Inductive detection of magnetostrictive resonance

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Received 31 August 2006; received in revised form 8 June 2007; accepted 8 June 2007
Available online 17 June 2007

Abstract

We report an inductive method detecting a magnetostrictive resonance signal, which is applied to an ultrasonic magnetostrictive transducer sample. Slab shaped ferrite samples are mounted in a rf coil and actuated by a pulsed rf magnetic field. A dc magnetic field is also applied and the resonance signal from the sample is detected by the same coil after the rf field is turned off. The detector system is identical to a conventional pulse NMR system with quadrature detection. The detected signal is Fourier transformed and wide band spectrum data are obtained. The resonance spectrum data show strong dependencies on the bias dc field strength and direction as well as the dimension of the sample.

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PACS: 72.55.+s; 75.80.+q; 75.60.−d; 75.60.Ch

Keywords: Inductive detection; Magnetostriction; Fourier transform; Pulse resonance; Magneto-elastic wave

1. Introduction

To study elastic properties of electric or magnetic materials, pulse resonance techniques composed of electromagnetic excitation and induced signal detection have been used [1–3]. Especially, for piezoelectric materials, Choi and Yu developed an piezoelectric resonance technique to study ferroelectric properties [3]. For magnetic materials, a coupling between electromagnetic field and sample magnetization mediates the excitation and detection. Possible sources for this coupling are the Lorentz force, the magnetization force, and the magnetostriction force [4]. The magnetostriction [5–7] phenomena originated from elastic domain wall motion was used for an oscillator first by Pierce [8]. This phenomenon has been used for actuators and sensors by oscillating them and measuring the frequencies of elastic vibrations accurately. A representative example is magnetostrictive transducer converting electrical energy into mechanical energy. The magnetostriction transducers have been applied for ultrasonic sound generators, magnetostrictive optical wavelengths tuning, and acoustic delay lines [9]. Recently, highly magnetostrictive materials are investigated for practical application such as iron rare-earth compounds of terfenol-d [10] or ferromagnetic oxide composites [11].

Lanotte et al. [12,13] have studied widely the bias field dependency of the amplitude and frequency of the acoustic waves in ferromagnetic materials by using pulsed electromagnetic excitation. They used exciting and detecting coils with several hundred turns. The magneto-elastic wave amplitude was measured as a function of the exciting pulse burst frequency in the range of 2–120 kHz. In a similar manner, the electromagnetic acoustic transducer (EMAT) technique has been used for measuring acoustothermal stress, attenuation coefficient, grain size of metals, and magnetostriction coefficients [14–17,4]. For EMAT technique, a ferromagnetic sample is located beneath of a meander-line which is beneath of a permanent magnet or a disk shape sample is located in a solenoid coil. The solenoid coil is used for applying constant bias magnetic field along the sample axis and the meander-line coil is to induce the dynamic field in the circumferential direction through magnetostrictive effect and receive the shear wave through the reversed magnetostrictive effect.

Recently, our group reported the experimental instrumentation on magnetostrictive resonance using NMR spectrometer [18]. In this paper, we analyze the previous results obtained by
the rf pulse type resonance detection method for magnetoacoustic wave in a slab shape ferrite material used for an ultrasonic magnetostrictive transducer. The unique features of our method are single impulse excitation and Fourier transformation detection.

2. Experiments

Overall experimental setup is similar to a pulse type NMR spectrometer and the sample is a commercially available magnetostrictive transducer ferrite material commonly used for an ultrasonic cleaner produced by TDK corp [19].

A schematics of the experimental spectrometer setup used in our experiment is shown in Fig. 1. Our spectrometer is composed of a series-tuned sample coil and quadrature detection receiver [20,3]. The setup consists of the power amplifier which applies a pulse-modulated high voltage rf magnetic field to the sample inside the sample coil and the quadrature detection receiver which picks up the resonance signal from the sample. The sample and sample coil are placed inside an electromagnet which applies the static magnetic field to the sample. The signal from the sample is transmitted to an analog-digital board in a PC with 1 mV voltage resolution and 1024 pt digitization for each channel. The sample coil we use is a solenoid of 25 mm diameter and 10 mm height with 11 turns tightly wound. As shown in the Fig. 1, the dc bias magnetic field is perpendicular to the pulsed rf magnetic field. When we applied the static field parallel to the rf field, no signal was found. The ferrite samples are cut into various sizes using a diamond saw. The samples are slab shape of 1 mm thickness, 10 mm width, and 50 mm length. A supporting structure made by thin teflon sheet clamps one end of the sample. The sample is rotatable by the teflon support. The spectrometer is tuned to 5 MHz and pulses of 0.5 μs width and 10 ms repetition time are applied throughout this work.

3. Results and discussion

The detected signal from the slab shape sample of 0.79 mm × 9.06 mm × 42.85 mm is shown in Fig. 2. The signal is 64 times sampled to average out noise. The bias magnetic field intensity 0.6 kG is applied parallel to the sample surface. Fig. 2 shows the ring-down signal, when the sample is parallel to magnetic field (θ = 0°). The inset of Fig. 2 is the Fourier transformed (FT) waveform of the signal. The several peaks in the spectrum are shown with equal spacing. The series of peaks has frequencies:

\[ f(n) = \frac{nc}{2d} \]

where \( n \) is the positive integer, \( c \) the acoustic wave velocity, \( d \) the length of the acoustic wave [17]. The highest peak corresponds to 12th harmonic (\( f^{(12)} = 4.84 \) MHz) and the frequency spacing \( \delta f = 0.403 \) MHz.

We investigate the dependency of resonance frequency on the sample geometry. The magnetic field is applied parallel to the sample surface and kept to 0.6 kG. After the resonance signal of a sample is measured, the sample is dismounted and the width is decreased by cutting with a diamond saw. The frequency separation between the peaks is shown as a function of sample width in Fig. 3 (a). The error bar is attributed to that we have only three or four resonance peaks in the spectrum. The graph shows the inverse proportionality between the width \( W \) of sample and the frequency separation \( \delta f \) of harmonics peaks, as

\[ \delta f \propto \frac{1}{W}. \]

Judging from this dependency, the acoustic waves are traveling in width direction. Therefore, \( d \) in Eq. (1) is corresponding...
to \( W \) and the acoustic wave velocity \( c \) is estimated as \( 7.31 \times 10^3 \) m/s.

We inspect the sample thickness dependency of the resonance signal. Samples are prepared with 9.06 mm width, 42.85 mm length and various thicknesses in the range of 0.6–0.95 mm. The magnetic field is applied parallel to the sample surface and kept to 0.6 kG, as the same as for previous measurement. Fig. 3(b) shows the dependency of resonance frequency on the sample thickness. Because the acoustic waves are traveling in width direction, the frequency should not depend on thickness. Real data show a slight dependency on thickness. We attribute the change of the resonance frequency to change of the internal strain influenced by size effect.

The resonance frequency and amplitude are measured as function of magnetic field \( H \), as shown in Fig. 4 (a) and (b), respectively. The dimension of this sample is 0.79 mm \( \times 9.06 \) mm \( \times 42.85 \) mm and the bias field is applied parallel to the sample surface. Among many peaks in Fourier transformed signal, the highest peak frequency is shown in Fig. 4(a) The increase of the resonance frequency depending on the bias field reflects the increase of stiffness of the sample. The inset in Fig. 4(a) shows the separation \( \delta f \) between the harmonics of resonance frequency versus the bias field. The harmonics of resonance frequency are measured in our measurable spectral range between 4 and 6 MHz. These data show a tendency that resonance frequencies grows rapidly at low magnetic field and becomes saturated in high magnetic field. This looks a typical behavior of a magnetization change depending on the external field. Therefore, the resonance frequency shift is affected by a mechanical strain induced by the bias field. Similar behaviors on the other kinds of magnetic samples have been reported by others, which were explained as Young’s modulus change (\( \Delta E \) effect) [12,13]. No noticeable hysteresis of the resonance frequency is found within our experimental accuracy, during increasing and decreasing the bias magnetic field. The possible reason is that the sample has very low coercivity to minimize the hysteresis loss in vibrator operation.

As shown in Fig. 4(b), the dependency of the amplitude on \( H \) shows a peak behavior at \( H = 0.7 \) kG. Similar behaviors have been found [22,12] and explained by three mechanisms coupled; Lorentz force, magnetization force, and magnetostriction [21]. Ogi suggested a theoretical model concluding that the magnetostrictive contribution is dominant [4]. We also attribute it to the field dependency of magnetostriction coefficient. As \( H \) increases, magnetic domains begin to move against its stable configuration. Once \( H \) is larger than its saturation field, the domain wall motion will disappear. Therefore, for \( H \) greater than the saturation field, the \( E \) and \( f \) do not change anymore and \( A \) decreases down to zero.

The \( f \) and \( A \) are measured, as the bias field direction is varied by rotating the teflon sample holder. The sample dimension is
Fig. 5. The bias field direction on the sample affects the resonance frequency (a) and the signal amplitude (b). $\theta$ indicates the angle between the sample and the bias field. The inset shows the dependency of $\delta f$ on the field direction.

In order to figure out the crystal structure of the sample, we performed the X-ray diffraction measurement, as shown in Fig. 6. There are three main peaks at $2\theta = 30.4, 35.8,$ and $63.1$ corresponding to $(220), (311),$ and $(440)$ of the cubic spinel structure, respectively.

Acknowledgements

This work is supported by the National Core Research Center program of the Korea Science and Engineering Foundation (KOSEF) through the NANO Systems Institute of Seoul National University.

References


[19] Ferrite magnetostrictive material (V2X \( \pi \)20), produced by TDK co. in Japan.


Biographies

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