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Fe-based composited cores for single-phase transformers fabricated with high-induction amorphous material

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A composite-structured, high-induction, double-layered soft magnetic composite core (SMC) comprised of magnetic amorphous HB1-M, HB1, and SA1 materials was developed. A finite element analysis simulated results for the magnetic loss and magnetic flux density for three types of amorphous cores are quite different from findings for traditional magnetic core structures, such as laminated silicon steel, because the magnetostriction and permeability properties of composite-laminated no-cutting structures can be restrained. The SMC structure showed interesting results for magnetic loss, magnetic flux lines, core vibration, and sound level. The main advantage of transformers assembled with composited-cores of SA1 and HB1 over a higher-induction core single-phase transformer is the significant reduction of magnetic loss. However, the SA1 and HB1 composite core also showed worse results in terms of vibration and sound level because the magnetostriction and magnetic flux density in the core distribution are not quite identical to the results for other core types. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4867752]

Several recent studies on transformers have focused on improving core joints, and these studies have reported experimental results on longitudinal flux density and its harmonics at the limb, yoke, and corner.[1] As demonstrated in previous research,[2] designing transformers using composite magnetic cores constructed with a combination of different soft magnetic materials can effectively reduce costs and core losses. Core losses in different specimens of soft magnetic composite material have been measured using circular and elliptical rotating magnetic fields at different frequencies.

Soft materials with amorphous, composite-type cores denoted as SA1 (A), HB1 (B), and HB1-M (C), with core thicknesses of 0.1 and 20 mm, were designed as outer and inner cores. The properties of these three types of ferromagnetic composite cores are summarized in Table I. The ferromagnetic core materials and dimensions of the main structural characteristics are reported in Fig. 1. Figure 2 has shown the experimental environment of amorphous core.

Rotation of moments to align with the applied field can be modeled by the quadratic relation

$$\lambda = \frac{3}{2}\lambda_s\left(\frac{M}{M_s}\right)^2, \quad (1)$$

where λ_s and M_s, respectively, denote the saturation magnetostriction and magnetization. As reference discussed,[3] the pre-stress levels needed to optimize transducer performance are often of a magnitude such that stress anisotropy dominates crystalline anisotropy, and thus the relation in Eq. (1) adequately models the strain generated by the material. Furthermore, for the magnetic properties of the amorphous material,[4] the initial permeability μ_i is directly related to the average anisotropy constant values $\langle K\rangle$ by

$$\mu_i = p_\mu \frac{J_s^2}{\mu_0 K}, \quad (2)$$

where J_s is the average saturation polarization of the material, various values of p_μ are dimensionless pre-factors of the order of unity, and μ_0 is the vacuum permeability. Accordingly, coercivity and permeability are expected to vary with grain size as $H_c \propto D^6$ and $\mu \propto 1/D^6$. In general, the coercivity H_c and the initial permeability μ_i of various soft magnetic alloys are a function of the grain size D. Additionally, for measurement of rotational core loss P_c, the field-metric method was employed.

According to Poynting's theorem, the total core loss P_c in the specimen can be calculated by

$$P_c = \frac{1}{T\rho_m}\int_0^T H\frac{dB}{dt}dt, \quad (3)$$

TABLE I. Typical amorphous core properties with composited structure.

Alloy	HB1-M	HB1	SA1
Density (g/cm^3)	7.33	7.39	7.18
Saturation induction (Tesla)	1.63	1.63	1.56
Coercivity (A/m)	0.9	1.1	1.4
Electric resistivity ($10^{-6}\,\Omega m$)	1.2	1.2	1.3
Magnetostriction (ppm)	27	27	27

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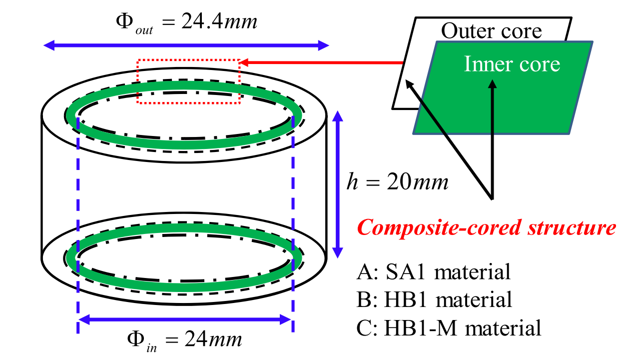

FIG. 1. The soft magnetic composite core with amorphous material.

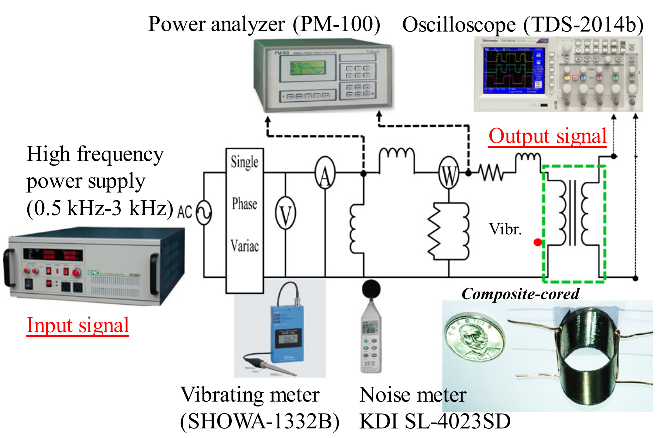

FIG. 2. Experimental setup and measurement for different amorphous cores.

where T is the time period of magnetization and ρ_m is the mass density of the specimen.

To measure the transformer core vibration and sound level,[5] these values can be summarized as $a_{core} \propto \varepsilon_s$, where ε_s is the coefficient of the soft magnetic material in saturation magnetostriction (m/m).

Then, well-accepted methods for establishing the core's sound level involve inducing core sound level (dB) by correlating this level with H_c, B_m, ε. The resulting sound level caused by the magnetostriction vibration in the fundamental frequency of $2f$, which can be attributed to the acceleration (m/s^2) and the core vibration can be expressed as $N_c \propto \varepsilon_s$.

As indicated by Eqs. (1) and (2), the core's magnetostriction and permeability will be affected by the material's magnetic anisotropy and its saturation induction. Therefore, finite element analysis (FEA) software was used to show the core's cross-sectional area and its magnetic flux density variation, as shown in Fig. 3. The hysteresis loop result for the composite core with the SA1 (outer) and HB1 (inner) structures has lower core loss because of the higher saturation induction and lower coercivity of the inner HB1 core, as shown in Fig. 4. Equation (3) can be used to calculate the core loss for different magnetic cores, and this structure shows lower core loss and exciting power for SA1 and HB1 because the composited core was assembled with HB1 material; for this material, the magnetic flux lines are concentrated in the inner core of HB1, as shown in Fig. 5. Table II summarizes the FEA and measurement results for a single-phase transformer with a composite core assembled from

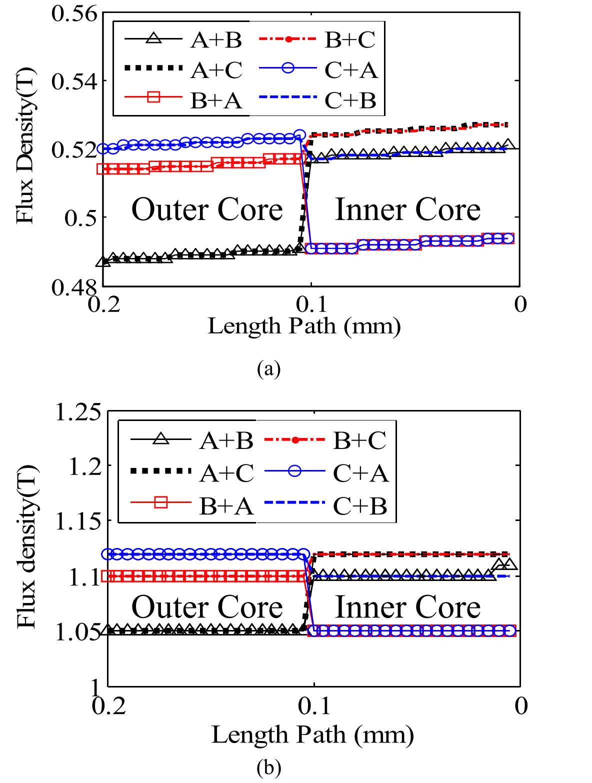

FIG. 3. The simulation results of FEA in core magnetic flux density operated at different frequencies: (a) 500 Hz and (b) 3000 Hz.

HB1-M, HB1, and SA1 materials. Referring to Sec. III, both the sound level and core vibration are dependent on the core's magnetostriction vibration at the fundamental frequency of $2f$, with this core vibration expressed as $N_c \propto \varepsilon_s$, as shown in Fig. 6.

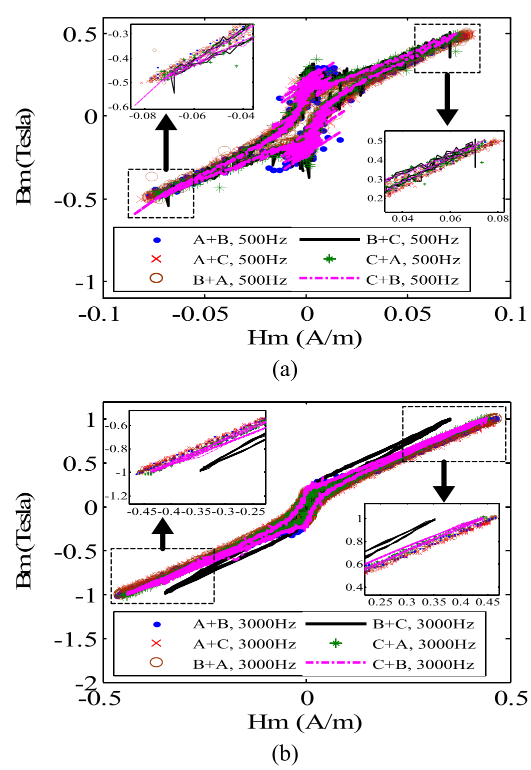

FIG. 4. The measured results of hysteresis loop for different cores: (a) 500 Hz and (b) 3000 Hz.

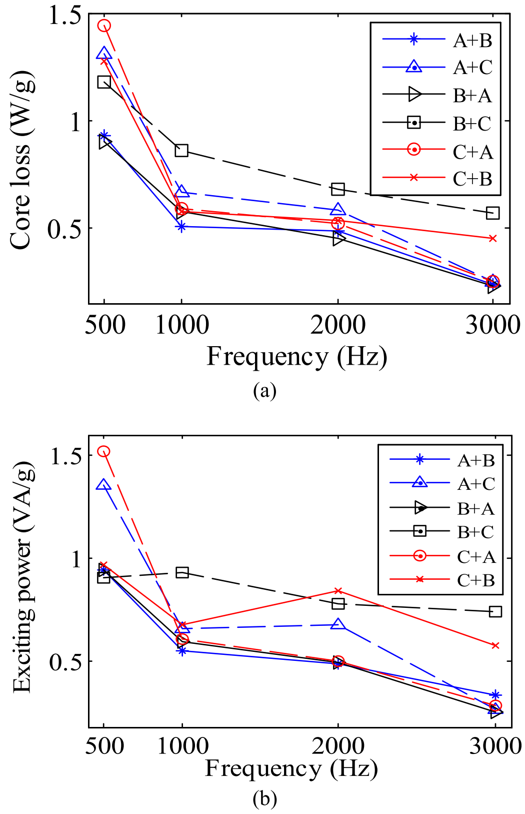

FIG. 5. Magnetic measurement results: (a) core loss and (b) exciting power.

TABLE II. Comparison of FEA and measured results for different composite-cored structures, type A: SA1, B: HB1, and C: HB1-M.

Category	Composite-cored structure (Outer + Inner)	Magnetic induction (Tesla)	Measured core loss (Watt/g)	FEA core loss (Watt/g)
…	A + B	…	0.899	0.98
…	A + C	…	1.44	1.35
500 Hz	B + A	…	0.92	1.01
…	B + C	1.09	1.272	1.51
…	C + A	…	1.312	1.45
…	C + B	…	1.179	1.58
…	A + B	…	0.229	0.232
…	A + C	…	0.252	0.457
…	B + A	…	0.237	0.254
3000 Hz	B + C	0.5	0.449	0.433
…	C + A	…	0.248	0.457
…	C + B	…	0.567	0.473

According to the aforementioned experimental results, the soft magnetic cores showed excellent magnetic properties compared with new HB1-M materials comprised of other soft magnetic materials, such as SA1 and HB1, which show worse results and lead to higher total manufacturing costs.

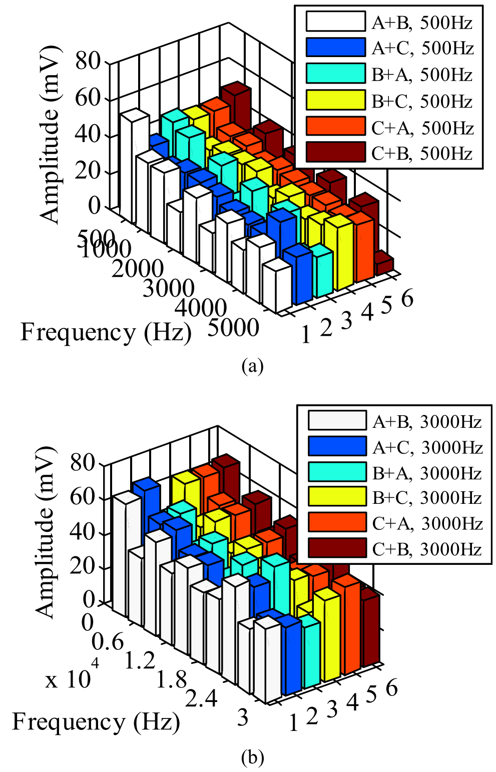

FIG. 6. The measured results of composite-cored vibration: (a) 500 Hz and (b) 3000 Hz.

This paper proposed a method for realizing high-frequency amorphous composited-core transformers exhibiting excellent magnetic properties and reduced manufacturing and operating costs. The contribution of the composited core is integral for improving the economic performance of single-phase transformers because this core enables operation at frequencies of 0.5–3 kHz. This method has validated the integration of a double-layer core (comprised of SA1 and HB1) into a transformer, which resulted in lower magnetic loss and higher permeability. However, magnetostriction and permeability showed worse results for vibration and sound level.

[1]G. Loizosa, "Flux distribution in single phase, Si-Fe, wound transformer cores," J. Magn. Magn. Mater. **320**(20), e874–e877 (2008).
[2]T. D. Kefalas and A. G. Kladas, "Development of distribution transformers assembled of composite wound cores," IEEE Trans. Magn. **48**(2), 775–778 (2012).
[3]Y.-H. Chang *et al.*, "Magnetomechanical vibrations of three-phase three-leg transformer with different amorphous-cored structures," IEEE Trans. Magn. **47**(10), 2780–2783 (2011).
[4]G. Herzer *et al.*, "Grain size dependence of coercivity and permeability in nanocrystalline ferromagnets," IEEE Trans. Magn. **26**(5), 1397–1402 (1990).
[5]C.-H. Hsu *et al.*, "Effects of magnetomechanical vibrations and bending stresses on three-phase three-leg transformers with amorphous cores," J. Appl. Phys. **111**, 07E730-1-3 (2012).