METGLAS® 2605-SA1 core
datasheet

Grid Asset Performance > Next Generation Transformers

data sheet

The amorphous tape wound core is manufactured with iron-based 2605-SA1 amorphous foil. The 2605-SA1 amorphous foil is provided by METGLAS, Inc. and the core is manufactured by MK Magnetics. The 2605-SA1 amorphous foil is made up of mainly Iron, with small percentages of Silicon and Boron. Applications include transformers, pulse power cores, motors, and high frequency inductors.

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Revision 0.1

Fig. 1: METGLAS 2605-SA1 core

Dimensions

Table 1: Core dimensions

Description	Symbol	Finished dimension (mm)
Width of core	A	180
Height of core	B	240
Depth of core (or cast width)	D	30
Thickness or build	E	50
Width of core window	F	80
Height of core window	G	140

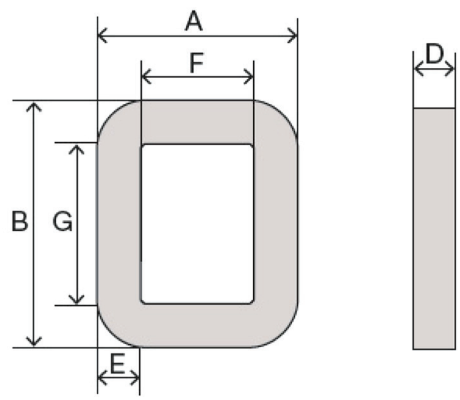

Fig. 2: Illustration of core dimensions

Acknowledgement

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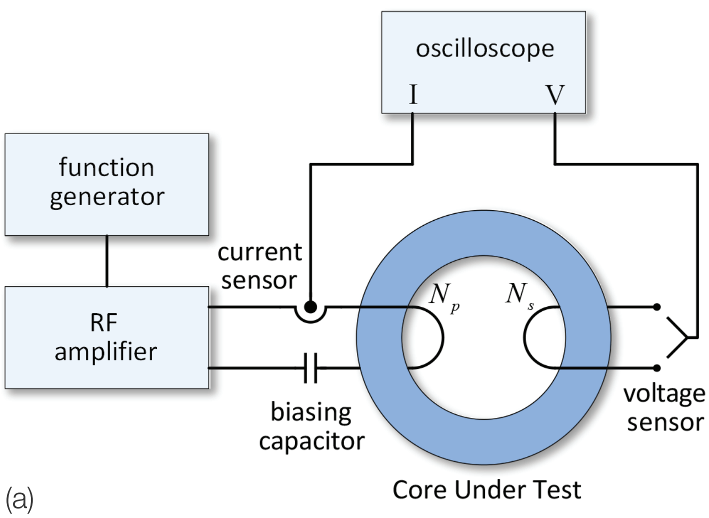
NATIONAL ENERGY TECHNOLOGY LABORATORY

Characteristics

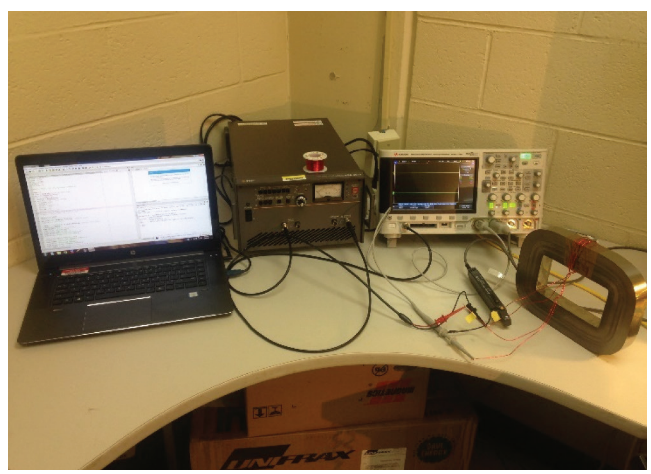
Table 2: Core physical characteristics

Description	Symbol	Typical value	Unit
Core stacking factor	k_f	0.82	Dimensionless
Effective area	A_e	1,230	mm^2
Mean magnetic path length[1]	L_m	583	mm
Mass (before impregnation)		5.22	kg
Mass (after impregnation)		5.95	kg
Lamination thickness		0.001 (0.0254)	inch (mm)
Chemistry		$Fe_{80}\,Si_9\,B_{11}$	at%
Grade		Amorphous	
Anneal		Standard – No Field	
Impregnation		100% Solids Epoxy	
Supplier		MK Magnetics	
Part number		4216L1R-B	

Measurement Setup



(a)



(b)

Fig. 3: Arbitrary waveform core loss test system (CLTS) (a) conceptual setup (b) actual setup

The BH curves, core losses, and permeability of the core under test (CUT) are measured with an arbitrary waveform core loss test system (CLTS), which is shown in Fig. 3. Arbitrary small signal waveforms are generated from a function generator, and the small signals are amplified via an amplifier.

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[1] Mean magnetic path length is computed using the following equation. OD and ID are outer and inner diameters, respectively. $L_m = \dfrac{\pi(\mathrm{OD}-\mathrm{ID})}{\ln\left(\dfrac{\mathrm{OD}}{\mathrm{ID}}\right)}$

Two windings are placed around the CUT. The amplifier excites the primary winding, and the current of the primary winding is measured, in which the current information is converted to the magnetic field strengths H as

$$H(t)=\frac{N_p\cdot i(t)}{l_m}\ , \tag{1}$$

where N_p is the number of turns in the primary winding. A dc-biasing capacitor is inserted in series with the primary winding to provide zero average voltage applied to the primary winding.

The secondary winding is open, and the voltage across the secondary winding is measured, in which the voltage information is integrated to derive the flux density B as

$$B(t)=\frac{1}{N_s\cdot A_e}\int_0^T v(\tau)\,d\tau\ , \tag{2}$$

where N_s is the number of turns in the secondary winding, and T is the period of the excitation waveform.

Fig. 4 illustrates three different excitation voltage waveforms and corresponding flux density waveforms. When the excitation voltage is sinusoidal as shown in Fig. 4(a), the flux is also a sinusoidal shape. When the excitation voltage is a two-level square waveform as shown in Fig. 4(b), the flux is a sawtooth shape. The average excitation voltage is adjusted to be zero via the dc-biasing capacitor, and thus, the average flux is also zero. When the excitation voltage is a three-level square voltage as shown in Fig. 4(c), the flux is a trapezoidal shape. The duty cycle is defined as the ratio between the applied high voltage time and the period. In the sawtooth flux, the duty cycle can range from 0% to 100%. In the trapezoidal flux, the duty cycle range from 0% to 50%. At 50% duty cycles, both the sawtooth and trapezoidal waveforms become identical.

It should be noted that only limited ranges of the core loss measurements are executed due to the limitations of the amplifier, such ±75V & ±6A peak ratings and 400V/μs slew rate. The amplifier model number is HSA4014 from NF Corporation. For example, it is difficult to excite the core to high saturation level at high frequency due to limited voltage and current rating of the amplifier. Therefore, the ranges of the experimental results are limited.

Additionally, the core temperature is not closely monitored; however, the core temperature can be assumed to be near room temperature.

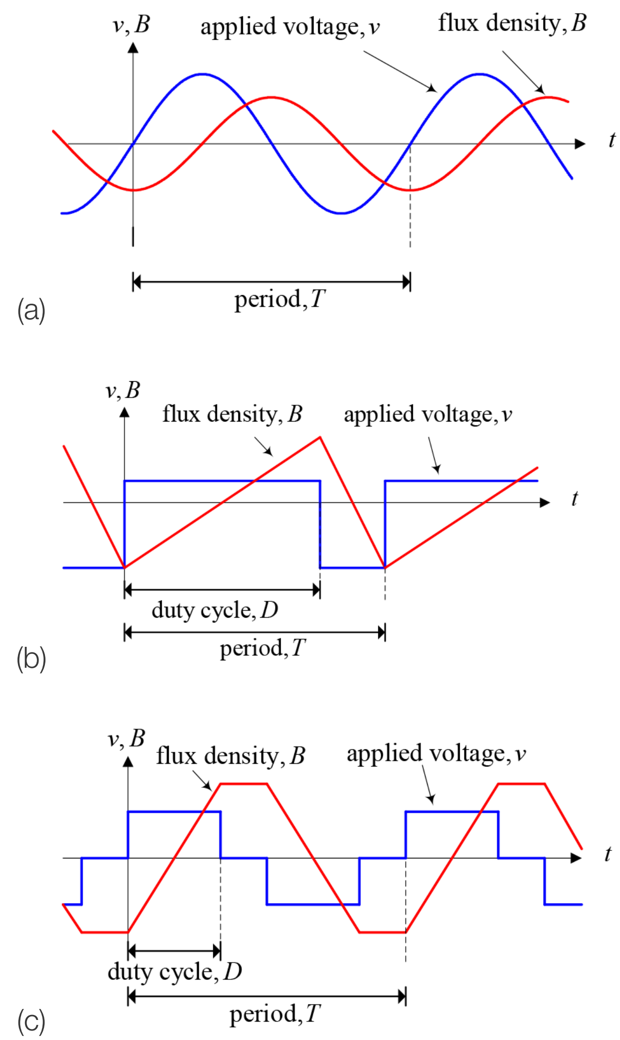

Figure 4. Excitation voltage waveforms and corresponding flux density waveforms (a) Sinusoidal flux, (b) Sawtooth flux, and (c) trapezoidal flux

Anhysteritic BH Curves

Fig. 5 illustrates the measured low frequency BH loops at 100 Hz. Using the outer most BH loop, the anhysteretic BH curve is fitted. The anhysteretic BH curves can be computed as a function of field intensity H using the follow formula.

$$B = \mu_H(H)H$$
$$\mu_H(H) = \mu_0 + \sum_{k=1}^{K} \frac{m_k}{h_k} \frac{1}{1+|H/h_k|^{n_k}} \tag{3}$$

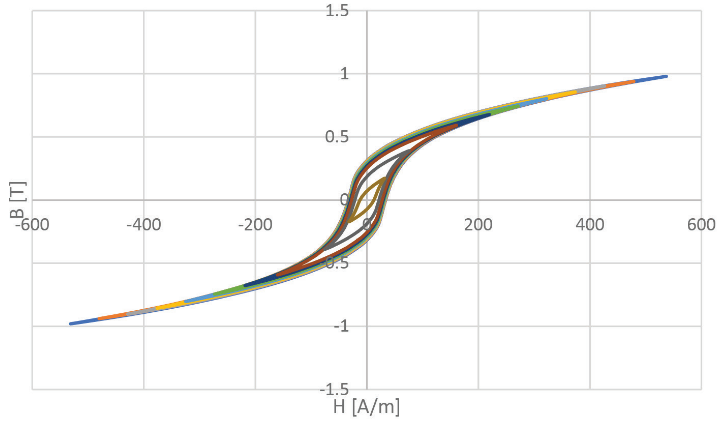

Fig. 5: Low frequency BH loops (excitation at 100 Hz, Np = 43, Ns = 43)

Similarly, the anhysteretic BH curves can be computed as a function of flux density B using the follow formula.

$$B = \mu_B(B)H$$
$$\mu_B(B) = \mu_0 \frac{r(B)}{r(B)-1}$$
$$r(B) = \frac{\mu_r}{\mu_r - 1} + \sum_{k=1}^{K} \alpha_k |B| + \delta_k \ln\left(\varepsilon_k + \zeta_k e^{-\beta_k |B|}\right) \tag{4}$$
$$\delta_k = \frac{\alpha_k}{\beta_k}, \varepsilon_k = \frac{e^{-\beta_k \gamma_k}}{1+e^{-\beta_k \gamma_k}}, \zeta_k = \frac{1}{1+e^{-\beta_k \gamma_k}}$$

Table 3 and Table 4 lists the anhysteretic curve coefficients for eqs. (3) and (4), respectively.

The core anhysteretic characteristic models in eqs. (3) and (4) are based on the following references.

Scott D. Sudhoff, "Magnetics and Magnetic Equivalent Circuits," in *Power Magnetic Devices: A Multi-Objective Design Approach*, 1, Wiley-IEEE Press, 2014, pp.488-

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.

The estimation of the anhysteretic characteristic is performed using a genetic optimization program, which can be found in the following websites:

https://engineering.purdue.edu/ECE/Research/Areas/PEDS/go_system_engineering_toolbox

Table 3: Anhysteretic curve coefficients for B as a function of H

k	1	2	3	4
m_k	1.42349197109713	0.150315028083879	-0.193972076996947	-0.269922862697259
h_k	131.748299040353	25.3776161728309	220.646170969346	533.629141542570
n_k	1	2.24802664153633	2.86432068393265	3.24722527305998

Table 4: Anhysteretic curve coefficients for H as a function of B

k	1	2	3	4
μ_r	16083.8541186965	0.150315028083879	-0.193972076996947	-0.269922862697259
α_k	0.623150745434575	0.0749639789518501	0.00131337189057372	0.00131337046133539
β_k	65.8063408906339	17.8022351180829	2.02022687832383	4.54498137661652
γ_k	1.42423166533048	1.41022908458104	9.99999986009086	0.496600383863354
δ_k	0.00946946353498386	0.00421093073170931	0.000650111086366405	0.000288971582610337
ε_k	1.97884697016947e-41	1.25007842438165e-11	1.68370603100897e-09	0.0947439796669412
ζ_k	1	0.999999999987499	0.999999998316294	0.905256020333059

Fig. 6 illustrates the measured BH curve and fitted anhysteretic BH curves as functions of H and B using the coefficients from Table 3 and Table 4. Fig. 7 and Fig. 8 illustrates the absolute relative permeability as functions of field strength H and flux density B, respectively. Fig. 9 illustrates the incremental relative permeability.

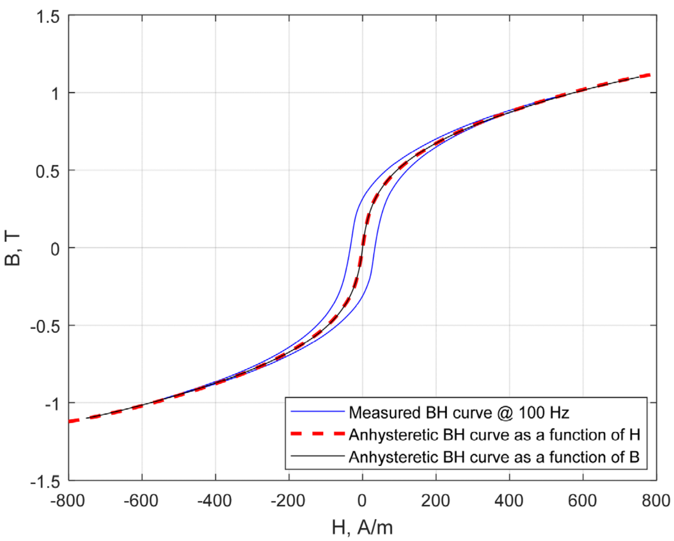

Fig. 6: Measured BH curve and fitted anhysteretic BH curve as functions of H and B

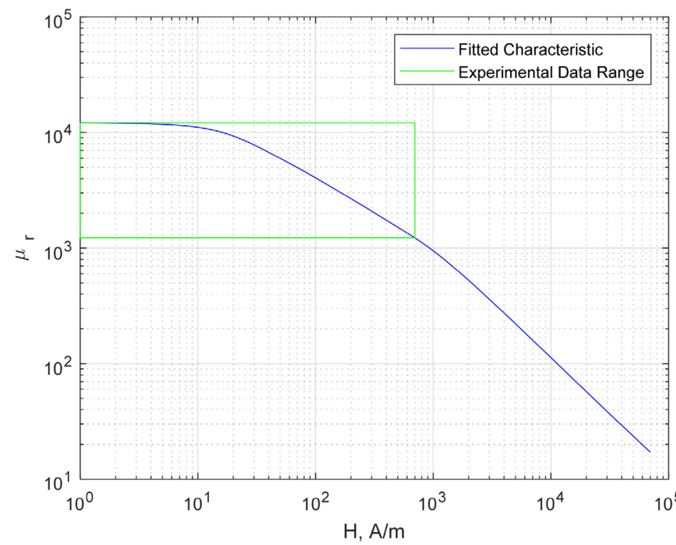

Fig. 7: Absolute relative permeability as function of field strength H

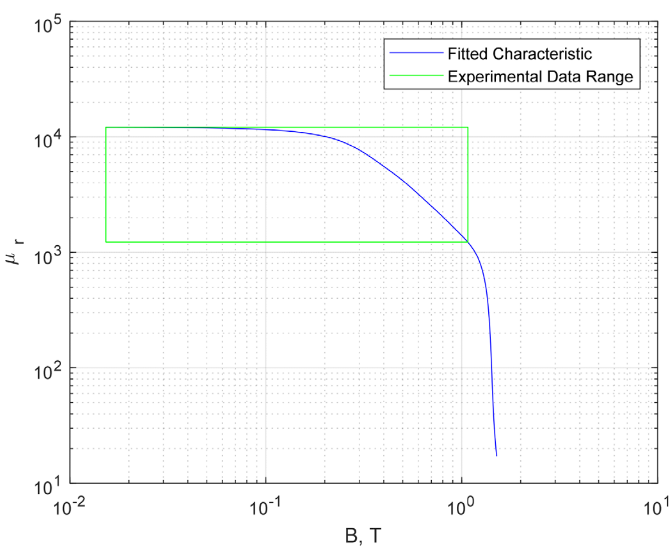

Fig. 8: Absolute relative permeability as function of flux density B

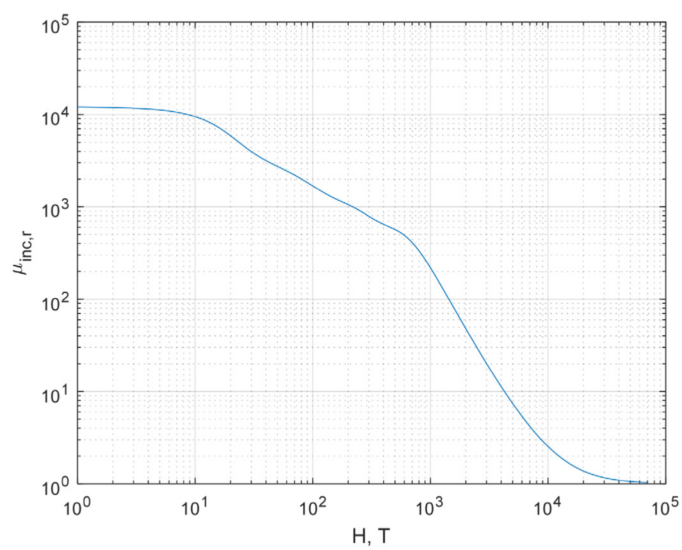

Fig. 9: Incremental relative permeability

Core Losses

Core losses at various frequencies and induction levels are measured using various excitation waveforms. Based on measurements, the coefficients of the Steinmetz's equation are estimated. The Steinmetz's equation is given as

$$P_w = k_w \cdot (f / f_0)^{\alpha} \cdot (B / B_0)^{\beta} \tag{5}$$

where P_w is the core loss per unit weight, f_0 is the base frequency, B_0 is the base flux density, and k_w, α, and β are the Steinmetz coefficients from empirical data. In the computation of P_w, the weight before impregnation in Table 2 is used, the base frequency f_0 is 1 Hz, and the base flux density B_0 is 1 Tesla.

Fig. 10 illustrates the measured BH curve at different frequencies. The field strength H is kept near constant for all frequency. At 1 kHz and 2 kHz excitations, the BH curve is similar, which indicates that the hysteretic losses are the dominant factor at frequencies below 1 kHz. As frequency increases, the BH curves become thicker, which indicates that the eddy current and anomalous losses are becoming larger.

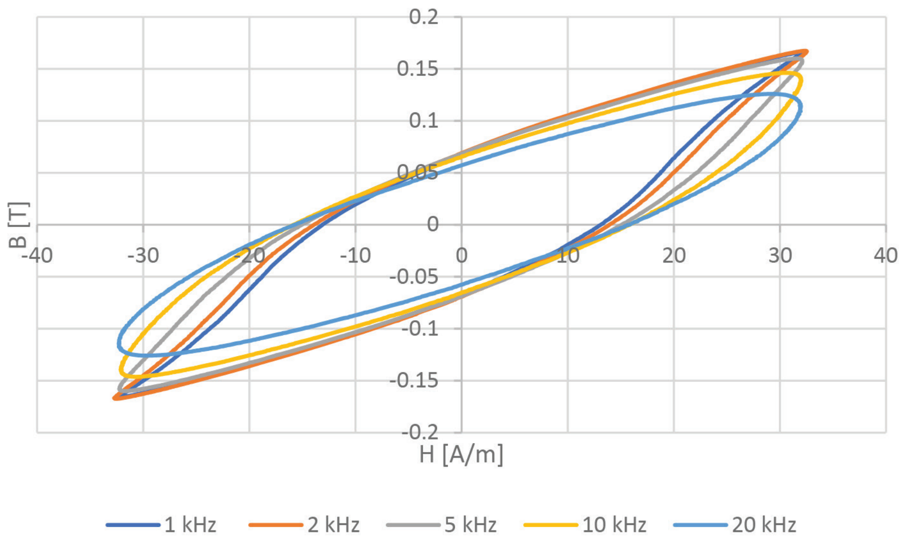

Fig. 10: BH curve as a function of frequency (Np = 4, Ns = 4, Ip = 9.4A)

Table 5 lists the Steinmetz coefficients at different excitation conditions, and Fig. 11 illustrates the core loss measurements and estimations via Steinmetz equation.

Table 5: Steinmetz coefficients

	k_w	α	β
sine	0.00336922369454695	1.30103359460677	2.13595976775746
Sawtooth/Trapezoidal 50% duty	0.00355181904635424	1.28521618008723	2.17280378011837
Sawtooth 30% duty	0.00286605711571677	1.31608598357857	2.19190780960191
Sawtooth 10% duty	0.00196862009744675	1.39295811175637	2.18756372359758
Trapezoidal 30% duty	0.00151692484796744	1.41158141023495	2.18960351245929
Trapezoidal 10% duty	0.000947882242820038	1.51736678718175	2.18178968493193

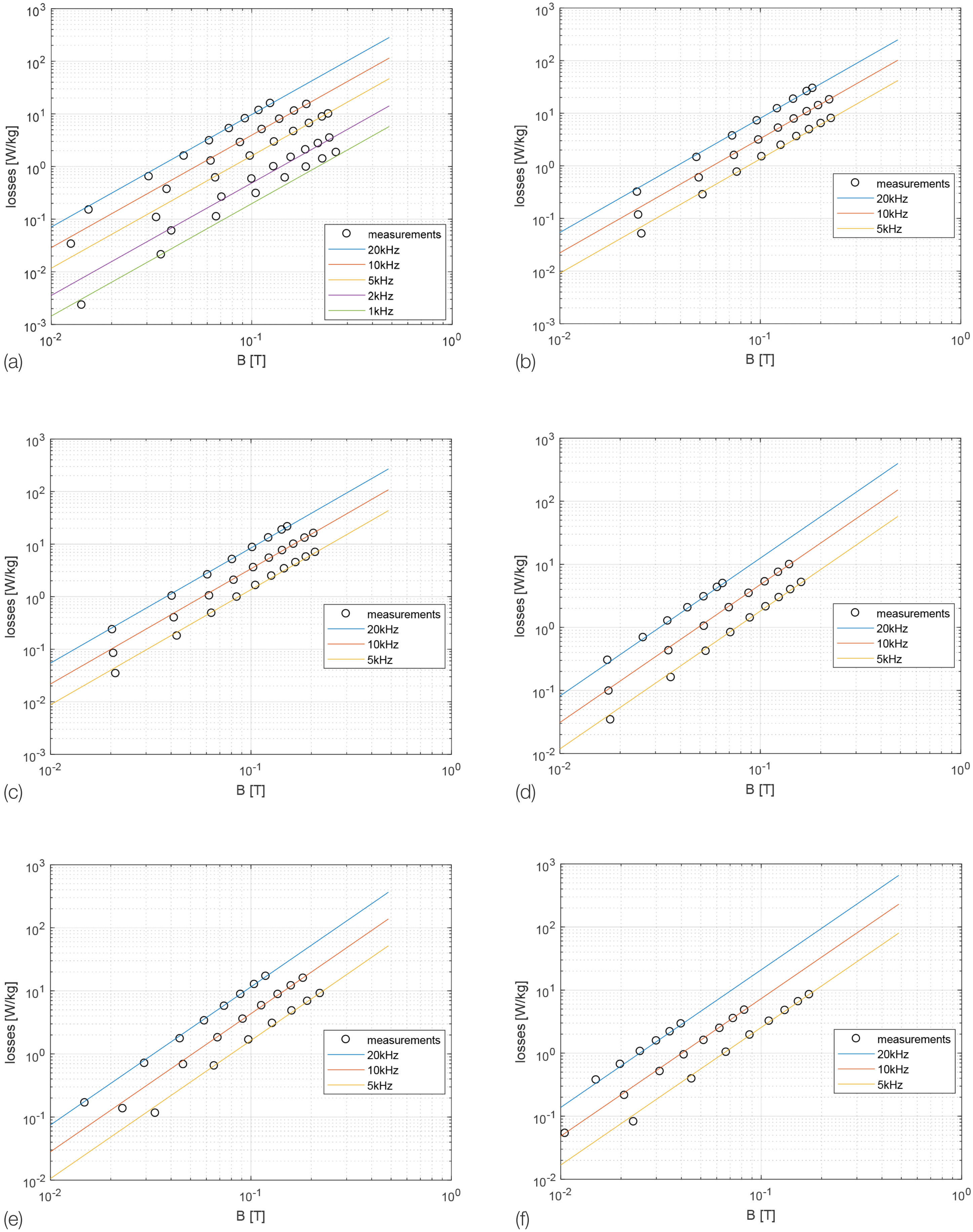

Fig. 11: Core loss measurements and estimations via Steinmetz equation: (a) Sine (b) Sawtooth/Trapezoidal 50% duty (c) Sawtooth 30% duty (d) Sawtooth 10% duty (e) Trapezoidal 30% duty (f) Trapezoidal 10% duty

Core Permeability

The permeability of the core is measured as functions of flux density and frequency. Fig. 12 illustrates the measured absolute relative permeability μ_r values, which is defined as

$$\mu_r = \frac{B_{peak}}{\mu_0 \cdot H_{peak}} \tag{6}$$

where B_{peak} and H_{peak} are the maximum flux density and field strength at each measurement point.

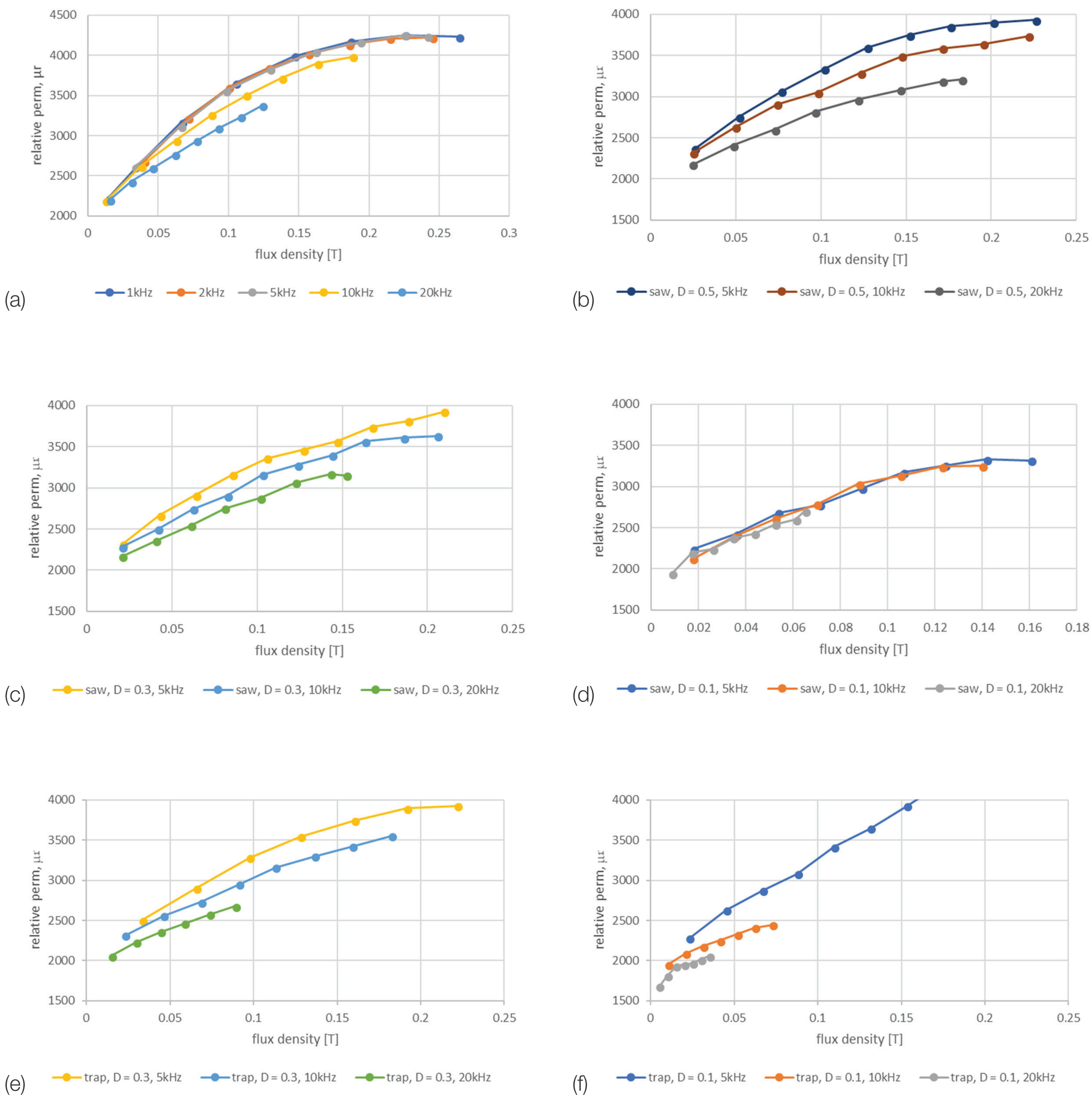

Fig. 12 Relative permeability as a function of flux density and frequency: (a) Sine (b) Sawtooth/Trapezoidal 50% duty (c) Sawtooth 30% duty (d) Sawtooth 10% duty (e) Trapezoidal 30% duty (f) Trapezoidal 10% duty