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FREQUENCY DEPENDENCE OF MAGNETOSTRICTION FOR MAGNETIC ACTUATORS

Thant P. P. Phway[*] — Antony J. Moses[**] — David C. Jiles[*,]**

The frequency dependence of magnetostriction is an important characteristic of magnetic materials when considering possible applications in sensors and actuators. In this study, magnetostriction of grain oriented silicon steel sheets, 303 mm long by 30 mm wide by 0.27 mm thick has been measured in the transverse rolling direction at frequencies in the range of 500Hz to 3000Hz. One end of a sample was clamped and displacement amplitude of the other end of the sample was measured using a "Single Point Laser Doppler Vibrometer" and from this, the magnitude of peak-to-peak magnetostriction was determined. Results show a large variation in magnitude of peak-to-peak magnetostriction between 1500Hz and 2500Hz. A sharp increase in magnitude of magnetostriction was found at 2250Hz.

Keywords: magnetostriction, frequency, resonance, laser vibrometer, electrical steels

1 INTRODUCTION

Magnetostriction of magnetic materials has been a subject of extensive study in recent years because its measurement and the related phenomenon of thermal expansion provide basic information on magnetoelastic coupling which is important in determining the applicability in sensors and actuators.

Distinction is drawn between the spontaneous magnetostriction that arises when a material is cooled through its Curie point and field induced or technical magnetostriction. The range of magnetic field induced changes in strain is from 5% in some magnetic shape memory alloys [1] through values of up to 2000 ppm in Terfenol [2], to 200 ppm in manganese doped cobalt ferrite [3] and as low at 10 ppm in iron [4].

When the frequency dependence of magnetostriction is measured a resonance occurs as the combination of frequency of excitation and velocity of magnetostrictively induced sound waves causes an anti-node to be set up at the free end of a sample.

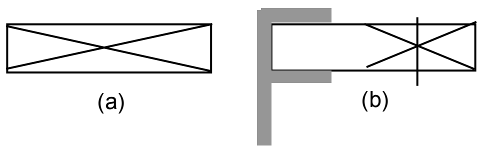

Fig. 1. Resonance condition of the sample with (a) free end and (b) clamped end

If a sample is clamped at one end, as shown in Fig. 1 (b), then the resonant condition occurs when the length of the sample is one quarter of the wavelength of sound. Higher harmonics arise when the frequency is high enough to cause the waves to traverse the length an integer number of times. The n^{th} harmonic frequency f_n occurs when

$$f_n = \frac{n}{4\ell}\sqrt{\frac{E}{\rho}} \quad (1)$$

Where the modulus of elasticity, E for the sample was 193 GPa, the density ρ was 8051kg/m^3 having mass of 19.76g and volume of 303mm (l length) × 30mm (width) × 0.27mm (thickness) = 2.45 10^{-6} m^3. Therefore, a resonant frequency of 4166Hz was expected.

2 PREVIOUS RESEARCH

Jagielinski et al [5] have measured the magnetostriction coefficients λ_{111} and λ_{100} using the resonance method under the action of applied stress. The magnetoelastic coupling caused a shift in the resonance frequency under stress, so that

$$M_s \Delta H(\sigma) = \frac{3}{2}\lambda\Delta\sigma \quad (2)$$

and hence the magnetostriction can be determined from the equation

$$\lambda = \frac{2}{3} M_s \frac{\partial H_{res}}{\partial \sigma} \quad (3)$$

Where M_s is the saturation magnetization, H_{res} is field resonance and σ is the uniaxial stress.

Various techniques have been used to measure the displacement caused by magnetostriction. Methods such as resistance strain gauges, semiconductor strain gauges, accelerometers and laser velocimeters have been used to measure displacement at specific magnetizing frequencies. Previous researchers have investigated magnetostriction at magnetizing frequencies of 50Hz – 2000Hz. However at the higher magnetizing frequencies within this range, typically at 1000Hz and above, optical methods such as the laser displacement meter and the laser vibrometer have become more widely used. The main advantage of the

[*] Wolfson Centre for Magnetics Technology, Cardiff School of Engineering, P O Box 925, Cardiff CF24 0YF, thantp@cf.ac.uk, mosesaj@cf.ac.uk, jilesd@cf.ac.uk [**] Permanent Address: Ames Laboratory, Iowa State University, Ames, Iowa 50011, USA, Email: gauss@ameslab.gov

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laser vibrometer is that it allows non-contact measurement of displacement with high spatial resolution, which is needed in the case of materials with low magnetostriction. It also has the advantage of being not susceptible to magnetic fields or extreme operating temperatures. It allows measurement of magnetostriction in any direction of anisotropic material.

Results obtained by Kakuno and Gondo [6] using the laser vibrometer method was validated using strain gauges. Nakakta et al [7] have also measured magnetostriction coefficients using the laser Doppler vibrometer method and were able to achieve resolution of displacements of 4×10^{-8} m. Wakiwaka et al [8] have measured the mechanical vibrations of samples indirectly through the determination of impedance characteristics. They have described the behavior of an acoustic vibration element in which the measurements were made using a laser doppler vibrometer but their analysis was based on an analogy with the vibration of a mass on a spring which is not appropriate for this situation. Analysis in terms of standing waves in a solid continuum is the correct procedure to use where the whole specimen is vibrating and the mass is distributed.

Takada [9] investigated magnetomechanical resonance in both strip and toroidal samples and was able to show that the resonance occurred at the expected frequency. Mogi et al [10] have also used a laser Doppler vibrometer to measure the ac magnetostriction at frequencies up to 4000Hz. Benda and Klima [11] calculated magnetostriction using laser speckle interferometer, by which they obtained a resolution of 5×10^{-6} m. Karimi *et al* [12] have looked at the magnetomechanical behavior of alloy films. Resonant behavior similar to that shown elsewhere was observed. Chicarro [13] has demonstrated that the elastic modulus can be calculated from the resonance frequency. Bayou et al [14] have investigated the field dependence of elastic modulus by measuring the ΔE effect through changes in the resonance and anti-resonance frequencies.

Hirano *et a.* [15] described measurement of magnetostriction using a laser displacement meter and compared the results to those obtained with a laser Doppler vibrometer. The laser displacement meter was able to measure displacements as low as 5×10^{-8} meter and there was good agreement between the results obtained by the two methods. Moses *et al* [16] have reported a reduction of magnetostriction with frequency in non-oriented electrical steels. Here, the stress sensitivity of magnetostriction was dependant on the degree of texture.

3 EXPERIMENTAL DETAILS

A 40MHz arbitrary waveform generator was used for ac signal generation. A pre-amplifier was connected in parallel with the power amplifier and was used for feedback control of the power amplifier. A digital multimeter was used to monitor the average voltage induced in a secondary search coil while a power analyser was used to display its form factor (FF). A digital oscilloscope with a high voltage isolation module (10 MS/s sampling rate) was used to display displacement output from the laser vibrometer, voltage signal in the search coil (V_{ind}) and magnetizing signal in the primary coil. The voltage signal in the primary coil was taken as a reference signal for triggering. National Instrument Software Labview 7.0 was used for data collection and analysis purposes.

Fig. 2 shows the experimental setup. The primary coil had only 39 turns to maintain low impedance at high frequency. A 10 turn secondary coil was used for monitoring the flux density. The secondary coil was connected to the oscilloscope and the multimeter. The sample was clamped at one end with the laser beam directed on the other. The laser beam was focused on a reflective thin film, which was attached on the sample for optimum reflection back to the laser.

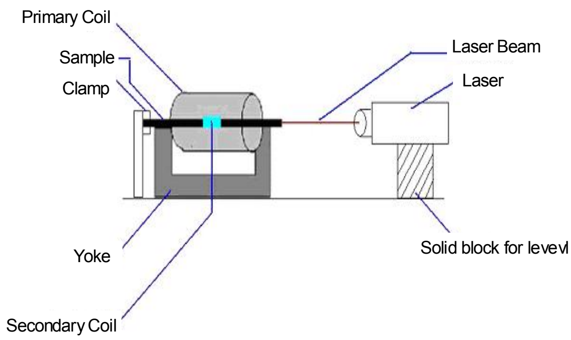

Fig. 2. Diagram of experimental setup

In the present research a single point laser vibrometer (SPLV) was used. The laser vibrometer has 12-bit digital resolution could resolve signal differences of 0.0039 volts, which corresponds to a change in length of Δl = 1.95 nm. For samples of length 300 mm this corresponds to a strain resolution of 6.5×10^{-9}.

The magnetic flux density, B of the sample was measured using a flux coil wound on the sample. Under sinusoidal ac conditions this gave an average output voltage V which can be related to the amplitude of the magnetic flux density $B_{\max}$ by the equation

$$V = \frac{NA\omega B_{\max}}{\sqrt{2}} \cong 4NAfB_{\max} \qquad (4)$$

Where N is the number of turns in the search coil, ω is $2\pi f$ with f being the magnetizing frequency and A is the cross sectional area of the search coil.

The magnetic field was generated using a solenoid. Excitation frequencies from dc to 3000Hz were used under voltage control to determine the magnetostrictive response of the material. The amplitude of the field strength generated by the solenoid changed with frequency even when the voltage amplitude remained constant. The characteristics of solenoid are defined in Table 1.

Tab. 1. Characteristics of Solenoid

l_s	Length of solenoid	0.17	m
d	Diameter of Solenoid	0.1	m
R	Resistance of Solenoid	0.3	Ω
L	Inductance	$\frac{\mu_o \mu_r A_s N_s^2}{l_s}$ =0.088	mH

Where A_s is the cross sectional area of the solenoid and N_s is the number of turns in the solenoid.

From these characteristics the impedance Z was determined at various frequencies, from the standard equation, $Z = \sqrt{R^2 + \omega^2 L^2}$ and from this the current ($i = \frac{V}{Z}$) was determined at a function of voltage at different frequencies. Once the current was known the magnetic field strength was determined using the equation for a finite length solenoid [17]

$$H = \frac{Ni}{\sqrt{(\ell_s^2 + d^2)}} \tag{5}$$

The strength of the magnetic field generated by the solenoid for various applied voltages at different frequencies is shown in the following table.

Table 2. Magnetic Field Strength in Solenoid for Various Applied Voltages at Different Frequencies

Freq (Hz)	Voltage (V)	Resistance (Ω)	Inductance (Henries)	Impedance (Ω)	Current (Amps)	Field (A/m)	Field (Oe)
10	1	0.30	0.000088	0.30	3.333	659.0	8.28
10	5	0.30	0.000088	0.30	16.664	3295.1	41.41
10	10	0.30	0.000088	0.30	33.328	6590.1	82.82
10	20	0.30	0.000088	0.30	66.655	13180.3	165.64
10	30	0.30	0.000088	0.30	99.983	19770.4	248.47
10	40	0.30	0.000088	0.30	133.311	26360.5	331.29
10	50	0.30	0.000088	0.30	166.638	32950.7	414.11
20	30	0.30	0.000088	0.30	99.932	19760.3	248.34
50	30	0.30	0.000088	0.30	99.575	19689.7	247.45
100	30	0.30	0.000088	0.31	98.331	19443.7	244.36
500	30	0.30	0.000088	0.41	73.402	14514.3	182.41
1000	30	0.30	0.000088	0.63	47.543	9401.0	118.15
2000	30	0.30	0.000088	1.15	26.085	5158.0	64.82
4000	30	0.30	0.000088	2.24	13.389	2647.4	33.27

4 RESULTS AND DISCUSSION

Eddy current heating can be a significant factor when making measurements of the properties of these materials at high frequencies. This has to be taken into account preferably by making the measurements before significant rise in temperature has occurred, or by monitoring and allowing for changes in temperature when comparing results. Fig. 3 shows the increase of temperature with time from the start of magnetizing at B_{max} = 1.0T over the frequency range of 500Hz to 4000Hz.

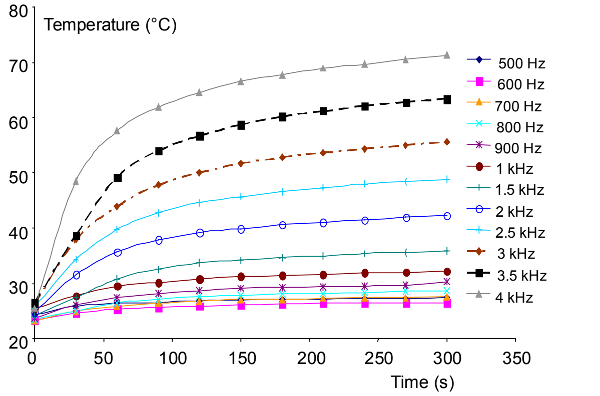

Fig. 3. Increase of temperature with time of magnetisation at different magnetising frequencies (B_{max} = 1.0T)

Magnetostriction was measured at B_{max} = 0.7T, 0.9T and 1.0T and frequencies from 500Hz to 3000Hz at 250Hz increments. At these flux densities, the form factor remained within 1% of 1.11.

In order to validate the reproducibility of the system, measurements were taken: firstly at the initial condition of the digital oscilloscope and secondly after resetting it. This was carried out because the start and end of measurement points saved by the digital oscilloscope differed every time it is reset.

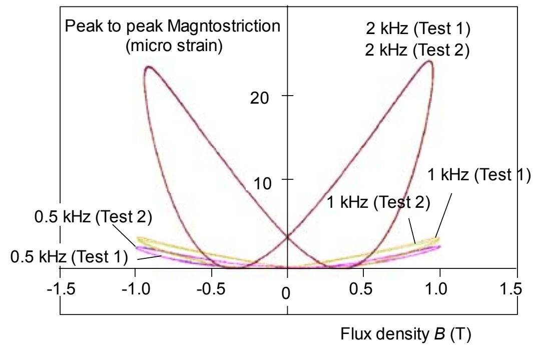

Fig. 4. Magnetostriction, λ vs Flux Density, B at 500Hz, 1000Hz, 2000Hz at B_{max} 1.0T

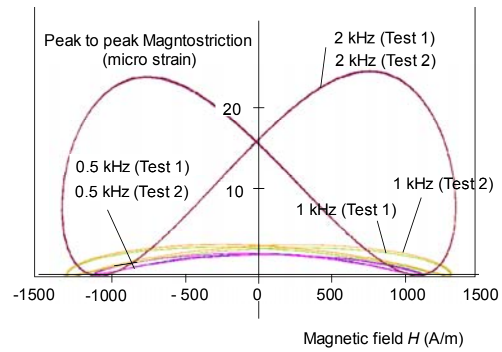

Fig. 5. Magnetostriction, λ vs Magnetic Field, H at 500Hz, 1000Hz, 2000Hz at B_{max} 1.0T

Figs. 4-5 show the peak-to-peak magnetostriction, λ versus flux density B_{max} at 1.0T and magnetic field H at 500Hz, 1000Hz and 2000Hz. It was observed that peak-to-peak magnetostriction differs by less than 10% in the reproducibility tests.

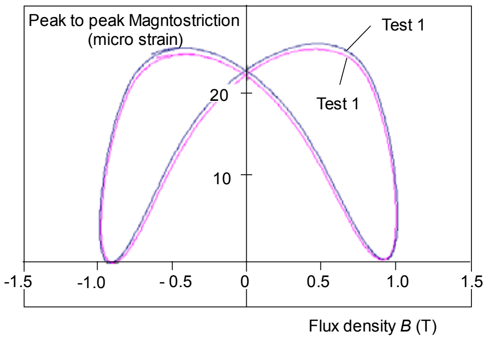

Fig. 6. Magnetostriction, λ vs Flux Density, B at 2250Hz at B_{max} = 1.0T

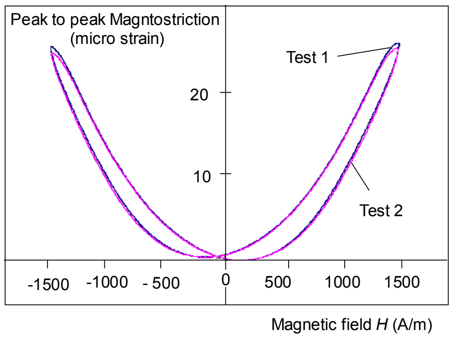

Fig. 7. Magnetostriction, λ vs Magnetic Field, H, at 2250Hz at B_{max} = 1.0T

Figs. 6-7 shows peak-to-peak magnetostriction versus flux density, B and magnetic field, H at 2250Hz. A phase change in the plots was observed compared to figs. 4-5, confirming the characteristic of passing through a resonance point. Fig. 8 shows a plot of peak-to-peak magnetostriction λ versus magnetizing frequency at flux densities 07T, 09T and 1.0T. The plot shows a sharp rise of magnetostriction at 2250Hz. Another sharp rise in magnitude of peak-to-peak magnetostriction is expected at 4500Hz since the calculated resonant frequency for the sample is 4166Hz.

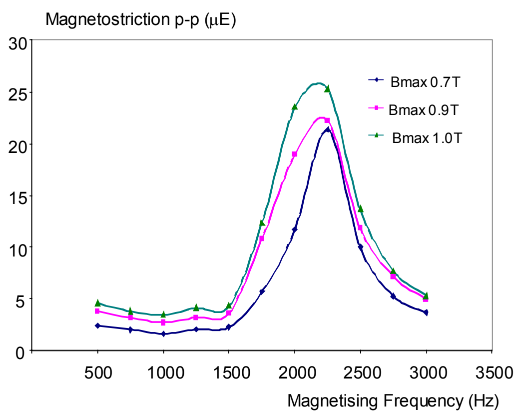

Fig. 8. Peak-peak Magnetostriction, λ vs Magnetising Frequency, ν at B_{max} = 0.7T, 0.9T and 1.0T

5 CONCLUSION

It was observed that magnetostriction is not only a function of magnetic properties but also dependant on the physical condition of the sample. A resonant frequency at 2250Hz was found for the sample used under the given experimental conditions and physical dimensions. Temperature was found to rise with magnetising time and frequency but this did not significantly affect magnetostriction.

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