Dynamic Magneto-mechanical Behavior of an Iron-nickel-based Ferromagnetic Alloy with Constant Elasticity

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The dynamic magneto-mechanical behaviors in a type of iron-nickel-based ferromagnetic alloy with constant elasticity were investigated as a function of both the DC bias magnetic field (H_{dc}) and the frequency. The rectangular plate-like samples were excited to vibrate at a half-wavelength, longitudinal resonance by an AC magnetic field superimposed with various H_{dc}. The experimental results found that the strain coefficient at resonance reached 819.34 nm/A and the effective mechanical quality factor (Q_m) was greater than 2000. The ratio of the maximum variation of the Young's modulus over H_{dc} to the value of the Young's modulus at a zero bias field was only ~0.83‰ because of the so-called constant elasticity. The resonant strain coefficients and Q_m are strongly dependent on H_{dc}, which indicates a promising potential for use in DC and quasistatic magnetic field sensing.

Keywords : magnetostrictive material, magneto-mechanical behavior, strain coefficient, quality factor

1. Introduction

When a ferromagnetic material is placed in magnetic field, it becomes magnetized because the magnetic moments in the material align in such a way that the net magnetic moment points in a particular direction; this realignment of the individual magnetic domains in the material also causes a shift in the material's dimensions, an effect known as magnetostriction [1]. Typical magnetostrictive materials are iron, nickel, cobalt, and their compounds or alloys, such as Fe-Ni, Fe-Co and Fe-Al [2, 3], but the effective mechanical quality factors (Q-factor) of these materials are not large [4-8]. The rare-earth-iron alloy Terfenol-D ($Tb_xDy_{1-x}Fe_y$) features giant magnetostriction and a good magneto-mechanical coupling factor, and so it has generated a great deal of interest over the past few decades. However, the mechanical Q-factor of Terfenol-D is also very small (less than 40) [9, 10], and it is difficult to machine Terfenol-D material into small size due to its brittleness.

In this paper, we discuss the dynamic magneto-mechanical behaviors in FeNi-FACE, an iron-nickel-based ferromagnetic alloy with constant elasticity which exhibits a high mechanical Q-factor and low thermal coefficients of Young's modulus and expansion. FeNi-FACE is generally used as an elastic element, a vibrator in mechanical filter, or a resonator. Recently it was discovered that FeNi-FACE exhibits a very high magnetically-induced strain coefficient at resonance. To investigate the dynamic magneto-mechanical behaviors of this material, we applied an AC magnetic field superimposed with various DC bias magnetic fields to rectangular plate-like samples of the material to cause them to vibrate in the half-wavelength ($\lambda/2$) longitudinal resonance mode, and we observed the vibration characteristics with a laser doppler vibrometer (LDV). Our experimental results show that the giant strain coefficient in FeNi-FACE results from the high Q-factor. In addition, the resonant strain coefficient and the mechanical Q-factor are strongly dependent on the DC magnetic field. With these results in hand, we discuss the potential application of the FeNi-FACE for DC and quasistatic magnetic field sensing.
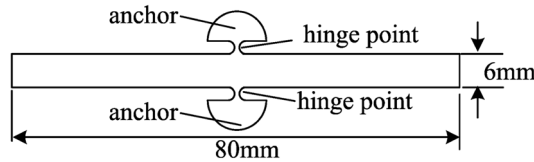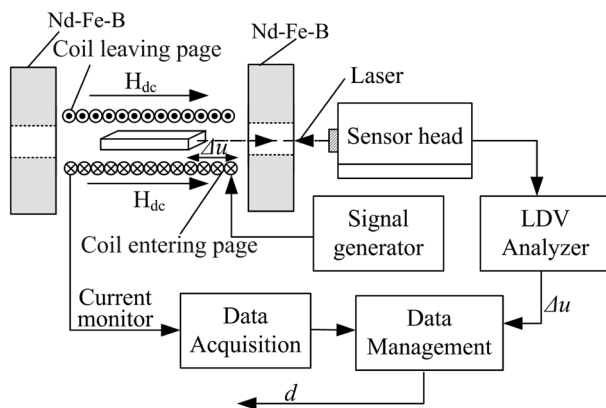
2. Experiments

Experimental data were obtained from commercially available FeNi-FACE produced by the Chongqing Instru-

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Table 1. The main components and their content percentages in the alloy.

Component	Ni	Cr	Ti	Al	C	Si	Mn	Fe
Content (%)	41.5~43	5.2~5.8	2.2~2.8	0.3~0.8	≤ 0.05	≤ 0.8	≤ 0.8	margin

Fig. 1. The architecture of the plate-like samples. The thickness (not shown) is 0.6 mm.

Fig. 2. The experimental setup.

ment Materials Research Institute in China. The main components of the alloy are shown in Table 1. FeNi-FACE is a precipitation-hardening alloy. It is provided in the form of ribbons, which for the purpose of this experiment were cut into rectangular plates 6 mm wide, 80 mm long, and 0.6 mm thick, as shown in Fig. 1. At the middle of each rectangular plate were two anchors connected to the plate with micro-hinges, which were integrally machined so as to minimize energy loss to the support mechanism.

The experimental setup for investigating the dynamic magneto-mechanical behavior is shown in Fig. 2. The samples were placed at the center of a long, straight solenoid which generated a small AC magnetic field (H_{ac}). A bias DC magnetic field (H_{dc}) was generated with a pair of annular permanent magnets (Nd-Fe-B), and it was measured with a Gauss meter. H_{dc} and H_{ac} were applied along the longitudinal direction of the samples. During the experiments, the samples were driven to vibrate around the $\lambda/2$ longitudinal resonance by H_{ac} superimposed with H_{dc}. The vibrational displacement at the end faces of the samples was measured with an LDV (Polytec OFV-5000, Germany). The experiments were carried out at room temperature and ambient pressure.

3. Results and Discussion

In the $\lambda/2$ longitudinal resonance mode, the strain coefficient of the samples can be calculated by [11]

$$d = \frac{\Delta \varepsilon}{\Delta H} \tag{1}$$

where $\varepsilon = 2\Delta u/l$ is the magnetically induced strain, H is the magnitude of the exciting magnetic field, Δu is the magnetically induced longitudinal displacement measured by the LDV, and l is the undeformed length of the sample.

Fig. 3 shows the measured strain coefficient as a function of frequency (strain coefficient spectra) for a typical sample near resonance under a magnetic field H_{dc}=35Oe. The strain coefficient is found to be 802.5 nm/A at the resonance frequency of ~30.650 kHz. The effective mechanical Q-factor (Q_m) of the FeNi-FACE plate is given by

$$Q_m = f_r/\Delta f, \tag{2}$$

where f_r is the resonance frequency and Δf is the 3-dB bandwidth, observed from the strain coefficient spectrum. From Eq. (2), we find the Q_m of the FeNi-FACE sample to be 2270 at $H_{dc} = 35$Oe. The strain coefficient at resonance is much greater than that of Terfenol-D [10], which is due to the fact that the Q_m of the FeNi-FACE is much greater than that of the Terfenol-D. Compared with the static strain coefficient (piezomagnetic coefficient), the strain coefficient at resonance is magnified by the factor of Q_m. In other words, the resonant strain coefficient is directly proportional to the product of Q_m and the piezomagnetic coefficient [9].

Fig. 4 shows the resonant strain coefficient and the
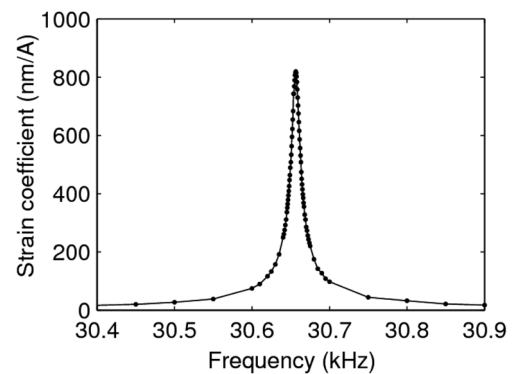
Fig. 3. Strain coefficient spectrum for a typical sample around the resonance.
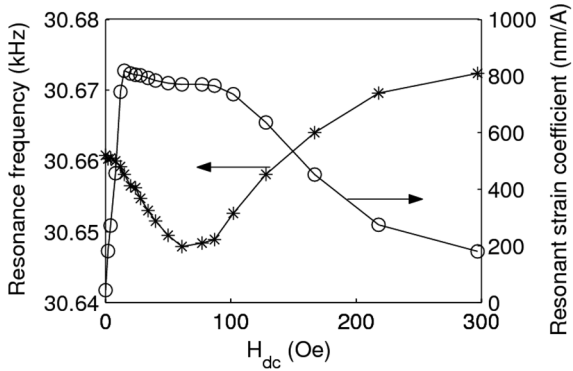
Fig. 4. The resonant strain coefficient and the resonance frequency of the sample as a function of the DC bias magnetic field.

resonance frequency of the sample versus H_{dc}. The H_{dc} dependence of the resonant strain coefficient results from the H_{dc} dependence of the piezomagnetic coefficient. In general, with increasing H_{dc} the piezomagnetic coefficient of a magnetostrictive material increases up to a certain maximum and then decreases. From Fig. 4, we can see that the resonant strain coefficient has an almost flat response versus H_{dc} in the range from 1Oe to 9Oe, which indicates a wide range of optimal H_{dc}. This can be understood as a result of the dependence of Q_m on H_{dc} (as shown in Fig. 5). As indicated in Fig. 5, the value of Q_m varies according to the strain coefficient spectra under various H_{dc}. In contrast to the pattern of change of the piezomagnetic coefficient, as H_{dc} increases, Q_m first decreases until it reaches a certain minimum and then increases past that point. Taking into consideration the fact that the resonant strain coefficient is directly proportional to the product of Q_m and the piezomagnetic coefficient, it is easy to understand the almost flat response characteristic. As Fig. 5 shows, Q_m strongly depends on H_{dc}. At its point of maximum variation, Q_m is only 0.4 of
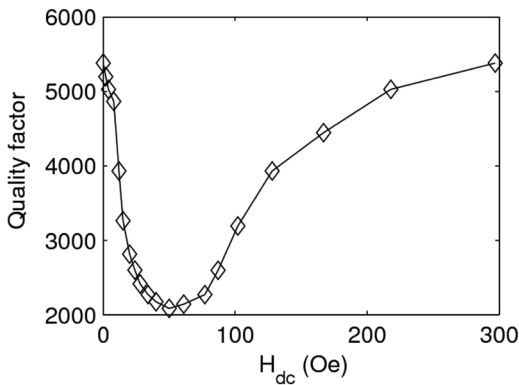
the value of Q_m at zero bias field, and the differential of Q_m with respect to H_{dc} is significantly large.

We can also see from Fig. 4 that the resonance frequency of the sample depends on H_{dc}, which can be explained by ΔE effect [1]. The Young's modulus of FeNi-FACE under various H_{dc} can be derived from the resonance frequency. In the $\lambda/2$ longitudinal resonance mode, the mechanical resonance frequency is given by
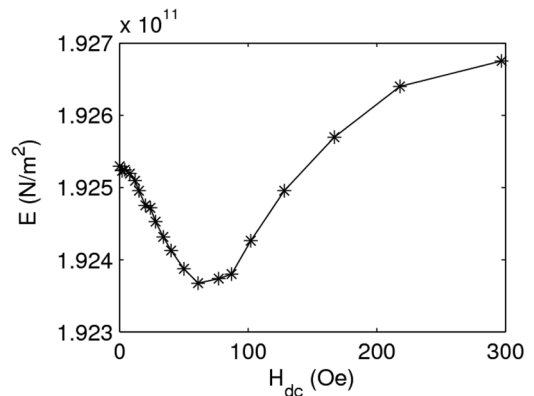
$$f_r = \frac{1}{2l}\sqrt{\frac{E}{\rho}} \qquad (3)$$

where $\rho = 8000$ kg/m³ is the density of FeNi-FACE and E is the Young's modulus at a constant magnetic field along the longitudinal direction. From Eq. (3), we see that the Young's modulus of FeNi-FACE is given by

$$E = 4(f_r l)^2 \rho \qquad (4)$$

Using the data shown in Fig. 4, we calculate the dependence of Young's modulus on H_{dc}, and the results are shown in Fig. 6. As the alloy is a so-called constant-elasticity alloy, the ΔE effect is intrinsically small. As shown in Fig. 6, the maximum variation of Young's modulus as H_{dc} changes is only 0.83‰ of the value of the Young's modulus at zero bias field. This characteristic creates high-frequency stability when the FeNi-FACE is used to make a magnetically excited mechanical resonator.

It can be seen from Figs. 5 and 6 that the Q_m and Young's modulus change in similar ways with H_{dc}, while the resonant strain coefficient changes in the opposite direction. This can be explained by phenomenological theory, as follows. The Q-factor is an inverse measure of damping in a material (or system). The damping arises from the magnetostrictive stress-strain hysteresis loop which is caused by the irreversible motion of magnetic domains and domain walls [12, 13]. The shapes and areas of the stress-strain hysteresis loops depend on H_{dc} because


Fig. 5. The effective mechanical Q-factor of the sample as a function of the DC bias magnetic field.

Fig. 6. The Young's modulus of the sample as a function of the DC bias magnetic field.

of the various domain magnetizing behaviors under various values of H_{dc}. This means that the magneto-mechanical damping depends on the DC magnetic field. This hysteresis-related damping has a great influence on Q_m. The fact that the Young's modulus and the piezomagnetic coefficient depend on H_{dc} can also be traced to the different domain magnetizing behavior under various values of H_{dc} [10]. At low magnetic field values, only the domain-wall movement occurs, i.e., the magnetic domains whose moments align with the field grow at the expense of the domains that are not aligned with the field. This results in an initial increase in piezomagnetic coefficient as well as an initial decrease in the Young's modulus as H_{dc} increases. When the H_{dc} is increased further, domain rotation occurs, and the magnetic moments within domains rotate into the easy magnetizing axis closest to the field direction. When H_{dc} is near the so-called "burst region," the rotation of the domains is at a maximum, and the material reaches a maximum piezomagnetic coefficient and a minimum Young's modulus. At higher fields, almost all of the magnetic moments rotate to align with the direction of external field, and rotating the domains becomes difficult, which causes the Young's modulus to increase with increasing H_{dc} and the piezomagnetic coefficient to decrease with increasing H_{dc}. The motion of the domain is the major contributor to hysteresis loss. At low and high magnetic field levels, the domain motion is inhibited, but at moderate field intensities the domain moves actively, especially in the burst region. Thus, as H_{dc} increases, Q_m decreases at first, up to a certain minimum, and then increases beyond that point.

FeNi-FACE is a potentially feasible material for use in high-sensitivity DC or quasistatic magnetic field sensors. One approach would be to fabricate a magnetoelectric (ME) laminated resonator by combining a piezoelectric material with FeNi-FACE. Since the strain coefficient is intrinsically dependent on H_{dc}, such a resonator could detect a small H_{dc} signal by using the operational mode proposed in Ref. [14]. In a result that will be reported elsewhere, we have demonstrated that the ME sensitivity of the ME voltage to H_{dc} achieves 84 mV/Oe under the resonant drive of a 0.1-Oe AC magnetic field.

Another possible approach would be to fabricate a composite sensor composed of a piezoelectric transformer with FeNi-FACE attached to it on either side (i.e., composite piezoelectric transformer, CPT), as illustrated in Fig. 7. Because of the H_{dc} dependence of the effective mechanical Q-factor Q_m in FeNi-FCEA, the loss in the CPT would be dependent on H_{dc}. In turn, the output V_{out} of the CPT would depend on H_{dc}. Thus the CPT has the potential to detect small H_{dc} by applying a constant
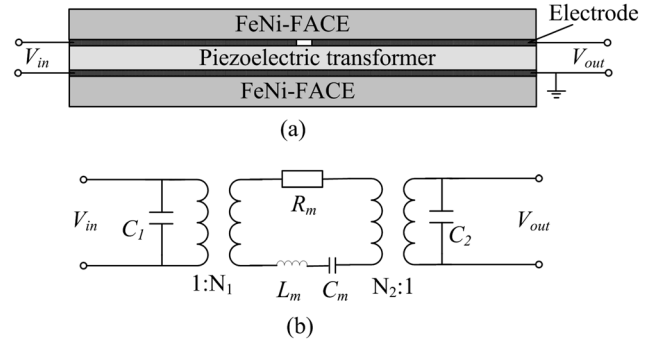
Fig. 7. A piezoelectric transformer with FeNi-FACE for use in DC magnetic field detection: (a) the configuration of the composite transformer, and (b) the equivalent circuit of the transformer. R_m is a lumped representation of all the viscous losses in the CPT. C_m and L_m are the electric analogs of the effective mechanical spring constant and the mass or inertia of the transformer, respectively. N_1 and N_2 are elasto-electric coupling factors, and C_1 and C_2 are clamped capacitance in the input and output terminal respectively.

voltage V_{in} to the input terminal of the CPT. Compared with the method in Ref. [14], this method has the merit of being coil-less.

From the equivalent circuit in Fig. 7(b), we can show that the resonant gain of the transformer is directly proportional to the effective mechanical Q-factor Q_{eff} of the composite. This gives

$$V_{out} = \beta Q_{eff} V_{in}, \tag{5}$$

where β is a coefficient related to the parameters of the piezoelectric material and of FeNi-FACE. The effective mechanical Q-factor of the CPT Q_{eff} can be given by [15]

$$\frac{1}{Q_{eff}} = \frac{n}{Q_m} + \frac{1-n}{Q_p}, \tag{6}$$

where Q_m is the effective mechanical Q-factor of FeNi-FACE, Q_p is the effective mechanical Q-factor of the piezoelectric material, and n is the volume ratio of FeNi-FACE in the CPT.

Combining (5) and (6) and differentiating V_{out} with respect to H_{dc}, we obtain

$$\frac{\partial V_{out}}{\partial H_{dc}} = \beta \beta' V_{in} \frac{\partial Q_m}{\partial H_{dc}}, \tag{7}$$

where $\beta' = \dfrac{n}{[n + (1-n)\gamma]^2}$, $\gamma = Q_m / Q_p$.

If a piezoelectric quartz crystal with a high Q-factor ($>10^5$) is used for the piezoelectric transformer element in the CPT, then $\gamma < 1$. In this case, it is reasonable to assume that β' has little influence on the H_{dc} dependence

of the detection sensitivity under the optimal parameter n. The CPT should then show high sensitivity to small changes of H_{dc} because of the strong H_{dc} dependence of Q_m.

4. Conclusion

We investigated the dynamic magneto-mechanical behaviors in FeNi-FACE relative to both the DC bias magnetic field (H_{dc}) and the frequency of the AC magnetic field (H_{ac}). The FeNi-FACE displayed a significantly high strain coefficient at resonance and a large effective mechanical Q-factor. Both the strain coefficient at resonance and the effective mechanical Q-factor are strongly dependent on the bias magnetic field. These properties are promising for use in magnetic field sensing.

Acknowledgment

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References

[1] G. Engdahl, Magnetostrictive Materials Handbook, San Diego:Academic Press (2000).

[2] Y. Kikuchi, IEEE Trans. Magn. **Mag-4**, 107 (1968).

[3] IEEE Standard on Magnetostrictive Materials: Piezomagnetic Nomenclature, IEEE std. 319, (1990).

[4] V. F. Coronel and D. N. Beshers, J. Appl. Phys. **64**, 2006 (1988).

[5] D. P. Petarra and D. N. Beshers, J. Appl. Phys. **34**, 2739 (1963).

[6] B. F. Rothenstein and Q. F. G. Aczel, J. Appl. Phys. **40**, 4675 (1969).

[7] J. Robert Birchak and George W. Smith, J. Appl. Phys. **43**, 1238 (1972).

[8] A. Karimi, Ch. Azcoitia, and J. Degauque, J. Magn. Magn. Mater. **215-216**, 601 (2000).

[9] F. Claeyssen, N. Lhermet, R. Le Letty, and P. Bouchilloux, J. Alloys Comp. **258**, 61 (1997).

[10] S. W. Or, N. Nersessian, and G. P. Carman, Proc. SPIE, **4699**, 451 (2002).

[11] S. W. Or, C. S. Yung, and C. Y. Lo, IEEE Trans. Magn. **42**, 47(2006).

[12] D. P. Bultea and R. A. Langman, J. Magn. Magn. Mater. **251**, 229 (2002).

[13] K. B. Hathaway, A. E. Clark, and J. P. Teter, Metall. Mater. Trans. A **26A**, 2797 (1995).

[14] S. X. Dong, J. Y. Zhai, J. F. Li, and D. Viehland, Appl. Phys. Lett. **88**, 082907 (2006).

[15] F. Yang, Y. M. Wen, P. Li, M. Zheng, and L. X. Bian, Sens. Actuators A **141**, 129 (2008).