Comparison of Computational Aeroacoustics Prediction of Acoustic Transmission through a 3D Stator with Experiment

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Background

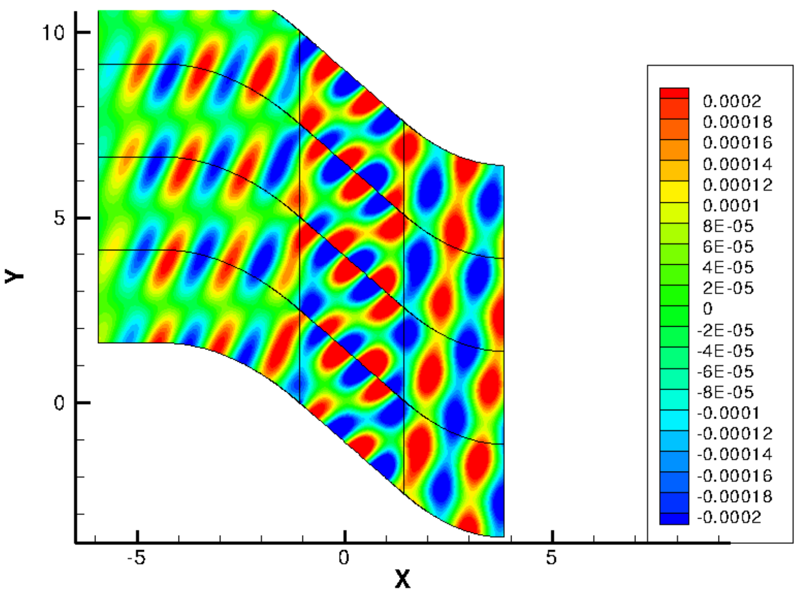
- Computational Aeroacoustics (CAA) is concerned with the accurate numerical prediction of unsteady flow and noise.
- To accomplish this goal, high-accuracy time-marching schemes are combined with high-resolution spatial differencing methods to reduce the number of grid points necessary to resolve unsteady flow features.
- Accurate boundary conditions are vitally important in order to reduce the computational domain as much as possible.

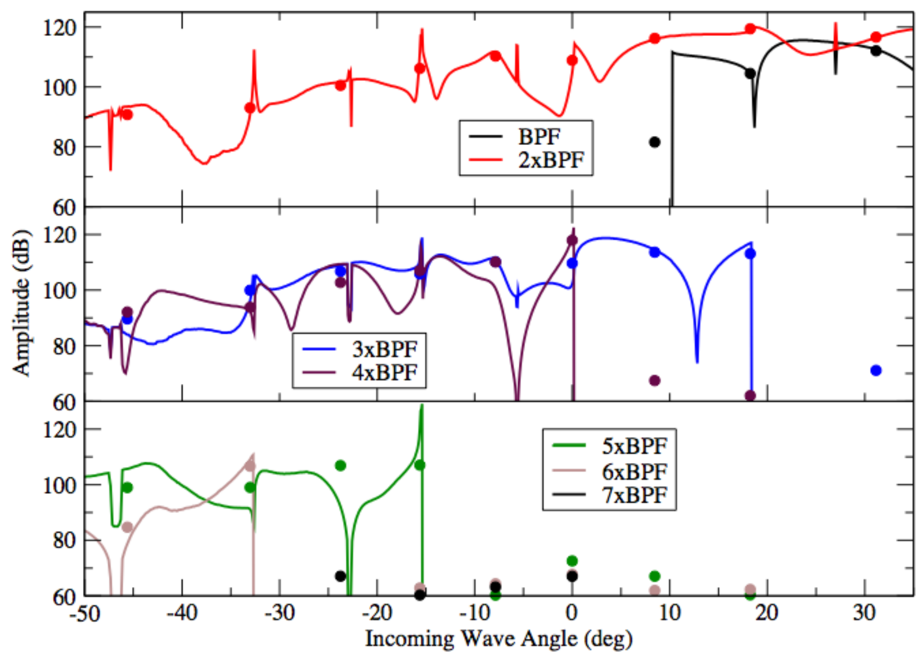
NASA GRC BASS1.5 Code

- The NASA GRC BASS1.5 code is a general-purpose nonlinear CAA solver:
  - 2D/3D Navier-Stokes or Euler equations.
  - Curvilinear coordinates with grid motion for topological flexibility.
  - Block-structured grids for efficient computation of complex geometries.
  - Up to 6th order compact differencing in space.
  - 4th order optimized explicit time marching.
  - Blended 2nd/10th order shock capturing artificial dissipation.
  - Fortran 2003, MPI-2 parallelization.
  - Verified for unsteady nonlinear temporal and spatial accuracy solving the 3D Euler equations on curvilinear grids (EVA-III).

Previous Validation Work

- Previously, the BASS code has been validated for 2D acoustic transmission cases using the LINSUB linearized flat plate method of Whitehead (1987):
  - Stators: AIAA Paper 2012-0836, January 2012.
  - Rotors: AIAA Paper 2012-2286, June 2012

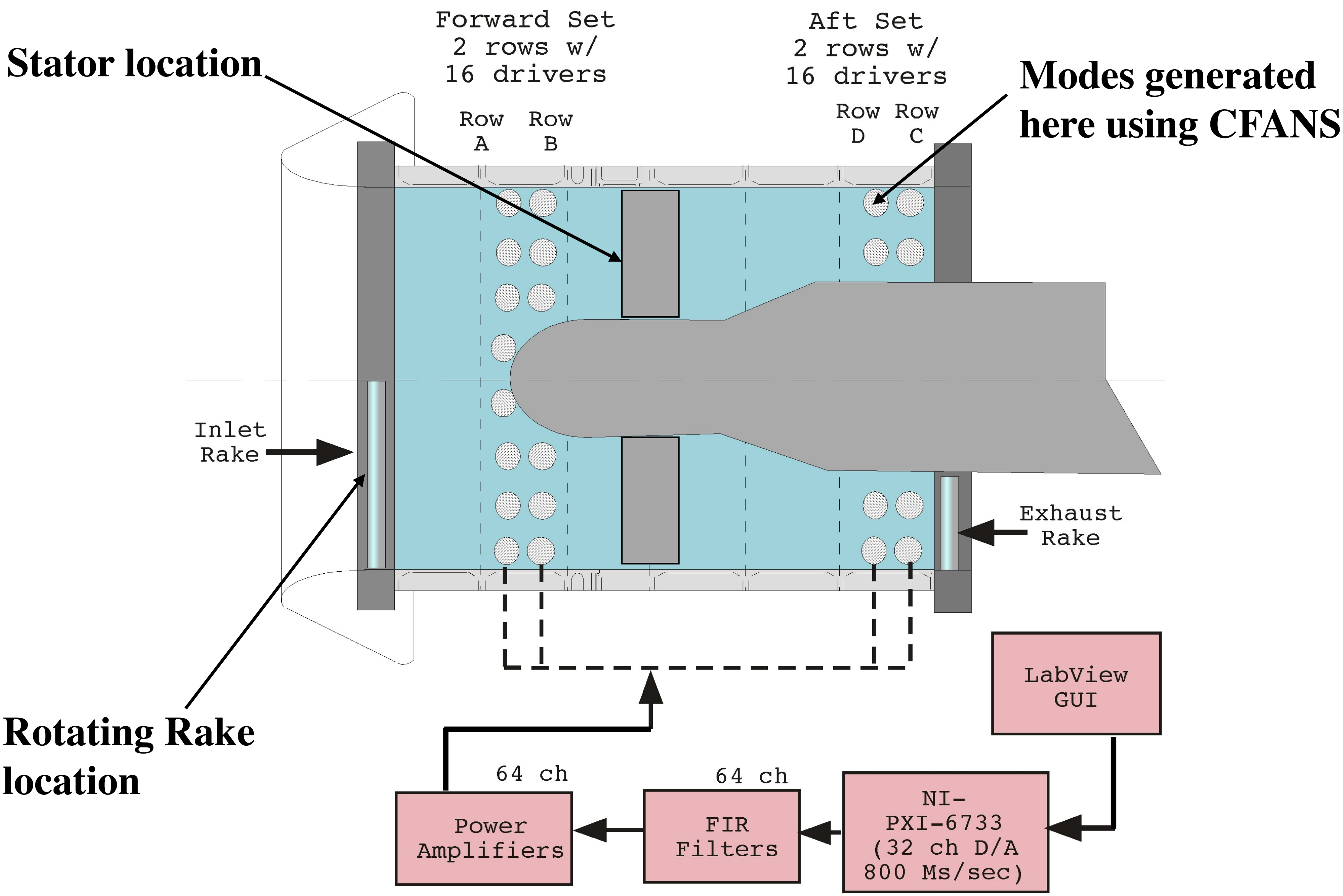




3D Stator Transmission

- Recently, an experimental stator transmission database has been obtained at NASA GRC:
  - D. Sutliff, 'A Mode Propagation Database Suitable for Code Validation Utilizing the NASA Glenn Advanced Noise Control Fan and Artificial Sources'
- The database was acquired on the Advanced Noise Control Fan (ANCF) testbed.
- The Configurable Fan Artificial Noise System (CFANS) was used to generate and control circumferential (m) and radial modes (n) in the absence of a mean flow.
- These modes were measured at the inlet using the Rotating Rake mode measurement system.

Experimental Setup



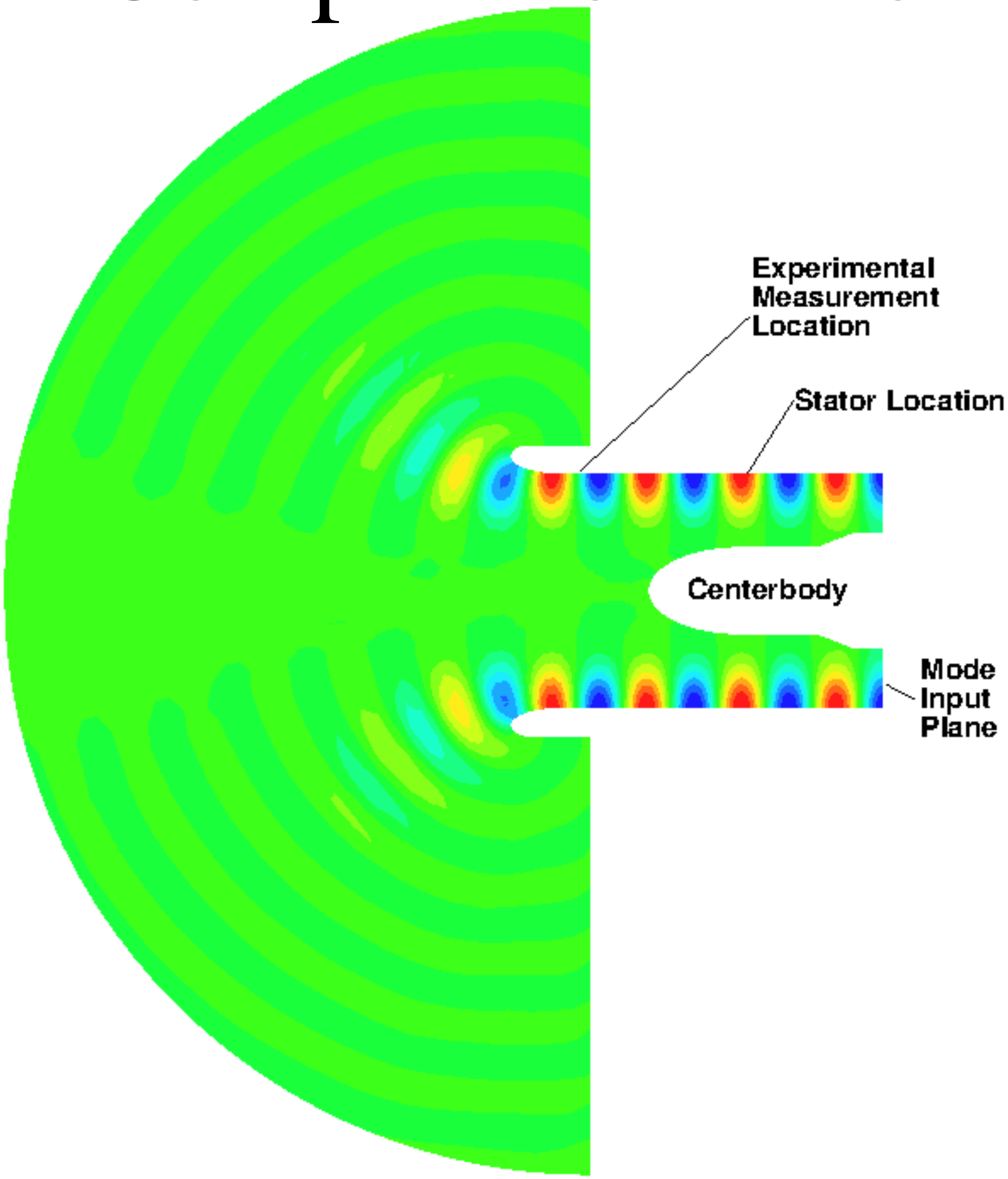
Experimental Errors

- There are two primary sources of error in the experimental measurements:
  - Error in the physical measurement (±1 dB).
  - Modeling error, arising from the postprocessing.
    - The current rotating rake has one row of microphones, and cannot distinguish between the modes transmitted through the stator and its reflection from the inlet of the duct.
    - A new dual-microphone method has been developed, which will reduce or eliminate the modeling error:
      - Dahl, M.D., Hixon, R., and Sutliff, D. L., 'Further Development of Rotating Rake Mode Measurement Data Analysis, AIAA 2013-2246.

Test Cases

- For each input mode, three stator geometries were tested:
  - 'Clean': no stator in the duct.
  - 14 stator vanes at a 45^o stagger angle.
  - 28 stator vanes at a 20^o stagger angle.
- Three representative cases were chosen from the database:
  - 480 Hz: $m = \pm 2, n = 0$.
  - 960 Hz: $m = \pm 6, n = 0$
  - 480 Hz: $m = \pm 4, n = 0$.

Computational Domain



Computational Grid

- Three structured multiblock grids were generated, one for each stator configuration.
- Program Development Company's GridPro structured grid generator was used.
- Each stator grid was generated for the vanes at zero stagger angle.
- The AFRL/GridWarp grid deformation tool of Reid Melville was used to rotate the stators to the desired stagger angle after the grids were generated.
- A minimum of 10 grid points per wavelength was used, minimizing dispersion errors.

Inflow/Outflow Boundary Conditions

- In the current BASS formulation, the boundary conditions are split into three components:
  1. Mean flow BC (not used for these cases)
  2. Nonreflecting BC (Giles)
  3. Imposed flow BC (Acoustic mode)

$$\left.\frac{\partial Q}{\partial t}\right|_{boundary} = \left.\frac{\partial Q}{\partial t}\right|_{MFBC} + \left.\frac{\partial Q}{\partial t}\right|_{Nonreflecting} + \left.\frac{\partial Q}{\partial t}\right|_{imposed}$$

Calculation Procedure

- The acoustic transmission calculation procedure for a given input mode followed these steps:
  - Set a reference mode amplitude of 1.4 Pa at the driver location
  - Calculate the unsteady mode propagation through each stator configuration.
  - Run until converged.
  - Postprocess the 'clean' configuration data to obtain the mode power level at the measurement location.
  - Determine the mode power level at the driver location.
  - Scale all three mode amplitudes using this scaling factor.

Numerical Errors

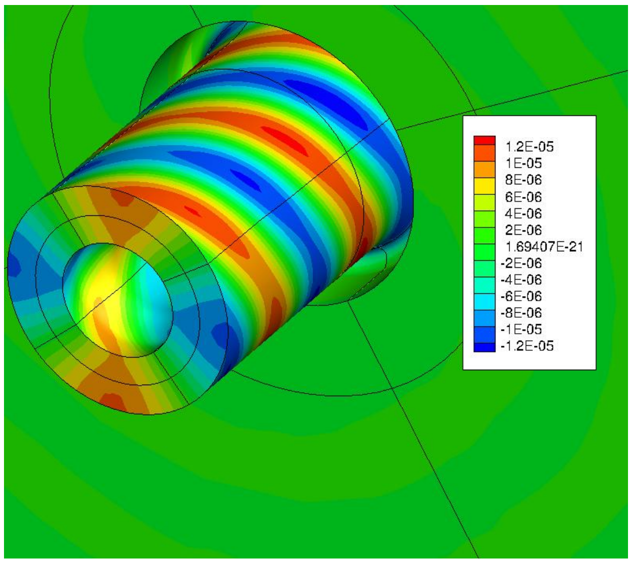
- There are three primary sources of numerical errors that may occur in the calculations:
  - Incorrect wave speeds due to numerical dispersion.
    - The grids had a minimum of 10 grid points per wavelength, which is well within the accuracy range of the DRP scheme.
  - Incorrect imposition of the incoming acoustic modes.
    - For well cut-on modes, the input mode power level was accurate to within ± 0.3 dB.
    - In the worst case (nearly cut-off modes), the input mode power level was accurate to within ± 1 dB.
  - Nonphysical reflections of modes from the Giles boundary condition at the imposition plane.
    - In most cases, the reflections were low amplitude.

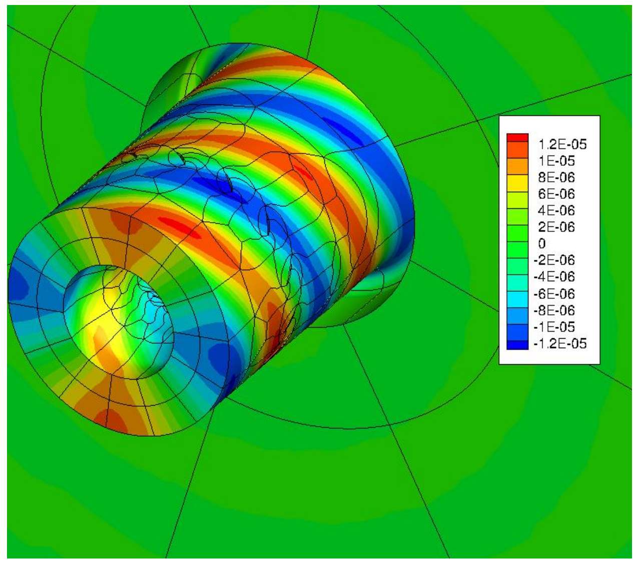
Test Case 1: Mode (2,0), 480 Hz

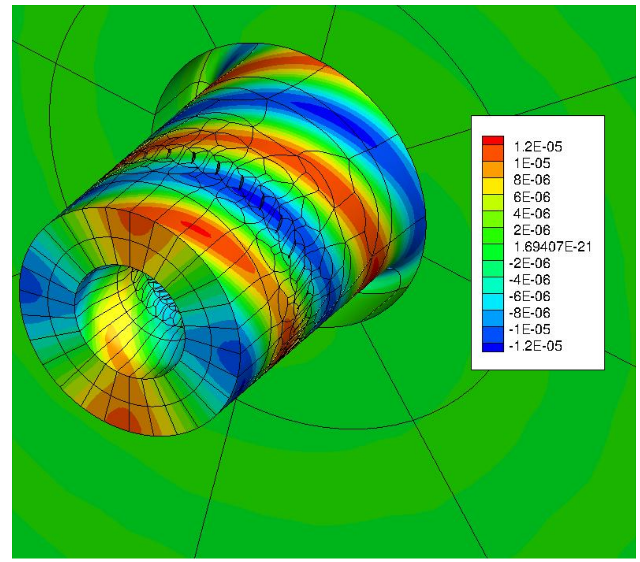
- Cutoff ratio at driver location: 2.01
- Cutoff ratio at inlet location: 1.77
- Mode power level at inlet: 111.1 dB (measured)
- Mode power level at driver location: 111.1 dB (predicted)
- Reflected mode power level at inlet: 90.7 dB (predicted)
  - 0.03 dB difference due to reflections.

Test Case 1: Mode (+2,0), 480 Hz

Clean | **14 Vanes, 45° angle** | **28 Vanes, 20° angle**





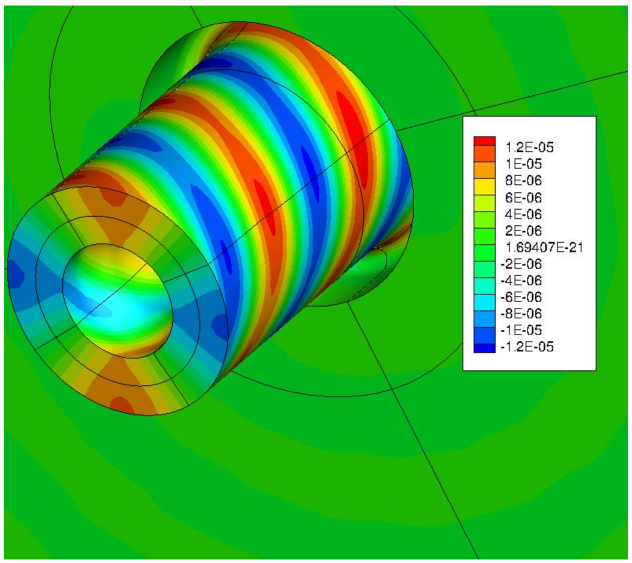


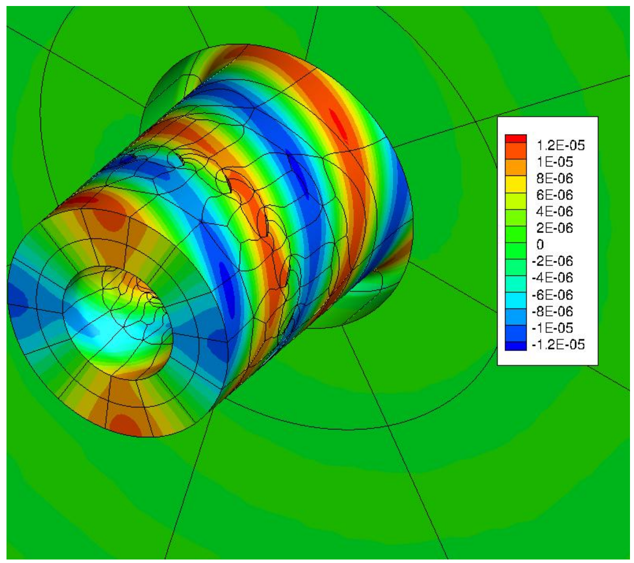
Clean	14 Vanes, 45° angle	28 Vanes, 20° angle
111.1 dB	**110.9 dB**	**111.1 dB**
111.1 dB	**111.3 dB**	**110.7 dB**

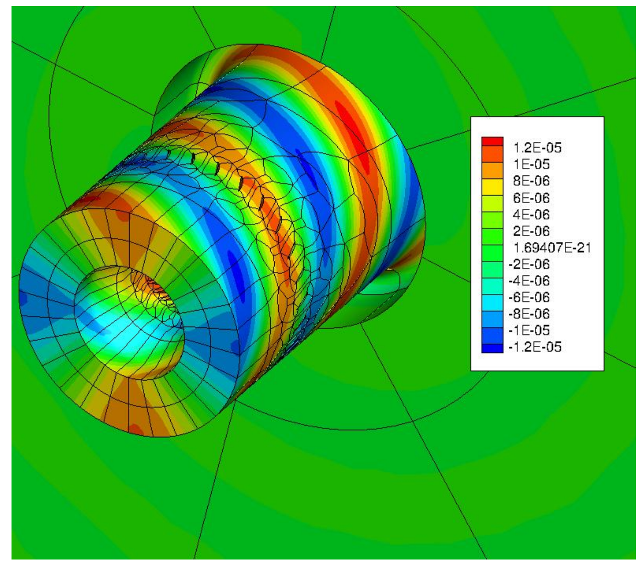
Transmitted mode power level at measurement location (Numerical, Experimental)

Test Case 1: Mode (-2,0), 480 Hz

Clean	**14 Vanes, 45° angle**	**28 Vanes, 20° angle**







Clean	14 Vanes, 45° angle	28 Vanes, 20° angle
111.1 dB	**110.9 dB**	**111.1 dB**
111.1 dB	**111.3 dB**	**110.7 dB**

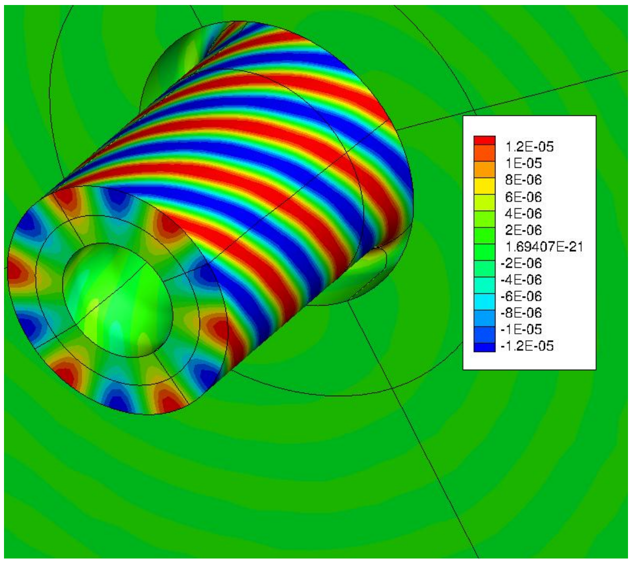
Transmitted mode power level at measurement location (Numerical, Experimental)

Test Case 2: Mode (6,0), 960 Hz

- Cutoff ratio at driver location: 1.45
- Cutoff ratio at inlet location: 1.44
- Mode power level at inlet: 106.6 dB (measured)
- Mode power level at driver location: 106.6 dB (predicted)
- Reflected mode power level at inlet: 79.1 dB (predicted)
  - 0.007 dB difference due to reflections

Test Case 2: Mode (+6,0), 960 Hz

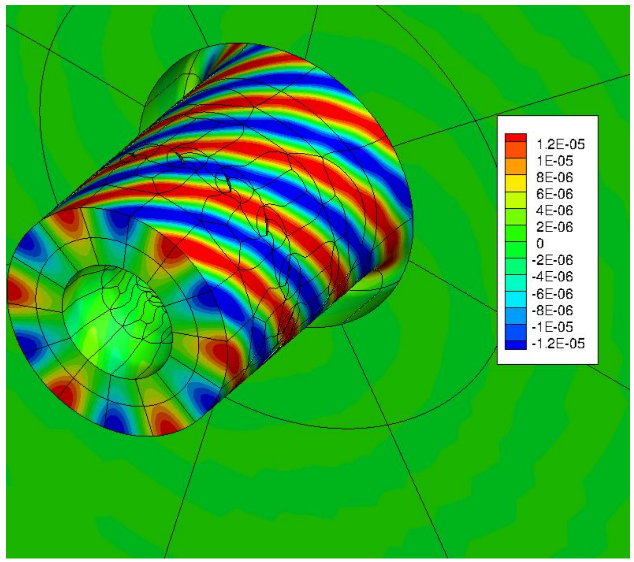
Clean



106.2 dB

106.2 dB

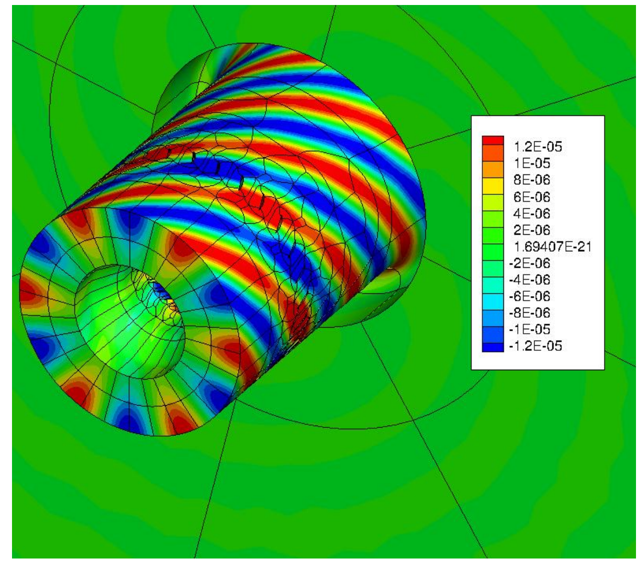
14 Vanes, 45^o angle



106.2 dB

105.8 dB

28 Vanes, 20^o angle



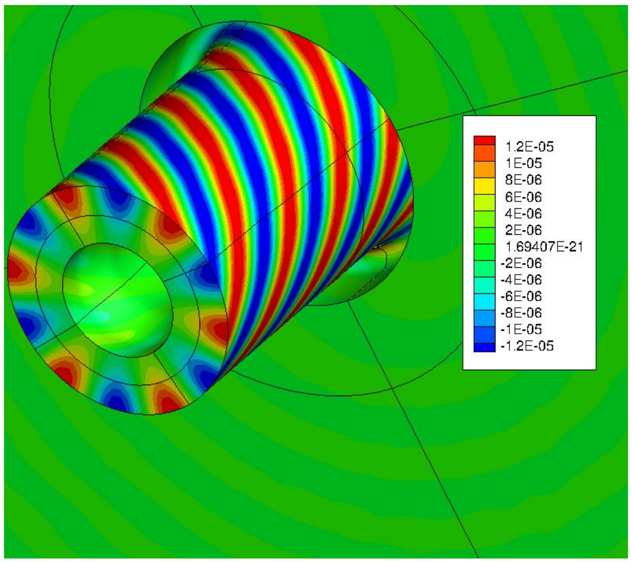
106.1 dB

105.5 dB

Transmitted mode power level at measurement location (Numerical, Experimental)

Test Case 2: Mode (-6,0), 960 Hz

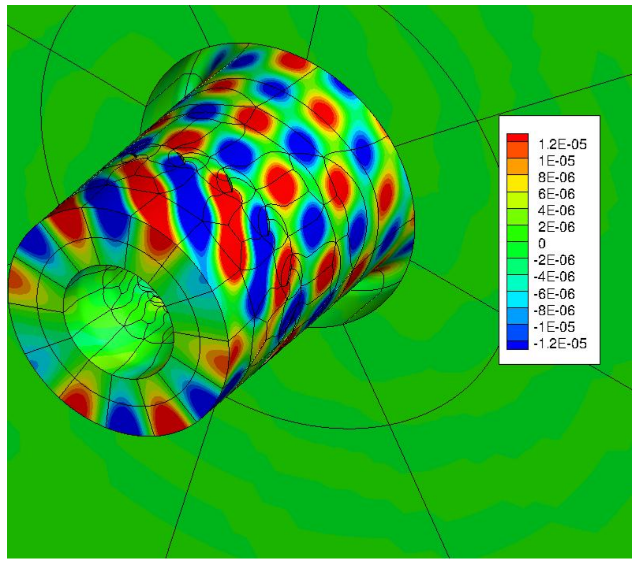
Clean



106.6 dB

106.6 dB

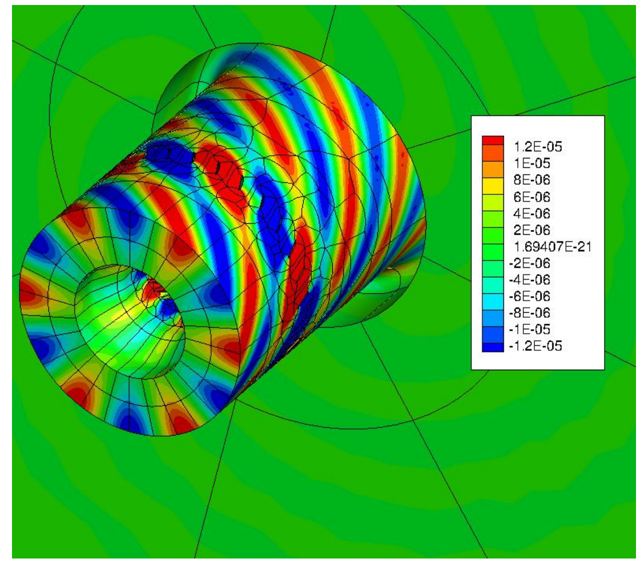
14 Vanes, 45° angle



103.7 dB

103.6 dB

28 Vanes, 20° angle



105.4 dB

106.2 dB

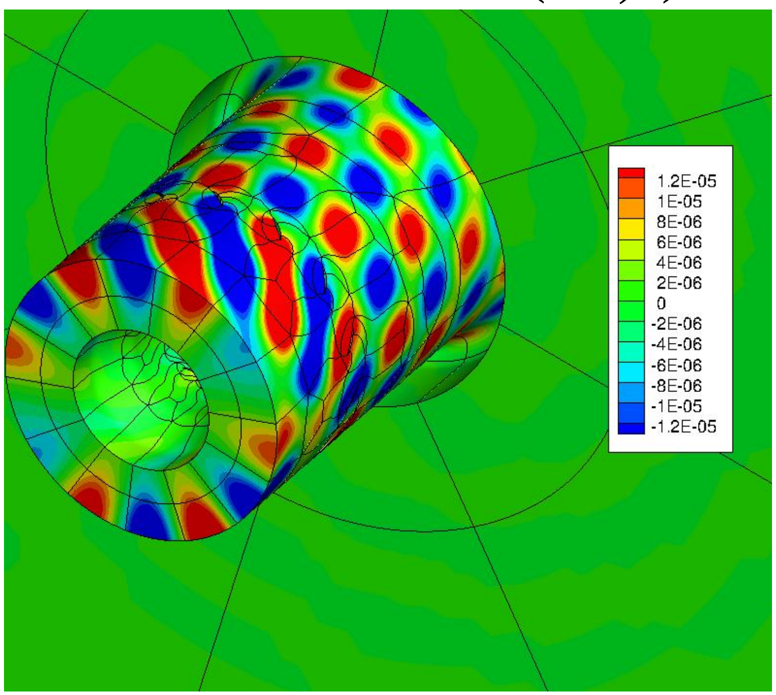
Transmitted mode power level at measurement location (Numerical, Experimental)

Scattered Mode (8,0)

- Tyler-Sofrin theory predicts the possibility of a counter-rotating circumferential mode 8 for the case of 14 stator vanes.
- Mode (8,0) is cut-on for these conditions, so it will propagate if present.
- Both the experimental and numerical results show a strong (+8,0) mode in the (-6,0) test case, and a weak (-8,0) mode in the (+6,0) test case.

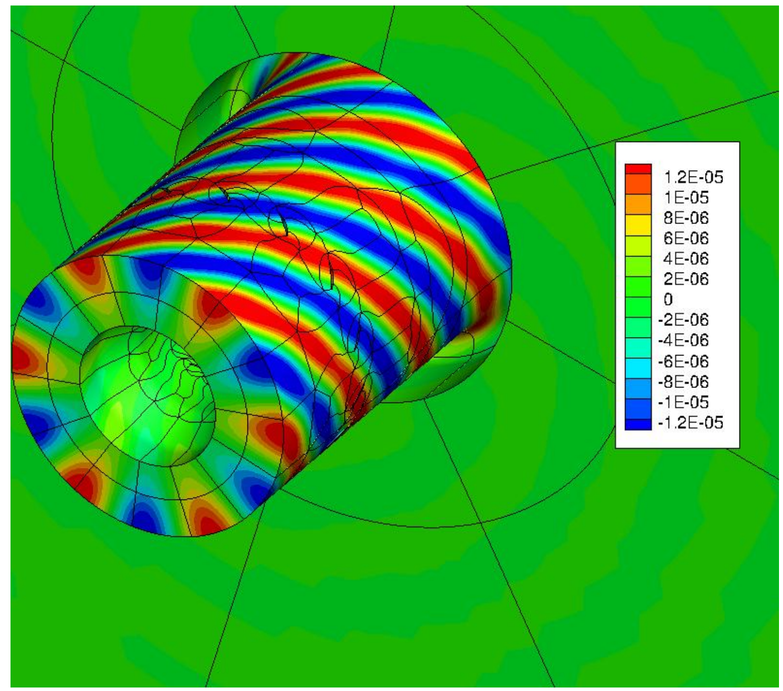
Test Case 2: Scattered Mode 8

Input Mode (-6,0)
Scattered Mode (+8,0)



98.3 dB
97.1 dB

Input Mode (+6,0)
Scattered Mode (-8,0)

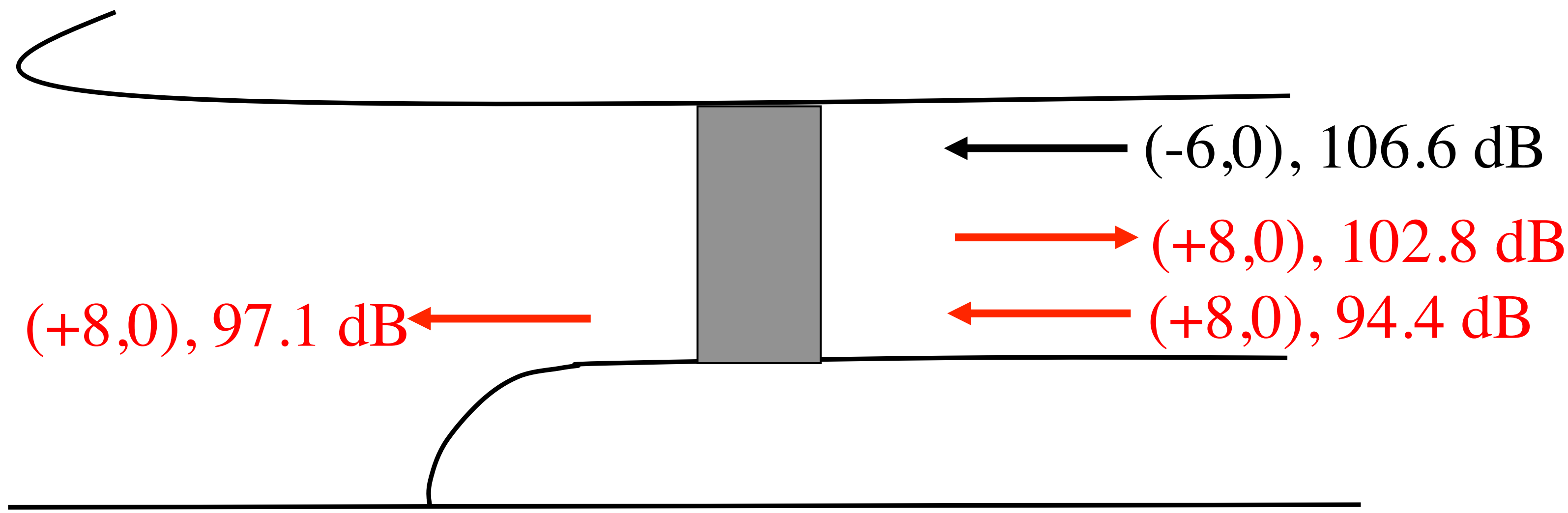


79.9 dB
91.0 dB

Scattered mode power level at measurement location (Numerical, Experimental)

Numerical Issues

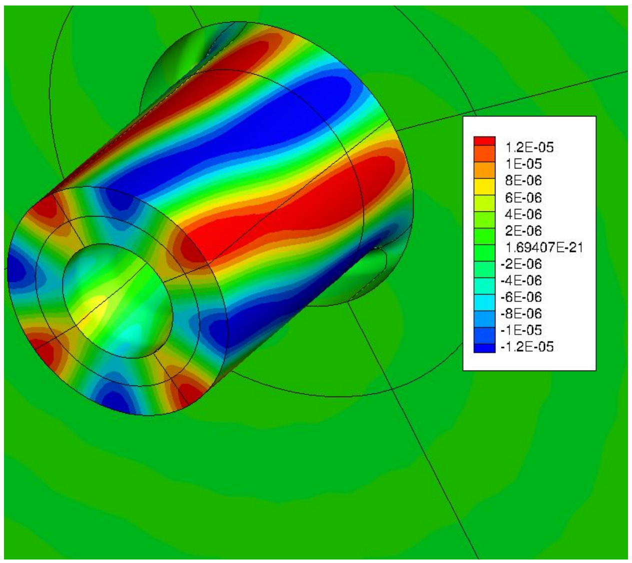
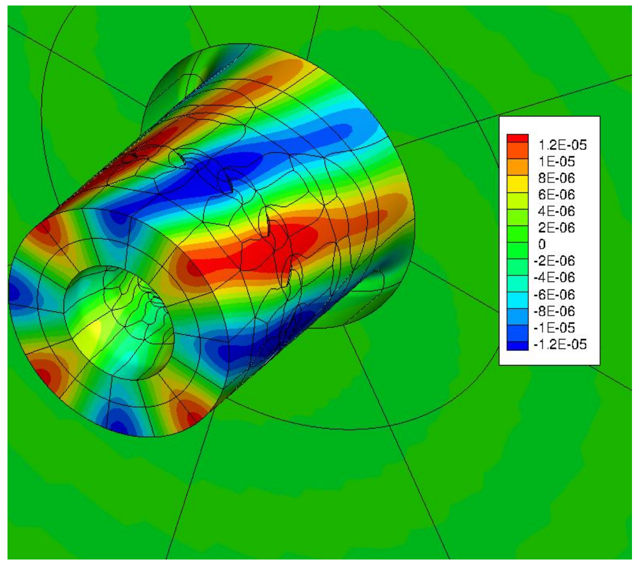
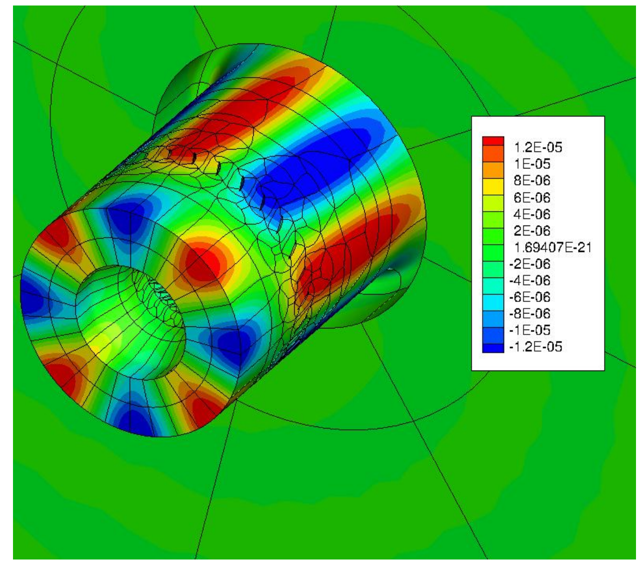
- In the results for mode (+8,0), strong nonphysical reflections from the boundary conditions may be affecting the predicted result at the inlet by as much as 2 dB, depending on the transmission losses through the stator:



Test Case 3: Mode (4,0), 480 Hz

- Cutoff ratio at driver location: 1.04
- Cutoff ratio at inlet location: 1.02
- Mode power level at inlet: 113.0 dB (measured)
- Mode power level at driver location: 115.1 dB (predicted)
- Reflected mode power level at inlet: 108.7 dB (predicted)
  - 1.4 dB difference due to reflections.

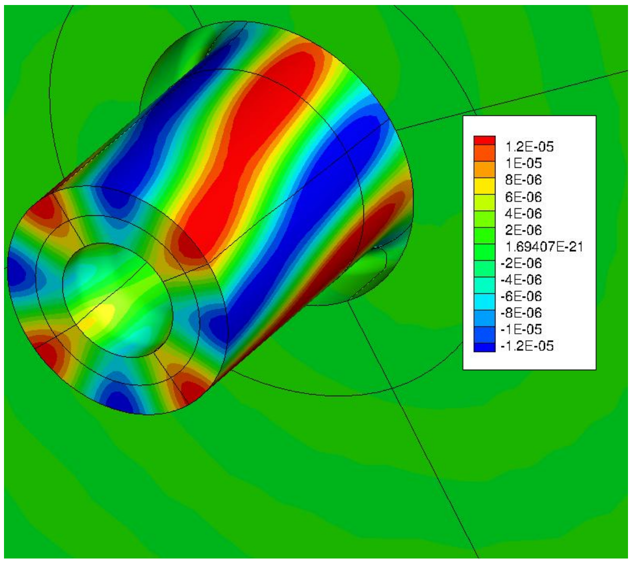
Test Case 3: Mode (+4,0), 480 Hz

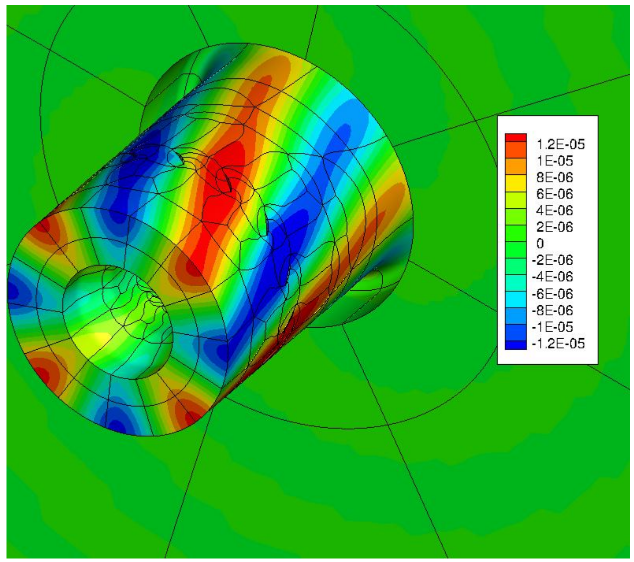
Clean	14 Vanes, 45° angle	28 Vanes, 20° angle
		
113.5 dB	**111.4 dB**	**111.8 dB**
113.5 dB	**107.1 dB**	**102.4 dB**

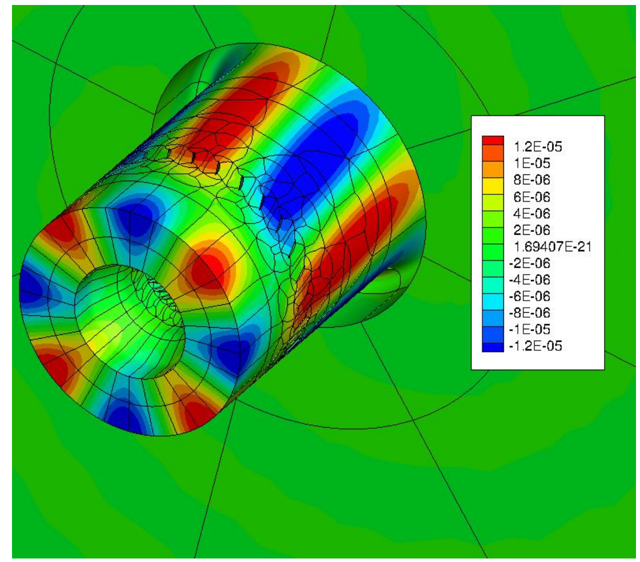
Transmitted mode power level at measurement location (Numerical, Experimental)

Test Case 3: Mode (-4,0), 480 Hz

Clean	**14 Vanes, 45^{o} angle**	**28 Vanes, 20^{o} angle**







Clean	14 Vanes, 45^{o} angle	28 Vanes, 20^{o} angle
113.0 dB	**110.9 dB**	**111.3 dB**
113.0 dB	**106.8 dB**	**103.0 dB**

Transmitted mode power level at measurement location (Numerical, Experimental)

Conclusions

- In this work, the NASA BASS code has been extended for the prediction of acoustic transmission through 3D stator geometries.
- Parametric studies have been performed to test the effect of changes in stator vane count and stagger angle.
- The results compare well with the experimental data, for well cut-on modes.
- In future work, the BASS code will be used to predict acoustic transmission through 3D rotor geometries.