

HIGH-PERFORMANCE
SIGNAL & POWER INTEGRITY

HIGH-PERFORMANCE
IC DESIGN & VERIFICATION

FIRST-PASS
SYSTEM
SUCCESS

APPLICATION WORKSHOPS FOR
HIGH-PERFORMANCE ELECTRONIC DESIGN

“Analysis of Eddy
Current Brakes using
Maxwell 3D Transient”

Presenters:

Mark Christini, Vincent
Delafosse, Qingming Chen

Ansoft Corporation

HIGH-PERFORMANCE
ELECTROMECHANICAL SYSTEMS

HIGH-PERFORMANCE
RF & MICROWAVE



What are Eddy Current Brakes?

- ◆ Eddy current brakes, like conventional friction brakes, are responsible for slowing an object, such as rotating machinery, a moving train, or even a roller coaster
- ◆ There are two basic types: rotational and linear



How do they work?

- ◆ A magnetic field induces a voltage in moving objects due to Faraday's Law
 - ◆ The induced voltage causes an eddy current to flow in any conducting objects
- ◆ This current produces a counter-opposing flux and Lorentz force to slow the moving object
- ◆ The current also produces ohmic losses and significant heating



Goliath Roller Coaster at Walibi World in the Netherlands is stopped by eddy current brakes using permanent magnets instead of electromagnets



Introduction

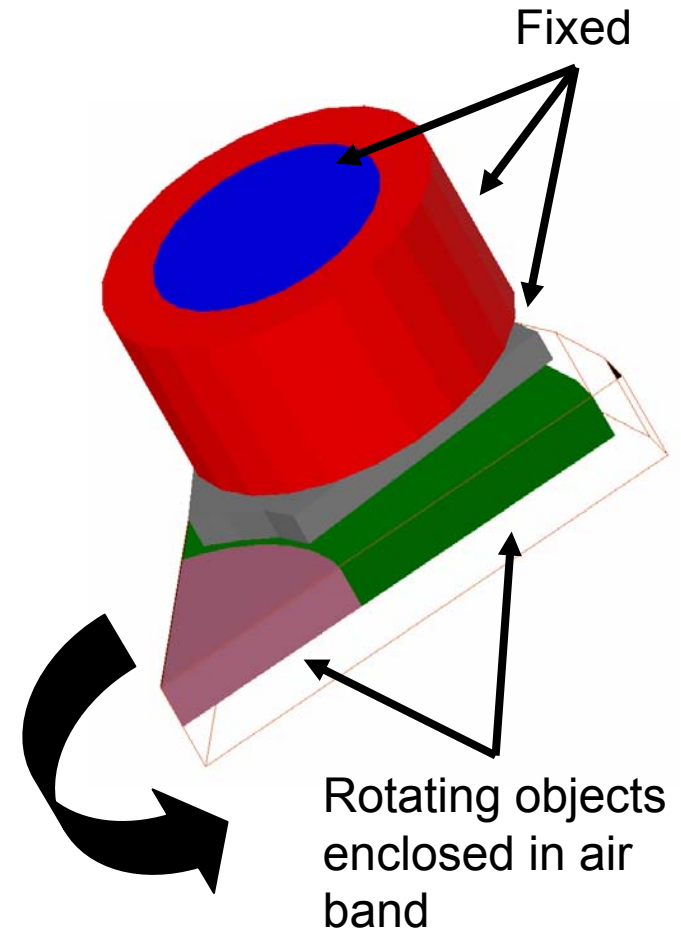
- ◆ The simulation eddy current brakes is difficult because:
 - ✓ Physical effects such as nonlinear saturation, skin effects and motion induced eddy currents must be considered simultaneously
 - ✓ A fine mesh is required due to very small skin depths
 - ✓ A transient solution with time-stepping is necessary
 - ✓ Multiple domain eddy current regions are needed including master/slave boundaries
- ◆ The results from three unique simulations will be shown while pointing out the challenges of each design and the methodology needed to allow the simulation to be successful

Collaborative Partners:



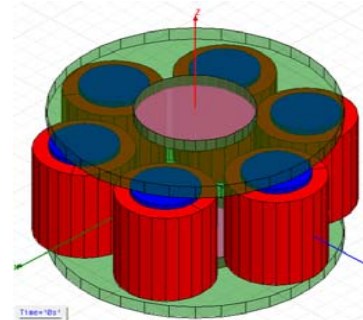
How can they be analyzed?

- ◆ Maxwell 3D Transient solver which is well suited for magnetic problems with motion
- ◆ Solves transient magnetic fields caused by time-varying or moving electrical sources and permanent magnets
- ◆ Uses both linear and nonlinear materials
- ◆ Excitation can be DC, sinusoidal, and transient voltages or currents. An external schematic circuit is available
- ◆ Considers skin and proximity effects
- ◆ Considers motion-induced eddy currents
- ◆ Considers time-diffusion of magnetic fields

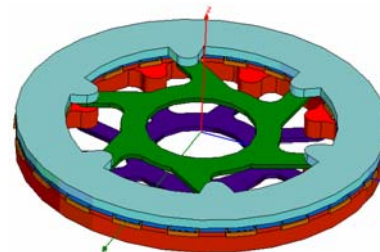
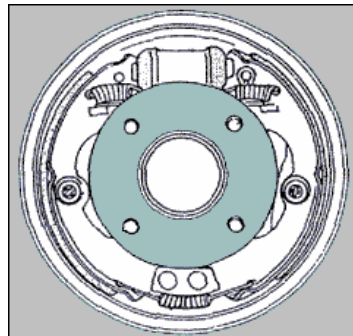


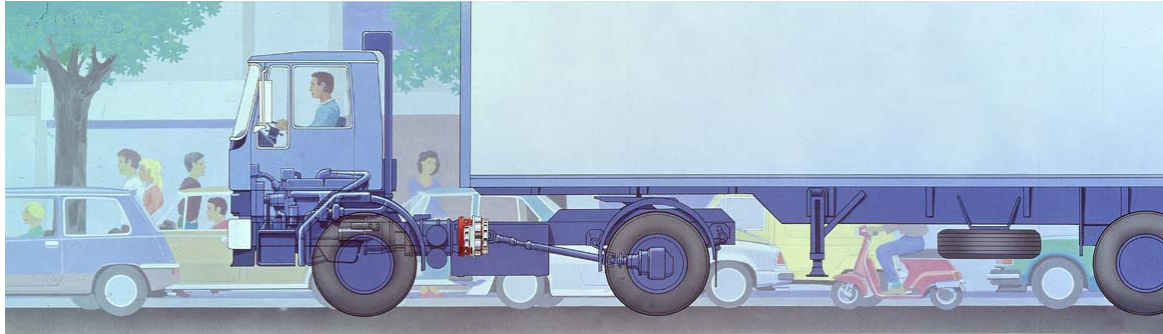
Two designs to be discussed

Valeo-Telma eddy-current brake



Hybrid eddy-current brake





Design #1

Valeo-Telma Eddy

Brake



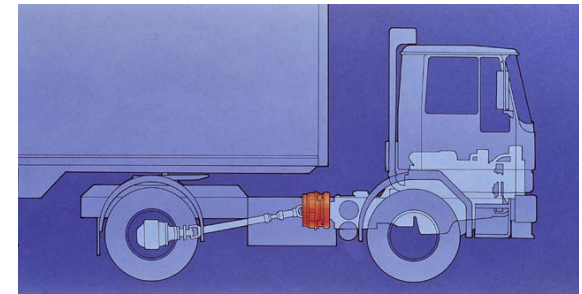
Overview

Goals of Analysis:

- ◆ Use 3D transient to simulate this problem for different speeds between 0 and 3000 rpm

Challenge:

- ◆ Air-gap is small (2 mm total)
- ◆ FOUCAULT's (or Eddy) currents are supposed to exist only in the rotor
- ◆ Only 1/12 of the geometry is modeled
- ◆ The direction of the current on each successive coils is alternated

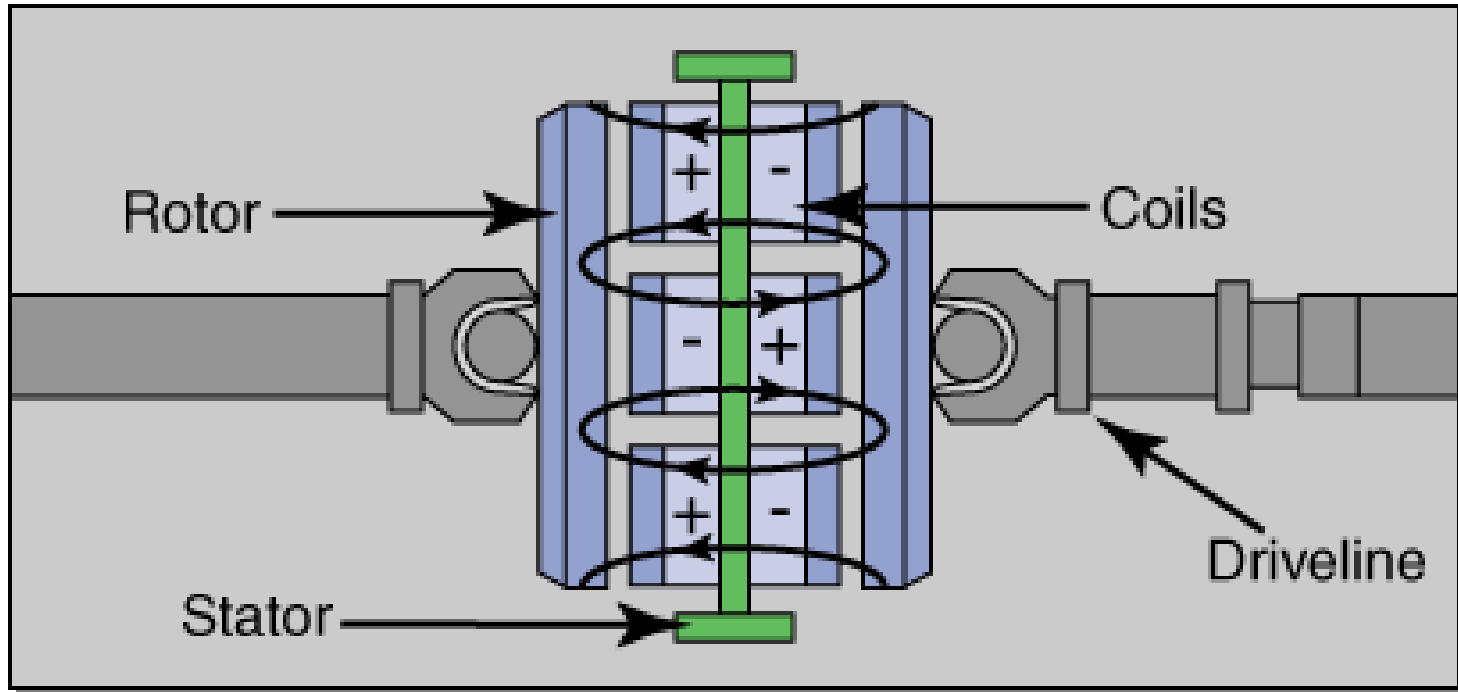


Internal View of Eddy Current Brake

- ◆ These brakes are used in various locations in vehicles



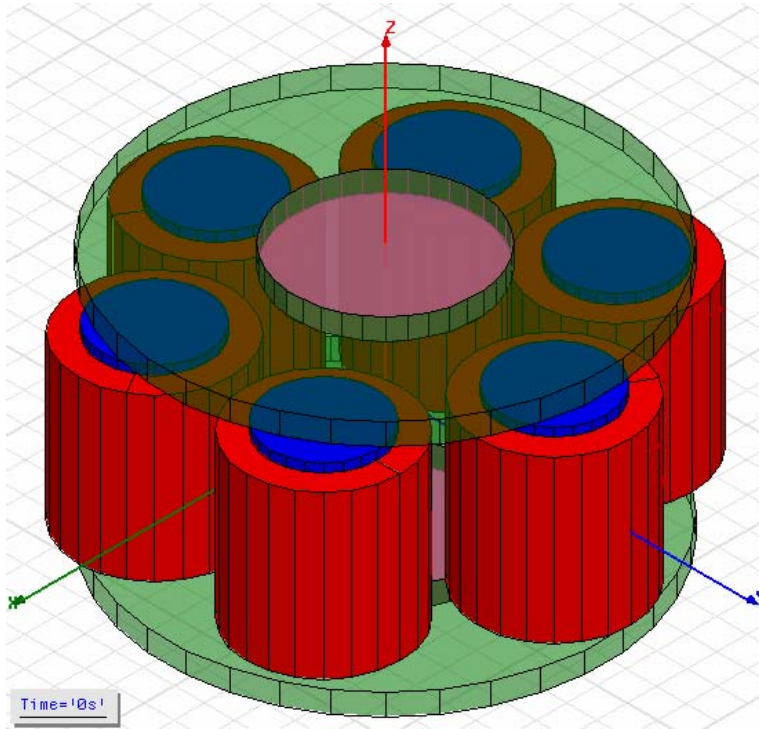
How does it work?



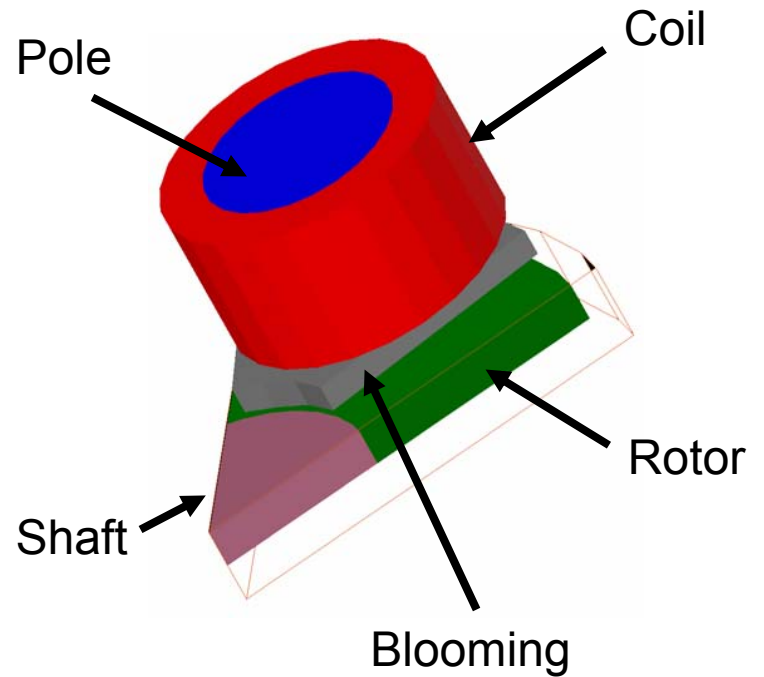
- Electrical current is sent to coils which alternate polarities, creating an electromagnetic field
- Eddy currents, generated in two rotors as they spin through the field, slow the rotation of the driveshaft



Model Setup



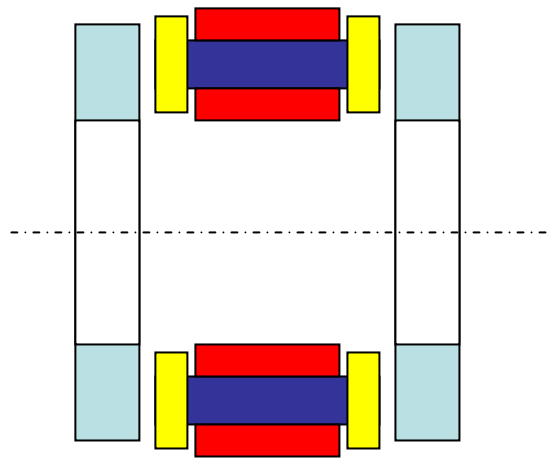
Full Model



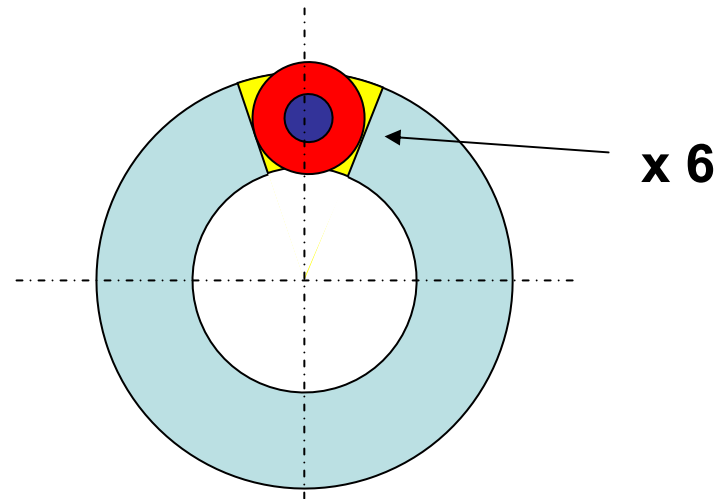
60° wedge – half model



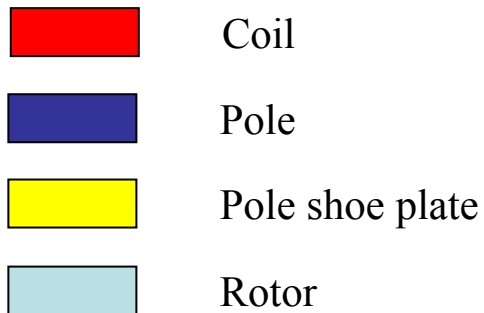
Model Setup



Side view



Front view

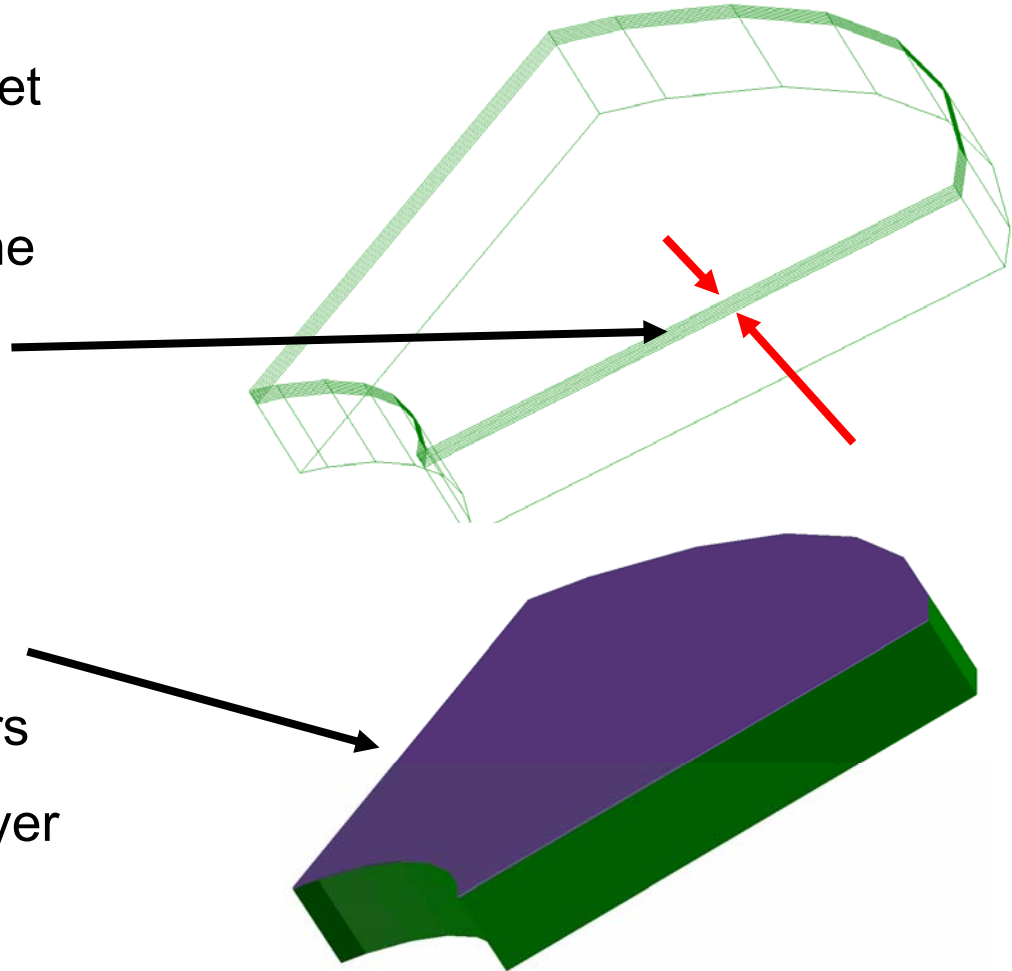


- ◆ Red coils are fed by a continuous DC current, that creates a permanent magnetic field
- ◆ Poles, blooming, and rotor use the same non linear iron
- ◆ The rotation of the light blue rotor, produces FOUCAULT's currents that brake the device.



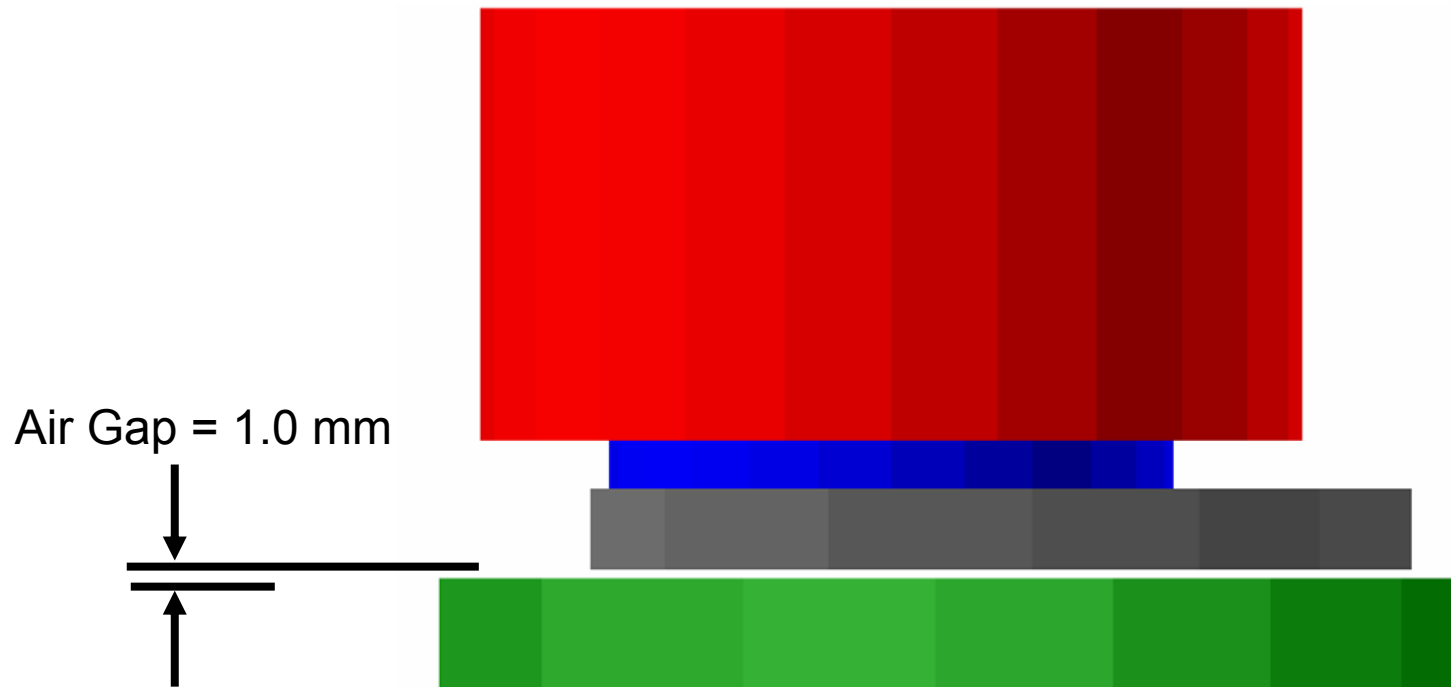
Key Simulation Points

- ◆ A fine mesh was required in order to get a good solution
- ◆ Many thin layers in the rotor are required to capture the eddy currents
- ◆ The thickness of the layers created in the Rotor is 0.3 mm and there are seven layers
- ◆ Add 0.25mm thick layer on top of Rotor to improve the mesh



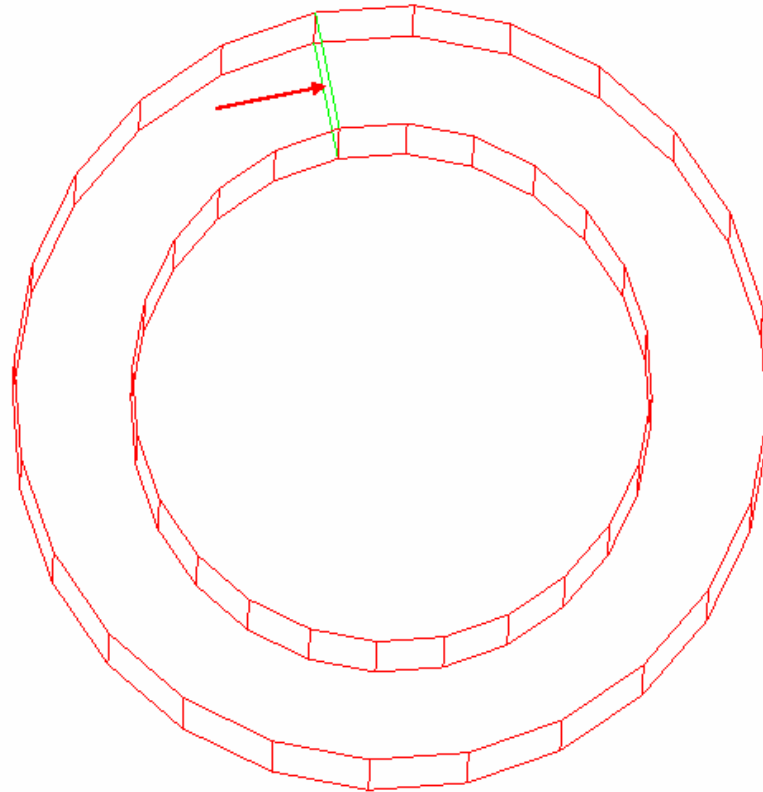
Geometry – coil, blooming, and rotor

- ◆ There is a small airgap between the moving and stationary parts
- ◆ The band object must pass through the airgap



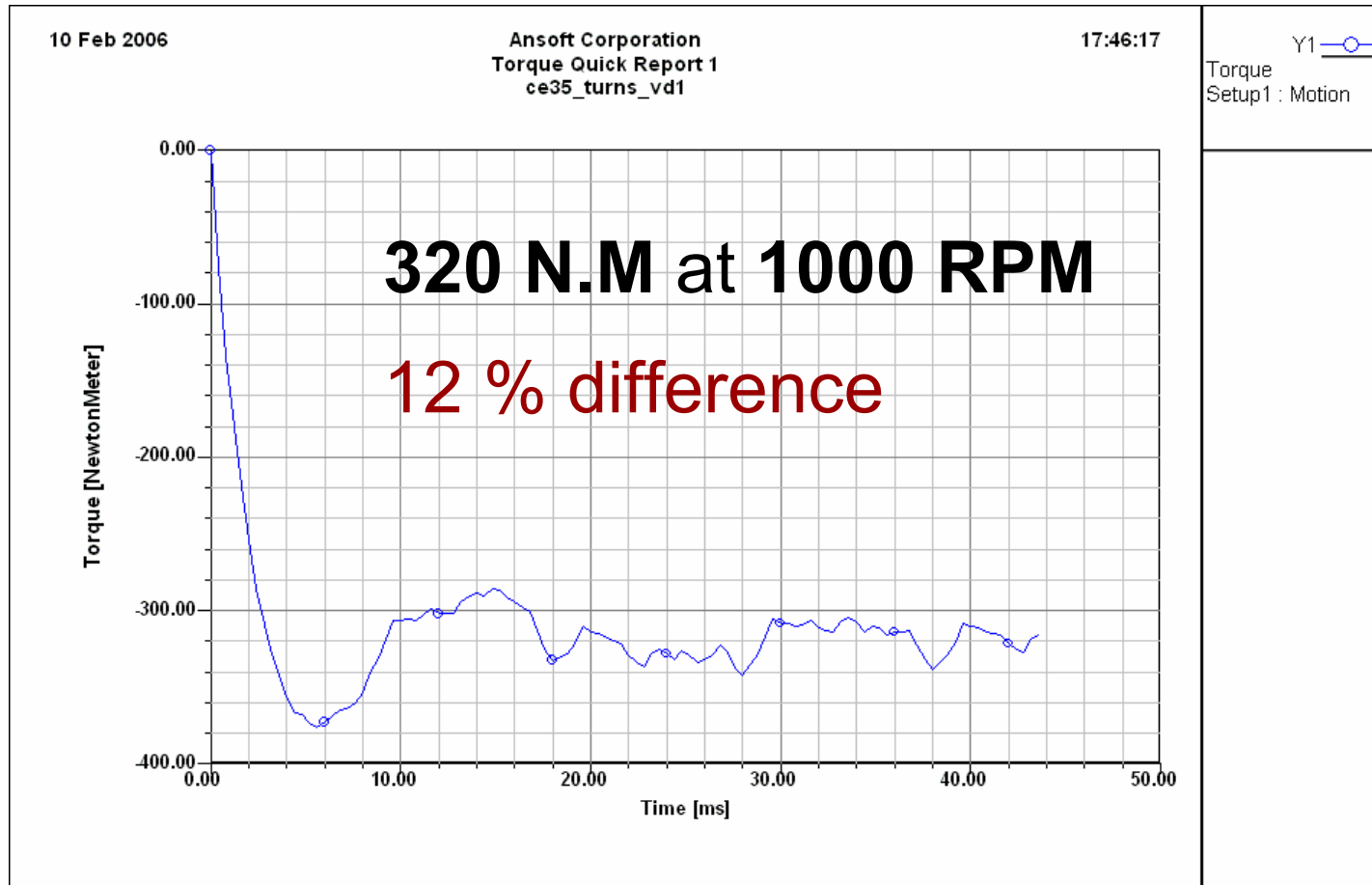
Coil Excitation

- ◆ The coil consists of many turns, but is modeled as a single, stranded coil
- ◆ $(14.4 \text{ amps} * 379 \text{ turns}) / 2 = 2729 \text{ amp-turns}$. We divide by 2 because we are modeling only half the coil.



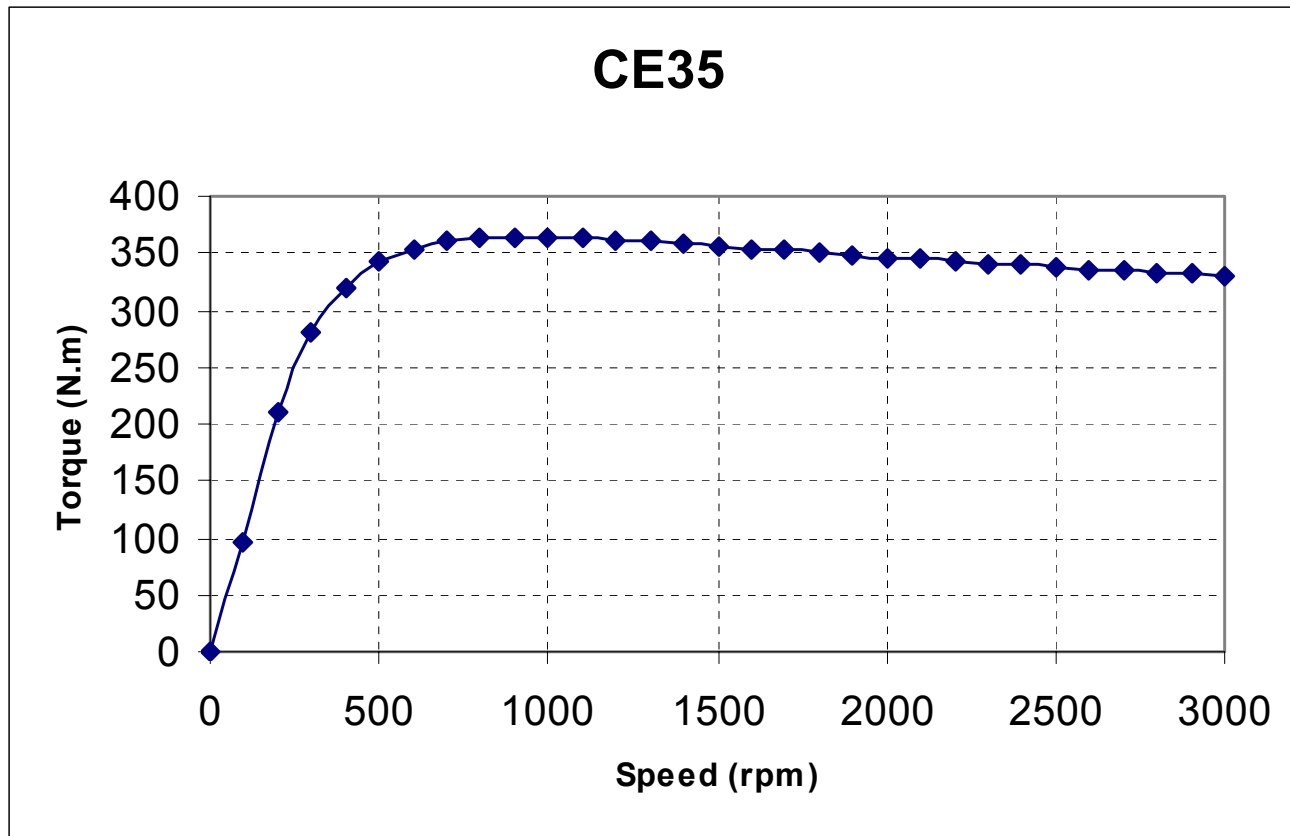
Torque Profile

- ◆ Results obtained are close to tested values



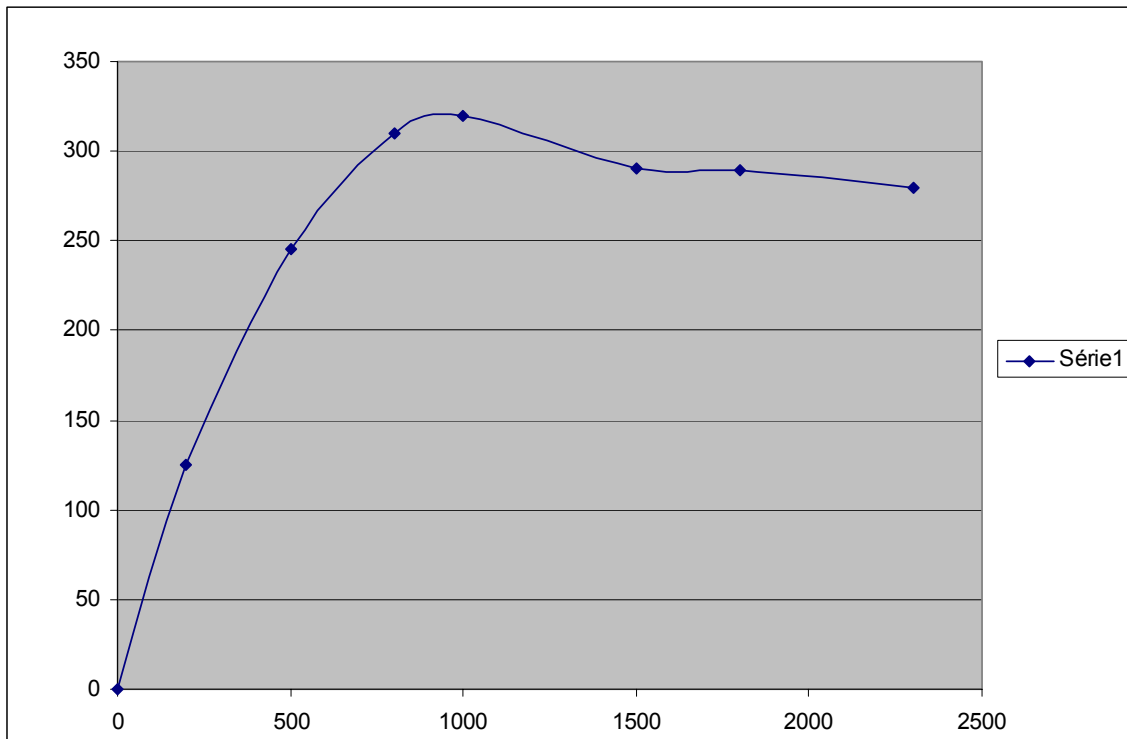
Objective Curve

- ◆ Curve below is the goal for Torque vs. Speed



Obtained Curve

- ◆ Each point is a single simulation at a given speed which takes about 2 days to solve using a mesh density of about 115,000 elements
- ◆ This curves closely matches the objective curve on previous slide

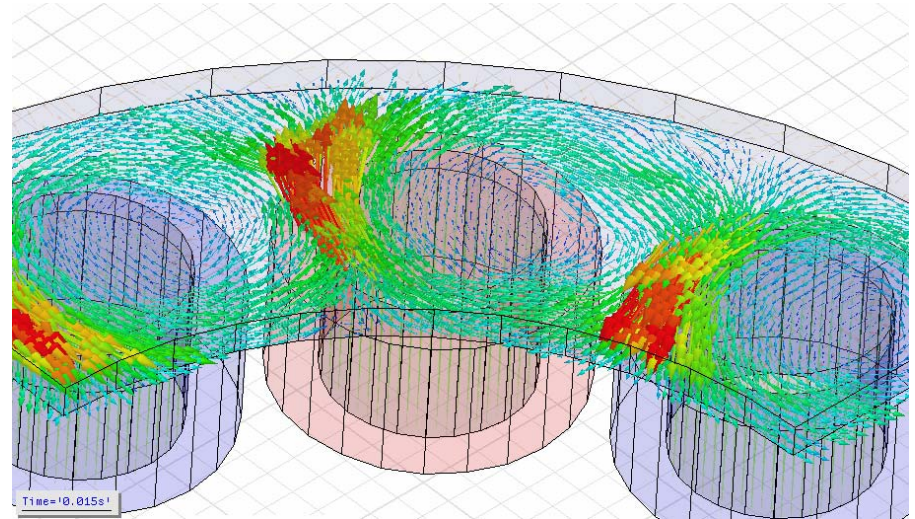
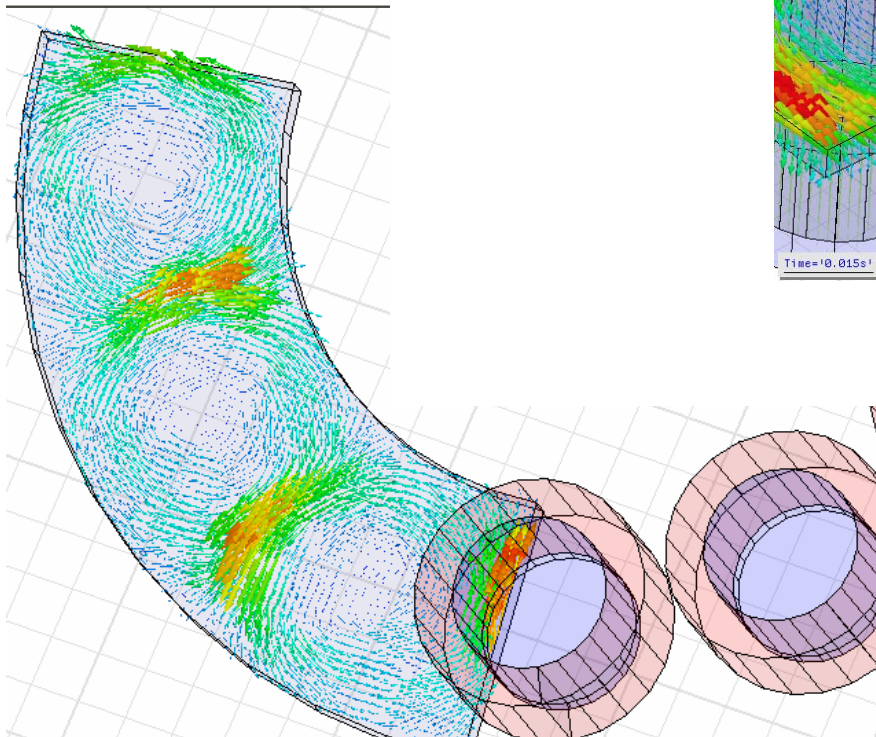


Rotational Speed (rpm)	Torque (NM)
0	0
200	125
500	245
800	310
1000	320
1500	290
1800	289
2300	280



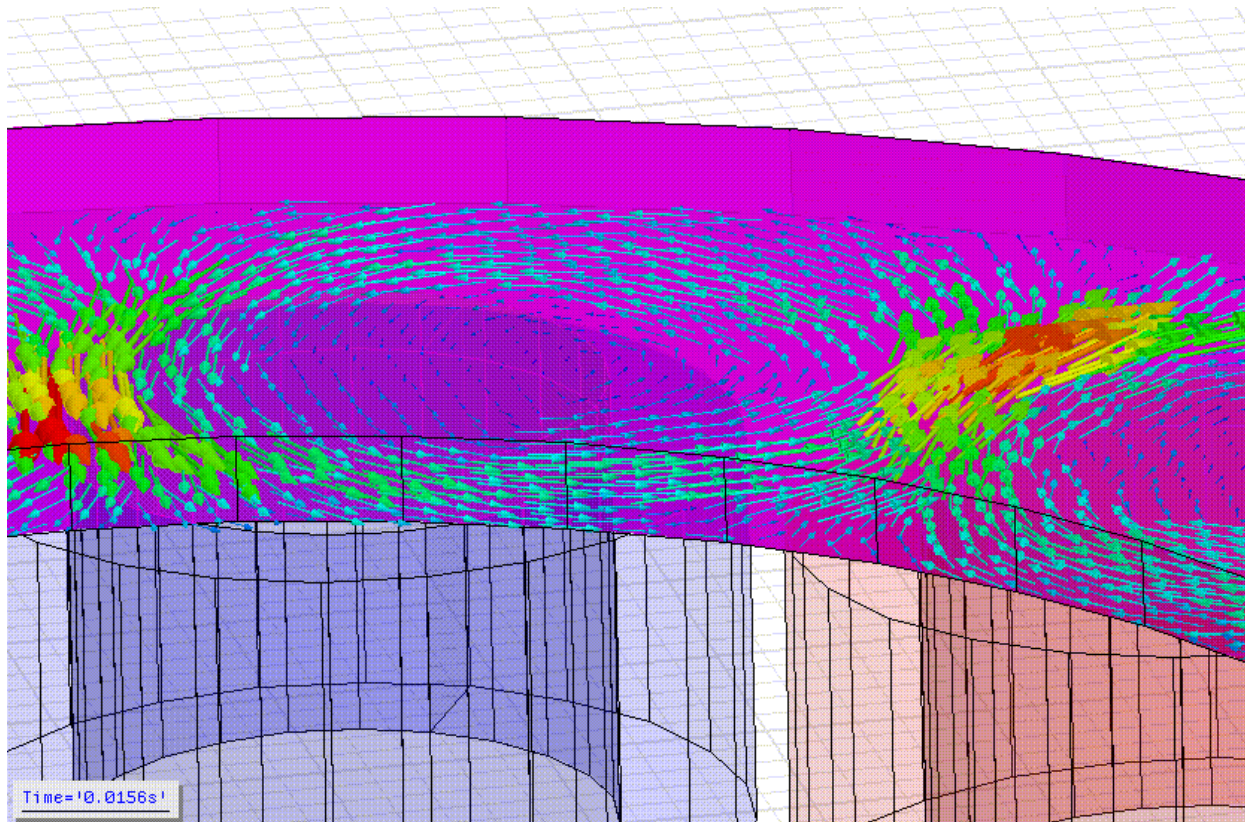
J-vector Plot

- ◆ The eddy currents on the rotor creating a counter-opposing flux are shown



J-vector Plot - movie

- ◆ Animations were provided by Valeo Electrical Systems -Telma



Design #1 - Conclusions

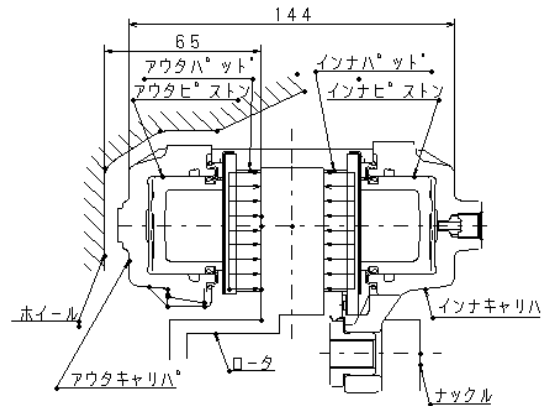
- ◆ Maxwell can solve the combination of saturation/eddy current/movement accurately
- ◆ Remaining challenges to be considered in future:
 - ◆ cut simulation time
 - ◆ two way coupling with thermal solver to take into account resistivity and b-h curves that depend upon temperature





Design #2

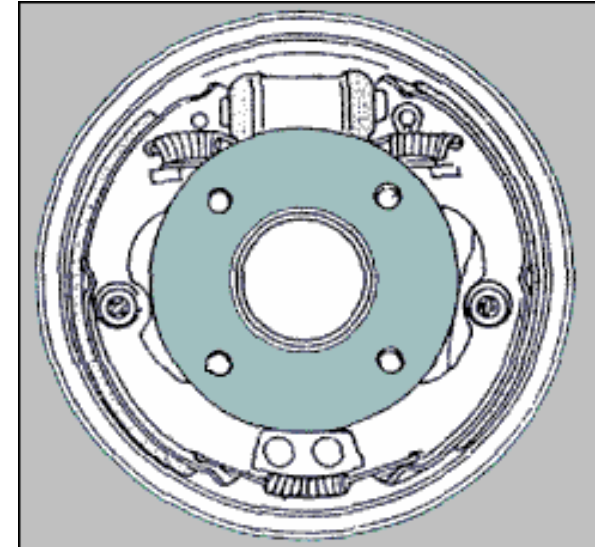
Hybrid Eddy Brake



Overview

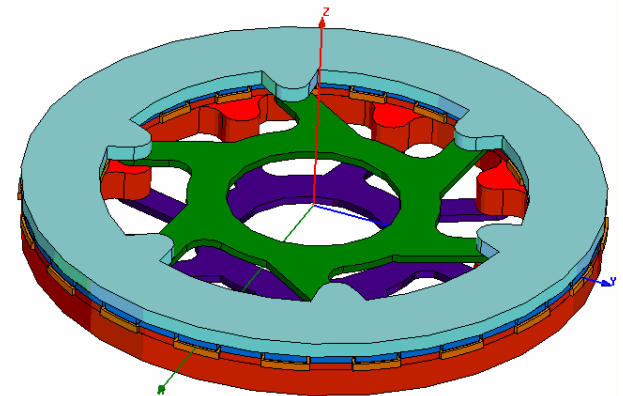
Current Friction Brake for Vehicle

- ◆ Used for both braking at high speed and on a steep hill using axial force (magnetic or mechanical)
- ◆ Has high force and noise at high speed with high temperature.
- ◆ Low efficiency



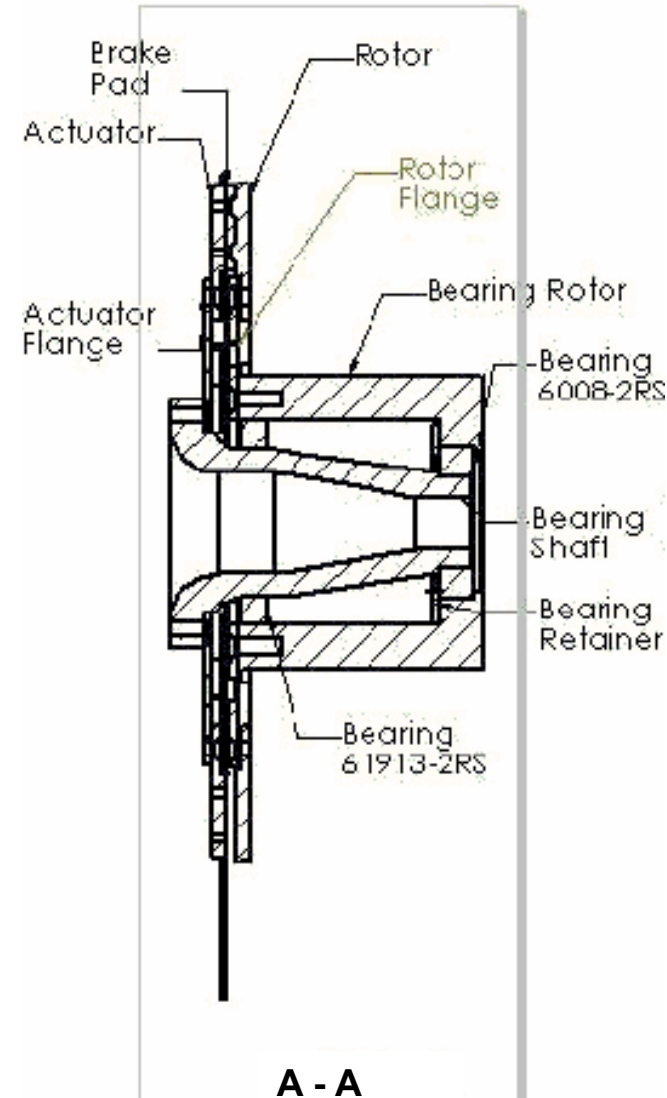
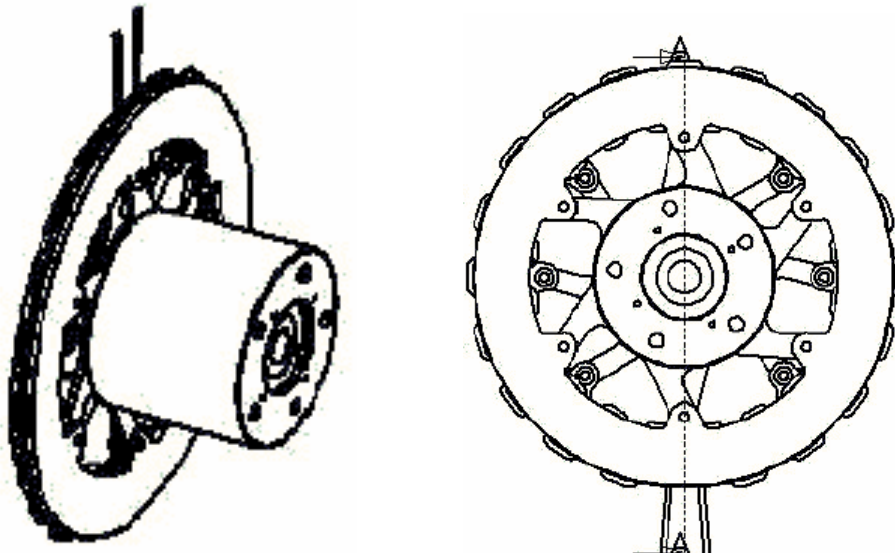
New Hybrid Brake for Vehicle

- ◆ Eddy current brake for braking at high speed for two front wheels
- ◆ Simple structure has low force, noise and temperature



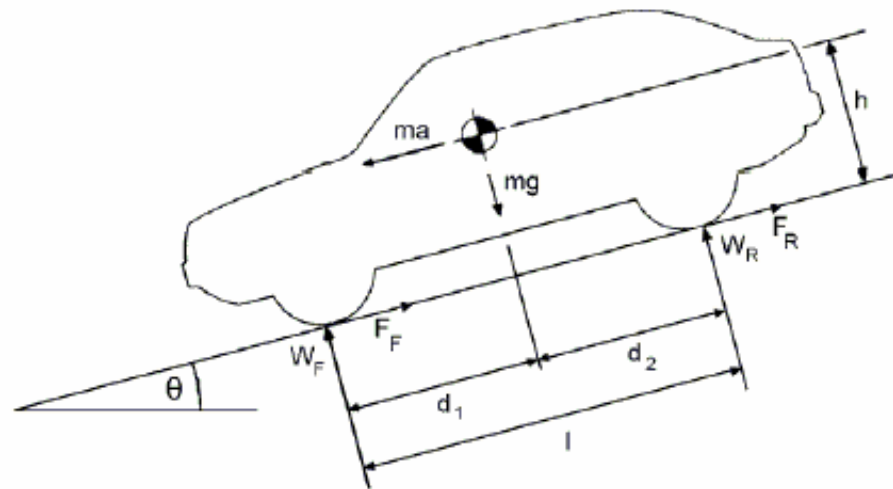
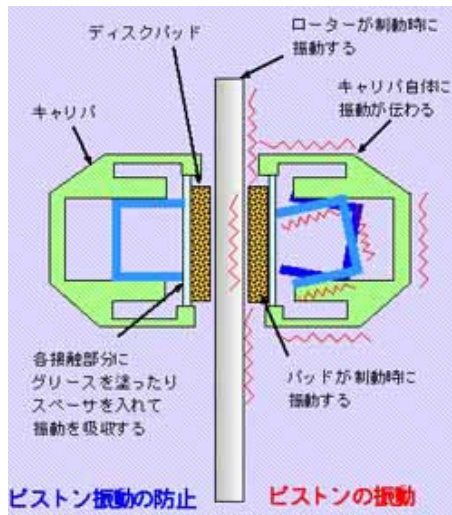
Original Reference

- ◆ Based on Bachelor of Engineering Thesis: “Electronic Brake-by-wire” by Chris David Lister, 31th OCT 2003.
- ◆ Maxwell 3D used for the concept design of the hybrid brake. All shapes & dimensions are from paper.



Our Target

- ◆ Assume the worst case emergency stopping condition
- ◆ Rotor speed reduced by eddy current torque from full speed 150km/h to zero in 0.15 sec using a pulse current of 500A input in a copper coil
- ◆ For wheel lock-up, also need to check braking with full skidding assuming gross vehicle mass of 850kg.



Materials

Rotor: Cast iron

- ◆ Permeability = 60
- ◆ Conductivity = 1500000 S/m

Stator: SUY

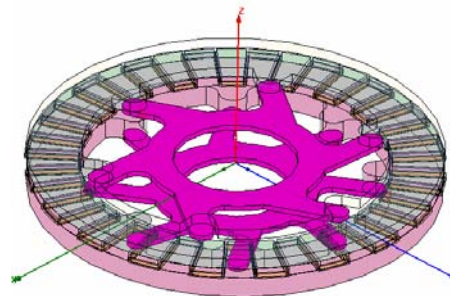
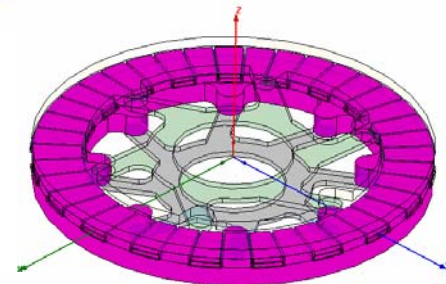
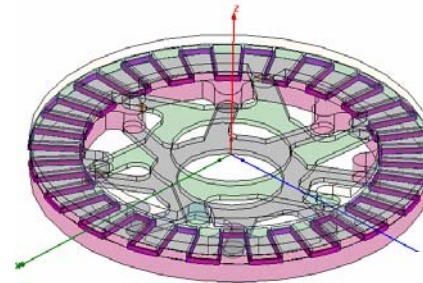
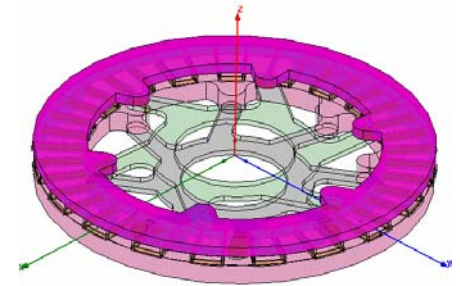
- ◆ Permeability = 2000 or Nonlinear
- ◆ Conductivity = 2000000 S/m

Friction Pad: Cast Steel

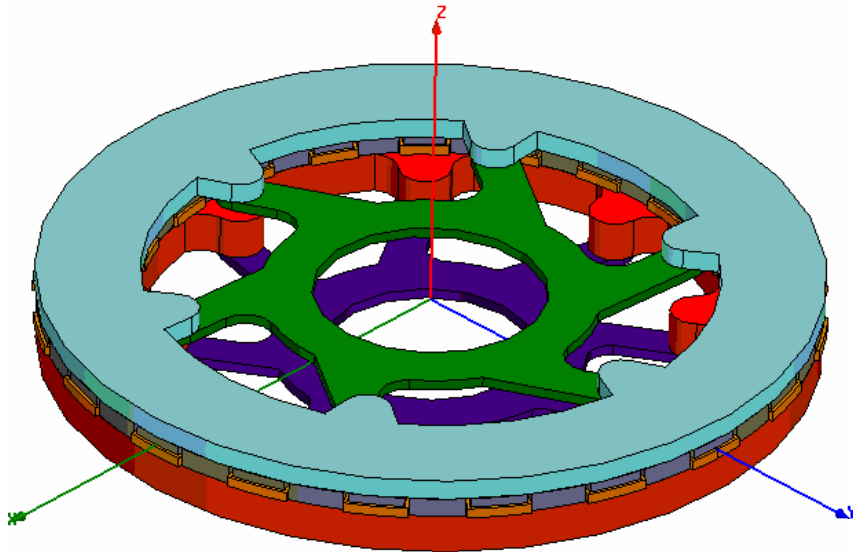
- ◆ Permeability = 8 (for Magnetostatic model)

Flange: Aluminum

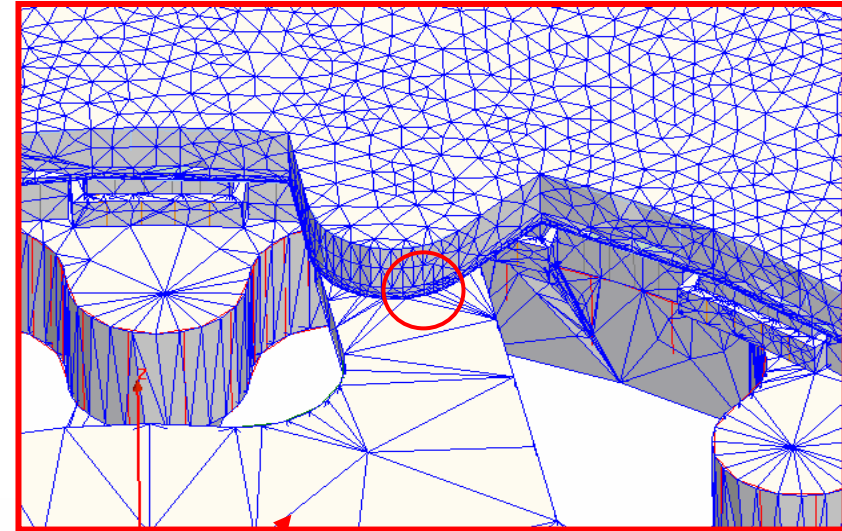
- ◆ Permeability = 1
- ◆ Conductivity = 3800000 S/m



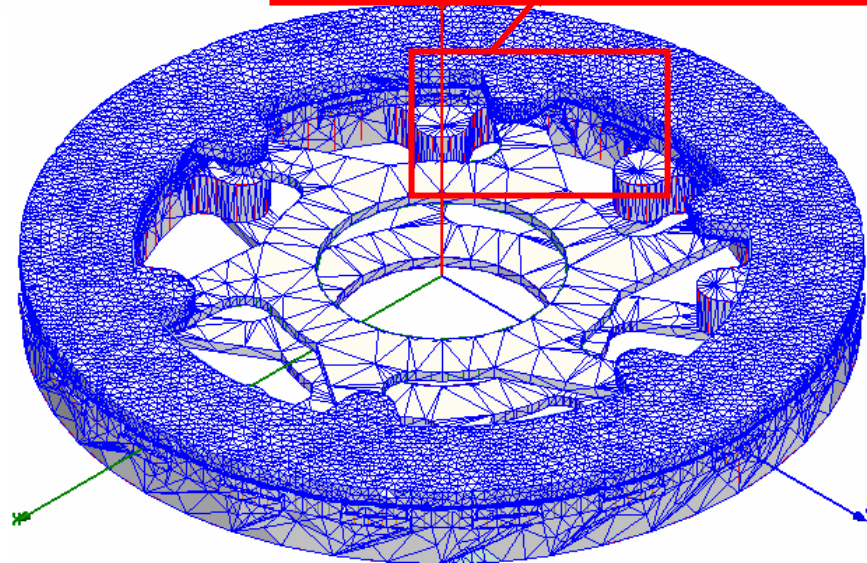
Model & Mesh



Full Model



- ◆ 3 dummy sheets used to create 3 layers of fine mesh in the rotor
- ◆ Total mesh: 342958 tets



mesh



SUY nonlinear saturation

- We select high-permeability material for stator & the low-half part of pads

The screenshot displays the ANSYS software interface for defining material properties and a BH curve. The left panel, titled "View / Edit Material", shows the material name "SUP_nl" and its properties. The right panel, titled "BH Curve", shows a table of coordinates and a corresponding graph of magnetic flux density (B) versus magnetic field strength (H).

Material Properties:

Name	Type	Value	Units
Relative Permeability	Nonlinear	BH Curve...	
Bulk Conductivity	Simple	2000000	siemens/m
Magnetic Coercivity	Vector		
- Magnitude	Vector Mag	0	A_per_meter
Core Loss Type		None	w/m^3
Mass Density	Simple	7200	kg/m^3
Composition		Solid	

BH Curve Coordinates:

Coordinates	H (A_per_meter)	B (tesla)
10	288.5	1
11	408.5	1.132
12	638.5	1.28
13	838.5	1.36
14	1138.5	1.44
15	1400	1.485
16	1638.5	1.519
17	1850	1.54
18	2138.5	1.559
19	2500	1.58
20		

BH Curve Graph:

The graph shows the relationship between magnetic field strength (H) and magnetic flux density (B). The x-axis is labeled "H (A_per_meter)" and ranges from 0.00 to 17500.00. The y-axis is labeled "B (tesla)" and ranges from 0.00 to 2.00. The curve shows a non-linear relationship that saturates at approximately 1.58 tesla for field strengths above 2500 A/m.

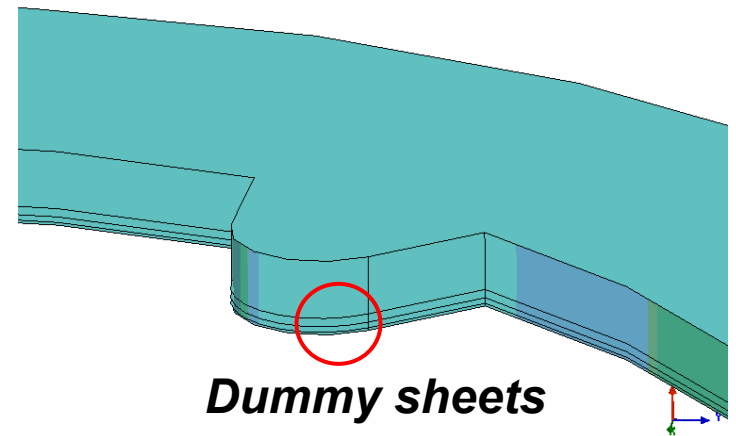
Intercepts and Units:

	H	B
Intercepts	0	0
Units	A_per_meter	tesla



Key Simulation Points

- ◆ Dummy Sheets needed to insure fine mesh
- ◆ Distance of dummy sheets from bottom surface of rotor is:
 - = 0.3mm (< 1/5 skin depth)
 - = 0.6mm (from first sheet)
 - = 0.9mm (from second sheet)
- ◆ For rotor at full speed = 1326.3 rpm
 - freq = (1326.3/60) * 40 = 884Hz
 - Skin depth = 1.784 mm
- ◆ Small timestep needed
 - Timestep <= 1/freq/8 = 1.414e-4
 - Set Timestep = 0.000125 sec.

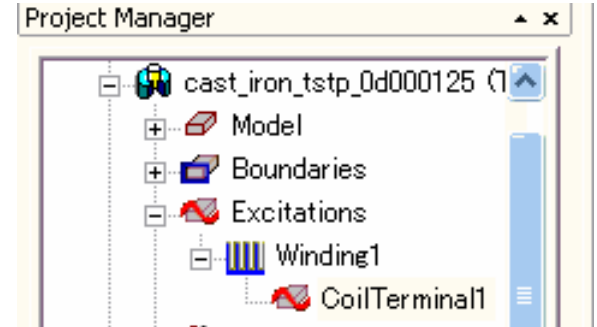


$$\delta = \sqrt{\frac{2}{\omega \mu_o \mu_r \sigma}}$$



Transient Source Setup

- ◆ Excitation setup uses stranded voltage source
- ◆ 200usec rise-time



Winding

General | Defaults

Name:

Parameters

Type: Solid Stranded

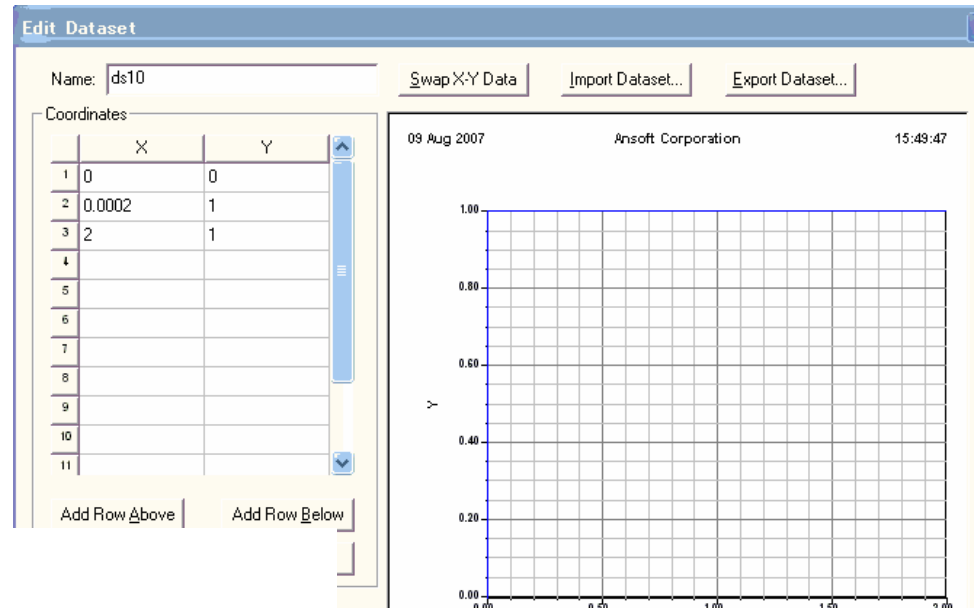
Initial Current:

Resistance:

Inductance:

Voltage:

Number of parallel branches:



Transient Motion Setup

- ◆ For motion set up, Band and inner_region are needed.
- ◆ Normally there will be some parts linked with rotor, in this example we simply set the inertia as three times of the rotor.

The screenshot displays the ANSYS Modeler interface for a project named 'brake_new_070808 - cast_iron_tstp_0d000125'. The main window shows a 3D model of a motor assembly with a central rotor and an outer band. Red arrows point to the 'Inner_region' and 'Band' components. A coordinate system with X, Y, and Z axes is visible. The 'Project Manager' on the left shows a tree view with 'Model', 'Band', 'Moving', 'Boundaries', 'Excitations', 'Parameters', 'Mesh Operations', 'Analysis', 'Optimetrics', 'Results', 'Field Overlays', and 'Notes'. The 'Properties' window shows a table with 'Name' and 'Value' columns, with 'Name' set to 'Moving' and 'Type' set to 'Moving'. The 'Motion Setup' dialog is open, showing 'Type' as 'Mechanical' and 'Motion Type' as 'Rotation'. The 'Moving Vector' is set to 'Global:Z'. The 'Motion Setup' dialog also shows 'Initial Angular Velocity' as 1326.3 rpm and 'Moment of Inertia' as 0.048. A text box at the bottom right states 'Three times of that of rotor'.

Name	Value	Unit
Name	Moving	
Type	Moving	

Motion Setup

Type | Data | Mechanical |

Motion Type: Translation Rotation Non-Cylindrical

Moving Vector: Global:Z

Motion Setup

Type | Data | Mechanical |

Consider Mechanical Transient

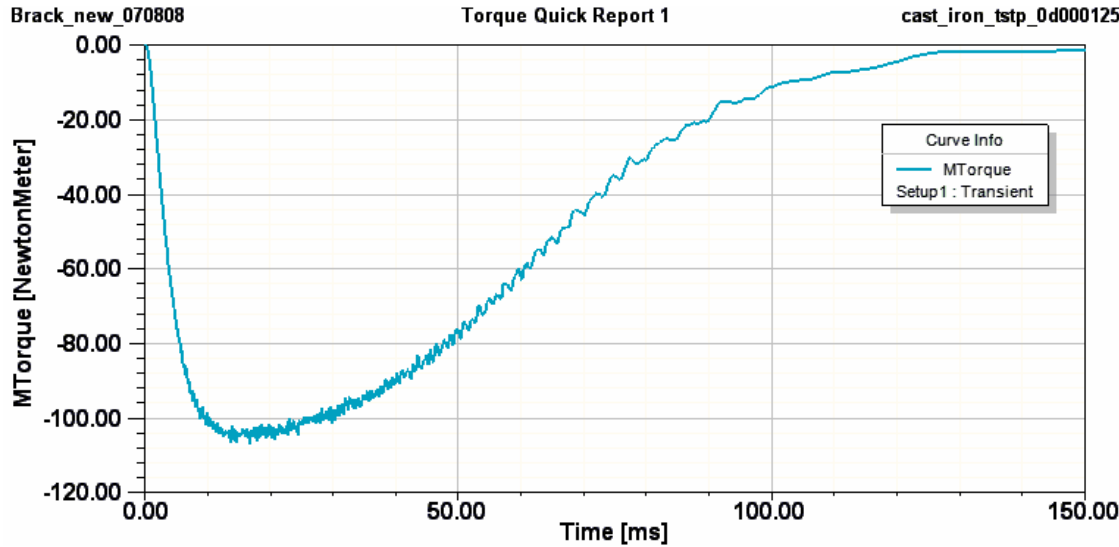
Initial Angular Velocity: 1326.3 rpm

Moment of Inertia: 0.048

Three times of that of rotor

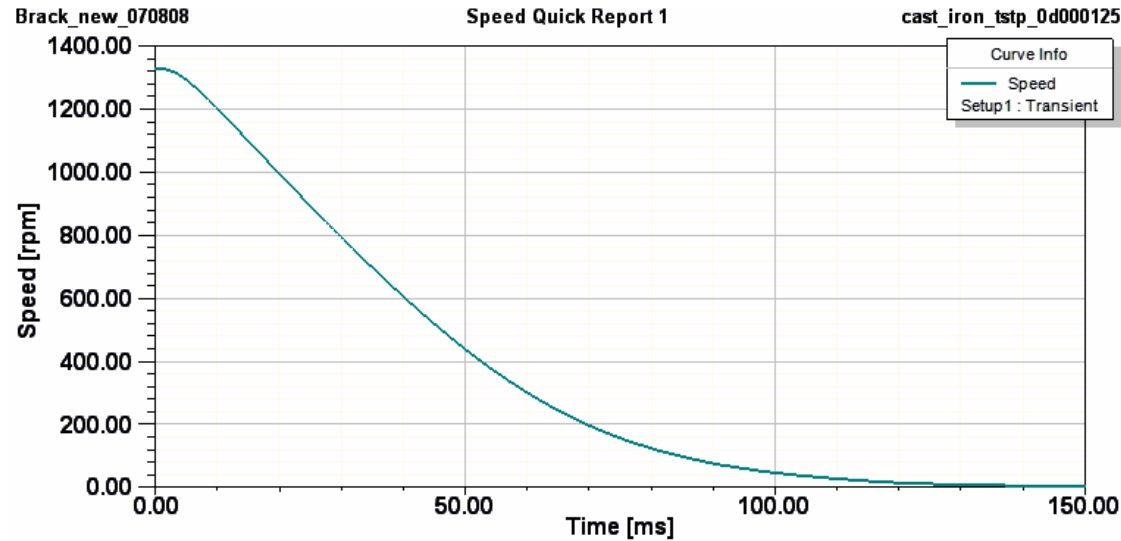


Transient Results

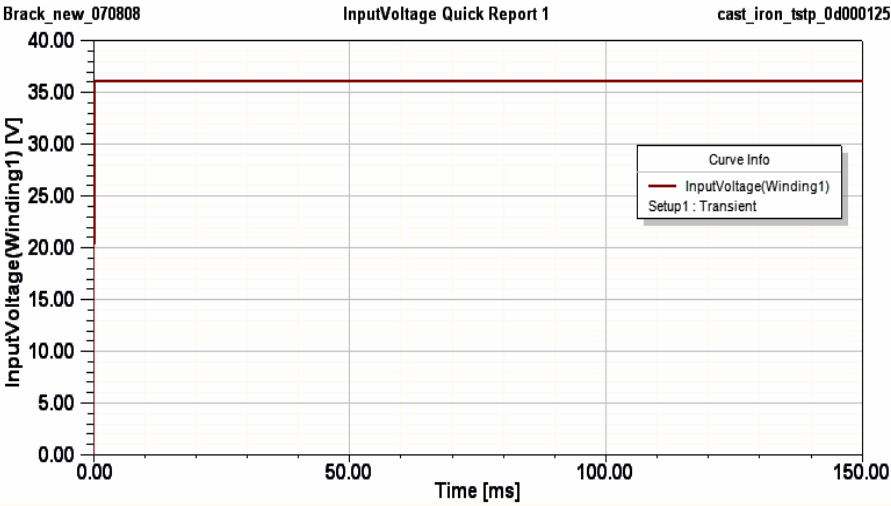


Torque vs. Time

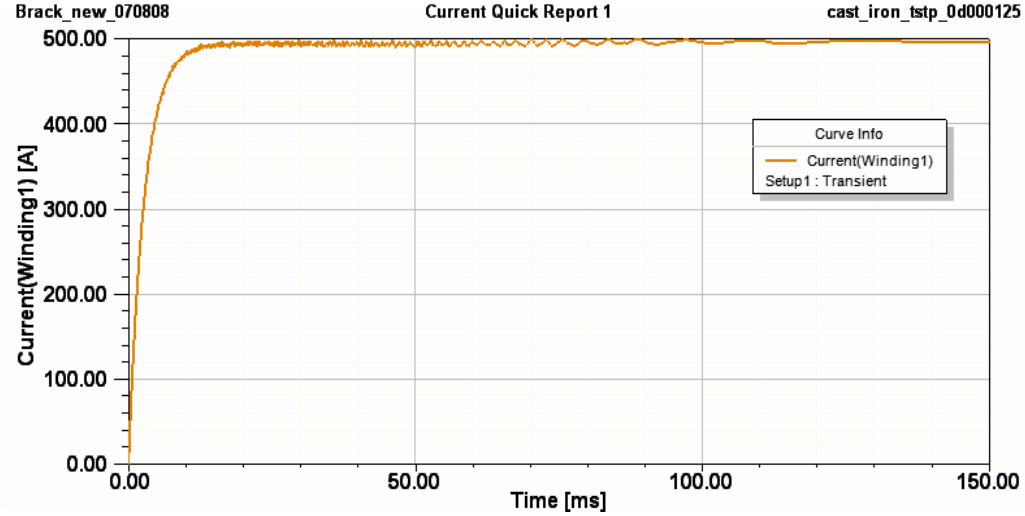
Speed vs. Time



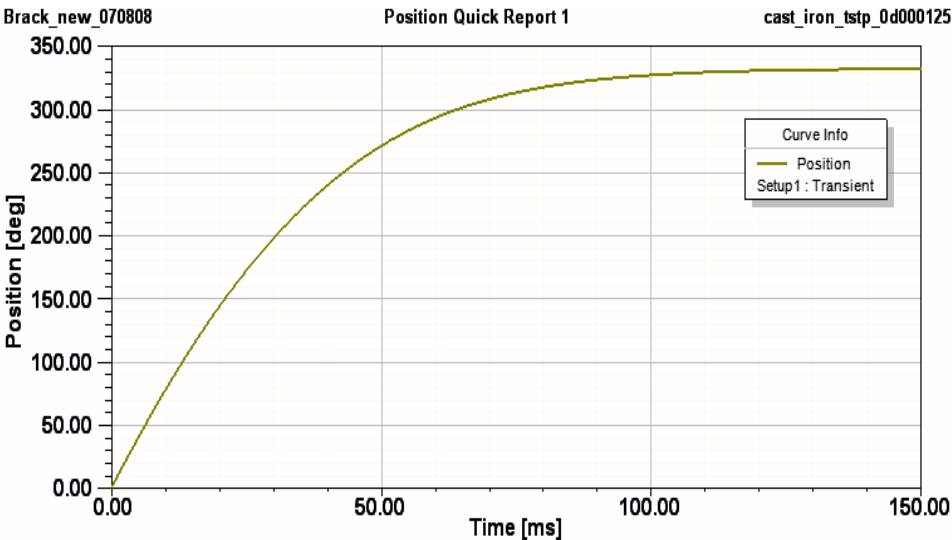
Transient Results



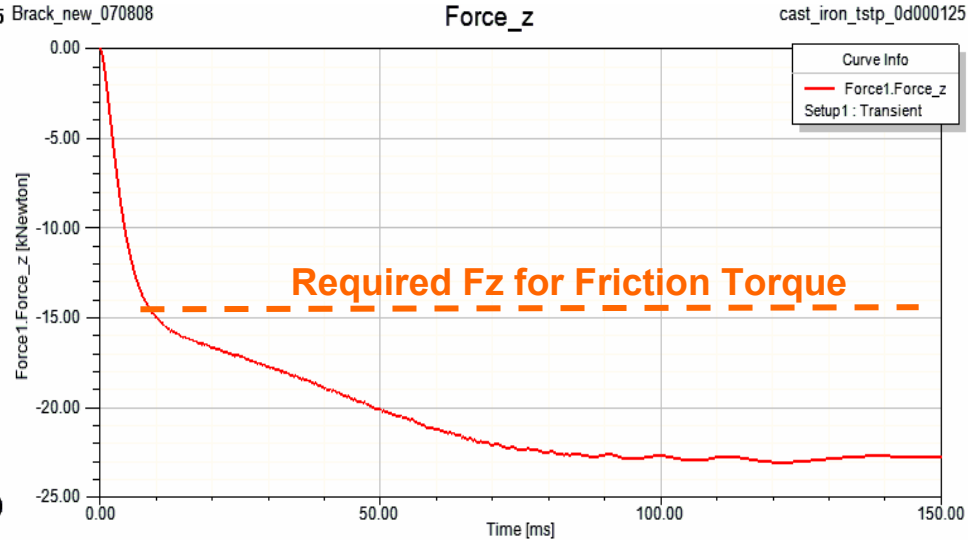
Input Voltage vs. Time



Current vs. Time

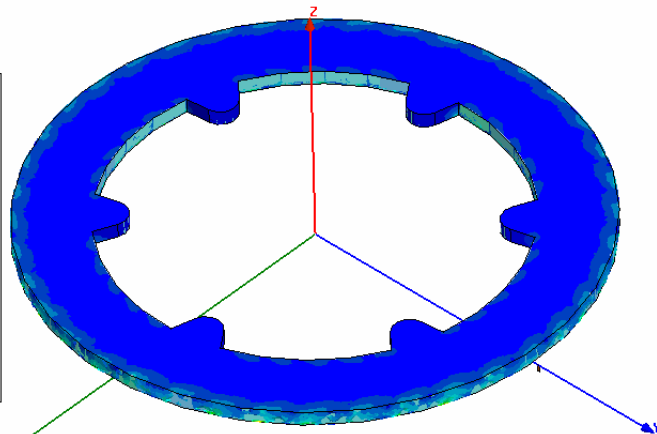
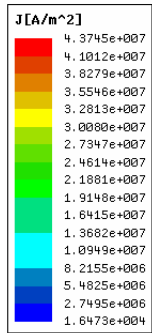


Position vs. Time

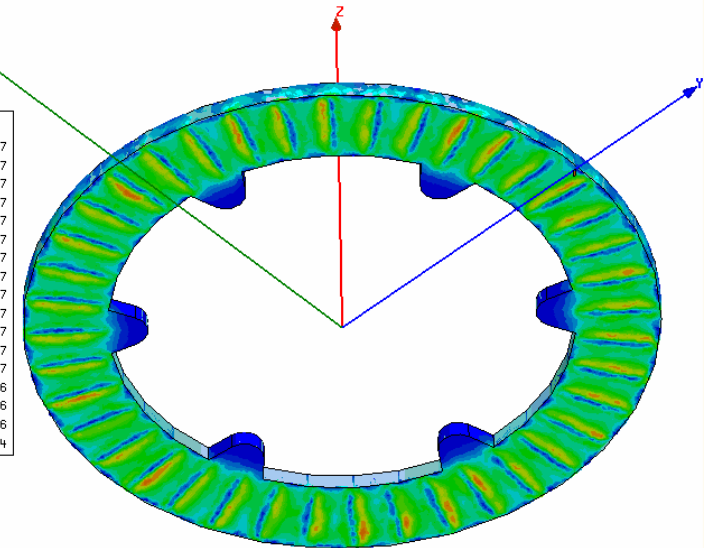
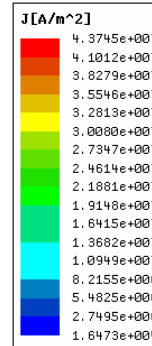


Force_z vs. Time

Jmag on Rotor at 0.005 sec



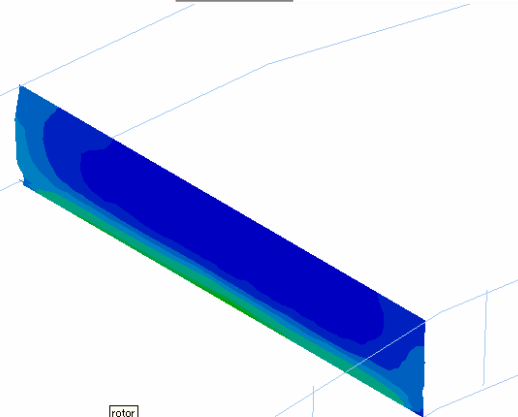
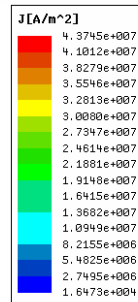
Top view



Bottom view

Time=0.005s

Time=0.005s

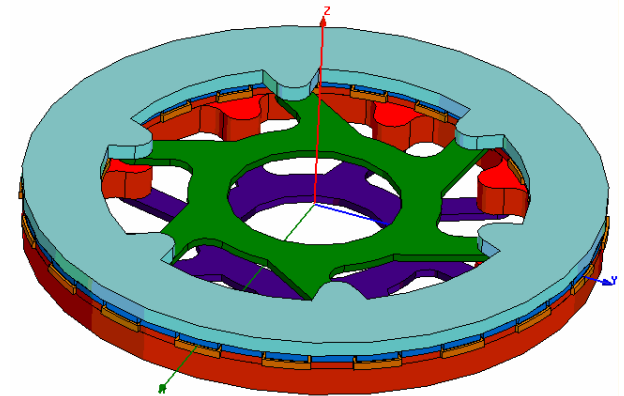
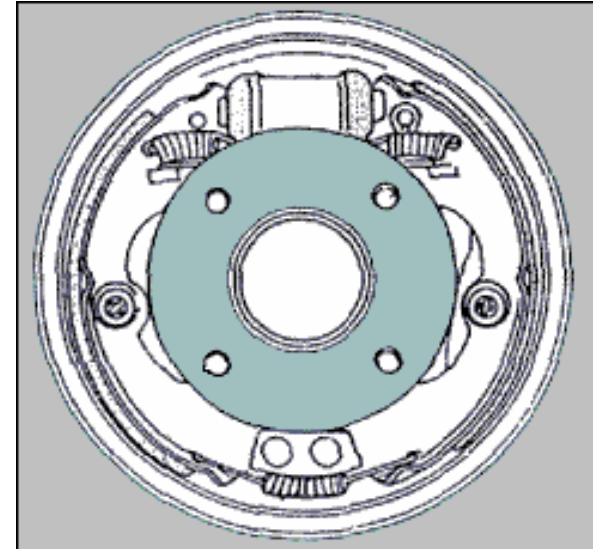


Cross-sectional view



Design #2 - Conclusions

- ◆ This example shows how to use Maxwell 3D to analyze a hybrid eddy current brake for Automotive Vehicles
- ◆ Rotor can be locked within 0.15 sec and less than 360 deg (one turn, about 1.9m of distance).
- ◆ The eddy torque alone ($\leq 105\text{Nm}$) is not enough for braking. Therefore, friction torque is still necessary to stop the vehicle.
- ◆ For future work, the increasing temperature on the surfaces of friction-pads and the rotor disk needs to be simulated.



Summary

- ◆ Maxwell 3D Transient can successfully solve complicated 3D simulations with motion-induced eddy currents in nonlinear materials
- ◆ DSO option can allow for a more efficient solution solving large projects in hours instead of weeks
- ◆ Design parameters can be varied using DSO to improve and optimize design

