

Shapeopt v 1.0

August, 2002

Jiankun Hu, Charles Sullivan, Robert Jensen, Dan Gestwick, and Reid Hutchins

Introduction

This is a Matlab program that finds the optimal shape for the wire winding in a gapped inductor.

Typical inductor designs fill as much of the bobbin as possible to decrease dc resistance. However, it is undesirable to place wire close to the core gap, because the high fringing B field in this region can lead to excessive eddy current losses [1]. Shapeopt finds the optimal placement of the wire such that total power loss is minimized, balancing the tradeoff between eddy-current losses and resistive losses.

Using this method, it is possible to achieve lower power losses than in a distributed or quasi-distributed gap design [1]. First, the field due to the gap and the windings is calculated using the image method (2-D analysis). Finite-element analysis has shown that this two-dimensional analysis is very accurate [1]. Finding the shape for minimum loss requires an optimization because changing the wire placement will change the field in the whole window. For more information about the specialized algorithm used, see [1].

Before Running Shapeopt

The inductor designer will have to determine several parameters before Shapeopt is run.

1. An inductor core must be chosen
2. The number of turns must be chosen based on loss and saturation constraints.
3. The gap length must be calculated to give the desired inductance.
4. The user must pick a diameter of litz wire – more details on how to optimize the choice of litz wire strand are given in [2].
5. Dimensions of the core are shown in Figures 1, 2, and 3 below – use these diagrams to decide what values to enter for the window width and window height.
6. The packing factor must be estimated – use the definition given below.

It common for the inductor designer to specify the number of strands of litz wire to be used. However, this is not necessary when using Shapeopt. The relationship given below shows this.

$$N n = F_p A_{\text{used}} / d^2,$$

N is the number of turns, n is the number of strands, F_p is the packing factor (defined below), d is the diameter of a strand, and A_{used} is the cross section of winding area that will be used. All parameters except n and A_{used} will be specified by the user. A_{used} will be found by Shapeopt during the optimization process, because it may be beneficial to not fill the entire winding window with wire. This means the number of strands, n , can

be calculated using the above equation. Thus, the number of strands is optimized by shapeopt, and need not be calculated beforehand.

Requirements

You will need Matlab version 5.3 (R11) or later.

To Run Shapeopt

To run shapeopt, download the .m file from the website <http://thayer.dartmouth.edu/inductor>. Set the Matlab path so that it can see the shapeopt.m file. Type shapeopt at the command window and press return. At this point, you will be asked if you would like to account for the inductor centerpost radius or ignore it. Ignoring this effect is equivalent to saying that the radius is large compared to the window height (hw). It is almost always more accurate to account for the effect of the centerpost radius, and this option is recommended for most users.

Several conference papers have been written about the older version (COOS) that ignored the radius effect. These papers can be accessed at <http://thayer.dartmouth.edu/inductor/papers.html>

Once you have chosen whether to ignore or account for the radius effect, you will be asked to enter a filename and chose a place to save the information. This is not an option, and the program will terminate if a filename is not entered. This happens because the program needs a place to store the parameters (given by the user) and the other variables it generates. The program will save them in a .mat file. If you would like to open the .mat file after shapeopt has been run to view the data, you may type load(filename) at the command window to load those variables into memory. However, shapeopt will display the most important results in the Matlab command window.

Input

Once the filename has been entered, a GUI (Graphical User Interface) figure will open, and you will see several empty boxes where the parameters need to be entered. At any point before the run button is pressed, you can gain more information about a parameter by clicking on the box with the parameter's name. A help box will pop up to give more details, including units. Here are the descriptions of the parameters; for a graphical explanation, see p. 4.

Bobbin Breadth: b_b . Breadth of the bobbin in millimeters—the dimension parallel to the leg with the gap in it.

Bobbin Height: h_b . The available winding height—calculated as the distance from the inner radius of the bobbin to the inner edge of the core.

Window Breadth: b_w . Breadth of the winding window in millimeters—the dimension parallel to the leg with the gap in it. For example, with the gapped centerpost, this is the length of the centerpost (not including the parts beyond the window)

Window Height: h_w Height of the winding window in millimeters—the dimension perpendicular to the leg with the gap in it. For example, with the gapped centerpost, this is the distance from the centerpost to the inside of the outer core leg.

Gap Length: This is the length of the air gap, normally in the centerpost. All distances are in millimeters.

Frequency: The frequency of sinusoidal current in the winding in hertz. For non-sinusoidal waveforms "equivalent frequency" can be used.

$$f_{eq} = \frac{1}{2\pi} \frac{\text{rms} \left\{ \frac{dI}{dt} \right\}}{I_{rms}}$$

where I_{rms} is total rms current including ac and dc components. For a sinusoid with dc offset,

$$f_{eq} = f_{\text{sin e}} \sqrt{\frac{I_{ac}^2}{I_{ac}^2 + I_{dc}^2}}$$

where I_{ac} is the rms value of the ac component. For more detail, see Appendix C in C.R. Sullivan. "Optimal Choice for Number of Strands in a Litz-Wire Transformer Winding." IEEE Transactions on Power Electronics, 14(2), March 1999, pp. 283-291, available at <http://thayer.dartmouth.edu/inductor/papers.html>.

Strand Diameter: Diameter of one individual strand. The winding is assumed to be wound with litz wire comprising a number of these strands; the program will calculate the optimal number of strands to be used. AWG 44, 50 μm diameter, is often a good compromise between cost and loss.

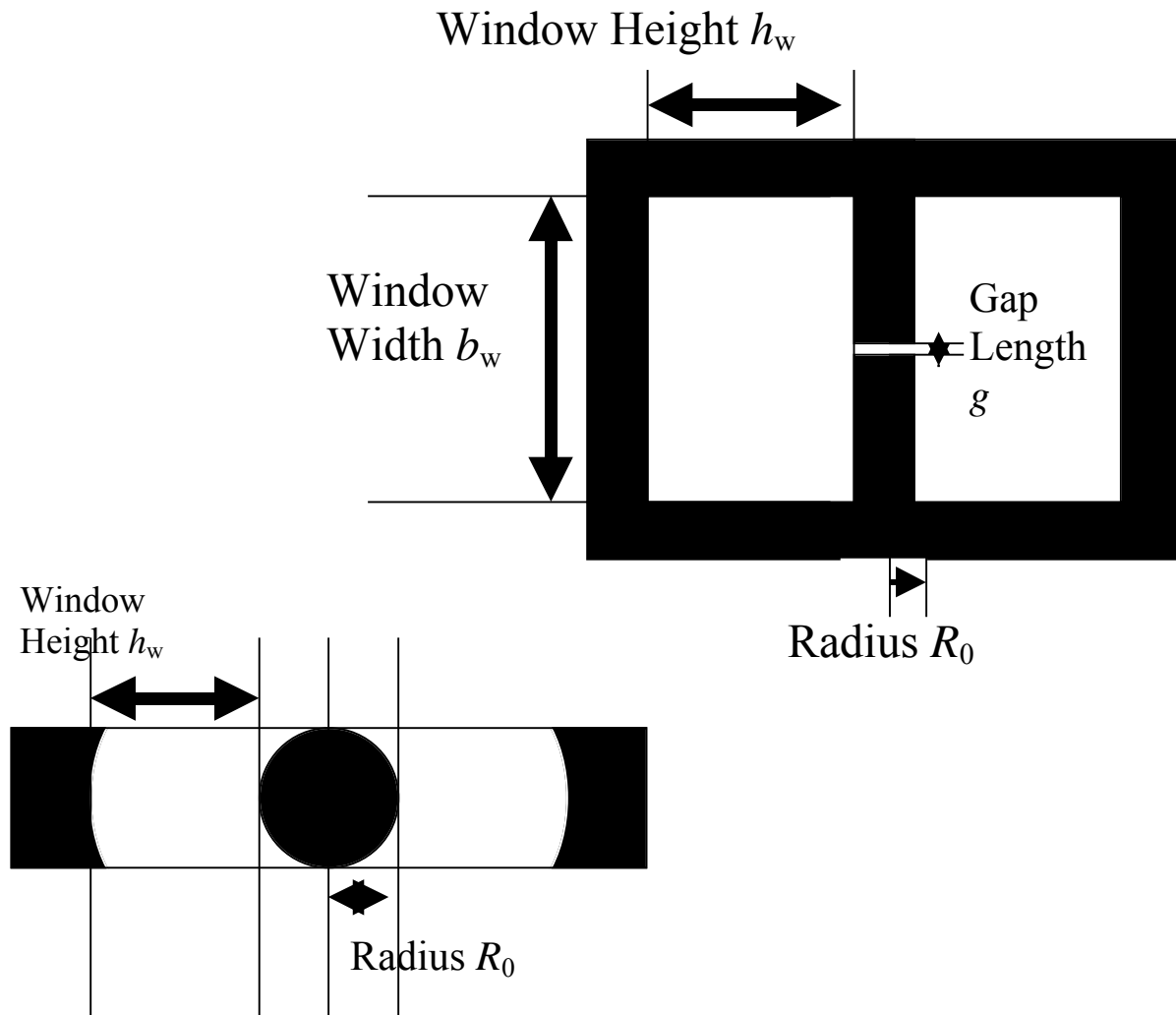
Number of turns in the winding: This must be calculated based on core loss and saturations characteristics before running this winding optimization program. After running Shapeopt, it may be desirable to reconsider the number of turns based on optimizing the winding-loss/core-loss tradeoff.

Packing Factor: The fraction of cross-sectional area that is copper in a space filled with wire is $F_p \pi/4$. In other words, F_p is the packing factor relative to perfect square packing of cylinders. It accounts for both insulation space and for imperfect packing. A typical number for litz wire is $F_p = 0.35$, resulting in $F_p \pi/4 = 28\%$ of winding area occupied by copper.

Total current: This is the current through the winding terminals; i.e., through each turn, I_{rms} in amps.

Turn Length: This is the average length of a turn in millimeters. For better accuracy, chose the axisymmetric model and specify the centerpost radius (ie run the program taking into account the centerpost radius).

Centerpost diameter: The diameter of the core centerpost. For a square centerpost, use diameter = perimeter/ π .



Gaps Selection

On the main Shapeopt window, the user must specify the type of gaps that they will put in the inductor core. In all cases, the outer legs are assumed to have a square geometry. Gapping all of the legs leads to the lowest power losses; however, this type of design can create more EMI problems for your circuit than a design with a gapped centerpost.

Buttons in GUI window

The close/save button closes the window. When Shapeopt closes, all parameters that the user has entered are saved automatically. Load/New will restart the program (and asks for a new filename or a file to load). The Run button can be pushed when all the parameters are entered to run the optimization.

The Options button allows the user several additional features. For example, you might like to try a design that uses the full bobbin, instead of optimizing the shape. This design will have high AC loss, however, this option is provided for comparison purposes. Another option is to specify the number of strands, and use a rectangular winding. This option is also included for comparison purposes.

Figure Pull-down Menu

If you click on the “options” menu bar, you will see that you have the option of changing the resolution of the grid and the number of images. The default setting is a 20x20 grid and 5x5 matrix of image units. Increasing the grid resolution is only recommended for calculations that require extremely high accuracy. The cost of doing this can be very long computation times. Increasing the number of image units is recommended if the aspect ratio (b_w/h_w) is larger than 5 or smaller than 1/5. If the aspect ratio is in between those values, increasing the number of image units will slightly increase accuracy, at expense of longer computation times

Shapeopt - Optimization of Inductor Shape

Parameters -
Click for
Description

Enter
Parameters

Bobbin breadth	<input type="text" value="21.2"/>	mm
Bobbin height	<input type="text" value="10"/>	mm
Window Breadth	<input type="text" value="21.2"/>	mm
Window Height	<input type="text" value="10"/>	mm
Gap Length	<input type="text" value="0.1"/>	mm
Frequency	<input type="text" value="120000"/>	Hz
Strand Diameter	<input type="text" value="0.127"/>	mm <input type="text" value="AWG"/>
Number of Turns	<input type="text" value="1"/>	
Packing Factor	<input type="text" value="0.35"/>	
Current (RMS)	<input type="text" value="1"/>	A
Centerpost Diameter	<input type="text" value="20"/>	mm

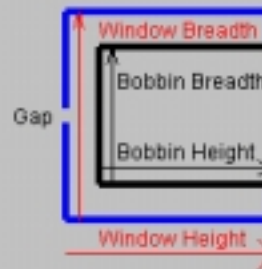
Options

Load/ New

Run

Close/Save

- Gapped Centerpost Only
- Outer Legs Gapped Only
- All Legs Gapped (round centerpost)
- All Legs Gapped (square centerpost)



Output

While the optimization is running, a progress bar will appear showing the progress as the program calculates the magnetic field. While shapeopt runs the optimization, the shape is displayed allowing the user to see the progress toward an optimal shape. In general, lower frequencies will take less time and fewer iterations.

When the optimization is finished, you will see three plots. They are:

1. A cross section of the inductor, with the optimal placement of the wire shaded in green. The centerpost is on the left, and the gap is in the left center.
2. Contour plots of the magnitude of the magnetic field B
3. Quiver plots of the magnetic field B

Shapeopt calculates the magnetic field for both the plane parallel to the core, and the plane perpendicular to the core.

If you do not wish for shapeopt to display these plots, un-check the check boxes in the GUI window. The default is to display all plots.

In the command window, the results of the following calculations are displayed:

Totalloss

Acloss

Dcloss

Total Area of winding

Area used

Fraction of Area used

Average magnitude of B squared

Ac Resistance

Dc Resistance

n = number of parallel strands per turn

Shapeopt will then round n to the nearest integer, and re-calculate the loss.

This information is also saved in the .mat file (but not the plots)

More information

Watch <http://thayer.dartmouth.edu/inductor> for more updates.

References

- [1] J. Hu and C.R. Sullivan. "Optimization of Shapes for Round Wire, High Frequency Gapped Inductor Windings." IEEE Industry Applications Annual Meeting, Oct. 1998, St. Louis, pp. 907-911.
- [2] C.R. Sullivan, J.D. McCurdy and R.A. Jensen, "[Analysis of Minimum Cost in Shape-Optimized Litz-Wire Inductor Windings](#)," IEEE Power Electronics Specialists Conference, June 2001, Vancouver.