Finite Element Method Magnetics

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What is FEMM?

- 2D/Axisymmetric Finite Element Program
  - Magnetics
    - DC
    - Eddy Currents
  - Electrostatics
  - Heat Conduction
  - Current Flow / Quasielectrostatic
- Graphical Pre-/Post- Processing
- Interfaces with many popular analysis tools

Philosophy

- Focus is on solving practical problems
  - Users shouldn't *have* to write code to solve problems
  - Users shouldn't even have to be PDE experts to build and solve problems
  - It should be easy for users to get derived results from the solution (e.g. loss, power, energy, etc.), not just field plots.
- Meant to be used with commonly available desktop/laptop hardware
- Algorithms/Methods are usually "fastest algorithms that are easy to implement"

Availability

- Distributed under Aladdin Free Public License
  - Source code available
  - No restrictions on using the code, e.g. to solve problems for commercial applications
  - Prevents some third party from co-opting some or all of the program for their commercial product without a special license.
- Primarily available at http://www.femm.info
- Yahoo Group: http://tech.groups.yahoo.com/group/femm/

Information on Website

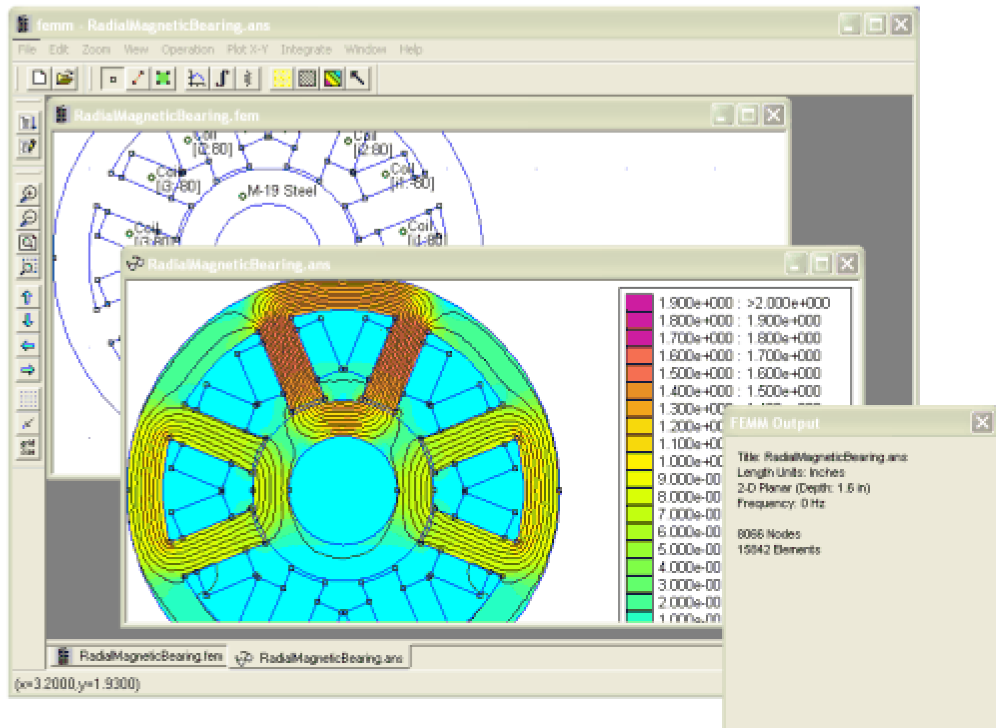
- FAQ
- Bug Tracker
- Step-by-Step Tutorials
- Manuals
  - Translated into French, Bulgarian, Romanian, Vietnamese
  - Examples in Spanish
  - Third-party website hosts German documentation
  - Book on FEMM available in Russian
- Many documented example problems
- User Contributions area

Platforms

- Primarily intended to run on Windows machines
  - Compatible with all versions from Win95-Windows 7
  - Executable distributions currently compiled with MSVC++ 6.0, but does compile with later versions
    - Requires Professional version due to use of MFC
    - Presently, only 32-bit .exe available
- Runs on Linux, Mac machines under Wine
  - Program was modified to fix parts that didn't work right under Wine
  - Performance on Wine now comparable to Windows.

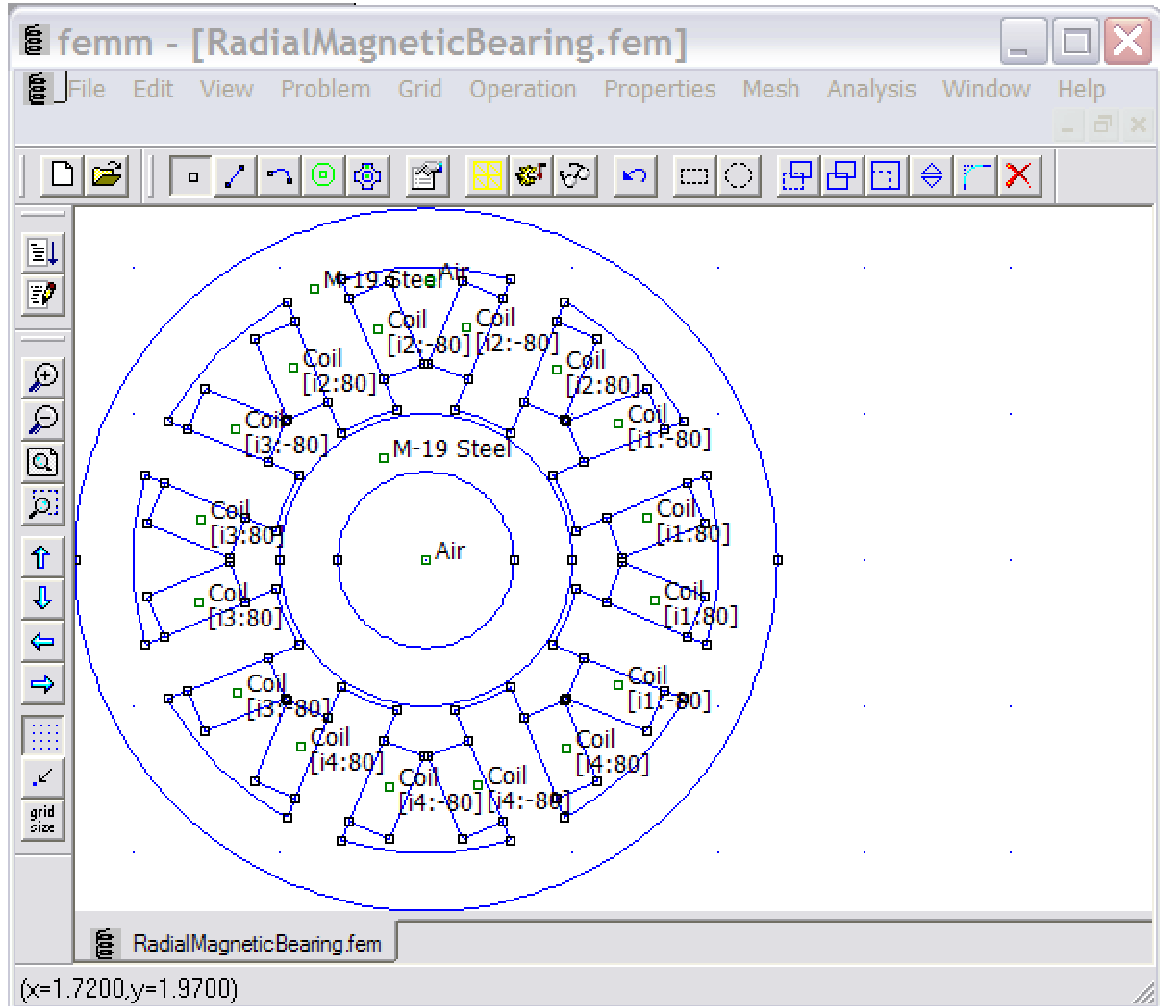
Basic Structure

- MDI application
- Input Document
- Solution Document
- Output Window
- Taskbars / buttons for most functions



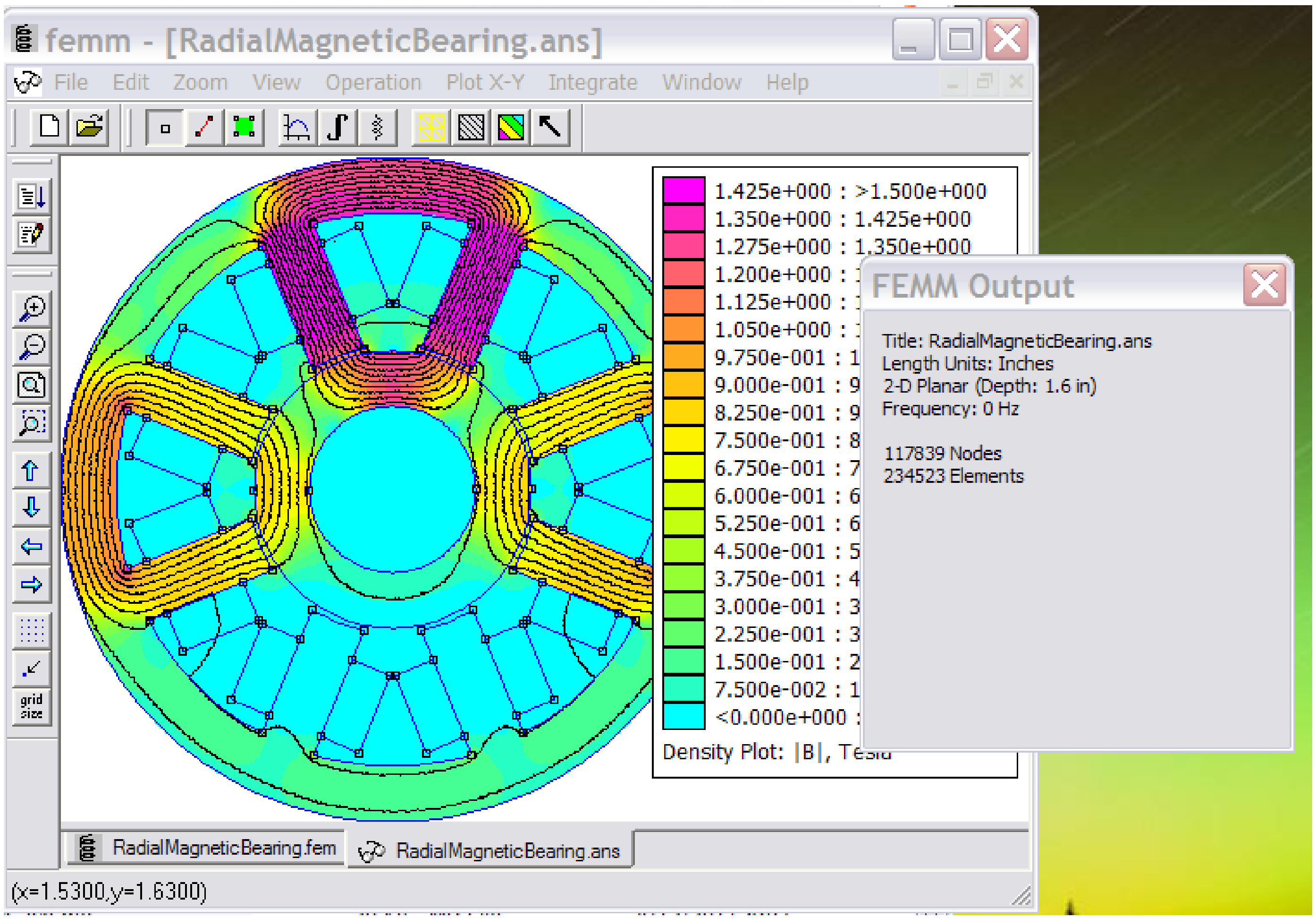
Input Document

- Point, Line, Arc, Block Label, and Group Modes
- DXF Import/Export
- Define Materials, Boundary conditions, “Circuit” Properties
- Copy, Move, Rotate, Mirror
- Initiate meshing, Analysis, Solution Viewing



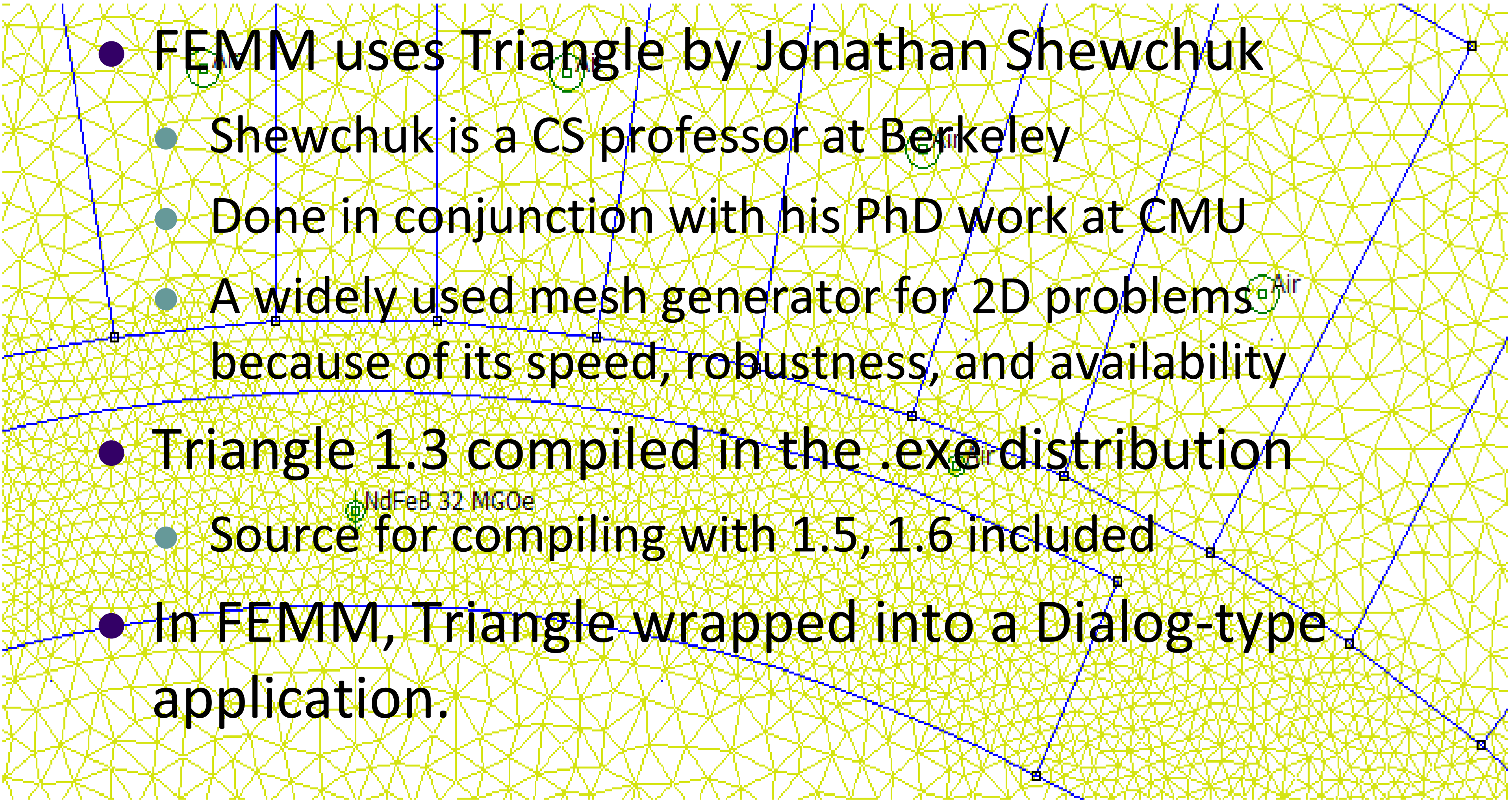
Solution Document

- Point, Contour, Block modes
- Perform Integrals
- “Circuit” Properties
- Line Plots
- Vector Plots
- Density Plots
- Contour Plots



Mesh Generation

- FEMM uses Triangle by Jonathan Shewchuk
  - Shewchuk is a CS professor at Berkeley
  - Done in conjunction with his PhD work at CMU
  - A widely used mesh generator for 2D problems because of its speed, robustness, and availability
- Triangle 1.3 compiled in the .exe distribution
  - Source for compiling with 1.5, 1.6 included
- In FEMM, Triangle wrapped into a Dialog-type application.



Triangle Geometry Definition

- Triangle expects a PSLG (Planar-Straight-Line Graph) as input.
  - Set of points that define endpoints of lines
  - List of segments connecting defined lines
- No rigid *a priori* notion of regions
  - Block Labels, like pins on a map, define different regions of the problem
  - Determination of the shape of the region associated with the label is a by-product of the meshing process

FEMM as Triangle GUI

- Original FEMM design conceived as a way of building geometries that Triangle could parse
- Geometry Construction Steps:
  - Define Points at ends of line segments in the geometry
  - Define Line Segments that join up the points
  - Define Block Labels that break the problem into regions
  - Label Line Segments with BCs, as appropriate.

Finite Element Formulation

- All solvers use 1st Order triangular elements
  - Driven by ease of coding.
  - Can usually overpower 2D problems with a dense mesh
- Vector potential formulation for magnetics
- Selection of “right” Axisymmetric Magnetic formulation was nontrivial
  - Some approaches yield poor accuracy near r=0
  - Henrotte *et al, Trans. Magn. 29(2):1352-1355 Mar 1993.*
- “Superconvergent Patch Recovery” to smooth the piece-wise constant flux density

Nonlinear Time Harmonic Magnetics

- Goal is to correctly compute the amplitude of the fundamental for constant frequency AC problems
- Computation effort is much lower than performing a time-stepping analysis
- “Effective” B-H curves for nonlinear materials
- Other “effective” materials that model eddy currents & hysteresis in laminated materials, skin effect and proximity effect in windings.

Numerical Methods—Matrix Solver

"Homegrown" linear solvers used in FEMM

Solver for Real Symmetric problems:

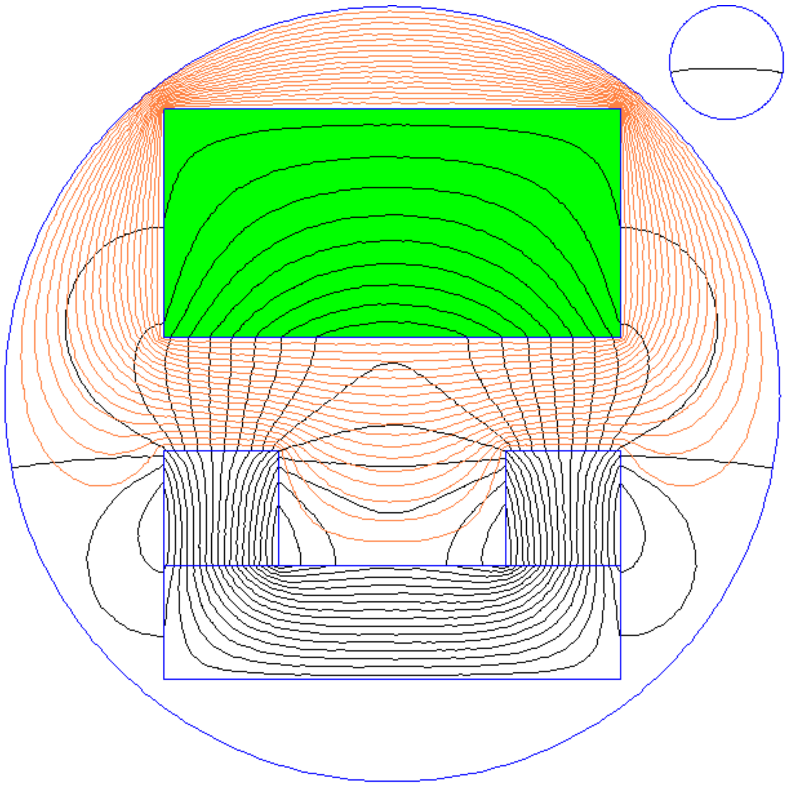
- Reverse Cuthill-McKee algorithm used to renumber nodes, elements
- Preconditioned Conjugate Gradient
- Uses SSOR ("Evans Method") Preconditioner
  - Trivial to build, no space to store, net speed similar to Incomplete Cholesky
- Sparse storage via a tree of linked lists

Solver for Complex Symmetric problems (AC Magn.)

- BiCG with SSOR Preconditioner

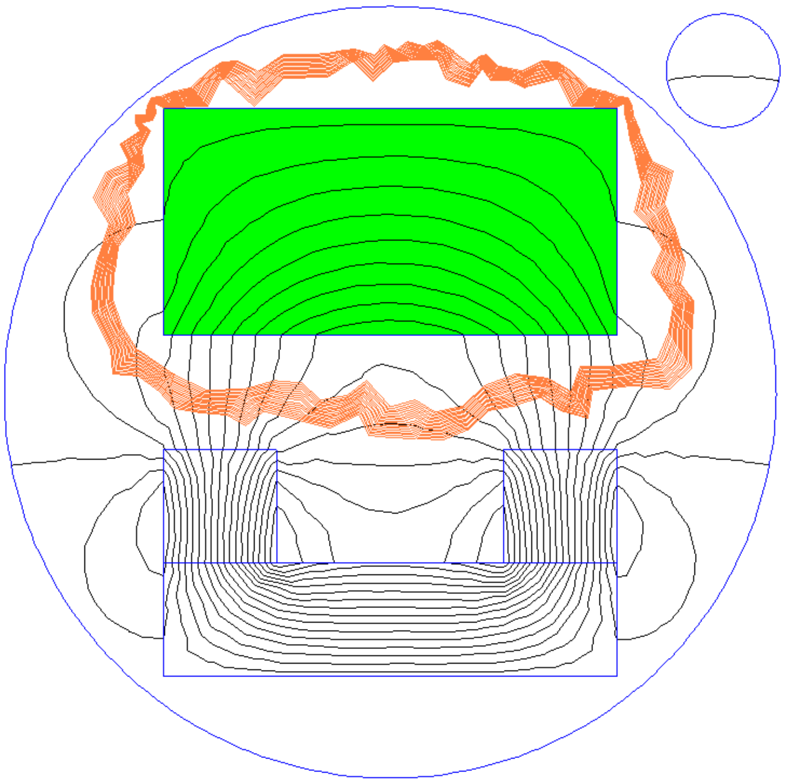
Force Calculation: “Weighted Stress Tensor”

- Maxwell Stress Tensor line integral not very accurate
- Convert to a volume integral to “average over many possible paths.
- Auxiliary $\nabla^2 u = 0$ problem solved
- Stress tensor contours follow curl(u)



Weighting Scheme

- Several different weighting schemes investigated
- Most quickly converging turns out to be one obtained by rounding the results of the field solution
- Rounded weighting scheme is the default; others possible if code is recompiled.

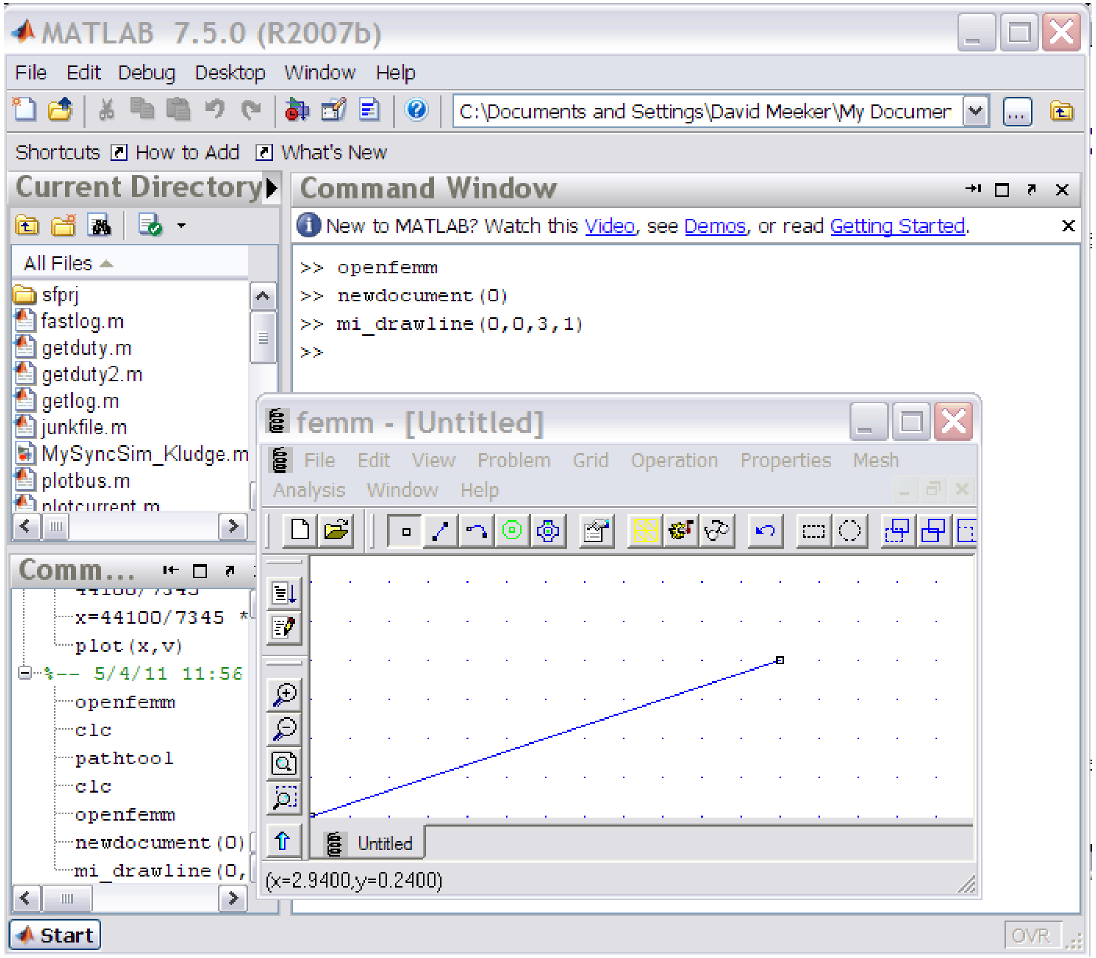


Scripting Engine

- Lua is used by FEMM for scripting
- "Lua is a powerful, fast, lightweight, embeddable scripting language."
- Version Lua used with FEMM is 4.0
  - Hacked Lua to make complex numbers the base number type, make trig functions use radians
  - Newer Lua (5.1.4) available, but motivation to update the Lua version used by FEMM is weak.

Matlab/Octave Interface

- Uses Matlab/Octave Actxserver functions to instantiate and communicate with FEMM
- Back-up temporary file communication if activex not available or not installed.
  - Native install of Octave able to talk to FEMM running in Wine on Linux
- Every LUA function mirrored as a Matlab function



Scilab Interface

- Most recently added interface
- Uses Scilab support for functions DLLs to use ActiveX interface to FEMM
- Every Lua function implemented as an analogous Scilab funtion
- Ported to Scicoslab, a fork of Scilab

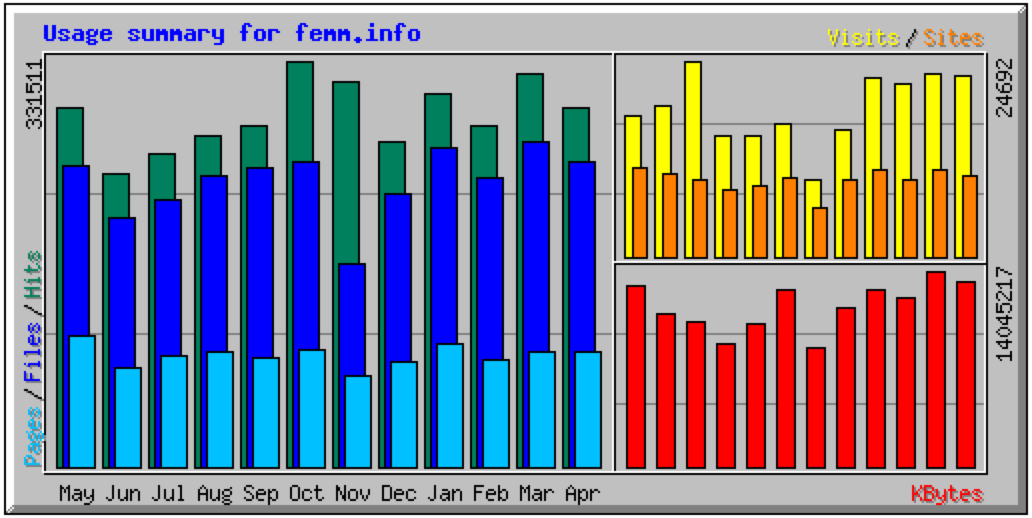
Mathematica Interface

- Uses “Mathlink”, a sort of wrapper for a Named Pipes interface to Mathematica
- Tested with versions 4 - 7
- Again, all Lua functionality mirrored as “native” Mathematica functions
- Set of detailed Mathematica examples included in the .exe distribution.

Other Interfaces

- Java interface “JFEMM” was recently contributed
- Talk to MS Excel via ActiveX interface
- Visual C++ connection example
- Recently contributed C# example

Level of Usage



- On average, about 4000 downloads of the .exe per month
- About 1000 source code downloads per month, on average
- Over 13 yrs, possibly getting near 500,000 downloads of exe
- Although many download are probably old users upgrading or installing on new machines, seems possible that the user base could be on the order of 50,000.

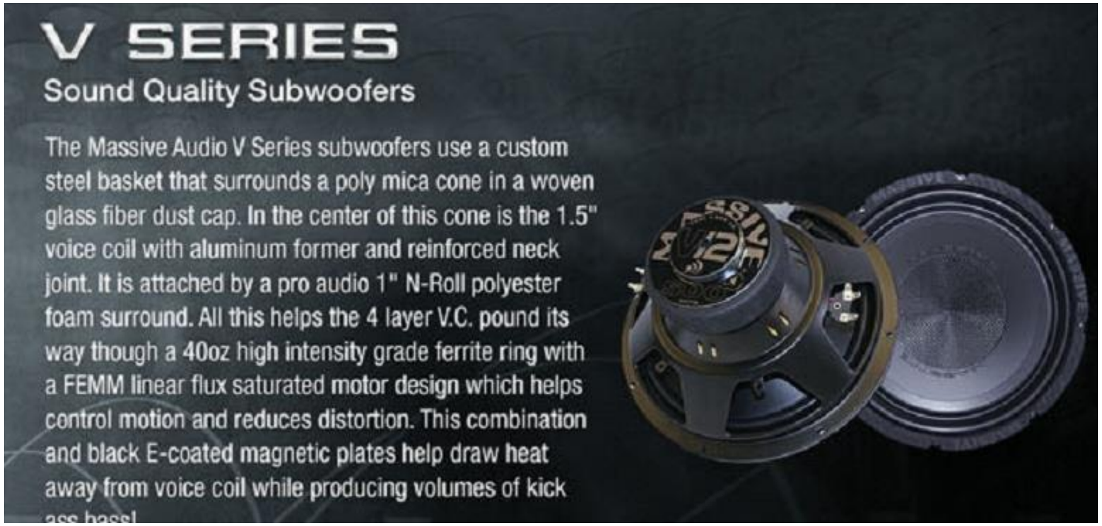
Use in Academic Publications

- Search of IEEExplore yields 130 documents
- 8 papers in COMPEL
- 25 papers in Elsevier journals
- Many dissertations, theses
- Many more documents where results, figures are used but program is not attributed

Example Uses: 2010 IEEE Trans. Magn.

- Transformer Joints FE Analysis Using Pseudo-Source Technique
- Comparative Study Between Mechanical and Magnetic Planetary Gears
- 2-D Exact Analytical Model for Surface-Mounted Permanent-Magnet Motors With Semi-Closed Slots
- Eddy-Current Loss and Temperature Rise in the Form-Wound Stator Winding of an Inverter-Fed Cage Induction Motor
- A Cosimulation Framework for Multirate Time Integration of Field/Circuit Coupled Problems
- Analytical Computation of the Magnetic Field Distribution in a Magnetic Gear
- Convexity-Oriented Mapping Method for the Topology Optimization of Electromagnetic Devices Composed of Iron and Coils
- Toroidally-Wound Self-Bearing BLDC Motor With Lorentz Force
- Computation of NdFeB-Halbach Cylinders With Circular and Elliptical Cross Sections in Three Dimensions

Typical Use: Speaker Design



- Has been used to design many production speakers
- Used in conjunction with speaker design codes from RedRock Acoustics, LoudSoft

Electromagnetics Education

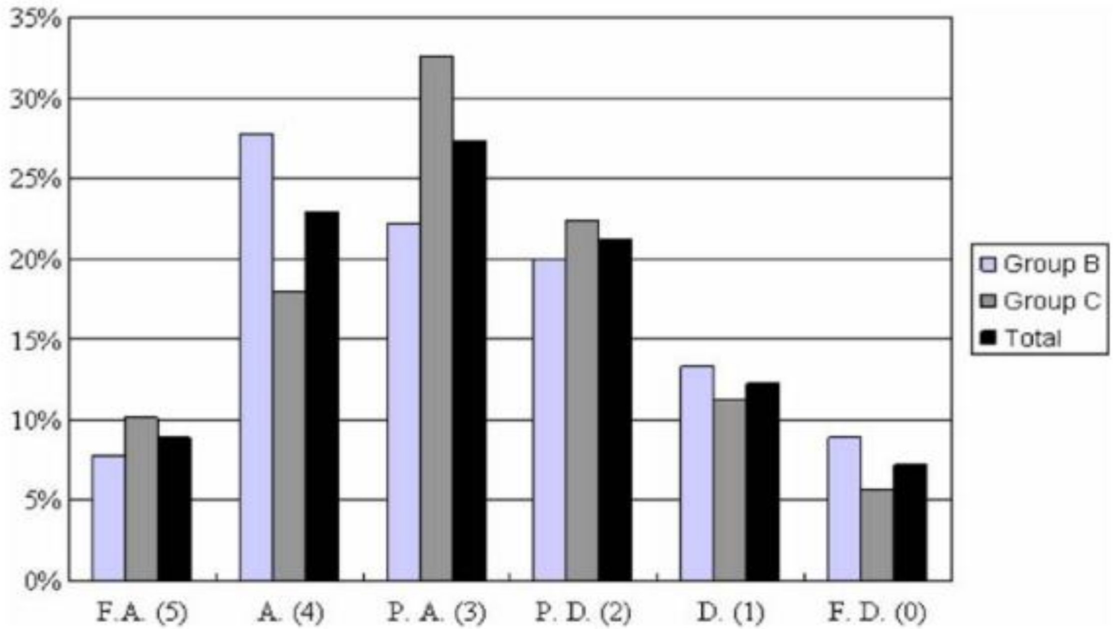


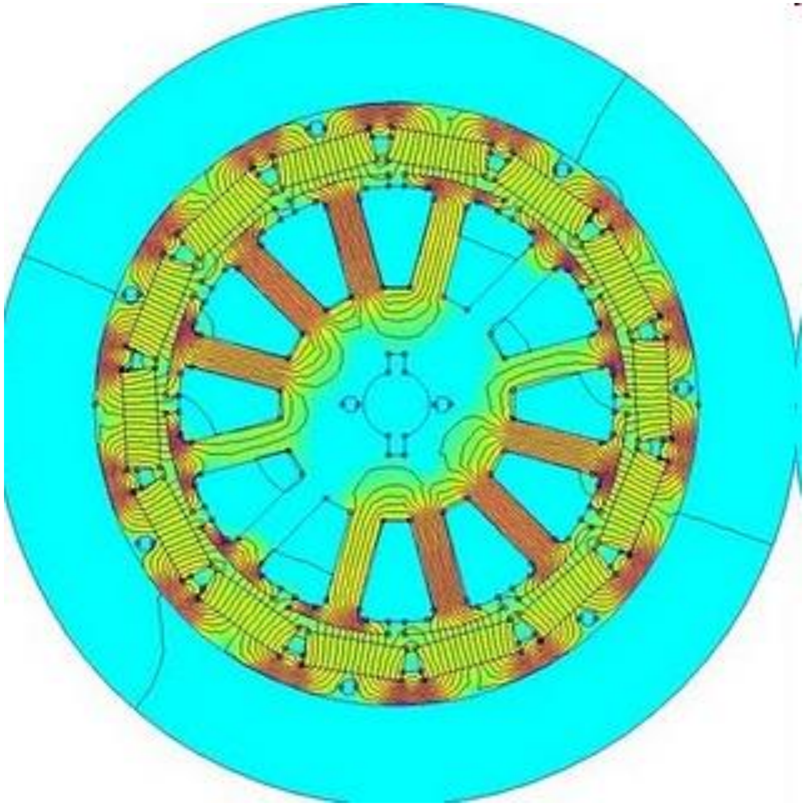
Fig. 13 [Q2.3], Software interest

- K. Baltzis, "The finite element method magnetics (FEMM) freeware package: May it serve as an educational tool in teaching electromagnetics?" Education and Information Technologies 15(1):19-36, 2010.

http://www.springerlink.com/content/q1p6284553665717/fulltext.pdf

Use by Hobbyists

- LRK motors for model aircraft
- Motors for electric vehicles: cars, scooters, bikes
- Low-Power wind turbines
- DIY Speakers

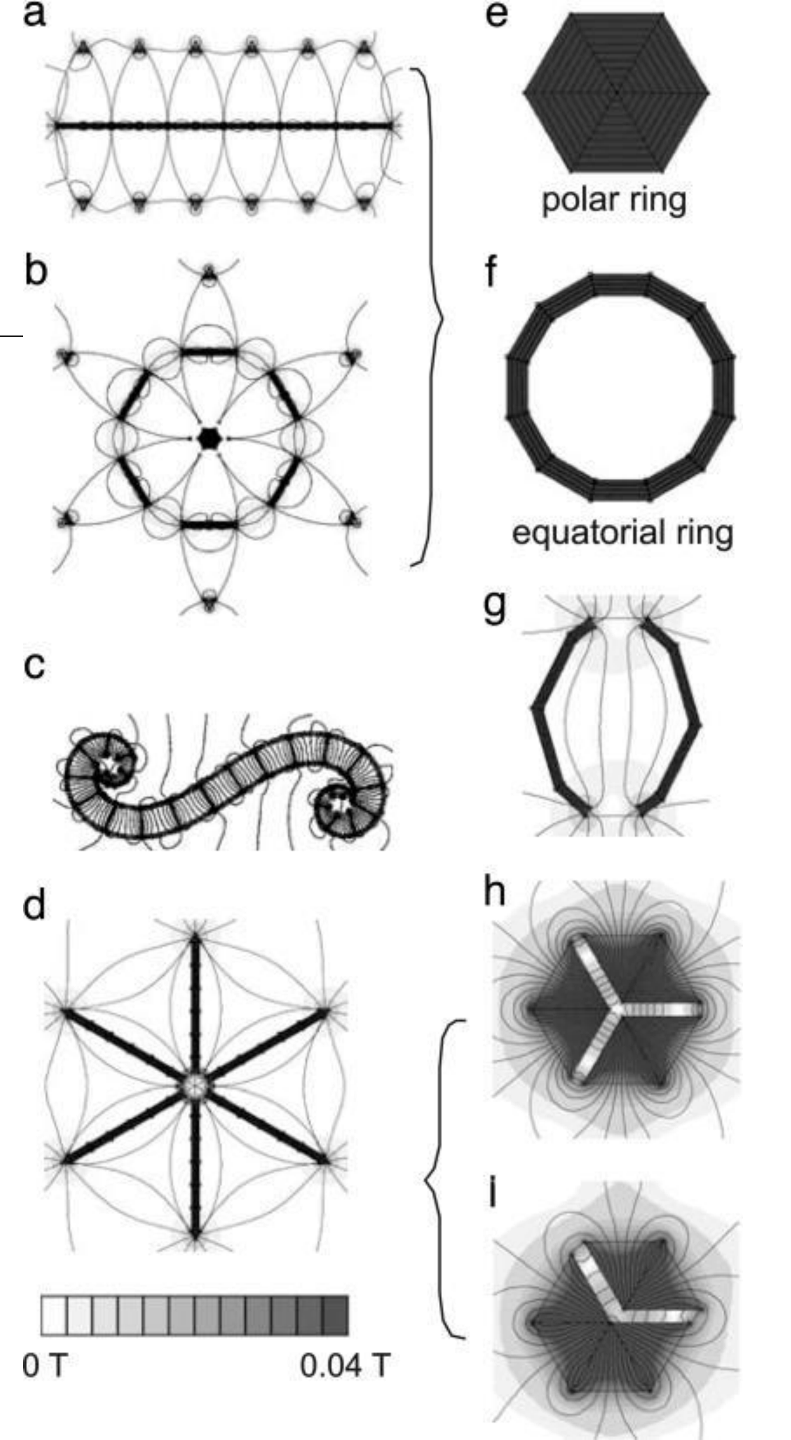


Unusual Applications

- M. Boncheva *et al.,* "Magnetic self-assembly of three-dimensional surfaces from planar sheets," Proc Natl Acad Sci U S A. 2005 March 15; 102(11): 3924–3929.

http://www.ncbi.nlm.nih.gov/pmc/articles/PMC554830/

- G. Kletetschka *et al*., Magnetic zones of Mars: Deformation-controlled origin of magnetic anomalies. Meteoritics & Planetary Science, 44: 131–140, 2009



Future Directions

- 64-bit version
- "Harmonic Balance" formulation for solving magnetic problems where there is an AC variation on top of a DC set point
- Time-transient / Motion
- Connection to external circuits, perhaps some Spice-like program
- Now that machines with more than 2 cores are common, time to reformat analysis to accept a parallel solver that can use multiple cores on one machine
- Adaptive mesh