Efficient Simulation of Acoustic Fluid-Structure Interaction Models by Means of Model Reduction

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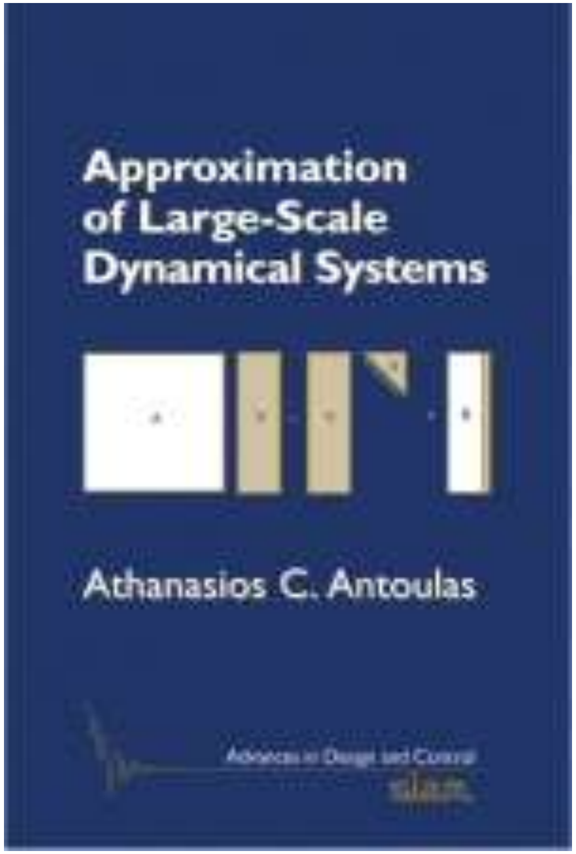
Outline

- Introduction to model reduction
- Model reduction for acoustics
- Case study: loudspeaker sound field

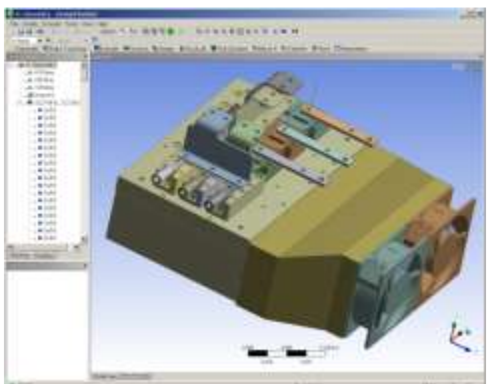
Model Order Reduction

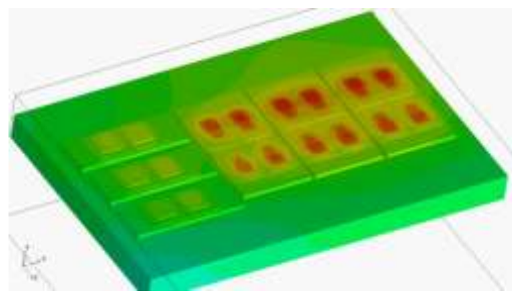
- Relatively new technology
- Solid mathematical background:
  - Approximation of large scale dynamic systems
- Dynamic simulation:
  - Harmonic or transient simulation
- Industry application level:
  - Linear dynamic systems only

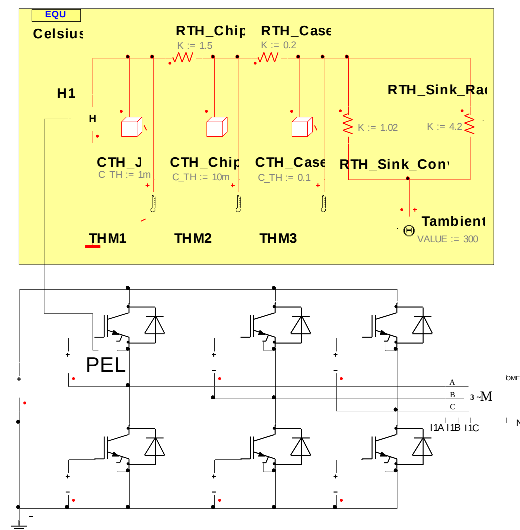


From Finite Elements to System Simulation

Physics & Geometry → FEM → System of n ODEs → MOR → Reduced System of $r << n$ ODEs





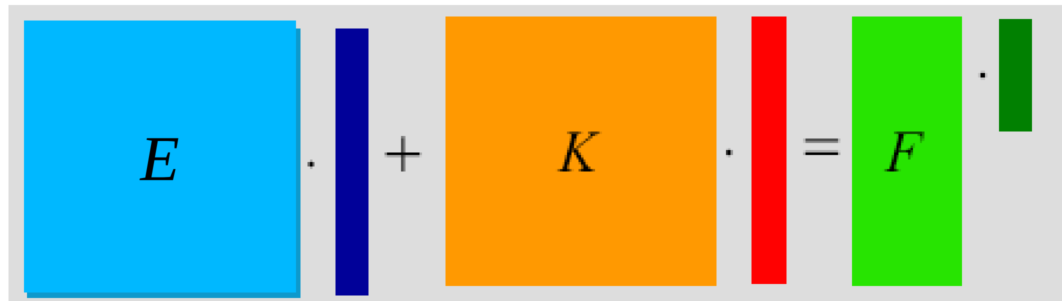


- Electrothermal Simulation with IGBTs.

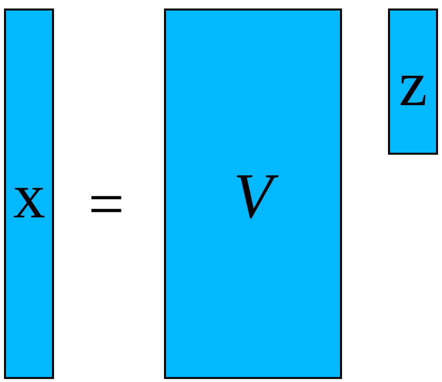
Model Reduction as Projection

- Projection onto low-dimensional subspace

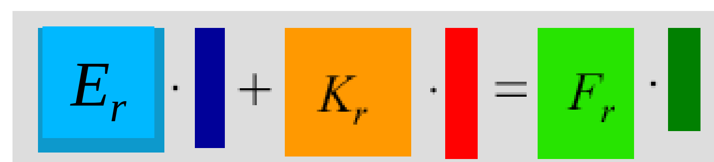
$$E\dot{\mathbf{x}} + K\mathbf{x} = B\mathbf{u}$$



$$\mathbf{x} = V\mathbf{z} + \varepsilon$$



$$V^T E V\dot{\mathbf{z}} + V^T K V\mathbf{z} = V^T B\mathbf{u}$$



- How to find subspace?
- Mode superposition is not the best way to do it.

Implicit Moment Matching

- Padé approximation
- Matching first moments for the transfer function

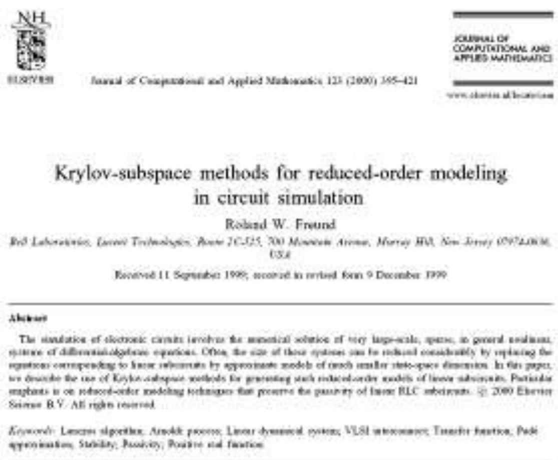
$$E\dot{\mathbf{x}} + K\mathbf{x} = B\mathbf{u}$$

$$H(s) = (sE + K)^{-1} B$$

$$H = \sum_{0}^{\infty} m_i (s - s_0)^i$$

$$H_{red} = \sum_{0}^{\infty} m_{i,red} (s - s_0)^i$$

$$m_i = m_{i,red}, \quad i = 0, \ldots, r$$


Journal of Computational and Applied Mathematics 123 (2000) 395–421

Krylov-subspace methods for reduced-order modeling in circuit simulation

Roland W. Freund

- Implicit Moment Matching:
  - via Krylov Subspace

$$s_0 = 0$$

$$V = span\{\Im(K^{-1}E, K^{-1}b)\}$$

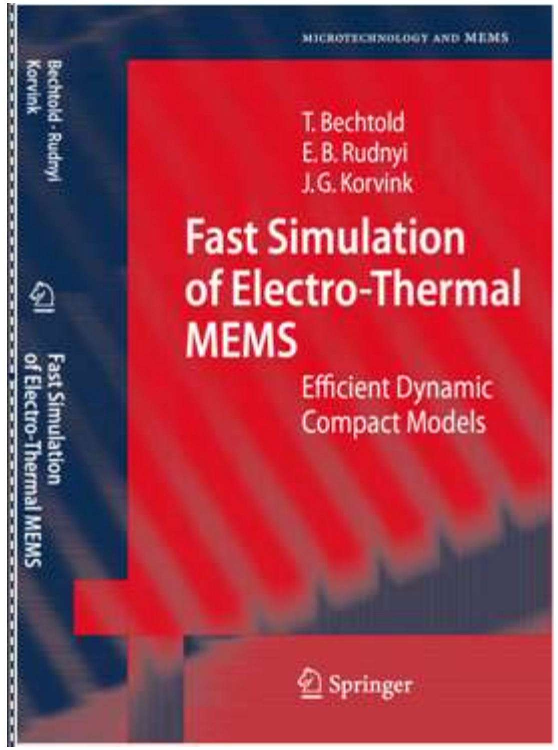
MOR for ANSYS: http://ModelReduction.com

ANSYS Model

FULL files

$$M\ddot{x} + E\dot{x} + Kx = Bu$$
$$y = Cx$$

Linear Dynamic System, ODEs



Simulink, Simplorer, VHDL-AMS

Small dimensional matrices

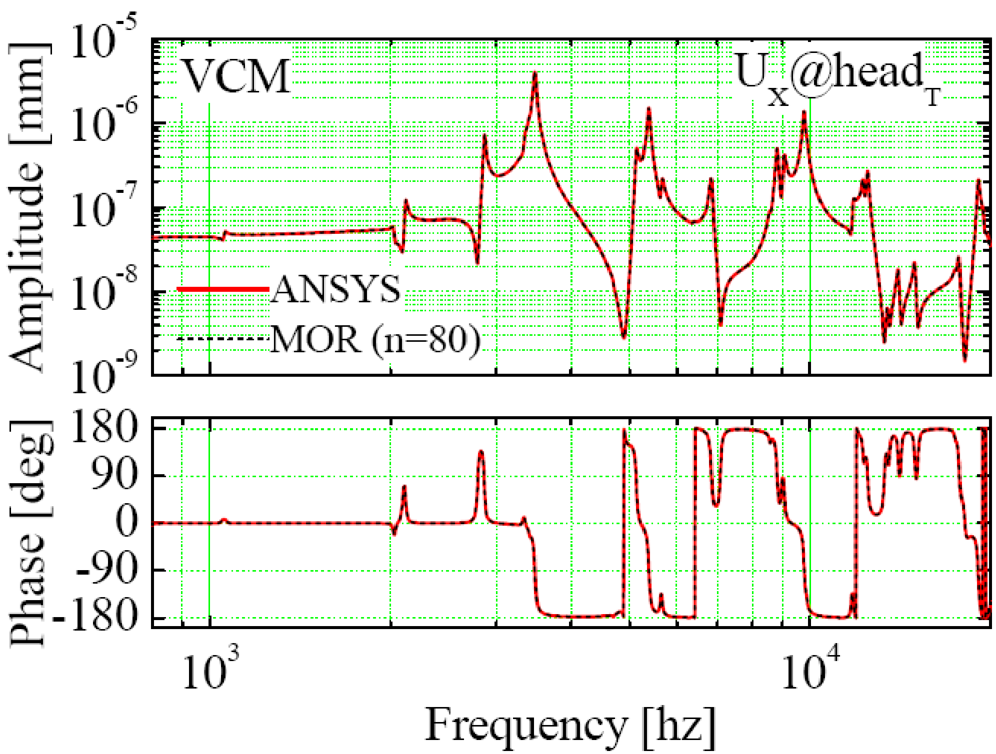
MOR Algorithm

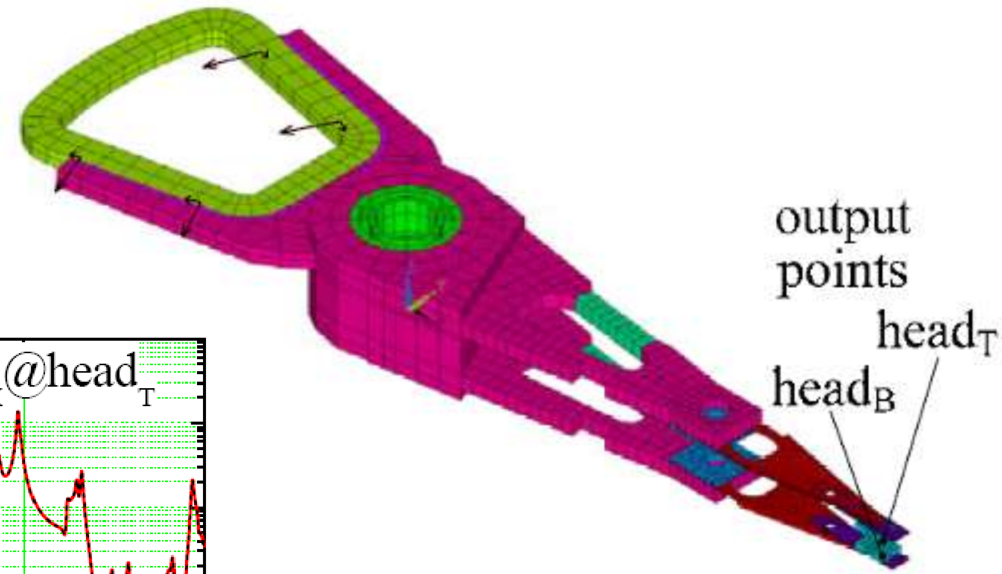
Current version 2.5

SIMetris CADFEM

HDD actuator and suspension system

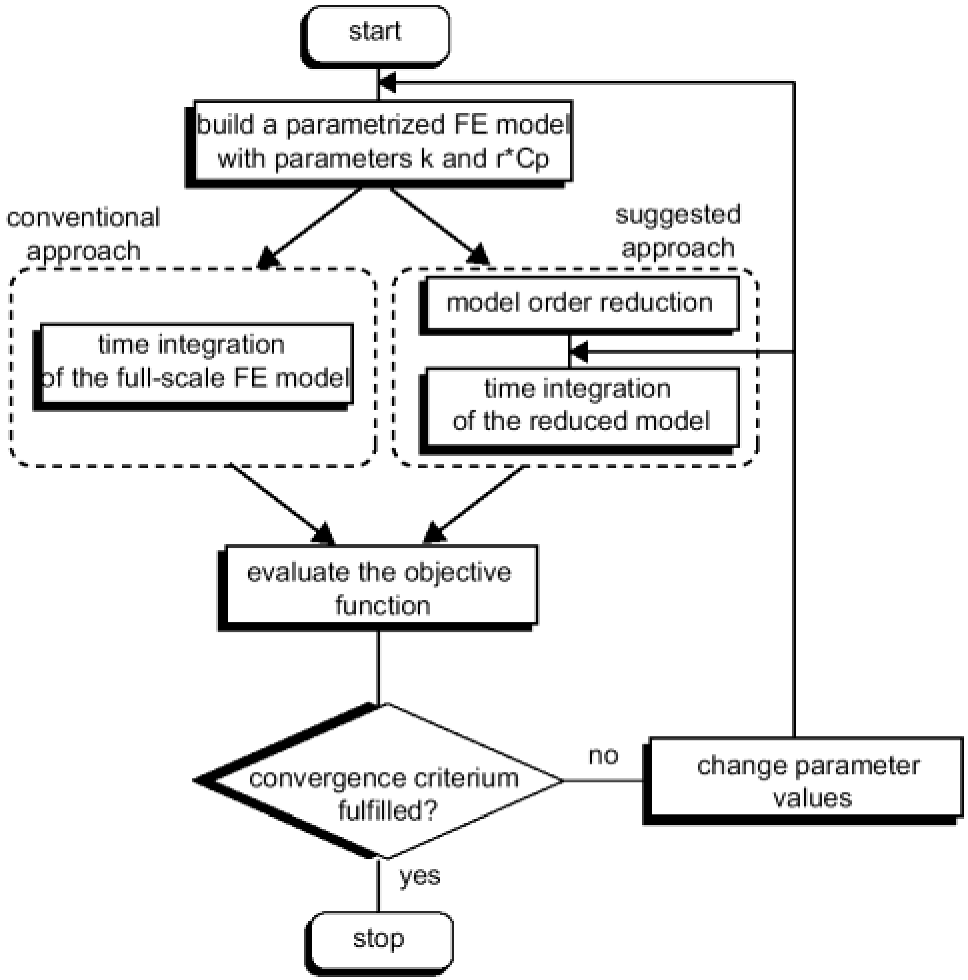
- Prof J. S. Han. Transactions of the KSME, A, Vol. 31, No. 5, pp. 541-549, 2007.





Model Reduction as Fast Solver

- Simulation of the reduced model is a few seconds.
- Arnoldi Process is fast:
  - Transient and harmonic response analysis for the cost comparable with that of a static solution.
- It is advantageous to use MOR even the reduced model is used only once:
  - Design,
  - Geometry optimization.



Finite Element Discretization for Acoustic with FSI

$$\left(-\omega^2\begin{bmatrix} M_s & 0 \\ M_{fs} & M_a \end{bmatrix} + j\omega\begin{bmatrix} C_s & 0 \\ 0 & C_a \end{bmatrix} + \begin{bmatrix} K_s & K_{fs} \\ 0 & K_a \end{bmatrix}\right)\begin{Bmatrix} u \\ p \end{Bmatrix} = \begin{Bmatrix} F_s \\ F_a \end{Bmatrix}$$

- FLUID29/FLUID30 in ANSYS
- The element size should be smaller than wavelength
  - High dimensional models
- Unsymmetric matrices
- Not proportional damping: Second Order Arnoldi (SOAR)

SIAM J. SCI. COMPUT.
Vol. 26, No. 5, pp. 1692–1709

DIMENSION REDUCTION OF LARGE-SCALE SECOND-ORDER DYNAMICAL SYSTEMS VIA A SECOND-ORDER ARNOLDI METHOD[*]

ZHAOJUN BAI[†] AND YANGFENG SU[‡]

Abstract. A structure-preserving dimension reduction algorithm for large-scale second-order dynamical systems is presented. It is a projection method based on a second-order Krylov subspace. A second-order Arnoldi (SOAR) method is used to generate an orthonormal basis of the projection subspace. The reduced system not only preserves the second-order structure but also has the same order of approximation as the standard Arnoldi-based Krylov subspace method via linearization. The superior numerical properties of the SOAR-based method are demonstrated by examples from structural dynamics and microelectromechanical systems.

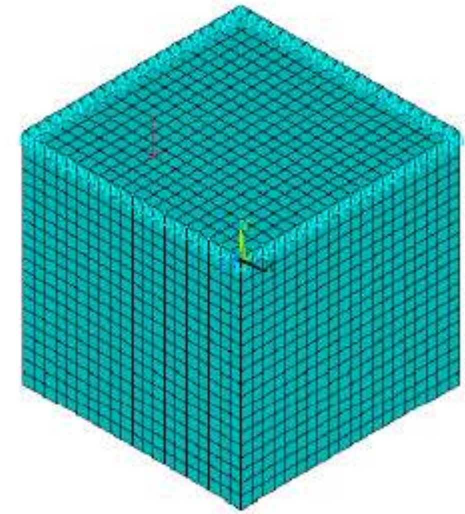
Thesis

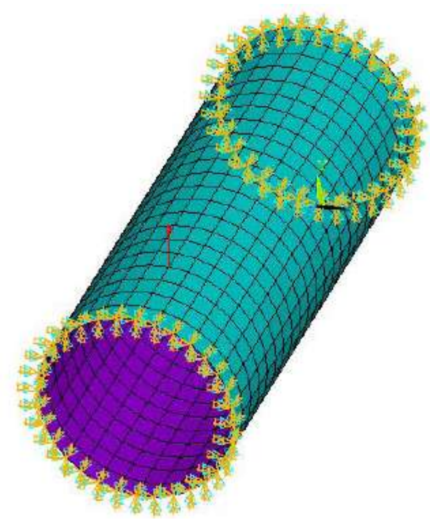
Krylov Subspace Based Direct Projection Techniques for Low Frequency, Fully Coupled, Structural Acoustic Analysis and Optimization.

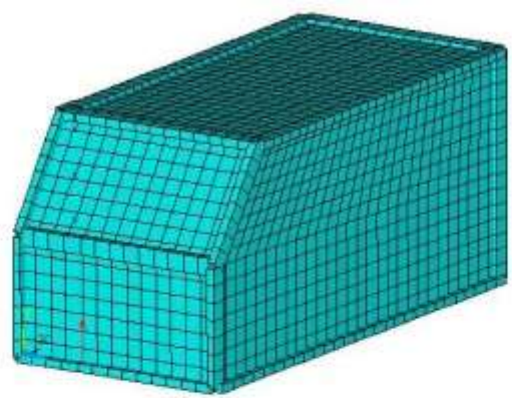
R. Srinivasan Puri

A thesis submitted in partial fulfillment of the requirements of Oxford Brookes University for the degree of Doctor of Philosophy.

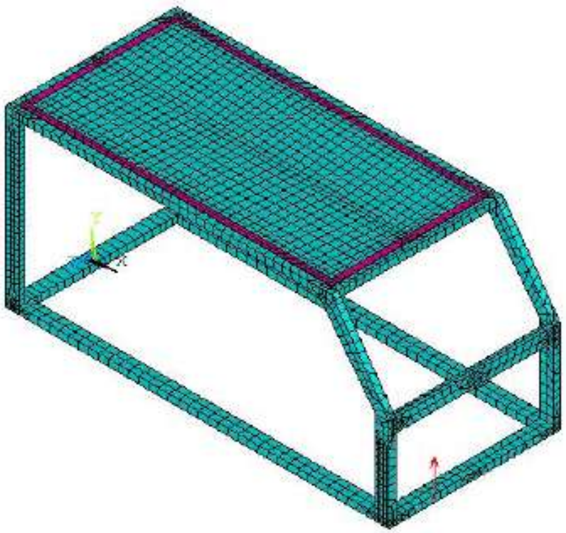
13th March 2008

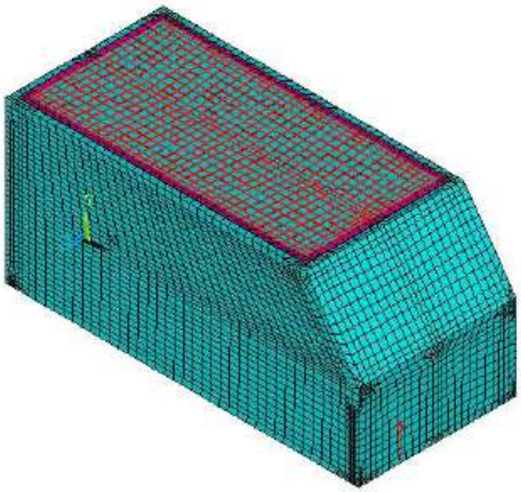






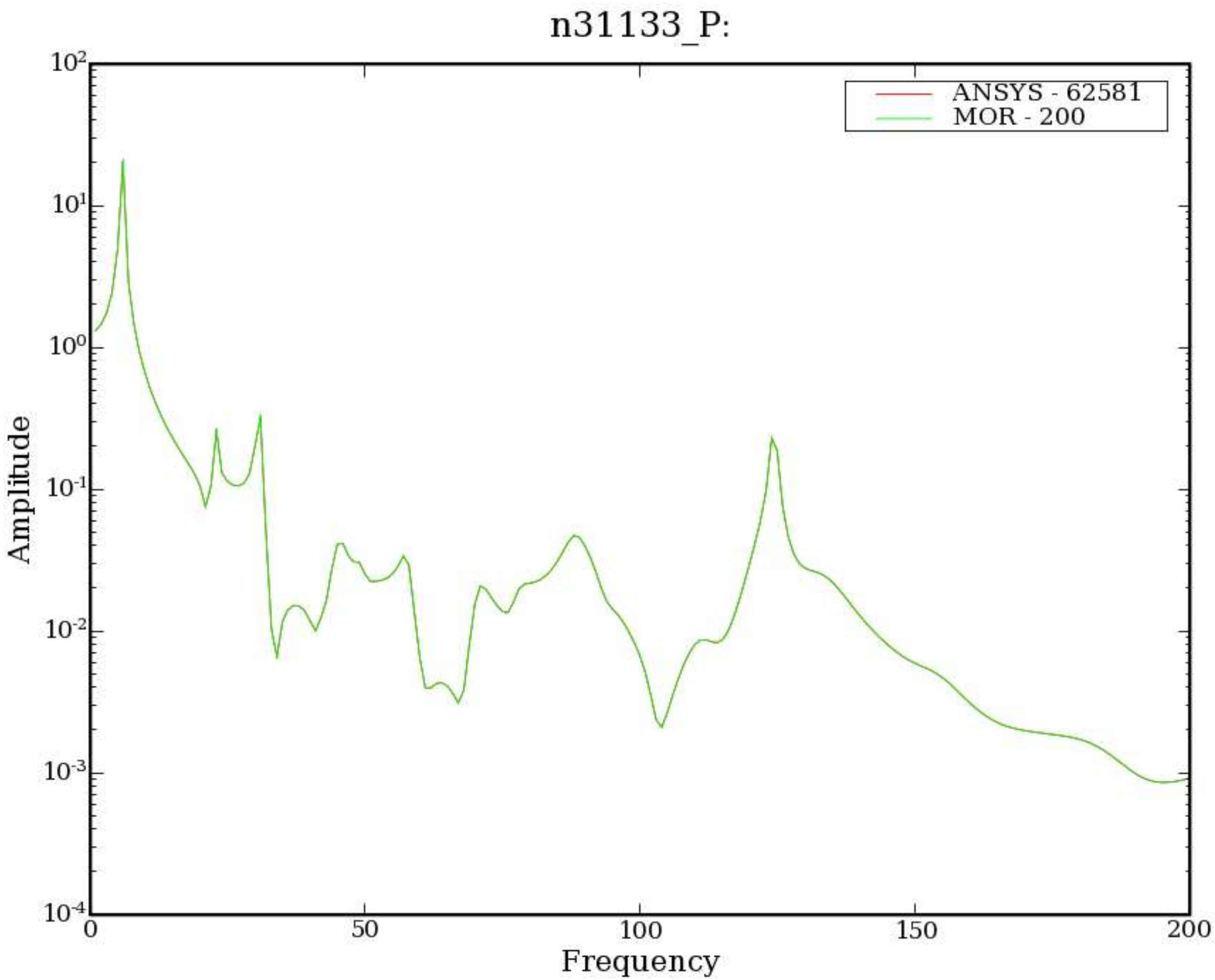
Adhesive Bonded Joint Benchmark





- Mechanical Structure - SHELL181
- Adhesive – SOLID45
- Fluid – FLUID30
- Single excitation point
- Global and local damping

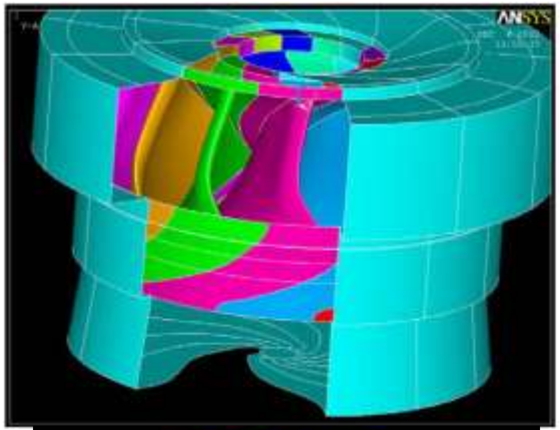
Comparison

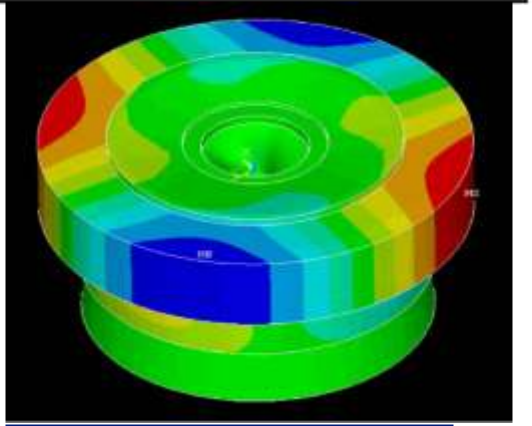

n31133_P:
ANSYS - 62581
MOR - 200
Amplitude
Frequency
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
50
100
150
200

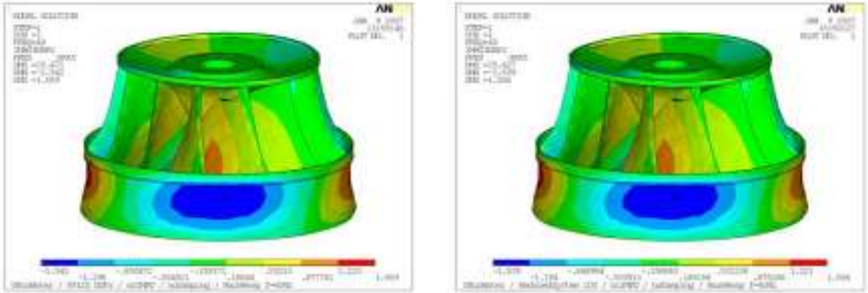
Timing

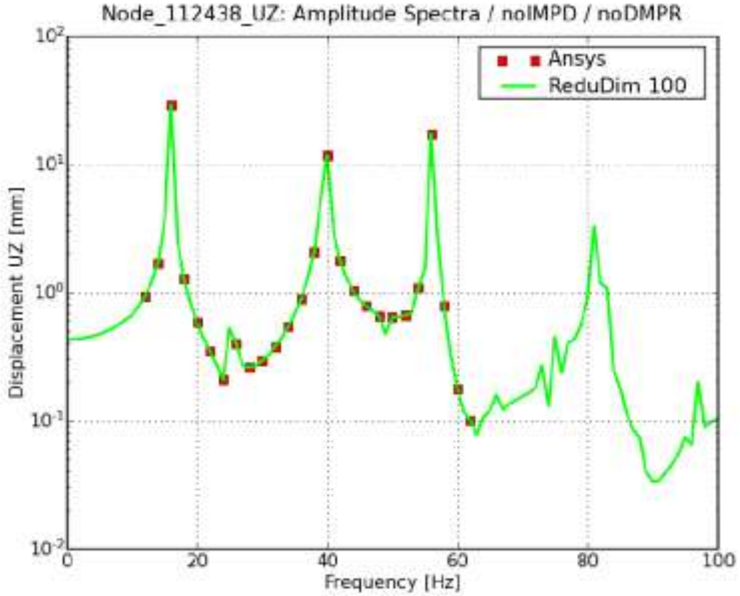
- Problem in ANSYS
  - 37988 elements, 38712 nodes, 62581 free DoFs
- Full solution in ANSYS for 200 frequencies
  - 16695 s – 4.6 hours – 83 s per frequency
  - Proportional to the number of frequencies
- MOR for ANSYS
  - Reading ANSYS files – 3 s
  - Model reduction – 170 s
  - Proportional to the number of vectors
- Simulation of the reduced model
  - 4 s

Fluid Structure Interaction at Acoustic Level



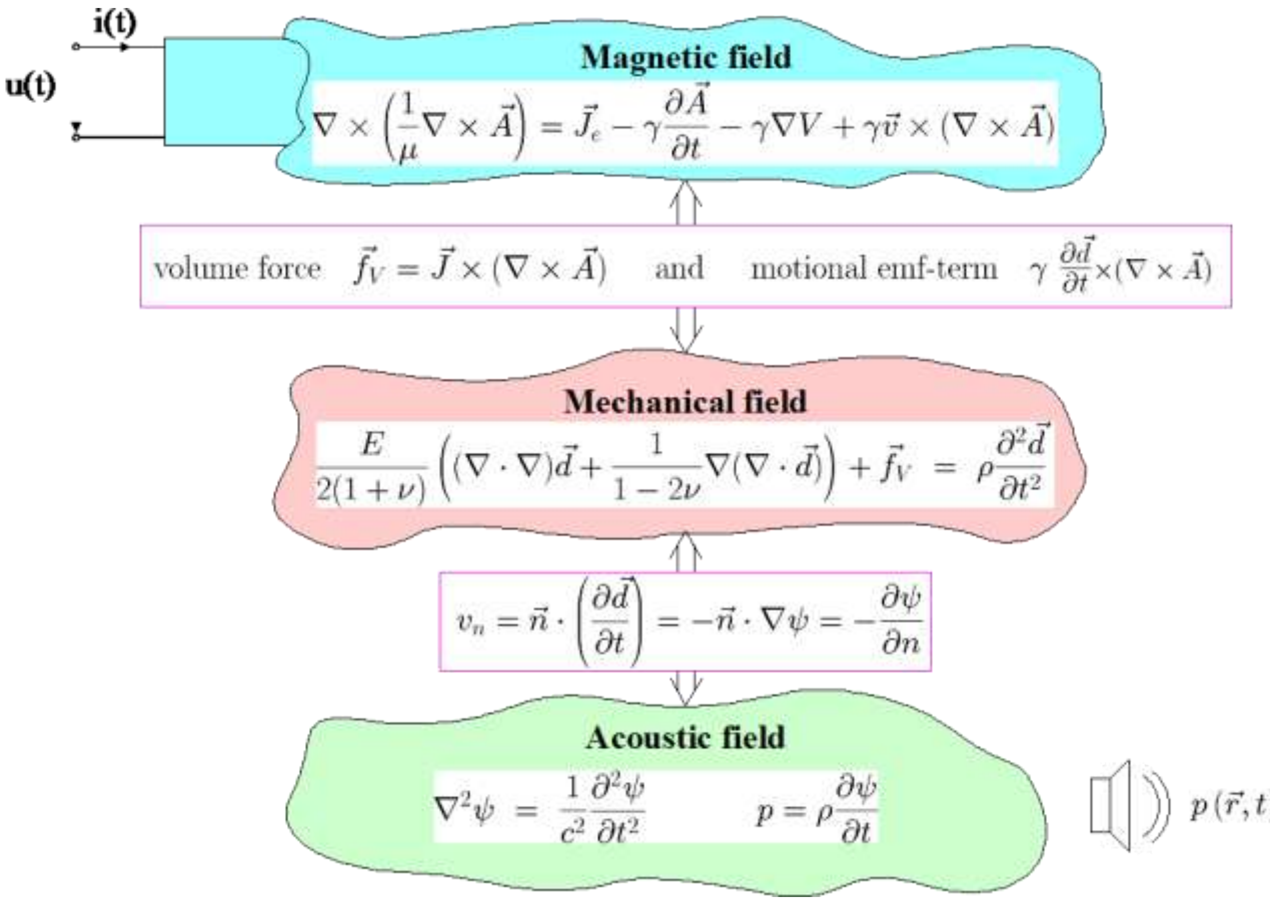






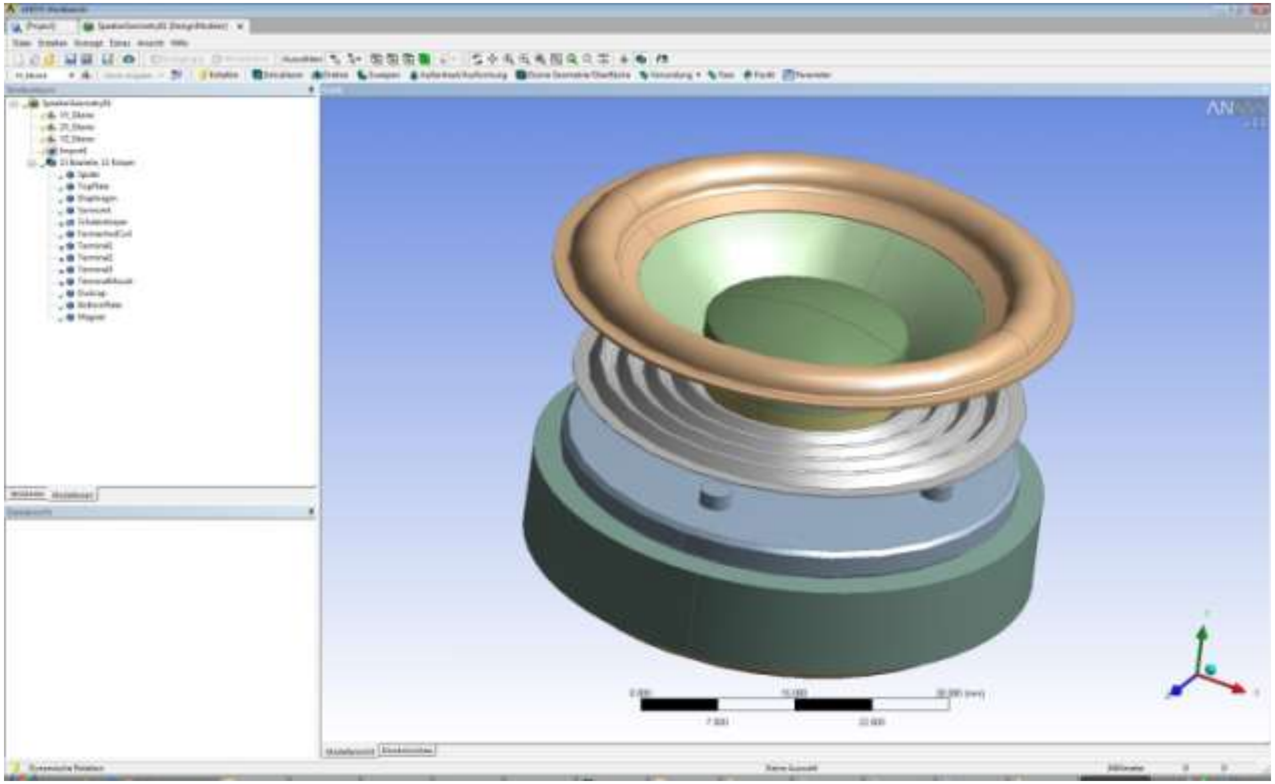
By courtesy of Voith Siemens Hydro Power Generation GmbH & Co. KG

Loudspeaker – Calculation Scheme



Tymphany Speaker - Modeling

- Import of geometry data into ANSYS Workbench



  - Geometry repair and export to ANSYS classic for further processing with NACS interface

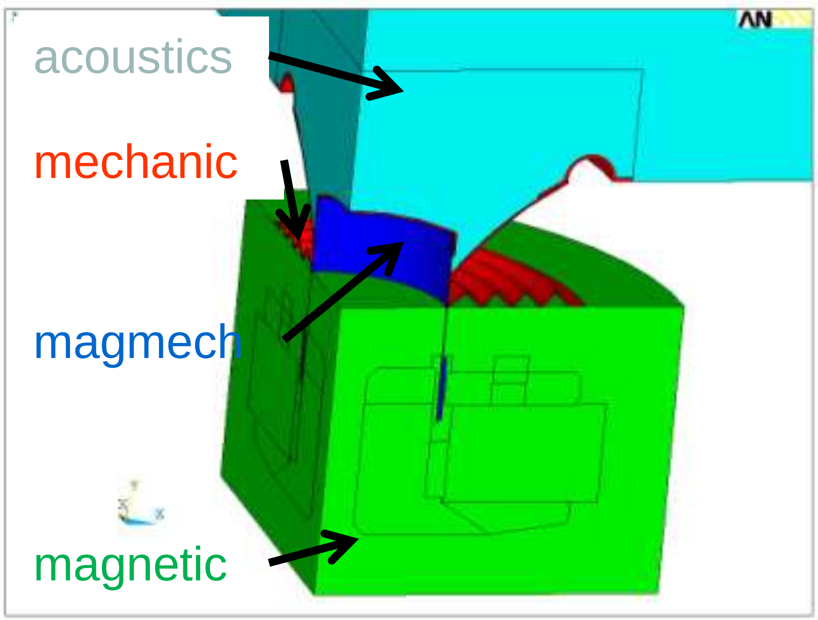
Tymphany Speaker

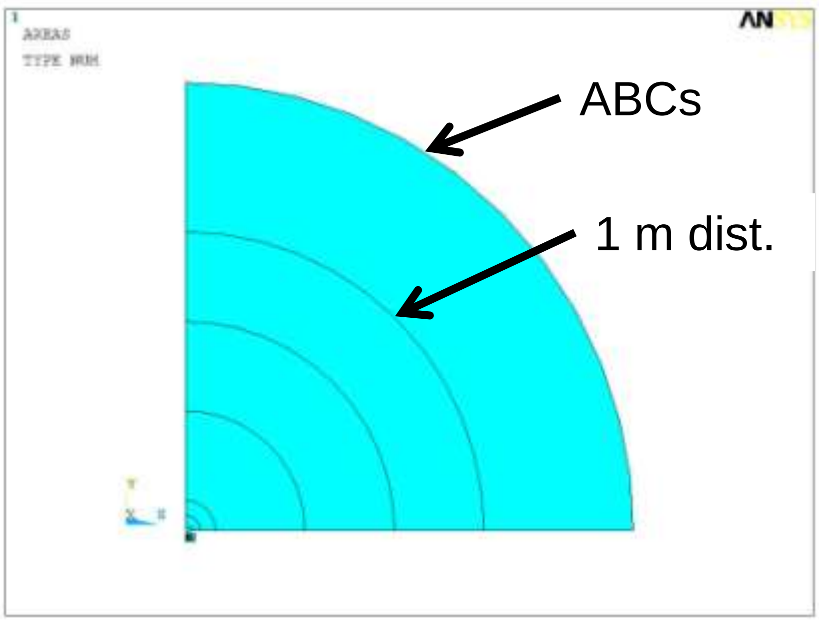
Quartermodel

Typ.: nonlinear, < 200.000 el.

Cross-section model

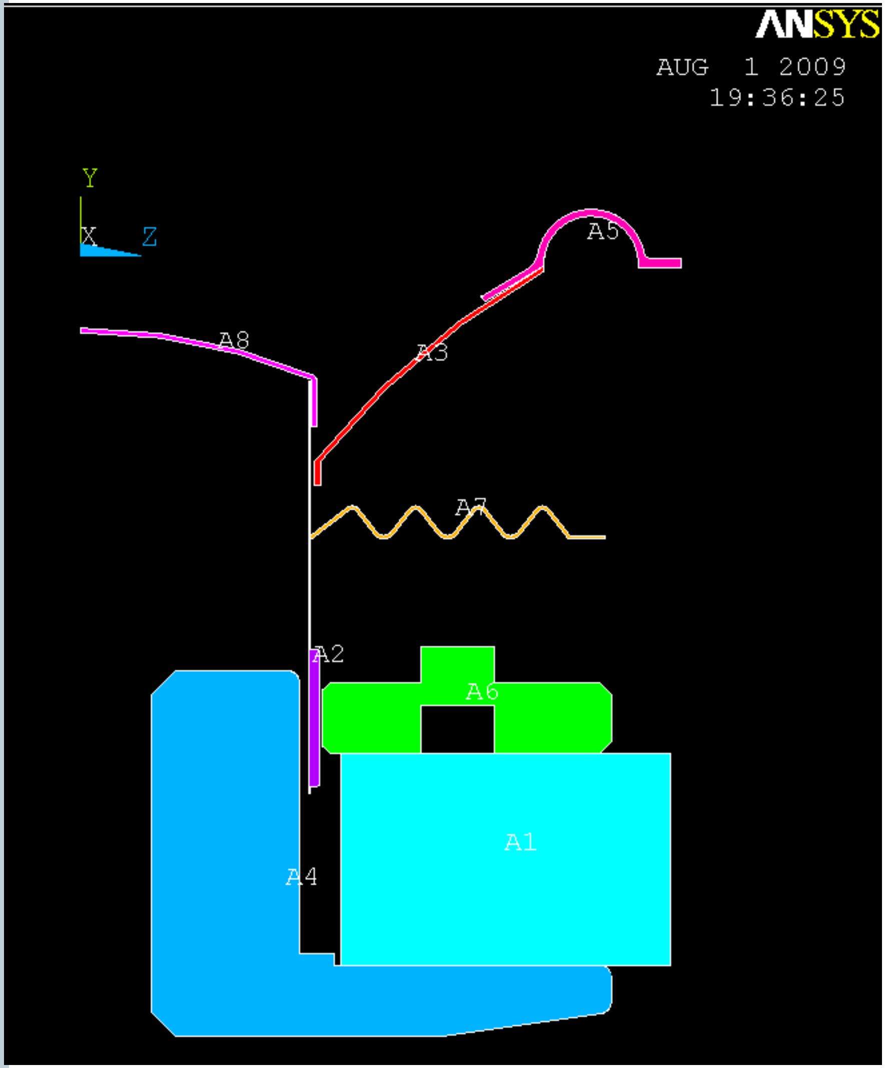
Typ.: linear, > 1 Mio. el.

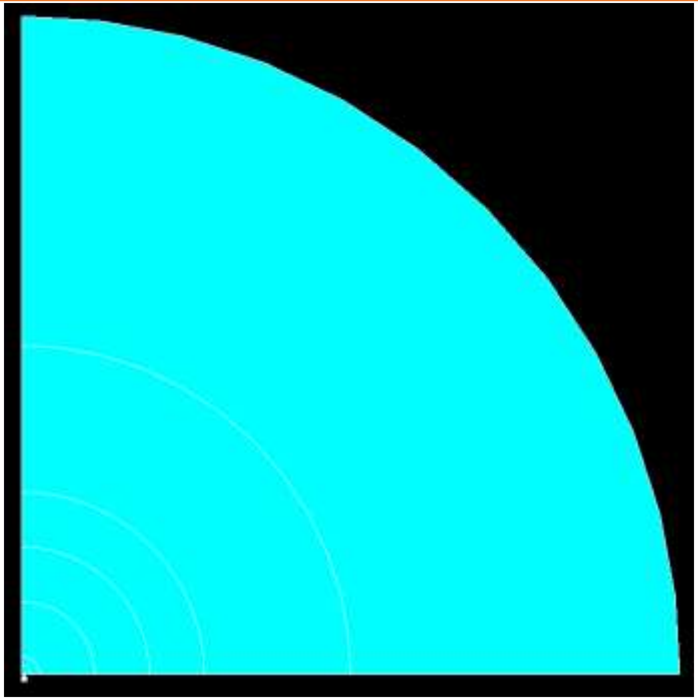


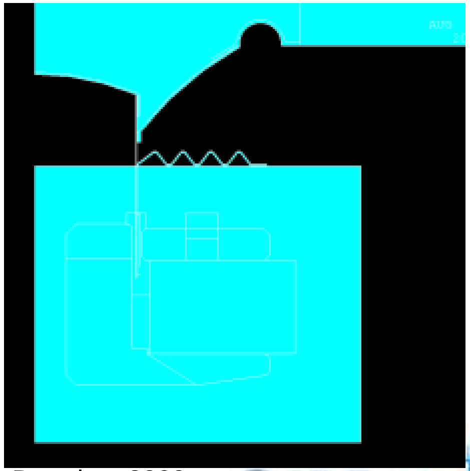


Assumption: baffled setup

Some pictures from ANSYS







Procedure

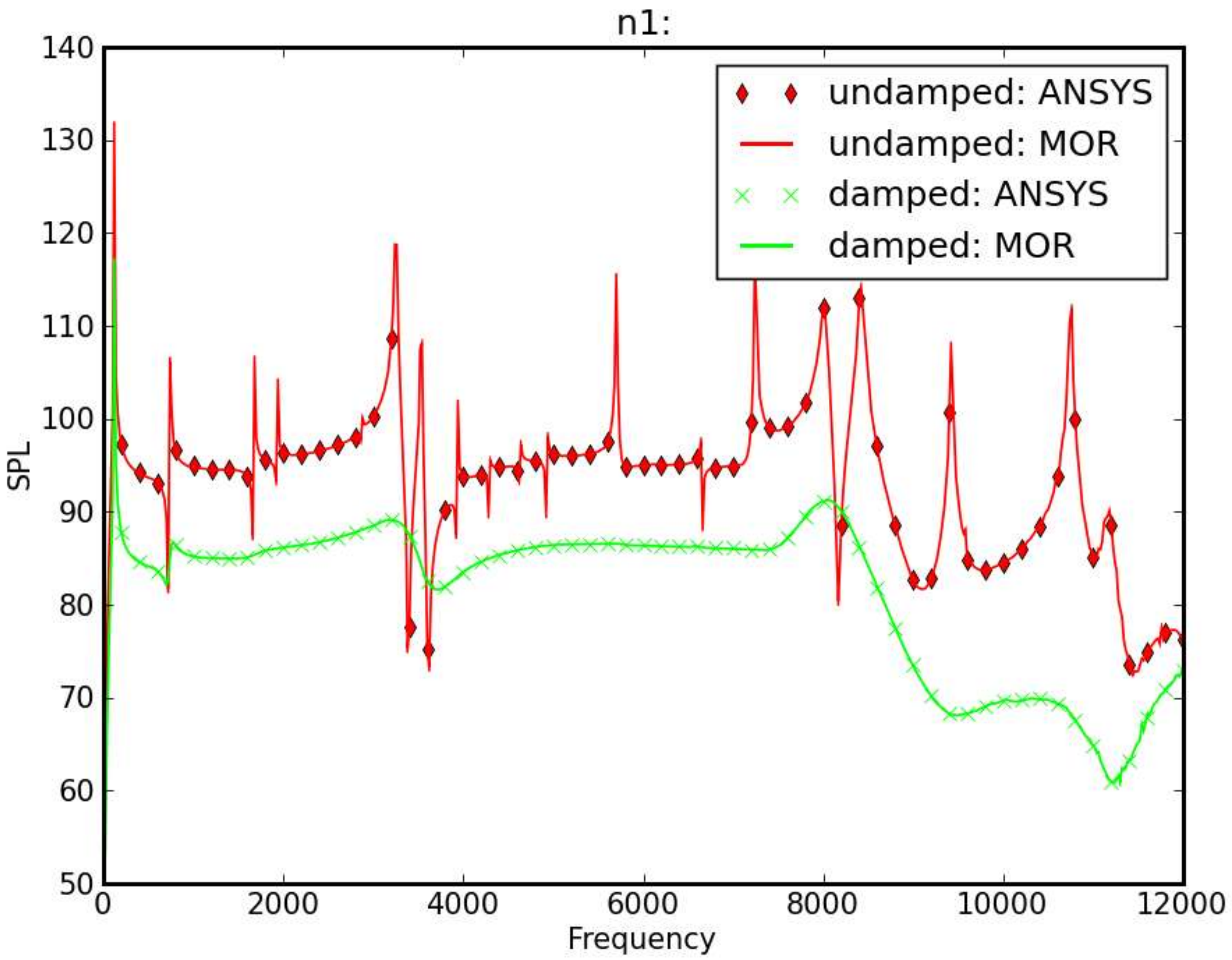
- Two cases:
  - Undamped: Damping only due to the adsorbing BC.
  - Damped: Materials damping in the loudspeaker.

- ANSYS and MOR:
  - Linux, 4 processors, 16 Gb RAM
  - ANSYS: 60 frequencies in the range 0-12000 Hz
  - The mechanical force does not depend on frequency (only FSI)
    - Electrical properties of the loud speaker were neglected

  - Expansion point is 60000 rad (omega = 2 Pi f)
  - Dimension of the reduced model is 1000

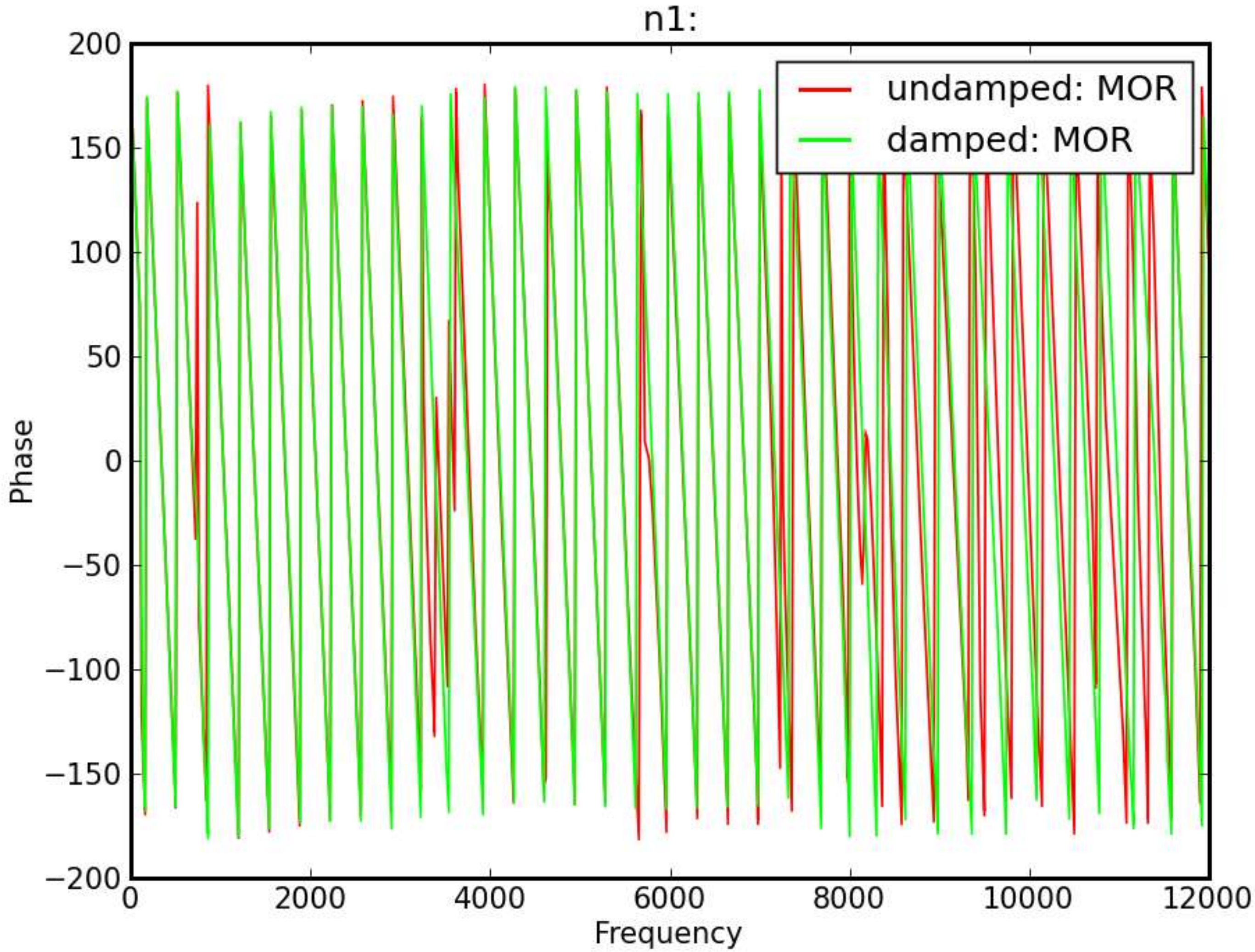
- Postprocessing in Python on Windows
  - 600 frequencies in the range 0-12000 Hz

SPL

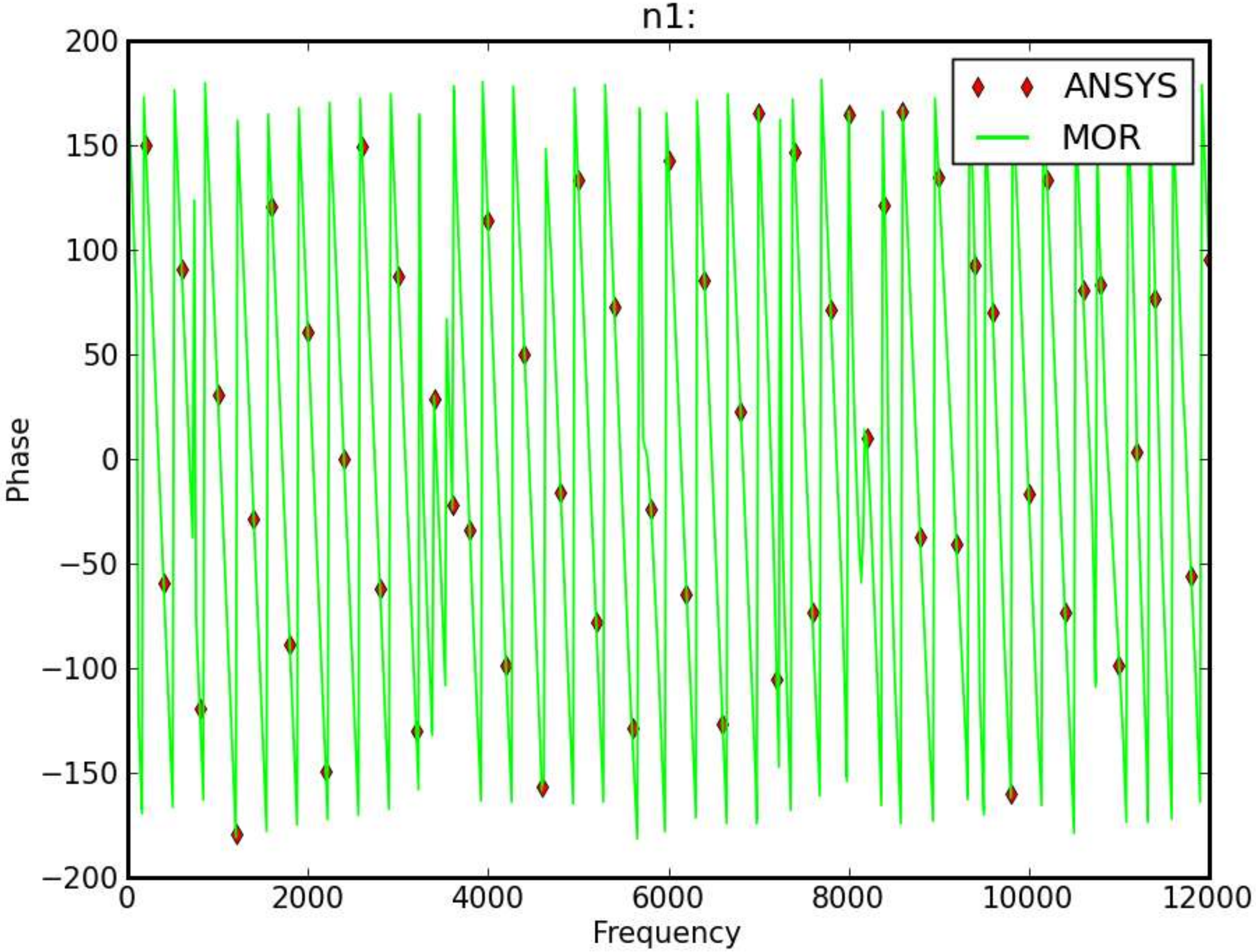


Damped and undamped results are shifted in respect to each other

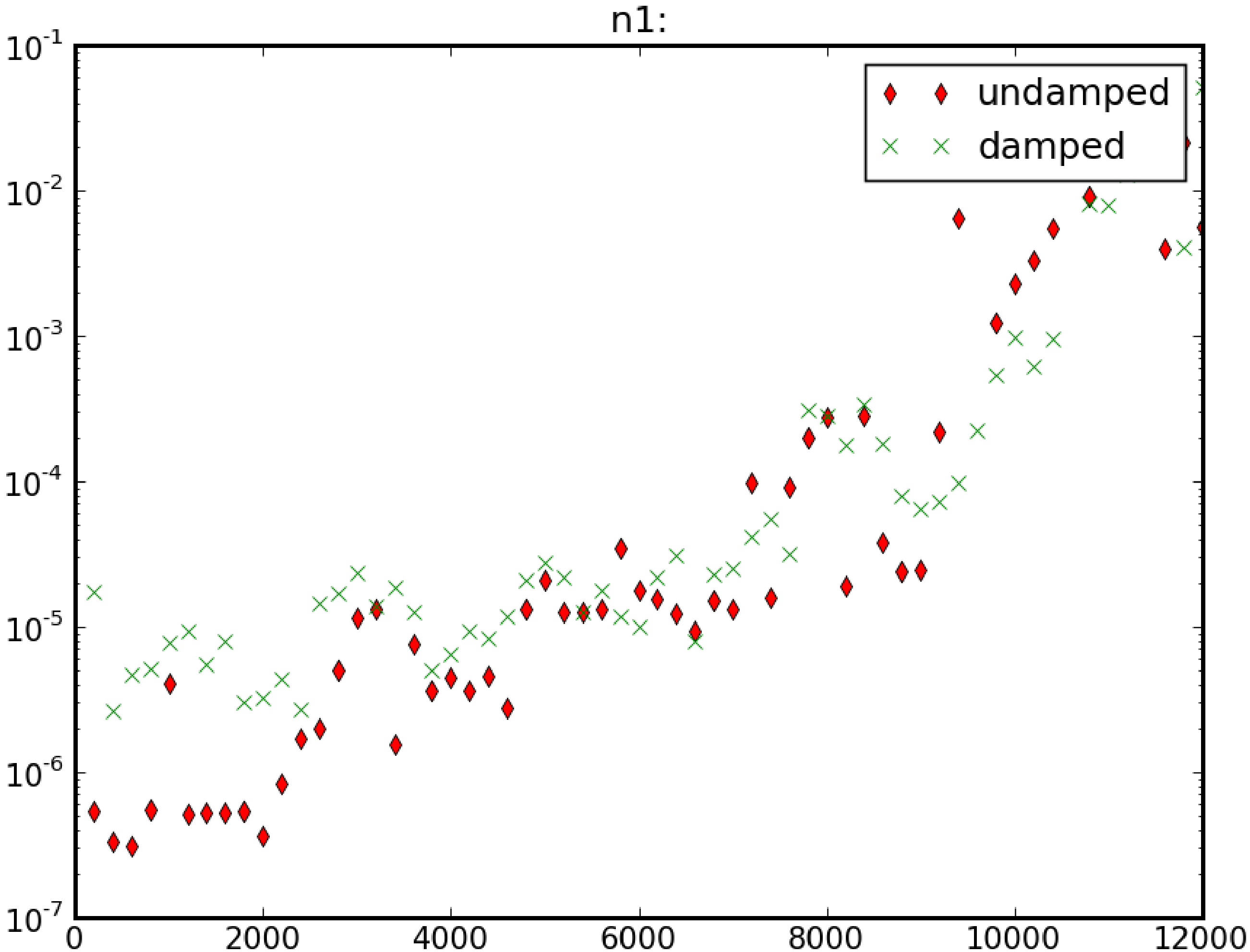
Phase Angle


n1:
undamped: MOR
damped: MOR
Phase
Frequency
200
150
100
50
0
−50
−100
−150
−200
0
2000
4000
6000
8000
10000
12000

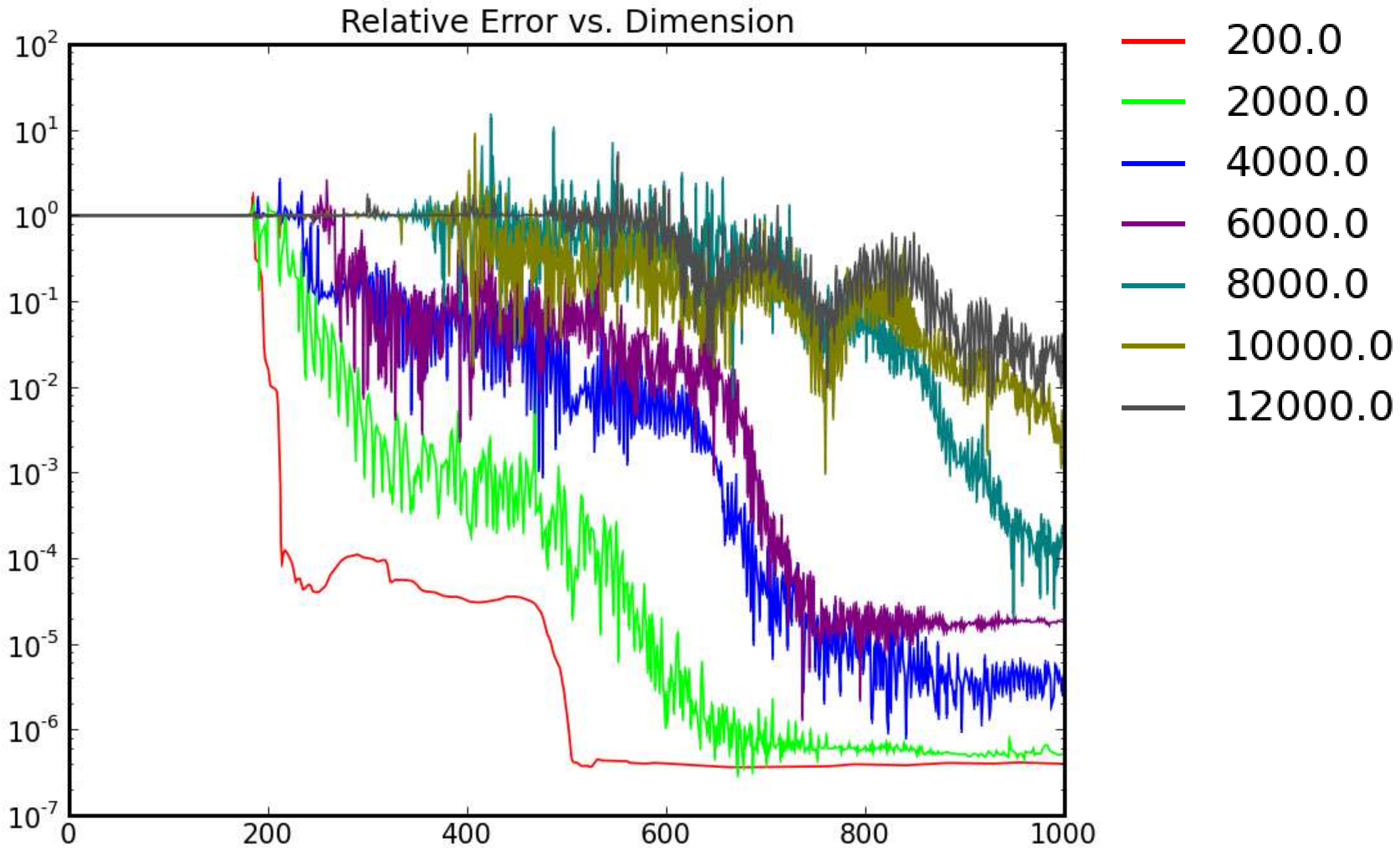
Undamped: Phase Angle



Relative Difference for Pressure

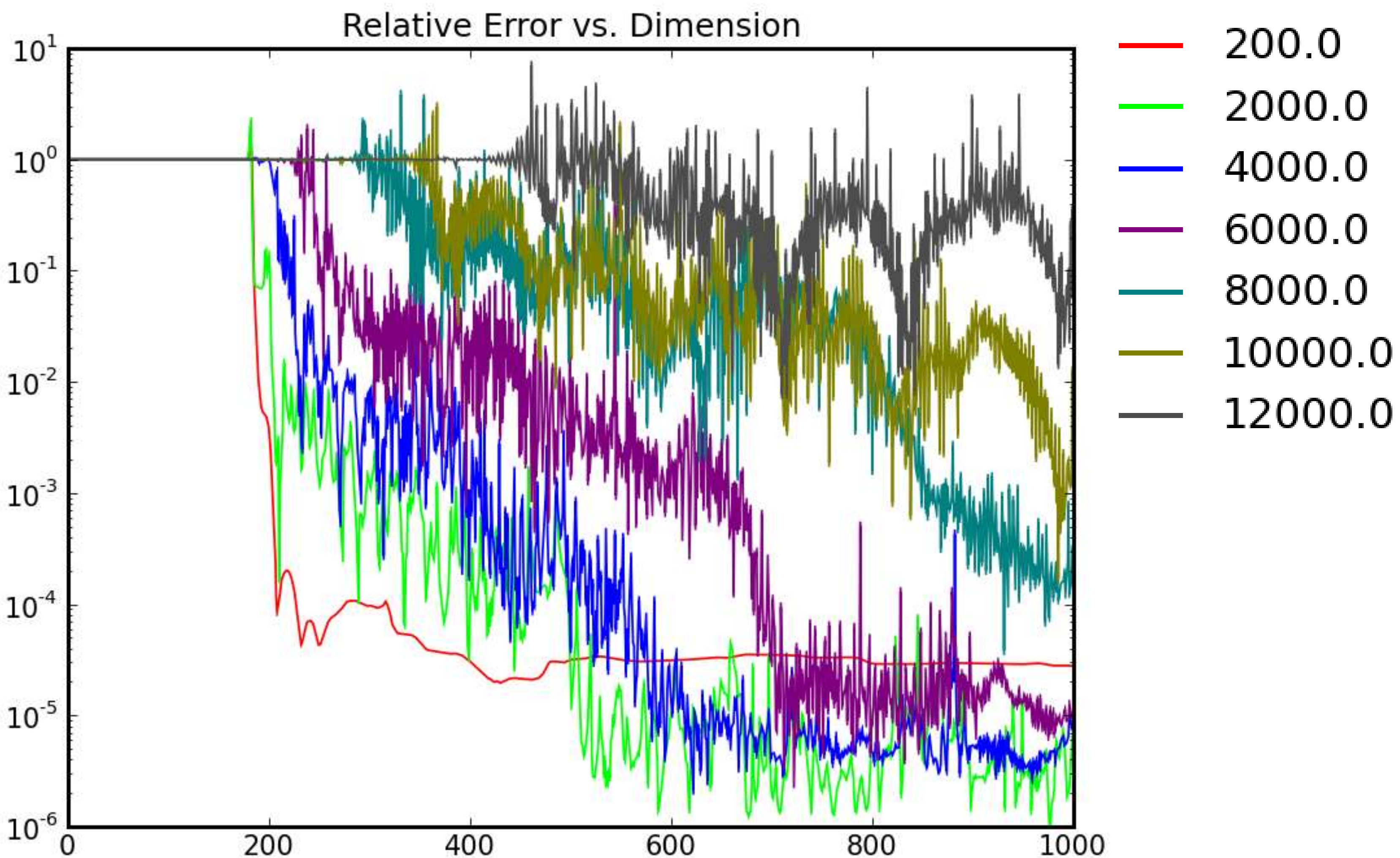


Undamped: Convergence (relative error for pressure)



SIMetris CADFEM

Damped: Convergence (relative error for pressure)



Timing

- Problem in ANSYS
  - 1170389 nodes, 1176817 DoFs

- Full solution in ANSYS for 60 frequencies
  - 13498 s – 3.8 hours – 224 s per frequency
  - Proportional to the number of frequencies:
  - 600 frequencies is about 38 hours

- MOR for ANSYS
  - Reading ANSYS files – 10 s
  - Model reduction – 11927 s – 3.3 hours

- Simulation of the reduced model (Python, SciPy, 1 processor)
  - 300 s

Conclusion

- Model reduction is working for the case study, but the convergence is rather slow.
  - It is still faster than the full solution in ANSYS though.

- Further would-be research:
  - Multiple-expansion points?
  - Imaginary expansion point?