Vibroacoustic loads on spacecraft: FEM/BEM simulation

1. Introduction
2. The acoustic load case in spacecraft structural analysis and testing
3. Structural and acoustic analysis
4. Particular Modeling Topics
5. Application examples
6. Conclusions

1. Introduction

Qualification:

Validation of design, models, materials and processes.

Correlation and tuning of mathematical models.

Margins of safety to qualification loads.

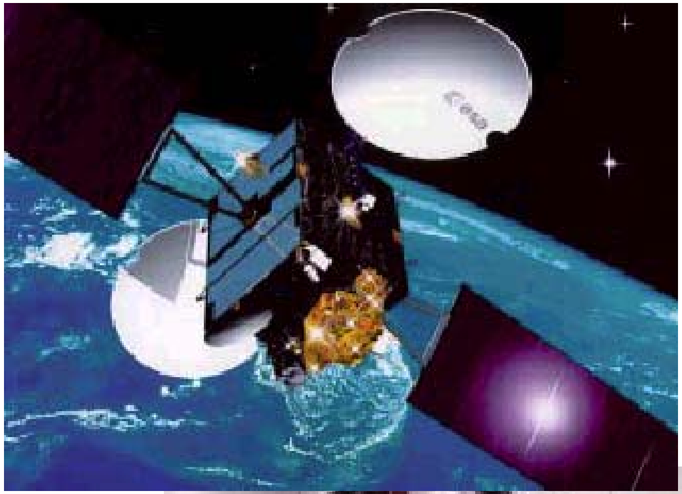
Flight acceptance:

Verification of flight specimen to possible manufacturing and material flaws.

Sensitive Components:

Direct acoustic loading of lightweight structural elements, antenna reflectors, and solar panels, sun shields.

Acceleration of equipments mounted on lightweight structural elements.



2. The acoustic load case in spacecraft structural analysis and testing 1/5

Ignition and lift-off: blast waves excite lateral vibrations, mainly between 5 and 10 Hz. These are transient, although treated as a quasi-static load for structural dimensioning.

The Vulcain main engine and boosters vibrations, turbulent mixing of exhaust jet with atmosphere.

2. The acoustic load case in spacecraft structural analysis and testing 2/5

Ignition and lift-off: blast waves excite lateral vibrations, mainly between 5 and 10 Hz. These are transient, although treated as a quasi-static load for structural dimensioning.

The Vulcain main engine and boosters vibrations, turbulent mixing of exhaust jet with atmosphere.

Transonic flight: Turbulent boundary layer noise is generated and buffeting in the vehicle aft excites the nozzle pendulum mode at 10 Hz.

Effect of the fairing: internal cavity modes, noise reduction by absorbing materials and Helmholtz ressonators.

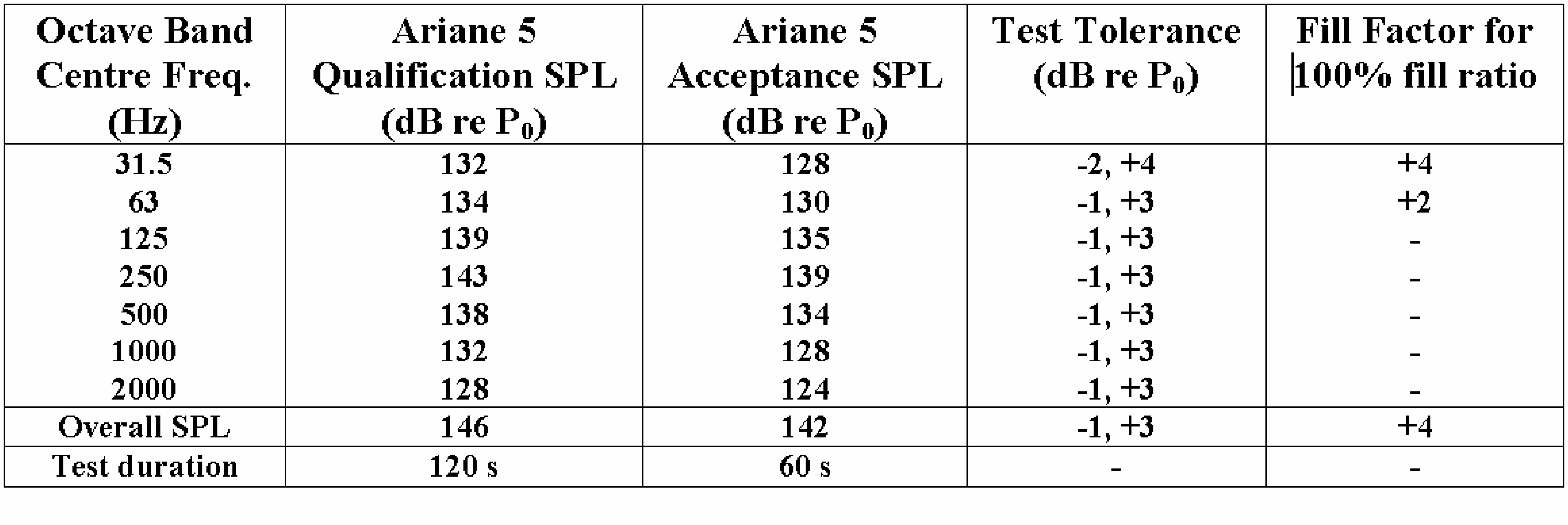
Effect of payload: increase of SPL in LF due to new cavity modes and radiation.

2. The acoustic load case in spacecraft structural analysis and testing 3/5

Acoustic Test Specification by the launch authority:

Random pressure, stationary and ergodic diffuse field

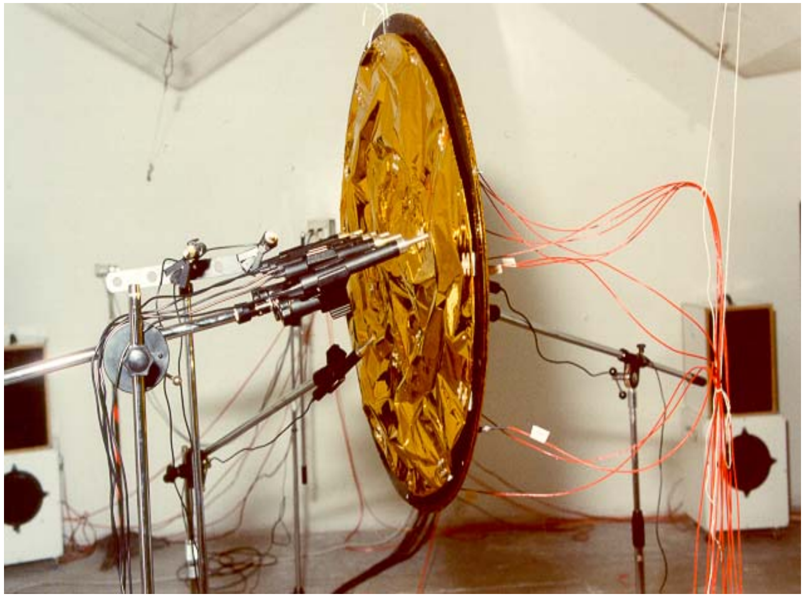
Ariane 5 acoustic test specification. $P_0 = 2\cdot10^{-5}$ Pa.



Octave Band Centre Freq. (Hz)	Ariane 5 Qualification SPL (dB re P_0)	Ariane 5 Acceptance SPL (dB re P_0)	Test Tolerance (dB re P_0)	Fill Factor for 100% fill ratio
31.5	132	128	-2, +4	+4
63	134	130	-1, +3	+2
125	139	135	-1, +3	-
250	143	139	-1, +3	-
500	138	134	-1, +3	-
1000	132	128	-1, +3	-
2000	128	124	-1, +3	-
Overall SPL	146	142	-1, +3	+4
Test duration	120 s	60 s	-	-

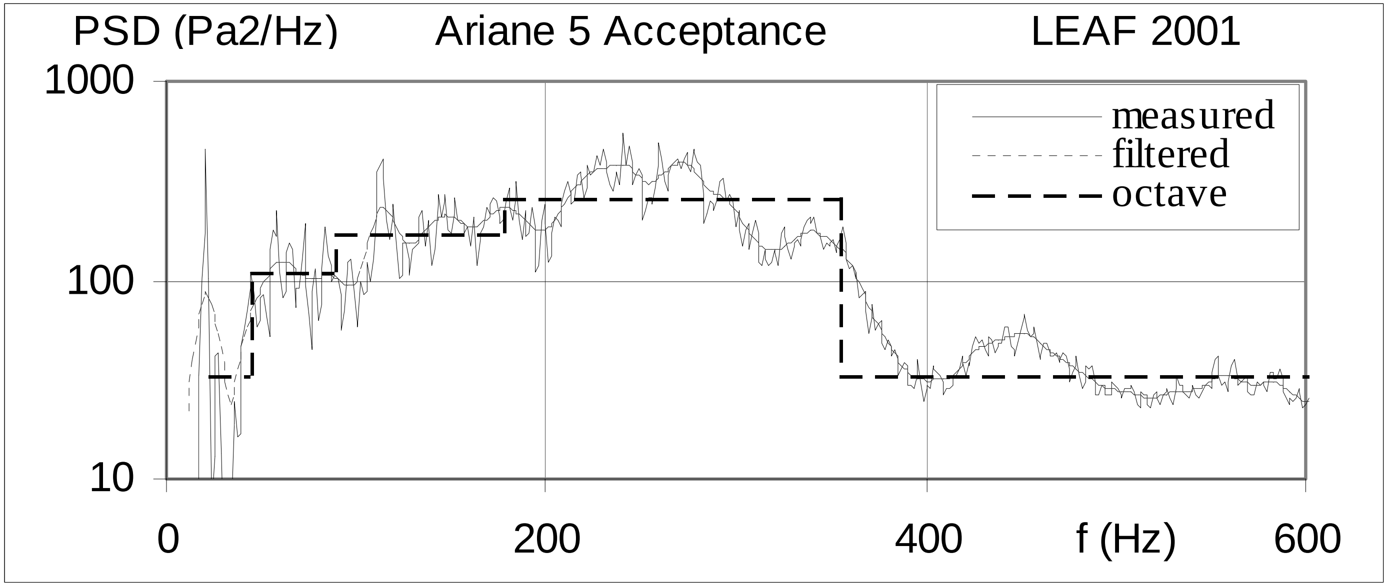
2. The acoustic load case in spacecraft structural analysis and testing 4/5

Study carried out by EADS CASA (ES)



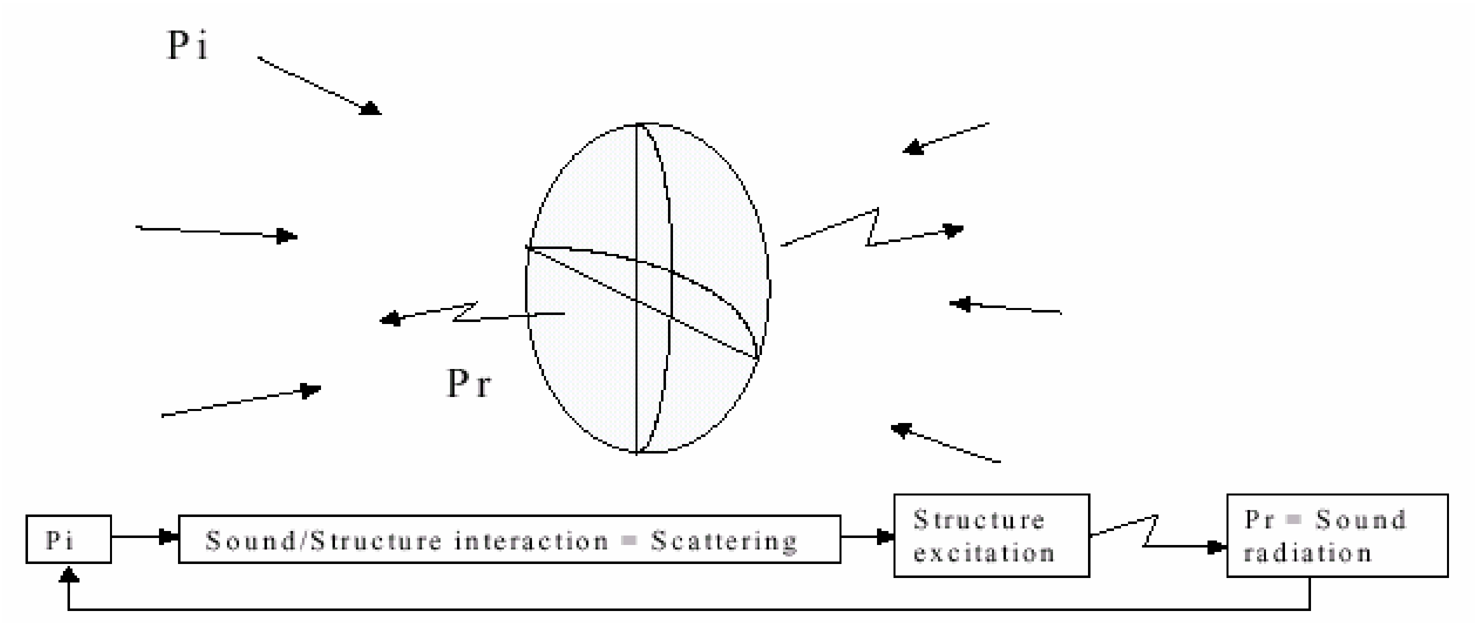
2. The acoustic load case in spacecraft structural analysis and testing 5/5

Test Environment:



3. Structural and acoustic analysis 1/5

Structural-Acoustic Coupling:



3. Structural and acoustic analysis 2/5

Structural-Acoustic Coupled Equations:

$$\left(\nabla^2 + k^2\right)P = 0$$

$$\left.\begin{aligned} \frac{\partial \sigma_{ij}}{\partial x_j} + \rho_s \omega^2 w_i = 0 \\ \sigma_{ij} = C_{ijkl}\frac{\partial w_k}{\partial x_l} \end{aligned}\right\},$$

$$\left.\begin{aligned} \frac{\partial P}{\partial n} - \rho_f \omega^2 w_i n_i = 0 \\ \sigma_{ij} n_j + P n_i = 0 \end{aligned}\right\},$$

$$\lim_{r\to\infty} r\left(\frac{\partial P}{\partial r} + \mathrm{j}kP\right) = 0 \cdot$$

$$g(r - r_0) = -e^{jk|r-r_0|}/(4\pi|r - r_0|),$$

$$P(r) = P_I - 2\int_{S_0}\left(P(r_0)\frac{\partial g}{\partial n_0} - \rho_f \omega^2 \mathbf{w}\cdot\mathbf{n}_0\, g\right) \mathrm{d}\, S_0 .$$

Structural analysis:

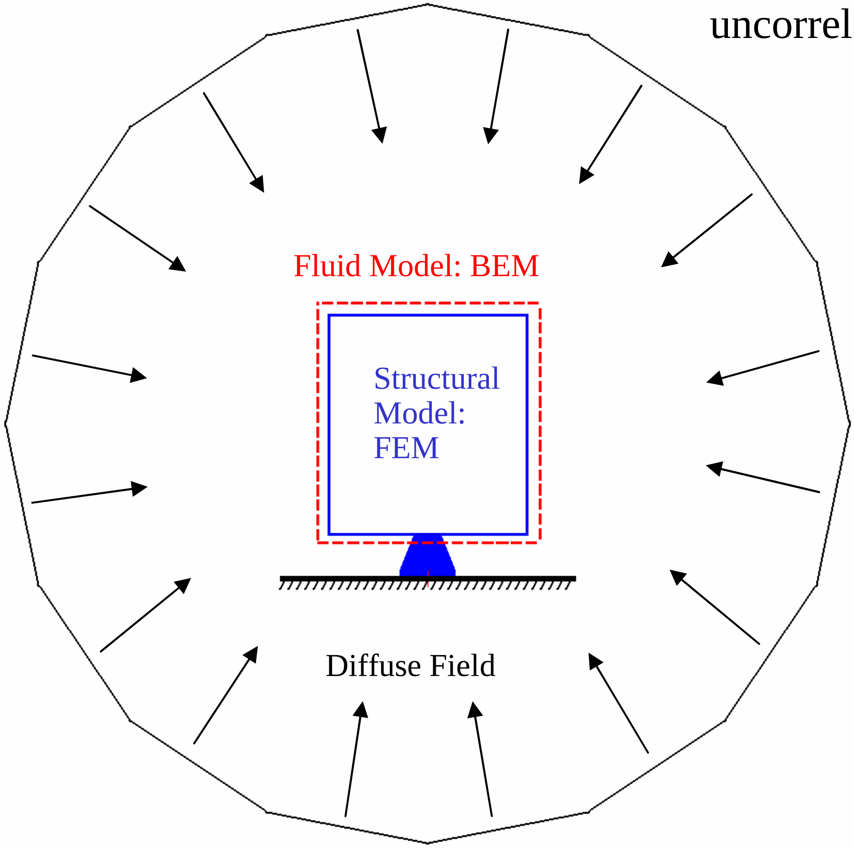
- **Finite Element Method**

Acoustic Analysis:

- **Uncoupled (FEM,JAA,rigid BEM/FEM)**
- **Coupled (BEM/FEM, FEM/FEM)**
- **Statistical Energy Analysis**

3. Structural and acoustic analysis 3/5 (Exterior Problems)

Coupled BEM/FEM Principles:



Diffuse Field Simulation based on superposition of uncorrelated plane waves

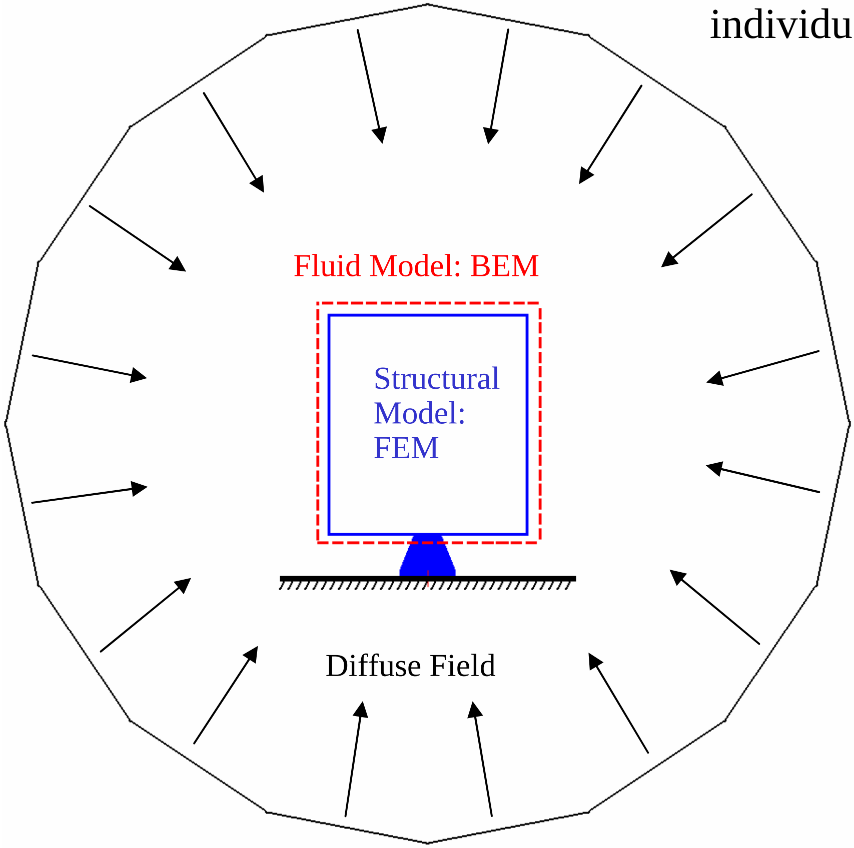
$$S_{\gamma_i \gamma_j}(\Omega) = \sum_{s,t=1}^{T} G^{*}_{p_s \gamma_i}(\Omega) S_{p_s p_t}(\Omega) G_{p_t \gamma_j}(\Omega)$$

$$S_{p_s p_t}(\Omega) = S_{diff}(\Omega) \delta_{st} \alpha_t$$

$$S_{\gamma_i \gamma_j}(\Omega) = S_{diff,pp}(\Omega) \sum_{t=1}^{T} \alpha_t G^{*}_{p_t \gamma_i}(\Omega) G_{p_t \gamma_j}(\Omega)$$

3. Structural and acoustic analysis 4/5 (Exterior Problems)

Coupled BEM/FEM Principles:



Transfer Function of structural response due to excitation by individual plane waves of unit amplitude

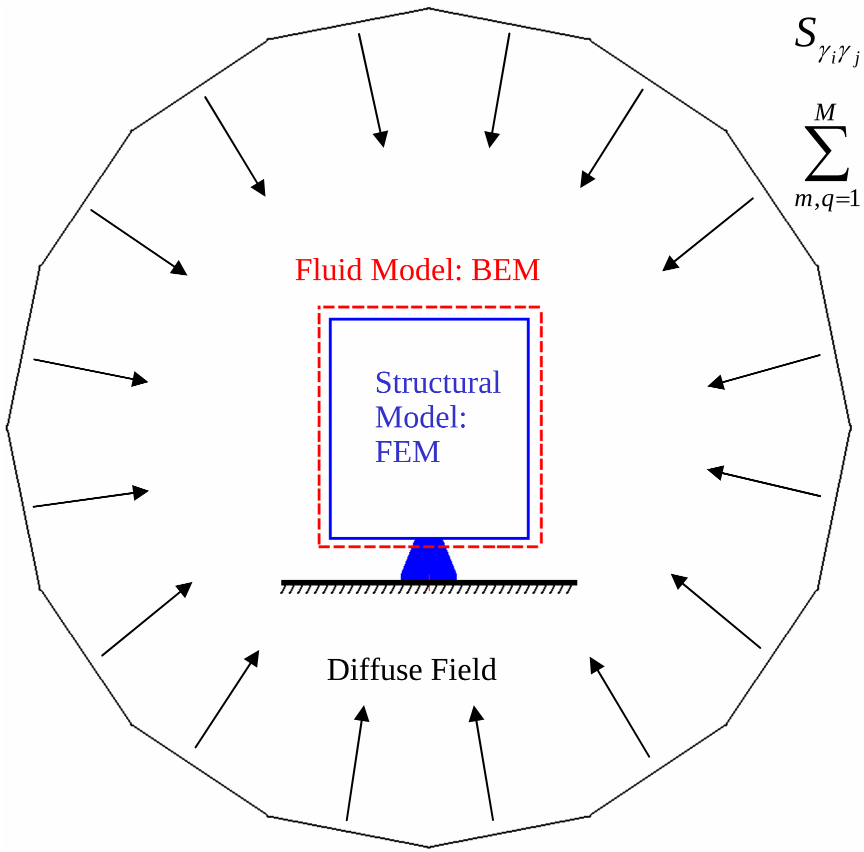
$$S_{\gamma_i\gamma_j}(\Omega) = S_{diff,pp}(\Omega)\sum_{t=1}^{T}\alpha_t G^{*}_{p_t\gamma_i}(\Omega) G_{p_t\gamma_j}(\Omega)$$

$$G_{p_t\gamma_i}(\Omega) = \frac{1}{j\Omega}\sum_{n=1}^{M}\varphi_n^{\vec{s}}\left(\vec{x}_i\right)\sum_{m=1}^{M}\underline{Z}_{mn}^{-1}\hat{p}_{blk,tm}$$

$$\underline{Z}_{mn} = \underline{Z}_{struc,mn} + \underline{Z}_{rad,mn}$$

3. Structural and acoustic analysis 5/5 (Exterior Problems)

Coupled BEM/FEM Principles:



$$S_{\gamma_i \gamma_j}(\Omega) = S_{diff,pp}(\Omega)$$

$$\sum_{m,q=1}^{M} \varphi_m^{\vec{s}}\left(\vec{x}_i\right)\left[\sum_{n,r=1}^{M} \frac{Z_{mn}^{-H}(\Omega)}{\Omega}\left[\sum_{t=1}^{T} \hat{p}_{blk,tm}(\Omega)\alpha_t \hat{p}_{blk,tq}(\Omega)\right]\frac{Z_{qr}^{-1}(\Omega)}{\Omega}\right]\varphi_q^{\vec{s}}\left(\vec{x}_j\right)$$

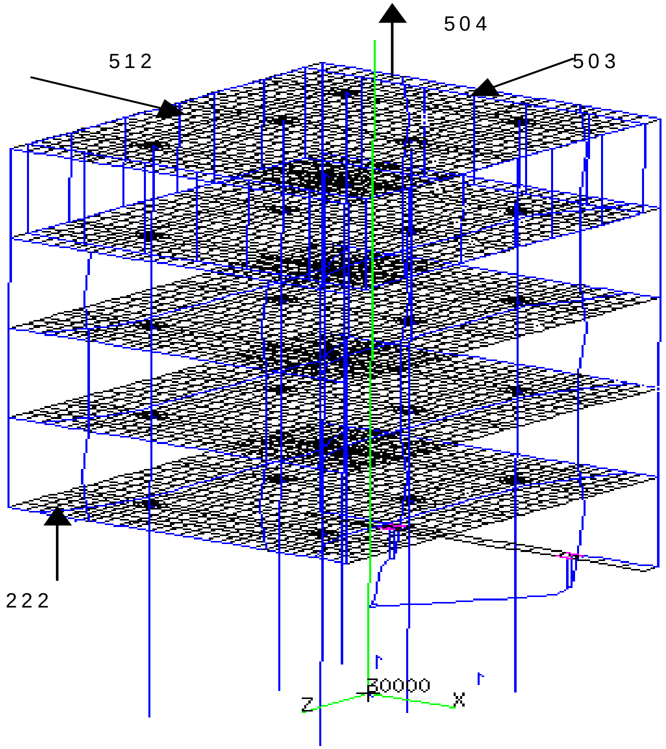
BEM mesh less refined than FEM mesh

Only acoustically blocking interfaces meshed with BEM

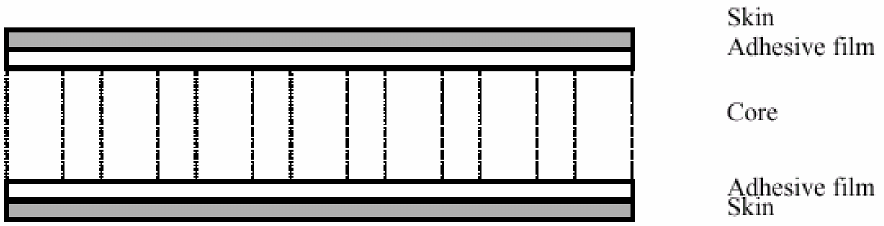
4. Particular modeling topics

Solar Array Stack under Acoustic Excitation

- Study carried out by Dutch Space (NL) and Metravib RDS (F) under ESA contract
- Mechanical tests:
  - Modal survey test in air and helium
  - Sine test (shaker)
  - Acoustic plane wave test
  - Acoustic noise test
- Effects of the air on the dynamic response modeled by a boundary element approach (particular difficulty: thin air gaps in between the individual panels of the wing)
- Extensive test-analysis correlation and model updating activities (responses evaluated in terms of structural accelerations, stresses, acoustic pressures in the inter panel gaps and the surrounding fluid)



5. Application Examples 1/6: Composite circular plate

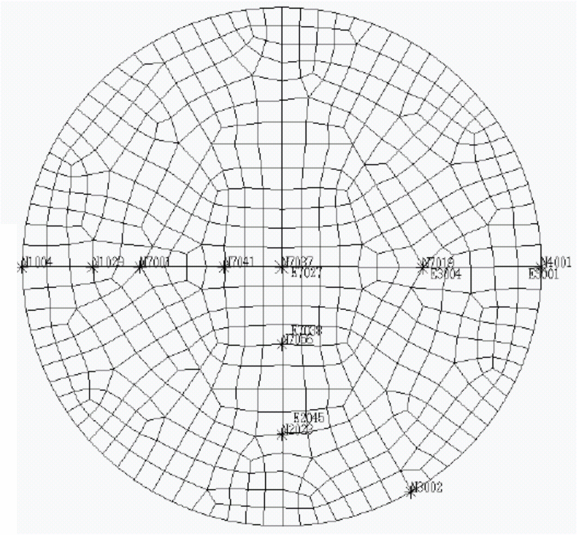


- Diameter = 700 mm
- Thickness = 6.82 mm
- Material : CFRP skins and Aluminium honeycomb core.

Material properties are listed in Table 5.1.

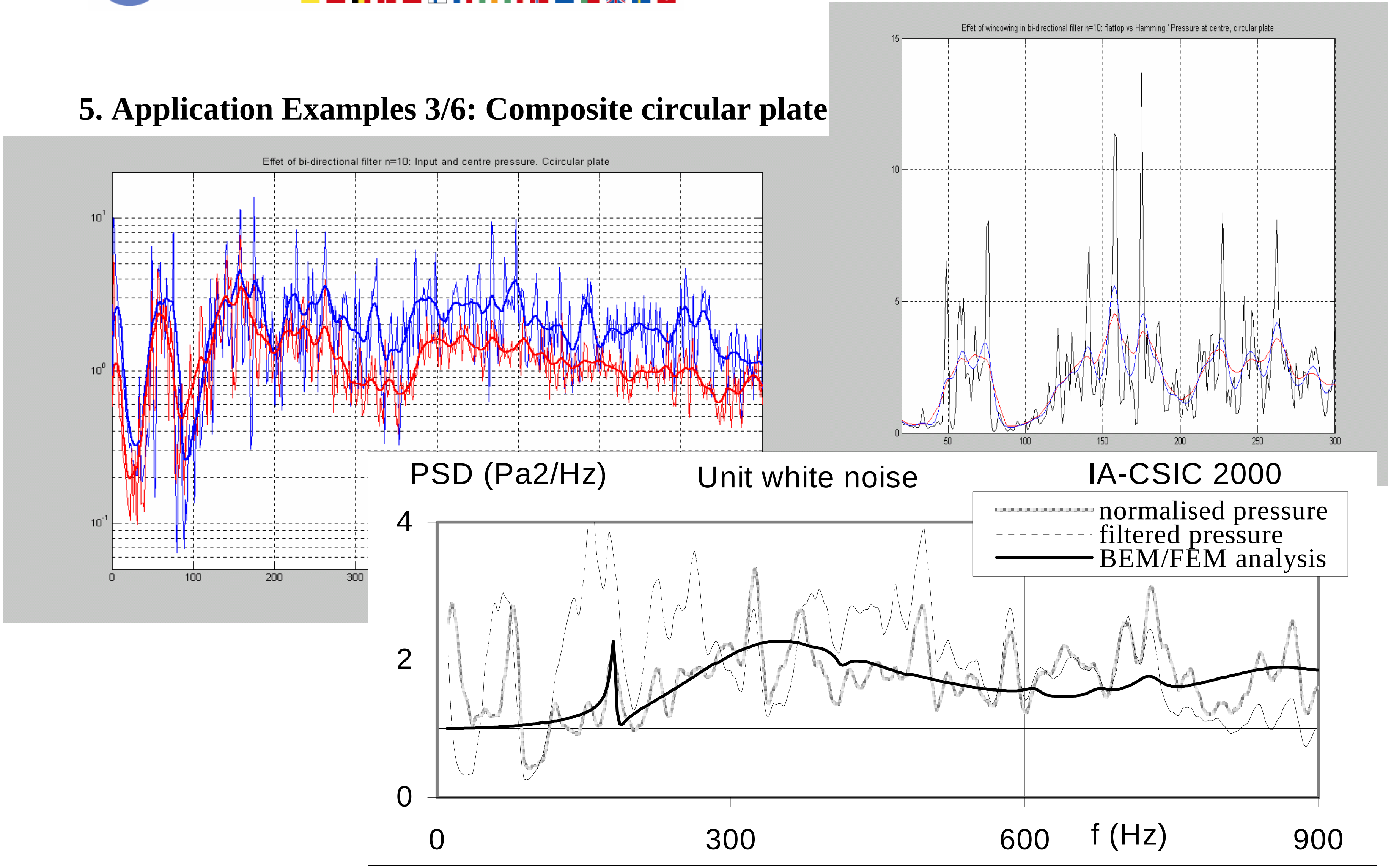
PROPERTY	M55J/CYCOM 950	Aluminium core: 1/4-5056-.0007
E_1 (N/mm^2)	267300	183.4
E_2 (N/mm^2)	5846	155.0
G_{12} (N/mm^2)	4070	82.7
G_{13} (N/mm^2)	-	172.9
G_{23} (N/mm^2)	-	82.7
ν	0.304	0.33
ρ (Kg/m^3)	1670	25.6

5. Application Examples 2/6: Composite circular plate

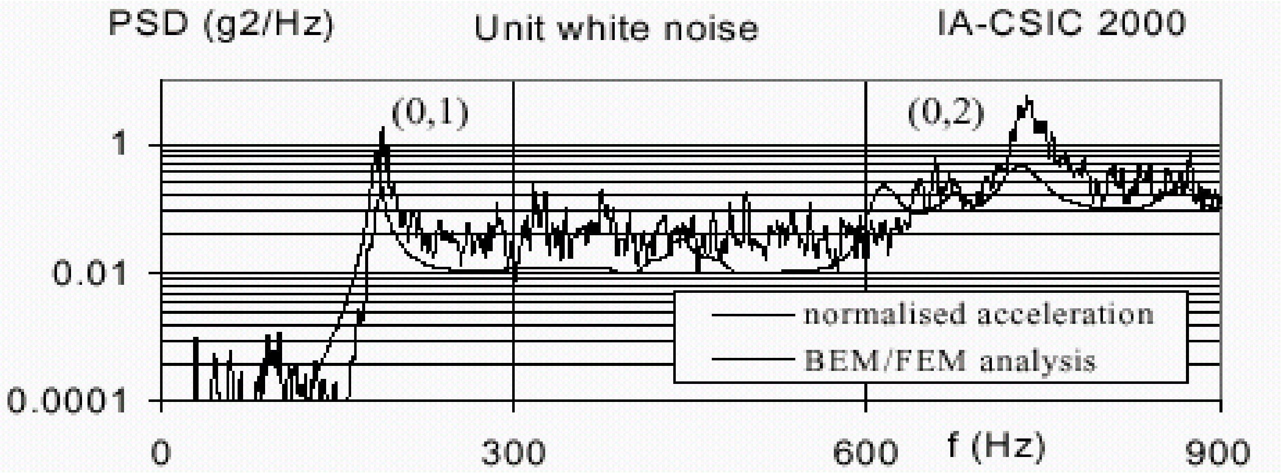


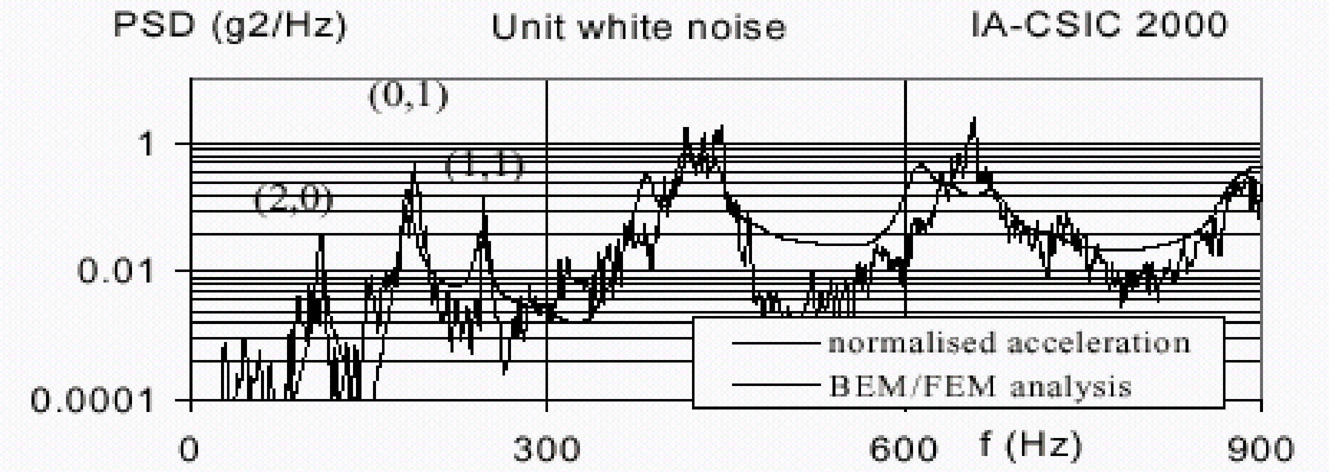
Mode	Eigenfreq. In vacuo	Eigenfreq. In air	Prediction in vacuo (Blevins R.D.5)	Mode shape (i,j)
1	1.31E+02	1.23E+02	129	2,0
2	1.34E+02	1.26E+02	--	2,0
3	2.26E+02	2.10E+02	223	0,1
4	3.02E+02	2.87E+02	300	3,0
5	3.03E+02	2.88E+02	--	3,0
6	4.92E+02	4.64E+02	503	1,1
7	5.01E+02	4.72E+02	--	1,1
8	5.19E+02	4.97E+02		4,0
9	5.19E+02	4.98E+02		4,0
10	7.75E+02	7.47E+02		5,0
11	7.77E+02	7.49E+02		5,0
12	8.18E+02	7.80E+02	864	2,1
13	8.25E+02	7.87E+02	--	2,1
14	8.99E+02	8.58E+02	945	0,2

5. Application Examples 3/6: Composite circular plate



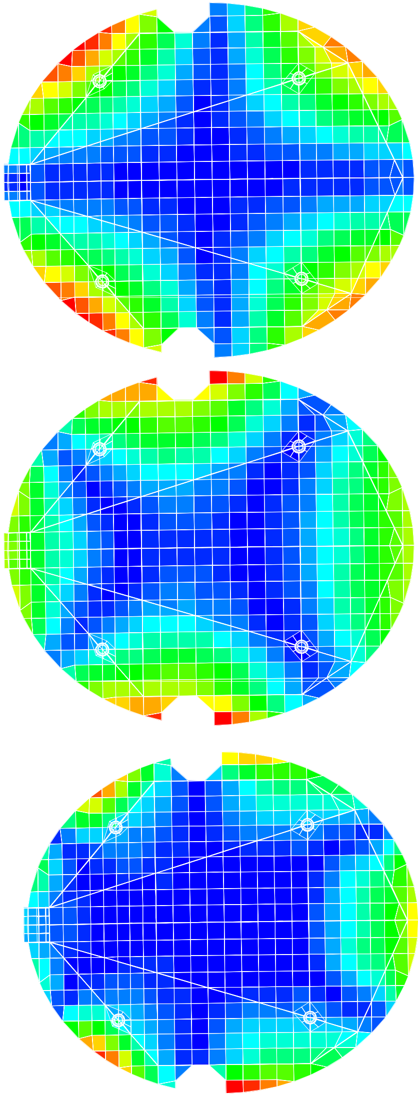
5. Application Examples 4/6: Composite circular plate

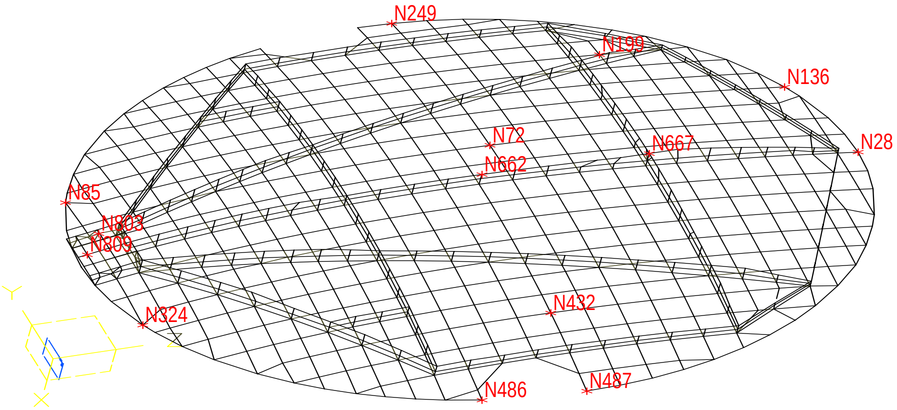




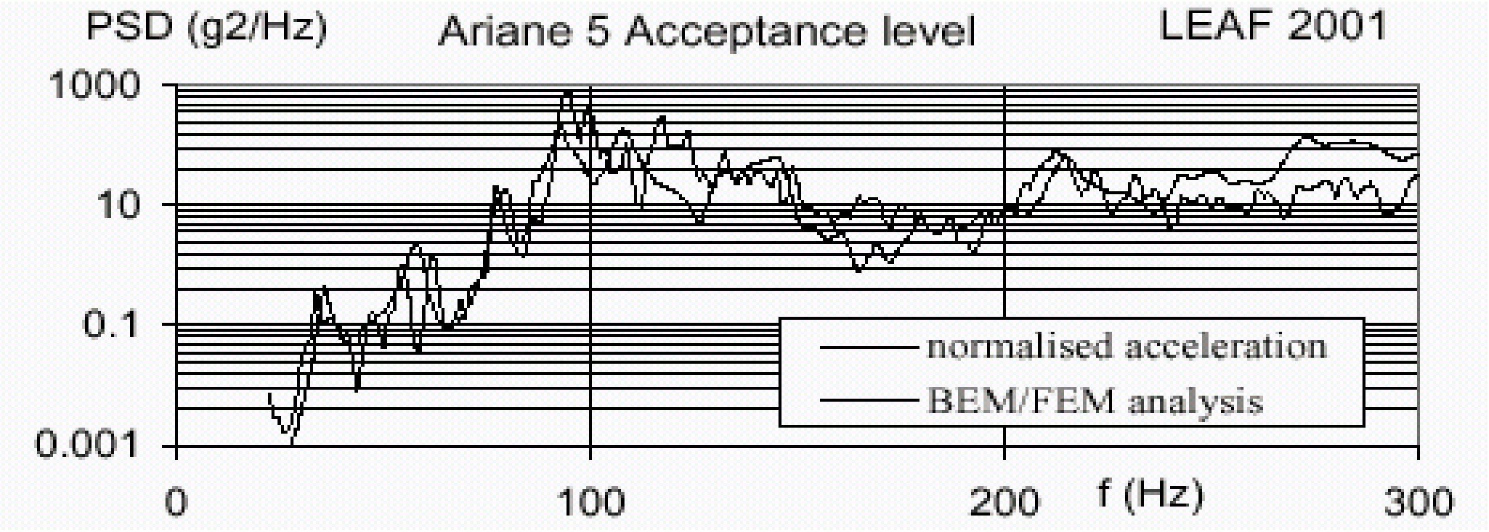
5. Application Examples 5/6: ARTEMIS antenna reflector

Analysis	Test freq. and damping	Mode shape
f1= 18.5 Hz	f1= 18.9 Hz, 0.18%	Equivalent to mode (2,0) antisymmetric
f2= 36.3 Hz	f2= 33.1 Hz, 0.27%	Equivalent to mode (2,0) symmetric, but distorted enhancing tip and cut-out bending
f3= 58.6 Hz	f3= 54.8 Hz, 0.29%	Equivalent to mode (3,0) symmetric, but distorted enhancing ADM dish zone bending
f4= 59.3 Hz	f4= 57.5 Hz, 0.27%	Equivalent to mode (3,0) antisymmetric





5. Application Examples 6/6: ARTEMIS antenna reflector



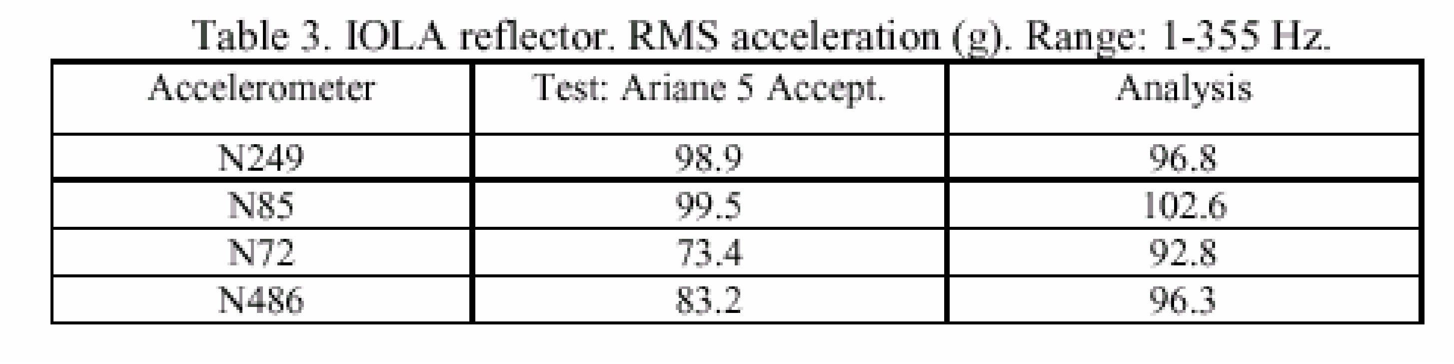


Table 3. IOLA reflector. RMS acceleration (g). Range: 1-355 Hz.

Accelerometer	Test: Ariane 5 Accept.	Analysis
N249	98.9	96.8
N85	99.5	102.6
N72	73.4	92.8
N486	83.2	96.3

6. Conclusions

The purpose of Vibroacoustic simulation in space activities is the qualification of space structures and the acceptance for flight :

Tests in Reverberant Chambers.
Simulation with BEM and FEM

Current Limitations:

Representativity of specified environment with respect to real launch environment.

Assumption of linearity, stationarity, ergodicity and diffuse field.

Limitations of reverberant chambers: eigenmodes and sound generation and control.