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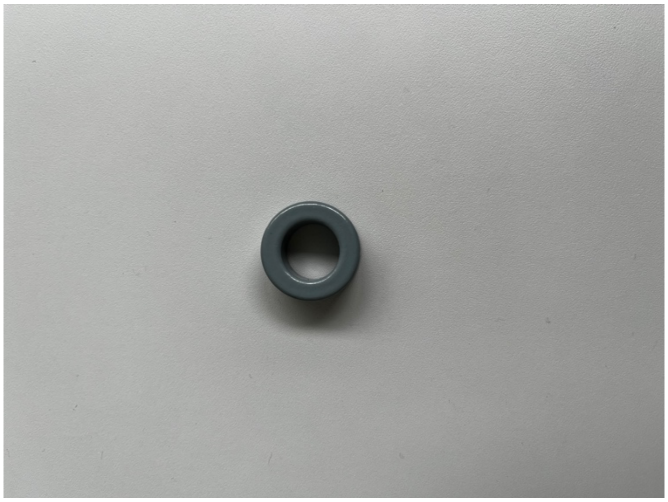
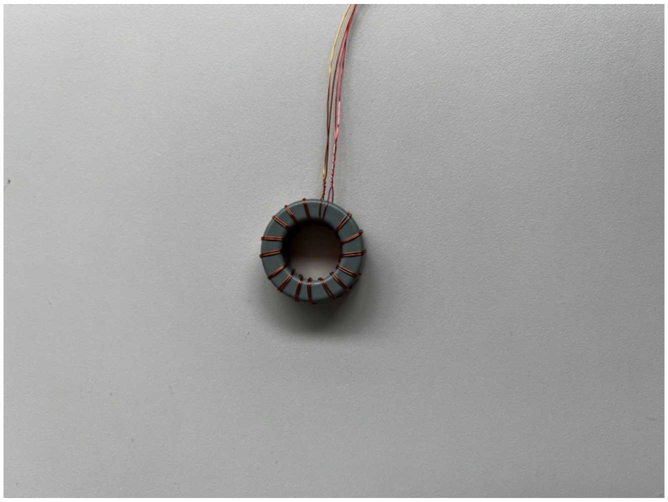
Ferrite Material
Datasheet

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

AMPED

Revision: A

Description of Core Under Test (CUT).

Magnetics, Inc. ZF42508TC is a ferrite material for choices in applications involving the use for Electromagnetic Interference (EMI) and Radio Frequency Interference (RFI) Filtering, both in attempts of far-field and near-field measurements, as well as for broadband transformers. Generally for power transformers, inductor, and filer material. Composition involved with this particular core is Magnetics Inc's F Material with a potential saturation induction of 0.470 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:	http://engineering.pitt.edu/amped

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	November 6, 2023	Edited sinusoidal excitation data, removed additional waveform 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.

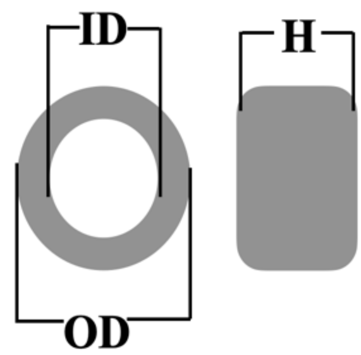
Person(s) responsible for finalizing the marking of this declaration, approving of best effort of capability:

Name	Title	Date
PAUL R. OHODNICKI, JR., PHD	Associate Professor	December 1, 2023
ALEX LEARY, PHD	Materials Research Engineer	December 1, 2023

Core Specifications

Dimensions			
Description	**Symbol**	**Sample Dimension (mm) [1]**	**Actual Dimension Used (mm) [1]**
Core Inner Diameter	ID	15.00	15.45
Core Outer Diameter	OD	25.57	25.34
Core Height	H	10.14	9.8

[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	48.00	mm^2
Mean Magnetic Path Length	L_m	62.03	mm
Core Mass	C_M	0.014344291	kg
Density	D	4800	kg / m^3
Lamination Thickness	L_M	0	µm
Chemistry	F Material Ferrite	**Grade**	
Anneal		**Impregation**	Unimpregnated
Core Supplier	MAGNETICS	**Part Number**	ZF42508TC
Wire Supplier	Remington Industries	**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	16	16
2	100 – 500 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 A), and l_e is the mean path length of the core.			

Section One: Room Temperature Environmental Measurements. Magnetic Core Characterization Testing with Two Winding Method: 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
WAV0002	Arbitrary Waveform Generator	Keysight Technologies	33500B	None
AMP0002	RF Amplifier (DC - 1MHz)	AE Techron	7224	7224-0523-3205-B
ANA0002	Power Analyzer	Yokogawa	WT5000	C27E0021V
OSC0005	Oscilloscope (1 GHz)	Teledyne-Lecroy	3104Z	LCRY3714C19876
PRO0007	AC / DC Current Probe	Keysight Technologies	1147B	JP61071359
PRO0008	2 kV Differential Probe	Teledyne-Lecroy	RP1100D	20180742
CAP0003	1000 uF Capacitor	Cornell Dubilier Electronics (CDE)	947D102K901CJRSN	947D102K901CJRSN
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, IEEE-393, and IEC 62044-1, IEC 62044-2, IEC 62044-3, 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 90.

d. Set the Oscilloscope to the following settings.
    - Specify Probe Attenuation.
        - Measurements were performed with a Teledyne-Lecroy current probe, having a fixed attenuation ratio of 0.1 V/A.
        - Measurements were performed with a Teledyne-Lecroy voltage probe, having a fixed attenuation ratio of 250X.

e. Set the Power Analyzer to the following settings.
    - Attempt at a refresh time that provides at least four to five periods of the excitation signal. If limited where more periods are observed, note the frequencies and any other relevant information.
        - 10 ms refresh time, with 10 period for 100 kHz.
        - 10 ms refresh time, with 20 periods for 200 kHz.
        - 10 ms refresh time, with 51 periods for 500 kHz.

f. Turn output of Arbitrary Waveform Generator on.

g. 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 PRO0008 does not have the capability (only autozero).

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 4 - 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 Density 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. Auto zero the voltage probe, either where shifting may begin to occur, or after each frequency measured.

k. Setup included correction components for DC Biasing part of the setup. See the test setup section for a diagram. Note a 1000 uF capacitor was used for this effect.

l. Repeat steps a - f for Square Waveform, Triangle Waveform, or other excitation waveforms for examined interest.

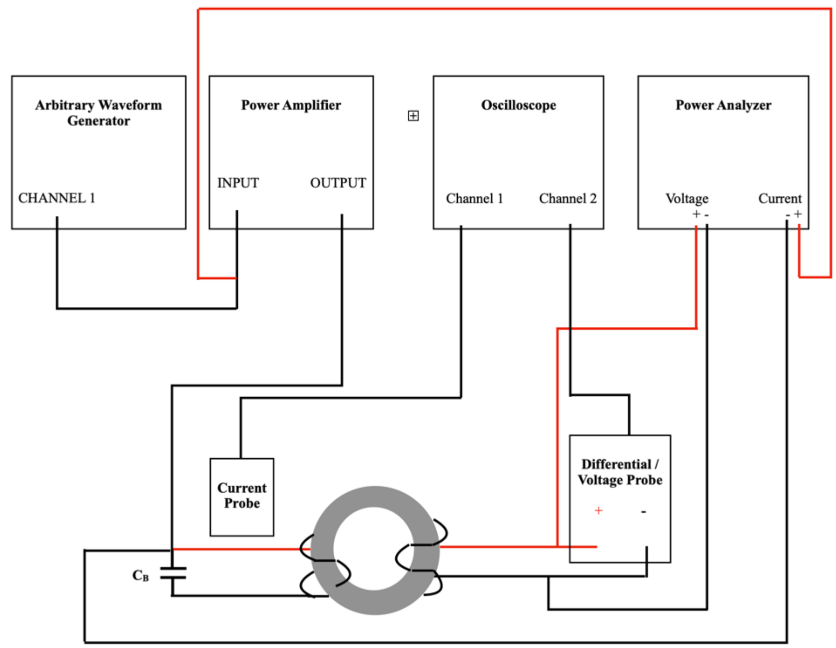
m. Record relevant data for Data Presentation.

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.

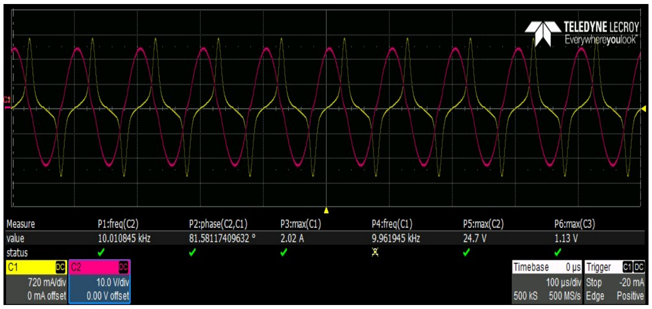
Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup: Cable Layout.

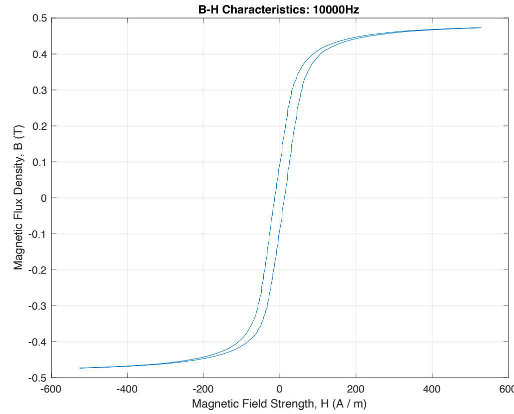


Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup: System Block Diagram.

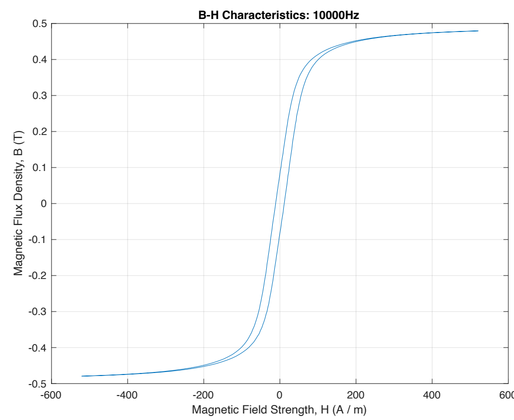
Data Presentation.

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



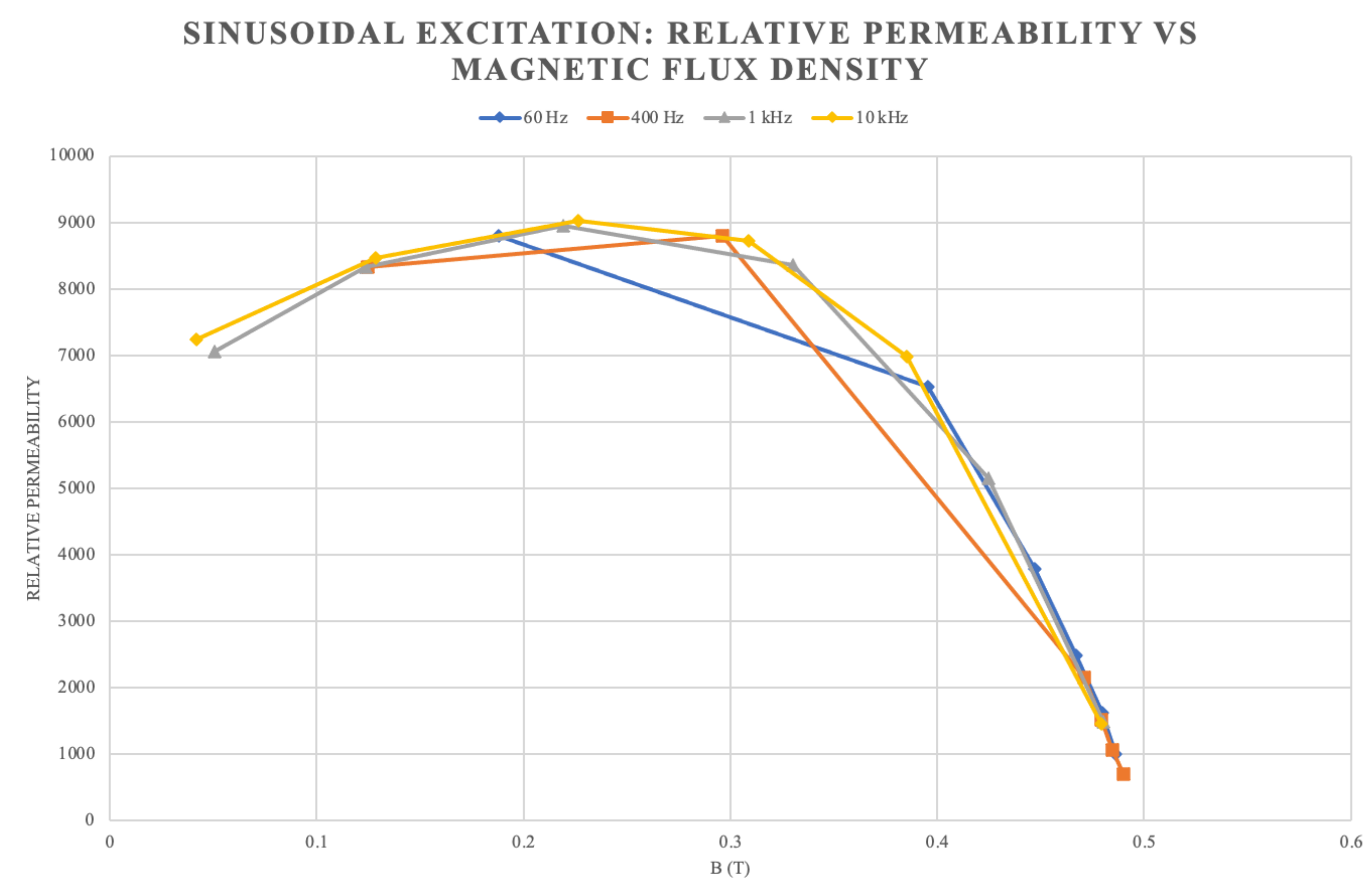


Sample Sinusoidal Excitation Waveform and B-H Plot via Oscilloscope. Sinusoidal Signal. 1.295 V_{pp} 10kHz, Amplifier Gain 90.



Sample Sinusoidal Excitation Waveform and B-H Plot via Power Analyzer. Sinusoidal Signal. 1.295 V_{pp} 10kHz, Amplifier Gain 90.

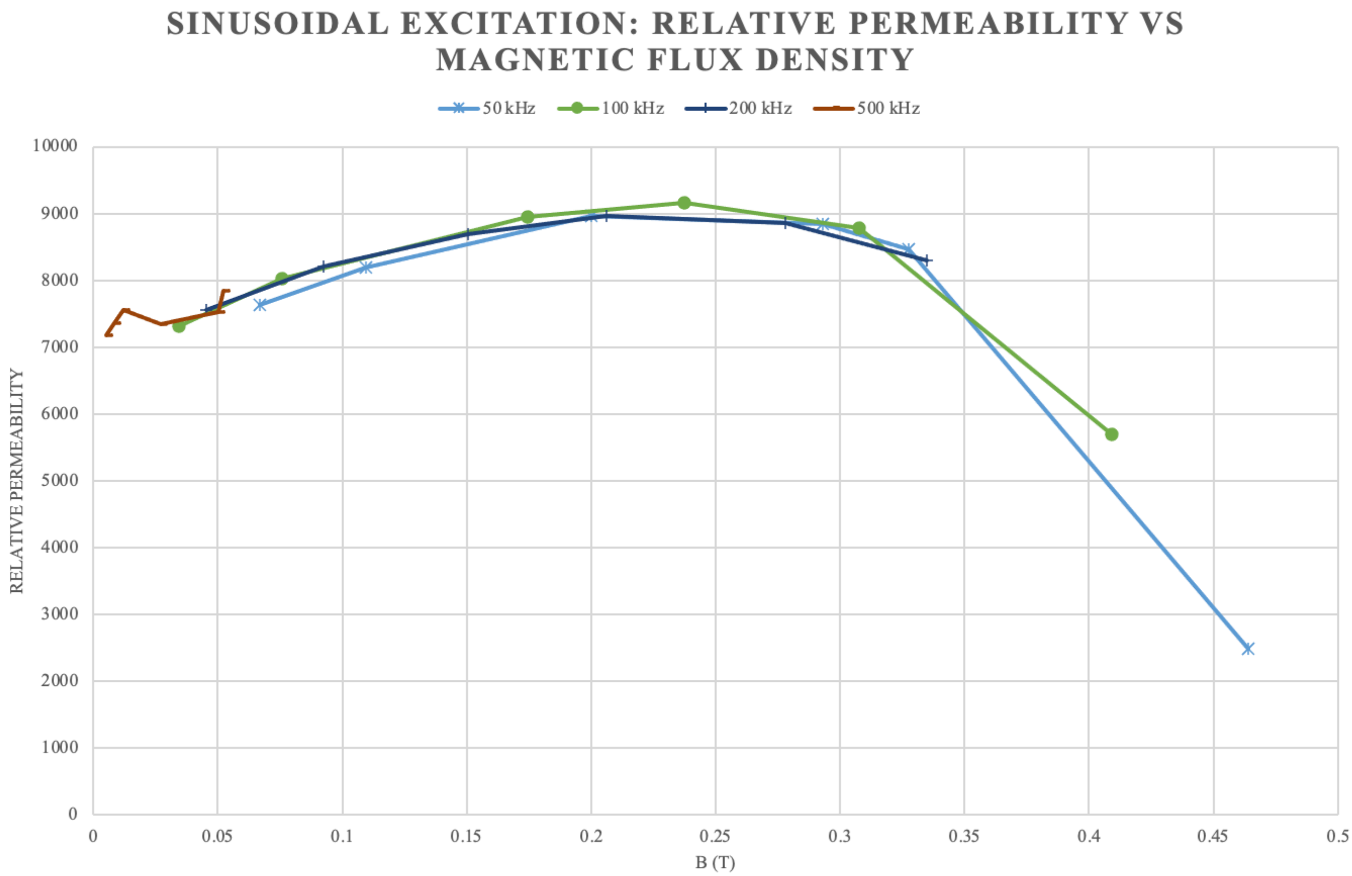
a. Sinusoidal Excitation Magnetic Characterization.



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

60 Hz			**400 Hz**			**1 kHz**			**10 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.49	1003.7		0.49	700.5		0.48	1488.2		0.48	1463.56
0.48	1627.4		0.48	1059.8		0.42	5151.7		0.39	6984.17
0.47	2484.7		0.48	1523.0		0.33	8366.3		0.31	8728.78
0.45	3787.5		0.47	2150.5		0.22	8957.2		0.23	9031.11
0.40	6533.4		0.30	8797.0		0.12	8325.2		0.13	8459.97
0.19	8798.5		0.12	8325.3		0.05	7062.1		0.04	7233.02

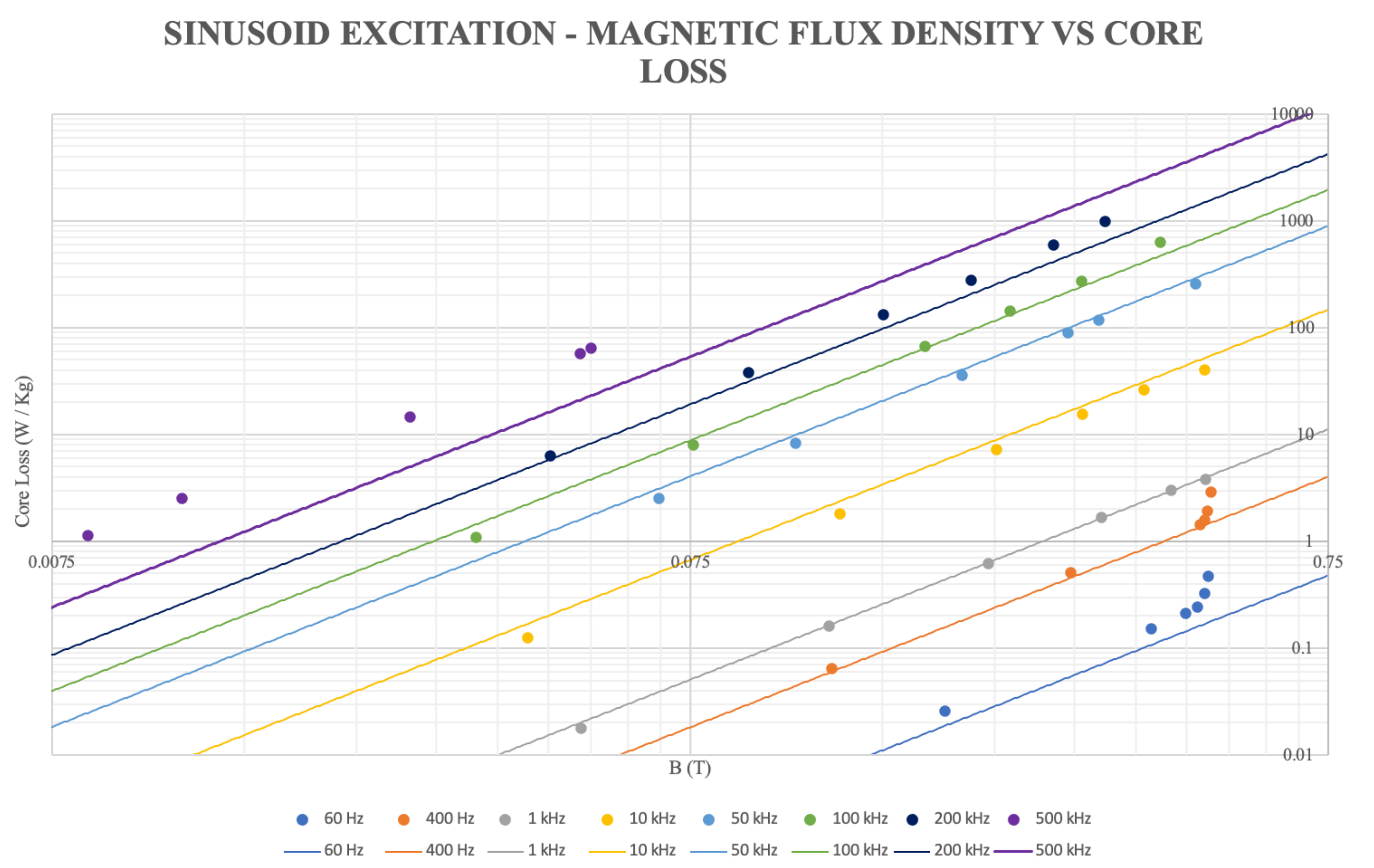
Note: All data was curve fit with power analyzer data.



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

50 kHz			**100 kHz**			**200 kHz**			**500 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.46	2492.64		0.41	5690.60		0.33	8304.62		0.05	7839.20
0.33	8472.51		0.31	8789.60		0.28	8854.07		0.05	7524.19
0.29	8837.92		0.24	9168.62		0.21	8966.97		0.03	7347.69
0.20	8961.42		0.17	8953.88		0.15	8689.26		0.01	7560.90
0.11	8187.27		0.08	8028.29		0.09	8201.59		0.01	7364.11
0.07	7634.71		0.03	7321.03		0.05	7550.76		0.01	7181.79

Note: All data was curve fit with power analyzer data.



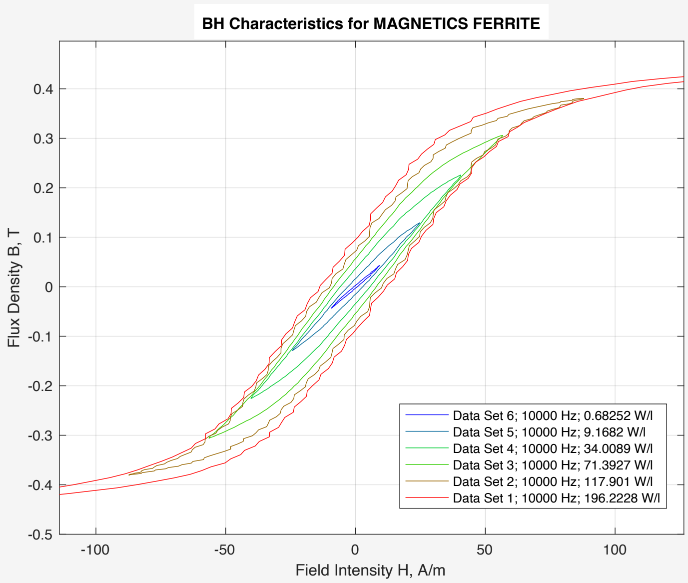
Core Loss Measurements - Sinusoidal Excitation - Flux Density vs Core Loss

Magnetic Flux Density vs Core Loss - Table

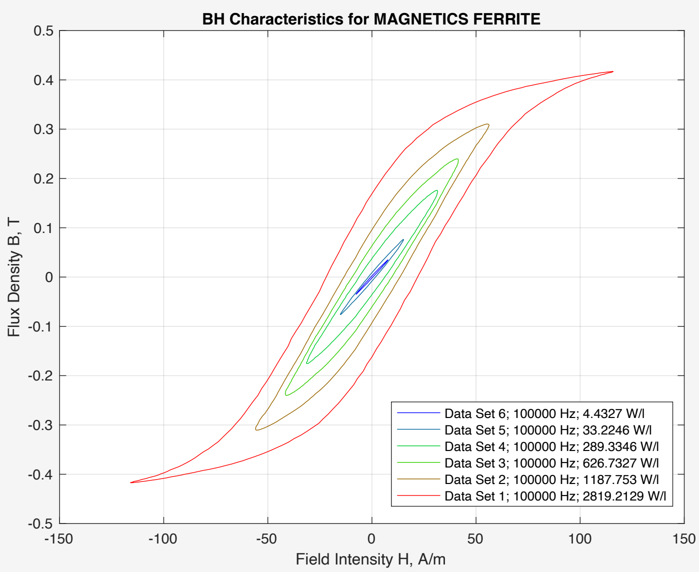
f = 60 Hz			**f = 400 Hz**			**f = 1 kHz**			**f = 10 kHz**	
B (T)	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**
0.49	0.47		0.49	2.94		0.48	3.82		0.48	40.45
0.48	0.33		0.48	1.94		0.42	3.02		0.39	26.62
0.47	0.25		0.48	1.58		0.33	1.70		0.31	15.58
0.45	0.22		0.47	1.45		0.22	0.63		0.23	7.37
0.40	0.15		0.30	0.52		0.12	0.16		0.13	1.82
0.19	0.03		0.12	0.06		0.05	0.02		0.04	0.13
f = 50 kHz			**f = 100 kHz**			**f = 200 kHz**			**f = 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)**
0.46	261.77		0.41	638.72		0.33	1001.50		0.05	64.55
0.33	118.25		0.31	276.41		0.28	602.43		0.05	57.90
0.29	90.42		0.24	144.44		0.21	282.88		0.03	14.65
0.20	36.34		0.17	67.18		0.15	132.96		0.01	2.53
0.11	8.43		0.08	8.06		0.09	38.60		0.01	1.16
0.07	2.56		0.03	1.09		0.05	6.32		0.01	0.43

Note: All data was curve fit with power analyzer data.

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



(a)



(b)

Empirical Model Plot Sample – (a) 10 kHz. 100 kHz

Steinmetz Equation

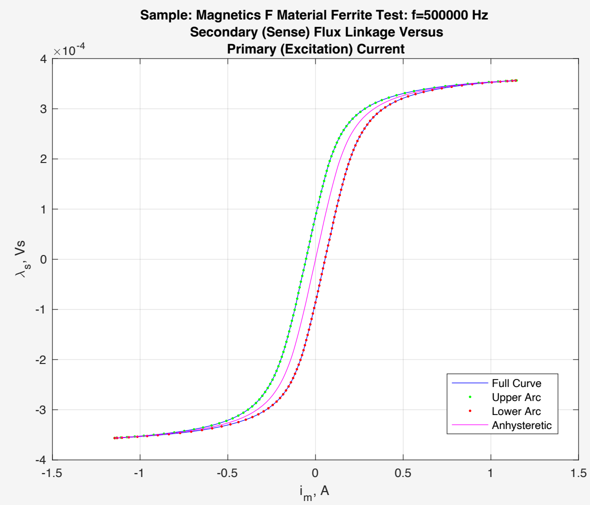
$$p_w = k_h \left(\frac{f}{f_b}\right)^{\alpha} \left(\frac{B_{pk}}{B_b}\right)^{\beta}$$

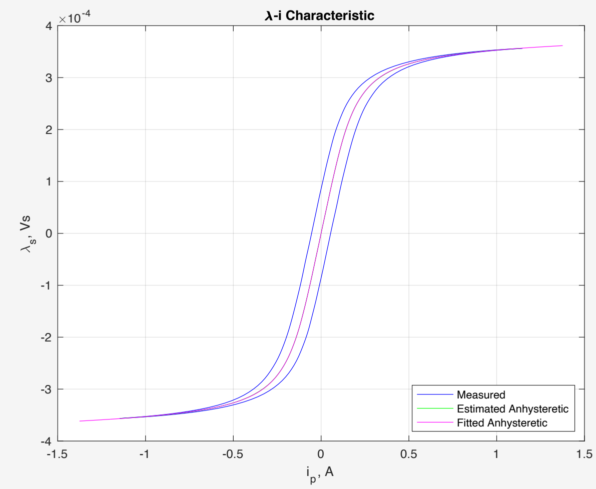
Steinmetz Coefficients for Curve Fit

α	1.12	
β	2.3447	
k_h	0.0096242	W / kg

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..

Anhysteric BH Plots at 50 kHz.





μ_r	α (1/T)	β (1/T)	γ (T)
6253.4685	0.79576	29.86698	0.61661
	0.31262	41.0589	0.7102
	0.038859	69.5693	0.47742
	0.0032085	12.789	0.46262

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

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

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

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

The anhysteric 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 Anhysteretic Characterization and Permeability Modeling,” in *IEEE Transactions on Magnetics*, vol. 46, no. 11, pp. 3834-3843, Nov. 2010.

Section Two: Room Temperature Environmental Measurements. Magnetic Core Characterization Testing with Capacitive Cancelling: 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
WAV0002	Arbitrary Waveform Generator	Keysight Technologies	33500B	None
AMP0002	RF Amplifier (DC - 1MHz)	AE Techron	7224	7224-0523-3205-B
OSC0005	Oscilloscope (1 GHz)	Teledyne-Lecroy	3104Z	LCRY3714C19876
PRO0007	AC / DC Current Probe	Keysight Technologies	1147B	JP61071359
PRO0008	2 kV Differential Probe	Teledyne-Lecroy	RP1100D	20180742
PRO0009	2kV Differential Probe	Teledyne Lecroy	HVD3220	363
PRO0010	2kV Differential Probe	Teledyne Lecroy	HVD3220	282
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, IEEE-393, and IEC 62044-1, IEC 62044-2, IEC 62044-3, 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 90.

d. Set the Oscilloscope to the following settings.
   - Specify Probe Attenuation.
     - Measurements were performed with a Teledyne-Lecroy current probe, having a fixed attenuation ratio of 0.1 V/A.
     - Measurements were performed with a Teledyne-Lecroy voltage probe on the current sensing resistor, having a fixed attenuation ratio of 250X.
     - Measurements were performed with a Teledyne-Lecroy voltage probe on the sensing / secondary winding, having a fixed attenuation ratio of 250X.
     - Measurements were performed with a Teledyne-Lecroy voltage probe from the sensing / secondary positive polarity to the negative of the resonant capacitor, having a fixed attenuation ratio of 250X.

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 PRO0008, PRO0009, or PRO0010 does not have the capability (only autozero).

g. 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 4 - 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 waveforms flatten. See Data Presentation for examples.
   - Magnetic Flux Density is optional for oscilloscope waveforms but recommended.

h. 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.

i. Auto zero the voltage probe, either where shifting may begin to occur, or after each frequency measured.

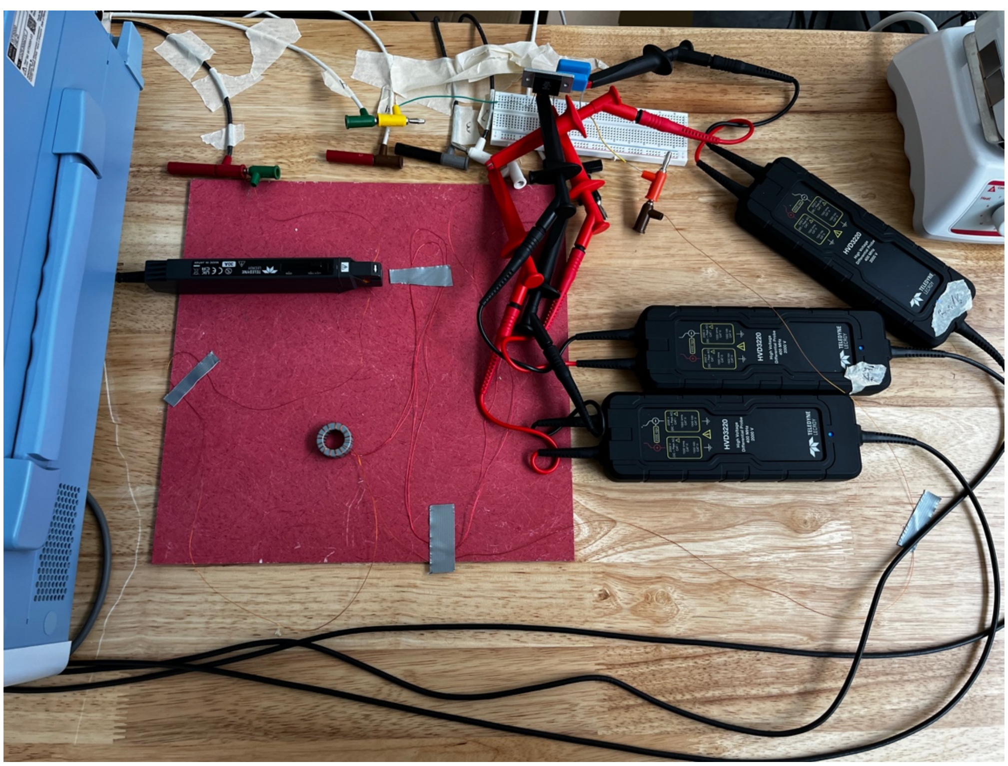
j. Setup included capacitor calculated at a specific resonance frequency. See the test setup section for a diagram. See table within the section populating with the details (of calculation and of values).

k. Record relevant data for Data Presentation.

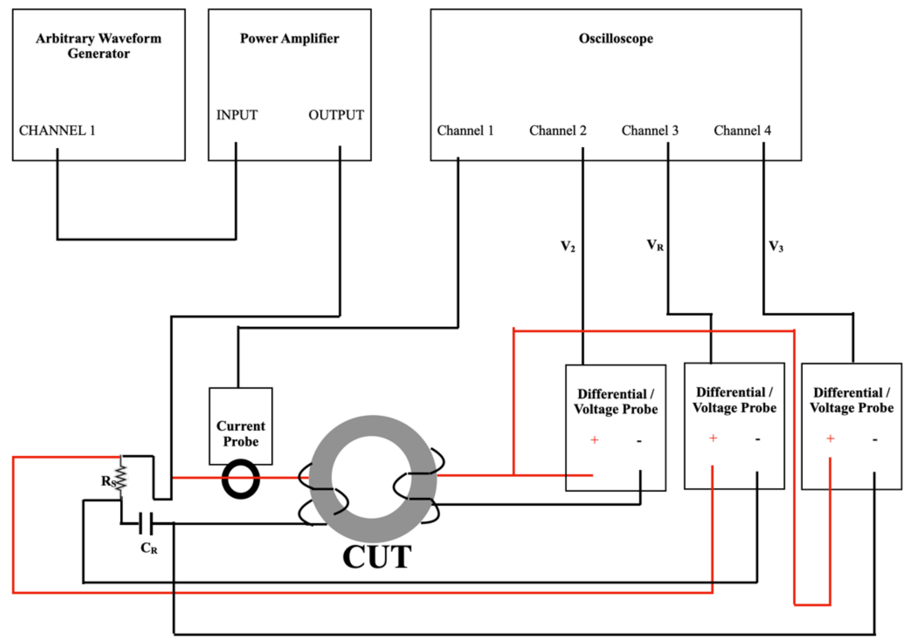
Setup.

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. Typical Test Setup: Cable Layout.



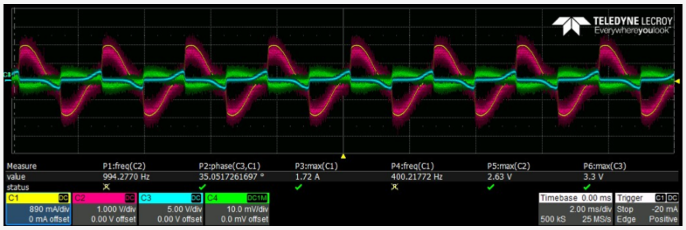
Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup: System Block Diagram.

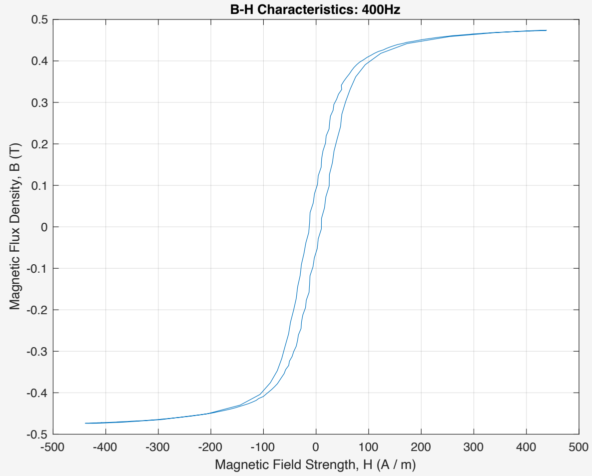
List of Resonant Capacitors				
Frequency (Hz)	**Quantity**	**Capacitor Value**	**Manufacturer**	**Part Number**
400	2[1]	660 uF	Chemi-Con	KTD250B337M99A0B00
10000	1	1 uF	KyoCera AVX	SV09AC105KAR
50000	1	33 nF	Cornell Dubilier	CD42FD333FO3F

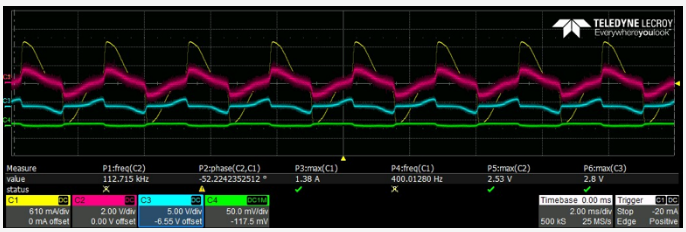
[1] = Two in Parallel

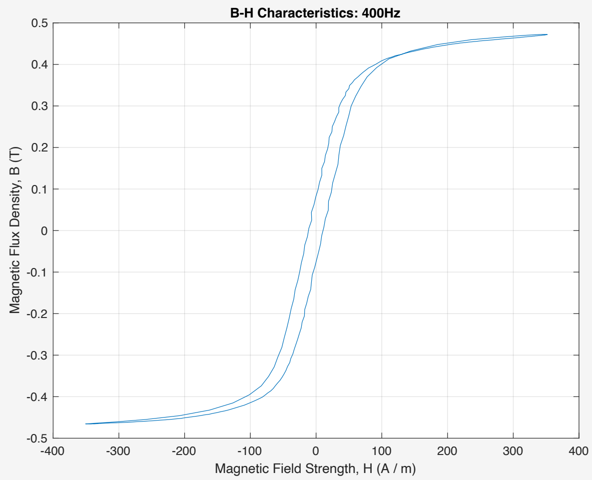
400 Hz

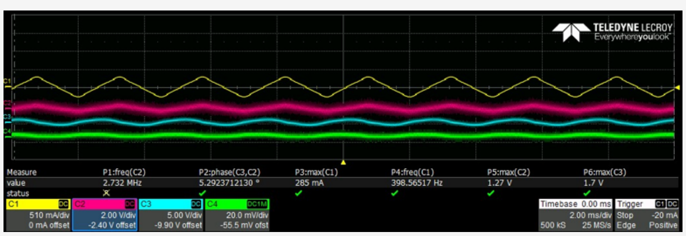
Core Loss with 660 uF Resonant Capacitor.

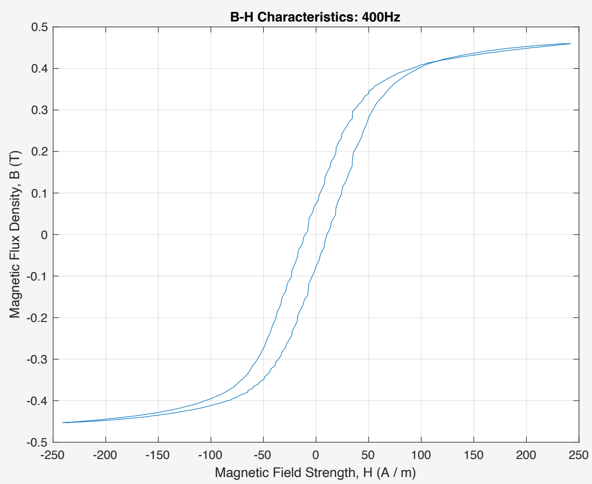


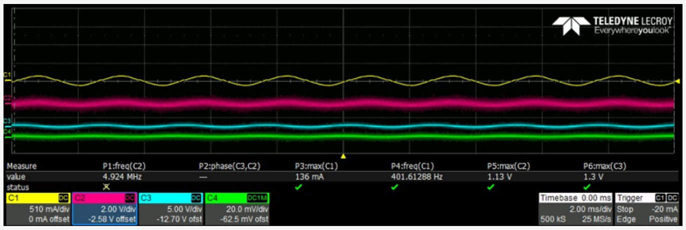


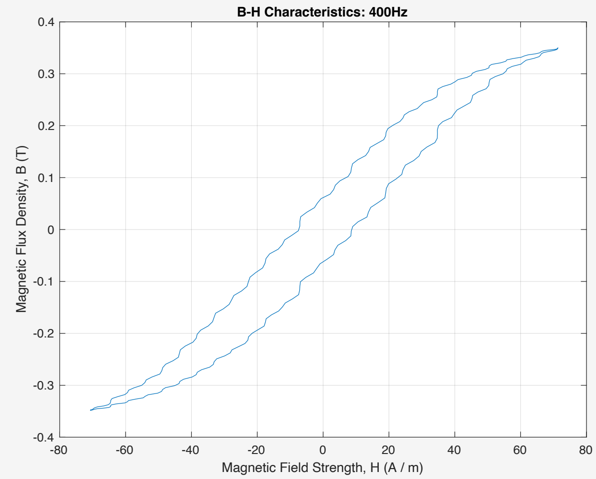


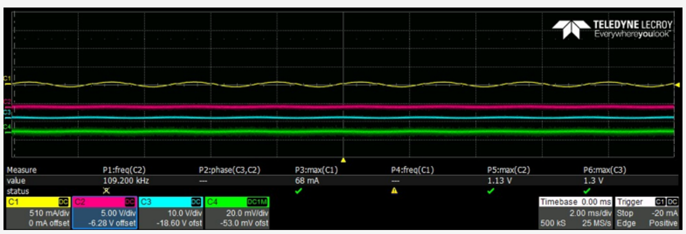


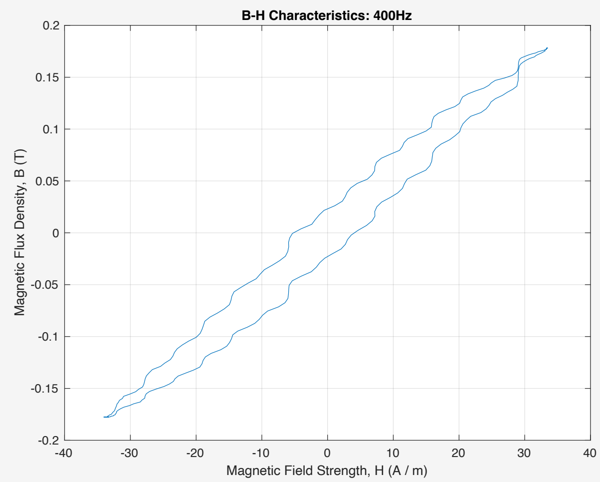


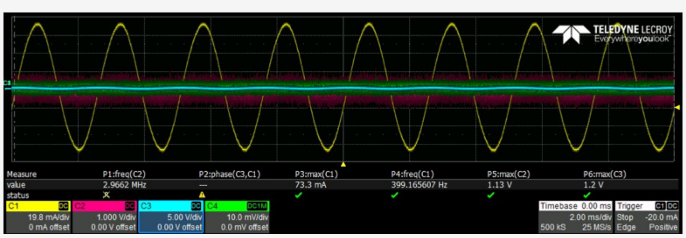


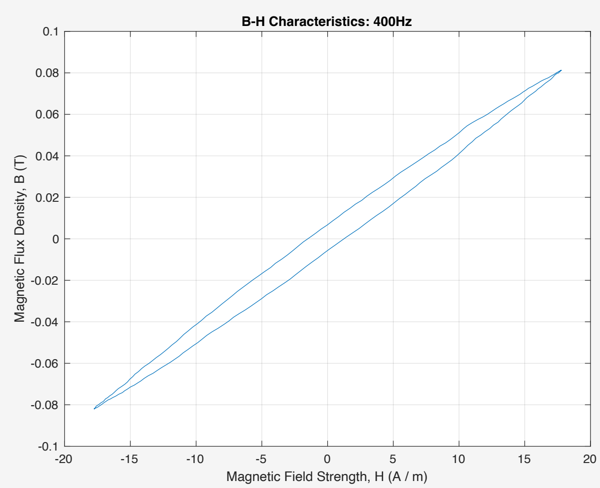

TELEDYNE LECROY

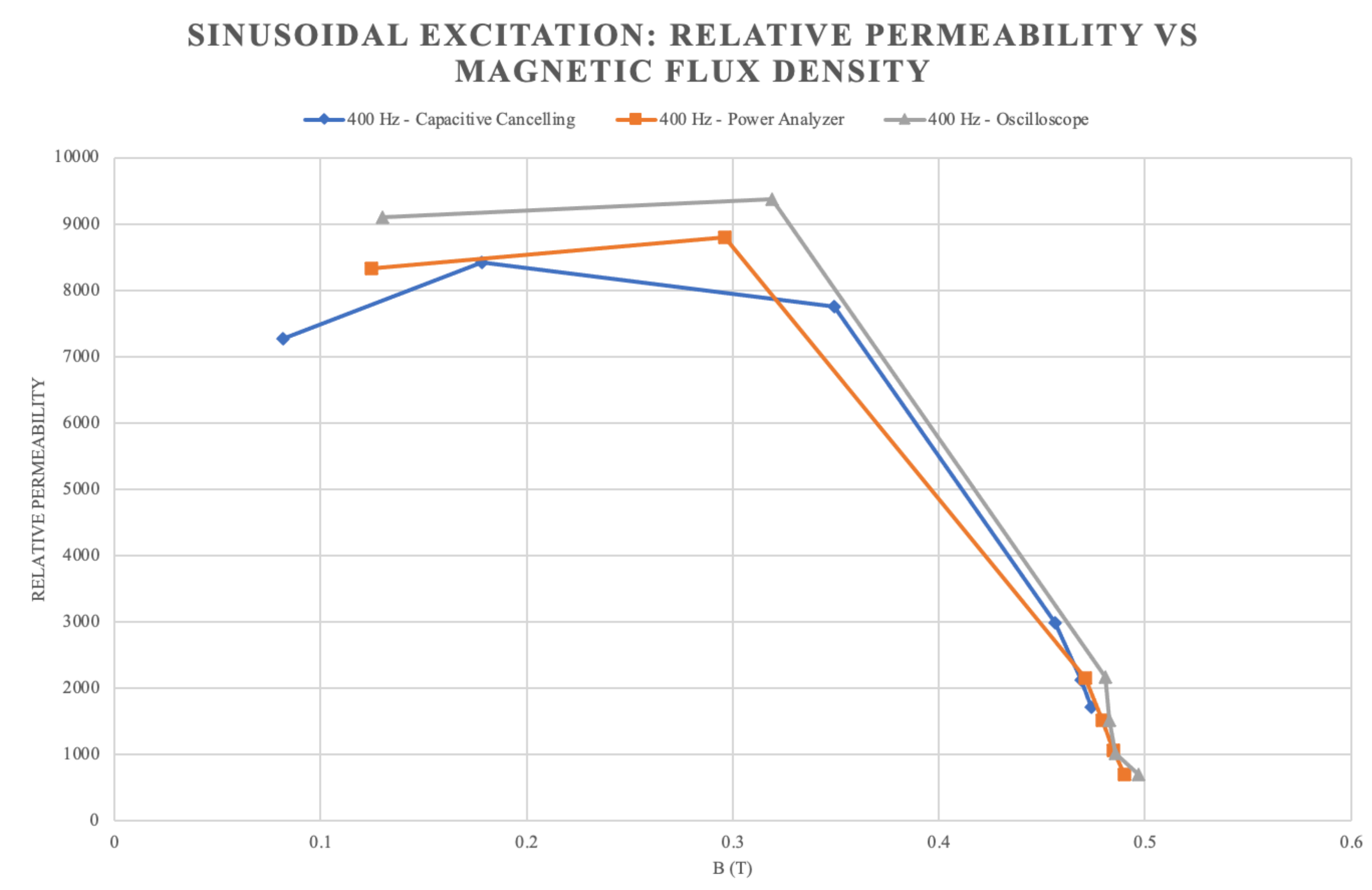

B-H Characteristics: 400Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)


TELEDYNE LECROY


B-H Characteristics: 400Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)

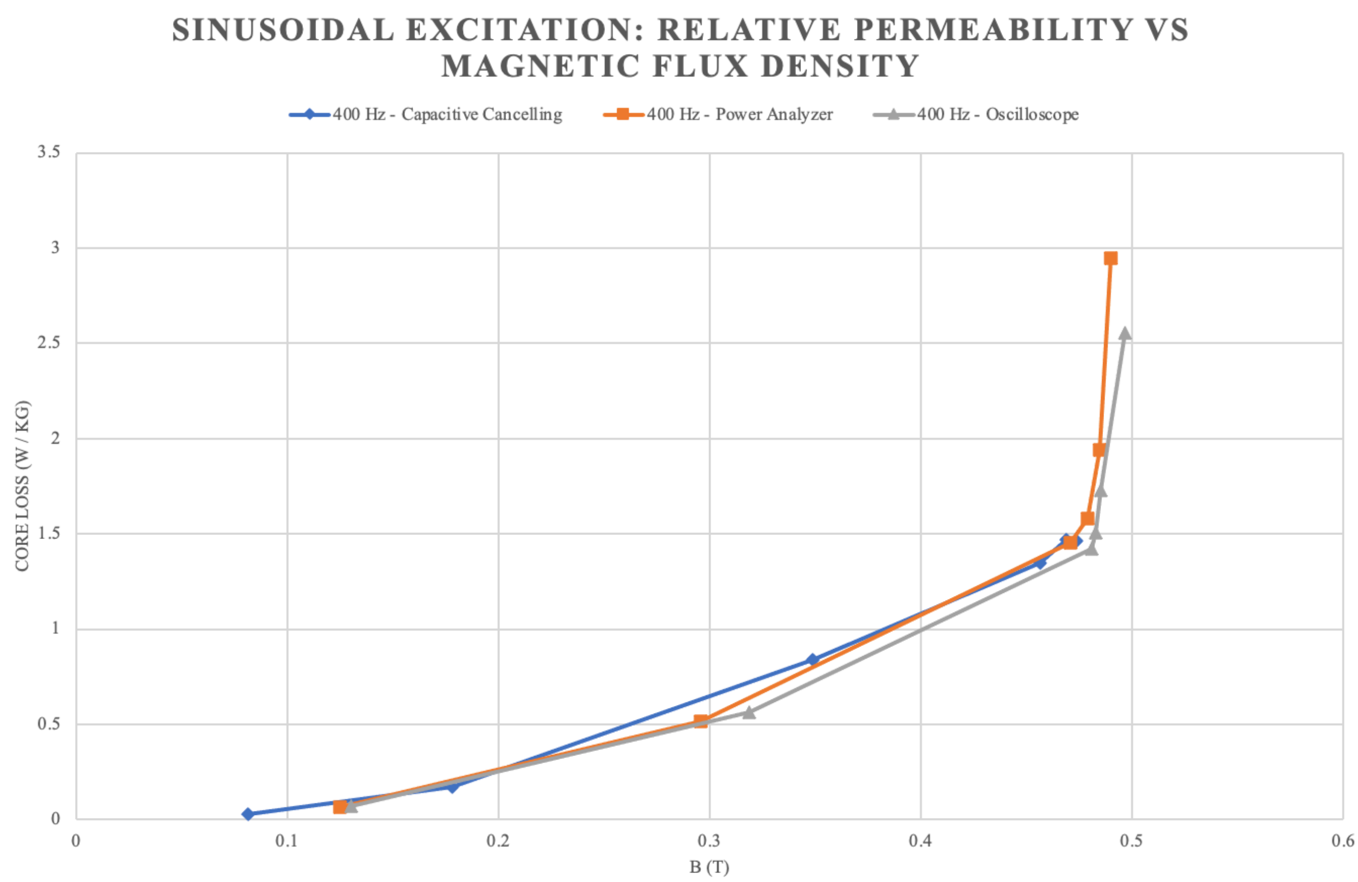

TELEDYNE LECROY


B-H Characteristics: 400Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

400 Hz – Capacitive Cancelling			**400 Hz – Power Analyzer**			**400 Hz – Oscilloscope**				
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**			
0.47	1719.5		0.49	700.5		0.50	696.8			
0.47	2118.7		0.48	1059.8		0.49	1027.1			
0.46	2992.7		0.48	1523.0		0.48	1522.2			
0.35	7750.4		0.47	2150.5		0.48	2164.8			
0.18	8415.8		0.30	8797.0		0.32	9380.3			
0.08	7268.6		0.12	8325.3		0.13	9095.2			

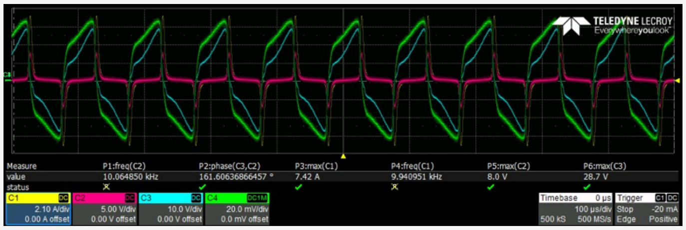


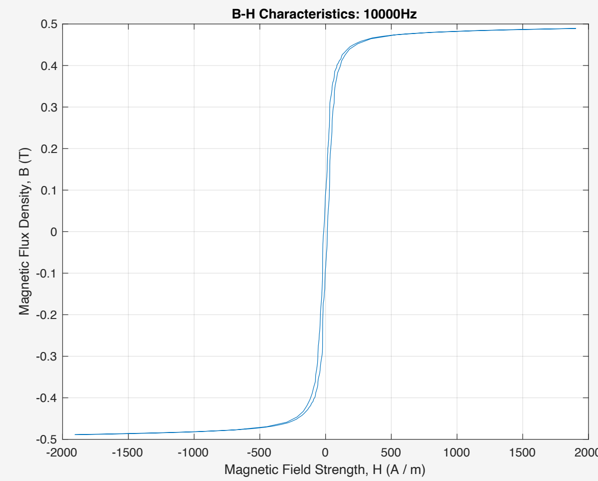
Core Loss Measurements - Sinusoidal Excitation - Flux Density vs Core Loss

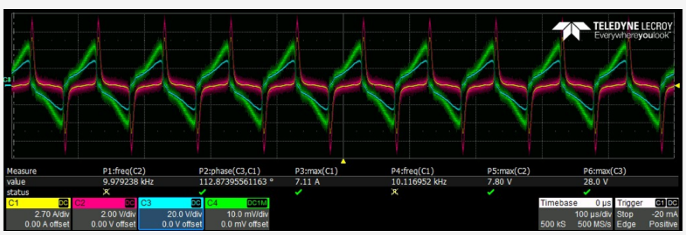
Magnetic Flux Density vs Core Loss - Table										
f = 400 Hz – Capacitive Cancelling			**f = 400 Hz – Power Analyzer**			**f = 400 Hz - Oscilloscope**				
B (T)	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**			
0.47	1.5		0.49	2.9		0.50	2.6			
0.47	1.5		0.48	1.9		0.49	1.7			
0.46	1.3		0.48	1.6		0.48	1.5			
0.35	0.8		0.47	1.5		0.48	1.4			
0.18	0.2		0.30	0.5		0.32	0.6			
0.08	0.0		0.12	0.1		0.13	0.1			

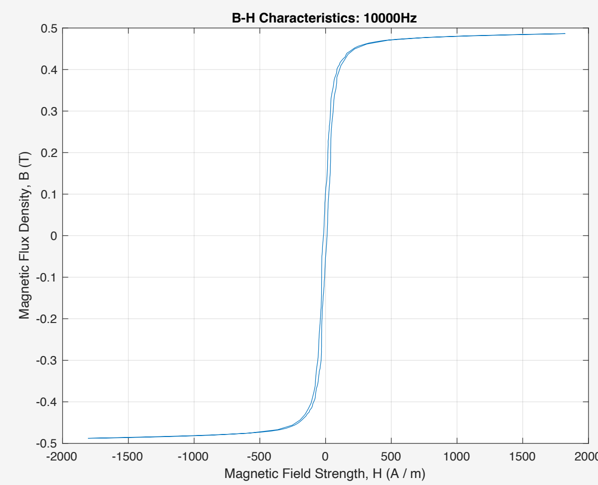
10 kHz

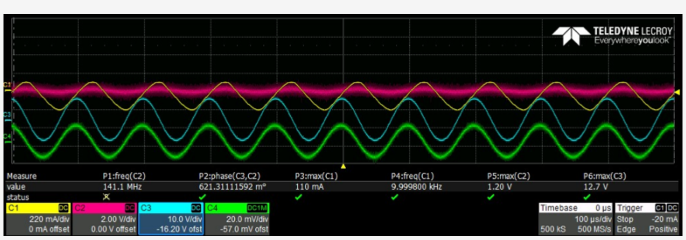
Core Loss with 1 uF Resonant Capacitor.

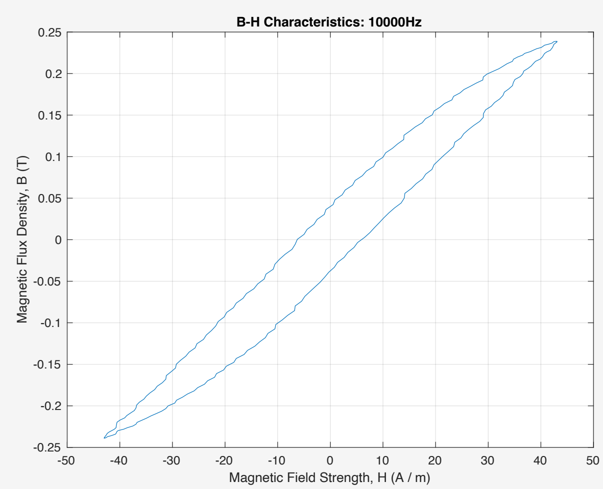


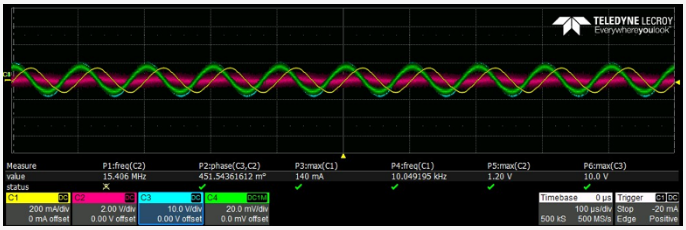


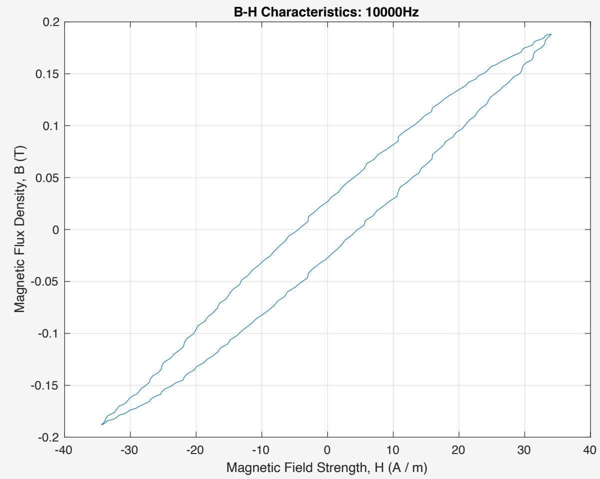


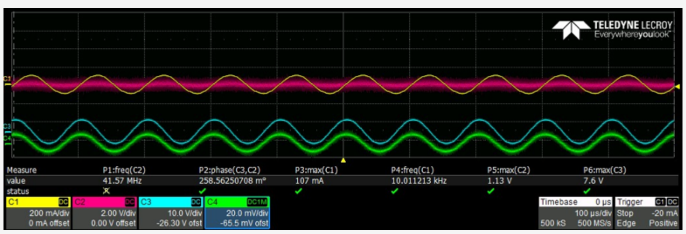


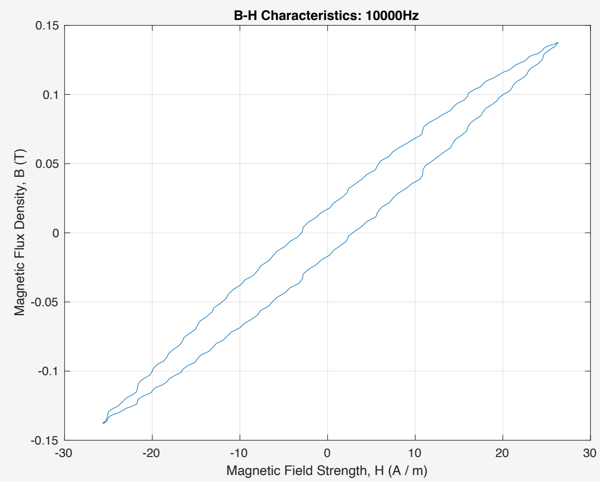


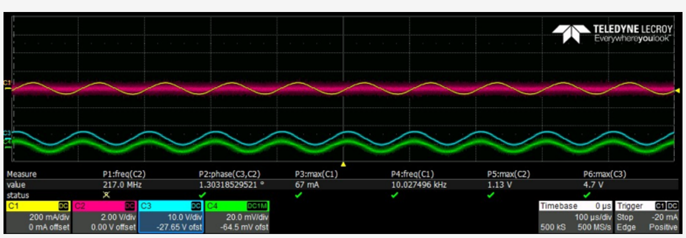


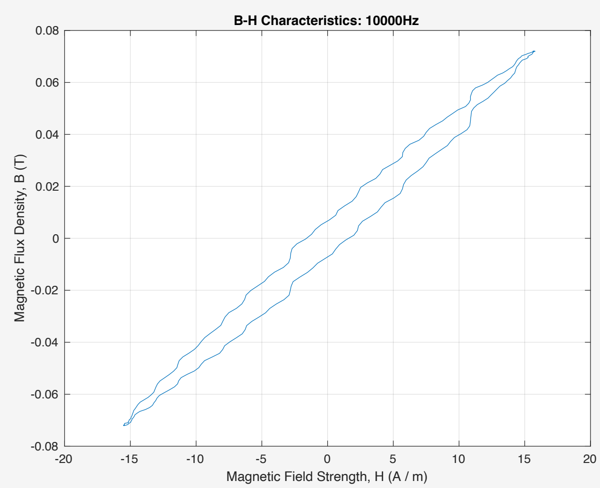

TELEDYNE LECROY
Everywhereyoulook
Measure P1:freq(C2) P2:phase(C3,C2) P3:max(C1) P4:freq(C1) P5:max(C2) P6:max(C3)
value 15.406 MHz 451.54361612 m° 140 mA 10.049195 kHz 1.20 V 10.0 V
status
C1 DC 200 mA/div 0 mA offset
C2 DC 2.00 V/div 0.00 V offset
C3 DC 10.0 V/div 0.00 V offset
C4 DC1M 20.0 mV/div 0.0 mV offset
Timebase 0 µs 100 µs/div 500 kS 500 MS/s
Trigger C1 DC Stop -20 mA Edge Positive

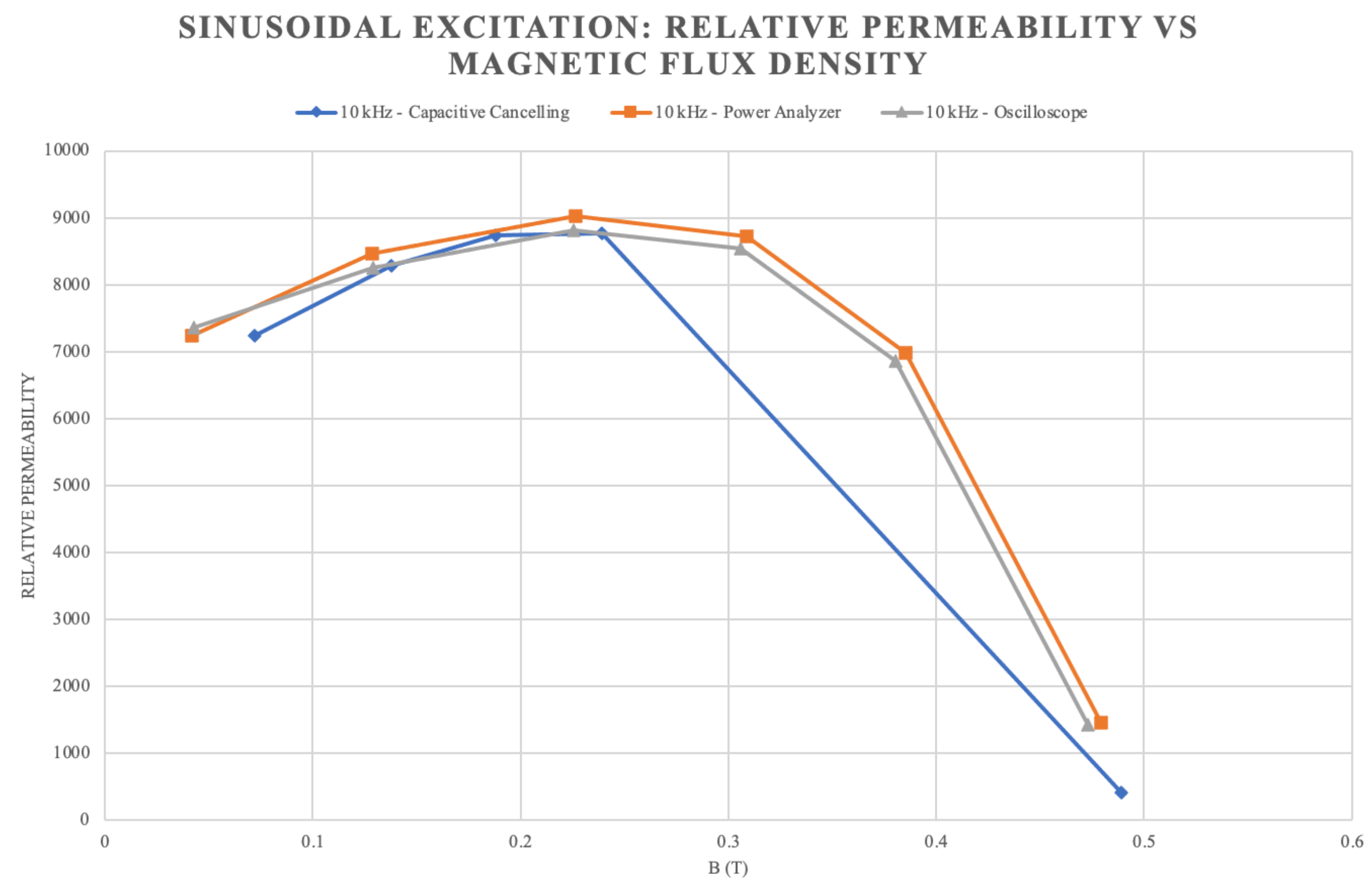

B-H Characteristics: 10000Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)


TELEDYNE LECROY
Everywhereyoulook
Measure P1:freq(C2) P2:phase(C3,C2) P3:max(C1) P4:freq(C1) P5:max(C2) P6:max(C3)
value 41.57 MHz 258.56250708 m° 107 mA 10.011213 kHz 1.13 V 7.6 V
status
C1 DC 200 mA/div 0 mA offset
C2 DC 2.00 V/div 0.00 V offset
C3 DC 10.0 V/div -26.30 V ofst
C4 DC1M 20.0 mV/div -65.5 mV ofst
Timebase 0 µs 100 µs/div 500 kS 500 MS/s
Trigger C1 DC Stop -20 mA Edge Positive


B-H Characteristics: 10000Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)

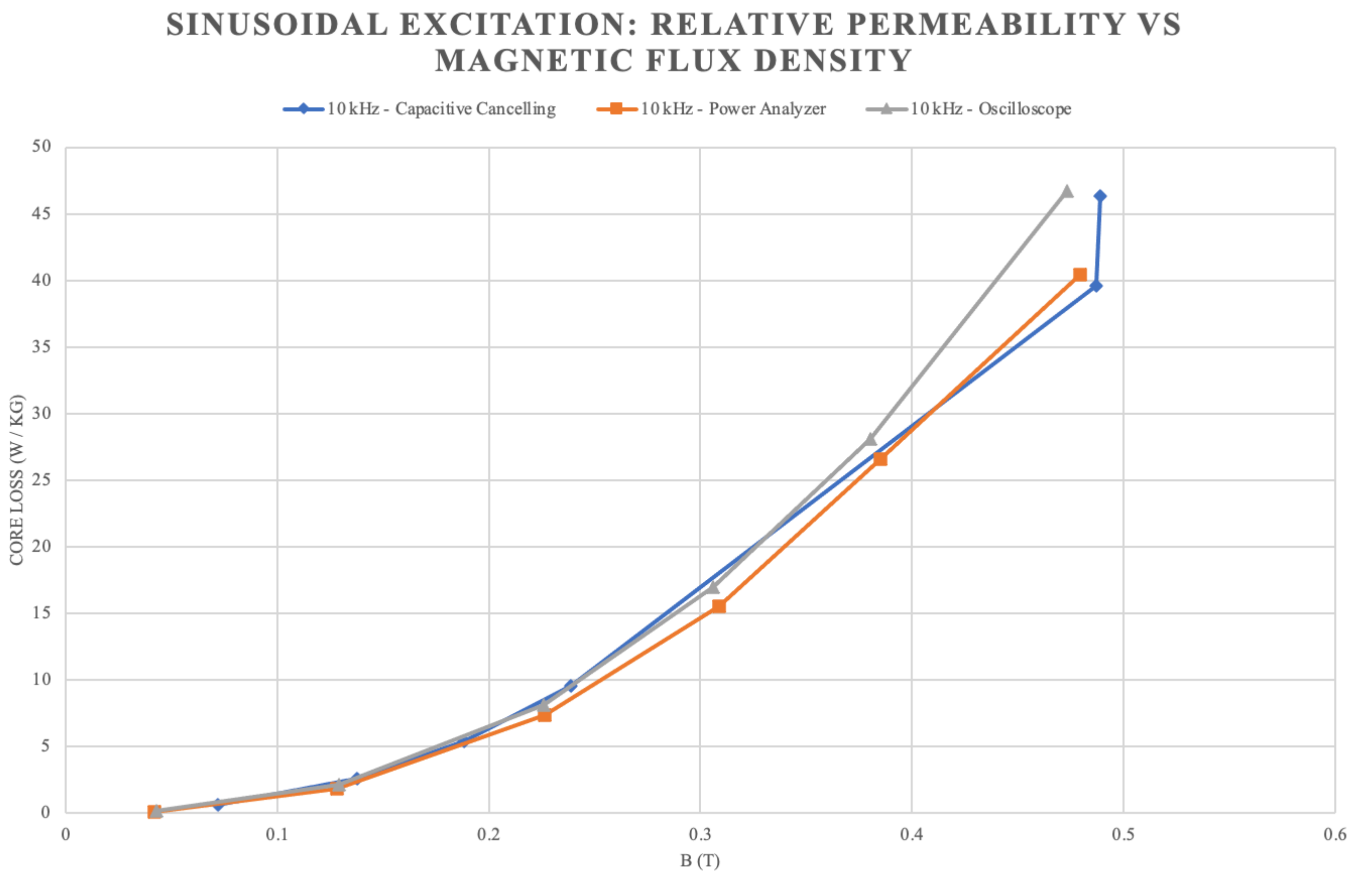

TELEDYNE LECROY
Everywhereyoulook
Measure P1:freq(C2) P2:phase(C3,C2) P3:max(C1) P4:freq(C1) P5:max(C2) P6:max(C3)
value 217.0 MHz 1.30318529521 ° 67 mA 10.027496 kHz 1.13 V 4.7 V
status
C1 DC 200 mA/div 0 mA offset
C2 DC 2.00 V/div 0.00 V offset
C3 DC 10.0 V/div -27.65 V ofst
C4 DC1M 20.0 mV/div -64.5 mV ofst
Timebase 0 µs 100 µs/div 500 kS 500 MS/s
Trigger C1 DC Stop -20 mA Edge Positive


B-H Characteristics: 10000Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

10 kHz – Capacitive Cancelling			**10 kHz – Power Analyzer**			**10 kHz – Oscilloscope**				
B (T)	μ_r		**B (T)**	μ_r		**B (T)**	μ_r			
0.49	408.7		0.49	700.5		0.50	696.8			
0.24	8772.3		0.48	1059.8		0.49	1027.1			
0.19	8742.4		0.48	1523.0		0.48	1522.2			
0.14	8279.2		0.47	2150.5		0.48	2164.8			
0.07	7234.3		0.30	8797.0		0.32	9380.3			
			0.12	8325.3		0.13	9095.2			

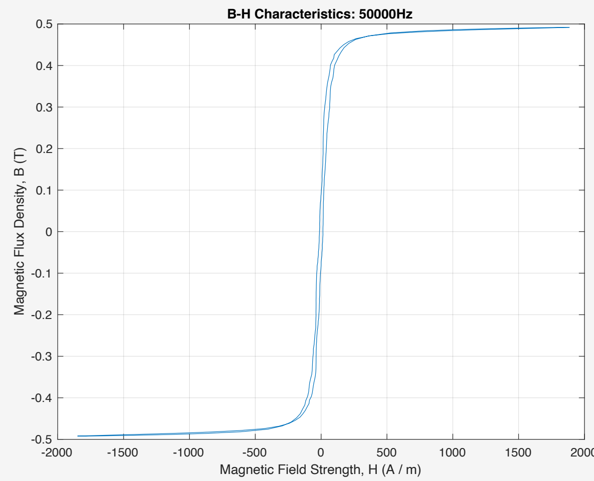


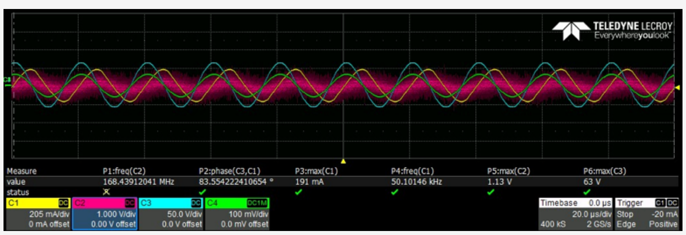
Core Loss Measurements - Sinusoidal Excitation - Flux Density vs Core Loss

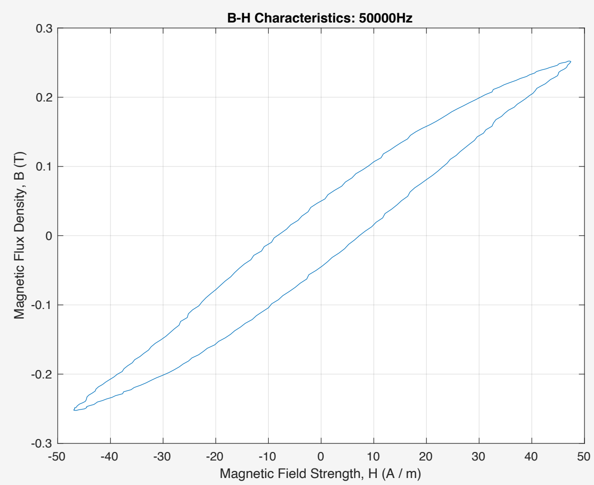
Magnetic Flux Density vs Core Loss - Table										
f = 10 kHz – Capacitive Cancelling			**f = 10 kHz – Power Analyzer**			**f = 10 kHz - Oscilloscope**				
B (T)	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**			
0.49	46.4		0.48	40.45		0.47	46.73			
0.49	39.6		0.39	26.62		0.38	28.07			
0.24	9.6		0.31	15.58		0.31	16.99			
0.19	5.4		0.23	7.37		0.23	8.10			
0.14	2.6		0.13	1.82		0.13	2.18			
0.07	0.6		0.04	0.13		0.04	0.16			

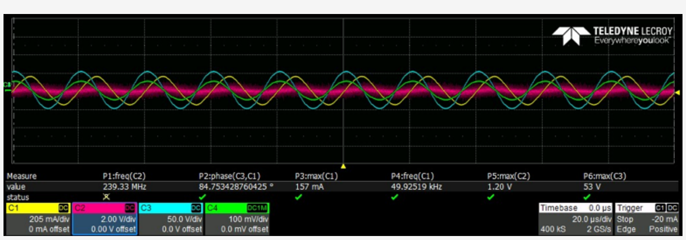
50 kHz

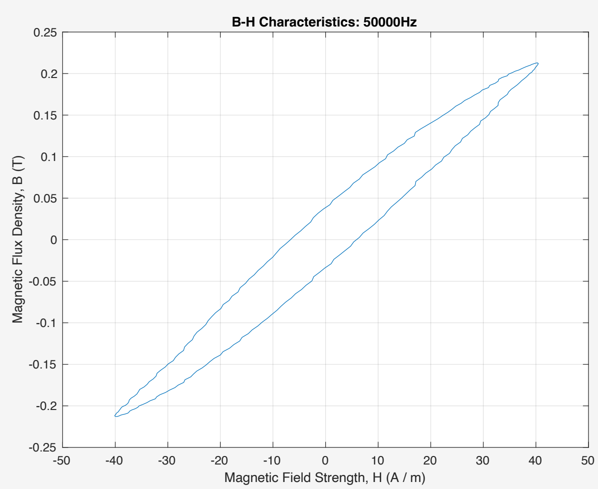
Core Loss with 33 nF Resonant Capacitor.

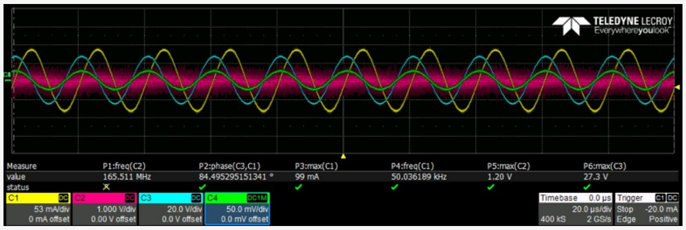


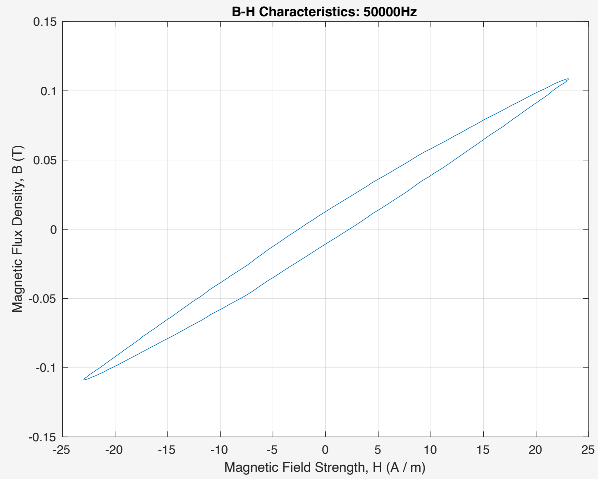


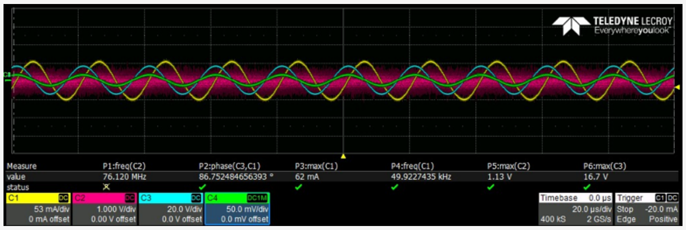


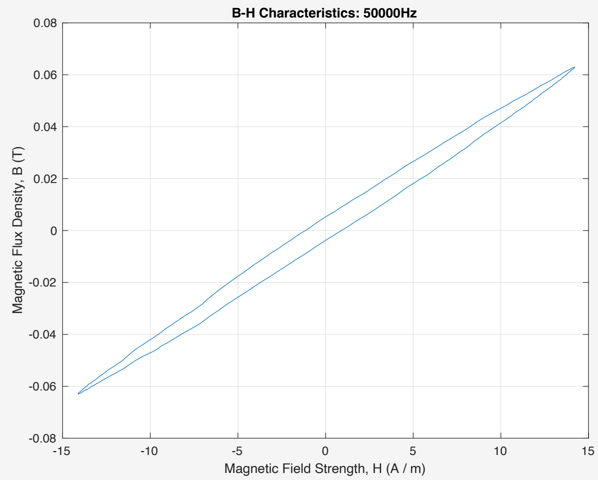


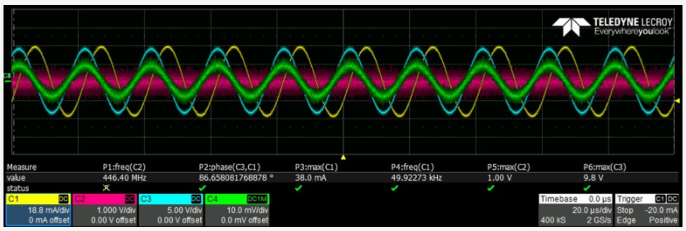


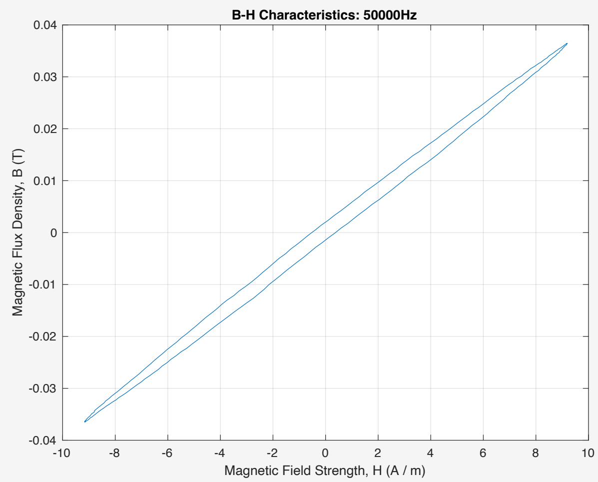

TELEDYNE LECROY
Everywhereyoulook
Measure P1:freq(C2) P2:phase(C3,C1) P3:max(C1) P4:freq(C1) P5:max(C2) P6:max(C3)
value 165.511 MHz 84.495295151341 ° 99 mA 50.036189 kHz 1.20 V 27.3 V
status
C1 DC 53 mA/div 0 mA offset
C2 DC 1.000 V/div 0.00 V offset
C3 DC 20.0 V/div 0.0 V offset
C4 DC1M 50.0 mV/div 0.0 mV offset
Timebase 0.0 µs 20.0 µs/div 400 kS 2 GS/s
Trigger C1 DC Stop -20.0 mA Edge Positive

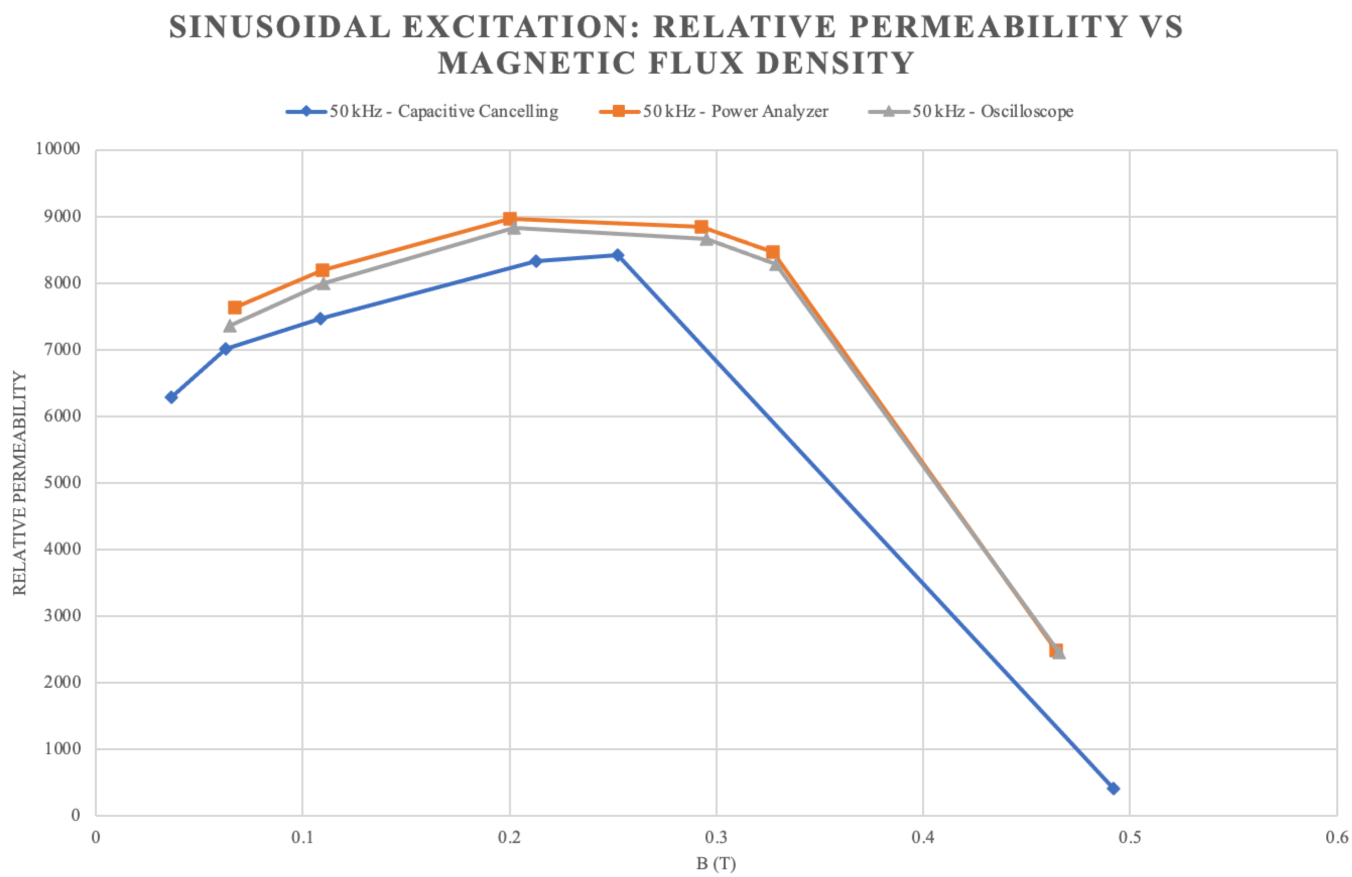

B-H Characteristics: 50000Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)
0.15 0.1 0.05 0 -0.05 -0.1 -0.15
-25 -20 -15 -10 -5 0 5 10 15 20 25


TELEDYNE LECROY
Everywhereyoulook
Measure P1:freq(C2) P2:phase(C3,C1) P3:max(C1) P4:freq(C1) P5:max(C2) P6:max(C3)
value 76.120 MHz 86.752484656393 ° 62 mA 49.9227435 kHz 1.13 V 16.7 V
status
C1 DC 53 mA/div 0 mA offset
C2 DC 1.000 V/div 0.00 V offset
C3 DC 20.0 V/div 0.0 V offset
C4 DC1M 50.0 mV/div 0.0 mV offset
Timebase 0.0 µs 20.0 µs/div 400 kS 2 GS/s
Trigger C1 DC Stop -20.0 mA Edge Positive


B-H Characteristics: 50000Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)
0.08 0.06 0.04 0.02 0 -0.02 -0.04 -0.06 -0.08
-15 -10 -5 0 5 10 15

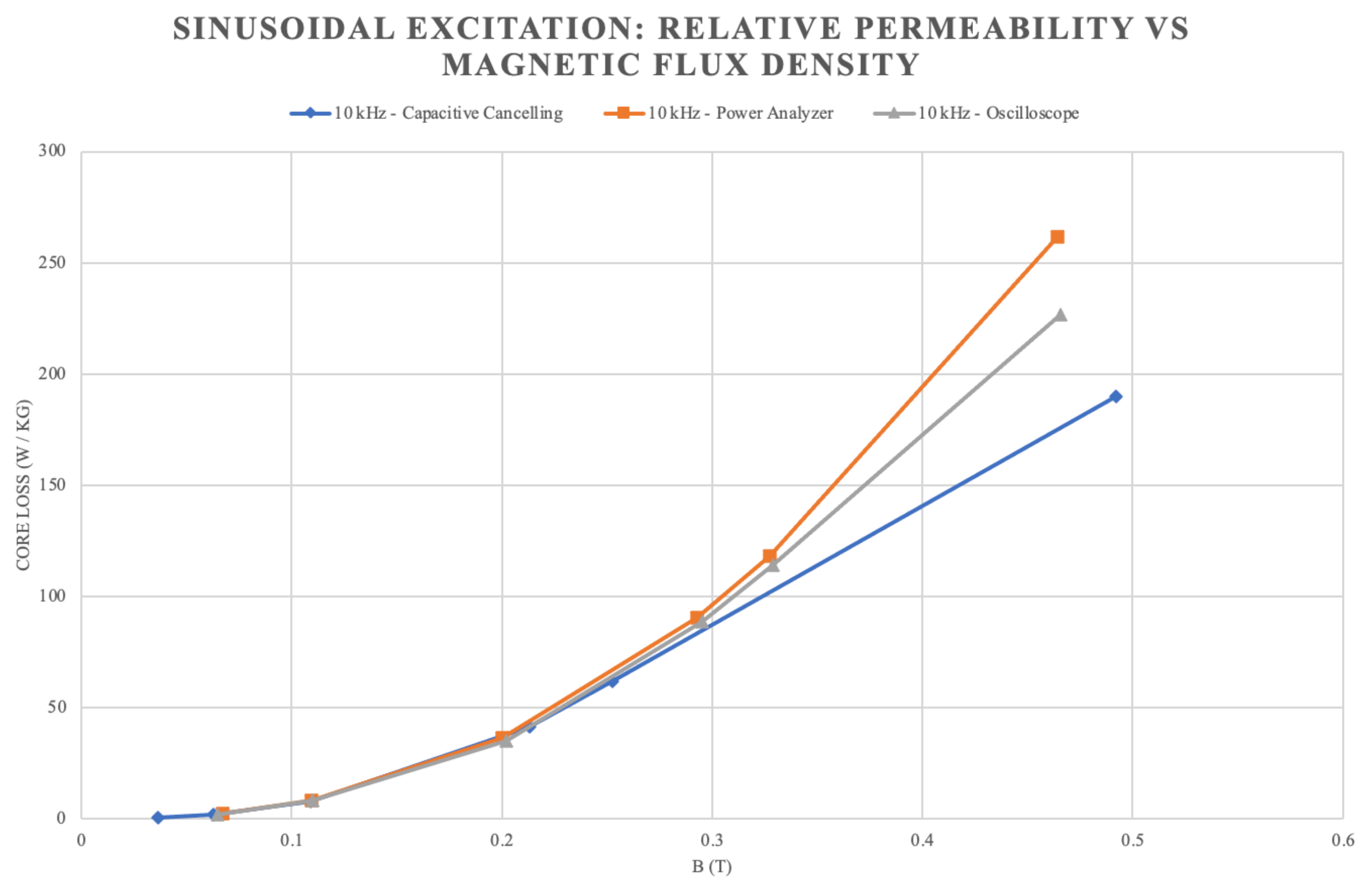

TELEDYNE LECROY
Everywhereyoulook
Measure P1:freq(C2) P2:phase(C3,C1) P3:max(C1) P4:freq(C1) P5:max(C2) P6:max(C3)
value 446.40 MHz 86.658081768878 ° 38.0 mA 49.92273 kHz 1.00 V 9.8 V
status
C1 DC 18.8 mA/div 0 mA offset
C2 DC 1.000 V/div 0.00 V offset
C3 DC 5.00 V/div 0.00 V offset
C4 DC1M 10.0 mV/div 0.0 mV offset
Timebase 0.0 µs 20.0 µs/div 400 kS 2 GS/s
Trigger C1 DC Stop -20.0 mA Edge Positive


B-H Characteristics: 50000Hz
Magnetic Flux Density, B (T)
Magnetic Field Strength, H (A / m)
0.04 0.03 0.02 0.01 0 -0.01 -0.02 -0.03 -0.04
-10 -8 -6 -4 -2 0 2 4 6 8 10



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

50 kHz – Capacitive Cancelling			**50 kHz – Power Analyzer**			**50 kHz – Oscilloscope**				
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**			
0.49	415.3		0.46	2492.6		0.47	2462.1			
0.25	8424.1		0.33	8472.5		0.32	8286.5			
0.21	8327.4		0.29	8837.9		0.29	8655.8			
0.11	7468.8		0.20	8961.4		0.20	8836.1			
0.06	7017.5		0.11	8187.3		0.11	8002.9			
0.04	6288.3		0.07	7634.7		0.065	7365.8			



Core Loss Measurements - Sinusoidal Excitation - Flux Density vs Core Loss

Magnetic Flux Density vs Core Loss - Table										
f = 50 kHz – Capacitive Cancelling			**f = 50 kHz – Power Analyzer**			**f = 50 kHz - Oscilloscope**				
B (T)	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**			
0.49	190.0		0.46	261.8		0.47	226.9			
0.25	62.1		0.33	118.3		0.33	114.3			
0.21	41.6		0.29	90.4		0.30	88.6			
0.11	7.7		0.20	36.3		0.20	35.2			
0.06	1.9		0.11	8.4		0.11	8.2			
0.04	0.5		0.07	2.6		0.06	2.2			

Section Three: Room Temperature Environmental Measurements. Impedance Analysis 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
ANA0001	Bode 100: Network Analyzer	Omnicron Lab	None	None
ADA0001	Bode 100: Impedance Adapter	Omnicron Lab	None	None
LAB0001	Computer	AMPED	None	None

Test Procedures.

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

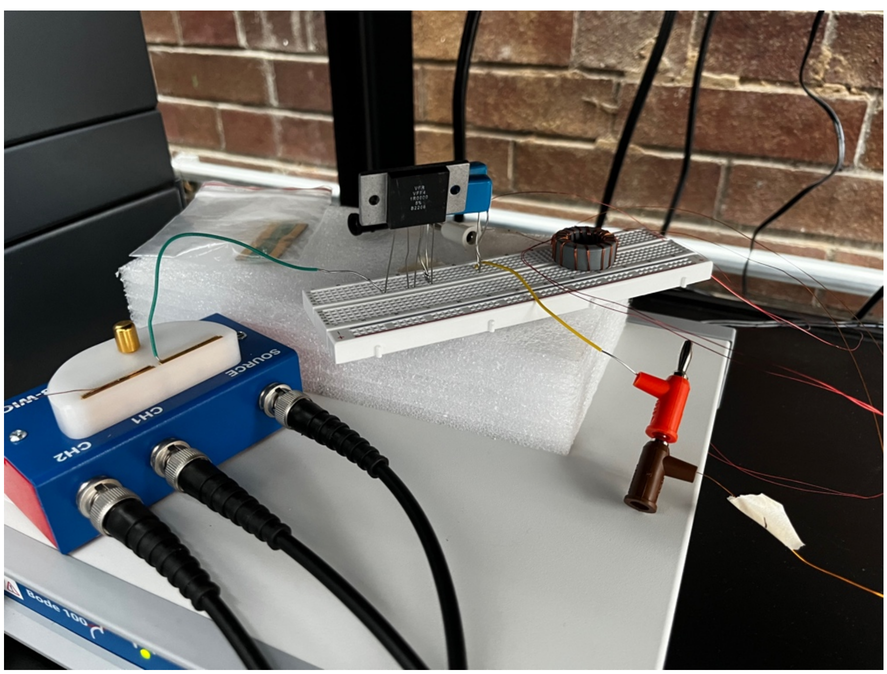
Per AMPED Standard AMP-STD-001, IEEE-393, and IEC 62044-1, IEC 62044-2, IEC 62044-3, below is the procedure for manual operation of equipment for the Low Signal Setup, to be applied as follows. For a more detailed and general procedure to apply the test, refer to the referenced standard described here.

a. Turn on the measurement equipment and allow sufficient time for stabilization (e.g. 20 minutes).
b. Establish the frequency span to examine the measurements.
   - The span chosen was 60 Hz – 40 MHz.
c. Perform the calibration of the impedance anlyzer.
   - Calibration was performed with the Bode 100 in the following manner:
     - Open Measurement. A measurement taken with the impedance analyzer with an open circuit at the measurement fixture.
     - Short Measurement. A measurement taken with the impedance analyzer with a short circuit fixture connected in the measurement fixture.
     - Load Measurement. A measurement taken with the impedance analyzer with a load resistor circuit fixture connected in the measurement fixture.
     - Signal Level. Choose a suitable signal strength for the Bode 100, respectively.
       - -11 dB was the signal strength for the calibration.
d. Connect the configuration of the core with the resonant capacitor used with the capacitive cancelling method.
   - See Section 2 for results of those core loss measurements.
e. In the software for the Bode 100, click run to obtain the impedance amplitude and phase plot.
f. Save the plot, either as pdf or excel format.
g. Repeat for other test conditions, if applicable.
h. 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.

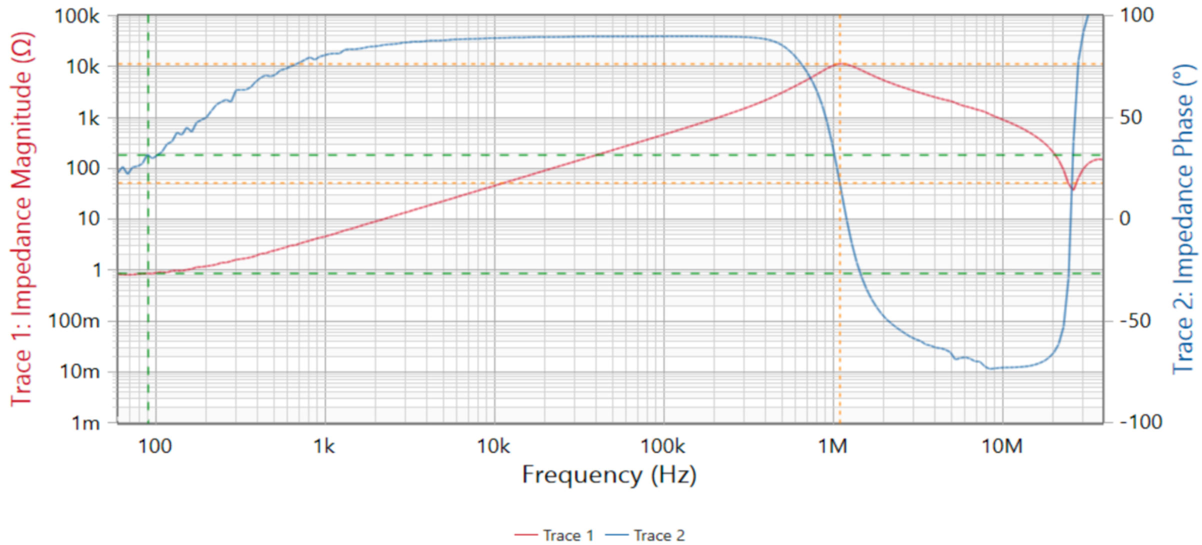
Impedance Analysis Testing. Typical Test Setup.



Impedance Analysis Testing. Typical Test Setup. Core Under Test, Capacitor, and Sensing Resistor Configuration.

Impedance Analysis: Core of 16 Turns with no capacitor.

Measurement: Impedance Adapter



	Cursor 1	Cursor 2	Delta C2-C1
Frequency	90.72 Hz	1.112 MHz	1.112 MHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
Measurement	855.028 mΩ	11.199 kΩ	11.199 kΩ
Trace 2	**Phase (°)**	**Phase (°)**	**Phase (°)**
Measurement	31.462 °	17.755 °	-13.707 °

Sweep	
Start frequency:	60 Hz
Stop frequency:	40 MHz
Center frequency:	20 MHz
Span:	40 MHz
Sweep mode:	Logarithmic
Numer of points:	201

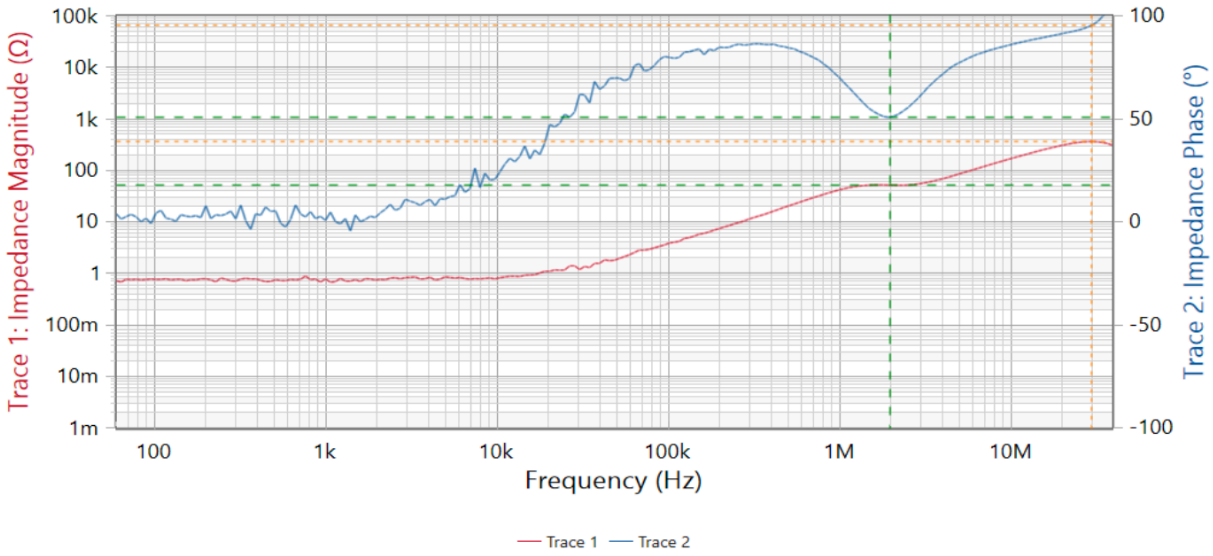
Calibration	Full-Range	User-Range
Impedance	Active	-

Hardware setup	
Device type:	Bode100R2
Serial number:	TE817K
Receiver bandwidth:	300 Hz
Output level:	-12 dBm
DUT settling time:	0 ms

Impedance Analysis: Core of 1 Turns with no capacitor.

Measurement: Impedance Adapter

OMICRON LAB



	Cursor 1	Cursor 2	Delta C2-C1
Frequency	1.97 MHz	30.044 MHz	28.073 MHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
Measurement	51.69 Ω	361.596 Ω	309.905 Ω
Trace 2	**Phase (°)**	**Phase (°)**	**Phase (°)**
Measurement	50.736 °	95.395 °	44.659 °

Sweep	
Start frequency:	60 Hz
Stop frequency:	40 MHz
Center frequency:	20 MHz
Span:	40 MHz
Sweep mode:	Logarithmic
Numer of points:	201

Calibration	Full-Range	User-Range
Impedance	Active	-

Hardware setup	
Device type:	Bode100R2
Serial number:	TE817K
Receiver bandwidth:	300 Hz
Output level:	-12 dBm
DUT settling time:	0 ms

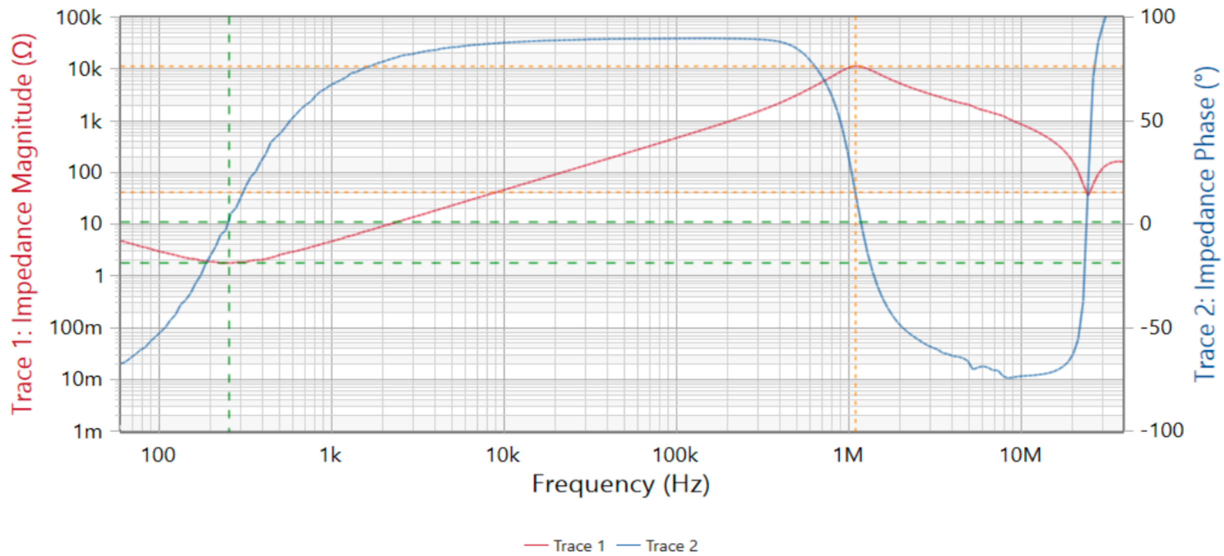
AMPED

Revision: A

Impedance Analysis: Core of 16 Turns with 660 □F capacitor.

Measurement: Impedance Adapter

OMICRON LAB



	Cursor 1	Cursor 2	Delta C2-C1
Frequency	253.676 Hz	1.112 MHz	1.111 MHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
Measurement	1.771 Ω	11.197 kΩ	11.195 kΩ
Trace 2	**Phase (°)**	**Phase (°)**	**Phase (°)**
Measurement	1.003 °	15.392 °	14.389 °

Sweep	
Start frequency:	60 Hz
Stop frequency:	40 MHz
Center frequency:	20 MHz
Span:	40 MHz
Sweep mode:	Logarithmic
Numer of points:	201

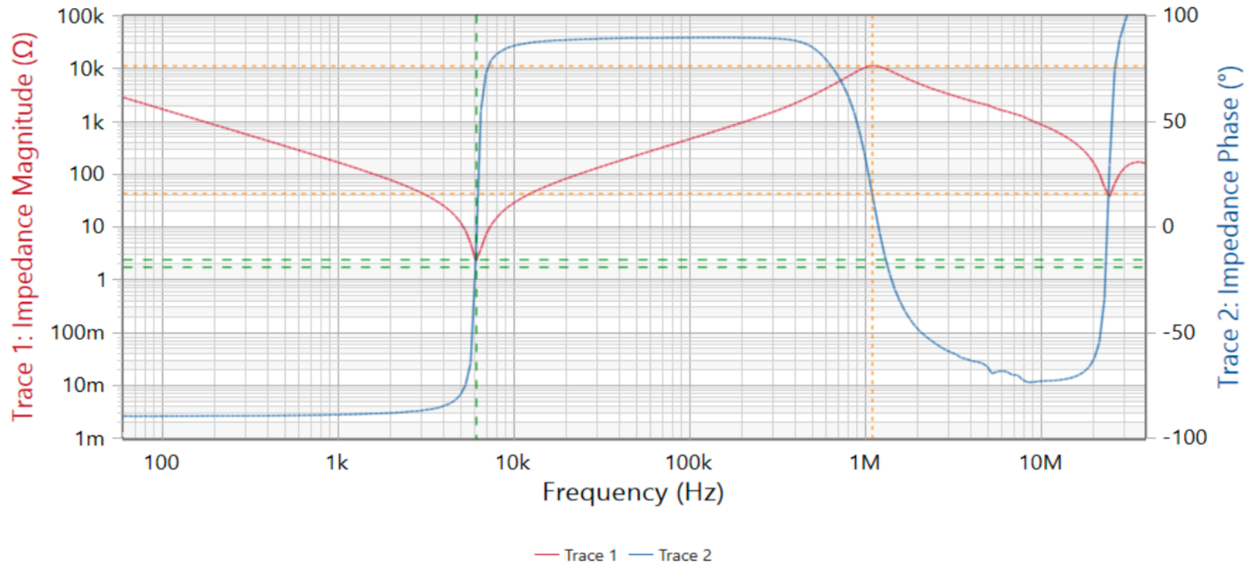
Calibration	Full-Range	User-Range
Impedance	Active	-

Hardware setup	
Device type:	Bode100R2
Serial number:	TE817K
Receiver bandwidth:	300 Hz
Output level:	-12 dBm
DUT settling time:	0 ms

Impedance Analysis: Core of 16 Turns with 1 □F capacitor.

Measurement: Impedance Adapter

OMICRON LAB



	Cursor 1	Cursor 2	Delta C2-C1
Frequency	6.102 kHz	1.112 MHz	1.105 MHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
Measurement	2.389 Ω	11.197 kΩ	11.194 kΩ
Trace 2	**Phase (°)**	**Phase (°)**	**Phase (°)**
Measurement	-19.083 °	15.783 °	34.866 °

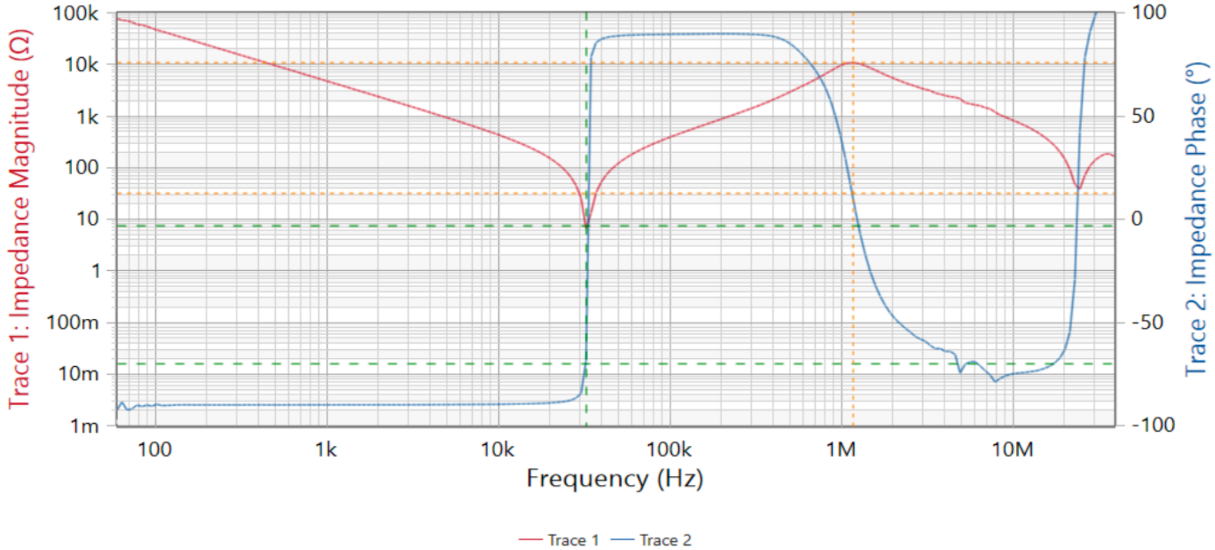
Sweep	
Start frequency:	60 Hz
Stop frequency:	40 MHz
Center frequency:	20 MHz
Span:	40 MHz
Sweep mode:	Logarithmic
Numer of points:	201

Hardware setup	
Device type:	Bode100R2
Serial number:	TE817K
Receiver bandwidth:	300 Hz
Output level:	-12 dBm
DUT settling time:	0 ms

Calibration	Full-Range	User-Range
Impedance	Active	-

Impedance Analysis: Core of 16 Turns with 33 nF capacitor.

Measurement: Impedance Adapter



	Cursor 1	Cursor 2	Delta C2-C1
Frequency	32.573 kHz	1.172 MHz	1.14 MHz
Trace 1	**Magnitude**	**Magnitude**	**Magnitude**
Measurement	7.441 Ω	10.802 kΩ	10.795 kΩ
Trace 2	**Phase (°)**	**Phase (°)**	**Phase (°)**
Measurement	-70.082 °	12.515 °	82.597 °

Sweep	
Start frequency:	60 Hz
Stop frequency:	40 MHz
Center frequency:	20 MHz
Span:	40 MHz
Sweep mode:	Logarithmic
Numer of points:	201

Calibration	Full-Range	User-Range
Impedance	Active	-

Hardware setup	
Device type:	Bode100R2
Serial number:	TE817K
Receiver bandwidth:	300 Hz
Output level:	-12 dBm
DUT settling time:	0 ms

Section Two: Elevated Temperature Environmental Measurements. Magnetic Core Characterization Testing with Hot Plate: 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
PLA0001	Hot Plate	Ohaus	HSMNHP4CAL	None
WAV0002	Arbitrary Waveform Generator	Keysight Technologies	33500B	None
AMP0002	RF Amplifier (DC - 1MHz)	AE Techron	7224	7224-0523-3205-B
ANA0002	Power Analyzer	Yokogawa	WT5000	C27E0021V
OSC0005	Oscilloscope (1 GHz)	Teledyne-Lecroy	3104Z	LCRY3714C19876
PRO0007	AC / DC Current Probe	Keysight Technologies	1147B	JP61071359
PRO0008	2 kV Differential Probe	Teledyne-Lecroy	RP1100D	20180742
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.

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 90.

d. Set the Oscilloscope to the following settings.
  - Specify Probe Attenuation.
    - Measurements were performed with a Teledyne-Lecroy current probe, having a fixed attenuation ratio of 0.1 V/A.
    - Measurements were performed with a Teledyne-Lecroy voltage probe, having a fixed attenuation ratio of 250X.

e. Set the Power Analyzer to the following settings:
  - Attempt at a refresh time that provides at least four to five periods of the excitation signal. If limited where more periods are observed, note the frequencies and any other relevant information.
    - 10 ms refresh time, with 10 period for 100 kHz.
    - 10 ms refresh time, with 20 periods for 200 kHz.
    - 10 ms refresh time, with 51 periods for 500 kHz.

f. Turn output of Arbitrary Waveform Generator on.

g. 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 PRO0008 does not have the capability (only autozero).

h. Prepare setup with Hotplate and oil bath for heating core for elevated temperatures.
  - Identify oil used for testing.
    - Fisher Scientific Silicone Oil. Catalog Number: AAA127280E.
  - At each temperature change, let the core soak for about five minutes before taking any measurements. Note if there is a temperature range that is observed with the measurements.
  - Be sure thermocouple is placed directly on the core. See test setup photos of configuration.
  - Record any variation in temperature, and report in procedure.
    a. At 50°C: Temperature varied between 48.7 and 54 °C.
    b. At 100°C: Temperature varied between 97.6 and 103.1 °C.
    c. At 150°C: Temperature varied between 148.2 and 152.9 °C.

i. 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 4 - 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 Density is optional for oscilloscope waveforms but recommended.

j. 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.

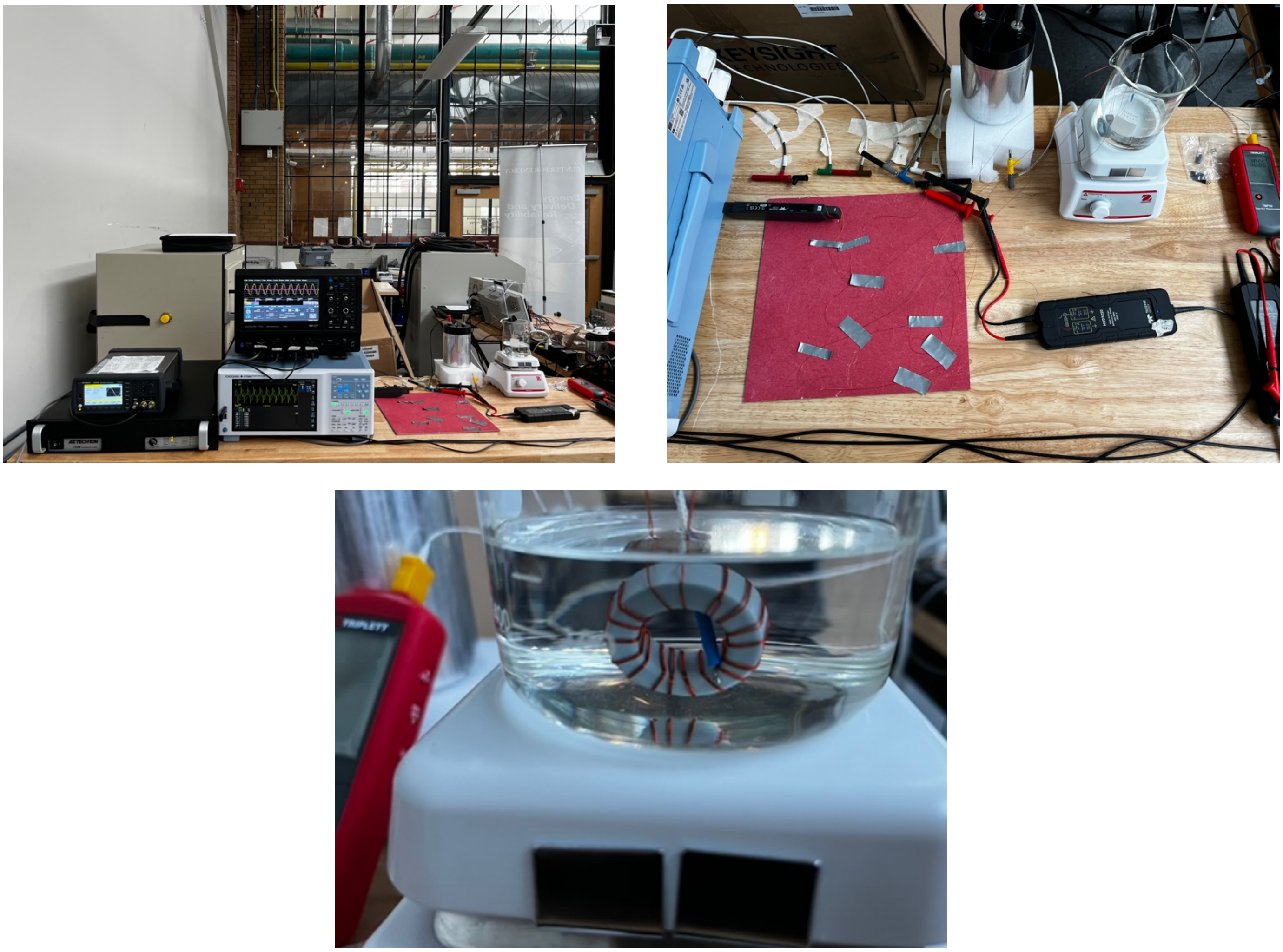
k. Setup included correction components for DC Biasing part of the setup. See the test setup section for a diagram. See table within the section populating with the details.

l. Repeat steps a - f for Square Waveform, Triangle Waveform, or other excitation waveforms for examined interest.

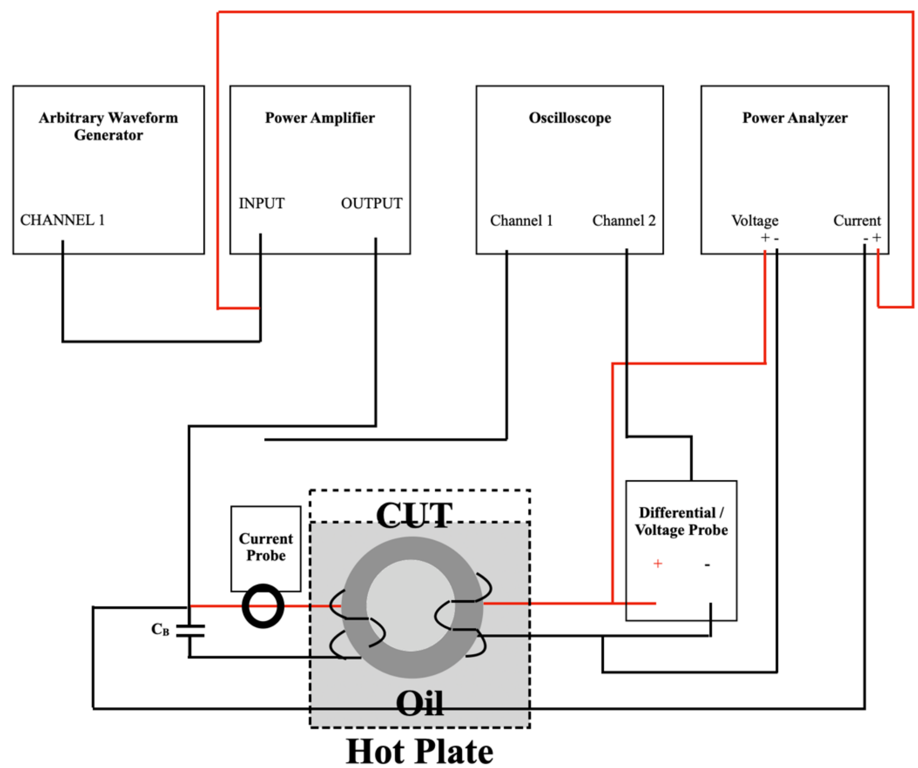
m. Record relevant data for Data Presentation.

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.

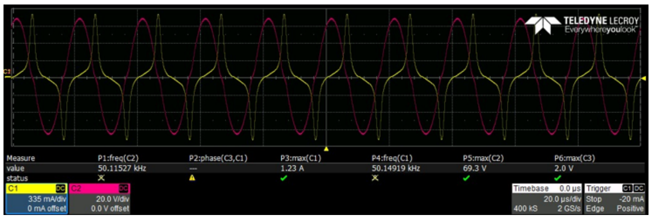


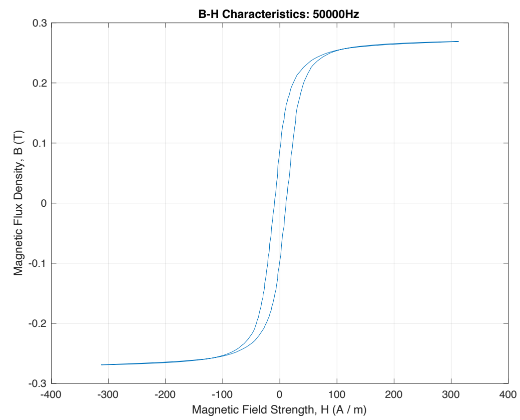
Core Loss Testing - Low Voltage with Amplifier. Typical Test Setup: System Block Diagram.

Data Presentation.

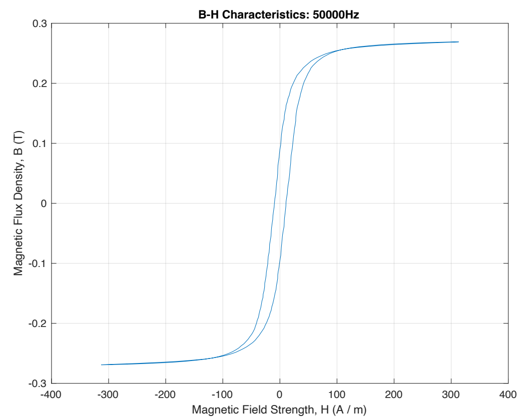
In this section, data is presented as each section indicates below.

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



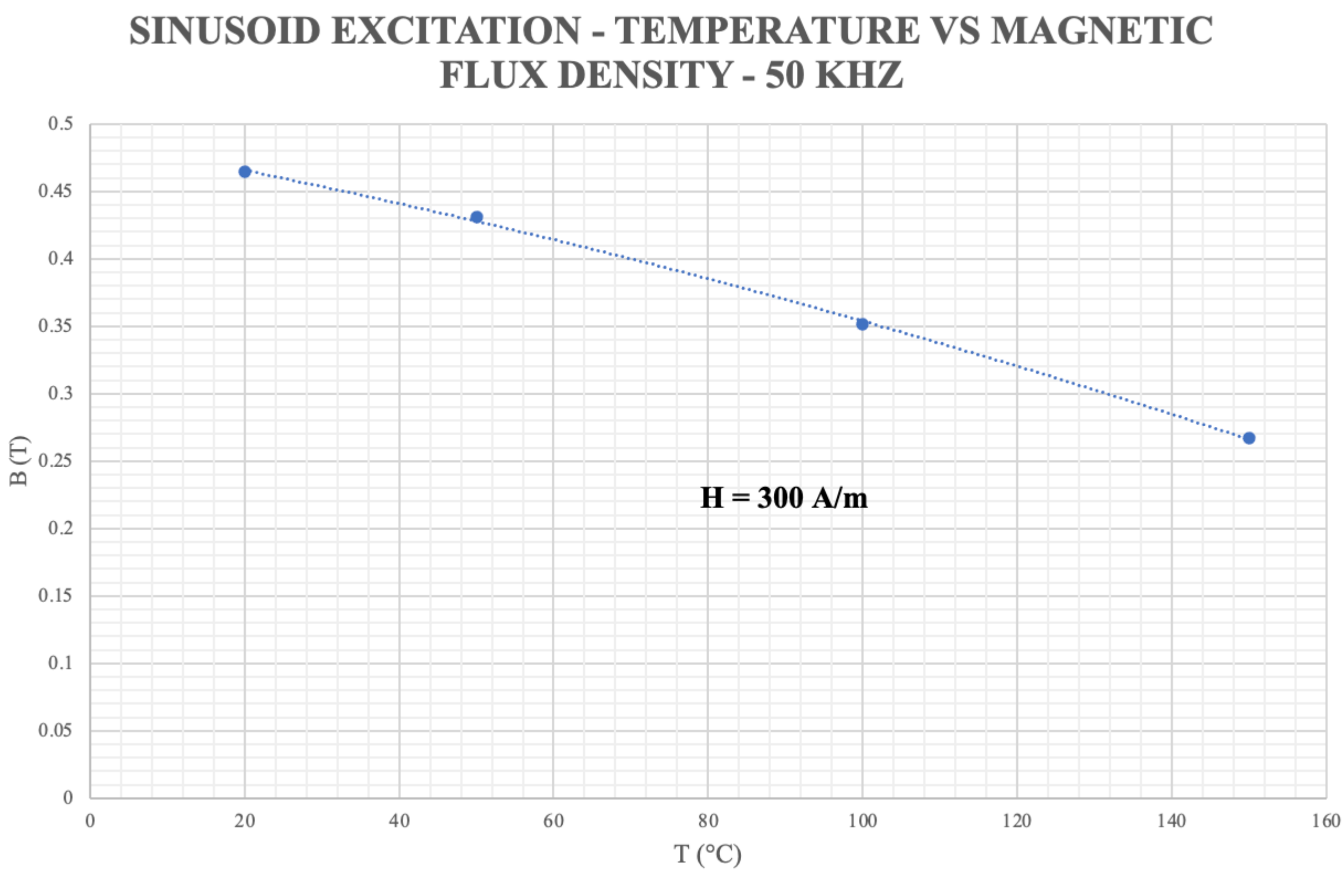


Sample Sinusoidal Excitation Waveform and B-H Plot via Oscilloscope. Sinusoidal Signal. 3.599 V_{pp} 50kHz. ***150°C.*** *Amplifier Gain 90.*



Sample Sinusoidal Excitation Waveform and B-H Plot via Power Analyzer. Sinusoidal Signal. 3.599 V_{pp} 50kHz. ***150°C.*** *Amplifier Gain 90.*

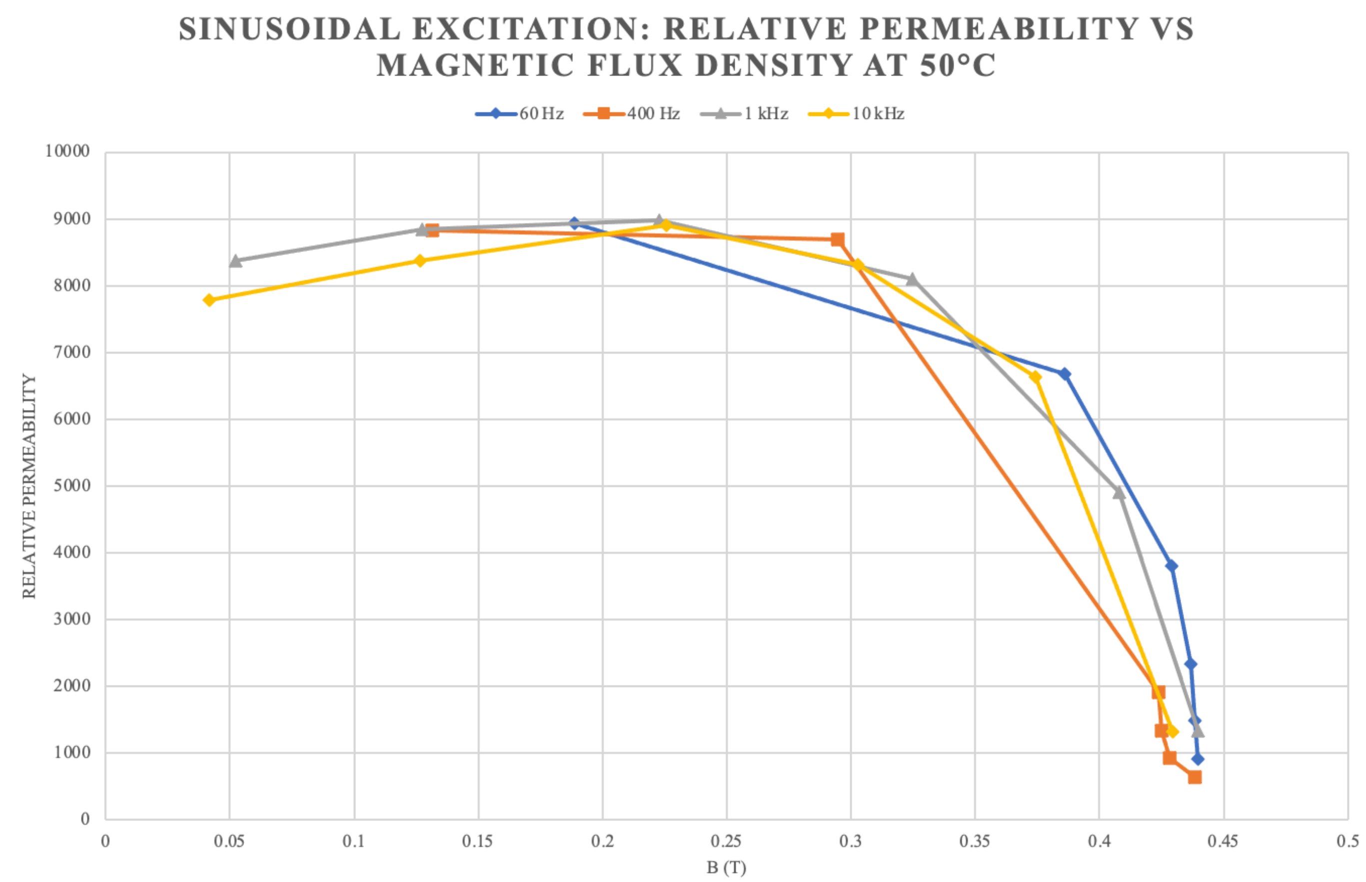
a. Sinusoidal Excitation Magnetic Characterization.



Temperature Dependence - Sinusoidal Excitation - as function of Magnetic Flux Density and frequency.

b.

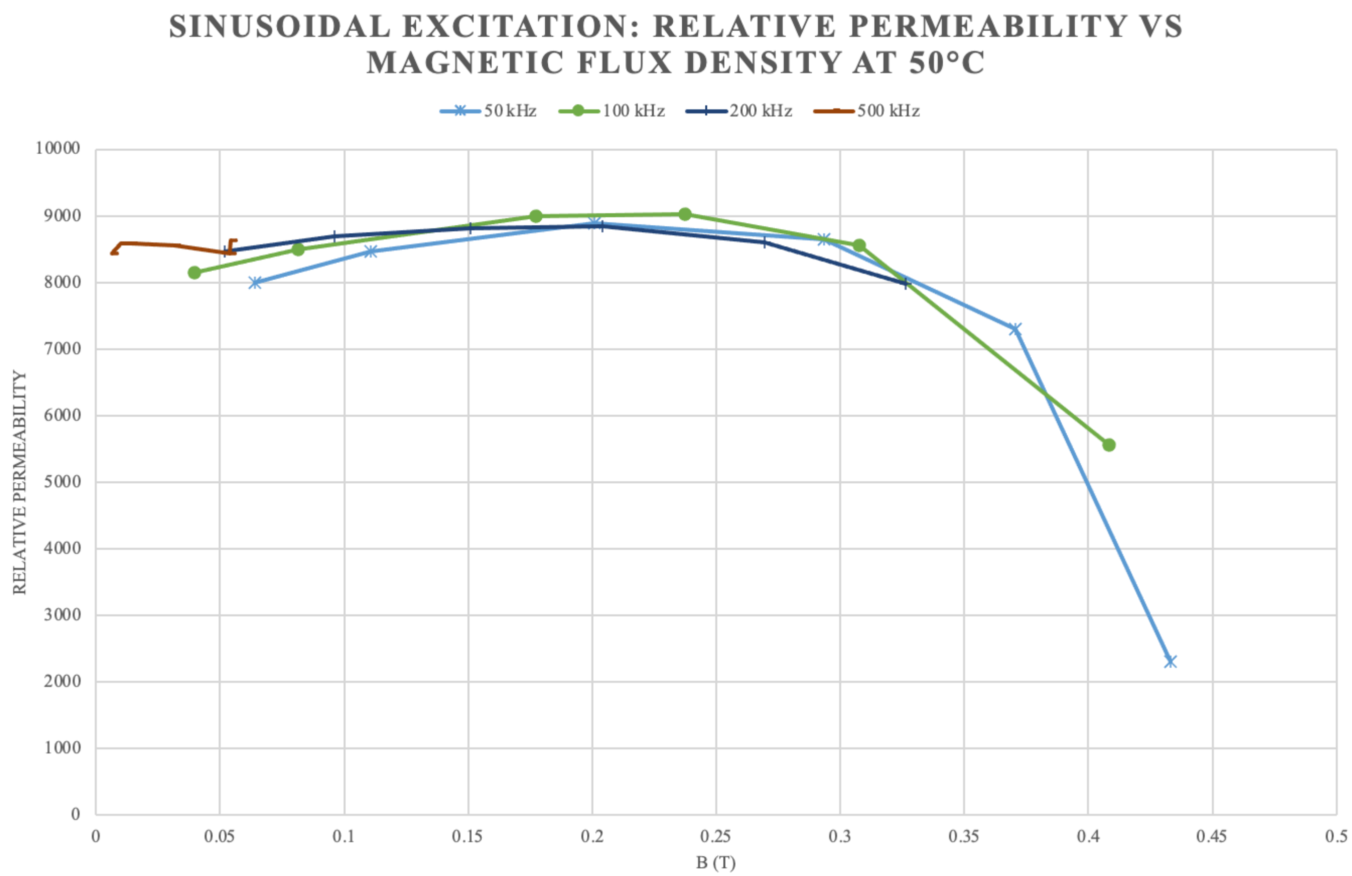
f = 60 Hz			f = 400 Hz			f = 1 kHz			f = 10 kHz	
T (°C)	**B (T)**		**T (°C)**	**B (T)**		**T (°C)**	**B (T)**		**T (°C)**	**B (T)**
20	0.49		20	0.49		20	0.48		20	0.48
50	0.45		50	0.44		50	0.44		50	0.43
100	0.31		100	0.31		100	0.31		100	0.31
150	0.29		150	0.28		150	0.28		150	0.27
f = 50 kHz			**f = 100 kHz**			**f = 200 kHz**			**f = 500 kHz**	
T (°C)	**B (T)**		**T (°C)**	**B (T)**		**T (°C)**	**B (T)**		**T (°C)**	**B (T)**
20	0.46		20	0.41		20	0.33		20	0.05
50	0.43		50	0.41		50	0.33		50	0.05
100	0.35		100	0.31		100	0.31		100	0.05
150	0.27		150	0.27		150	0.23		150	0.05



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

60 Hz			**400 Hz**			**1 kHz**			**10 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.44	912.8		0.44	643.1		0.44	1333.7		0.43	1328.67
0.44	1493.0		0.43	936.8		0.41	4910.4		0.37	6639.94
0.44	2334.5		0.42	1340.2		0.32	8098.7		0.30	8315.11
0.43	3805.8		0.42	1919.4		0.22	8984.9		0.23	8900.00
0.39	6675.7		0.29	8697.5		0.13	8844.7		0.13	8378.25
0.19	8942.1		0.13	8828.6		0.05	8381.6		0.04	7786.97

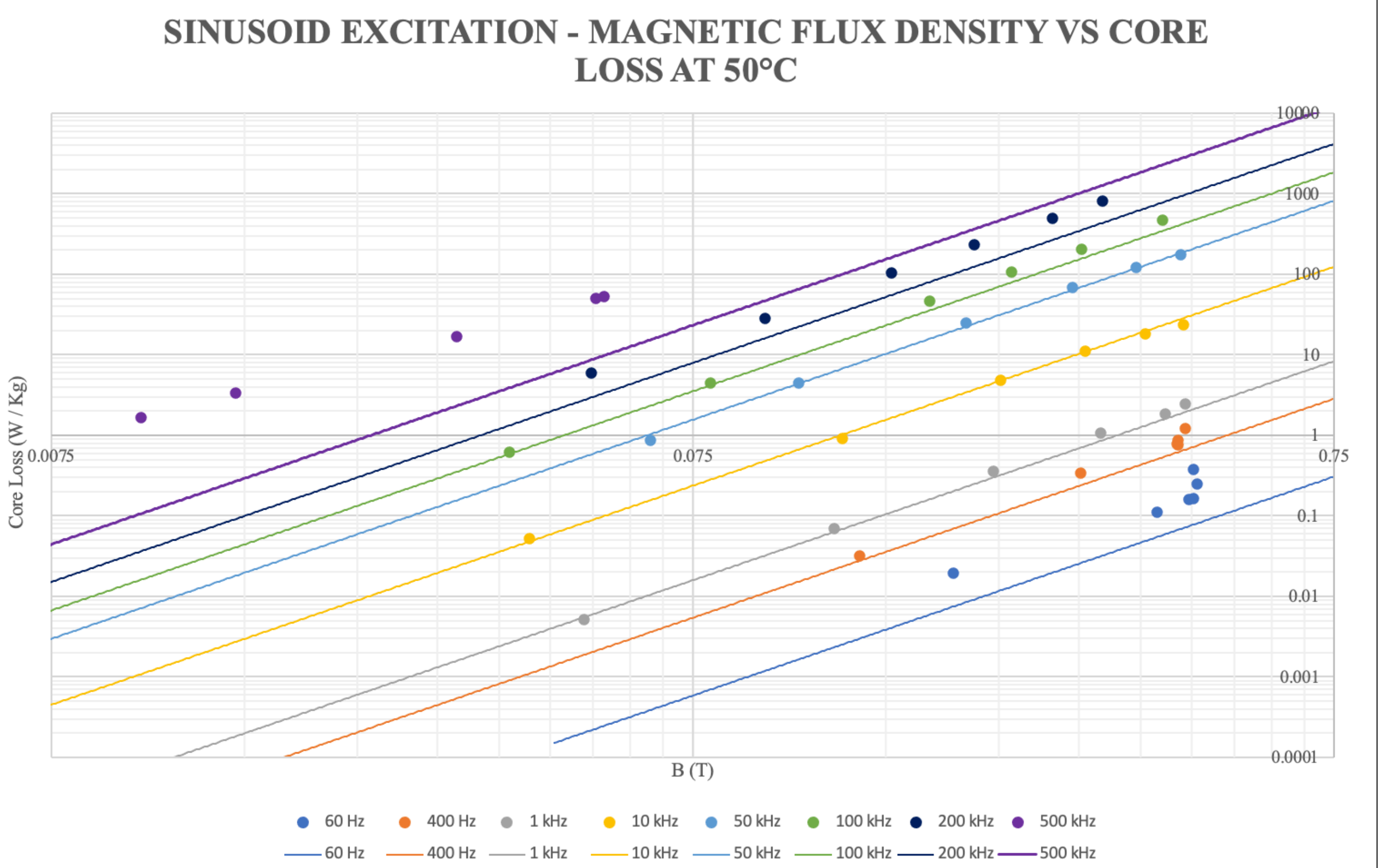
Note: 60 – 400 Hz; 200 – 500 kHz from acquired via Oscilloscope. 1 – 100 kHz from acquired via Power Analyzer.



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

50 kHz			**100 kHz**			**200 kHz**			**500 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.43	2308.15		0.41	5561.80		0.33	7983.44		0.05	8634.75
0.37	7298.46		0.31	8556.57		0.27	8597.47		0.05	8434.26
0.29	8648.76		0.24	9031.95		0.20	8850.91		0.03	8554.17
0.20	8888.44		0.18	9002.07		0.15	8811.07		0.01	8582.07
0.11	8471.22		0.08	8496.28		0.10	8694.86		0.01	8588.98
0.06	8001.62		0.04	8142.81		0.05	8469.51		0.01	8434.81

Note: 60 – 400 Hz; 200 – 500 kHz from acquired via Oscilloscope. 1 – 100 kHz from acquired via Power Analyzer.



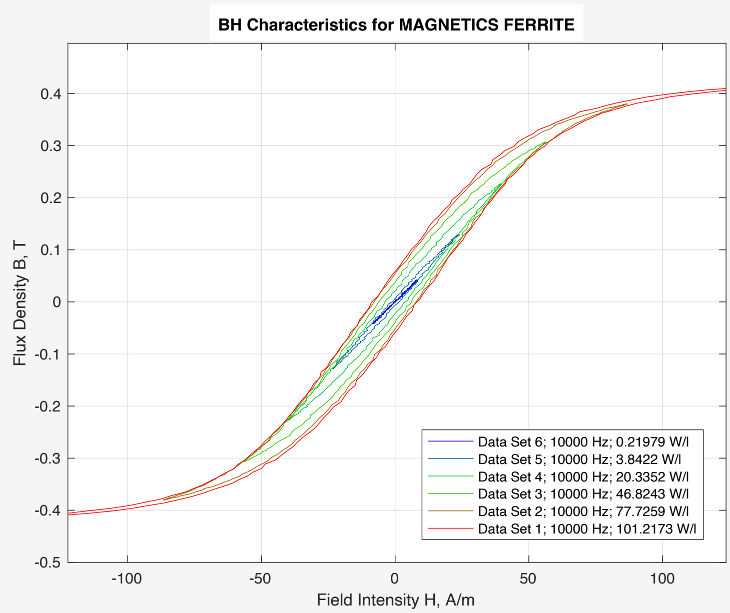
Core Loss Measurements - Sinusoidal Excitation - Flux Density vs Core Loss

Magnetic Flux Density vs Core Loss - Table

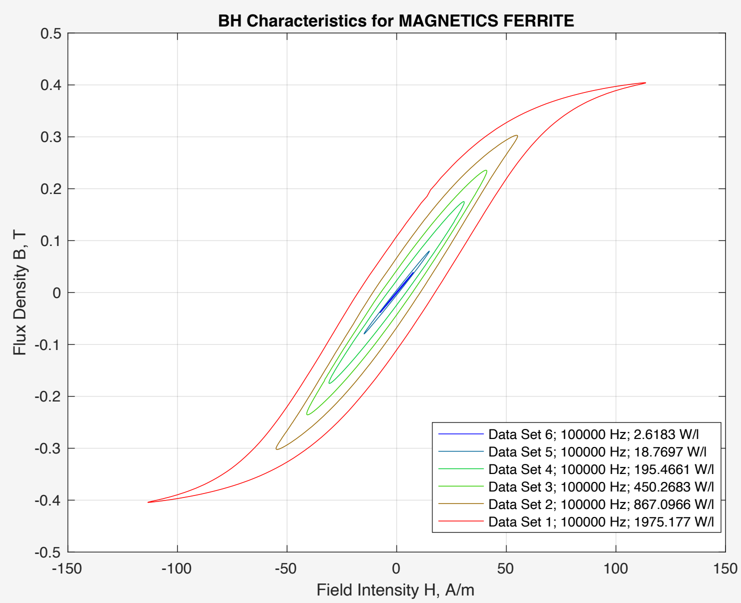
f = 60 Hz			**f = 400 Hz**			**f = 1 kHz**			**f = 10 kHz**	
B (T)	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**		**B (T)**	**Core Loss (W/kg)**
0.45	0.38		0.44	1.23		0.44	2.51		0.43	24.12
0.46	0.25		0.43	0.87		0.41	1.89		0.37	18.50
0.45	0.17		0.43	0.80		0.32	1.07		0.30	11.15
0.44	0.16		0.43	0.78		0.22	0.36		0.23	4.84
0.40	0.11		0.30	0.34		0.12	0.07		0.13	0.91
0.19	0.02		0.14	0.03		0.05	0.01		0.04	0.05
f = 50 kHz			**f = 100 kHz**			**f = 200 kHz**			**f = 500 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)**
0.43	178.82		0.41	470.21		0.33	817.80		0.05	54.16
0.37	122.87		0.31	206.42		0.27	496.34		0.05	50.94
0.29	70.25		0.24	107.19		0.21	232.70		0.03	17.10
0.20	25.35		0.18	46.53		0.15	105.26		0.01	3.38
0.11	4.50		0.08	4.47		0.10	28.87		0.01	1.67
0.06	0.88		0.04	0.62		0.05	6.02		0.01	0.62

Note: 60 – 400 Hz; 200 – 500 kHz fit from acquired Oscilloscope. 1 – 100 kHz fit from acquired Power Analyzer.

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



(a)



(b)

Empirical Model Plot Sample – (a) 10 kHz. 100 kHz

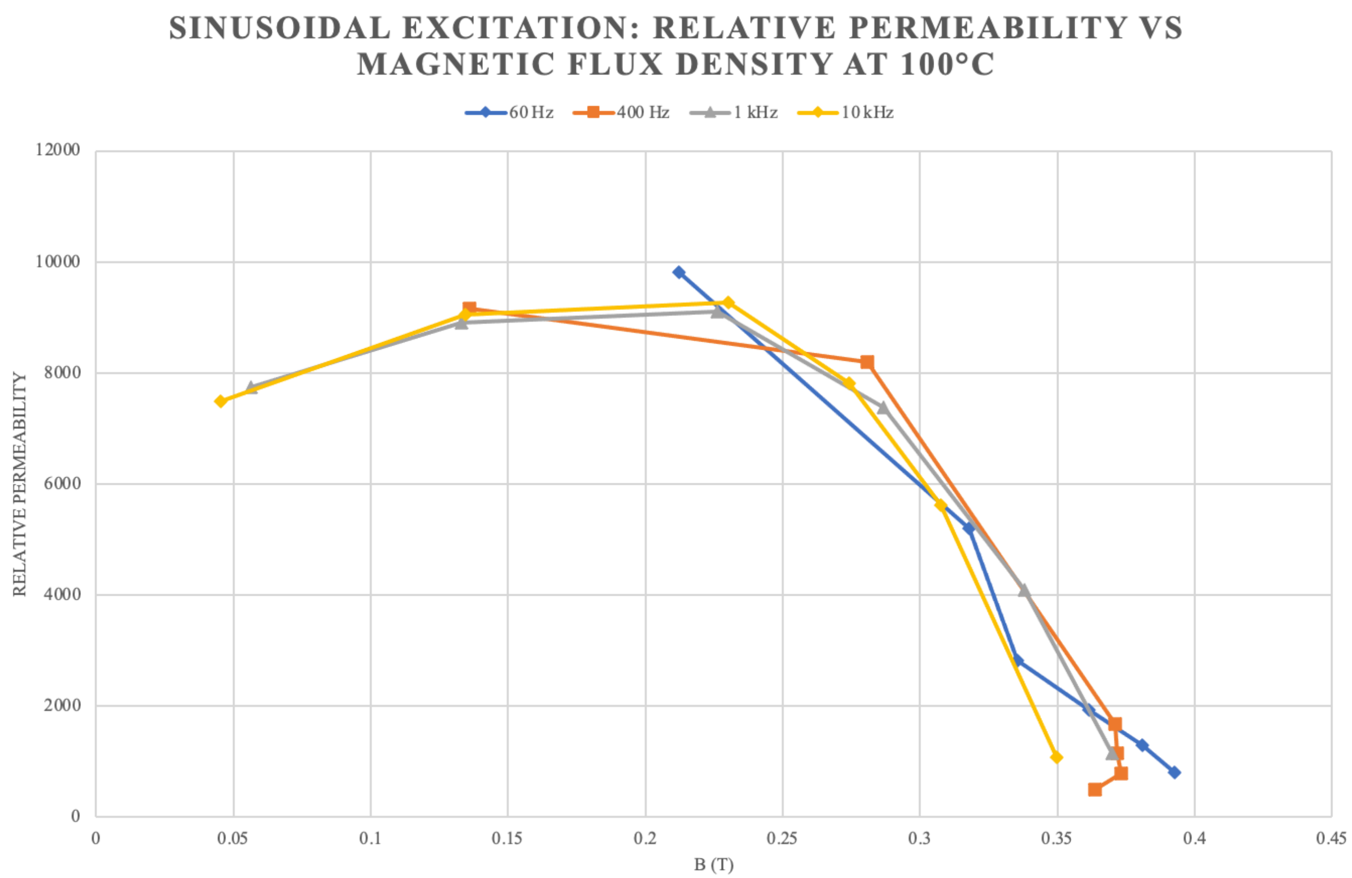
Steinmetz Equation

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

Steinmetz Coefficients for Curve Fit

α	1.1728	
β	2.7192	
k_h	0.00551116	W / kg

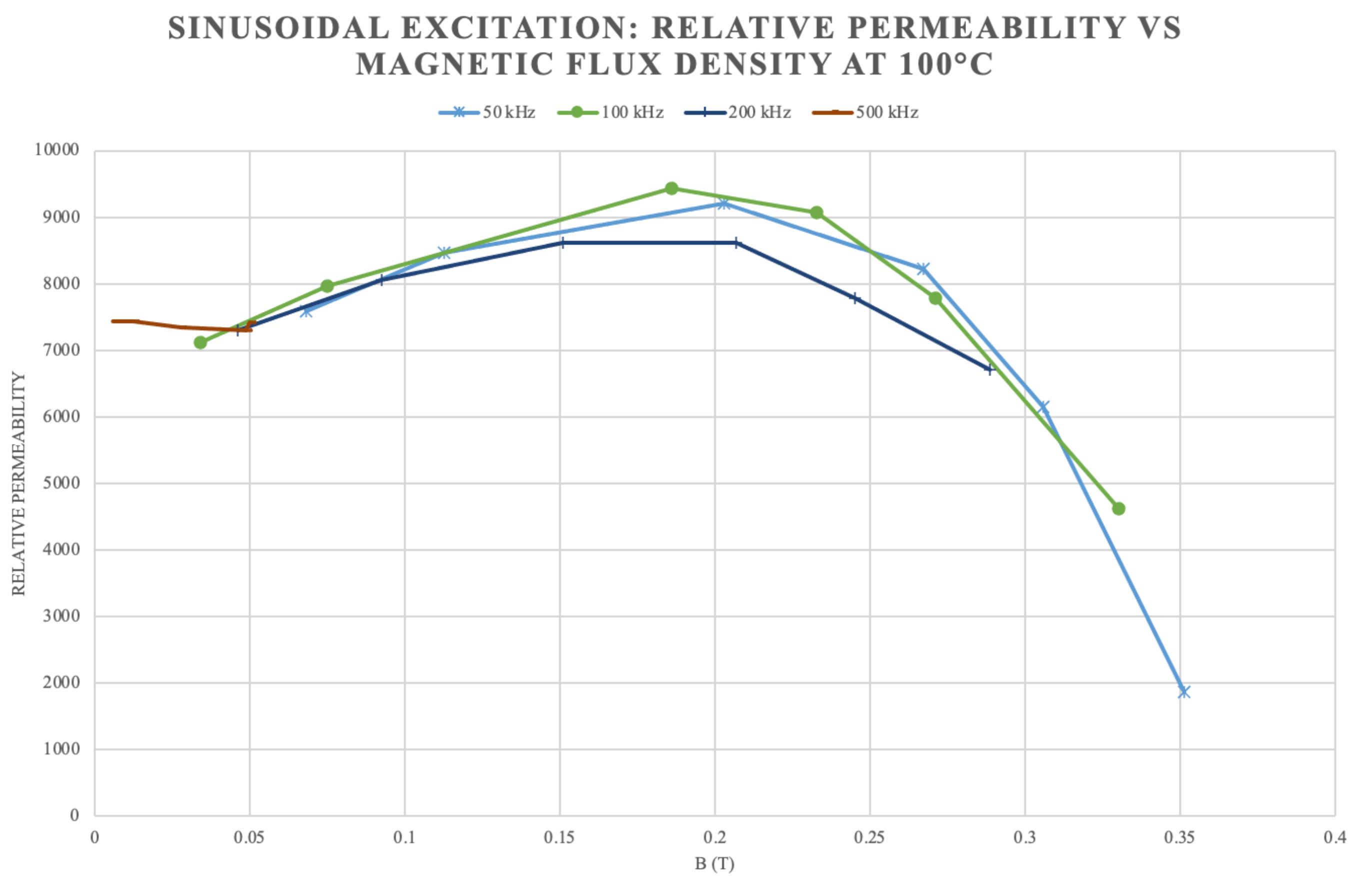
Based on measured data of core losses at various frequencies and considering the changes in the core's configuration, provided is the Steinmetz Estimation. k_h, α, and β are Steinmetz Coefficients from empirical data, p_w = core loss per unit weight, f_b base frequency, and B_b is base flux density. 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..



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

60 Hz			**400 Hz**			**1 kHz**			**10 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.39	809.8		0.36	503.6		0.37	1144.5		0.35	1081.55
0.38	1297.1		0.37	790.8		0.34	4084.8		0.31	5613.96
0.36	1934.1		0.37	1153.6		0.29	7381.6		0.27	7821.13
0.34	2814.2		0.37	1684.3		0.23	9104.3		0.23	9267.39
0.32	5198.7		0.28	8190.9		0.13	8912.2		0.13	9059.27
0.21	9809.6		0.14	9154.3		0.06	7742.5		0.05	7491.46

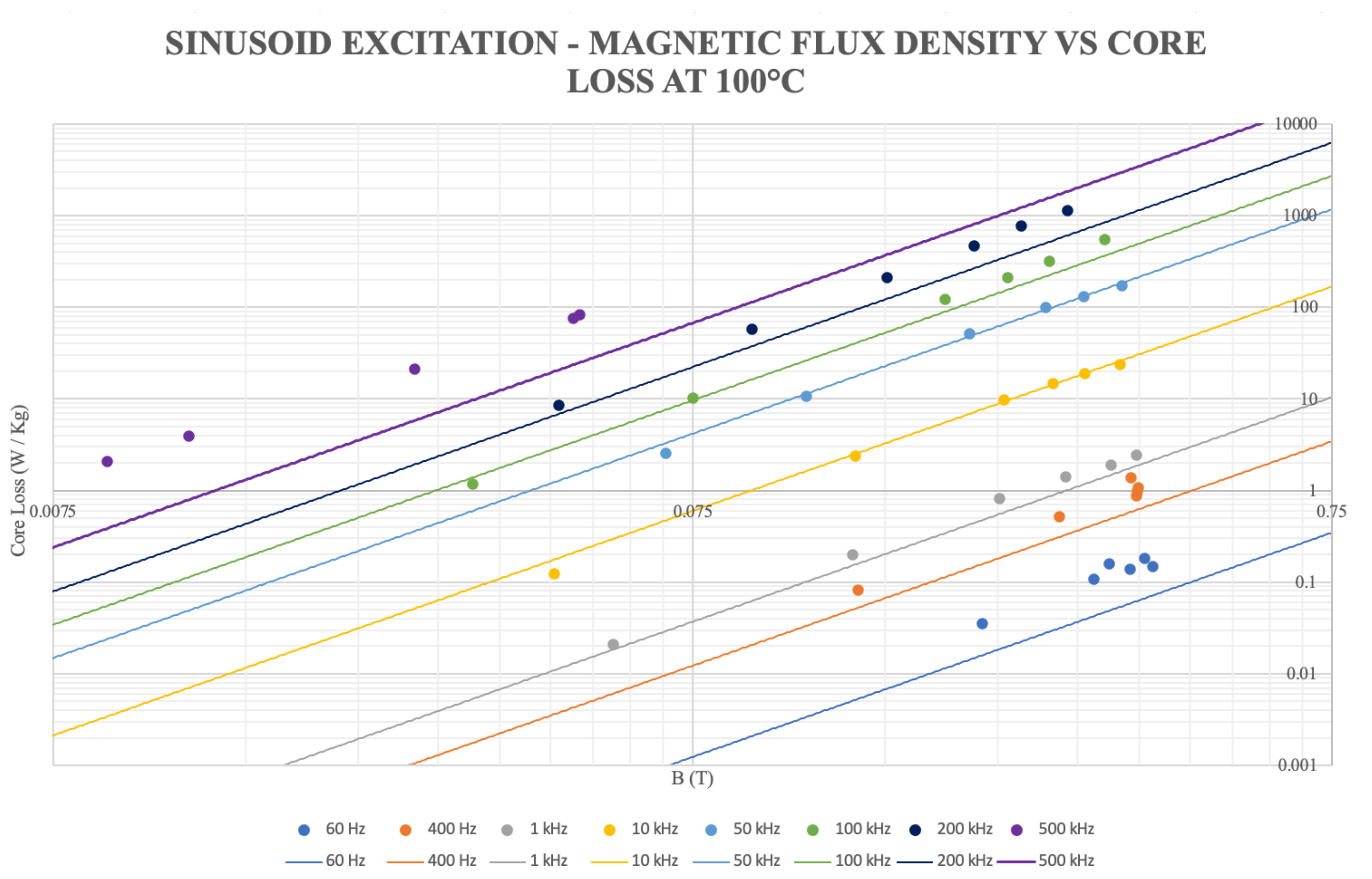
Note: 60 – 400 Hz; 200 – 500 kHz from acquired via Oscilloscope. 1 – 100 kHz from acquired via Power Analyzer.



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

50 kHz			**100 kHz**			**200 kHz**			**500 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.35	1862.89		0.33	4626.22		0.29	6717.12		0.05	7419.83
0.31	6149.48		0.27	7784.56		0.25	7788.64		0.05	7306.01
0.27	8217.16		0.23	9066.86		0.21	8614.78		0.03	7346.25
0.20	9202.09		0.19	9438.40		0.15	8612.86		0.01	7444.21
0.11	8467.83		0.07	7964.77		0.09	8054.63		0.01	7438.28
0.07	7590.11		0.03	7120.57		0.05	7306.95		0.01	7443.23

Note: 60 – 400 Hz; 200 – 500 kHz from acquired via Oscilloscope. 1 – 100 kHz from acquired via Power Analyzer.



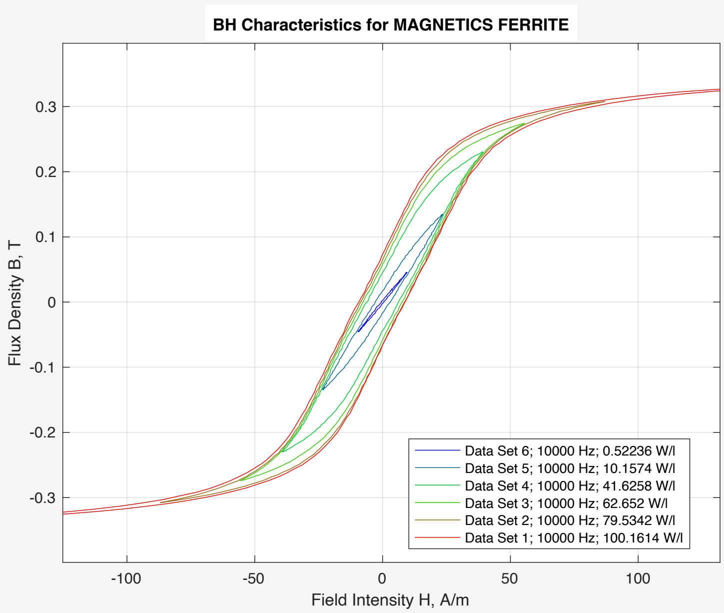
Core Loss Measurements - Sinusoidal Excitation - Flux Density vs Core Loss

Magnetic Flux Density vs Core Loss - Table

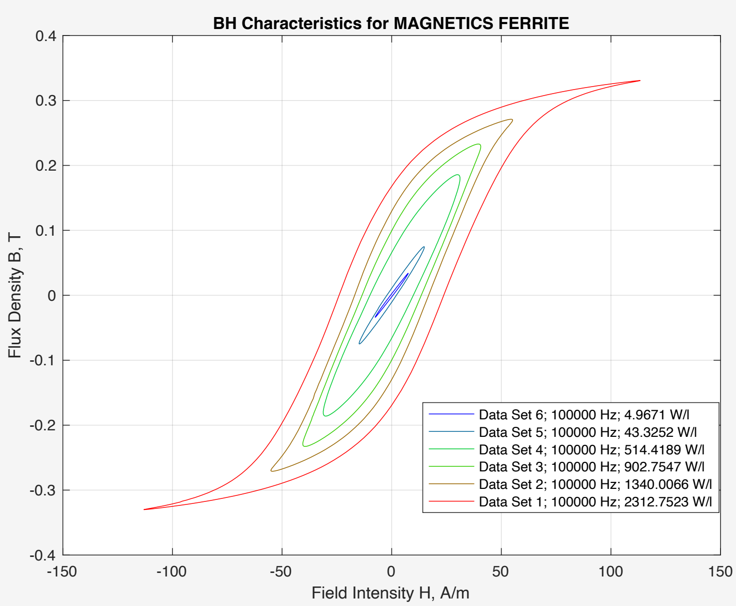
f = 60 Hz			f = 400 Hz			f = 1 kHz			f = 10 kHz	
B (T)	Core Loss (W/kg)		B (T)	Core Loss (W/kg)		B (T)	Core Loss (W/kg)		B (T)	Core Loss (W/kg)
0.39	0.15		0.36	1.38		0.37	2.45		0.35	23.87
0.38	0.19		0.37	1.08		0.34	1.91		0.31	18.93
0.36	0.14		0.37	0.98		0.29	1.43		0.27	14.92
0.34	0.16		0.37	0.88		0.23	0.82		0.23	9.91
0.32	0.11		0.28	0.52		0.13	0.20		0.13	2.42
0.21	0.04		0.14	0.08		0.06	0.02		0.05	0.12
f = 50 kHz			f = 100 kHz			f = 200 kHz			f = 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)
0.35	175.31		0.33	550.58		0.29	1154.40		0.05	83.97
0.31	133.33		0.27	319.00		0.25	778.98		0.05	77.12
0.27	99.59		0.23	214.91		0.21	473.40		0.03	21.38
0.20	52.02		0.19	122.46		0.15	213.59		0.01	3.94
0.11	10.82		0.07	10.31		0.09	58.20		0.01	2.12
0.07	2.56		0.03	1.18		0.05	8.52		0.01	0.82

Note: 60 – 400 Hz; 200 – 500 kHz fit from acquired Oscilloscope. 1 – 100 kHz fit from acquired Power Analyzer.

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



(a)



(b)

Empirical Model Plot Sample – (a) 10 kHz. 100 kHz

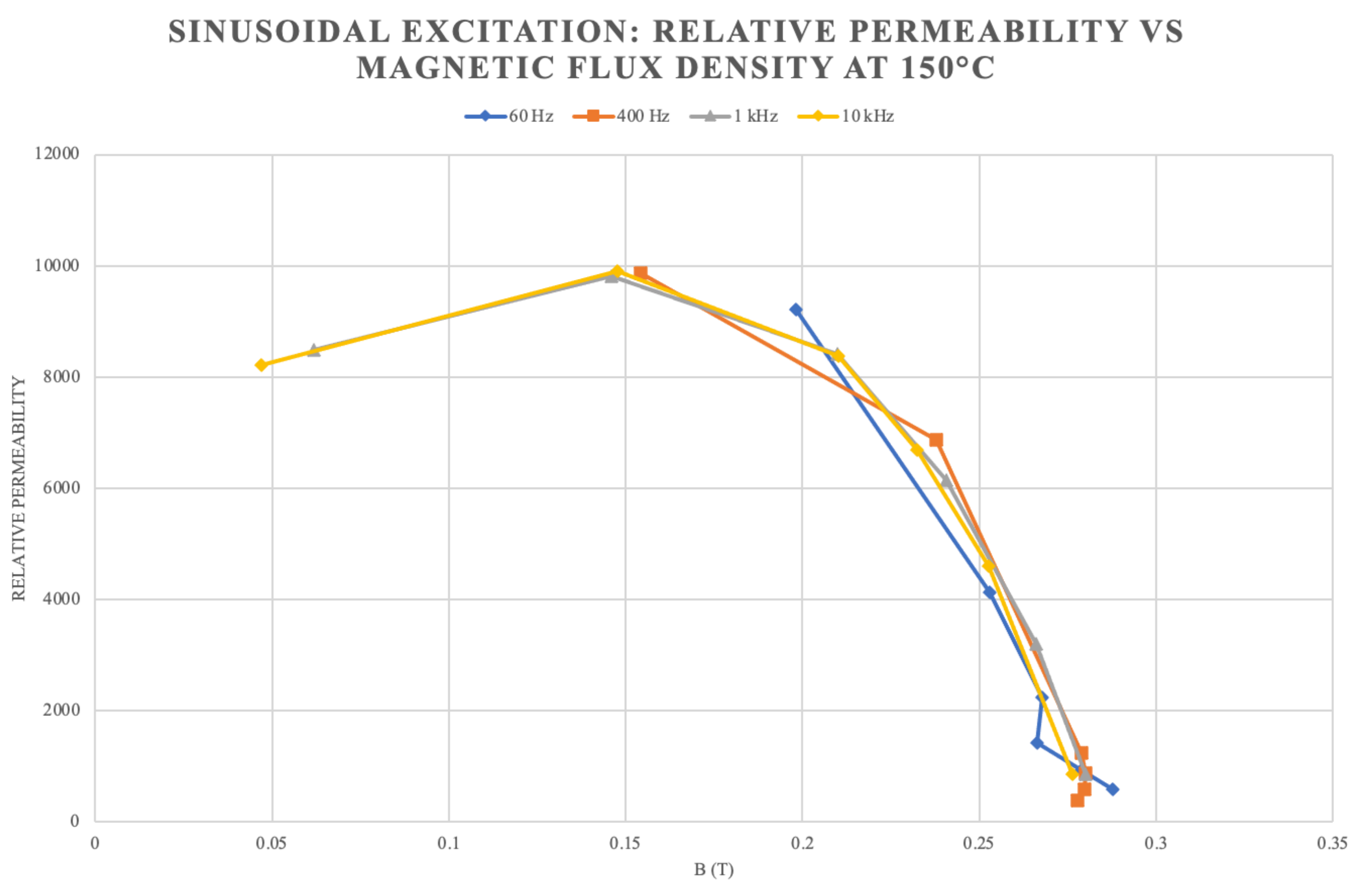
Steinmetz Equation

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

Steinmetz Coefficients for Curve Fit

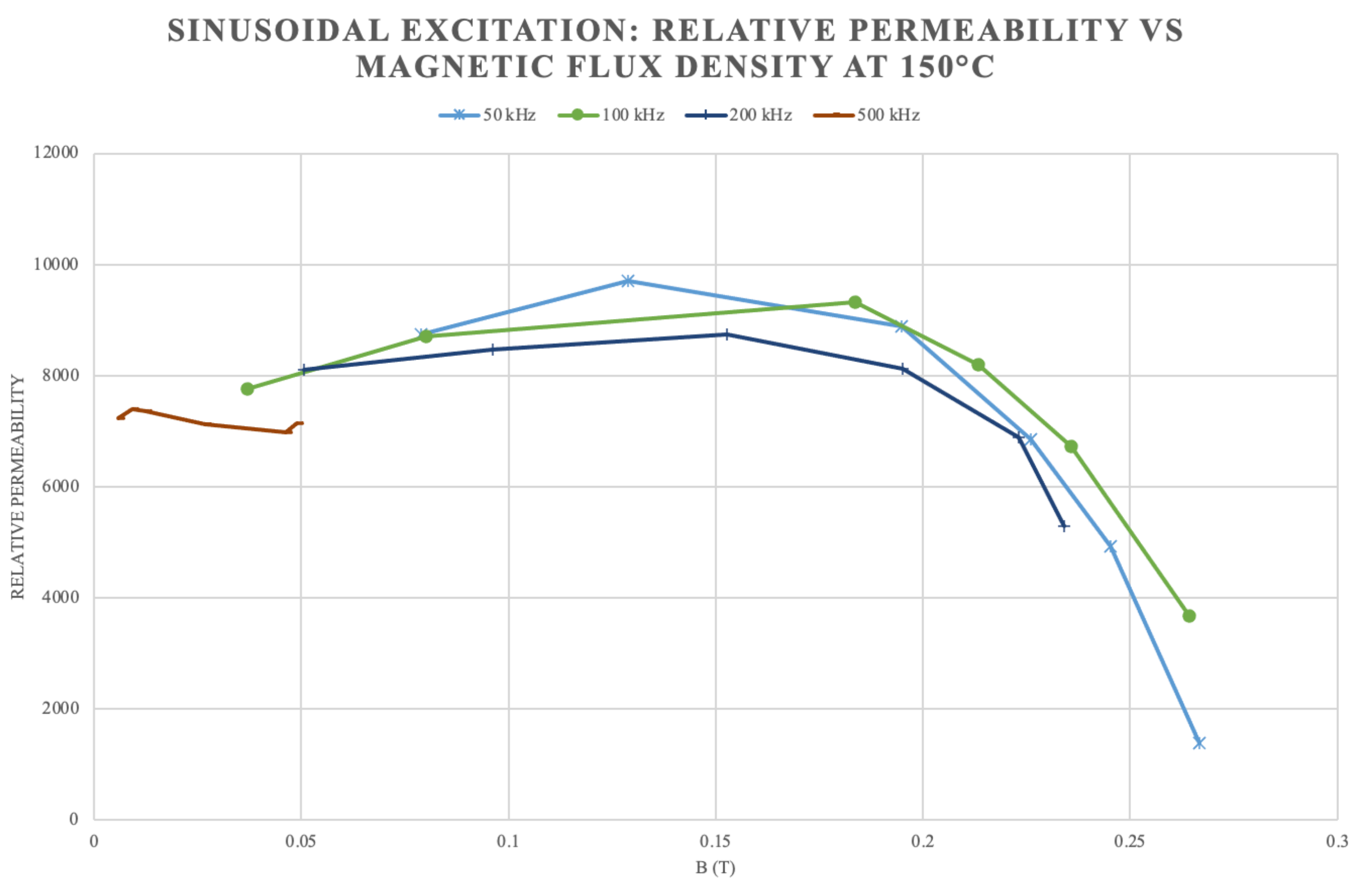
α	1.208	
β	2.4485	
k_h	0.00499608	W / kg

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..



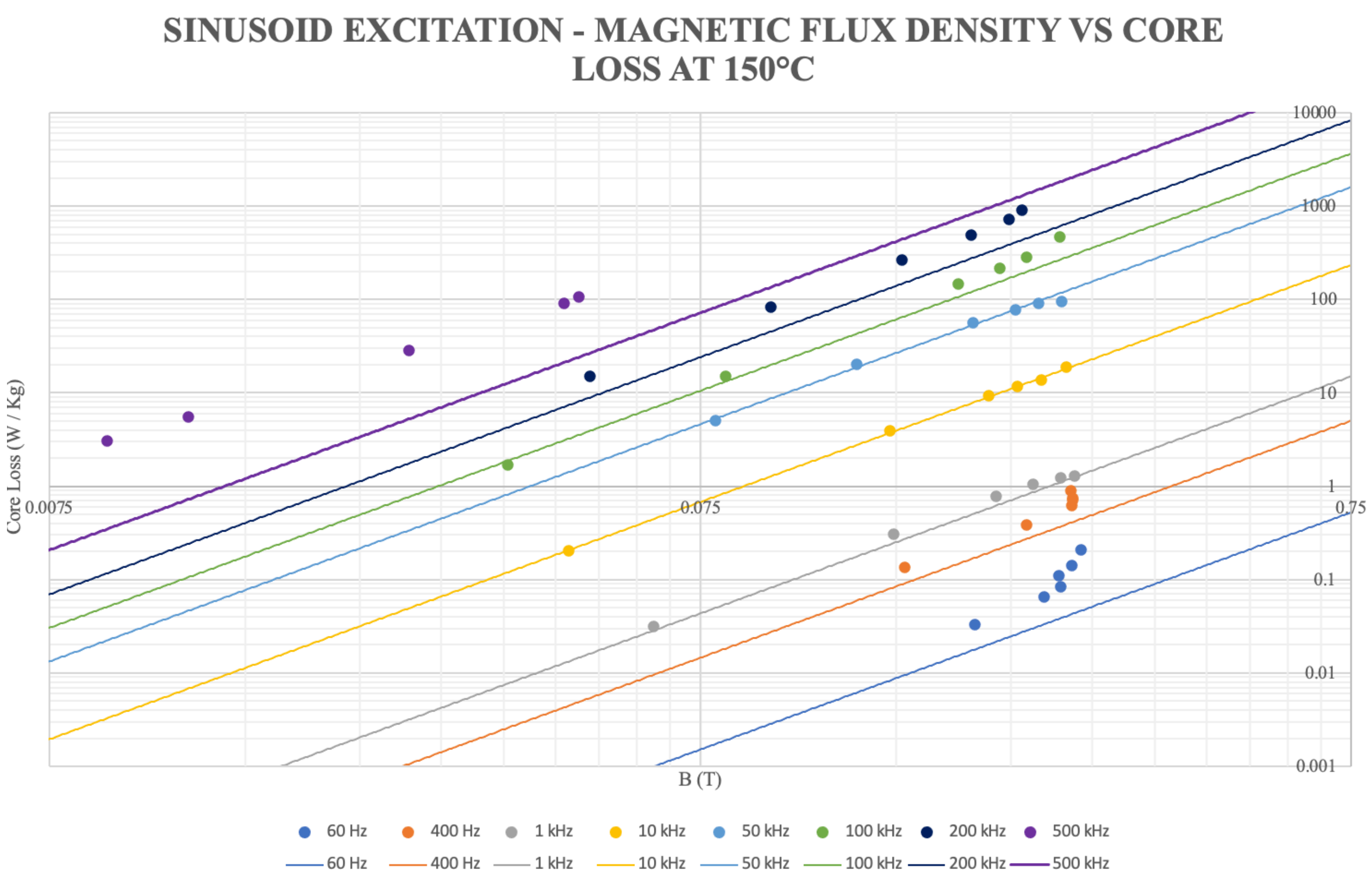
Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

60 Hz			**400 Hz**			**1 kHz**			**10 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.29	593.6		0.28	381.1		0.28	856.8		0.28	853.14
0.28	939.6		0.28	596.1		0.27	3201.9		0.25	4610.87
0.27	1417.7		0.28	875.9		0.24	6143.4		0.23	6685.81
0.27	2246.8		0.28	1240.3		0.21	8420.4		0.21	8374.12
0.25	4139.2		0.24	6865.9		0.15	9811.3		0.15	9902.06
0.20	9213.8		0.15	9863.1		0.06	8482.0		0.05	8216.14



Absolute Relative Permeability - Sinusoidal Excitation - as function of Magnetic Flux Density and Frequency.

50 kHz			**100 kHz**			**200 kHz**			**500 kHz**	
B (T)	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**		**B (T)**	**μ_r**
0.27	1380.16		0.26	3674.61		0.23	5292.05		0.05	7152.43
0.25	4930.85		0.24	6724.02		0.22	6884.41		0.05	6986.93
0.23	6862.27		0.21	8196.62		0.19	8125.70		0.03	7131.83
0.19	8893.66		0.18	9314.64		0.15	8734.92		0.01	7358.13
0.13	9708.06		0.08	8697.21		0.10	8479.19		0.01	7401.59
0.08	8736.96		0.04	7770.13		0.05	8112.49		0.01	7238.31

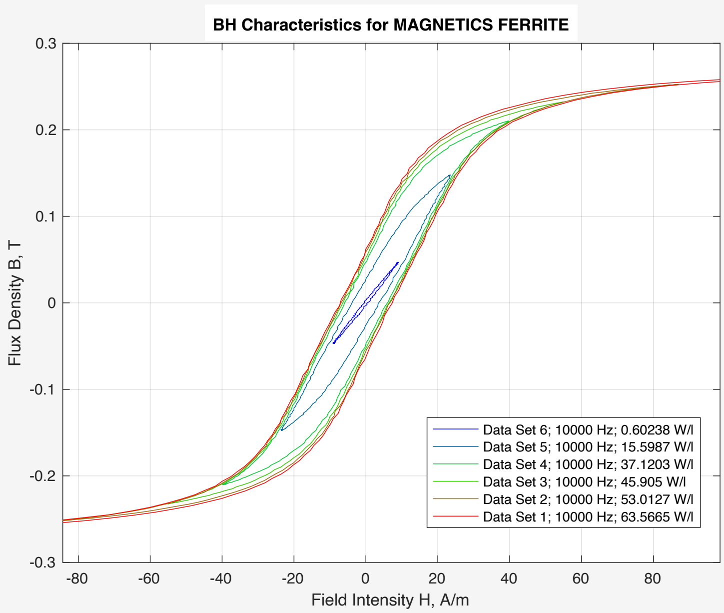


Core Loss Measurements - Sinusoidal Excitation - Flux Density vs Core Loss

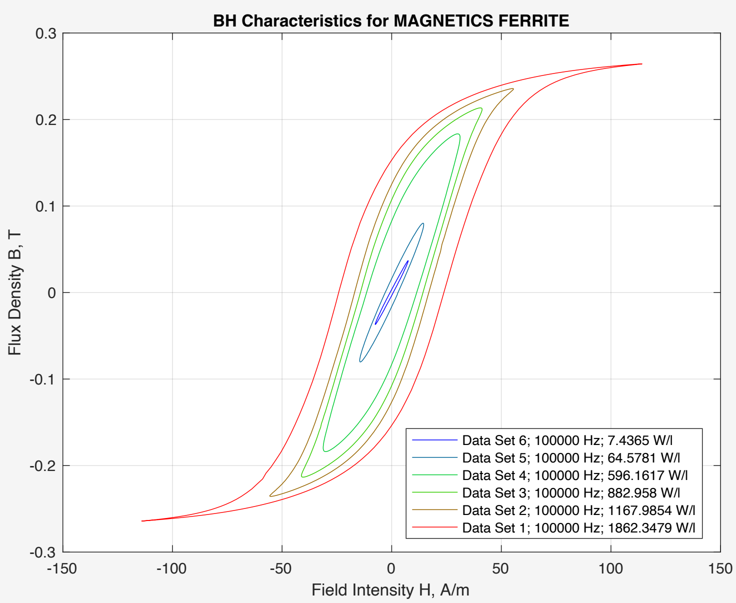
Magnetic Flux Density vs Core Loss - Table

f = 60 Hz			f = 400 Hz			f = 1 kHz			f = 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)**
0.29	0.28		0.28	1.11		0.28	1.31		0.27	18.98
0.28	0.34		0.28	0.76		0.27	1.24		0.25	13.88
0.27	0.11		0.28	0.73		0.24	1.06		0.23	11.79
0.27	0.08		0.28	0.62		0.21	0.79		0.21	9.47
0.25	0.07		0.24	0.39		0.15	0.31		0.15	3.99
0.20	0.03		0.15	0.14		0.06	0.03		0.05	0.21
f = 50 kHz			**f = 100 kHz**			**f = 200 kHz**			**f = 500 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)**
0.27	96.80		0.27	470.93		0.23	920.31		0.05	107.66
0.25	91.05		0.24	289.67		0.22	727.59		0.05	92.48
0.23	78.10		0.22	218.43		0.19	493.49		0.03	28.50
0.20	56.99		0.19	148.07		0.15	266.05		0.01	5.58
0.13	20.40		0.08	15.36		0.10	84.13		0.01	3.09
0.08	5.14		0.04	1.72		0.05	15.16		0.01	1.14

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



(a)



(b)

Empirical Model Plot Sample – (a) 10 kHz. 100 kHz

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	1.1728	
β	2.7192	
k_h	0.00551116	W / kg

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..