FIRST-PASS SYSTEM SUCCESS

APPLICATION WORKSHOPS FOR HIGH-PERFORMANCE ELECTRONIC DESIGN

Design Optimization of Fast-Acting Actuators Including Eddy Effects and Magnetic Diffusion

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Delphi

Fast-Acting Actuators

1. Introduction
   - Background of issues.
   - Ansoft simulation approach.

2. Actuation verification model.
   - Demonstrate 3D transient solver with eddy effects.
   - Simulation results with Distributed Analysis Option.

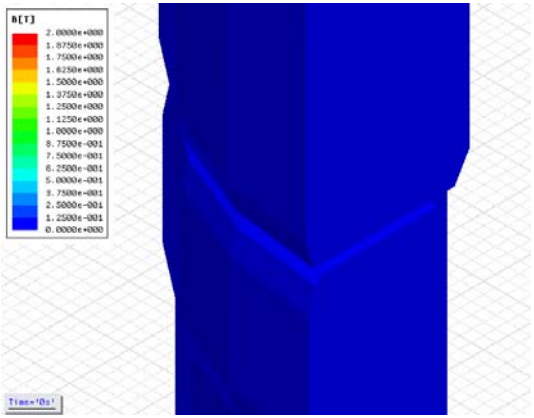
3. Delphi Study
   - Baseline model results.
   - Parametric Transient Study; Coil Design, Material, Mass.
   - Distributed Analysis of transient models over several computers.

Delphi Multec® Gasoline Multi-Port Fuel Injectors

Fact Acting Actuators

- Closing Time - Limitations.
  1. Coil Current rise-time limited by Coil Design.
  2. Diffusion time in conductive materials.
  3. Moving mass, inertial effects.

$\tau_e = L/R$



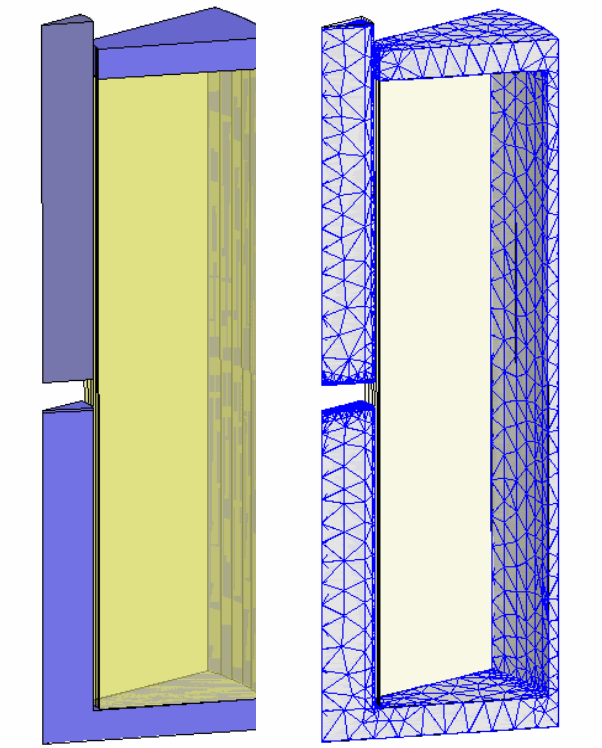
Diffusion time: fn(σ, μ, size, di/dt)

Ansoft Simulation Approach

- Maxwell 3D FEA Advantages:
  - Voltage sourced, coupled with an arbitrary drive circuit.
  - Simultaneous electrical and mechanical time stepped solution.
  - Band object used to conserve re-meshing for every time step.
  - Eddy effects in conductive materials induced from coil current and Motion.
  - Magnetic diffusion.
  - Non linear material effects.

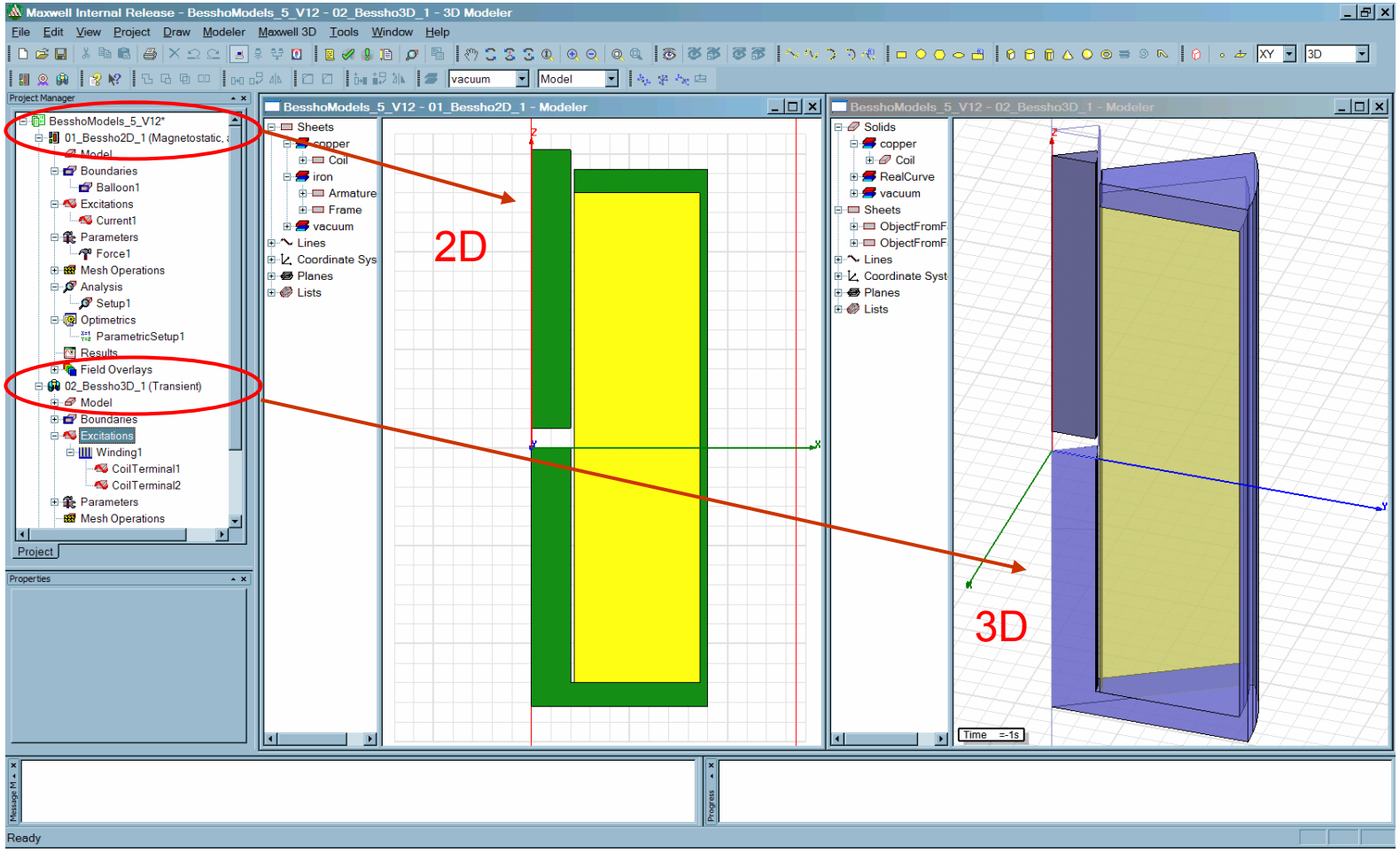
Validation

- Well known Bessho[1] actuator modeled using 3D FEA.
- 30 degree Wedge,
  5 degree segments.
- Transient with Motion and eddy effects for steel objects.
- 5ms time step solved to 300ms.
- Voltage source = 100 Volts step,
  R = 200 Ohms.



[1] Brauer, John R. “Magnetic Actuators and Sensors,” John Wiley & Sons, Inc., Hoboken, New Jersey, 2006.

Validation – V12 Interface



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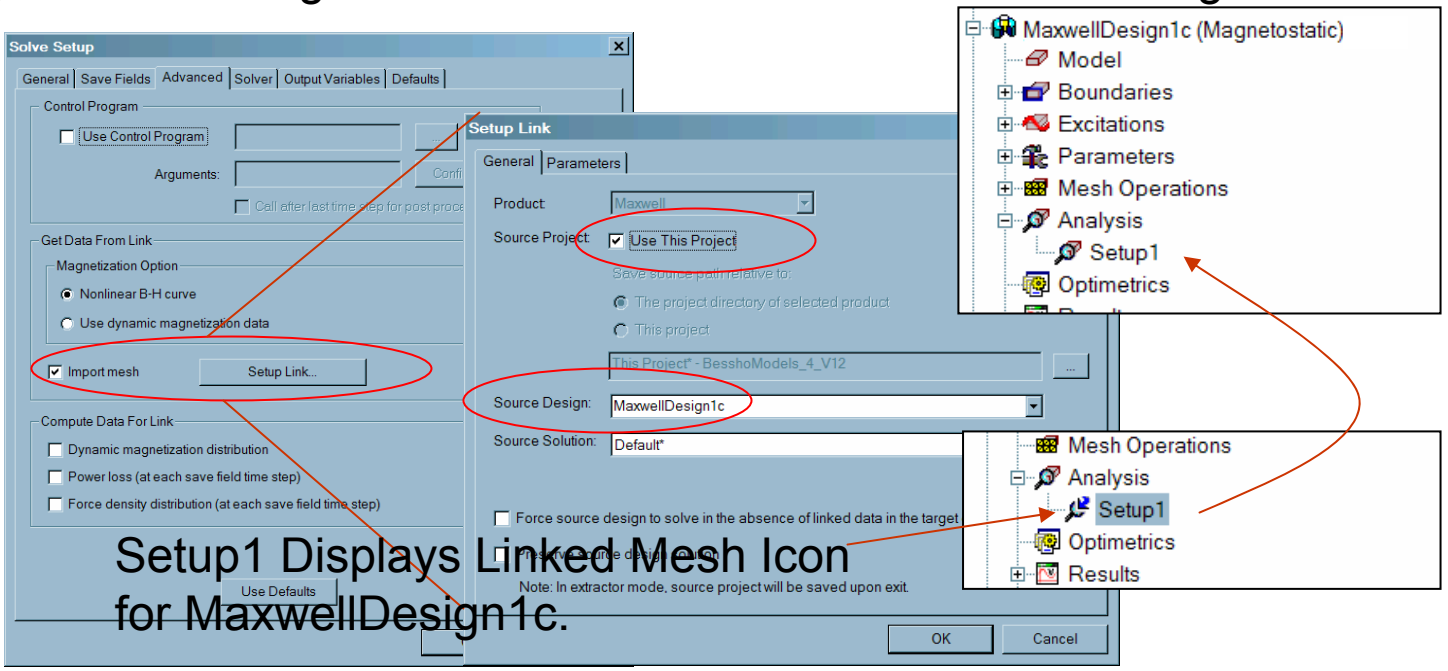
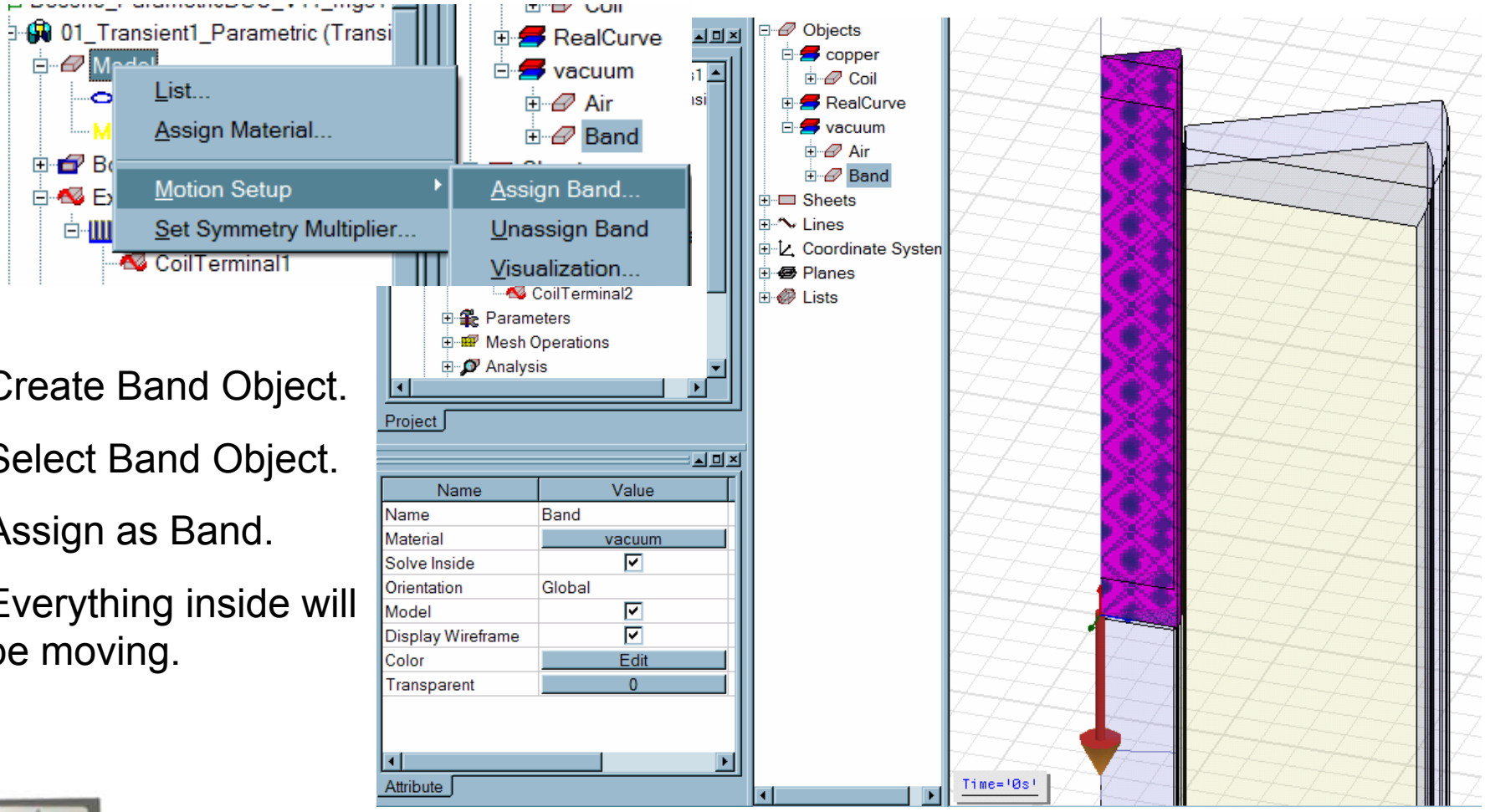
Validation – Meshing

- Two Approaches:

1. Use mesh operations to mesh the geometry
2. Use mesh operations *and* adaptive meshing from a *magnetostatic* or E*ddy Current* Design and *Link the mesh* to the transient Design.



Validation – Motion Setup



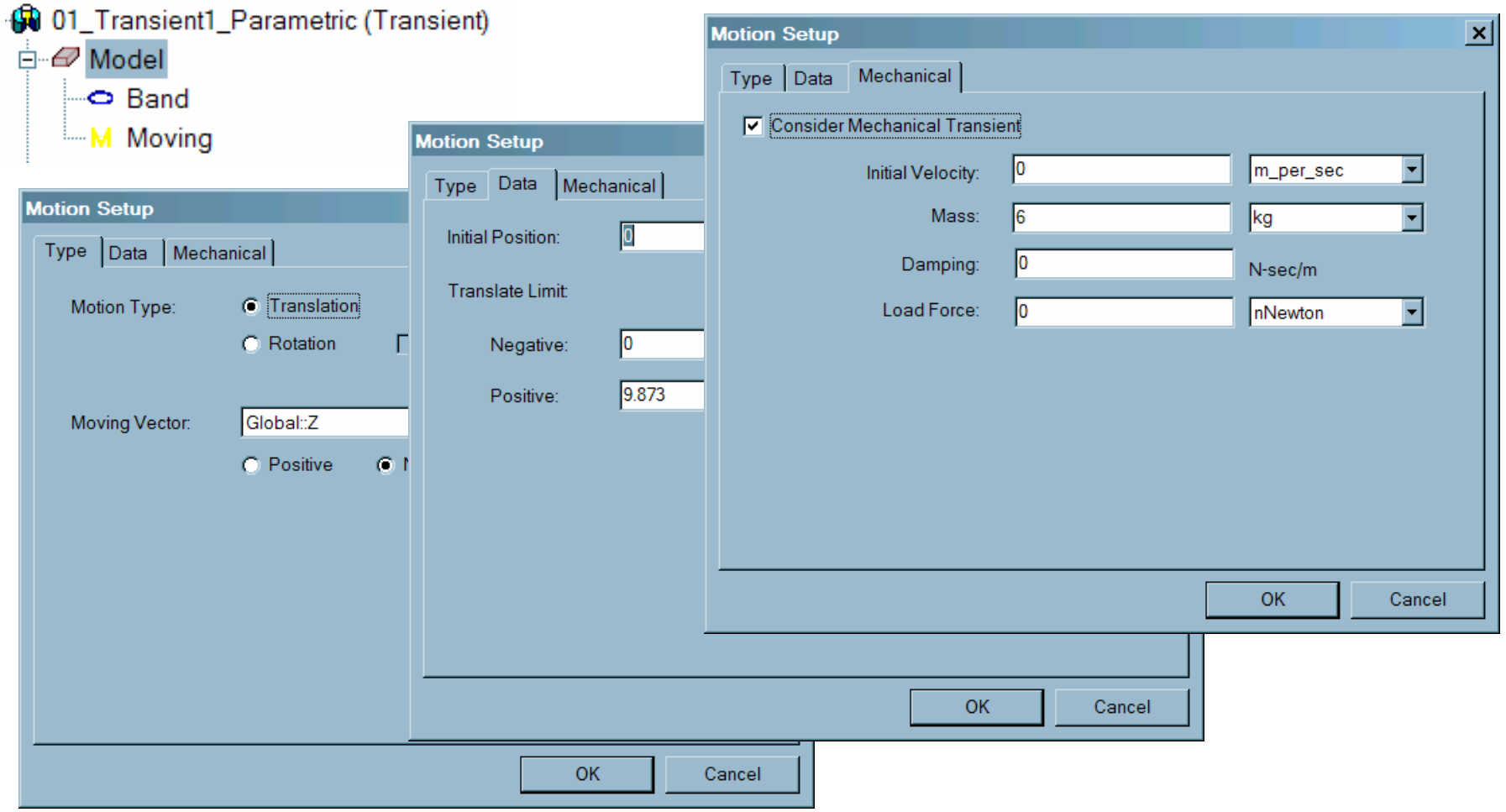
Create Band Object.

Select Band Object.

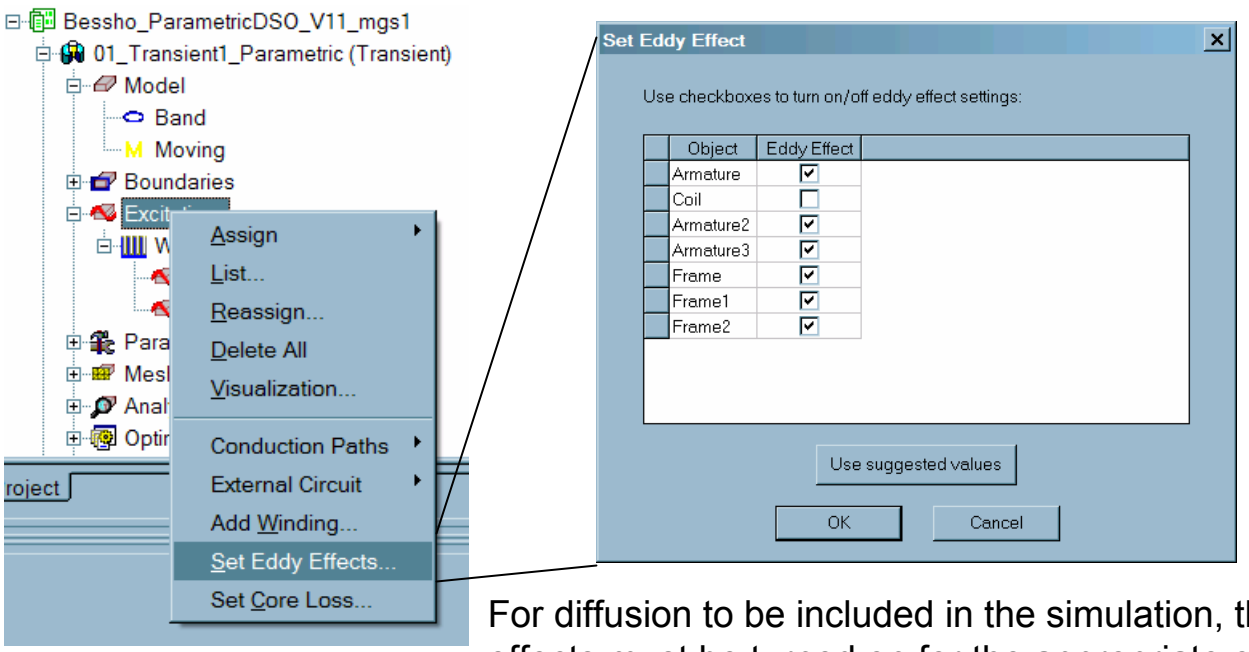
Assign as Band.

Everything inside will be moving.

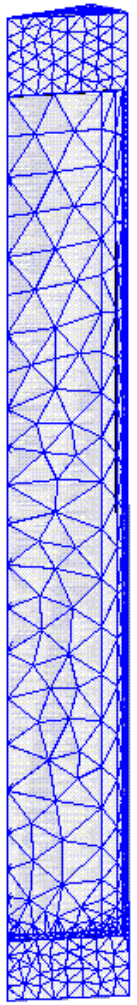
Validation – Motion Setup



Validation – Band, Eddy Effects



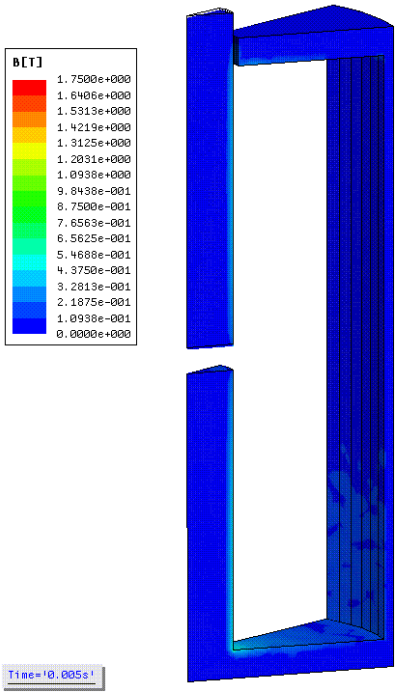
For diffusion to be included in the simulation, the eddy effects must be turned on for the appropriate objects.



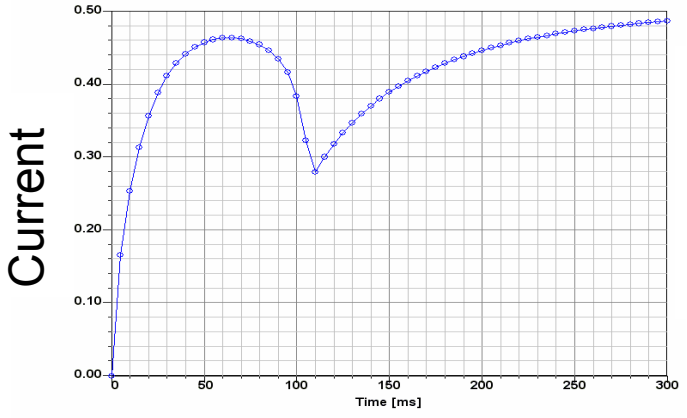
For each time step where motion occurs, the mesh is only re-meshed between the band and the moving object.

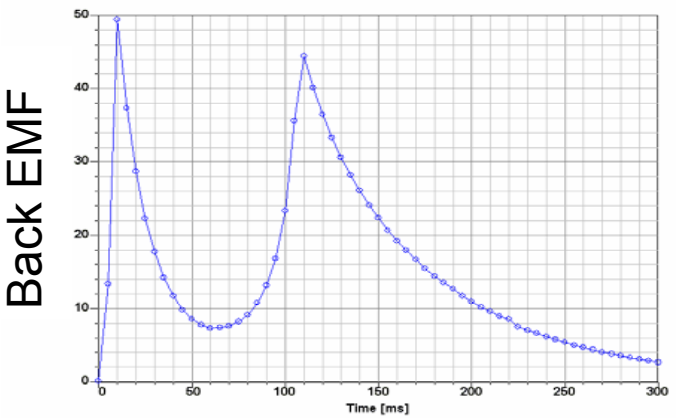
Time =0ns
Speed =0.000000m_per_sec
Position =-0.000000mm

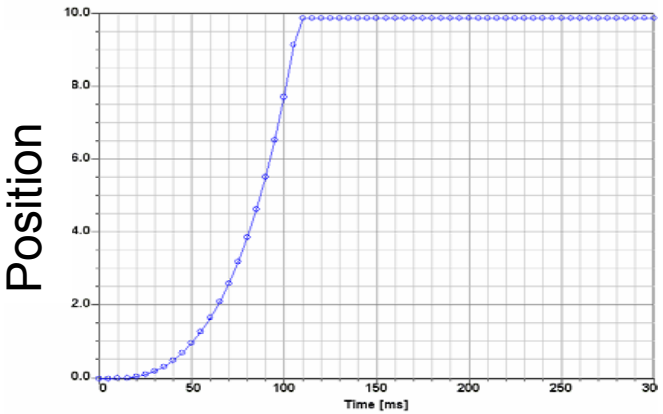
Validation – Transient Closing

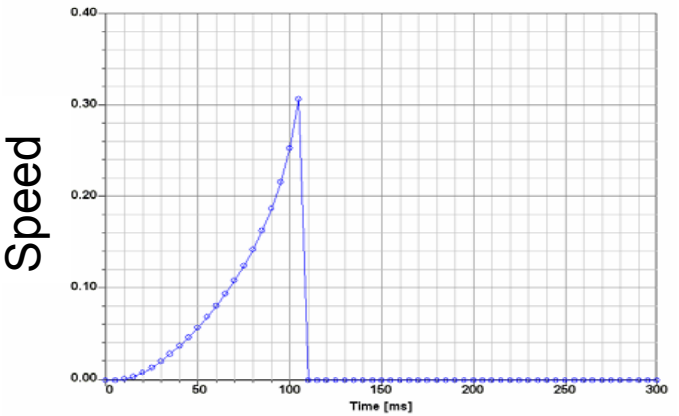


Diffusion time: fn(σ, μ, size, di/dt)









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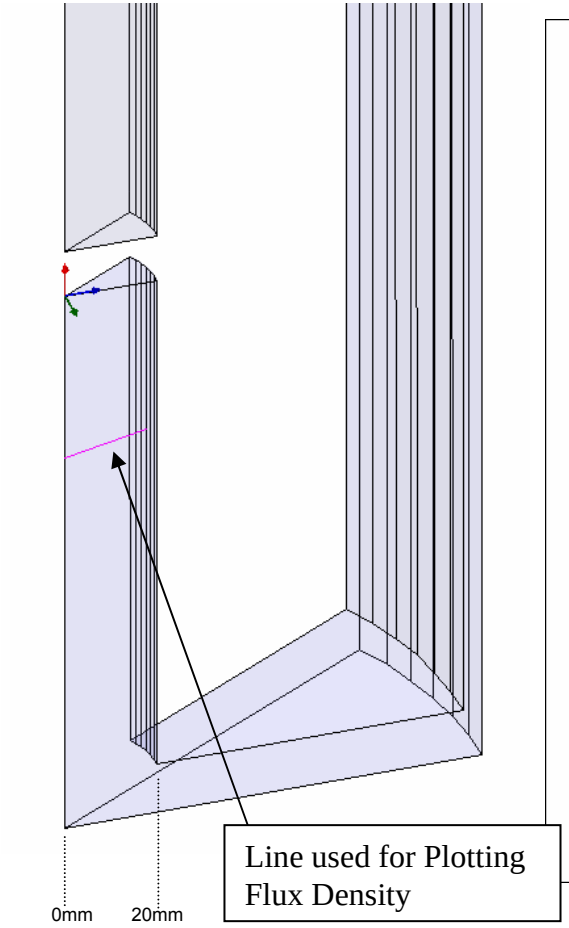
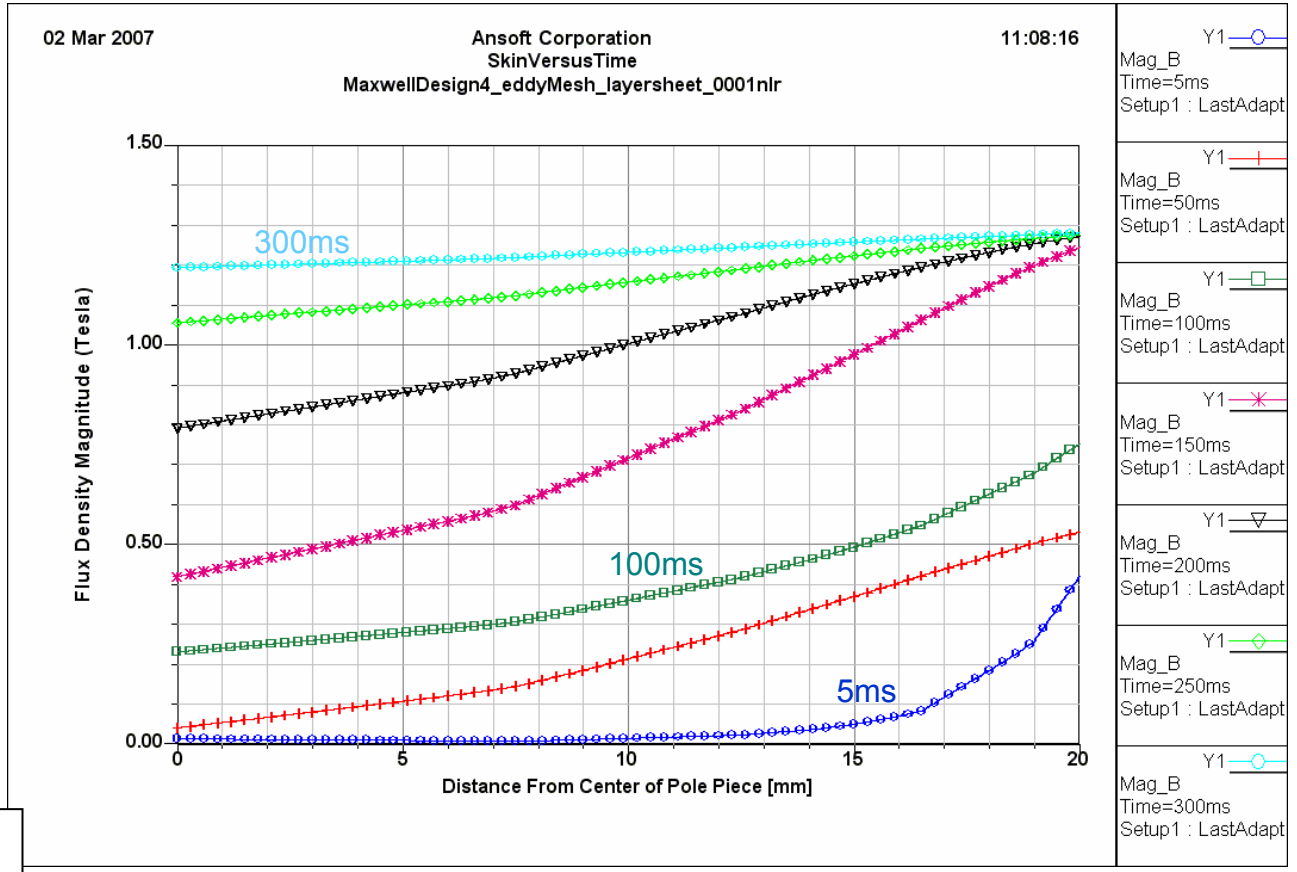
Validation - Magnetic Diffusion





Plot of Magnetic Field as a function of position and time.

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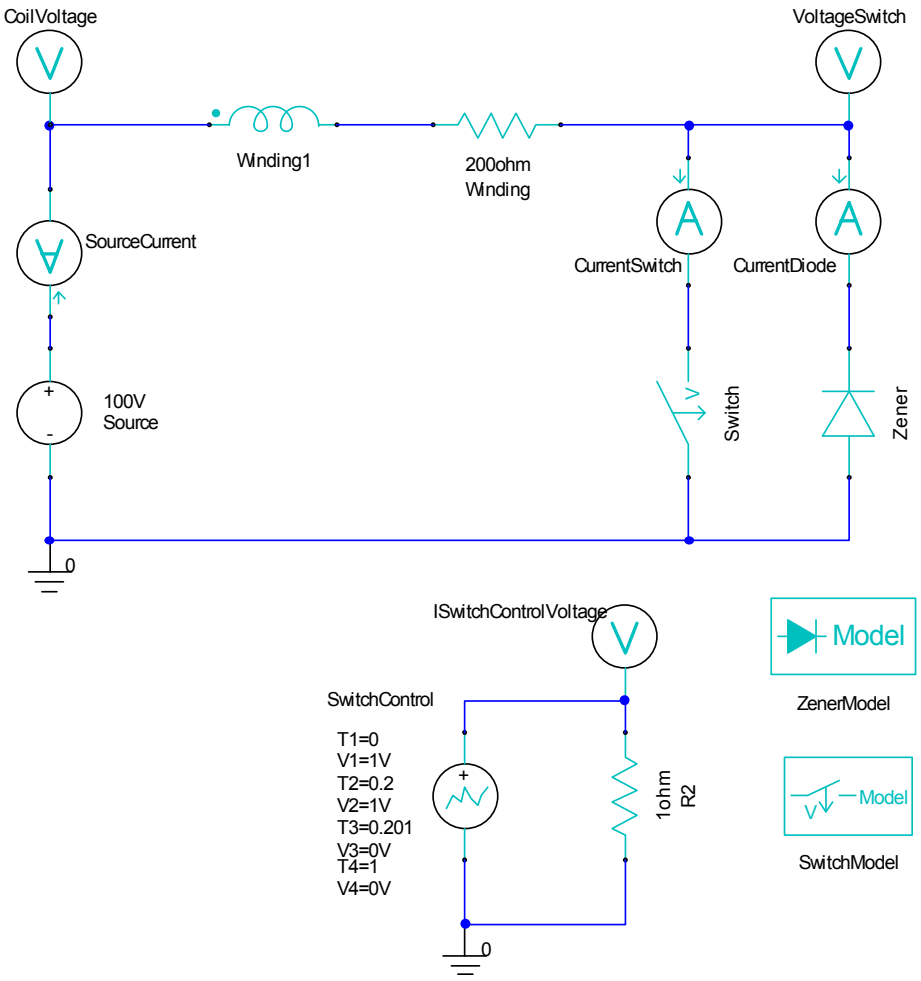
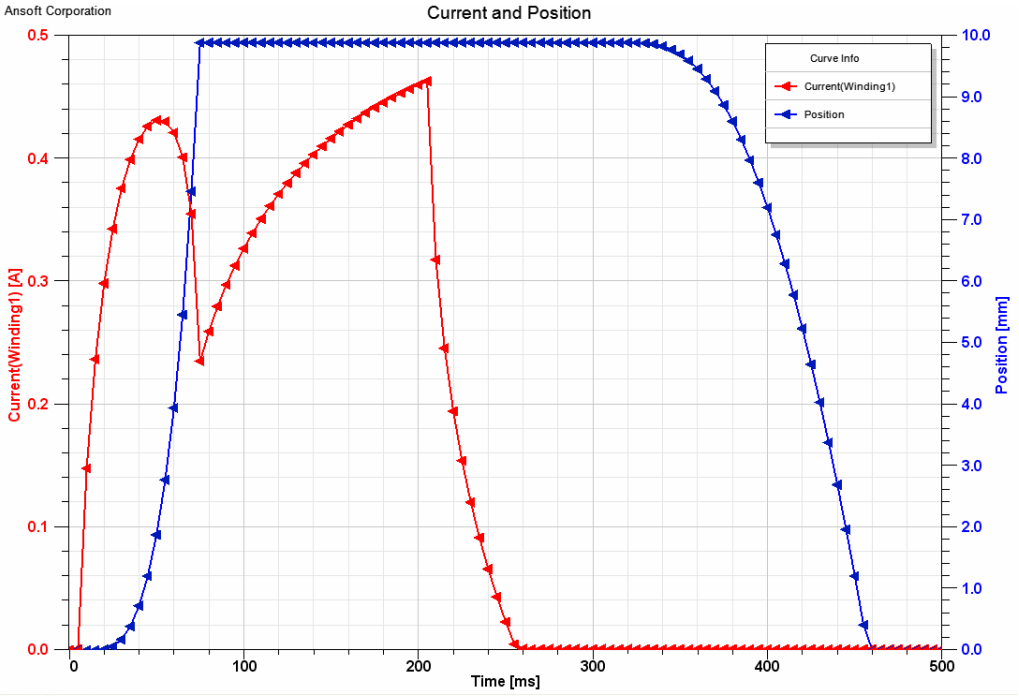
Validation – Additional Options

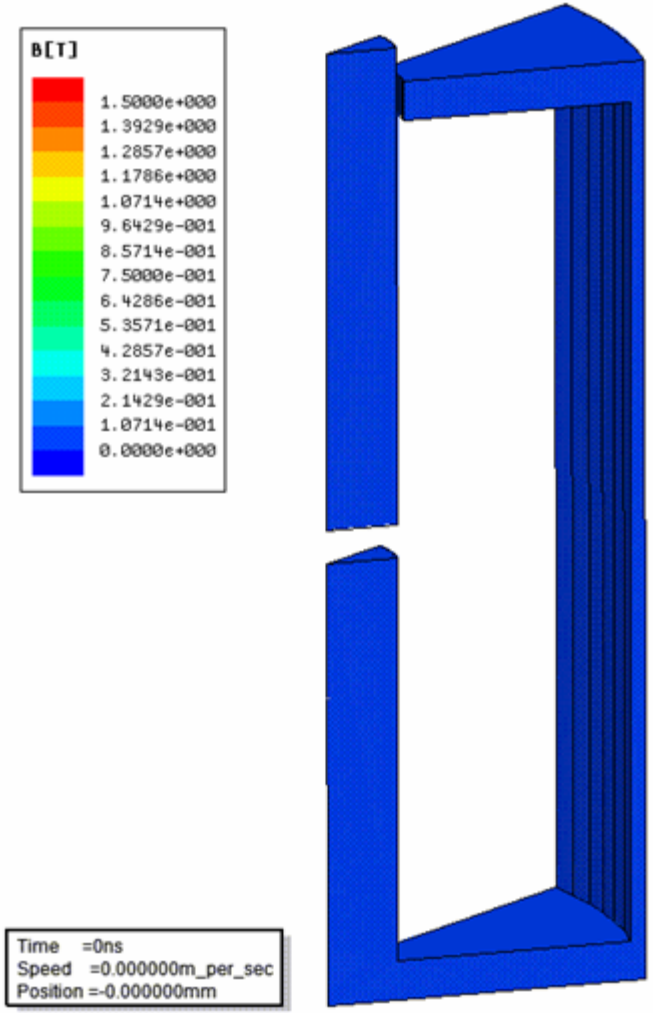
- Maxwell Circuit Editor
- Use Attached Circuit to Drive Device.
- Use Switch to perform Open actuator.
- Use current controlled switch for hysteresis current control.



Validation – Close and Open

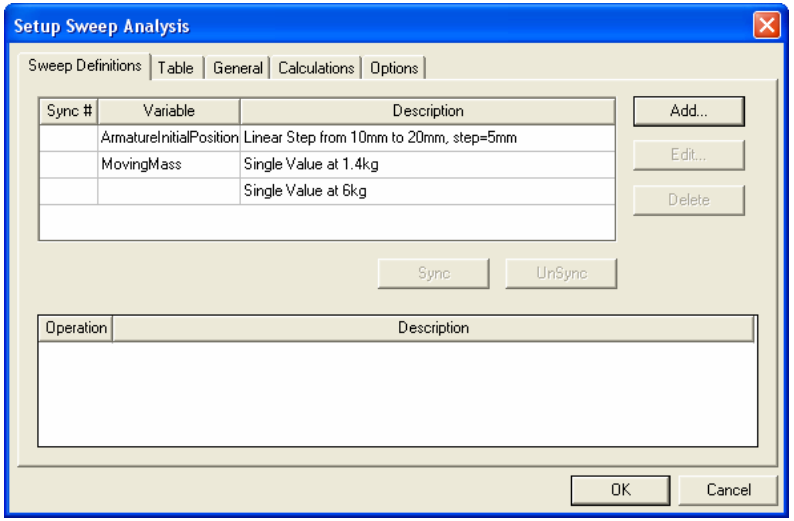
- Results showing Armature Close and Open.
- Switch is opened at 200 ms.
- Note: Weak spring was used, slow Opening.

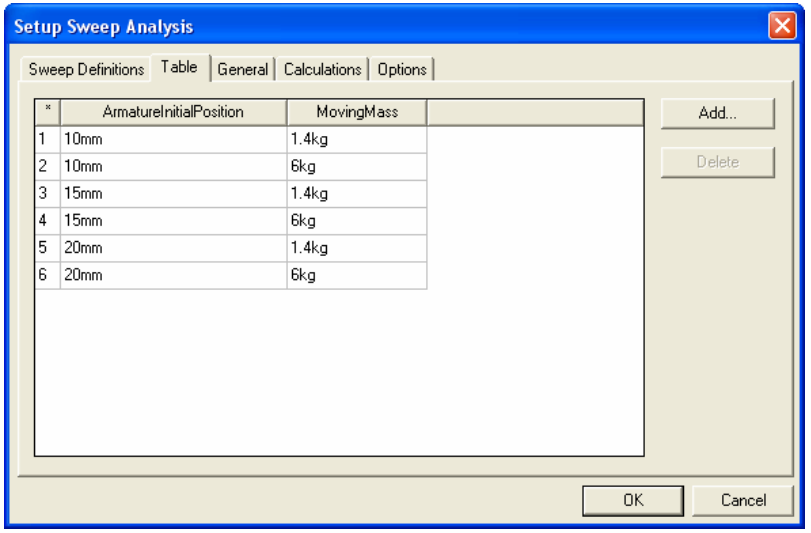




Validation - Parametric Transient Study with Distributed Analysis

- Varied starting position (10, 15, 20 mm).
- Varied Moving Mass (1.4, 6 kg).
- Observe parametric solution of transient results.





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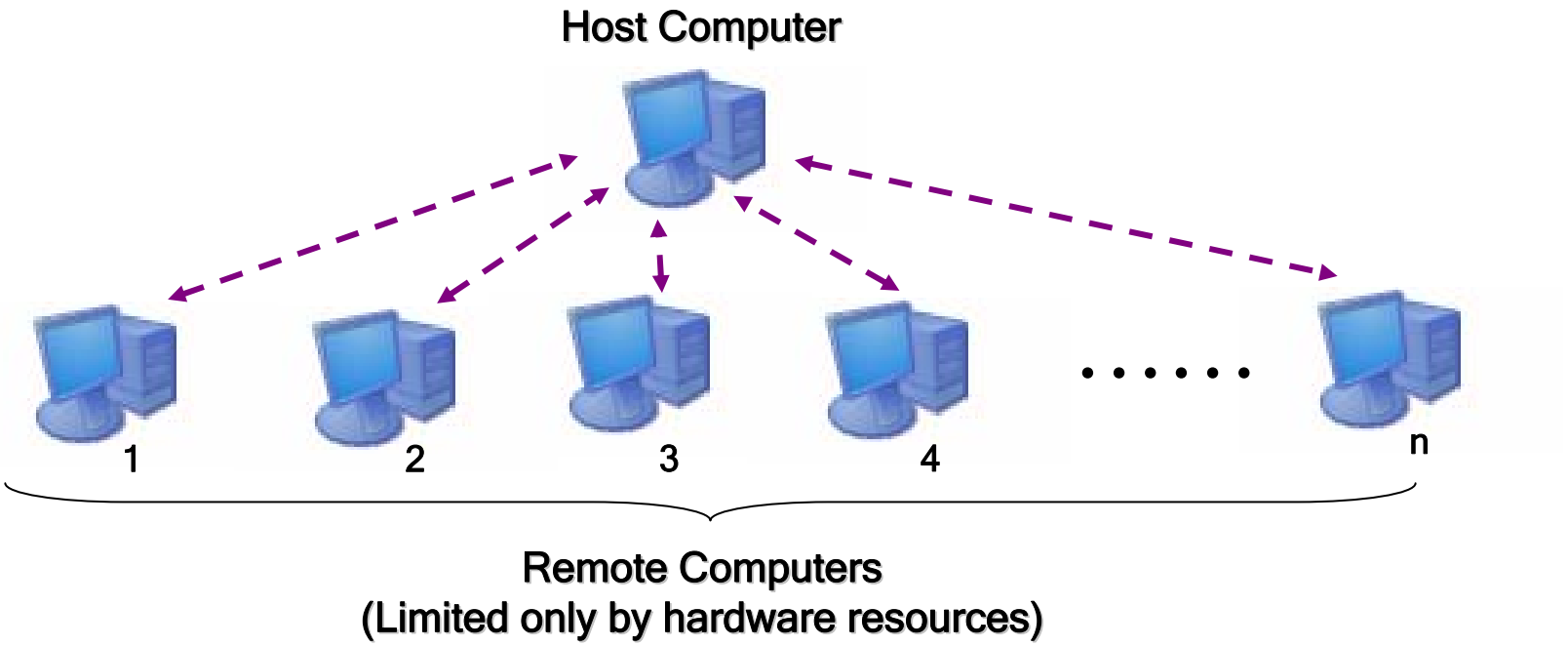
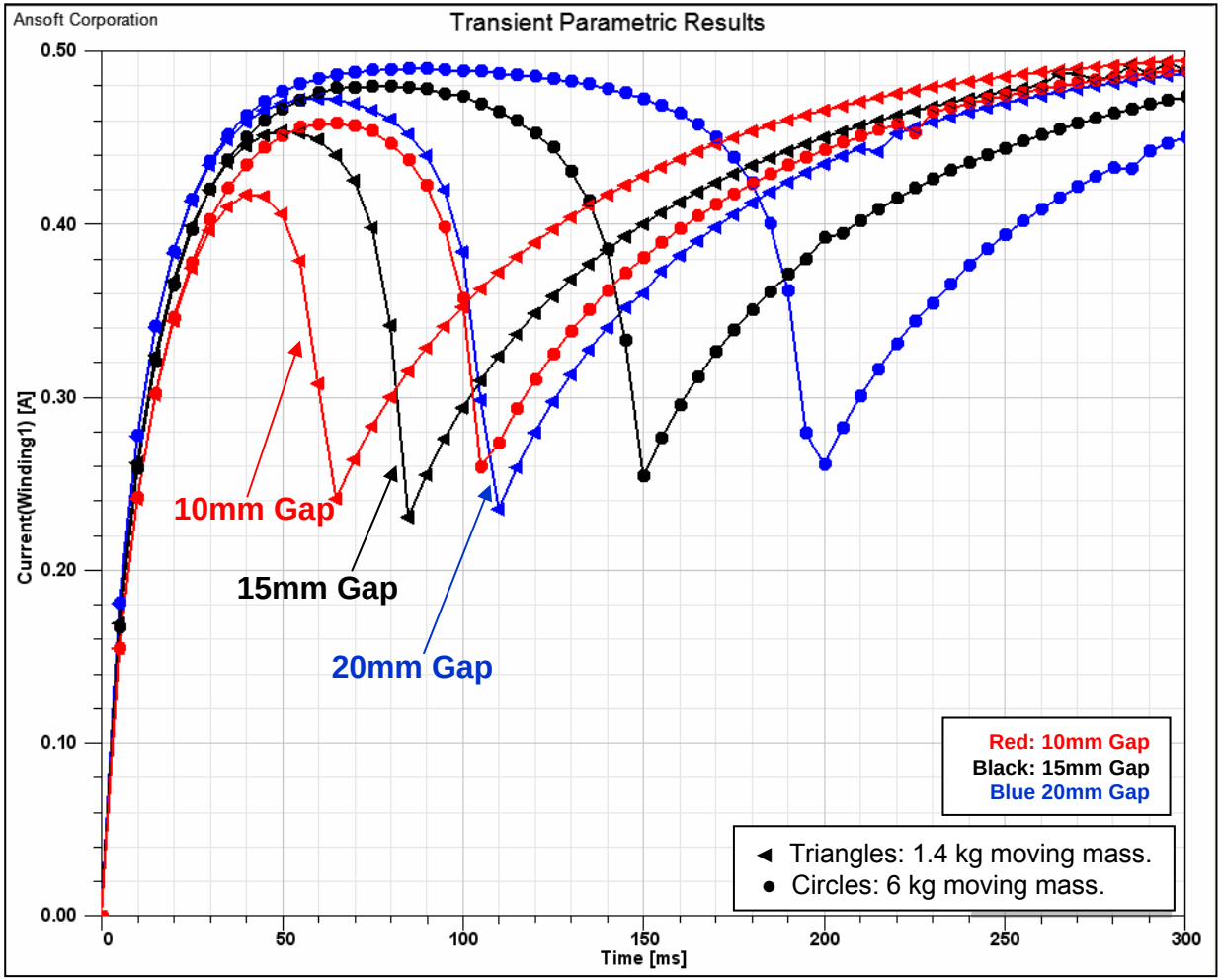
About Distributed Analysis

- **Distributed Analysis**

  Distributes parametric studies across available hardware to expedite electromagnetic extraction, characterization, and optimization.



Validation - Parametric Transient Study with Distributed Analysis



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Validation - Conclusions

- 3D Analysis using Maxwell shows excellent correlation with published results[1] with respect to current waveforms and closing times.

Mass (kg)	Gap (mm)	Closing Times (msec) 3D FEA	Published[1]
1.4	10	65	67
6	10	105	115

- Post processing in Maxwell 3D allows for a unique look at magnetic diffusion in a transient analysis.

- Distributed Analysis reduced the transient parametric solution time from about 181 hours to 32 hours.

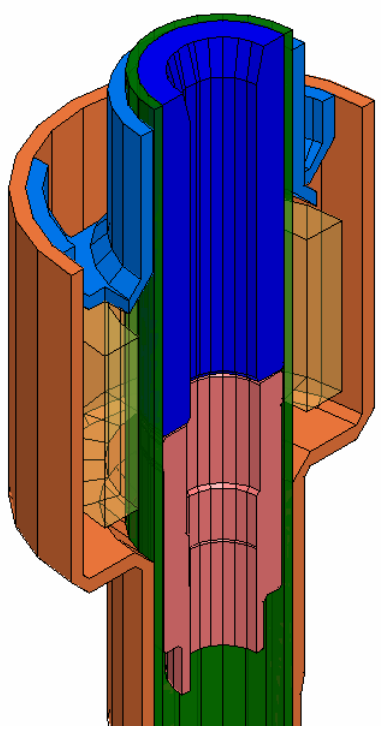
Delphi Actuator Parameters

- Goal: Reduce closing time.
- Physical Parameters for Actuator.
  - Spring rate
  - Stroke
  - Working air gap
  - Saturated Switch Driver
  - Coil Design Parameters
  - Damping coefficient
  - Moving mass
  - Fuel pressure
  - Pressure ratio = $P_{director}/P_{ball\text{-}seat}$

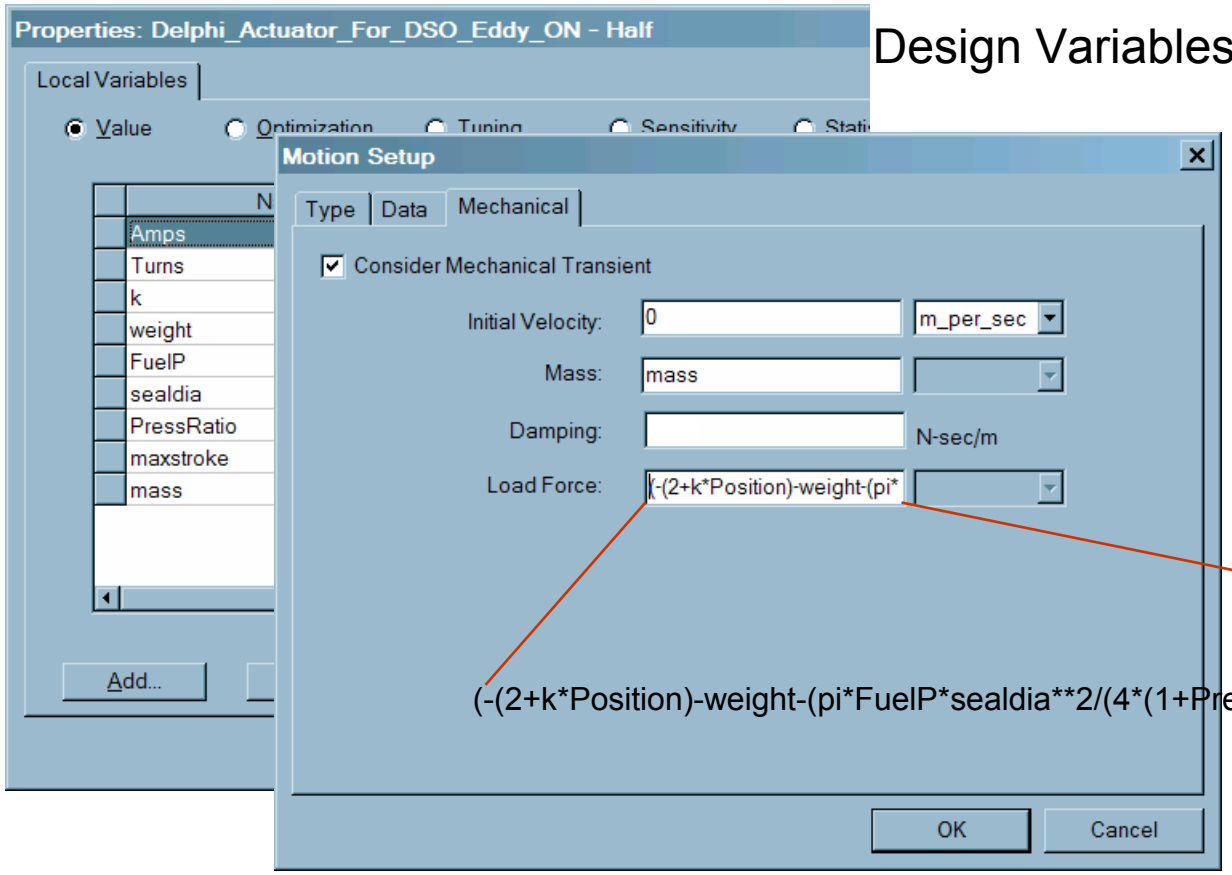
Delphi Multec ® Multi-Port Fuel Injectors are available in various design configurations to meet a wide range of customer requirements.

Delphi Actuator

- Model geometry imported from existing Maxwell 2D model and .stp file.
- Non-axisymmetric features require a half model.



Delphi Actuator Setup Details



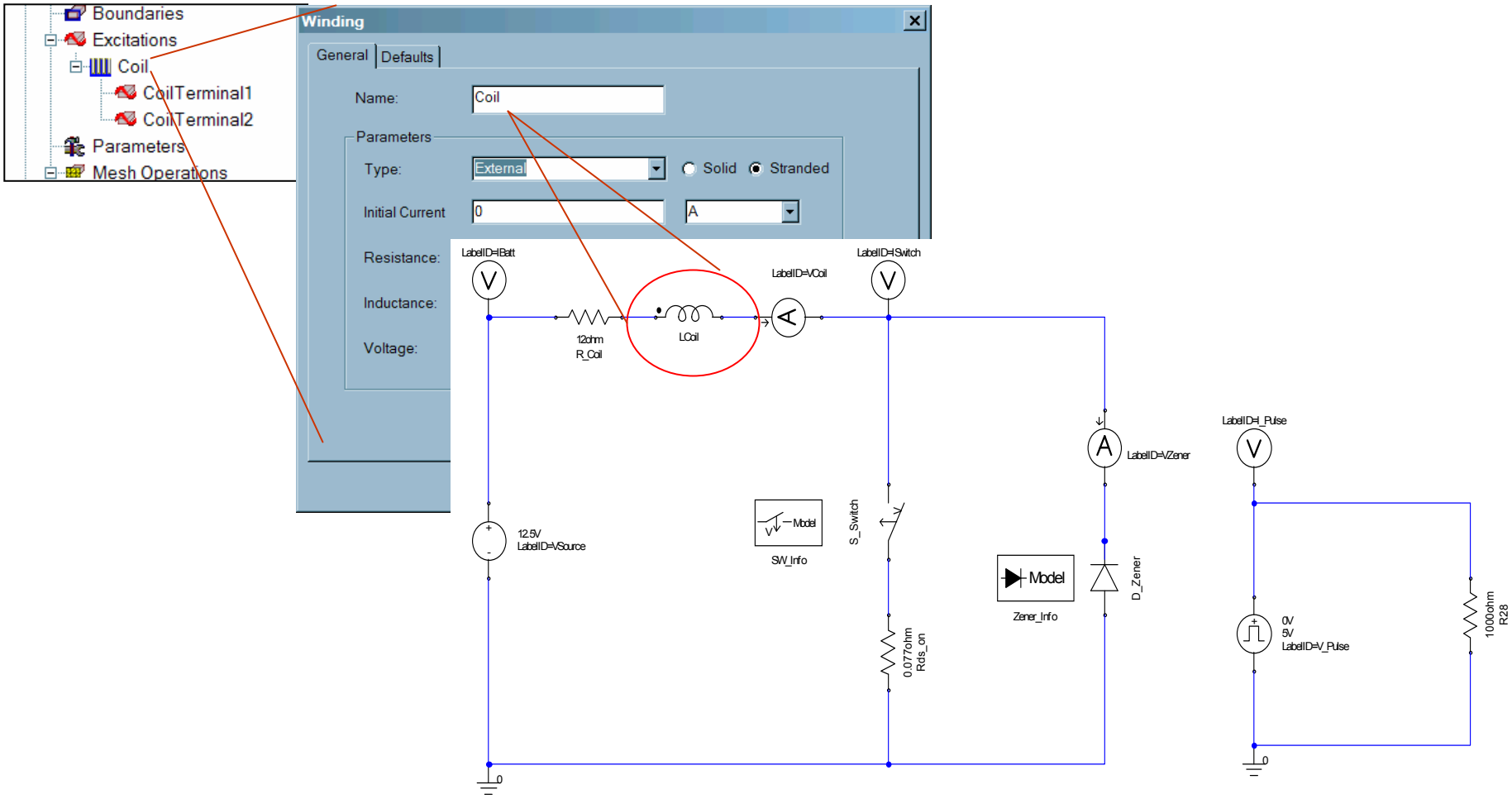
Design Variables assigned.

Mechanical Parameters.

(-(2+k*Position)-weight-(pi*FuelP*sealdia**2/(4*(1+PressRatio*(Position/maxstroke)**2))))

Functional Load Force defined using Local Design Variables.

Delphi Actuator Setup Details



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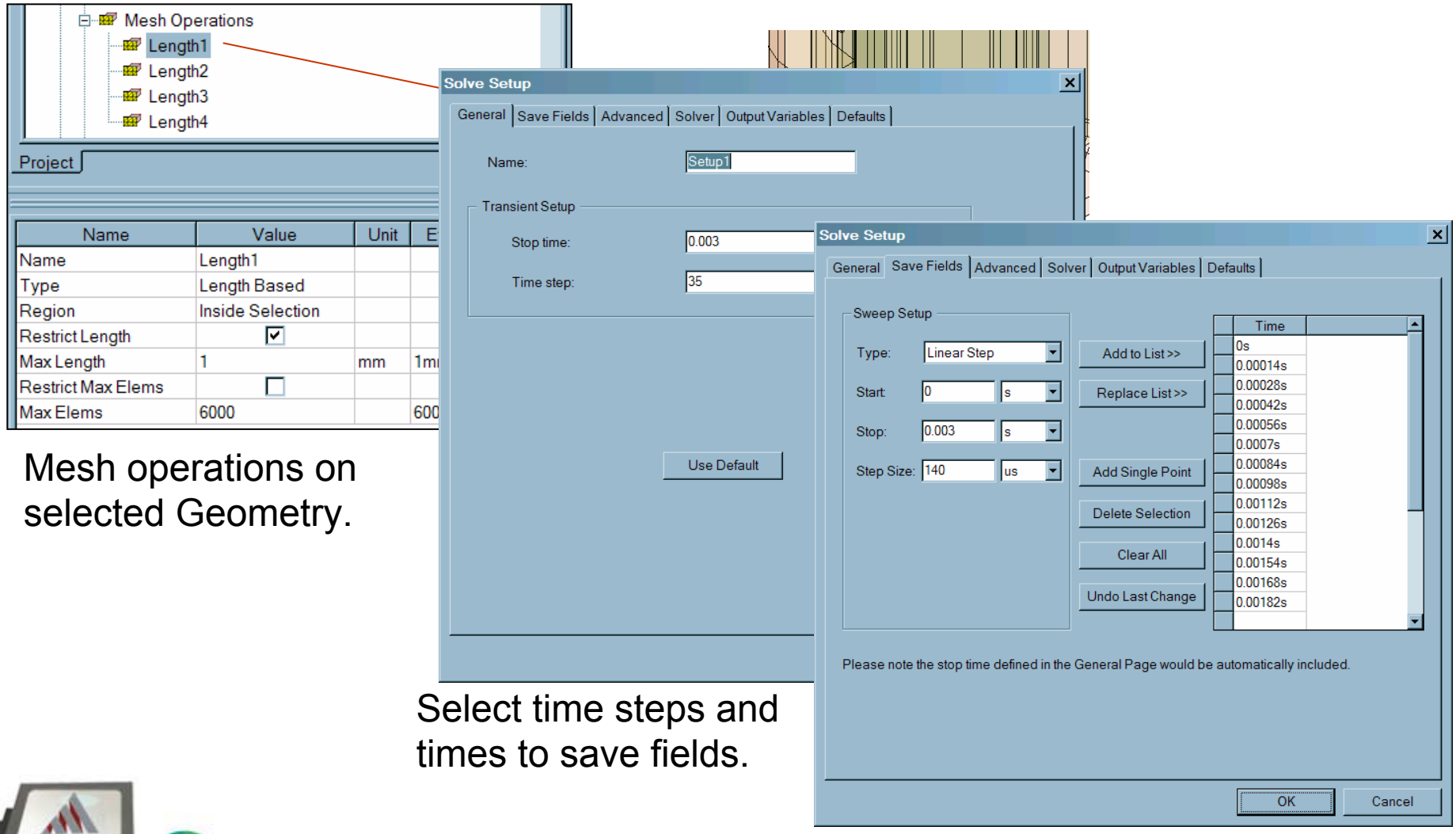
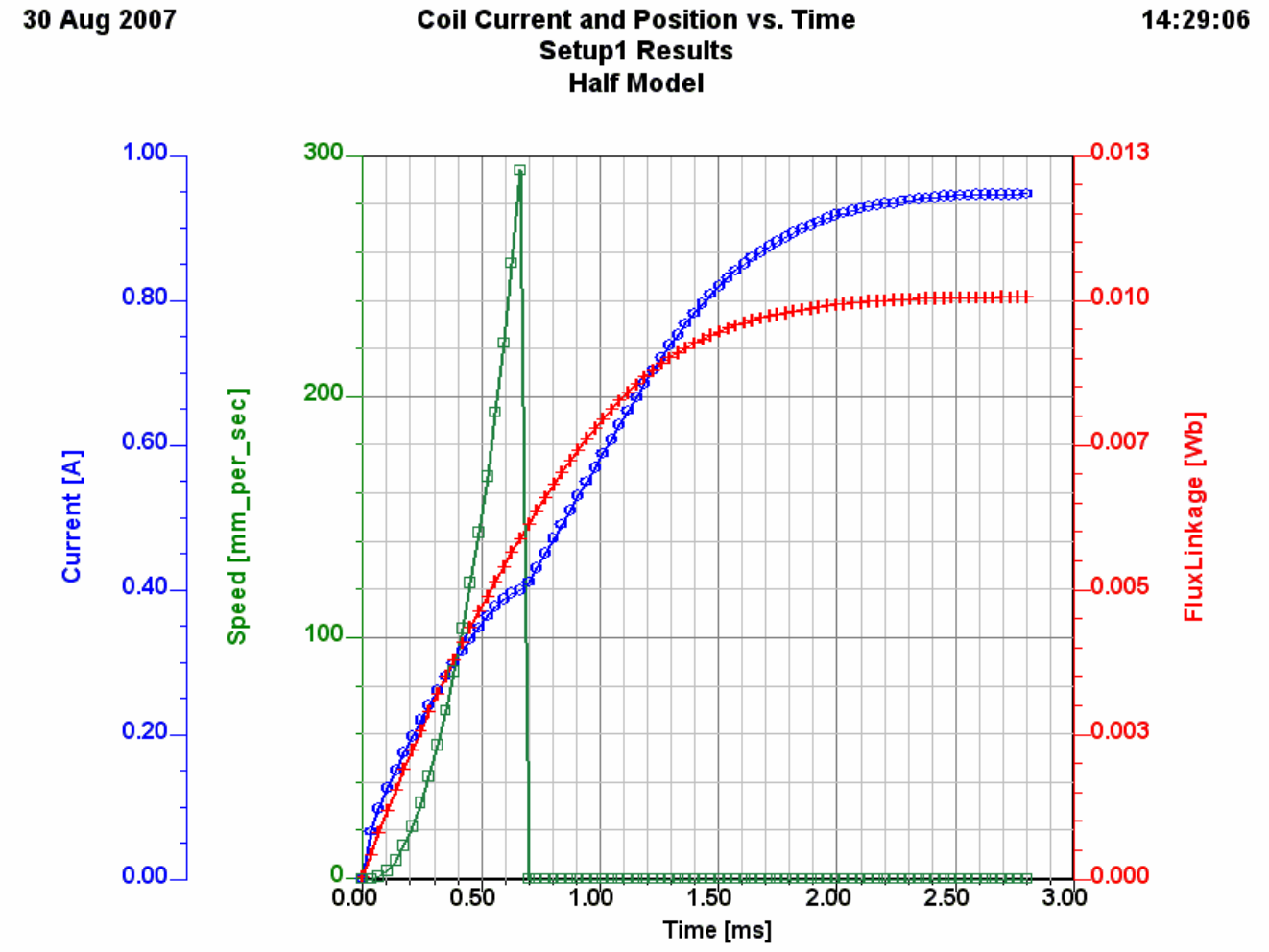
Delphi Actuator Setup Details



Mesh operations on selected Geometry.

Select time steps and times to save fields.

Delphi Actuator Results



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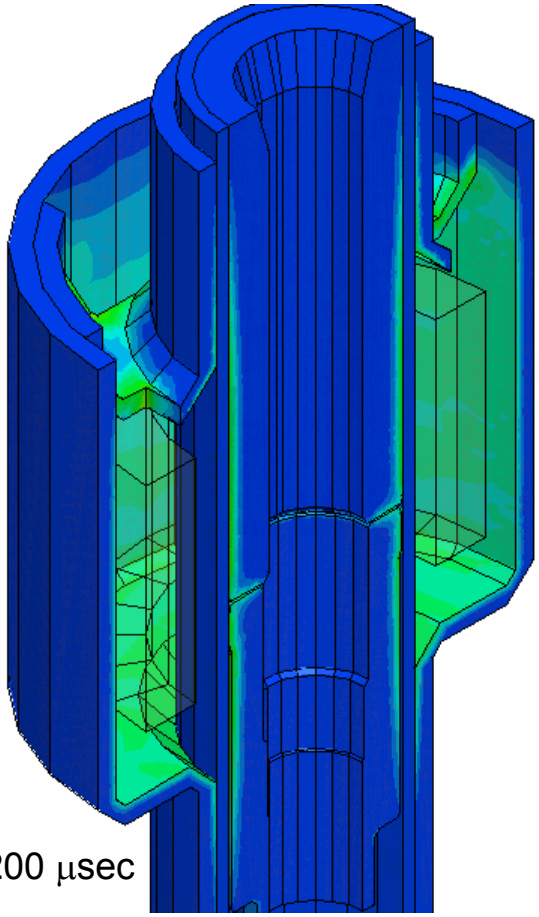
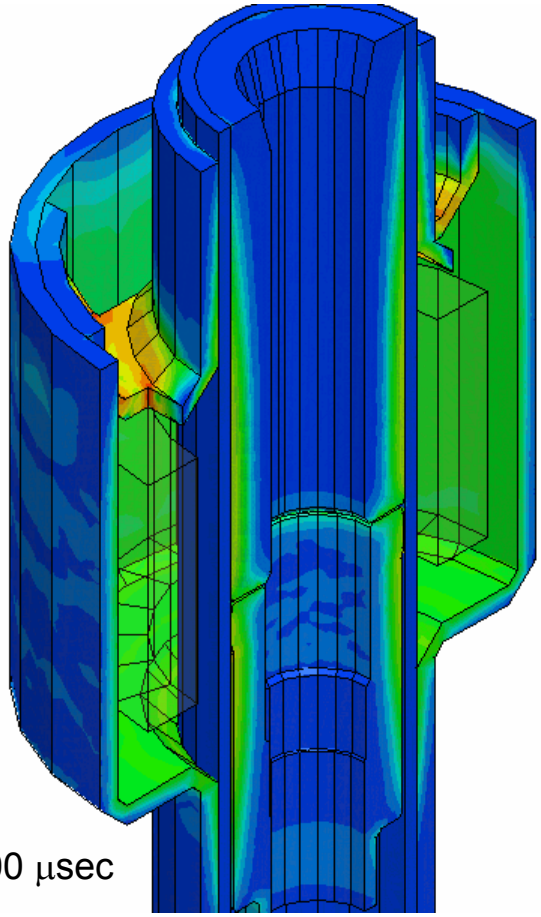
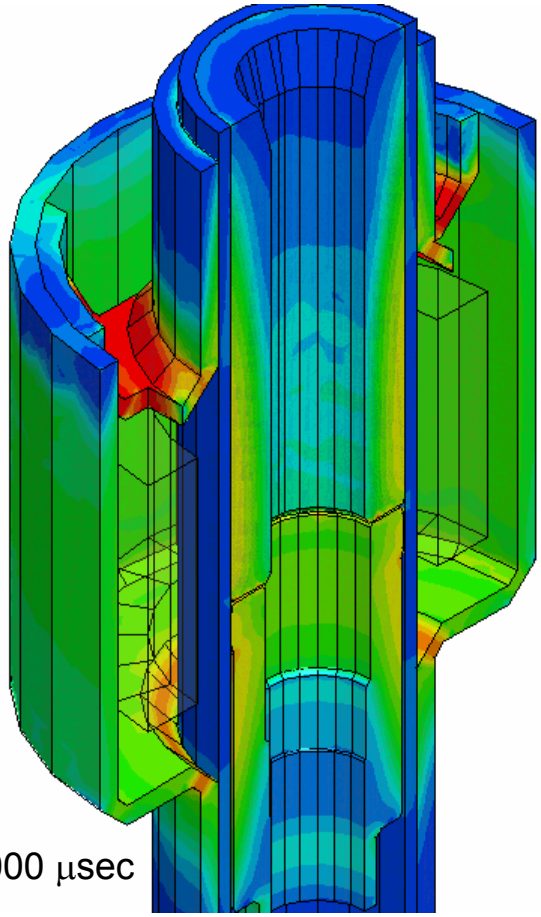
Delphi Actuator Results



200 μsec

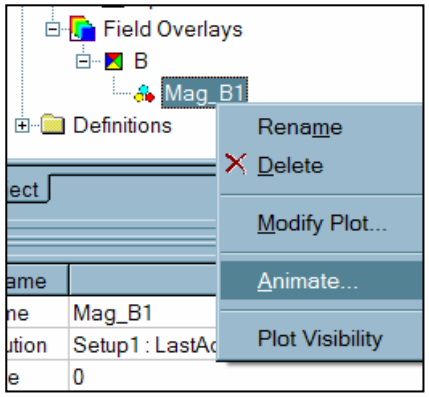


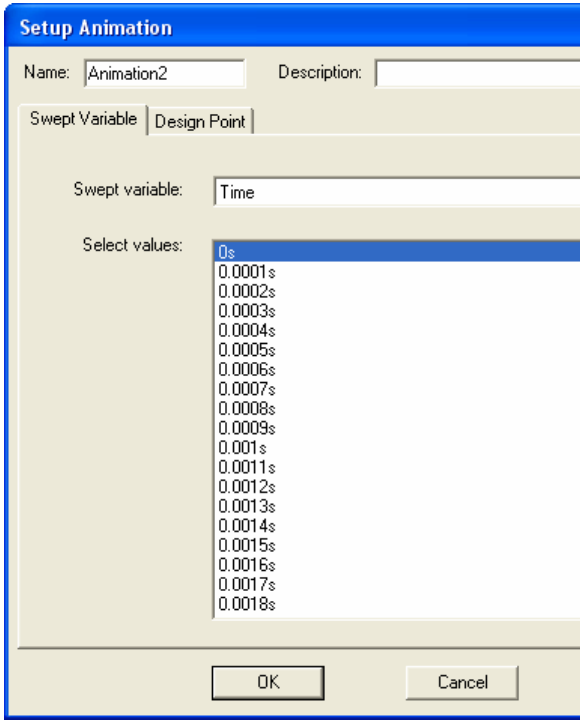
500 μsec

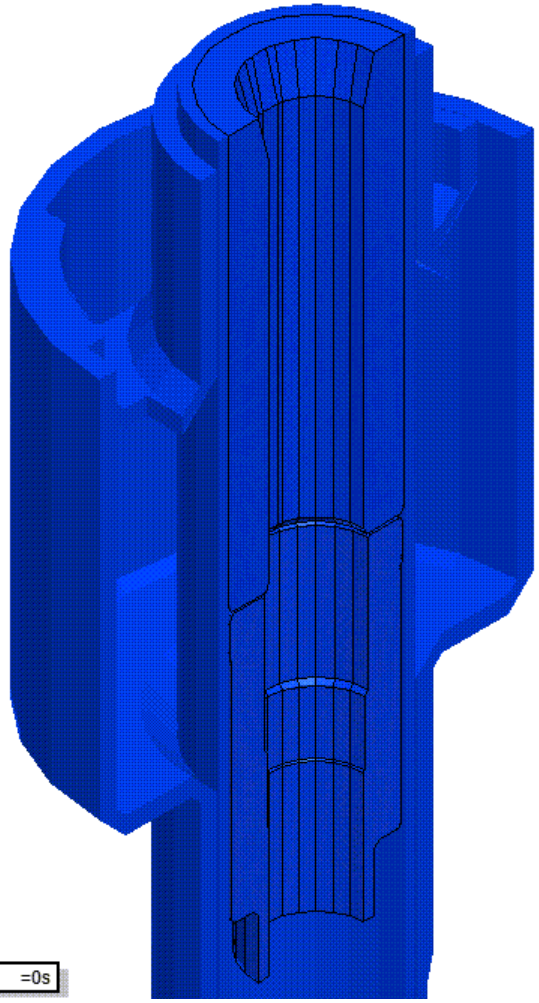


1000 μsec

Delphi Actuator Results







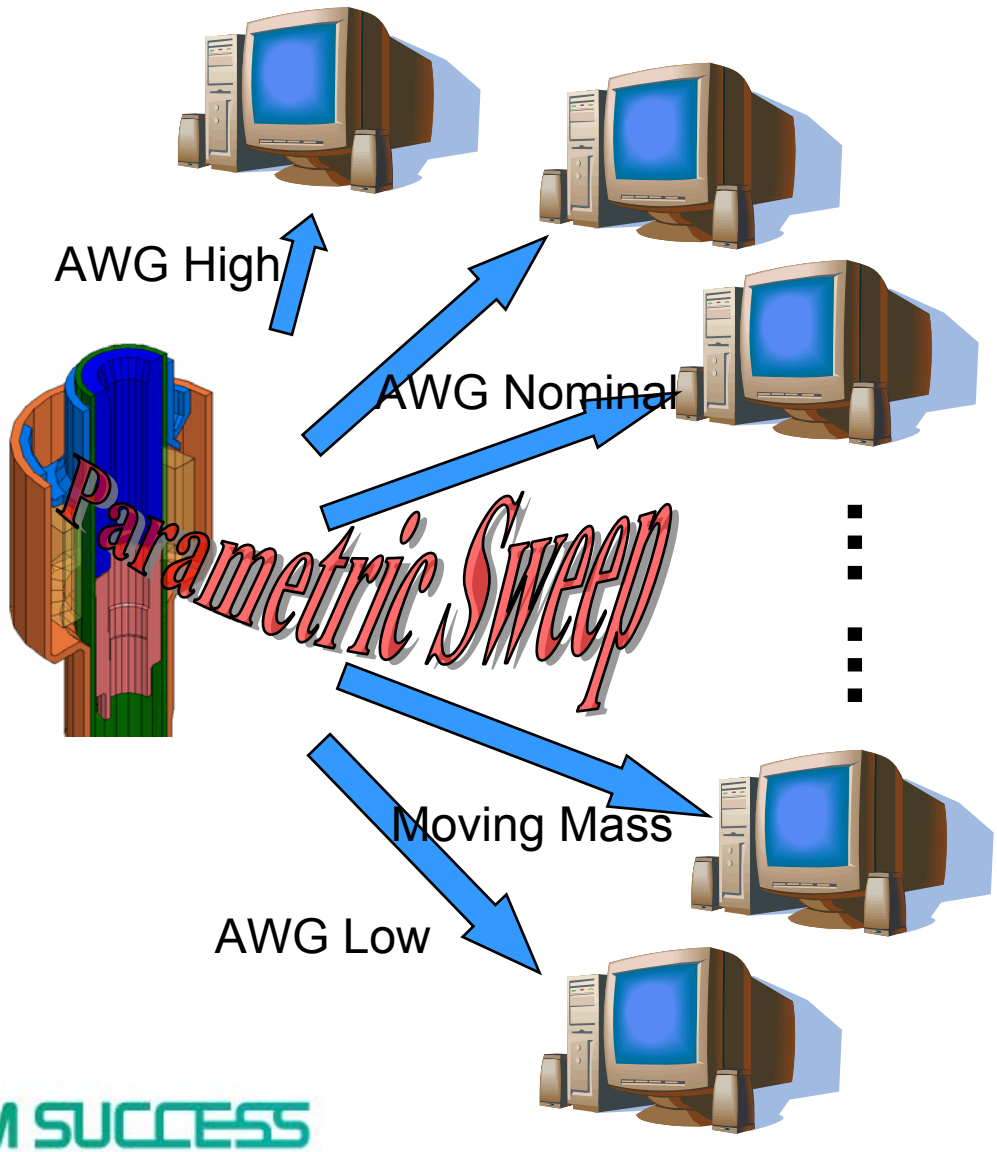
Delphi Parametric Study

- Transient Parametric Study:
  - ***Wire gauge*** one AWG above and one below the nominal case, maintain Coil Resistance by designing number of Turns.
  - ***Moving Mass*** Nominal and Half .
  - ***Material Conductivity*** (with and without to determine effect of diffusion time).
- Observe closing time.
- Show benefit of distributed processing.

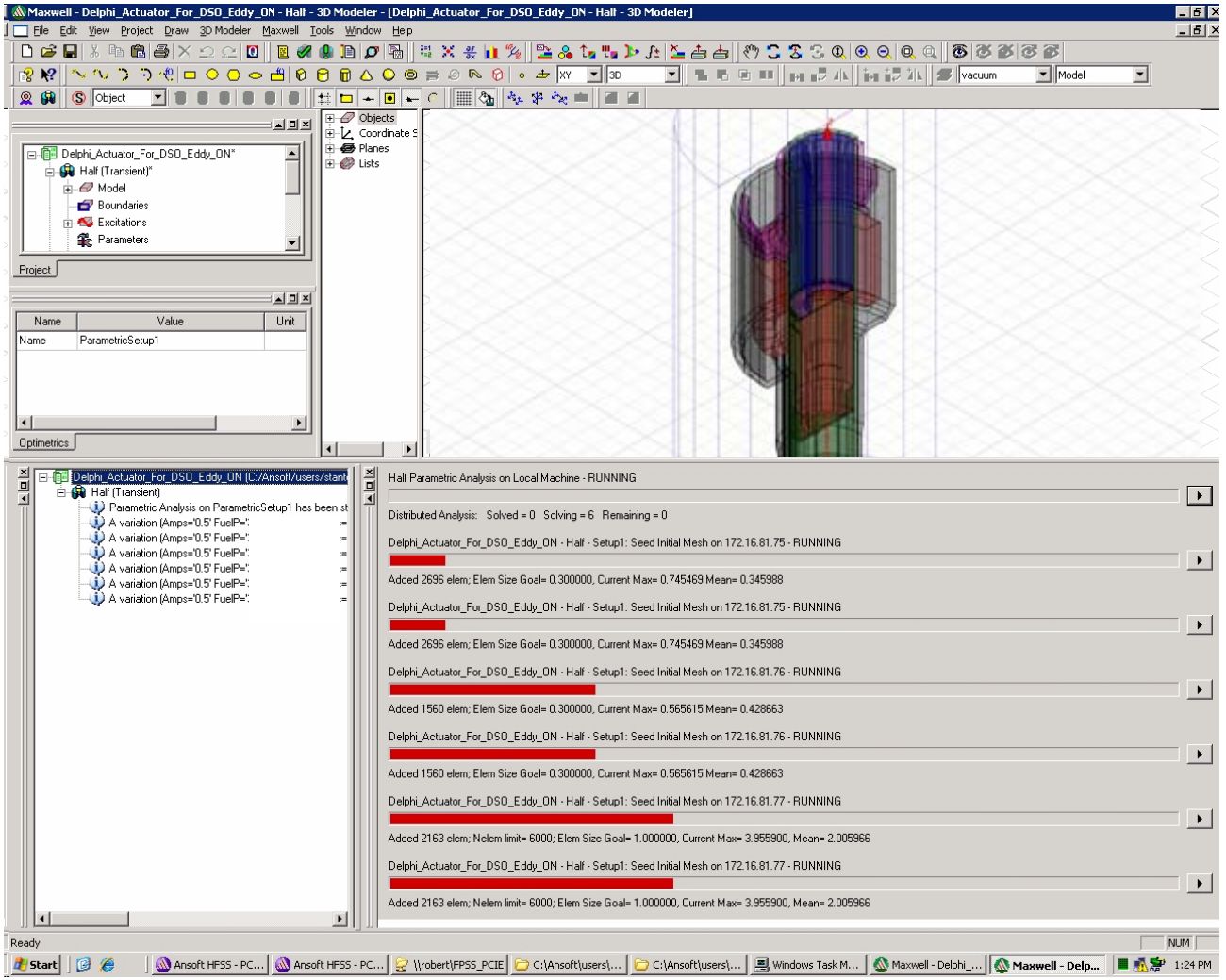
Distributed Analysis: Transient Parametric Sweep

Process

- One computer runs adaptive analysis
- Each transient model is sent to a different computer available for distributed analysis
- As each computer finishes a solution, the first of any remaining sweeps is sent to that computer



Delphi Distributed Analysis



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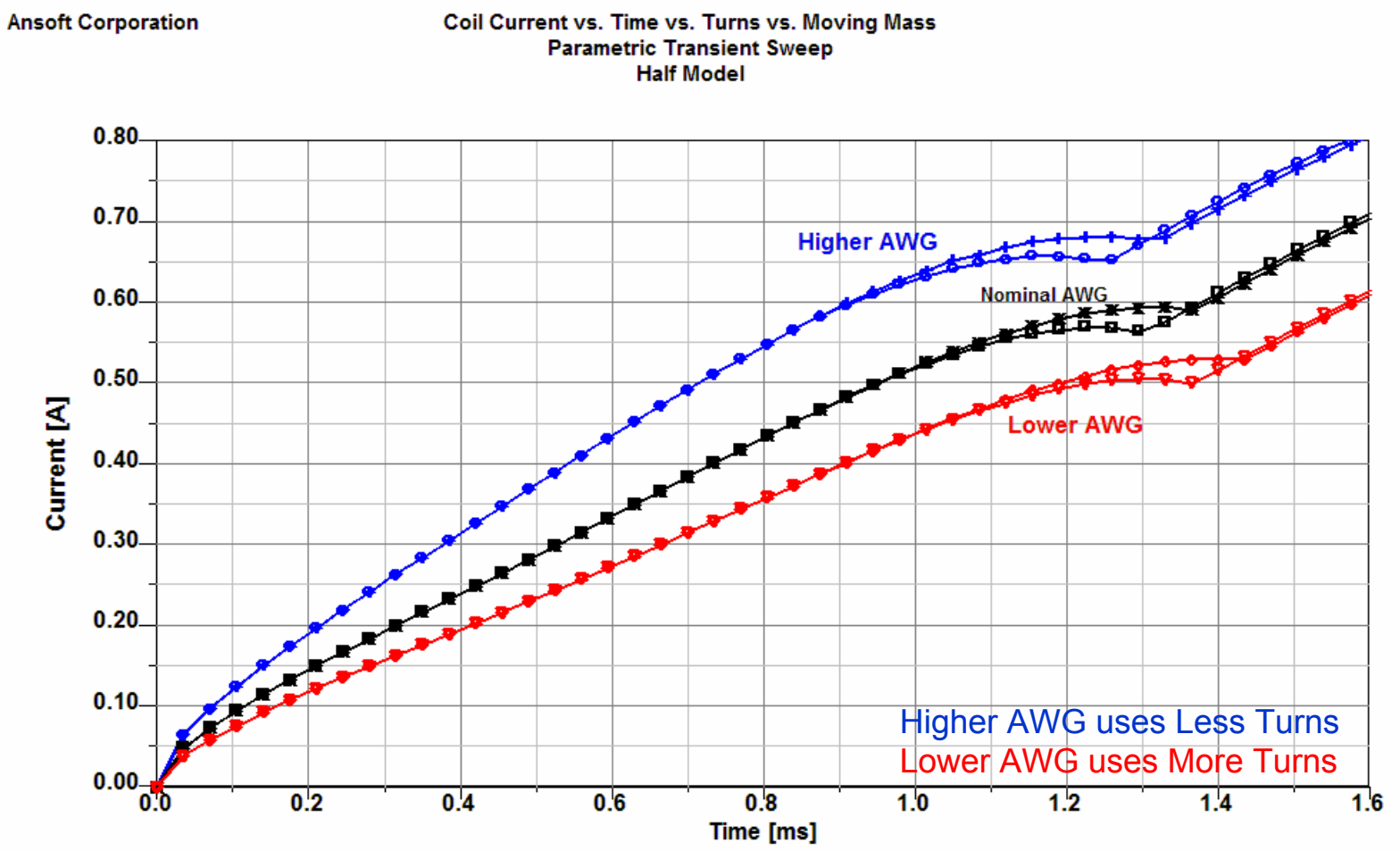
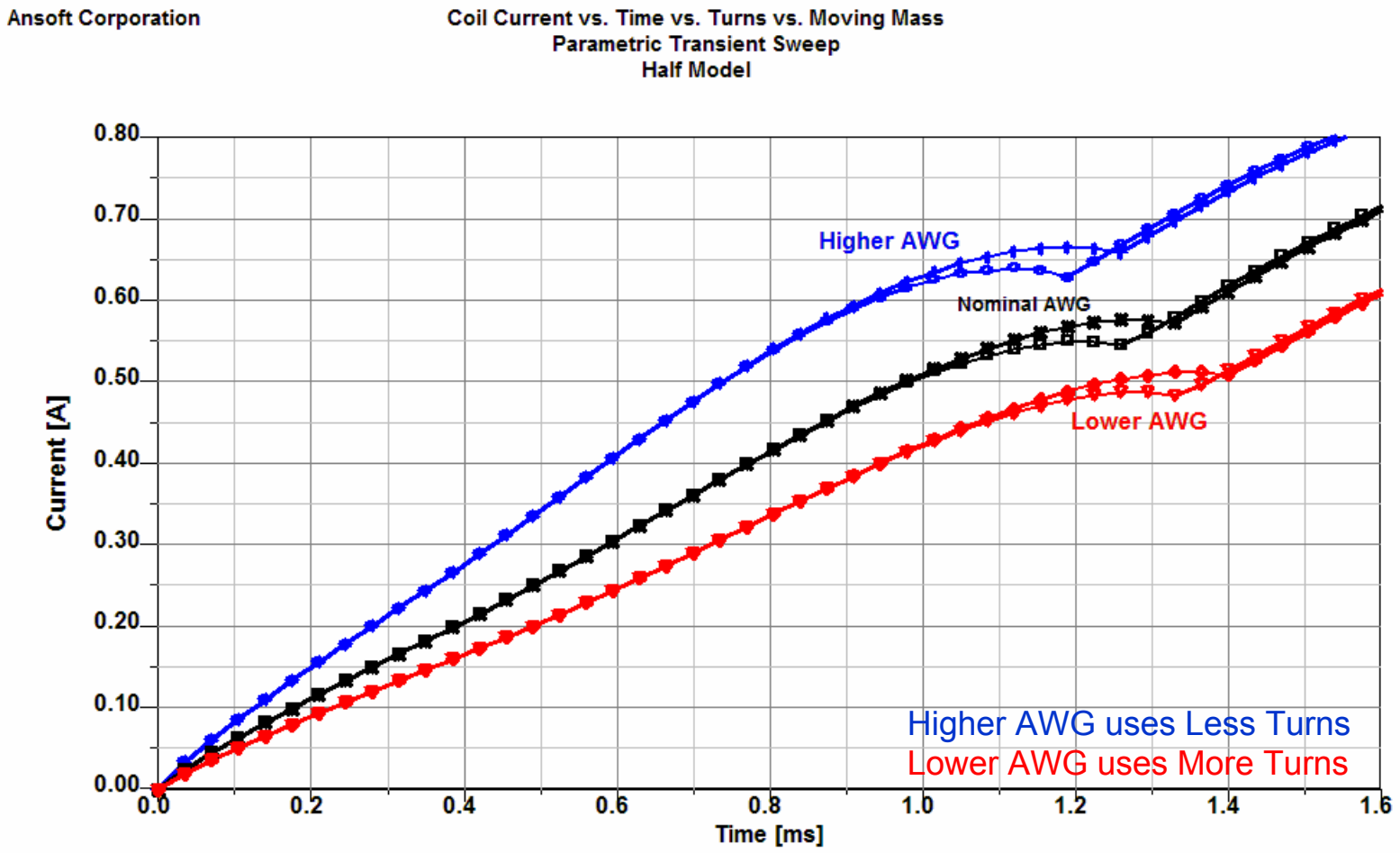
Delphi Distributed Analysis Results

(with conductivity)



Delphi Distributed Analysis Results

(without conductivity)



Delphi Model Conclusions

General

Faster closing time results in more accurate fueling to the engine thus providing improved hydrocarbon emissions.

Coil Design

AWG size has a measurable impact on closing time and was quantified by the model.

Moving Mass

The Moving Mass has a measurable impact on closing time and was quantified by the model.

Magnetic Diffusion

Material Conductivity has a measurable impact on closing time and was quantified by the model.

Delphi Model Future Work

- Continue study of non-axisymmetric features to determine affect on closing time in 2D and 3D models.
- Investigate lower conductivity materials to reduce closing time. Note: material appropriate BH curves should also be used.
- Include additional drive circuit studies to investigate how to decrease the opening and closing time.
- Comparison to measured results upon completion of prototype.

Delphi Multec® Multi-Port Fuel Injectors are available in various design configurations to meet a wide range of customer requirements.