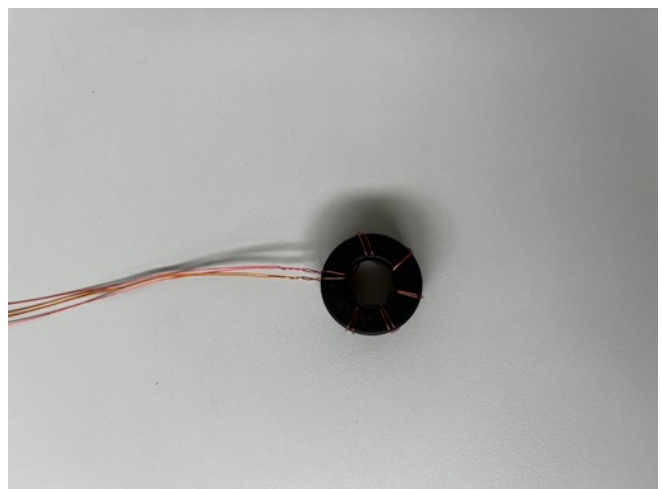


Nanocrystalline Material Datasheet

Prepared for:	CBMM North America
	1000 Omega Drive
	Pittsburgh, PA 15205



Description of Core Under Test (CUT).

Magnetics, Inc. CMC025016010 is a nanocrystalline material for choices in applications involving the use for common mode choke (CMC) applications with its exhibition of high permeability, low power loss, and high saturation. Common applications associated with the nanocrystalline core include switched-mode power supplies, uninterruptable power supplies, solar inverters, EMC filters, and multiple automotive and welding applications. Composition involved with this particular core is Magnetics Inc's Nanocrystalline Material with a potential saturation induction of 1.25 T.

Test Facility	
Test Laboratory	AMPED
Address	1435 Bedford Avenue
City, State, Zip Code	Pittsburgh, PA 15219
Phone	412-802-0988
Fax:	412-802-0779
Website:	https://pittamped.github.io

Test Personnel	
Name	Chris Bracken
Title	Research Associate
Signature	

Datasheet Revision History

Revision	Date	Description	Revised By
N / C	Date of Release	Initial Release	CSB (Initials of Revisor)
A	21JUN2023	Formatting, adding 25 kHz – 200 kHz data.	CSB

Declaration of Sufficiency

The following results for the Core Under Test fulfill requirements of best effort of capability based on standards and manufacturer representative data. Results are subject to the following conditions:

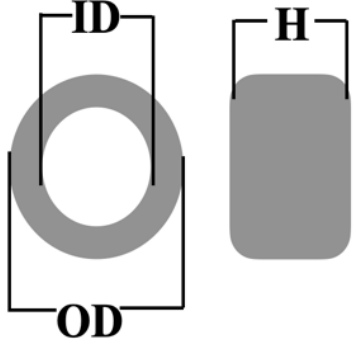
- (1) The results are within margin of the of the calculated raw values obtained via experiment.
- (2) The results are within a reasonable margin of reported data from the manufacturer or other facilities.

The result has been evaluated by Test Personnel and Supervisors under quality procedures and shown here in the datasheet. It is understood that the results shown are subject to repeatability and third-party testing analysis, encouraging debate and transparency amongst testing personnel.

The test facility noted as where the testing was conducted is also responsible for this declaration.

Person(s) responsible for finalizing the marking of this declaration, approving of best effort of capability:

Name	Title	Date
PAUL R. OHODNICKI, JR., PHD	Associate Professor	June 21, 2023
RICHARD B. BEDDINGFIELD, PHD	Postdoctoral Research Scholar	June 21, 2023

Dimensions				
Description	Symbol	Sample Dimension (mm) ¹	Actual Dimension Used (mm) ¹	
Core Inner Diameter	ID	13.7	16	
Core Outer Diameter	OD	27.3	25	
Core Height	H	12.46	10	
¹ Sample Dimension refers to the dimensions that include coating. These dimensions do not pertain to the effective area used, as this effective area was stated in the provided core manufacturer datasheet. A correction factor accounts for this where plausible, taking the ratio of Sample Dimension-to-Actual Dimension, multiplying the cross-sectional area with this term (See AMPED standard AMP-STD-0C for this calculation, and for other calculations).				

Magnetic Characteristics			
Description	Symbol	Finished Dimension	Unit
Effective Area	A _e	37	mm ²
Mean Magnetic Path Length	L _m	64.3	mm
Core Mass	C _M	0.0169	kg
Density	D	7350	kg / m ³
Lamination Thickness	L _M	0	μm
Chemistry	Nanocrystalline Material	Grade	
Anneal		Impregation	Unimpregnated
Core Supplier		Part Number	CMC025016010
Wire Supplier		Wire Gauge	30 AWG

Configuration.

Core Testing. Testing performed using the configuration changes as noted, used to complete the evaluation. The actual test parameters are specified in the Setup, the Test Procedure and the Data Presentation sections.

Configuration Number	Frequency Range	Primary Turns (N_P)	Secondary Turns (N_S)
1	60 Hz – 50 kHz	6	6
2	100 kHz	2	2
3	200 kHz	1	1

Note: The choice of primary and secondary turns was chosen such that estimates the probe and core saturation points by the relation defined in IEEE-393 and IEC 62044-3: $N_P = H_e l_e / i$, and $N_S = V_{rms} / k f A_e B_e$. k is dependent on the waveform in question, f is frequency of each test, A_e is core effective area, B_e is the saturation flux density, V_{rms} is 90% of the maximum voltage the probe is rated for at the given setting it takes the measurement, i is 90 percent of the current the current probe is rated for, H_e is the estimated value the setup can provide for field strength (assumed from $i = 7 \text{ A}$), and l_e is the mean path length of the core.

Section One: Room Temperature Environmental Measurements. Magnetic Core Characterization Testing: Test Procedures and Results.

Purpose.

This test procedure is used to measure the B-H Curves, core losses, and permeability of the core under test at room temperature.

Test Equipment.

The test equipment shall be used as follows:

Lab Asset Number	Description	Manufacturer	Model Number	Serial Number
WAV0003	Arbitrary Waveform Generator	Keysight Technologies	EDU33212A	CN61310043
AMP0001	High Speed Power Amplifier	NF Electronic Instruments	4025	4025-112
OSC0003	Oscilloscope (500 MHz)	Keysight Technologies	MSOX4054A	MY61260112
PRO0002	Differential Probe	Rigol	RP1025D	2014187
PRO0003	10:1 200 MHz Differential Probe	Keysight Technologies	N2792A	PH61260009
PRO0005	AC / DC Current Probe	Keysight Technologies	1147B	JP61071359
CAP0003	0.01 uF Capacitor	Cornell Dubilier Electronics (CDE)	SCRN244R-F	None
CAP0004	260 uF Capacitor	AVX-TPC	FFLI6L0267K	1D8B537871FO
RES0001	5 Ohm Resistor	Riedon	UB15-5RF1	None
LAB0001	Computer	AMPED	None	None

Test Procedures.

I. Core Loss Testing - Low Signal with Amplifier Setup – Room Temperature – Manual Procedure.

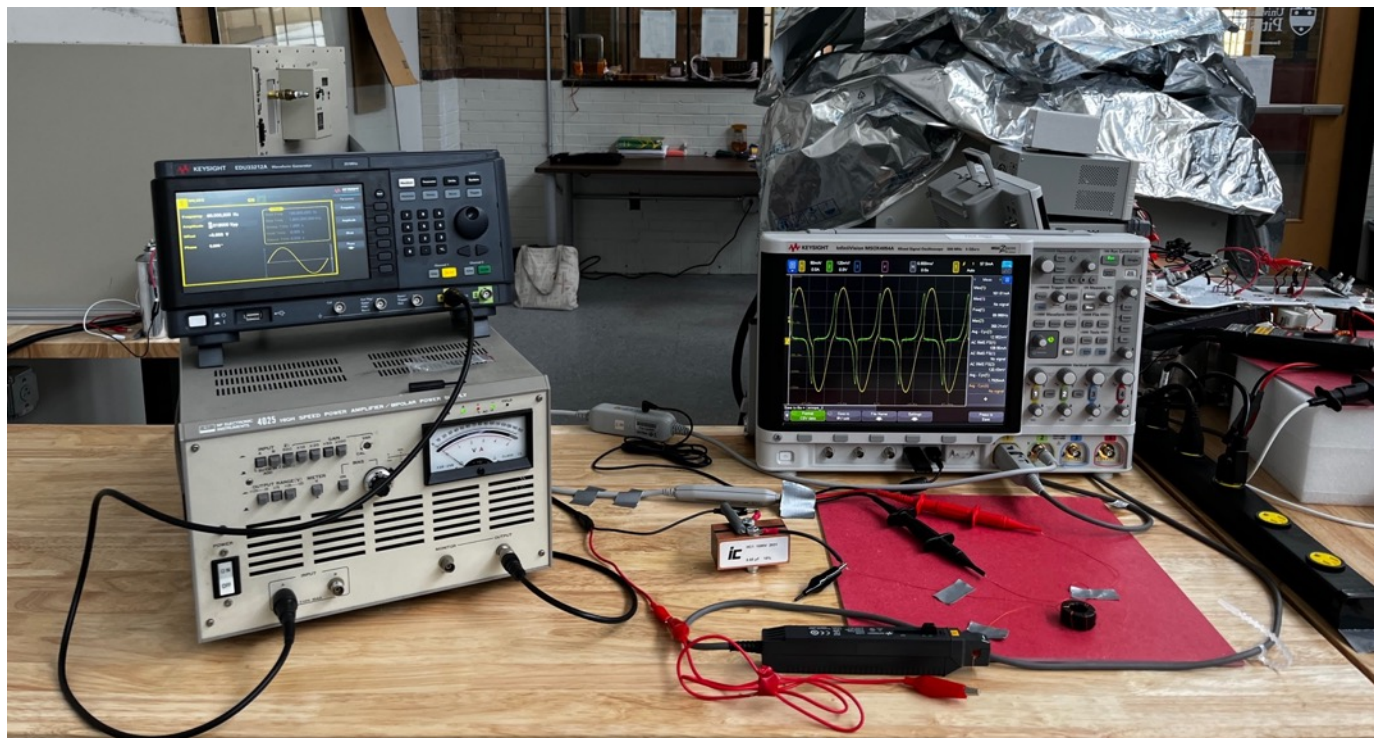
Per AMPED Standard AMP-STD-001, below is the procedure for manual operation of equipment for the Low Signal Setup, to be applied as follows. For a more detailed and general procedure to apply the test, refer to the referenced standard described here.

- Turn on the measurement equipment and allow sufficient time for stabilization (e.g. 20 minutes).
- Set the Arbitrary Waveform Generator to the following settings.
 - Begin with a low signal.
 - Frequency. Set frequency as initial starting point at 60 Hz. Increment based on the desired frequencies necessary to perform measurements.
 - Amplitude. Begin with an amplitude value, in terms of peak-to-peak (V_{PP}), at 10 milli. Increase where deemed appropriate to make sure a fully functioning signal is observed in an acceptable tolerance.
- Set the Power Amplifier values.
 - Be sure to press input cable connected to on (usually A).
 - Press the desired gain. Performed in these tests at “X50”.
- Set the Oscilloscope to the following settings.
 - Specify Probe Attenuation.

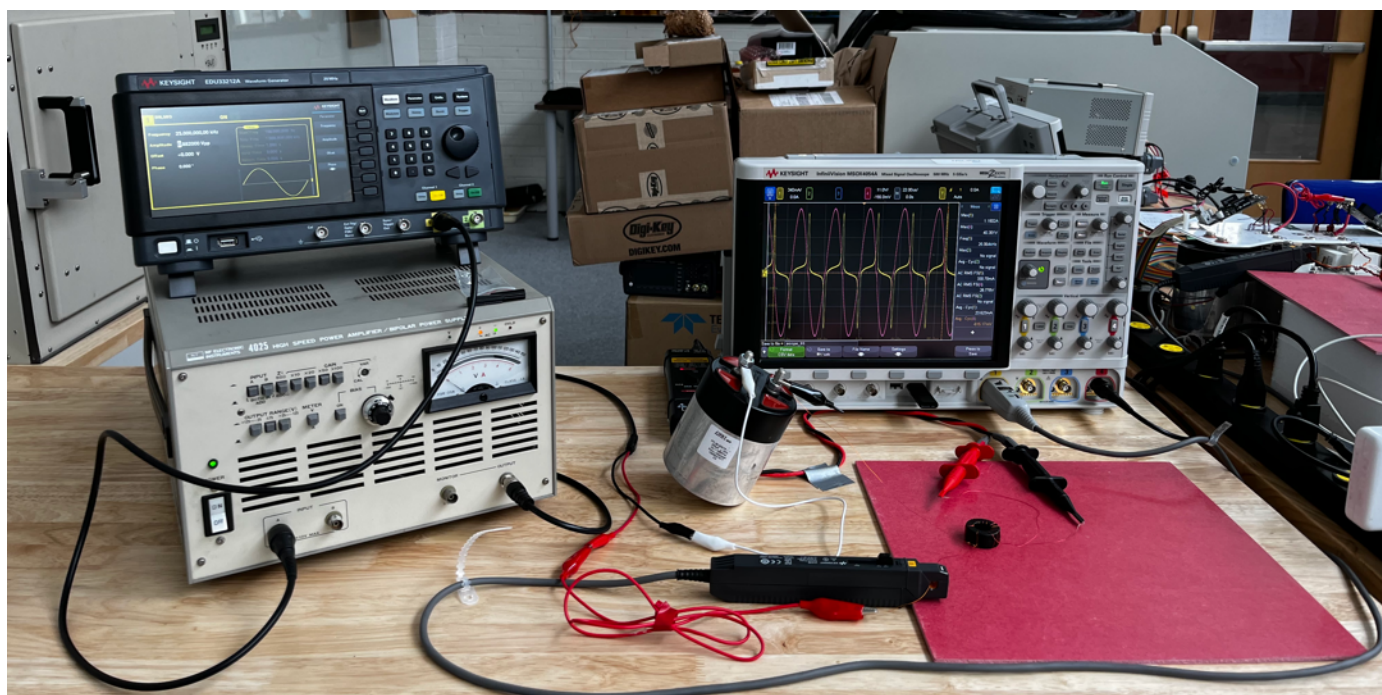
- Measurements were performed with a Keysight 1147B Current Probe has a fixed attenuation ratio of 0.1 V/A and cannot be changed.
- Voltage Probe from Keysight, the N2792, was used for measurements, and has fixed attenuation ratio of 5:1 after calibration with oscilloscope. Probe with Asset Number PRO0003 was used to acquire data from 60 Hz – 10 kHz.
- Voltage Probe from Rigol, the RP1025D, was used for measurements, and has fixed attenuation ratio of 200:1 after calibration. Probe with Asset Number PRO0002 was used to acquire data from 25 – 200 kHz.
- All data, 60 Hz– 200 kHz, was captured with High Resolution Settings under Waveform-Acquire Menu.
- e. Level the output voltage at the offset adjust with flat head screw driver, if possible. Note if probe does not have that capability.
 - For data presented, Voltage probe with asset number PRO0002 does not have the capability.
- f. Examine the Waveform on the Oscilloscope read from the Current Probe on the input side and the Differential Probe on the Output Side.
 - Be sure to capture 3 - 5 periods of the excitation signal being applied.
 - Look for point of saturation for the core. This can be visually examined when the waveform's maximum value no longer increases. Sine and Triangle waveforms flatten, Square becomes more in a curve. See Data Presentation for examples.
 - Magnetic Flux is optional for oscilloscope waveforms but recommended.
- g. Auto zero and Degauss the Current Probe before step i. Also Degauss where Average Current Waveform value climbs above an acceptable tolerance of +/- 10 mA.
- h. Setup included correction components for DC Biasing part of the setup. See the test setup section for a diagram. Note a 5 Ohm Resistor was in parallel with one 0.01 uF Capacitor from 60 – 400 Hz, and a 260 uF Capacitor was used from 1 – 200 kHz.
- i. Repeat steps a - f for Square Waveform, Triangular Waveform, or other excitation waveforms for examined interest.
- j. Record relevant data for Data Presentation.

Setup.

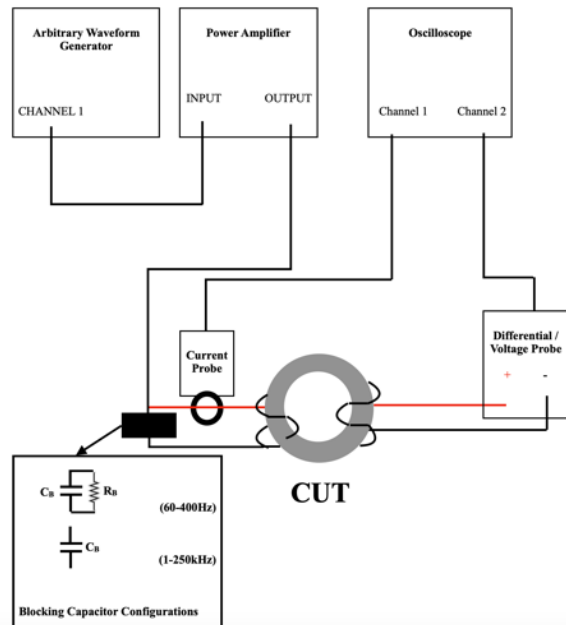
Core Testing. Configure the test equipment as shown below, with one figure showing the actual test setup, and another as the block diagram.



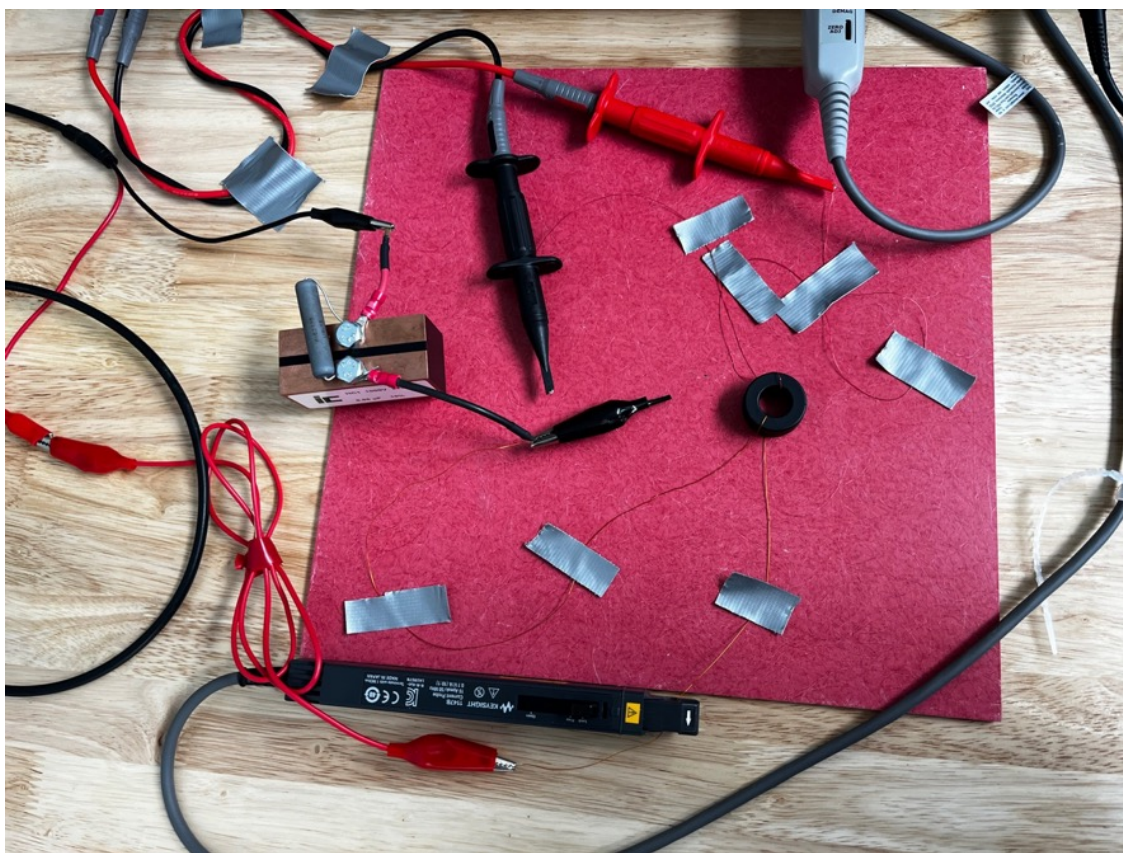
Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup (60 Hz – 10 kHz).



Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup (25 – 200 kHz).



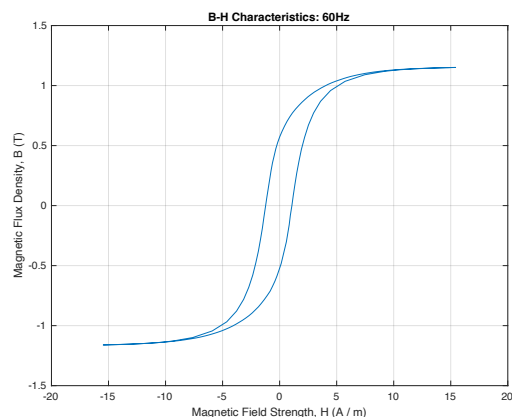
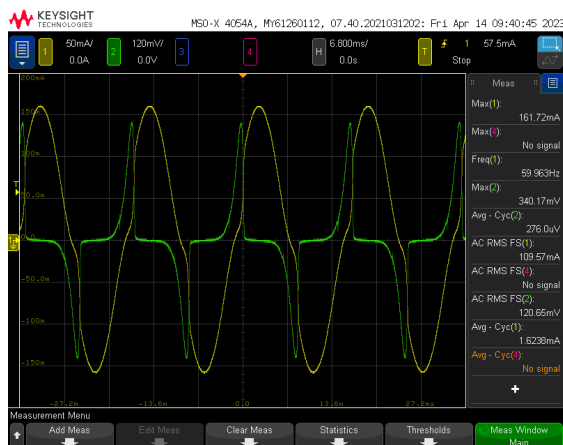
Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup: System Block Diagram.



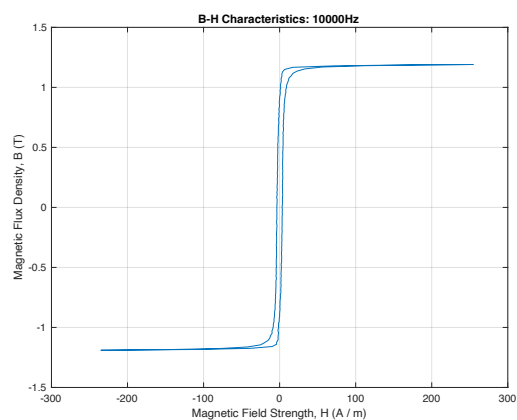
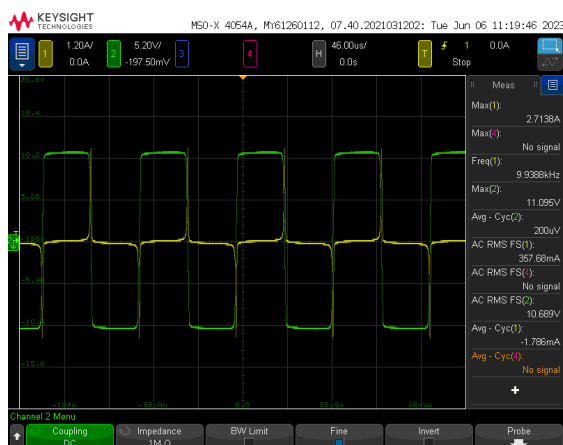
Core Loss Testing - Low Voltage with Amplifier. Cable Layout.

Data Presentation.

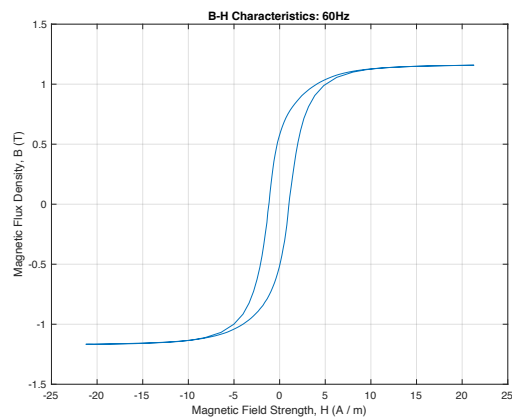
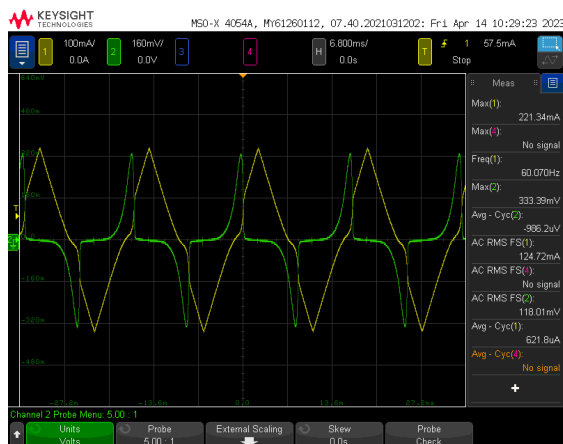
In this section, data is presented as each section indicates below.



Sample Sinusoidal Excitation Waveform and B-H Plot. Sinusoidal Signal. 19.00 mV_{pp} 60Hz, Amplifier Gain X50.

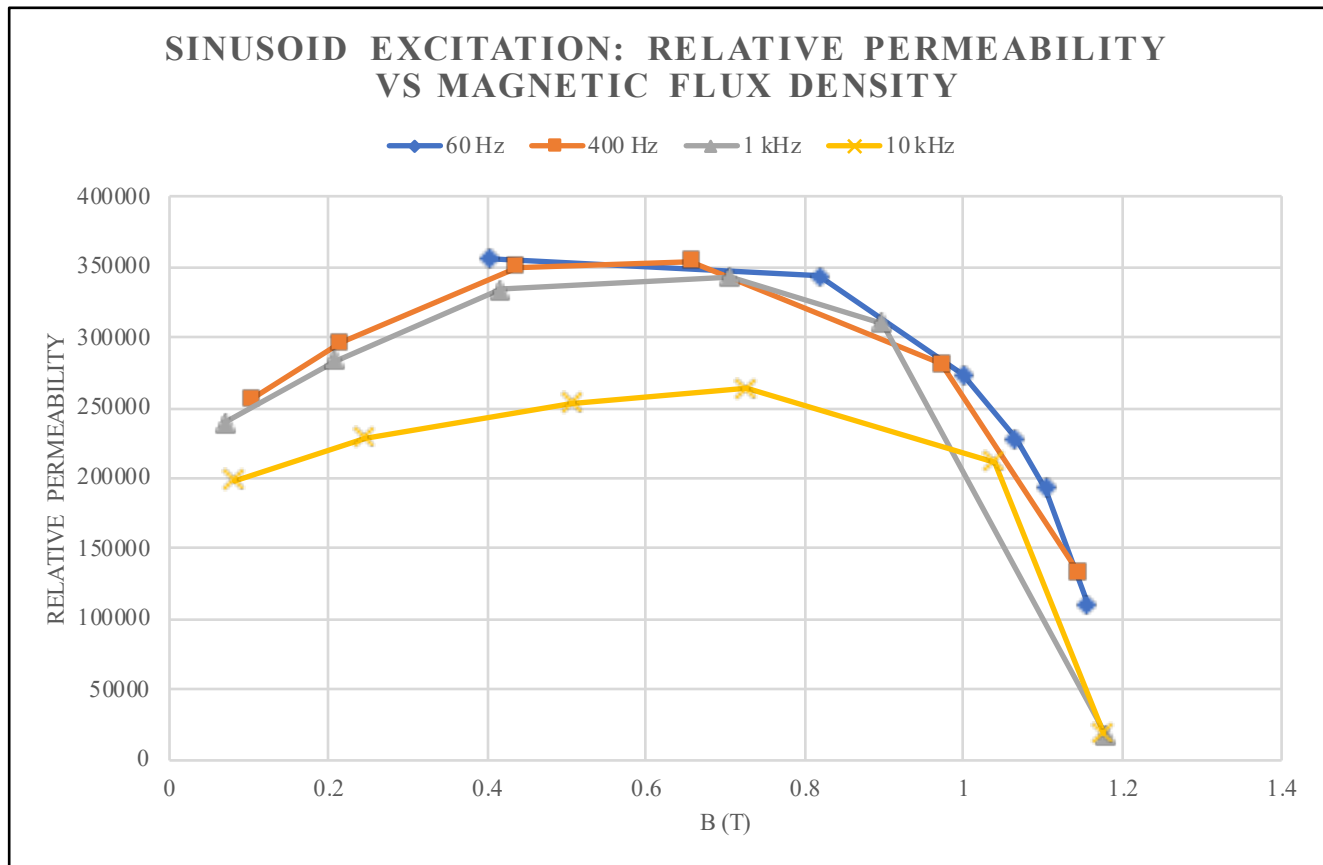


Sample Square Excitation Waveform and B-H Plot. Square Signal. 230.00 mV_{pp} 10kHz, Amplifier Gain X50.



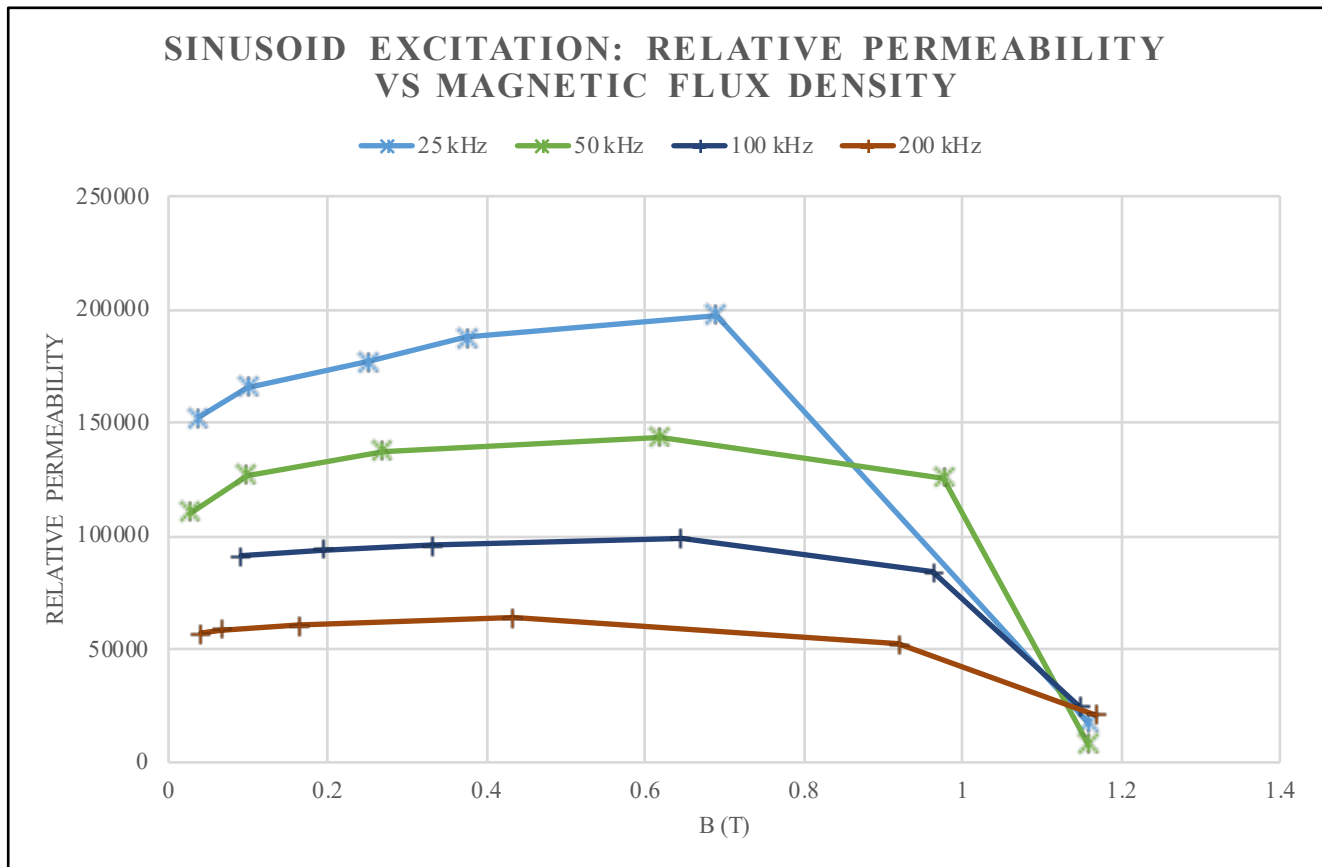
Sample Triangular Excitation Waveform and B-H Plot. Triangular Signal. 27.00 mV_{pp} 60Hz, Amplifier Gain X50.

a. Sinusoid Excitation Magnetic Characterization.



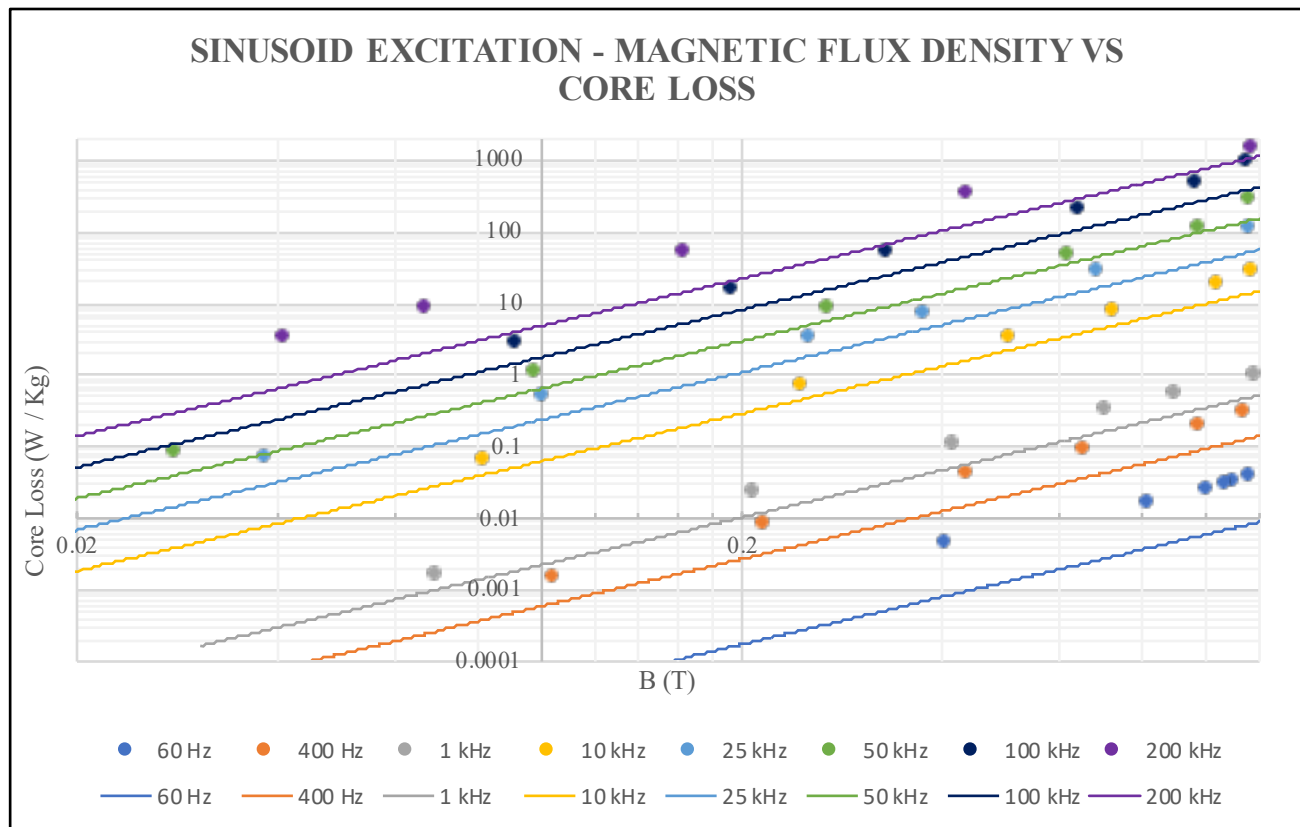
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.16	110904.3	1.14	132756.68	1.18	18253.48
1.10	192453.5	0.97	280725.62	0.90	310262.57
1.07	227917.5	0.66	353520.97	0.71	342642.49
1.00	273096.2	0.44	350162.63	0.42	333866.77
0.82	342877.1	0.22	295759.90	0.21	283486.09
0.40	355646.3	0.10	256462.85	0.07	238859.09

10 kHz	
B (T)	μ_r
1.18	19229.27
1.04	211361.44
0.73	263884.16
0.51	253384.17
0.25	228583.37
0.08	198431.44



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.16	17441.35	1.16	8421.02	1.15	24361.84
0.69	197261.78	0.96	83648.67	0.92	52129.96
0.38	187453.70	0.65	98881.79	0.43	63979.33
0.25	176894.92	0.33	95781.11	0.16	60487.33
0.10	166018.42	0.19	93682.01	0.07	58395.85
0.04	152475.56	0.09	91052.88	0.04	56911.32

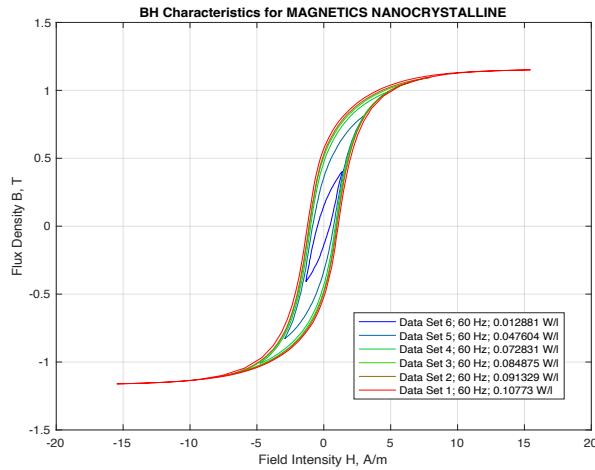
200 kHz	
B (T)	μ_r
1.17	20868.65
0.92	52129.96
0.43	63979.33
0.16	60487.33
0.07	58395.85
0.04	56911.32



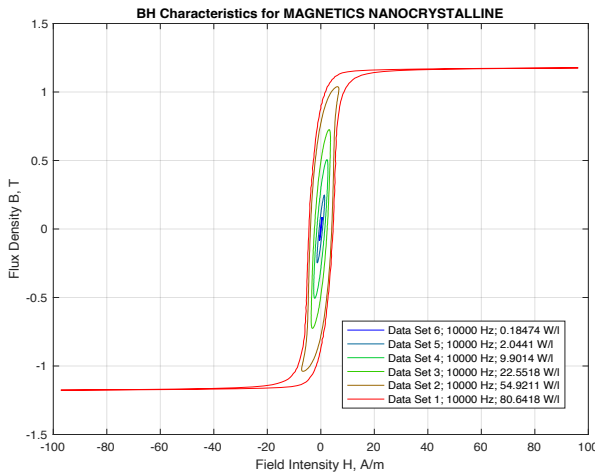
Magnetic Flux Density vs Core Loss - Table							
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.16	0.04	1.14	0.29	1.18	0.99	1.18	27.10
1.10	0.03	0.97	0.20	0.90	0.53	1.04	18.45
1.07	0.03	0.66	0.09	0.71	0.32	0.73	7.58
1.00	0.02	0.44	0.04	0.42	0.11	0.51	3.33
0.82	0.02	0.22	0.01	0.21	0.02	0.25	0.69
0.40	0.00	0.10	0.00	0.07	0.00	0.08	0.06

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.16	114.86	1.16	286.35	1.15	910.50	1.17	1402.50
0.69	27.78	0.98	110.46	0.96	465.32	0.92	2076.90
0.38	7.30	0.62	48.54	0.65	202.18	0.43	348.57
0.25	3.23	0.27	8.15	0.33	51.35	0.16	50.47
0.10	0.49	0.10	1.07	0.19	15.18	0.07	8.75
0.04	0.07	0.03	0.08	0.09	2.77	0.04	3.32

Empirical Model for Core Loss using Steinmetz Equation: Sinusoid Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

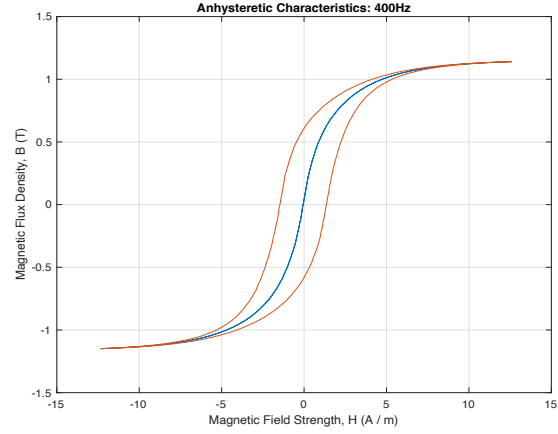
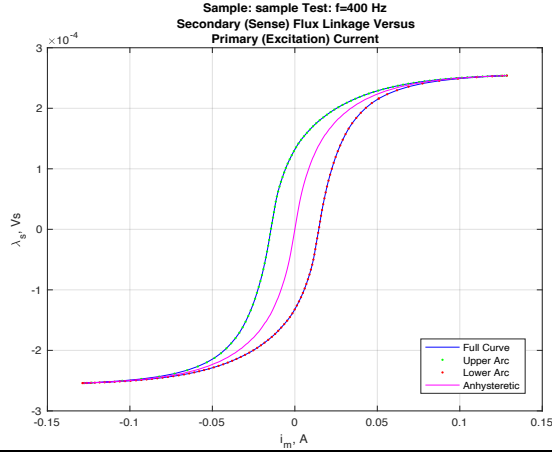
Steinmetz Coefficients for Curve Fit

α	1.4521	
β	2.2016	
k_h	1.56559E-05	W / kg

Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

Anhyseric BH Plots: Sinusoid Excitation



μ_r	α (1/T)	β (1/T)	γ (T)
999999.7367	0.3217	21.9613	0.91421
	0.31242	38.4615	0.97845
f (Hz)	0.0026955	39.364	0.66547
400	0.001	39.1108	0.48231

$$B = \mu_B(B)H$$

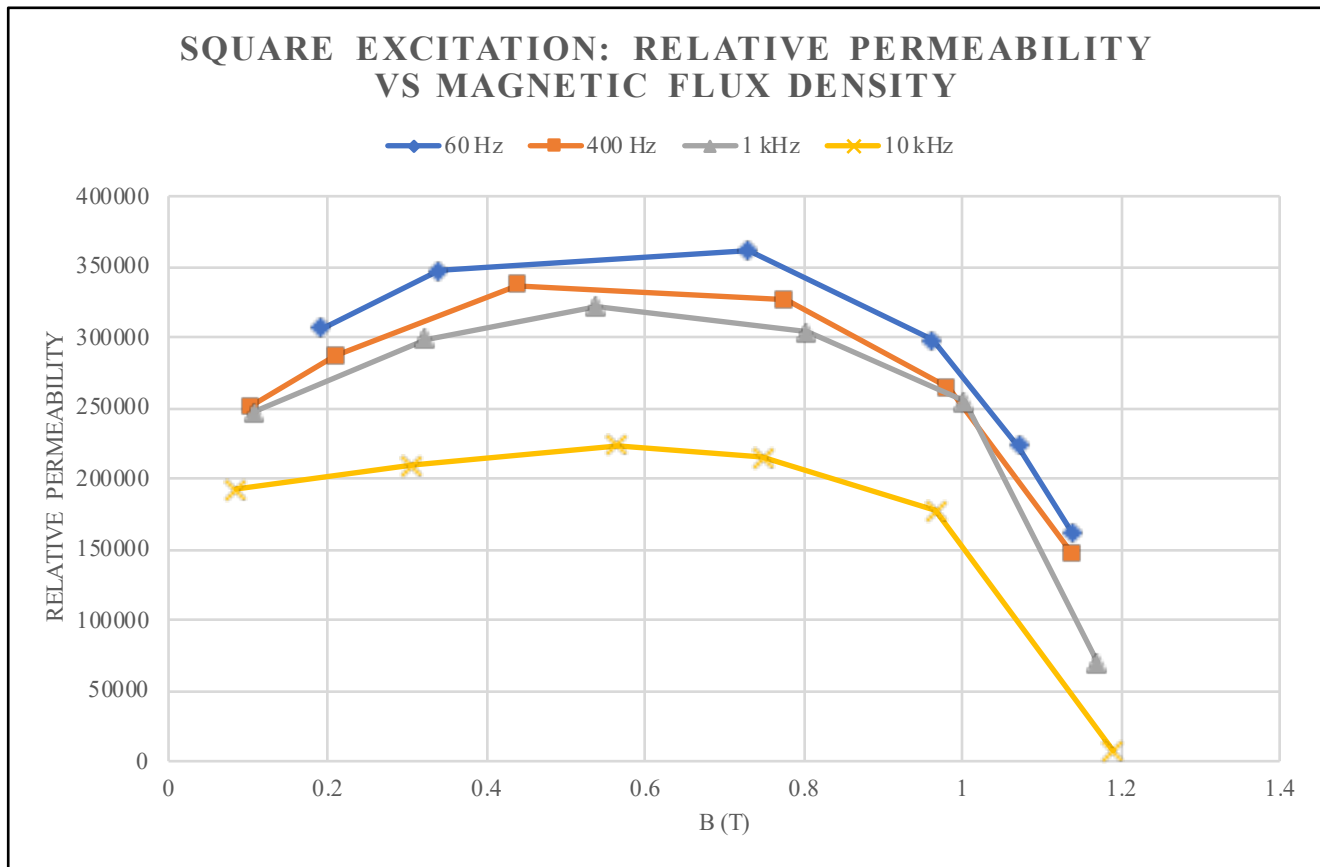
$$\mu_B(B) = \mu_B \frac{r(B)}{r(B) - 1}$$

$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^K \alpha_k |B| + \delta_k \ln(\epsilon_k + \zeta_k e^{-\beta_k |B|})$$

$$\delta_k = \frac{\alpha_k}{\beta_k} \quad \zeta_k = \frac{1}{1 + e^{-\beta_k \gamma_k}} \quad \epsilon_k = \frac{e^{-\beta_k \gamma_k}}{1 + e^{-\beta_k \gamma_k}}$$

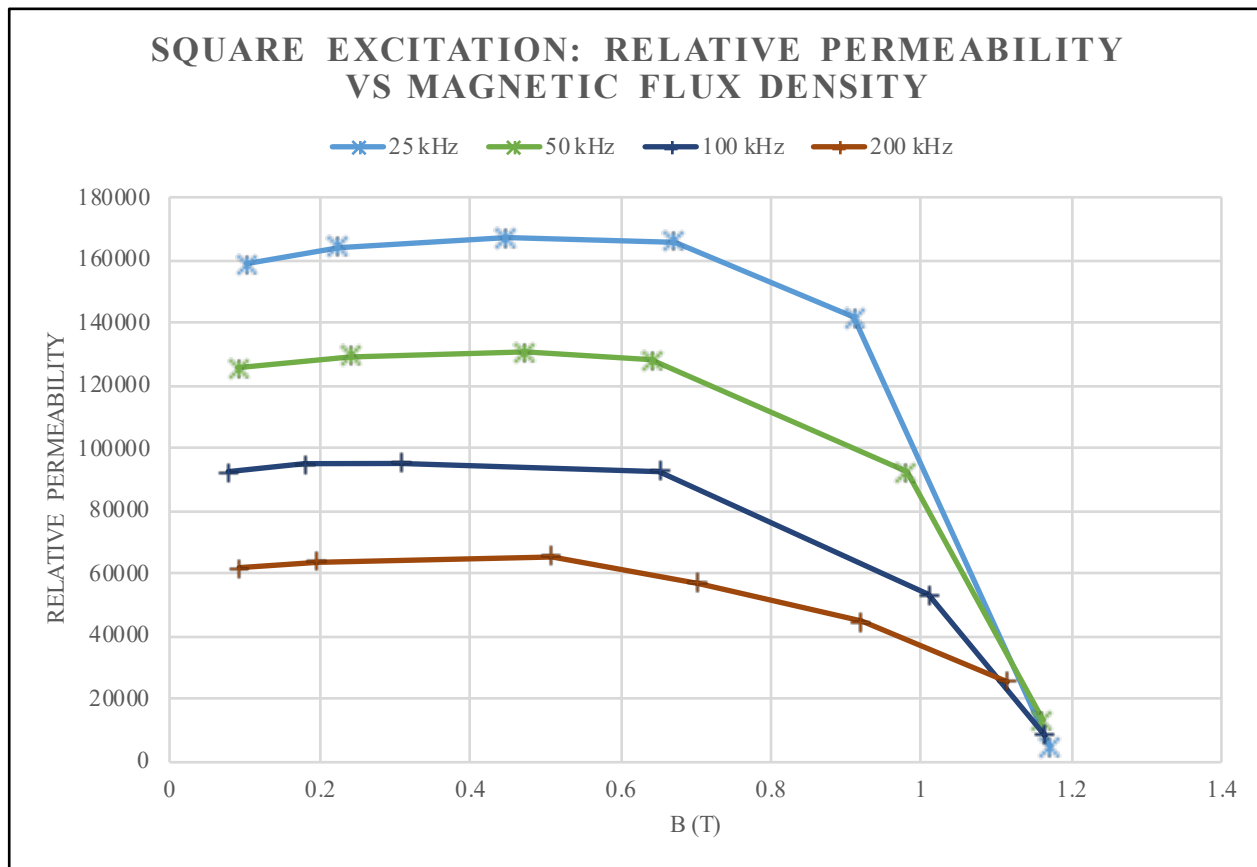
The anhyseric plot is computed by fitting the outer most BH curve within the plot, which coefficients are obtained as a function of flux density B from this equation. For more of the characteristic model equation shown above, see: G. M. Shane and S. D. Sudhoff, "Refinements in Anhyseric Characterization and Permeability Modeling," in *IEEE Transactions on Magnetics*, vol. 46, no. 11, pp. 3834-3843, Nov. 2010.

b. Square Excitation Magnetic Characterization.



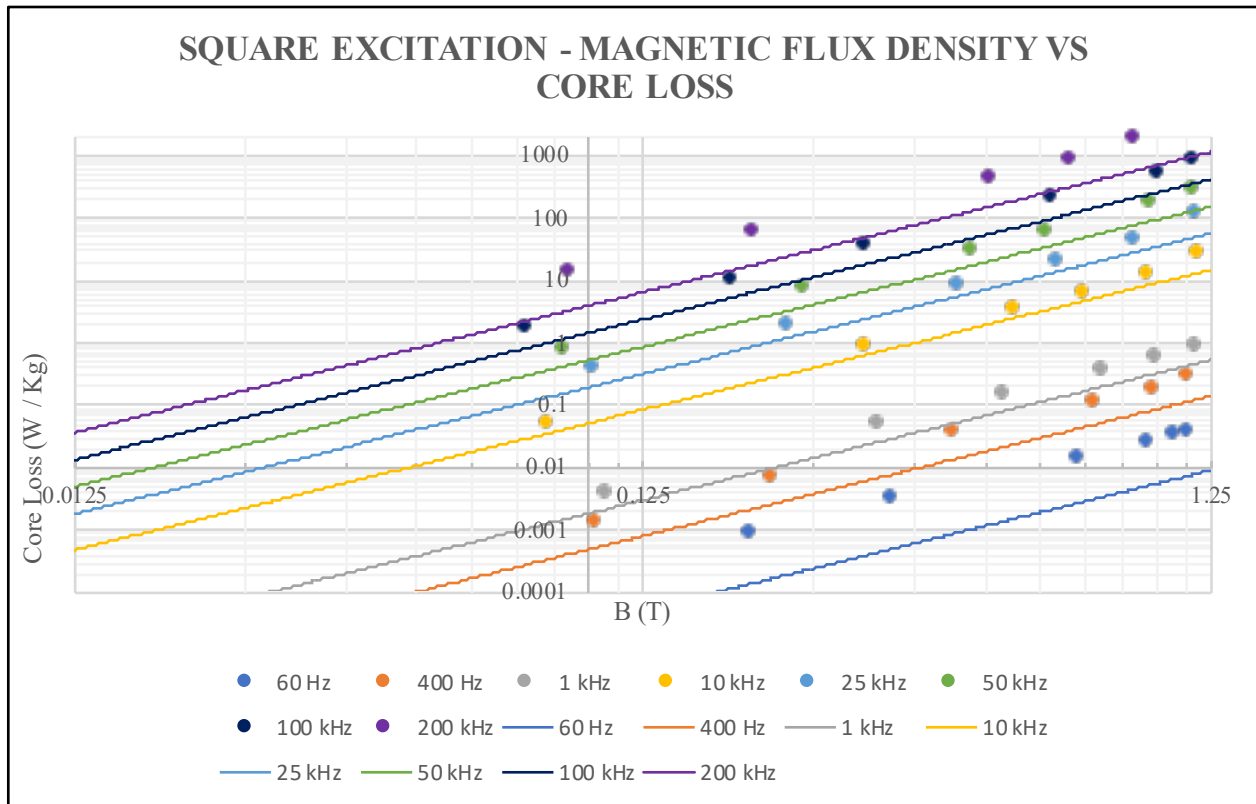
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.14	161613.13	1.14	145827.01	1.17	69887.75
1.07	223067.53	0.98	264185.80	1.00	254385.96
0.96	298361.23	0.78	326610.41	0.80	303940.31
0.73	361484.05	0.44	336496.18	0.54	321831.65
0.34	346805.99	0.21	286300.13	0.32	299358.60
0.19	306131.90	0.10	250336.45	0.11	246955.09

10 kHz	
B (T)	μ_r
1.19	7407.03
0.97	177277.96
0.75	215357.38
0.56	223227.18
0.31	209582.91
0.09	192129.00



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.17	5027.55	1.16	13465.62	1.16	8568.24
0.91	141748.54	0.98	92387.66	1.01	53400.25
0.67	165890.26	0.64	128141.08	0.65	92881.47
0.45	167160.46	0.47	130735.41	0.31	95185.91
0.22	164336.97	0.24	129508.86	0.18	94733.07
0.10	158554.58	0.09	125552.50	0.08	92282.22

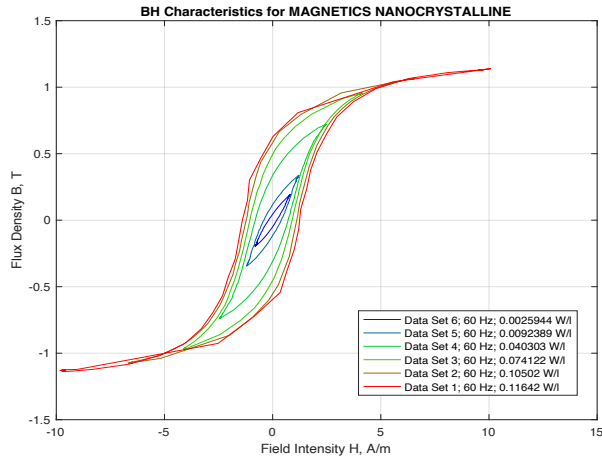
200 kHz	
B (T)	μ_r
1.11	25648.56
0.92	44751.20
0.70	57131.69
0.51	65388.56
0.20	63886.23
0.09	61917.92



Magnetic Flux Density vs Core Loss - Table							
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.14	0.04	1.14	0.29	1.17	0.89	1.19	26.94
1.07	0.03	0.98	0.19	1.00	0.58	0.97	12.54
0.96	0.02	0.78	0.11	0.80	0.35	0.75	6.49
0.73	0.01	0.44	0.04	0.54	0.15	0.56	3.33
0.34	0.00	0.21	0.01	0.32	0.05	0.31	0.86
0.19	0.00	0.10	0.00	0.11	0.00	0.09	0.05

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.17	119.83	1.16	302.03	1.16	820.50	1.11	3702.40
0.91	44.49	0.98	174.62	1.01	544.65	0.92	1798.40
0.67	20.52	0.64	58.79	0.65	207.13	0.70	856.06
0.45	8.31	0.47	30.19	0.31	35.98	0.51	409.58
0.22	1.97	0.24	7.54	0.18	10.50	0.20	59.22
0.10	0.38	0.09	0.76	0.08	1.73	0.09	13.58

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



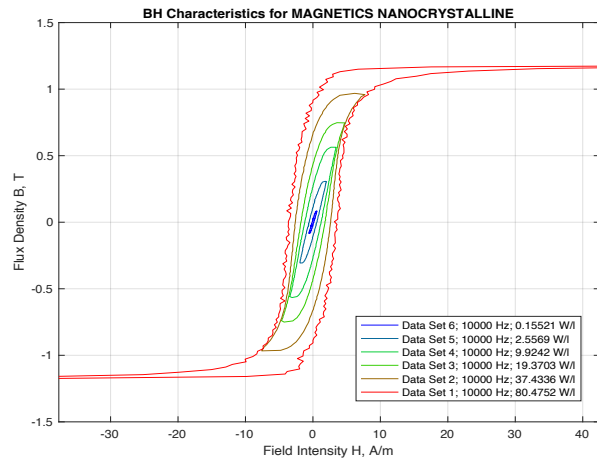
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit

α	1.4467	
β	2.2458	
k_h	1.49975E-05	W / kg

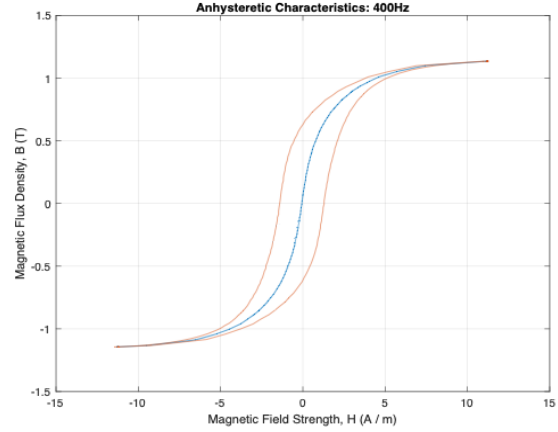
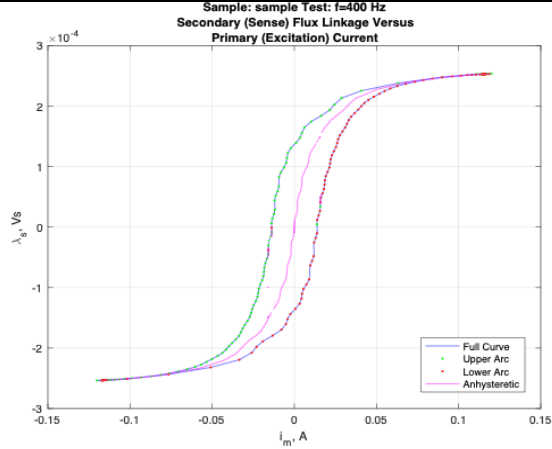


(b)

Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

Anhyseric BH Plots: Square Excitation



μ_r	α (1/T)	β (1/T)	γ (T)
417054.3687	0.97217	32.36255	0.73275
	0.075792	72.19302	0.7
f (Hz)			
400	0.052901	102.4462	0.83415
	0.0018701	367.5594	0.52389

$$B = \mu_B(B)H$$

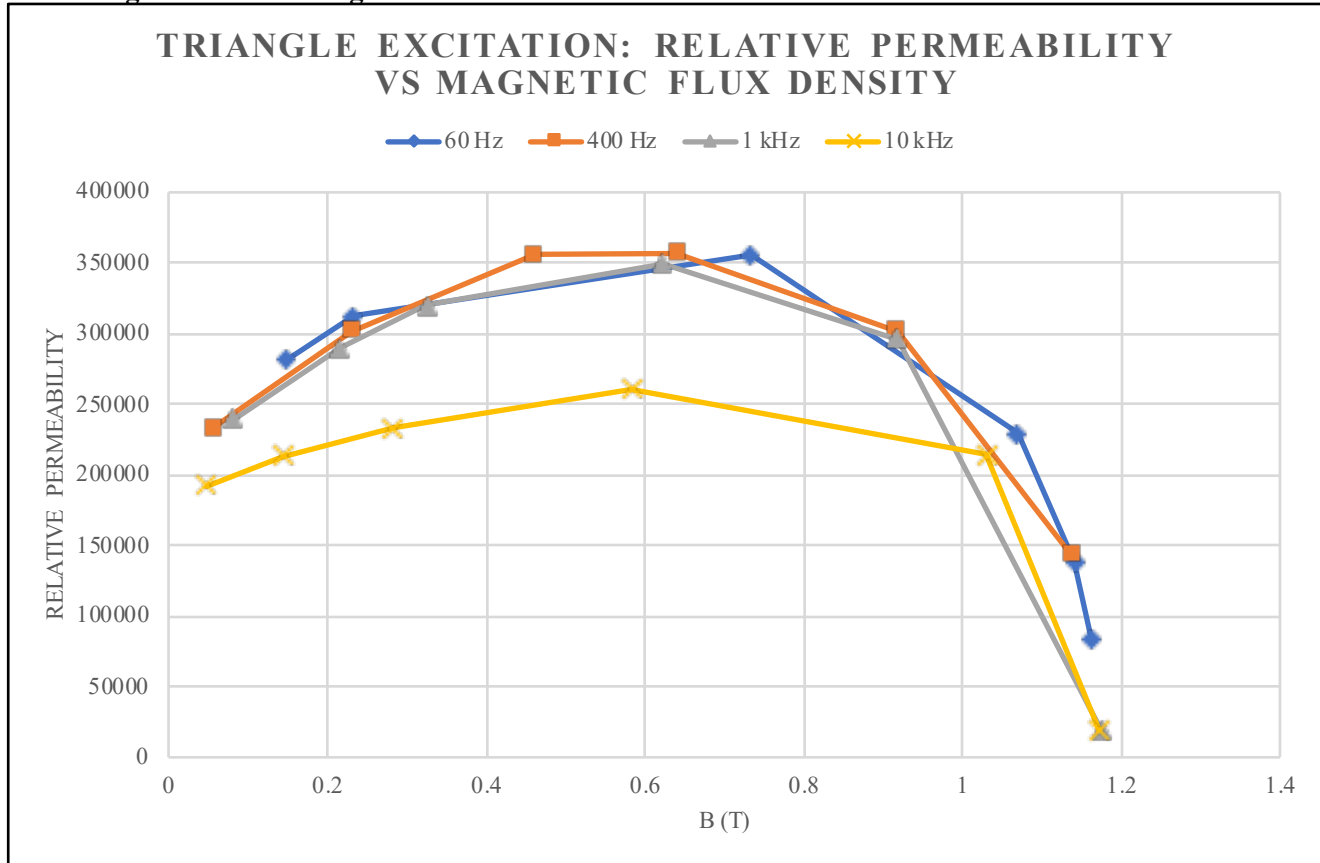
$$\mu_B(B) = \mu_B \frac{r(B)}{r(B) - 1}$$

$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^K \alpha_k |B| + \delta_k \ln(\epsilon_k + \zeta_k e^{-\beta_k |B|})$$

$$\delta_k = \frac{\alpha_k}{\beta_k} \quad \zeta_k = \frac{1}{1 + e^{-\beta_k \gamma_k}} \quad \epsilon_k = \frac{e^{-\beta_k \gamma_k}}{1 + e^{-\beta_k \gamma_k}}$$

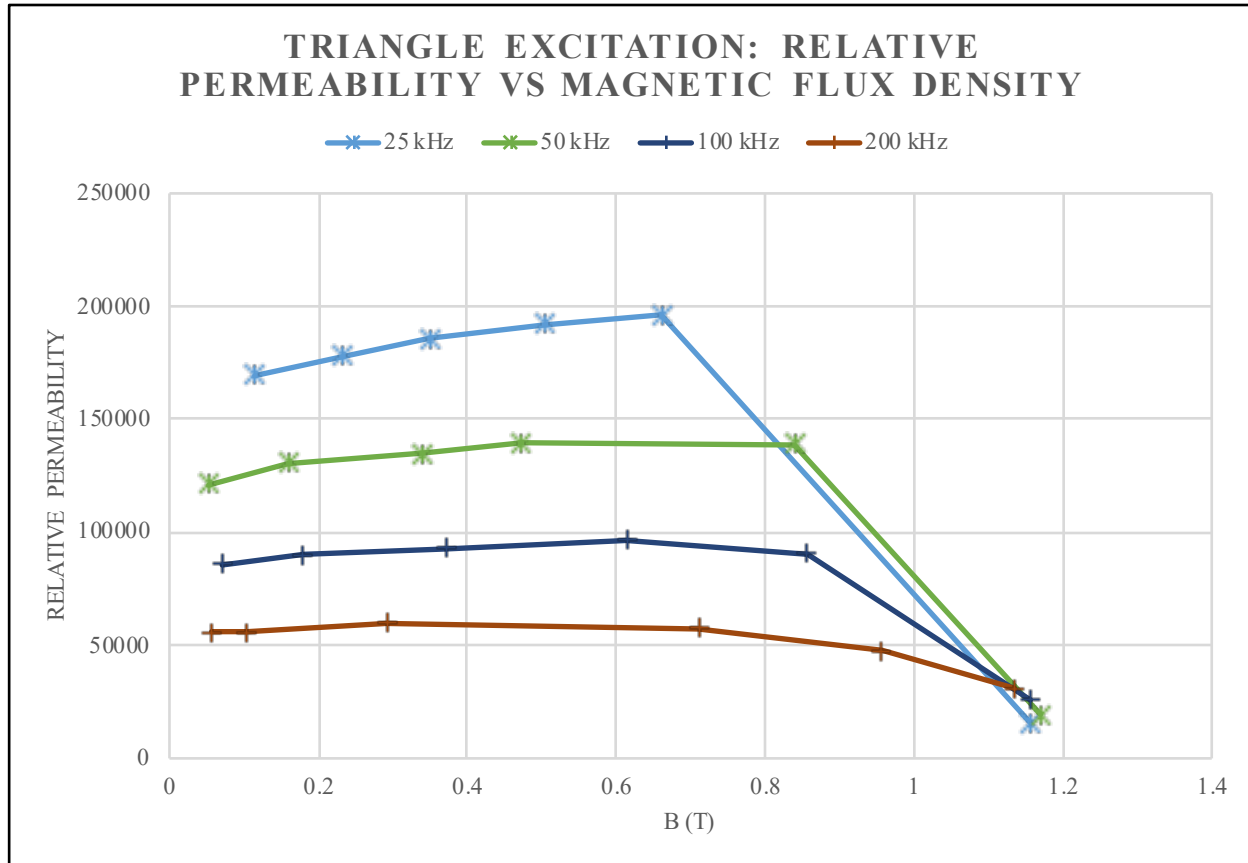
The anhyseric plot is computed by fitting the outer most BH curve within the plot, which coefficients are obtained as a function of flux density B from this equation. For more of the characteristic model equation shown above, see: G. M. Shane and S. D. Sudhoff, "Refinements in Anhyseric Characterization and Permeability Modeling," in *IEEE Transactions on Magnetics*, vol. 46, no. 11, pp. 3834-3843, Nov. 2010.

c. Triangle Excitation Magnetic Characterization.



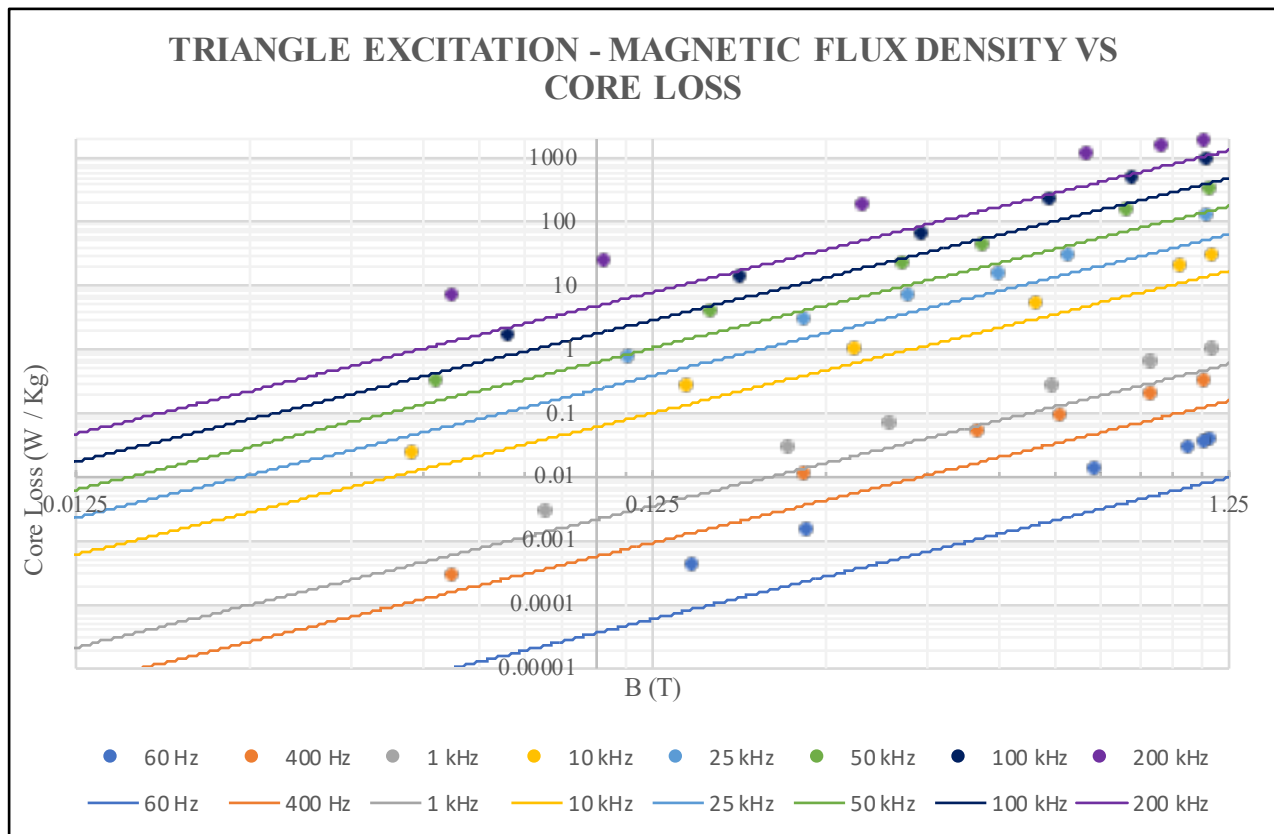
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.16	82419.27	1.14	143070.66	1.18	18285.91
1.14	138437.78	0.92	302244.30	0.92	295731.31
1.07	229140.25	0.64	356725.25	0.62	349285.71
0.73	355672.57	0.46	355321.95	0.32	319780.39
0.23	312553.32	0.23	302200.74	0.22	289232.78
0.15	280739.02	0.06	232567.93	0.08	239391.50

10 kHz	
B (T)	μ_r
1.17	19610.34
1.03	214228.65
0.58	260466.58
0.28	232944.60
0.14	213010.25
0.05	192704.51



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.16	15687.87	1.17	19488.73	1.16	25855.08
0.66	196283.77	0.84	138679.00	0.86	90527.67
0.50	192227.14	0.47	139674.41	0.61	96427.55
0.35	185767.74	0.34	134836.97	0.37	93121.08
0.23	178031.46	0.16	130447.64	0.18	89779.58
0.11	169790.95	0.05	121129.65	0.07	85780.39

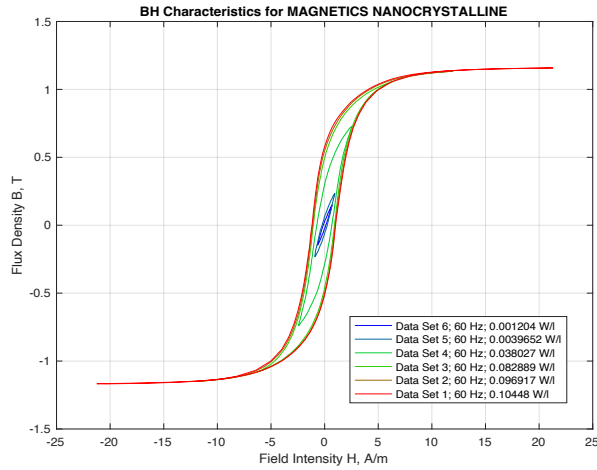
200 kHz	
B (T)	μ_r
1.14	31053.96
0.96	47502.19
0.71	57781.47
0.29	59714.35
0.10	55710.64
0.06	55540.48



Magnetic Flux Density vs Core Loss - Table							
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.16	0.04	1.14	0.29	1.18	1.00	1.17	27.35
1.14	0.03	0.92	0.18	0.92	0.58	1.03	18.91
1.07	0.03	0.64	0.09	0.62	0.25	0.58	4.92
0.73	0.01	0.46	0.05	0.32	0.07	0.28	0.99
0.23	0.00	0.23	0.01	0.22	0.03	0.14	0.24
0.15	0.00	0.06	0.00	0.08	0.00	0.05	0.02

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.16	117.96	1.17	302.77	1.16	925.40	1.14	1697.60
0.66	27.12	0.84	150.05	0.86	451.81	0.96	1490.40
0.50	14.56	0.47	41.61	0.61	201.04	0.71	1085.60
0.35	6.69	0.34	21.47	0.37	62.53	0.29	168.93
0.23	2.88	0.16	3.54	0.18	12.37	0.10	22.46
0.11	0.69	0.05	0.29	0.07	1.57	0.06	6.69

Empirical Model for Core Loss using Steinmetz Equation: Triangle Excitation via Sudhoff Simulation



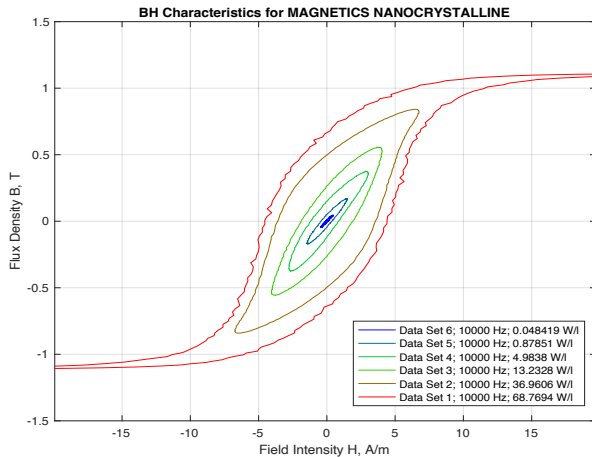
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit

α	1.4553	
β	2.2227	
k_h	1.55744E-05	W / kg

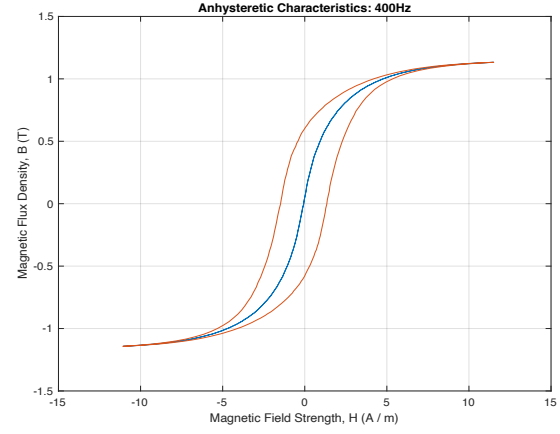
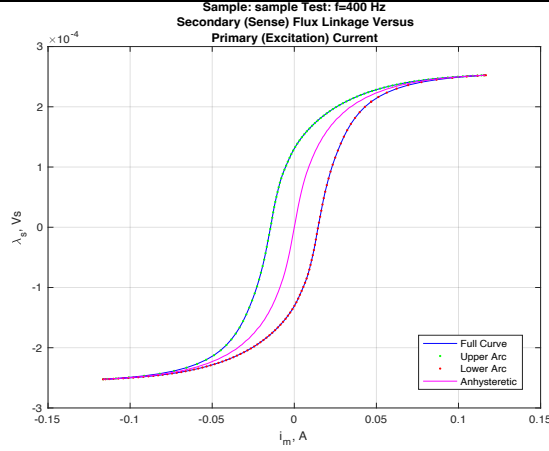


(b)

Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

Anhyseric BH Plots: Triangle Excitation



x	α (1/T)	β (1/T)	γ (T)
5400.197	1.1618	20.4369	0.66812
	0.062518	24.9454	0.68382
f (Hz)	0.0058192	24.7369	0.58382
400	0.0058192	97.4351	0.41853

$$B = \mu_B(B)H$$

$$\mu_B(B) = \mu_B \frac{r(B)}{r(B) - 1}$$

$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^K \alpha_k |B| + \delta_k \ln(\epsilon_k + \zeta_k e^{-\beta_k |B|})$$

$$\delta_k = \frac{\alpha_k}{\beta_k} \quad \zeta_k = \frac{1}{1 + e^{-\beta_k \gamma_k}} \quad \epsilon_k = \frac{e^{-\beta_k \gamma_k}}{1 + e^{-\beta_k \gamma_k}}$$

The anhyseric plot is computed by fitting the outer most BH curve within the plot, which coefficients are obtained as a function of flux density B from this equation. For more of the characteristic model equation shown above, see: G. M. Shane and S. D. Sudhoff, "Refinements in Anhyseric Characterization and Permeability Modeling," in *IEEE Transactions on Magnetics*, vol. 46, no. 11, pp. 3834-3843, Nov. 2010.

Section Two: Elevated Temperature Environmental Measurements. Magnetic Core Characterization Testing: Test Procedures and Results.

Purpose.

This test procedure is used to measure the B-H Curves, core losses, and permeability of the core under test at varying temperatures.

Test Equipment.

The test equipment shall be used as follows:

Lab Asset Number	Description	Manufacturer	Model Number	Serial Number
WAV0003	Arbitrary Waveform Generator	Keysight Technologies	EDU33212A	CN61310043
AMP0001	High Speed Power Amplifier	NF Electronic Instruments	4025	4025-112
OSC0003	Oscilloscope (500 MHz)	Keysight Technologies	MSOX4054A	MY61260112
PRO0002	Differential Probe	Rigol	RP1025D	2014187
PRO0003	10:1 200 MHz Differential Probe	Keysight Technologies	N2792A	PH61260009
PRO0005	AC / DC Current Probe	Keysight Technologies	1147B	JP61071359
CAP0003	0.01 uF Capacitor	Cornell Dubilier Electronics (CDE)	SCRN244R-F	None
CAP0004	260 uF Capacitor	AVX-TPC	FFLI6L0267K	1D8B537871FO
RES0001	5 Ohm Resistor	Riedon	UB15-5RF1	None
LAB0001	Computer	AMPED	None	None
WAV0003	Arbitrary Waveform Generator	Keysight Technologies	EDU33212A	CN61310043

Test Procedures.

I. Core Loss Testing - Low Signal with Amplifier Setup – Room Temperature – Manual Procedure.

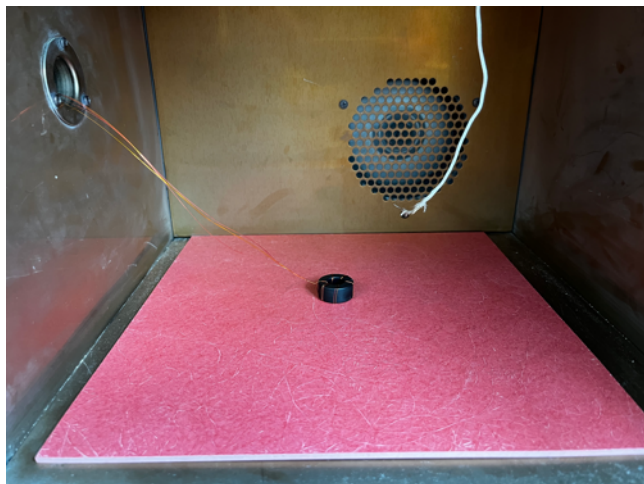
Per AMPED Standard AMP-STD-001, below is the procedure for manual operation of equipment for the Low Signal Setup, to be applied as follows. For a more detailed and general procedure to apply the test, refer to the referenced standard described here.

- a. Turn on the measurement equipment and allow sufficient time for stabilization (e.g. 20 minutes).
- b. Set the Arbitrary Waveform Generator to the following settings.
 - Begin with a low signal.
 - Frequency. Set frequency as initial starting point at 60 Hz. Increment based on the desired frequencies necessary to perform measurements.
 - Amplitude. Begin with an amplitude value, in terms of peak-to-peak (V_{PP}), at 10 milli. Increase where deemed appropriate to make sure a fully functioning signal is observed in an acceptable tolerance.
- c. Set the Power Amplifier values.
 - Be sure to press input cable connected to on (usually A).
 - Press the desired gain. Performed in these tests at “X50”.

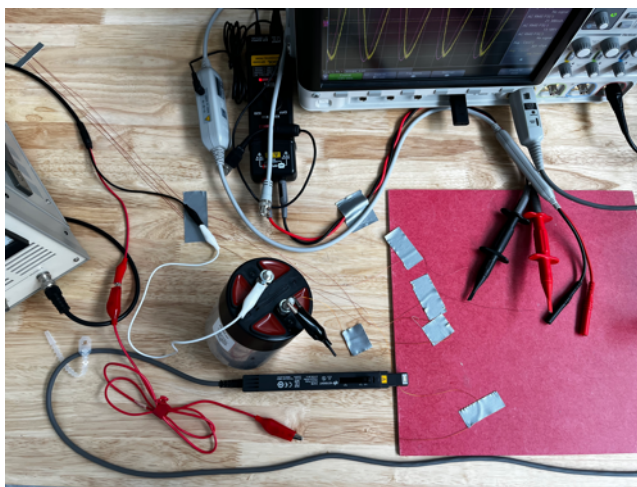
- d. Set the Oscilloscope to the following settings.
 - Specify Probe Attenuation.
 - Measurements were performed with a Keysight 1147B Current Probe has a fixed attenuation ratio of 0.1 V/A and cannot be changed.
 - Voltage Probe from Keysight, the N2792, was used for measurements, and has fixed attenuation ratio of 5:1 after calibration with oscilloscope. Probe with Asset Number PRO0003 was used to acquire data from 60 Hz – 10 kHz.
 - Voltage Probe from Rigol, the RP1100D, was used for measurements, and has fixed attenuation ratio of 50:1 after calibration. Probe with Asset Number PRO0009 was used to acquire data from 50 – 200 kHz.
 - All data was captured with High Resolution Settings under Waveform-Acquire Menu.
- e. Turn output of Arbitrary Waveform Generator on.
- f. Level the output voltage at the offset adjust with flat head screw driver, if possible. Note if probe does not have that capability.
 - For data presented, Voltage probe with asset number PRO0009 does not have the capability.
- g. At each temperature change, let the core soak for about five minutes before taking any measurements.
- h. Examine the Waveform on the Oscilloscope read from the Current Probe on the input side and the Differential Probe on the Output Side.
 - Be sure to capture 3 - 5 periods of the excitation signal being applied.
 - Look for point of saturation for the core. This can be visually examined when the waveform's maximum value no longer increases. Sine and Triangular waveforms flatten, Square becomes more in a curve. See Data Presentation for examples.
 - Magnetic Flux is optional for oscilloscope waveforms but recommended.
- i. Auto zero and Degauss the Current Probe before step i. Also Degauss where Average Current Waveform value climbs above an acceptable tolerance of +/- 10 mA.
- j. Setup included correction components for DC Biasing part of the setup. See the test setup section for a diagram. Note a 5 Ohm Resistor was in parallel with one 0.01 uF Capacitor from 60 – 400 Hz, and a 260 uF Capacitor was used from 1 – 200 kHz.
- k. Repeat steps a - f for Square Waveform, Triangular Waveform, or other excitation waveforms for examined interest.
- l. Record relevant data for Data Presentation.

Setup.

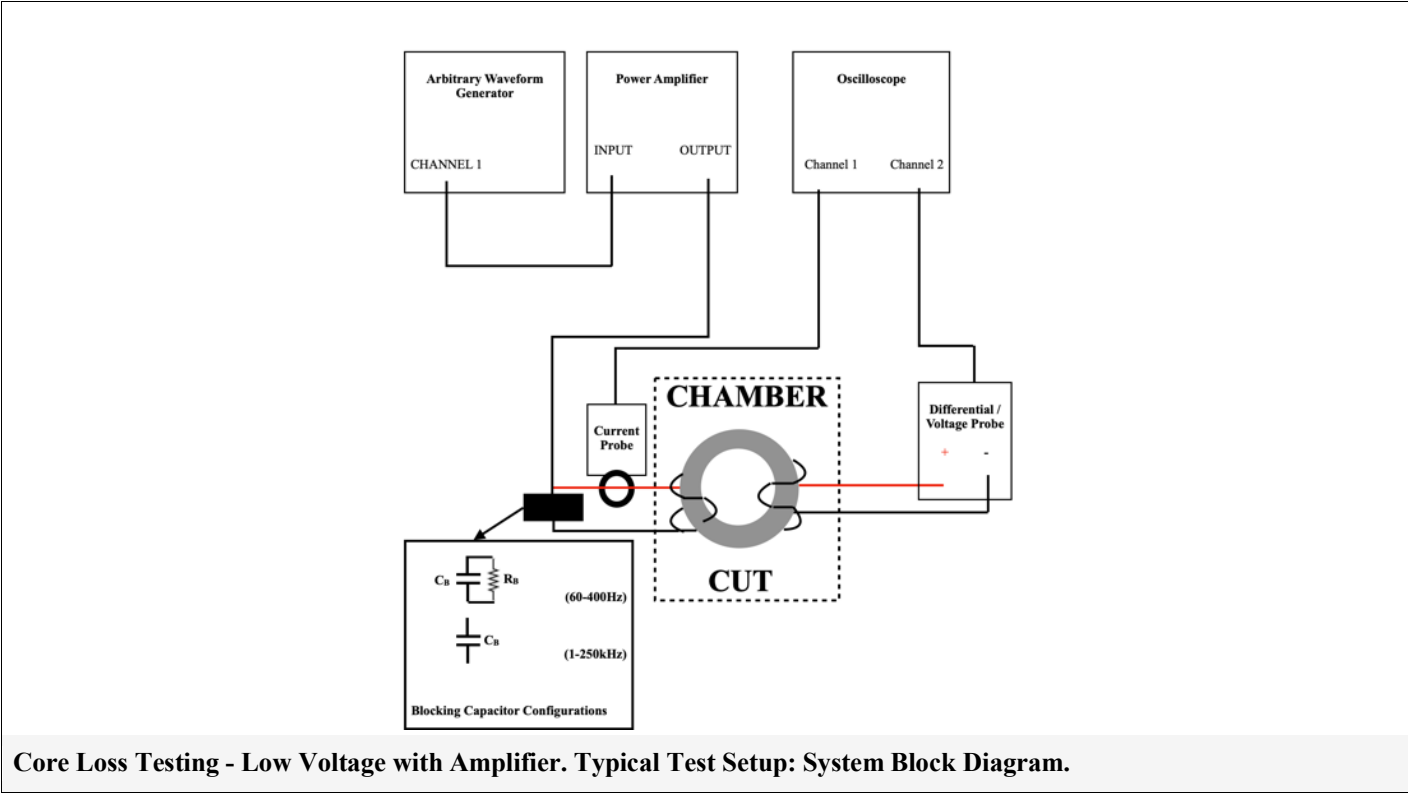
Core Testing. Configure the test equipment as shown below, with one figure showing the actual test setup, and another as the block diagram.



Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup.

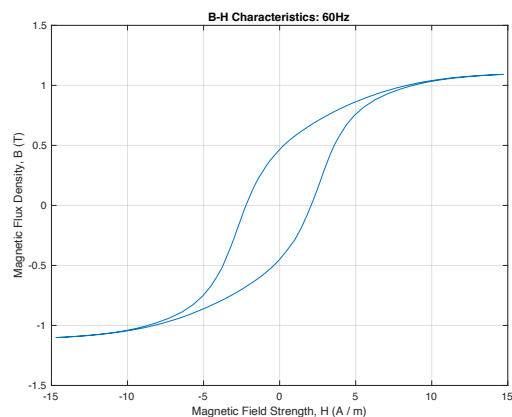
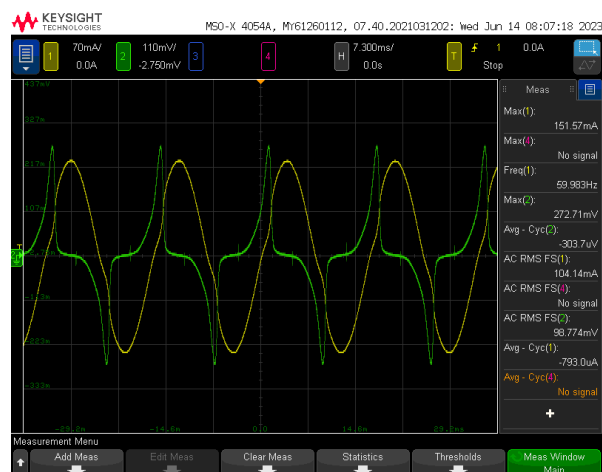


Core Loss Testing - Low Voltage with Amplifier. Cable Layout.

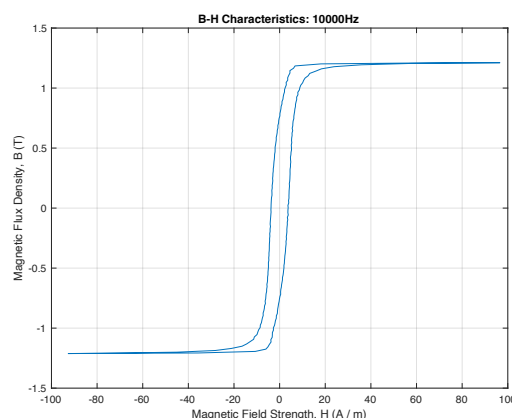
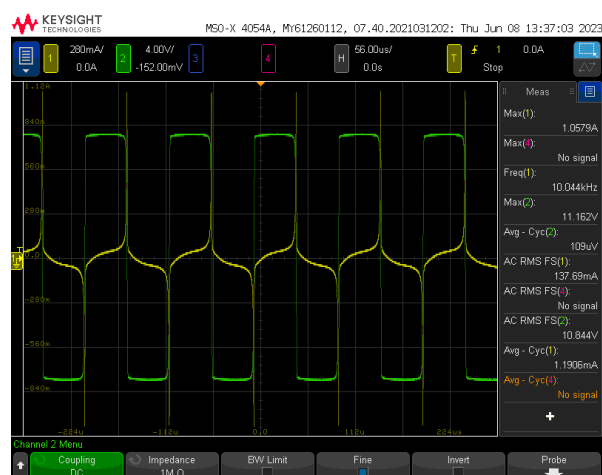


Data Presentation.

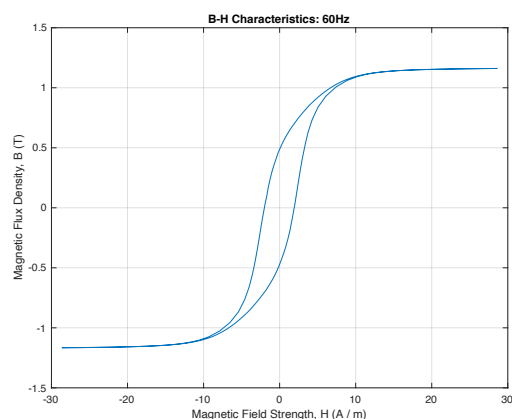
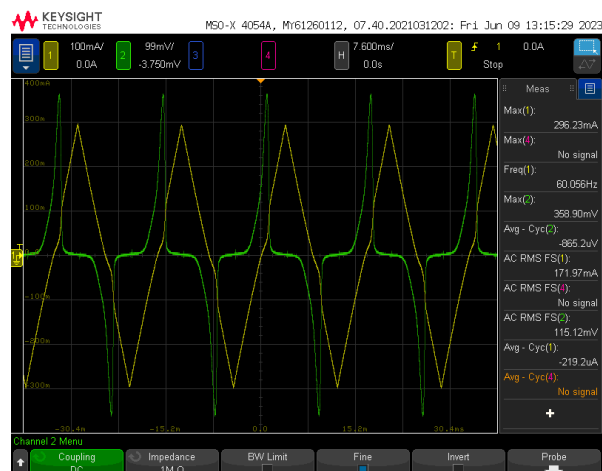
In this section, data is presented as each section indicates below.



150°C. Sample Sinusoidal Excitation Waveform and B-H Plot. 23.50 mV_{pp} 60Hz, Amplifier Gain X50.

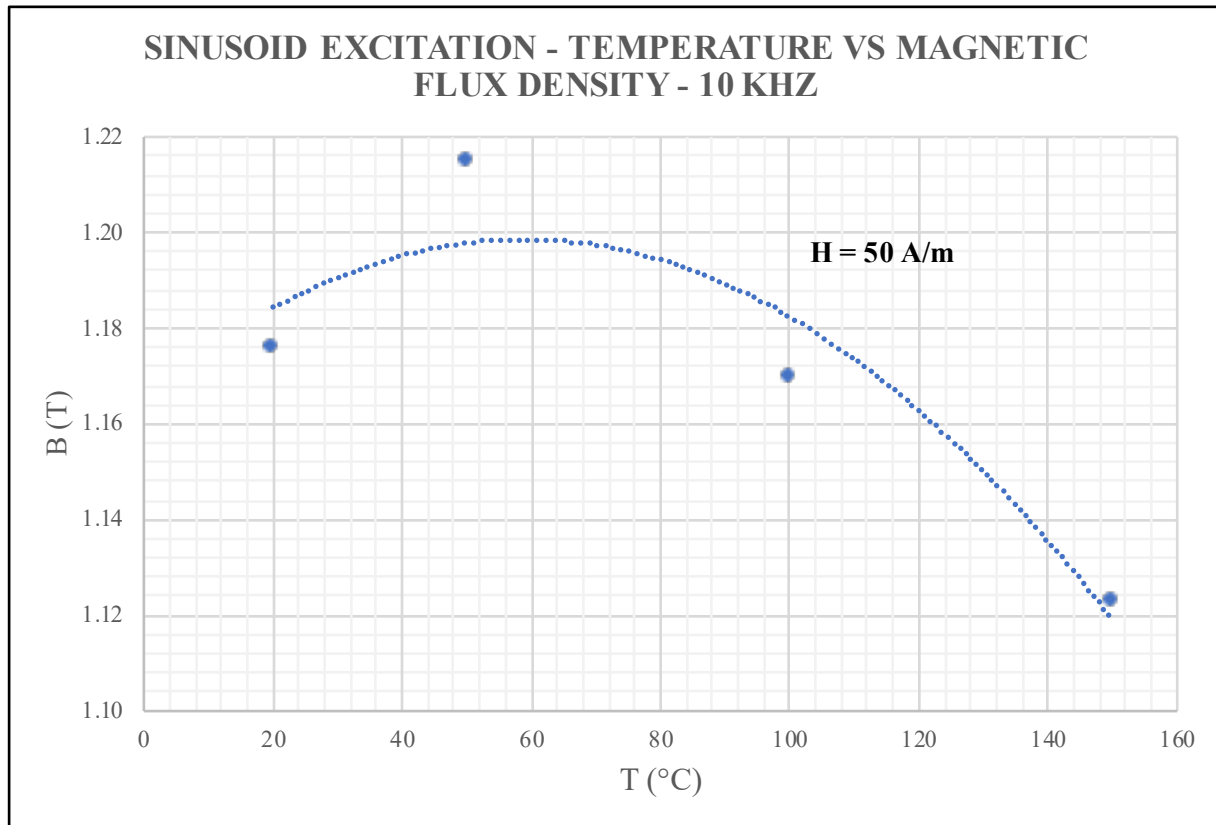


50°C. Sample Square Excitation Waveform and B-H Plot. 234.00 mV_{pp} 10kHz, Amplifier Gain X50.



100°C. Sample Triangular Excitation Waveform and B-H Plot. 47 mV_{pp} 60Hz, Amplifier Gain X50.

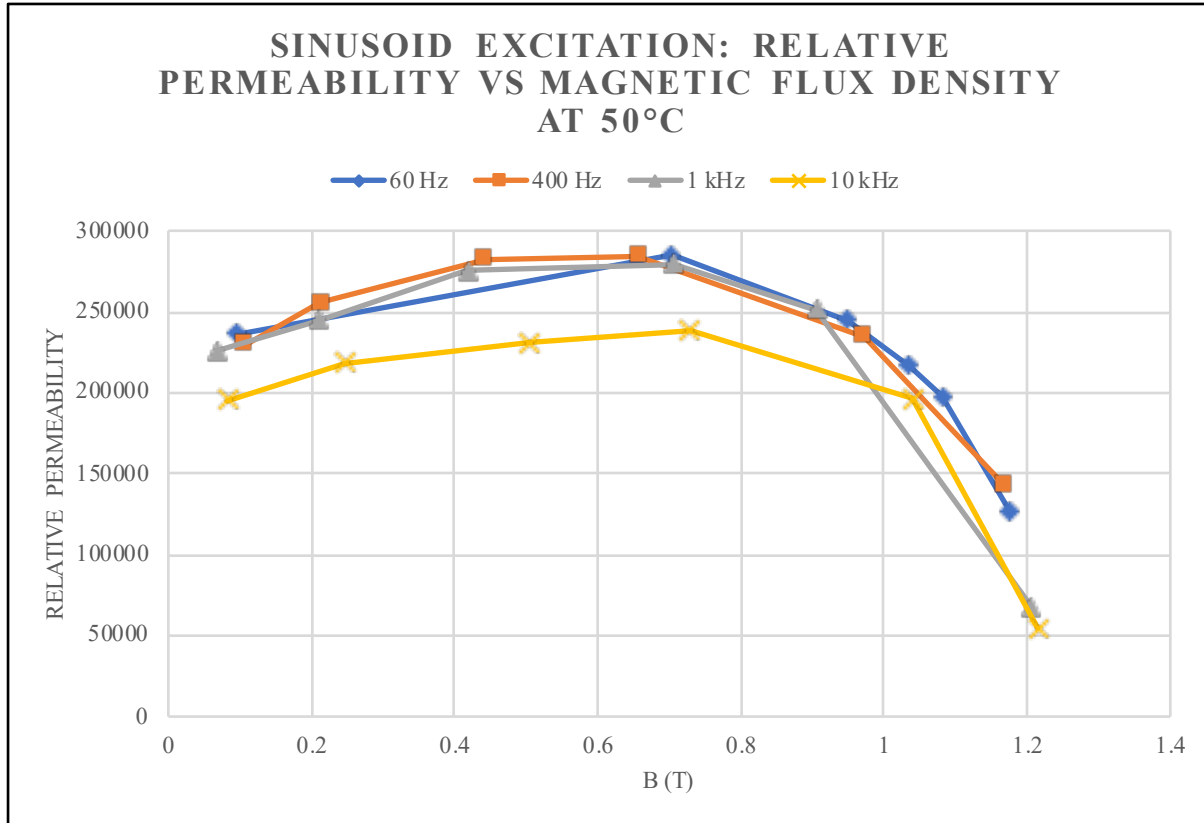
d. Sinusoid Excitation Magnetic Characterization.



Temperature Dependence vs Core Loss - Table

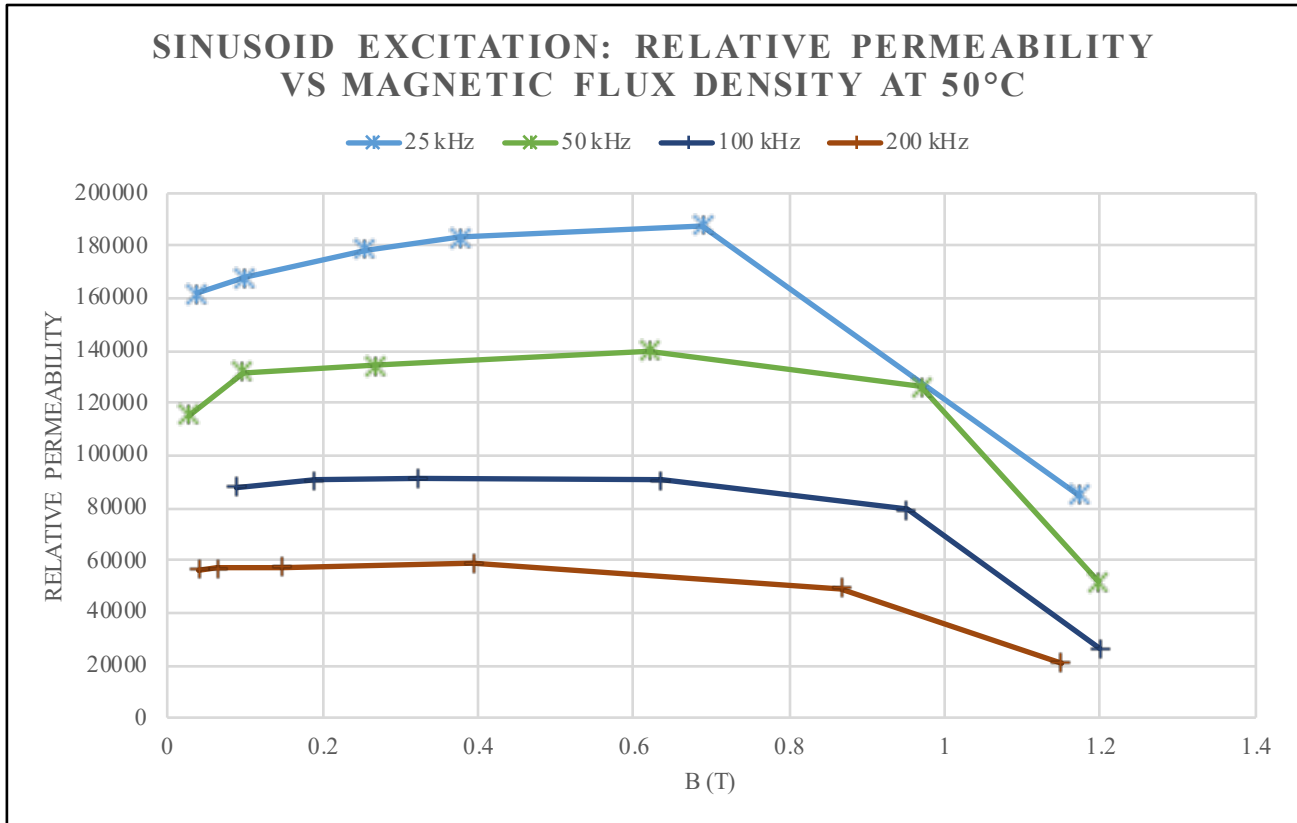
60 Hz		400 Hz		1 kHz		10 kHz	
T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)
20.00	1.16	20.00	1.14	20.00	1.18	20.00	1.18
50.00	1.18	50.00	1.17	50.00	1.21	50.00	1.21
100.00	1.13	100.00	1.12	100.00	1.16	100.00	1.17
150.00	1.10	150.00	1.06	150.00	1.04	150.00	1.12

25 kHz		50 kHz		100 kHz		200 kHz	
T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)
20.00	1.16	20.00	1.16	20.00	1.15	20.00	1.17
50.00	1.17	50.00	1.20	50.00	1.15	50.00	1.15
100.00	1.14	100.00	1.14	100.00	1.12	100.00	1.12
150.00	1.07	150.00	1.08	150.00	1.05	150.00	1.05



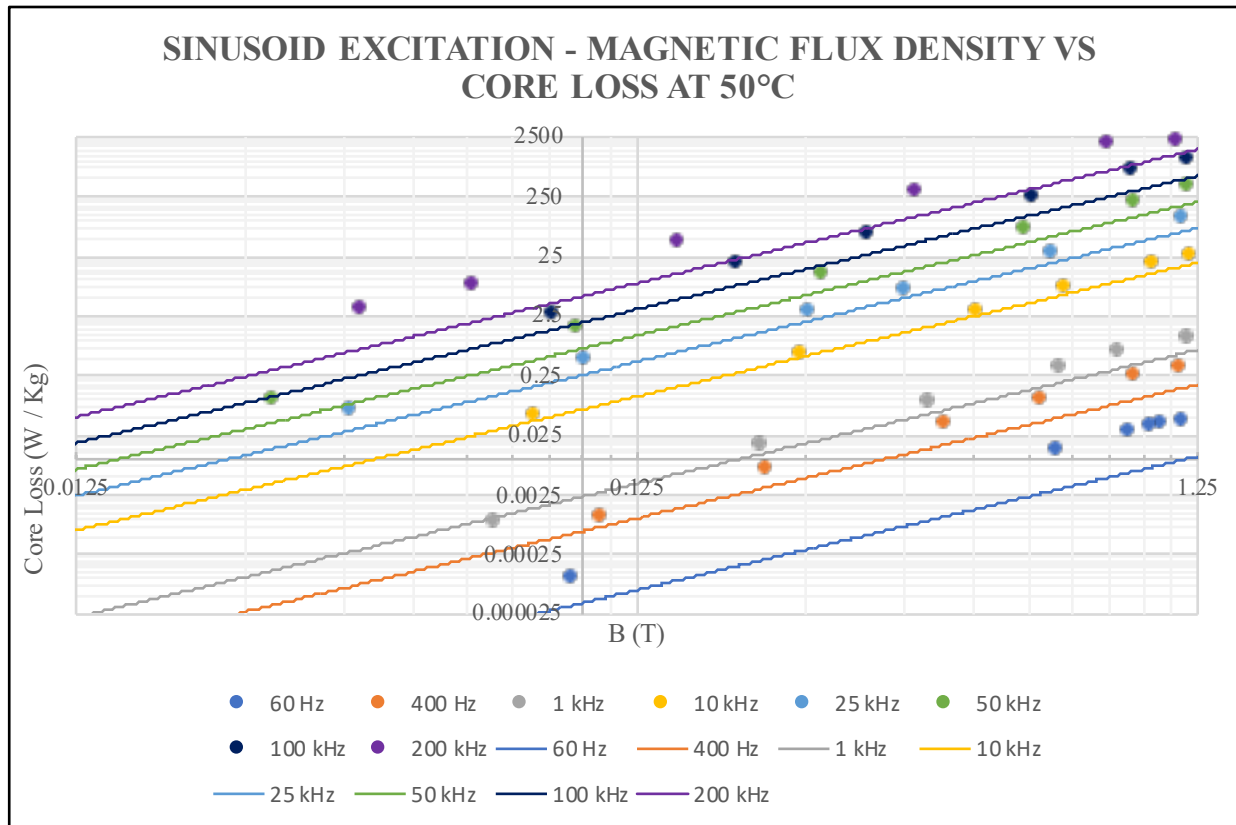
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.18	126740.16	1.17	143741.80	1.21	67141.41
1.08	197723.56	0.97	234607.80	0.91	251209.72
1.03	216390.47	0.66	284129.83	0.71	279083.00
0.95	244765.93	0.44	282831.20	0.42	274807.71
0.70	285091.53	0.21	255093.33	0.21	244716.29
0.10	236765.66	0.11	229768.04	0.07	225923.98

10 kHz	
B (T)	μ_r
1.21	54534.45
1.04	195870.26
0.73	238314.65
0.51	230597.08
0.25	218232.71
0.08	195649.60



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.17	84705.91	1.20	51915.88	1.20	26441.29
0.69	187560.69	0.97	125989.43	0.95	79593.36
0.38	183302.39	0.62	139757.24	0.63	90758.43
0.25	178332.60	0.27	134236.74	0.32	91267.77
0.10	167802.43	0.10	131591.14	0.19	90287.80
0.04	161703.17	0.03	115411.01	0.09	88046.71

200 kHz	
B (T)	μ_r
1.15	20738.64
0.87	49237.35
0.39	58928.58
0.15	57606.24
0.06	57146.33
0.04	56503.17

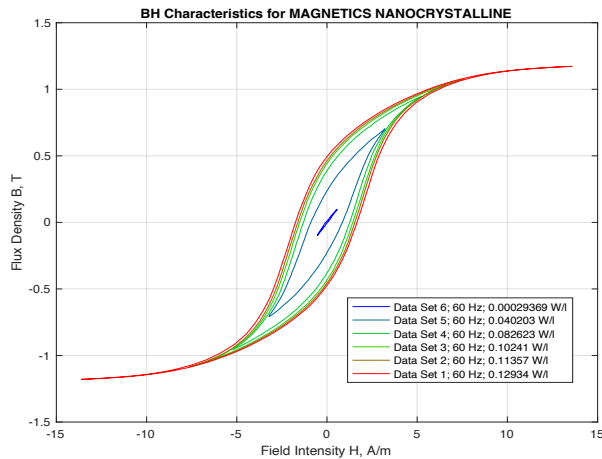


Magnetic Flux Density vs Core Loss - Table

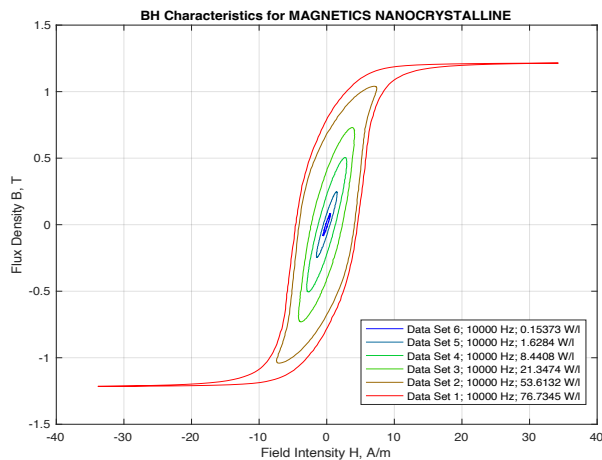
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.18	0.04	1.17	0.34	1.21	1.03	1.21	25.78
1.08	0.04	0.97	0.24	0.91	0.59	1.04	18.01
1.03	0.03	0.66	0.09	0.71	0.32	0.73	7.17
0.95	0.03	0.44	0.04	0.42	0.09	0.51	2.84
0.70	0.01	0.21	0.01	0.21	0.02	0.25	0.55
0.10	0.00	0.11	0.00	0.07	0.00	0.08	0.05

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.21	25.78	1.17	104.83	1.20	1026.20	1.15	2097.80
1.04	18.01	0.69	26.66	0.95	663.72	0.87	1960.10
0.73	7.17	0.38	6.63	0.63	240.14	0.39	296.15
0.51	2.84	0.25	2.94	0.32	59.80	0.15	42.96
0.25	0.55	0.10	0.45	0.19	17.59	0.06	8.08
0.08	0.05	0.04	0.06	0.09	2.60	0.04	3.22

Empirical Model for Core Loss using Steinmetz Equation: Sinusoid Excitation via Sudhoff Simulation



(a)



(b)

Steinmetz Equation

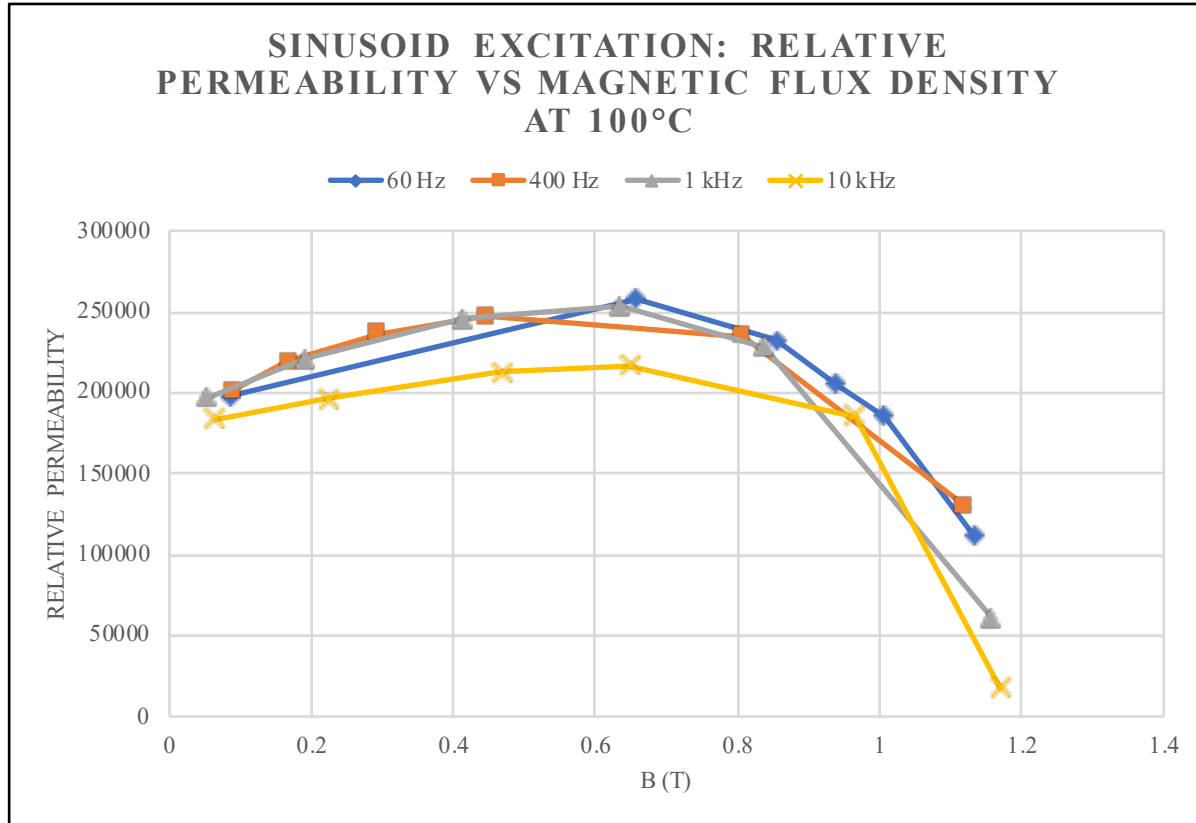
$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 50°C

α	1.4596	
β	2.242	
k_h	1.7243E-05	W / kg

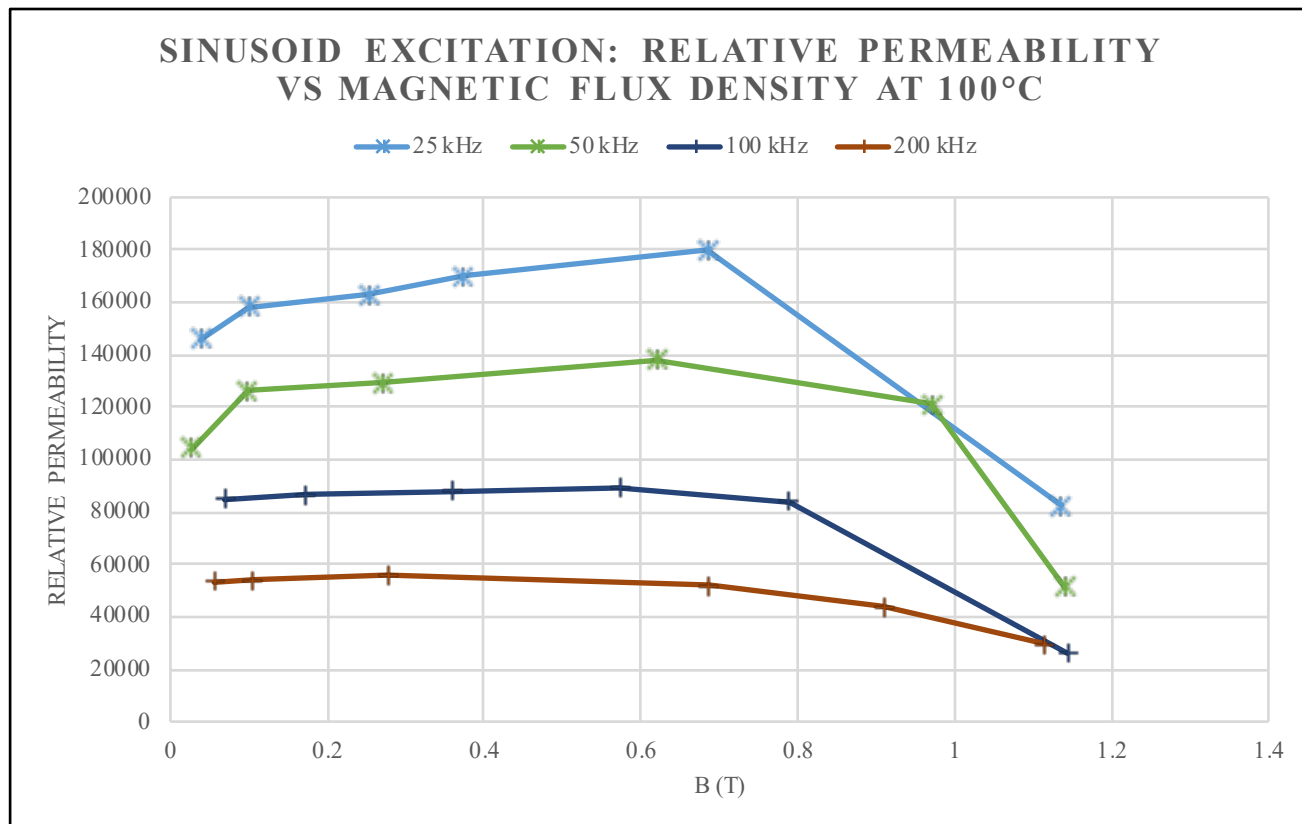
Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



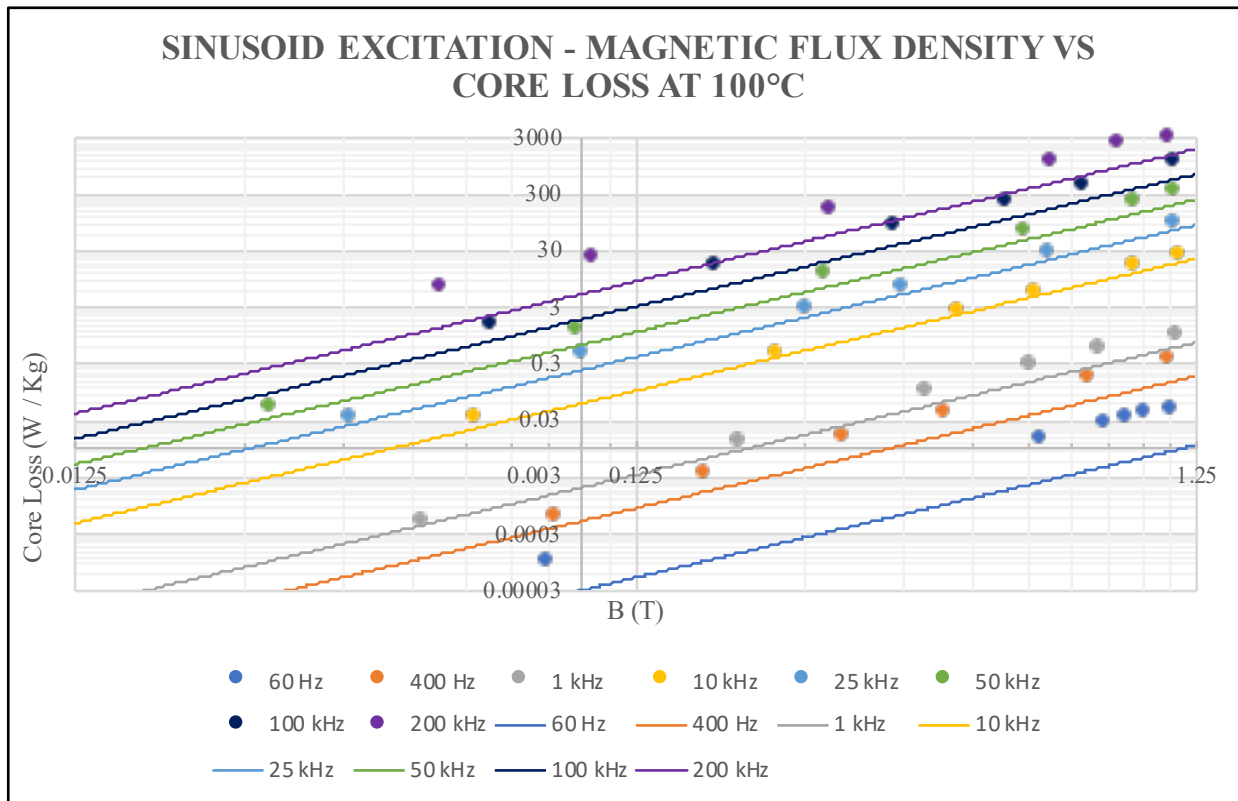
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.13	111603.33	1.12	130258.49	1.16	61280.64
1.01	185634.67	0.81	235007.36	0.84	228441.38
0.94	204967.98	0.45	247363.17	0.63	253454.03
0.86	232638.69	0.29	236440.18	0.41	245328.25
0.66	257722.18	0.17	218877.13	0.19	220587.62
0.09	198051.33	0.09	200828.34	0.05	196795.23

10 kHz	
B (T)	μ_r
1.17	17625.95
0.97	185236.36
0.65	216407.59
0.47	212518.39
0.22	195787.30
0.06	183432.77



25 kHz		50 kHz		200 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.14	82504.08	1.14	51174.26	1.14	26120.74
0.68	179958.29	0.97	121170.51	0.79	83942.87
0.37	169820.06	0.62	137824.23	0.57	89146.69
0.25	162891.19	0.27	129423.96	0.36	88046.95
0.10	157954.14	0.10	126007.95	0.17	86423.65
0.04	145732.69	0.03	104189.56	0.07	84879.77

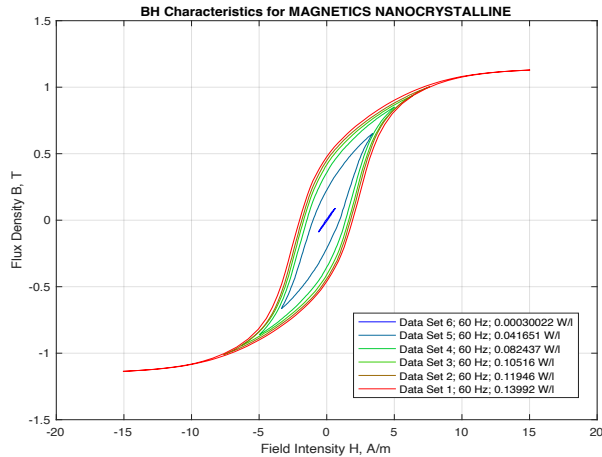
100 kHz	
B (T)	μ_r
1.12	29685.14
0.91	43875.86
0.69	52106.37
0.28	55907.10
0.11	53710.33
0.06	53205.62



Magnetic Flux Density vs Core Loss - Table							
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.13	0.05	1.12	0.35	1.16	1.03	1.17	24.95
1.01	0.04	0.81	0.18	0.84	0.57	0.97	15.88
0.94	0.04	0.45	0.04	0.63	0.29	0.65	5.84
0.86	0.03	0.29	0.02	0.41	0.10	0.47	2.53
0.66	0.01	0.17	0.00	0.19	0.01	0.22	0.47
0.09	0.00	0.09	0.00	0.05	0.00	0.06	0.03

25 kHz		50 kHz		100 kHz		100 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.14	96.85	1.14	327.35	1.14	1170.50	1.12	2979.40
0.68	27.83	0.97	209.80	0.79	447.33	0.91	2432.00
0.37	6.75	0.62	70.38	0.57	210.83	0.69	1144.40
0.25	2.97	0.27	12.05	0.36	80.13	0.28	162.03
0.10	0.45	0.10	1.19	0.17	15.73	0.11	23.74
0.04	0.03	0.03	0.05	0.07	1.56	0.06	6.71

Empirical Model for Core Loss using Steinmetz Equation: Sinusoid Excitation via Sudhoff Simulation



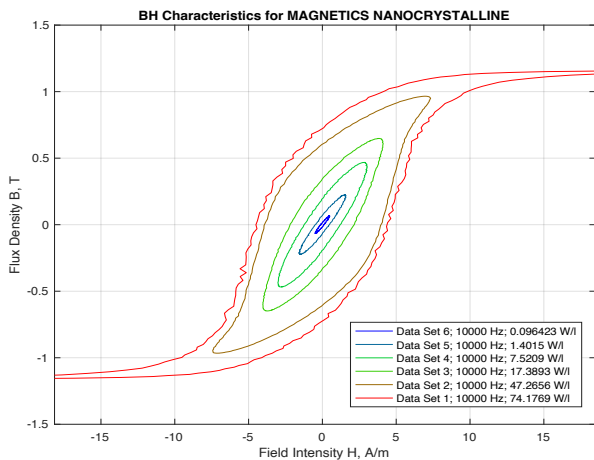
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 100°C

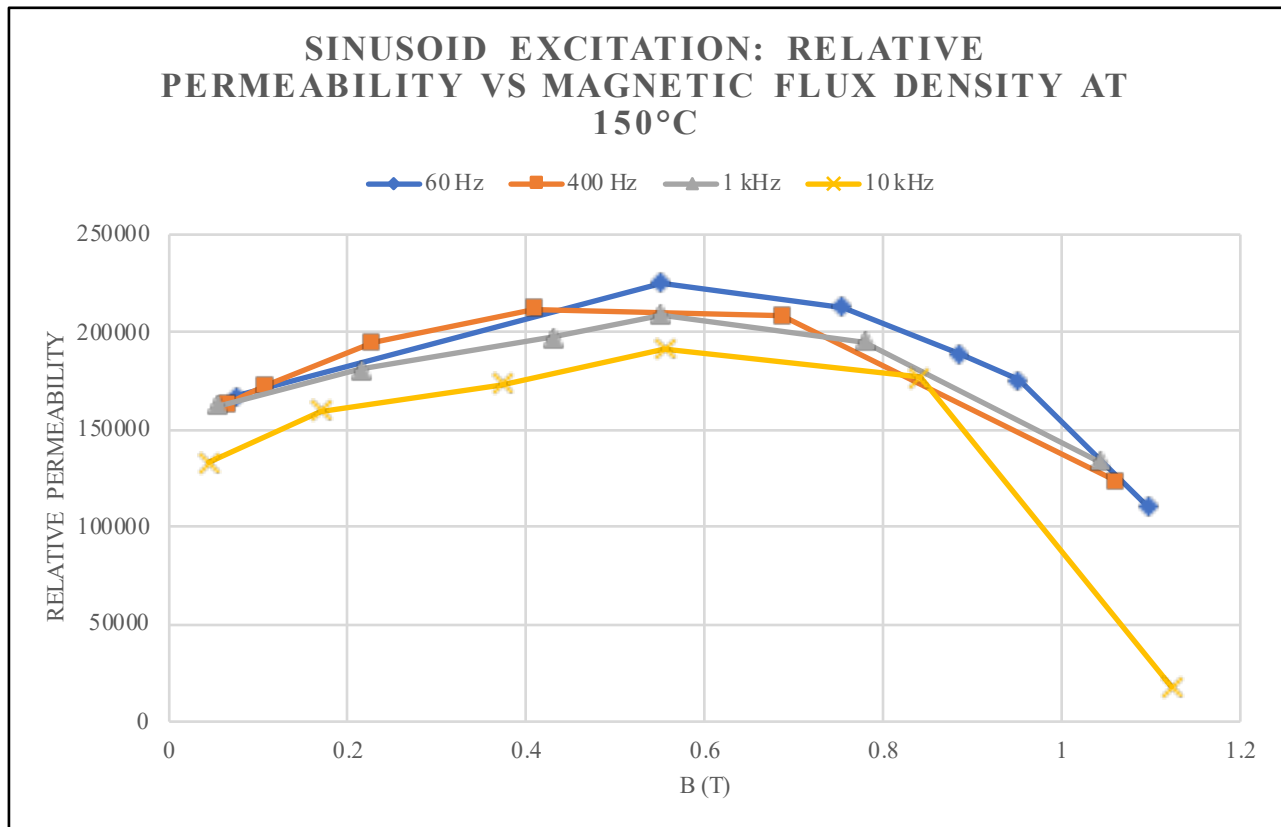
α	1.484	
β	2.3371	
k_h	1.54211E-05	W / kg



(b)

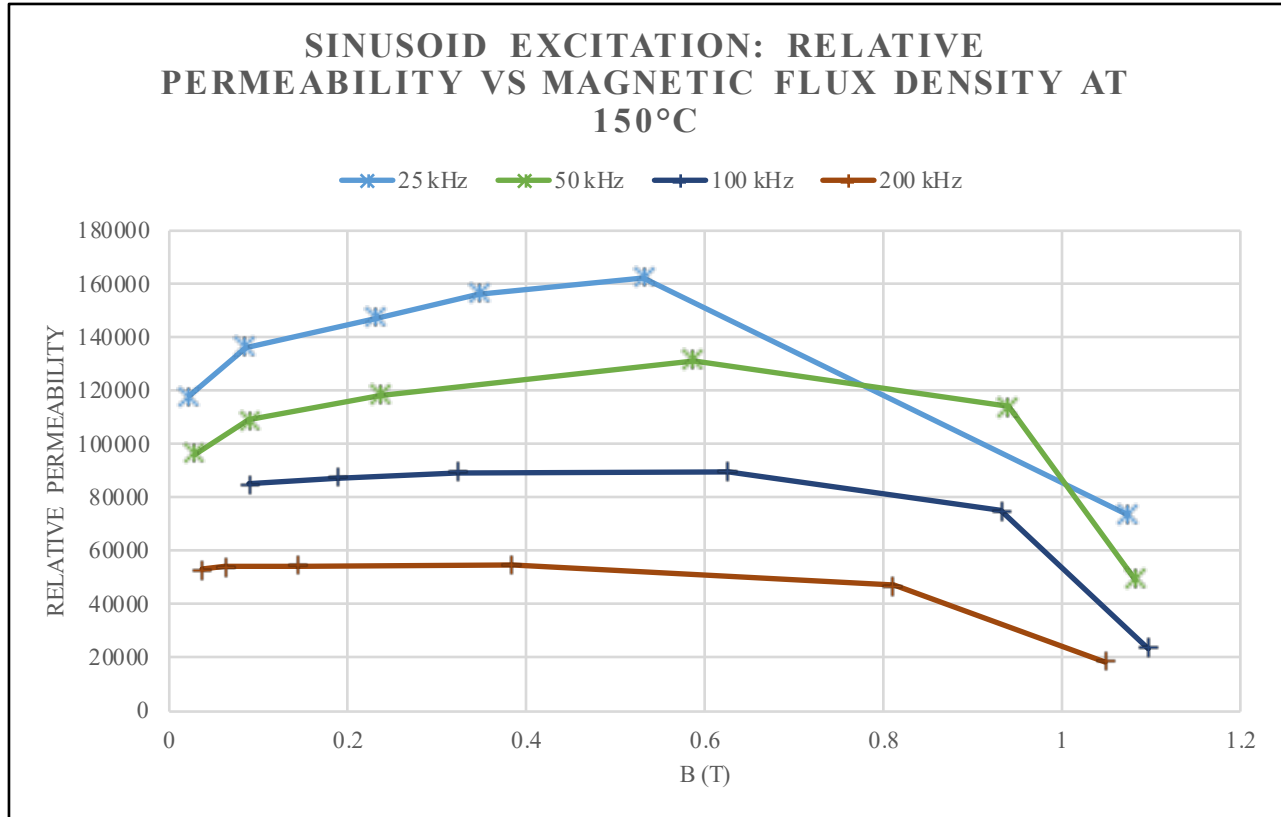
Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



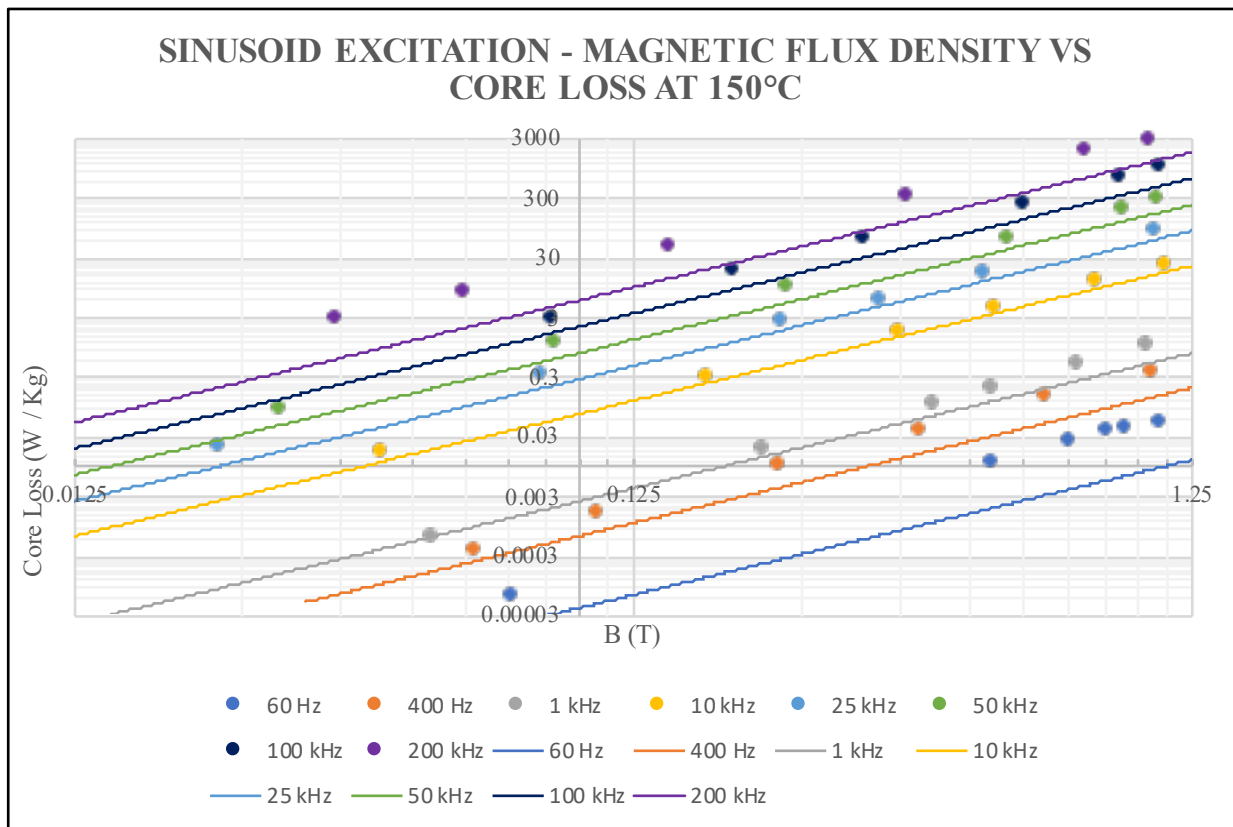
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.10	110398.94	1.06	123340.09	1.04	133152.59
0.95	175018.55	0.69	208353.92	0.78	195282.83
0.88	188804.26	0.41	211517.94	0.55	208603.60
0.75	212555.17	0.23	194212.14	0.43	196883.75
0.55	225000.76	0.11	172176.16	0.21	180587.97
0.08	167207.10	0.06	162741.32	0.05	161953.87

10 kHz	
B (T)	μ_r
1.12	17847.24
0.84	176255.60
0.56	191228.92
0.37	173183.84
0.17	159699.14
0.04	132922.36



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.07	73645.00	1.08	49381.11	1.10	23534.64
0.53	162323.65	0.94	113826.25	0.93	75147.77
0.35	156418.06	0.59	131260.27	0.63	89713.23
0.23	147435.71	0.24	118309.78	0.32	89557.91
0.09	136677.50	0.09	109162.62	0.19	87585.73
0.02	118096.66	0.03	96366.04	0.09	84823.72

200 kHz	
B (T)	μ_r
1.05	18541.43
0.81	47017.62
0.38	54876.24
0.15	54841.64
0.06	53978.69
0.04	53232.14

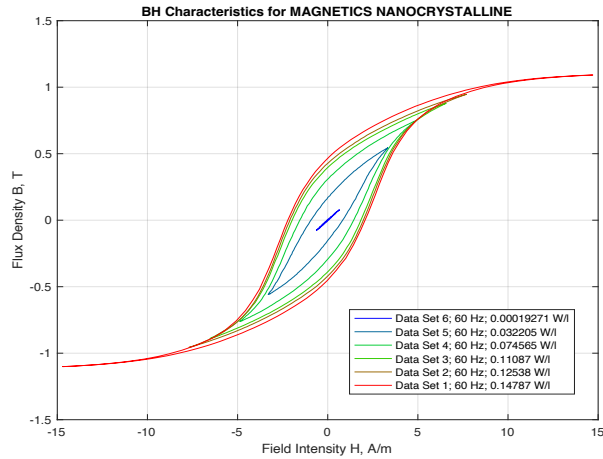


Magnetic Flux Density vs Core Loss - Table

60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.10	0.05	1.06	0.37	1.04	0.98	1.12	23.13
0.95	0.04	0.69	0.15	0.78	0.51	0.84	12.42
0.88	0.04	0.41	0.04	0.55	0.20	0.56	4.45
0.75	0.03	0.23	0.01	0.43	0.10	0.37	1.67
0.55	0.01	0.11	0.00	0.21	0.02	0.17	0.30
0.08	0.00	0.06	0.00	0.05	0.00	0.04	0.02

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.07	88.70	1.08	299.37	1.10	1004.10	1.05	2925.30
0.53	16.36	0.94	200.99	0.93	679.34	0.81	1798.90
0.35	6.10	0.59	64.89	0.63	249.49	0.38	314.56
0.23	2.60	0.24	9.46	0.32	60.78	0.15	43.78
0.09	0.33	0.09	1.11	0.19	17.70	0.06	8.03
0.02	0.02	0.03	0.09	0.09	2.87	0.04	2.81

Empirical Model for Core Loss using Steinmetz Equation: Sinusoid Excitation via Sudhoff Simulation



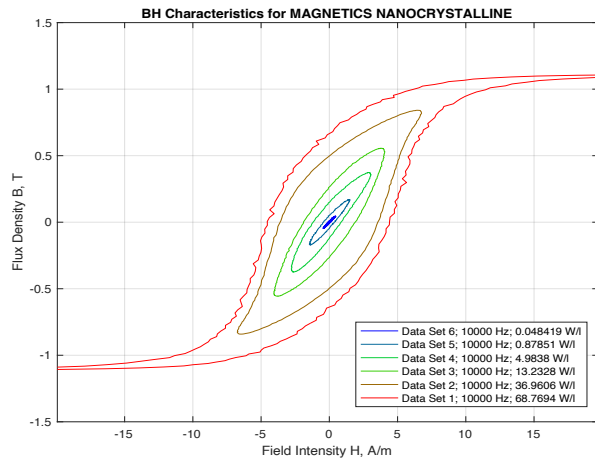
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 150°C

α	1.4637	
β	2.2645	
k_h	1.91134E-05	W / kg

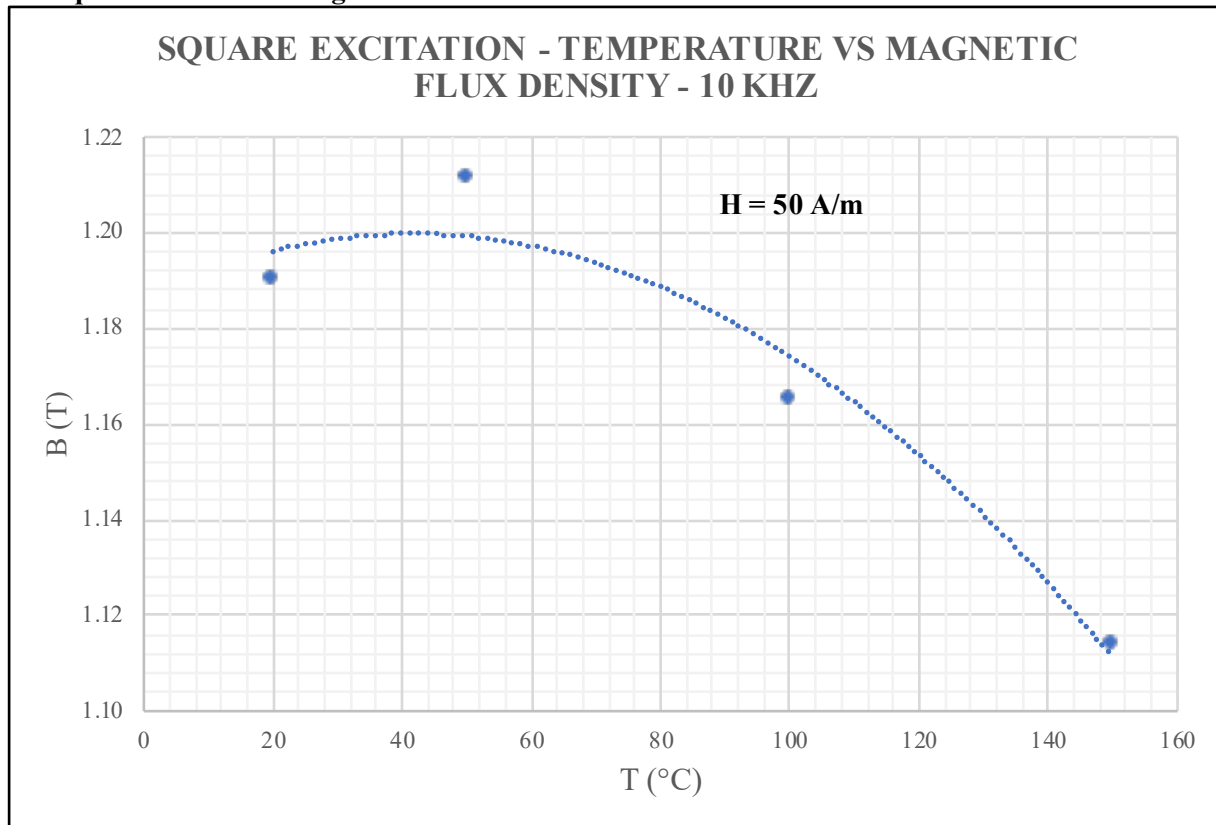


(b)

Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

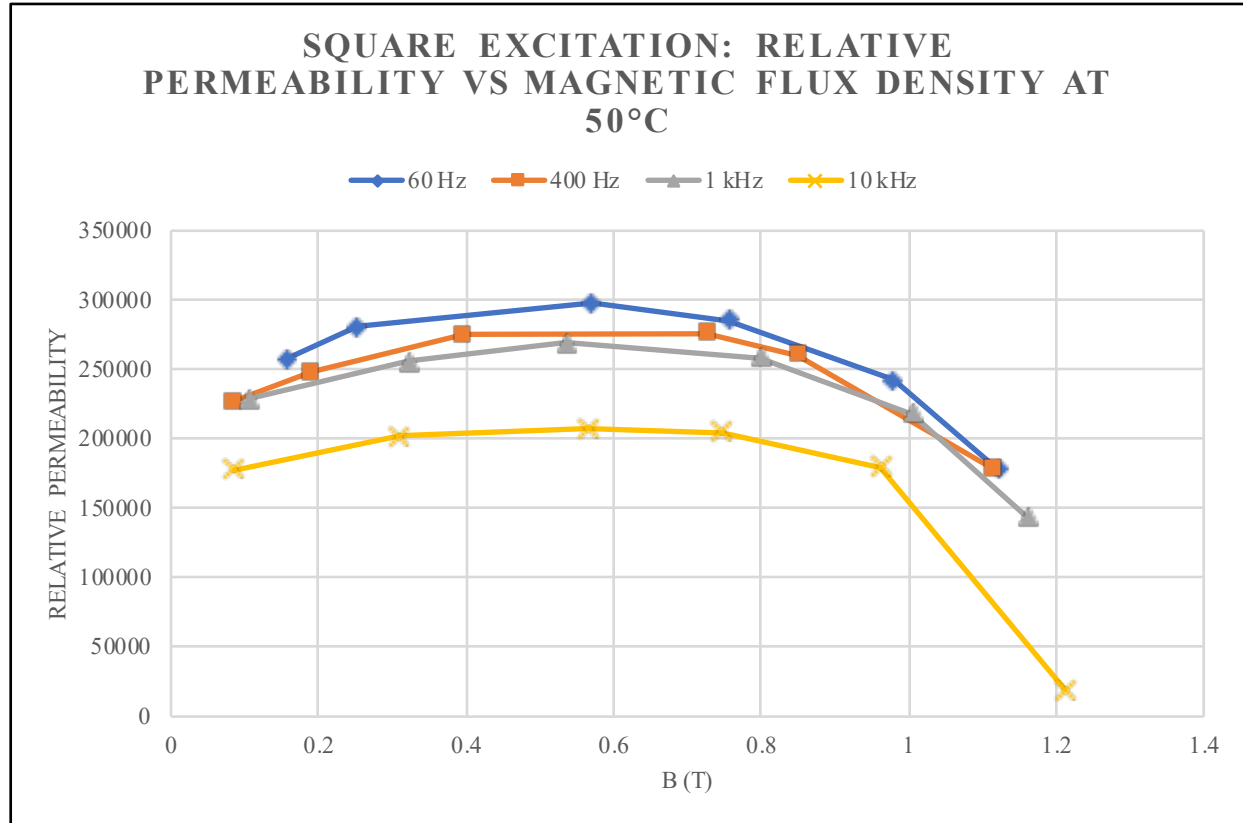
e. Square Excitation Magnetic Characterization.



Temperature Dependence vs Core Loss - Table

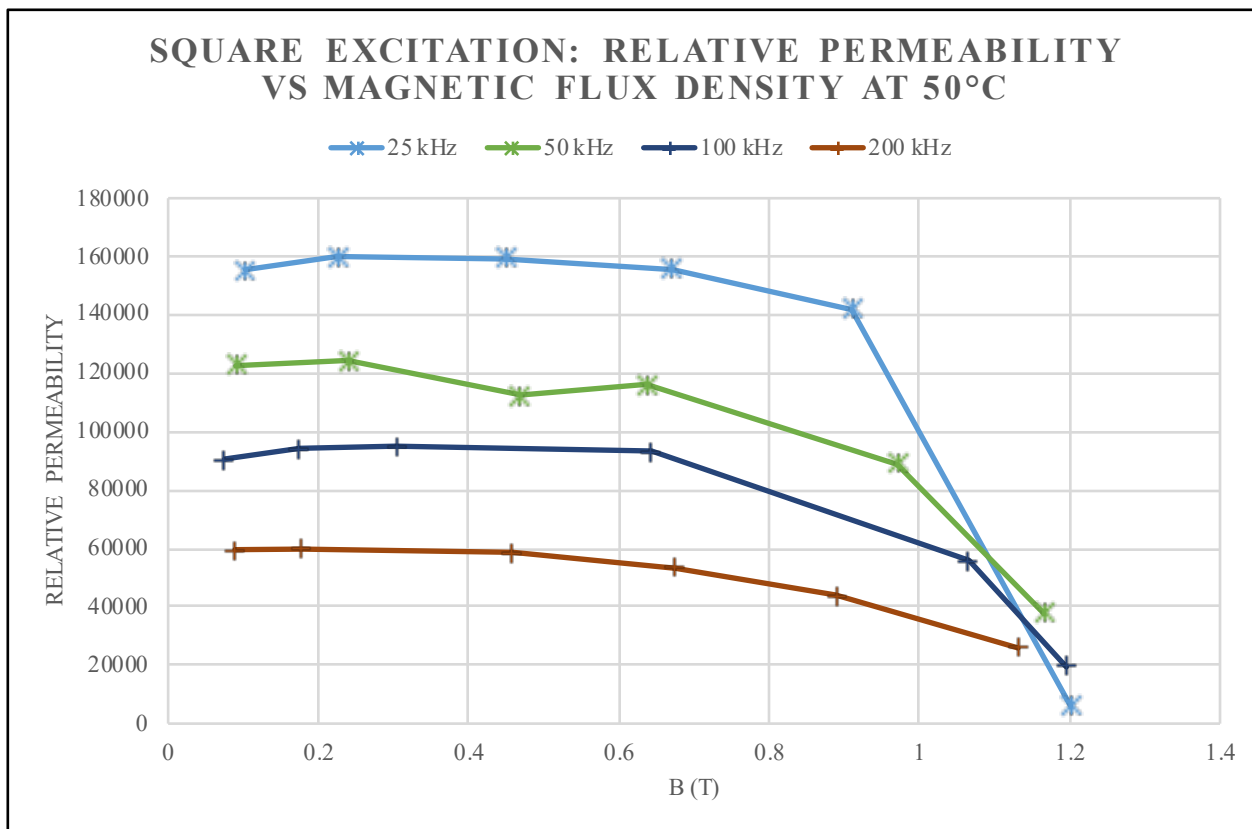
60 Hz		400 Hz		1 kHz		10 kHz	
T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)
20.00	1.14	20.00	1.14	20.00	1.17	20.00	1.19
50.00	1.12	50.00	1.12	50.00	1.16	50.00	1.21
100.00	1.05	100.00	1.10	100.00	1.11	100.00	1.16
150.00	0.97	150.00	1.02	150.00	1.04	150.00	1.11

25 kHz		50 kHz		100 kHz		200 kHz	
T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)
20.00	1.17	20.00	1.16	20.00	1.16	20.00	1.11
50.00	1.17	50.00	1.17	50.00	1.13	50.00	1.13
100.00	1.13	100.00	1.13	100.00	1.07	100.00	1.07
150.00	1.08	150.00	1.08	150.00	1.06	150.00	1.06



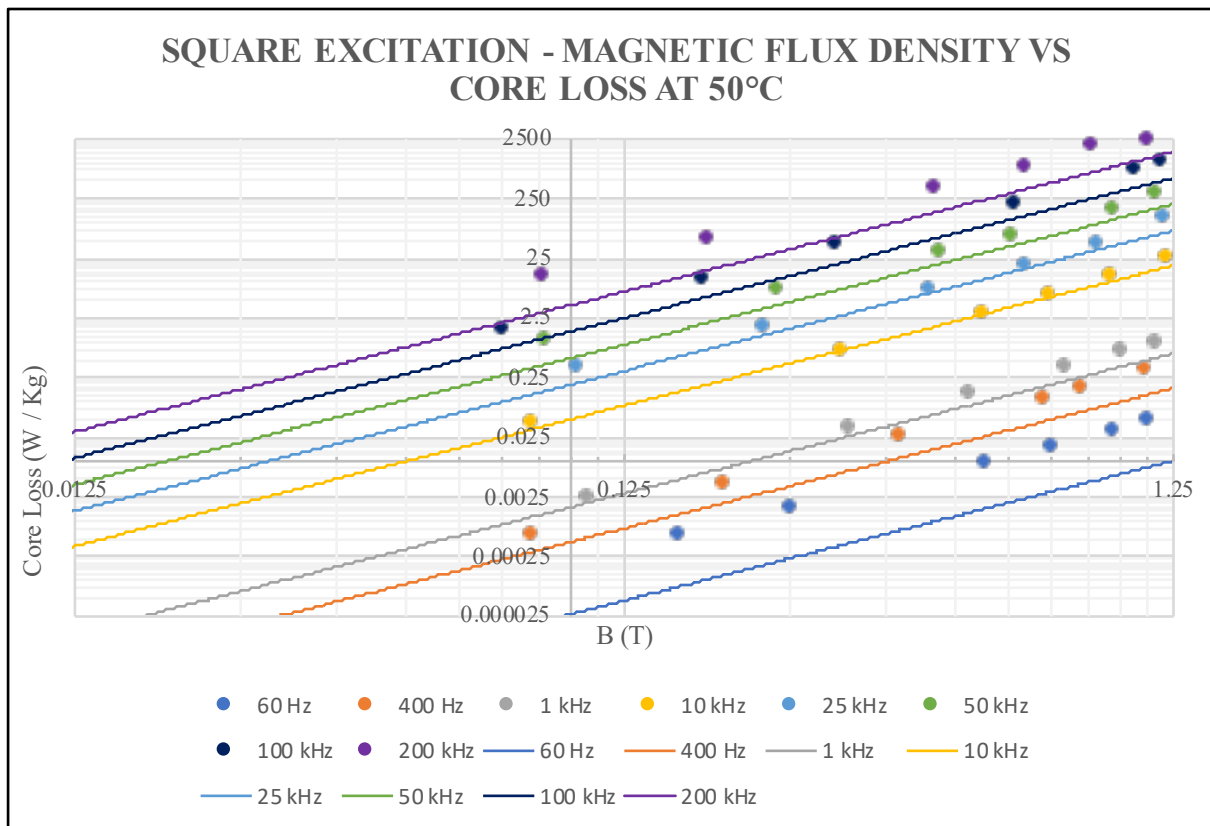
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.12	177696.04	1.12	178135.64	1.16	143319.91
0.98	242026.30	0.85	260079.41	1.01	217944.13
0.76	285554.90	0.73	275771.21	0.80	258217.21
0.57	297983.23	0.40	274497.03	0.54	269513.38
0.25	280460.84	0.19	247960.39	0.32	255592.99
0.16	258001.64	0.09	226921.42	0.11	229271.53

10 kHz	
B (T)	μ_r
1.21	19724.23
0.96	179475.05
0.75	204776.98
0.57	207491.32
0.31	201873.43
0.09	178317.66



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.20	6062.83	1.17	37781.95	1.20	19427.57
0.91	142042.88	0.97	88862.33	1.06	55727.27
0.67	155897.64	0.64	116131.27	0.64	92986.65
0.45	159343.02	0.47	112420.03	0.30	95054.88
0.23	160032.69	0.24	124426.35	0.17	94205.17
0.10	155427.70	0.09	122735.07	0.08	90244.08

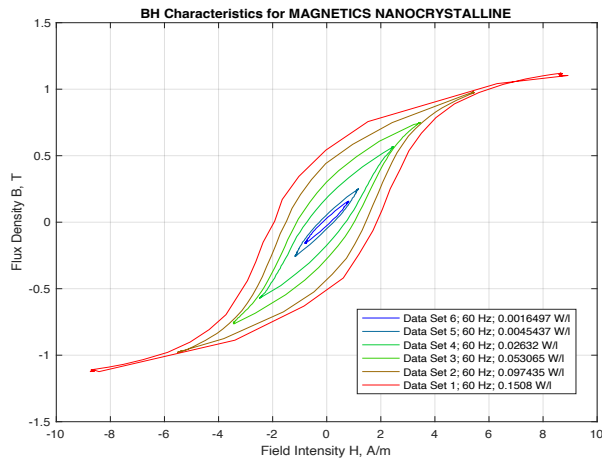
200 kHz	
B (T)	μ_r
1.13	25920.08
0.89	43913.70
0.68	53344.39
0.46	58270.14
0.18	59785.40
0.09	59297.00



Magnetic Flux Density vs Core Loss - Table							
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.12	0.05	1.12	0.32	1.16	0.95	1.21	25.88
0.98	0.03	0.85	0.15	1.01	0.67	0.96	12.03
0.76	0.02	0.73	0.11	0.80	0.36	0.75	5.84
0.57	0.01	0.40	0.03	0.54	0.13	0.57	2.79
0.25	0.00	0.19	0.00	0.32	0.04	0.31	0.70
0.16	0.00	0.09	0.00	0.11	0.00	0.09	0.04

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.20	119.43	1.17	311.47	1.20	1011.80	1.13	2269.60
0.91	42.41	0.97	168.32	1.06	787.64	0.89	1836.80
0.67	19.01	0.64	55.91	0.64	201.15	0.68	847.86
0.45	7.53	0.47	29.98	0.30	41.41	0.46	350.77
0.23	1.77	0.24	7.44	0.17	10.76	0.18	50.69
0.10	0.36	0.09	1.02	0.08	1.55	0.09	12.81

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



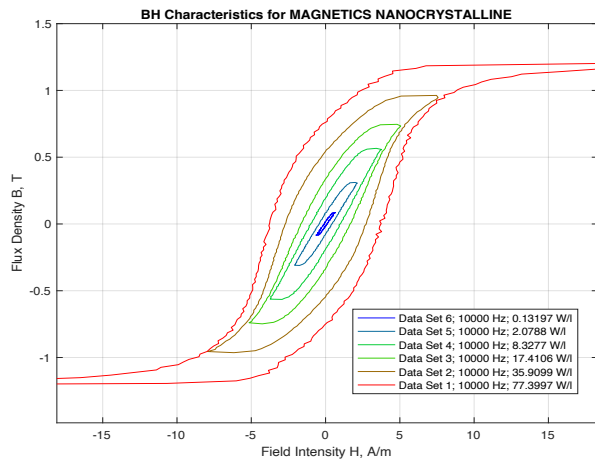
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 50°C

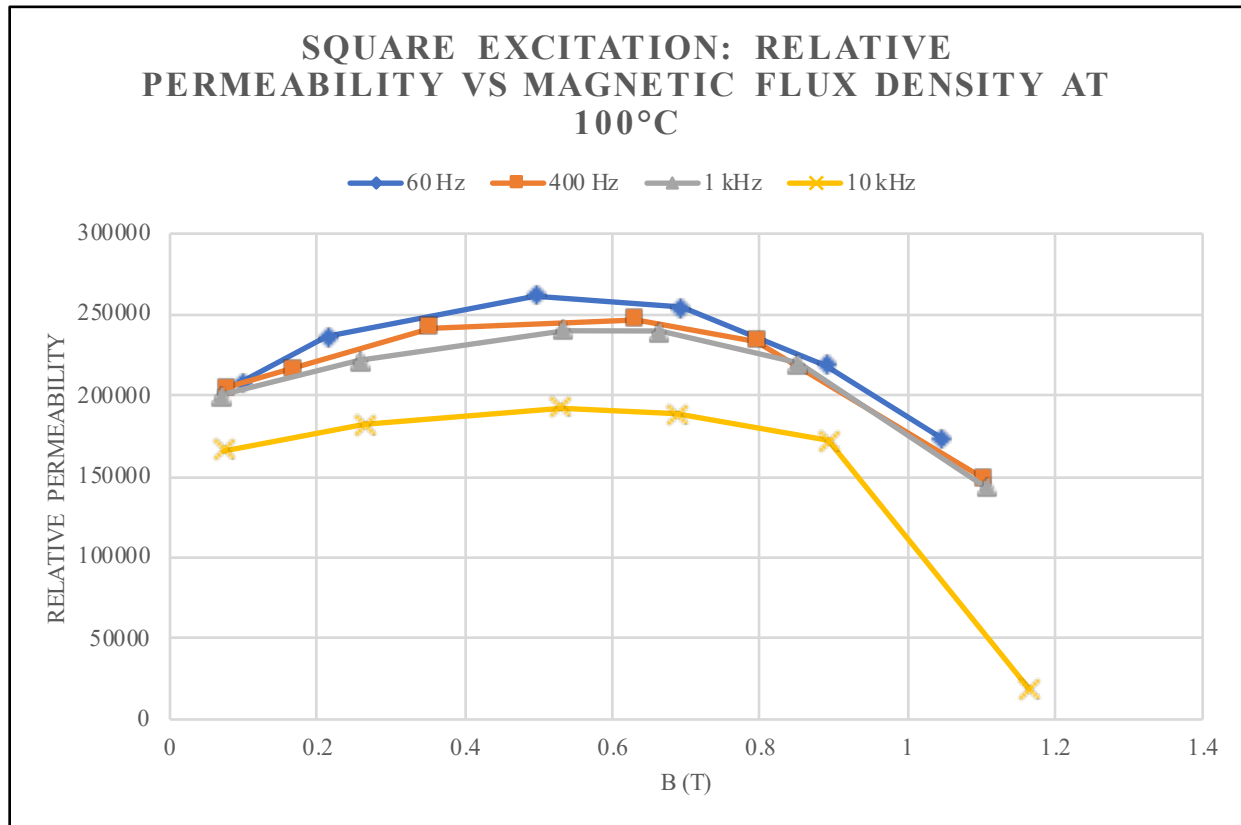
α	1.4701	
β	2.3465	
k_h	1.47368E-05	W / kg



(b)

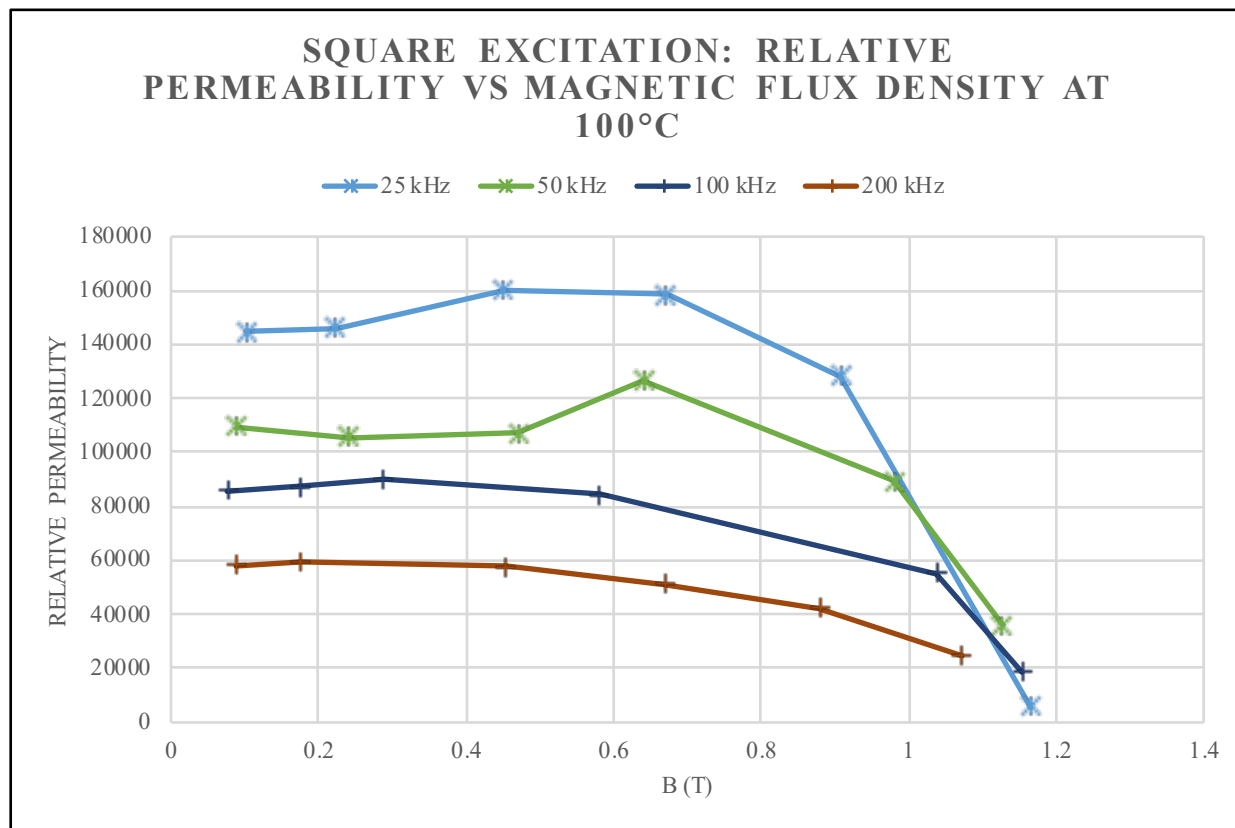
Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



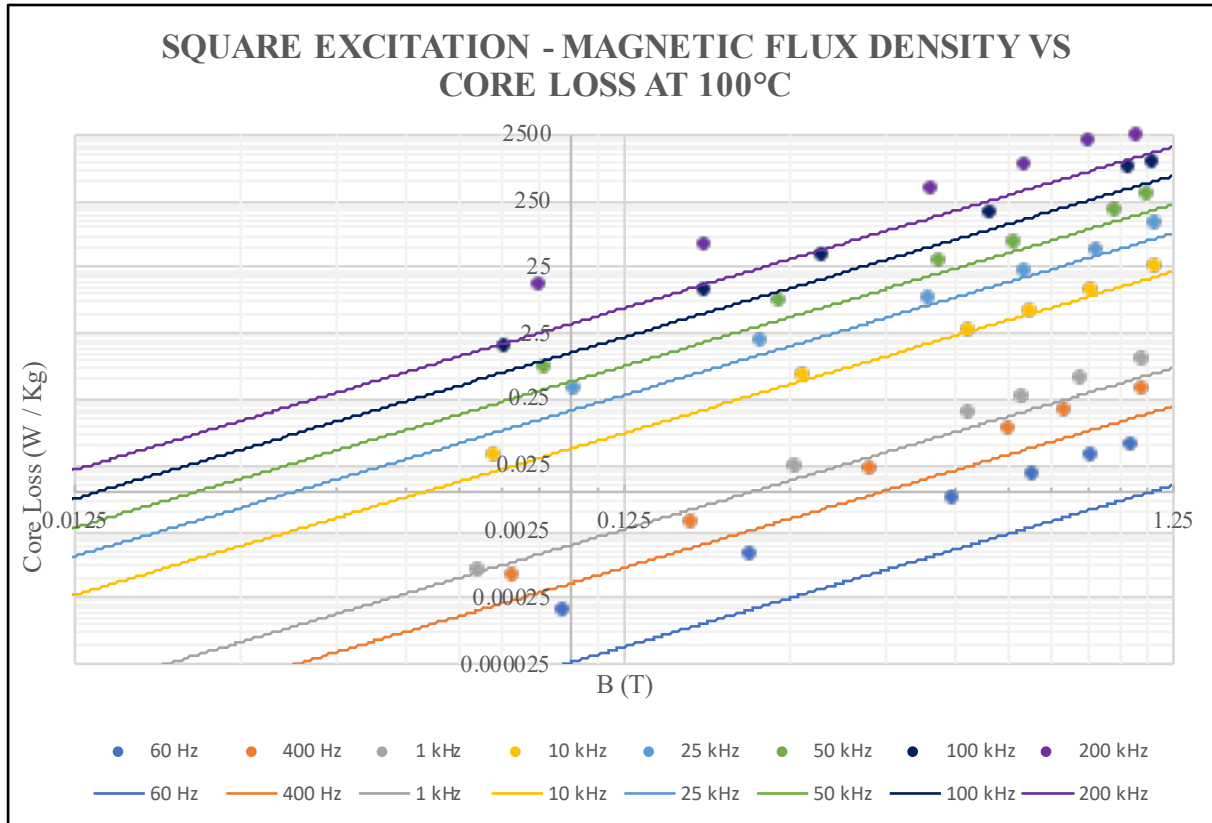
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.05	173325.43	1.10	148679.86	1.11	143437.63
0.89	219185.39	0.80	234019.37	0.85	219668.56
0.69	254628.80	0.63	246694.47	0.66	239479.13
0.50	261364.93	0.35	242313.09	0.53	240032.98
0.21	236555.29	0.17	216174.30	0.26	221759.75
0.10	208588.20	0.08	204577.59	0.07	199648.33

10 kHz	
B (T)	μ_r
1.16	18734.42
0.89	172346.86
0.69	188467.19
0.53	192135.54
0.27	182105.23
0.07	166019.69



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.17	5693.74	1.13	36205.15	1.15	18604.68
0.91	128141.56	0.98	89264.42	1.04	55043.56
0.67	158701.34	0.64	126627.62	0.58	84486.70
0.45	160110.37	0.47	106910.59	0.29	90121.51
0.22	146185.89	0.24	105746.71	0.18	87226.29
0.10	144849.46	0.09	109497.51	0.08	85894.86

200 kHz	
B (T)	μ_r
1.07	24700.83
0.88	42270.82
0.67	51303.59
0.45	57920.26
0.18	59495.91
0.09	58460.19

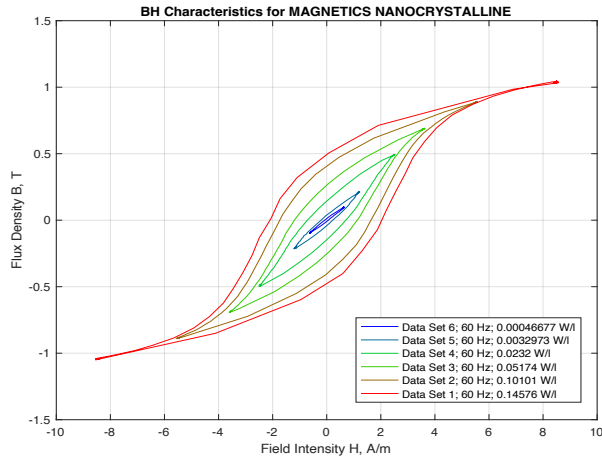


Magnetic Flux Density vs Core Loss - Table

60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.05	0.05	1.10	0.35	1.11	0.94	1.16	23.75
0.89	0.03	0.80	0.16	0.85	0.52	0.89	10.65
0.69	0.02	0.63	0.09	0.66	0.27	0.69	5.27
0.50	0.01	0.35	0.02	0.53	0.15	0.53	2.66
0.21	0.00	0.17	0.00	0.26	0.02	0.27	0.54
0.10	0.00	0.08	0.00	0.07	0.00	0.07	0.03

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.17	109.48	1.13	291.69	1.15	927.30	1.07	2350.30
0.91	44.75	0.98	176.78	1.04	755.57	0.88	1901.10
0.67	20.56	0.64	59.21	0.58	162.20	0.67	877.15
0.45	7.97	0.47	30.37	0.29	37.34	0.45	355.58
0.22	1.85	0.24	7.59	0.18	10.85	0.18	50.76
0.10	0.35	0.09	0.73	0.08	1.55	0.09	12.75

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



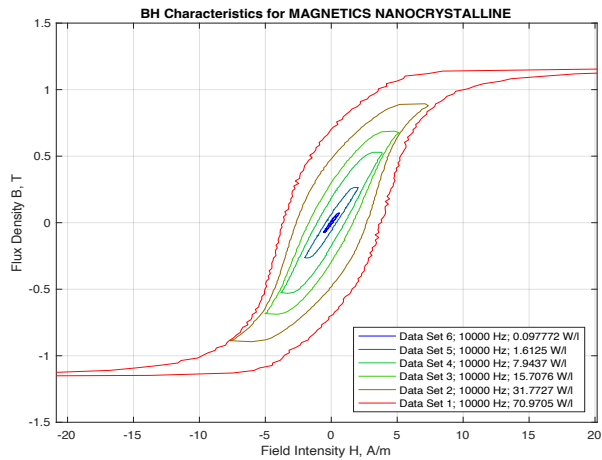
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 100°C

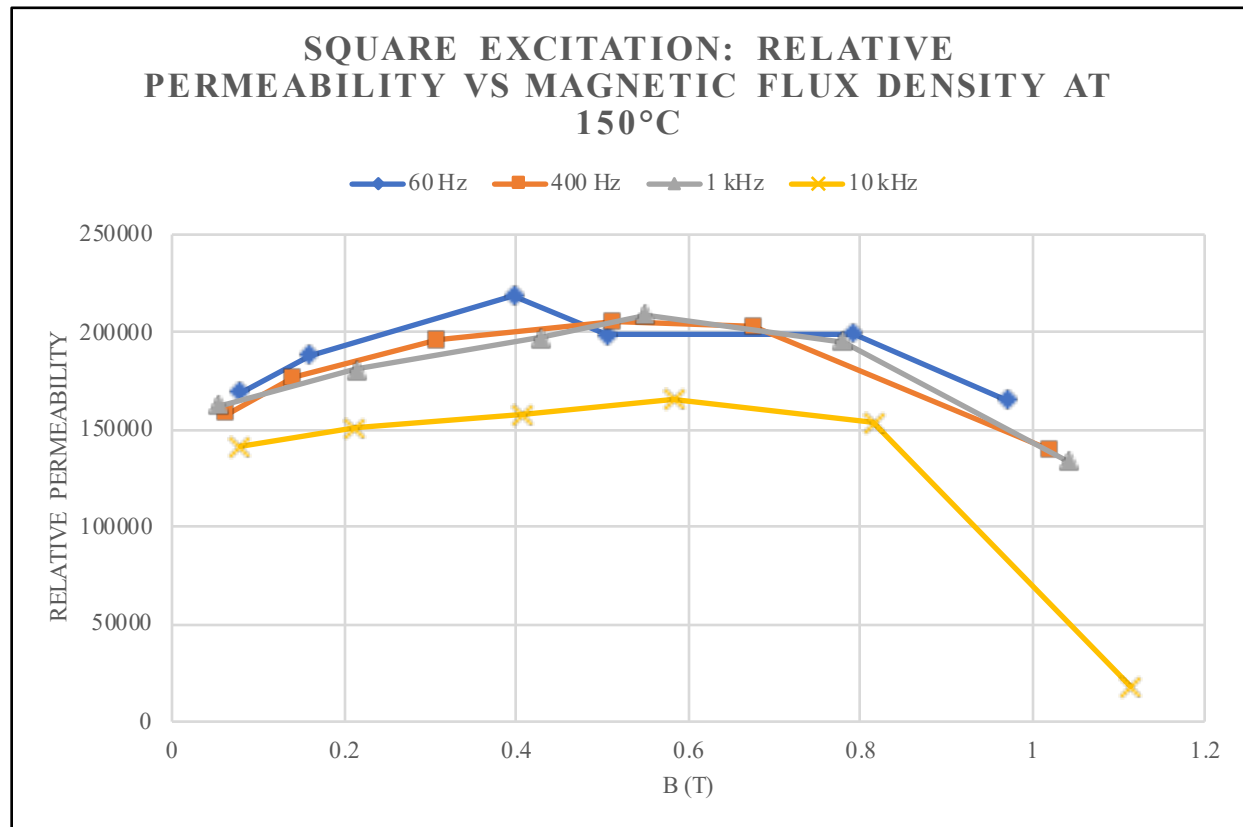
α	1.4548	
β	2.4438	
k_h	1.88995E-05	W / kg



(b)

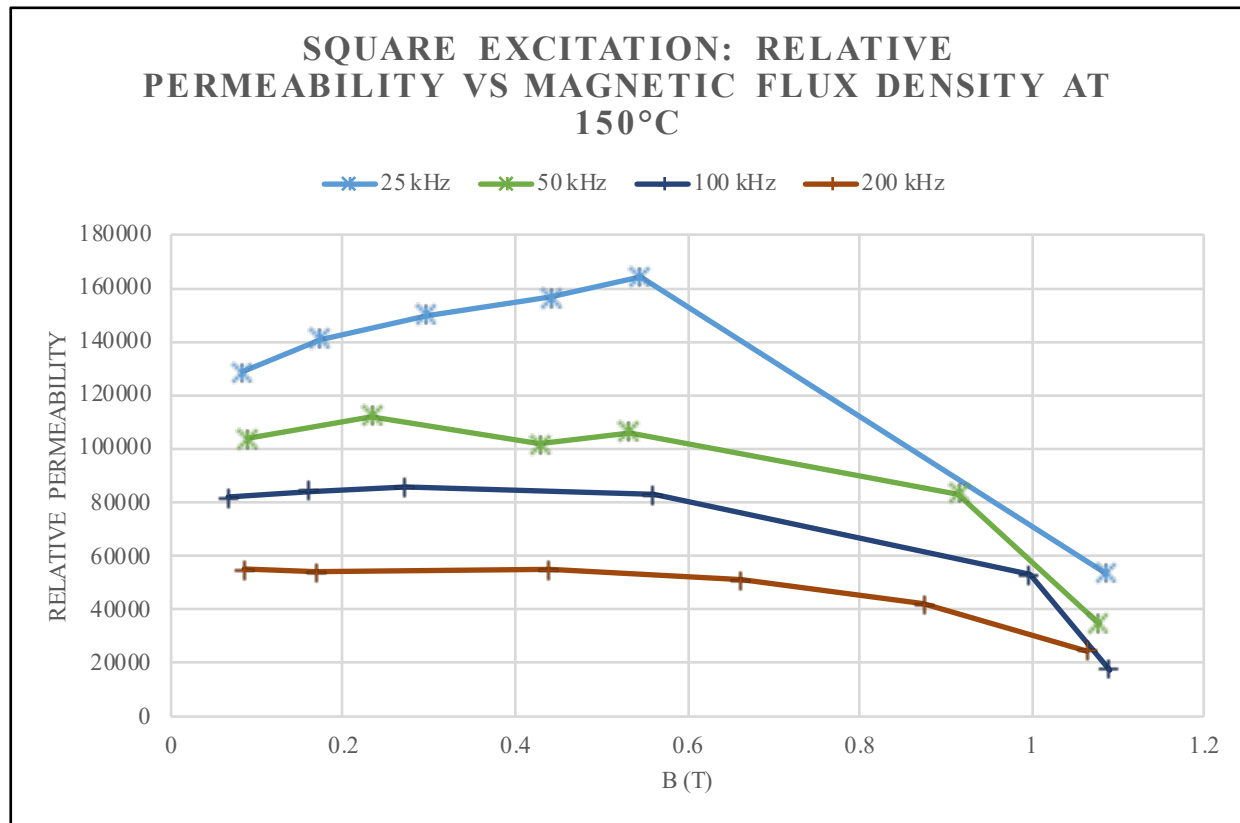
Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



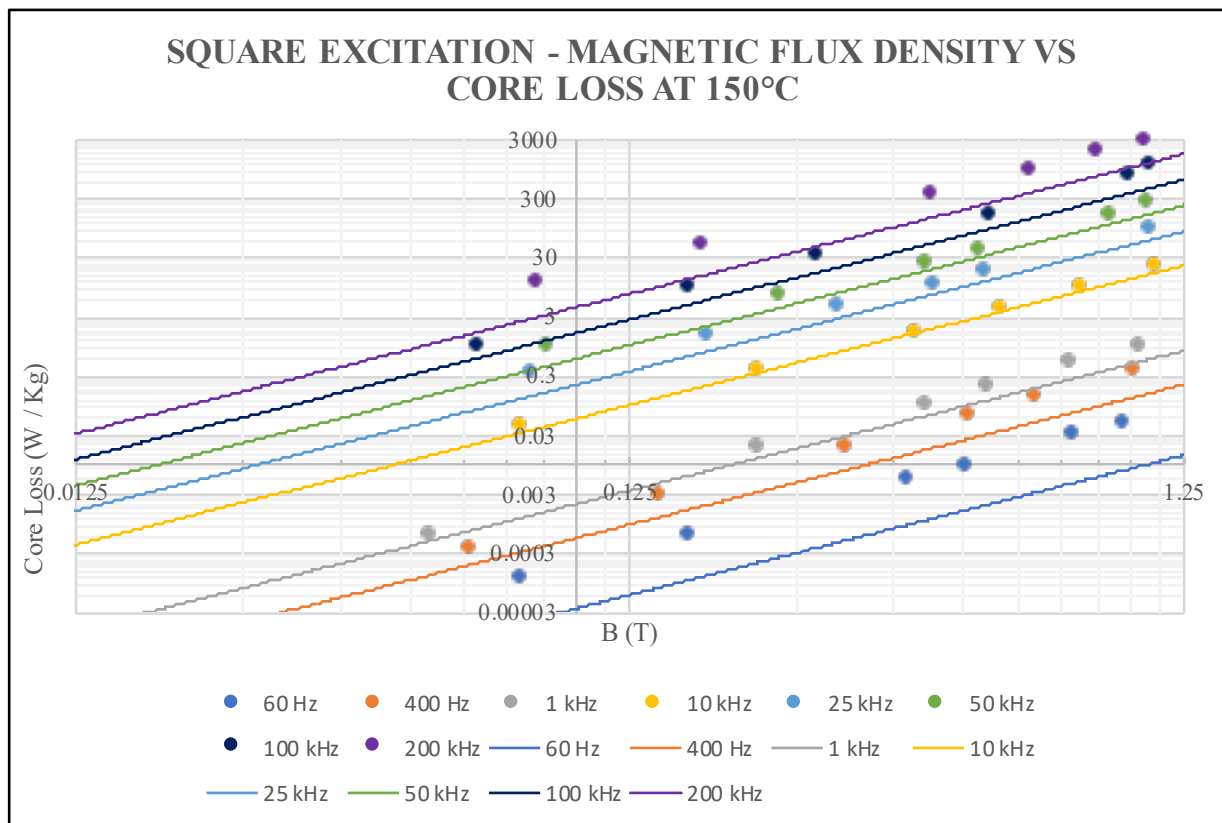
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
0.97	173325.43	1.02	139416.26	1.04	133152.59
0.79	219185.39	0.68	202504.77	0.78	195282.83
0.51	254628.80	0.51	205371.43	0.55	208603.60
0.40	261364.93	0.31	195511.87	0.43	196883.75
0.16	236555.29	0.14	176398.06	0.21	180587.97
0.08	208588.20	0.06	158035.24	0.05	161953.87

10 kHz	
B (T)	μ_r
1.11	18070.67
0.81	153433.59
0.58	165400.87
0.41	157565.86
0.21	150357.65
0.08	141293.83



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.09	53511.54	1.08	34687.29	1.09	17349.52
0.55	164212.83	0.92	83287.72	1.00	52665.44
0.44	156300.10	0.53	106380.52	0.56	82832.07
0.30	149818.73	0.43	101854.51	0.27	85752.24
0.17	141140.52	0.23	111962.48	0.16	84185.64
0.08	128700.06	0.09	103580.07	0.07	81602.31

200 kHz	
B (T)	μ_r
1.06	24449.50
0.87	41851.61
0.66	51071.08
0.44	54990.77
0.17	53908.97
0.09	54913.49

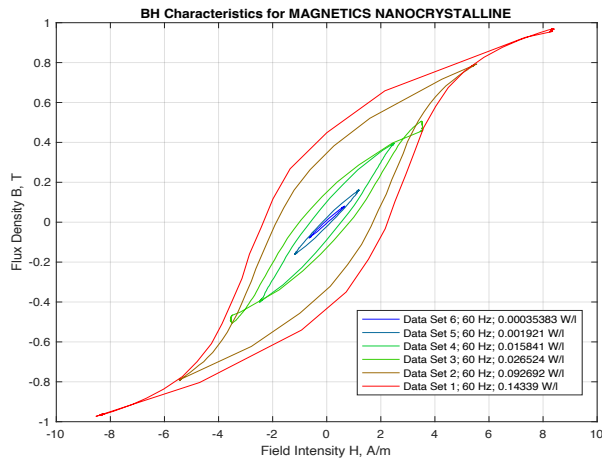


Magnetic Flux Density vs Core Loss - Table

60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
0.97	0.05	1.02	0.37	1.04	0.98	1.11	22.32
0.79	0.03	0.68	0.14	0.78	0.51	0.81	9.57
0.51	0.01	0.51	0.07	0.55	0.20	0.58	4.03
0.40	0.01	0.31	0.02	0.43	0.10	0.41	1.61
0.16	0.00	0.14	0.00	0.21	0.02	0.21	0.38
0.08	0.00	0.06	0.00	0.05	0.00	0.08	0.04

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.09	94.78	1.08	272.04	1.09	1102.80	1.06	2905.40
0.55	18.38	0.92	157.38	1.00	715.09	0.87	1902.00
0.44	10.97	0.53	40.37	0.56	156.92	0.66	892.71
0.30	4.65	0.43	25.13	0.27	34.16	0.44	344.75
0.17	1.51	0.23	7.17	0.16	9.74	0.17	47.96
0.08	0.33	0.09	0.99	0.07	0.97	0.09	12.12

Empirical Model for Core Loss using Steinmetz Equation: Square Excitation via Sudhoff Simulation



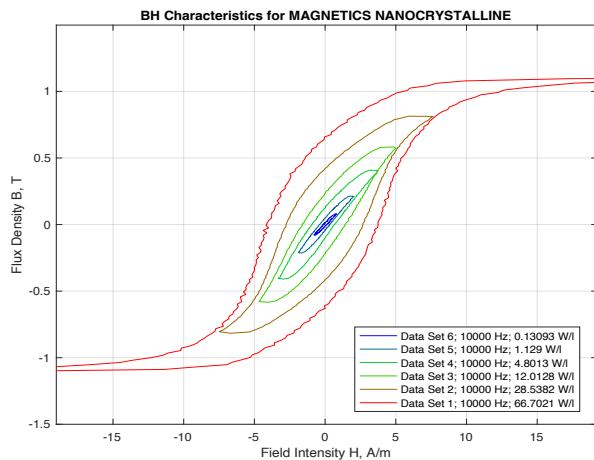
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 150°C

α	1.444	
β	2.362	
k_h	2.27796E-05	W / kg

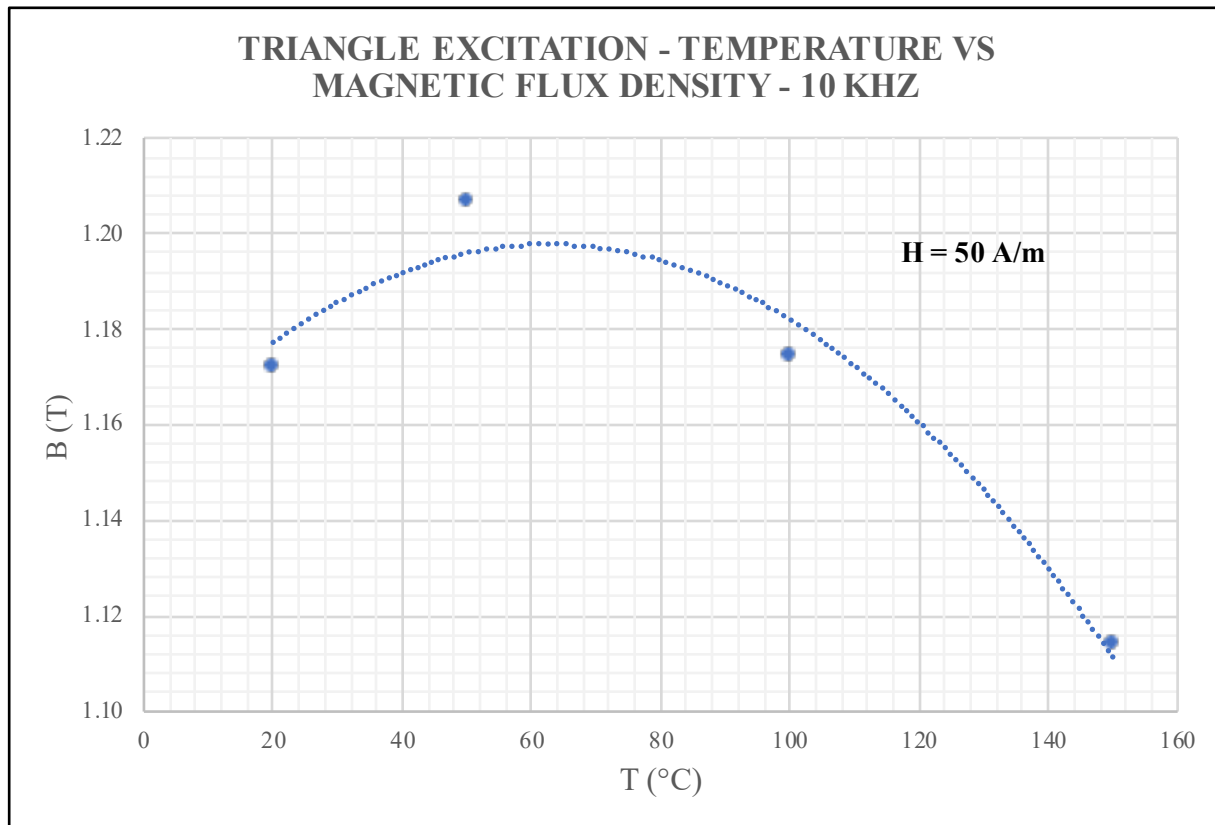


(b)

Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..

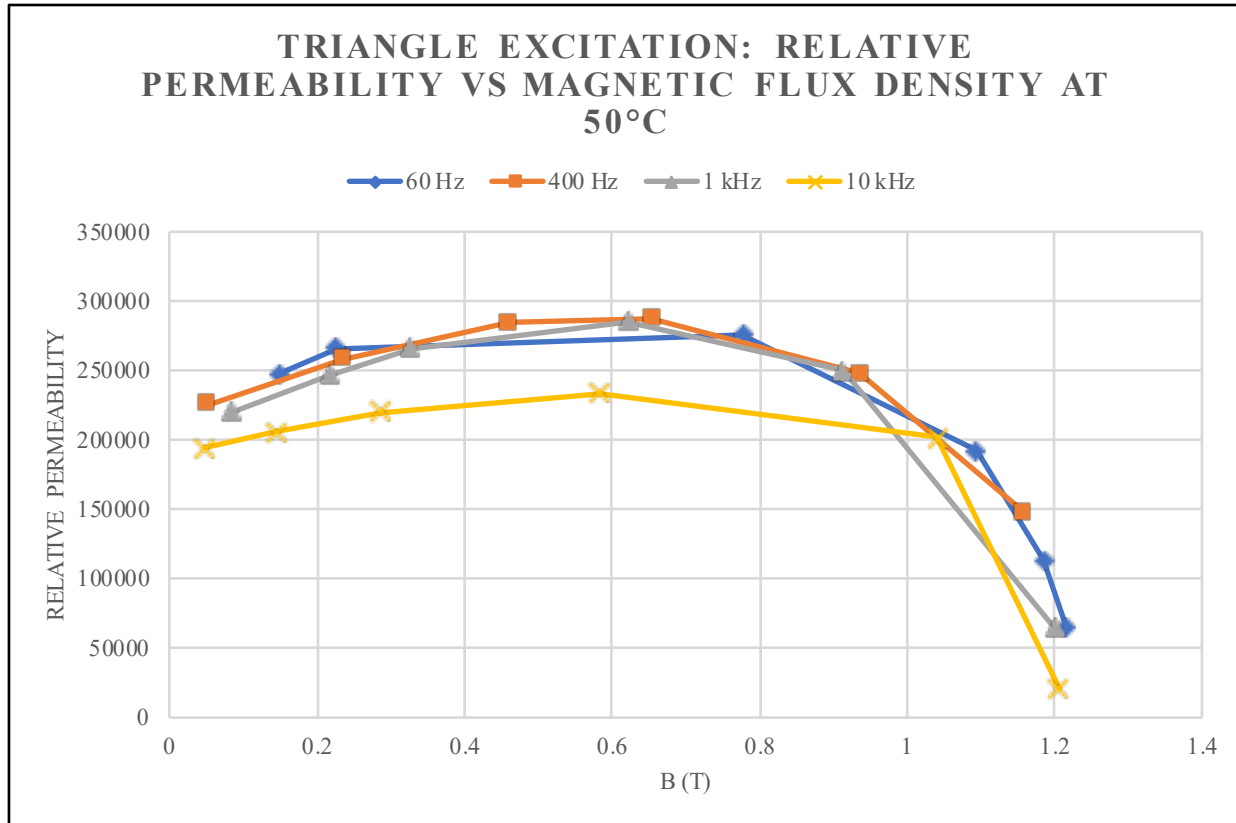
f. Triangle Excitation Magnetic Characterization.



Temperature Dependence vs Core Loss - Table

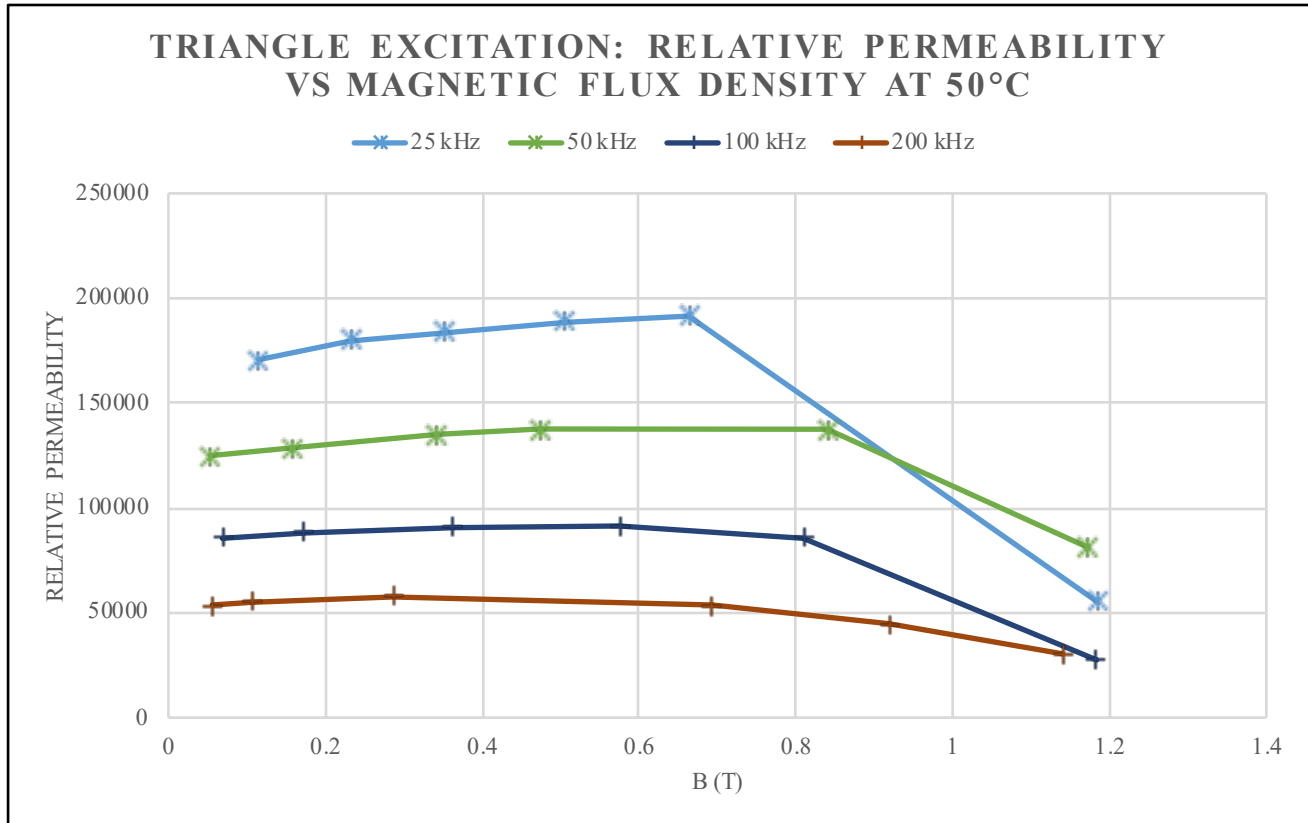
60 Hz		400 Hz		1 kHz		10 kHz	
T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)
20.00	1.16	20.00	1.14	20.00	1.18	20.00	1.17
50.00	1.22	50.00	1.16	50.00	1.20	50.00	1.21
100.00	1.16	100.00	1.11	100.00	1.17	100.00	1.17
150.00	1.11	150.00	1.04	150.00	1.10	150.00	1.11

25 kHz		50 kHz		100 kHz		200 kHz	
T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)	T (°C)	B (T)
20.00	1.16	20.00	1.17	20.00	1.16	20.00	1.14
50.00	1.18	50.00	1.17	50.00	1.18	50.00	1.14
100.00	1.14	100.00	1.15	100.00	1.14	100.00	1.12
150.00	1.09	150.00	1.10	150.00	1.09	150.00	1.07



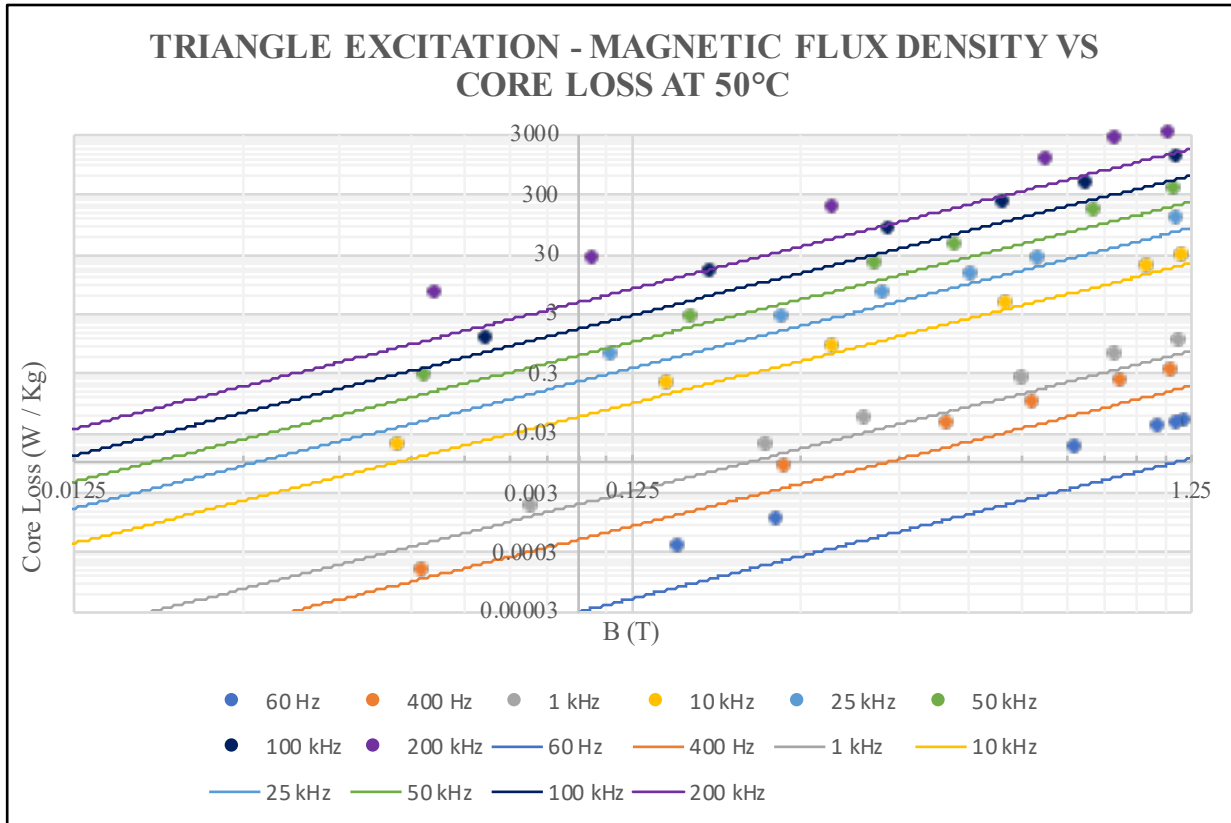
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.22	64795.53	1.16	147809.50	1.20	64400.19
1.19	113620.52	0.94	247933.90	0.91	249589.85
1.09	192489.21	0.65	287337.94	0.62	284964.10
0.78	275671.38	0.46	284502.26	0.33	266005.11
0.23	265786.29	0.24	257920.25	0.22	247043.32
0.15	247971.77	0.05	225398.57	0.08	220197.50

10 kHz	
B (T)	μ_r
1.21	21184.49
1.04	201363.87
0.58	233282.78
0.29	219743.91
0.14	205813.14
0.05	193588.63



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.18	55284.57	1.17	81162.38	1.18	27508.15
0.66	191493.37	0.84	137531.75	0.81	85957.89
0.51	188894.32	0.47	137107.92	0.58	91389.70
0.35	183537.46	0.34	134567.92	0.36	90665.66
0.23	179842.92	0.16	128722.93	0.17	88309.79
0.12	170119.76	0.05	124626.48	0.07	85870.08

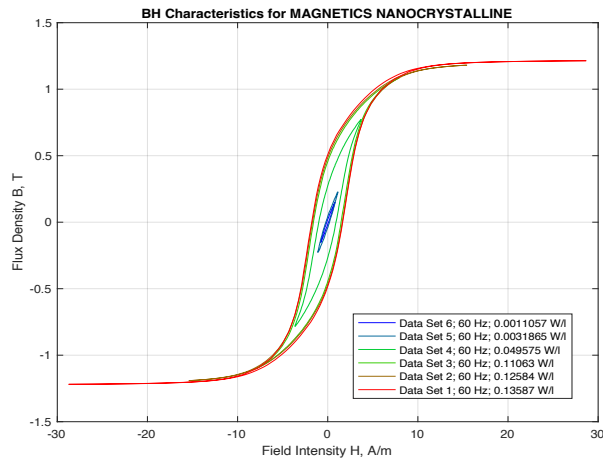
200 kHz	
B (T)	μ_r
1.14	30440.11
0.92	44354.16
0.69	53370.96
0.29	57546.48
0.11	55014.16
0.06	53086.42



Magnetic Flux Density vs Core Loss - Table							
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.22	0.05	1.16	0.34	1.20	1.05	1.21	27.03
1.19	0.04	0.94	0.22	0.91	0.62	1.04	18.65
1.09	0.04	0.65	0.09	0.62	0.25	0.58	4.40
0.78	0.02	0.46	0.04	0.33	0.05	0.29	0.81
0.23	0.00	0.24	0.01	0.22	0.02	0.14	0.19
0.15	0.00	0.05	0.00	0.08	0.00	0.05	0.02

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.18	112.02	1.17	349.53	1.18	1164.10	1.14	2975.20
0.66	25.80	0.84	149.88	0.81	460.58	0.92	2443.80
0.51	13.51	0.47	40.76	0.58	205.05	0.69	1115.20
0.35	6.12	0.34	20.80	0.36	78.87	0.29	168.32
0.23	2.60	0.16	2.46	0.17	14.38	0.11	23.89
0.12	0.63	0.05	0.28	0.07	1.11	0.06	6.77

Empirical Model for Core Loss using Steinmetz Equation: Triangle Excitation via Sudhoff Simulation



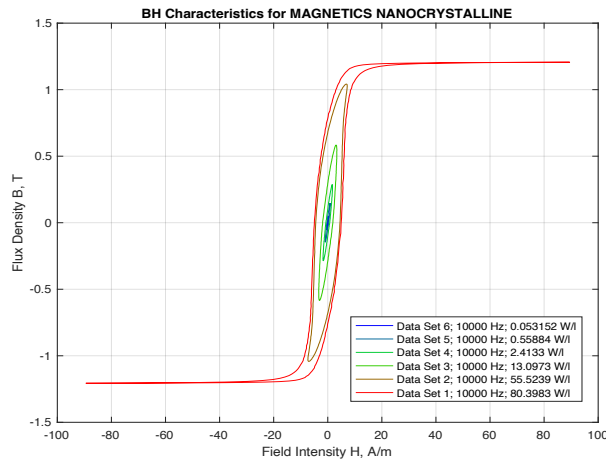
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 50°C

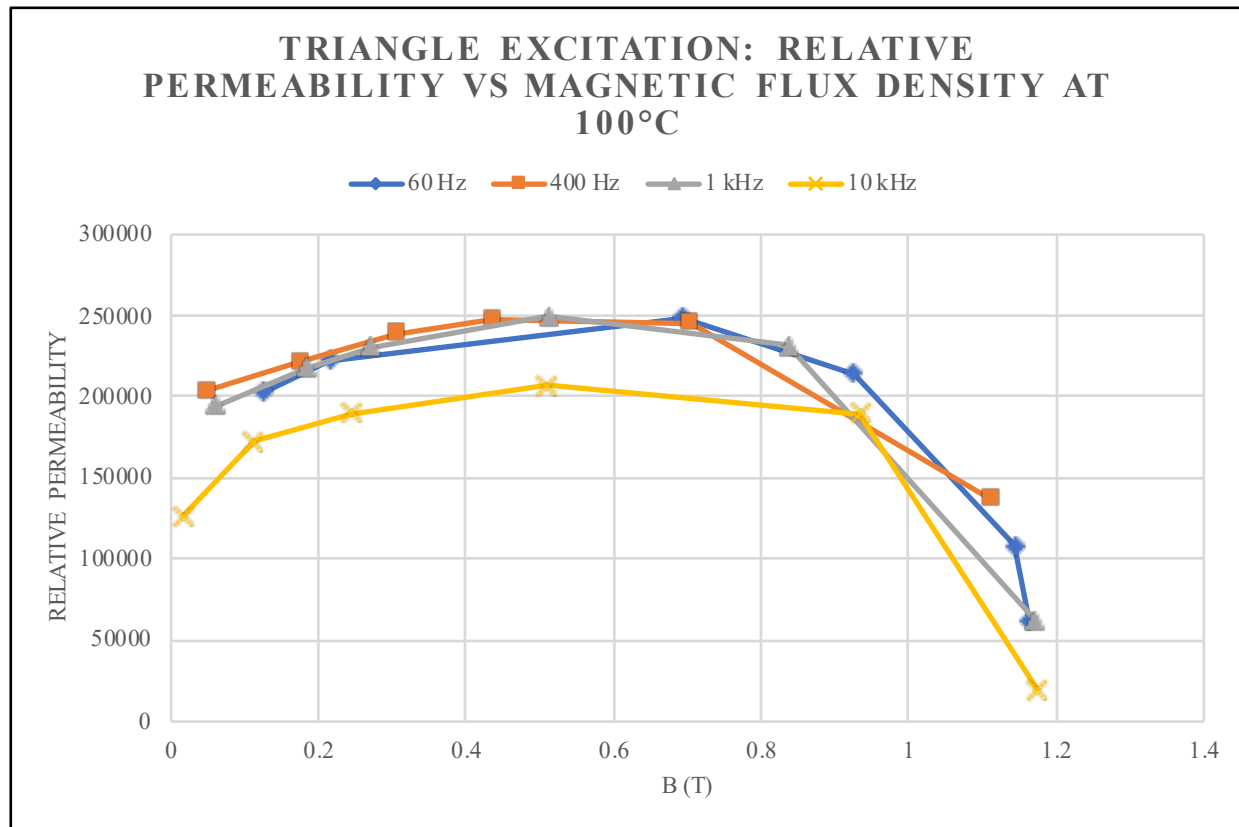
α	1.4731	
β	2.3479	
k_h	1.63468E-05	W / kg



(b)

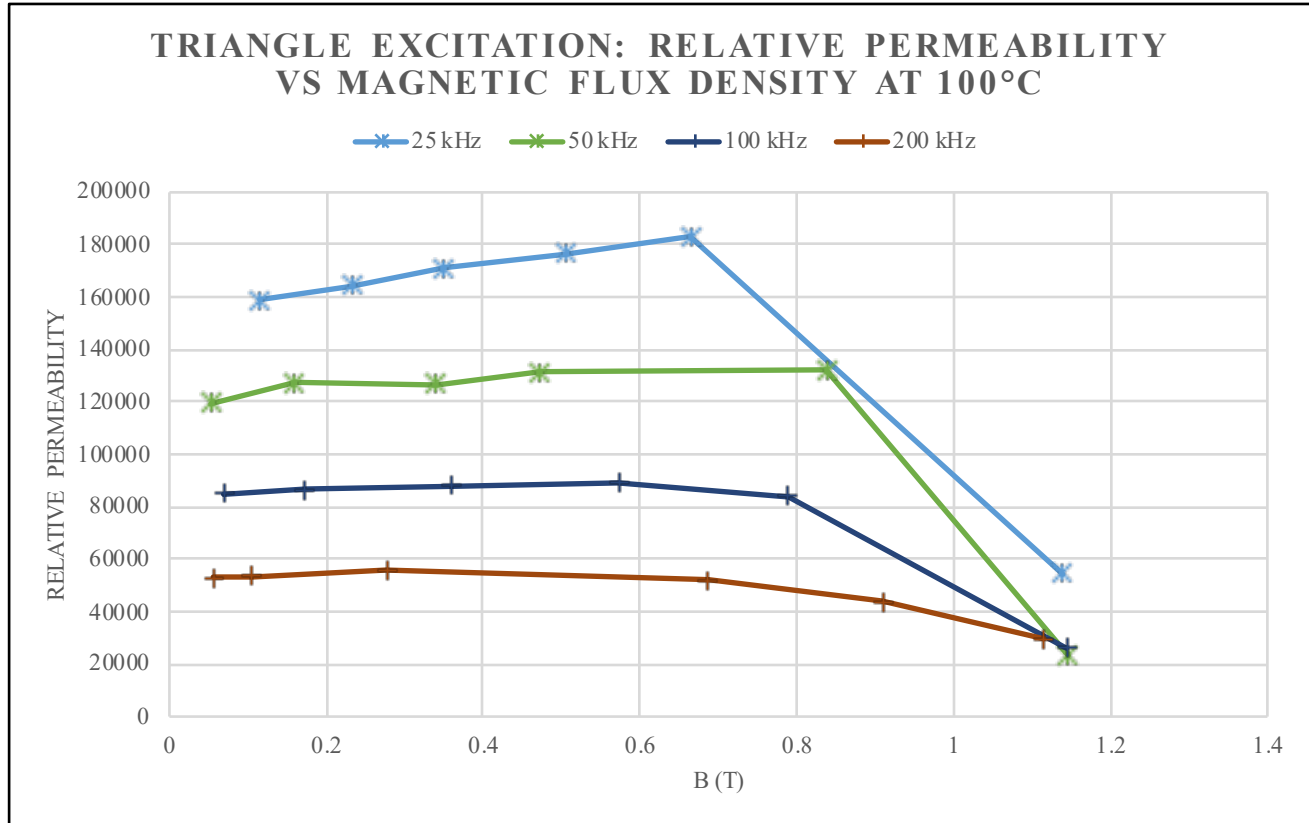
Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



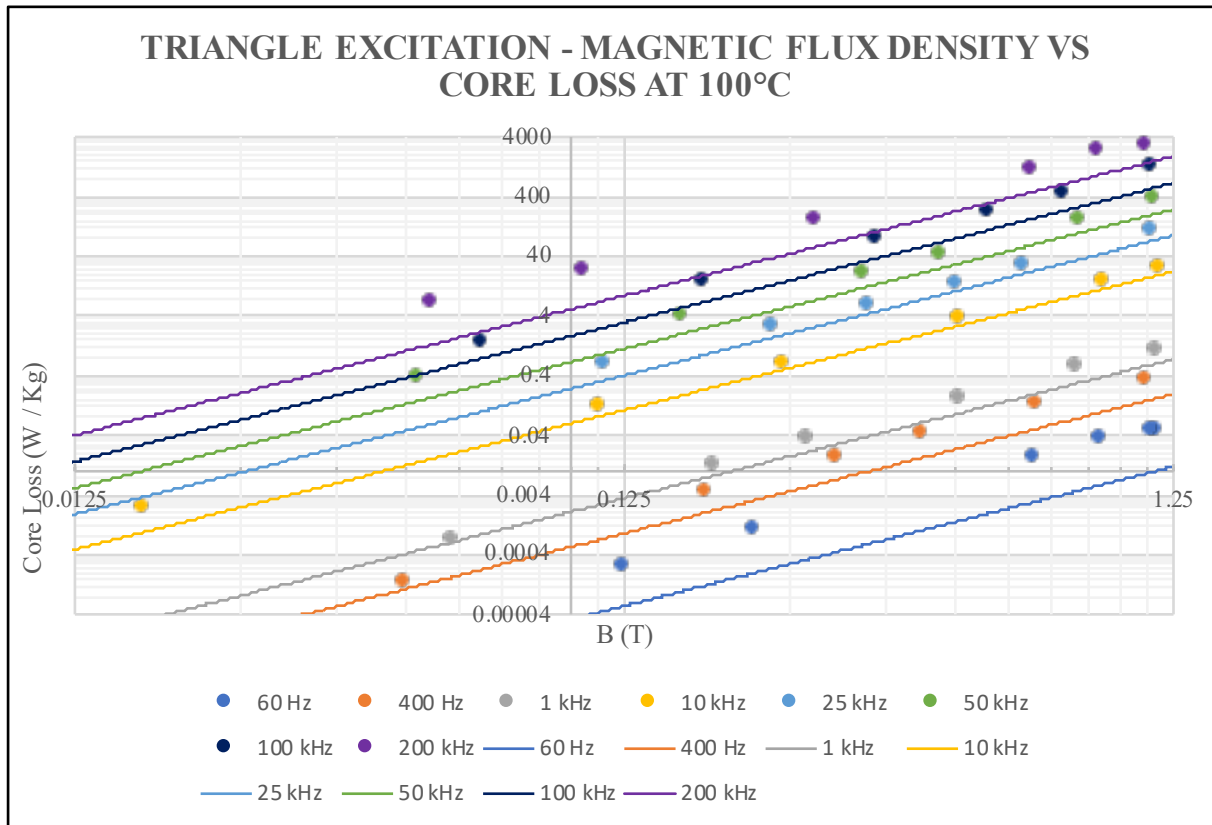
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.16	62197.13	1.11	137100.41	1.17	62670.00
1.14	108353.32	0.70	245388.25	0.84	231282.30
0.93	214204.34	0.44	247662.09	0.51	249766.53
0.69	248459.94	0.31	239226.25	0.27	230811.41
0.22	222642.20	0.18	221338.33	0.18	217852.44
0.12	203150.80	0.05	203887.62	0.06	194780.19

10 kHz	
B (T)	μ_r
1.17	20060.11
0.93	189603.10
0.51	207303.03
0.24	189682.81
0.11	172689.57
0.02	126507.19



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.14	54369.11	1.15	23309.92	1.14	26120.74
0.66	183161.42	0.84	132293.92	0.79	83942.87
0.51	176606.63	0.47	131311.31	0.57	89146.69
0.35	170999.83	0.34	126849.63	0.36	88046.95
0.23	164404.85	0.16	127366.48	0.17	86423.65
0.12	158948.02	0.05	119458.70	0.07	84879.77

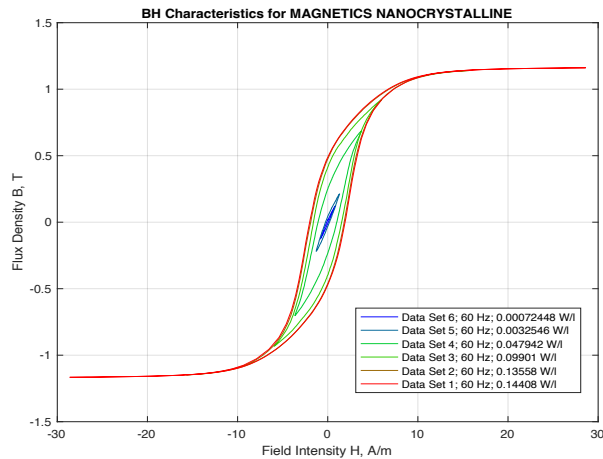
200 kHz	
B (T)	μ_r
1.14	26120.74
0.79	83942.87
0.57	89146.69
0.36	88046.95
0.17	86423.65
0.07	84879.77



Magnetic Flux Density vs Core Loss - Table							
60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.16	0.05	1.11	0.35	1.17	1.06	1.17	25.57
1.14	0.05	0.70	0.13	0.84	0.58	0.93	15.24
0.93	0.03	0.44	0.04	0.51	0.17	0.51	3.50
0.69	0.02	0.31	0.02	0.27	0.04	0.24	0.65
0.22	0.00	0.18	0.00	0.18	0.01	0.11	0.12
0.12	0.00	0.05	0.00	0.06	0.00	0.02	0.00

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.14	102.99	1.15	355.54	1.14	1270.50	1.12	2979.40
0.66	27.37	0.84	153.39	0.79	447.33	0.91	2432.00
0.51	14.12	0.47	41.50	0.57	210.83	0.69	1144.40
0.35	6.26	0.34	21.19	0.36	80.13	0.28	162.03
0.23	2.68	0.16	4.12	0.17	14.73	0.11	23.74
0.12	0.63	0.05	0.36	0.07	1.46	0.06	6.71

Empirical Model for Core Loss using Steinmetz Equation: Triangle Excitation via Sudhoff Simulation



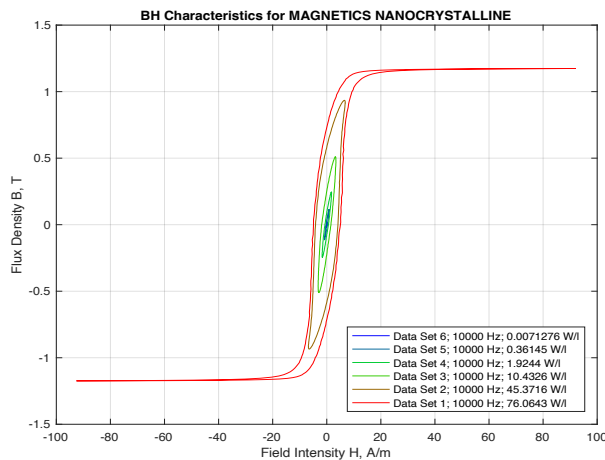
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 100°C

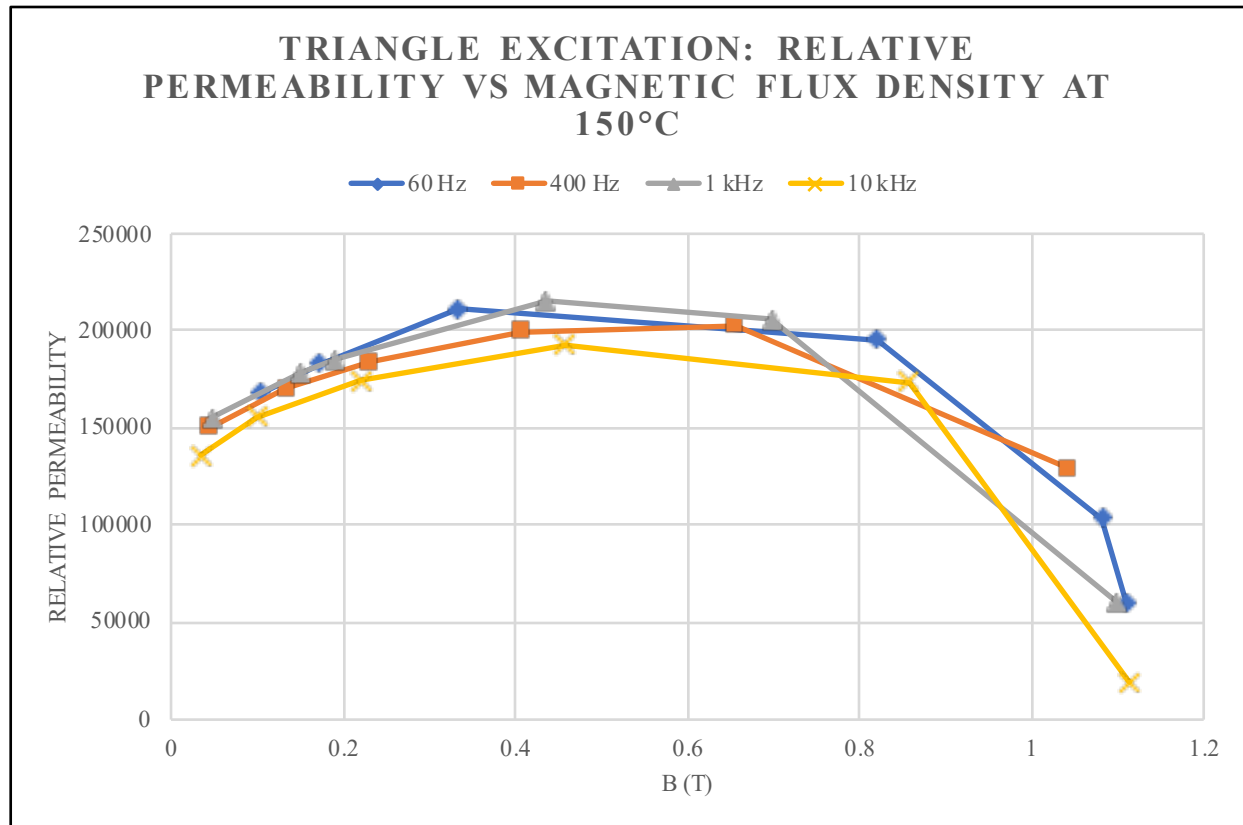
α	1.4761	
β	2.3367	
k_h	1.68652E-05	W / kg



(b)

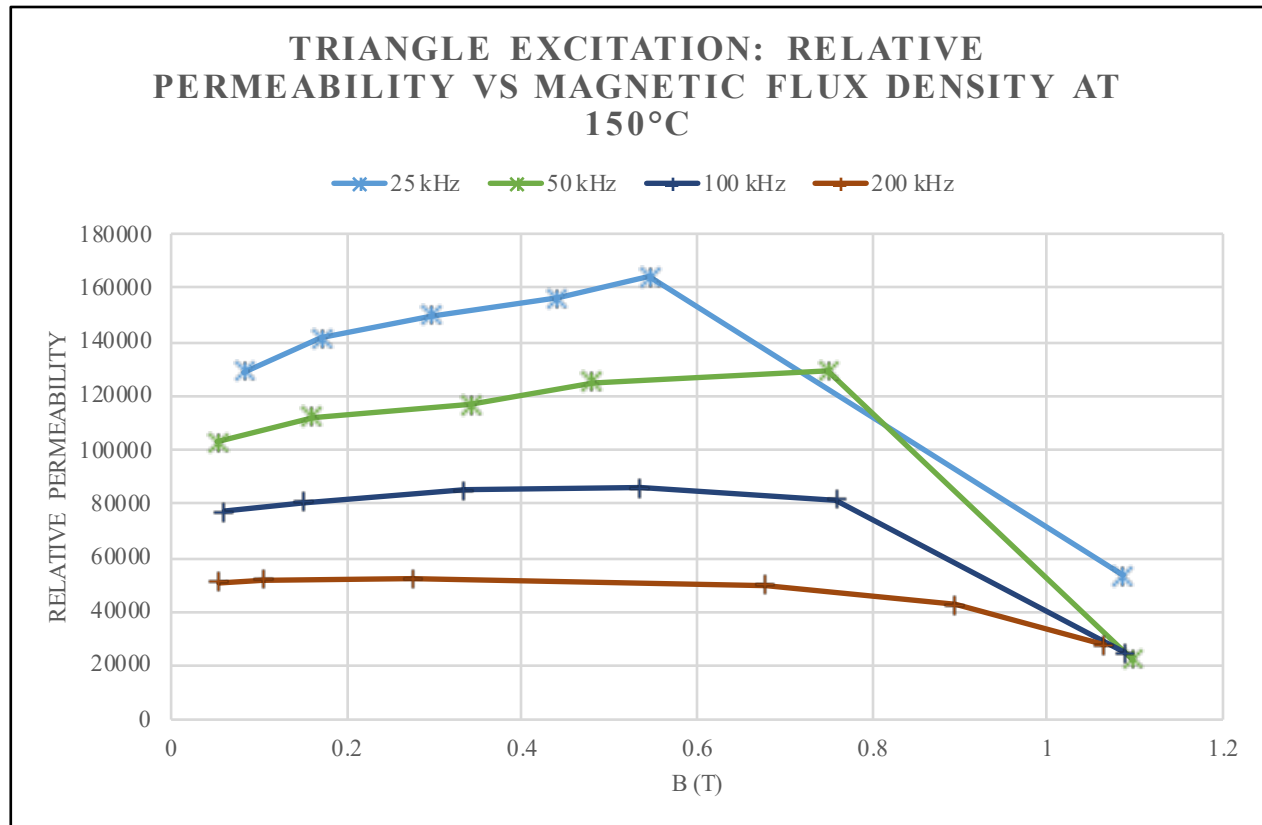
Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..



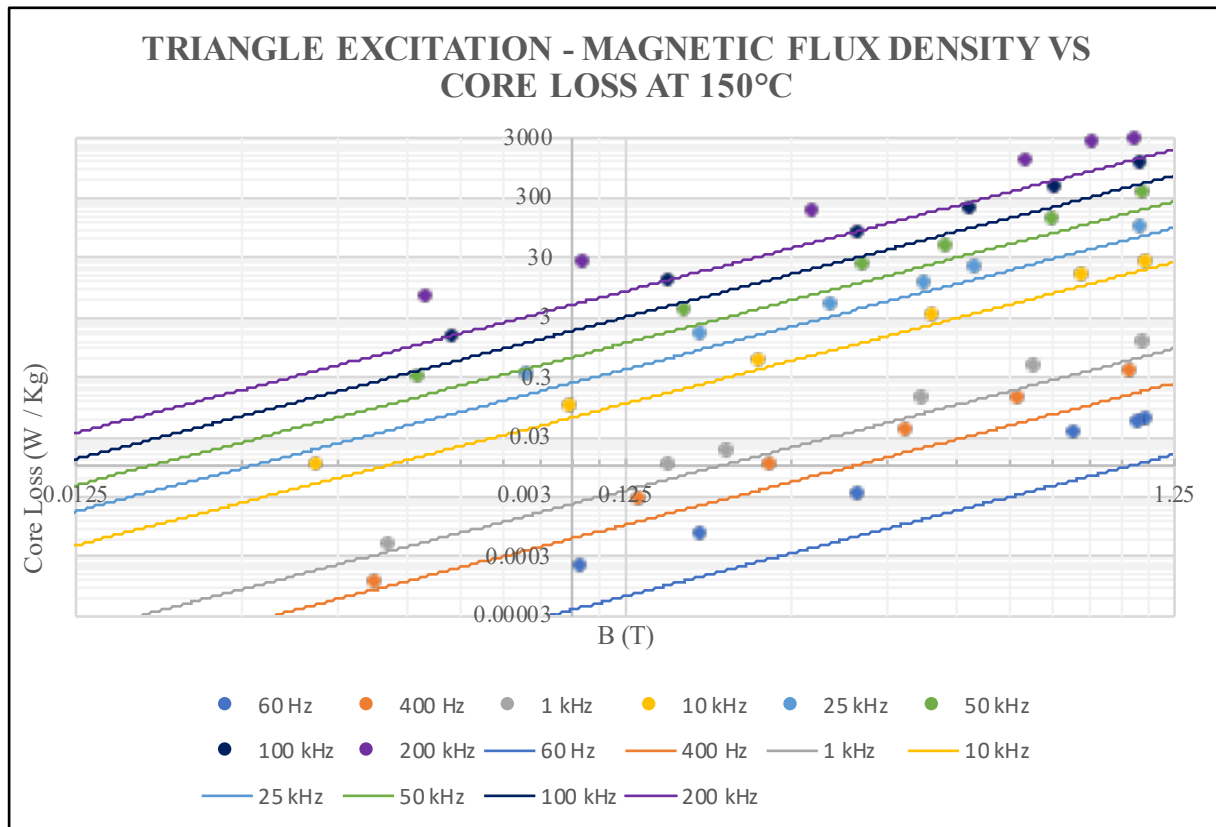
60 Hz		400 Hz		1 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.11	60493.92	1.04	129211.86	1.10	60357.00
1.08	103921.50	0.66	202564.77	0.70	205860.19
0.82	195336.04	0.41	199353.21	0.44	215497.57
0.33	211474.46	0.23	183634.84	0.19	185436.75
0.17	183048.58	0.13	169931.92	0.15	178299.47
0.10	167868.66	0.04	150242.86	0.05	155356.69

10 kHz	
B (T)	μ_r
1.11	19251.75
0.86	173304.34
0.46	192657.48
0.22	174008.14
0.10	155485.44
0.03	135554.97



25 kHz		50 kHz		100 kHz	
B (T)	μ_r	B (T)	μ_r	B (T)	μ_r
1.09	53511.54	1.10	22131.30	1.09	24910.75
0.55	164212.83	0.75	129224.69	0.76	81472.07
0.44	156300.10	0.48	124816.06	0.54	85995.01
0.30	149818.73	0.34	116607.15	0.33	84847.05
0.17	141140.52	0.16	112199.90	0.15	80426.71
0.08	128700.06	0.05	102597.87	0.06	76959.83

200 kHz	
B (T)	μ_r
1.07	27722.35
0.89	42312.52
0.68	49816.00
0.28	52237.38
0.10	51904.16
0.05	50924.11

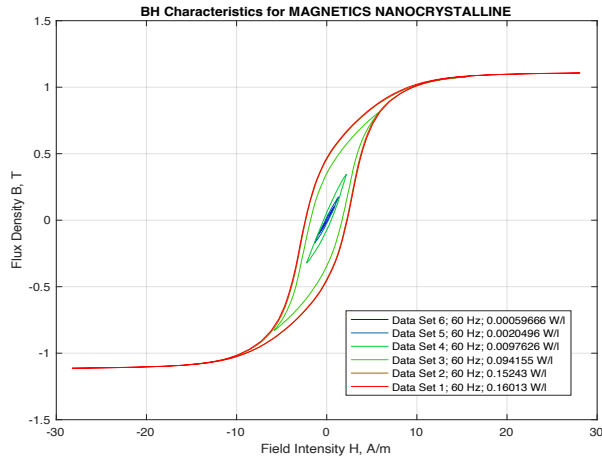


Magnetic Flux Density vs Core Loss - Table

60 Hz		400 Hz		1 kHz		10 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.11	0.05	1.04	0.37	1.10	1.07	1.11	23.89
1.08	0.05	0.66	0.13	0.70	0.45	0.86	13.60
0.82	0.03	0.41	0.04	0.44	0.13	0.46	2.96
0.33	0.00	0.23	0.01	0.19	0.02	0.22	0.54
0.17	0.00	0.13	0.00	0.15	0.01	0.10	0.09
0.10	0.00	0.04	0.00	0.05	0.00	0.03	0.01

25 kHz		50 kHz		100 kHz		200 kHz	
B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)	B (T)	Core Loss (W/kg)
1.09	94.78	1.10	327.50	1.09	1045.90	1.07	2803.70
0.55	18.38	0.75	123.45	0.76	422.87	0.89	2437.70
0.44	10.97	0.48	44.51	0.54	187.09	0.68	1176.90
0.30	4.65	0.34	21.84	0.33	69.93	0.28	162.99
0.17	1.51	0.16	3.62	0.15	11.30	0.10	23.79
0.08	0.33	0.05	0.28	0.06	1.36	0.05	6.55

Empirical Model for Core Loss using Steinmetz Equation: Triangle Excitation via Sudhoff Simulation



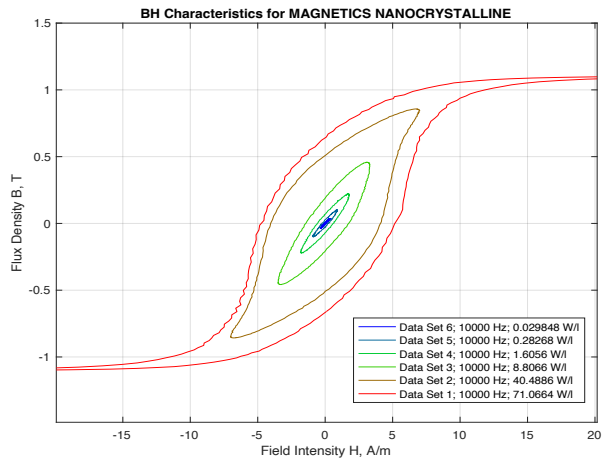
(a)

Steinmetz Equation

$$p_w = k_h \left(\frac{f}{f_b} \right)^\alpha \left(\frac{B_{pk}}{B_b} \right)^\beta$$

Steinmetz Coefficients for Curve Fit 150°C

α	1.4473	
β	2.3694	
k_h	2.41493E-05	W / kg



(b)

Empirical Model Plot Sample – (a) 60 Hz. (b) 10 kHz

Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h , α , and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. In computation, base frequency is 1 Hz and Base Flux Density is 1 Tesla. See S.D. Sudhoff Page 191 Equation 6.3-2: *Power Magnetic Devices: A Multi-Objective Design Approach*, First ed..