L3b: Magnetic Actuators Operated by AC

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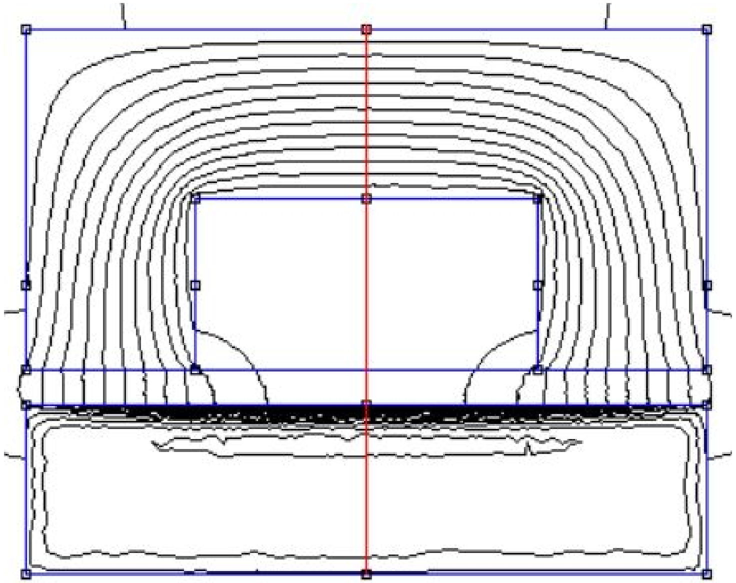
Why

- So far we have mostly focussed on DC operation.
- Many solenoids and motors operate on AC.
- We need to know what design changes are required.
- This lecture will focus on the impact of AC operation on steel cores. The impact on current carrying conductors will be addressed in L3c



Skin Depth

Why

Skin depth is one of the critical issues that arises in electromagnetics when we begin to deal with AC frequencies.

It is one of the main reasons laminated cores are required.

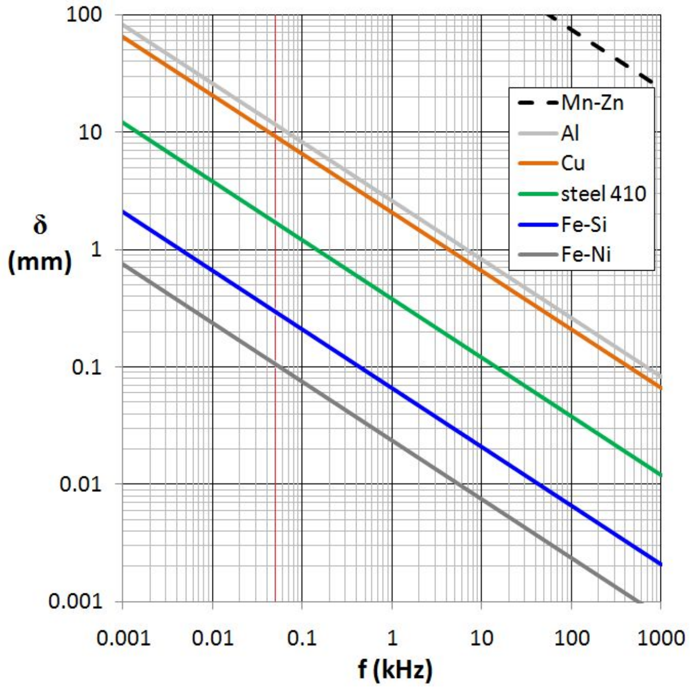
How

The skin depth is the depth at which and eddy currents have decayed to 1/e or 36.8% of their surface value.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (8.1)$$

Skin depth for different materials

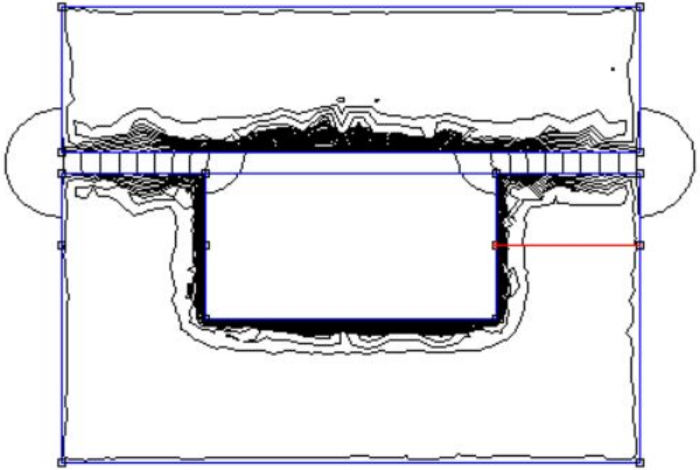
	Frequency (Hz)	Relative Permeability	conductivity (S/m)	Skin Depth (mm)
Carbon steel (1010)	50	2000	6.99E+06	0.6
Silicon Steel (M15)	50	2000	1.90E+06	1.2
Copper	50	1	5.96E+07	9.2
Carbon steel (1010)	500	2000	6.99E+06	0.2
Silicon Steel (M15)	500	2000	1.90E+06	0.4
Copper	500	1	5.96E+07	2.9

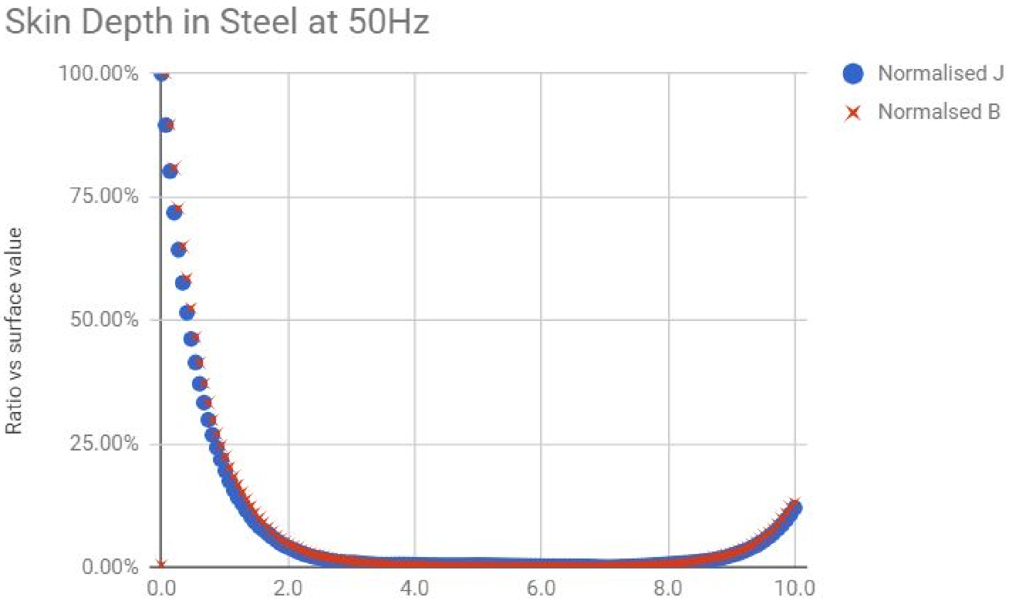


https://commons.wikimedia.org/wiki/File%3ASkin_depth_by_Zureks.png

Example 8.0 (7.1 at 50Hz)

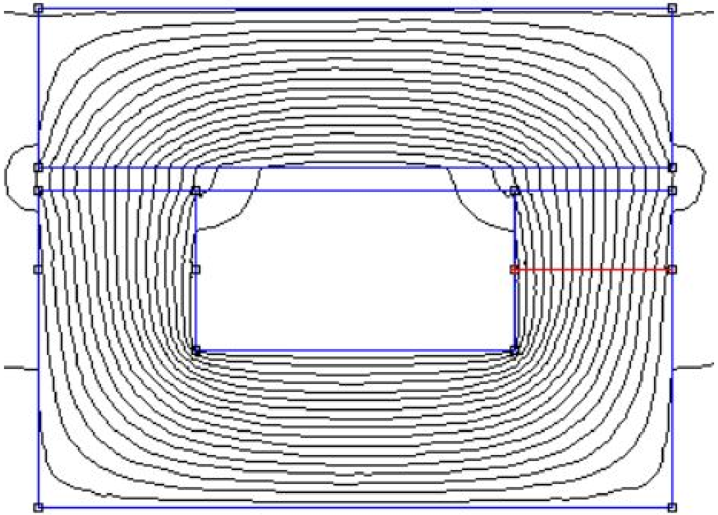
Solid Steel

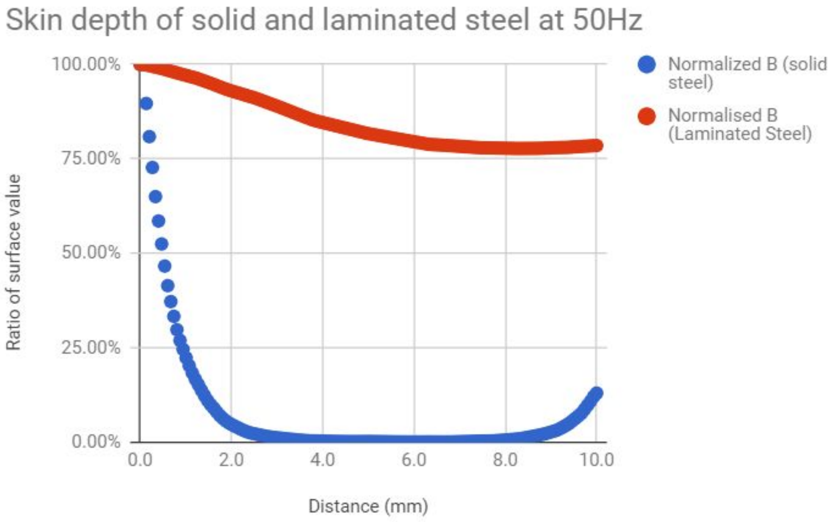




Example 8.0 (7.1 at 50Hz)

0.5 mm laminations





Lamination methods

- *For planar actuators with clapper armatures*, the stator is easily laminated, but often the armature is made of solid steel, especially if the armature is steel plate (or steel scrap) to be lifted by a *lifting magnet*.
- *For axisymmetric actuators with clapper armatures,* lamination is difficult and expensive, and thus both stator and armature steels are usually solid.
- *For planar actuators with plunger armatures,* both stator and armature are usually laminated, but a solid armature is sometimes required due to its greater mechanical rigidity.
- *For axisymmetric actuators with clapper armatures,* lamination is difficult and expensive, and thus both stator and armature steels are usually solid.

Test for understanding

For the same frequency, is the skin depth larger in:

a) Steel
b) Aluminium

A smaller skin depth allows:

a) More flux to flow
b) Less flux to flow

Power Losses in Steel: Laminated Steel

Why

One of the main losses in electric motors and actuators is “core loss”

Any high efficiency motor or AC actuator design will need to carefully consider core loss.

How

$$\frac{P_e}{v} = \frac{t^2\omega^2 B^2\sigma}{24} \quad (8.2)$$

$$\frac{P_h}{V} = K_h f B^n \quad (8.3)$$

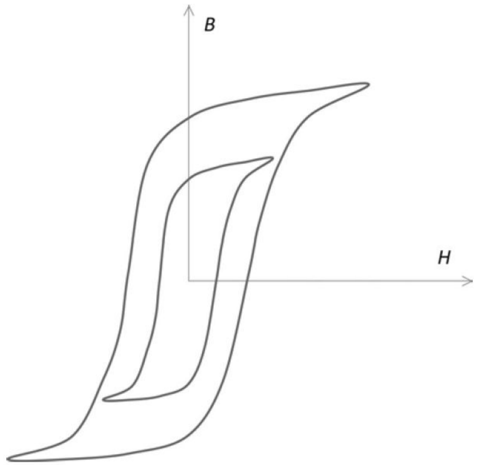


FIGURE 8.1 *B–H* hysteresis loops for AC *H* due to AC. The area enclosed is the energy lost per cycle. Two loops are shown for two different peak AC values.

How

The value of n in 8.3 is defined by fitting curves to loss data.

In the FEMM wiki (http://www.femm.info/wiki/SPMLoss) a reasonable starting point is n = 2.

$$\frac{P_e}{v} = \frac{t^2\omega^2 B^2\sigma}{24} \quad (8.2)$$

$$\frac{P_h}{V} = K_h f B^n \quad (8.3)$$

$$\frac{P_{core}}{m} = \frac{P_h}{m} + \frac{P_e}{m} = C_h \omega B^2 + C_e \omega^2 B^2$$

Example

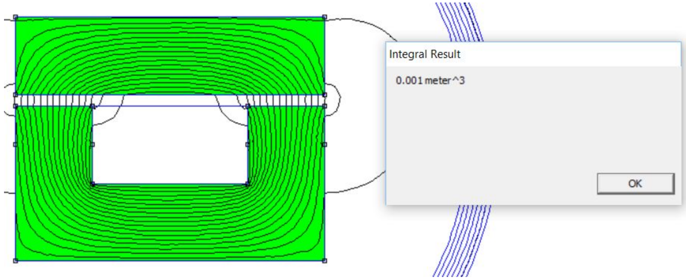
Modifying the coefficients from http://www.femm.info/wiki/SPM Loss for M19 steel 29 gauge (0.36mm) gives:

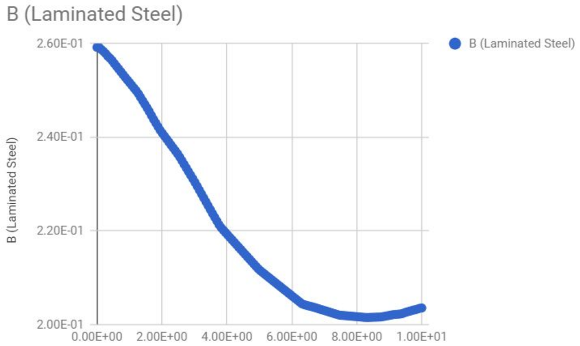
$$C_h = 0.0186 \frac{W}{kg.T^2.Hz}$$

$$C_e = 68.8e^{-6} \frac{W}{kg.T^2.Hz^2}$$

		Frequency (Hz)				
		50	100	200	400	1000
B (T)	0.3	0.1	0.2	0.6	1.7	7.9
	0.6	0.4	0.9	2.3	6.6	31
	0.9	0.9	2.1	5.2	15	71
	1.2	1.6	3.7	9.3	27	126
	1.5	2.5	5.7	15	42	197

Example





$$\frac{P_{core}}{m}(50Hz) = 0.04\frac{W}{kg}$$

$$V = 0.001m^3$$

$$\rho = 7800 \times 0.96 = 7488\frac{kg}{m^3}$$

$$m = 7488 \times 0.001 = 7.488kg$$

$$P_{core} = 0.04 \times 7.488 = 0.3W$$

		Frequency (Hz)				
		50	100	200	400	1000
B (T)	0.2	0.04	0.1	0.3	0.7	3.5
	0.3	0.1	0.2	0.6	1.7	7.9
	0.6	0.4	0.9	2.3	6.6	31
	0.9	0.9	2.1	5.2	15	71
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Industry core loss data

Traditionally core loss data has been published only at 50 and 60Hz

The coefficients from the FEMM wiki were extracted from data on the Protolam site http://www.protolam.com/page5.html

Thinner laminations (higher gauge number) will be better for eddy current losses

Semi processed steel is popular in the United States. Fully processed steel is standard elsewhere.

Table 5

Core Loss Limits for Fully Processed Material at 60 Hz* (ASTM A 677) (Watts/lb)

	15 kG		
AK Steel Grade	**0.014" (29 gauge)**	**0.0185" (26 gauge)**	**0.025" (24 gauge)**
DI-MAX M-15	1.45	1.60	—
DI-MAX M-19	1.55	1.65	2.00
DI-MAX M-22	1.60	1.80	2.10
DI-MAX M-27	1.75	1.90	2.25
DI-MAX M-36	1.85	2.00	2.35
DI-MAX M-43	1.95	2.10	2.50
DI-MAX M-45	2.05	2.40	2.75
DI-MAX M-47	—	2.80	3.20

*As-Sheared, 50/50.

Table 6

Core Loss Limits for Semi-Processed Material at 60 Hz* (ASTM A 683) (Watts/lb)

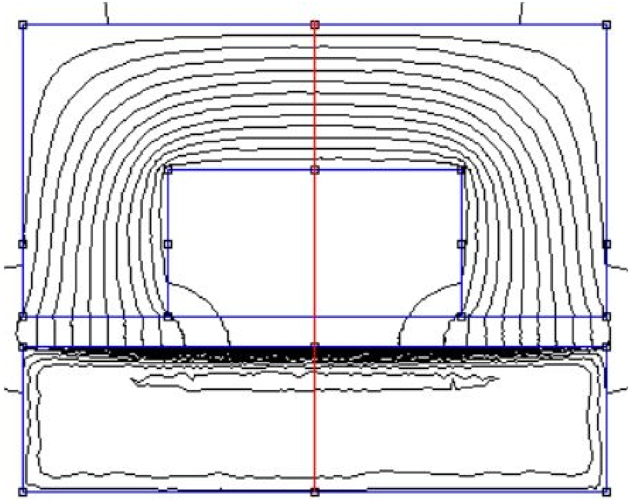
	15 kG	
AK Steel Grade	**0.0185" (26 gauge)**	**0.025" (24 gauge)**
DI-MAX M-43	1.55	2.00
DI-MAX M-47	1.65	2.10

http://www.aksteel.com/pdf/markets_products/electrical/non_oriented_bulletin.pdf

Test for understanding

Example 8.1 AC Flux Linkage and Equivalent Circuits of Solenoid of Example 7.1 with a Solid Steel Clapper Figure E8.1.1 shows the solenoid of Example 7.1 turned upside down to act as an AC lifting magnet. The stator is laminated but the clapper being lifted is solid steel. The stator winding shown has 200 turns carrying 2-A rms AC 60-Hz current. The dimensions are $w = 10$ mm, $Al_1 = 5$ mm, $Al_2 = 30$ mm, $Al_3 = 5$ mm, $Sl_1 = 15$ mm, $Sl_2 = 30$ mm, $Sl_3 = 15$ mm, $g = 2$ mm. Assuming all steel has relative permeability of 2000, and the clapper has conductivity 2.E6 S/m

Assume that the stator has a depth into the page of 1 m in the z direction



Plot the flux density along the red line shown in the figure. Compare the impact of skin depth shown in impact with the skin depth calculated from equation 8.1

Summary

For AC operation, laminations are required to avoid the impact of skin depth.

$$\frac{P_{core}}{m} = \frac{P_h}{m} + \frac{P_e}{m} = C_h \omega B^2 + C_e \omega^2 B^2$$