



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.



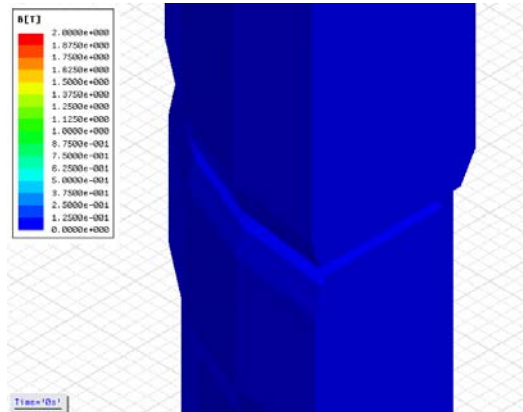
Delphi Multec[®] Gasoline Multi-Port Fuel Injectors



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: $fn(\sigma, \mu, \text{size}, di/dt)$



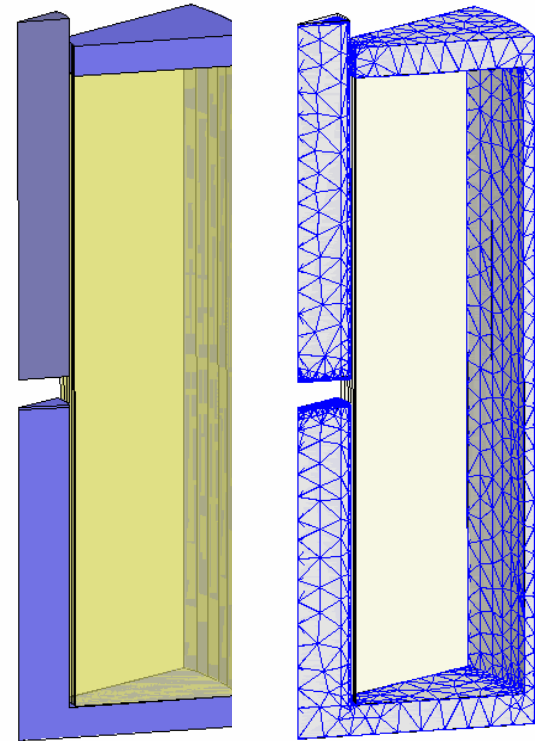
Ansoft Simulation Approach

- 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

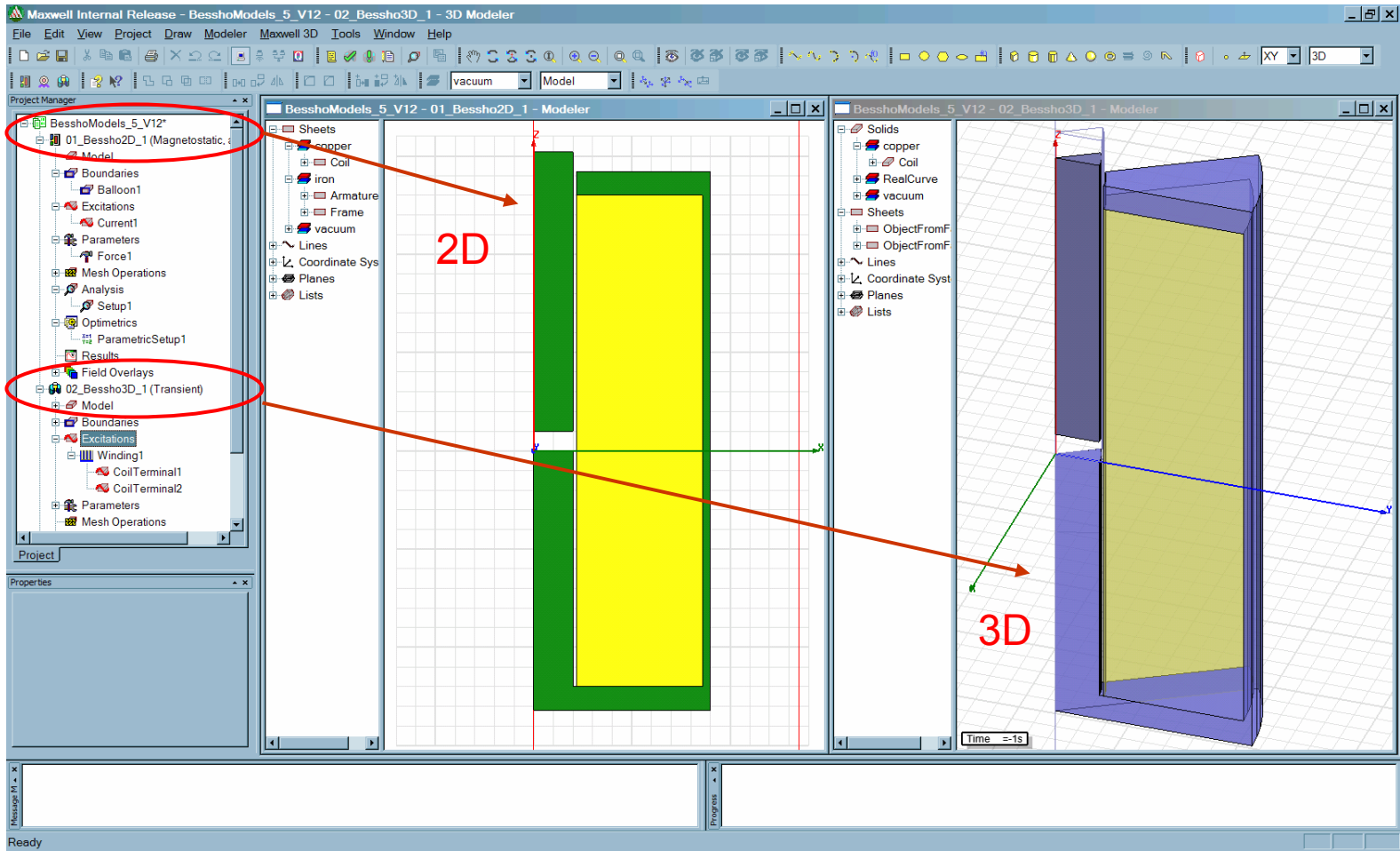
- Well known Bessho¹ actuator modeled using 3D FEA.
- 30 degree Wedge, 5 degree segments.
- Transient with Motion and eddy effects for steel objects.
- 5ms time step solved to 300ms.
- Voltage source = 100 Volts step, R = 200 Ohms.



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



Validation – V12 Interface



Validation – Meshing

- Two Approaches:
 1. Use mesh operations to mesh the geometry
 2. Use mesh operations *and* adaptive meshing from a *magnetostatic* or *Eddy Current Design* and *Link the mesh* to the transient Design.

Setup1 Displays Linked Mesh Icon for MaxwellDesign1c.



Validation – Motion Setup

The screenshot displays the ANSYS software interface. On the left, a tree view shows a model with a 'CoilTerminal1' object. A context menu is open over this object, with 'Motion Setup' selected. A sub-menu is also open, showing options like 'Assign Band...', 'Unassign Band', and 'Visualization...'. The 'Assign Band...' option is highlighted. In the center, a 'Project' panel shows a table of properties for the selected 'Band' object.

Name	Value
Name	Band
Material	vacuum
Solve Inside	<input checked="" type="checkbox"/>
Orientation	Global
Model	<input checked="" type="checkbox"/>
Display Wireframe	<input checked="" type="checkbox"/>
Color	Edit
Transparent	0

On the right, a 3D model of a coil is shown. A red arrow points downwards from the top of the coil, indicating the direction of motion. The time in the bottom right corner is 'Time=10s'.

Create Band Object.

Select Band Object.

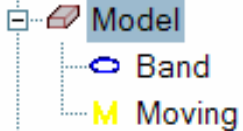
Assign as Band.

Everything inside will be moving.



Validation – Motion Setup

01_Transient1_Parametric (Transient)



Motion Setup

Type | Data | Mechanical

Motion Type: Translation Rotation

Moving Vector: Global::Z

Positive Negative

OK Cancel

Motion Setup

Type | Data | Mechanical

Initial Position: 0

Translate Limit

Negative: 0

Positive: 9.873

OK Cancel

Motion Setup

Type | Data | Mechanical

Consider Mechanical Transient

Initial Velocity: 0 m_per_sec

Mass: 6 kg

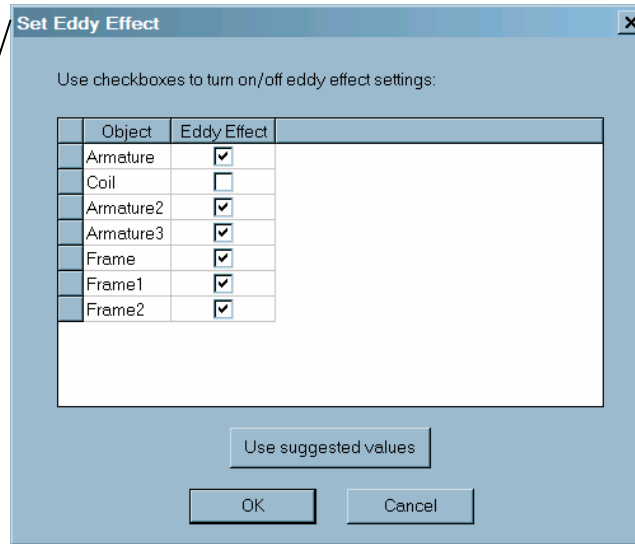
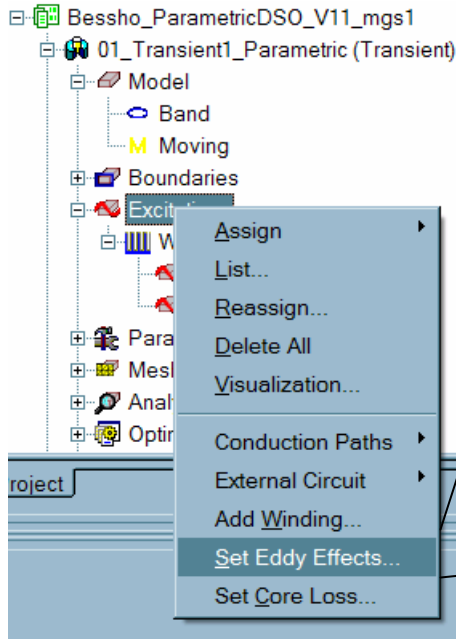
Damping: 0 N-sec/m

Load Force: 0 nNewton

OK Cancel

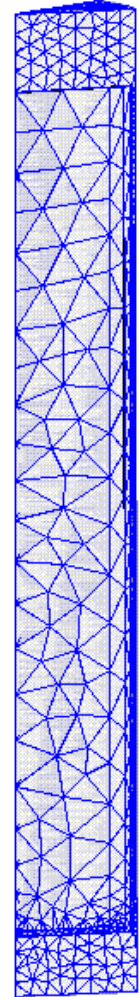


Validation – Band, Eddy Effects



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

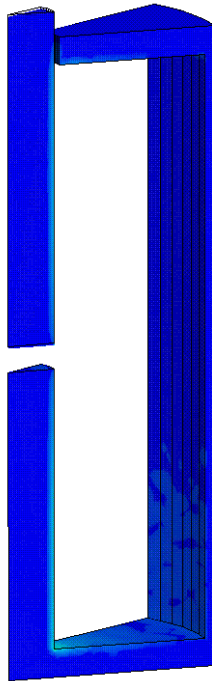
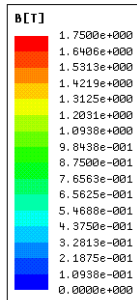
For each time step where motion occurs, the mesh is only re-meshed between the band and the moving object.



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

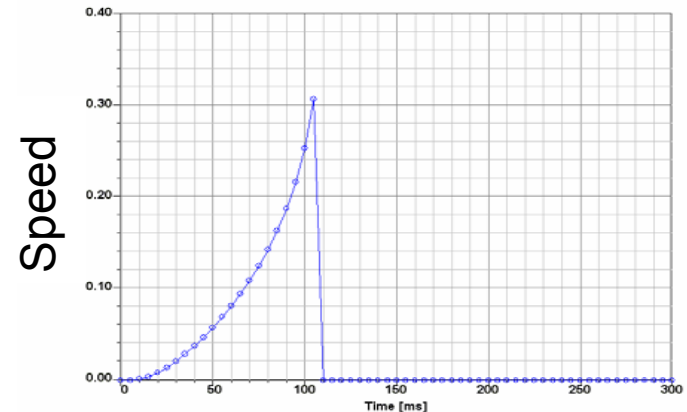
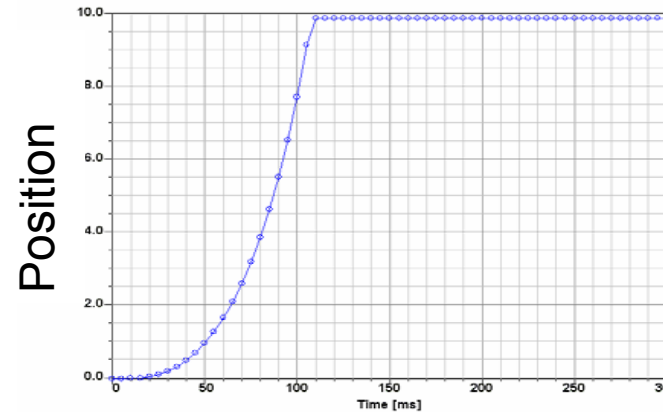
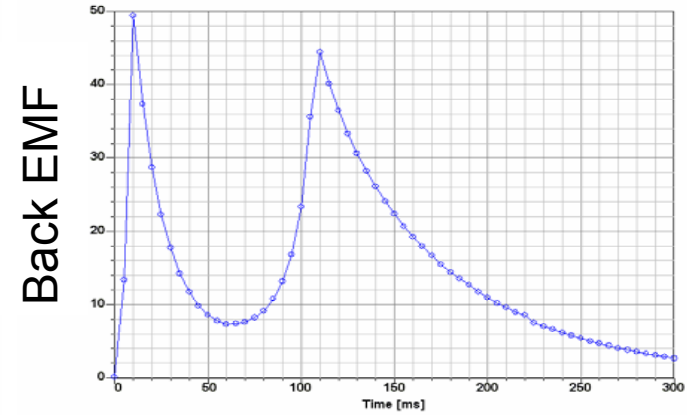
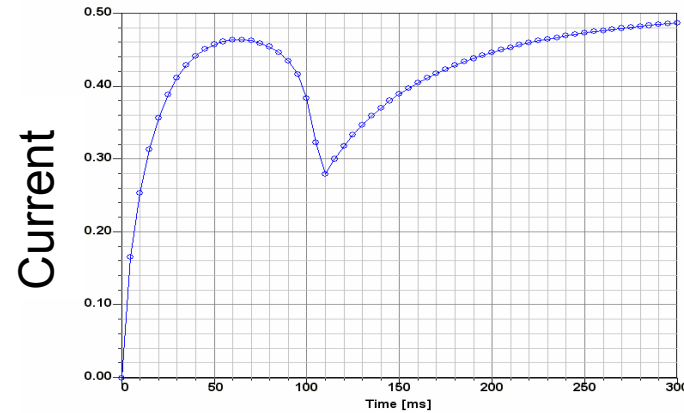


Validation – Transient Closing

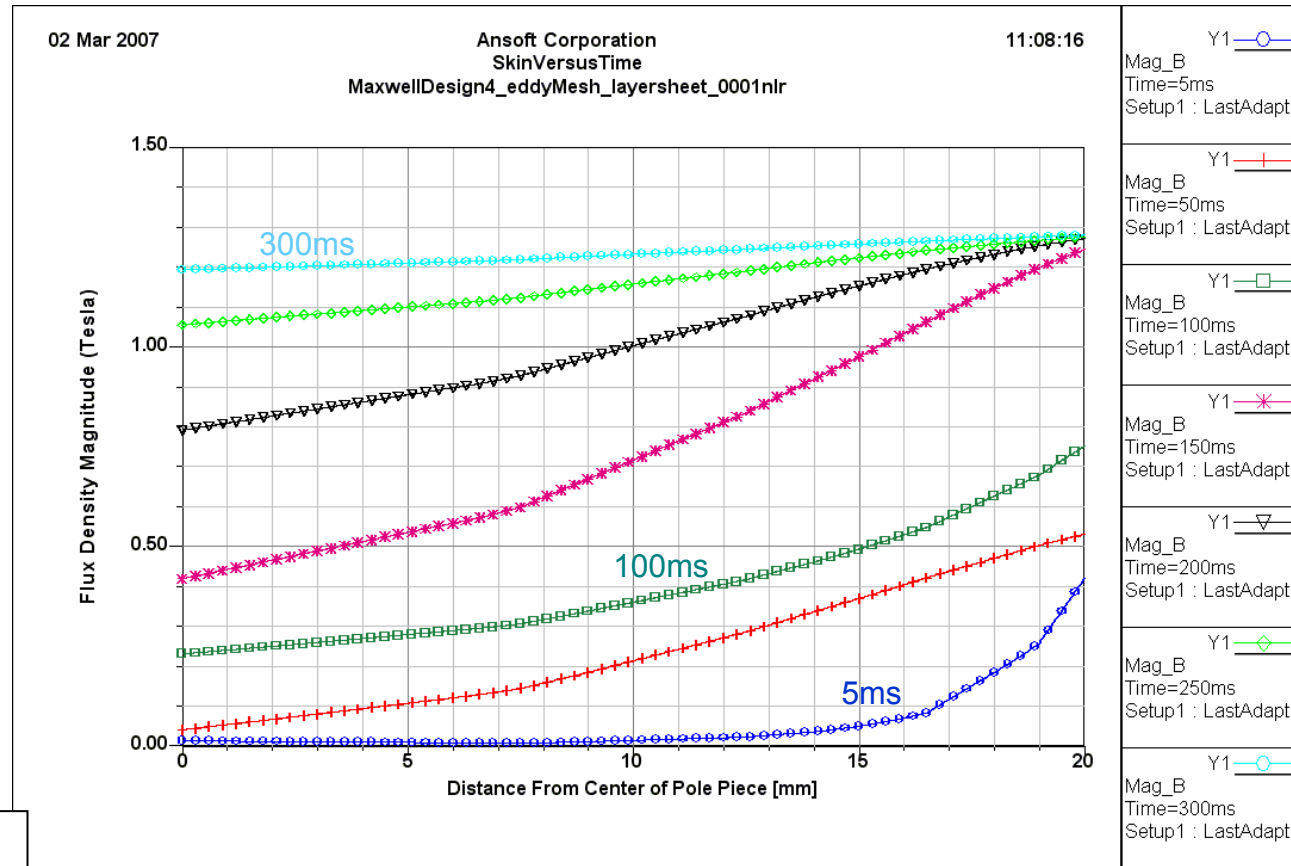
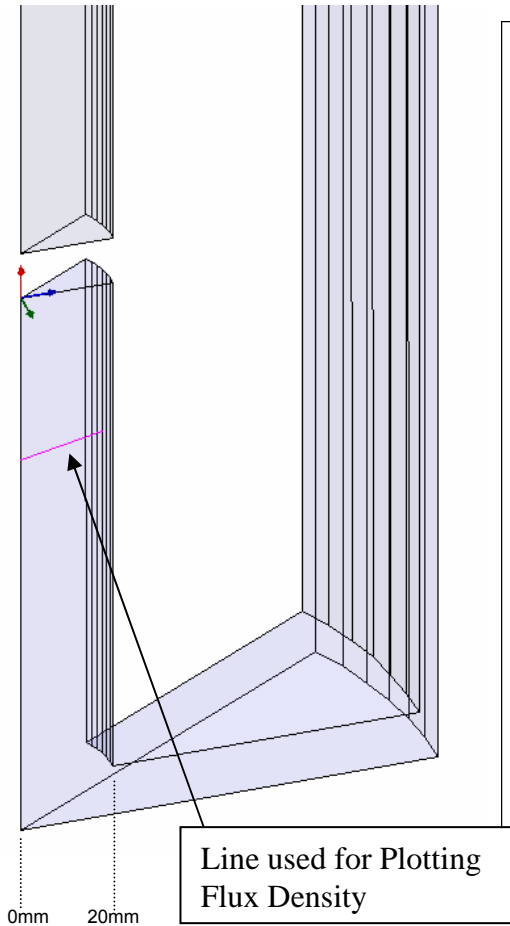


Time = 0.005 s

Diffusion time: $fn(\sigma, \mu, \text{size}, di/dt)$



Validation - Magnetic Diffusion

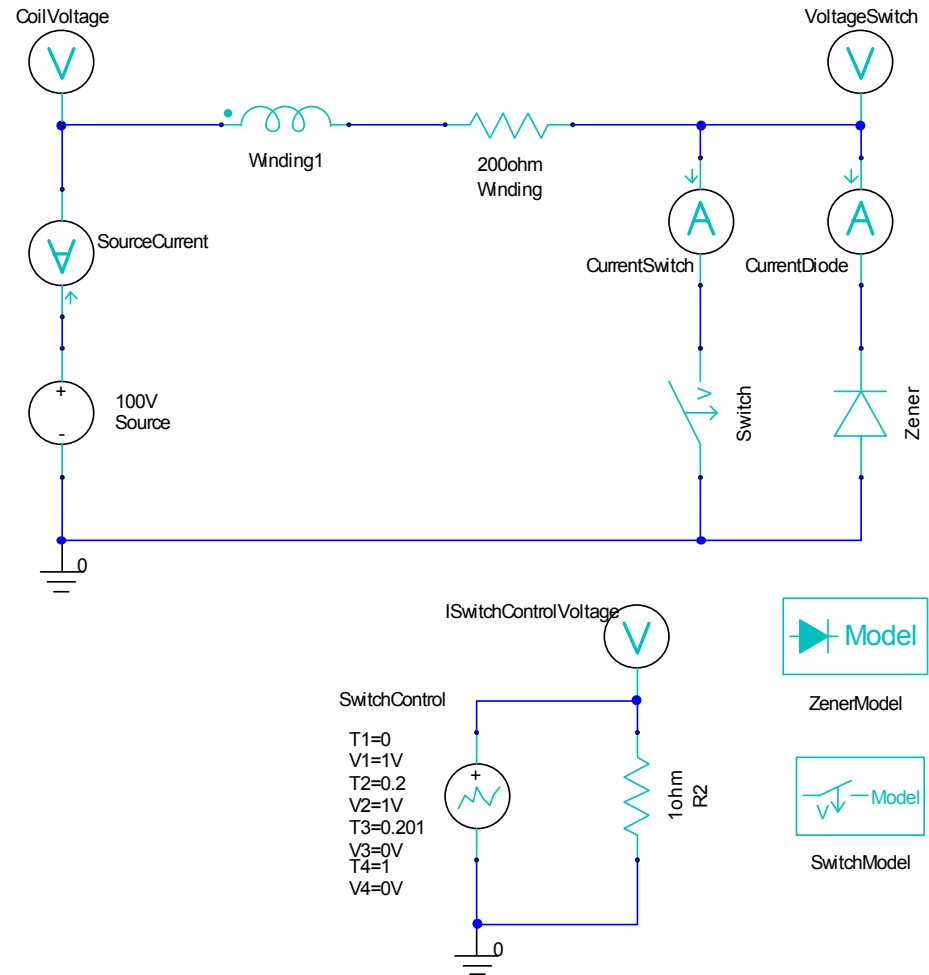


Plot of Magnetic Field as a function of position and time.



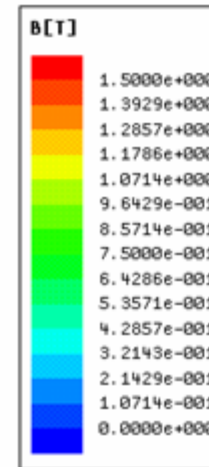
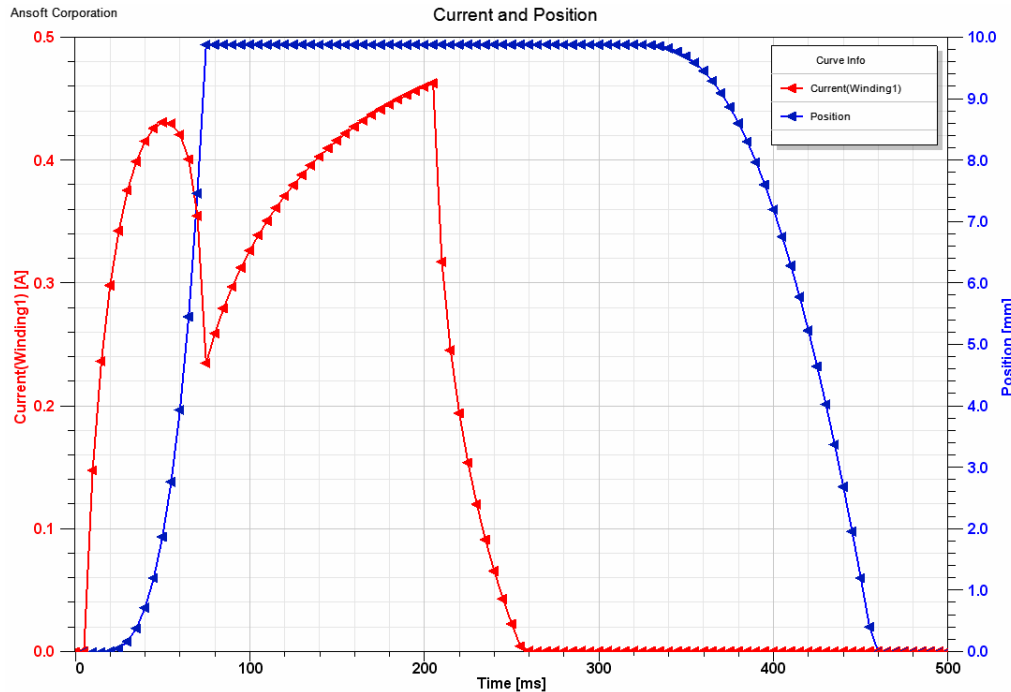
Validation – Additional Options

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

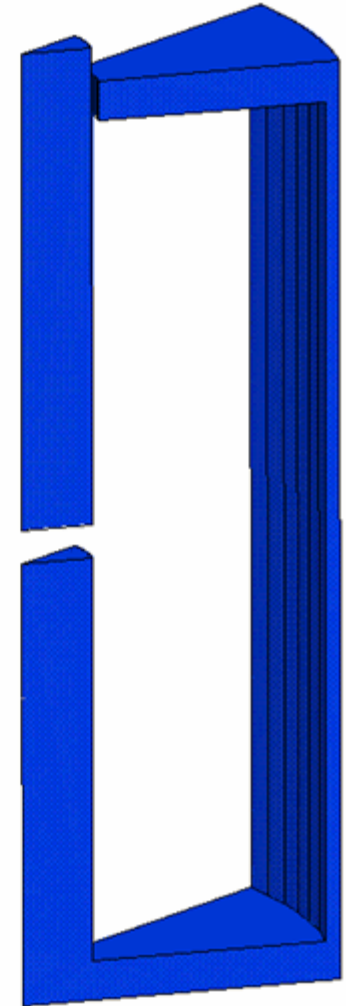


Validation – Close and Open

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

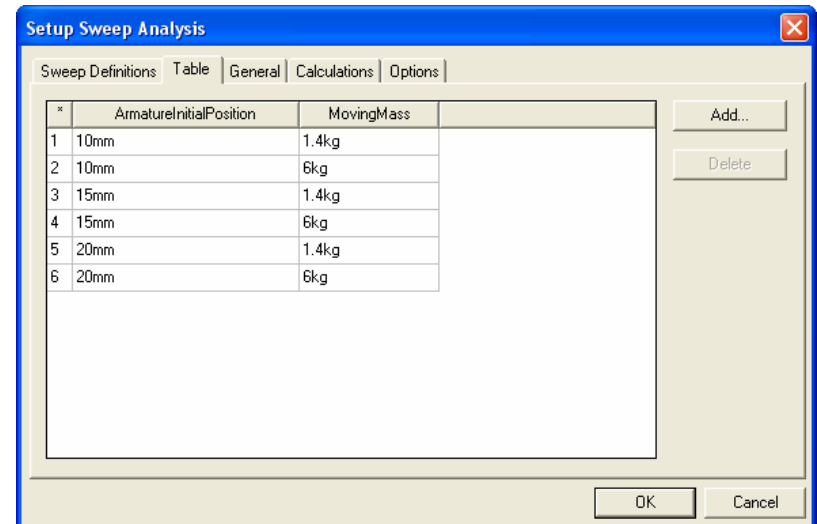
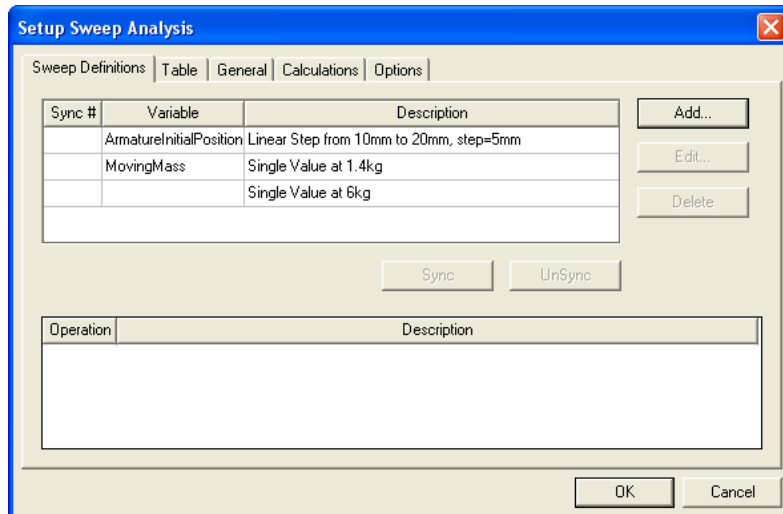


Time =0ns
Speed =0.000000m_per_sec
Position =-0.000000mm



Validation - Parametric Transient Study with Distributed Analysis

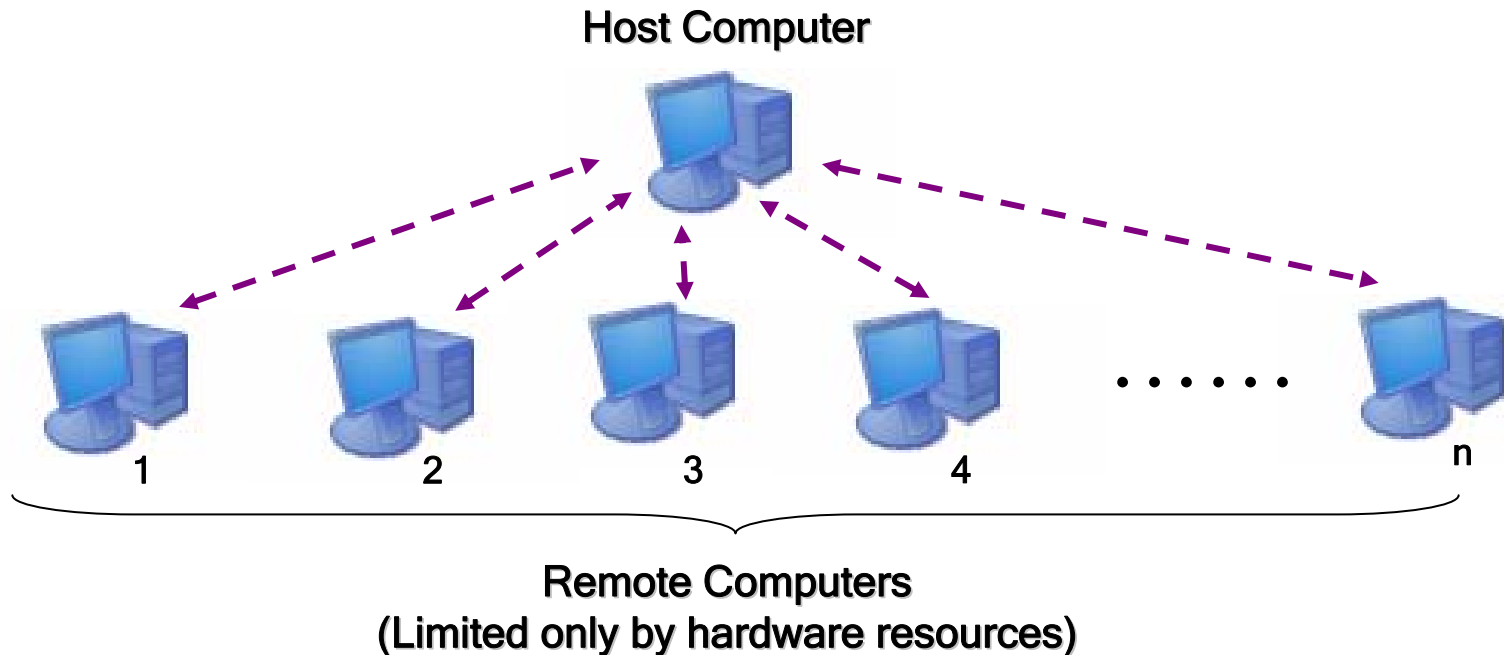
- Varied starting position (10, 15, 20 mm).
- Varied Moving Mass (1.4, 6 kg).
- Observe parametric solution of transient results.



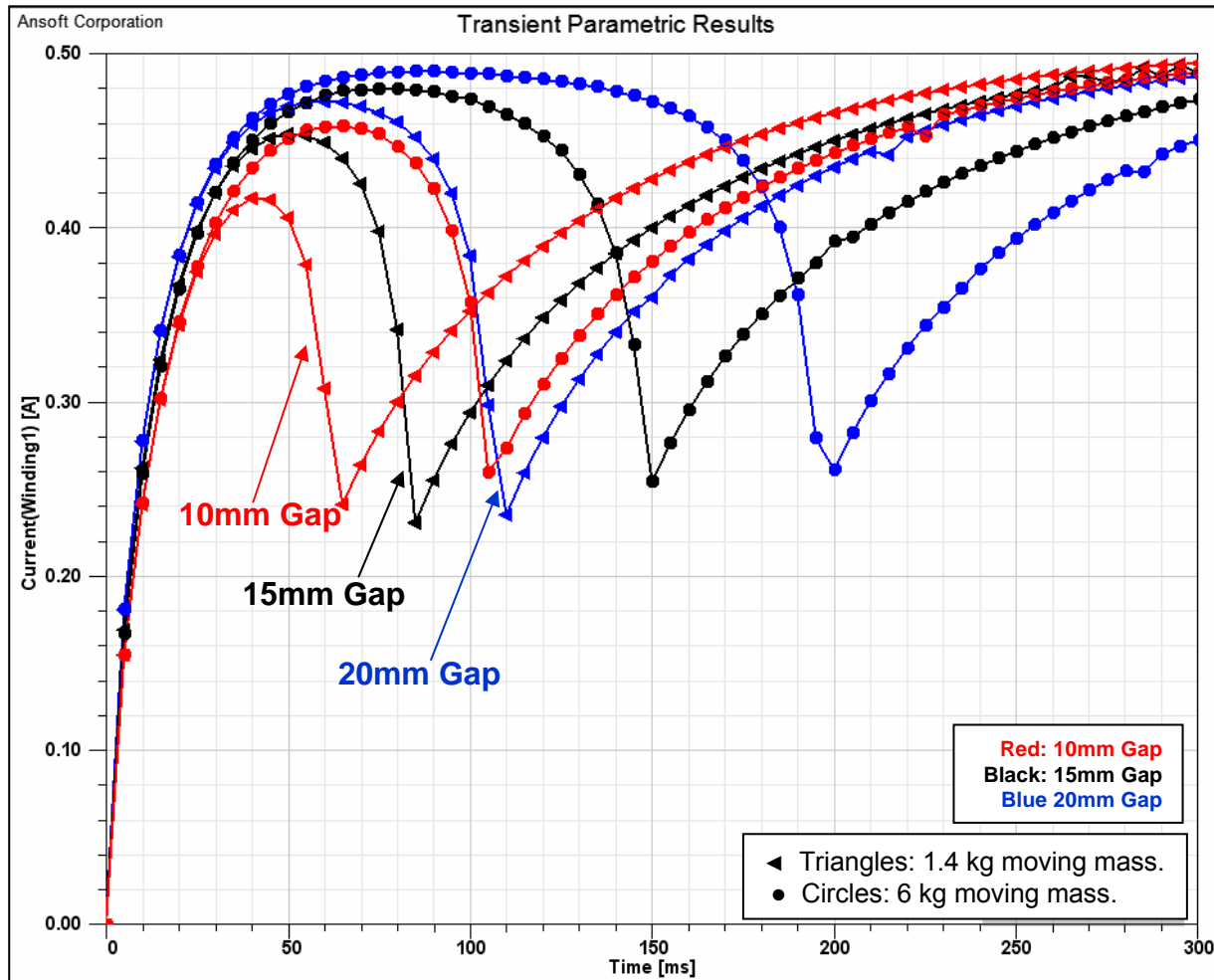
About Distributed Analysis

- **Distributed Analysis**

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



Validation - Parametric Transient Study with Distributed Analysis



Validation - Conclusions

- 3D Analysis using Maxwell shows excellent correlation with published results¹ 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 = $P_{\text{director}}/P_{\text{ball-seat}}$

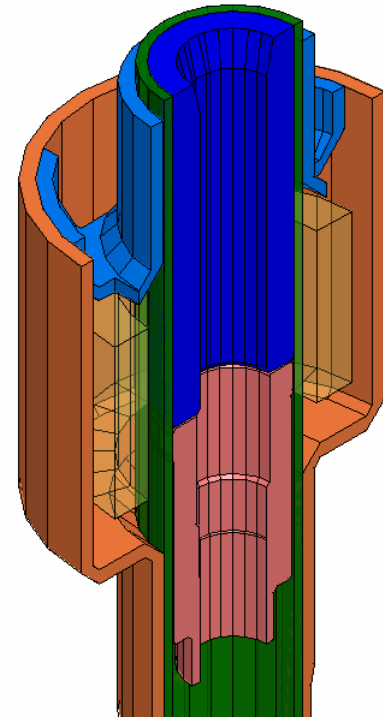


Delphi Multec® Multi-Port Fuel Injectors are available in various design configurations to meet a wide range of customer requirements.

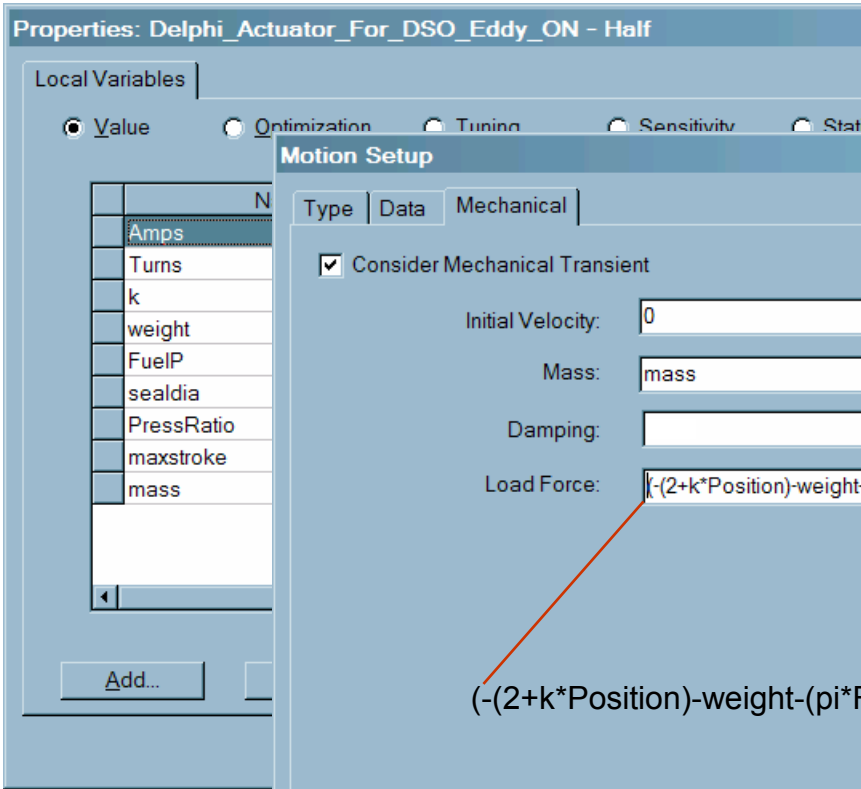


Delphi Actuator

- 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.

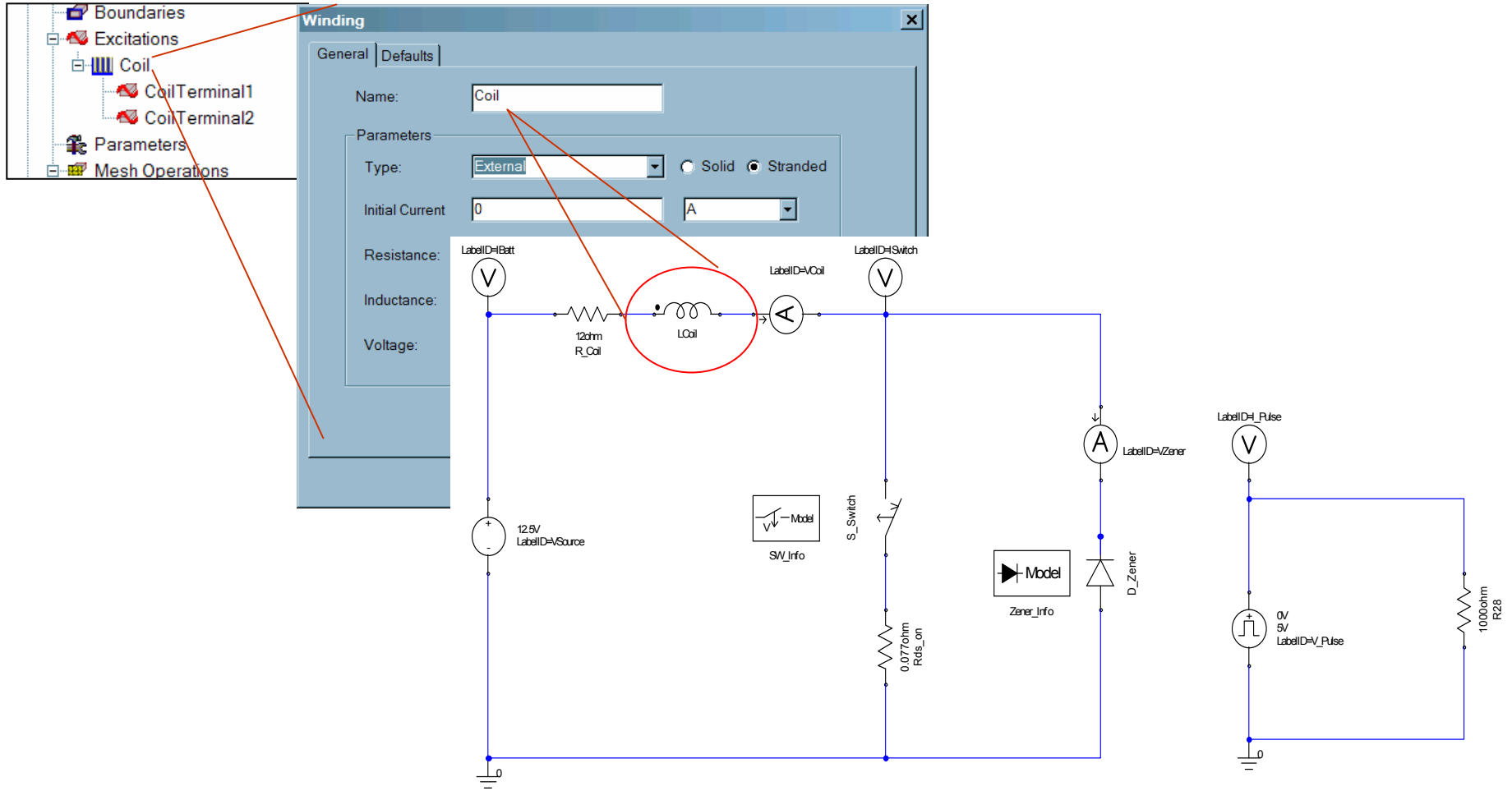
Mechanical Parameters.

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

Functional Load Force defined using Local Design Variables.



Delphi Actuator Setup Details



Delphi Actuator Setup Details

Name	Value	Unit	E
Name	Length1		
Type	Length Based		
Region	Inside Selection		
Restrict Length	<input checked="" type="checkbox"/>		
Max Length	1	mm	1m
Restrict Max Elems	<input type="checkbox"/>		
Max Elems	6000		600

Mesh operations on selected Geometry.

Solve Setup

General | Save Fields | Advanced | Solver | Output Variables | Defaults

Name: Setup1

Transient Setup

Stop time: 0.003

Time step: 35

Use Default

Select time steps and times to save fields.

Solve Setup

General | Save Fields | Advanced | Solver | Output Variables | Defaults

Sweep Setup

Type: Linear Step

Start: 0 s

Stop: 0.003 s

Step Size: 140 us

Add to List >>

Replace List >>

Add Single Point

Delete Selection

Clear All

Undo Last Change

Time
0s
0.00014s
0.00028s
0.00042s
0.00056s
0.0007s
0.00084s
0.00098s
0.00112s
0.00126s
0.0014s
0.00154s
0.00168s
0.00182s

Please note the stop time defined in the General Page would be automatically included.

OK Cancel

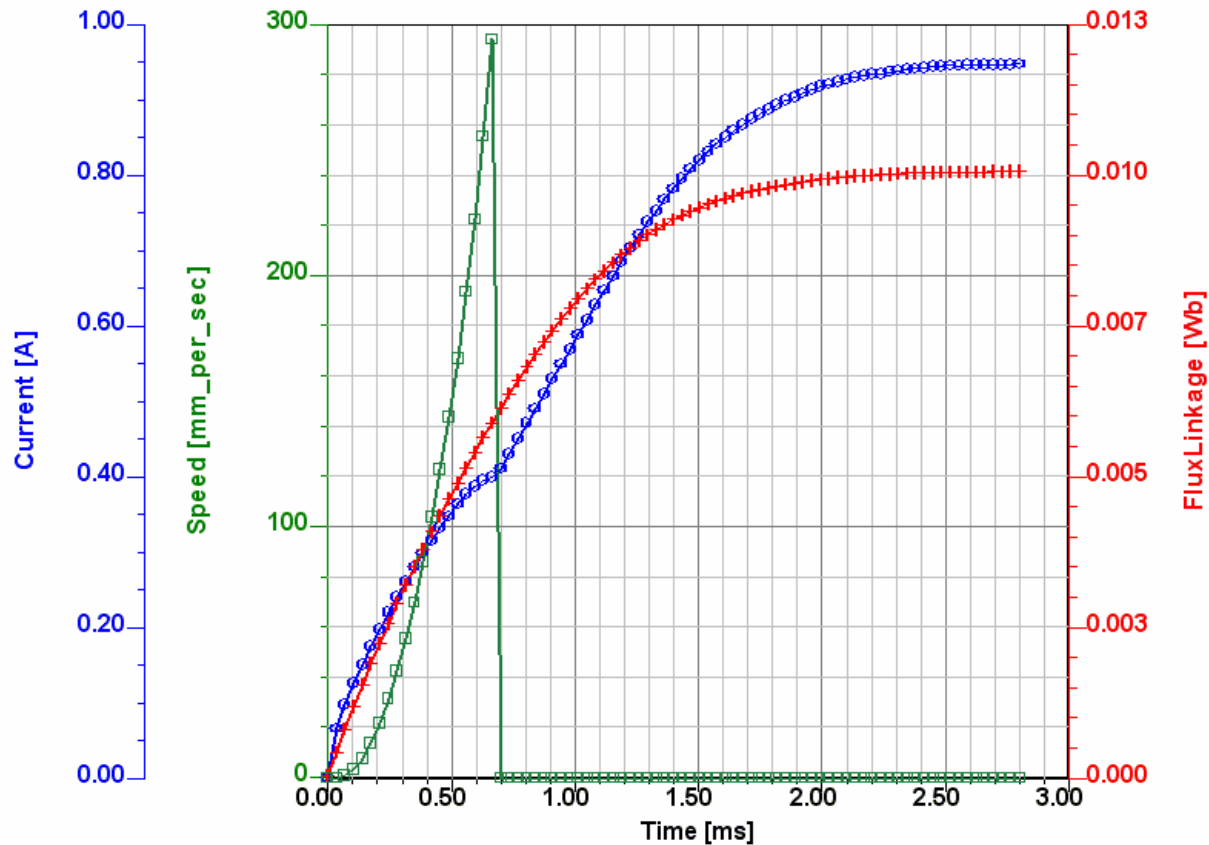


Delphi Actuator Results

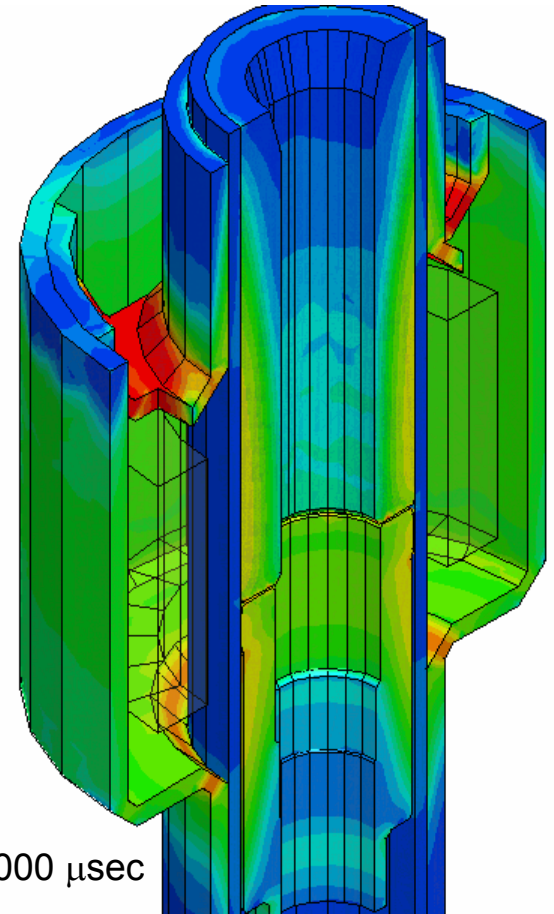
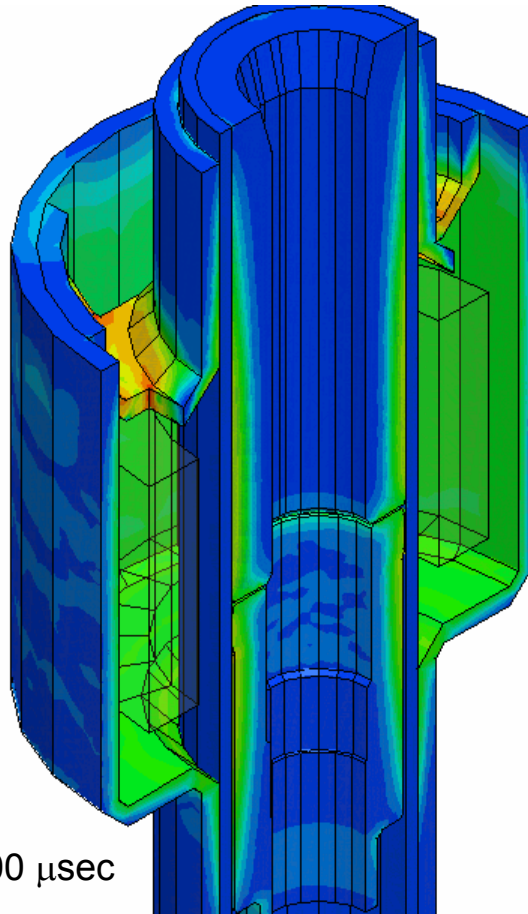
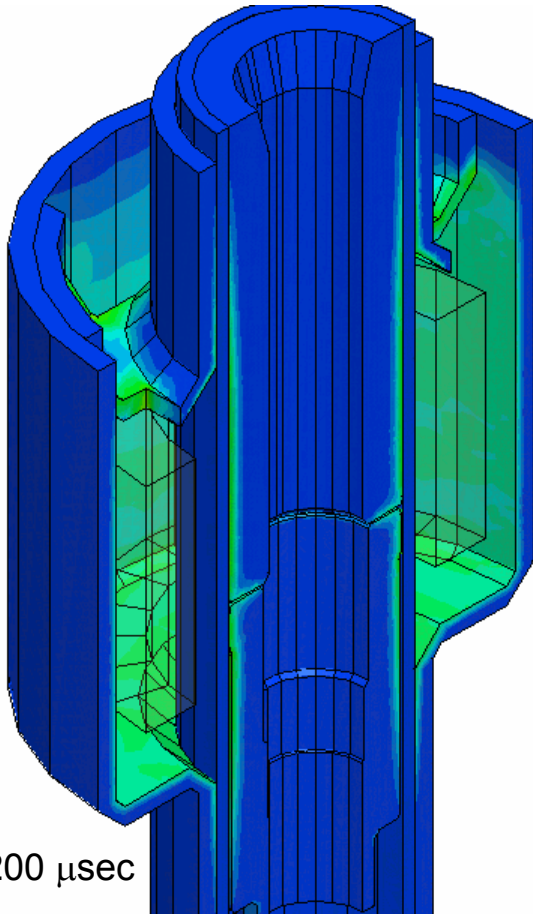
30 Aug 2007

Coil Current and Position vs. Time
Setup1 Results
Half Model

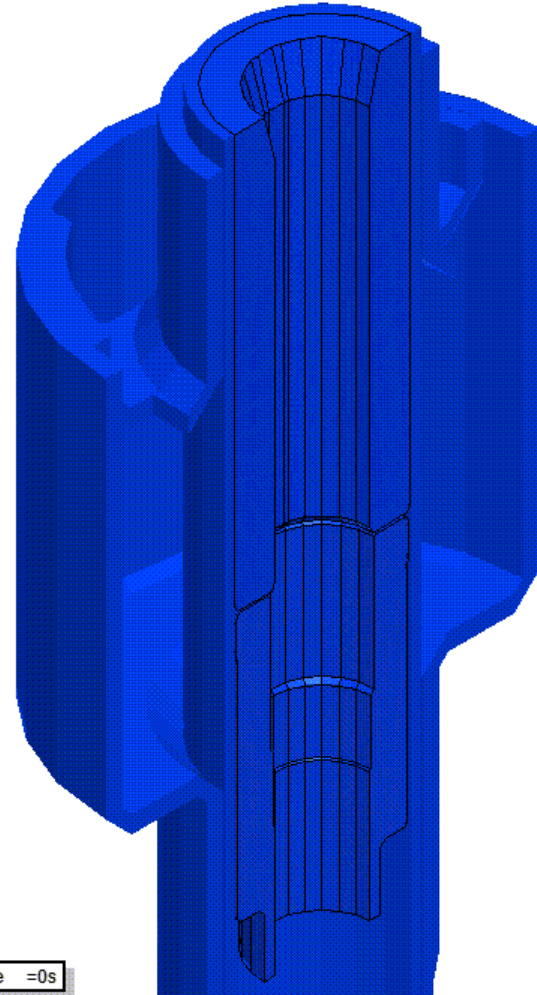
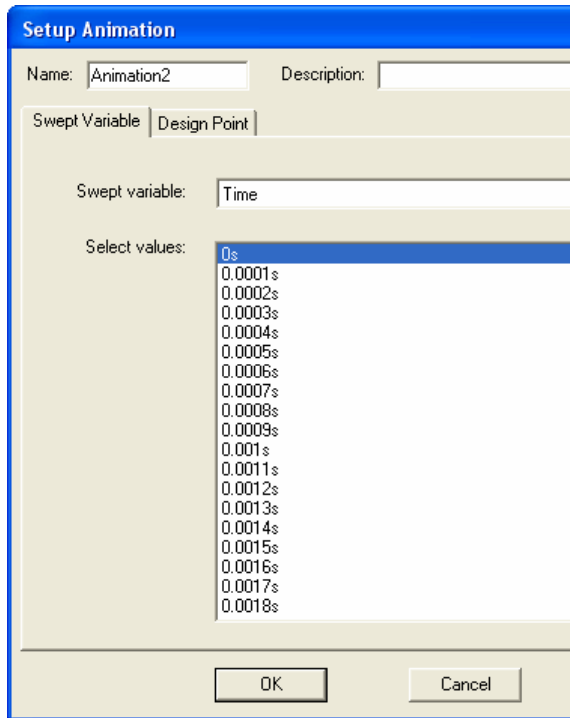
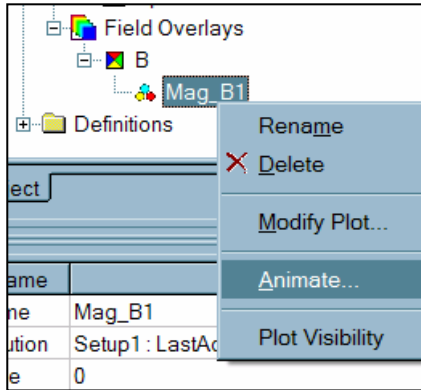
14:29:06



Delphi Actuator Results



Delphi Actuator Results



Time =0s



Delphi Parametric Study

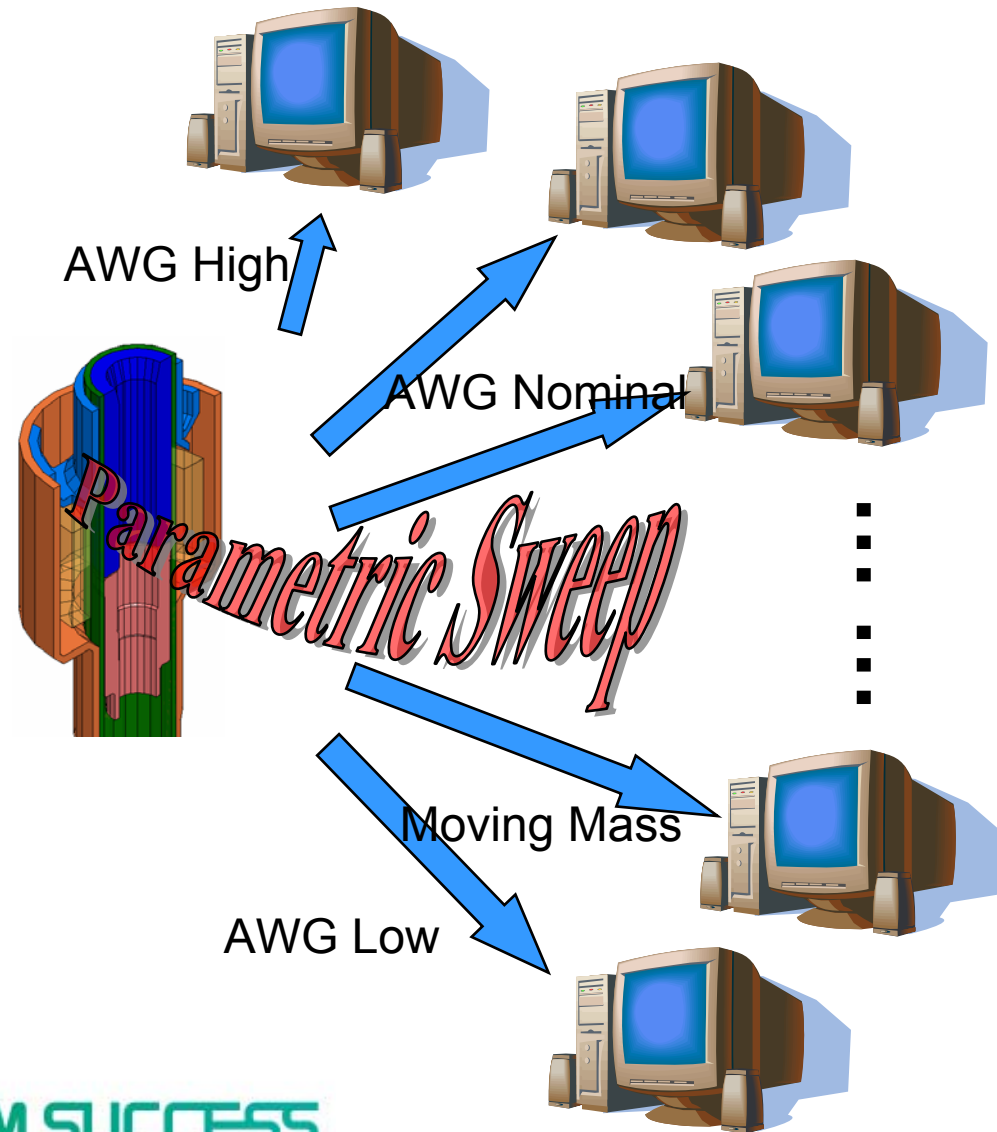
- Transient Parametric Study:
 - **Wire gauge** one AWG above and one below the nominal case, maintain Coil Resistance by designing number of Turns.
 - **Moving Mass** Nominal and Half .
 - **Material Conductivity** (with and without to determine effect of diffusion time).
- Observe closing time.
- Show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

The screenshot displays the ANSYS Maxwell 3D Modeler interface. The main window shows a 3D model of a Delphi actuator, a cylindrical component with a central shaft and a top cap, rendered in a semi-transparent purple and blue color. The interface includes a menu bar (File, Edit, View, Project, Draw, 3D Modeler, Maxwell, Tools, Window, Help), a toolbar with various modeling and analysis tools, and a left-hand panel with a project tree and a parameter table.

The project tree on the left shows the following structure:

- Delphi_Actuator_For_DS0_Eddy_ON*
- Hall (Transient)*
- Model
- Boundaries
- Excitations
- Parameters

The parameter table below the tree is as follows:

Name	Value	Unit
ParametricSetup1		

The bottom panel shows the distributed analysis log for a parametric analysis on a local machine. The log indicates that the analysis is running and provides details for each iteration:

```
Half Parametric Analysis on Local Machine - RUNNING
Distributed Analysis: Solved = 0 Solving = 6 Remaining = 0
Delphi_Actuator_For_DS0_Eddy_ON - Half - Setup1: Seed Initial Mesh on 172.16.81.75 - RUNNING
Added 2636 elem; Elem Size Goal= 0.300000, Current Max= 0.745469 Mean= 0.345988
Delphi_Actuator_For_DS0_Eddy_ON - Half - Setup1: Seed Initial Mesh on 172.16.81.75 - RUNNING
Added 2636 elem; Elem Size Goal= 0.300000, Current Max= 0.745469 Mean= 0.345988
Delphi_Actuator_For_DS0_Eddy_ON - Half - Setup1: Seed Initial Mesh on 172.16.81.76 - RUNNING
Added 1560 elem; Elem Size Goal= 0.300000, Current Max= 0.565615 Mean= 0.428663
Delphi_Actuator_For_DS0_Eddy_ON - Half - Setup1: Seed Initial Mesh on 172.16.81.76 - RUNNING
Added 1560 elem; Elem Size Goal= 0.300000, Current Max= 0.565615 Mean= 0.428663
Delphi_Actuator_For_DS0_Eddy_ON - Half - Setup1: Seed Initial Mesh on 172.16.81.77 - RUNNING
Added 2163 elem; Nelem limit= 6000; Elem Size Goal= 1.000000, Current Max= 3.955900, Mean= 2.005966
Delphi_Actuator_For_DS0_Eddy_ON - Half - Setup1: Seed Initial Mesh on 172.16.81.77 - RUNNING
Added 2163 elem; Nelem limit= 6000; Elem Size Goal= 1.000000, Current Max= 3.955900, Mean= 2.005966
```

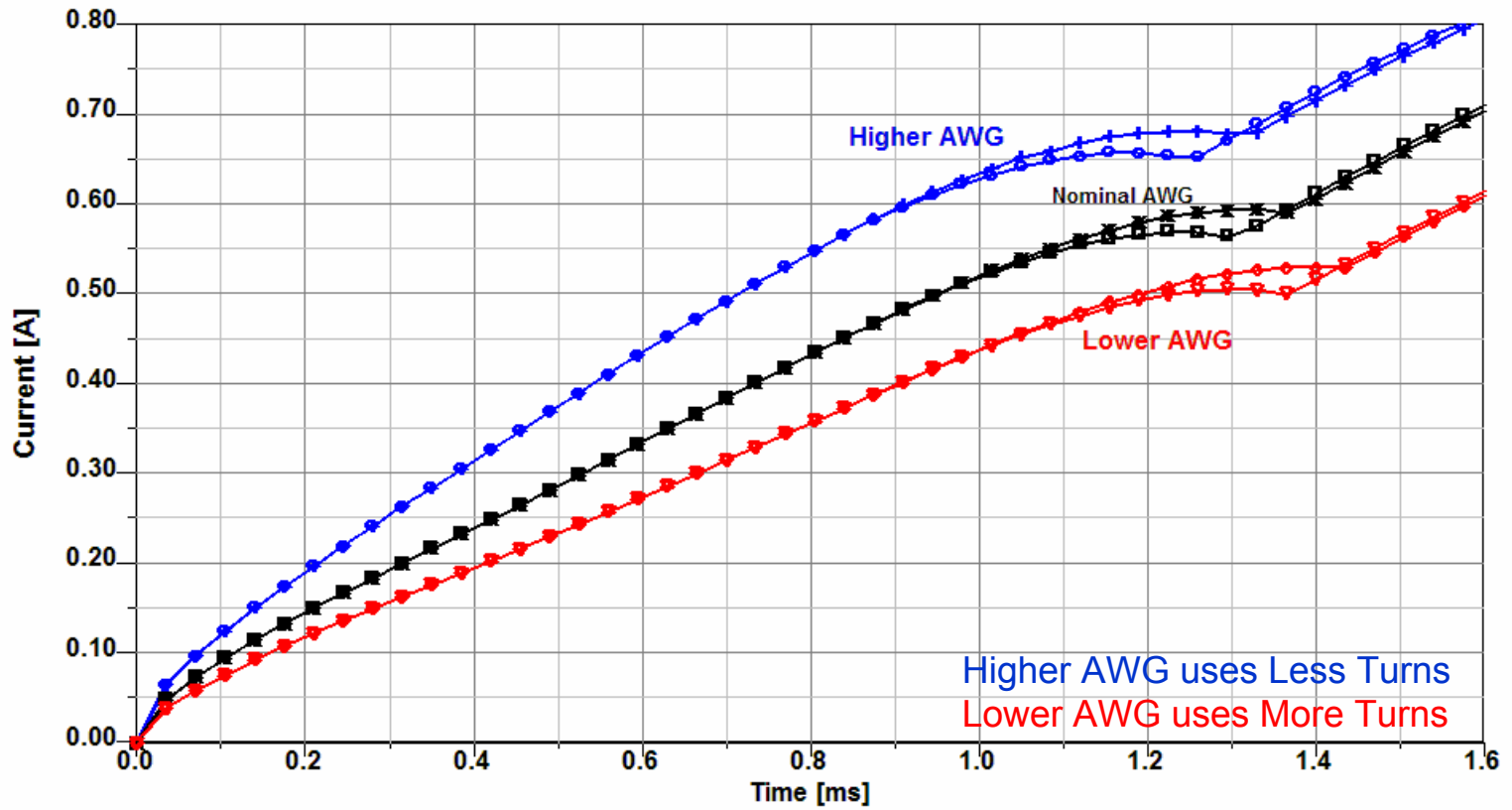


Delphi Distributed Analysis Results

(with conductivity)

Ansoft Corporation

Coil Current vs. Time vs. Turns vs. Moving Mass
Parametric Transient Sweep
Half Model

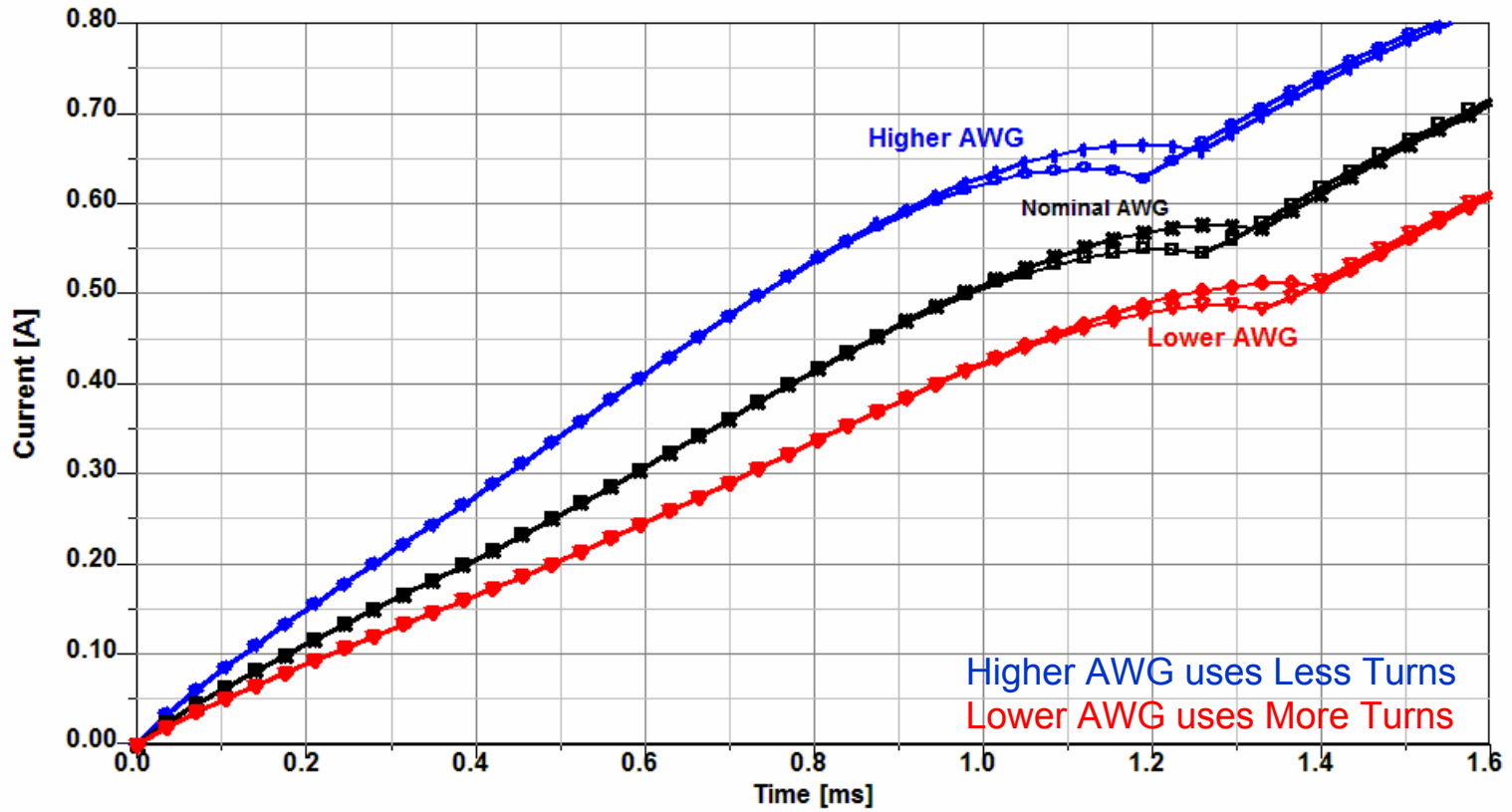


Delphi Distributed Analysis Results

(without conductivity)

Ansoft Corporation

Coil Current vs. Time vs. Turns vs. Moving Mass
Parametric Transient Sweep
Half Model



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.

