Acoustic Response of the Villari Effect for Measuring Dynamic Material Behavior:

PiezoMagnetic Acoustic Effect

Michael R Horne
National Institute of Aerospace Hampton VA
Eric I Madaras
NASA Langley Research Center

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Outline

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Objective and Hypothesis

The objective is to explore the coupling between self-generated magnetic and acoustic behavior of magnetostrictive materials under load.

The hypothesis is that acoustic noise can be detected when a varying stress is applied to a magnetostrictive material. The basis of this hypothesis is related to:

- Piezomagnetic behavior (Villari Effect, where stress changes magnetic permeability)
- Magnetic domain motion interacting with microstructure (Barkhausen noise and MagnetoAcoustic Emission)

Understanding the sources of this noise could yield a unique method for measuring stress rates, characterizing magnetic materials, and the early damage state of ferromagnetic materials. This could become the basis for smart sensor materials for characterizing structures.

Current Practice

While measuring stress and strain is foundational for engineering design, measuring stress rates are also fundamental to engineering design.

Strain sensor techniques:

Resistive strain gauges, Fiber optics,
Barkhausen noise (magnetic noise via cyclic magnetic field)

Full field techniques:

Image correlation, Laser speckle, Laser Vibrometry:

Stress Rates:

Piezoelectric based sensors (accelerometers, AE sensors, and ultrasonic sensors) in Split-Hopkinson pressure bar, Charpy impact machines, Kolsky bar type configuration, Taylor other types of impact experiment, and Shock Wave Experiments have been successful in measuring high stress rates in very controlled geometry

Common problems with existing techniques:

- Primarily surface measurement only,
- Limited dynamic capability, or
- Not IVHM-ready

Background: Acoustic Emission

- Traditional Acoustic Emission (AE) is the acoustic response of a structure under load and is not repeatable.
- AE event rates are related to the stress magnitude (Kaiser effect).
- Monitoring AE of structural steels has always had a “background noise floor”:
  - It interferes with indications of crack growth.
  - Test equipment set to ignore background noise can miss crack growth events.

In current practice, much effort goes to throwing away this background noise.

Theory

A general time behavioral model for magnetostrictive materials, where M = magnetization of the material, H = applied magnetic field, σ = stress, and t = time is given by:

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

For PMAE, H is constant. For $H \sim 0$, M is internal local field.

Solving for $\partial\sigma/\partial t$:

$$\frac{\partial \sigma}{\partial t} = \frac{\partial M(\sigma)}{\partial t}\left(\frac{\partial \sigma}{\partial M}\right)_H$$

This suggests that stress rate can be measured from $\partial M/\partial t$ and $\partial\sigma/\partial M$

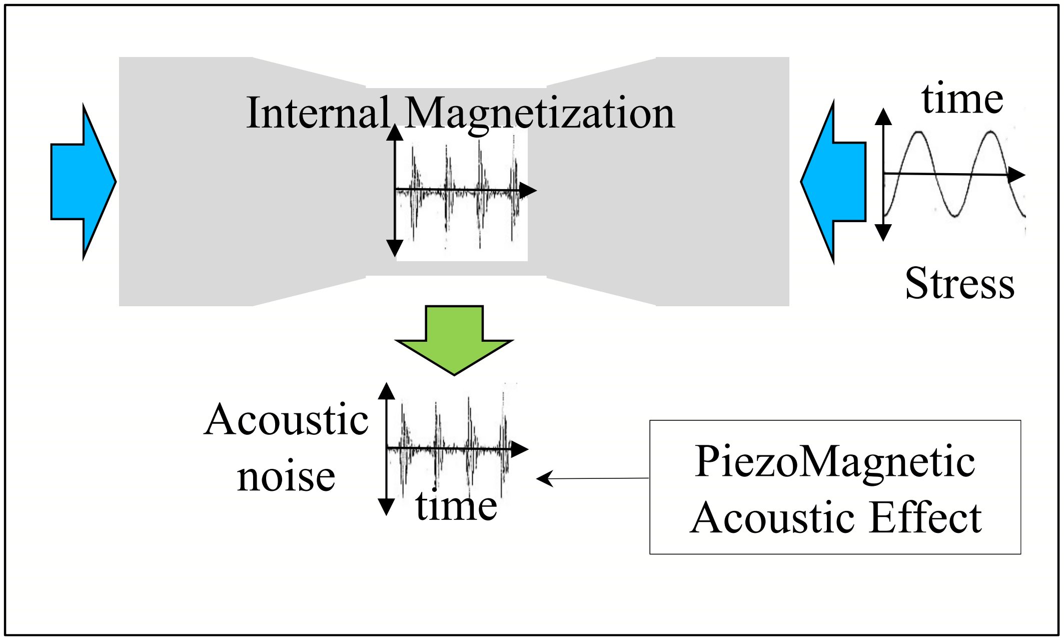
- $\partial M/\partial t$ is related to discontinuous pinning/unpinning of magnetic domains with micro-structure, thus related to pinning energy distribution over strain, and is repeatable
- $\partial\sigma/\partial M$ is related to PiezoMagnetic Effect (VE) or more correct the inverse, Magnetostriction

For BE and MAE, H is a time varying function and σ is typically has to held constant for accurate measurement, hence does not measure the stress rate.

Hypothesis: As the stress is changed, magnetic domain walls jump to reduce internal energy. Jumps (momentary stress discontinuity) can create a stress wave. Multiple jumps would look like acoustic noise. By measuring this acoustic noise, we should be able to measure stress rates

PiezoMagnetic Acoustic Effect

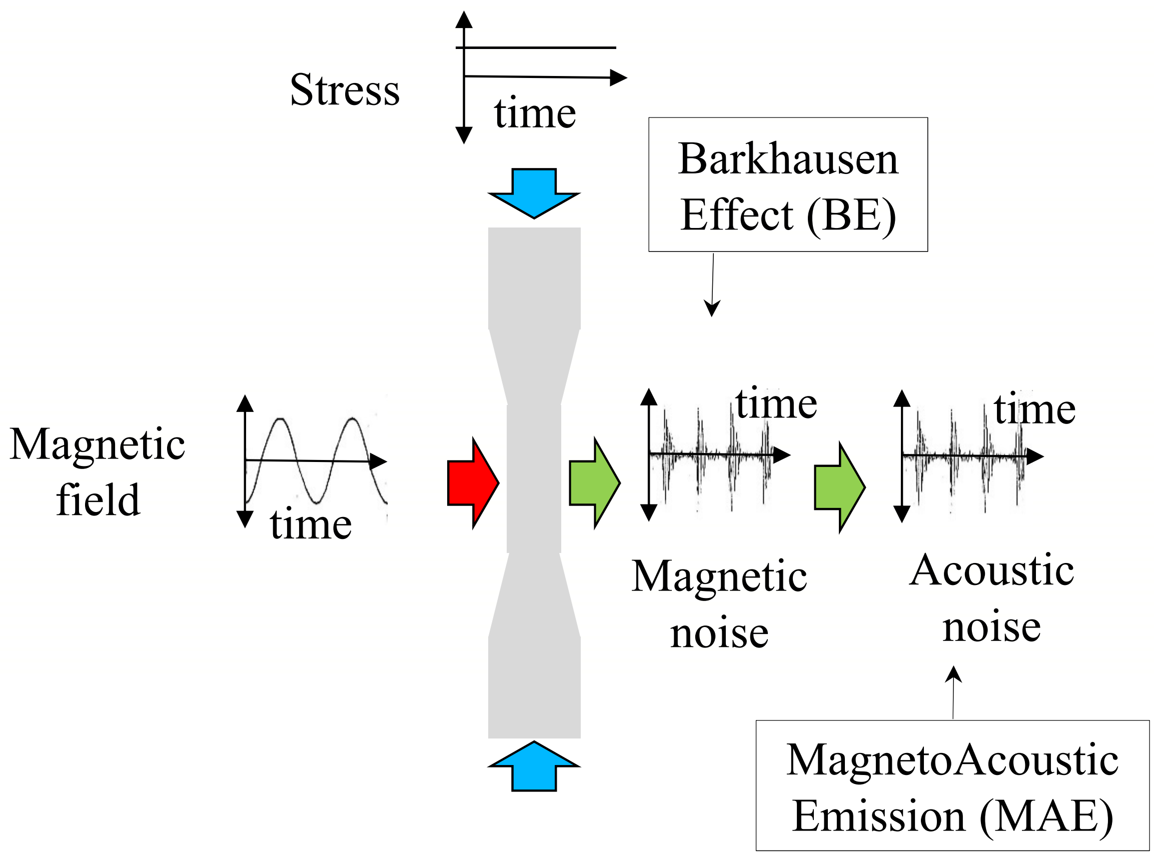
No applied magnetic field



Measurements are made in a synchronous manner, not asynchronously triggered like in conventional AE.

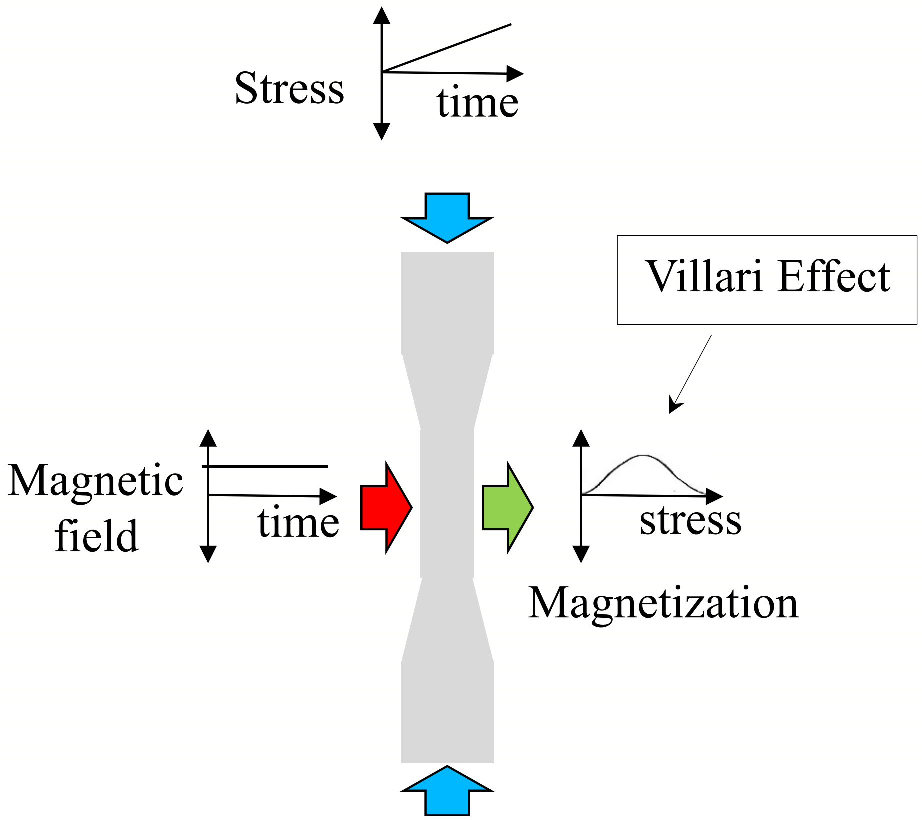
Corollary Techniques: Barkhausen and MagnetoAcoustic Emission

Interaction of moving magnetic domain walls and microstructure driven by a external magnetic field is not proportional to stress rate.



Corollary Techniques: Villari Effect Based Sensors

Stress driven change in global magnetic permeability or susceptibility

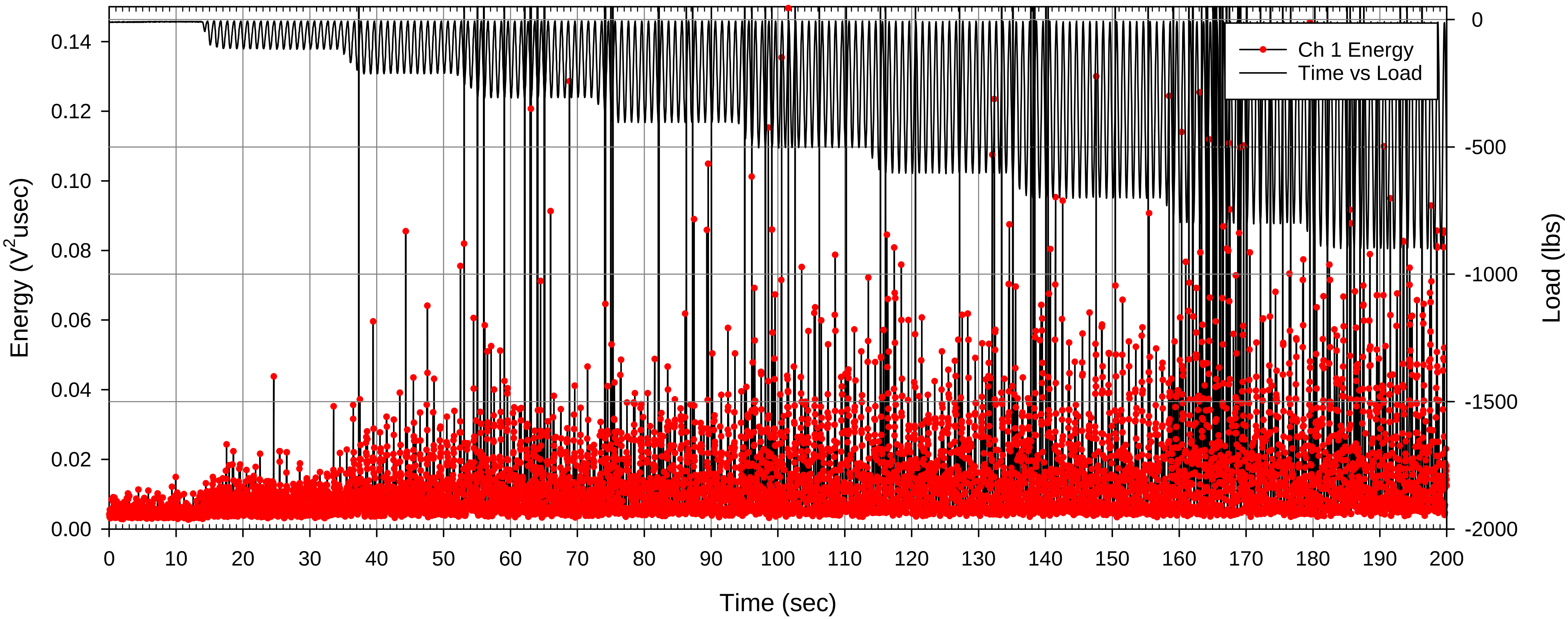


Current State of Research: Stress Noise Energy of Terfenol-D

Red Sensor: 250 kHz resonant (100-500 kHz bandwidth)

Compression fatigue tests of Terfenol-D:

- Stepped Increases in peak load
- Collected stress noise, regardless of amplitude.



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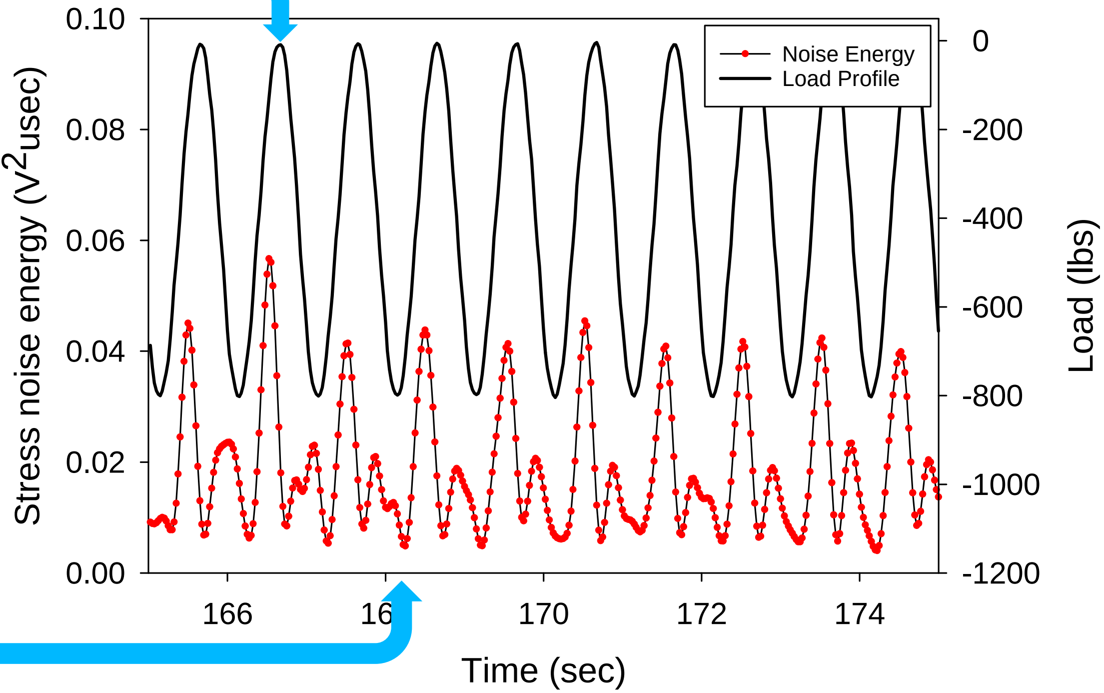
Fatigue load profile



Stress Noise energy during a fatigue "step" (10 cycles): Post- Filtered and Smoothed

Note:

- Each red data point is the signal energy calculated from synchronous time windows
- Repeatability of this stress noise energy from cycle to cycle

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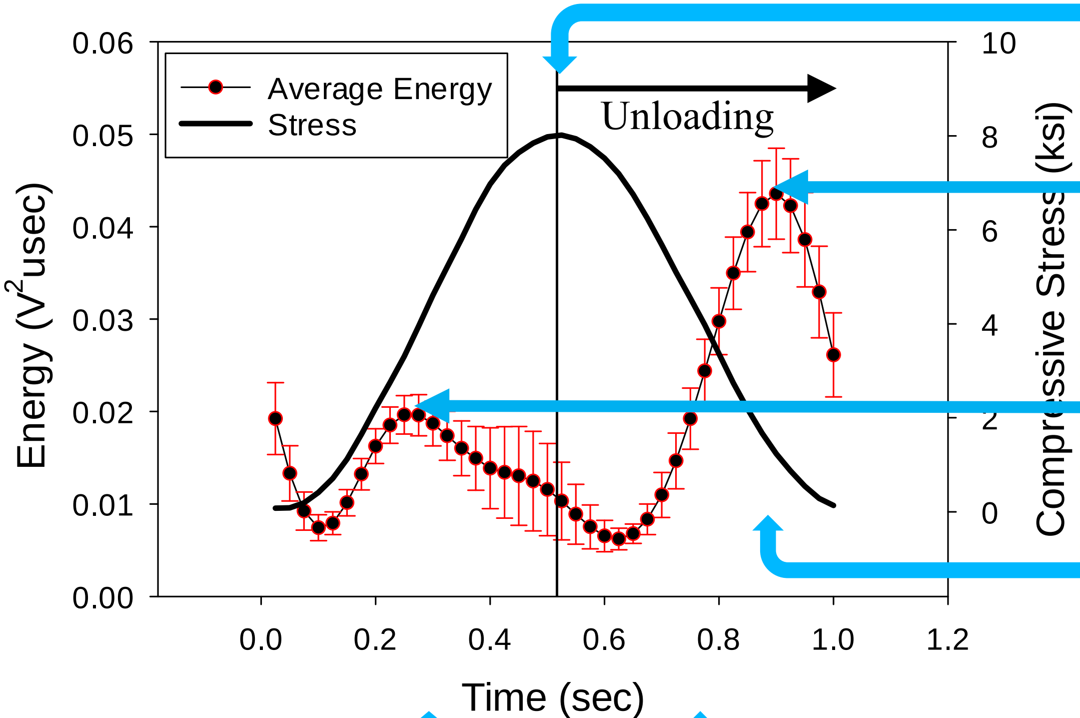
"Average" load cycle and energy per fatigue step with error bars



Peak stress ≠ Peak noise energy

If peak stress lower: Two energy peaks have comparable amplitudes and are closer in phase with maximum stress rate points.
If peak stress higher: Amplitude and phase discrepancy could indicate greater interaction with microstructure through the pinning distribution and hysteresis.

Maximum stress rate locations

Note:

- Two peaks of signal energy per load cycle and they occur near the points of highest strain rate.
- Stress noise is minimal at maximum stress and not proportional to load.

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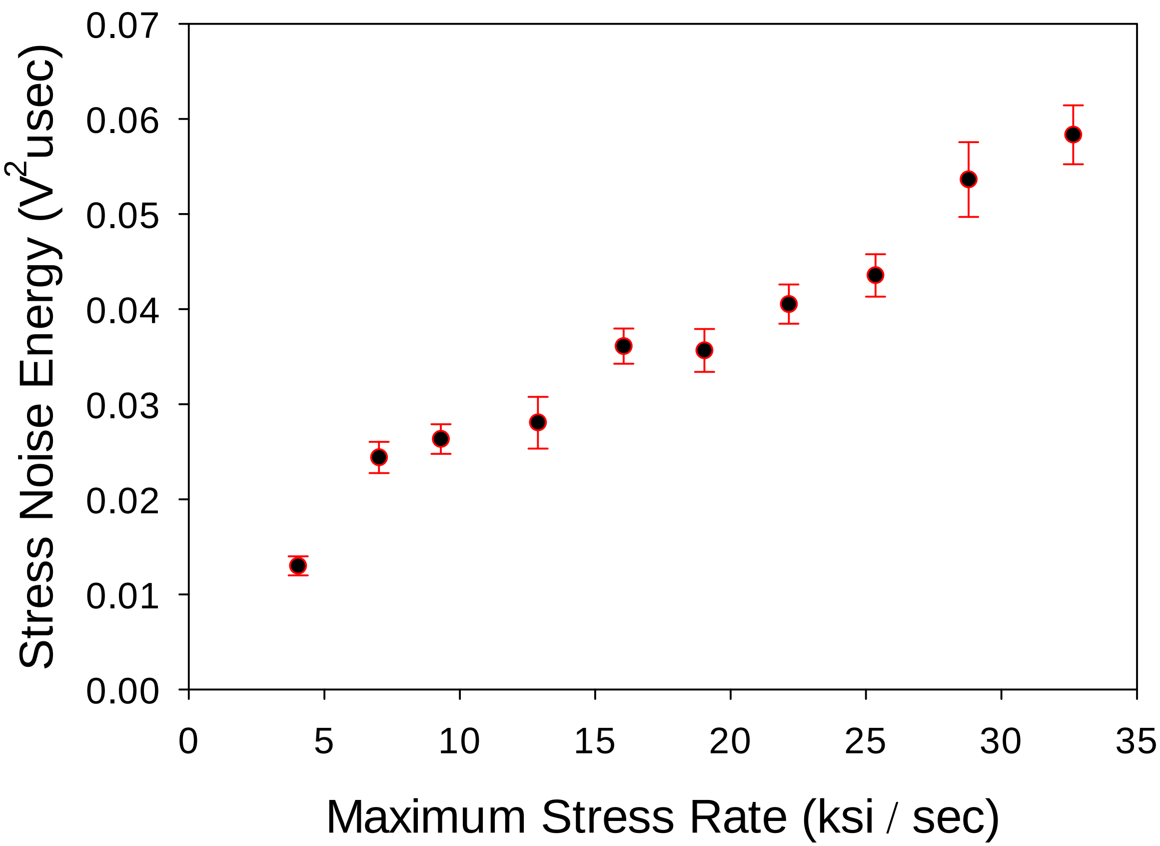

Peak noise energy is proportional with maximum stress rate

Summary and Impact

Summary

- Theory predicts that stress rates will be proportional to $\partial M/\partial t$.
- It is hypothesized that $\partial M/\partial t$ will be proportional to noise levels.
- Maximum noise energy tends to align with maximum stress rates, twice per load cycle.
- Maximum noise energy is not proportional with stress but with stress rate.
- It is noted that the discrepancy in the phase of the noise energy peaks increases as maximum stress rate increases.
- This indicates effects of hysteresis and microstructural effects.
- Sensitivity to microstructure should allow tracking of changes in microstructure.

Impact

- Remote detection of high strain rate events could find or predict pending damage in unexpected locations at unexpected times to allow better structural management, further increasing the margin of safety.
- Possible extension to composites by embedding magnetostrictive materials in composites.

Extra Charts