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Evaluation of Microphone Density for Finite Element Source Inversion Simulation of a Laboratory Acoustic Test

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Motivation: Simulation of an acoustic test requires correct FEM inputs

- Acoustic & aero-acoustic environments are significant for many aerospace structures
- Simulation of these environments is important for design and qualification activities
- Validated FE models for acoustic environments requires validation tests
- Characterizing the acoustic pressure loads encountered in a validation test is critical to making useful model assessments

This leaves some important questions to answer

- *How do you get full-field acoustic pressure measurements from an acoustic test?*
  - *Method: acoustic FEM source inversion simulation*
  - *PDE-constrained optimization, using test mic data as target*

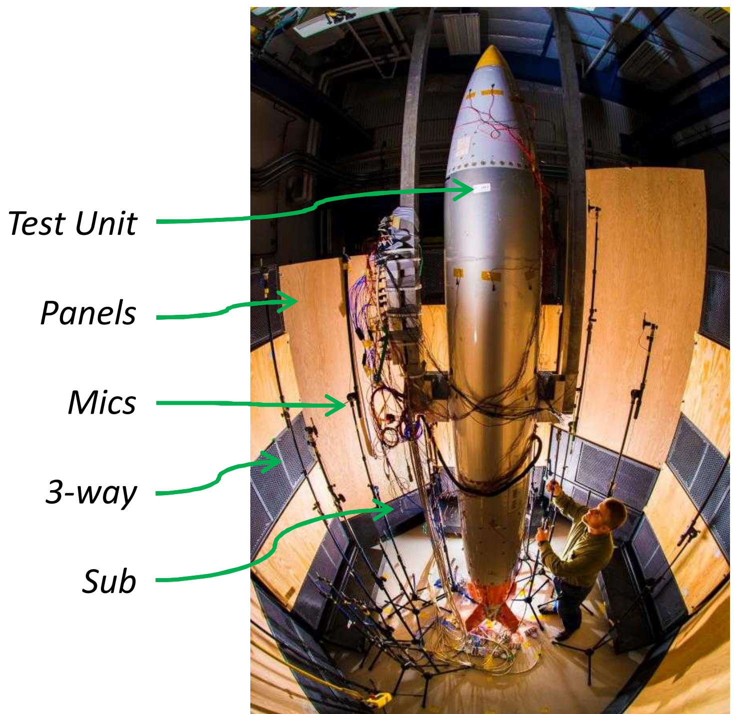
- ***How many mics do you have to have?***

Explore this question with a sensitivity study of a simulated test

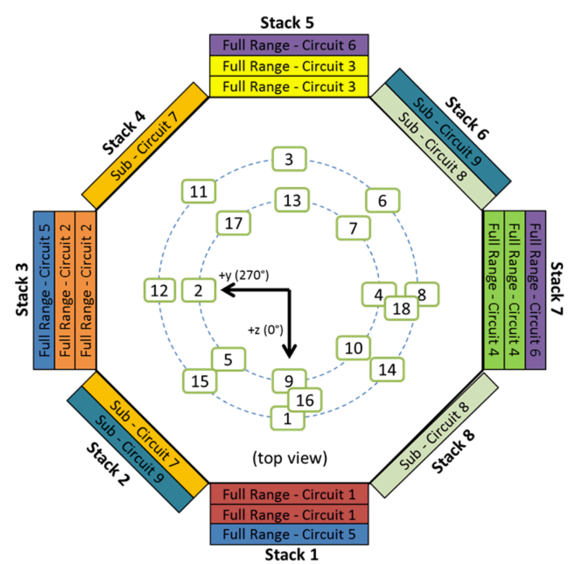
- Intended application: Laboratory acoustic test of an instrumented aerospace structure
  - Validation of structural dynamics FE models in acoustic loading
- Utilize a FE simulation-based source inversion method
  - Use test-measured point pressure data and expand to full-field pressure with acoustic FE simulation
- Study how resulting acoustic field from this simulation is affected by number of microphones (targets) fed to the optimization algorithm
  - Study with a synthetic field – test data lacks sufficient resolution
  - Apply numerous comparison metrics to compare original and replicated fields at structural surface

Acoustic Test of Interest: What we want to simulate

- Aerospace structure surrounded by loudspeakers & panels
  - Heavily instrumented unit, 159 ch.
  - 18 three-way loudspeakers, 6 subs
  - Panels increase OASPL & decrease angular pressure variation

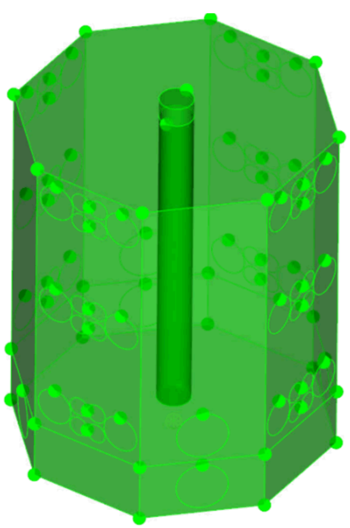


- 18 Microphones distributed around unit
  - 8 angular stations
  - 10 axial stations
  - 3 radial stations
- Test Acoustic Field is representative of flight environment
  - Spatial pressure gradients nose to tail
  - MIMO control using 6 control mics

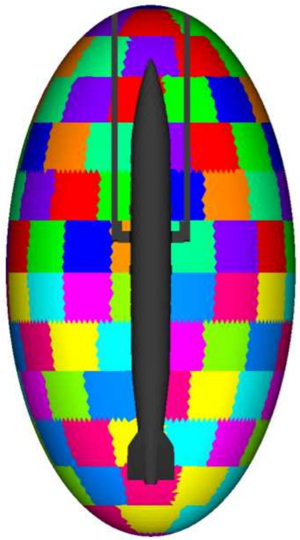


Acoustic FE Model

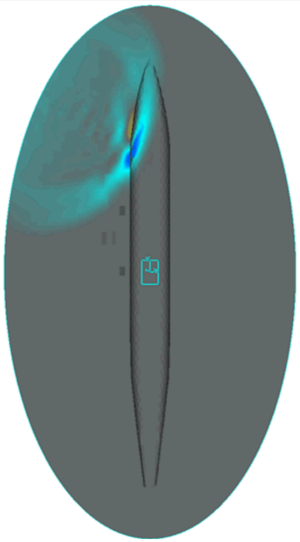
- Acoustic-Only Model
  - Much smaller than fully coupled
  - Between 2.5 million DOF
  - Tet4 elements
  - 8.4 elem./wavelength at max freq.
- Ellipsoidal (football) domain
  - Smaller domain (60% less volume)
  - Shape allows use of infinite elements
- Boundary Conditions
  - Absorbing condition on outside surface. No relation to physical BCs
- Discretize the surface with candidate sources (patches)
  - Each Patch is an independent source
- Void in the shape of our test unit
  - Reflective surfaces around the void



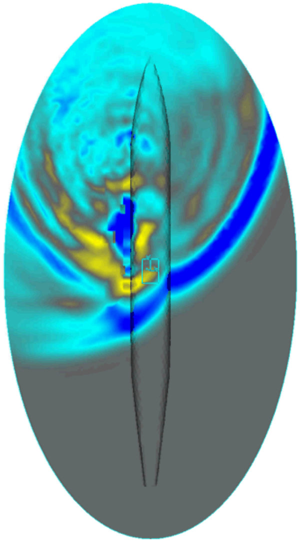
Physical Domain



Surrogate Domain



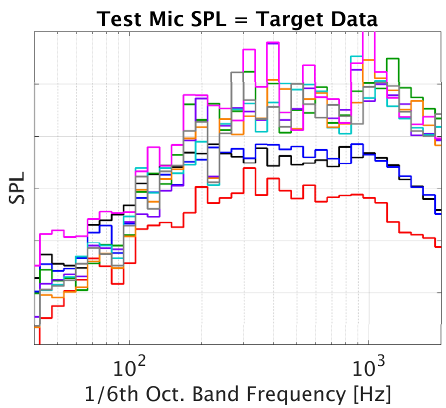
Reflection at Test Unit



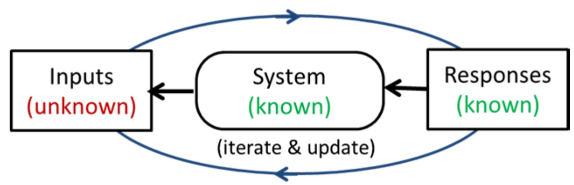
Absorption BC

Source Inversion Simulation Process

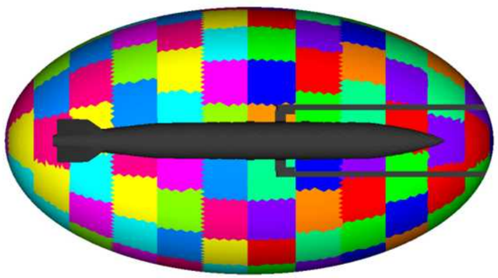
- Determine FE acoustic loads that replicate acoustic pressures at a set of Target Nodes
  - Target Nodes = Test Microphones



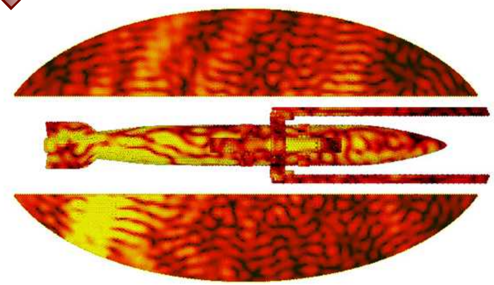
Provide Target Node Data (Mic Pressures)



Source Inversion Acoustic FE Simulation to Determine Acoustic Loads



Apply loads to patches & simulate



Compare Target pressures vs. resulting field

PDE-Constrained Optimization Strategy Used to Determine Acoustic Loads

- This is not simply a solution of the $\mathrm{X} = H^{-1}Y$ problem
  - Optimization problem utilizing gradients computed from FE solution
  - Update acoustic loads to approach target node pressures (microphone data)
- Implemented in massively parallel FE code, Sierra/SD
- Sierra/SD performs the optimization using adjoint-based gradients/ Hessians and ROL, a massively parallel optimization code
- Allows both time and frequency domain inversion
- Enables easy application of various regularization strategies (*e.g.* Tikhonov)
- 2 options for iterative solution:
  - First-order methods (e.g. BFGS).
  - Second-order methods (e.g. Newton iteration on optimality system)
- For acoustics: resulting pressure field satisfies the wave equation
  - Inherit – a forward simulation produces the resulting field

Source Inversion Under the Hood

- Determine the acoustic acceleration (loads) that provide the desired nodal pressures (responses)
- Minimization of an objective function:

$$J(\{\boldsymbol{u}\},\{\boldsymbol{p}\}) = \frac{\kappa}{2}\Big(\{\boldsymbol{u}\} - \{\boldsymbol{u}_m\}\Big)^{\mathrm{T}}[Q]\Big(\{\boldsymbol{u}\} - \{\boldsymbol{u}_m\}\Big) + \mathscr{R}(\{\boldsymbol{p}\}),$$

Computed acoustic pressures

Target acoustic pressures

Boolean matrix (extracts measured locations)

Regularization

Acoustic accelerations

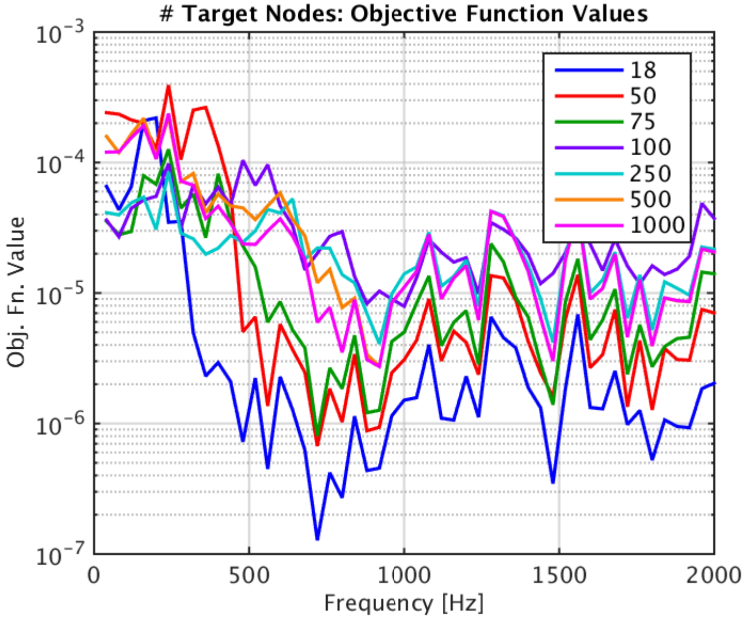
Source Inversion Simulation Details

Setup Details

- Direct Frequency Response Simulation
  - Inputs = acoustic acceleration linear spectra at patches on exterior
  - Outputs = acoustic pressure linear spectra
  - 40-2000 Hz, 50 Hz spacing
- Target Data
  - Acoustic pressure at microphone nodes
- Initial Guess
  - Patches have zero acoustic acceleration

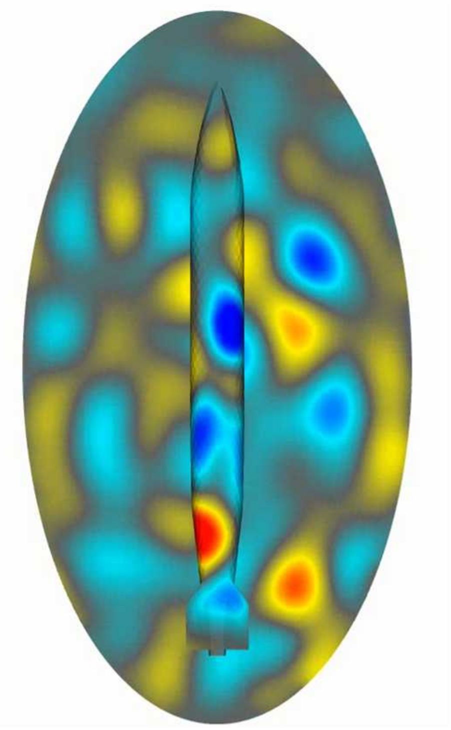
Run Details

- 1 frequency line at a time
- 6+ Optimization iterations
- Objective function typically 1e-6 to 1e-4
- ≈20 minutes per frequency line



Synthetic Field Created to Study Simulation Sensitivities

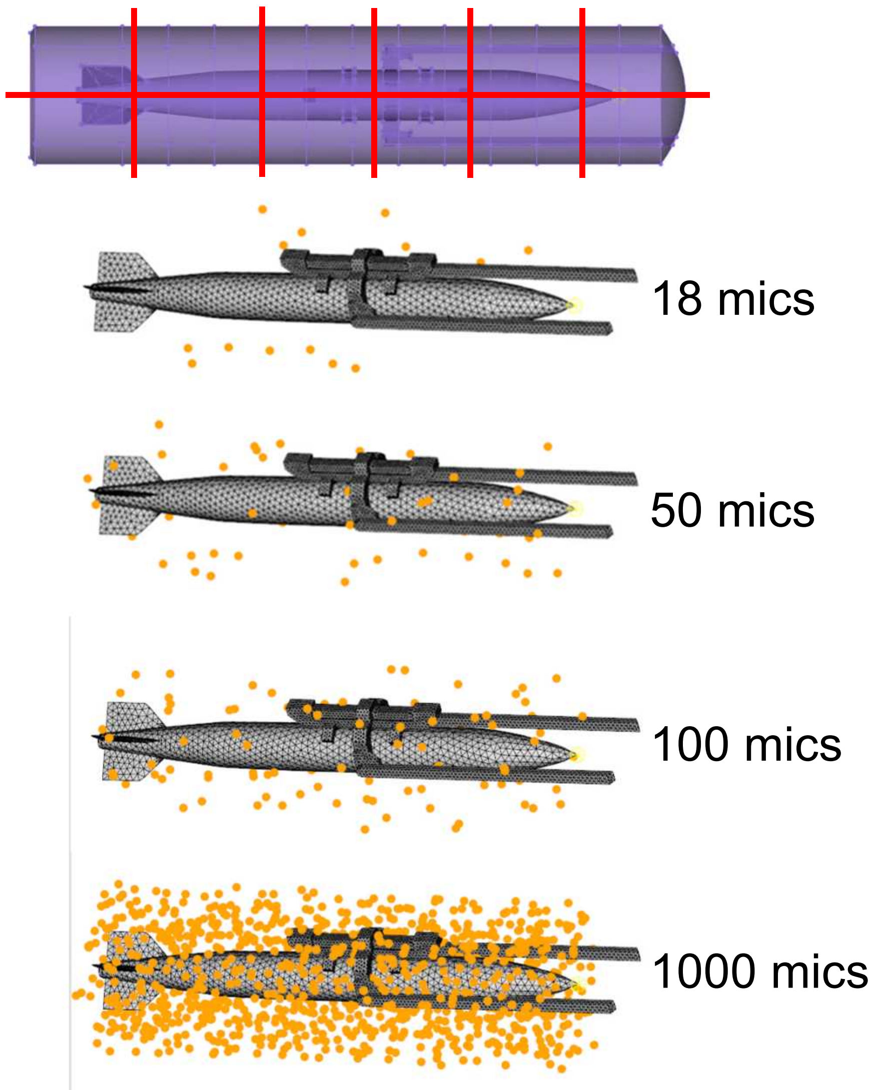
- Why Synthetic?
  - Know 100% the target field
  - Can choose any mic location / number of mics
- Run an initial forward run, save the data at locations of interest (at the mics)
  - User-defined acoustic particle acceleration at each patch
  - Resulting field is similar to typical test field
  - Mic pressure data = target data for subsequent inverse simulations



- *Output = full field acoustic pressure spectra*
  - *Data at mic nodes feed inverse sims*

Microphone Locations Chosen Quasi-Randomly

- Explore Target Mic counts of 18 to 1000
  - Reasonable to totally ridiculous
- Define a candidate volume
  - Where mics would be in a test
- Subdivide into pieces
  - Cuts made in radial, axial, angular
  - # pieces = # target mics
- Randomly choose a node in each piece



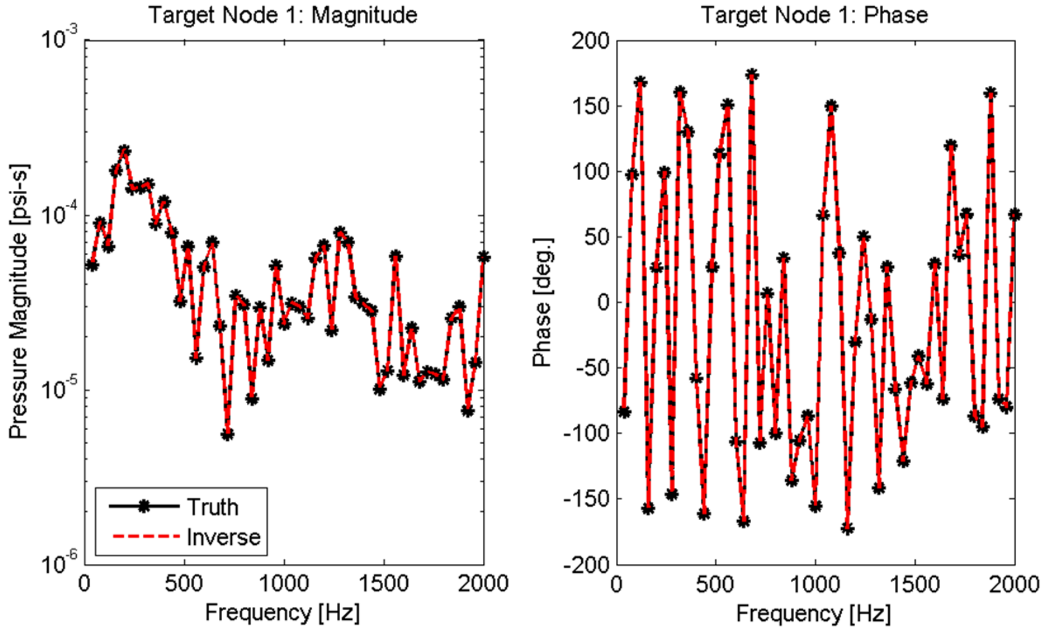
Source Inversion Simulation Performed for Each Mic Set

- Target pressure data is unique for each mic set
  - Each set has unique mic locations
- Same optimization method, settings used each time
- Try to get similar objective function & gradient change
  - Ensure we match the target pressure data
  - Ensure we are near the minimum, enough iterations used
- Save pressures from each resulting field
  - At wetted surface – what will load the structure
  - At the target microphones

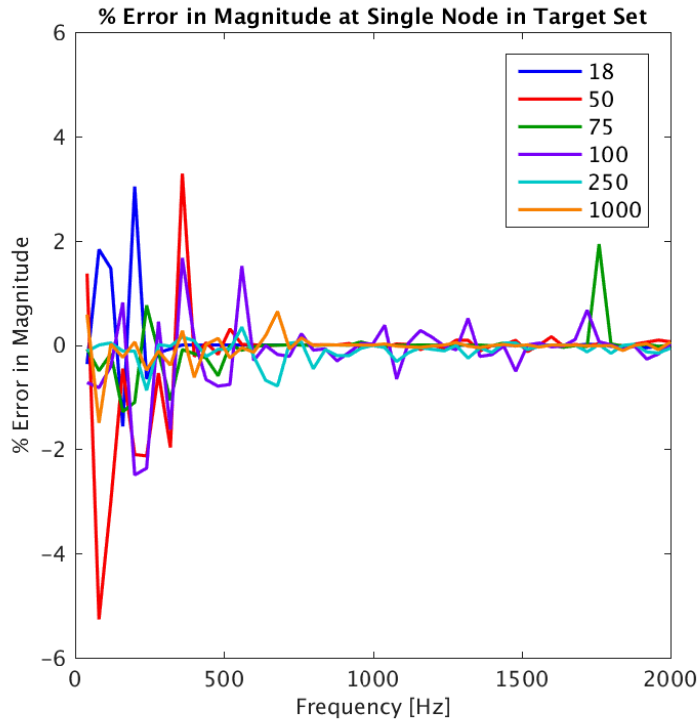
Field at Target Microphones is Replicated for All Sets

- Compare pressure at Target Mics vs. original (truth) field

Mag & Phase vs. Truth:
250 Target Node Set



% Error, All Sets

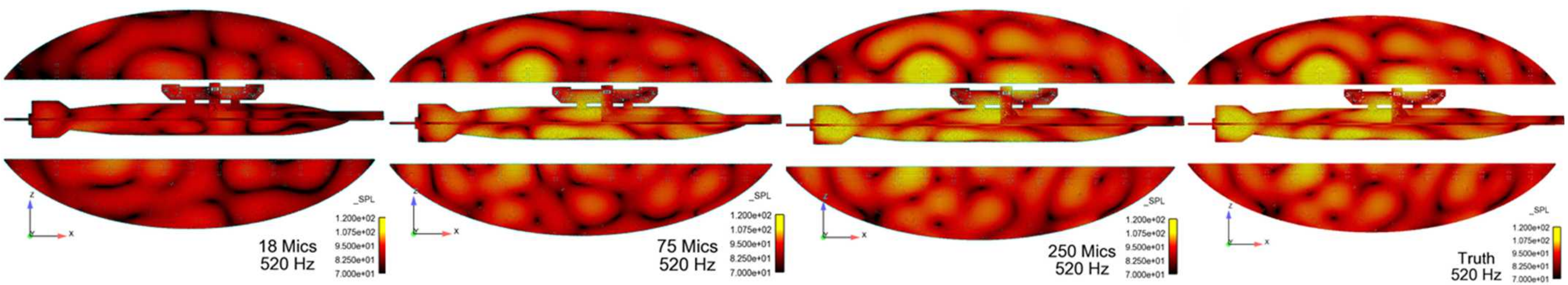


single node shown for brevity, others are similar

Comparison of Wetted Surface Pressure – Visualization

- Wetted surface pressure = loads on structural FEM
- Need to asses how well field is replicated for each target set
- Visualization of SPL is insightful, but not quantitative

Lower Frequency (520 Hz)



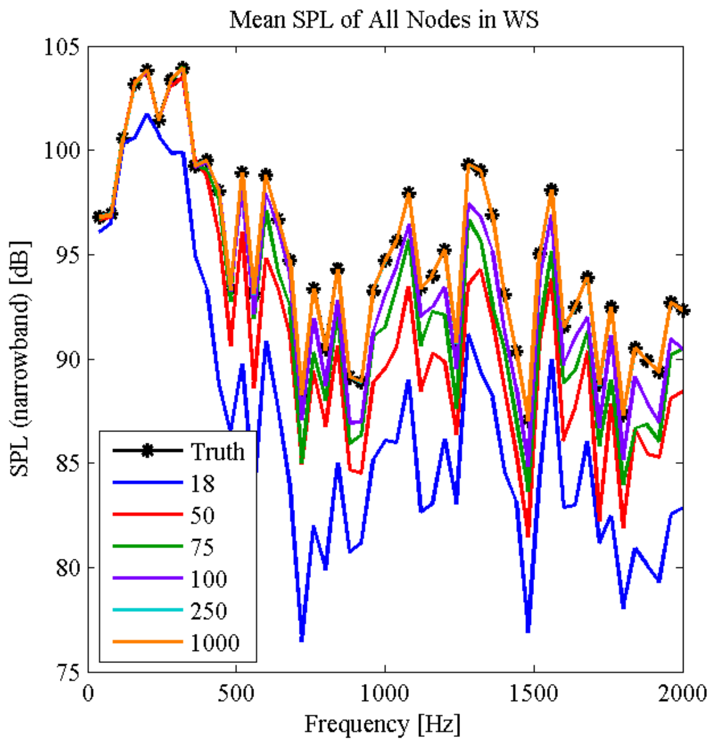
Original field

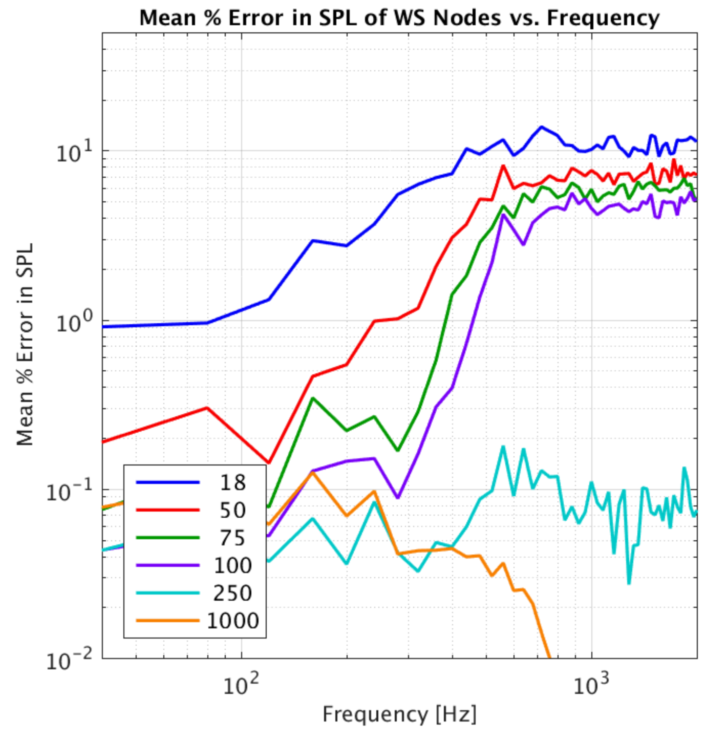
Increasing # Mics

- *Few Mics = wrong spatial distribution & lower level*
- *Level error is a function of frequency*

Comparison of Wetted Surface Pressure – Function of Frequency

- SPL vs. Frequency: mean of all wetted surface nodes
- Approach the Truth SPL from below – more Mics = higher SPL
  - Few Mics = Lower field level
  - Lower field level = Less loading on structure = Lower predicted response

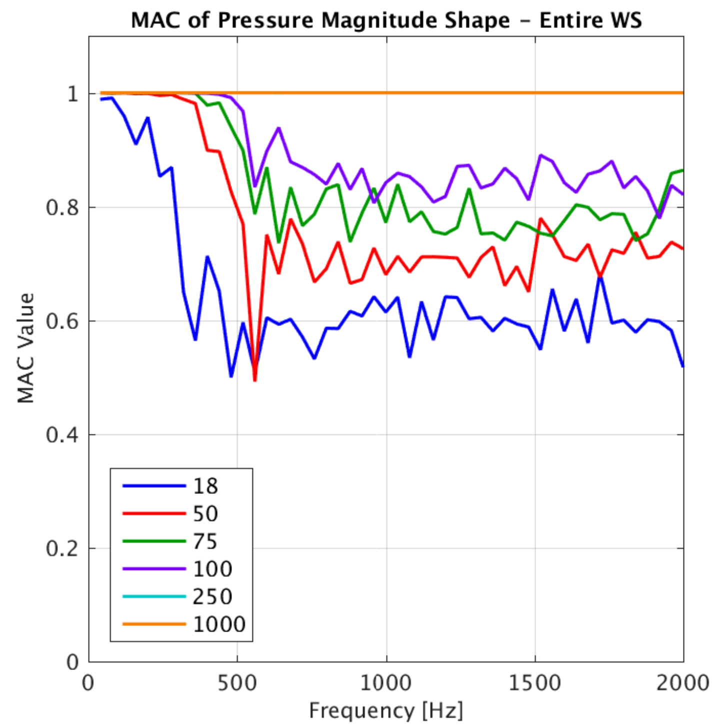




Compare the Pressure Shape with a MAC

- Is the wetted surface pressure distribution the same as the original field? How to quantify, easily?
- MAC provides a scalar value comparing the shapes of two vectors
  - The vectors are pressure magnitudes at all wetted surface nodes
  - Compute a value at each frequency (instead of each mode)
- High MAC indicates the replicated field has same spatial distribution as the original field

$$Pressure\ MAC = \frac{\left|p_{inv}^{T} * p_{truth}\right|^{2}}{\left(p_{inv}^{T} * p_{inv}\right)\left(p_{truth}^{T} * p_{truth}\right)}$$



- *More Mics = High MAC*
- *MAC value decreases with frequency*

Compare Fields as a Function of Mic Density (Number per Cubic Wavelength)

- Replicated field shape & amplitude appears to be a function of both frequency and microphone count
- Can results be generalized to a single minimum microphone count for a maximum test frequency?
  - Spatial variation in acoustic field is determined by wavelength
  - Wavelength is a function of frequency, $\lambda = c/f$
  - Higher mic counts can replicate higher frequency fields
  - By normalizing with respect to wavelength, the different mic sets can be aligned & results *should* be consistent
- Compare MAC at each value of Microphone Wavelength Density

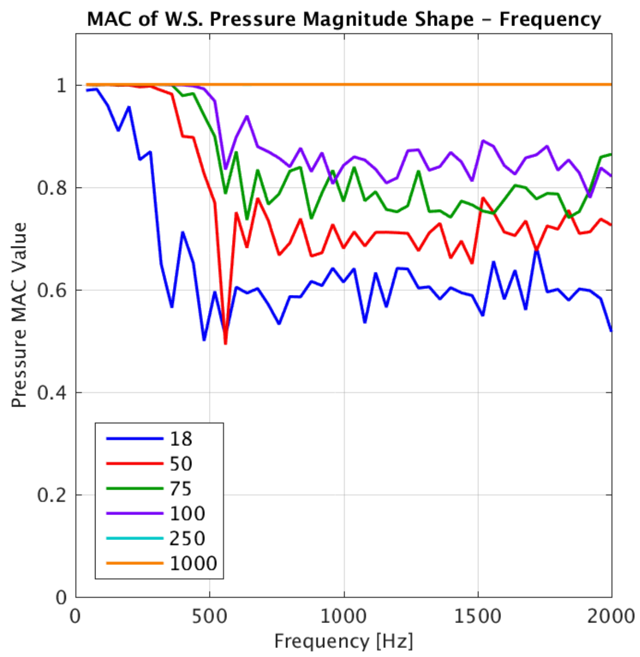
$$\rho_{Mic} = \frac{K\lambda^3}{V}$$

  - Number of Mics per Cubic Wavelength
  - K= Number of Mics, λ = wavelength $[m]$, V= candidate volume $[m^3]$
  - Few Mics at low frequency has same mic density as many Mics at high frequency

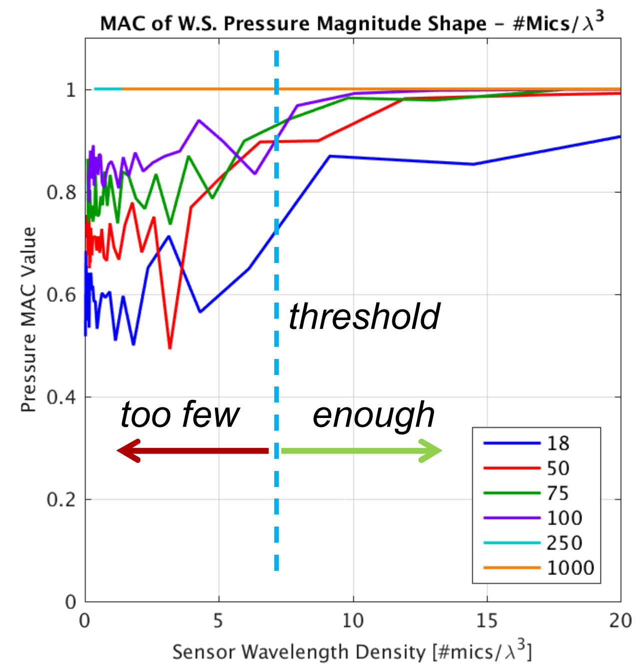
Mic Wavelength Density Improves Understanding of MAC Results

- Using Mic Wavelength Density is more informative
- 8 Mics per cubic wavelength looks pretty good
- Some sets are great for all frequency/density, some are bad for all
- Not every aspect of the problem is wavelength scaled
  - Constant source size, constant domain size, wetted surface size

vs. Frequency



vs. Mic Density



Conclusions: Recap

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- Why
  - Develop a method for replicating test acoustic loads for FE simulations
  - Need to understand how our method is affected by the number of target microphones fed to source inversion algorithm
  - Results will impact design of future acoustic validation tests
- What was done
  - Sensitivity of resulting acoustic field the number of target microphones for a representative acoustic FE model
  - Resulting acoustic fields compared with original synthetic field using a variety of metrics to assess convergence
- Results
  - Large number of microphones required to replicate original field in both shape and level
  - Microphone count is a function of frequency/wavelength

Conclusions: What did we learn

- Comparing pressure fields can require multiple metrics
- A small number of microphones, as in a typical laboratory acoustic test, is not sufficient to characterize a complicated acoustic field beyond the low frequency range
- Acoustic fields can be completely replicated using current source inversion algorithms, provided enough target microphones
- Normalizing Target sets by microphone wavelength density helps establish a minimum threshold microphone count
- The minimum microphone count indicated by this study is high and would require other test methods (roving microphones, etc.)

THANK YOU FOR YOUR ATTENTION