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Abstract

The coupling between the self-generated magnetic and acoustic behavior of magnetostrictive materials under load is explored. Results from experimental fatigue loading of a strongly magnetostrictive ferromagnetic material, Terfenol-D, suggests that the acoustic response is sensitive to internal stress rates. The ability of the acoustic signal to travel beyond the magnetic behavior that created it, suggests an ability to measure this behavior remotely. The hypothesis is that this noise is related to piezomagnetic behavior (Villari Effect). Understanding the sources of this noise could yield a unique method for characterizing the early damage state of ferromagnetic materials and become the basis for smart sensor materials for characterizing structures.

Keywords: piezomagnetic, magnetostrictive, acoustic emission, damage state

1. Introduction

For decades, acoustic emission (AE) measurements in ferromagnetic materials have been plagued by noises that do not appear in AE measurements made in other metals. This effect can make the detection of specific crack growth problematic. These noise sources have been attributed to magnetic strain effects [1] but have been generally ignored or suppressed as they interfere with the main focus of the AE testing (crack growth). This is logical since the current mindset and most engineering design is based on a definition of "damage" to be macroscopic flaws and cracks. As materials, designs, and manufacturing methods have progressed, the aerospace field has been actively investigating these improved structural design methods for ways to reduce mass while increasing strength, which has driven the size of a "critical flaw" to smaller and smaller sizes. As the critical flaw size shrinks, the distinction between inhomogeneity and defect may eventually become blurred. This requirement to detect smaller defects is a challenge for testing technologies and is a driver for developing new, more capable techniques.

This paper presents an initial investigation of the phenomenon of stress generated ultrasonic noise in magneto-elastic materials, which could lead to interesting measurement processes. Further, it may be possible to treat magneto-elastic materials as a viable smart material system that can characterize dynamic behavior as well as possibly identify early failure onset. As this method arises from stress-generated ultrasonic noise in ferromagnetic materials, one can refer to this effect as a piezo-magnetic acoustic effect (PMAE).

The basis of this method derives from two coexisting processes that exist in magneto-elastic materials along with the hypothesis that the effect of these processes will generate ultrasonic noise. The first process is related to piezo-magnetism, also known as the Villari Effect (VE) [2, 3], which states that the application of stress will affect a magneto-elastic material’s magnetic permeability. The second effect is that a magneto-elastic material’s magnetic permeability will change locally in a discontinuous manner. This latter effect is the well-known cause of Barkausen Noise (BN) [4,
Similarly, this electrical noise also has a mechanical corollary that manifests itself as acoustic noise called, Magnetic Acoustic Emission (MAE) [6-10]. Both Barkhausen Noise and Magnetic Acoustic Emission require a magnetic field to induce the effect measured (see Fig. 1a). In addition, typical applications of the Villari Effect that measure stress (see Fig. 1b), also magnetize the magneto-elastic material to affect their measurements. In contrast, the concept explored in this manuscript, the PMAE method is generated by stress effects within the material without the application of magnetic fields, (see Fig. 2), which in some applications will simplify the measurement equipment and method.

2. Background

Generally, quantitative dynamic stress/strain measurements are challenging to perform and the available measurement processes may be too limited for the purpose of addressing high rate measurements needs. It is common knowledge that most methods for measuring dynamic strain and stress states, in use today, have their limitations. For example, conventional methods for measuring stress in materials such as strain gages, LVDT sensors, and extensometers (mechanical and Doppler) tend to be limited to the surface, are very local and, while accurate at near DC frequencies, they are not used for high stress rate measurements. Fiber-Optic Bragg Grating (FBG) sensors are still very slow in their response function characteristics as well as their sensitivity levels. Methods such as Digital Image Correlation (DIC) and optical interferometer can achieve higher bandwidth measurements, but are limited by camera speeds and are basically an exposed surface monitoring system, and thus they can’t measure the interior of the structure directly or in regions that are hidden from view.
Piezoelectric based sensors (accelerometers, AE sensors, and ultrasonic sensors) that have been incorporated into laboratory systems (Split-Hopkinson pressure bar, Charpy impact machines, Kolsky bar type configuration, adiabatic shear band experiments in materials, Taylor impact and other types of impact experiment, and Shock Wave Experiments) have been successful in measuring high stress rates. Such piezoelectric sensors generally only make sensible measurements in very controlled geometry. They are not yet appropriate for complex structures in the field.

It is not clear if any of the methods for high stress rate measurements would be applicable to addressing structural health monitoring processes or integrated vehicle health monitoring environments. Generally, popular advanced IVHM systems are based on piezoelectric sensors or FBG networks. The FBG gratings systems being tested are very low frequency and are unable to accommodate high bandwidth measurements. Many of the recent commercial IVHM systems commonly use an array of piezoelectric sensors in a ‘pitch-catch’ or ‘pulse-echo’ configuration to try to detect and locate damage. These techniques require transmission circuitry and, of course, significant damage must already exist for it to be detected. Similarly, piezoelectric sensors can be used to listen for acoustic emission from brittle crack growth. Even NASA’s space shuttle employed a piezoelectric impact detection system on the orbiter wing’s leading edge after the Columbia accident. [11]

3. Theory

As noted in the introduction, the basis of this method derives from two coexisting processes that exist in magneto-elastic materials, combining to generate ultrasonic noise: piezo-magnetism (VE) and a local discontinuous change of magneto-elastic material’s magnetic permeability (as seen in BN and MAE).

A general time rate model for magnetostrictive materials was presented by Jiles [12] and by Dapino and [13, 14], which can be expressed as

![Figure 2 Schematic of the PiezoMagnetic Acoustic Effect](image)
Where $H$ is the external magnetic field, $M$ is the magnetization of the sample, and $\sigma$ is the stress. For the case where $H$ is constant, such as in the Villari process, the first term on the right is zero, which gives

$$\frac{\partial M(\sigma)}{\partial t} = \left( \frac{\partial M}{\partial \sigma} \right) \frac{\partial \sigma}{\partial t} + \left( \frac{\partial M}{\partial H} \right) \frac{\partial H}{\partial t}. \quad (1)$$

or, inversely,

$$\frac{\partial \sigma}{\partial t} = \frac{1}{M} \frac{\partial M(\sigma)}{\partial t} \left( \frac{\partial \sigma}{\partial M} \right)_H. \quad (2)$$

This equation suggests that the stress rate may be measured through the terms $\partial M/\partial t$ and $\partial \sigma/\partial M$. If these terms generate noise by internal magnetic domain de-pinning as the stress is varied, then the detected noise will be stress rate related. This is distinctly different than BN and MAE, where $H$ is a time varying function and $\sigma$ is constant so that

$$\frac{\partial M(H,\sigma)}{\partial t} = \left( \frac{\partial M}{\partial H} \right) \frac{\partial H}{\partial t} + \left( \frac{\partial M}{\partial \sigma} \right) \frac{\partial \sigma}{\partial t}. \quad (3)$$

In Equation 3, for the case being studied here the time dependence of $M$ is related to the rate changes of the magnetic permeability, which reflects a material’s magnetic domain organization. We hypothesize that a source of detectable noise will originate from the pinned magnetic domains undergoing discontinuous jumps, which is the same argument for the source of MAE. The more jumps that occur per second, the louder the sound. Since the individual noises arising from jumping events are not expected to be in phase with each other, the sound’s intensity should increase as the square root of the de-pinning jump rate. That rate is moderated by the fact that the distribution of pinning energies is most likely complex. If the distributions of pinning energies were flat, then it would be expected that the noise levels would be proportional to $\sqrt{\left( \frac{\partial M}{\partial t} \right)}$. The other term, $(\partial \sigma/\partial M)$ is related to the piezo-magnetic or Villari effect.

In Equation 3, $M$ can depend on many effects such as reversible and irreversible magnetic effects as well as hysteresis magnetization effects. Dapino, et al [14] used a model for the magnetization pinning based on a phenomenological model by Jiles [12] to derive such terms for the piezo-magnetic effect. In our case, for $H \approx 0$ and $\partial H/\partial t = 0$, the following relationship can be derived:
\[
\frac{\partial \sigma}{\partial t} = \frac{\partial M(t)}{\partial t} \left( \frac{1}{(1-c) \frac{\sigma(t)}{E\xi}(M_{an}(t)-M_{irr}(t))+c\frac{\partial M_{an}(t)}{\partial \sigma}} \right),
\]

where \(c\) is a factor that relates to the bulging of a magnetic domain wall just prior to its jump, \(E\) is Young’s modulus, \(\xi\) is an energy density coefficient, \(M_{an}(t)\) is the anhysteretic magnetization, \(M_{irr}(t)\) is the irreversible magnetization. If the external \(H\) field is zero, the \(M_{an}(t)\) is related to local magnetization effects in a material. The \(M_{irr}(t)\) is the part of the magnetic fields that are due to dissipative effect of the hysteresis. In effect, our calibration method measures this complex function and accounts for the distribution of pinning energies that affect the measured sound.

4. Experimental Testing

The functional testing involves a set up similar to the one suggested in Figure 3a. During normal operations of a structure or with a part under testing, the stress rate related noise from the structure is monitored using a typical broadband piezoelectric sensor. The signal from the transducer is amplified. The operational blocks for the power meter and recording were performed by digitizing the signal and converting the result to a signal energy value:

\[
\text{Signal Energy} = \sum_{i=1}^{n} V_i^2 \Delta t \quad (6)
\]

The system was set up to record waveforms at intervals of 0.025 seconds. At each interval, 102.4 microseconds of waveform were digitized at a sampling rate of 10 MHz.

The results presented here are from Terfenol-D, an iron alloy material that was chosen for its large magnetostrictive behavior. Since Terfenol–D is very brittle, the loading was performed in the compressive regime using a hydraulic load frame. The compression loading cycles ensured that the testing was tracking changes in the elastic regime. As seen in figure 3b, the Terfenol-D specimen, in the form of a right rectangular prism approximately 0.25” x 0.25” x 0.75”, was loaded across the short dimension. Potential magnetic materials were avoided in the setup to reduce the potential for external piezomagnetic acoustic emissions. To obtain uniform stress and improve grip noise isolation in the sample, the compression platen had a layer of rubber placed between the steel platen and two pairs of 1” diam. x 0.5” optical quality flat quartz plates, which ensured the sample was held flat and parallel without any canting of the jigs. There was an additional set of 0.5” diam. by 0.25” optical quality flat quartz plates that could compress the central part of the Terfenol-D sample, while accommodating the attachment of AE sensors at each end of the sample. The sensors were clamped to the ends of the sample with a simple plastic “C”-clamp and acoustically coupled to the specimen with coupling gel. Both sensors are considered resonant with high sensitivity. One has a center frequency of 250 kHz with 100-500 kHz bandwidth, and the other, 325 kHz center with 250-1000 kHz bandwidth. Even with the different frequency sensitivity of the two sensors, the results from each are very similar, so the results from only one are presented. The tests were conducted in load control so there was an increased displacement of the loading platen not indicative of the strain in the specimen. While displacement clip gauges could be used to measure
gauge section displacement, they were not used for these first tests to reduce the introduction of noise. For that reason, this data is presented as a function of applied stress.

To test for the level of machine-induced noises, an aluminum sample was tested and the background noise levels were recorded to verify that the machine noise levels were a minor effect. The noises that were measured with the aluminum sample were greatest at the points in the load cycle of maximum strain (minimum strain rate). During typical loading of the Terfenol-D samples the variations of the piezomagnetic noise was recorded and the cyclic noise pattern was tracked over a series of repeated loading cycles. The experimental protocol presented here utilized loading frequencies of 1 Hz. The peak load ranges were varied between 50 psi to 10,000 psi of compressive stress. The maximum peak load was kept below the material’s reported compressive strength of approximately 100,000 psi. However, during testing, there were still occasional large amplitude signals with the characteristics of traditional AE crack-like signals that indicated irreversible damage as the sample was fatigued. These types of AE signals were filtered out during data reduction.

5. Results

Figure 4 shows the output of the method as a function of the compressive loading. The solid black line is the load profile. Each red dot represents the energy calculated (see Equation 6) from sequential time windows of the noise signal yielding 40 energy measurements per load cycle. The raw energy profile has been smoothed with Savitzky-Golay time-domain smoothing, a least squares polynomial fit across a moving window within the data, creating the resultant energy profile in Figure 4.
In our testing, the similarity in the noise levels from cycle to cycle indicates reversible microstructural processes. Figure 5 is the behavior of an “average” cycle where each dot represents the average of the calculated signal energy from all waveforms collected at the same phase points.

Figure 4 Load profile and resulting stress noise data for one set of fatigue cycles

Red error bars of one standard deviation are included to further illustrate the repeatability of the behavior from cycle to cycle. The signal energy falls to minimum values near the nadir and...

Figure 5 Stress Noise Energy
maximum points in the loading, at 0.0 and 0.5 seconds, respectively, illustrating that the method is not proportional to the loading. In contrast, the maximum levels of the signals align more with the derivative of the cyclic load, which correspond to the maximum stress rates at approximately 0.3 and 0.8 seconds. The fact that the minimums and maximums do not align exactly at the noted locations may be attributed to hysteresis of the magnetic permeability of the material.

In these tests, by changing the compressive peak loads, at a constant cyclic frequency, different maximum stress rates are realized. The result is illustrated in Figure 6, which is a plot of maximum stress noise energy vs peak “average” stress rate (a la Figure 5). Each data point is from a set of similar fatigue cycles (same peak load) so the error bars of one standard deviation represent the variation in the peak over the cycles of the set. They again illustrate the repeatability of this behavior. As the stress rate increases, the signals show increasing noise intensity. For this test method, plots with different parameters such as RMS values look similar because the loading is sinusoidal. However for realistic stochastic fatigue, different parameters may be used to maximize sensitivity to particular effects. It was expected that the intensity of the signals derived from the noise levels will increase as the square root of the stress rate, which would be the case if domain pinning was the source of the noise and the domain pinning was being released randomly. In the case of these tests the greatest noise levels are evident in Figure 5 during the off loading part of a cycle as the stress is returning to zero. This suggests a large release of domain pinning during that part of the cycle. Results at smaller fatigue ranges, not shown here, have maximum noise energies with comparable heights that align closer to the points of maximum stress rates, possibly indicating less interaction with microstructure and that pinning energy distribution over strain, is not uniform.

Figure 6 Shows the relationship between the Maximum Stress Noise Energy vs. Maximum Stress Rate measured in a sample of Terfenol-D that underwent cyclic compressive loading.
6. Summary and Conclusions

Results from experimental fatigue loading of a strongly magnetostrictive ferromagnetic material, Terfenol-D, suggests that tracking energy of the acoustic response in a stress regime below failure can be used to measure stress rates. It is also suggested that this acoustic response is due to the magnetostrictive properties of ferromagnetic materials and, as such, should be available in structural steel and nickel alloys. This acoustic response occurs without an expressly applied magnetic field suggesting that the same properties measured by other techniques, which require applied magnetic fields, can be measured with less complex equipment. Deviations from expected behavior suggests that measurement of these deviations may be sensitive to changes that are precursors to damage and subsequent failure. These measurements can be made remotely because the acoustic signal can propagate away from the source with significantly less attenuation than the suggested magnetic behavior that created it.

Directly, this method will be able to provide a new method for monitoring a material’s stress rate, without having to measure its stress directly. This can be done whether the material is undergoing plain stress or plain strain testing configuration. Applications could include structures undergoing flutter or oscillations, vehicle crash performance, material yielding, and possibly impact/ballistic response, where high strain rate effects are of concern regarding the strength of these materials. It will be useful as a method of monitoring ductile material for tearing and failure precursors as those material events can involve rapidly changing local stress states. In appropriate applications, remote detection and location of high strain rate events that can predict pending damage in unexpected locations and at unexpected times should allow better structural management and safety. In general, the method can also have relevance to measuring dynamic stress concentration factors in ferrous materials. This method could be extended to non-magnetic materials, such as composites, by the embedding of the magneto-elastic materials. In fact, the method could be applied to the application of composite repair patches on aircraft where the certification of composite patches is problematic and incorporation of this concept will allow monitoring the integrity of the patch.

References