Comparative Analysis of DC magnetic Measurement by Different Magnetic Instruments

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Abstract. This paper reports an interlaboratory study on two typical DC magnetic test methods, ballistic and scanning test method, respectively. By measuring 10 different kinds of soft magnetic materials using five computerized DC hysteresis graphs, discrepancies of the result is witnessed. Phase shift also exists in DC magnetic test, which causes significant error in the measured static hysteresis loss. But different from the AC magnetic test, the phase drift is caused by drift of flux meter, which can't be eliminated by post-measurement adjustment routine in the commercial magnetic instrument. By analyzing intrinsic deficiency of scanning test method, which is adopted by most instrument manufacturers, ballistic test method could be a promising method for DC magnetic measurement.

Keywords: DC magnetic measurement, ballistic test method, soft magnetic material, magnetic measurement standard

1. Introduction

As far as engineering electromagnetic problem is concerned, generally speaking, such four steps are followed as specimen-level measurement, characterization, computational electromagnetics and product-level benchmarking, respectively. Specimen-level measurement is of first priority, providing the essential data for characterization. According to practical application, non-standard condition, such as DC bias, harmonics, temperature, stress are combined with 1D, 2D or even 3D magnetic measurement [1-2]. Of these, 1D case is the basic skill of 2D even 3D.

Regarding the 1D magnetic measurement, there are two important topics, static(DC) and dynamic(AC) magnetic property of ferromagnetic material. For the AC magnetic measurement, excitation waveform is defined in standard to keep magnetic induction sinusoidal[3], where the waveform factor of secondary winding EMF is required to be 1.111. This demand is so strict, making the measured AC property especially iron loss result repeatable and comparable between instruments made by different manufacturers. But for DC magnetic measurement, the situation is more complex. Ballistic test method is defined in ASTM standard for measuring the static magnetic property[4-5]. Anyway, it is the measurement instruments made by manufacturers to implement the magnetic test. With the development of measurement automation, electronic switch and flux meter(also called electronic integrator) is replacing the mechanic switch and ballistic galvanometer in the measurement setup to advance the measurement speed. Computerized ballistic method is not implemented compulsively in practical magnetic test, which may lead to inconsistent test result among different test platforms. This paper aims to evaluate the present status among the commercial DC magnetic test instruments, aiming to provide reference to workgroup of standard writing organization to standardize the DC magnetic test.

2. DC Magnetic Test Methods

For global magnetic instrument manufacturer, two typical methods are usually implemented in 1D DC magnetic measurement, the ballistic test method(called pseudo-impulse method in China)[6] and scanning test method. Both

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method use the same hardware structure, shown in Fig. 1, but with different excitation waveform and inspection strategy. The former measures the B-H curve and hysteresis loop point by point, the latter can obtain the B-H curve and whole DC hysteresis loop in single cycle excitation.

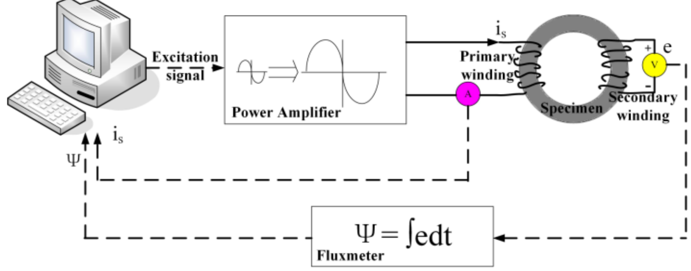

Fig. 1 Diagram of DC magnetic measurement

2.1. *Ballistic test method*

The equivalent excitation waveform of computerized ballistic method is shown in Fig. 2. When testing DC hysteresis loop with maximum field strength Hs, computer-controlled power source magnetizes the specimen to Hs, and taking it as the reference point, quickly decrease and maintain the field to certain value(H_A, H_B, H_C, H_D, H_E, H_F, etc.) within the timespan of Δt. For an instance, at the starting instant of Δt, fluxmeter is reset, at the end of Δt, fluxmeter variation $\Delta\Psi$ is detected to determine flux linkage Ψ_{up} and flux density B_{up}. By this way, such points on upper branch of hysteresis loop as B_A, B_B, B_C, B_D, B_E, B_F, etc. are obtained by (1) and (2). $D_{f,\Delta t}$ denotes the actual drift of flux meter within Δt, e denotes induced signal in the secondary winding, and Ψ_S denotes the flux linkage of secondary winding when specimen is magnetized to H_S. N_{sw} is the number of turns in secondary winding.

$$\Delta\Psi = \Psi_{up} - \Psi_S = \int_0^{\Delta t} edt + D_{f,\Delta t} \tag{1}$$

$$B_{up} = \frac{\Delta\Psi}{N_{sw}S} + B_S = \left(\frac{1}{N_{sw}S} \int_0^{\Delta t} edt + B_S \right) + \frac{D_{f,\Delta t}}{N_{sw}S} \tag{2}$$

After obtaining the upper branch of the loop, lower branch is assumed to be symmetrical with the upper one, generated by software. Note that electronic flux meter is not a perfect one, considering the drift, we should not ignore the last term in (1) and (2).

$$e_{bal} = \frac{D_{f,\Delta t}}{N_s S} \tag{3}$$

From (3), we know abs. error of flux density on each point of the upper branch of hysteresis loop is only proportional to and $D_{f,\Delta t}$, for specific magnetic ring with fixed cross section and secondary winding.

The static hysteresis loss is expressed as (4), with the unit of J/m^3, proportional to the area of the hysteresis loop.

$$P_h = \oint HdB \tag{4}$$

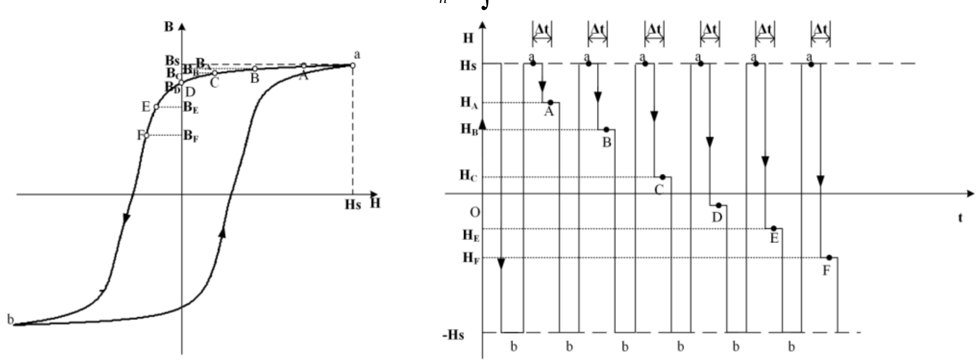

Fig. 2 Excitation waveform of ballistic test method

2.2. *Scanning test method*

Nowadays, scanning test method is adopted by most commercial instruments for its rapidity and simplicity, whose excitation waveform is shown in Fig. 3. Magnetize the specimen to desired field strength Hs from the demagnetized state, we can obtain the initial magnetization curve, and subsequently a complete magnetizing cycle to obtain whole hysteresis loop within time span of Ts. Similar to (1) and (2), the magnetic flux density during DC measurement can be expressed by (5) and (6). Here, $D_{f,\,t\text{-}t_0}$ denotes the drift of flux meter within the time span of $t\text{-}t_0$. A_e denotes the effective area of cross section of specimen.

$$\Delta\Psi = \Psi_{loop} - \Psi_S = \int_{t_0}^{t} e dt + D_{f,\,t-t_0} \tag{5}$$

$$B_{loop} = \frac{\Delta\Psi}{N_{sw}A_e} + B_S = \left(\frac{1}{N_{sw}A_e}\int_{t_0}^{t} e dt + B_S\right) + \frac{D_{f,\,t-t_0}}{N_{sw}A_e} \tag{6}$$

According to (6), abs. error of magnetic flux density at the end of Ts could be as (7).

$$e_{scan} = \frac{D_{f,\,T_s}}{N_{sw}A_e} \tag{7}$$

In most cases, due to drift of flux meter, at the end of Ts, the reading of flux meter is not equal to the value at the beginning of Ts, which leads to an open hysteresis loop. In this situation, a post-measurement adjustment by the software of measurement instrument is adopted to compensate the difference of these two values so that a complete closed loop is obtained.

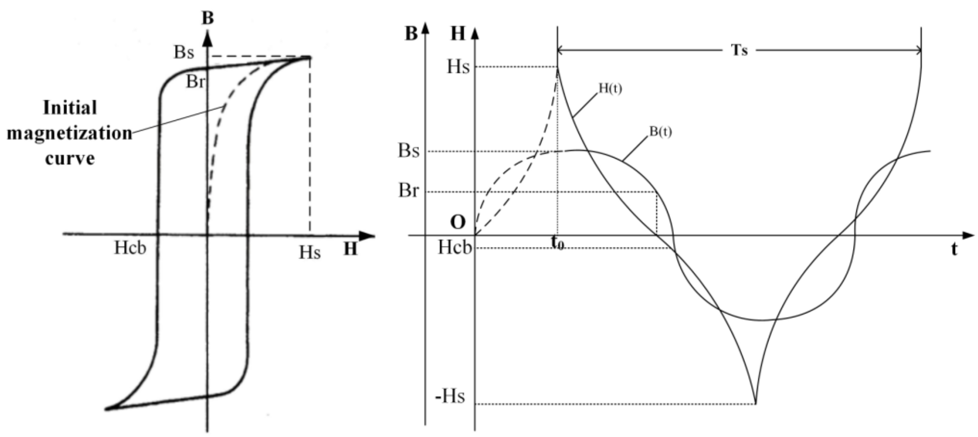

Fig. 3 Excitation waveform of scanning test method

2.3. *Key to precision and repeatability*

Recalling Fig. 1, during test, two signals need to be precisely sampled, primary winding current i_s and flux linkage Ψ of secondary winding, respectively. Then magnetic field strength H is calculated by (8), where N_{pw} denotes the number of turns in primary winding, Le the effective length of specimen. We see the quality of H channel signal is determined by controlled current source.

$$H = N_{pw} i_s / L_e \tag{8}$$

Compared with Hall Effect transducer, precision shunt is a good way to get the primary current signal for DC magnetic test, and there will be no phase lag between voltage drop of shunt and primary current. Therefore, precise acquisition of quasi-static H signal is not difficult nowadays. Quantization error of A/D converter in the acquisition board of computerized DC hysteresis graph should be very small and won't be considered in this paper.

Another important signal, B channel signal is influenced by drift of the flux meter as stated before. It should be the error source for all measured magnetic index, and relates to the precision and repeatability of the DC magnetic measurement system.

3. Measurement and Results

To evaluate above two DC magnetic measurement method, we have chosen ten different typical specimens of soft magnetic material, including silicon steel, amorphous alloy, solid steel, etc., and conducted DC magnetic test with five different magnetic measurement instruments in Hangzhou and Loudi city, China. Tab. 1 lists all five magnetic measurement instruments involved in this comparative test, during which, default setting parameters(scanning period Ts) are used for scanning hysteresis loop. Because FE-2100SD is capable of implementing both test method on the same hardware platform, so it is treated as two different instrument in this paper. Tab. 2 lists all the parameters of ring specimens for DC magnetic test. During DC measurement, the maximum magnetic field strength Hs is set by user, demagnetization is carried out automatically before test by the built-in function of instrument. The whole test is carried out in the air conditioner room with temperature about 25℃.

Tab. 1 Information about magnetic instruments involved in this interlaboratory DC test

Model	Original Equipment Manufacturer(OEM)	Country	Test Method
FE-2100SD	Hunan Forever Elegance Corporation	China	Ballistic
PHYSIK C-750	MAGNET	Germany	Scanning(Ts=60s)
PHYSIK C-750	MAGNET	Germany	Scanning(Ts=60s)
SK100 MTR2655	METRON	Japan	Scanning(Ts=30s)
FE-2100SD	Hunan Forever Elegance Corporation	China	Scanning(Ts=120s)

Tab. 2 All 10 specimens involved in the interlaboratory DC magnetic measurement

No.	Type of specimen	Grade	Le/mm	Ae/mm^2	Ve/cm^3	User set Hs/(A/m)	N_{pw}	N_{sw}
1.	Nano-crystalline	1K107	35.72	3.913	0.1398	80	1	30
2.	Pure iron	DT4	112.2	19.92	2.234	10000	172	20
3.	Soft ferrite	MnZn	60.18	48.93	2.944	600	20	40
4.	FeCo alloy	1J22	178.3	22.05	3.931	4000	141	20
5.	Soft Ferrite	FB45	65.9	17.79	1.172	1200	20	40
6.	FeNi alloy	1J79	88.37	10.44	0.9227	80	20	40
7.	Non oriented Si steel	unknown	69.62	46.14	3.212	5000	45	47
8.	FeSiAl powder core	GS106060	61.1	69.56	4.251	10000	82	85
9.	Grain oriented Si steel	23Z110	216.4	68.64	14.85	800	25	25
10.	FeNi alloy	1J50	112.2	15.93	1.787	1600	40	40

Experimental procedure for evaluating the DC magnetic measurement is as follows.

(1) Measure such five index as max magnetic permeability μm, static hysteresis loss Pu(J/m^3), magnetic induction Bs(T), remanence Br(T) and coercivity Hc(A/m) of all 10 specimens at reference Hs(A/m).
(2) Mail to affiliations where other instrument resides, redo step 1.
(3) For each specimen, after elimination of singularity, take the average value of five measured index by five instruments as reference.
(4) Find the maximum deviation for each index and the instrument which achieves that.

Among the five magnetic instruments, the maximum tracing error between actual H_s^{act} and setting H_s^{set} is 4.6%, achieved by MAGNET-PHYSIK C-750. By doing the comparative analysis of the measured data, we give the maximum discrepancy of measured magnetic index by these instruments, shown in Tab. 3. [2]

(1) Of the five measured DC magnetic index, maximum permeability index (μm) is hard to reach an agreement among five different magnetic instruments, discrepancy reaches 33.2% when measuring such a high permeability material as nano-crystalline 1K107. Compared with other indexes, magnetic induction (Bs) is most reliable. Static hysteresis loss index (Pu) is not credible, with a 26.9% deviation, achieved by FE-2100SD(SM) when measuring FeSiAl powder core GS106060.
(2) Of the ten specimens, FeSiAl powder core(GS106060) is the biggest challenge for instruments to achieve a consistent result, followed by FeNi Alloy 1J50 and nano-crystalline 1K107.
(3) Of the five instruments, Chinese instrument FE-2100SD behaved badly when measuring three of five magnetic indexes, whose result is most likely to be influenced by drift, so fluxmeter of FE-2100SD may need improvement. Considering that there is an error between actual and setting H for MAGNET PHYSIK C-750, so it is reasonable that maximum deviation of Bs is achieved by German instrument. Japanese instrument achieves the maximum deviation when measuring coercivity(Hc) of FeNi alloy 1J50.

Tab. 3 Maximum error of measured magnetic index by five different instruments and the corresponding specimen and instrument

	μm	Pu/(J/m^3)	Bs/(T)	Br/(T)	Hc/(A/m)
Max. Devi.	33.2%	26.9%	2.5%	18.1%	19.8%
Grade	1K107	GS106060	GS106060	GS106060	1J50
Instrument	FE-2100SD(SM)	FE-2100SD(SM)	MAGNET-PHYSIK C-750	FE-2100SD(SM)	METRON SK1100

From the result above, we notice that FE-2100SD(PIM) doesn't appear in the Tab. 3, while FE-2100SD(SM) appears for three times. While the test result of these two instruments are based on the identical hardware platform, including the flux meter. From the statistical view, it seems that ballistic test method is better than scanning method for DC magnetic measurement.

4. Discussion

[2] All the original test data will be included in the attachment.

Ballistic galvanometer is used in the traditional ballistic test method, which is a mechanic integrator, thus hardly influenced by electronic noise and drift. Although mechanic unit is more stable than electronic one, while electronic unit is the essential part for test & measurement automation. In fact, if the fluxmeter is not a perfect one, there is an intrinsic paradox for scanning test method. A large Ts means a slow magnetizing process, the test result will be less influenced by eddy current effect. Meanwhile, Influence of drift on the result is more significant. What is the best Ts for scanning test method? It depends on many factors and cannot be described in a word. Even the instrument manufacturers enable the user to change it during the test. This is one of the reasons for discrepancy in practical DC magnetic test.

Static hysteresis loss(Pu) is very important for soft magnet. In Tab. 3, why relative error of Bs and Hs is small, but Pu has a huge deviation, even reach 26.9%? By further analysis, the only possibility is phase shift of B signal. We should know that post-measurement adjustment can only eliminate DC component in the B signal, but fundamental component caused by the drift is superimposed on the real flux linkage signal, which cause a little variation on Bs amplitude and phase. But static hysteresis loss is sensitive to phase shift, especially when B approaches saturation point. However, we never have chance to separate the drift signal. This is the difficulty of DC magnetic test.

The key point of DC magnetic test is to implement a low drift flux meter. Drift index of EF5 made by MAGNET PHYSIK claims to be less than 10^{-6} Vs/min[3]. By measuring the drift for each specimen with secondary winding connected to the flux meter and no excitation fed, the drift is irregular, with the maximum of is 14.7×10^{-6} Vs/min for FE-2100SD(SM). A bad flux meter and a long scanning time(120s), jointly make FE-2100SD(SM) behave so badly.

For reducing discrepancy of DC magnetic test result, referring to (3) and (7), such hints are summarised below.

(1) Choose ballistic test method. Δt is much smaller than Ts. Furthermore, there is no error accumulation for ballistic method, while for scanning method, error can be accumulated and passed to subsequent point.

(2) Increase the number of turns in secondary winding. It is helpful to reduce error of magnetic flux density.

5. Conclusions

Compared with 1D AC magnetic measurement, DC magnetic test is not strict for computerized measurement apparatus, which may lead to diversity of measurement result. By an interlaboratory study, this paper exhibited a discrepancy of measured magnetic indexes, and analysed the root cause of deviations. Considering the shortcoming of scanning method, ballistic test method is a promising method for DC magnetic test. 1D static magnetic measurement is basic technology for 2D and 3D static magnetic measurement. When we consider 2D or 3D magnetic measurement, we should not ignore that 1D static magnetic measurement is not that perfect up to now.

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