Dutch Space

An adapted FEM/BEM approach to analyse the structural responses of solar arrays exposed to a reverberant sound field

Jaap Wijker

Dutch Space BV

PO Box 32070, NL-1991 2303 DB, Leiden, Netherlands

E-mail: j.wijker@dutchspace.nl

Overview of presentation

Dutch Space

- Introduction/Dutch Space and Solar Arrays
- Problem definition
- Analysis methods
- VANGSA study
- Adapted FEM/BEM models
- Conclusions

Dutch Space and Solar Arrays

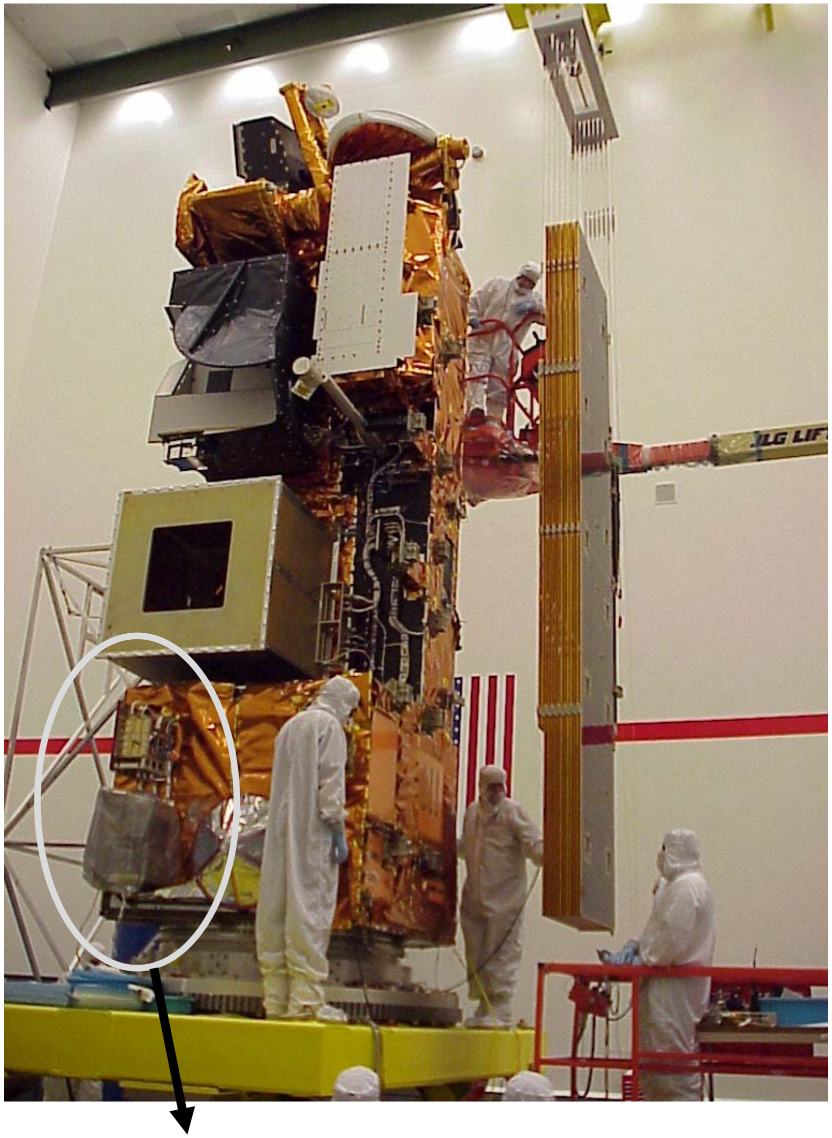
Dutch Space

- Dutch Space is in Europe the most important provider of solar arrays for spacecraft systems

  - Flat Pack (large) Solar Arrays for LEO (5-10kW)
  - ARA Mark III Solar Array for LEO, MEO, GEO, up 18 kW (Gaas cells)
  - Small Missions Solar Arrays (0.5-5kW)

EOS Aqua and Aura Satellites

Dutch Space

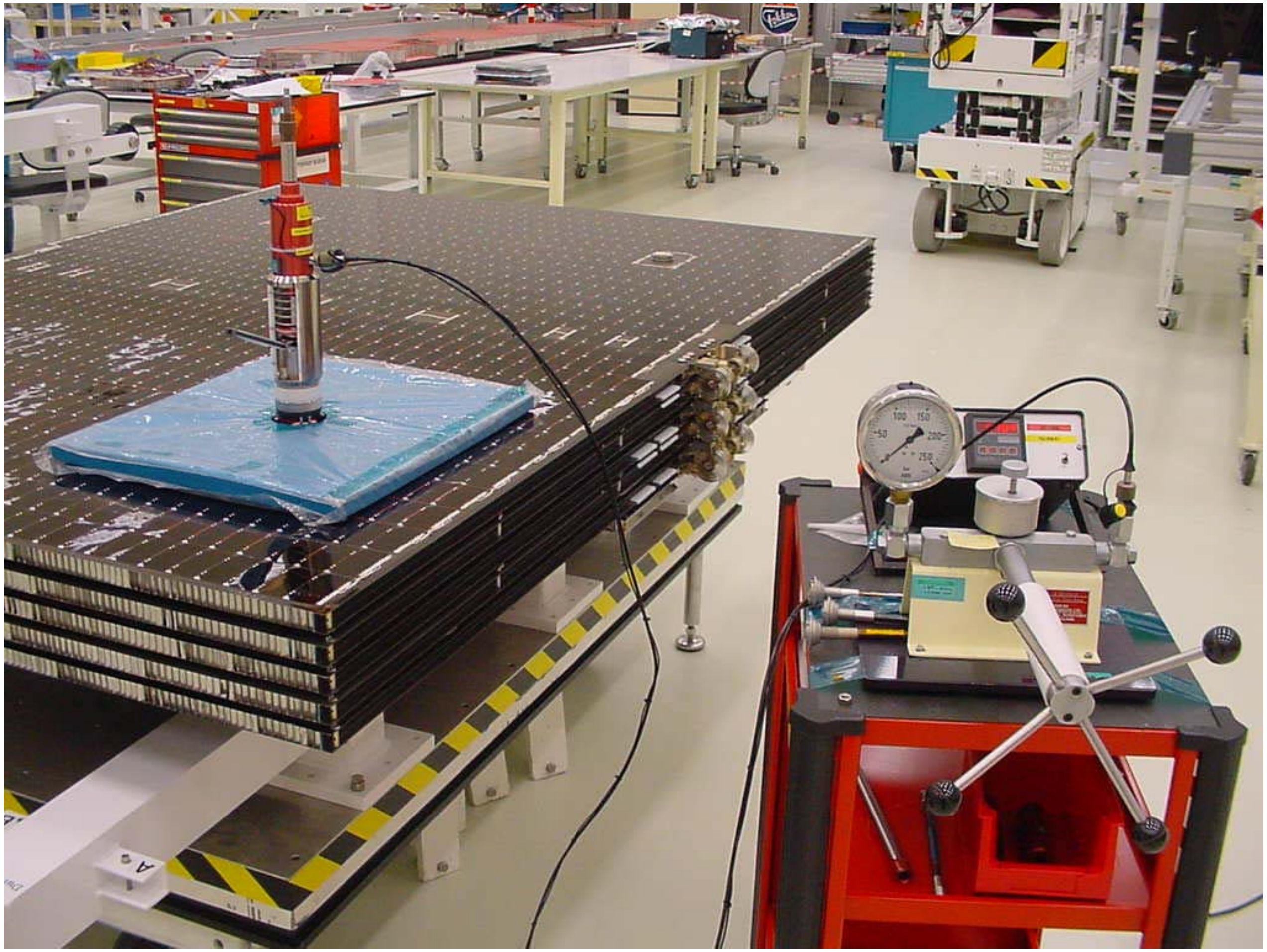


Dutch Ozone Monitoring Instrument (OMI)

The Aqua and Aura solar arrays both consist of a single wing, containing 12 thin panels equipped with solar cells (4.6x1 m2) (181.5*39.4 inch2) and 2 yoke panels (to keep the solar cells out of the shadow of the satellite under all sun angles). (4400 Watts end of life)

DAWN Spacecraft Solar Array

Dutch Space



NASA Deep Space Mission

Two wings

5 panels per wing ($2.27*1.61\ m^2$) ($89.4*63.4\ inch^2$)

BOL 11 kW

EOL 1.3 kW (in deep space)

ATV Solar Arrays

Dutch Space

Artist impression of ATV heading for the International Space Station.

- Highly modular very stiff (for AOCS purposes) deployable array with compact storage volume
- 2 to 4 very stiff CFRP panels per wing
- Single beam Yoke
- Ultra stiff hinges (1 hinge per hinge line)
- Power range 0.5 - 2.5 kW
- Speed controlled deployment
- Designed for high launcher separation shocks
- Thermal knife release
- Typically applied for LEO missions

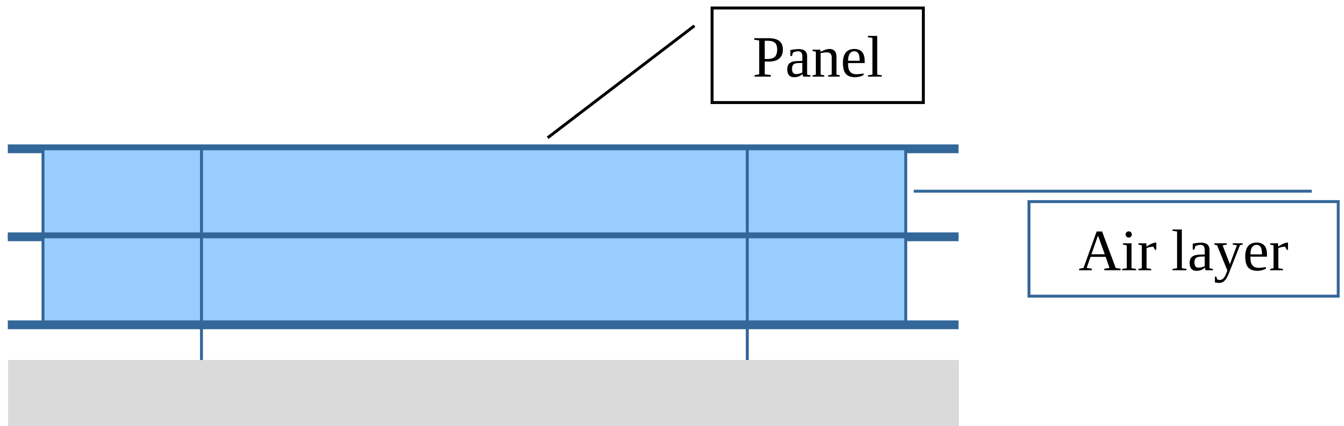
Modal Characteristics Solar Arrays

Dutch Space

- Modal characteristics of stacked “rigid” solar panels are significantly influenced by the moving air layers in between the sandwich panels
- Dutch Space developed an simply air layer model to account for moving air layers

Dutch Space (DS) Air layer model

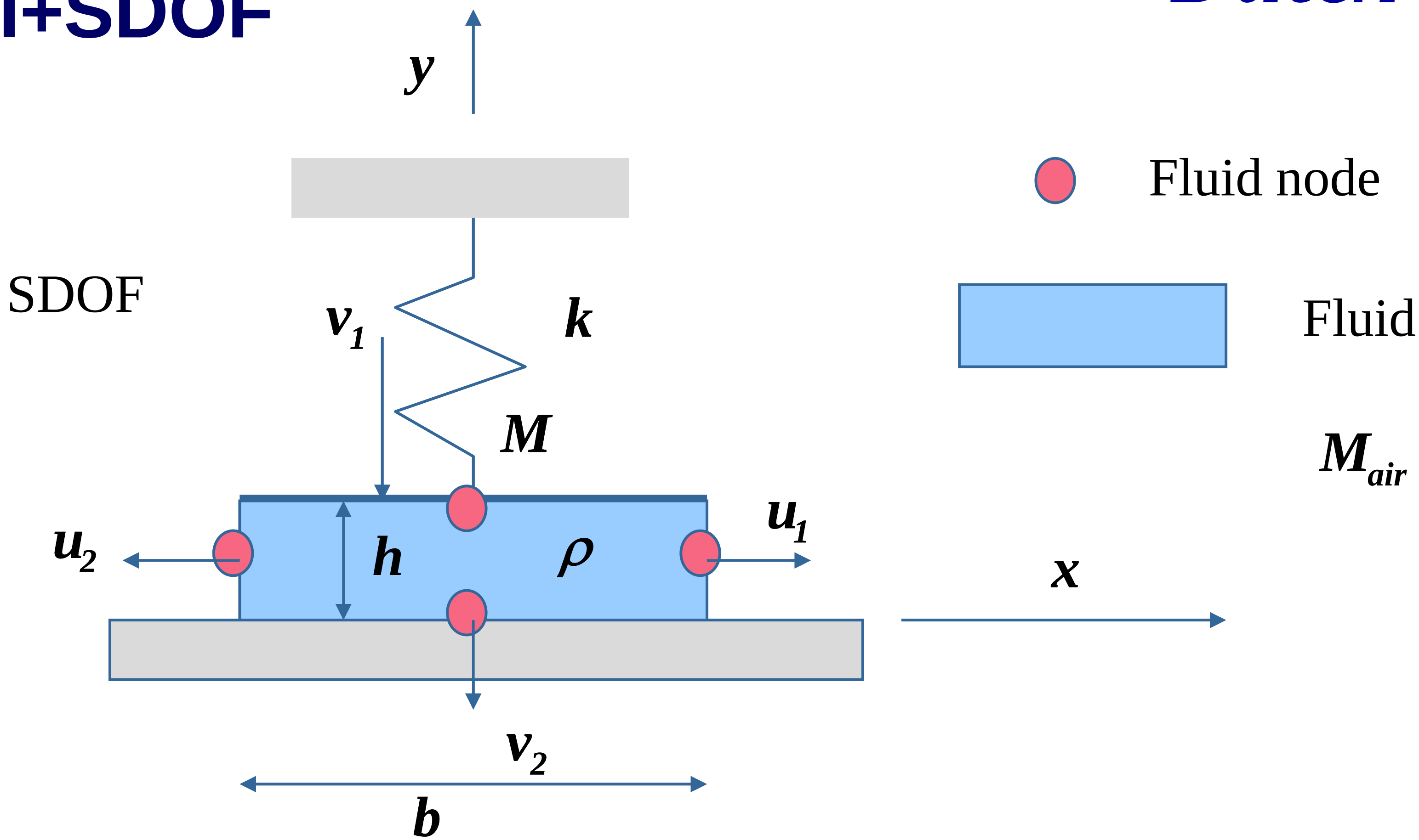
Dutch Space



Side wall

- Air effects on the dynamic behavior of stowed solar array wings
    - Theoretical Manual (TM), FSS-R-87-134
    - Software User's Manual (SUM), FSS-R-87-135

FSI+SDOF



$$M_{air} = bh\rho$$

$u_1 = u_2$ symmetry

$v_2 = 0$ ground

$h\rho u_1 + h\rho u_2 = b\rho v_1$ Mass balance

$$u_1 = u_2 = \frac{b}{h} v_1 \qquad m_{node} = \frac{1}{2} bh\rho$$

Rayleigh quotient

Dutch Space

$$R(u) \approx \omega_o^2 = \frac{U(u)}{T^*(u)} = \frac{\frac{1}{2}\sum k_i u_i^2}{\frac{1}{2}\sum m_i u_i^2}$$

$$R(u) \approx \omega_o^2 = \frac{\omega_{sdof}^2}{\left(1 + \frac{M_{air}}{M}\frac{b^2}{h^2}\right)}$$

Decreasing the air gap height "h" will result in a lower natural frequency

Typical Mechanical Loads Specified for Solar Arrays

Dutch Space

- Sinusoidal Loads (5-100 Hz) (Enforced acceleration)
- Acoustic Loads (1/1, 1/3 Octave band) (SPL)
- Shock Loads (SRS)
- Acoustic Loads are in general the design driver and must analyzed to investigate sonic fatigue and strength
  - Fatigue life prediction, (s-N curves, Palgren-Miner Cumulative Damage Rule, 1-Sigma values, Positive zero-crossings)
  - 3-Sigma Strength

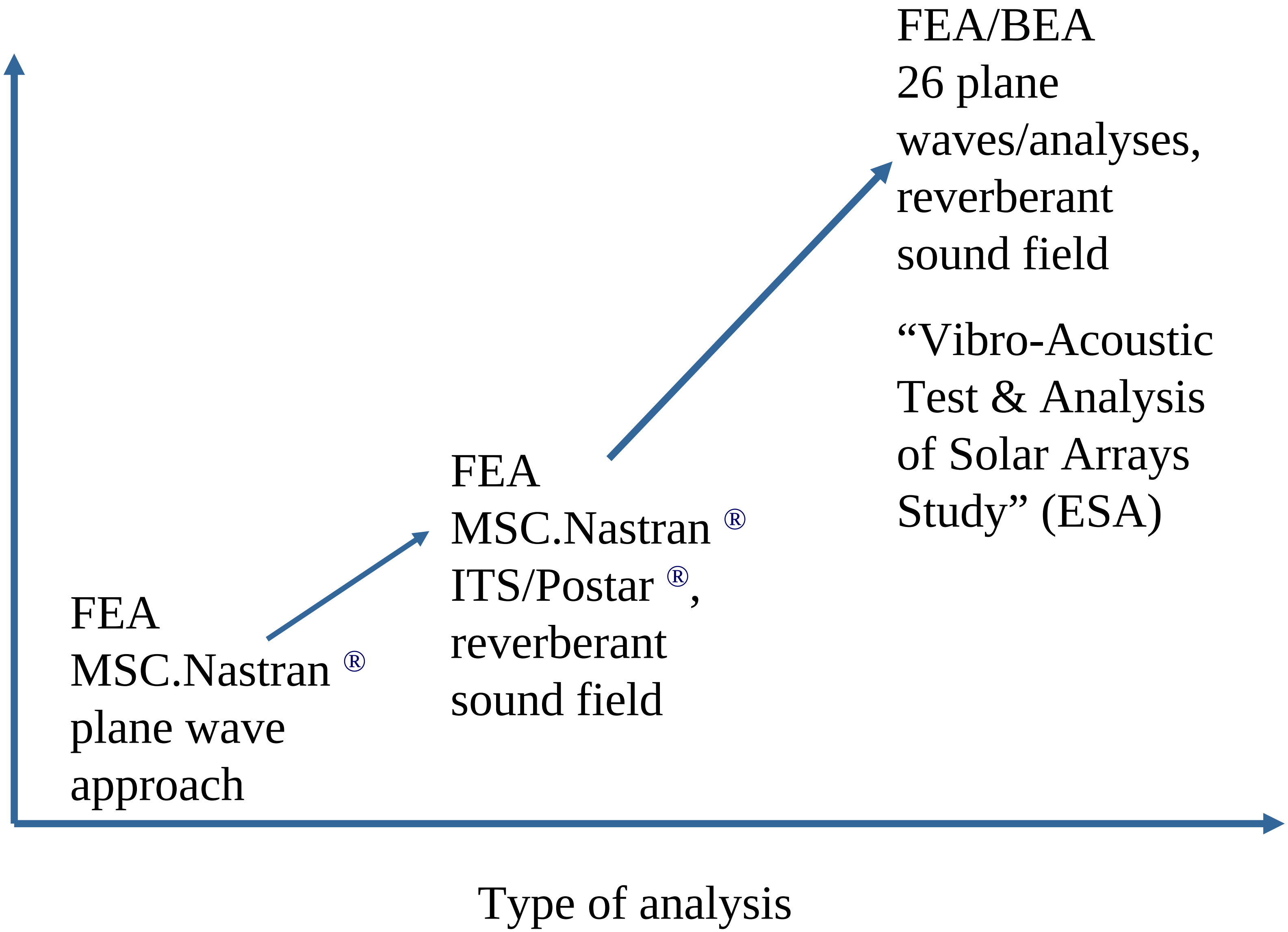
Analysis Methods Structural Response Acoustic Loads

Dutch Space

- **Finite Element Analysis (FEA)**
  - MSC.Nastran® (Gouda)
  - Plane waves (fully correlated pressure field)
  - One sided pressure
- **Finite Element Analysis (FEA)**
  - MSC.Nastran ®
    - Modal characteristics (natural frequencies, modes, equivalent areas from unit pressure, generalized masses)
  - ITS/POSTAR ® (Intespace, Toulouse)
    - Reverberant Sound field (**sin(kr)/kr** correlation coefficients)
    - One sided pressure
    - Added mass and damping
    - Blocked pressure 2*free pressure field
- **Finite Element Analysis (FEA) /Boundary Element Analysis (BEA)**
  - MSC.Nastran®
    - Finite element model (FEM)
    - Modal characteristics (natural frequencies, modes, stress modes, generalized masses)
  - ASTRYD ® (BEA) (01dB Metravib, Lyon)
    - Boundary element model (BEM)
    - Fluid Structure interaction
    - Reverberant Acoustic pressure field (26 plane waves)
    - Pressure differences (pressure jump)

Computer Power Needed

Dutch Space



General Conclusions Study

- "Vibro-Acoustic Test & Analysis of Solar Arrays Study"
  - Due to the very specific geometrical characteristics of the solar array structure (very large panels, very small gaps in between the panels), it is not possible to make the boundary element size comparable with the smallest characteristics size of the problem! We thus have faced an intrinsic problem, which is recognized as the most difficult one to solve with a purely BEA approach, be it time or frequency domain.
  - An optimization of the air modeling in between the panels will lead to increase the global efficiency of ASTRYD® when applied to solve the solar array vibro-acoustic problem.

Recommendations/Consequences

- New ESA Study initiated:

  "Coupling of FEM and BEM approach for solar array stack vibro acoustic analysis"

- This name had to be changed be in:

  "Vibro-Acoustics and the New Generation of Solar Arrays" (VANGSA)

  - Part 1: Introduction Dutch Space air layer in combination with the BEA. In fact a continuation of the previous study.
  - Part 2: Non linear vibrations of TFT based solar arrays in combination with the BEA. This part concerns the New Generation of Solar Array (NGSA). (not discussed in this presentation)

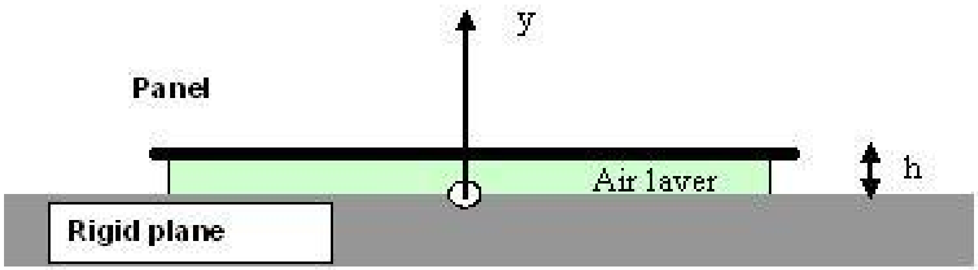
VANGSA Study Part 1

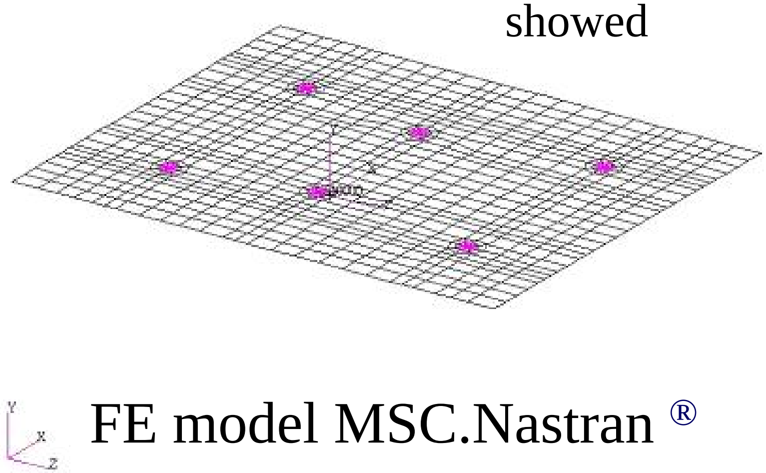
Dutch Space

- Study Approach
  - Coupling Stack FE Model with Description of Surrounded Fluid
    - To couple the **DS air layer** model to the BEM for a single panel above a rigid side wall with an varying height of the air gap h between the panel and the side wall
  - Revisiting previous study results, producing new analysis and evaluating improvement
    - To couple the **DS air layer** models between the panels of the complete solar array FEM and the side wall to the BEM describing the acoustic field

One panel model

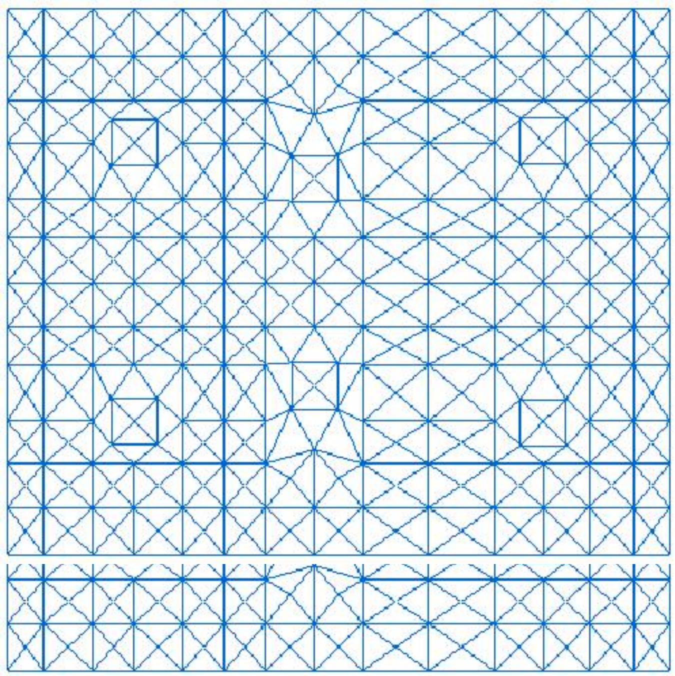
Dutch Space





Air layer not showed

FE model MSC.Nastran ®



BE model ASTRYD®

Models Investigated (1)

Dutch Space

Model 1A

In-vacuo condition

Panel

In-vacuo condition

Model 1B

Fluid modeled by BEM method

Panel

Fluid modeled by BEM method

Model 1C

External domain : Fluid modeled by BEM method

Panel

External domain : Fluid modeled by BEM method

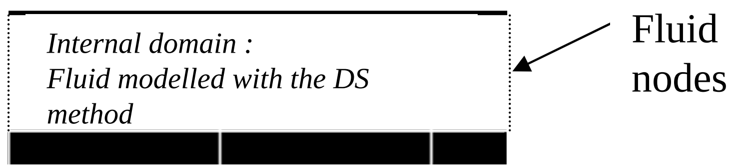
Rigid wall

External domain : Fluid modeled by BEM method

Models Investigated (2)

Model 2A

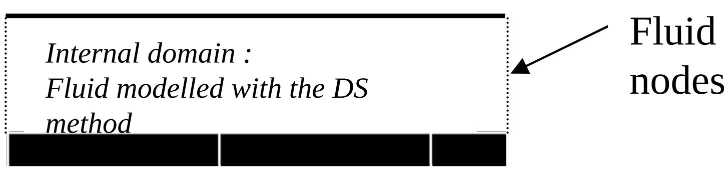
External domain :
In vacuo condition



External domain :
In vacuo condition

Model 2B

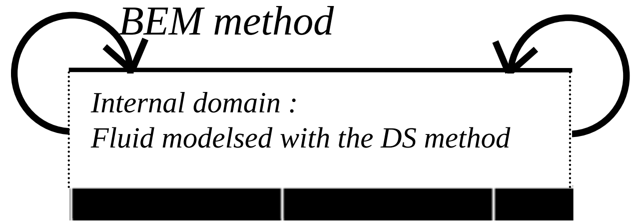
External domain :
Fluid modelled by BEM method



External domain :
Fluid modelled by BEM method

Model 3

External domain :
Fluid modelised by BEM method



Fluid acceleration affects the external force applied on the panel

External domain :
Fluid modelized by BEM method

$$\Delta p(M_0) = \int_{\Sigma} \frac{\rho}{\left|M - M_o\right|} \frac{\partial V_{fluid}}{\partial t} d\Sigma(M)$$

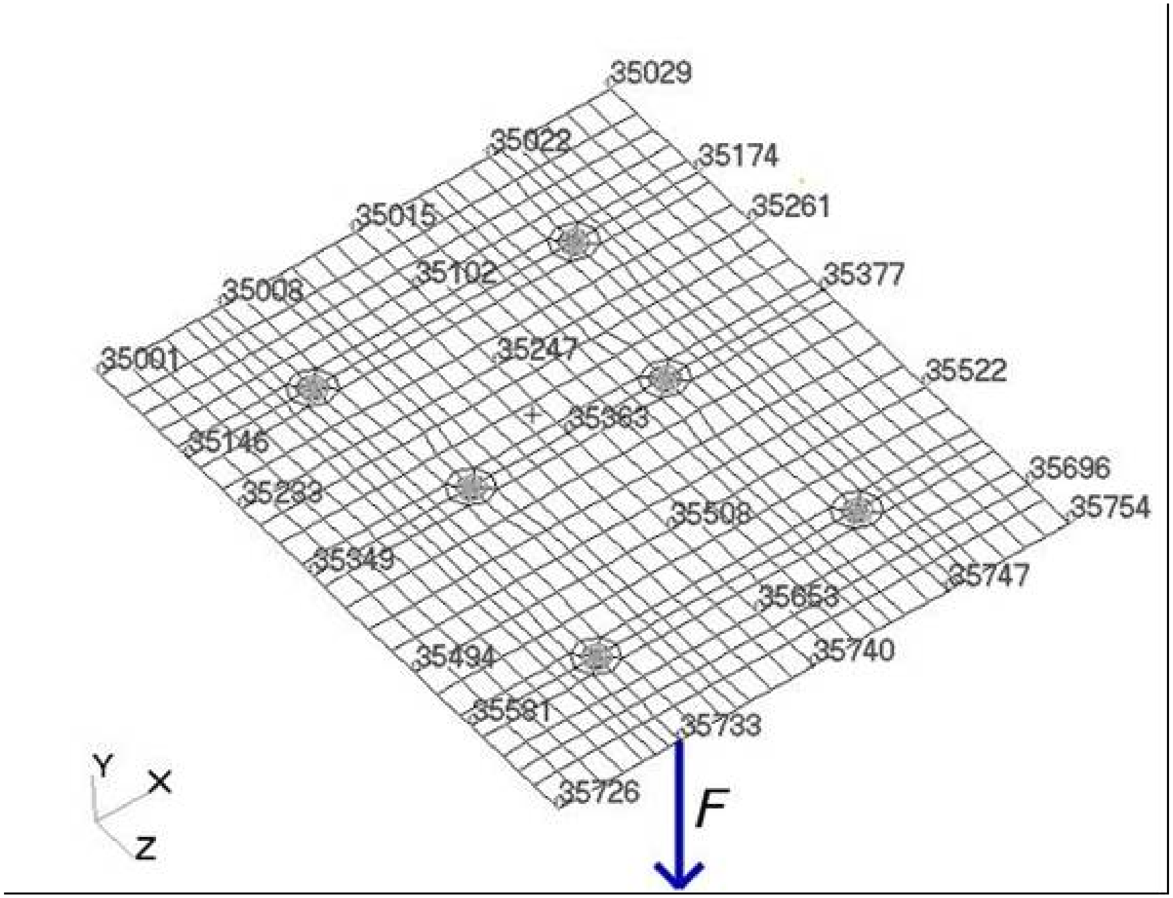
Evaluation of models

Dutch Space

h=12 mm	h=25 mm	h=50 mm	h=100 mm
1C (660+660)	1C (660+660)	1C (660+660)	1C
1C(760)	1C (3000)	1C (3000)	2B
1C (3000)			
2A			
2B			
3			

Evaluation of acceleration results

Dutch Space

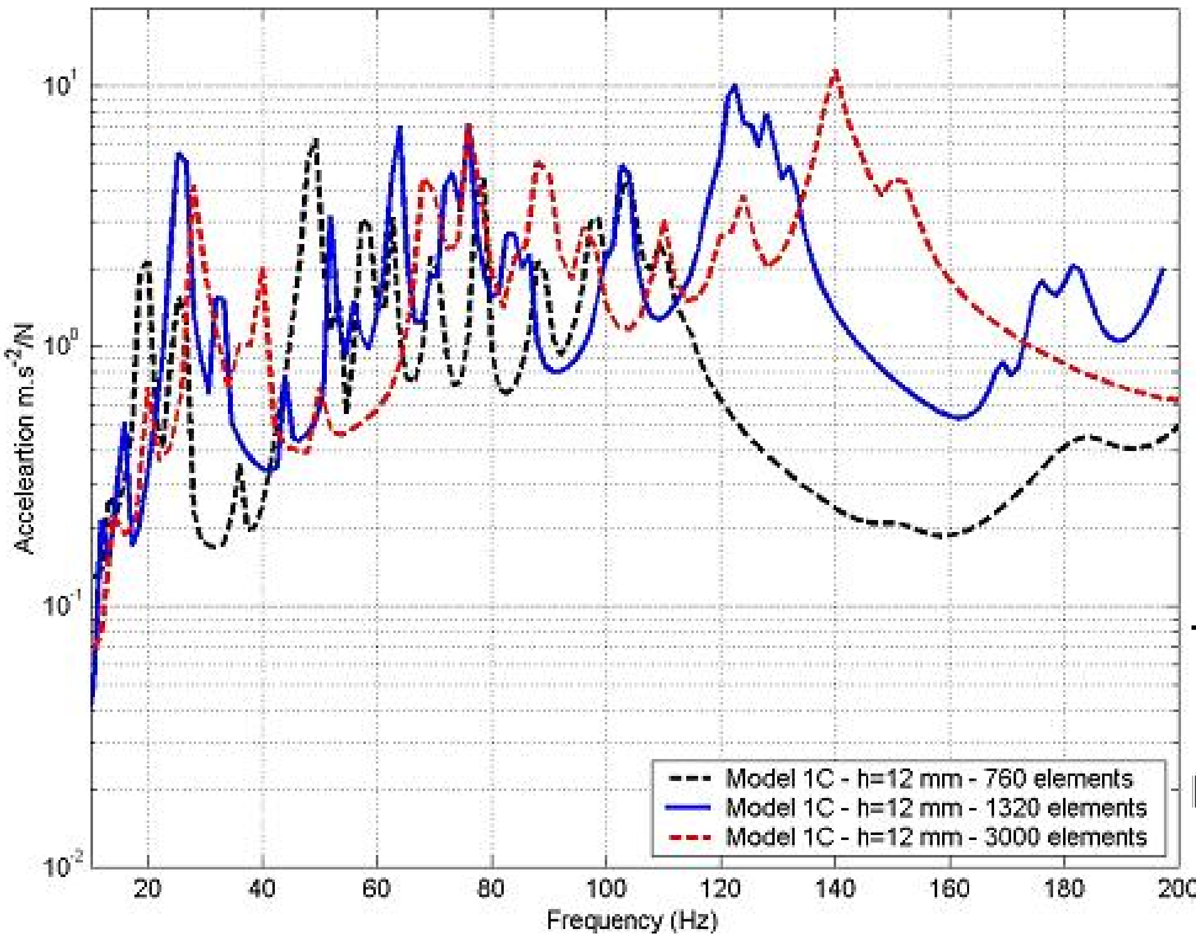


Average Accelerations over 25 nodes

$$H_{ave,acce}(f)=\sqrt{\frac{1}{25}\sum_{i=1}^{25}\left|H_i(f)\right|^2}$$

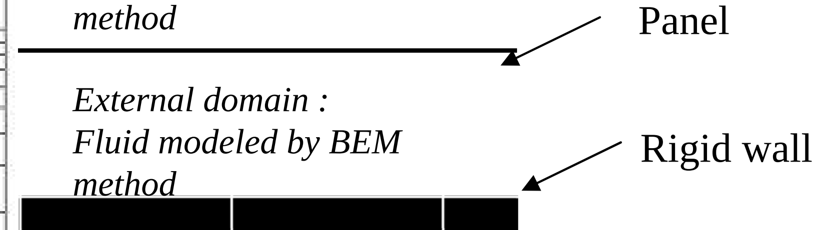
Model 1C, h=12 mm

Dutch Space



Model 1C

External domain : Fluid modeled by BEM method

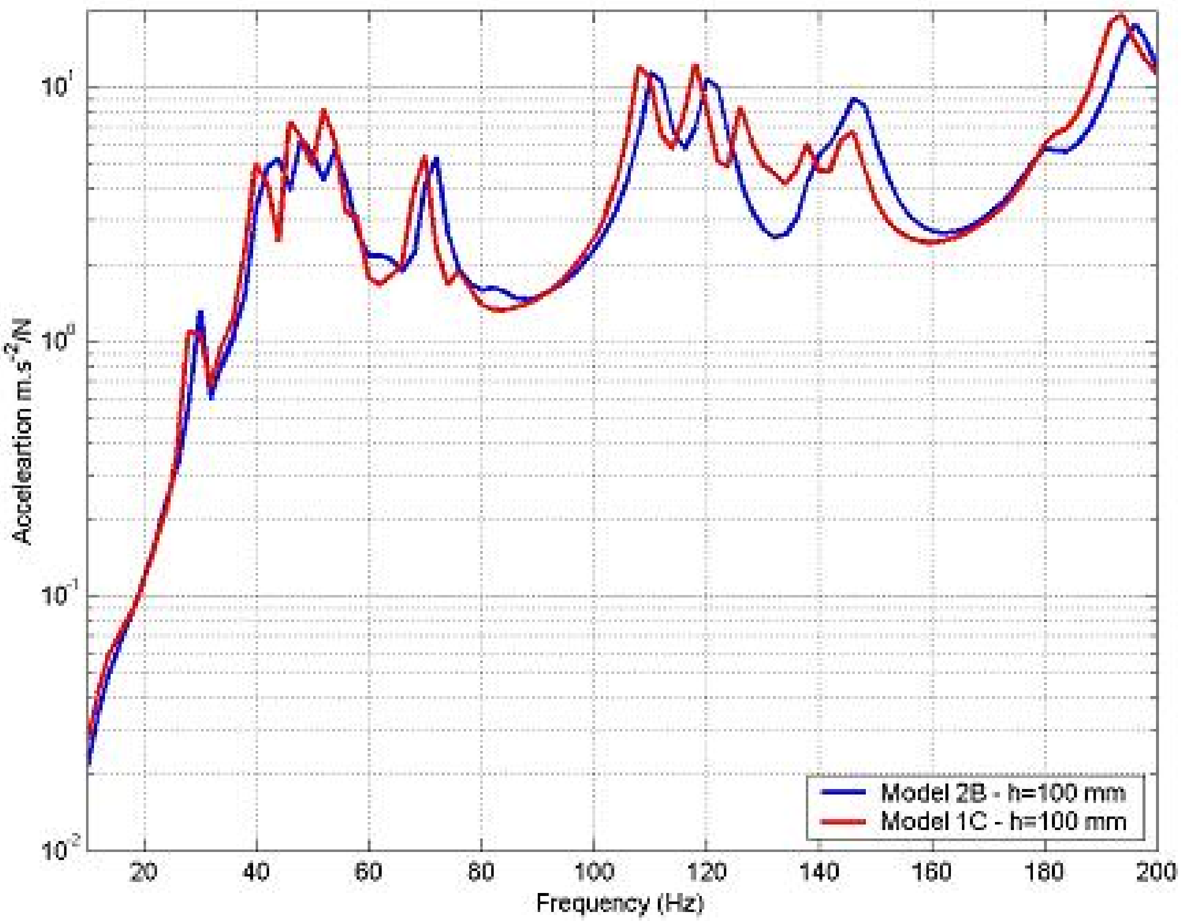


External domain : Fluid modeled by BEM method

External domain : Fluid modeled by BEM method

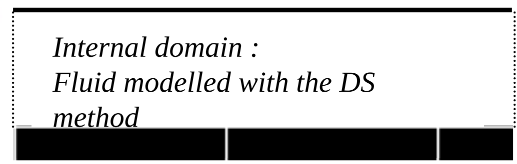
Comparison models 1 C /2B, h=100 mm

Dutch Space



Model 2B

External domain : Fluid modelled by BEM method

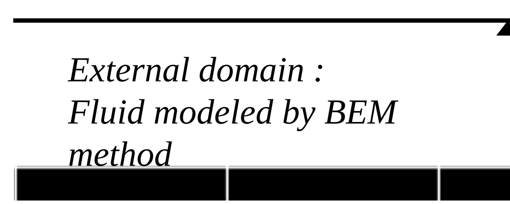


Fluid nodes

External domain : Fluid modelled by BEM method

Model 1C

External domain : Fluid modeled by BEM method



Panel

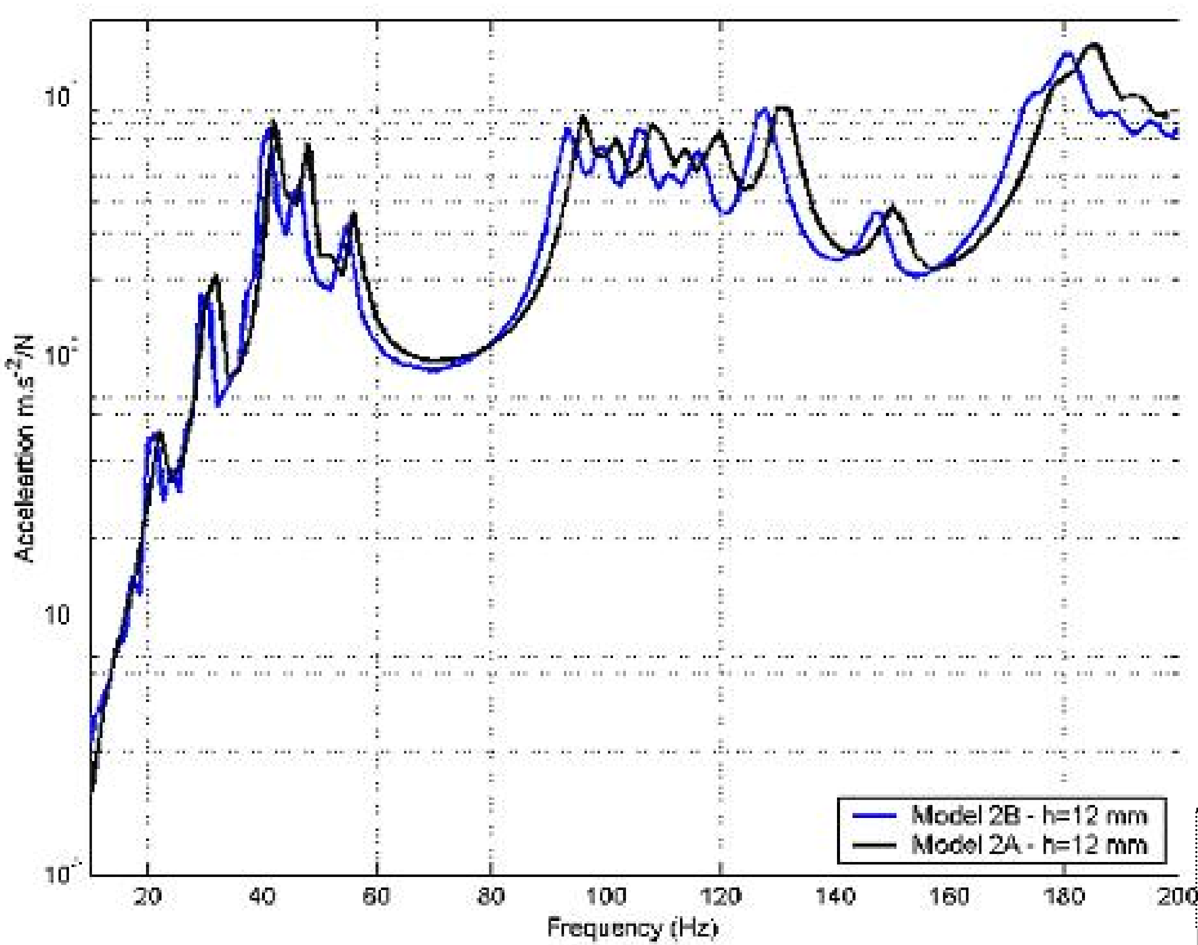
External domain : Fluid modeled by BEM method

Rigid wall

External domain : Fluid modeled by BEM method

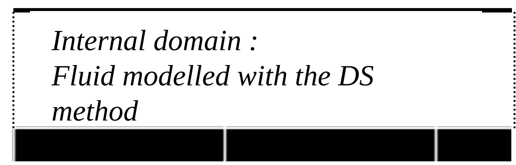
Comparison models 2A/2B

Dutch Space



Model 2A

External domain :
In vacuo condition

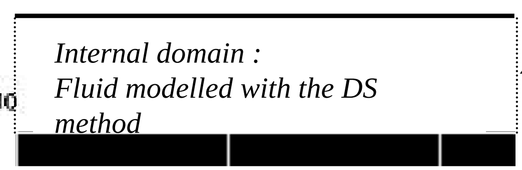


Fluid nodes

External domain :
In vacuo condition

Model 2B

External domain :
Fluid modelled by BEM method

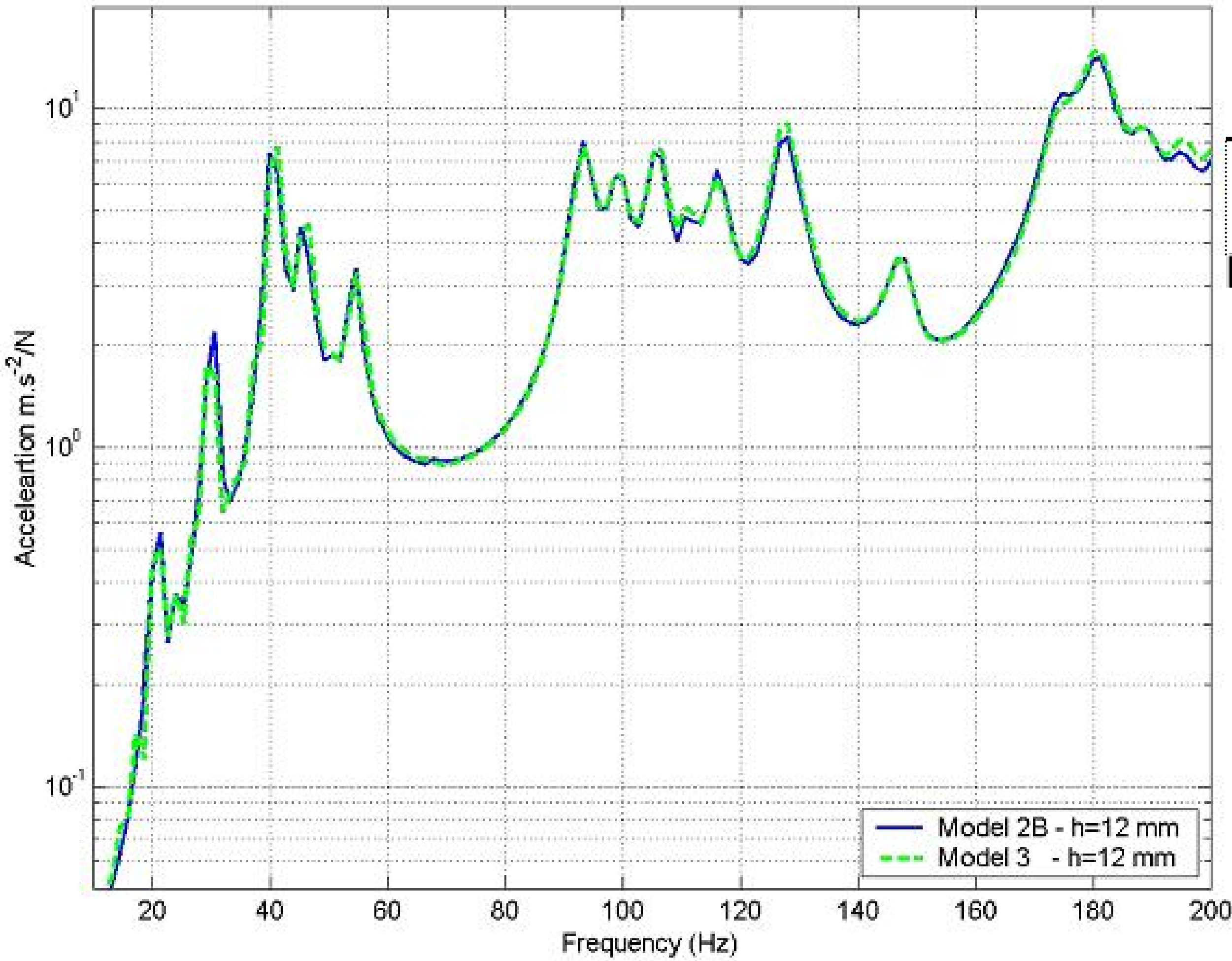


Fluid nodes

External domain :
Fluid modelled by BEM method

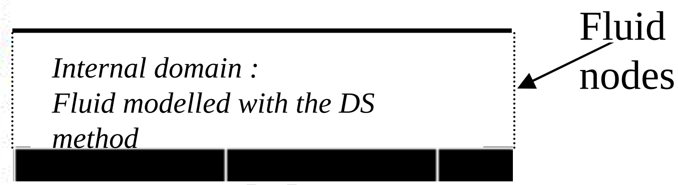
Comparison models 2B/3

Dutch Space



Model 2B

External domain :
Fluid modelled by BEM method

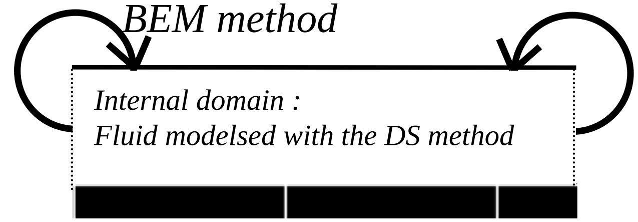


Model 3

External domain :
Fluid modelled by BEM method

Model 3

External domain :
Fluid modelised by BEM method



External domain :
Fluid modelized by BEM method

$$\Delta p(M_0) = \int_{\Sigma} \frac{\rho}{|M - M_o|} \frac{\partial V_{fluid}}{\partial t} d\Sigma(M)$$

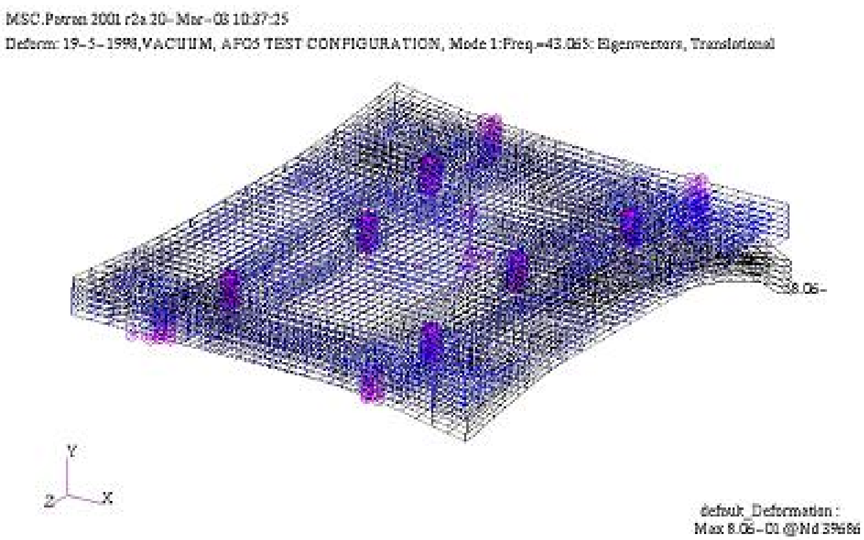
Conclusions one panel evaluation

Dutch Space

- The air layer thickness has a significant influence on the dynamic responses.
- The DS air layer model has been successfully interfaced with the ASTRYD ® BE software package.
- It is demonstrated that the coupling with the DS air layer model with the external domain using boundary elements is very weak.

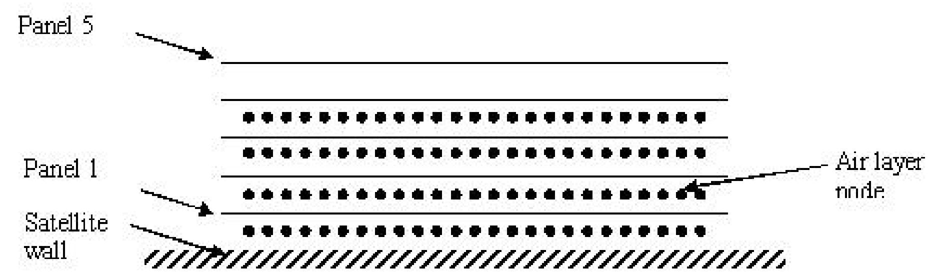
Complete Solar Array

Dutch Space

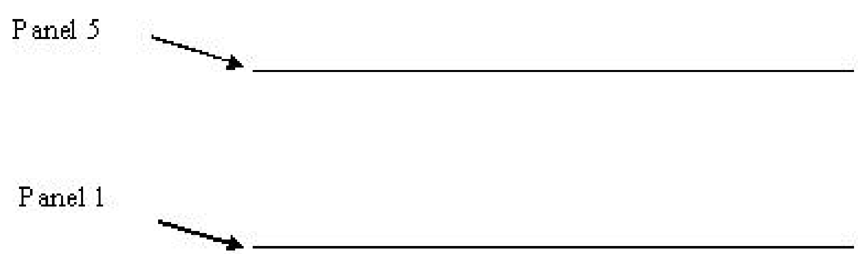


FEM used to calculated modal base

Loss factor 3% (1.5% modal damping ratio)



FEM + DS air layers



BEM ASTRYD ®

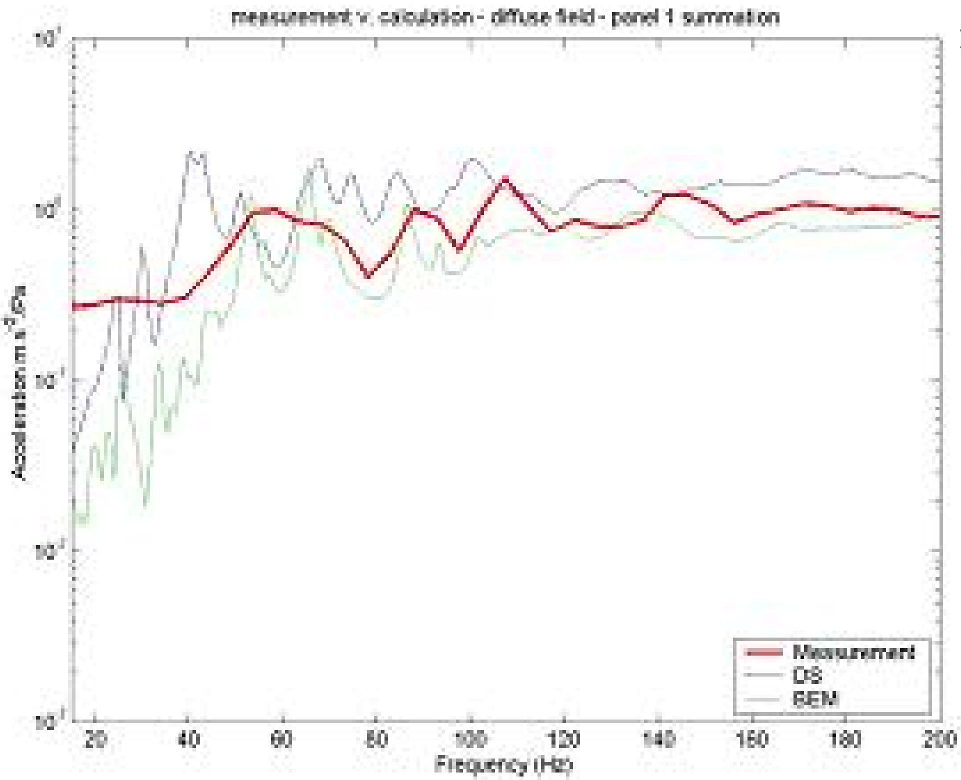
Evaluation of results

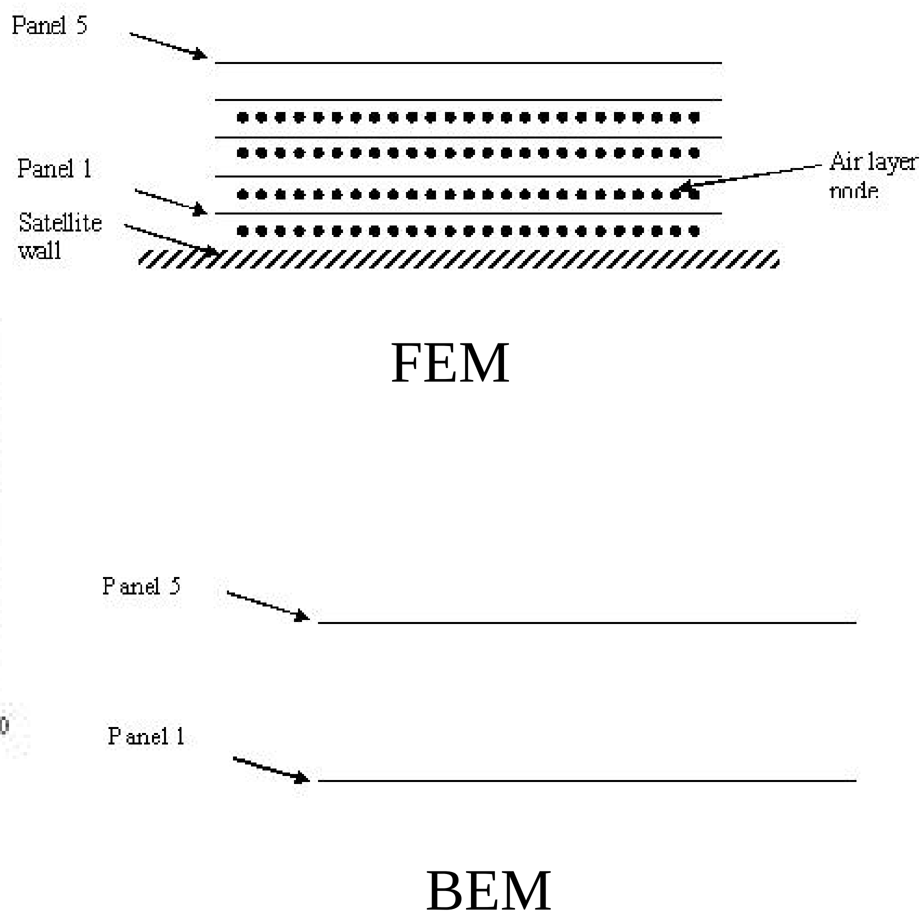
Dutch Space

- Measurements from former study “Vibro-Acoustic Test & Analysis of Solar Arrays Study”
- Complete BEA taken from “Vibro-Acoustic Test & Analysis of Solar Arrays Study”
- Combination FEM/BEM (with DS air layer model)

Spatial Average Accelerations panel 1

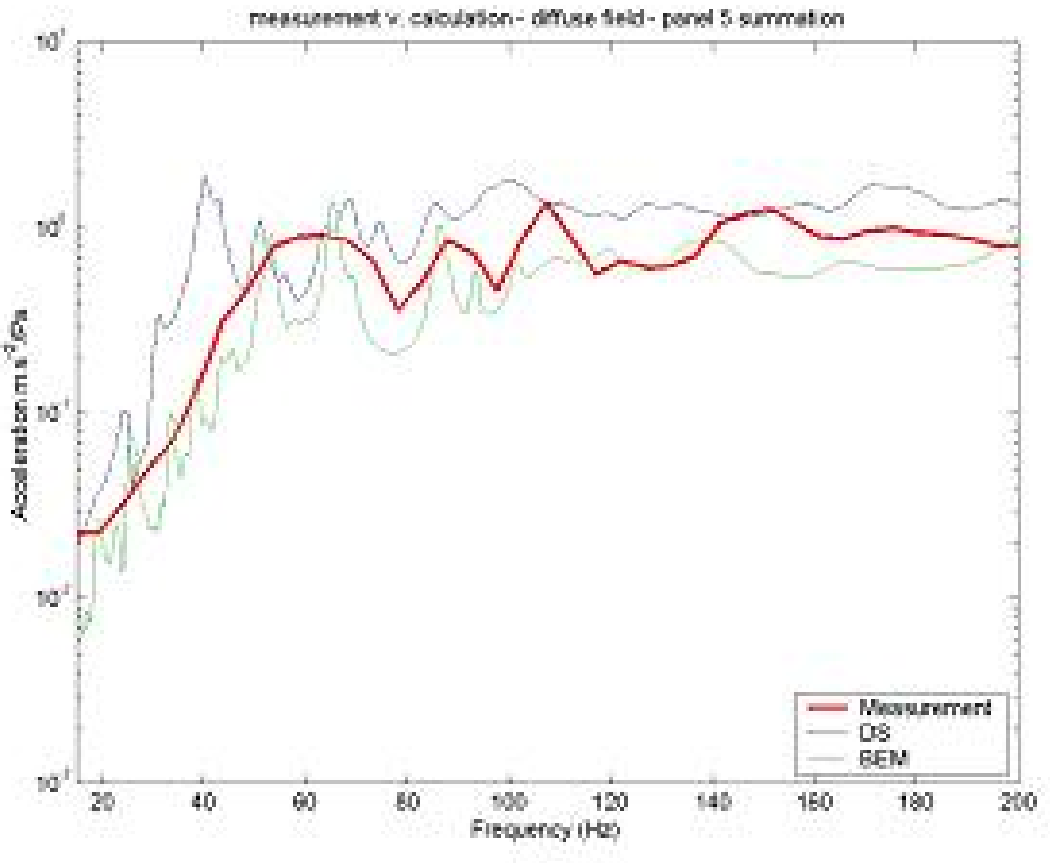
Dutch Space

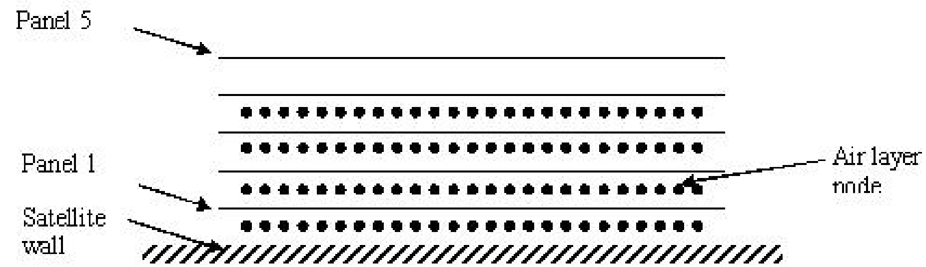




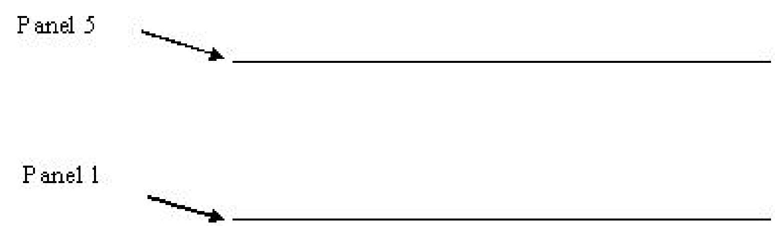
Spatial Average Accelerations panel 5

Dutch Space





FEM



BEM

Computational Effort

Dutch Space

	Normalized CPU times
"Vibro-Acoustic Test & Analysis of Solar Arrays Study" BEA 864 elements	1
DS 224 BE elements	0.003
DS 864 BE elements	0.14
DS 3000 BE elements	2.0

Final Conclusions

Dutch Space

- Vibro-acoustic computations based on DS air layer model are more stable than those relying on a full BEA
- The introduction of the DS air layer model in between the panels of the solar array in stead of applying the BE modeling shows acceptable accuracy with respect to response characteristics.
- The lengthy computation time concerning the BEM idealization is reduced to a much more economical one.