Transducer Design and Modeling

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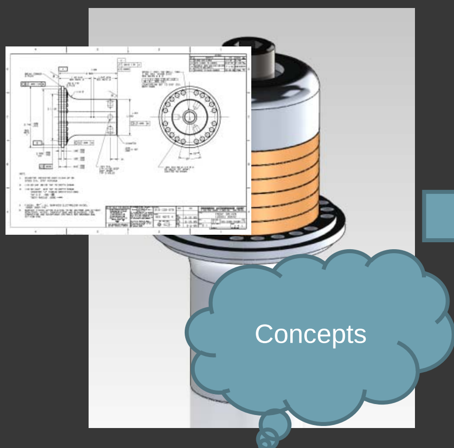
Transducer Design and Modeling

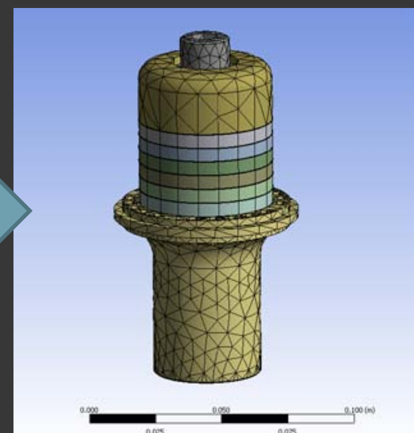
- Introduction
- ANSYS Workbench Introduction
  - The project format
  - Setting up different analysis – Static, Modal and Harmonic
  - Connection to the solid modeling package
  - Material library
  - ANSYS mechanical
  - Setup challenges
- The converter stack solid model
  - Components
  - Modeling Techniques
- Model example - modal analysis
  - Use of APDL programming language
  - Set up of piezoelectric materials / assignments
  - Theory – series and parallel analysis
  - Boundary conditions – series and parallel analysis
  - Examining results
- Model example – harmonic analysis
  - Use of APDL programming language
  - Boundary conditions – harmonic analysis
  - Examining results – single point and frequency sweep
- Model example – static analysis (pre-load)
  - Model setup options
  - Examining results

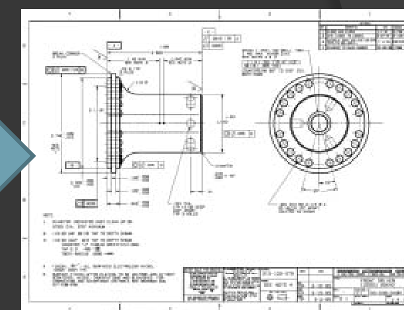
Transducer Design and Modeling
- Introduction -

Recent advancements in finite element software and computing power have changed the methods to analyze ultrasonic transducers

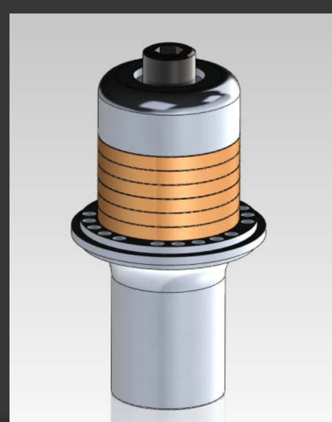
OLD Way

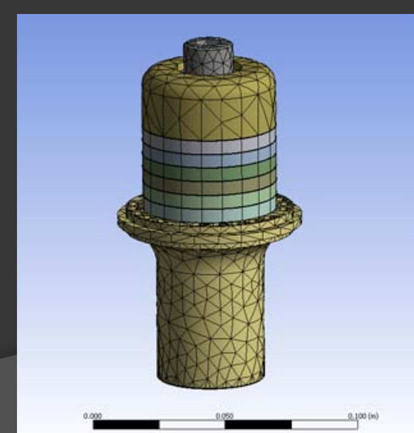






New Way

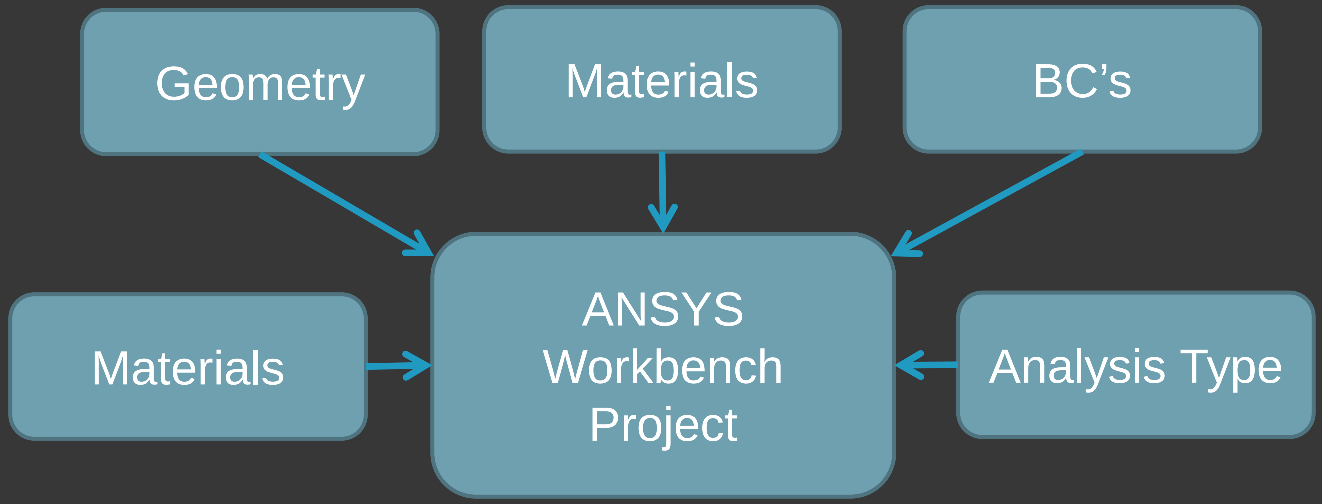




Transducer Design and Modeling
- Introduction -

ANSYS Workbench provides a seamless connection between the design data (solid model) and the analysis (FE model, analysis type, BC's)

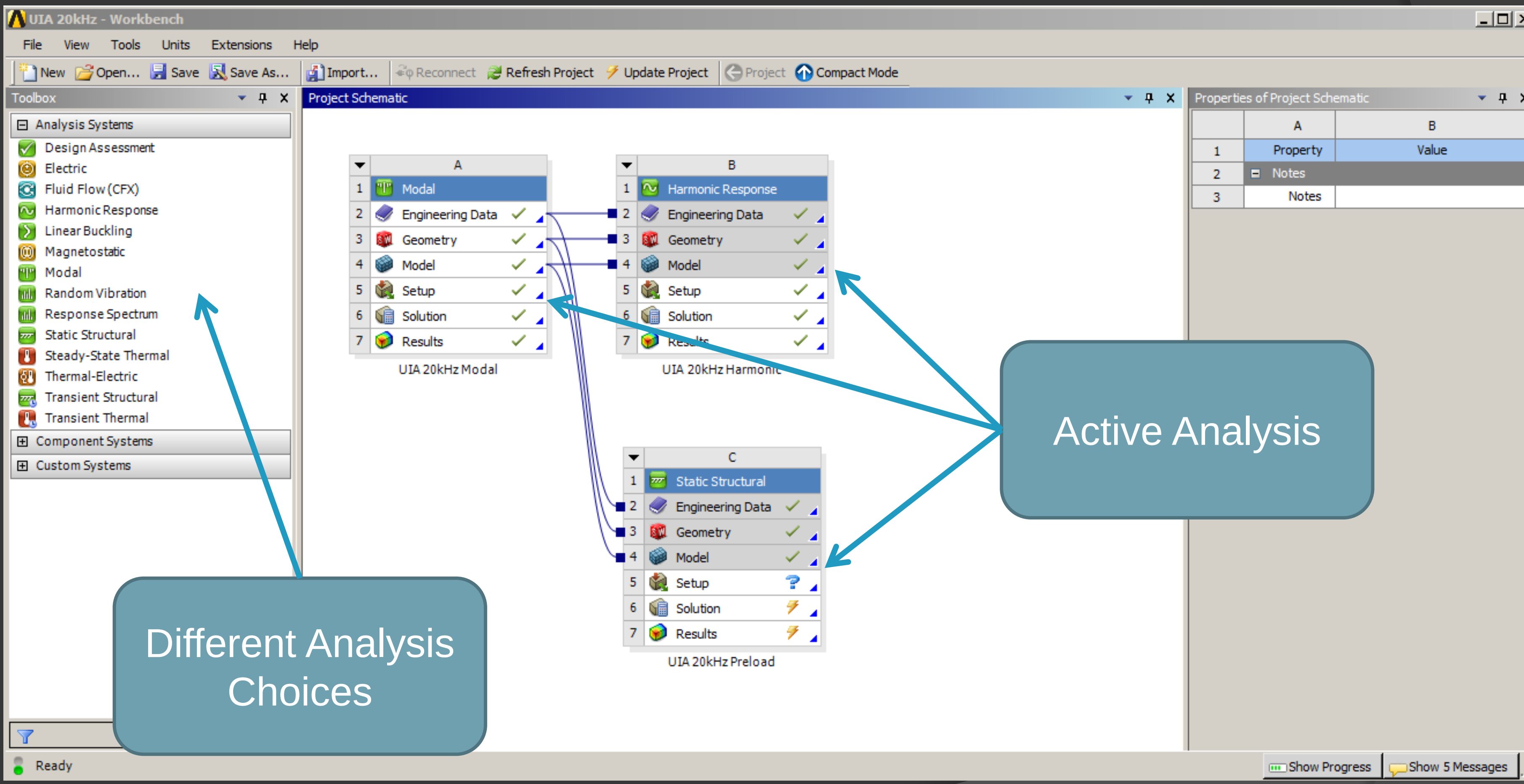
- *Advantages* – Single point to connect different analysis, types, BC's, geometry
- *Disadvantages (for US analysis)* – Piezo materials ***not*** incorporated in standard library



The disadvantages can be overcome through the use of ANSYS APDL coding

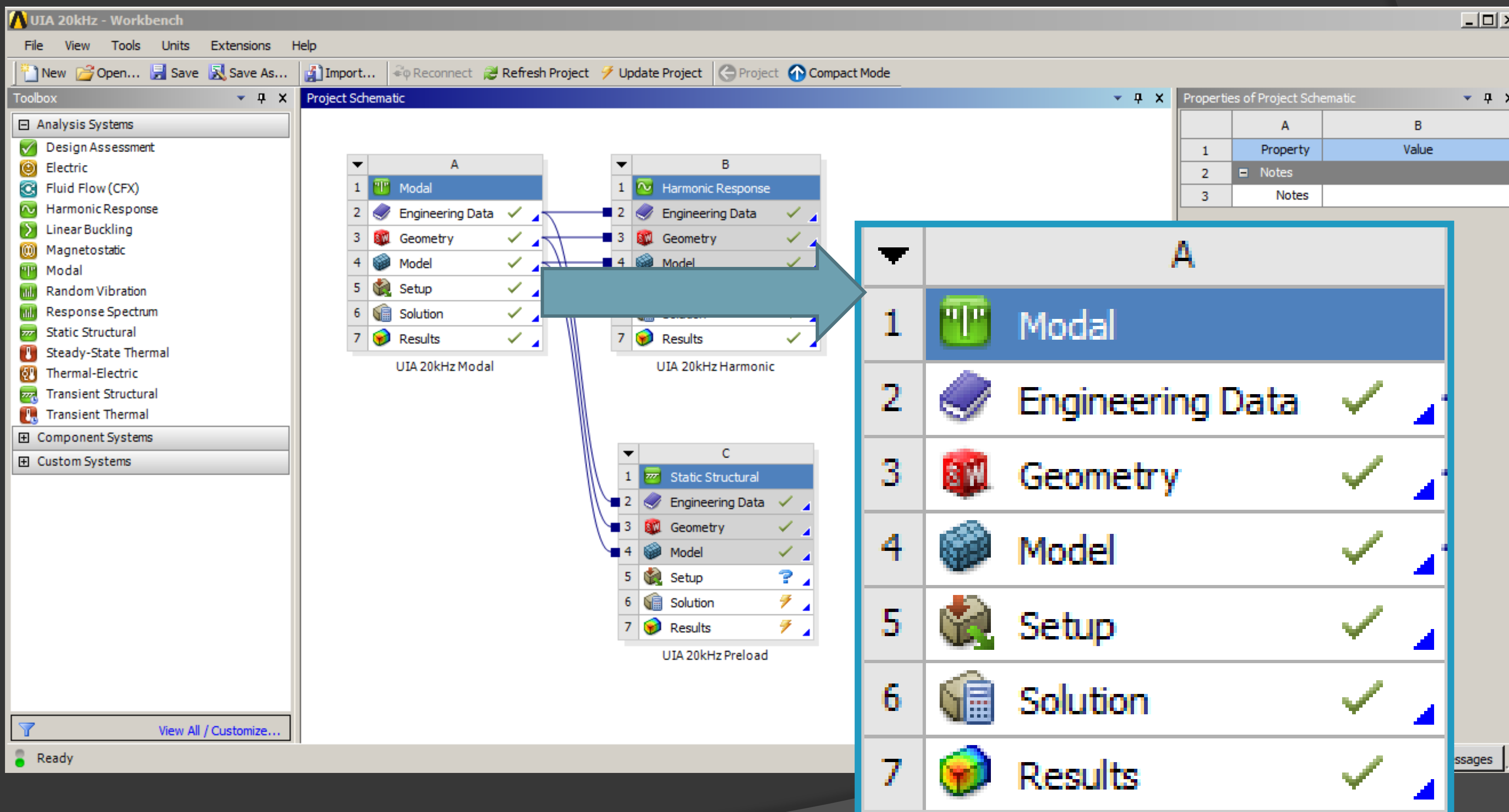
Transducer Design and Modeling
- ANSYS Workbench, The Project Format -

ANSYS Workbench is set up in an object orientated project format
“Drag and Drop”



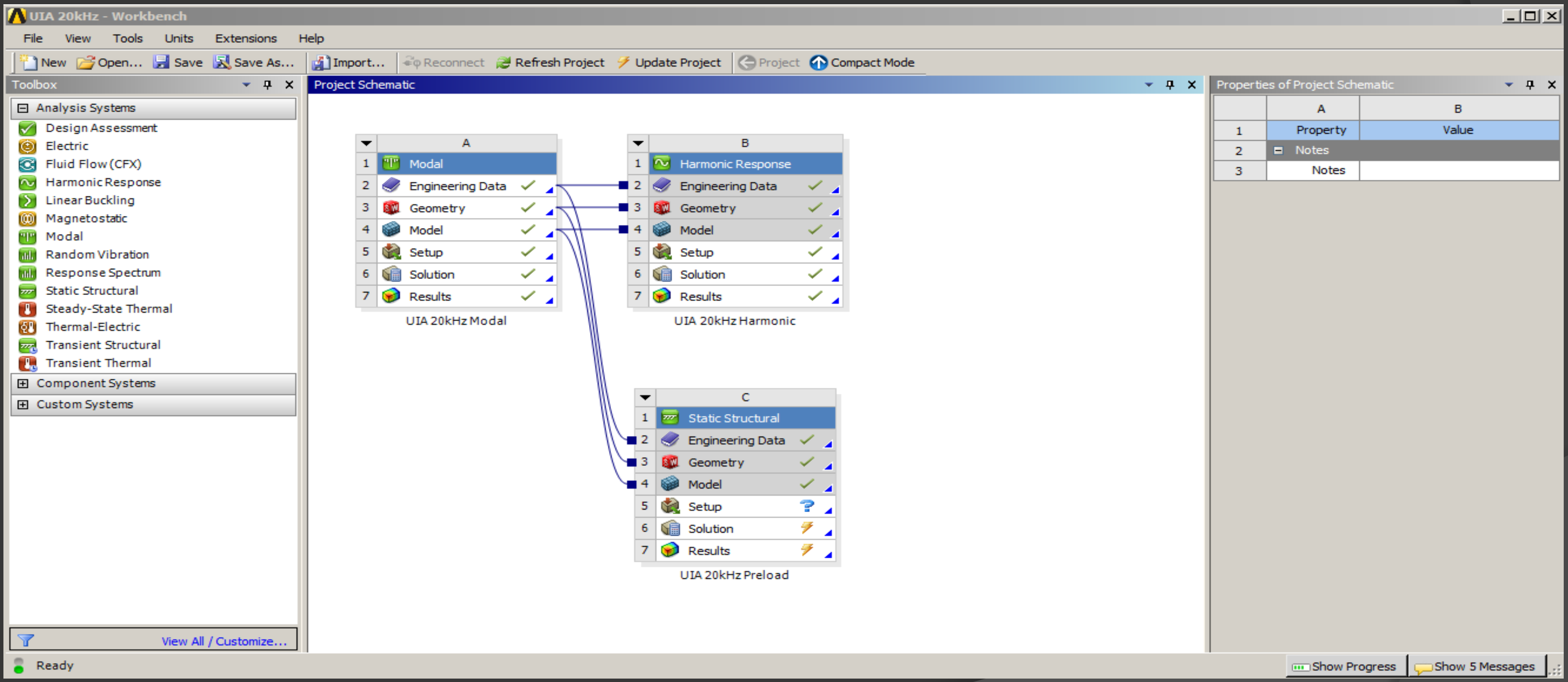
Transducer Design and Modeling
- ANSYS Workbench, The Project Format -

Each analysis is self contained. Certain analysis elements can be connected (Materials, geometry)



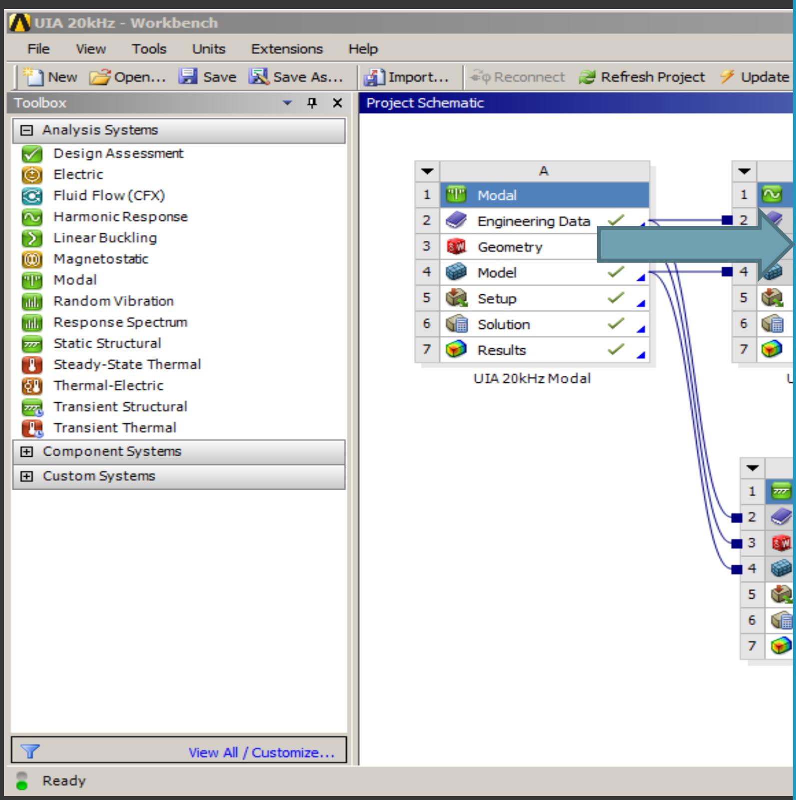
Transducer Design and Modeling
- ANSYS Workbench, Setting Up Different Analysis -

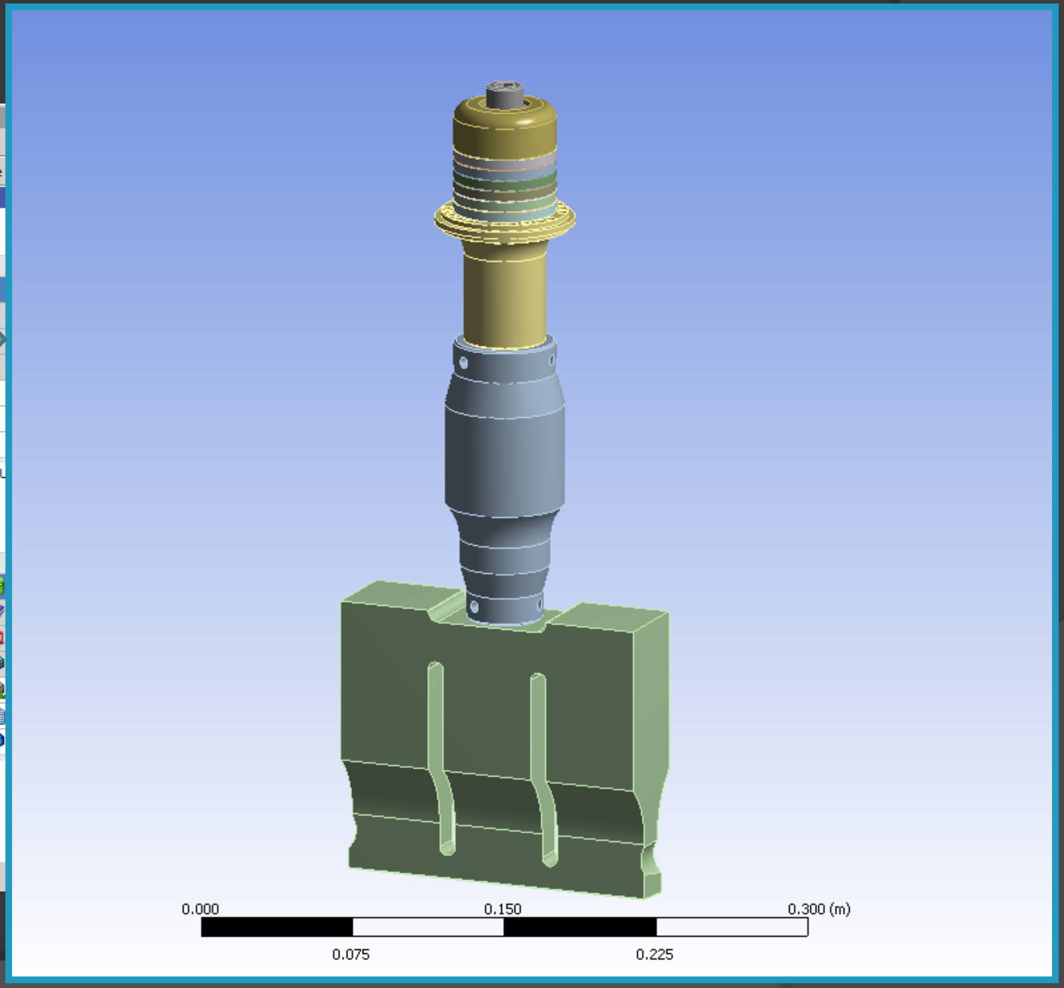
- Grab available analysis from the toolbox. Connect analysis elements as required
- This presentation will look at a modal, harmonic, and static preload analysis connected to common geometry and material
- Welding stack analysis – Stack Bolt thread Stress



Transducer Design and Modeling
- ANSYS Workbench, Connection to the Solid Modeling Package -

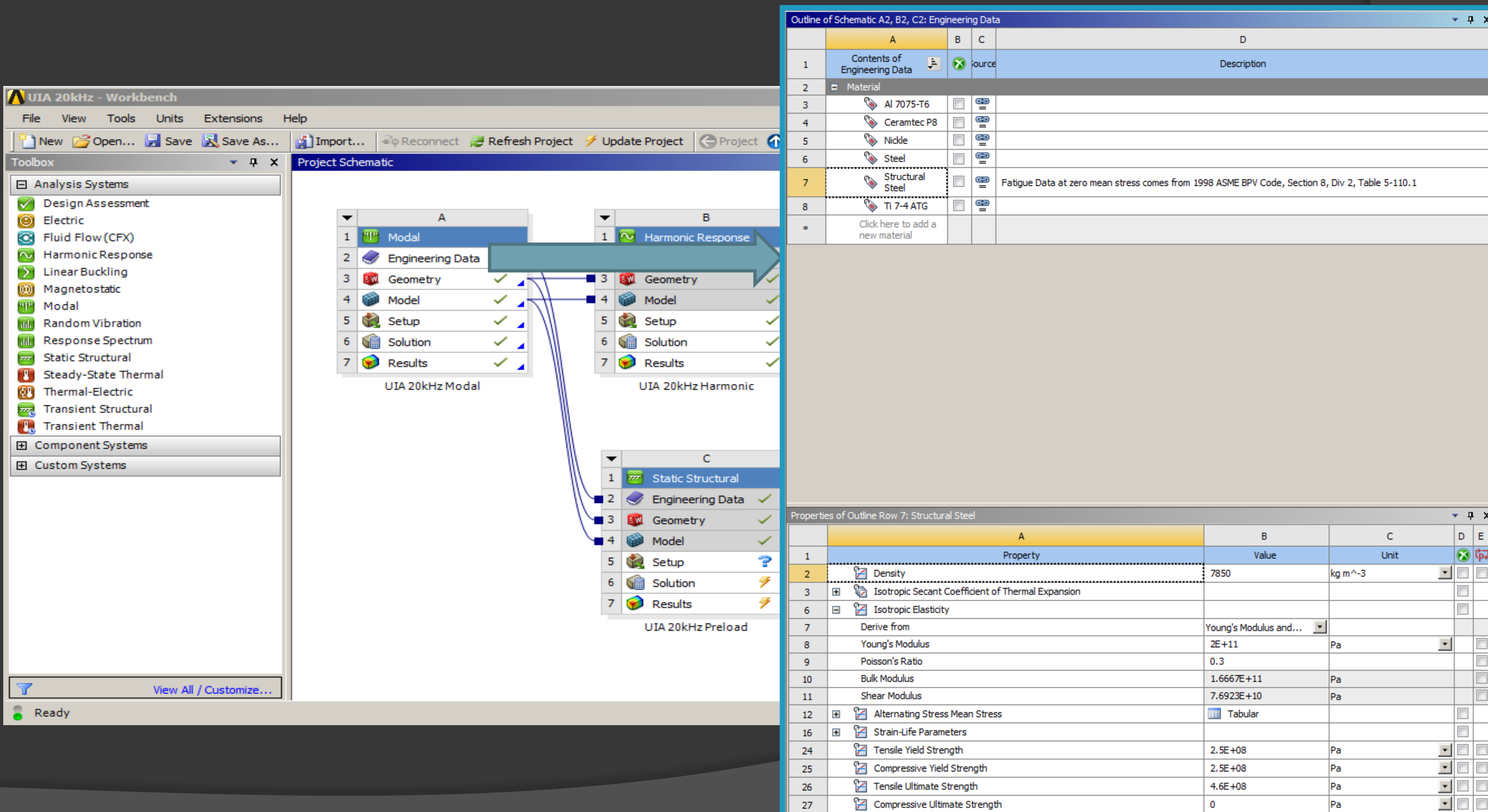
- All three analysis point to the same geometry in solid works
- Changes here affect all three analysis





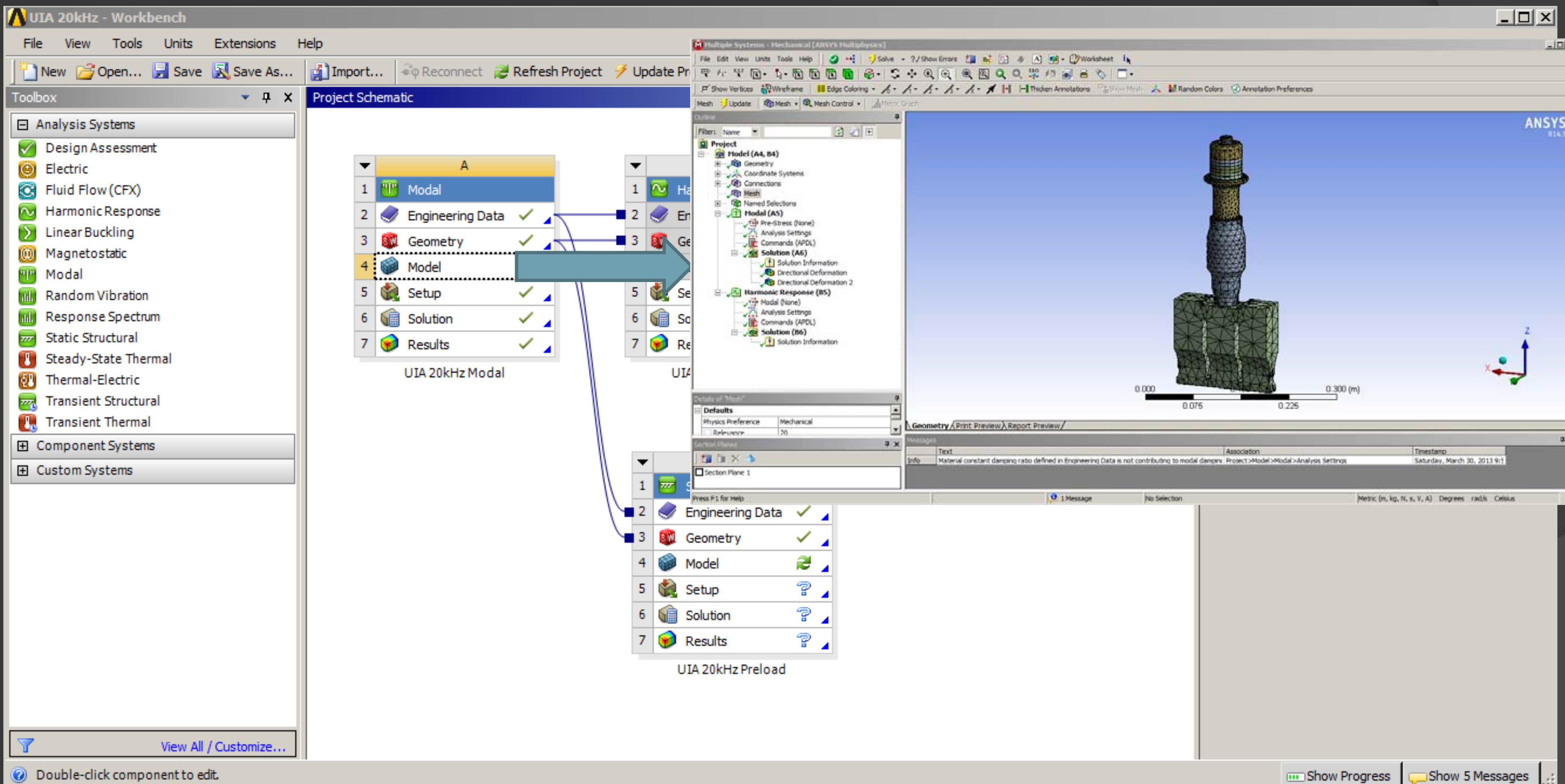
Transducer Design and Modeling
- ANSYS Workbench, Material Library -

- All three analysis point to the same material library
- Changes here affect all three analysis
- Standard acoustic materials only – *does not include Piezo materials*



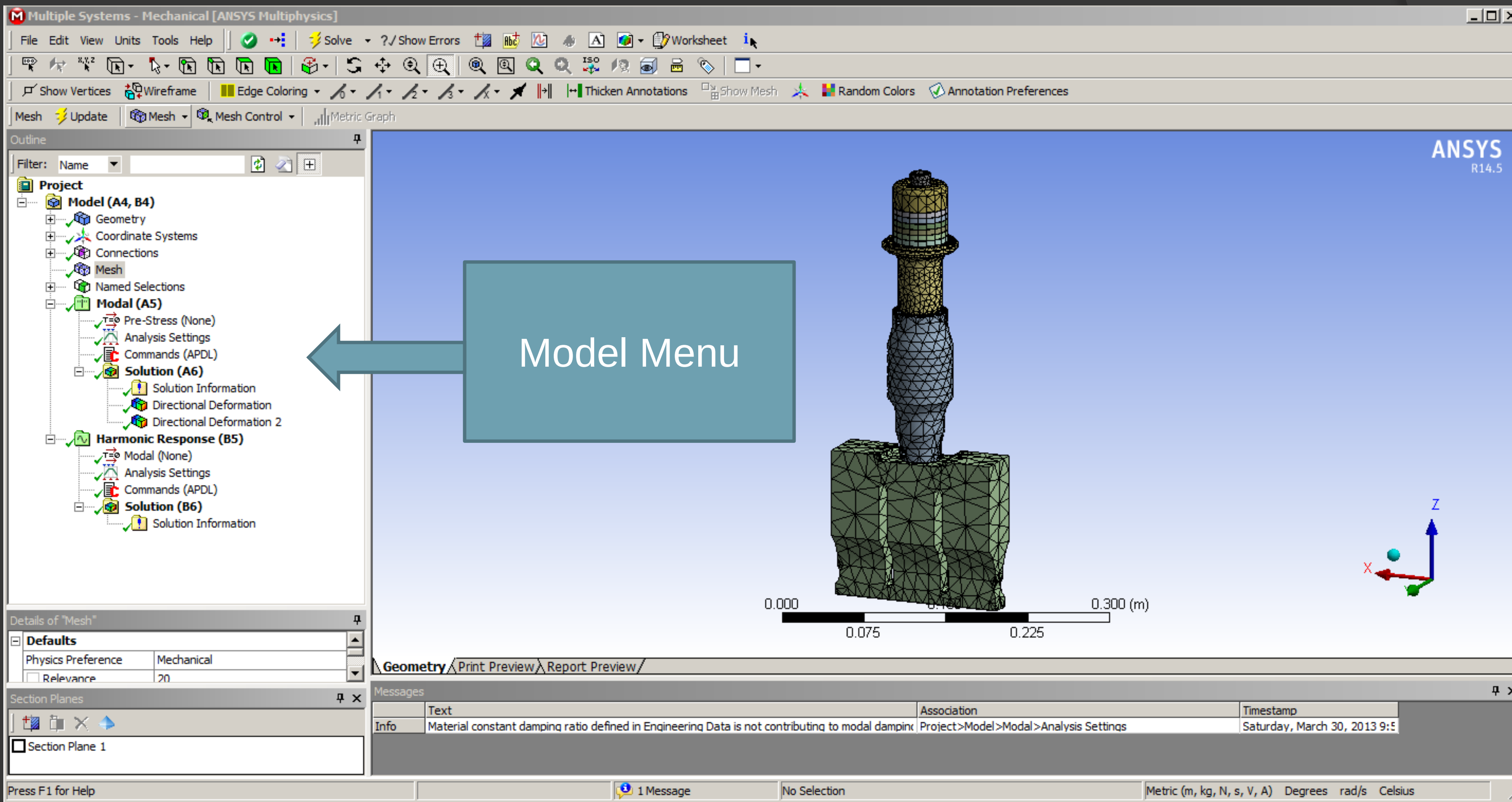
Transducer Design and Modeling
- ANSYS Workbench, ANSYS Mechanical -

- ANSYS finite element interface
- Meshing, naming, apply BC's, run, examine results
- Modal and harmonic model connected, static preload separate



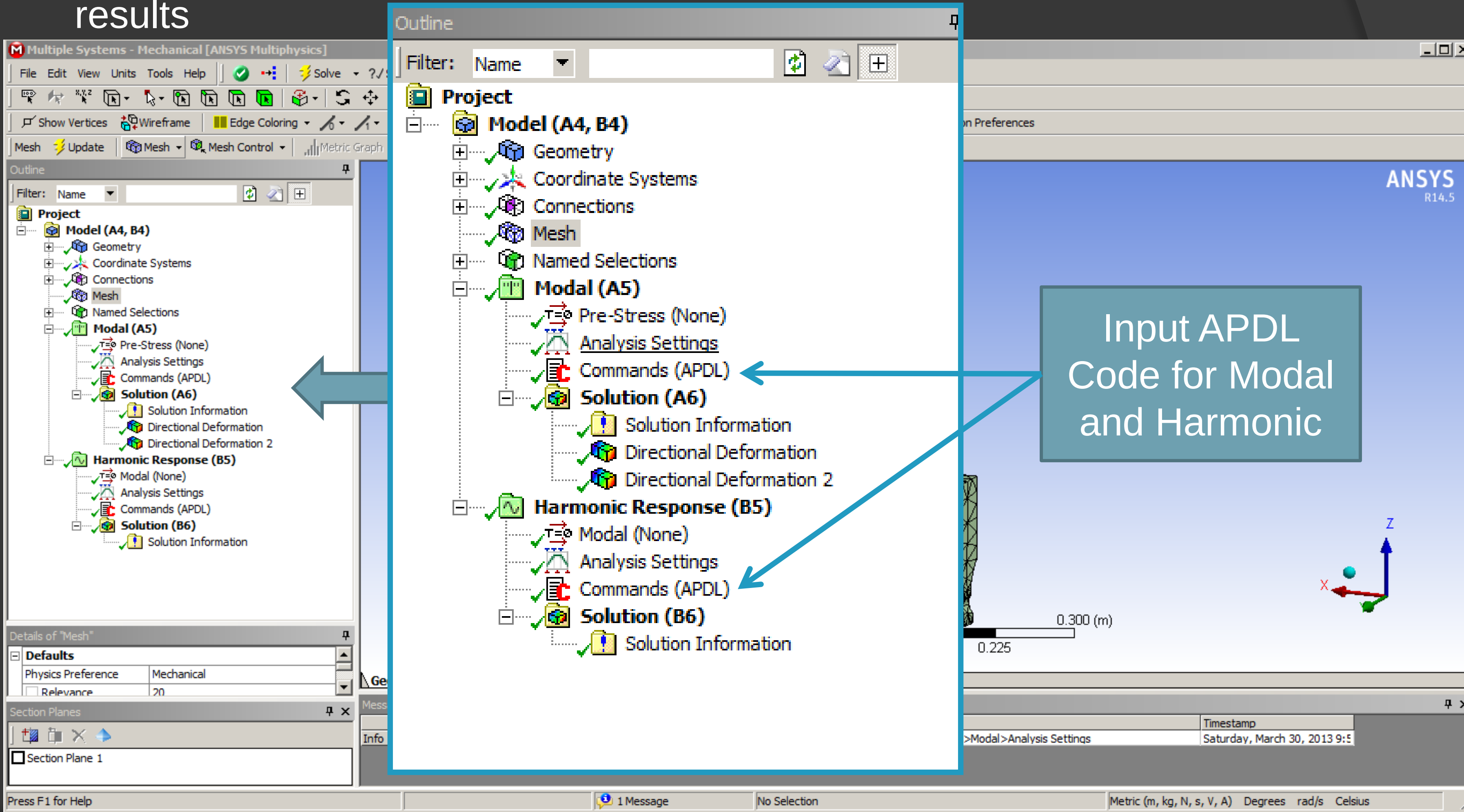
Transducer Design and Modeling
- ANSYS Workbench, ANSYS Mechanical -

- ANSYS finite element interface
- Meshing, naming, apply BC's, run, examine results
- Model menu



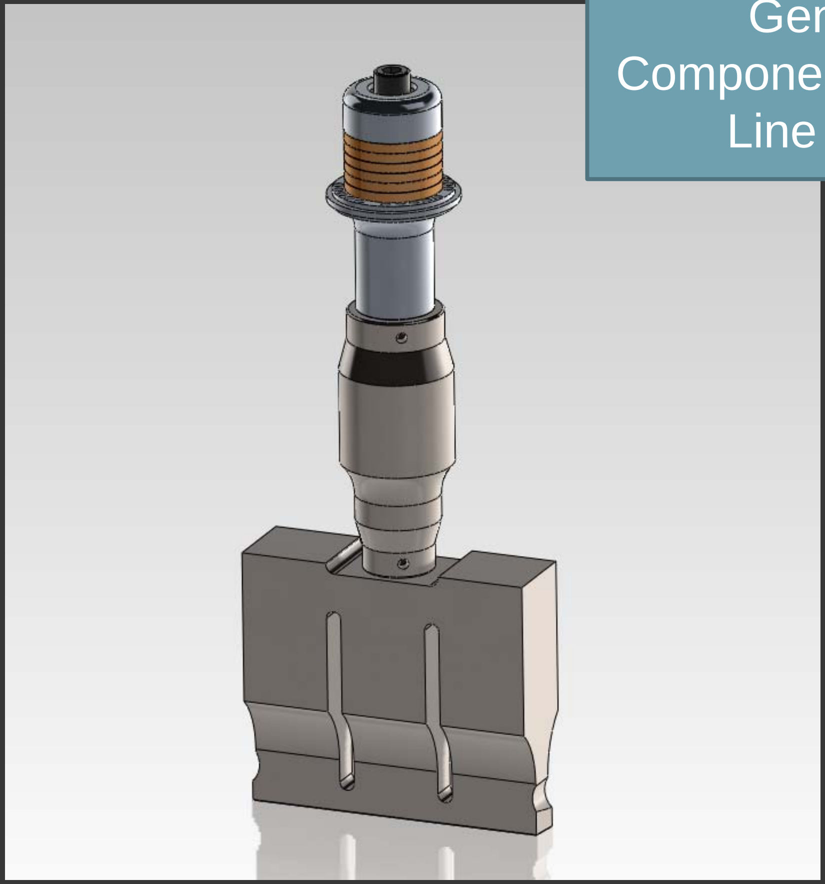
Transducer Design and Modeling
- ANSYS Workbench, Set Up Challenges for Ultrasonic Analysis -

- Piezo materials do no exist in standard model library
- Need to input into ANSYS using APDL programming language
- Use APDL for material definition, and boundary conditions, special piezo results

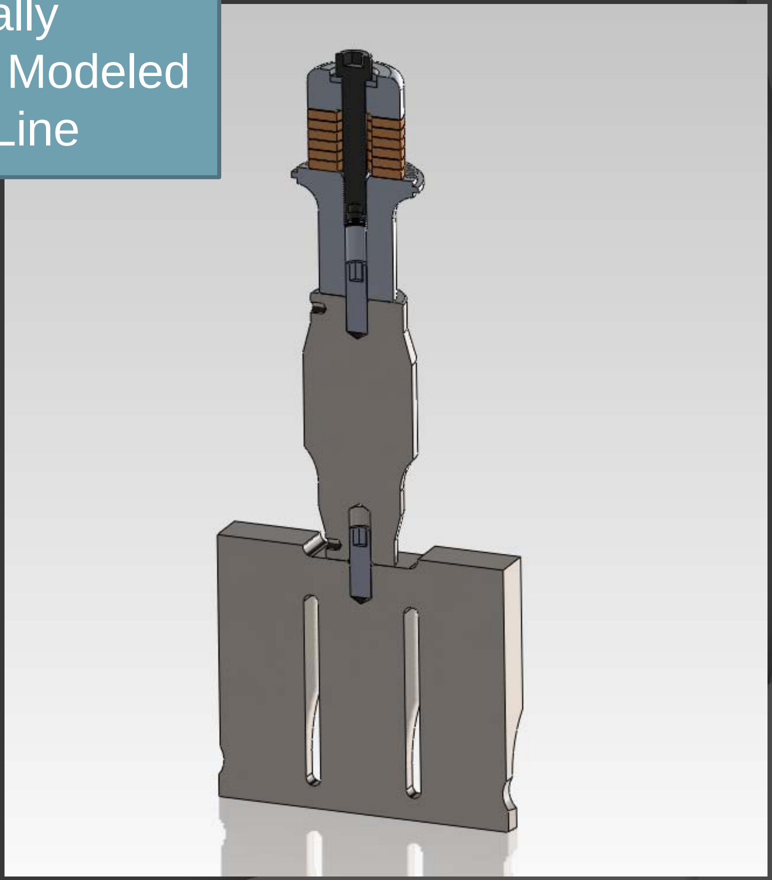


Transducer Design and Modeling
- Converter Stack Solid Model, Components -

- One common model for all analysis
- All stack components Modeled

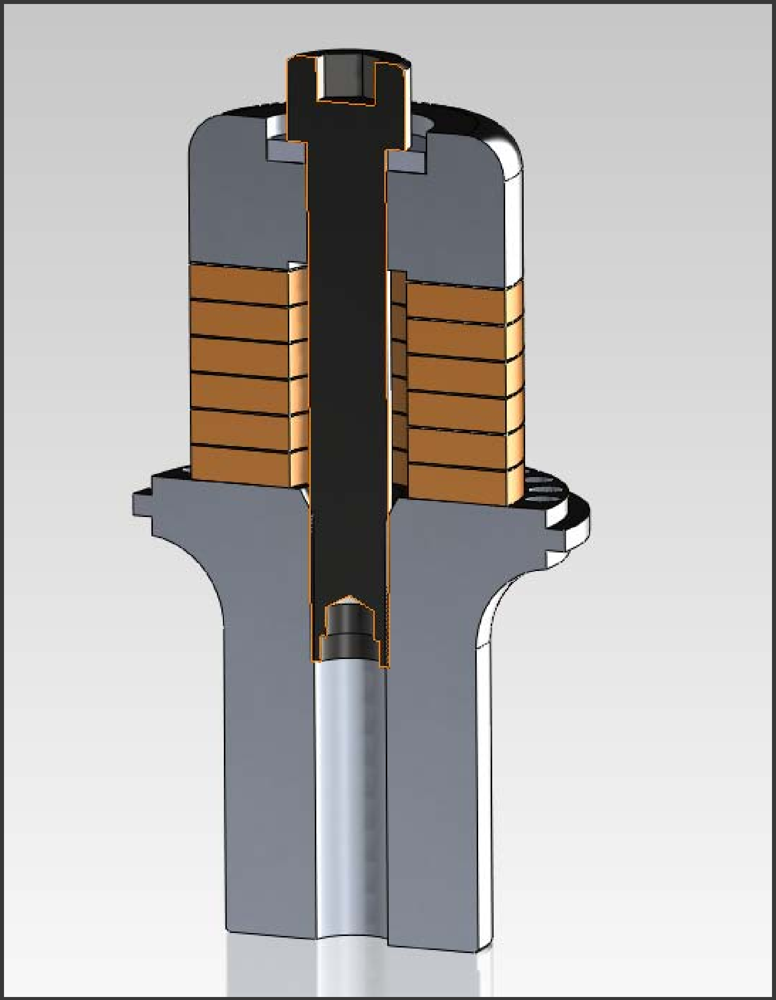


Generally Components Modeled Line to Line

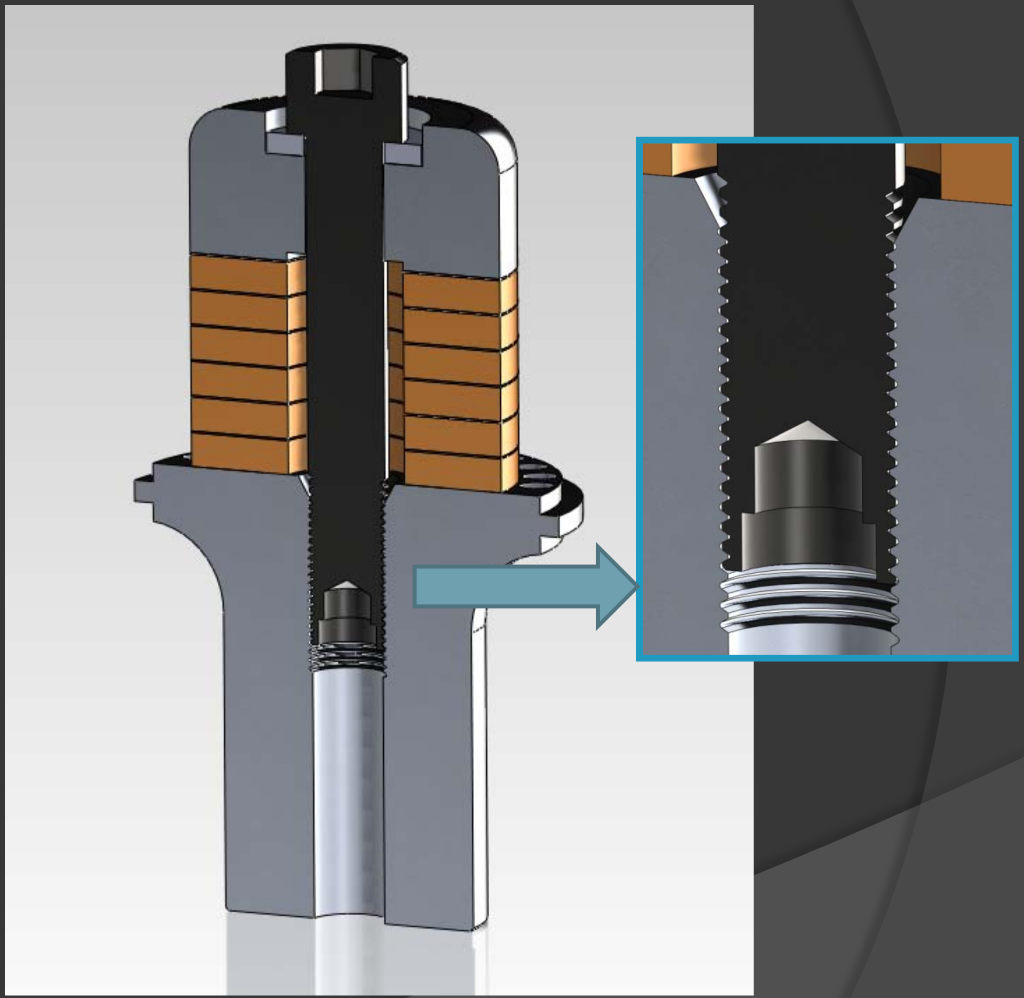


Transducer Design and Modeling
- Converter Stack Solid Model, Modeling Techniques -

- Use solid modeling configuration utility to include or remove analysis details



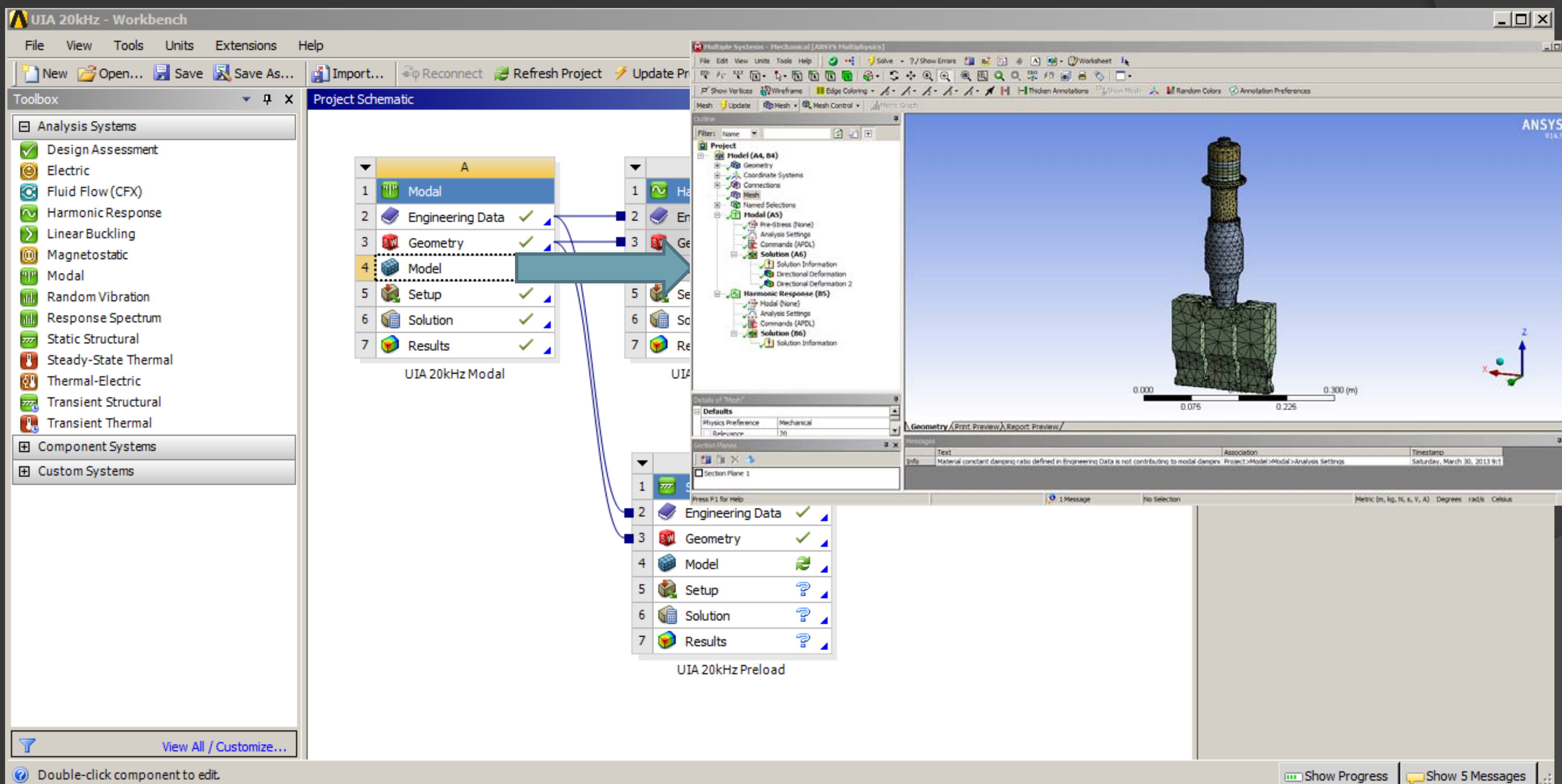
Non Thread Configuration



Thread Configuration

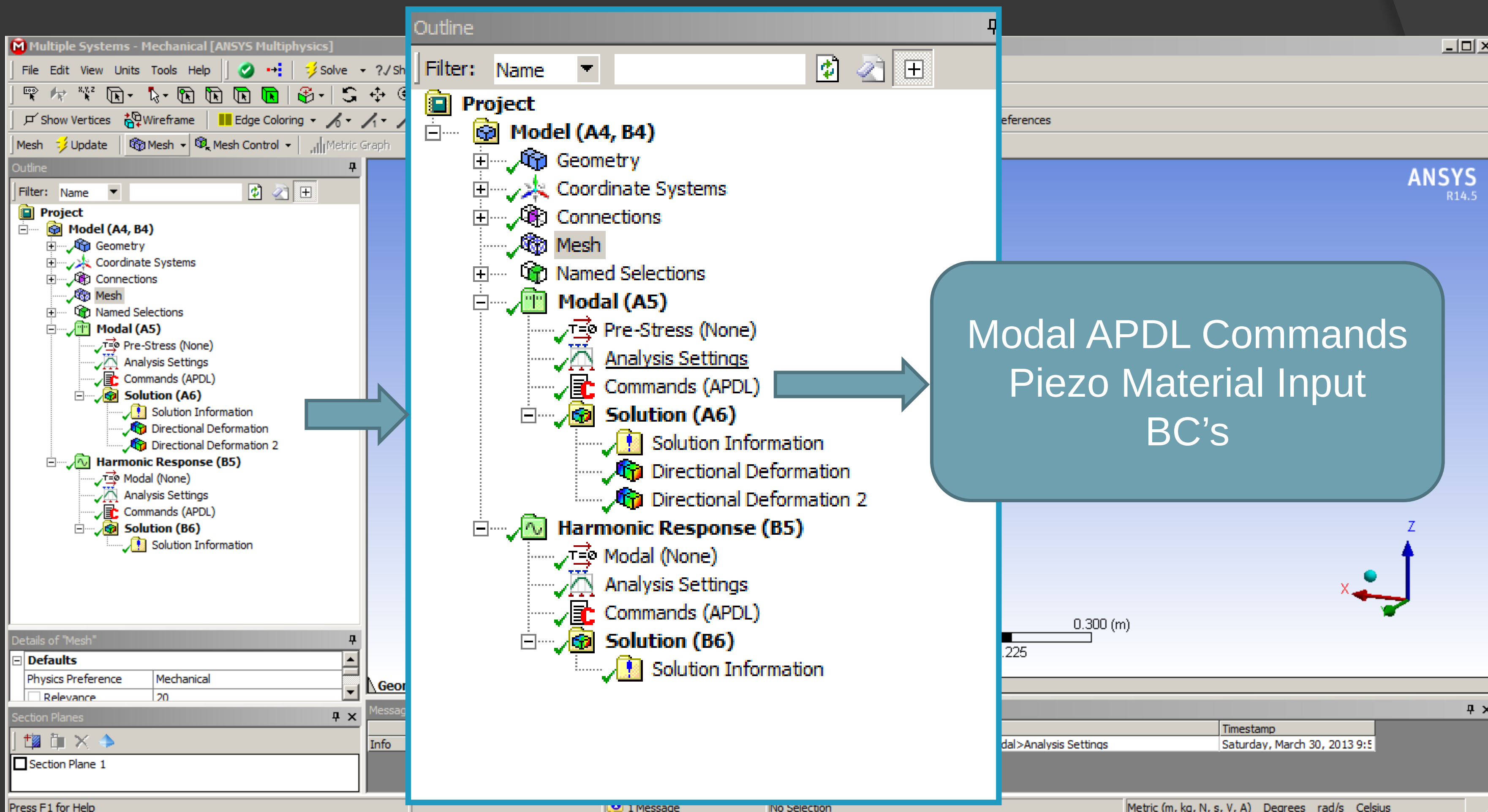
Transducer Design and Modeling
- Model Example - Modal Analysis -

- All model setup done in ANSYS Mechanical
- 2 of the three analysis are connected (modal and harmonic). Both will use the same meshed model (Preload is separate)



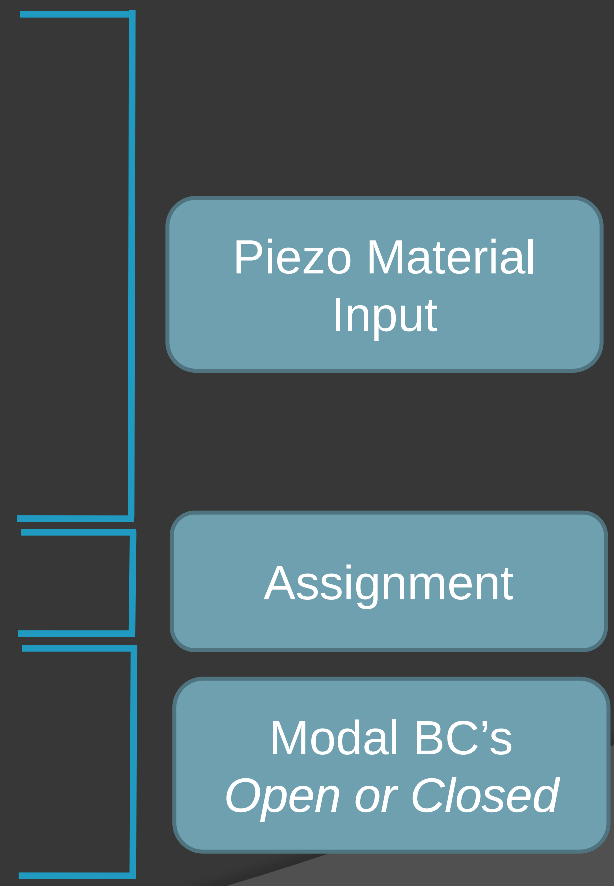
Transducer Design and Modeling
- Modal Analysis, Use of APDL programming Language -

- All model setup done in ANSYS Mechanical
- Standard model setup for geometry, connections, mesh, modal setup
- Insert APDL command under Modal (A5) for Piezo input



Transducer Design and Modeling
- Modal Analysis, Set-up of piezo materials / assignments -

- ANSYS APDL Code for a modal analysis
- Material input, assignment, Modal BC's



Transducer Design and Modeling
- Modal Analysis, Set-up of piezo materials / assignments -

- Electrical / mechanical performance in high end FEA packages (ex ANSYS, Abaqus) is analyzed using coupled field elements.
- 3 input material matrices required – Piezo elasticity, piezo stress matrix, piezo permativity matrix

$$\{T\} = [c^E]\{S\} - [e]\{E\}$$

$$\{D\} = [e]^T\{S\} + [\varepsilon^S]\{E\}$$

or equivalently

$$\begin{Bmatrix} \{T\} \\ \{D\} \end{Bmatrix} = \begin{bmatrix} [c^E] & [e] \\ [e]^T & -[\varepsilon^S] \end{bmatrix} \begin{Bmatrix} \{S\} \\ -\{E\} \end{Bmatrix}$$

where:

$\{T\}$ = stress vector (referred to as $\{\sigma\}$ elsewhere in this manual)
$\{D\}$ = electric flux density vector
$\{S\}$ = strain vector (referred to as $\{\varepsilon\}$ elsewhere in this manual)
$\{E\}$ = electric field intensity vector
$[c^E]$ = elasticity matrix (evaluated at constant electric field (referred to as [D] elsewhere in this manual))
$[e]$ = piezoelectric stress matrix
$[\varepsilon^S]$ = dielectric matrix (evaluated at constant mechanical strain)

$$[c] = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ & & c_{33} & c_{34} & c_{35} & c_{36} \\ & \text{Symmetric} & & c_{44} & c_{45} & c_{46} \\ & & & & c_{55} & c_{56} \\ & & & & & c_{66} \end{bmatrix}$$

Piezo Elasticity

$$[e] = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \\ e_{41} & e_{42} & e_{43} \\ e_{51} & e_{52} & e_{53} \\ e_{61} & e_{62} & e_{63} \end{bmatrix}$$

Piezo Stress

$$[\varepsilon^S] = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}$$

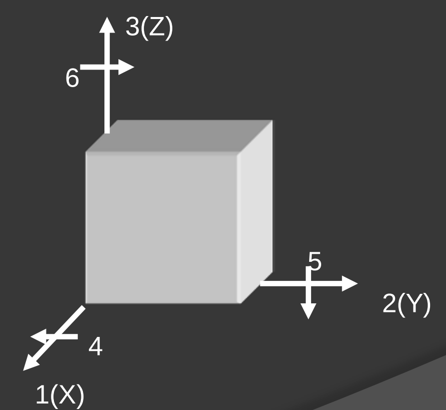
Piezo Perm

Transducer Design and Modeling
- Modal Analysis, Set-up of piezo materials / assignments -

- Piezoelectric Material properties gathered from manufacturers catalogs
  - Need d33, d31, d15, d32, d24 (d matrix)
  - Need s11E, s33E, s44E, s12E, s13E, s23E, s55E, s66E (compliance)
  - Need e11S, e22S, e33S (permittivity)

Useful Relations for Catalog Values

- d33 and d31 need to account for preload
- d32 = d31
- d24 = d15
- s23E = s31E
- s55E = s44E
- S66E = 2(s11E –s13E)



Axis System for Matrix Calculations Catalog Values

Transducer Design and Modeling
- Modal Analysis, Set-up of piezo materials / assignments -

- Material compliance input [s] and Piezoelectric Matrix Input [d] (ANSYS and ABAQUS)
- Some mathematical manipulation is required (Matrix operations, ANSYS shear terms adjusted)

$[s]^E$ Compliance Matrix (m^2/N) - Closed Circuit

1.14E-11	-4.80E-12	-3.70E-12	0	0	0
-4.80E-12	1.37E-11	-4.80E-12	0	0	0
-3.70E-12	-4.80E-12	1.14E-11	0	0	0
0	0	0	3.19E-11	0	0
0	0	0	0	3.24E-11	0
0	0	0	0	0	3.19E-11

$[c]^E$ Stiffness Matrix (N/m^2) - Closed Circuit

1.484E+11	8.079E+10	8.219E+10	0	0	0
8.079E+10	1.296E+11	8.079E+10	0	0	0
8.219E+10	8.079E+10	1.484E+11	0	0	0
0	0	0	3.135E+10	0	0
0	0	0	0	3.086E+10	0
0	0	0	0	0	3.135E+10

ANSYS Input

[c] Stiffness Matrix (N/m^2) - Closed Circuit

1.484E+11	8.079E+10	8.219E+10	0	0	0
8.079E+10	1.296E+11	8.079E+10	0	0	0
8.219E+10	8.079E+10	1.484E+11	0	0	0
0	0	0	3.135E+10	0	0
0	0	0	0	3.135E+10	0
0	0	0	0	0	3.086E+10

Note: Shear terms adjusted for ANSYS input

[d] Piezoelectric Matrix (C/N)

0	0	0	0	0	3.80E-10
-9.50E-11	2.50E-10	-9.50E-11	0	0	0
0	0	0	3.80E-10	0	0

[d] Piezoelectric Matrix Transposed (C/N)

0	-9.5E-11	0
0	2.5E-10	0
0	-9.5E-11	0
0	0	3.8E-10
0	0	0
3.8E-10	0	0

[d] * [c] = Piezoelectric Matrix (C/m^2)

0	-1.71	0
0	17.05	0
0	-1.71	0
0	0	11.91
0	0	0
11.91	0	0

ANSYS Input

[d] * [c] = Piezoelectric Matrix (C/m^2)

0	-1.71	0
0	17.05	0
0	-1.71	0
11.91	0	0
0	0	11.91
0	0	0

Note: Shear terms adjusted for ANSYS input

<u>Note on Shear Term Manipulation From the ANSYS Manual</u>

For most published piezoelectric materials, the order used for the piezoelectric matrix is x, y, z, yz, xz, xy, based on IEEE standards (see ANSI/IEEE Standard 176–1987), while the ANSYS input order is x, y, z, xy, yz, xz as shown above. This means that you need to transform the matrix to the ANSYS input order by switching row data for the shear terms.

Transducer Design and Modeling

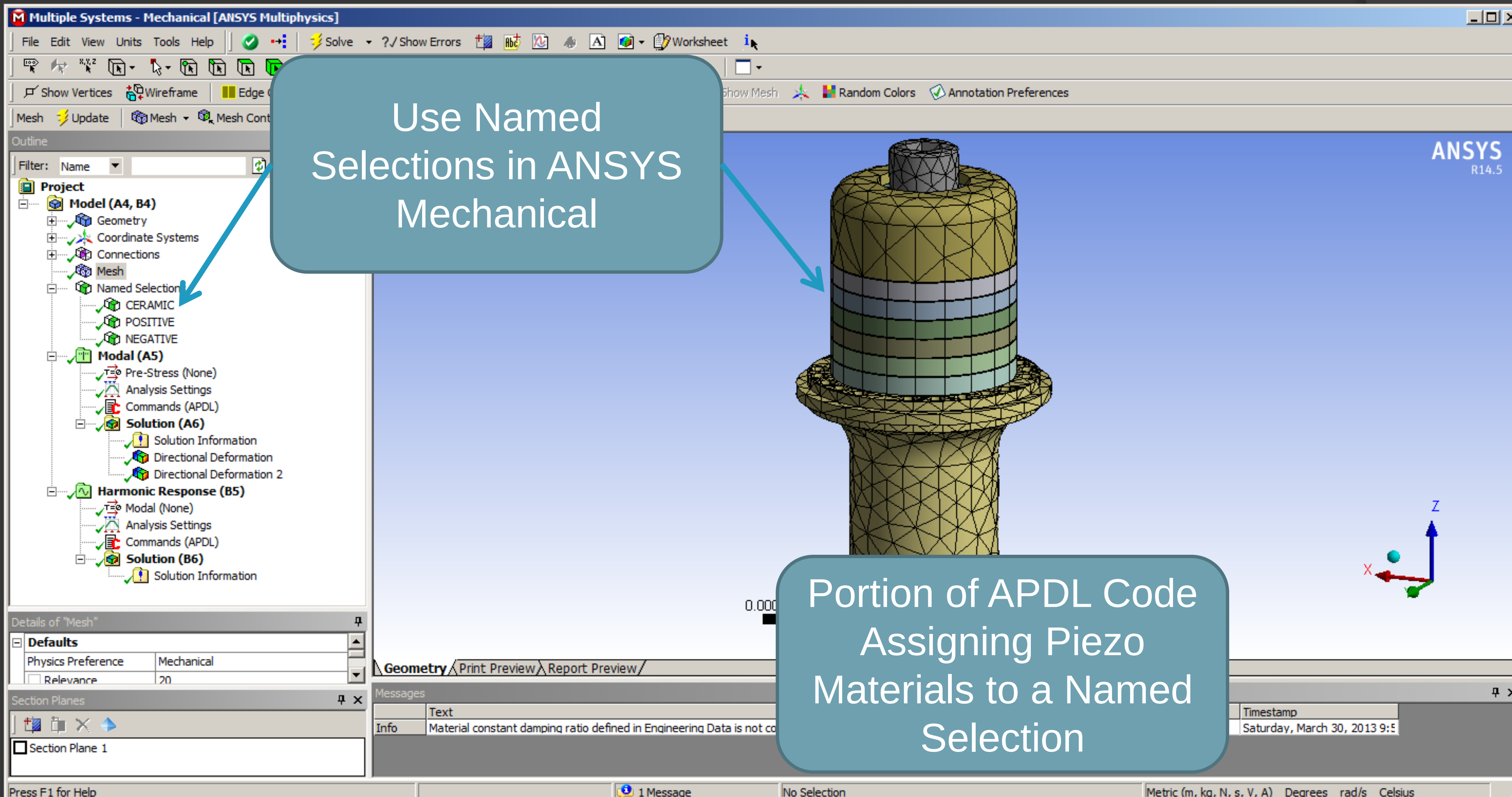
- Modal Analysis - Modal Analysis, Set-up of piezo materials / assignments -

- ANSYS APDL Code for piezo materials

Portion of ANSYS APDL Code Permittivity, Piezo, Compliance Matrix

Transducer Design and Modeling
- Modal Analysis - Modal Analysis, Set-up of piezo materials / assignments -

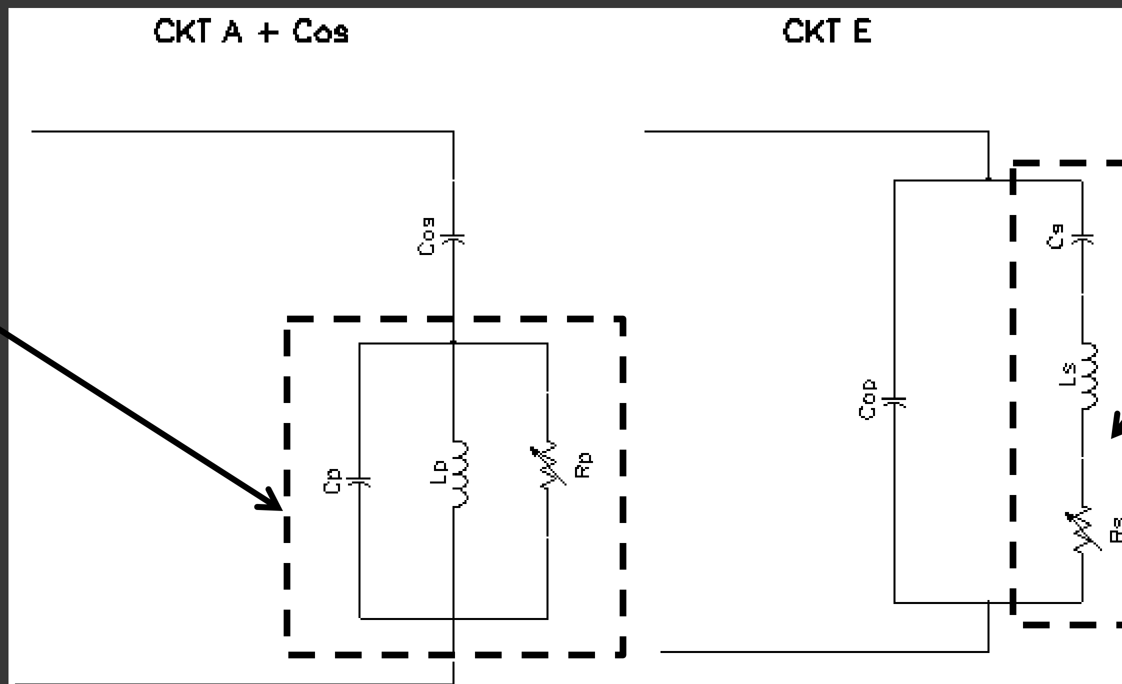
- Assign materials using ANSYS Mechanical Named Selections



Transducer Design and Modeling
- Modal Analysis, Theory – Series and Parallel Analysis -

- Transducer Equivalent Circuit
- The transducer system can be modeled as a lumped parameter system
- Either circuit model below is valid for modeling a transducer using lumped parameters

transducer modeled as a parallel circuit

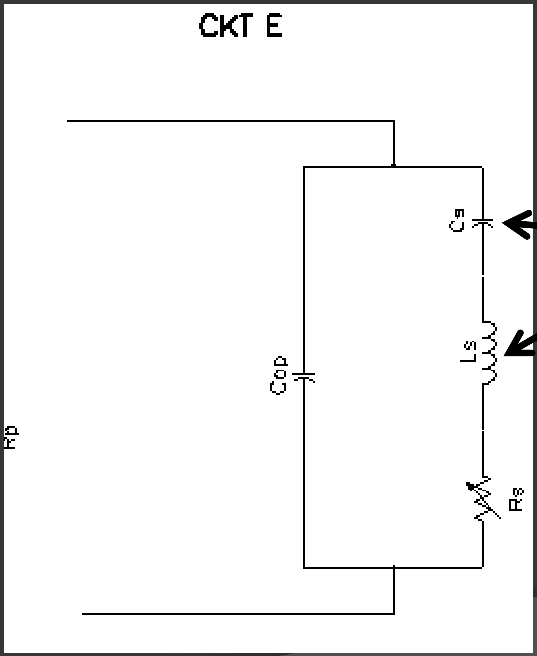


transducer modeled as a series circuit

Cos/Cop = transducer capacitance
Cs/Cp = transducer stiffness
Ls/Lp = transducer mass
Rs/Rp = transducer loss (load)

Transducer Design and Modeling
- Modal Analysis, Theory – Series and Parallel Analysis -

- Series Resonance is the frequency where Cs resonates with Ls
- Cs and Ls effectively cancel, creating a short circuit (when Rs = 0). This creates maximum current for minimum voltage = low impedance point
- This is called series resonance, short circuit resonance, or mechanical resonance
- In series resonant systems, converter amplitude is proportional to current (In the motional branch)
- In a load varying system, series resonant systems usually employ some sort of current control

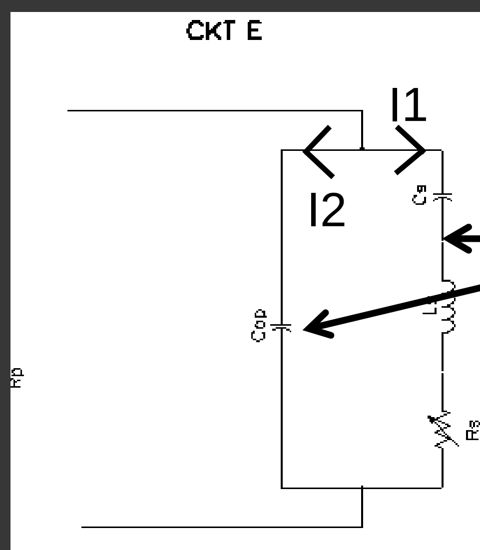


These reactive components cancel. Creates a short circuit when Rs=0

$$F_s = 1/2\pi \sqrt{1/(L_s C_s)}$$

Transducer Design and Modeling
- **Modal Analysis,** Theory – Series and Parallel Analysis -

- <u>Parallel Resonance</u> is the frequency where the Cs/Ls combination resonates with Cop
- The I1 and I2 currents are equal and opposite in phase. They effectively cancel each other. No net current flows (when R=0). Circuit now looks like an open circuit.
- The is called <u>parallel resonance</u>, or <u>open circuit resonance</u>
- In parallel resonant systems, transducer amplitude is proportional to voltage (In the motional branch)
- In a load varying system, parallel resonant systems usually employ some sort of voltage control



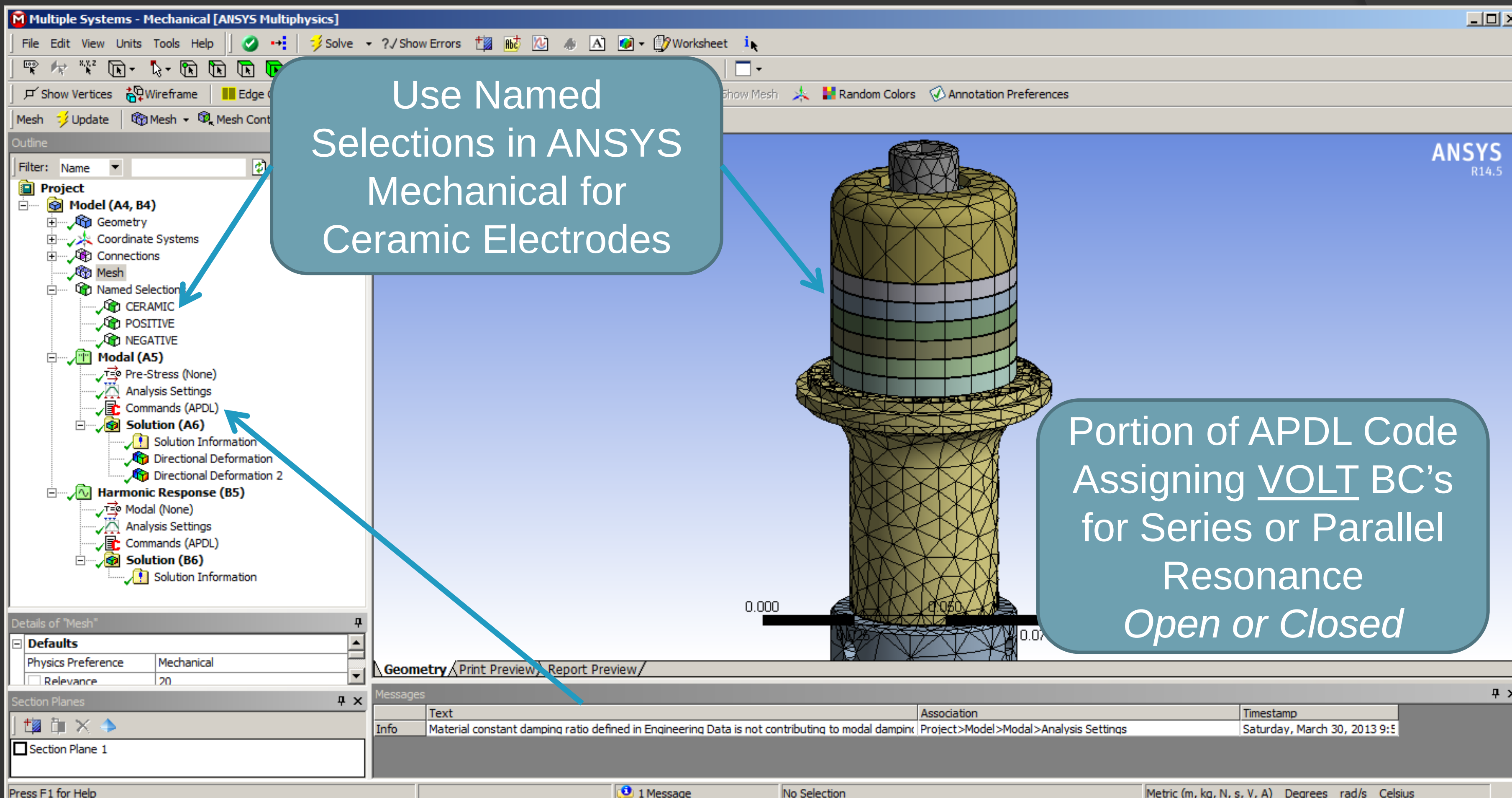
Cs/Ls combination resonates with Cop

$$Fp = 1/2\pi \sqrt{1/LsCs+(1+Cs/Co)}$$

Transducer Design and Modeling

- Modal Analysis, Boundary conditions – series and parallel analysis -

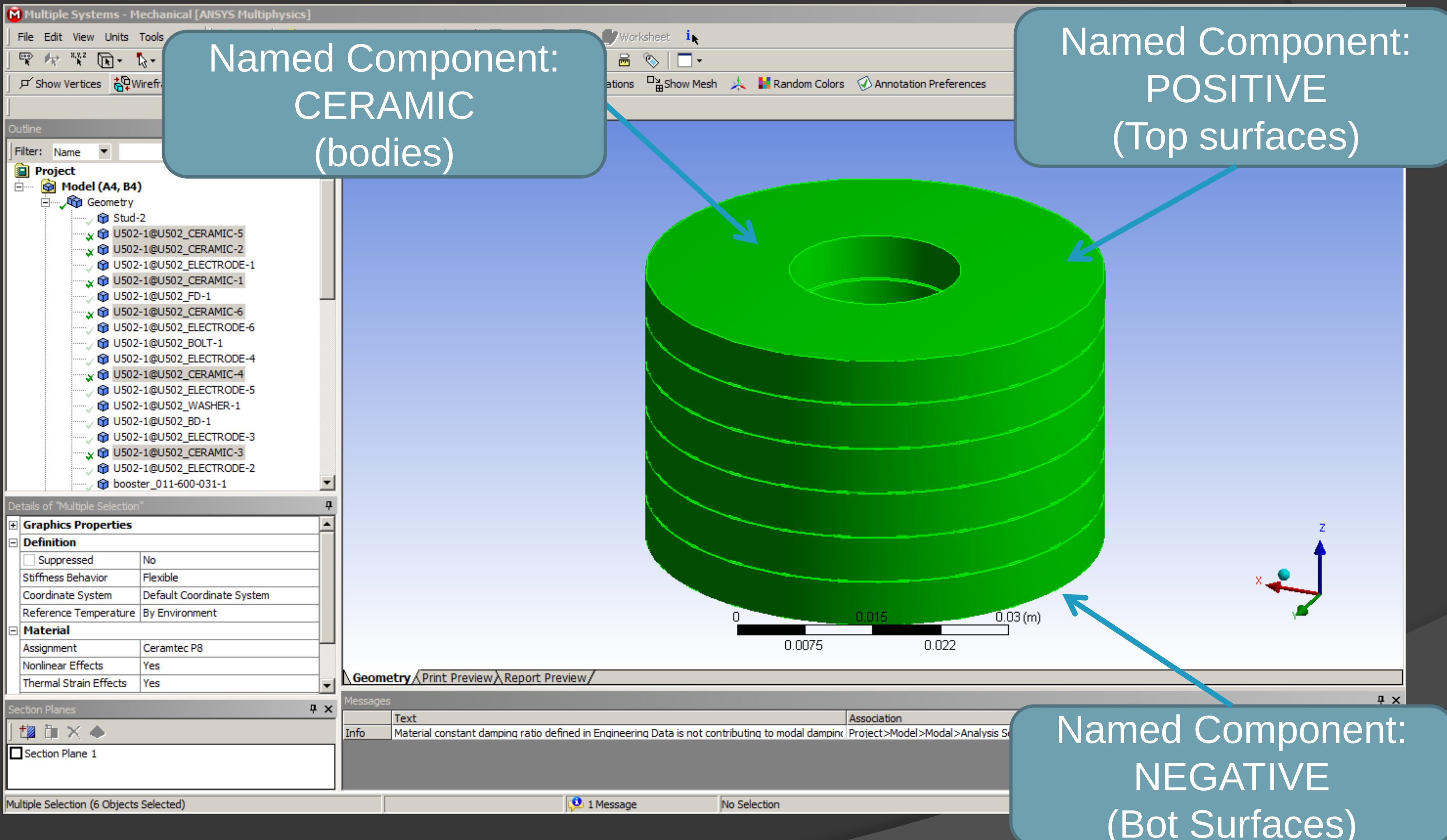
- ANSYS APDL Code, Apply BC's for parallel or series modal analysis



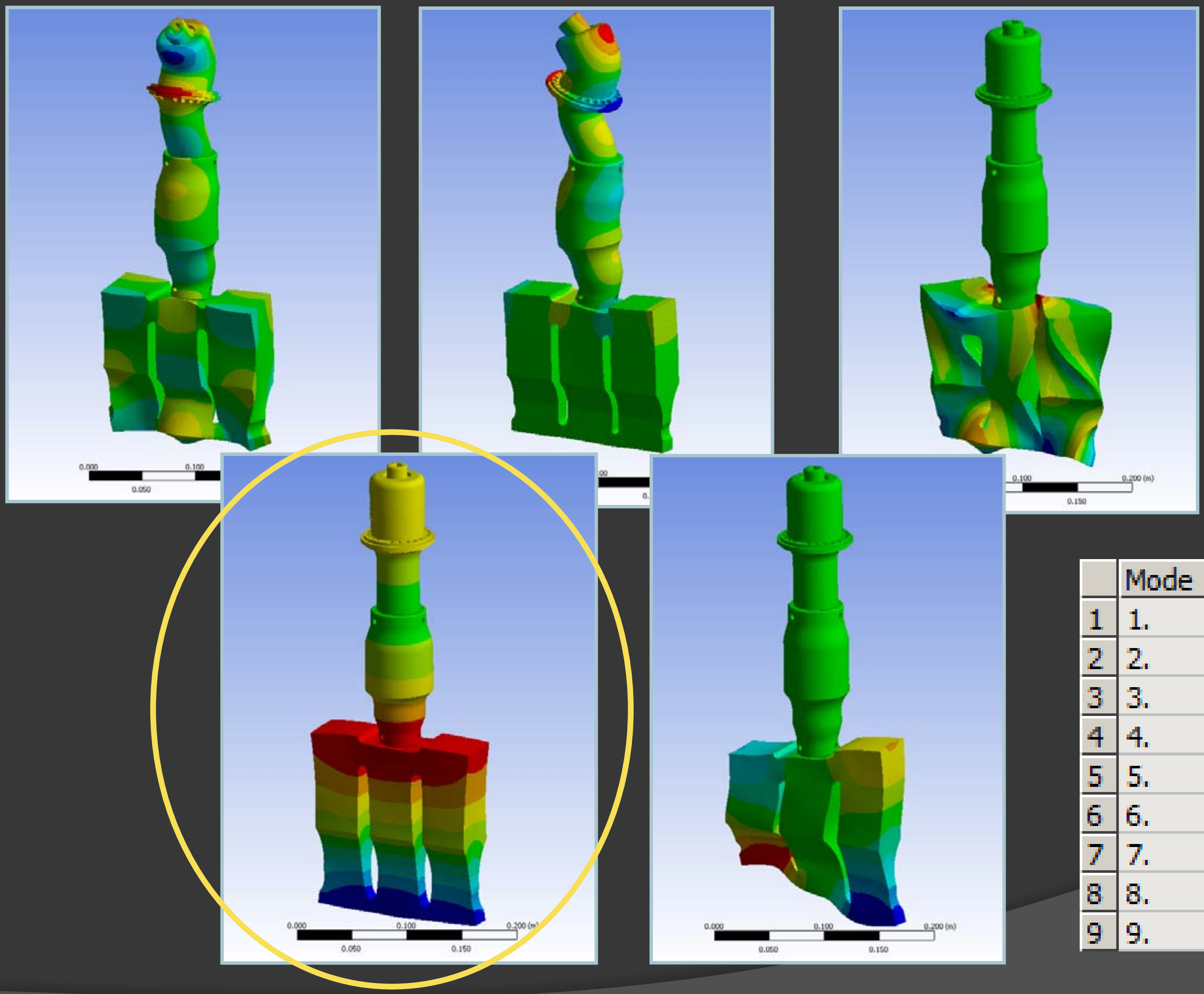
Transducer Design and Modeling

- Modal Analysis, Boundary conditions – series and parallel analysis -

- ANSYS APDL Code, Apply BC's for parallel or series modal analysis



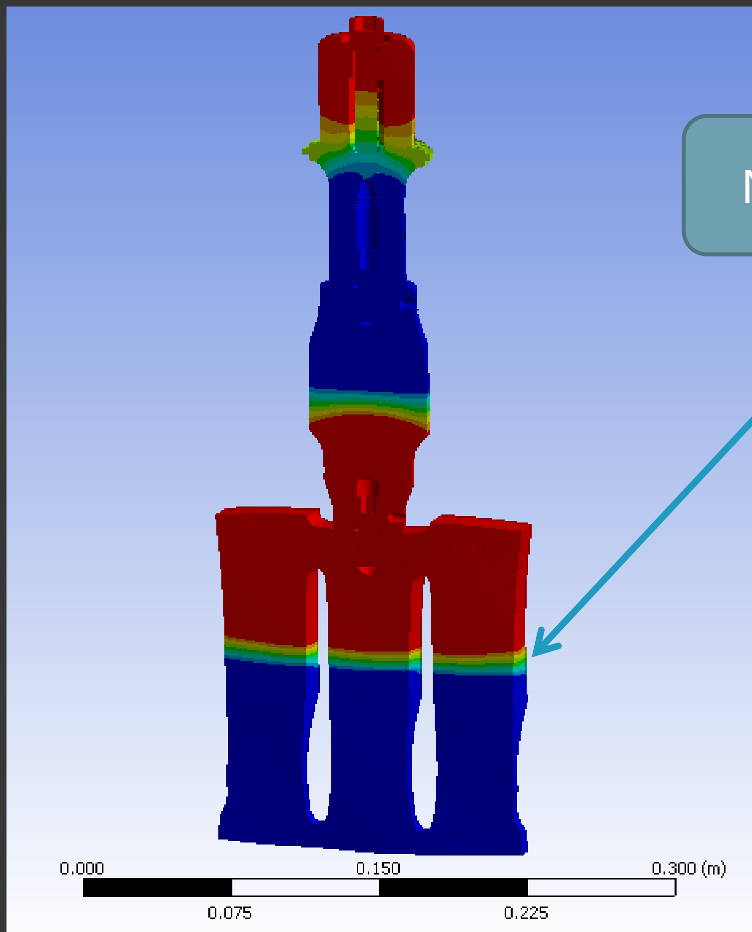
Transducer Design and Modeling
- Modal Analysis, Examining results -



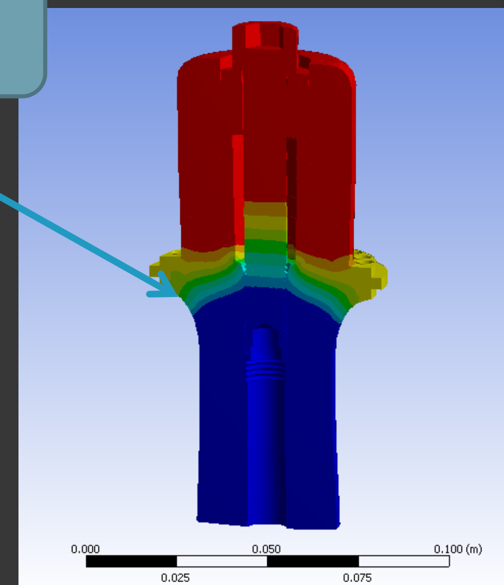
	Mode	Frequency [Hz]
1	1.	18014
2	2.	18318
3	3.	19482
4	4.	19654
5	5.	20107
6	6.	20147
7	7.	21048
8	8.	21324
9	9.	21918

Axial Resonance

Transducer Design and Modeling
- Modal Analysis, Examining results -

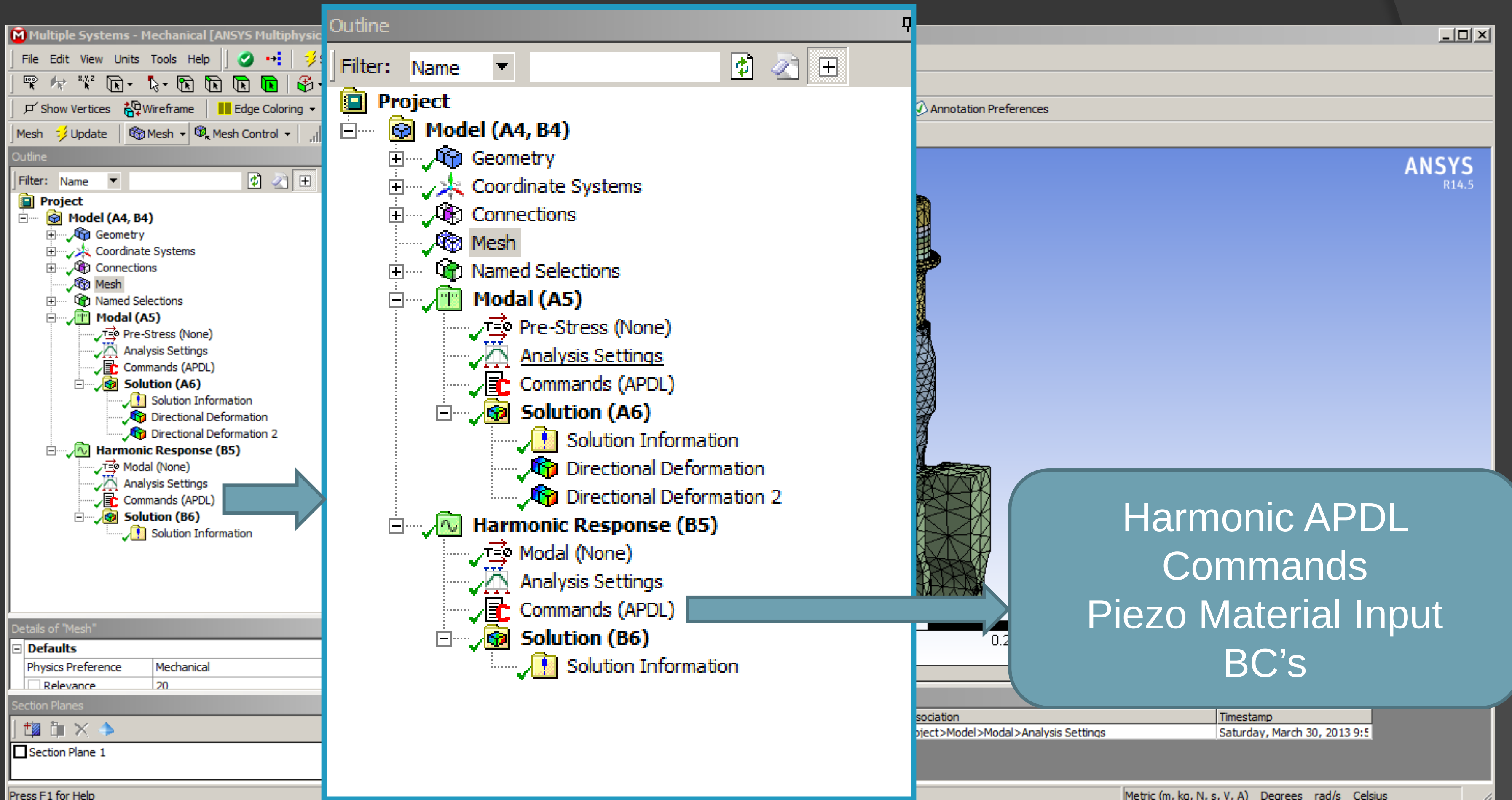


Node Locations



Transducer Design and Modeling
- Harmonic Analysis, Use of APDL programming Language -

- All model setup done in ANSYS Mechanical
- Standard model setup for geometry, connections, mesh, modal setup
- Insert APDL command under Harmonic Response (B5) for Piezo input



Transducer Design and Modeling

- Harmonic Analysis, Use of APDL programming language -

- ANSYS APDL Code for a harmonic analysis
- Material input, assignment, harmonic BC’s

Piezo Material Input
(Same as Modal)

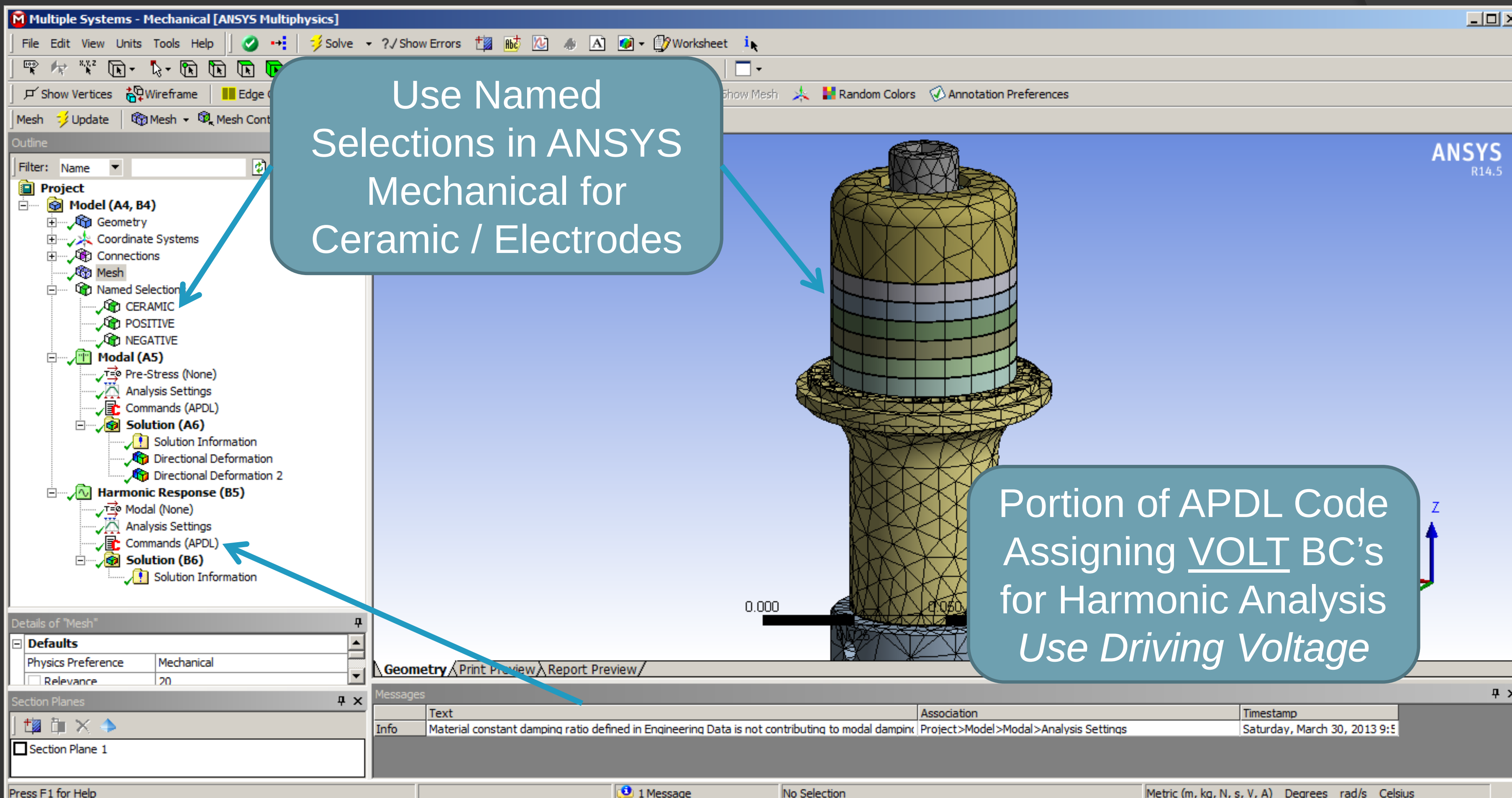
Assignment
(Same as Modal)

Harmonic BC’s
Use Driving Voltage

Transducer Design and Modeling

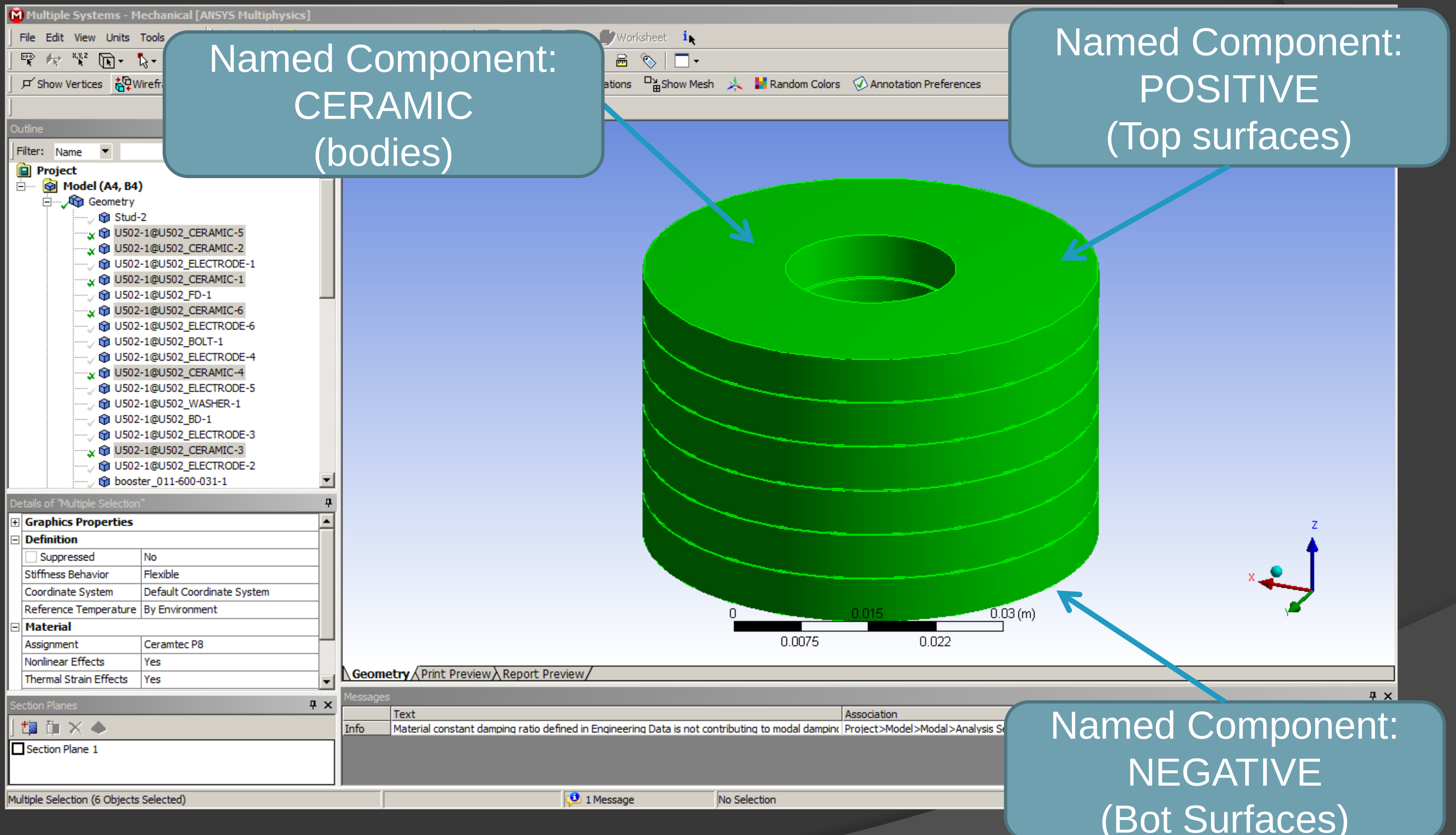
- Harmonic Analysis, Boundary Conditions -

- ANSYS APDL Code, Apply BC's for harmonic analysis



Transducer Design and Modeling
- Harmonic Analysis, Boundary conditions -

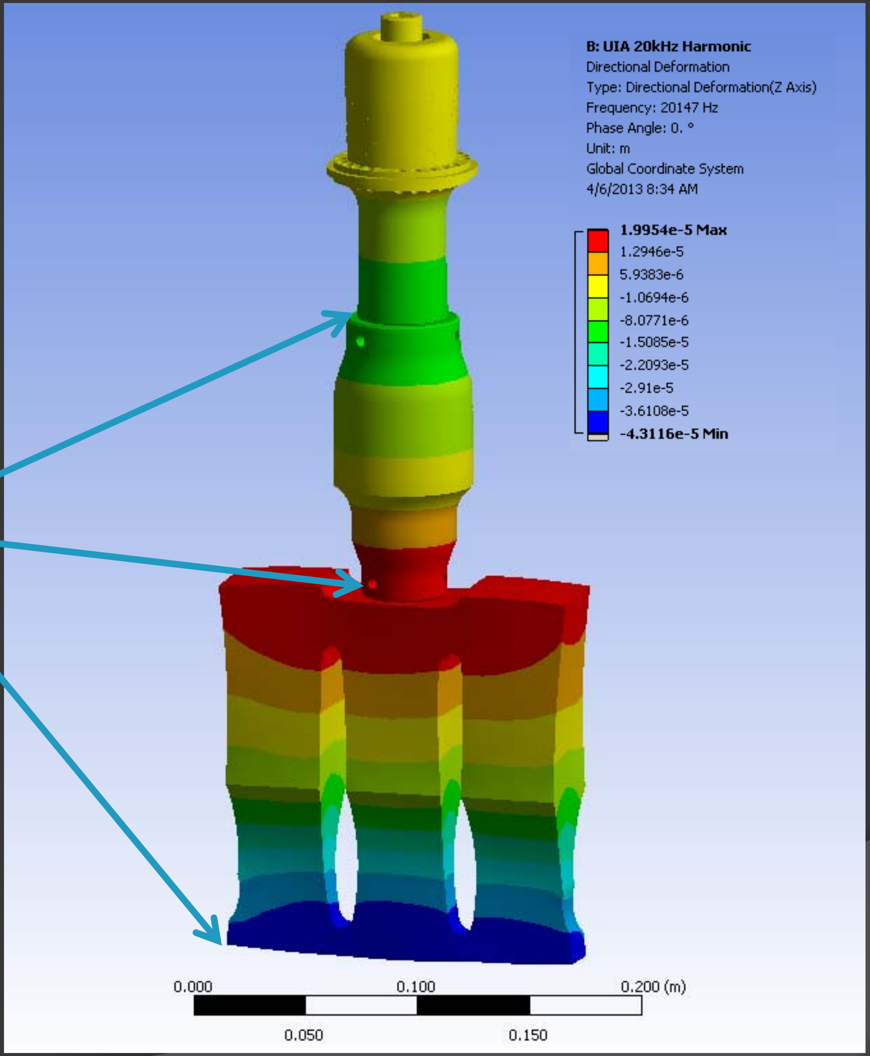
- ANSYS APDL Code, Apply BC's for harmonic analysis



Transducer Design and Modeling
- Harmonic Analysis, Examining Single Point Results -

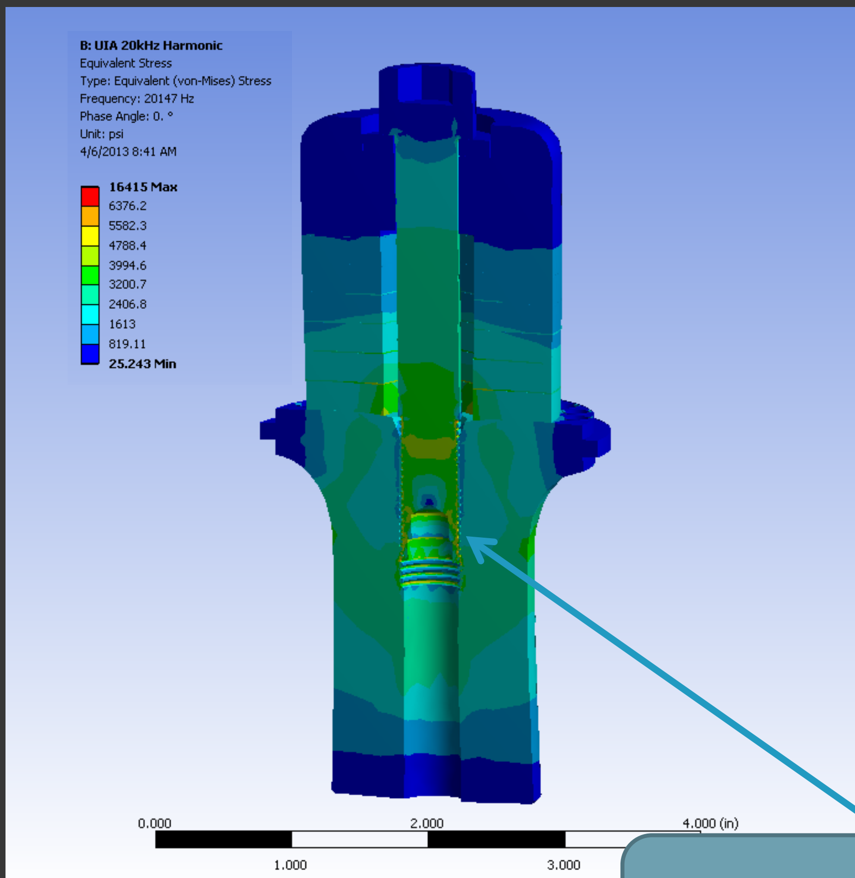
- In this example model is run at the parallel operating point

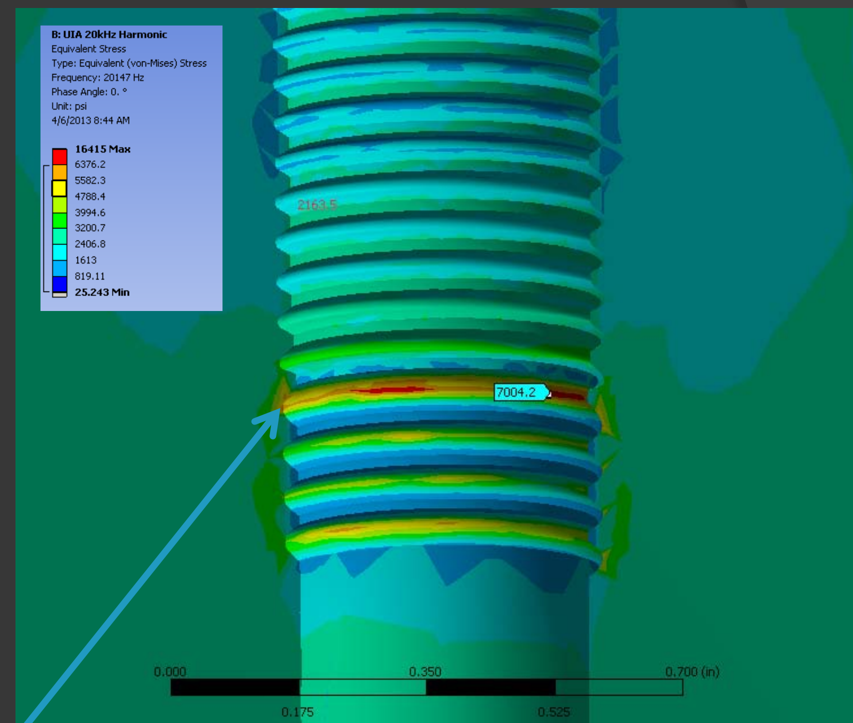
Harmonic Results
Verify model
Amplitudes



Transducer Design and Modeling
- Harmonic Analysis, Examining Single Point Results -

- In this example model is run at the parallel operating point

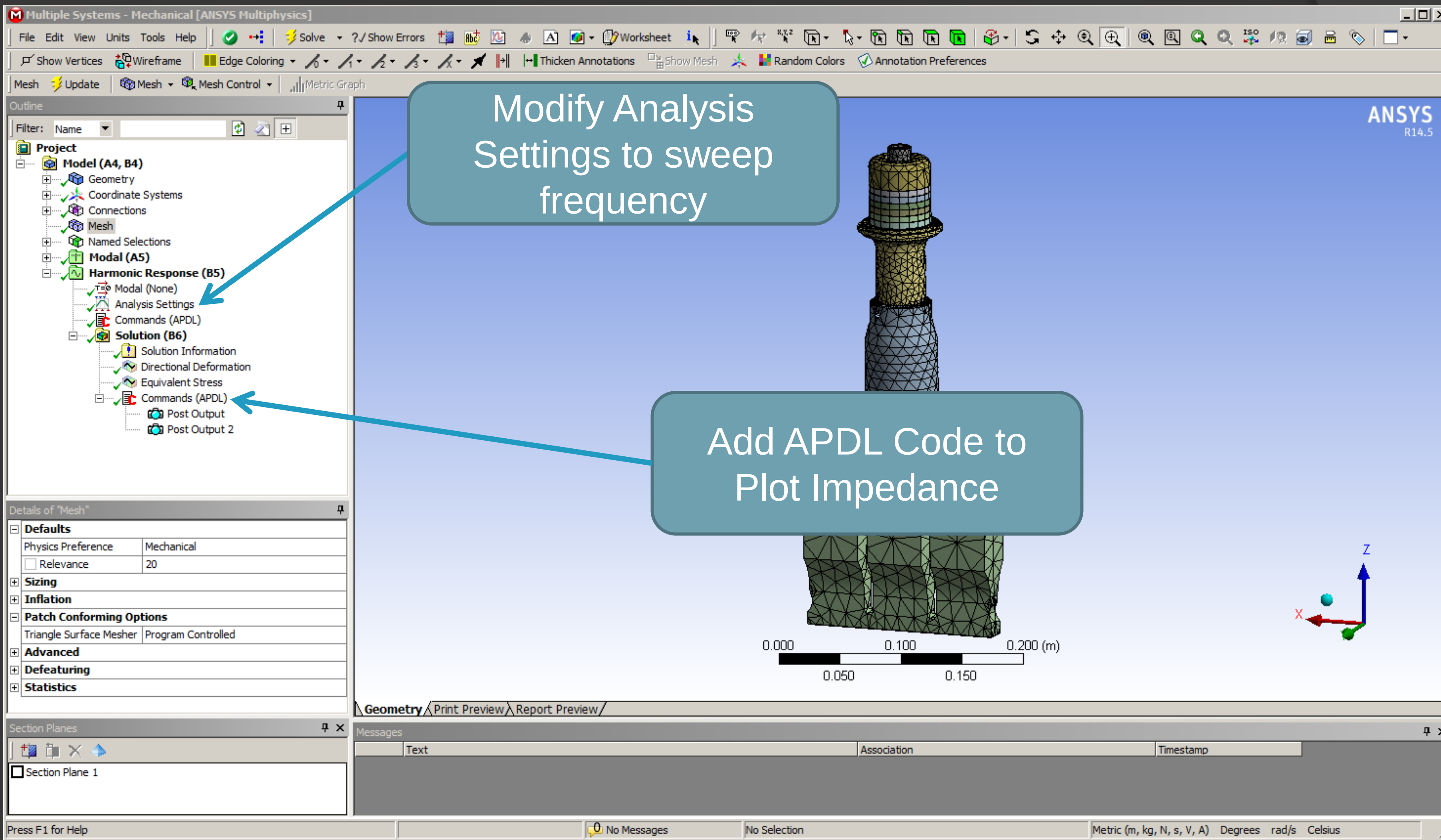




Harmonic Results Transducer Stress

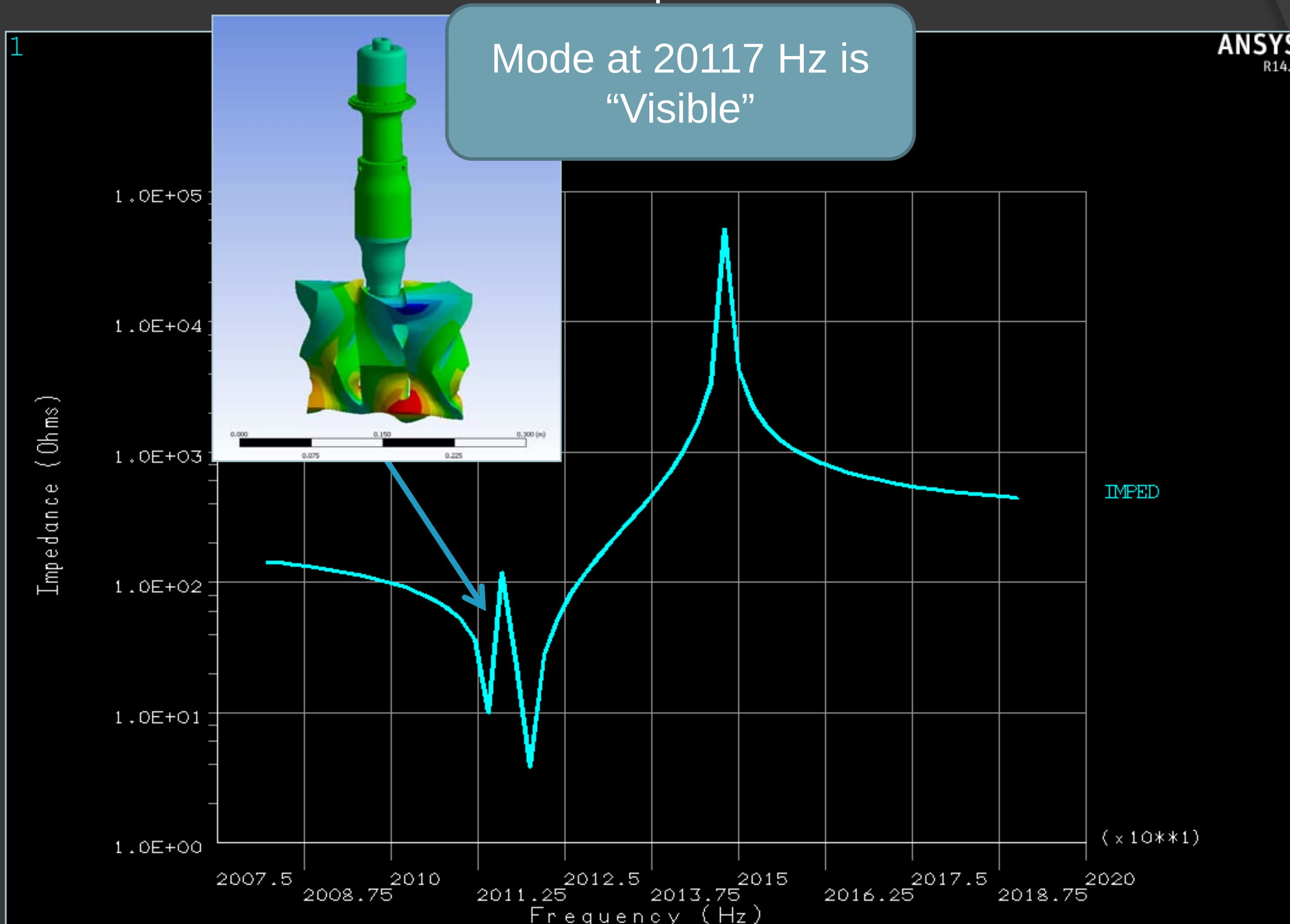
Transducer Design and Modeling
- Harmonic Analysis, Frequency Sweep Analysis -

- By modifying the Analysis Settings a frequency sweep can be performed
- APDL code can be added to examine Impedance



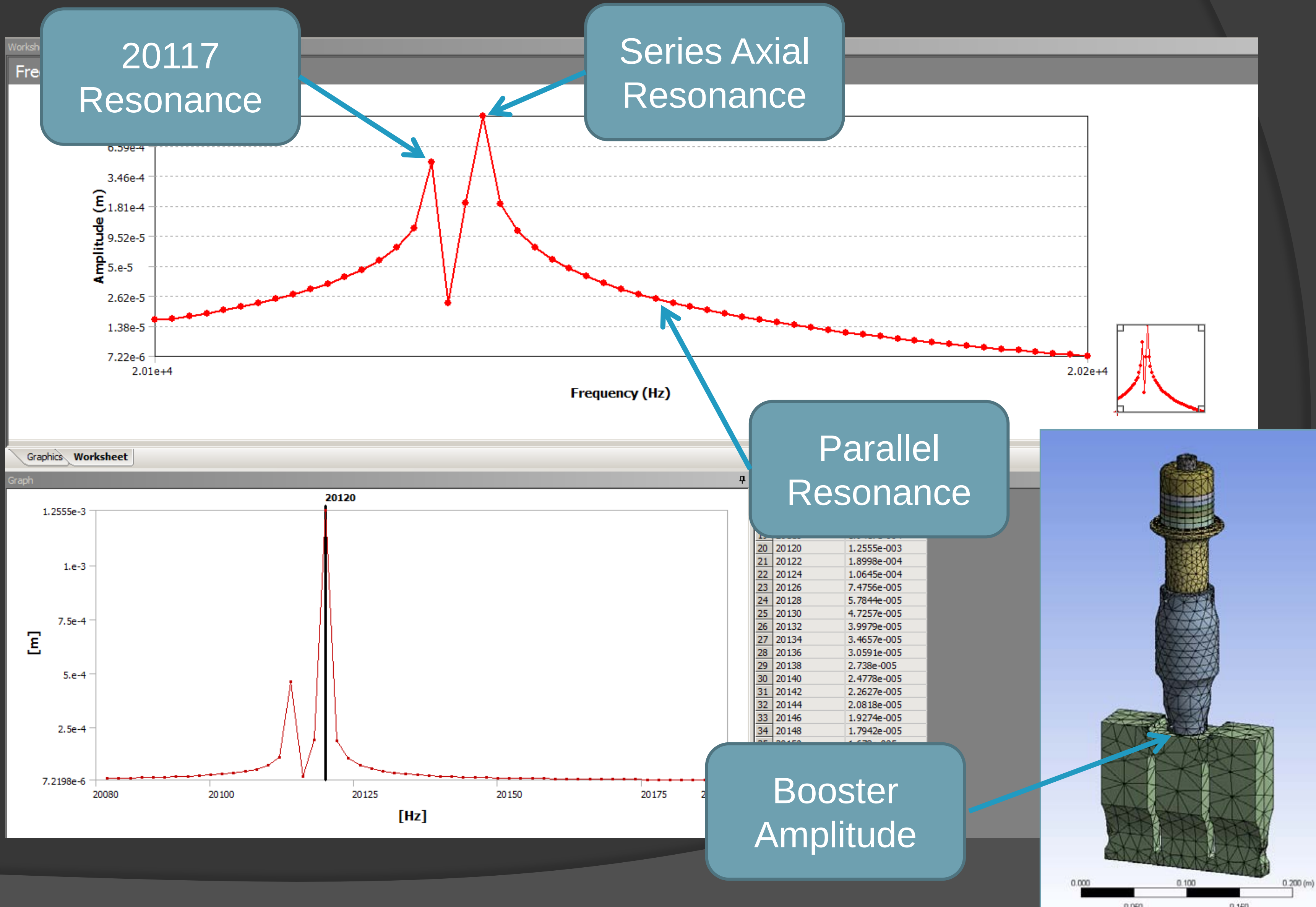
Transducer Design and Modeling
- Harmonic Analysis, Examining Results Frequency Sweep -

- Graphs of Zmag and Zphase viewed through ANSYS
- Note that mode at 20117 Hz shows up



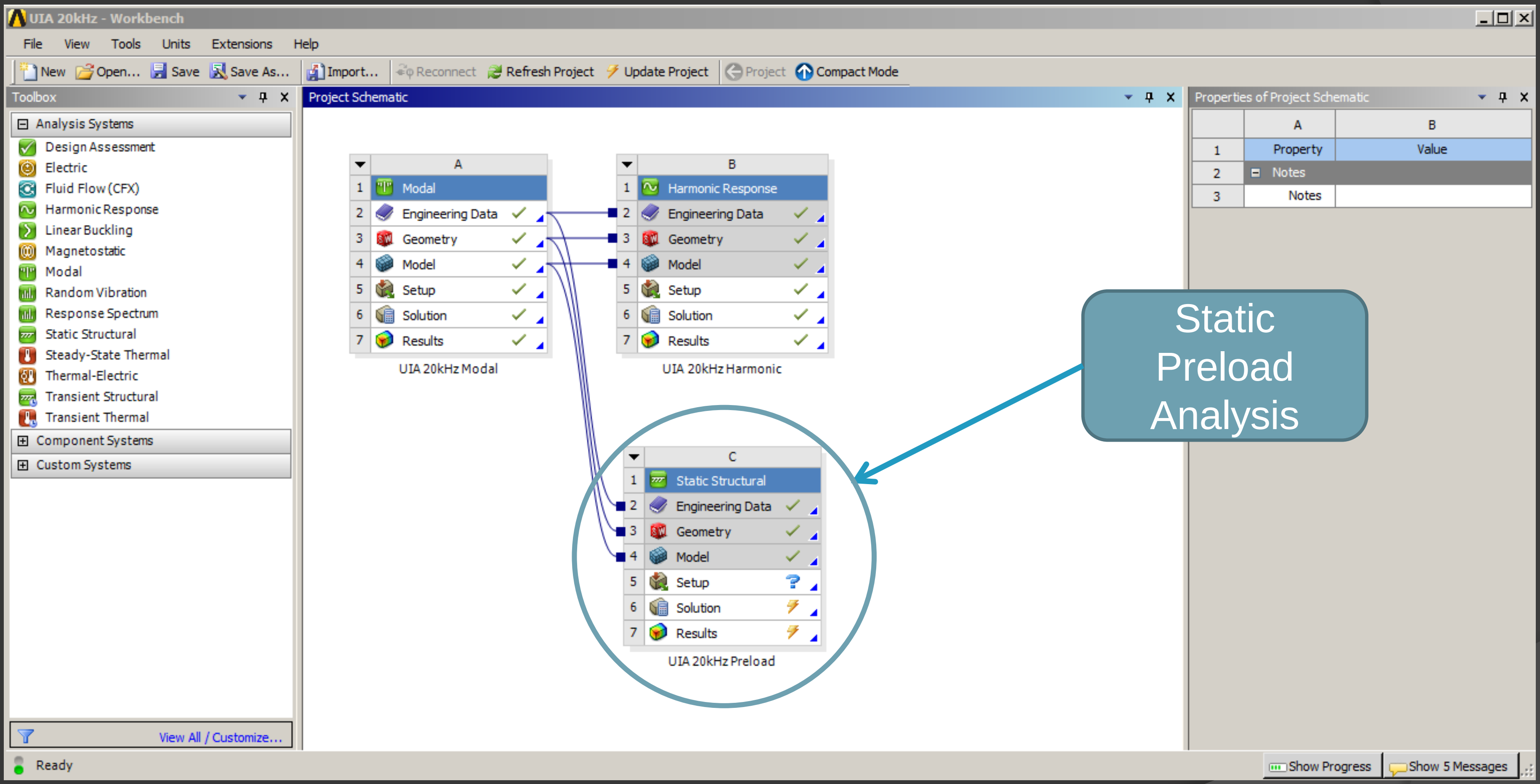
Transducer Design and Modeling
- Harmonic Analysis, Examining Results Frequency Sweep -

- Graphs of mechanical features



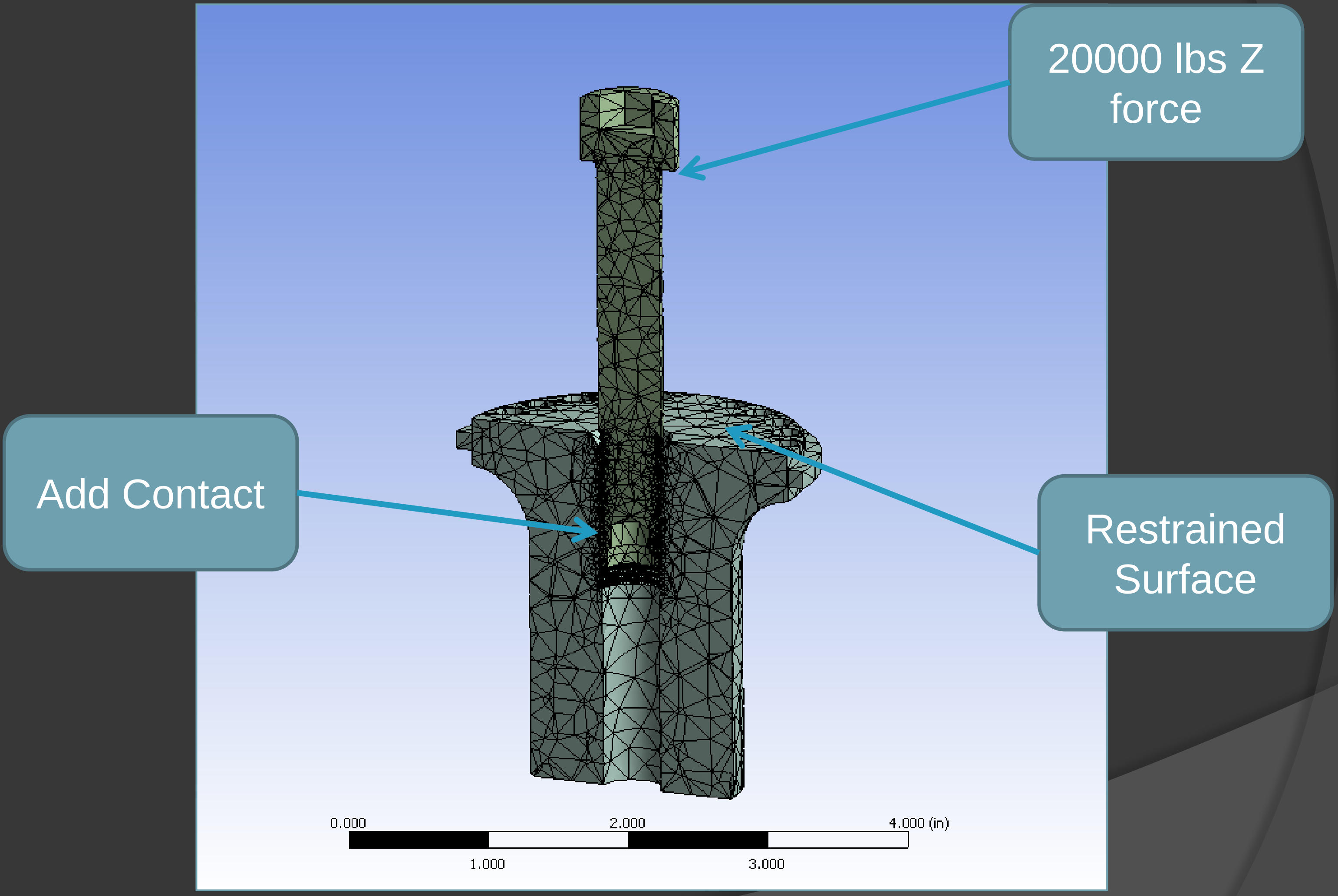
Transducer Design and Modeling
- Static Analysis, Preload Setup -

- Create Static Analysis in Workbench



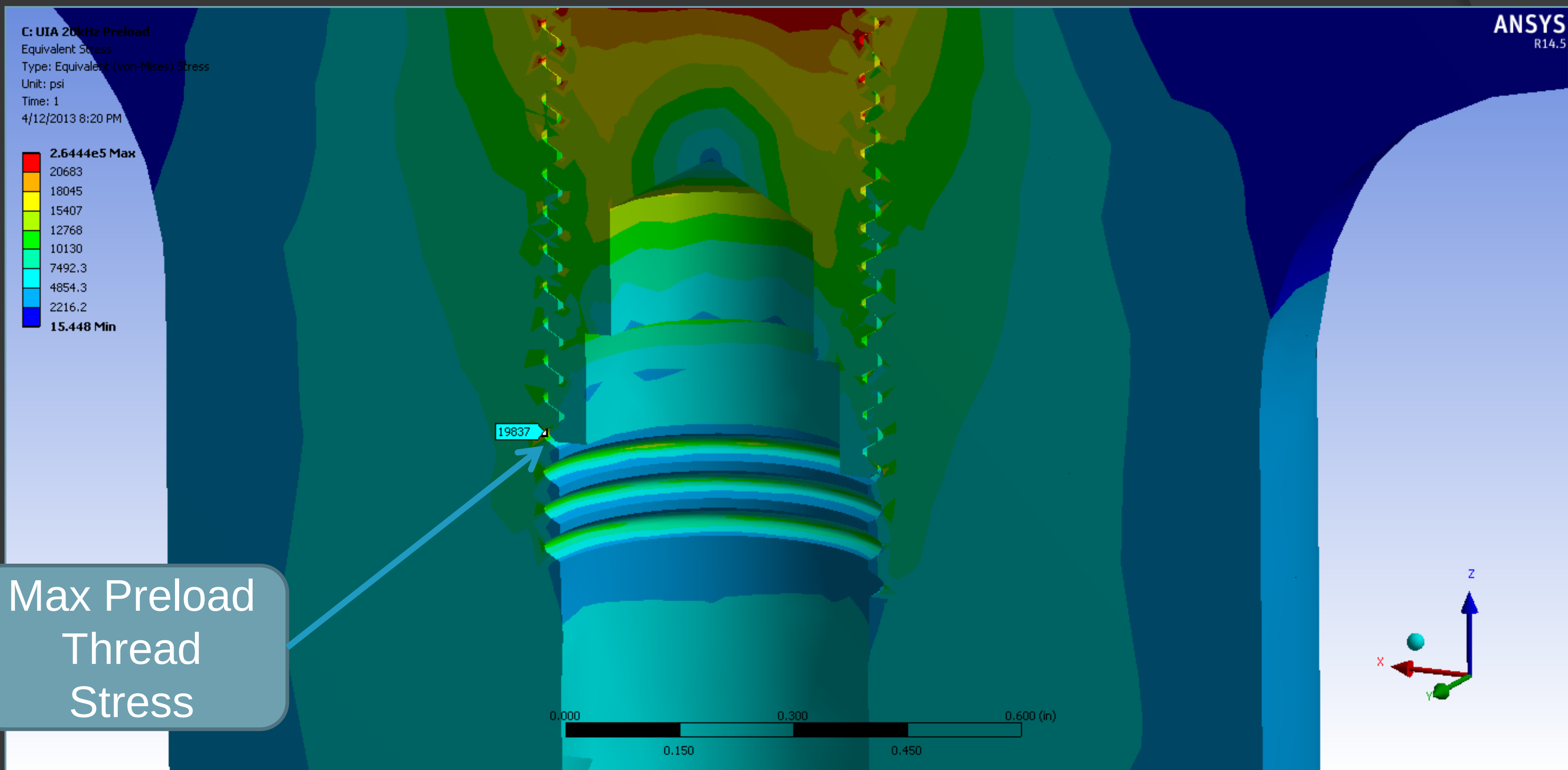
Transducer Design and Modeling
- Static Analysis, Preload Setup -

- Shut off non-required geometry, apply loads



Transducer Design and Modeling
- Static Analysis, Preload Results -

- Plot Stress



Max Preload Thread Stress

Transducer Design and Modeling
- Conclusion -

- ANSYS can be setup to be an excellent tool for analysis of ultrasonic transducers
- Direct link to solid model is a great advantage in the management of transducer designs and manufacturing data
- ANSYS workbench in its current form requires coding to achieve true piezo-electric analysis

Thank you for your time !!