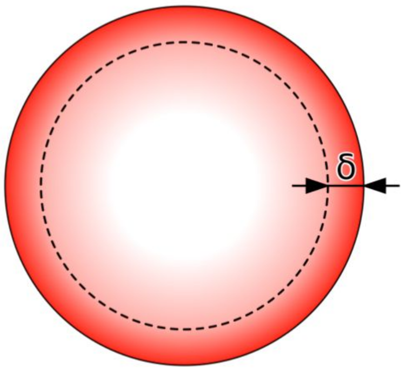
Investigation of the skin effect in alternating currents

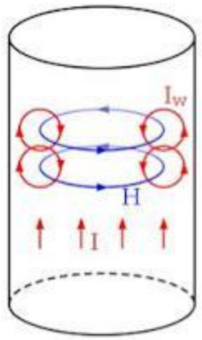
What is the skin effect?

The skin effect is when the current density is highest at the surface of the conductor, and will decrease as it is closer to the centre of the conductor. This causes the resistance to increase, as it reduces the effective cross sectional area of the conductor.



How does it happen?

- When the current flows through the conductor, it creates a circular magnetic field.
- This induces a current, which resists the original flow of current.
- The path of the induced current converges to the center, resisting the current flowing through the center the most.



What made me interested to study it?

- Singapore has limited space and resources.
- As such, alternative sources of energy like nuclear energy cannot be harnessed fully. Thus, our country emphasises a lot on energy conservation
- Thus, I would like to learn about how I can improve the existing solutions we have, which would be able to save more energy.

Hypotheses

- The surface of the conductor will have the highest current density, and the current density decreases as it gets closer to the centre of the conductor.
- As the frequency increases, the skin effect becomes more apparent in the solid conductor.

This project is thus broken down into 3 key components

- Mathematical
- Computational
- Experimental

Mathematical derivation

Equations first start off with the two Maxwell equations of electromagnetism:

$$\nabla \times \mathbf{H} = \mathbf{J}$$

and

$$\nabla \times \mathbf{E} = -\mu j \omega \mathbf{H}$$

Mathematical derivation

$\nabla \times \mathbf{H} = \mathbf{J}$

$\nabla \times \mathbf{E} = -\mu j \omega \mathbf{H}$

$J(r) = \alpha \times J_0(kr)$

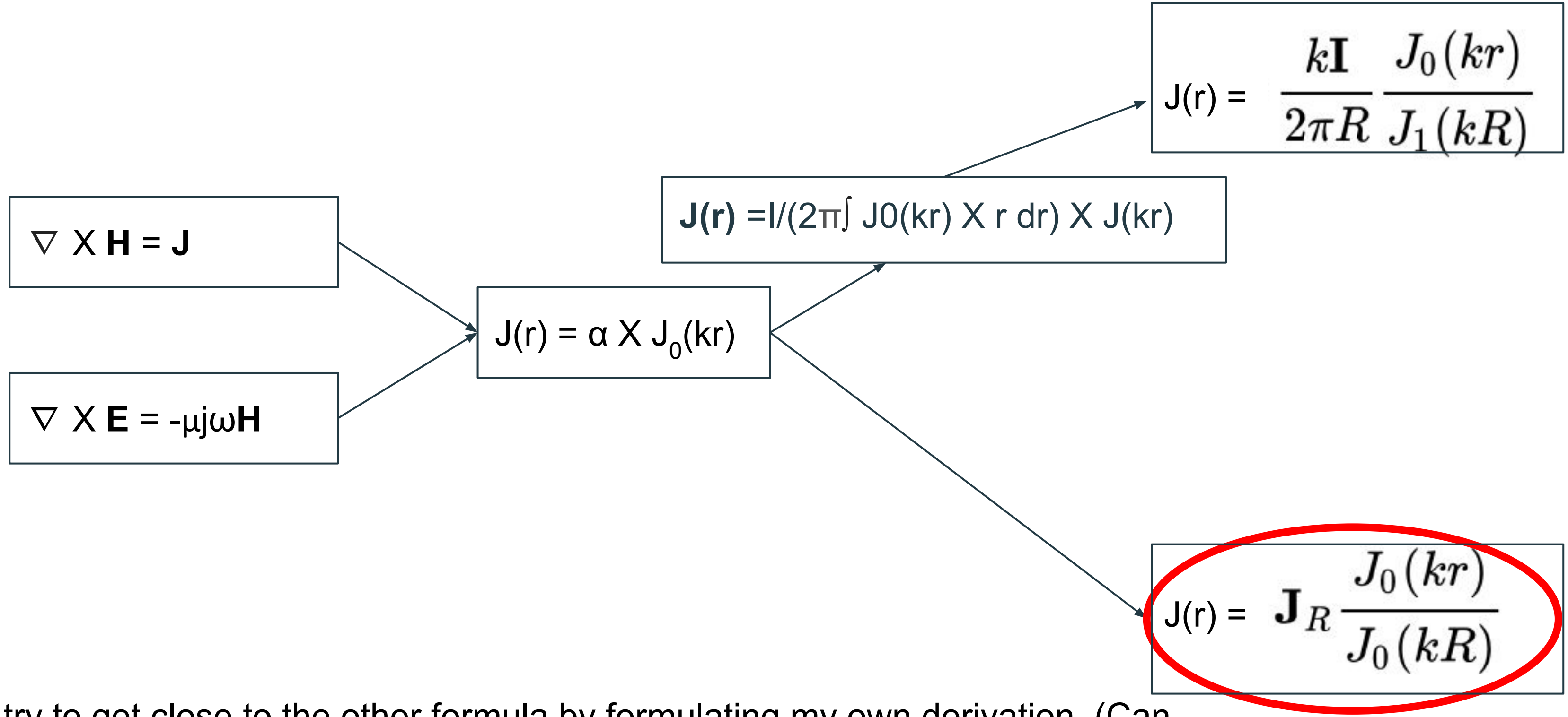
No research paper that shows mathematical link

$$J(r) = \frac{k\mathbf{I}}{2\pi R} \frac{J_0(kr)}{J_1(kR)}$$

$$J(r) = \mathbf{J}_R \frac{J_0(kr)}{J_0(kR)}$$

However, experimentally we cannot measure the current density at the surface, so the formula circled in red cannot be used.

Mathematical derivation



So, I try to get close to the other formula by formulating my own derivation. (Can be shown after this presentation.)

Computational solution

We simply put in the equation, **J(r)** =I/(2π X ∫ J0(kr) X r dr) X J(kr), that we have derived mathematically into a program, and also adding the required parameters, such as the frequency, material permeability, wire radius, and the total current.

Computational solution

My solution:

```
% with reference to Jz = a*J0(kr)

% I = integrate(Jz*2*pi*r)

% I = integrate(a*J0(kr)*2*pi*r)

% I = 2*pi*a * integrate(J0(kr)*r)

% Thus a = (I/integrate(J0(kr)*r))/(2*pi)



fun = @(ra) besselj(0,k.*ra).*ra

format long;


%substitute a back into equation Jz = a*J0(kr)

J1= abs(((A./integral(fun,0,Rad))/(2.*pi))*besselj(0,k*abs(ra)));
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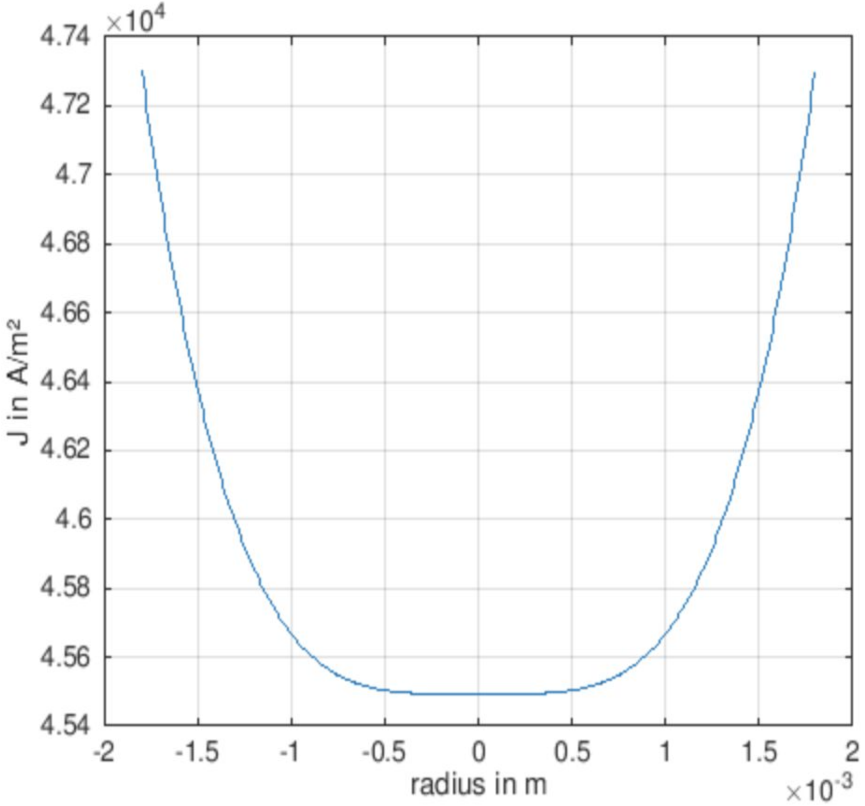


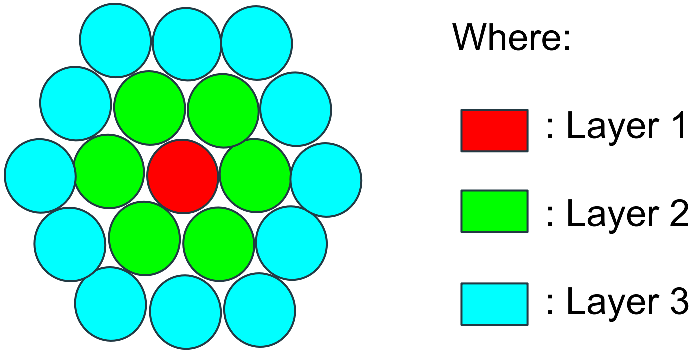
Computational solution

Comparing that with a solution made by Sven, and putting in the same parameters, we see that we can generate the same graph with the exact start and end points(if we were to zoom in very closely).

This also means that the mathematical derivation that I have created is correct.

Experimental setup

- Bunched up a few silver wires together such that it would be used to simulate one wire with a big cross sectional area. Then, they are attached together using a glue gun. Make a total of 3 layers.



Experimental setup

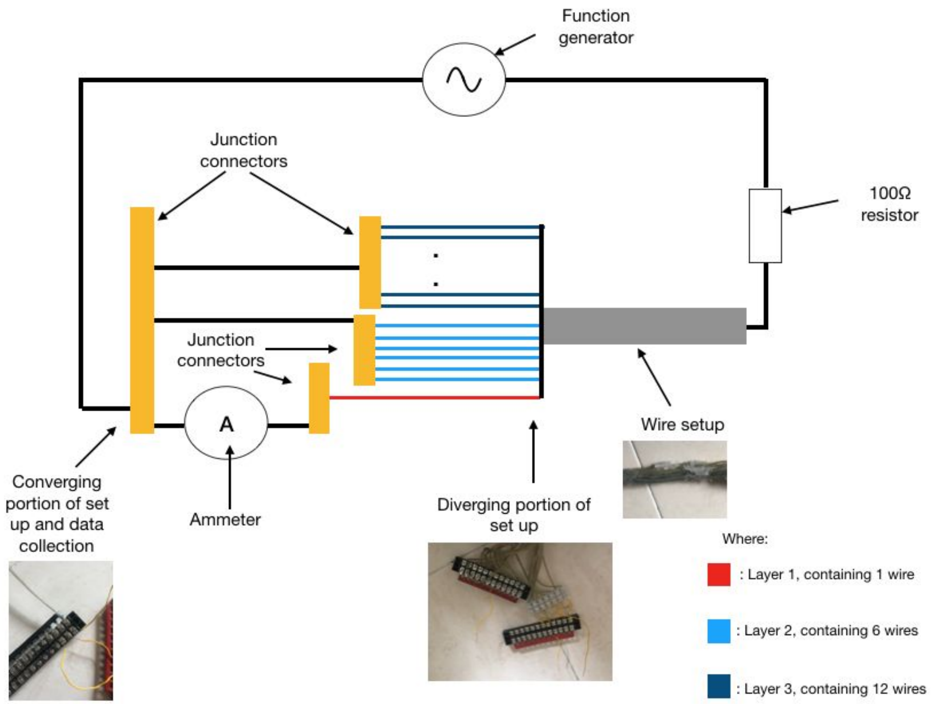
Experimental methods

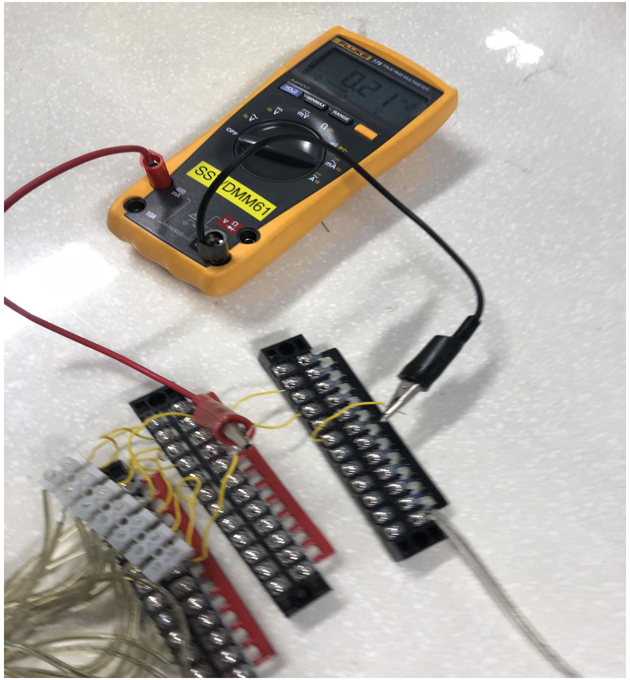
- One end of the big wire has a 100Ω resistor connected to it, which is attached to the positive end of the function generator.
- For the other end, the wires are separated based on which layer they are in. An ammeter would be connected to the layer that I wish to measure, before it connects to a junction connector.

Experimental methods

- For the other layers, it would be connected directly back to the junction connector. This junction connector is then connected back to the negative node of the function generator.

Experimental methods





Experimental variables and controls

Variables:

- Frequency used during the experiment

Controls:

- The amount of voltage used, 4.6VAC
- Effective resistance of the setup, which would be 100Ω assuming wires have negligible resistance

Controls(continued)

- Big wire material setup(Silver).
- Thickness of the individual wires that make up the big wire, which is AWG 21
- “Layers” the conductor has, which would be 3

Experimental results

1 Hz

	Test 1	Test 2	Test 3	Average	Standard Deviation
A1	0.09	0.13	0.12	0.11	0.0
Sum of B1-B6	0.89	0.97	0.89	0.92	0.0
Sum of C1-C12	1.62	1.61	1.65	1.63	0.0
Total current	2.78	2.71	2.66	2.72	0.1

Experimental results

1000Hz

	Test 1	Test 2	Test 3	Average	Standard Deviation
A1	0.09	0.12	0.09	0.10	0.0
Sum of B1-B6	0.82	0.82	0.84	0.83	0.0
Sum of C1-C12	1.75	1.79	1.76	1.77	0.0
Total current	2.7	2.7	2.7	2.7	0.1

Experimental results

10,000 Hz

	Test 1	Test 2	Test 3	Average	Standard Deviation
A1	0.04	0.03	0.03	0.03	0.0
Sum of B1-B6	0.44	0.38	0.33	0.38	0.1
Sum of C1-C12	1.21	1.13	1.15	1.16	0.0
Total current	1.69	1.54	1.51	1.58	0.1

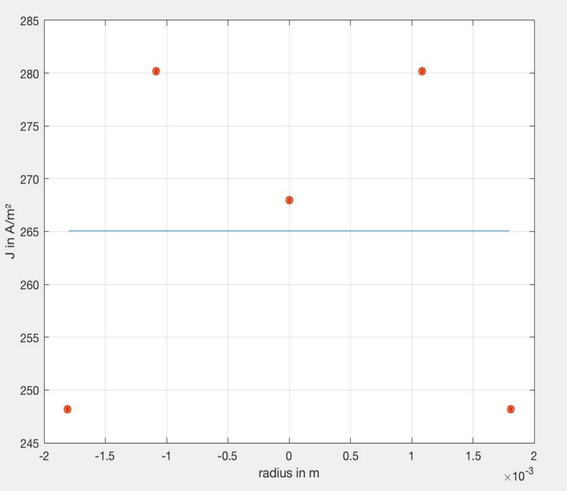
Plotting of results

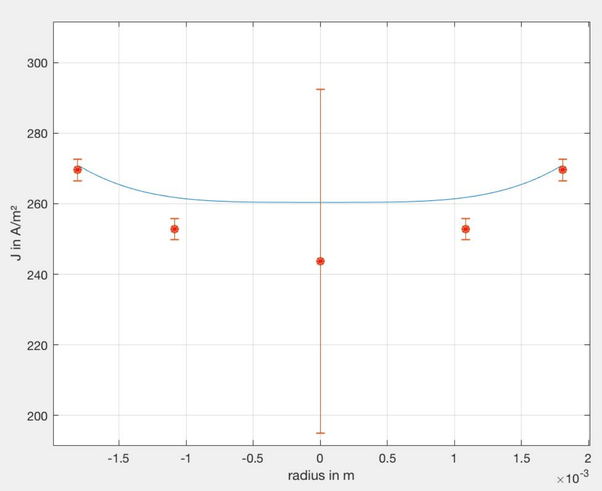
Making use of the computational solution developed previously, we then plot our results into matlab to compare the practical results with the theoretical model

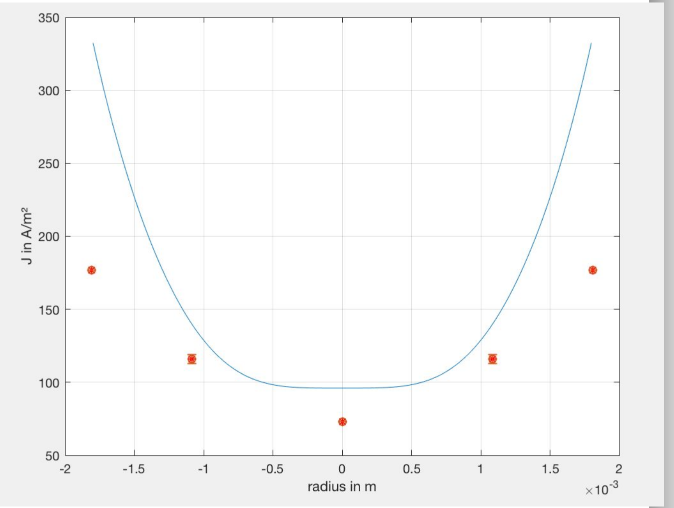
1 Hz

1000 Hz

10 000 Hz







Discussion of results and area for improvement

From our results, we can thus conclude that as depth of the conductor increases, the current density would decrease exponentially.

This fulfils our first hypothesis, and our results agree with both our mathematical model, and the research done by J.W. Macdougall from the University of the West Indies.

Discussion of results and area for improvement

However, our second hypothesis, which is the skin effect becoming more apparent as the frequency increases, cannot be verified.

This is because our data does not match with our mathematical model properly, thus it may not be accurate and thus we cannot verify our second hypothesis.

Discussion of results and area for improvement

However, these also happened in the experiment done by J.W. Macdougall from the University of the West Indies, as his readings also could not match very well with his theoretical results.

Discussion of results and area for improvement

Why we cannot get more accurate readings:

- Wires were insulated, which reduces the skin effect.
- Moving the wires to collect readings would affect the readings adversely due to the change in electromagnetic fields.

Discussion of results and area for improvement

How to fix these:

- Get thicker wires that has no insulation
- Get a multi channel ammeter such that I can take measurements from all the wires at once without moving them.

Project applications

With this in mind, tubular conductors like pipes can be constructed. This is because since the centre carries very little current, so by making the conductor a tube-like structure, it could save weight and cost of the conductor.

Future project idea

To investigate on the effectiveness of the litz wire implementation, in terms of how much power loss it has.

The Litz wire is multiple strands of insulated wires twisted and woven together, reducing the skin effect by distributing current equally.

Future Project procedures

- We can sum up the total current flowing through the litz wire, and then compare it against another wire that does not use the litz wire implementation.
- Repeat this with different frequencies, to see if the effectiveness of the litz wire implementation would change with different frequencies.

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Thank you