Predictions of Vibrations in Aircraft Structure

Master's Thesis

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Background

- Thesis performed at the department of Environmental Engineering and Thermal Analysis
- Investigation of IWB (Internal Weapon Bay)
  - Evaluation of the vibrational environment during the conceptual phase of aircraft design

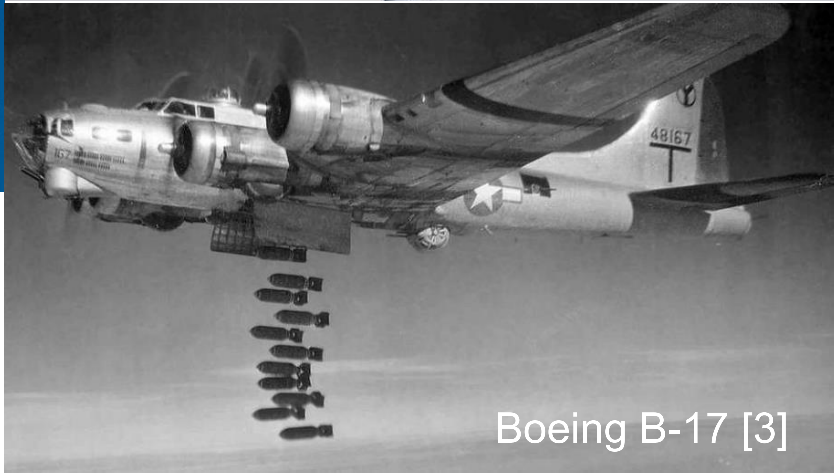
- Problem statements
  - How should a generic CAD model be updated to have a viable dynamic behaviour in the frequency range of interest
  - How well does the model capture the dynamic behaviour in the frequency range of interest
  - How do damping mats influence the vibrational response
  - How does the instalment position and mass of equipment influence the vibrational response (see report)

Theory – Internal Weapon Bay

- Reduces radar cross section by carrying the load inside the aircraft fuselage
- Exposing the cavity leads to high sound pressure levels and a severe vibrational environment

F-22 Raptor [2]

F-35 Lightning II [1]

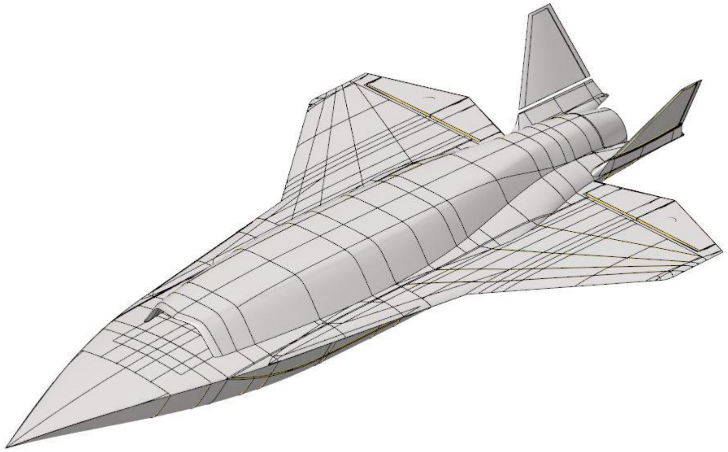


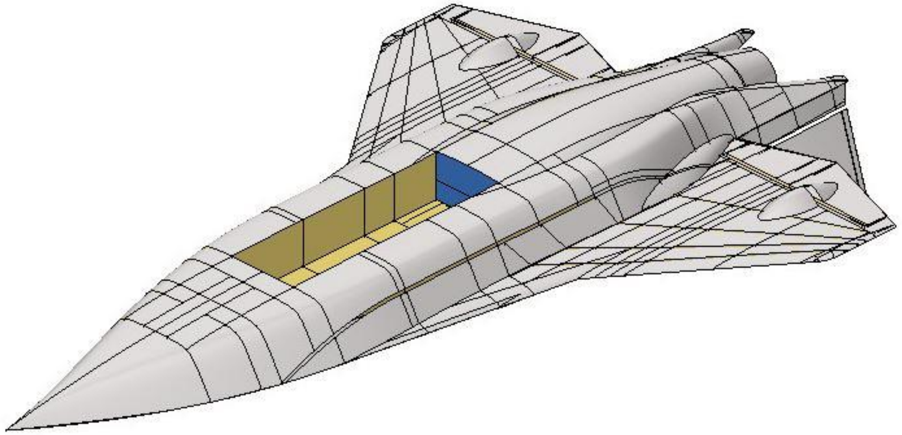
Boeing B-17 [3]

[1] - https://www.pexels.com/photo/the-underside-of-an-f-35-fighter-jet-13926191/
[2] - https://commons.wikimedia.org/wiki/File:F-22_Raptor_showing_off_its_bomb_bay_%287674479498%29.jpg
[3] - https://picryl.com/media/boeing-b-17g-2-bg-dropping-bombs-4e675e

Theory – Internal Weapon Bay

- When opening the doors of the IWB an open cavity is exposed
- Examples of cavities in an aircraft: landing gear bay and IWB
  - Landing gear bay – used for subsonic speeds
  - IWB – used for supersonic speeds

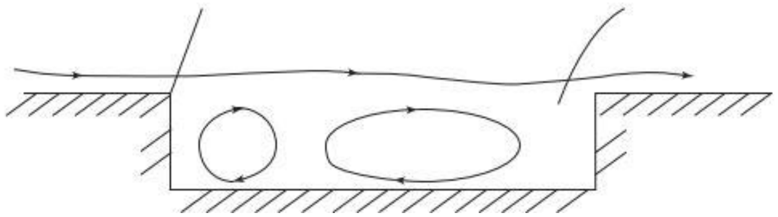




Theory – Cavity Oscillations

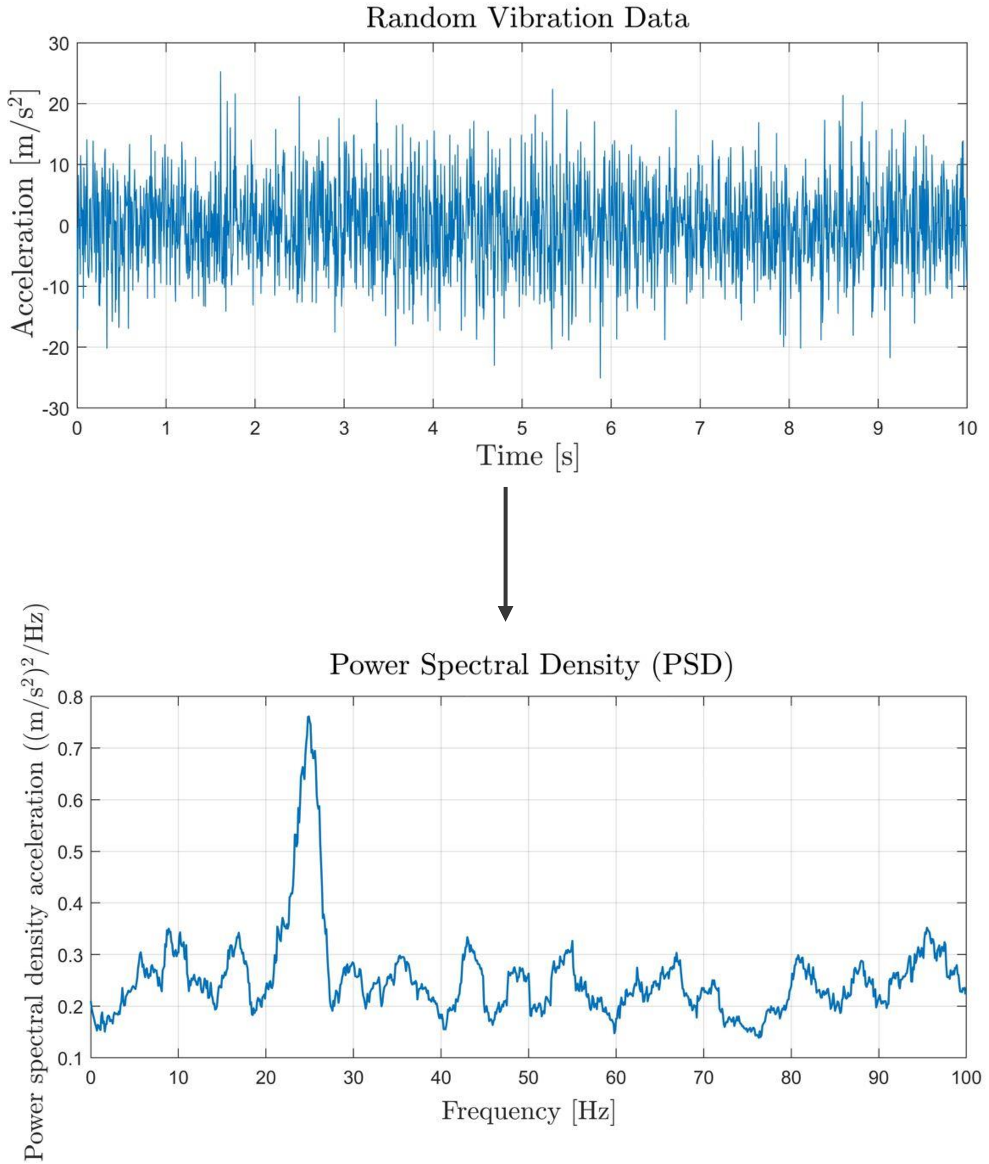
- Flying in supersonic velocities with an open cavity leads to high sound pressure levels and harsh vibrational environment, which will propagate through the structure
- Turbluent flow inside of the cavity
- Highest sound pressure levels at the downstream wall
- Rossiter modes
    - Pressure oscillations in open cavity flow caused by a feedback loop between shear layer vortices and acoustic waves traveling inside the cavity.

Open cavity flow



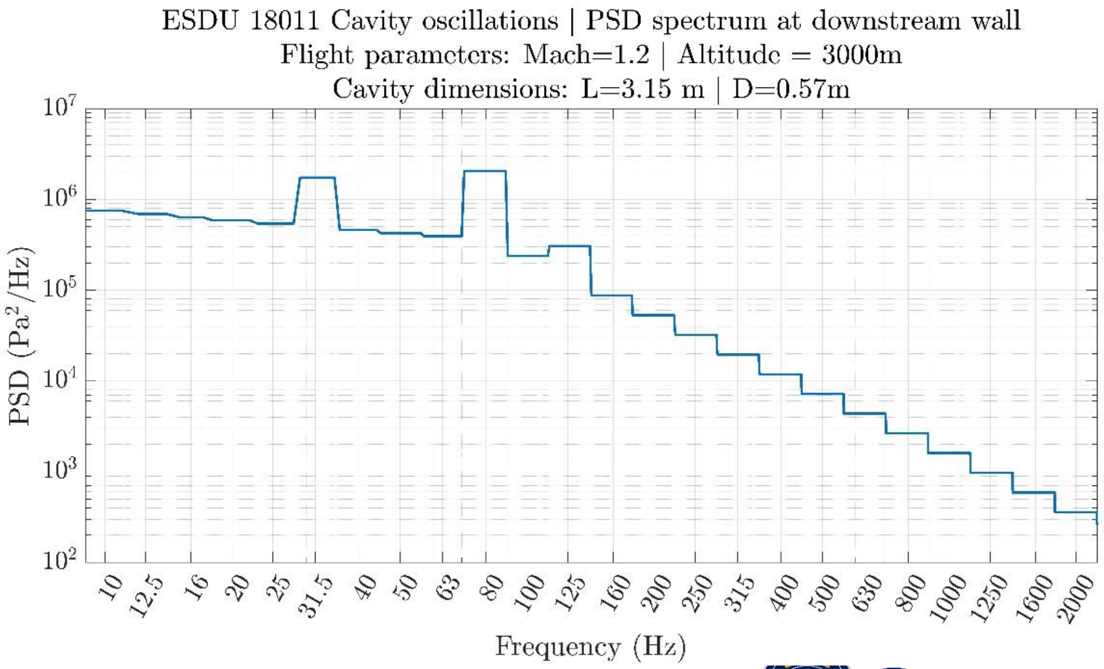
Theory – Power spectral density & Root mean square

- Cavity oscillations and turbulent flow are non-determinsitic
- Power Spectral Density to get a statistical representation of the fluctating pressure
- A PSD curve describes the energy content of the fluctating pressure in frequency range
- The integral of the PSD curve yields the RMS (root mean square) – Average intensity in the frequency range
- Cumulative RMS – How the RMS builds up over the frequency range



Theory - Handbook

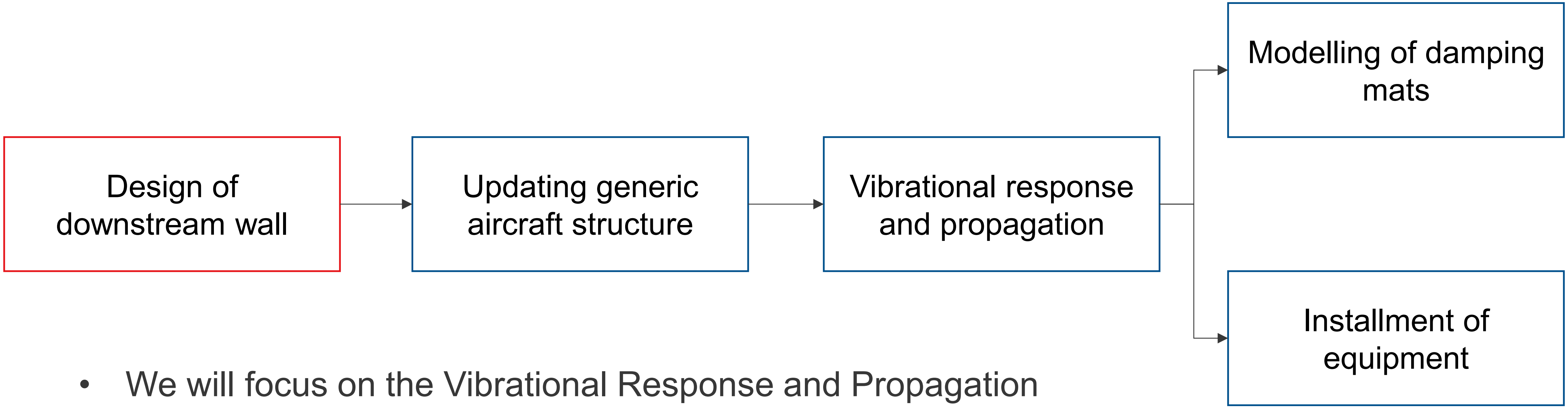
- ESDU 18011
  - Semi-empirical standards that describes modelling of cavity oscillations
  - Based on Rossiters theory and experimental data
  - Prediction depending on Length/depth ratio of the cavity and flight case
  - Flight parameters
    - Mach
    - Altitude



Theory - Analysis

- Solving the basic equation of motion
- $M\ddot{u} + C\dot{u} + Ku = F(t)$
- Assuming harmonic exictation and response
- $de^{i\omega t}(-\mathrm{M}\omega^2 + Ci\omega + K) = fe^{i\omega t}$
- Gives the FRF
- $H(\omega) = \frac{d(\omega)}{f(\omega)}$
- Random response
- $S_d = |H(\omega)|^2 S_f$

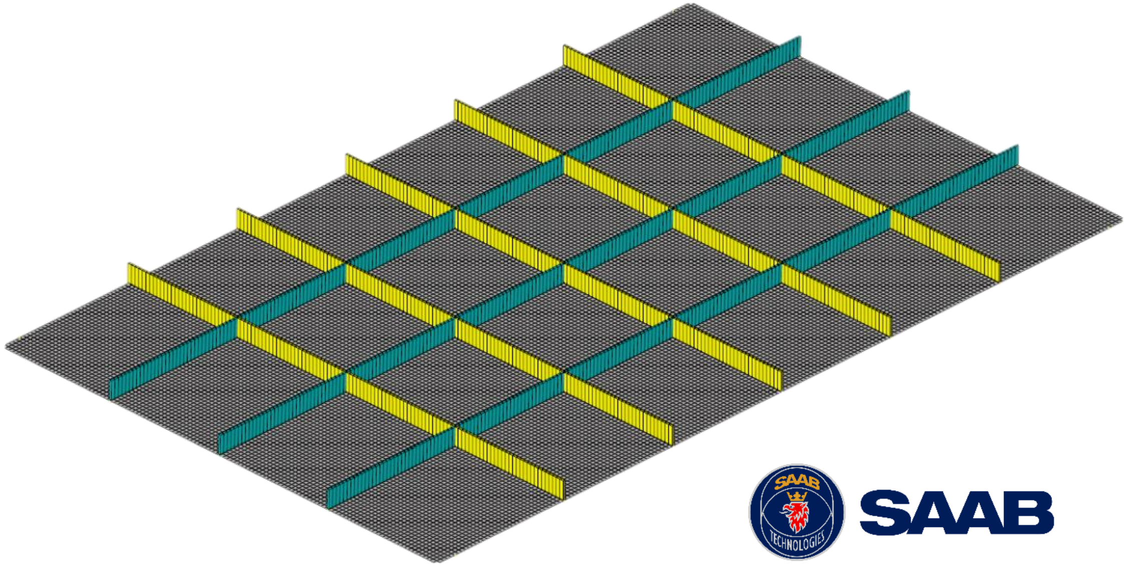
Workflow



- We will focus on the Vibrational Response and Propagation and Modelling of Damping Mats in this presentation.

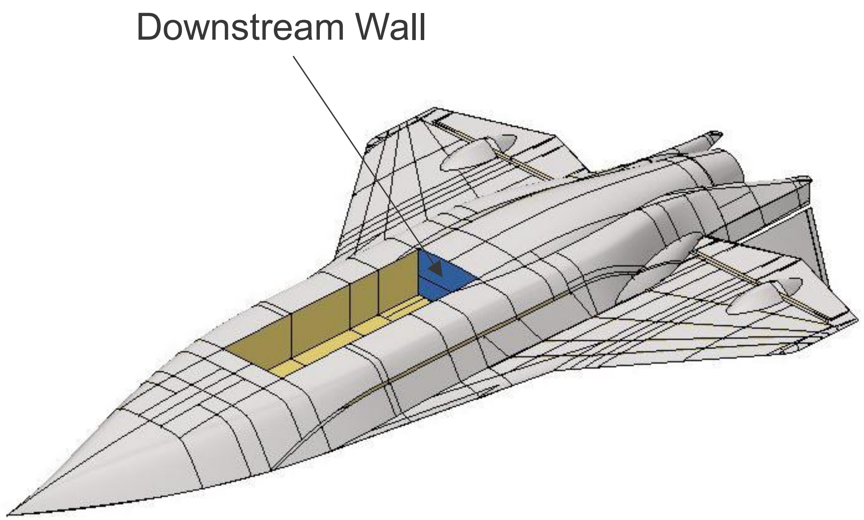
Downstream Wall

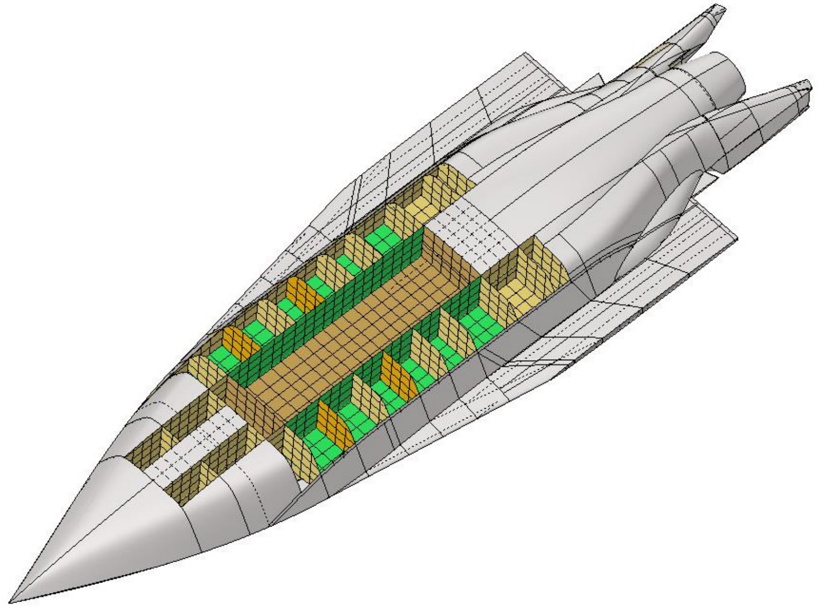
- Designed to avoid fatigue and to prevent resonance coinciding with Rossiter modes
  - Modal analysis
  - Random response analysis with excitation based on ESDU 18011
- Final design,
  - 5x3, reinforcement pattern
  - 2.2x22 mm, reinforcement dimension
  - Dimensions, 960 x 600 x 2.5 mm



Method – Aircraft Structure

- Implement the downstream wall
- Update the aircraft structure to be suitable for a random response analysis
  - Add reinforcements and equipment to get at global behavior of the aircraft
  - Wings and fins omitted to reduce the model and the computational time
  - Model fuel on the IWB side walls and connecting ”floor” as Virtual Fluid Mass (green surfaces)
- Simulation set-up
  - Frequency range: 10-2000 Hz
  - Comparison to a general vibration requirement for equipment of 0.1 g^2/Hz
  - Element size 30 mm
  - Free-Free boundary condition to simulate flight

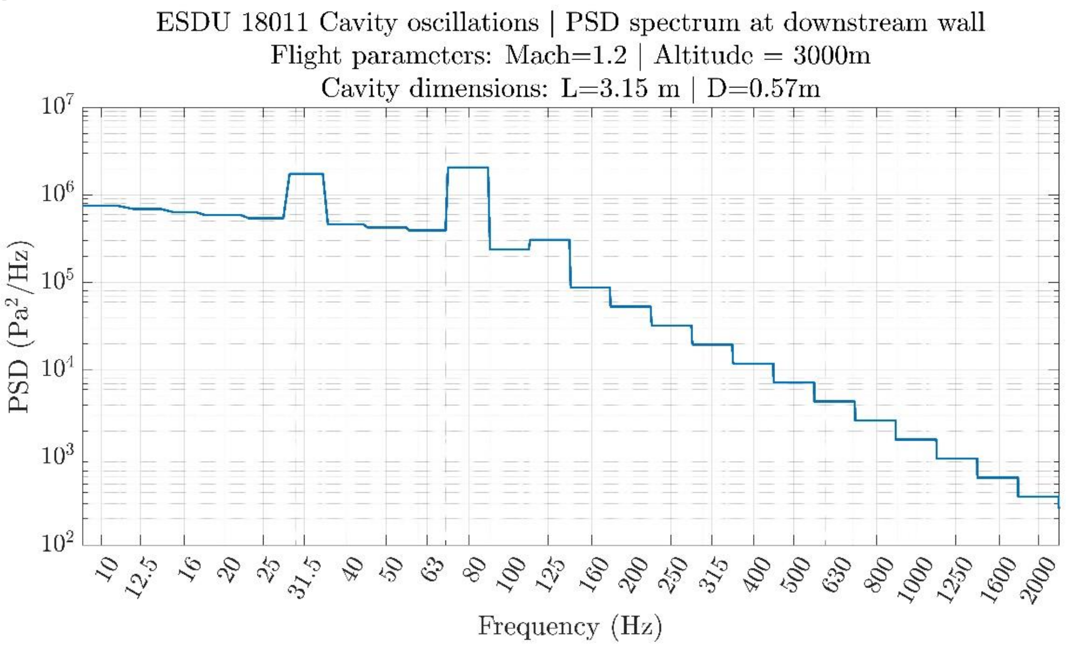


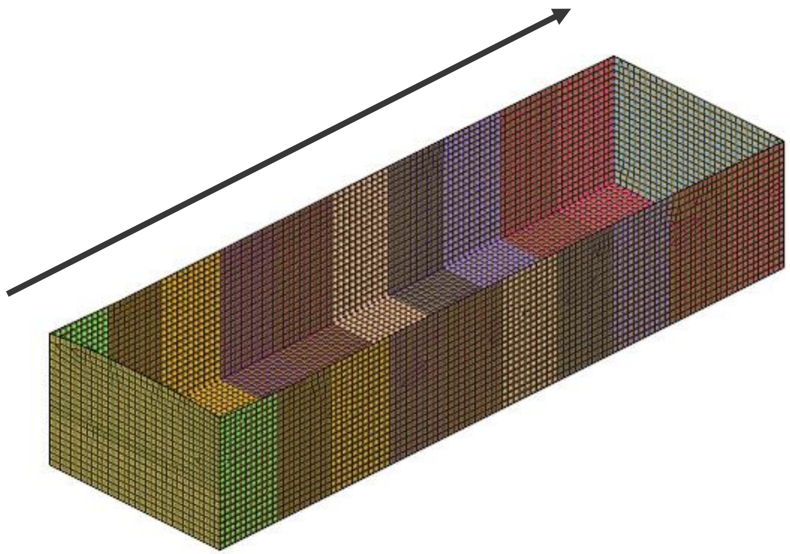


Aircraft Structure - Excitation

- The excitation is applied in the cavity of the IWB
- Sound pressure estimated using ESDU 18011, based on position along the cavity
- Cavity divided in 12 zones
  - Sound pressure increasing along the length of cavity. Highest levels on downstream wall.

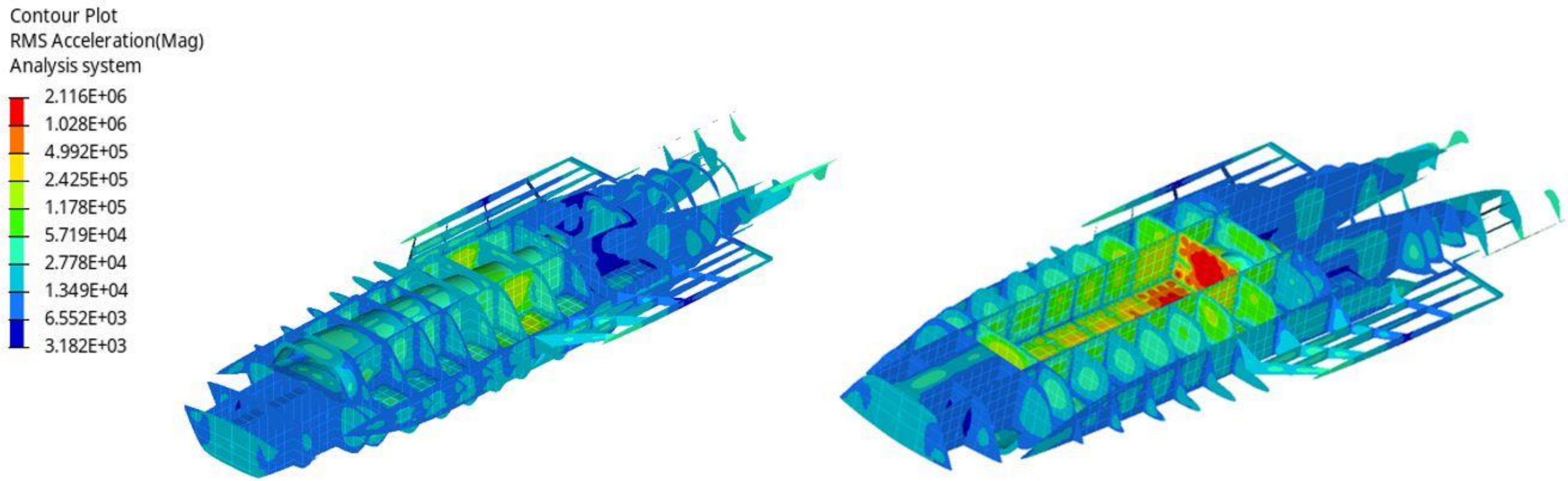
Excitation on downstream wall





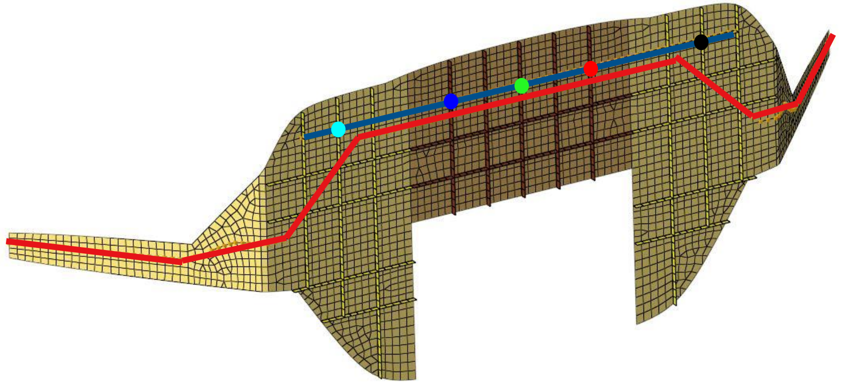
Results Aircraft Structure

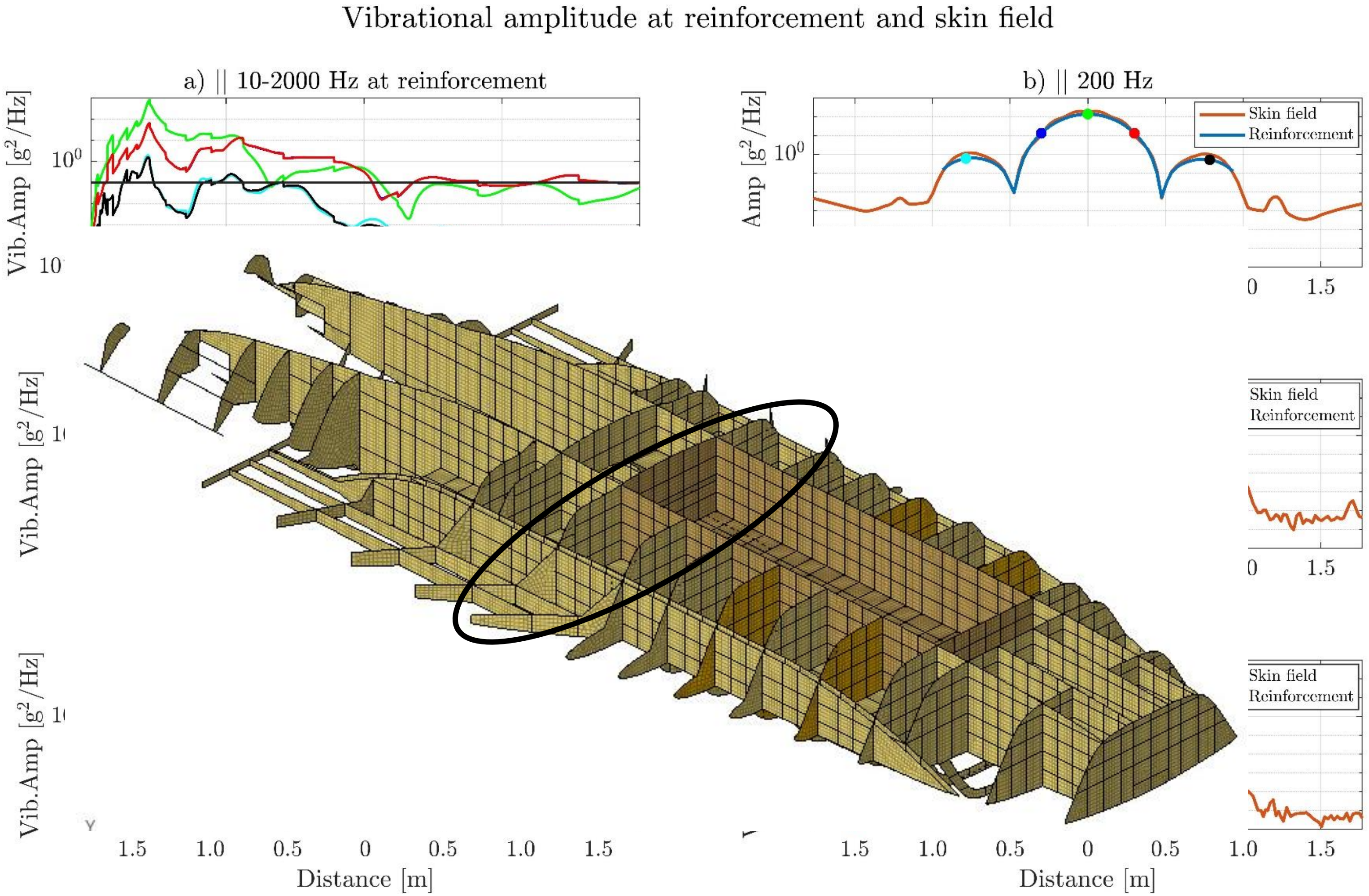
- Results from the random response analysis
- Shows the RMS acceleration (mm/s^2 [RMS]) in logarithmic scale
  - Downstream wall shows high levels of vibrations in the frequency range
  - Vibrations propagate outside the cavity to the rest of the structure



Results Aircraft Structure

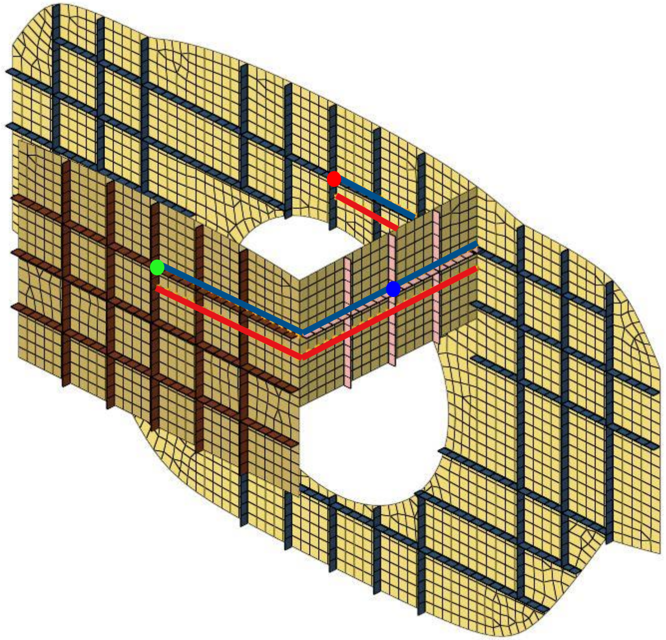
- Vibration propagation from the downstream wall to the wings
- Highest response amplitude at 220 Hz
- Exceeds requirement
- Large degree of skin field resonance

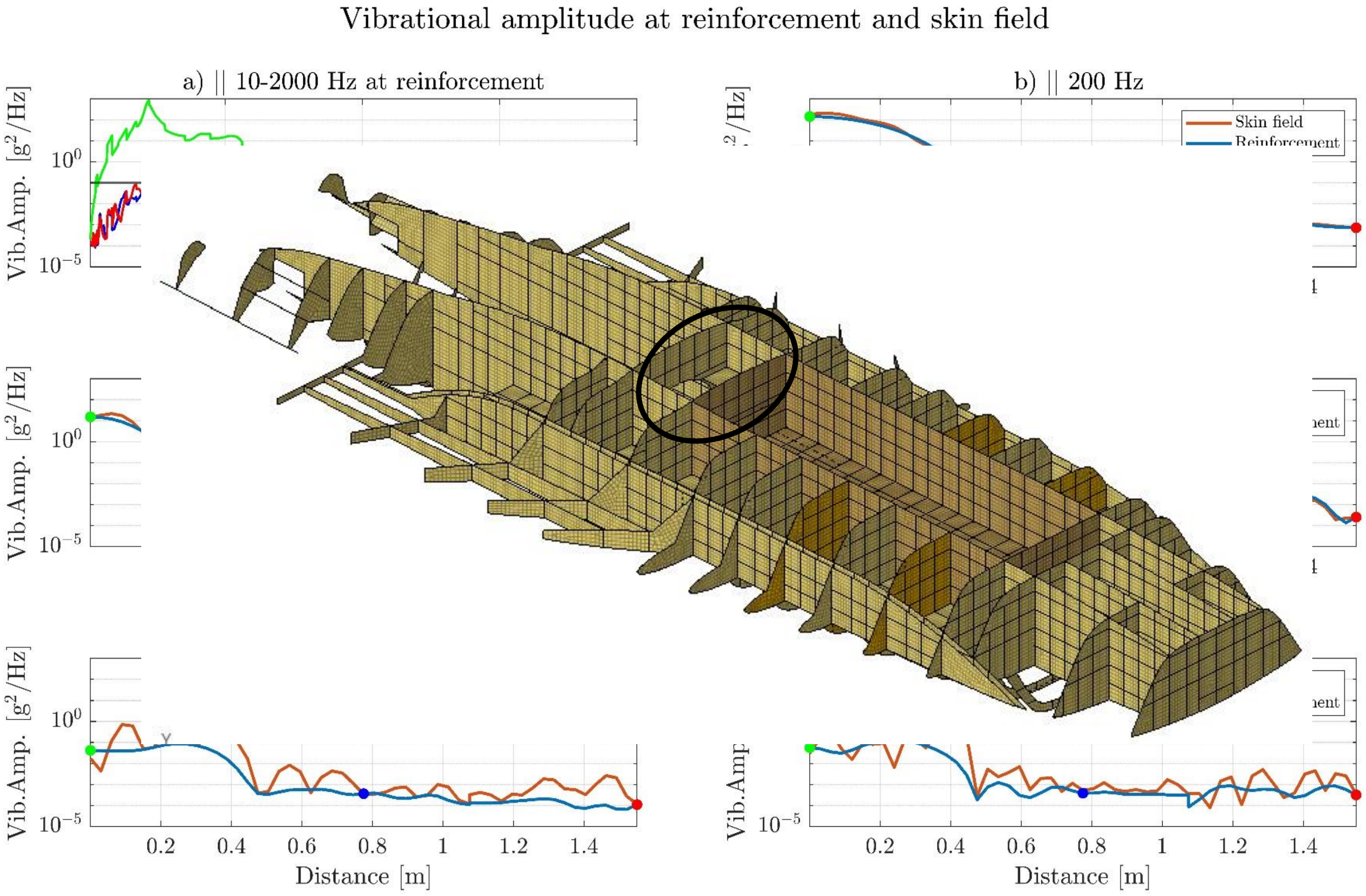




Results Aircraft Structure

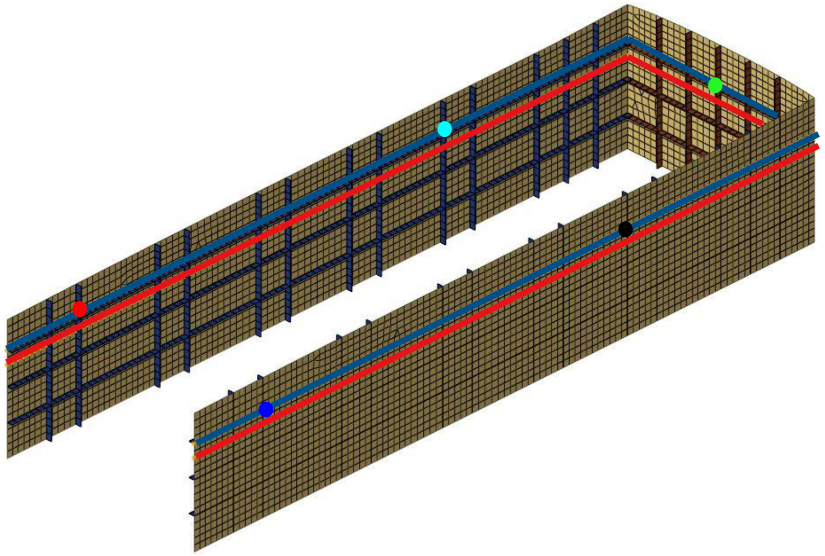
- Vibration propagation from downstream wall to adjecent frame
- Seams affect the propagation
- Levels decrease away from the cavity

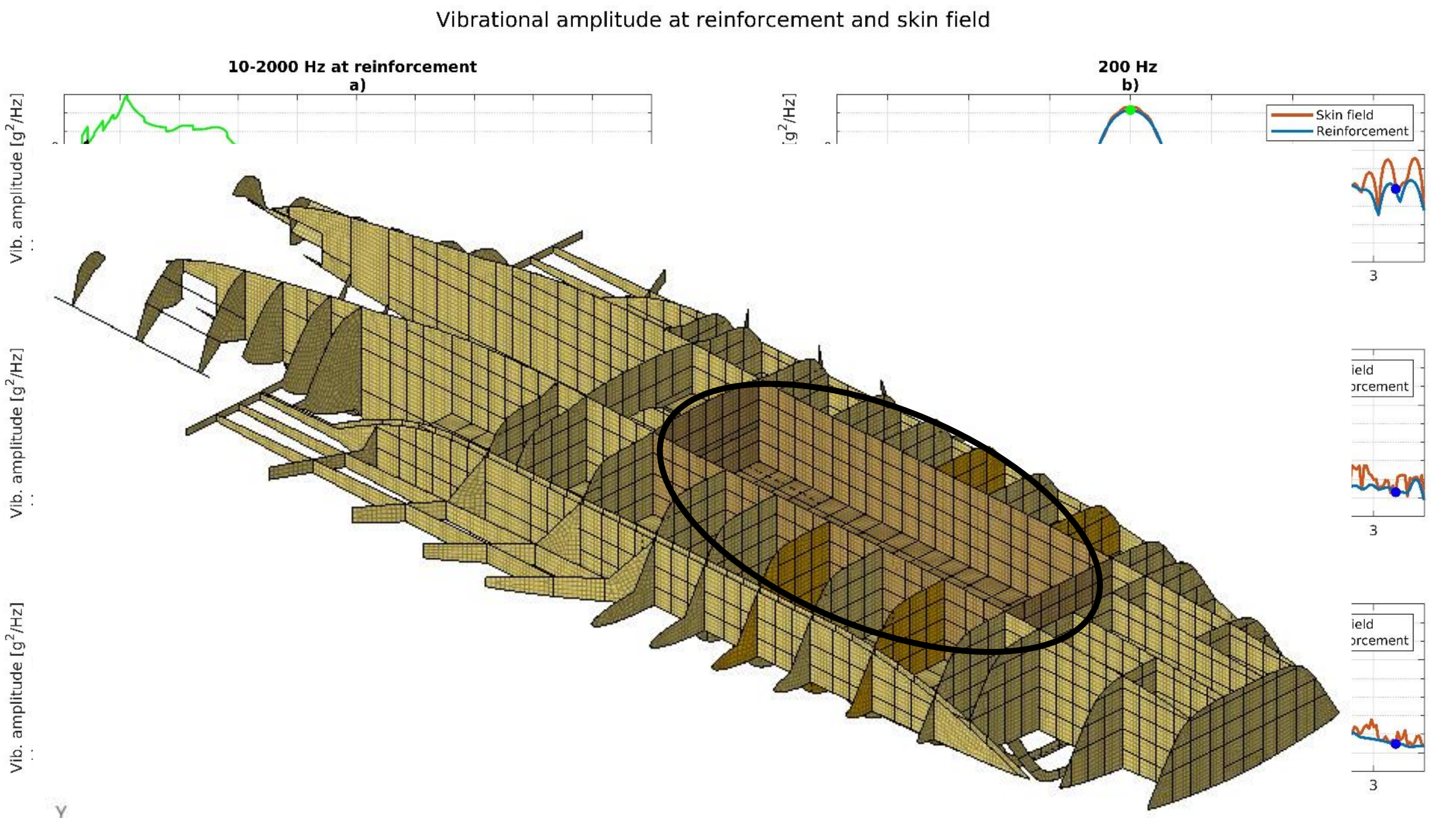




Results Aircraft Structure

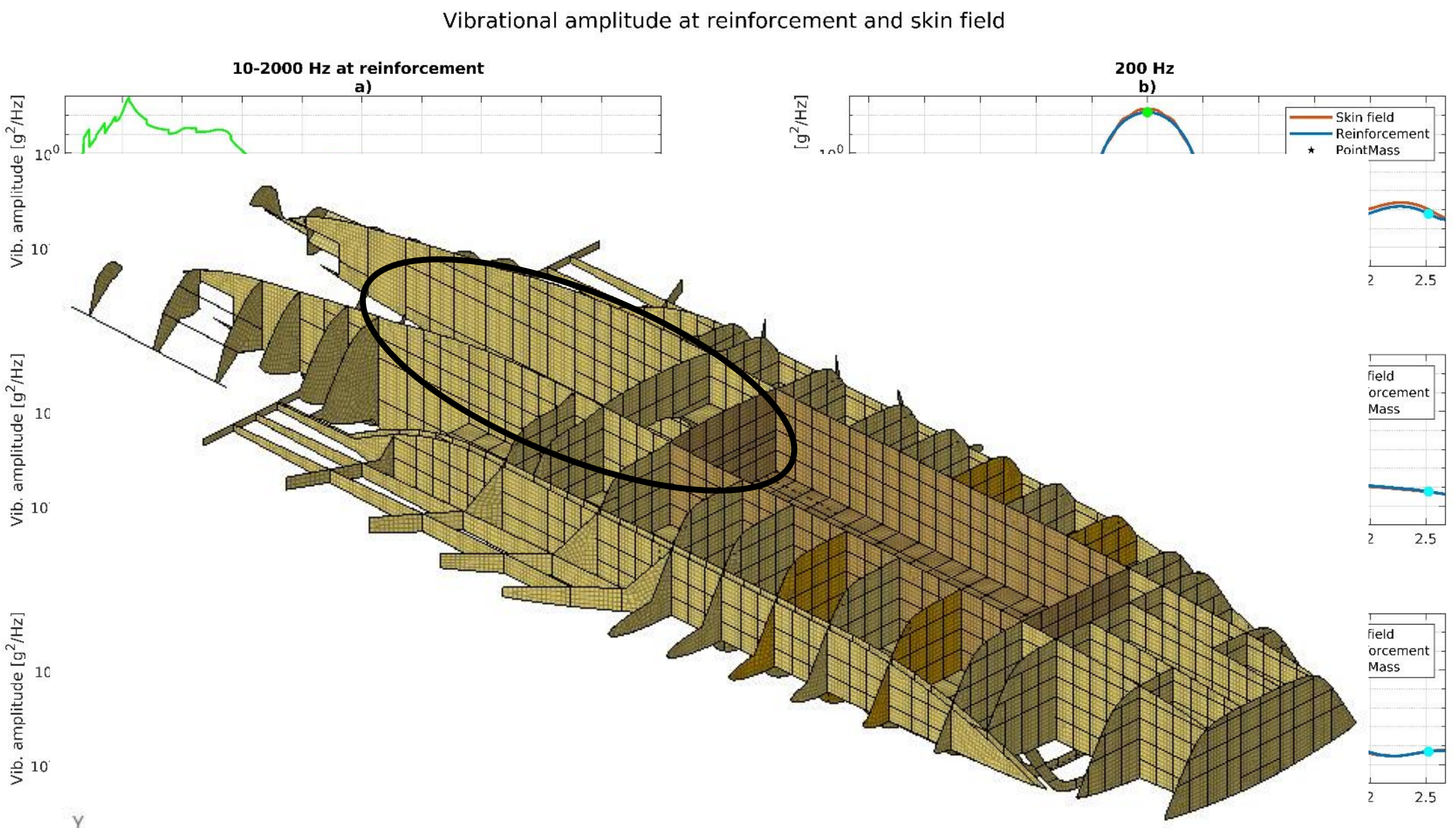
- Vibration propagation around the IWB
- Highest amplitude for nodes on the side wall coincide with the energetic Rossiter modes
- Oscillative behaviour for high frequencies

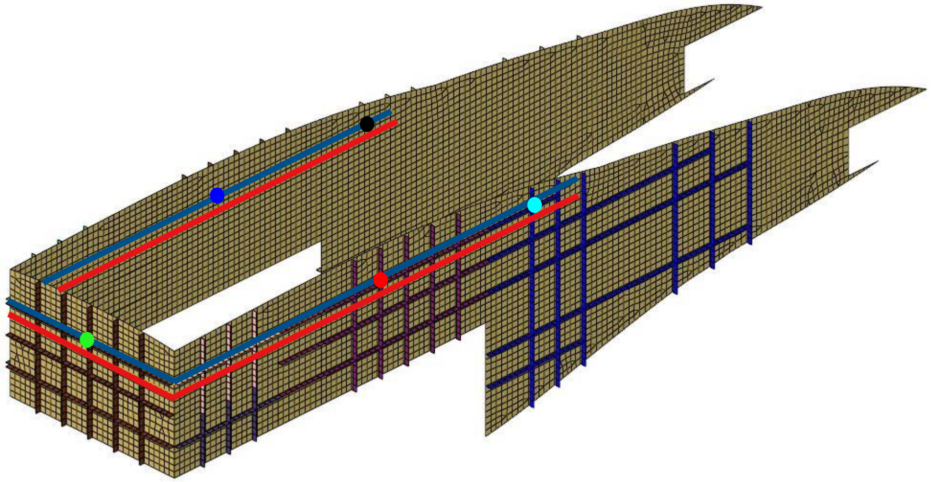




Results Aircraft Structure

- Vibration propagation to the rear of the Aircraft
- Localization at higher frequencies
- Equipment affecting the response locally



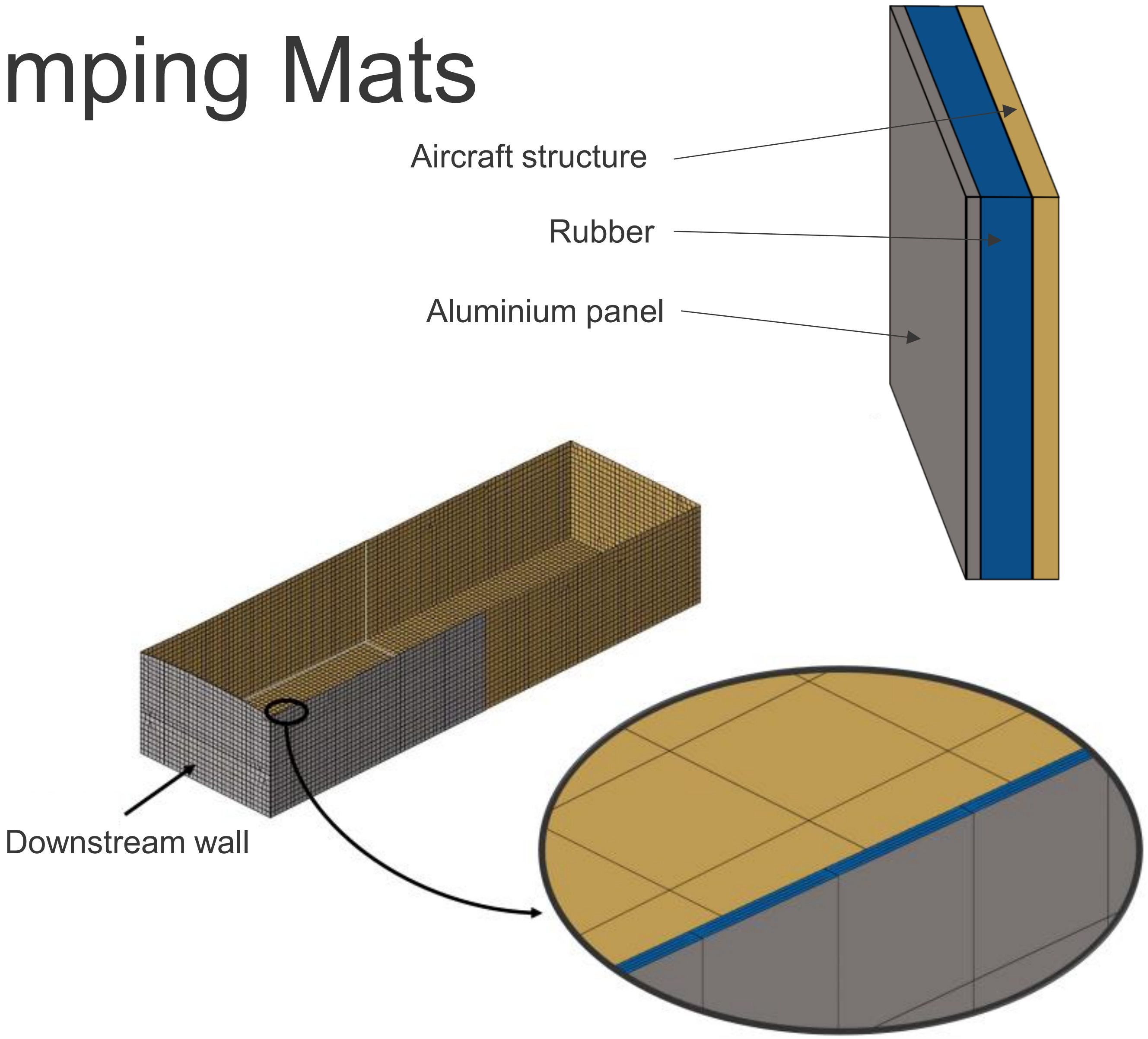


Discussion - Aircraft Structure

- This method can be applied during the design phase to predict the vibrational environment, identify potential problem areas, and determine viable mounting positions for equipment
- Level of detail should be high in and around the IWB to get a sufficient results
- Reinforcements and seams are more favourable mounting positions compared to skin fields
- No equipment should be mounted on the downstream wall, however a rapid decrease in vibration levels are observed at a distance from the cavity
- Method allows for mitigations to be implemented early in the design phase of a conceptual aircraft, such as
  - Reinforcement patterns
  - Surface thicknesses
  - Damping mats

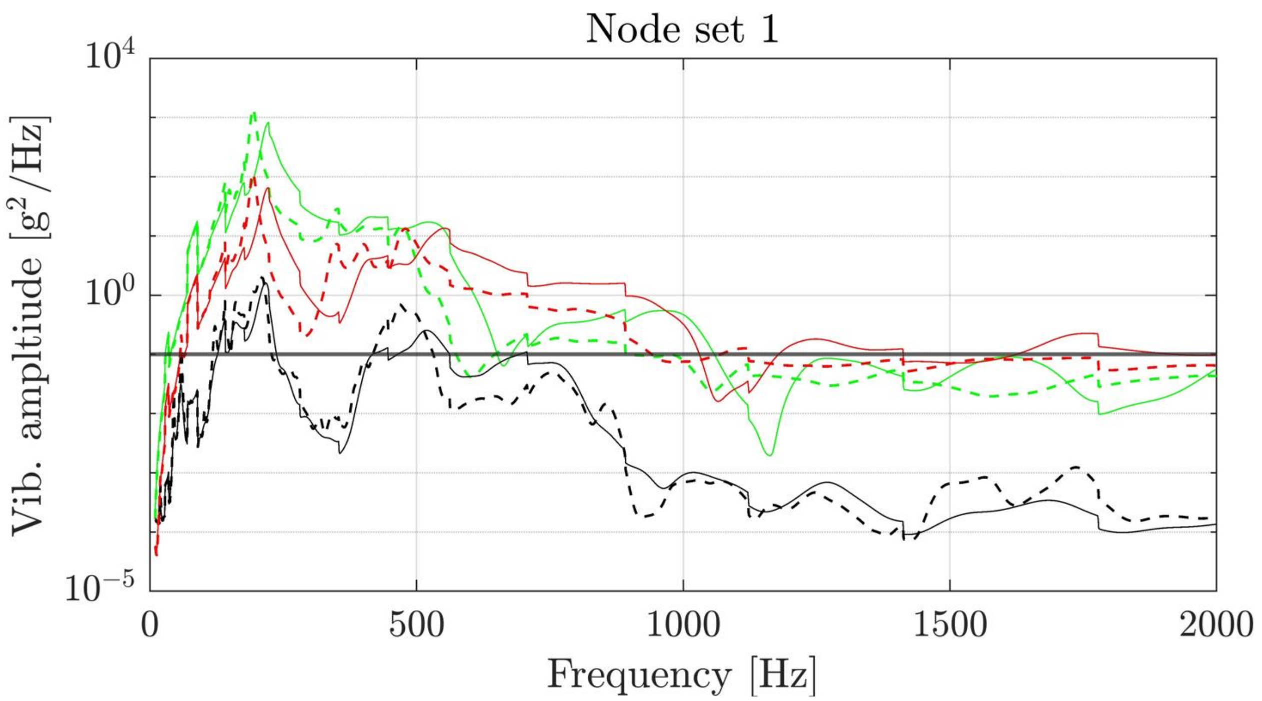
Implementation of Damping Mats

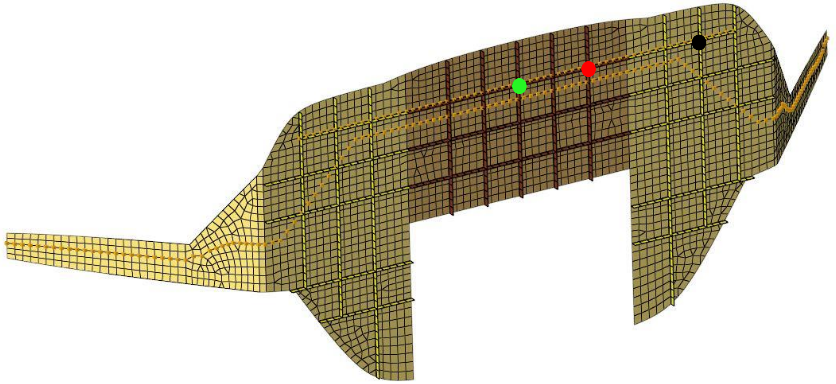
- Damping Mats can be used to reduce the vibrational response in the structure
- Dissipation of energy by shear deformation in the rubber material
- Simplified modelling with frequency dependent rubber-material
- Baseline configuration of rubber layer thickness 3 mm and aluminium panel 0.5 mm
- Aluminium panel is modelled with shell and rubber is modelled with solid elements



Result Damping Mats

- Vibration response for three different points
  - Dashed – Damping mat configuration
  - Solid – No mounted damping mats
- Exceeds vibration requirement, especially at low frequencies
- Influence locally on the downstream wall but also at surfaces without damping mats (black lines)
- Dynamic behaviour altered but no clear trend





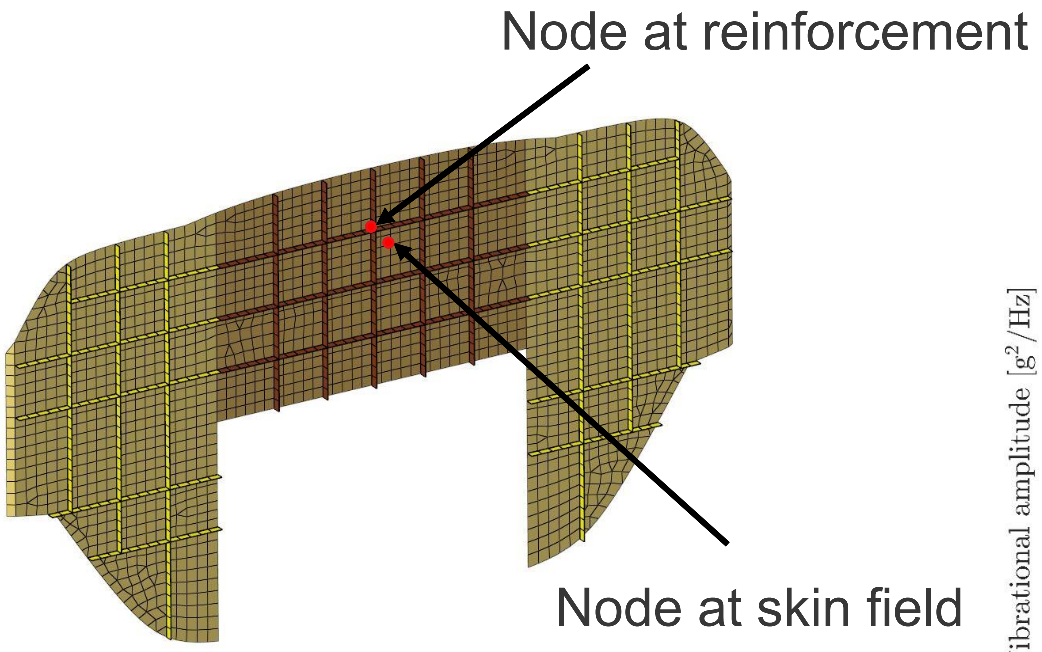
SAAB

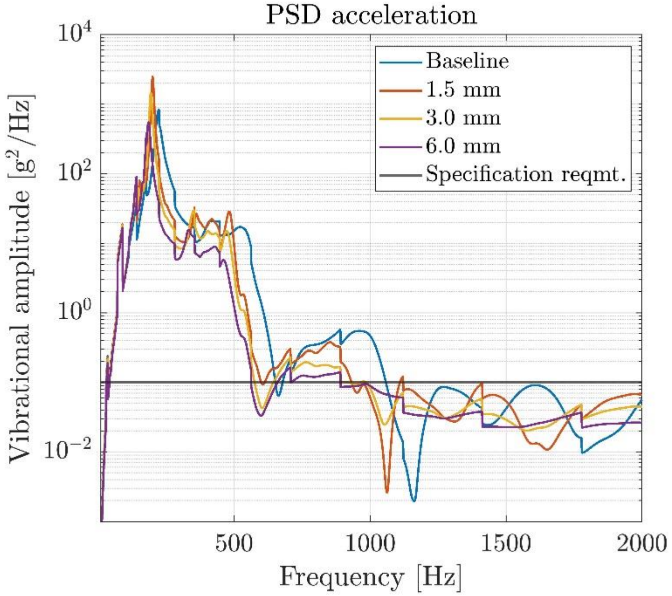
Sensitivity Analysis – Damping Mats

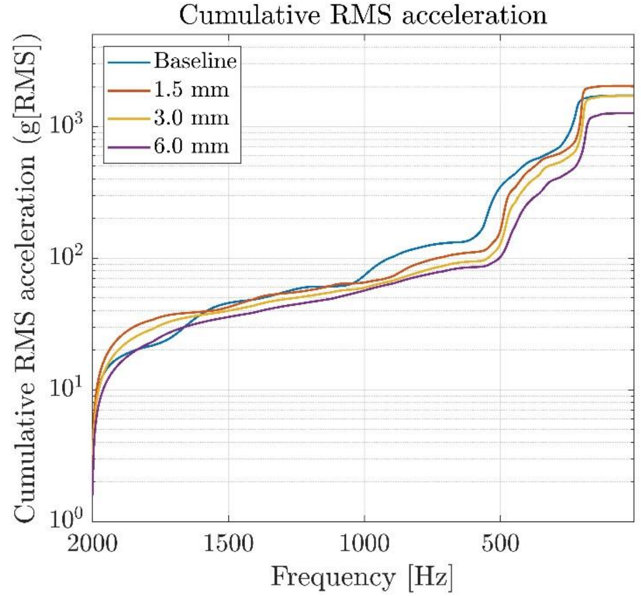
- Sensitivity analysis
  - Youngs modulus, shear modulus and structural damping (see report)
  - Thickness of rubber
  - Thickness of aluminium panel (see report)
- Comparison of PSD acceleration and RMS between configurations with and without damping mats
  - Cumulative RMS summed from 2000-10 Hz to capture higher frequency effects

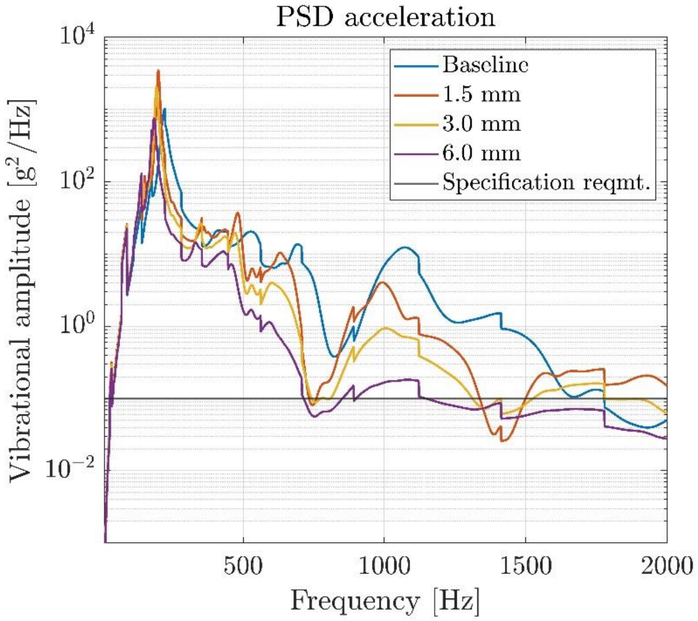
Results Damping Mat

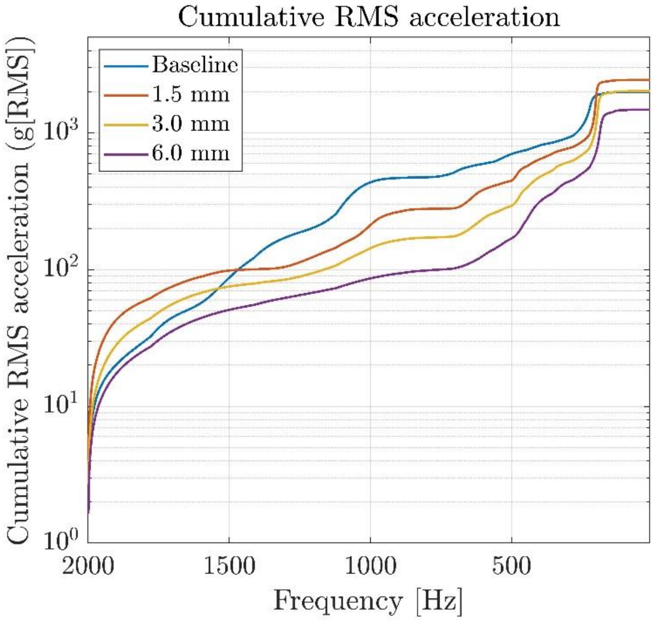
- Varied thickness of rubber layer
- Compared to vibration requirement





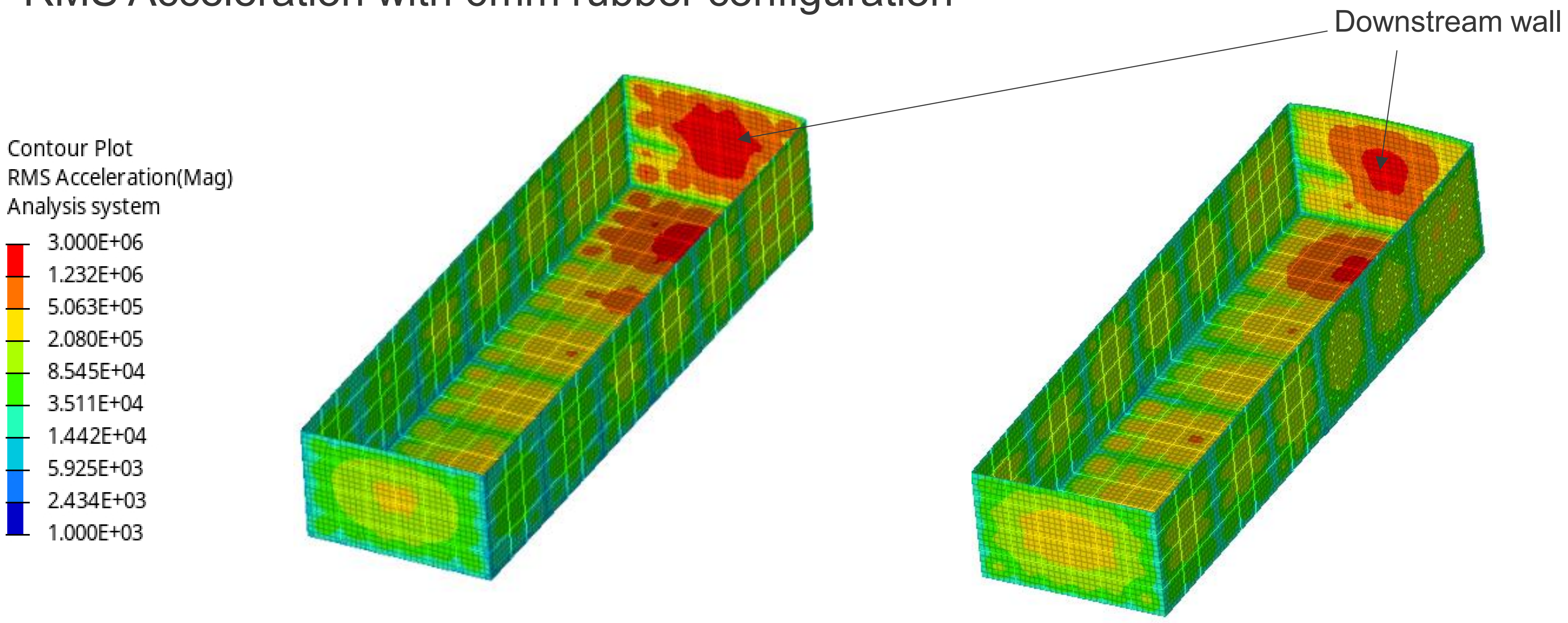






Implementation of Damping Mats

- Decrease of levels locally where damping mats are implemented
- RMS Acceleration with 6mm rubber configuration



No damping mat

Damping mat

Conclusion

- Flying with an open internal weapon bay leads to high sound pressure levels acting on the surface of the cavity leading to a harsh vibrational environment within the aircraft structure
- This method allows for early analysis of the vibrational environment which can be used as support for design decisions
- Mitigations can be tested and analysed and their effectiveness assessed at an earlier stage in the design phase

Questions?