# Investigation of the skin effect in alternating currents

Liang Ying Hao Matthew

SCHOOL OF SCIENCE AND TECHNOLOGY, SINGAPORE

## Introduction

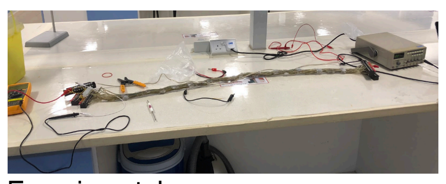
My research is on the investigation of the skin effect in alternating currents. The skin effect is when an alternating current tends to flow on the surface of the conductor, such that the current density is highest near the surface, and decreases with greater depths in the conductor. This is due to the alternating current inducing changing magnetic fields, which in turn induces currents that oppose the original flow of current, resisting the current flowing through the centre the most. This reduces the effective cross-sectional area of the conductor and increases the resistance, causing increased power losses. This effect becomes more apparent as the frequency increases. My project is broken down into 4 sub-aims. The first aim would be, to mathematically model the distribution of current in the radius of the wire, which consists of the application of the Maxwell equations and solving zeroth order Bessel equations of the first kind. The next aim would be to computationally plot out the desired current readings as the depth of the wire increases from the surface, using the Matlab software. The third aim that I have is to conduct an experiment, which involves bundling it multiple silver wires together, and a section of it is where the wires would diverge from each other before they converge into a bundle again. An alternating current is passed through them, before measuring the current distribution flowing through each layer. Lastly, it is to compare on which mathematical model is the most accurate in modelling the skin effect in the wire. This would be a contribution to physics, in the field of electromagnetism as this shows the interaction of the electromagnetic fields within a conductor, and it is also a contribution to the engineering field as engineers can better design conductors to minimise power losses.

$$J_z(r) = \alpha J_0(kr)$$

Mathematical

MATLAB

Computational



Experimental

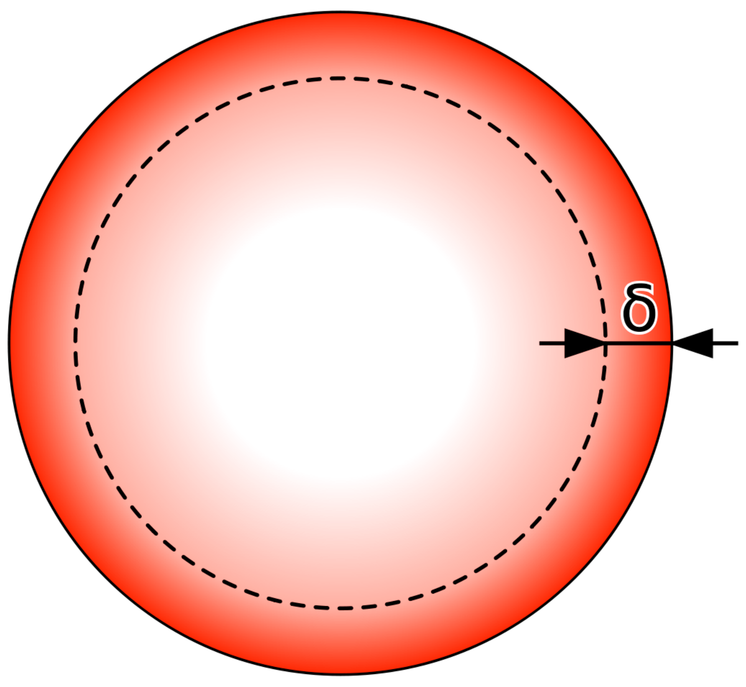
## Hypotheses

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.

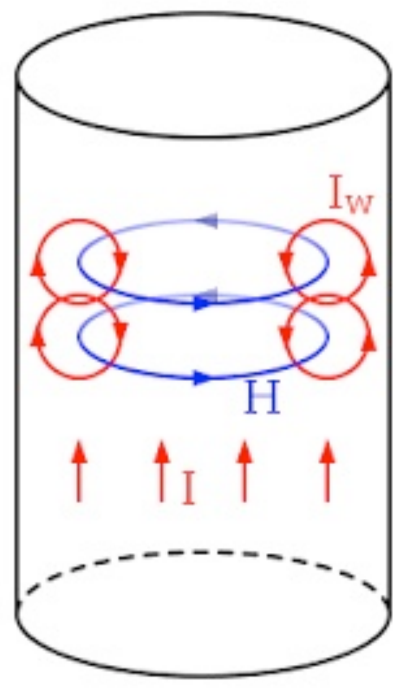
As the frequency increases, the skin effect becomes more apparent in the solid conductor.

## Research questions

How do different frequencies affect the current density in a solid conductor?
How is the skin effect mathematically modelled?



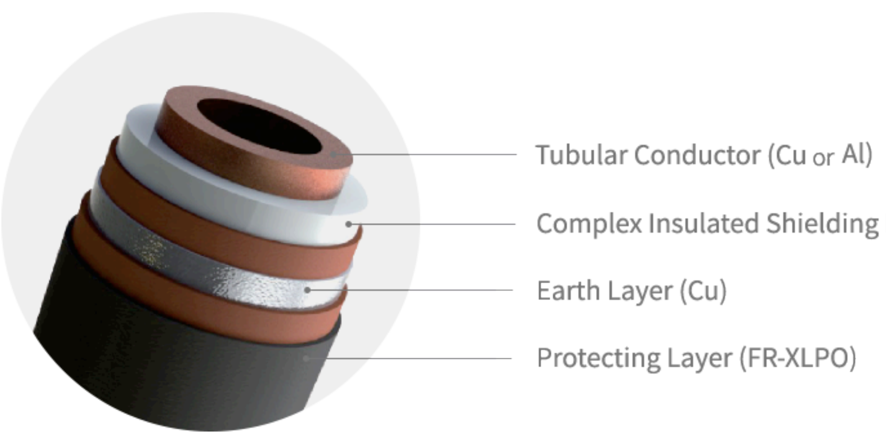

Current distribution in a solid conductor, where the red areas show greater current density.



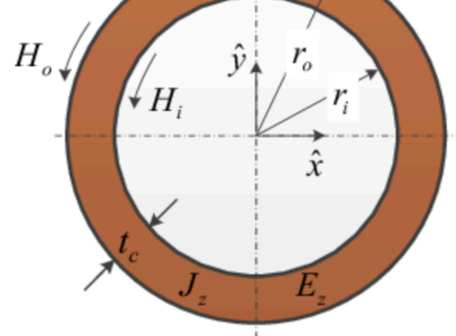

Cause of the skin effect is due to magnetic fields inducing currents opposing the original flow of current

## Applications

Since the centre of the conductor carries very little current, thus tubular conductors like pipes can be constructed. By making the conductor a tube-like structure, it could save weight and cost of the conductor because less material is needed to create it, and also it reduces power losses, saving money in the long run.




Tubular conductor




Tubular conductor schematic

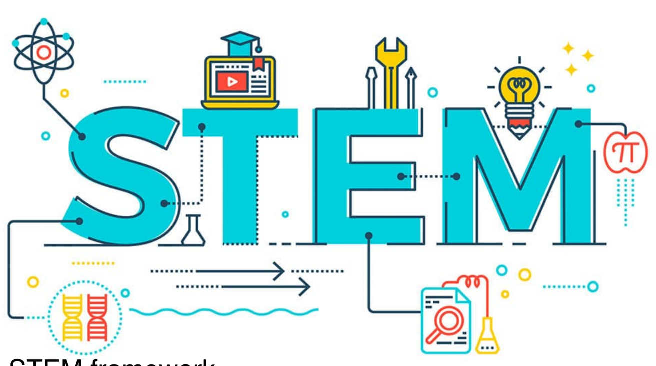
## What I learned

From this project, I learn how physics, mathematics, technology and engineering can nicely come together in this research, and how applied learning is then fulfilled as after deriving the mathematics and computationally modelling it, the experiment is then done, allowing for hands-on learning and experience. I also learnt that I should be very critical of myself whenever I do something so that I can deliver work to the best of my ability.

## Future research

From this investigation, I can then investigate on the effectiveness of the Litz wire implementation, regarding how much power loss is minimised as compared to another solid conductor that does not make use of the Litz wire implementation. This can allow engineers to improve the Litz wire design further to minimise power losses further.

Litz wire




STEM framework

## Acknowledgements

I would like to thank my science teacher, Mr Tan Hoe Teck, who patiently guided me on the conceptual knowledge, as well as providing me with the equipment and materials for this project.

Silver wire drum

## Procedures

1) Create the big wire prototype by sticking the silver wires layer by layer using a glue gun. A total of three layers should be created. Refer to image below for arrangement.

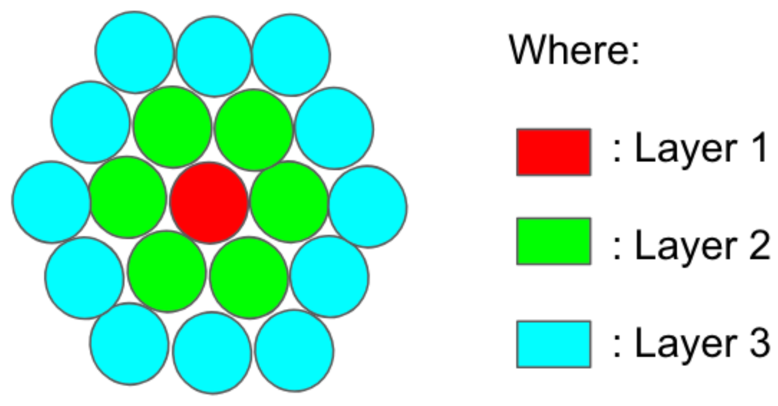
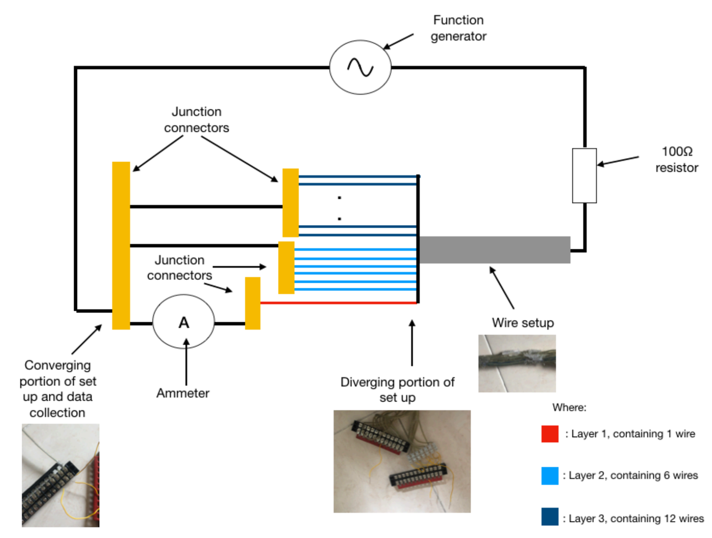



Diagram on how to layer wires

Actual model

2) On one end of the prototype, converge all the small wires together using the junction connectors, before connecting the junction connectors to a 100Ω resistor. Connect the resistor to the positive end of the function generator.
3) For each layer of the prototype, converge the wires that are in the same layer together using a junction connector.
4) Connect one end of an ammeter to the layer that you want to measure. Connect the other end of the ammeter to a separate junction connector using jumper wires. For the other layers that are not being measured by the ammeter, connect their respective junction connectors to that same junction connector that the ammeter is connected to with the jumper wires.
5) Connect that junction connector to the negative end of the function generator. Set the function generator to 1Hz. Take readings for the layer you are measuring by taking a picture of the ammeter display. Repeat this step 3 times and take the average. Put these readings into a table.
6) Next, repeat steps 4-5 again, but this time for the other layers of the prototype.
7) Calculate the current density by taking the reading divided by the cross sectional area. Plot these results into the program in Matlab.
8) Repeat steps 4-7, but using the frequencies of 1000Hz and 10,000Hz for the function generator.

Experimental set up




Circuit diagram of the experiment

## Results and analysis

From our results, we can see that the surface of the wire model has the greatest current density, which is supported by various research papers. Also, we see that as the depth increases(when it is closer to the centre of the model), the current density decreases exponentially. We can also see that as the frequency increases, the skin effect becomes more apparent, meaning more current is seen concentrated on the surface of the conductor.

Our results do show how the surface of the conductor will have the highest current density, and then the current density decreases exponentially, with the centre of the conductor having the lowest current density. This verifies our first hypothesis because our data correctly shows skin effect phenomenon, and agrees with both our mathematical model and the research done by J.W. Macdougall from the University of the West Indies.

However, our second hypothesis cannot be verified easily even if our data can somewhat show how the skin effect becomes more apparent as the frequency increases, because it cannot match our mathematical model very well, meaning that the data is not very accurate. The reasons to this would be due to the use of insulated wires, which would not allow the wires to be close to each other, and also because the readings can change adversely when I shift the wires to collect readings. This is further supported by the experiment done by J.W. Macdougall from the University of the West Indies.

From this, there are two things I could work on to better improve on this project. Firstly, I could get thicker wires with no insulation, allowing me to bind them together easily and to gather my data more accurately. Secondly, I can make use of the multi-channel ammeter, so I can collect readings for every layer of the conductor without shifting the wires around.

```
A = 0.00158;
double conduct;
conduct = 6.3e7; %copper conductivity
perm =  4*pi*10^-7; %permeability
double k;
k = (-j*2*pi*freq*perm*conduct)^0.5;

% 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)));
```

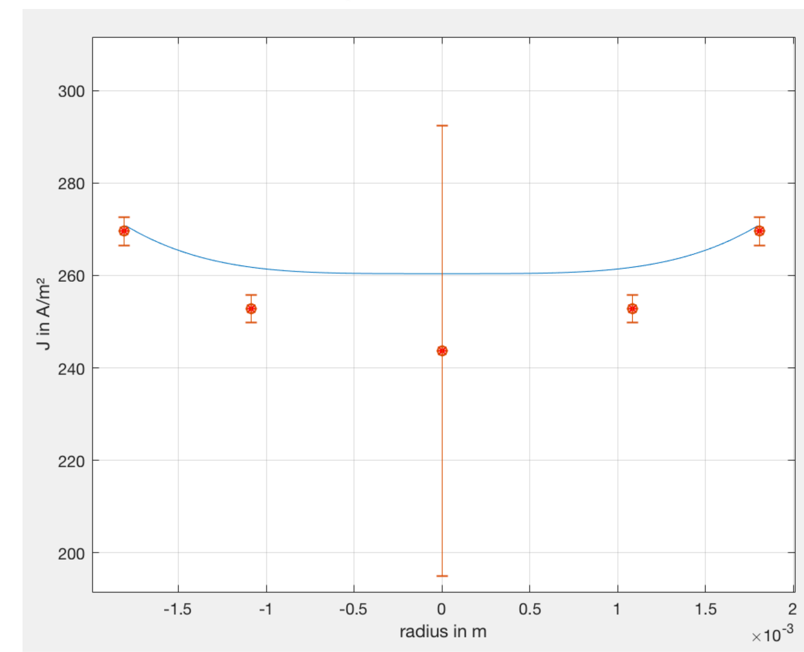
Matlab source code

| 3 Layer silver wire readings @ 1000 Hz | | | | | |
|---|---|---|---|---|---|
| Resistance: 100Ω | | | | | |
| Voltage: 4.6 VAC | | | | | |
| | Current readings in mA | | | | |
| | Test 1 | Test 2 | Test 3 | Average | Standard Deviation |
| A1 | 0.09 | 0.12 | 0.09 | 0.10 | 0.02 |
| Sum of B1-B6 | 0.82 | 0.82 | 0.84 | 0.83 | 0.01 |
| Sum of C1-C12 | 1.75 | 1.79 | 1.76 | 1.77 | 0.02 |
| Sum | 2.7 | 2.7 | 2.7 | 2.7 | 0.04 |

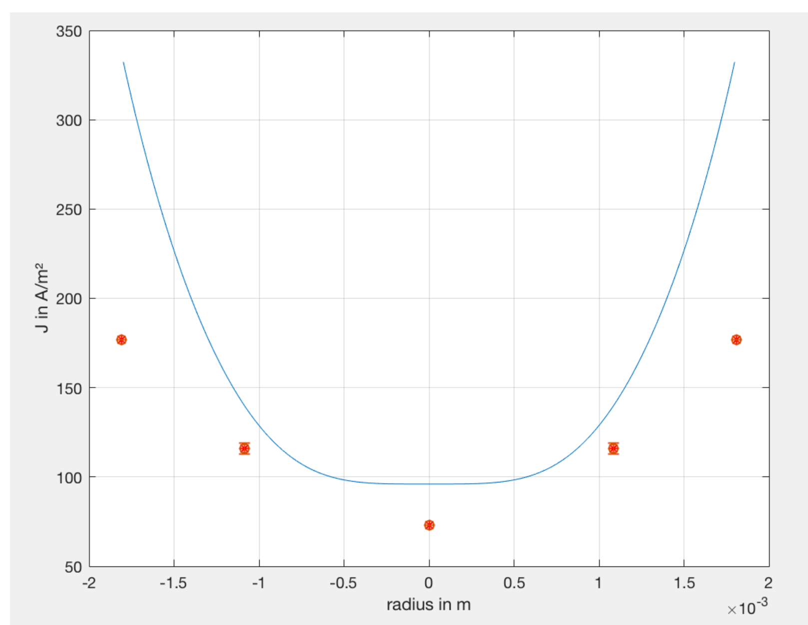
Data collection of 1000Hz readings

| 3 Layer silver wire readings @ 10K Hz | | | | | |
|---|---|---|---|---|---|
| Resistance: 100Ω | | | | | |
| Voltage: 4.6 VAC | | | | | |
| | Current readings in mA | | | | |
| | 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 Phasor(Sum of all currents in wires) | 1.69 | 1.54 | 1.51 | 1.58 | 0.1 |

Data collection of 10,000Hz readings




Current density vs depth graph with 1000Hz




Current density vs depth graph with 10,000 Hz

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