Realistic Litz Wire Characterization Using Fast Numerical Simulations

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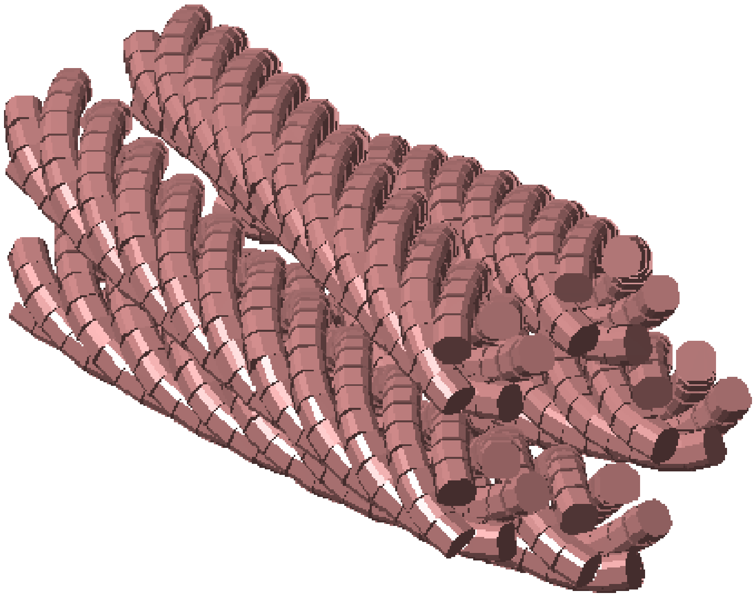
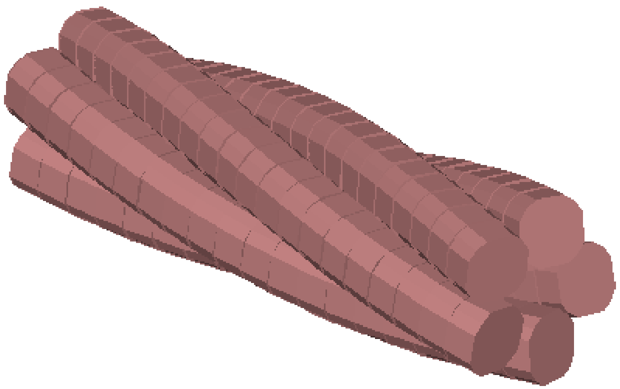
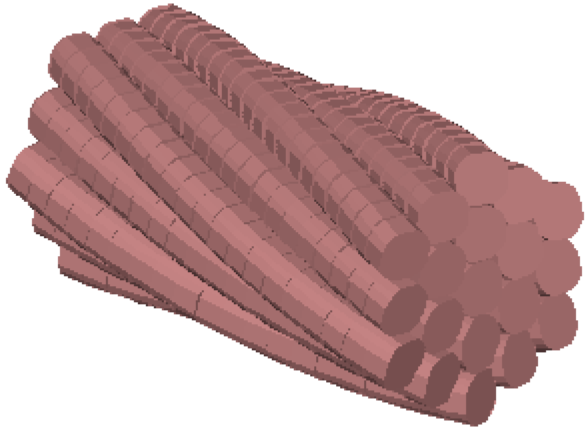
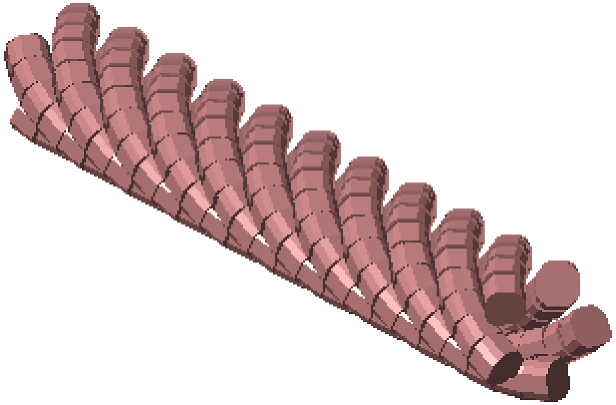
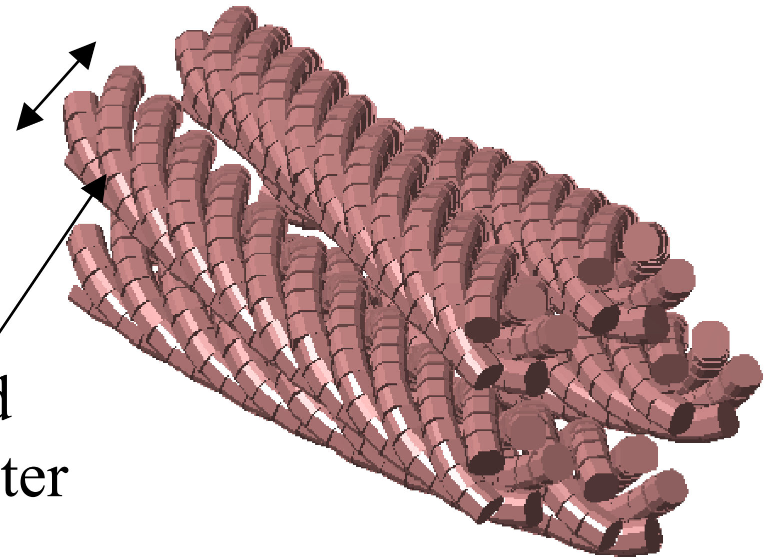






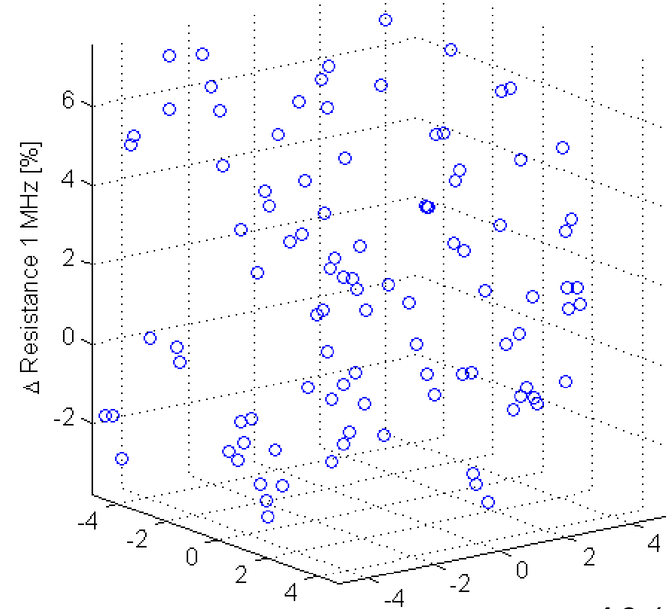


Strand spacing



Strand diameter

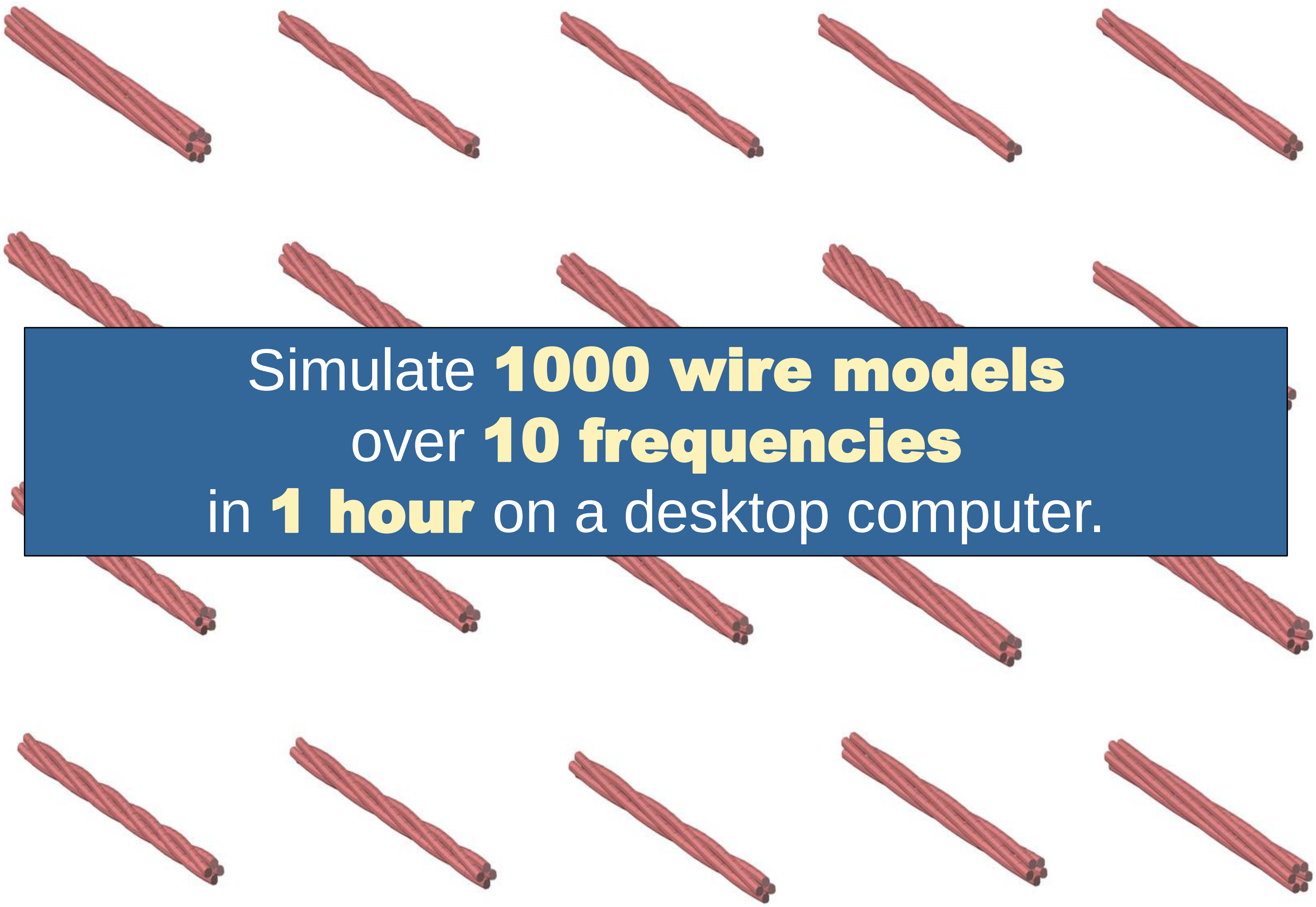
±7% Resistance



±4% Diameter

±4% Spacing

- Performance can be sensitive to tolerances.
- An inherently three-dimensional problem.



Simulate **1000 wire models**
over **10 frequencies**
in **1 hour** on a desktop computer.

In this Paper:

How does the litz wire designer benefit from fast simulations?

1. Fast & finely-controlled characterization.
2. Reveal sensitivities & underlying physics.
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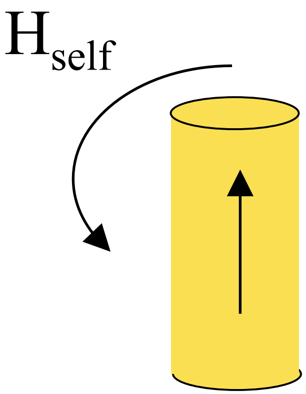
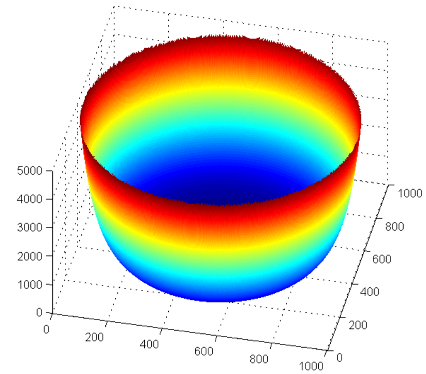
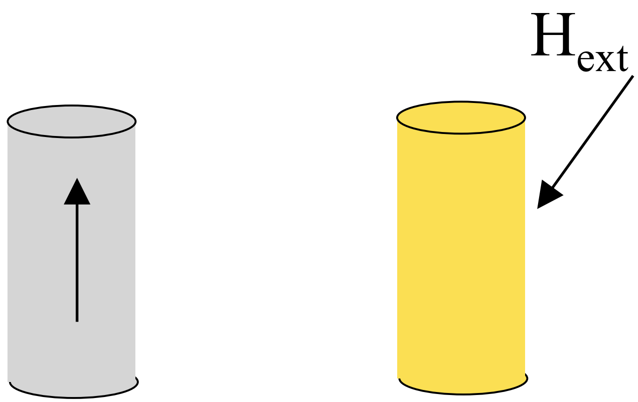
REVIEW: Copper loss theory

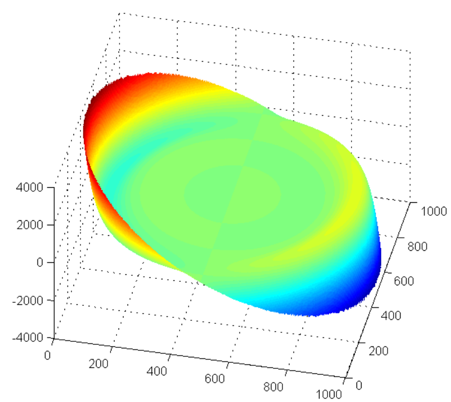
Consider the current density in a strand of wire…





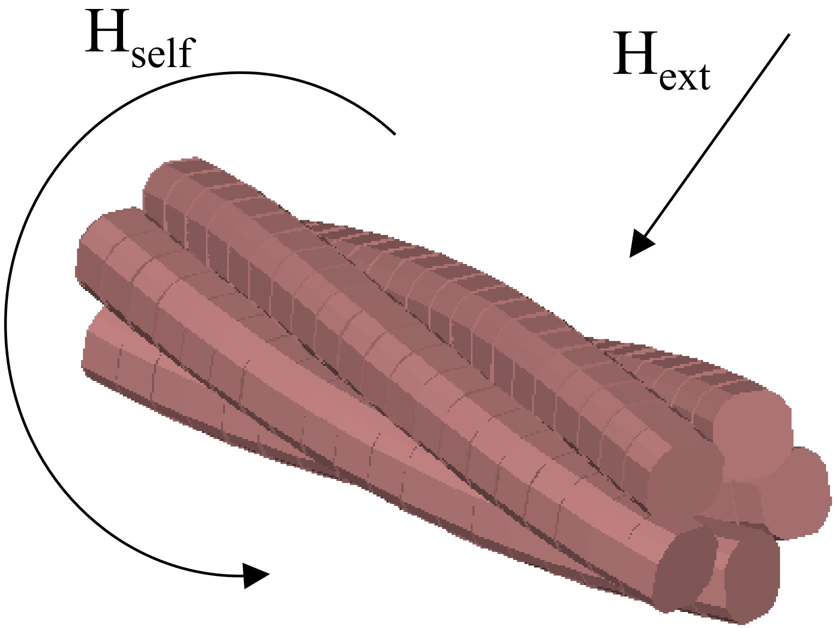
Skin effect

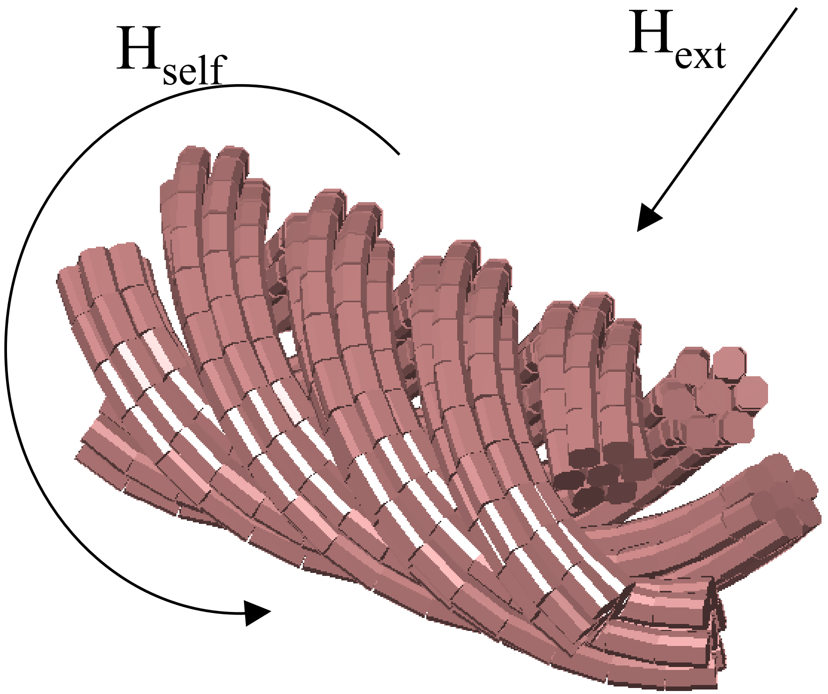




Proximity effect

REVIEW: How do litz wires work?





- Azimuthal transposition.
- Radial transposition.

REVIEW: Ferreira's method for ideal litz wires...

Current-driven *skin effect*, **Field**-driven *proximity effect*.

$$P_{skin}(f) = F(f)I^2R_{dc}, \quad P_{prox}(f) = G(f)|H|^2$$

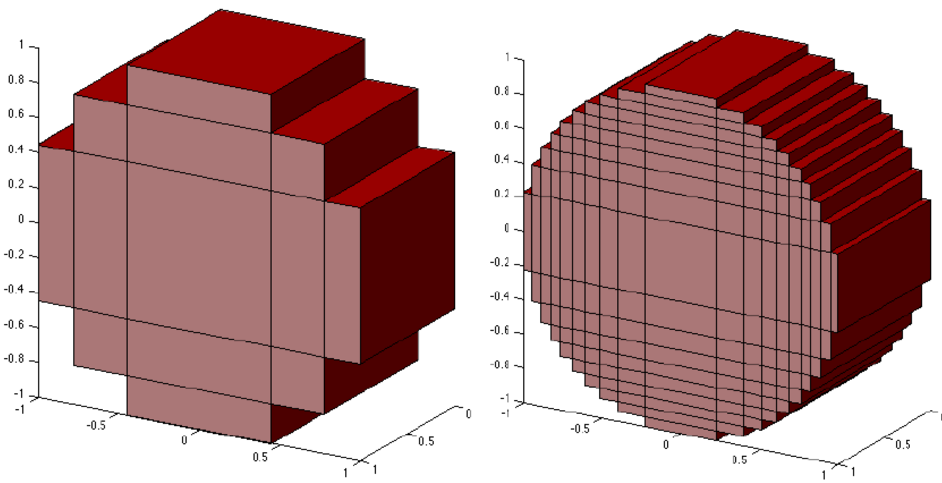
$$P_{tot}(f) = P_{skin}(f) + P_{prox}(f)$$

Closed form solutions for $F(f)$ and $G(f)$ can be derived for idealized litz wires and equivalent solid conductors.

OBJECTIVE. Characterize the F & G factors for general litz wire constructions with no closed form solutions.

[1] Ferreira, J. A. "Analytical computation of ac resistance of round and rectangular litz wire windings." *IEE Proceedings B (Electric Power Applications)*. Vol. 139. No. 1. IET Digital Library, 1992.

REVIEW: PEEC simulation method



(a) (b)

- Divide conductor (but not freespace) into elements.
- Interact the elements via self- and mutual- impedances.
- Compress dense matrix into sparse components. Solve iteratively as a circuit problem.

Mutual inductance matrix

$$L = \begin{bmatrix} L_{11} & L_{12} & L_{13} & \cdots & L_{16} \\ L_{21} & L_{22} & & & \\ L_{31} & & L_{33} & & \vdots \\ \vdots & & & \ddots & \\ L_{61} & & \cdots & & L_{66} \end{bmatrix}$$

Self resistance matrix

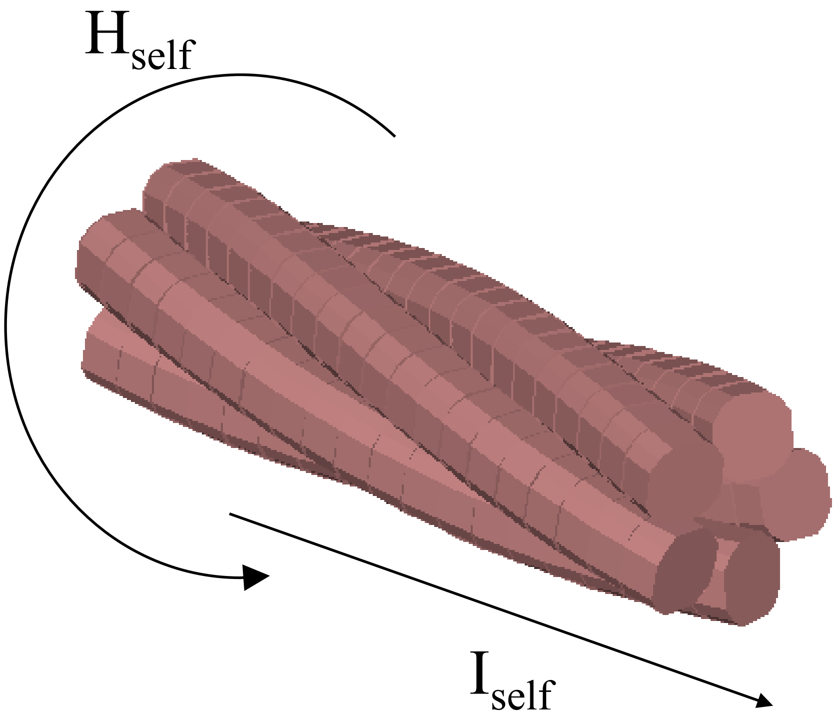
$$R = \begin{bmatrix} R_{11} & & & & \\ & R_{22} & & & \\ & & R_{33} & & \\ & & & \ddots & \\ & & & & R_{66} \end{bmatrix}$$

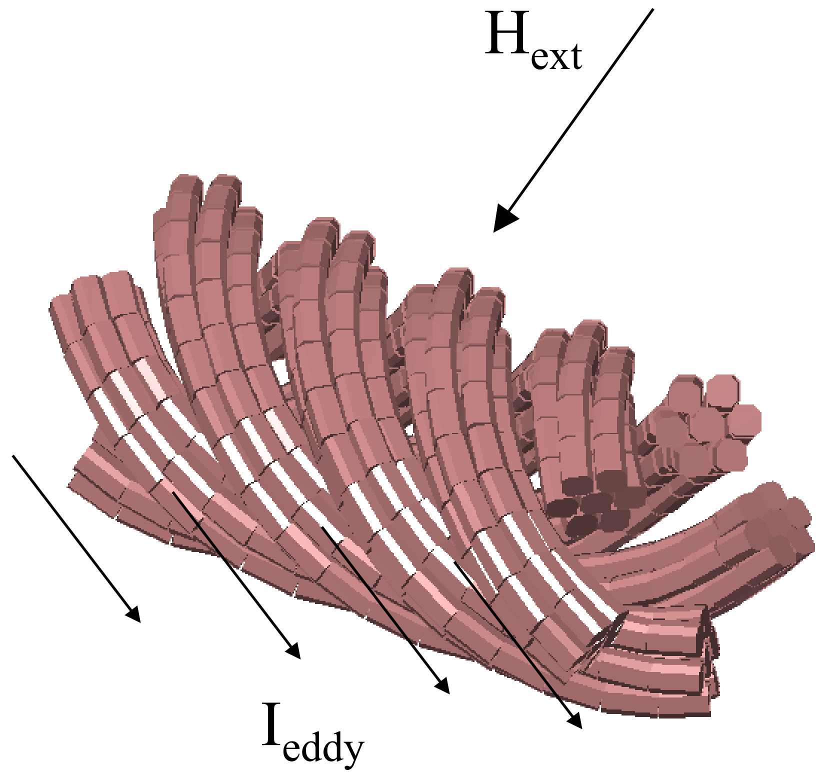
Impedance Law

$$(R + j\omega L)I_b = ZI_b = V_b$$

The characterization process

$$P_{skin}(f) = \underline{F(f)} I^2 R_{dc}, \qquad P_{prox}(f) = \underline{G(f)} |H|^2$$





- Sweep over a range of frequencies
- **Solution time: < 10 seconds per frequency**

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Case Study: Helical Twisted Strands

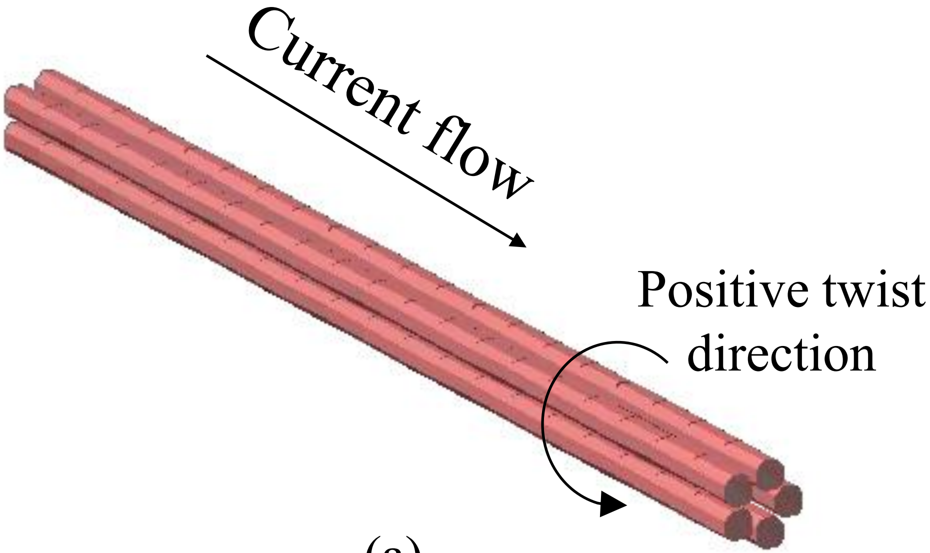
Degrees of freedom:

- Strand diameters
- Num. inner twists
- Num. outer twists

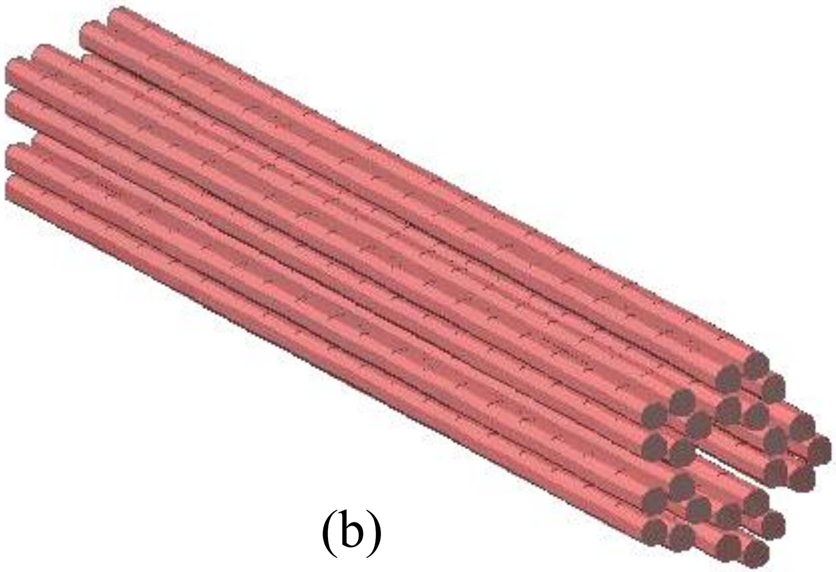
(Defined relative to global axes.)

- Num. inner strands, outer strands.

We will focus on the 5-strand and 5x5- strand structures.



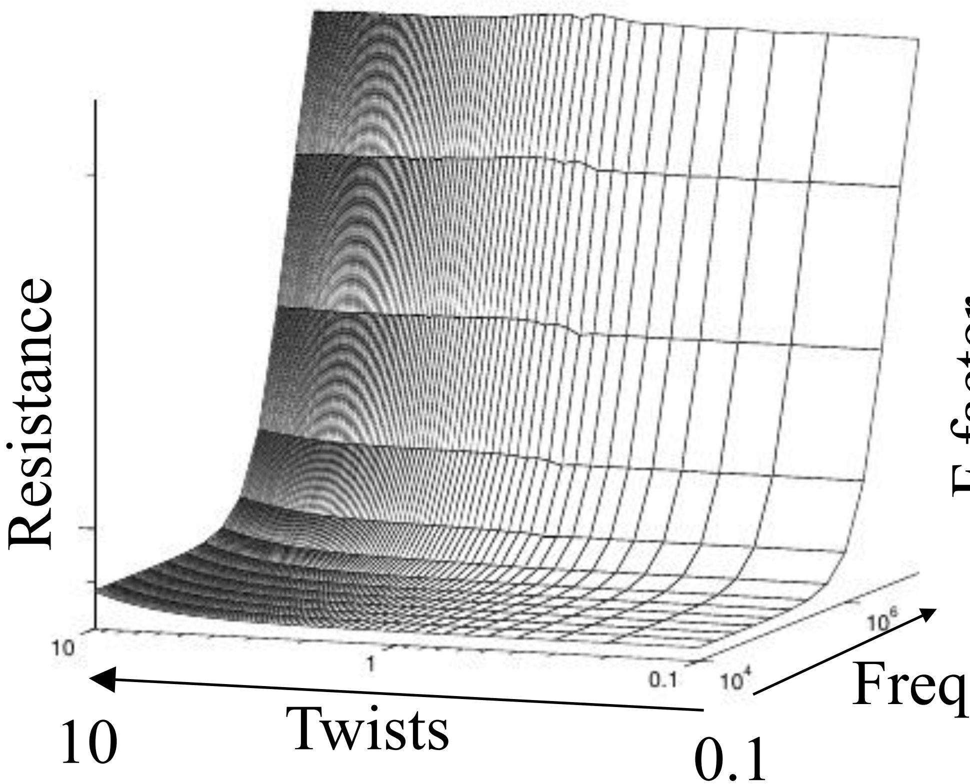
(a)



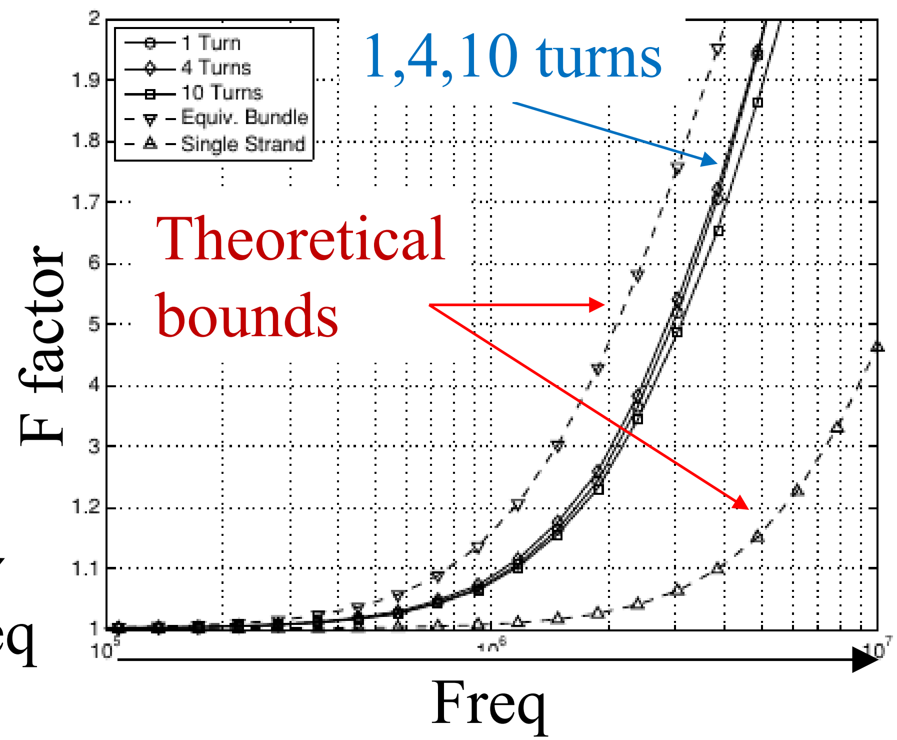
(b)

5-strand wire, AWG 38, 2cm, 10 kHz – 10 MHz

$$R_{ac} = F(f)\, R_{dc}$$

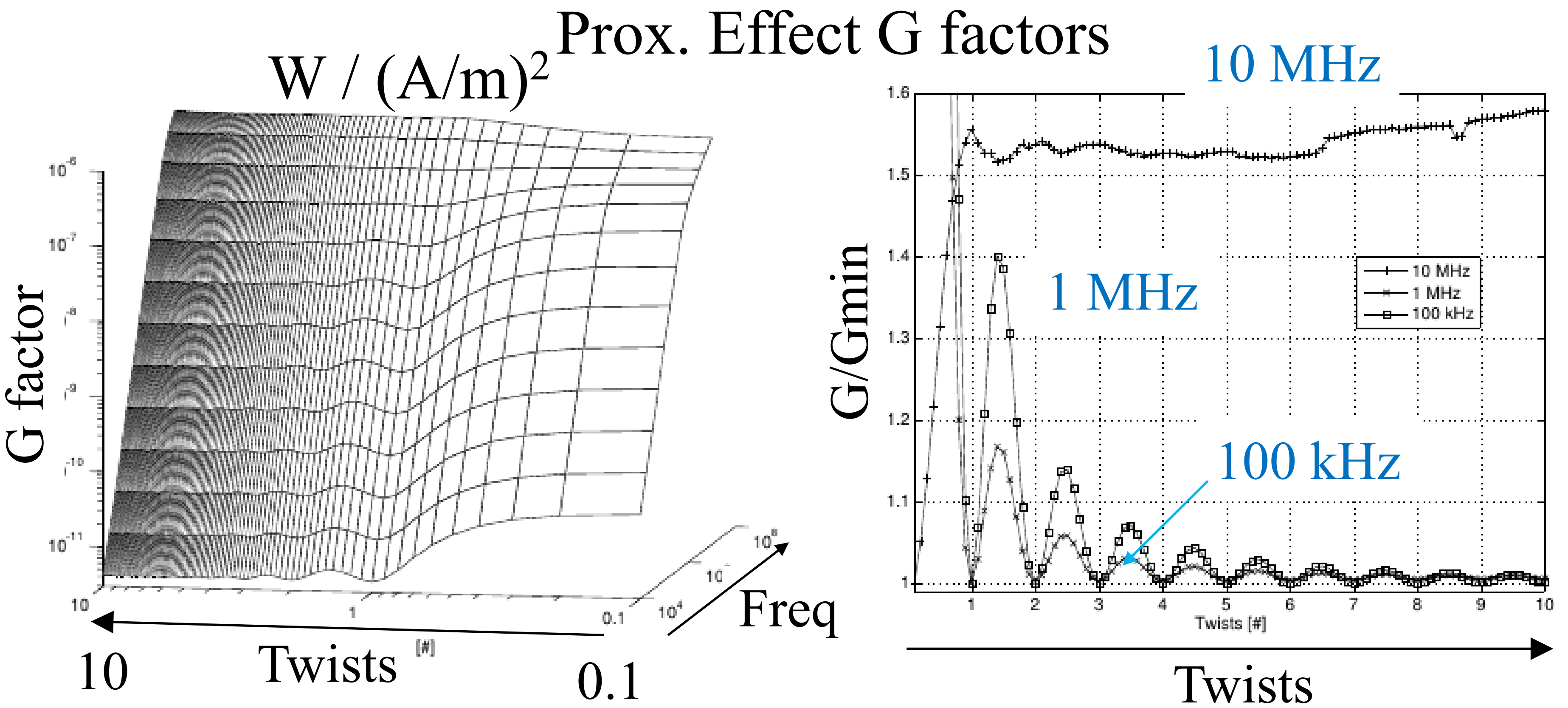


Skin effect F factors



Finding 1. Twisting the one-level, 5-stranded wire does not mitigate skin-effect losses.

5-strand wire, AWG 38, 2cm, 10 kHz – 10 MHz



Finding 2. Integer twists of the one-level wire create eddy current cancellations, thereby minimizing the proximity effect, i.e., making the wire less susceptible to external fields.

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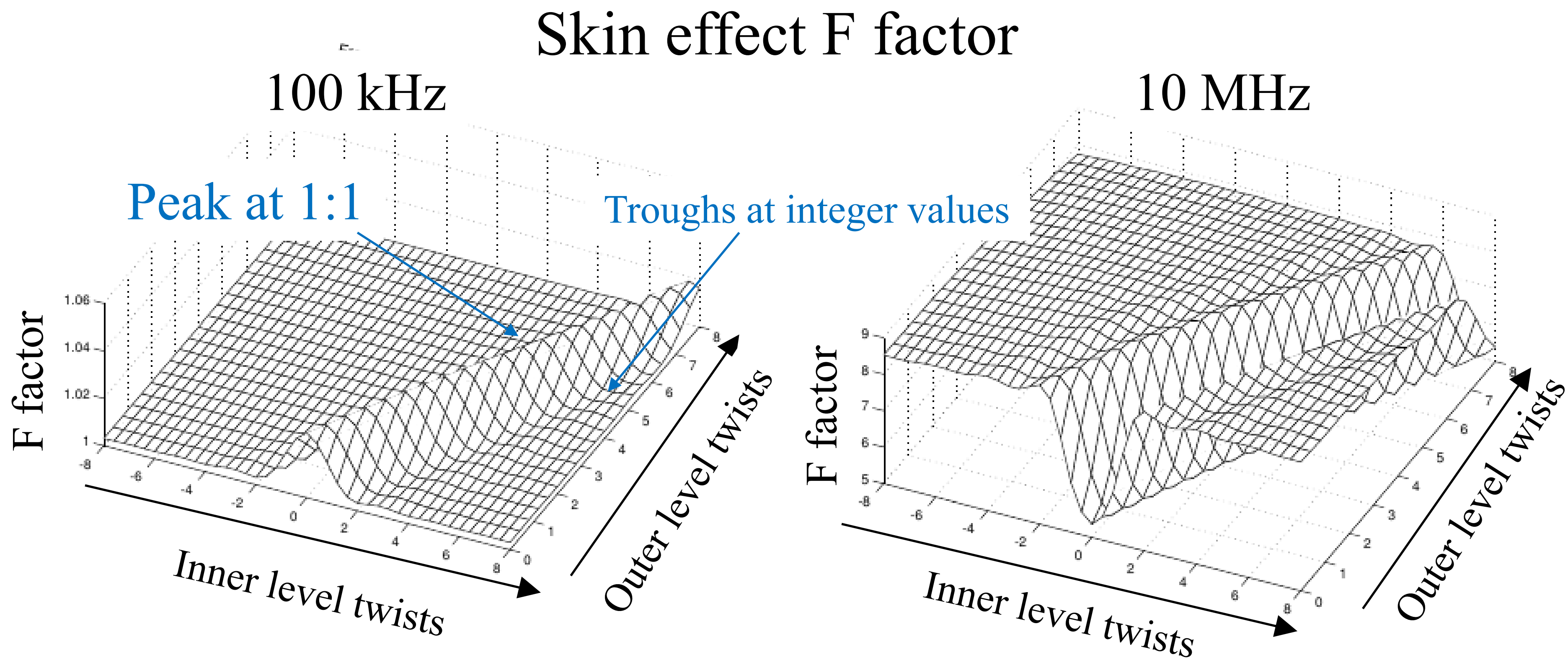
5x5-strand wire, AWG 38, 2 cm long samples



Finding 3. A characteristic peak / trough can be seen in the F factors of a two-level litz wire along the 1:1 inner / outer twists line.

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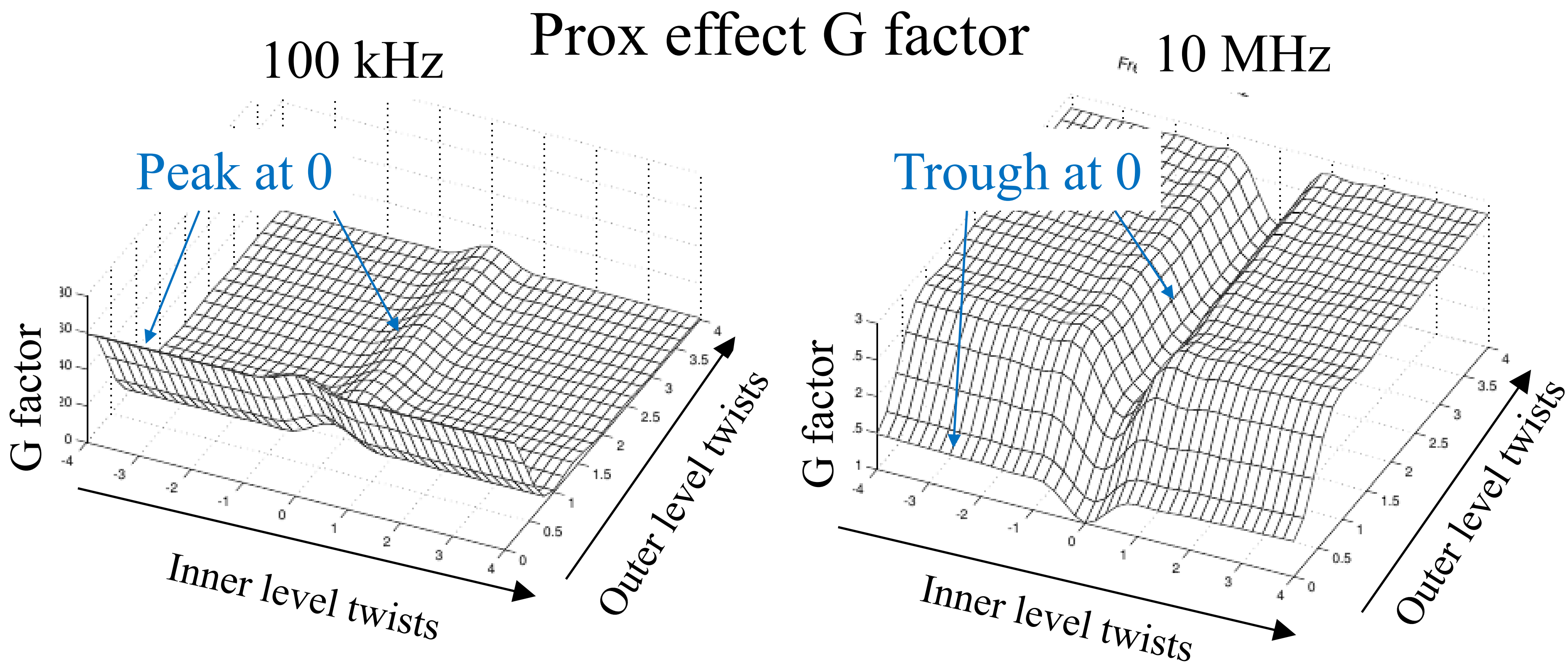
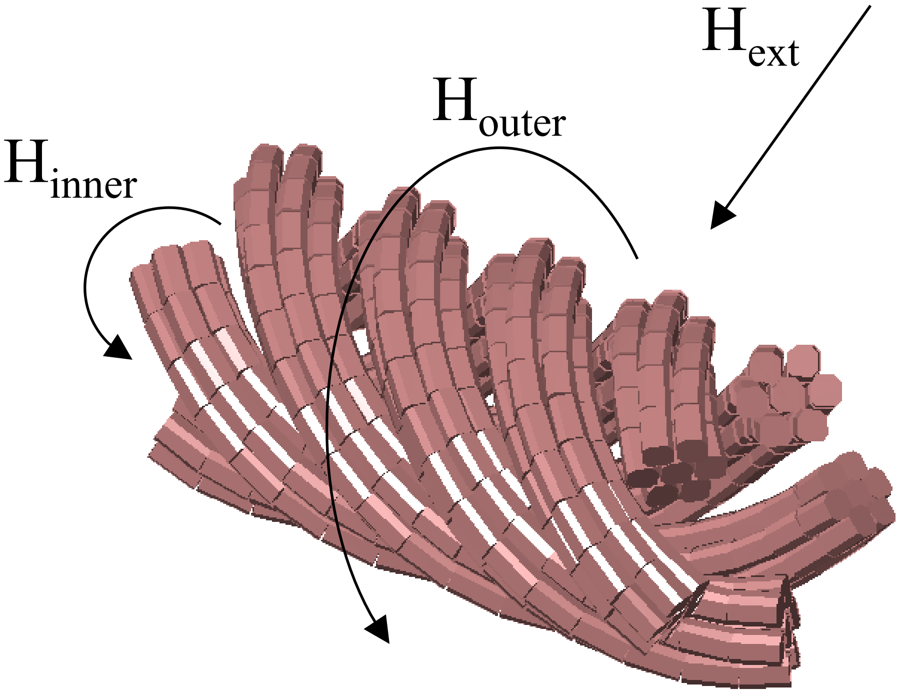
5x5-strand wire, AWG 38, 2 cm long samples



Finding 4. A characteristic peak / trough can be seen in the F factors of a two-level litz wire along the 0 inner / outer twists line.

Short Sketch of the physics:

- When ratio is 1:1, *inner turns have no twists relative to outer turns*. "Skin effect" F factor is affected.
- When inner or outer turns have zero twists, that level is untwisted relative to H_{ext}. Prox effect G factor is affected.



All of these physics were uncovered by numerical simulations.

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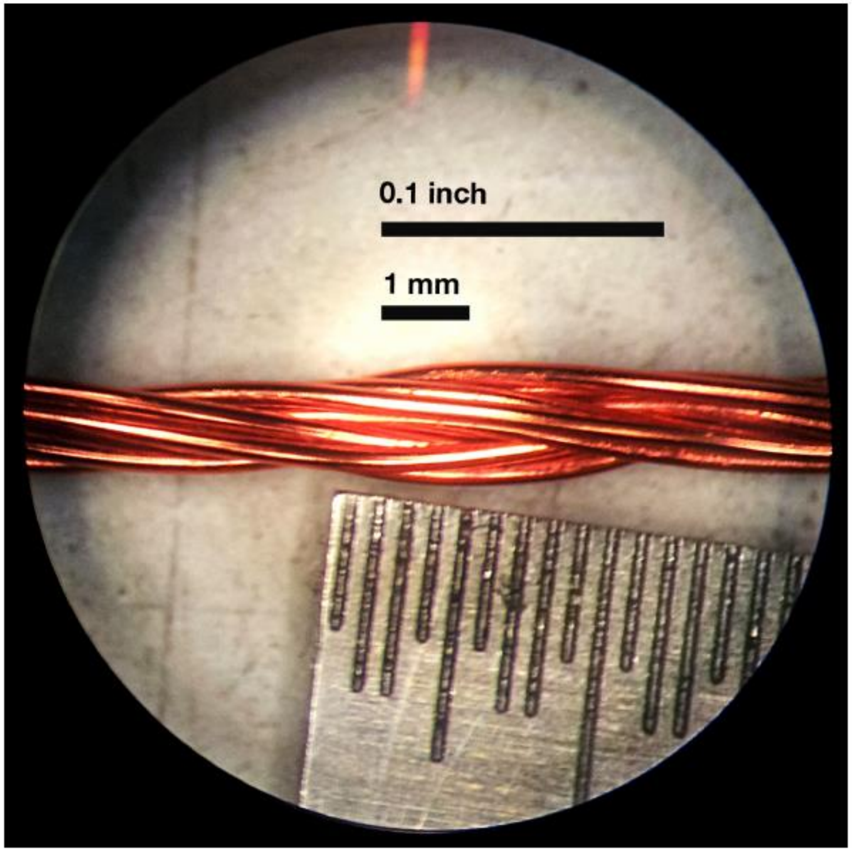
Experimental Confirmation

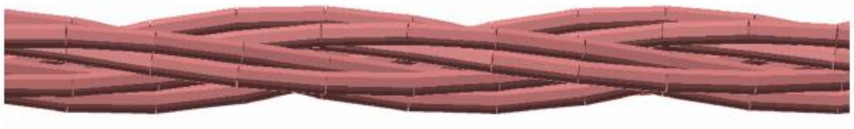
Two wire specimens made from AWG 32 strands

- 3 strands, +1 cm pitch, 66 cm long.
- 3x3 strands, +1 cm inner pitch, -1 cm outer pitch, 20 cm long.

Non-ideal but highly symmetric construction.



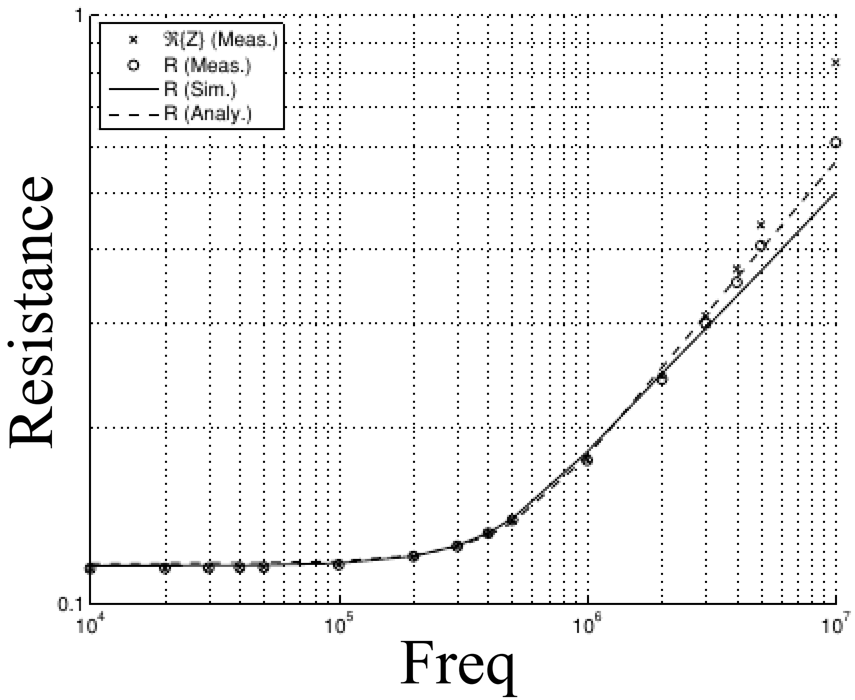
(a)



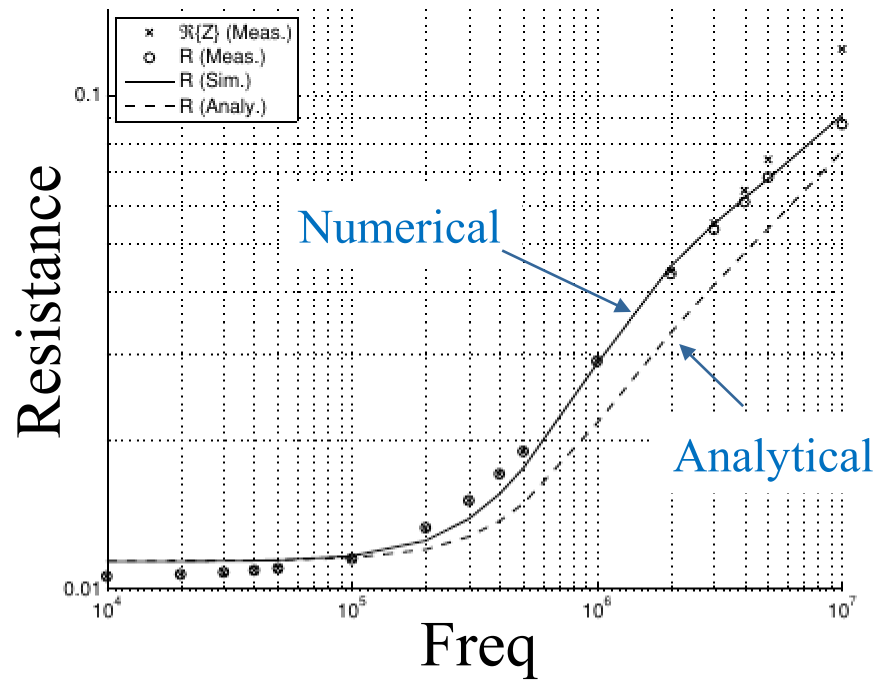
(b)

Experiments matches prediction as expected

3-strand wire



3x3-strand wire



But beware of two crucial caveats

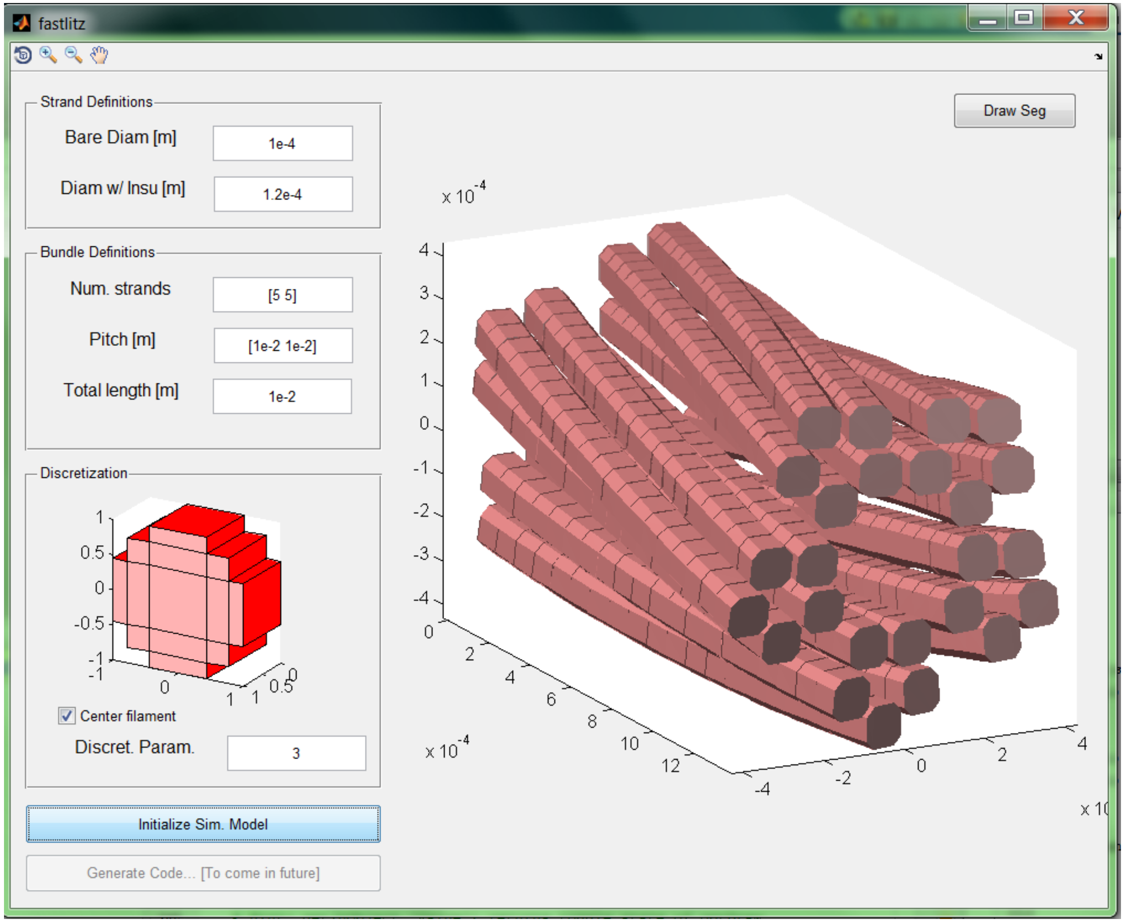
- The *model must match the specimen.*
- The mesh must be finer than the perturbation.

Fast simulations – a valuable tool for designers

- Characterize all wire constructions.
- Extensively explore design space over many dimensions.
- Obtain insights into wire construction sensitivities & physics.
- Make predictions that account for geometry and variations.

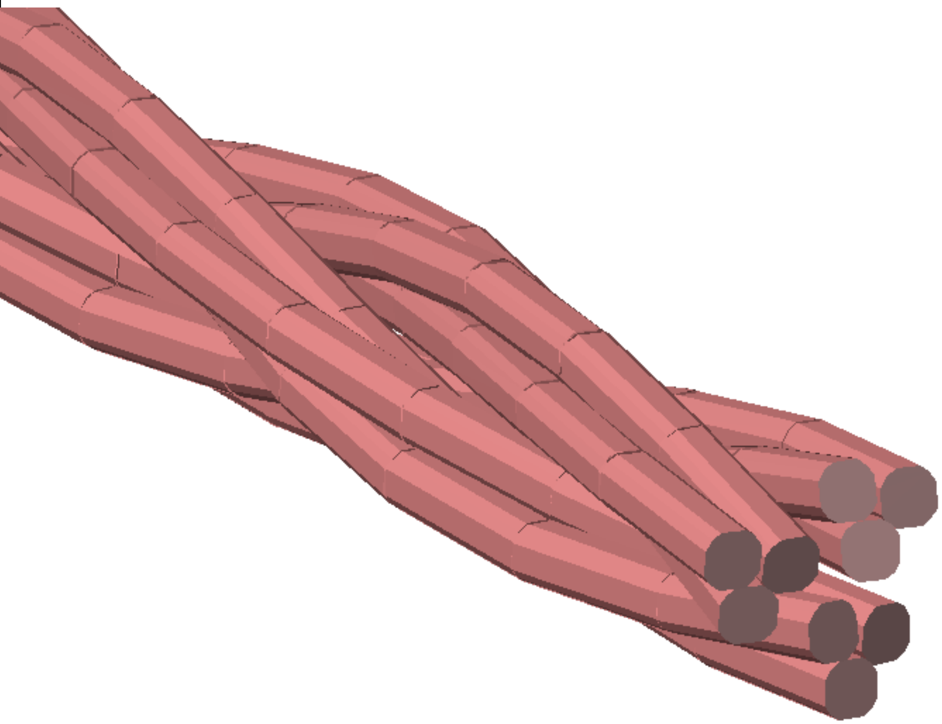
This Work is Open-Source Software!

- MATLAB-based.
- Critical components written in C/C++ for speed. Pre-compiled for Windows & Mac
- GUI works straight out of the box. Simple command-line simulations.



Web address: http://web.mit.edu/ryz/www
Comments, suggestions, bug reports welcome!

Thank you for your attention



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