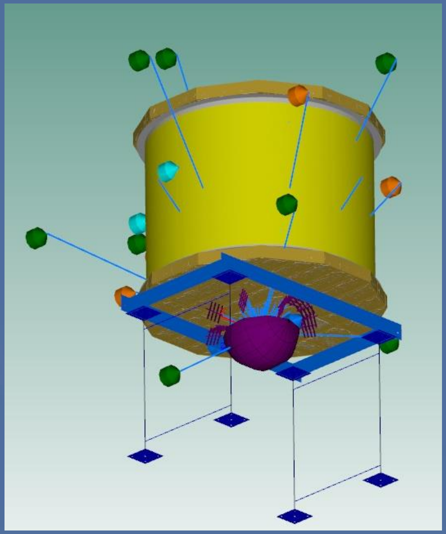
Virtual reproduction of a reverberant test environment



Alexis Castel, Aaron Godfrey, Peter Paras, Patrick Cleary
ZIN Technologies

Spacecraft and Launch Vehicle Dynamic Environments Workshop
June 4–6, 2019

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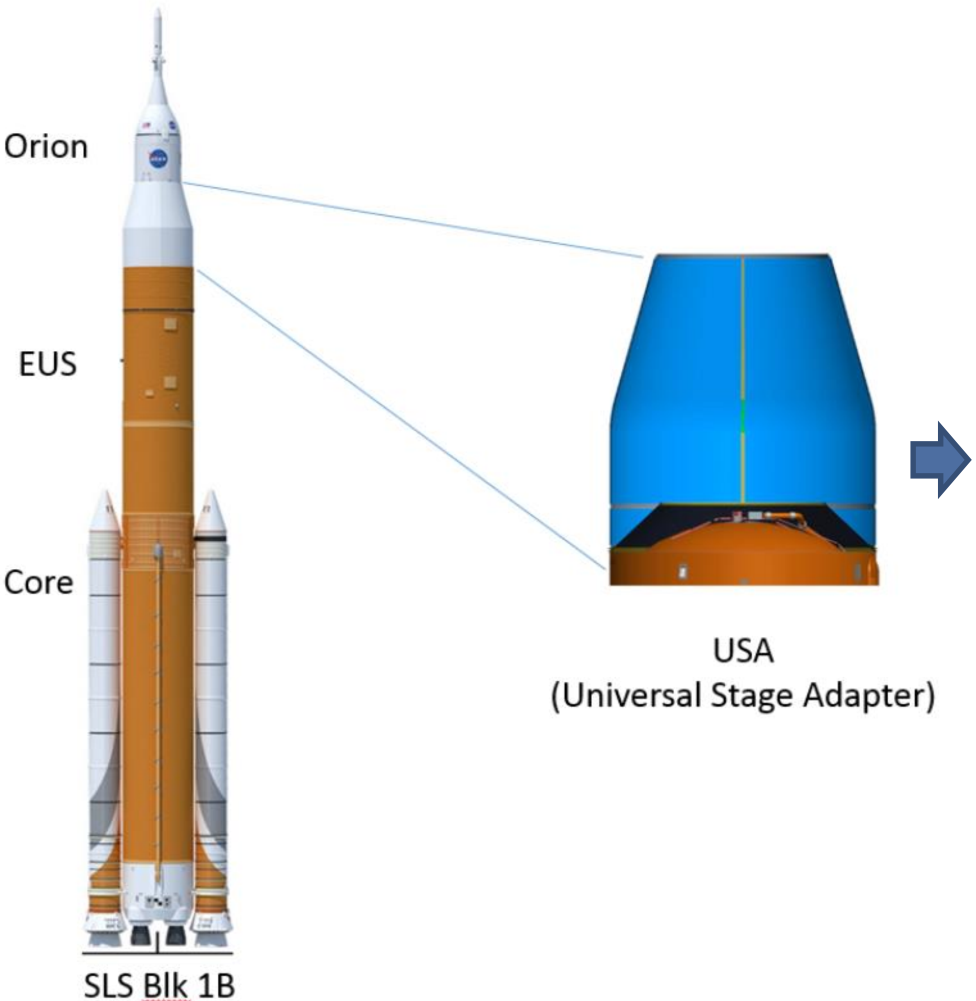
Universal Stage Adapter acoustic challenges



Large payload volume

Low frequency challenges due to modes created by the large volume

Validation of noise control treatment will require accurate low frequencies predictions

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Diffuse acoustic field

Simulation	Reverberant chamber
• Boundary Element Method (BEM): ❖ *Sum of incoherent plane waves* • Diffuse Acoustic Field (DAF) loading ❖ *Corresponds to patch method, accounting for cross-correlation*	• Creates a diffuse field by surrounding the test article with a large number of acoustic modes • Discrete modes in the low frequency ❖ *Non-diffuse in the lowest frequencies due to the finite size of the chamber* ❖ *Diffusivity and levels usually estimated in the 1/3rd octave band*

Simulation ≠ Reverberant Chamber

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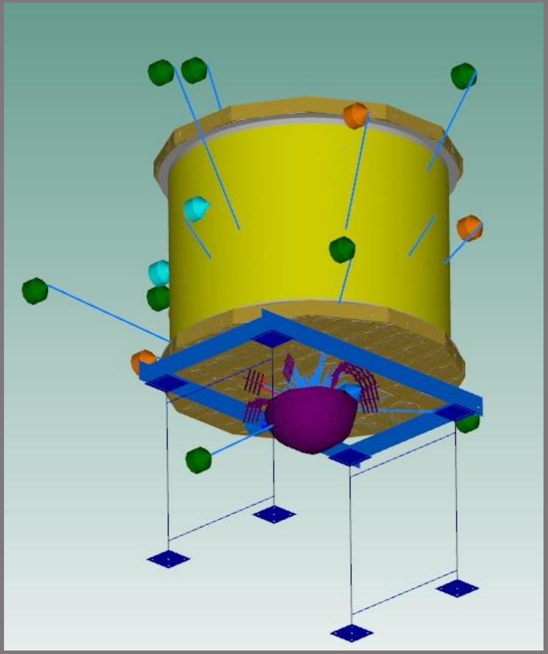
Diffuse acoustic field

Simulation	NASA Plum Brook Reverberant Chamber

For USA, we need to test and simulate accurately throughout the complete frequency range, starting **at 20 Hz**



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Old adage

- Everyone believes the test except the test engineer

- No one believes the simulation except the analyst

Old adage

- Everyone believes the test except the test engineer
  - *Testing introduces many configuration and loading changes relative to actual flight*

- No one believes the simulation except the analyst
  - *Math models tend to not always correlate well to test as they rely on assumptions*

How can we introduce some of the test components in the simulation?

Can we get everyone to believe the simulation?

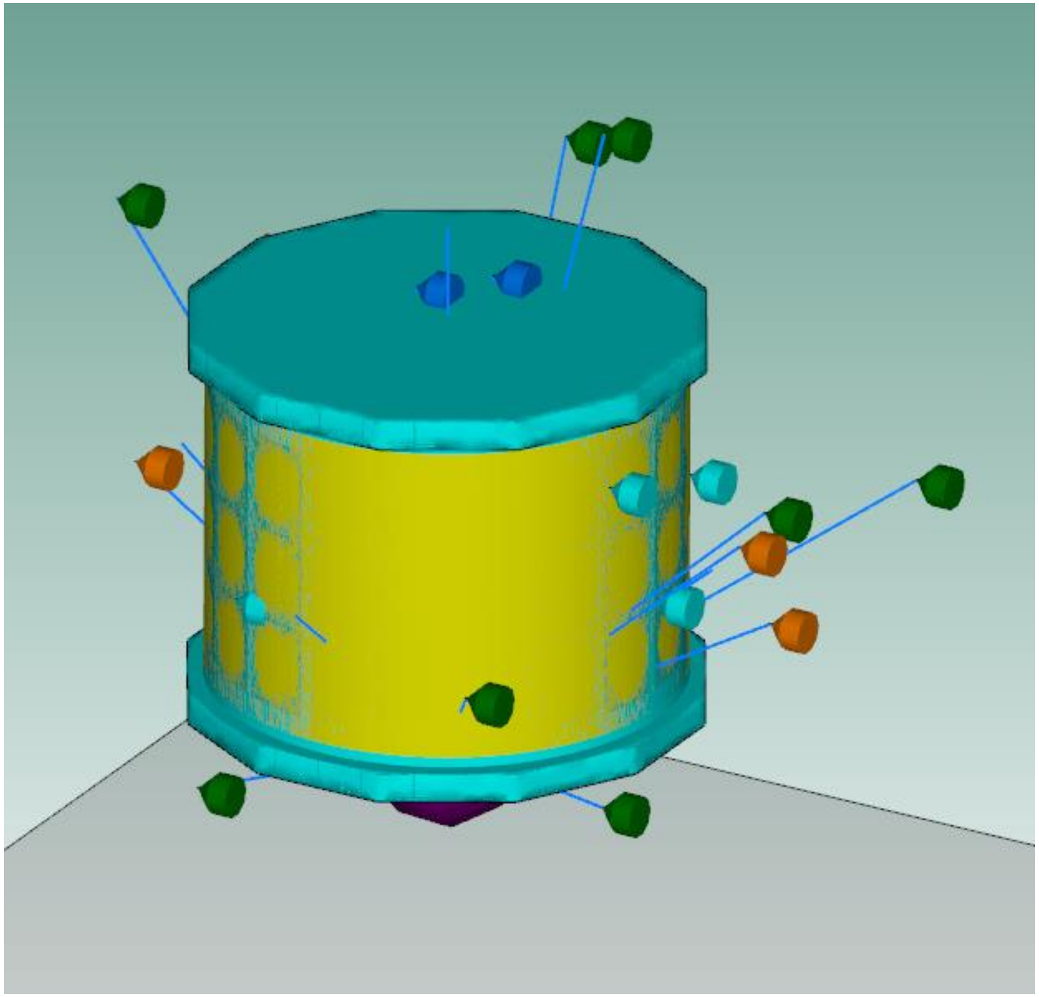
Fluted Cylinder acoustic test

Development test for USA in NASA Plum Brook's reverberant chamber conducted in November 2018

Fluted Composite Cylinder used as a simplified test article

Cylinder's internal response and Noise Reduction were measured

FE-BEM simulation setup



- External fluid is modeled using BEM
  - Excitation is done by a sum of 20 plane waves
  - Plane waves are initially incoherent to simulate a diffuse acoustic field
- Cylinder structure and cavities are modeled using the finite element method.
- External test microphones are placed in the model
- The average internal cavity pressure is monitored

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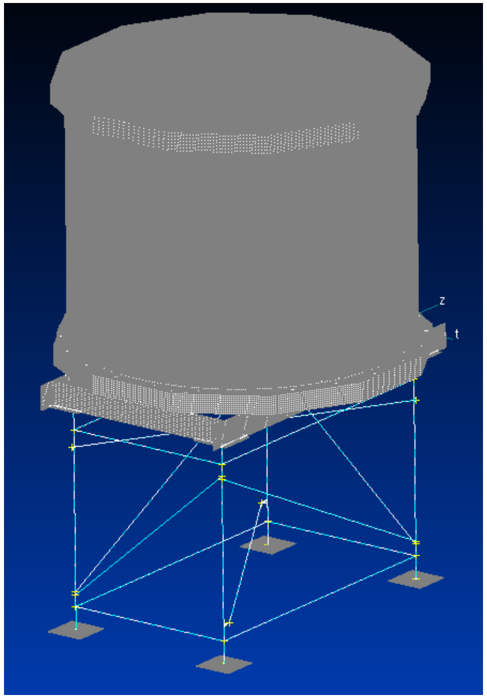
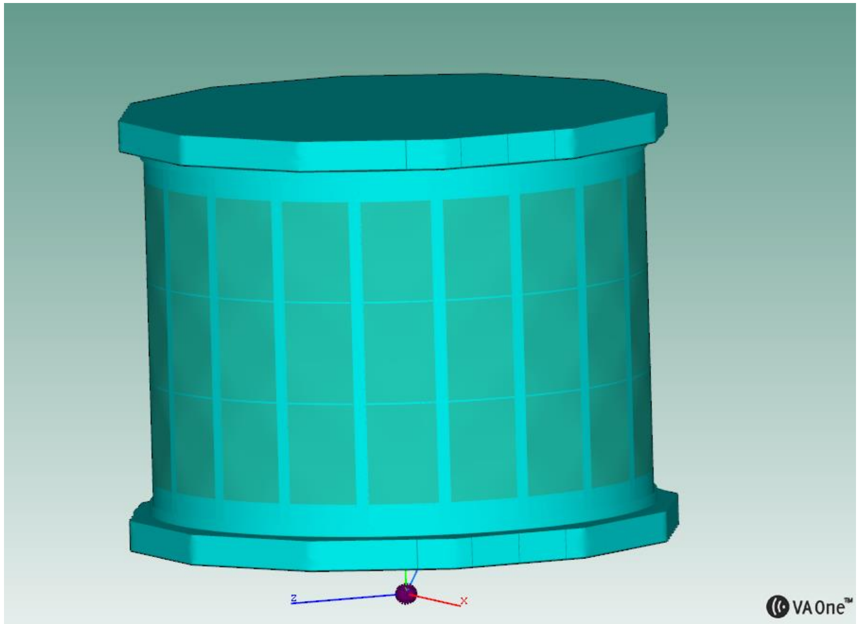
Fluted Cylinder acoustic simulation



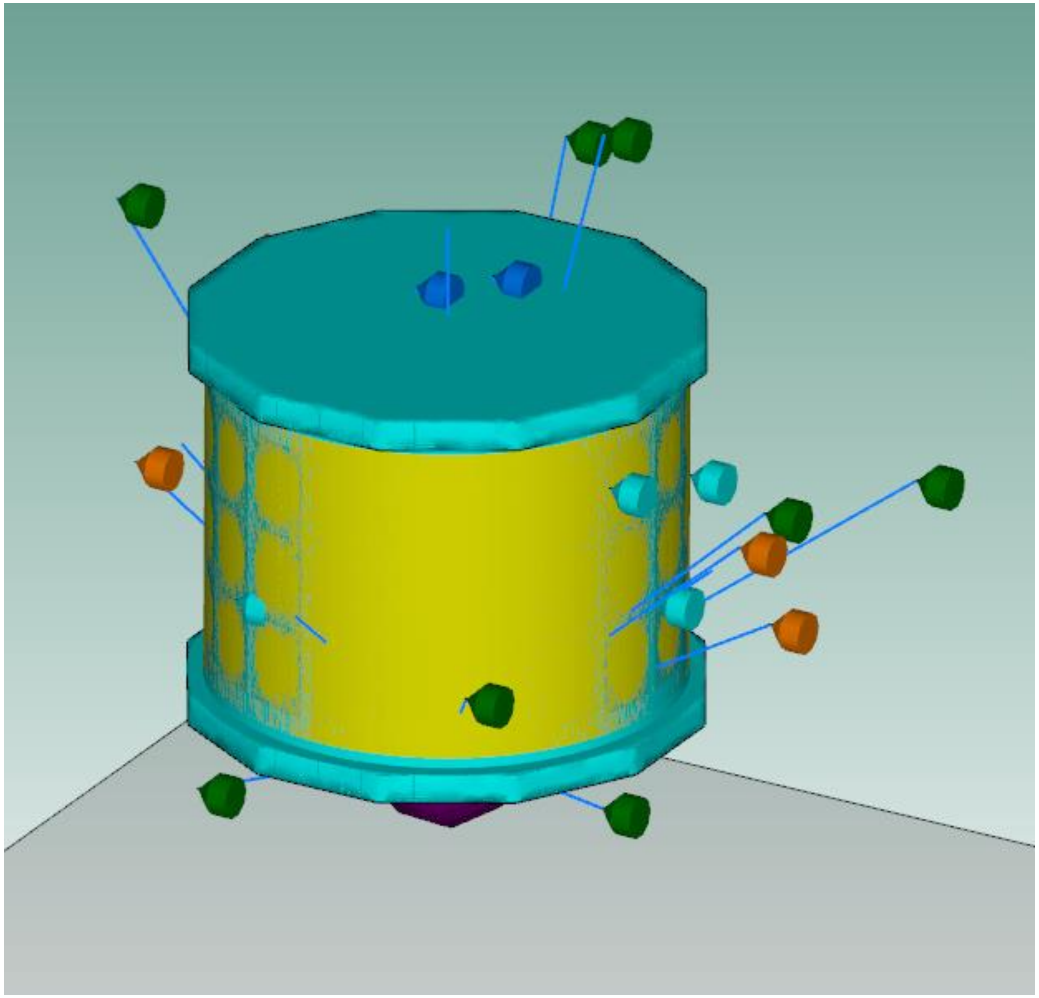


- Typically, a diffuse acoustic field is assumed for simulation
  - Test field is not diffuse in the low frequency:
    - Reverberant chamber has a modal behavior below the Schroeder frequency.

How can we make the simulation account for the measured reverberant room characteristics?

Fluted Cylinder acoustic simulation

- Test used 26 external microphones including
  - Control microphones
  - Free field microphones
  - Surface microphones



- Microphones present in test are placed in the simulation model to reproduce the external loading
  - Both levels and cross correlation information are used

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Modifying the BEM simulation

- $[S_{pp}] = [H_{pw}][S_{ww}][H^*_{wp}]$
  - ❖ $[S_{ww}]$ *is the cross-correlation matrix defining the plane wave excitation. Traditionally,* $[S_{ww}]$ *is diagonal.*
  - ❖ $[S_{pp}]$ *is the cross-correlation matrix defining the microphone response*
    - $[S_{pp}]$ usually matches a DAF, but can be altered to match a measured acoustic field
  - ❖ $[H_{pw}]$ *is provided by the BEM solver*

- If $[S_{pp}]$ is measured, $[S_{ww}]$ can be recalculated with
  - ❖ $[S_{ww}] = \mathrm{pinv}([H_{pw}])[S_{pp}^{\mathrm{measured}}]\mathrm{pinv}([H^*_{wp}])$

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Modifying the BEM simulation

- In summary:
  - *We are still using plane waves*
  - *Plane waves with the proposed method are not uncorrelated:*
    - Their amplitude and cross correlation are back-calculated from measurement data

Traditional BEM DAF simulation	Proposed method
Uncorrelated plane waves $[S_{ww}]$ is diagonal	Partially correlated plane waves $[S_{ww}]$ is not diagonal

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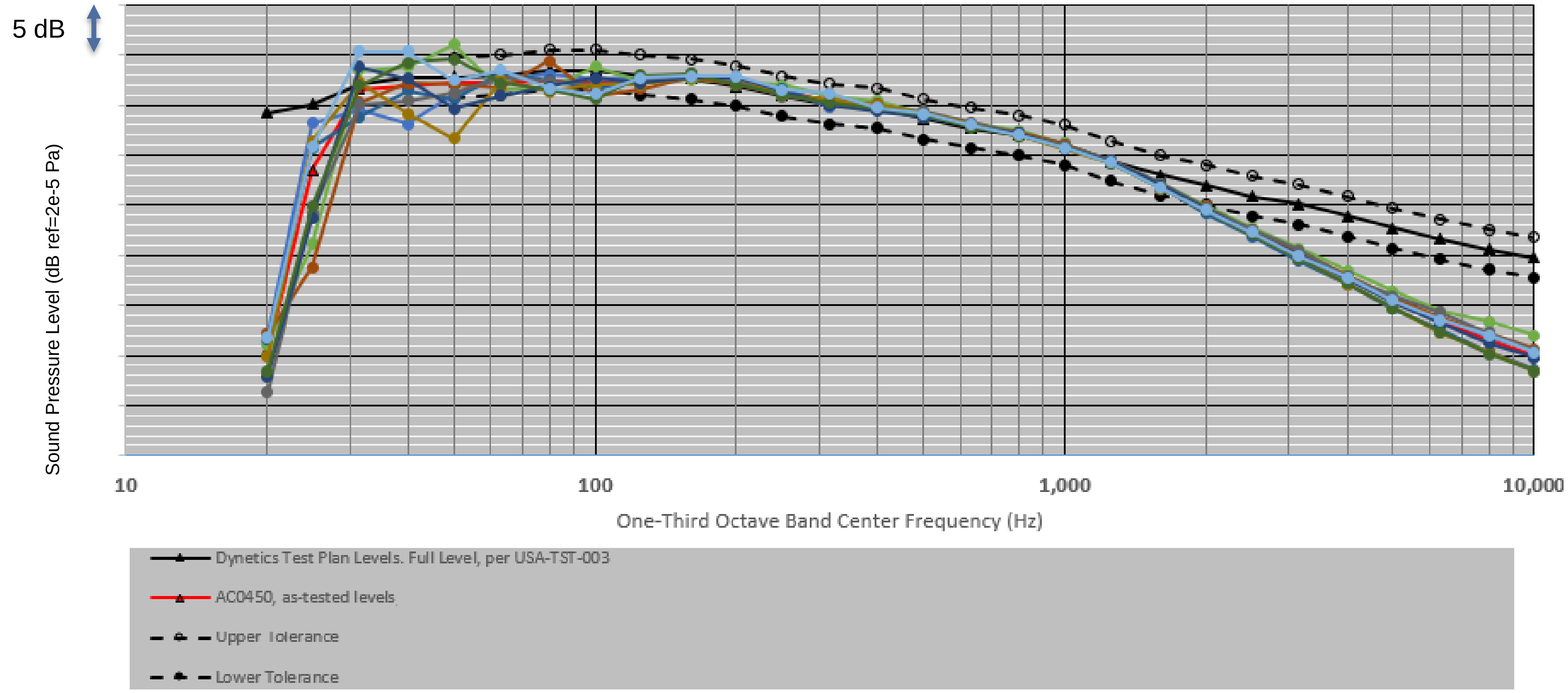
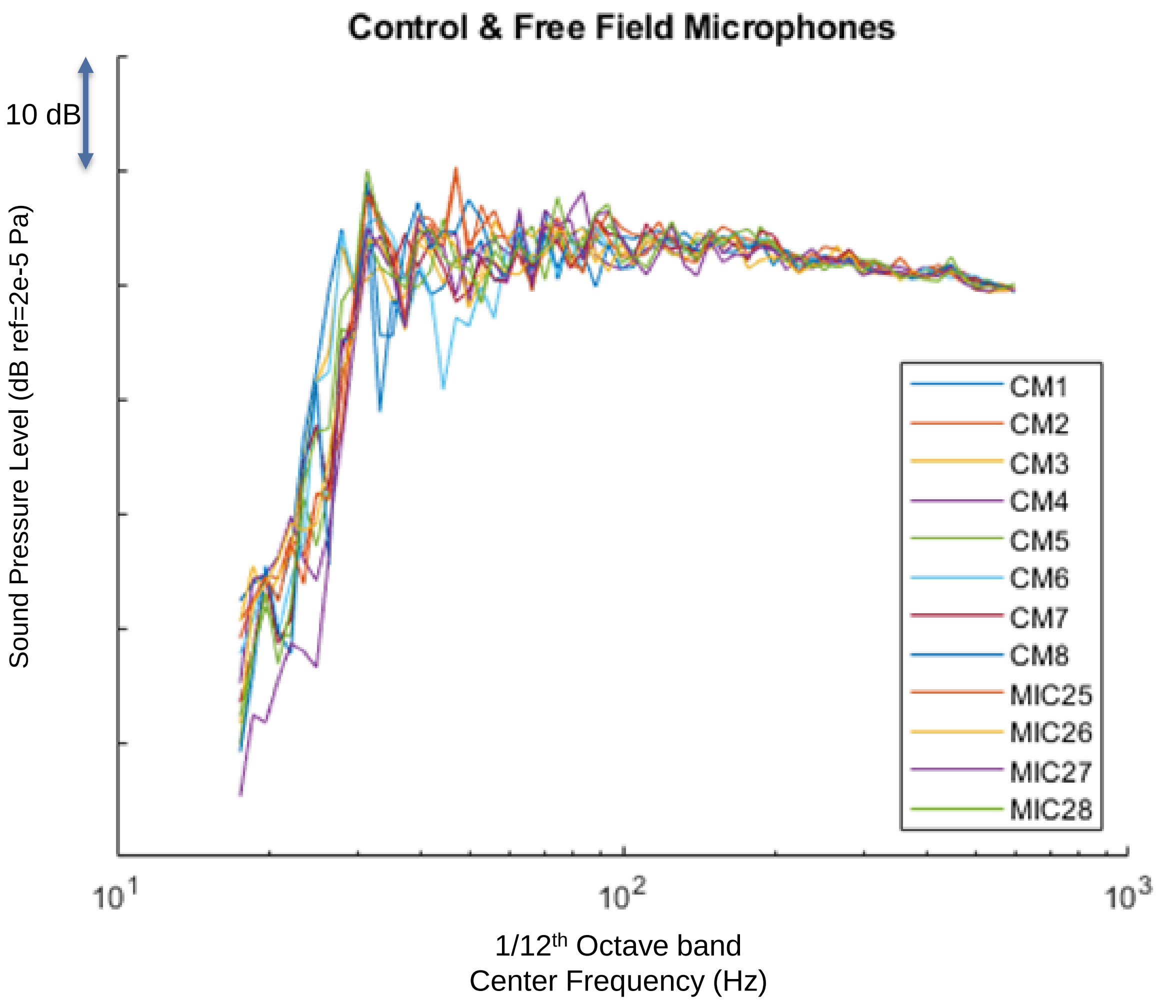
Measured Sound Pressure at control microphones during test

- Control is performed in the 1/3rd octave band



Measured Sound Pressure at outer field microphones during test



- Acoustic field appears non uniform in the low frequencies
- Expected at 50 Hz and below

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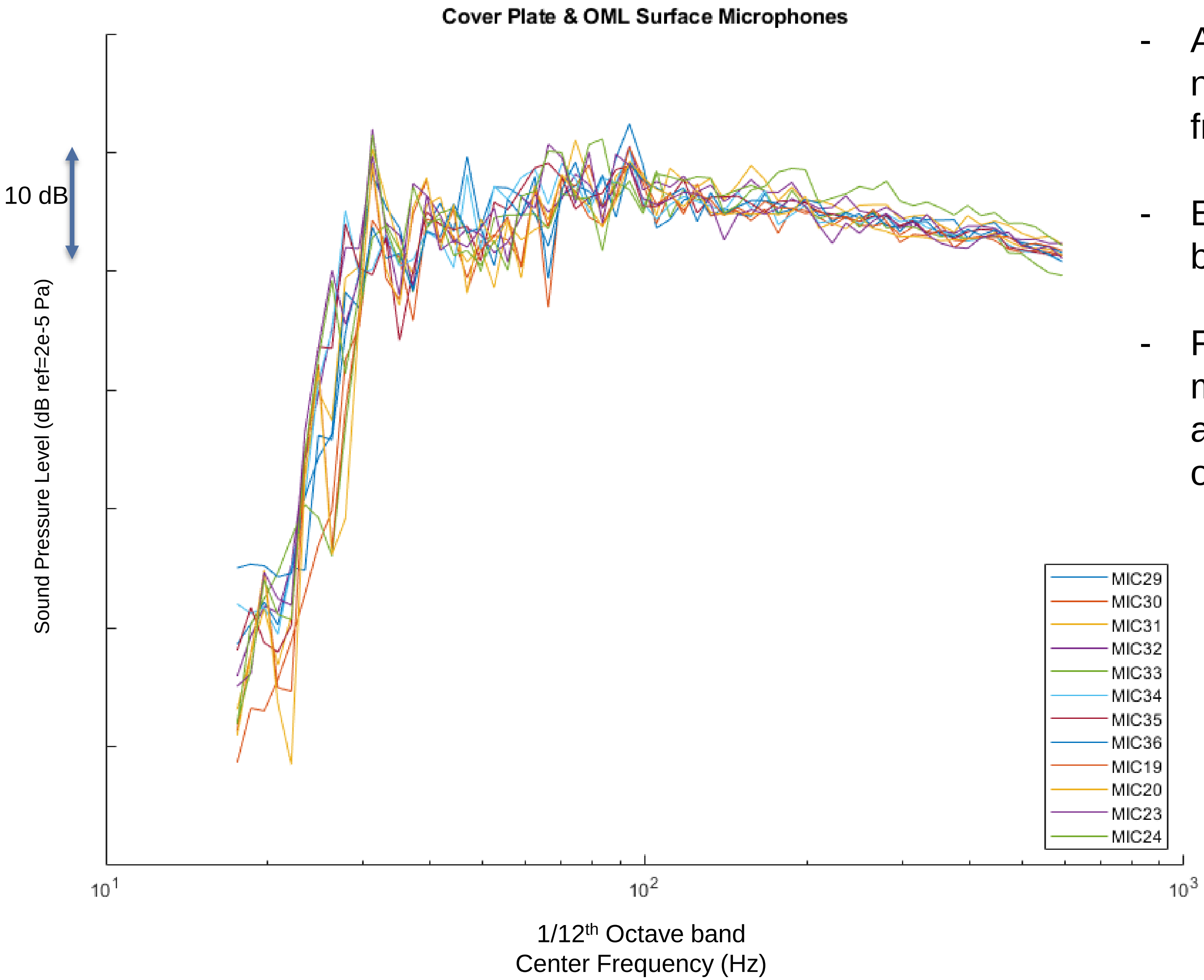
Measured Sound Pressure at outer surface microphones during test



- Acoustic field appears non uniform in the low frequencies
- Expected at 50 Hz and below
- Field and surface microphones also have an expected difference of level.
  - This is accounted for in the BEM calculation

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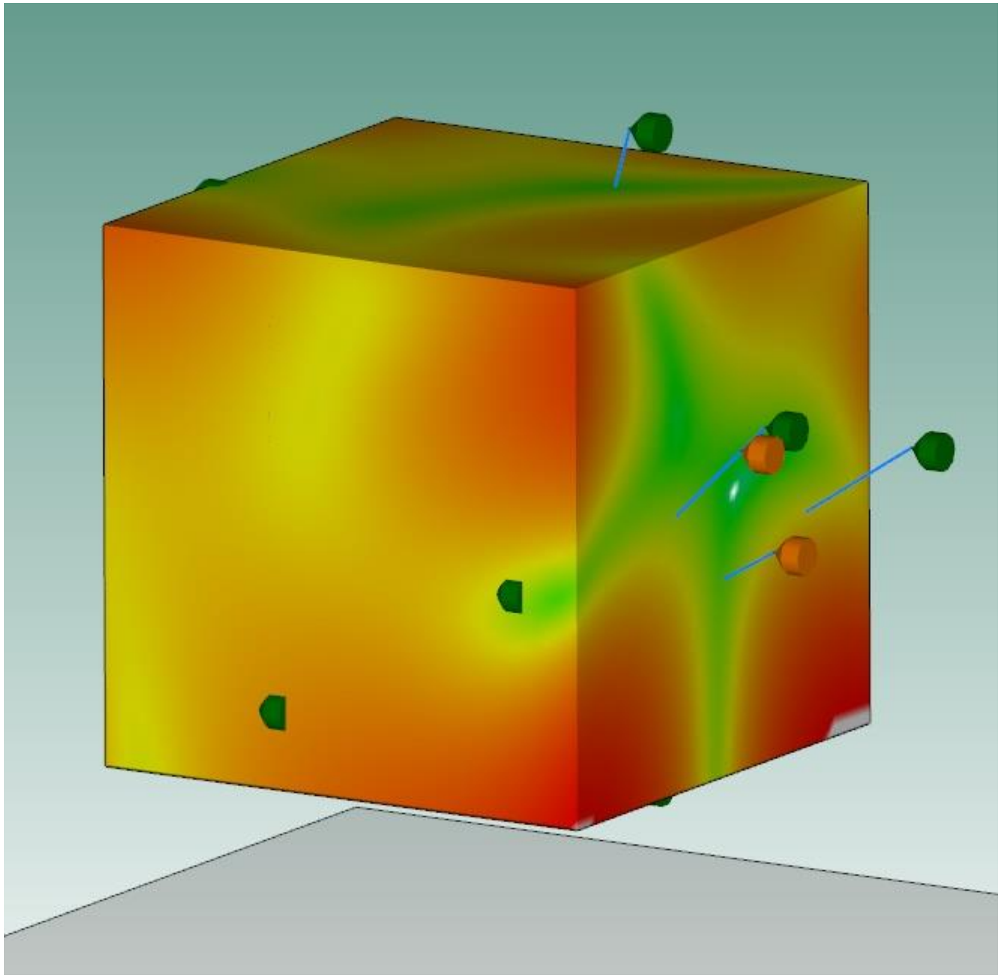
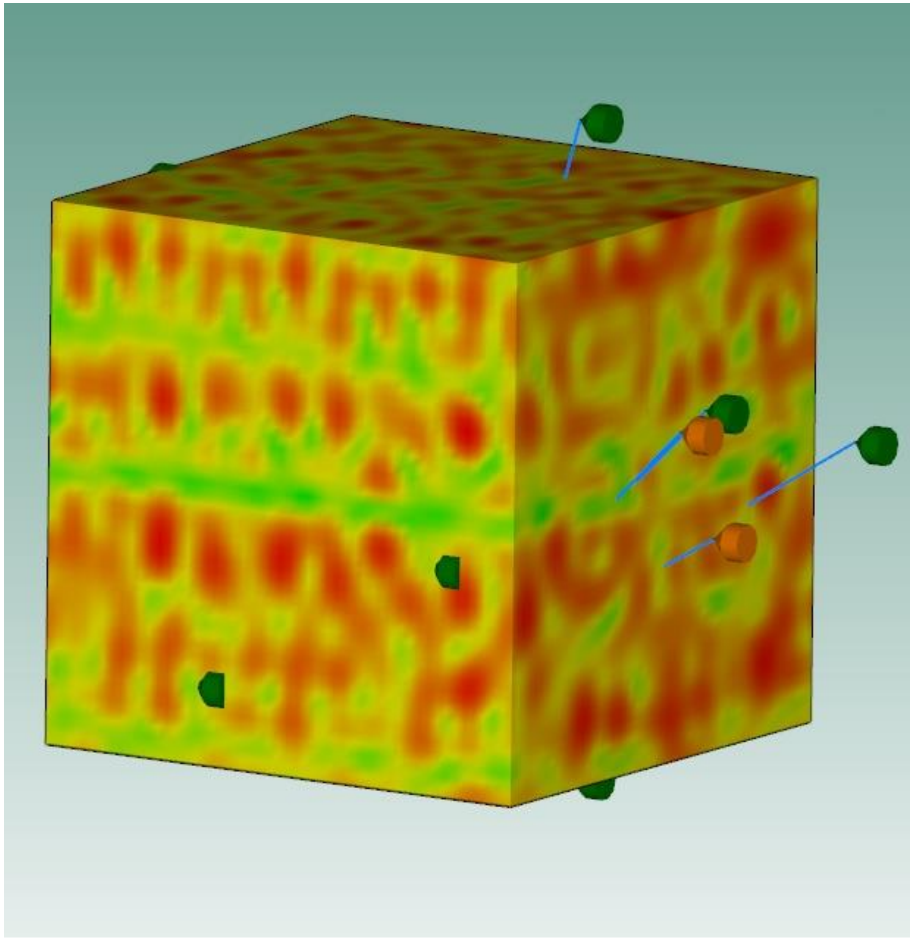
Pressure contour – center frequency of 25 Hz



Discrete 1/12th Octave band

Pressure is non uniform: contour plot shows typical room modes nodes.

Pressure contour – center frequency of 400 Hz



Discrete 1/12th Octave band

Typical pressure distribution with wavelength matching frequency

The finite number of plane waves may limit the accuracy of this prediction.

Modifying the BEM simulation

Normalized cross correlation matrix
(absolute values bounded between 0 and 1)

Incoherent plane waves $[S_{ww}]$ (20 planes waves)

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

This is the classical way of modeling a diffuse acoustic field with BEM

Recalculated plane waves $[S_{ww}]$ (20 planes waves)

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

25 Hz

- Matrix is not diagonal
- Select plane waves with a cross correlation coefficient are recreating the measured acoustic field

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

400 Hz

- Matrix is close to diagonal
- Closer to analytical diffuse acoustic field

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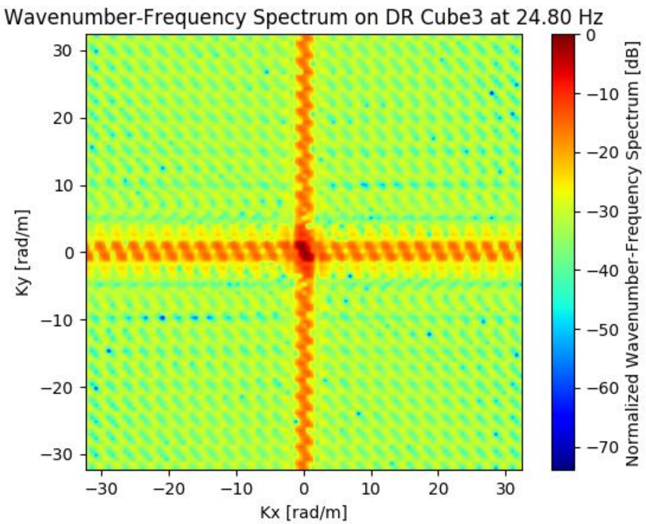
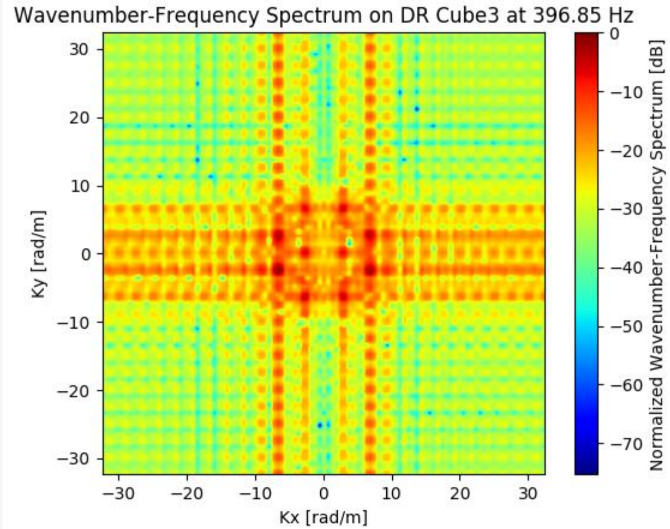
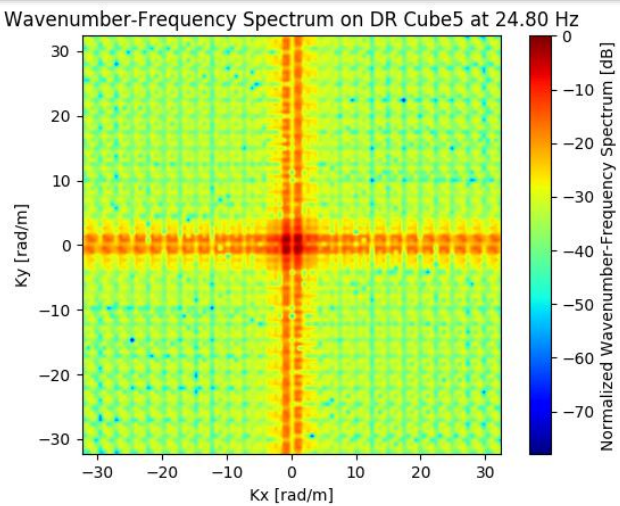
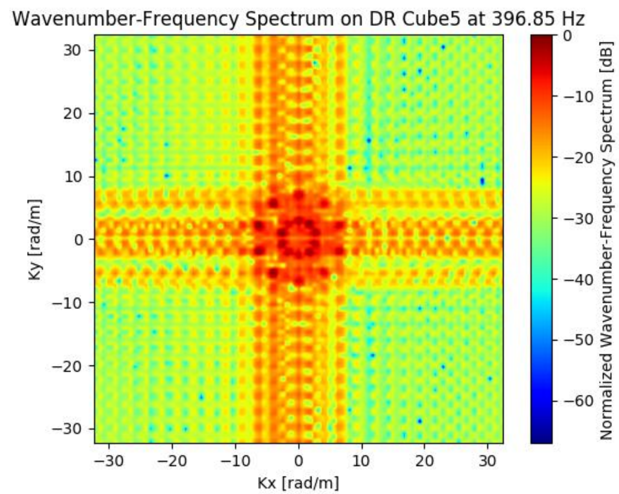
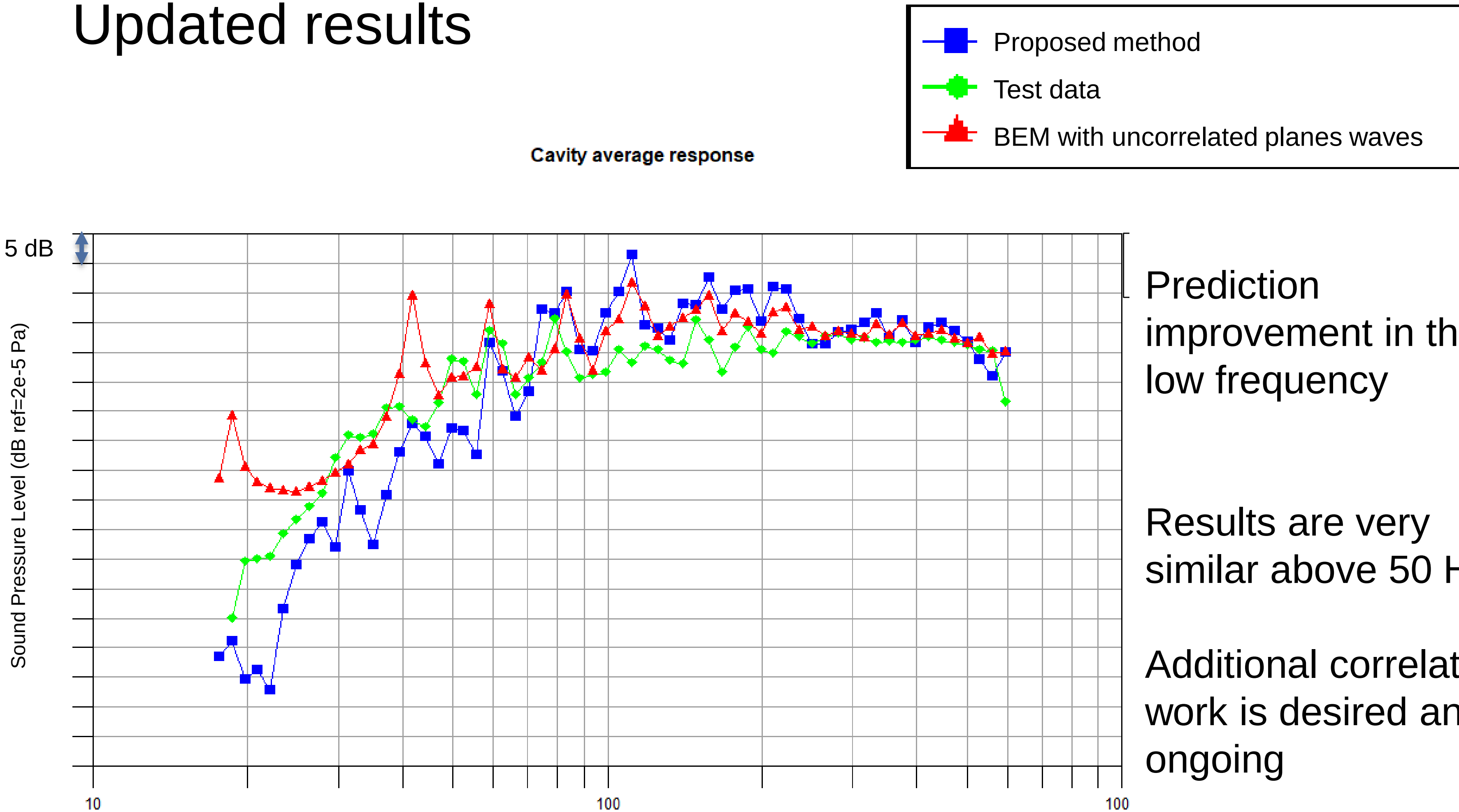
Diffusivity analysis (for a rigid test article)

	25 Hz	400 Hz
Horizontal plane		
Vertical plane		

- Low frequency shows privileged direction of propagation of energy
- High frequency is more circle like
- Circle like shape appear at 100 Hz and above which is an indication of field diffusivity

Updated results



1/12th Octave band
Center Frequency (Hz)

Prediction improvement in the low frequency

Results are very similar above 50 Hz

Additional correlation work is desired and ongoing

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Conclusions

- The proposed method replaces a nominal diffuse acoustic field loading by a test-based loading
  - *Proposed loading methodology shows better correlation with test data*
  - *Recreated acoustic field can be interpolated to better visualize and characterize the sound field.*
    - Wavenumber analysis of the interpolated data can be done

- For the measured acoustic field:
  - *At high frequencies, the measured acoustic field shows characteristics of a DAF*
  - *At low frequencies, the same field does not exhibit the characteristics of a DAF*

- For higher frequencies, a larger number of plane waves would be desired, this implies that additional microphones to characterize the field are then required

- Care must be taken when selecting the acoustic field test data as invalid results may perturbate the model.

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Thank you