Eddy Axial Finite Element Models of Steel Poles with Cuts to Reduce Eddy Currents

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Outline

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INTRODUCTION

- 1) Poles made of solid steel often have significant eddy current **losses**, even in “DC” apparatus, due to excitation turn-on and turn-off, motion of neighboring steel, etc.
- 2) The eddy currents also reduce the magnetic flux density and thus **further degrade the performance**.
- 3) Examples include poles in DC motors, generators, and solenoid actuators. Unless AC devices are of dimensions on the order of skin depth, their steel is usually made of laminated steel sheets separated by insulation (air, oxide, or coating).

INTRODUCTION continued

- 4) Steel sheet laminations are often impractical due to manufacturing costs, especially for cylindrical poles in axisymmetric devices.
- 5) Roters’ 1941 book *Electromagnetic Devices* mentioned putting cuts in solid steel poles to reduce eddy currents.
- 6) Here finite element models of poles with cuts are made, and the Eddy Axial capability of Maxwell2D is used to compute their losses and fluxes.

Basics of Eddy Axial

- In Maxwell2D, we users usually click on either "Magnetostatic" or "Eddy Current" to analyze magnetic apparatus.
- In both of these capabilities, the magnetic field lies in the plane of the screen. Any eddy current is assumed to be normal to the plane of the screen.
- The Eddy Axial capability of Maxwell2D assumes that the magnetic field is normal (axial) to the plane of the screen, and the eddy currents lie in the plane of the screen (which must be xy, not rz).

Basics of Eddy Axial p 2

- Eddy Axial is based upon Maxwell's expression of Ampere's Law that allows displacement currents:
- **del x H = J +** d**D**/dt (1)
- where **H** is magnetic intensity, **J** is current density, and **D** is permittivity ε times electric field **E**. Ohm's Law give **J** = σ**E**, where σ is conductivity. Then for sinusoidal fields of angular frequency ω, (1) becomes:
- **del x H =** S**E** (2)
- where the complex material tensor is defined as:
- S**=** s **+ j** w e (3)
- Premultiplying both sides of (2) by the reciprocal of (3) gives

Basics of Eddy Axial p 3

- **(**S**)** $^{-1}$ **del x H = E** (4)
- Taking the curl of both sides of (4) gives
- **del x (**S**)** $^{-1}$ **del x H = del x E** (5)
- Applying Faraday's Law gives:
- **del x (**S**)** $^{-1}$ **del x H = -** d**B**/dt (6)
- which for sinusoidal fields of angular frequency ω, and material of permeability μ becomes:
- **del x (**S**)** $^{-1}$ **del x H = - j** w m **H** (7)
- We recognize (7) as directly analogous to the conventional eddy current differential equation in terms of magnetic vector potential **A**. In 2D problems, **A** has only a z component.

Basics of Eddy Axial p 4

- After A is computed, the software then computes planar magnetic fields and flux lines using:
- **B** = **del x A** (8)
- Analogously, from **H** of (7), we can compute planar eddy current distributions using Ohm's Law and (2):
- $\mathbf{J_{tot}} = S\mathbf{E} = \mathbf{del\ x\ H}$ (9)
- The governing planar eddy current equations (7) and (9) are solved by Eddy Axial of Maxwell® 2D for **H** directed out of the screen in the z direction (H_z). The software also performs all related preprocessing, adaptive mesh generation, and postprocessing.

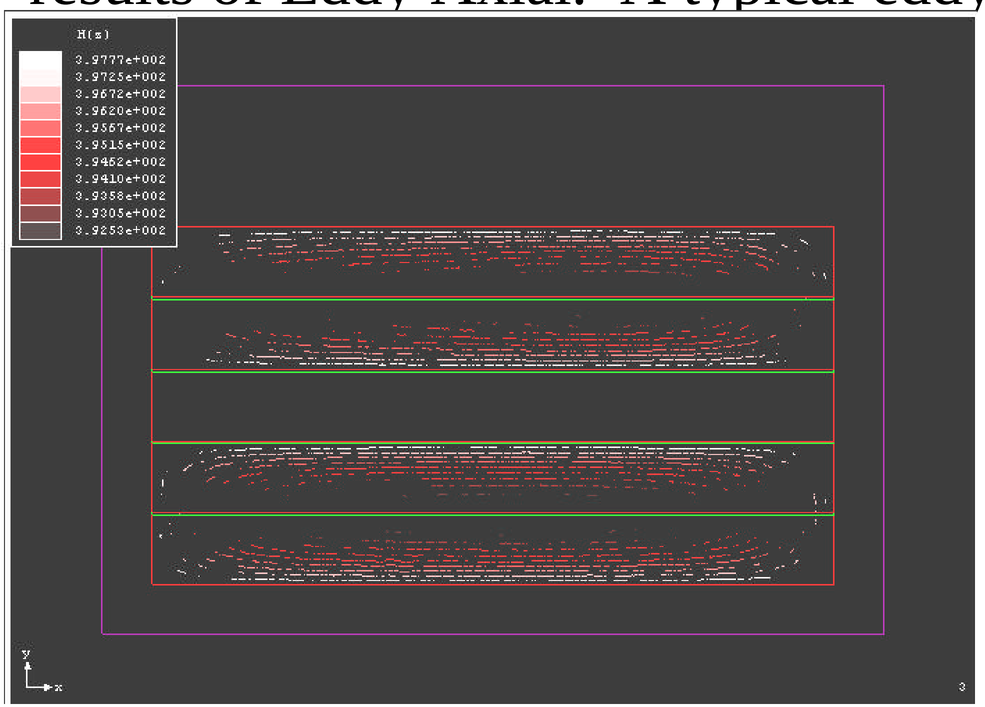
Some Past Applications of Eddy Axial

- Paper in 2000 *IEEE Transactions on Industry Applications* "Laminated steel eddy current loss versus frequency computed using finite elements" by Brauer and Cendes of Ansoft Corporation and Beihoff and Phillips of Rockwell Automation analyzed perfect steel laminations and their losses at frequencies from 50 Hz to 100 kHz, showing partial correlations with other theories and measurements.

- The 2000 Ansoft Maxwell Users Conference had a presentation by Brauer and Rettler titled "Eddy currents in large generators with imperfectly insulated laminations analyzed by Maxwell2D" with a portion describing use of Eddy Axial for imperfect laminations.

Past Applications of Eddy Axial cont.

- Paper presented at 2000 *IEEE Conference on Electromagnetic Field Computation* "Finite element computation of planar eddy currents in imperfect steel laminations" by Rettler and Brauer also contained similar results of Eddy Axial. A typical eddy current pattern is:

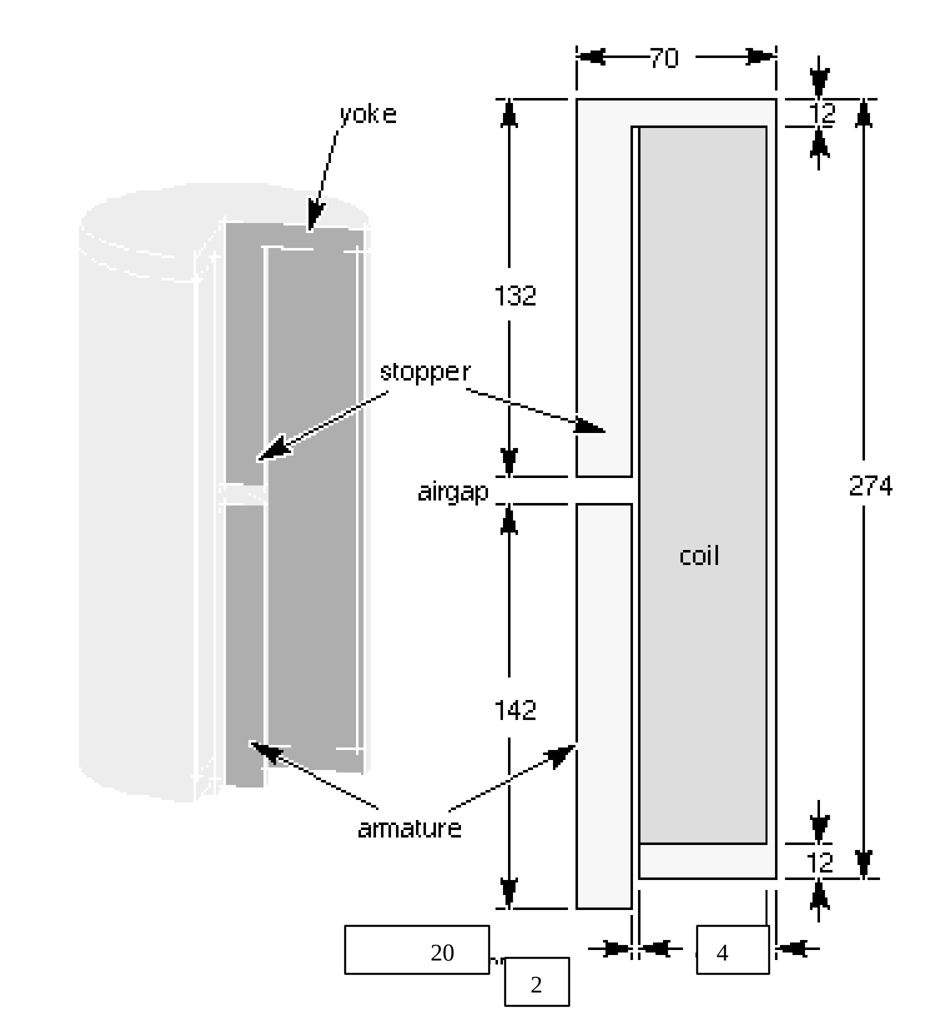


-- shorted lams

-- shorted lams

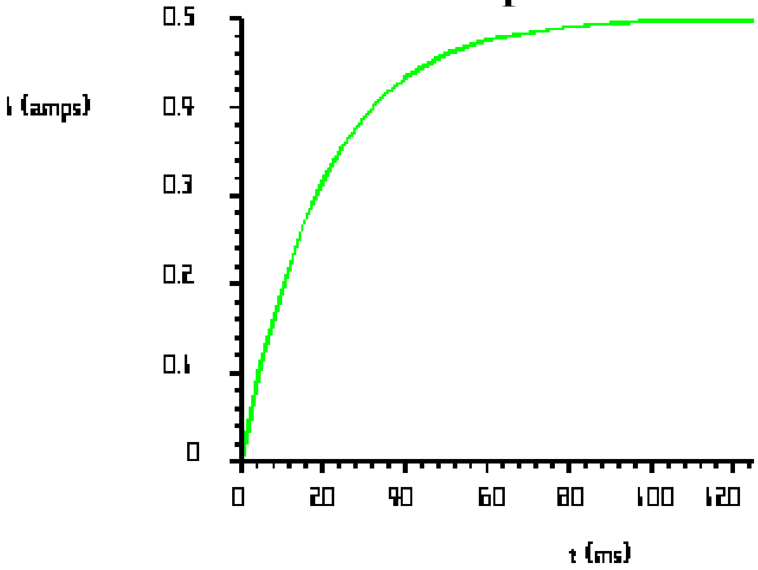
Examples of Steel Poles

Typical example: DC solenoid by Bessho of Japan with cylindrical (axisymmetric) steel poles for plunger and stopper.



Examples of Steel Poles cont.

- Coil current waveform specified by Bessho et al



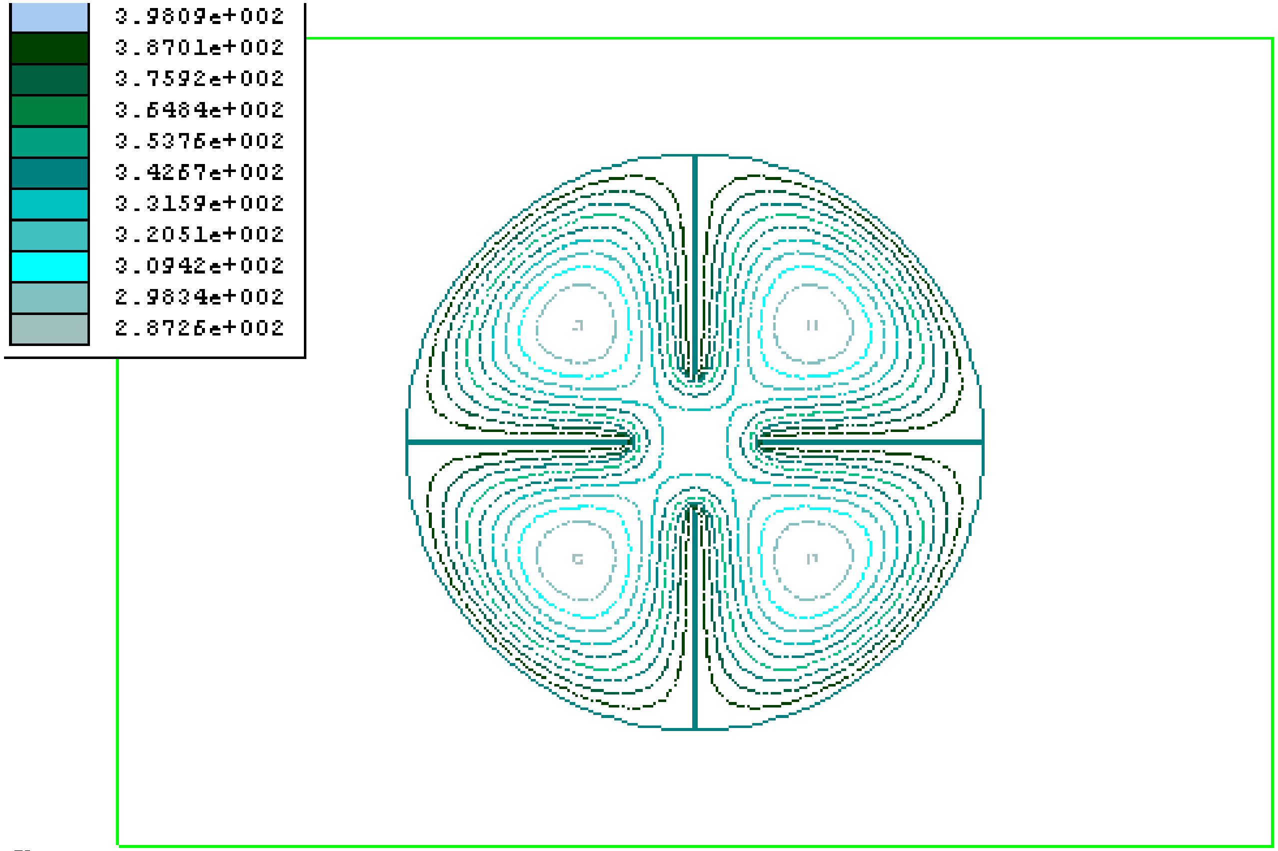
Transient eddy currents computed by Brauer & Chen in 2000 *IEEE Trans. Magnetics*
Plunger may close its 10 mm gap in approx. 100 ms; thus Effective frequency > 2.5 Hz

Finite Element Models of Steel Poles

- Here a pole diameter of 5 mm is assumed, with optional slots (.03 mm) cut to an inner diameter of 1.1 mm.
- Steel is assumed to have electrical conductivity = 2.E6 siemens/meter.
- Steel is assumed to have relative permeability = 2000.
- Applied H_z is assumed = 398 amps/meter , which gives B = 1 tesla in the outermost steel of the pole.
- Frequency assumed here = 60 Hz. Since ¼ th of its period corresponds to the approximate rise time, the equivalent transient rise time is approximately 4 ms (using Fourier analysis).

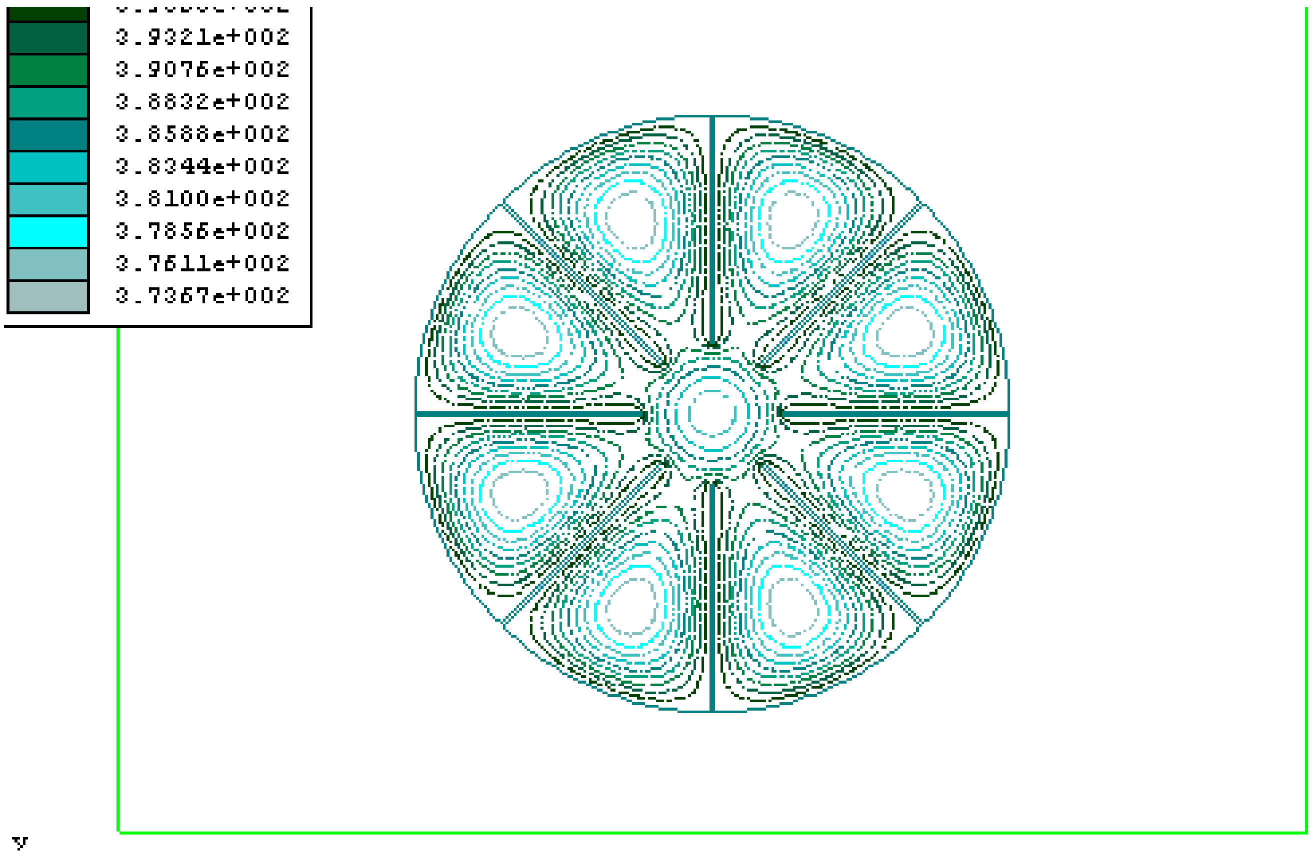
Computed Results & Their Significance

- 4 radial slots, contours of H_z real (eddy currents)



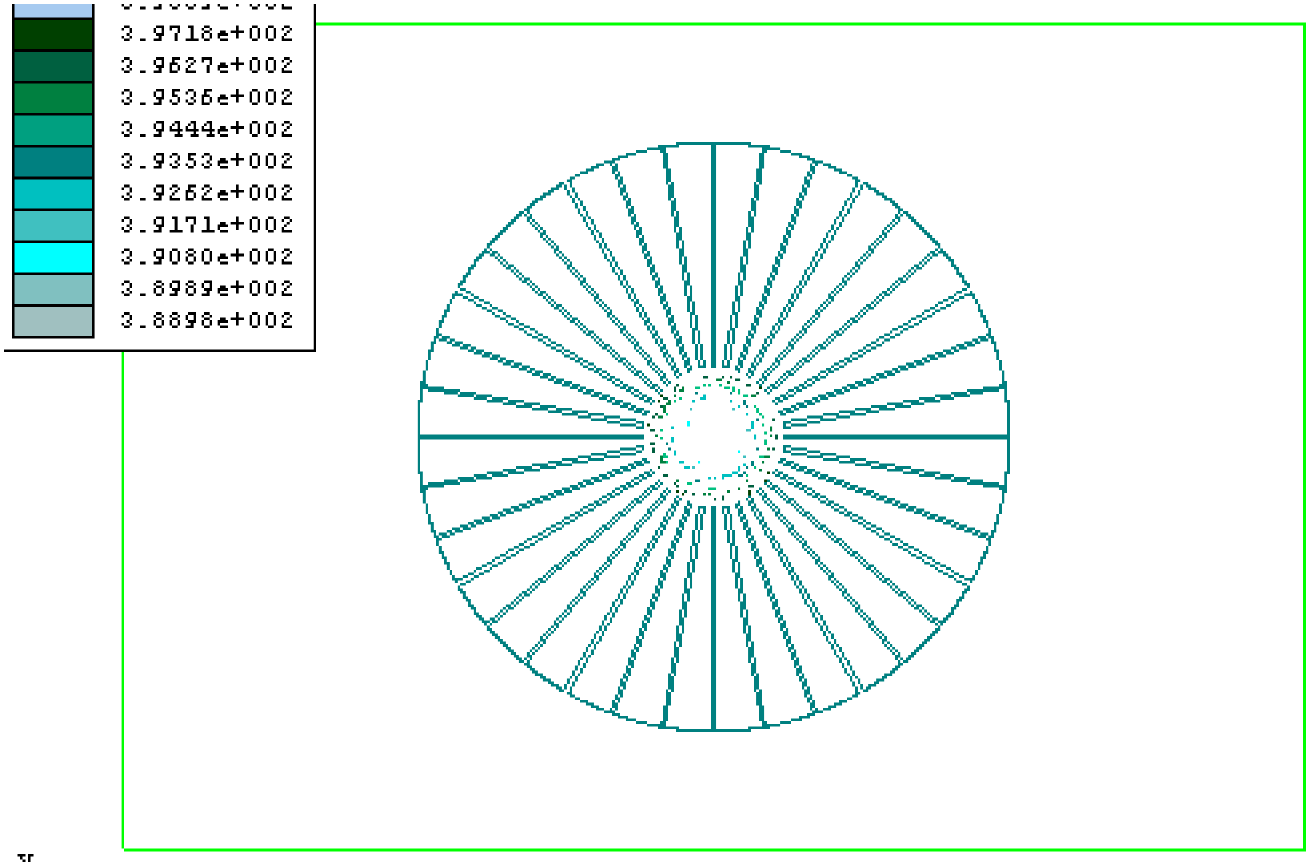
Computed Results & Their Significance cont.

- 8 radial slots, contours of H_z real (eddy currents)



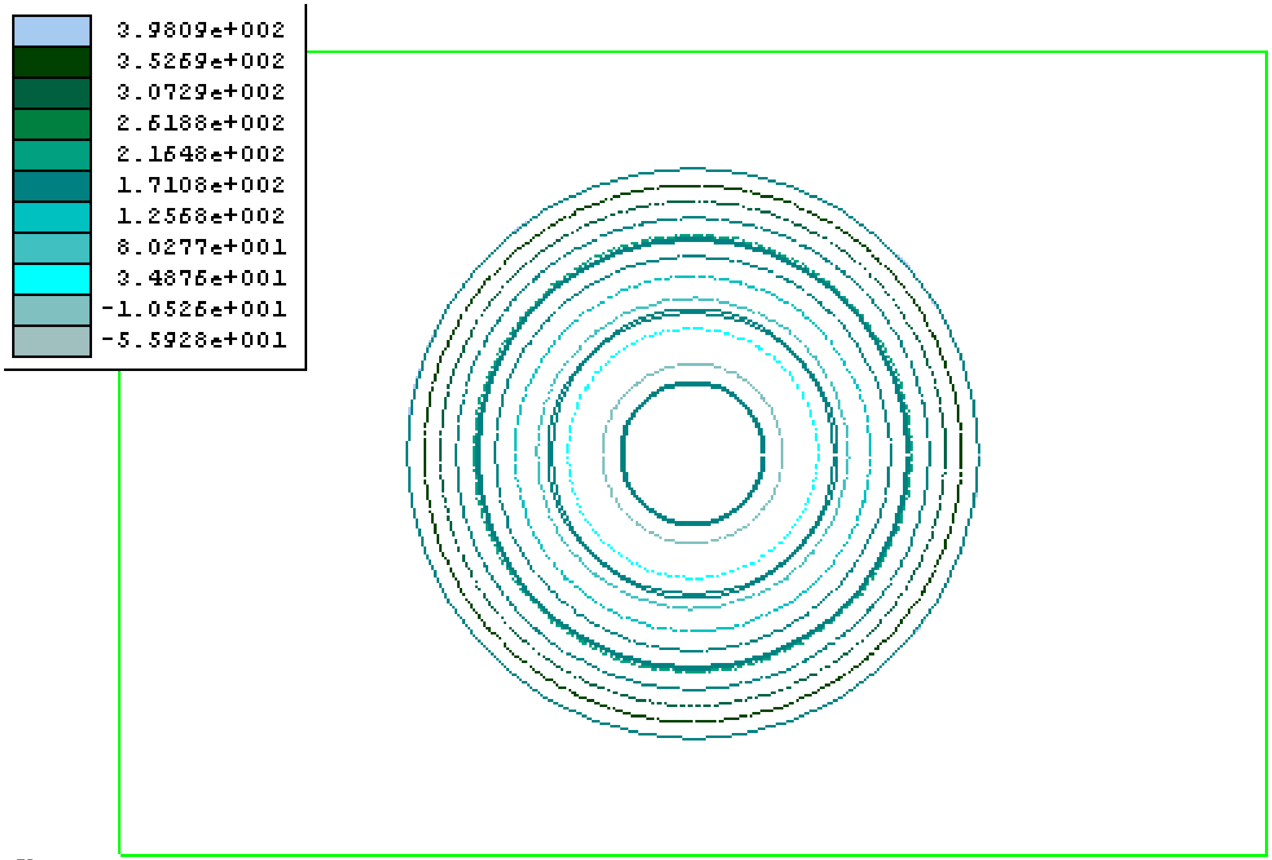
Computed Results & Their Significance cont.

- 36 radial slots, contours of H_z real (eddy currents)



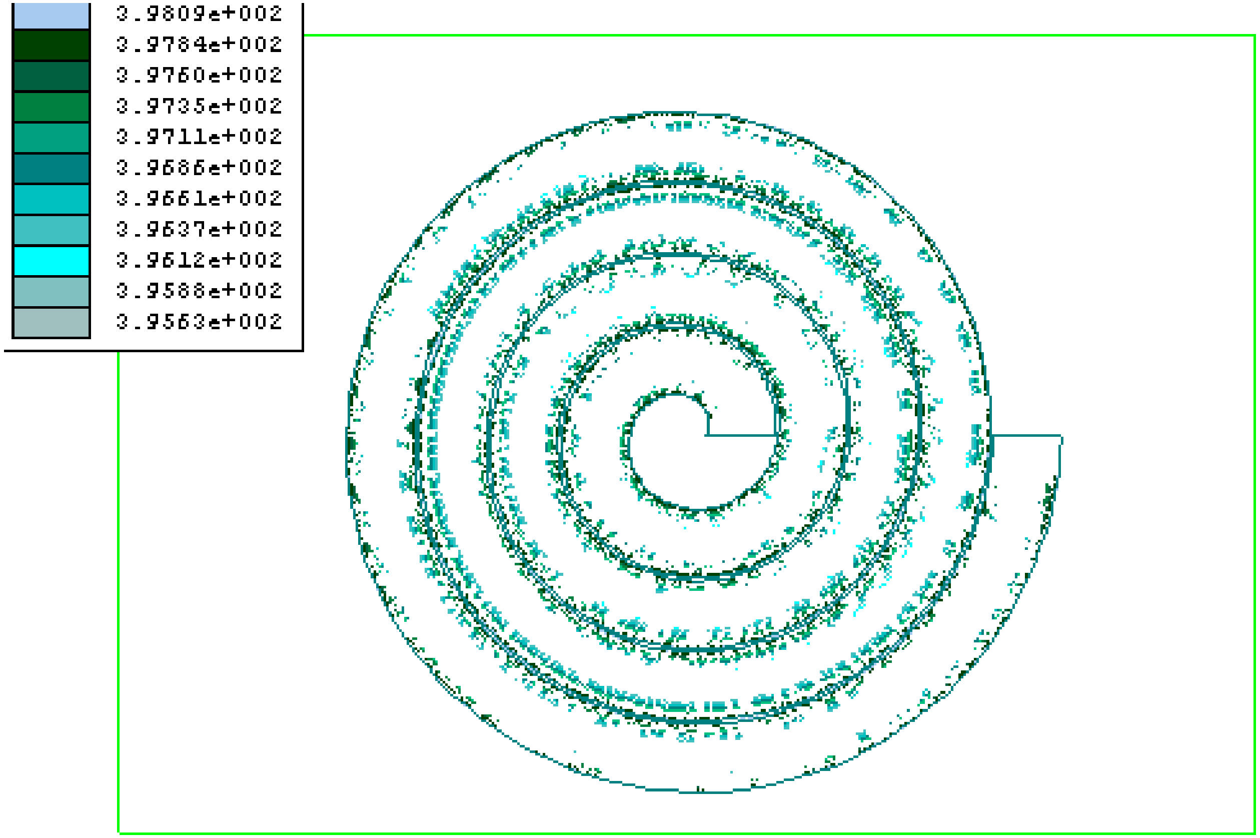
Computed Results & Their Significance cont.

- Circular cuts, contours of H_z real (eddy currents)



Computed Results & Their Significance cont.

- Spiral, contours of H_z real (eddy currents)



USE POST CALCULATOR to integrate H_z and obtain total flux. Get losses from convergence table.

TABLE 1. Computed results for steel poles at 60 Hz

Pole cuts	Triangles	Ploss(w)	Min H_z (A/m)	% of flux
4 radial	1978	0.411	287.3	86.4
8 radial	3938	0.198	373.7	95.1
36 radial	44064	0.021	389.0	89.5
Circular cuts	1422	0.479	-55.9	42.6
Spiral	20429	0.111	395.6	99.5

Circular cuts (or no cuts) are worst case. As radial cuts are increased from 4 on up, flux increases, except at 36 cuts the cuts themselves take up space. The spiral is an interesting alternative.

Conclusion

- Addition of radial cuts reduces eddy currents and increases flux carried, up to point where cuts take too much space.
- Spiraling blocks eddy currents completely, but may not be practical or beneficial for 3D flux.
- Eddy Axial would also help to analyze slots in steel rings or cans (also mentioned by Roters) and to analyze losses in segmented permanent magnets due to flux pulsations.
- Maxwell3D is recommended for further analysis of effects of cuts in actuators and other magnetic apparatus.
- My thanks go to Ansoft management for their support. For further information see the **accompanying 5 page paper.**