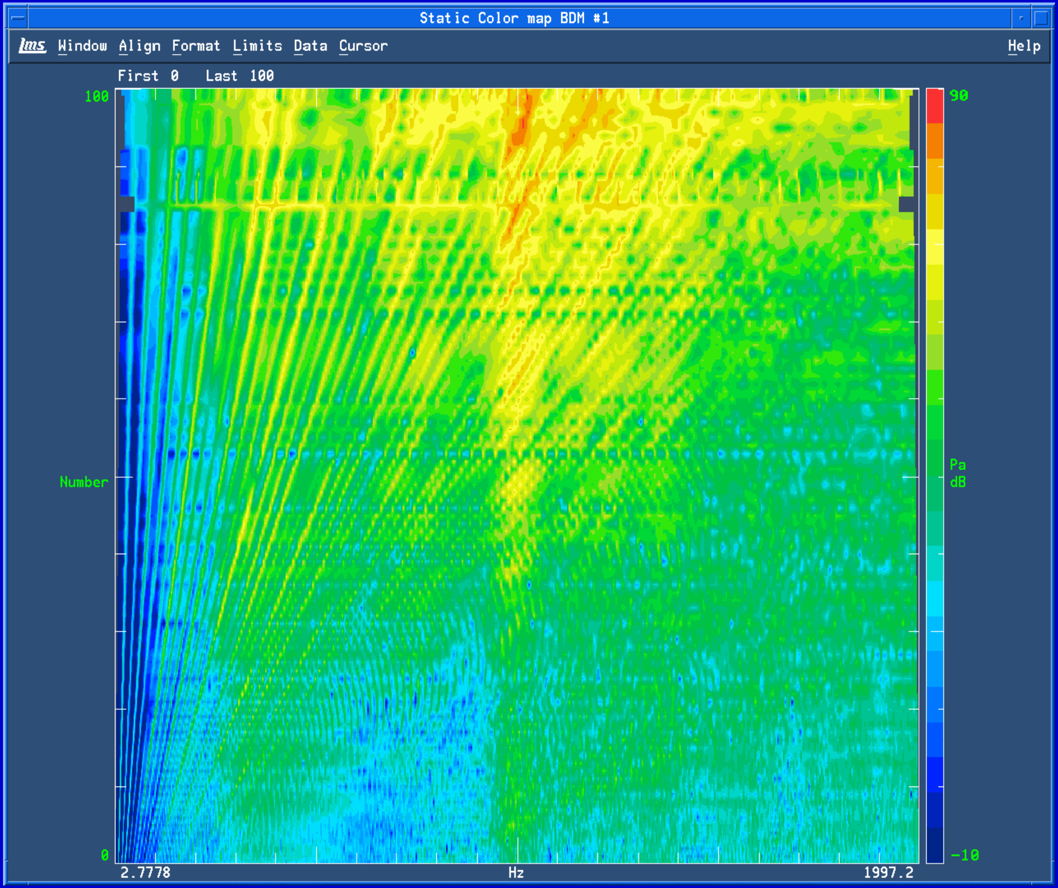
Engine Acoustic Radiation

Predict what we will Measure



Weak coupling

Multi-rpm acoustic radiation

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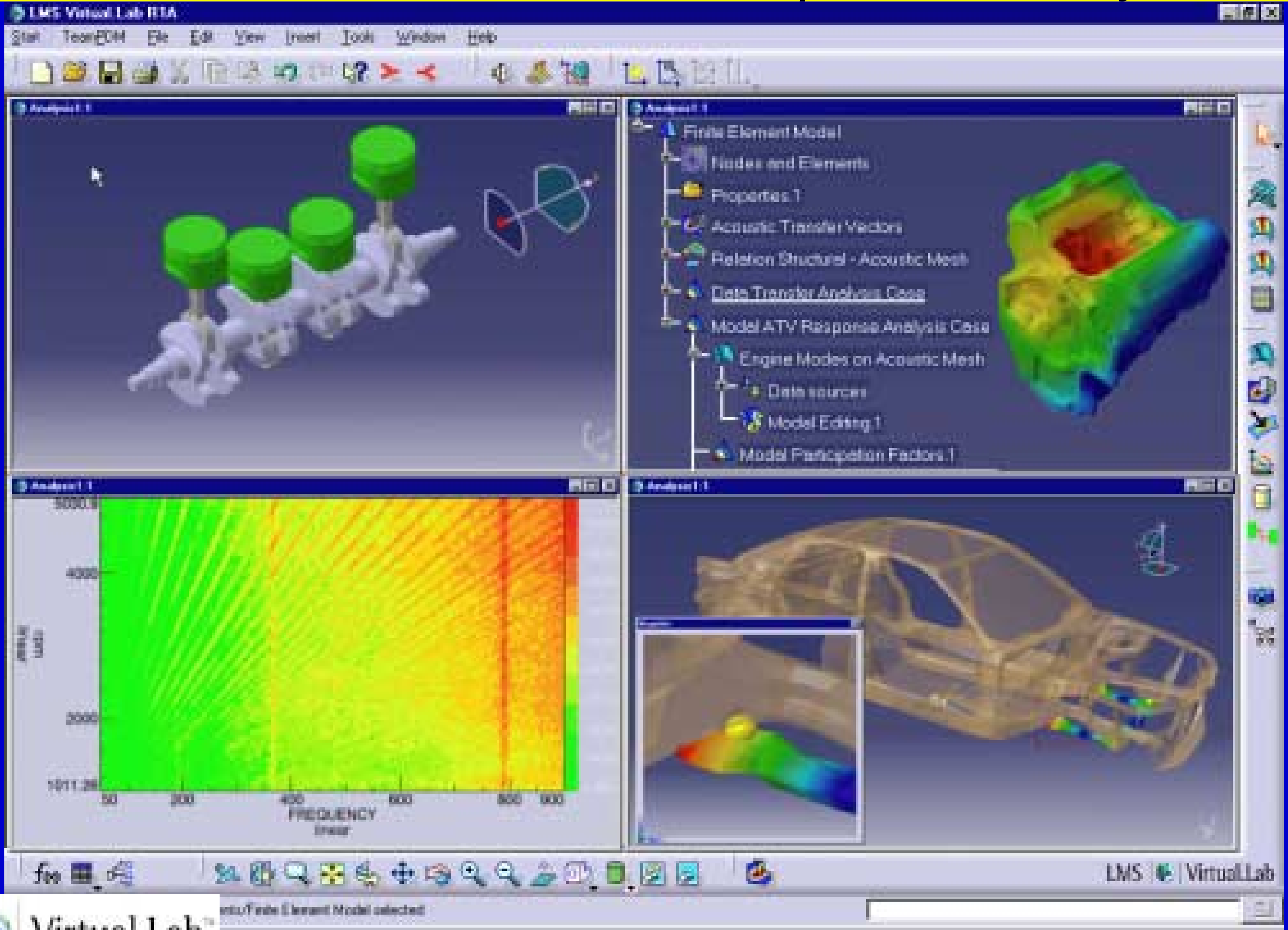
An Environment for Integration

One place to define, drive and assess all functional performance analyses…



LMS Virtual.Lab

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Back to the Aero-Acoustics…! Contents

- Motivation and History
- Current Activities and Resources
- LMS Approach to CAA : Analogy
- SYSNOISE Revision 5.6
- Validation Work
- Conclusion

Motivation

Automotive Industry

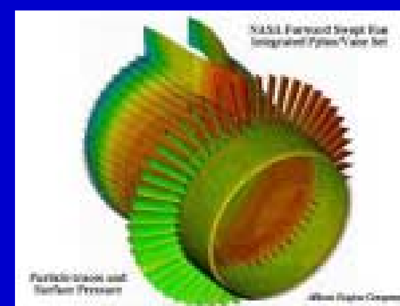
- Sunroofs, Mirrors
- Antennas, A-Pillars, wipers
- Exhaust Systems
- HVAC Blowers, Cooling Fans






Aerospace Industry

- Jet Noise
- Rotating Wing Noise




Other Industries

- Turbomachines
- Chemical Separators
- Computer fans, hard-disk drive
- Vacuum cleaner, Hair dryer

History

- **SYSNOISE**
  - Leading BEM and FEM acoustics code (Wave Equation => linear, inviscid, irrotational, …)
  - Convected waves (FEM) – effect of flow *on* noise
  - Non-linear sources (FEM) – thermally/chemically-induced noise

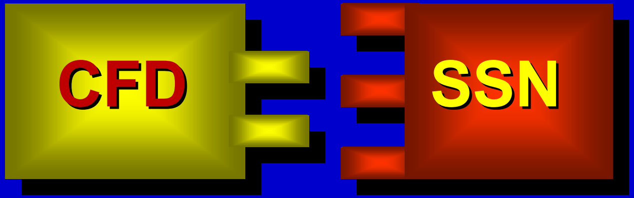
- **CAA = CFD + CA …   R&D, European projects…**
  - ALESSIA: Application of Large Eddy Simulation to the Solution of Industrial Problems
    - concluding
  - WISSLE: FloW Induced Sound SimuLation and Evaluation
    - 5 man-years; on-going

Current Activities and Resources

- R&D
  - Supervisor and 3 full-time post-grad/post-doc researchers
  - Other (shared) software development and support resources
- Code Implementation and Deployment
  - SYSNOISE β and Revision 5.6 release
  - Interfaces
- Validation
  - Test cases with industrial partners (comparison with literature, experiments, …)

Aero-Acoustics
The LMS Approach

- **Objective:**
  - Build in SYSNOISE a high-quality and pragmatic industrial approach to model Flow Induced Noise - accurately - in real life cases



- **How:**
  - One-way coupling of major CFD codes with SYSNOISE (StarCD, …)
  - Exploit Aero-Acoustic Analogies (AAA)
    - Lighthill, Curle, Ffowcs-Williams-Hawkings

Aero-Acoustics Challenges

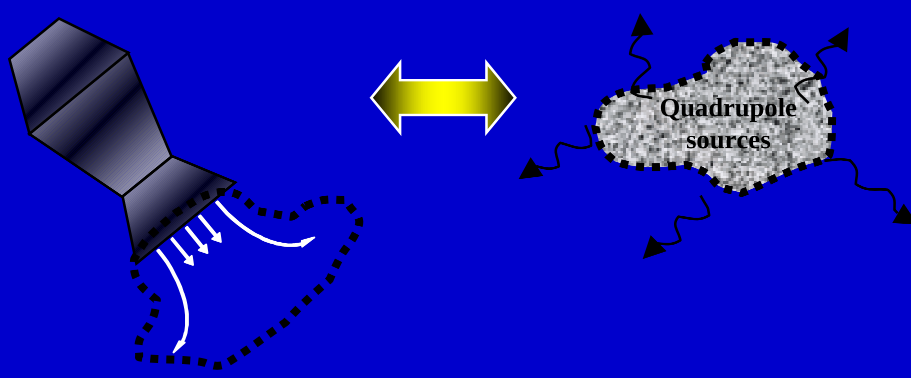
- **Flow induced Noise prediction is a Challenge!**
  - **Accurate flow (CFD) prediction for real-life problems is already difficult - Turbulence modeling is still a research area**
  - **Acoustic physics happens multiple orders of magnitude lower than aero-dynamic physics (typically 5 orders of magnitude)That's why the CFD code won't by itself capture the propagation from these acoustic sources.**
- **And, the CFD code cannot account for the acoustic behaviour like scattering and diffraction, which occur away from the region of the 'compact sources'.**
- **Regions of interest (to be modeled) are different: acoustic waves propagate at long distances**
- **But**
  - **CRITICAL INDUSTRIAL INTEREST FOR SOLUTIONS**

Aero-Acoustics
An important distinction…

- **Two very-different phenomena:**
  - **The effect of flow ON the sound field**
    - ***Convection of sound waves***
    - **Possible with SYSNOISE already (in FEM module)**
    - **Requires steady-state flow field**
      - **which can be transferred from CFD**
  - **The effect of flow PRODUCING a sound field**
    - ***Creation of acoustic sources***
    - **Uses Aero-Acoustic Analogies (AAA)**
    - **Requires Unsteady flow results from CFD**
      - **RANS, LES, DNS, Lagrangian**
      - ***today's subject…***

Aero-Acoustic Analogy
Jet Noise

- **Lighthill** work performed to tackle the problem of <u>jet noise</u> is the starting point of the theory referred to as the Aero-Acoustic Analogy (AAA)
- **Lighthill** reformulated NS equations to derive a wave equation with a source term including all flow effects.



Noise Due to Disturbed Flows
=
<u>Quadrupoles</u> radiation

Aero-Acoustic Analogy
Some Equations

1. **Lighthill Equation :**

$$\Delta \tilde{\rho}(x,t) - \frac{1}{c_0^2}\frac{\partial^2 \tilde{\rho}(x,t)}{\partial t^2} = -\frac{\partial^2 T_{ij}(x,t)}{\partial y_i \, \partial y_j}$$

With

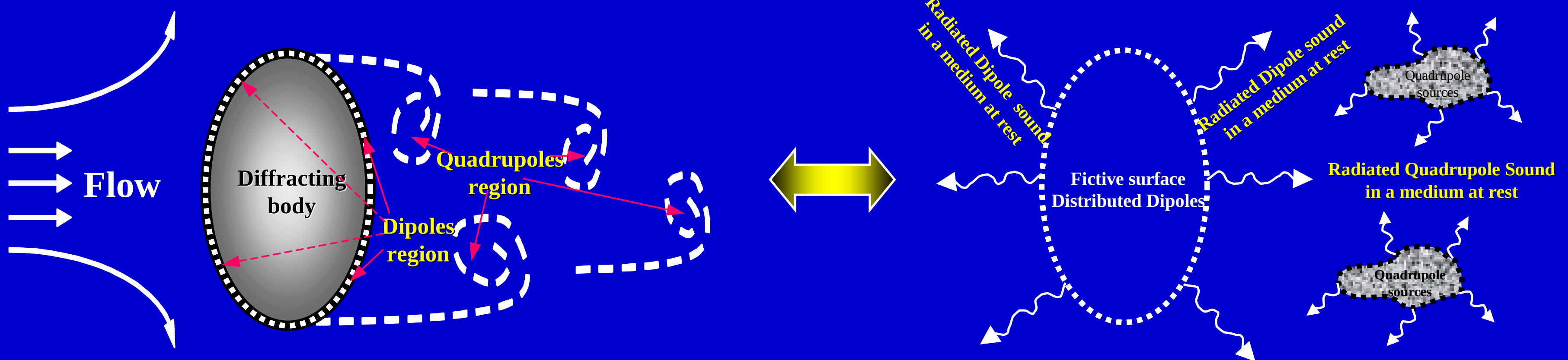
$$T_{ij}(x,t) = \rho(x,t)\, v_i v_j(x,t) + \tilde{P}_{ij}(x,t) - c_0^2\, \tilde{\rho}(x,t)\, \delta_{ij}$$

$$\tilde{P}_{ij}(x,t) = (P - P_0)\delta_{ij} - \tau_{ij}$$

$$\tau_{ij} = \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) + \delta_{ij}\, \lambda \frac{\partial v_k}{\partial x_k}$$

Aero-Acoustic Analogy
Flow Interacting with stationary Surface

- **Lighthill's** work has been extended by <u>Curle</u> to handle the Influence of Solid Boundaries upon Aerodynamic Sound.



Noise Due to (Disturbed Flows + Stationary Surfaces)
=
<u>Dipoles</u> on the surface
+
<u>Quadrupoles</u> outside the surface

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Aero-Acoustic Analogy
Some Equations

2. **Curle Equation :**

Solve Lighthill Equation when rigid boundaries are present in the domain

Quadrupoles

$$\tilde{\rho}(x,t) = \frac{1}{4c_0^2\pi}\frac{\partial^2}{\partial x_i\,\partial x_j}\int_V \frac{T_{ij}(y,\tau)}{r}dy - \frac{1}{4c_0^2\pi}\frac{\partial}{\partial x_i}\int_S \frac{P_i(y,\tau)}{r}dS(y)$$

Dipoles

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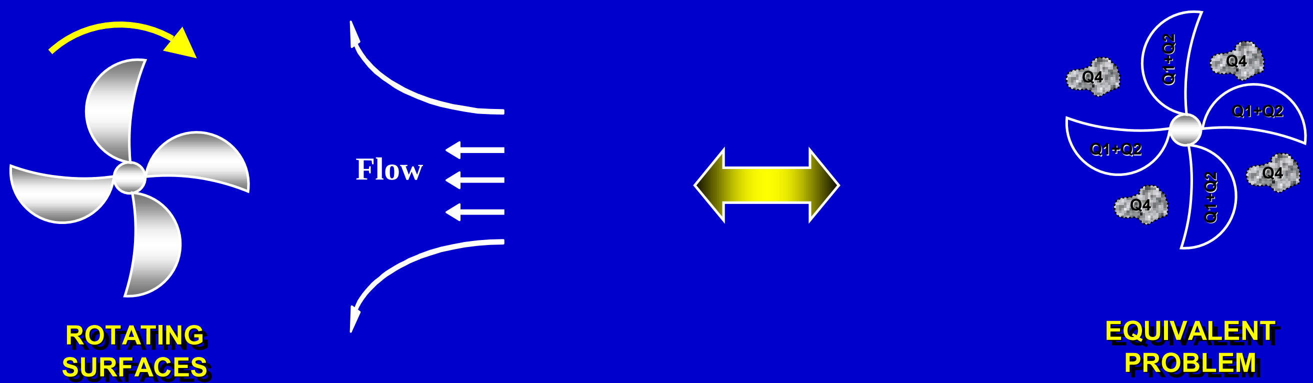
Aero-Acoustic Analogy
Flow Interacting with Rotating Surface

- **Curle's** work has been extended by **<u>Ffowcs-Willams</u>** & **<u>Hawkings</u>** to deal with rotating surfaces interacting with a flow



Noise Due to (Disturbed Flows + Rotating Surfaces)
=
<u>Rotating Dipoles</u> on the blades
+
<u>Quadrupoles</u> outside the Blades

Aero-Acoustic Analogy
Some Equations

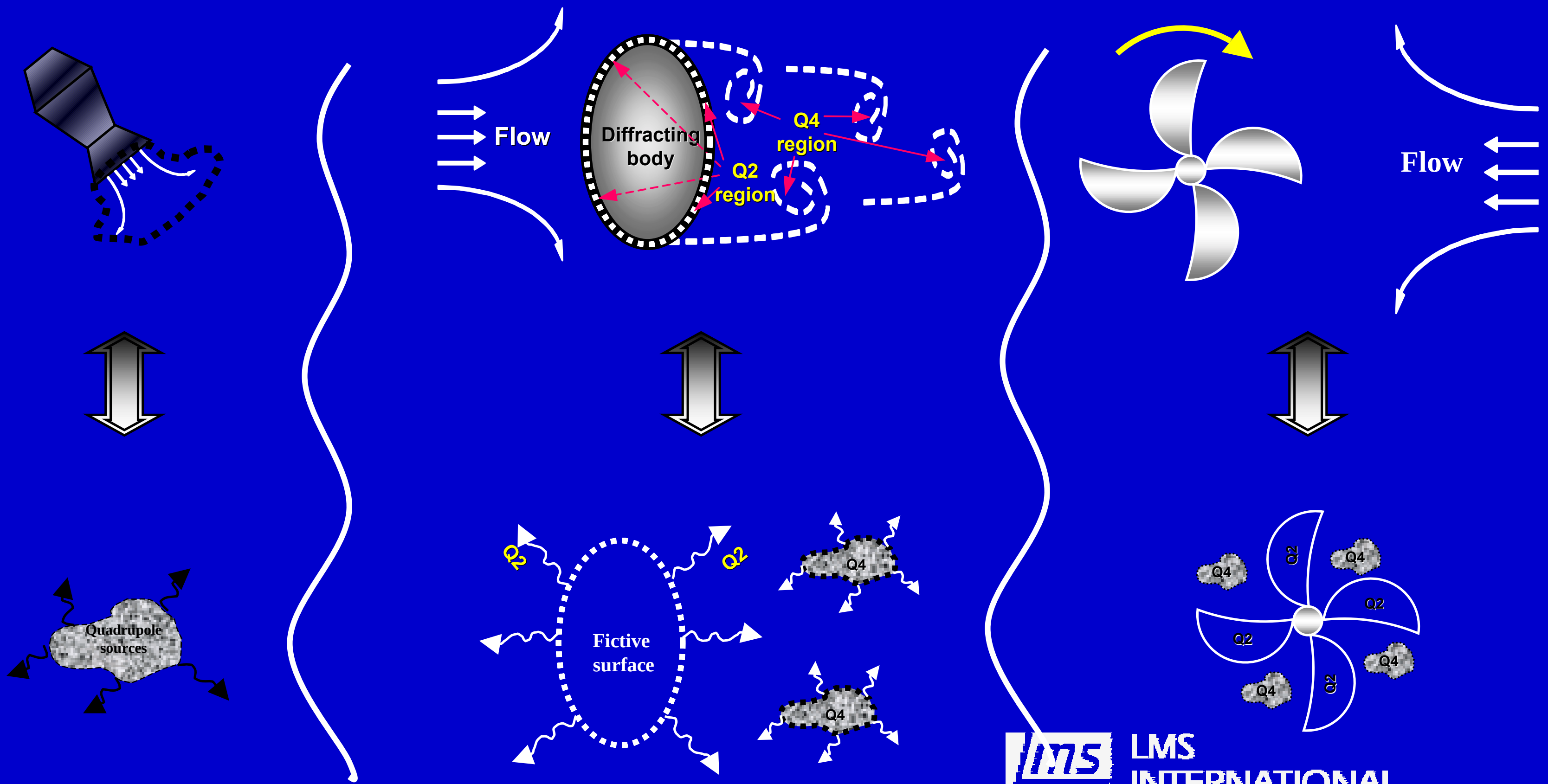
3. **Ffowcs-Williams Equation :**

Ffowcs-Williams and Hawkings reformulated NS equation introducing mathematical surfaces (that coincide with the surface of the moving solid) and imposing boundary conditions on it:

$$\Delta \tilde{\rho}(x,t) - \frac{1}{c_0^2}\frac{\partial^2 \tilde{\rho}(x,t)}{\partial t^2} = -\frac{\partial^2 T_{ij}(x,t)}{\partial y_i \, \partial y_j} + \frac{\partial}{\partial x_i}\left(P_{ij}\, \delta(f)\frac{\partial f}{\partial x_j}\right) + \frac{\partial}{\partial t}\left(\rho_0 \, V_{S_i} \delta(f)\frac{\partial f}{\partial x_j}\right)$$

Aero-Acoustic Analogy
From CFD to SYSNOISE

- **To summarise:**



Aero-Acoustic Analogy
From CFD to SYSNOISE

- **To summarise:**

- We have **THREE** kinds of Aero-Acoustic Sources:
  1. Quadrupoles (Q4)
  2. Dipoles (Q2)
  3. Rotating Dipoles (Q2)

- These sources are given by :
  1. Quadrupoles === Flow Velocity,turbulence
  2. Dipoles === Pressure on the walls
  3. Rotating Dipoles === Forces on the Blades

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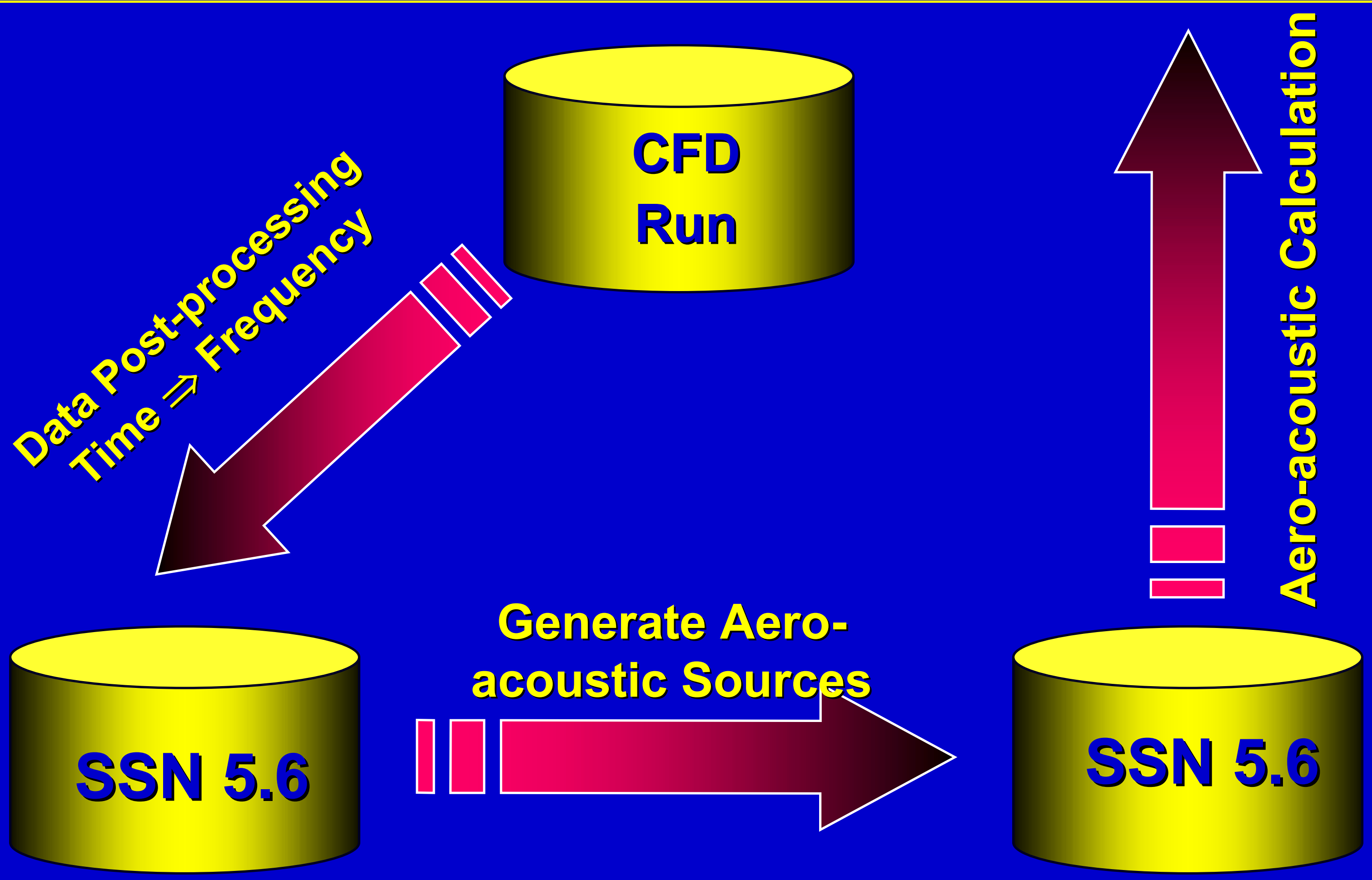
FROM CFD TO SYSNOISE



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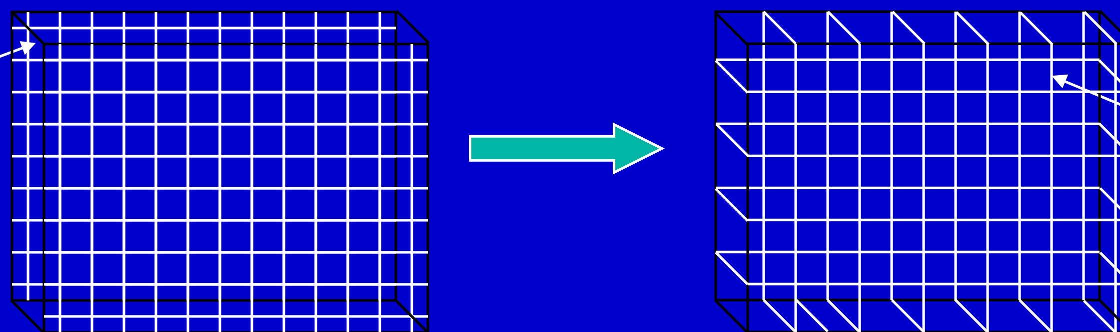
Aero-Acoustics with SYSNOISE Revision 5.6

- **Quadrupoles**

CFD Mesh

Acoustic Mesh

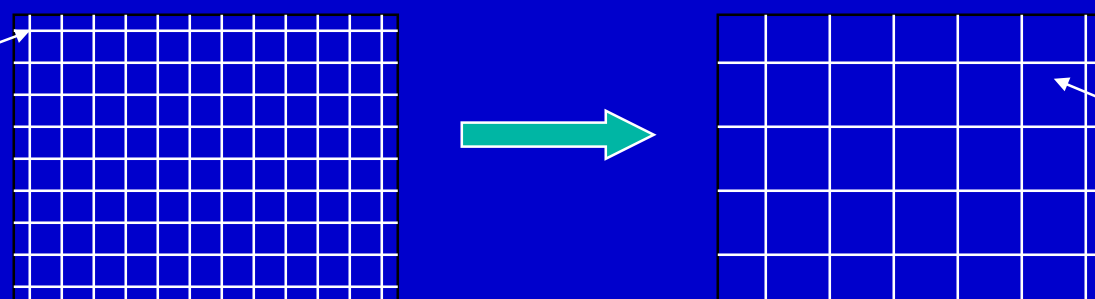
Velocity on the volumetric mesh



Quadrupoles continuous distribution

- **Dipoles**

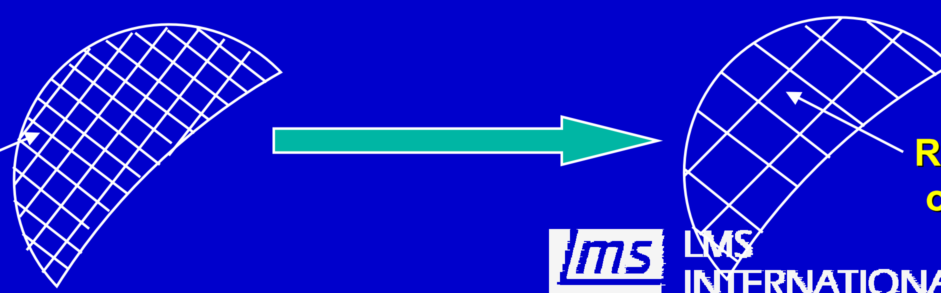
Pressure on the nodes



Dipoles continuous distribution

- **Rotating dipoles**

Forces on the blade's elements



Rotating Dipoles on the elements

Implementation and Deployment
SYSNOISE Rev 5.6 Aero-acoustic Modules

- **Automatic creation of distributed sources - "GENERATE"**
  - **Unequal CFD and acoustic meshes**
  - **Quadrupoles within a special volume mesh**
  - **Stationary dipoles**
  - **Rotating dipoles**
- **Interfaces to major CFD codes (StarCD, …)**
  - **New Fast FFT to transform cfd data in the frequency domain**
- **Solutions in Acoustic FEM and Acoustic BEM**
  - **Scattering, diffraction… (all 'acoustic-scale' phenomena)**
- **Post-processing**
  - **Compute the incident field**
  - **Curle Integral**
  - **…**

Validation Work : On-going

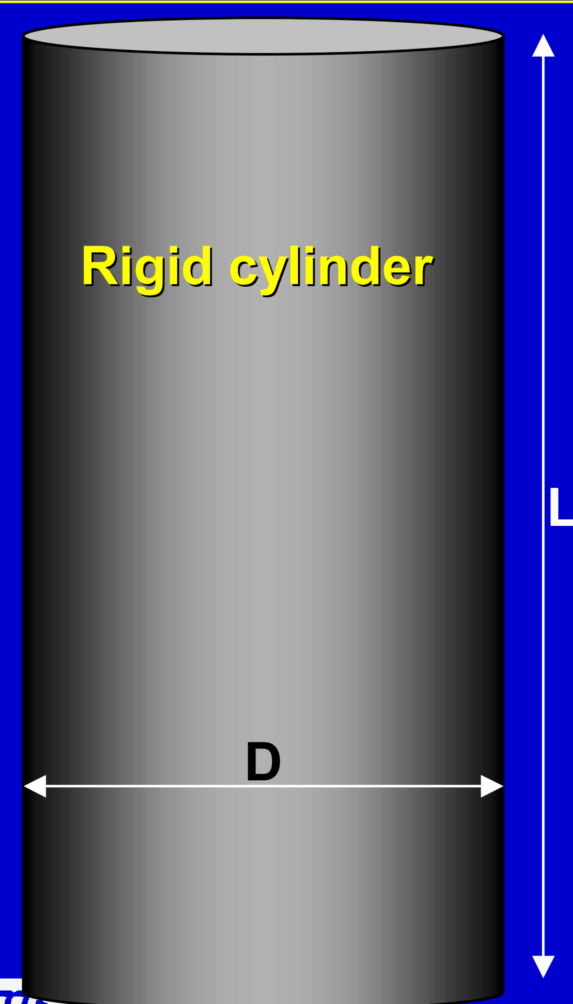
- Cylinder (two velocities)
- Cylinder in duct
- Cylinder between plates
- Pipe junction
- Fan noise
- Jet nozzle with strut
- Sun-roof
- … others …

- Verify methods and procedures
- Compare with analytical results, literature, experiments

Aero-Acoustic Modules
Validation Work

Cylinder Test-case (TUM/ALESSIA)

incompressible flow (Re=3900)



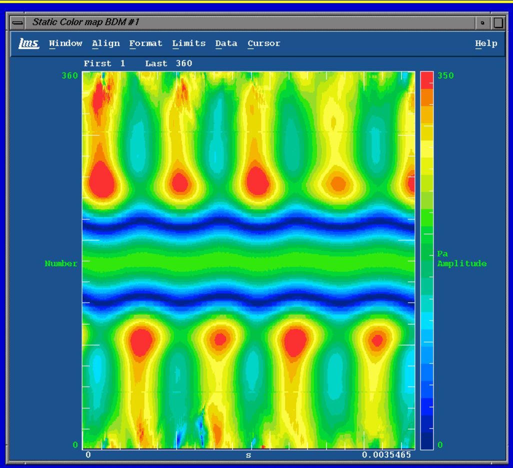
$$U_\infty = 17.9\,\mathrm{m/s} \quad P_\infty = 101325\,\mathrm{Pa}$$

$$\rho_\infty = 1.225\,\mathrm{kg/m^3} \quad C_\infty = 340.29\,\mathrm{m/s}$$

$$M_\infty = 0.05 \quad D = 0.00318\,\mathrm{m} \quad L = 3.5D$$

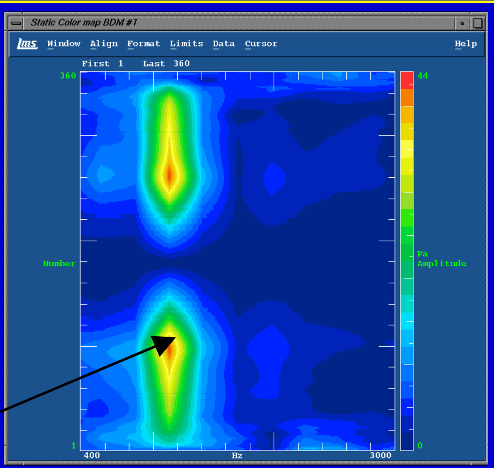
$$\Delta t = 3.55\mathrm{x}10^{-6} \quad n_t = 1000$$

Aero-Acoustic Modules
Validation Work: Cylinder test case



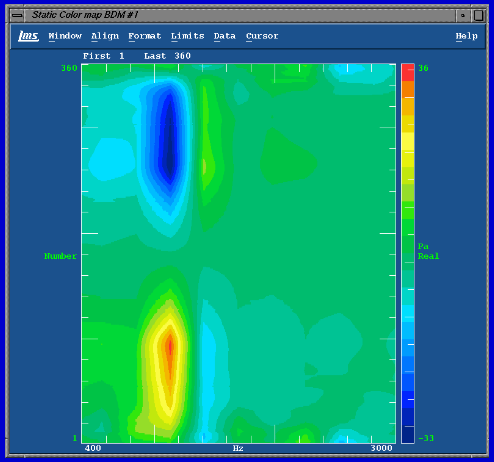
CFD time history p(t)

FFT



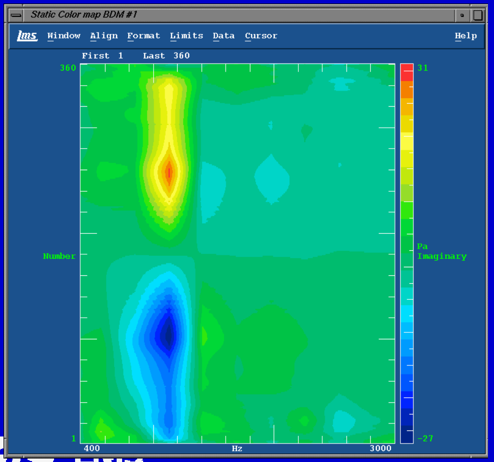
frequency spectrum p(f), amplitude

Peak at 1130 HZ

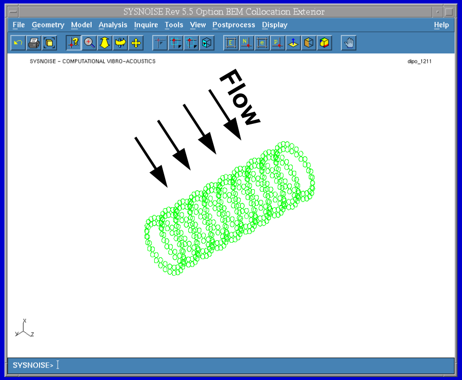


frequency spectrum p(f)

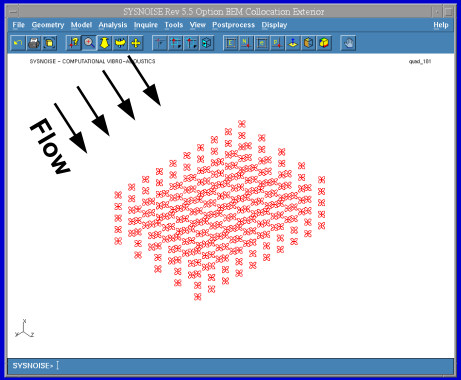
Real part   Imaginary part



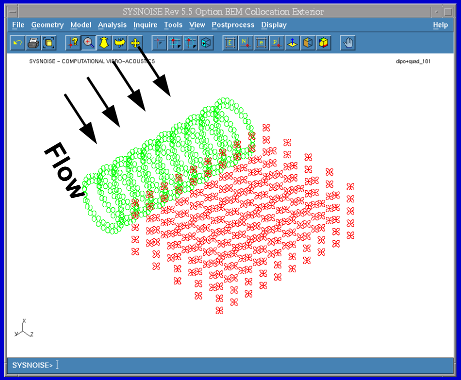
Aero-Acoustic Modules
Validation Work: Cylinder test case



We define at the peak frequency Dipole Sources on the surface



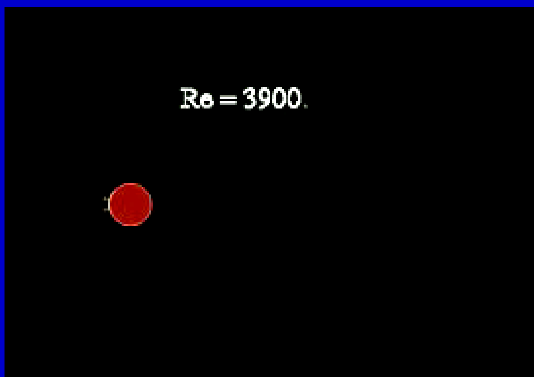
We define Quadrupole Sources in the Wake



Dipole + Quadrupole combination in SYSNOISE

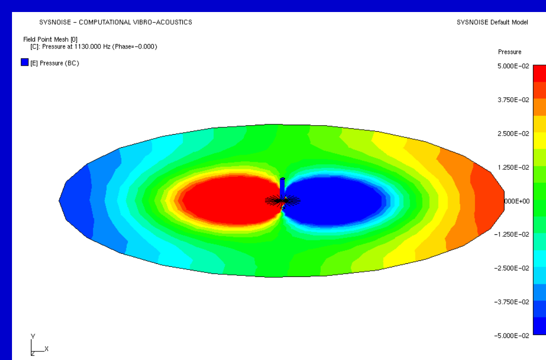
Aero-Acoustic Modules
Validation Work: Cylinder test case

Flow passing a cylinder (CFD)



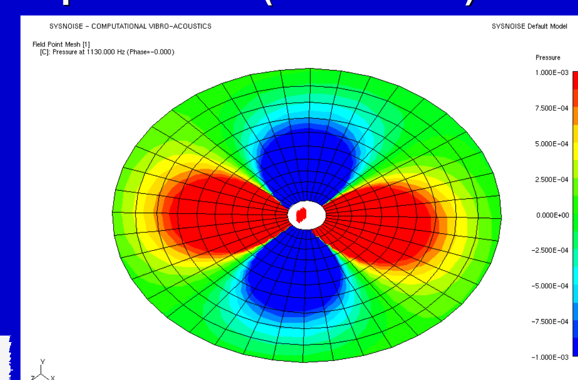
First, we solve the flow

Dipole-Noise (SYSNOISE)



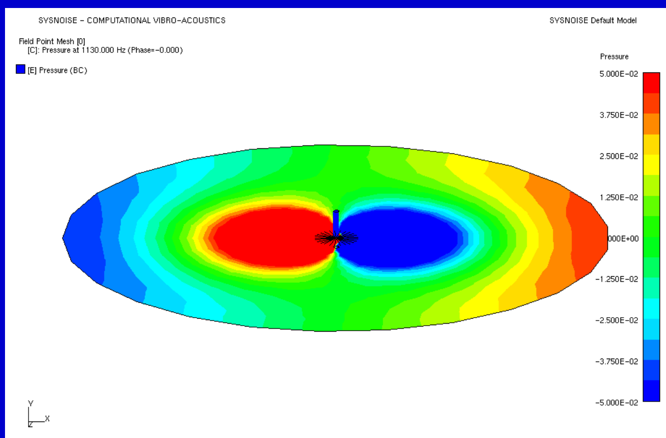
- Frequency of computation: 1130Hz
- Cylinder Length=3.5xDiameter
- 250 Dipoles on the surface
- 250 Quadrupoles in the wake
- Field Point mesh: Symmetrical Plane

Quadrupole-Noise (SYSNOISE)

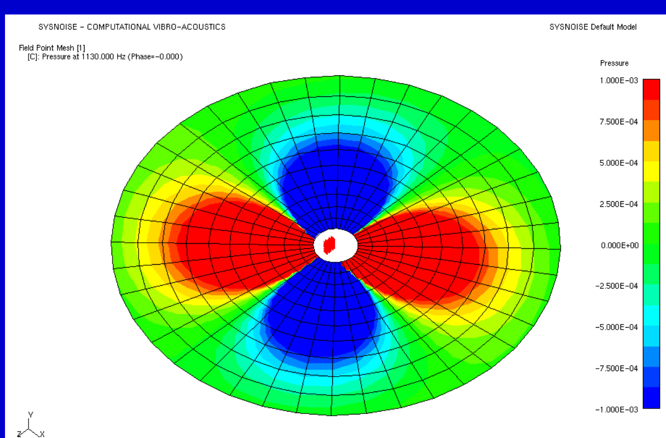


Next, we generate Aero-Acoustic Sources, Dipoles and Quadrupoles, from the CFD output, with use of SYSNOISE, and perform the calculation…

Aero-Acoustic Modules
Validation Work: Cylinder test case



The results show a good agreement with Philips Equation and the measurements (Alfa Laval)



The Quadrupole radiation shows a good qualitative behaviour

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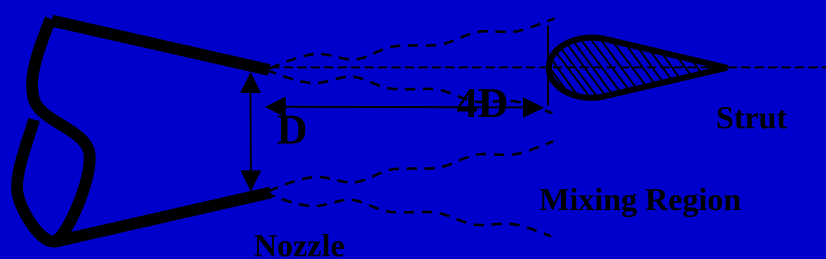
Aero-Acoustic Modules Validation Work

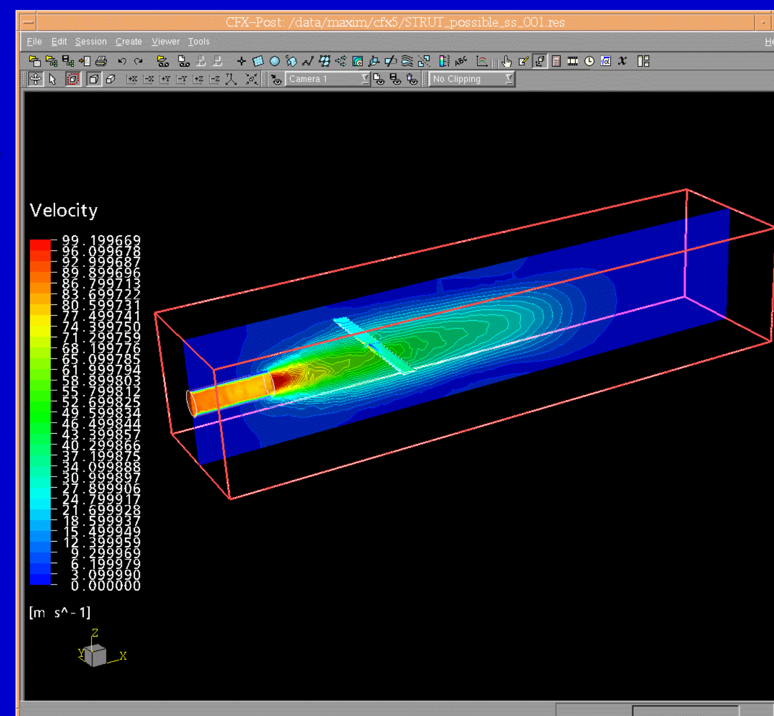
Strut/Nozzle

The study of the noise due to the presence of a strut in a turbulent subsonic flow.

CFD simulation using LES.

Comparison with measurements data available in the literature is very good





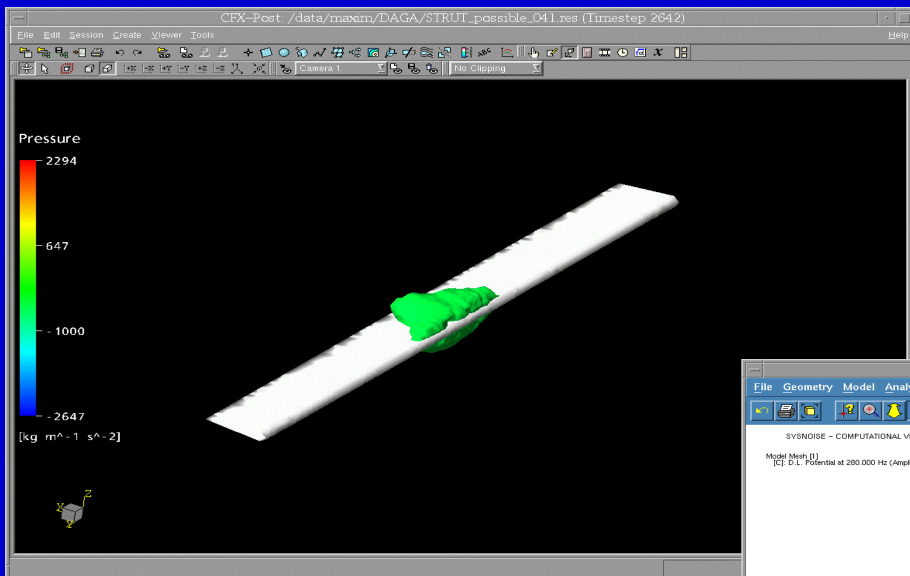
Chord = 0.05m

Nozzle Diameter = 0.1m

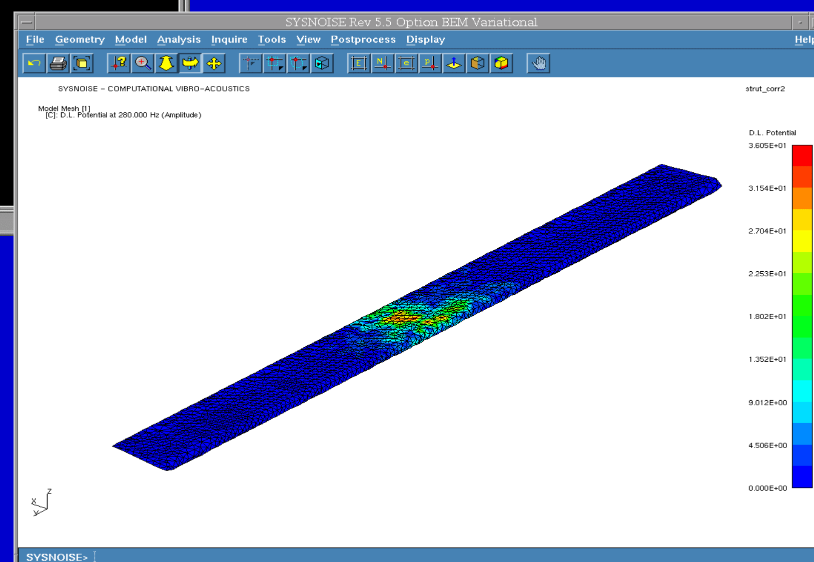
Re = 335930

M = 0.37

Aero-Acoustics Modules Validation Work: Strut/nozzle



The Aero-Acoustic Coupling



Pressure fluctuation as input to generate dipoles on surfaces

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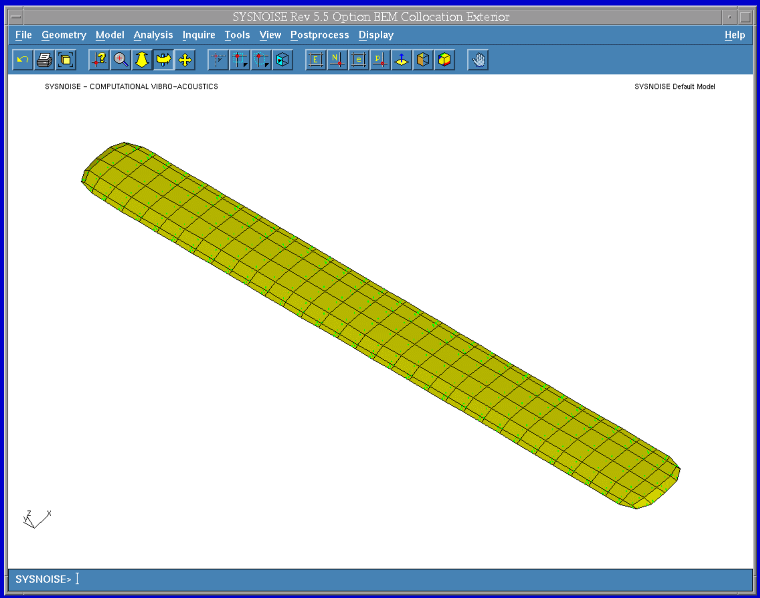
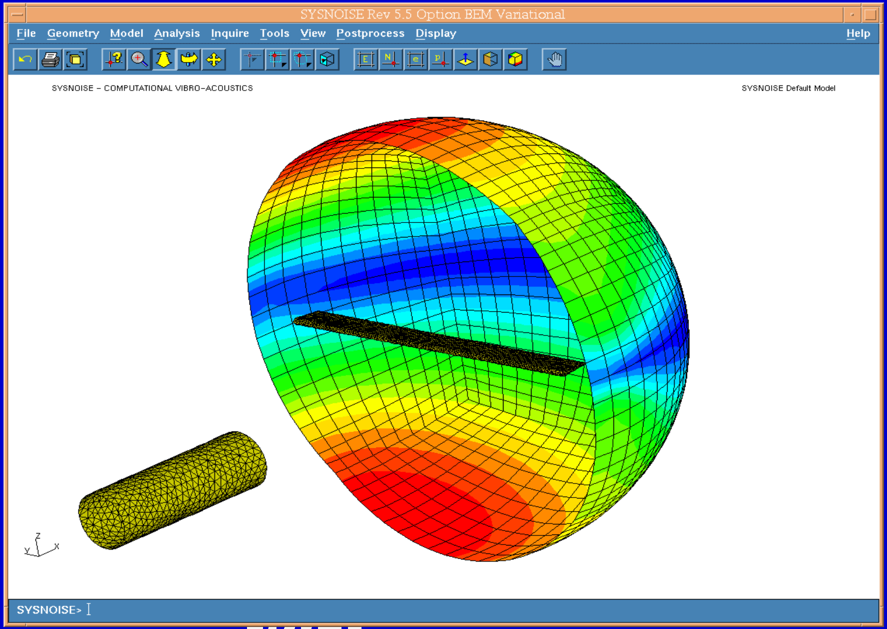
Aero-Acoustics Modules Validation Work: Strut/nozzle



Acoustic Mesh Data

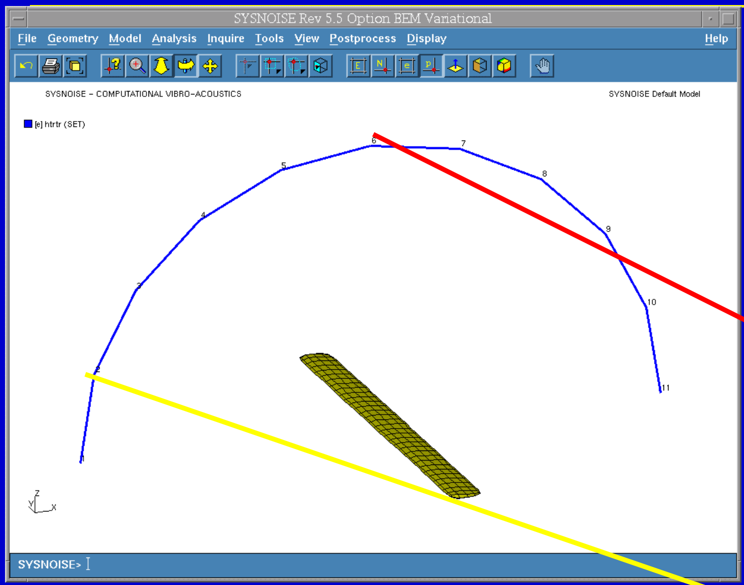
$$\text{Number of Nodes} = 402$$
$$\text{Number of Faces} = 400$$
$$\text{Number of Elements} = 400$$
$$\text{Kind of Elements: Quad4}$$

Dipoles on the acoustic mesh



Acoustic field of sound pressure level generated by dipoles and using a DBEM approach in SYSNOISE

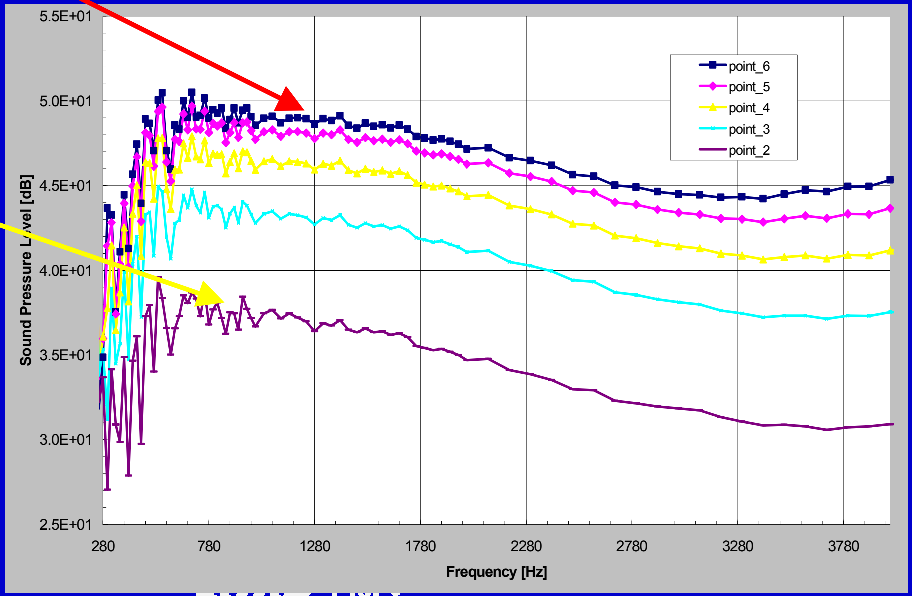
Aero-Acoustics Modules
Validation Work: Strut/nozzle



Field Points Results

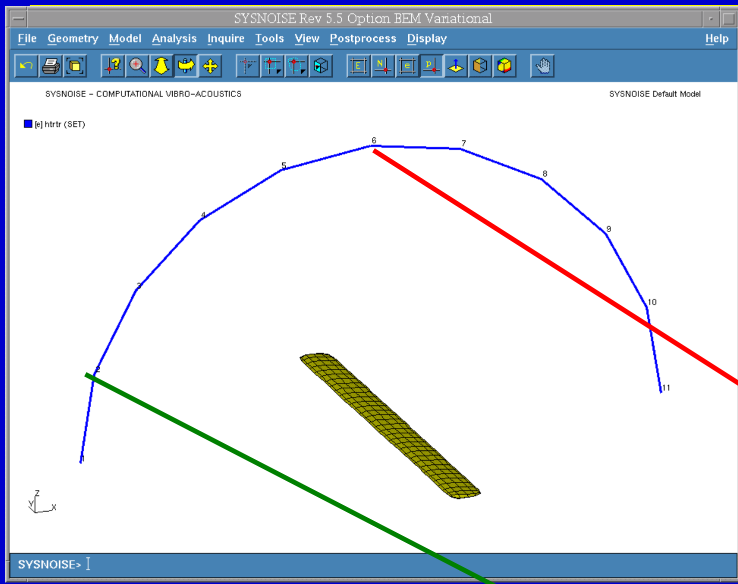
Field points Number = 11

Field points - strut Distance = 0.4 m



Field points Spectra
(Sound Pressure Levels)
Broadband Noise

Aero-Acoustics Modules
Validation Work: Strut/nozzle

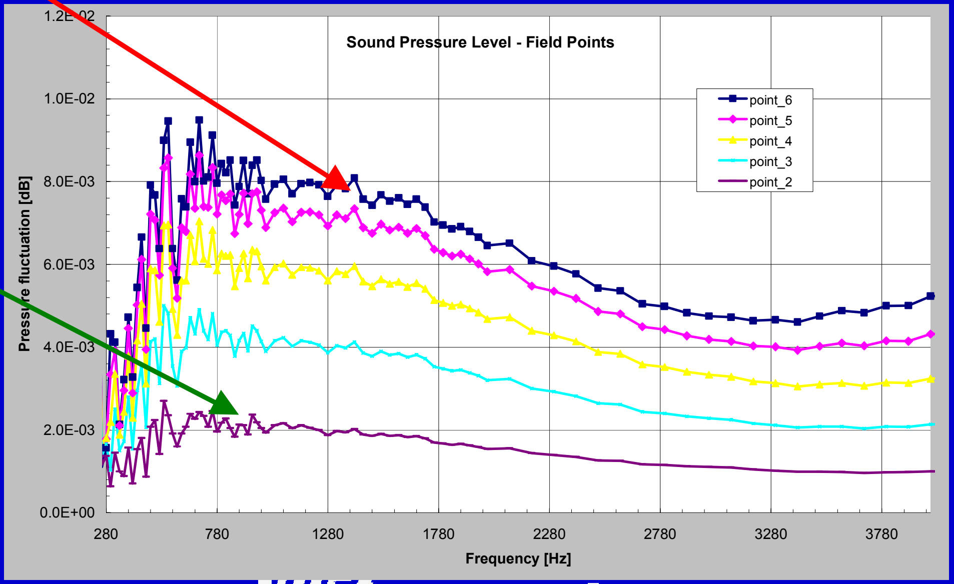


Field Points Results

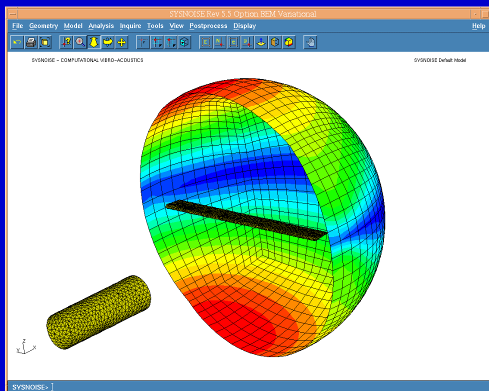
Field points Number = 11

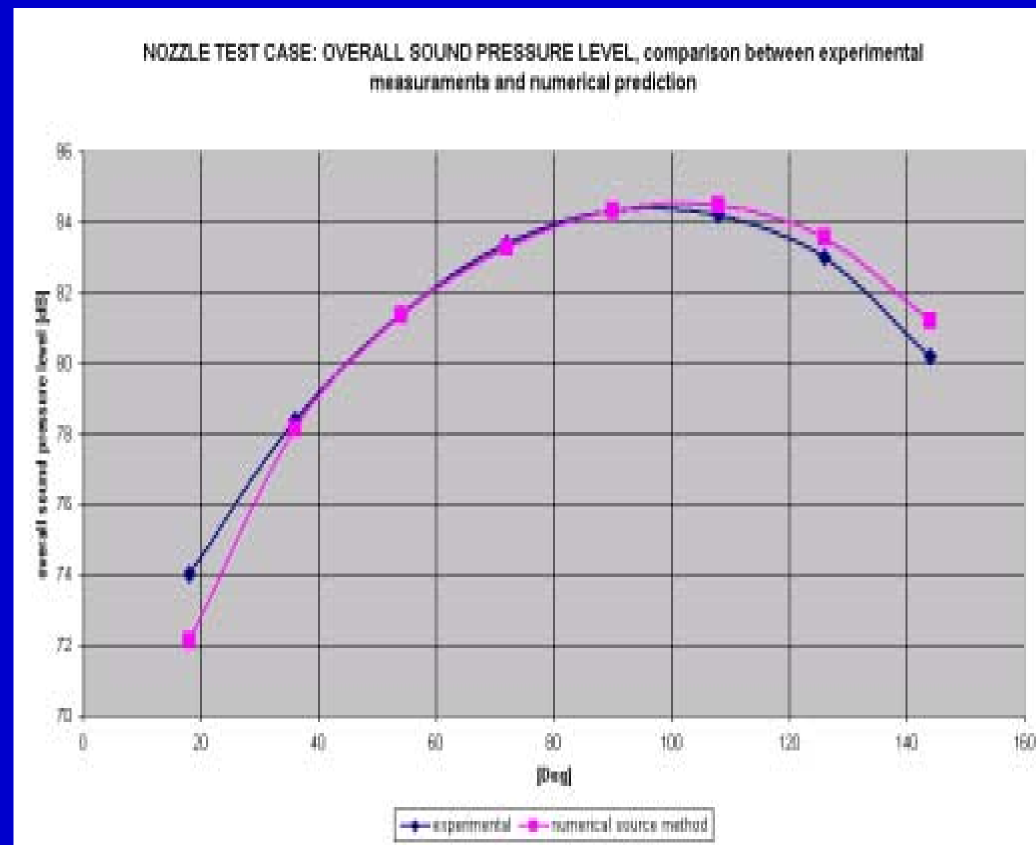
Field points - strut Distance = 0.4 m

Field points Spectra
(Pressure Fluctuation)
Broadband Noise



Strut/nozzle: Comparison with experimental results



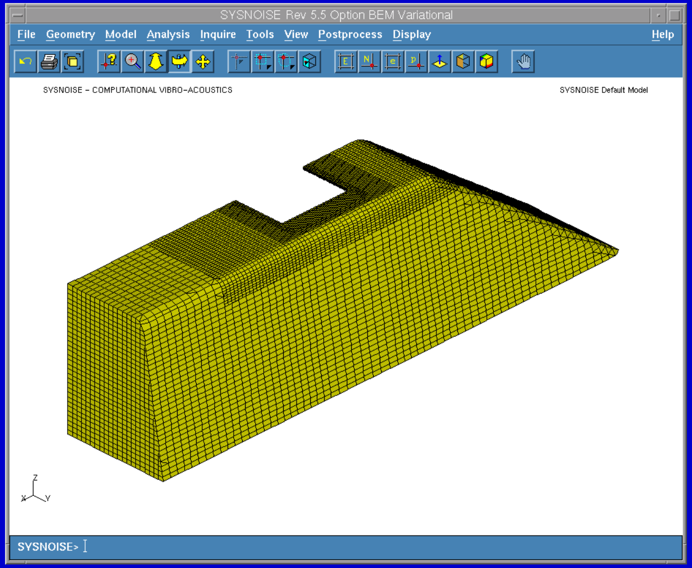


- **Experimental Results by W.A. Olsen of the Lewis Research Center**
- **The Experimental Results have been also compared with an analytical formulation present in Literature (Aeroacoustics-Goldstein) showing a good agreement**
- ***Very good agreement between Experimental and Numerical Results***

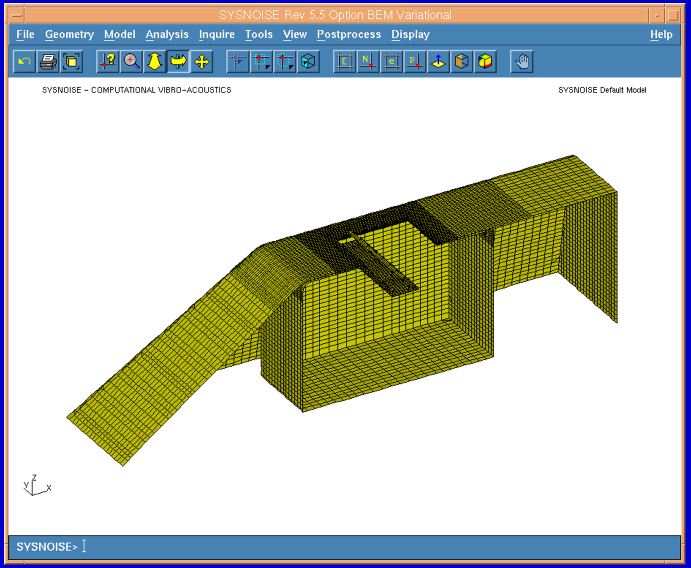
Aero-Acoustic Modules Validation Work

Generic vehicle cabin with a sunroof

Star-CD **and LMS SYSNOISE**



Sunroof without a Deflector



Sunroof with a wind Deflector

$U = 30.556 m/s$
$Re = 9.8 million$
$M = 0.09$

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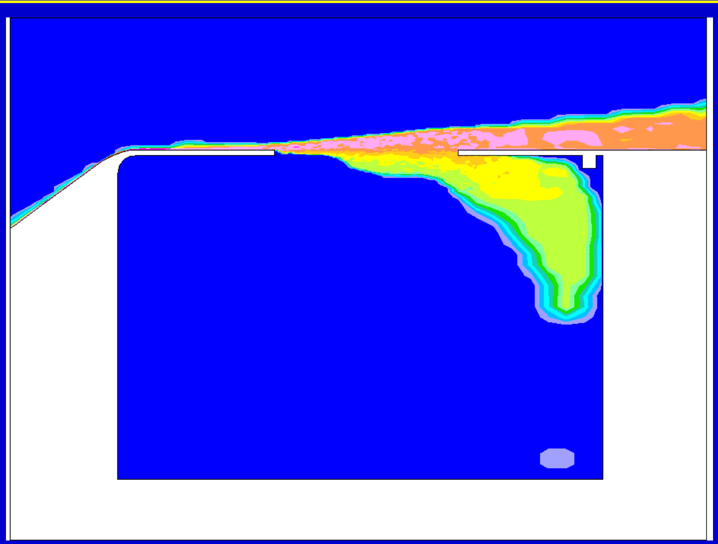
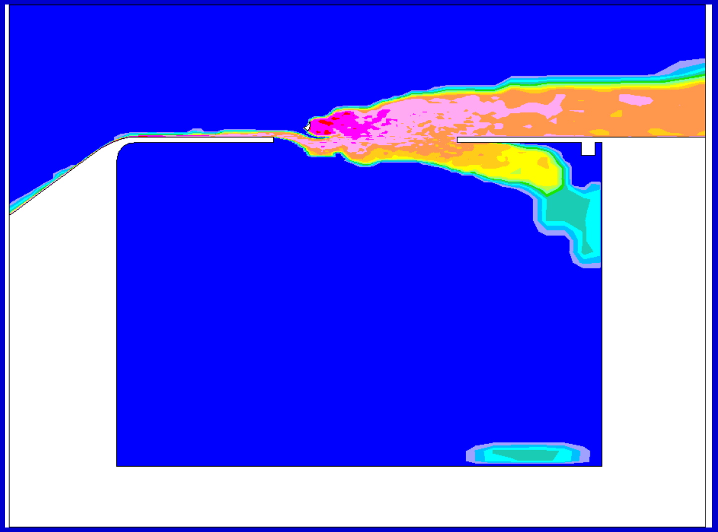
Aero-Acoustic Modules
Validation Work : Sunroof test case

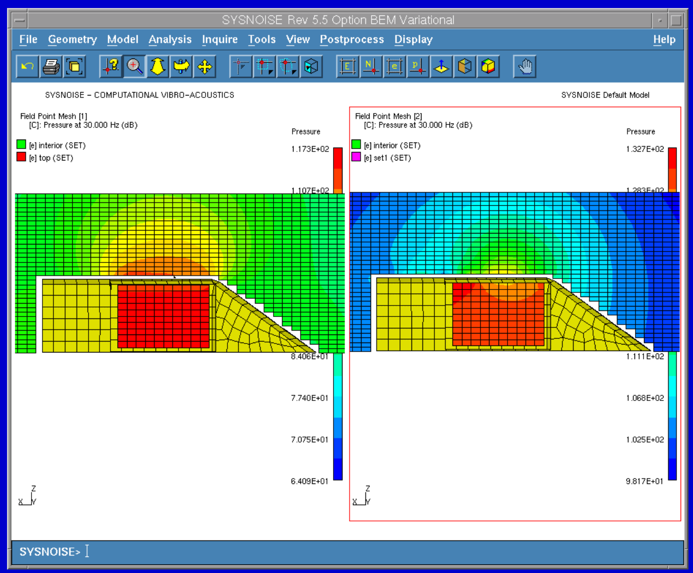


Shear Noise Source
symmetry plane, Clean car

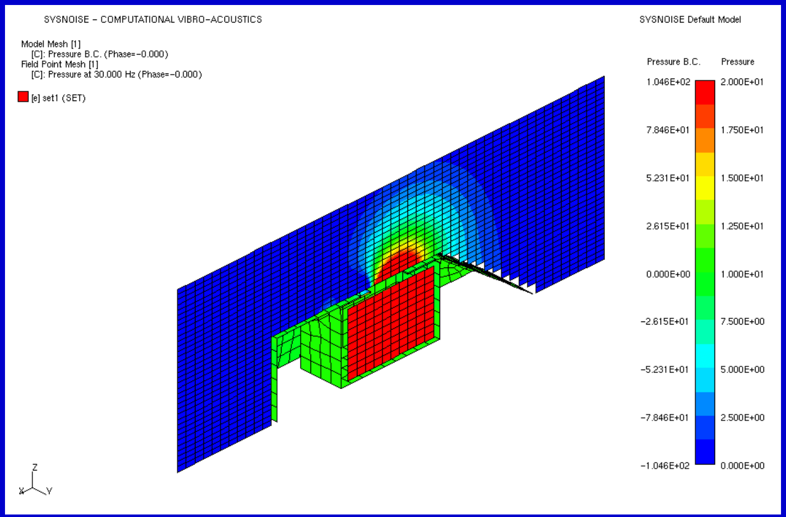


Shear Noise Source,
symmetry plane, deflector fitted

Aero-Acoustic Modules
Validation Work : Sunroof test case



Radiated and Reverberant Sound
Frequency = 30Hz
Right : original; Left : with deflector
(14 dB reduction in interior)
(different contour scales!)



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Conclusion

- **Technology**
  - Acoustic analogies : 'linkage' of CFD and acoustics
- **Implementation**
  - Special interfacing of SYSNOISE and CFD (Star CD…)
- **Validation**
  - On-going
  - Further validations, measurements, applications : tbd …
- **Deployment**
  - Beta version now, public release with SYSNOISE 5.6

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