System for Vibro-Acoustic Analysis

LMS Numerical Technologies
# A Few Words About Acoustics

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<thead>
<tr>
<th>Source</th>
<th>Propagation</th>
<th>Receiver</th>
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<tbody>
<tr>
<td>vibrating body</td>
<td>sound path &amp; absorption</td>
<td>microphone</td>
</tr>
<tr>
<td>speaker</td>
<td>• airborne</td>
<td>ear</td>
</tr>
<tr>
<td></td>
<td>• structure-borne</td>
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<tr>
<td></td>
<td>• mixed</td>
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</tbody>
</table>
Dealing with Vibration & Sound

Rigid wall

Flexible wall
Fluid-Structure Coupling

Vibration generates Sound

Vibro - \( F_s \)

Structure

Acoustic Excitation

\( F_a \)

Fluid

Sound induces vibration

up

Sound induces vibration
Harmonic vs Transient Analysis

0 Frequency domain
4 Helmholtz equation
4 Harmonic or narrow-band excitations
4 Solution with \textit{complex} variables

\[ \nabla^2 p + k^2 p = 0 \]

0 Time domain
4 Wave equation
4 Transient (e.g. shock) and broad-band excitations
4 Solution with \textit{real} variables

\[ \nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \]
Why Numerical Simulation?

- Numerical Methods
- Experimental Techniques

Efficiency

KNOW  UNDERSTAND  PREDICT
Usual Numerical Tools

0  (Semi-) **Analytical Methods**
   4  Closed form solutions
   4  Only for simple geometries

0  **Finite Element Method (FEM)**
   4  Volume discretization into Finite Elements

0  **Boundary Element Method (BEM)**
   4  Discretization of bounding surface into Boundary Elements

0  **Statistical Energy Methods (SEA)**
   4  Energy exchanges between system components

0  **Ray Methods**
   4  Geometrical Acoustics
   4  RAYNOISE, MOSART
Why Acoustic Analysis?

0 Acoustics becomes increasingly important
  4 Product quality
  4 Competitive advantage
  4 Part of design specifications
  4 Government regulations quality of Life

0 Analysis up-front in the design phase
  4 Concurrent engineering
  4 Early interaction with design engineers
  4 Evaluate design alternatives
  4 Reduce prototyping
  4 Significant cost and time savings
## Typical Acoustic Analysis

<table>
<thead>
<tr>
<th>0</th>
<th>Sound <strong>radiation</strong> from vibrating structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Acoustic <strong>reflection</strong> and <strong>diffraction</strong> of sound waves</td>
</tr>
<tr>
<td>0</td>
<td>Sound <strong>transmission</strong> between fluid regions separated by a structural partition</td>
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<table>
<thead>
<tr>
<th>0</th>
<th><strong>Acoustics</strong></th>
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<tr>
<td>4</td>
<td>Fluid behavior only</td>
</tr>
<tr>
<td>4</td>
<td>Boundary conditions</td>
</tr>
<tr>
<td>8</td>
<td>panel velocities</td>
</tr>
<tr>
<td>8</td>
<td>sound sources</td>
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<td>8</td>
<td>panel absorption</td>
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<table>
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<tr>
<th>0</th>
<th><strong>Vibro-acoustics</strong></th>
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<tbody>
<tr>
<td>4</td>
<td>Interactions between structure and fluid</td>
</tr>
<tr>
<td>4</td>
<td>Coupled response</td>
</tr>
<tr>
<td>8</td>
<td>structural vibration</td>
</tr>
<tr>
<td>8</td>
<td>acoustic pressure</td>
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</tbody>
</table>
Why SYSNOISE?

0 Most **mature** and **complete** interactive solution today

0 The user has the **right to choose** his method
  4 FEM or BEM
  4 Direct or indirect
  4 Coupled or uncoupled
  4 Transient or harmonic

0 Developed for **power users** as well as **occasional users**

0 **Compatible** with
  4 your **hardware environment**
    8 UNIX, CRAY, CONVEX, IBM SP2 and Windows platforms
  4 your **software investments**
    8 FE packages, TEST softwares (LMS CADA-X)
SYSNOISE Offers You ...

0  Modeling facilities (economy of time)
   4  Automatic mesh checking and coarsening
   4  Optimized solvers for all methods
   4  Non-linear matrix interpolation

0  Fully Interactive analysis
   4  Graphical user interface
   4  Wizards
   4  Customizable environment

0  Minimum memory requirements

0  Maximum speed for calculation

0  No inherent limit
   4  Dynamic memory allocation
   4  Out-of-core procedures for all the solvers
Methods & Frequencies

Acoustics

SYSNOISE

MOSART, RAYNOISE

Vibro-Acoustics

SYSNOISE

SEA

higher frequency
higher modal density
FEM & I-FEM

- interior/exterior domain
- volume mesh: slower
- heterogeneous or homogeneous fluid
- volume/surface absorber
- solution: fast
BEM

DBEM

Exterior

Interior

IBEM

0 homogeneous fluid
0 surface absorbers
0 meshing: faster
**Multi-domain methods**

- FEM + I-FEM
- DBEM or FEM + DBEM
Available Modules of SYSNOISE

- Transient
- Acoustic FEM
- I-FEM
- DBEM
- IBEM
- Struct. FEM
Calculation Sequence

**Calculation Option**
- Input Mesh & Field
- Fluid Properties
- Panel Properties
- Sound Sources
- Acoustic Analysis

**Post-analysis**
- Directivity, Contribution, Sensitivities

**Post-processing**
- XY, Contours, Vectors, Animation

Mesh
- e.g. FEM or BEM
- Mesh checking & correction
- Density and speed of sound
- Structural and absorption properties
- Panel velocities or nodal forces
- Spherical, Planar, User
- Modes, Response, Matrices

Vibration
- Directivity, Contribution, Sensitivities
- XY, Contours, Vectors, Animation
**Vibration Input**

0 From **FEA**
   4 Uncoupled (acoustic) analysis: *vibration patterns*
   4 Coupled (vibro-acoustic) analysis: str. **normal modes**

0 From **Test** (coupling effects included)
   4 Accelerometer or laser **measurements**
   4 Sorted per frequency or per measurement location

0 **Manual** input
   4 constant velocity over the considered frequency range
   4 through **frequency dependent** tables
Available Interfaces

Mesh Generator
Nodes, Elements, Groups
Structural FEA
Vibrations, Sensitivities, Mode Shapes
Test Data

SYSNOISE
Pre-processing
Vibro-Acoustic Analysis
Post-analysis
Dedicated Post-processing

Embedded 2-way interfaces

- MSC/NASTRAN - MSC/PATRAN
- LMS/CADA-X
- ANSYS
- I-DEAS Master Series
- FemGen/FemView
- HYPERMESH
- ABAQUS
- MARC
- ProMechanica
- SYSTUS
Pre-processing

0 Import meshes from external mesh generators
0 Mesh checking and coarsening
0 Automatic search and handling of junction lines
0 Automatic search and handling of free edges
0 Visual creation of item groups
0 Application of boundary conditions
   4 panel absorption
   4 panel vibration
   4 acoustic sources
Vibro-Acoustic Analysis

0 Normal modes
   4 Acoustic mode shapes
   4 Structural mode shapes (fluid loaded)

0 Vibro-Acoustic response
   4 Acoustic (and structural) results at nodes and field points
      8 uncoupled and coupled analysis
      8 transient, harmonic and random (BEM) solution
      8 automatic out-of-core solvers for all modules

0 Matrices
   4 Compute and export FE and BE matrices
   4 Added mass matrix
Post-analysis

0 Directivity
  4 polar diagrams
  4 3D balloons

0 Panel Contribution
  4 contribution to sound pressure or sound power
  4 total or effective contribution

0 Sensitivities
  4 structural and acoustic design variables
  4 global and acoustic sensitivities
## Dedicated Post-processing

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<th></th>
<th>XY plots</th>
<th>Contour plotting</th>
<th>Deformed geometry</th>
<th>Vector diagram</th>
<th>Animation</th>
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<td></td>
<td>time and frequency dependent response functions</td>
<td>pressure</td>
<td>superimposed meshes</td>
<td>transient response</td>
<td>transient</td>
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<td></td>
<td>weighted or not (dBA, B, C...)</td>
<td>vector field components</td>
<td>velocities, intensities, ...</td>
<td>frequency scanning</td>
<td>phase</td>
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<td>narrow band, octave, 1/3 octave</td>
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<td>Polar diagrams</td>
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<td>sound directivity</td>
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<td>complex contribution</td>
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<td>panel contributions</td>
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<td>modal participation factors</td>
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<td>sensitivities</td>
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Conclusion

**SYSNOISE is the leading software** for computational vibro-acoustics

**SYSNOISE** offers you a **broad choice of methods**

- to predict **sound** from vibrating structures
- to simulate the **interaction** between fluid and structure
- to optimize acoustically your **product design**

**Main benefits** of using **SYSNOISE**

- Integrated software
- Ease-of-use
- Calculation speed

- Open architecture
- Customization
- All major computers
LMS/SYSNOISE 應用實例

- 內部聲場
- 外部聲場
- 流場結構互動
- 設計改善

- 汽車
- 航太
- 家用產品
車內噪音分析
Body Noise Transfer Functions

0 Interior Noise Prediction using Acoustic BE Analysis
0 Analysis of Structure-Borne Noise
   4 structural excitation
   4 acoustic response
      8 frequency dependent pressure
      8 at driver ear

acoustic BE mesh + structural FE mesh + structural response vectors

SYSNOISE Direct BEM or Indirect BEM

acoustic FRFs at driver ear
Definition of BNTF

What?
- frequency response function
- of sound pressure at a field point
- caused by a unit force
- at a structural excitation point
  - engine mount
  - suspension point

Why?
- if same car body and same acoustic compartment
- but different engines, suspension systems
- you can use the same BNTF!
First Step = Structural FE Analysis

0 Structural FE Mesh
   4 8914 nodes, 11086 elements
   4 body in white

0 Excitation
   4 Unit force (engine mount)

0 Analysis
   4 Normal modes (up to 120 Hz)
   4 Modal superposition

0 Results = Body displacements
   4 from 5 to 70 Hz, step 1 Hz
   4 usually limited to 100 ... 150 Hz

Model Courtesy of Daewoo
Second Step = Acoustic BE Analysis

0 Incompatible Meshes
  1 acoustic BE mesh with only 1168 nodes and 1200 elements
  2 different wavelengths for fluid and structure (bending)
  3 different geometries and different element densities

0 Automatic Multi-Frequency Transfer
  1 structural displacements $\Rightarrow$ normal acoustic velocities
Acoustic Response Calculation

0. Acoustic Frequency Response Function (Field Point)
   - driver ear
   - pressure (dB)
   - all frequencies

0. Acoustic Field (Field Point Mesh)
   - whole cavity
   - pressure (dB)
   - one frequency

Acoustic calculation time negligible compared to structural analysis.
Conclusion

0 Driver ear response computed with **SYSNOISE**
0 Further information may be obtained from a **contribution analysis**
0 A tool for each problem
  4 low frequency (Vibro-)Acoustics: **SYSNOISE**
  4 medium to high frequency Acoustics: **MOSART**
  4 high frequency (Vibro-)Acoustics: **SEA**
0 Interface to **Sound Quality Monitor** (LMS CADA-X)
0 Equivalent results between acoustic FE and BE
0 **Very fast acoustic calculation**
引擎本體輻射噪音

Structural FE Mesh
7400 grids & 6400 elements

Acoustic BE Mesh
2800 grids & 2800 elements
0 **Comparison** between
   4 acoustic test
   4 BE radiation analysis

0 Use of experimental vibration data as input for **SYSNOISE**

0 **Modal Expansion**

```
acoustic BE mesh +
experimental FRFs +
structural
normal modes

SYSNOISE
Indirect BEM

acoustic FRFs
at microphones
```

input method output
Experimental Test Set-Up

0 Hammer excitation in bearing 4

0 Measurements

4 Structural
  8 13 points
  8 on front face

4 Acoustic (SPL)
  8 distance = 0.1 m
  8 averaged on 6 points
**Structural and Acoustic Meshes**

**Structural FE mesh**
- 4 volume elements
- 4 lumped masses
- 4 beam elements
- 4 interior surfaces

**Mesh Coarsening**
- 4 suppress internal parts
- 4 detect and remove the ribs
- 4 increase the size of the elements (6 elements per acoustic wavelength is enough for the radiation analysis)
- 4 end up with the radiating surface only = **BE Mesh**
Modal Expansion

0 Assumptions
  4 experimental data are reliable and sufficient
    8 accurate damping
    8 accurate boundary conditions
    8 accurate load
  4 mode shapes are correct
    8 correlated with measurements

0 For each frequency

\[
\text{MEASUREMENT} = \sum \left[ \text{MODE SHAPE} \times \text{PARTIC. FACT.} \right]
\]

0 Singular Value Decomposition
Acoustic Results and Conclusion

0 Diamonds in, diamonds out!
0 Comparison
(distance = 0.10m)
  4 measured pressure
  4 computed pressure
=> Very Good Correlation
0 Modal Expansion
  4 validated
0 Acoustic Radiation
  4 accurate if accurate boundary conditions
消音器傳輸損失計算
Double Line Exhaust System

Many tools for modeling **duct noise** and **shell radiation**

- **finite elements**
  - surface absorption and perforated pipes
  - inhomogeneous fluid (porous material, temperature gradients,...)
  - flow effects
  - time and frequency domain analysis

- **boundary elements**
  - surface absorption and perforated pipes
  - uncoupled or coupled (shell noise) analysis
Acoustic Model

0 Acoustic FE Mesh
   4 46966 nodes and 39254 elements

0 Acoustic Properties
   4 Acoustic medium = air
   4 Perforated pipes
   4 Strong temperature gradient
      (500 °C -> 50 °C)

0 Excitation
   4 2 inlet pipes
   4 engine pulsations = velocity BCs
   4 phase difference : 180 degrees

Model Courtesy of Bosal
Acoustic Response Calculation

0  Pipe noise
   4  for one single frequency or on a frequency range
   4  transmission loss (by combination of FRFs)
Flow Effects

0 2-step approach
   4  compute flow field
      8  in SYSNOISE: stationnary, inviscid, irrotational flow
      8  in CFD package + import to SYSNOISE
   4  compute acoustic field (convected wave equation)

0 Flow field
   4  flow potential and flow velocity BCs
   4  frequency independent

0 Acoustic field
   4  influenced by flow field
   4  frequency domain
Transient Analysis

- Acoustic FE or BE
- Time dependent acceleration BCs
- Impedance BCs for:
  - open outlet end
  - surface absorption

- Transient response

- Time Response Functions
  - you can listen to it
  - you can apply FFT to switch to the frequency domain
Conclusion

0 Multitude of tools for duct acoustics
   4 HVAC systems
   4 air in-take systems
   4 exhaust systems

0 Choice of method is application dependent
   4 flow effects ? temperature effects ?
   4 transient or harmonic ? uncoupled or coupled ?
   4 homogeneous fluid ? perforated pipes ? surface absorption ?

0 Further post-processing
   4 audio replay
   4 interface to Sound Quality Monitor (SQ-MON of LMS)
齒輪箱噪音
Gearbox Sound Radiation

0 Compliance with Pass-by-Noise Regulation

0 Automatic Model Handling
  4 automatic verification
  4 automatic correction

0 Non-Linear Matrix Frequency Interpolation
  4 faster solution
  4 same accuracy

Input: acoustic BE mesh + structural FEA results
Method: SYSNOISE Indirect BEM
Output: directivity diagrams + SPL results at field points
Pass-By-Noise Test (Europe : ISO 362)

0 Running Vehicle
   4 initial speed = 50km/h
   4 2 tests : second and third gear
   4 accelerate at full throttle

0 Measurement Points
   4 immobile, standardized position
   4 SPL < 77 dBA during the whole test

0 Many Contributions
   4 road/wheel noise
   4 engine noise
   4 aerodynamic noise
   4 noise of components : exhaust, gearbox, ...

Model Courtesy of BMW Munchen
Acoustic Model

0 **Acoustic BE Mesh**
  4 1,827 nodes, 1,899 elements

0 **Automatic Mesh Handling**
  4 normals correction
  4 junctions (523)
    8 detection of junctions
    8 junction constraints
  4 free edges

0 **Excitation**
  4 vibration of the gearbox shell
  4 gear noise

0 **Frequency**: 500 to 1500 (Step 5 Hz) = 201 Steps
Acoustic Response (CRAY C90)

0 Frequency Interpolation Technique
  4 master frequencies: system assembly + solution
  4 slave frequencies: system interpolation + solution

0 CPU time without Interpolation (frequency step = 5 Hz)
  4 assembly: 105 * 201 = 21105 sec
  4 solution: 20 * 201 = 4020 sec
  4 total: 25125 sec

0 CPU Time with Interpolation (frequency step = 50 Hz, interpolation every 5 Hz)
  4 assembly: 105 * 21 = 2205 sec
  4 solution: 20 * 201 = 4020 sec
  4 total: 6225 sec -> 4 times faster !!!
Conclusion

0 Fully Automatic Mesh Handling
   4 mesh verification
   4 mesh correction

0 Matrix Frequency Interpolation
   4 non linear
   4 important time saving
   4 quality of results kept

0 Pass-by-Noise Requirements are Satisfied
引擎閥蓋噪音
Valve Cover Radiation

0 Sound Radiated from Truck Engine Valve Cover

0 Automatic Mesh Treatment in SYSNOISE
  4 normals correction and rib removal

0 Symmetry planes and Reflective Halfspaces

0 Analysis
  4 radiation from structural normal mode
  4 comparison of radiation efficiencies

<table>
<thead>
<tr>
<th>acoustic BE mesh + structural normal modes</th>
<th>SYSNOISE Indirect BEM</th>
<th>acoustic radiated field + radiation efficiency</th>
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</thead>
<tbody>
<tr>
<td>input</td>
<td>method</td>
<td>output</td>
</tr>
</tbody>
</table>
**Structural Model**

0 **Structural FE Mesh**
   4 1771 nodes
   4 1758 elements
   4 symmetric
   4 contains ribs

0 **Structural Deflection**
   4 mode shape 6 - 843.3 Hz

0 **Rib Handling**
   4 interior ribs
   4 no direct contribution to acoustic field
   4 mesh coarsener of SYSNOISE
      8 automatic rib detection and removal
## Acoustic Model

<table>
<thead>
<tr>
<th>Topic</th>
<th>Details</th>
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<tbody>
<tr>
<td>Option BEM Indirect</td>
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<tr>
<td>Automatic Mesh Handling</td>
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</tr>
<tr>
<td></td>
<td>4 normals</td>
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<tr>
<td></td>
<td>4 junctions</td>
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<td></td>
<td>4 free edges</td>
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<tr>
<td>Model Handling</td>
<td>0</td>
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<tr>
<td></td>
<td>4 symmetry plane</td>
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<td></td>
<td>4 rigid halfspace plane</td>
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<tr>
<td>Automatic BCs Generation</td>
<td>0</td>
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<tr>
<td></td>
<td>4 incompatible meshes</td>
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<td>4 projection on normal</td>
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<td>4 conversion to velocities</td>
</tr>
</tbody>
</table>
Acoustic Radiated Field

0 Results

4 mesh
  8 potentials
  8 input and radiated power
  8 power densities
  8 radiation efficiency

4 field point mesh
  8 pressure
  8 velocity
  8 intensity
  8 radiated power
Conclusion

0 Starting from a Structural FE Model
   4 structural FE mesh
   4 structural modal basis

0 Automatic Handling of the Mesh
   4 very robust algorithms
   4 very fast update of the model

0 Easy Transfer of Structural Deflection

0 Acoustic Radiation Analysis

0 Vibro-Acoustic Results
   4 detailed results
   4 easy representation
飛機渦輪葉片噪音
Aircraft Fan Noise

0 Acoustic Radiation using Indirect BEM

0 Axisymmetric Model
  4 axisymmetric geometry
  4 non-axisymmetric excitation
  4 Fourier decomposition

0 Easy Post-processing

**Input**
- acoustic BE mesh (generator line) + field point mesh

**Method**
- SYSNOISE Indirect BEM (Axisymmetric)

**Output**
- Acoustic Field SPL, ...
Acoustic BE Model

0 Acoustic BE Mesh (Axisymmetric)
  4 only 60 nodes, 59 LINE2 elements
  4 automatic verification of normals

0 Automatic Axisymmetric Mesh Expansion
  4 3D mesh
  4 refinement = 5

0 Boundary Conditions
  4 order 5 => Fourier decomposition
  4 possible BCs in SYSNOISE
    8 velocity, pressure
    8 impedance/admittance
    8 continuous or discontinuous
    8 combination
Acoustic Field Evaluation

0  Very Fast Calculation (like a 2D Model)

0  Acoustic Field
   4  pure radiation
   4  scattering on fuselage

Pressure field - 500Hz

Scattered field - 500Hz
**Conclusion**

0 **Unique Features** for Solving Axisymmetric Problems like Aircraft Fan Noise Problems
   - 4 axisymmetric geometry
   - 4 automatic mesh expansion
   - 4 boundary condition
     - 8 general 3D
     - 8 harmonic (order to be specified)

0 **Very Short CPU Time**

0 Full 3D Post-processing Possible
喇叭流場結構互動行為分析

![喇叭流場結構圖](image)
Loudspeaker Radiation Analysis

0 Coupled BEM Indirect/FEM Structure
4 fluid inside and outside of the loudspeaker
4 rigid loudspeaker box
4 very thin flexible woofer
4 added mass effect
  8 of air on woofer
  8 responsible for sound characteristic of the woofer

Input : acoustic BE mesh + structural FE mesh and mode shapes of the woofer
Method : SYSNOISE Indirect BEM Coupled
Output : acoustic transmitted and radiated field
Acoustic Model

0 Acoustic BE Mesh
  4 498 nodes, 512 elements
  4 normals
    8 must point consistently
    8 automatic handling
  4 fluid = air
    8 density = 1.2 kg/m³
    8 sound speed = 340 m/s
  4 loudspeaker box
    8 rigid
  4 woofer
    8 flexible (see structural model)
  4 field point mesh
Structural FE Model

0 Woofer FE Mesh
   4 shell elements

0 Boundary Conditions
   4 clamped on the edges
   4 excitation
      8 point force

0 Woofer FE Modal Basis
   4 10 structural modes
   4 up to 1347 Hz

0 Coupling Models
   4 fluid-structure link
   4 on the woofer only
Radiated Pressure Field - 500 Hz
Conclusion

0 Loudspeaker Model
   4 rigid loudspeaker box
   4 very flexible and thin woofer (membrane)
   4 fluid on both sides of the box faces

0 Coupled BEM Indirect/FEM Structure
   4 fluid-structure link
   4 sound transmission (through the woofer)
   4 exterior acoustic field
      8 pressure field
      8 directivity pattern
油底殼設計靈敏度分析
Oilpan Global Sensitivity Analysis

0 Traditional acoustic BE analysis only gives results for
  4 radiated sound pressure
  4 radiated sound power

0 but no information on
  4 where to make design modifications?
  4 which changes to make?

0 Solution: Global Sensitivity Analysis

Input: acoustic BE mesh + structural sensitivities + structural response vectors

Method: Global Sensitivity Analysis with BEM Direct or Indirect

Output: global sensitivities
Structural FE Model

0 Define Thickness Design Variables
0 Compute Structural Sensitivities
0 Transfer to SYSNOISE

4 for every frequency
8 structural sensitivity vectors (1 per design variable)
8 response vector
Acoustic BE Model

0 Acoustic BE Mesh
   4 radiating surface
   4 1620 nodes, 1550 elements

0 Problem
   4 radiated power too high
   4 near 1.000 Hz

0 Solution Steps
   4 compute the **sensitivity** of radiated power with respect to panel thickness design variables
   4 see which part is the most **sensitive**
   4 **change** the thickness (stiffness) of this part
   4 **verify** the improved model

Model Courtesy of Honda
Global Sensitivity Results

0 **Show clearly what to do**
   4 where the sensitivity is high, the effect on radiated power is more important

0 **Solution**
   4 difficult to increase thickness
   4 => add stiffeners

0 **Radiated Power FRF**
   4 shows improvement
   4 about **4.6 dB**
Conclusion

0 No more trial-and-error iterations
0 SYSNOISE clearly indicates
  4 where changes have to be made on the structure
  4 what is the impact of these changes on the acoustic field
0 Significant cost savings
0 Reduced time-to-market
0 Further extensions
  4 sensitivities on a frequency range
  4 link to optimization techniques: LMS Optimus