Anisotropic Heat Transfer in Orthocyclically Wound Coils

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Abstract: It is important to understand heat transport through an orthocyclically wound coil for demanding motor applications in a high-tech setting, but it is difficult to model purely based on the geometry. Comsol's ability to model anisotropic materials provides a computationally efficient way to model these systems. This paper discusses how to apply this in a nontrivial geometry, and how to use the ability, new in COMSOL Multiphysics 4.3b, to use anisotropy in curvilinear coordinates.

Keywords: Anisotropy, heat transport, curvilinear coordinates, orthocyclically wound coils

1. Introduction

Tecnotion produces linear motors for the high tech automation and semiconductor markets.

In orthocyclically wound coils [1] each wire (with a circular cross section) is positioned in its allocated place. In cross section, see also figure 2, this results in a hexagonal array of circles. These coils give the best performance because the largest number of windings can be packed into a given volume, as opposed to "wild winding", where the windings fall where they may. Additionally, the anisotropic heat conduction perpendicular to the wire direction is optimized because each winding is positioned exactly next to all six of its neighbors, maximizing the contact surface.

A thorough understanding of the thermal performance is necessary to understand and predict the motor performance for those applications that require nanometer positioning accuracy, for example in the semiconductor industry.

2. Heat transfer with COMSOL Multiphysics

Heat transfer through such a structure can be modeled in two ways: with the emphasis either on geometry or on the material properties.

2.1 Geometrical approach

Figure 1 shows an example of what a typical orthocyclically wound coil in a linear motor looks like.

As a first, important, geometrical simplification, the single wire of such a coil is approximated by a number of closely packed ovoids. In terms of the electrical circuit this is of course very different, but in terms of the thermal conduction it is a very good approximation. Heat from a single point along a single wire can be conducted to a neighbor wire by following an entire winding around the coil through the conductor, or straight across the insulator. Because the typical insulator thickness is only 10 µm and the typical coil is 10 cm long, conduction through the insulator along the windings is a small factor that can be ignored.

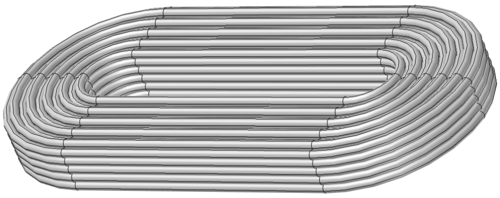

Figure 1. Typical orthocyclic coil for an ironless linear motor.

Figure 1 shows a coil with 5×10 windings, which is on the low end for typical applications. The mesh for such a model needs an unacceptably high number of tetrahedrons, especially because of the thin (10 µm) insulator domains.

On a quad core PC with 16 GB of memory, this made the model unusable with more than 10 windings.

2.2 Anisotropic approach

In a sense, an orthocyclically wound coil can be thought of as a type of metamaterial. For heat that diffuses along the windings, the conductivity is equal to that of copper (the most used conductor). Laterally, heat moves easily through the copper wires, but experiences a considerable resistance at the insulator.

In 2D, a thermal model of this was created in COMSOL Multiphysics. Each wire, as in reality, is surrounded by a thin layer of insulator. The outer diameter of the insulator determines the distance between neighboring wires. Outside of this diameter, a glue layer surrounds the insulator. However, when winding and pressing the coil, this glue layer is removed from between two neighboring wires, and is spread out to the sides, see figure 2.

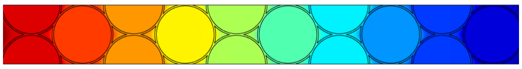

Figure 2. Cross section of an orthocyclically wound coil. Heat flows from left to right.

Pumping heat into the left of such a matrix of wires, and setting the right to a constant temperature gives figure 2, where red is hot and blue is cool. Taking the appropriate coil thickness and surface area into account allows us to find a value for the transverse thermal conductivity, if we treat this stack of wires as a single block of metamaterial.

A common standard for electric wire is DIN EN IEC 60317-0-1. A coil manufacturer will choose a grade and a wire thickness from this standard. The associated tolerances are tight, only a few micrometers on the insulator thickness, but this already has a profound impact on what we expect to find for the resulting transverse thermal conductivity of coils that are wound from this wire.

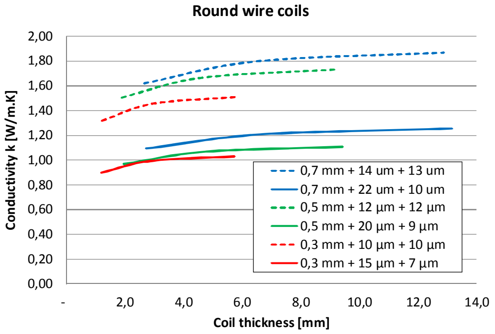

Figure 3. Effective transverse thermal conductivity of coils wound from various wires. The two insulator and glue layer thicknesses are chosen to find the maximum and minimum values of conductivity within the geometric tolerances of the wire.

From figure 3 we can see that wire diameter is not the biggest influence on the transverse thermal conductivity. Instead, it is insulator thickness (within manufacturer tolerance!)

For thin coils of only a few windings thick, we can see edge effects. The conductivity is reduced because the first and last windings are not connected as firmly to the outside world as they are to each other.

Heat conduction along the wires happens with the conductivity of the metal times the coil fill factor. We have just calculated the transverse conductivity. When the wire direction coincides with one of the system axes, this results in a diagonal conductivity matrix:

$$k = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 300 \end{pmatrix} \frac{W}{m \cdot K}$$

If we want to rotate the preferential conduction direction, e.g. around the x-axis, we use a rotation matrix:

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -sin(\theta) \\ 0 & sin(\theta) & \cos(\theta) \end{pmatrix}$$

In order to perform the rotation we use the following formula:

$$k_\theta = R^T kR$$

To give an example, for rotation along the x-axis over 15 degrees, this gives the following (symmetrical) matrix:

$$k_{15} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 21 & 75 \\ 0 & 75 & 280 \end{pmatrix} \frac{W}{m \cdot K}$$

To check this functionality in COMSOL Multiphysics, a simplified geometry was used of a cylinder with the above conductivity matrix k_{15}, in contact with a smaller cylinder at a constant temperature. Heat is dissipated uniformly through the larger cylinder.

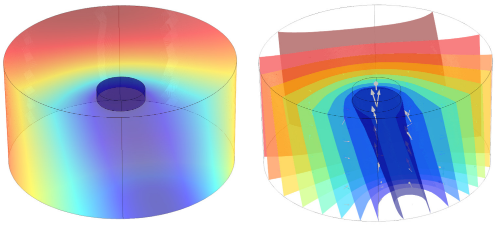

Figure 4. Anisotropic heat transfer is an example geometry.

A representative linear motor coil can now be modeled in the following geometry, see figure 5.

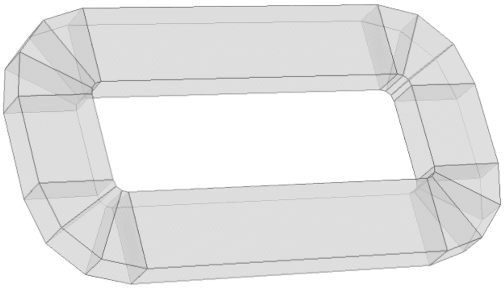

Figure 5. Basic geometry of a representative ironless linear motor coil, to be used in a model with anisotropic heat transfer.

When the geometry in figure 5 is provided with appropriate thermal conductivity matrices (a separate one for each segment), uniform heating throughout the coil is applied and the single rectangular face to the extreme left is set to a constant temperature, figure 6 is obtained.

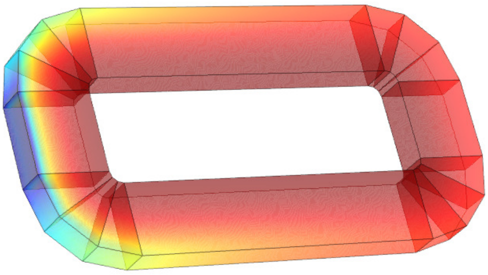

Figure 6. Anisotropic heat transfer through an orthocyclically wound coil. Heating is uniform, the face on the extreme left is at constant temperature.

Tecnotion manufactures high quality ironless motors based on the coil above. In sets of three (three phase synchronous motor) they are cast in resin (not shown) and provided with a motor housing that is intended to provide space for electrical connections, as well as cooling and mechanical coupling, see figure 7.

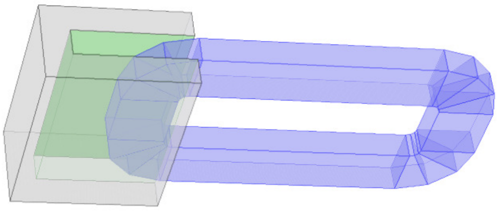

Figure 7. Basic element of the Tecnotion ironless linear motor. Being a three phase synchronous motor, the minimum of such coils is three in any motor type.

Figure 8 shows the resulting heat transfer through the motor. Cooling (through conduction) takes place at only one side of the motor, but heat flow from the far side is facilitated by the aluminum motor housing.

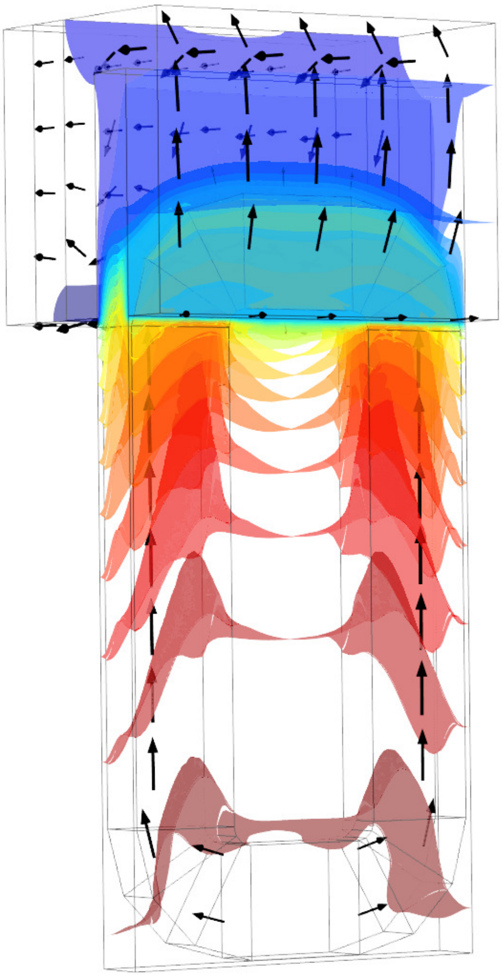

Figure 8. Temperature isosurfaces and arrows indicating heat flow in the basic Tecnotion ironless linear motor element.

The various, present in the design of the motor, can be shown more clearly in cross section, see figure 9.

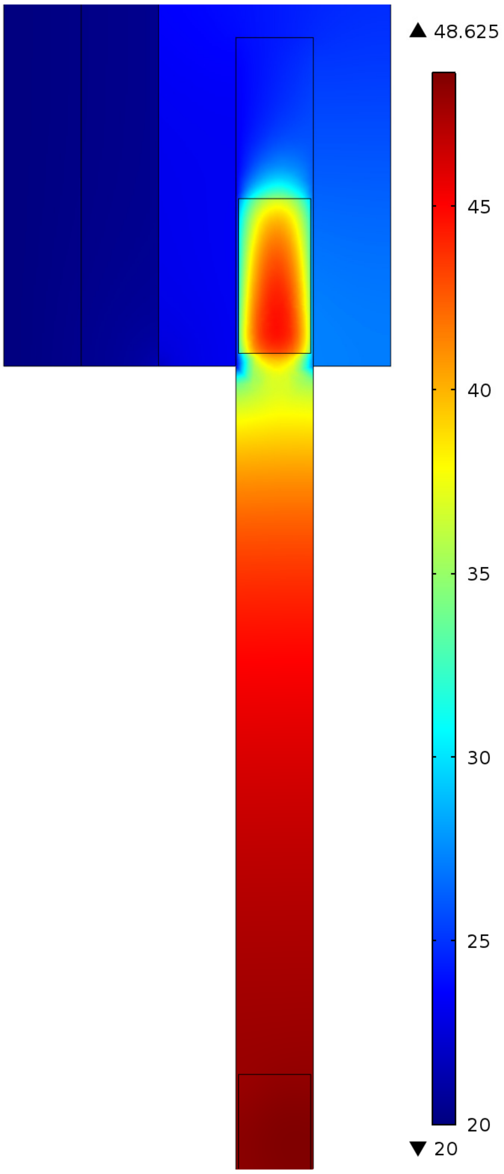

Figure 9. Cross section of the temperature distribution in the basic Tecnotion ironless linear motor element.

2.2 Curvilinear coordinates

Starting in COMSOL Multiphysics version 4.3b, it is possible to model anisotropic heat transport using curvilinear coordinates. This makes it possible to use curved coil segments, as in figure 10.

As a result, not only is the model easier to formulate, but the geometry is more accurate as well.

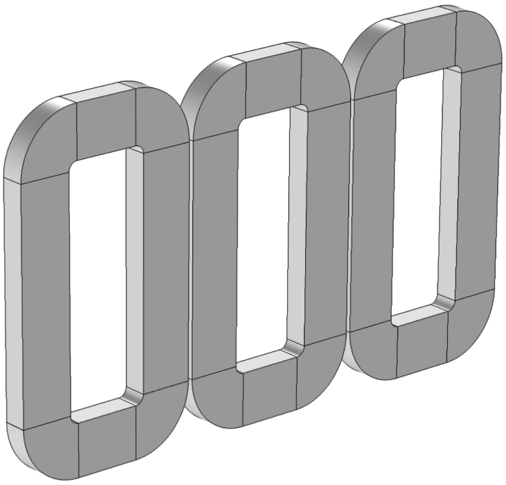

Figure 10. Geometry used in a simulation of three coils using curvilinear coordinates.

However, because the pie segment approximation used above is a good one, the simulation results are essentially identical.

3. Supporting measurements

Measurements of thermal conductivity were done for both individual coils and for entire motors.

3.1 Coils

The effective transverse thermal conductivity of the coil was measured with a setup shown schematically in figure 11. A known electric power is dissipated in the top block, while the bottom block is kept at a constant temperature with water cooling. Both temperatures are monitored.

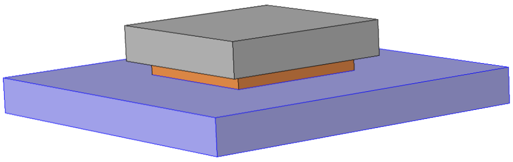

Figure 11. Setup for measuring thermal conduction.

Because the setup was not adapted to the size of the samples (the coils) there were large errors due to heat losses to the environment and directly across the gap from hot to cold, through the air. Figure 12 shows some of the resulting values.

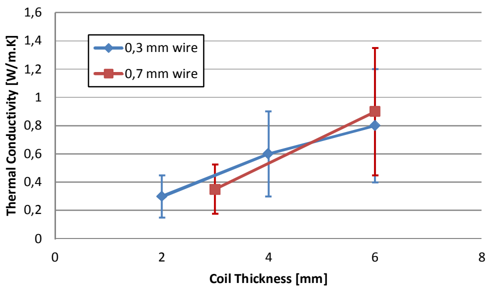

Figure 12. Selective measurement results for two different coils, showing the poor quality due to large errors.

The error bars in figure 12 are unacceptably large. For only one coil type we have been able to do a measurement with reasonable uncertainty so far (25%), by putting a large number of coils in parallel between the plates, thereby minimizing alternative heat paths and maximizing the heat flow under examination.

After error correction, this yields 1 W/m·K. This is on the low end of what is consistent with the computational model, see figure 3.

We are currently in the process of manufacturing an improved setup.

3.2 Motors

The computational results fit the measured data relatively well when considering entire motors. We can predict the thermal resistance of a motor to within 25%, which is satisfactory when considering hard-to-predict influences like thermal contact resistance.

7. Conclusions

By modeling the coil of a linear motor as a block of anisotropic metamaterial rather than a collection of insulated conductive wires, a huge reduction in computational complexity is achieved.

We can verify a 2D heat transfer model of stacked wires using a measurement of heat transfer through a coil. We are still working on a better measurement that will be able to show the accuracy of the calculation.

We can verify a 3D heat transfer model using the above anisotropy against measurements of our motors. Agreement is within 25%.

8. References

1. W. van der Hoek (Philips), Polygonal Electric Coil, *US Patent No. US2930014,* (1960)

9. Acknowledgements

The profile wire coil winding technique was partly developed using funds from the Dutch WBSO/RDA programs.