IOWA STATE UNIVERSITY

Center for Nondestructive Evaluation

ABC's of Nonlinear Resonance Ultrasound Spectroscopy: Alloys, Bones and Concrete are Just the Start

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April 25, 2022

Background

- Nonlinear Acoustics
  - Manifestations
  - Methods

What's covered here

- Nonlinear Resonance Approaches
  - Methods/Instrumentations
  - Examples of Applications and Results

Nonlinear Acoustics

How do we define/describe Nonlinear Acoustics?

What it isn't…linear

In acoustics, if the response of a material (output signal) due to the interaction of the material to varying strain applications (input signal) are proportional, this is a "linear" response.

The linear response (or the "Hookean" response) breaks down (becomes nonlinear) when either the inputs strains are extreme#1 or specific material conditions exist#2

Nonlinear acoustics specifically looks to operate at #1 or upon #2

Nonlinear Acoustics - Manifestations

- Amplitude dependent propagation velocity
  - Music – in wind instruments – “brassiness” in trombones or trumpets
- Contact Nonlinearity (Acoustic Rectification)
  - Partially closed or open cracks, disbonds
- Acoustic Streaming
  - Fluid flow
- Amplitude Dependent Resonance Frequency
  - Strain “softening” or “hardening”

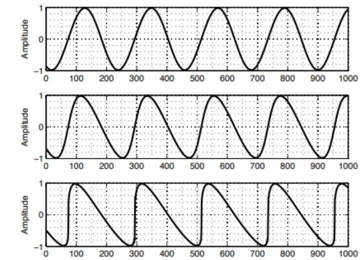


Figure 1: *Waveforms of sinusoidal pressure waves at low, medium and high pressure levels, after propagating the same distance.*

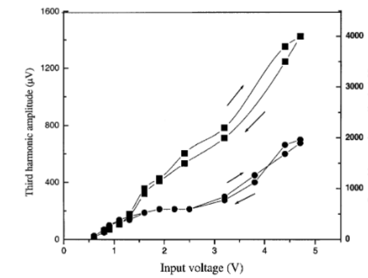


Fig. 9. Dynamic characteristics of the second (■) and third (•) SAW harmonics in the reflection from the crack.

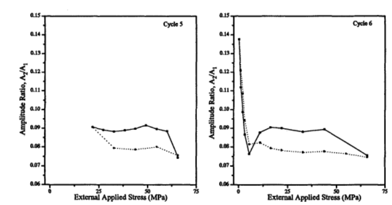
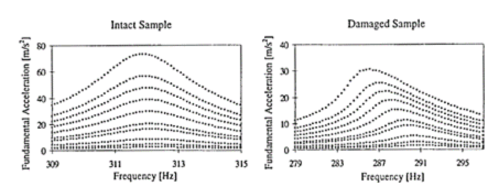


Fig. 8. Amplitude ratio vs. external applied bias stress for six unloading/loading cycles of commercially pure aluminum cylinders.



Cooper and Abel. "Digital simulation of “brassiness” and amplitude-dependent propagation speed in wind instruments." In *Proc. 13th Int. Conf. on Digital Audio Effects (DAFx-10)*, pp. 1-6. 2010.
Korshak, Boris A., I. Yu Solodov, and E. M. Ballad. "DC effects, sub-harmonics, stochasticity and “memory” for contact acoustic non-linearity." *Ultrasonics* 40, no. 1-8 (2002): 707-713.
Barnard, D. J., G. E. Dace, D. K. Rehbein, and O. Buck. "Acoustic harmonic generation at diffusion bonds." *Journal of nondestructive evaluation* 16, no. 2 (1997): 77-89.
Van Den Abeele, KE-A., Jan Carmeliet, James A. Ten Cate, and Paul A. Johnson. "Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part II: Single-mode nonlinear resonance acoustic spectroscopy." *Journal of Research in Nondestructive Evaluation* 12, no. 1 (2000): 31-42. Fig. 2

Nonlinear Acoustics - Methods

- Harmonic Generation Measurements
  - Monochromatic signal - TTU
  - Measure fundamental and higher harmonic ratios
  - Determine nonlinearity parameter, β *
  - Identify changes in microstructure, damage accumulation, etc.

- Contact Nonlinearity -
  - Monochromatic signal – PE or TTU
  - Measure fundamental and higher harmonic content
  - Relate to nature of the contacts…e.g., closure stresses

- Amplitude Dependent Resonance Shifts
  - Apply increasing strain inputs over a span of frequencies
  - Track peak frequencies, extract nonlinearity parameter, α *
  - Relates to damage, whether material will soften or harden, etc.

Nonlinear Resonance Approaches

Several methods, with various names/acronyms can be generally combined under the umbrella term nonlinear elastic wave spectroscopy (NEWS). The common theme is they all look at the amplitude-dependent frequency response of dynamic wave interactions in materials.

Today, we'll concentrate on nonlinear resonance ultrasound spectroscopy (NRUS).

Others include:
Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS)
Single-mode Nonlinear Resonance Acoustic Spectroscopy (SIMONRAS)
Nonlinear Resonant Acoustic Spectroscopy (NRAS)
Nonlinear Resonance Spectroscopy (NRS)
Nonlinear Reverberation Spectroscopy (NRS)

Nonlinear Resonance Approaches: Methods/Instrumentations

What is shown next are examples used for driving the material (inputs) and measuring the response (outputs)

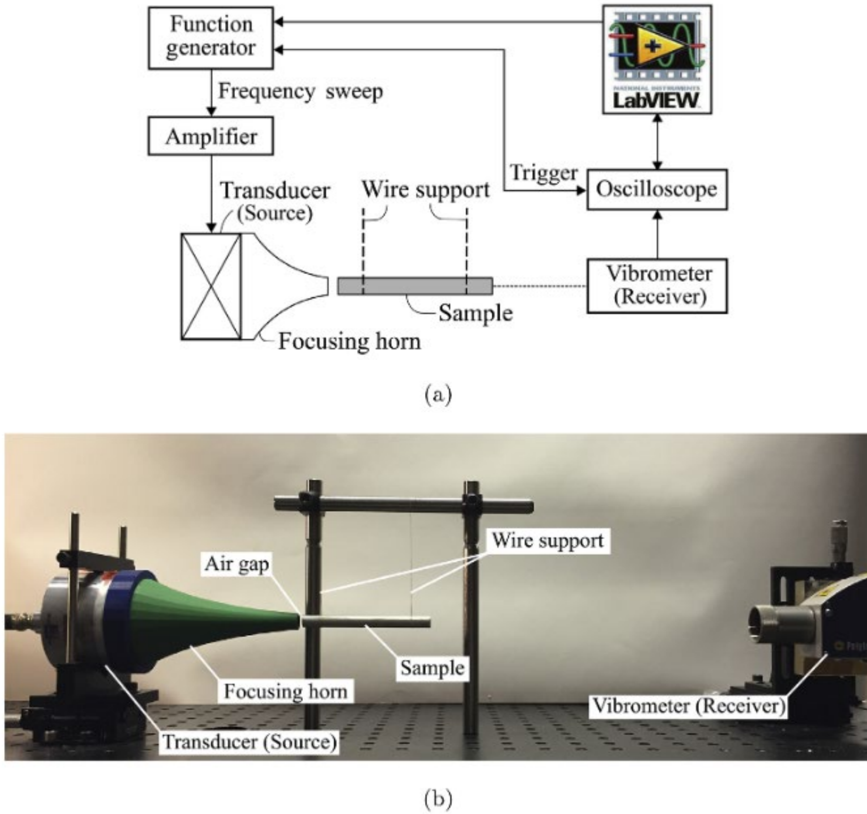


Fig. 1. a) Schematic and b) photo of noncontact NRUS experimental setup.

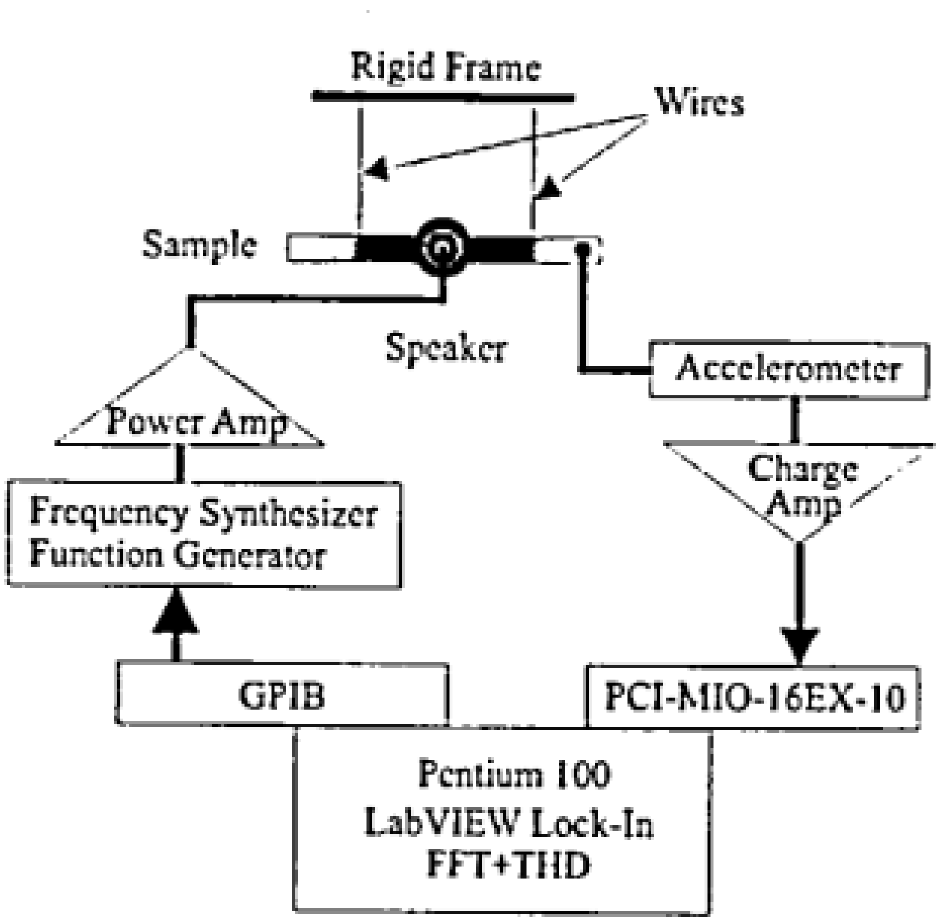
Input: Fxn Generator>Amplifier>Transducer>Horn

Output: Laser Vibrometer>Oscilloscope

non-contact on both input and output sides

Maier, Steffen, Jin-Yeon Kim, Marc Forstenhäusler, James J. Wall, and Laurence J. Jacobs. "Noncontact nonlinear resonance ultrasound spectroscopy (NRUS) for small metallic specimens." *NDT & E International* 98 (2018): 37-44.

Nonlinear Resonance Approaches: Methods/Instrumentations



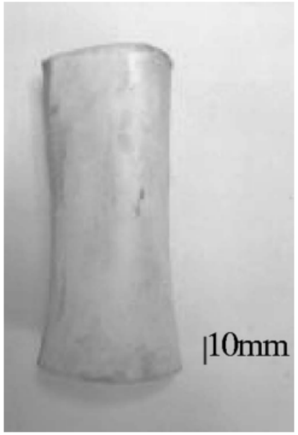
Input: Fxn Generator>Amplifier>Speaker

Output: Accelerometer>Conditioner>A/D card

non-contact on input side

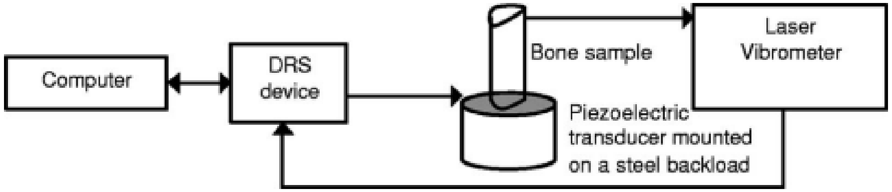
Van Den Abeele, KE-A., Jan Carmeliet, James A. Ten Cate, and Paul A. Johnson. "Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part II: Single-mode nonlinear resonance acoustic spectroscopy." *Journal of Research in Nondestructive Evaluation* 12, no. 1 (2000): 31-42.

Nonlinear Resonance Approaches: Methods/Instrumentations



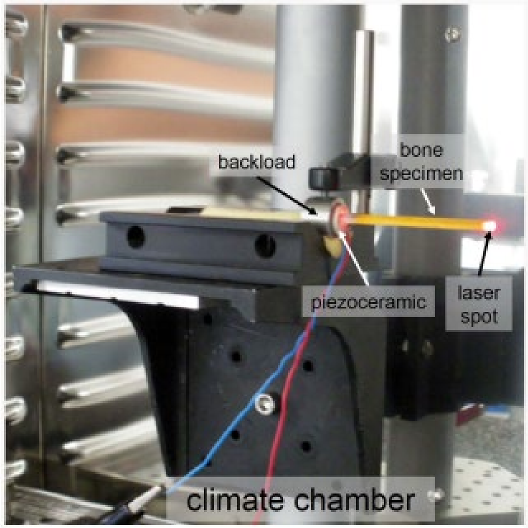
Input: Dynamic Resonance System>Transducer

Output: Laser Vibrometer>Dynamic Resonance System



Muller, Marie, Alexander Sutin, Robert Guyer, Maryline Talmant, Pascal Laugier, and Paul A. Johnson. "Nonlinear resonant ultrasound spectroscopy (NRUS) applied to damage assessment in bone." *The Journal of the Acoustical Society of America* 118, no. 6 (2005): 3946-3952.

non-contact on output side



Input: Dynamic Resonance System>Piezo

Output: Laser Vibrometer>Dynamic Resonance System

Haupert, Sylvain, Sandra Guerard, Françoise Peyrin, David Mitton, and Pascal Laugier. "Non destructive characterization of cortical bone micro-damage by nonlinear resonant ultrasound spectroscopy." *PLOS one* 9, no. 1 (2014): e83599.

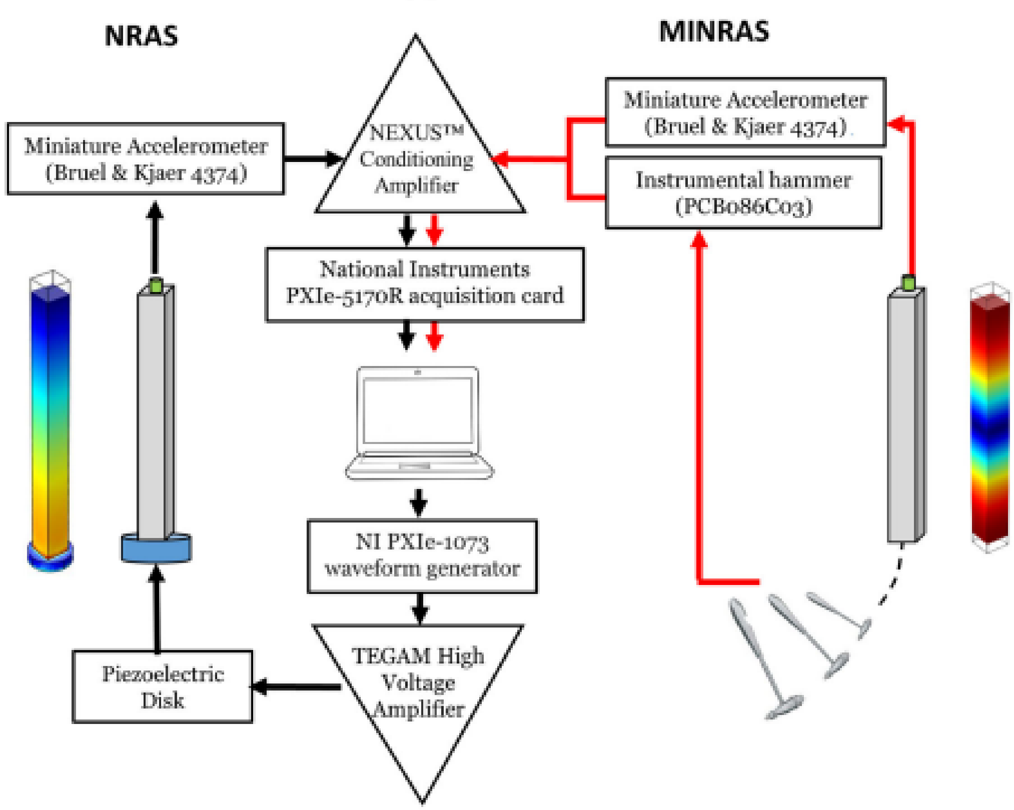
Nonlinear Resonance Approaches: Methods/Instrumentations

Input: Wfm Generator>Amplifier>Conditioner>Piezo disc

Output: Accelerometer>Amp>A/D Card

Input: Instrumented Hammer

Output: Accelerometer>Amp>A/D Card



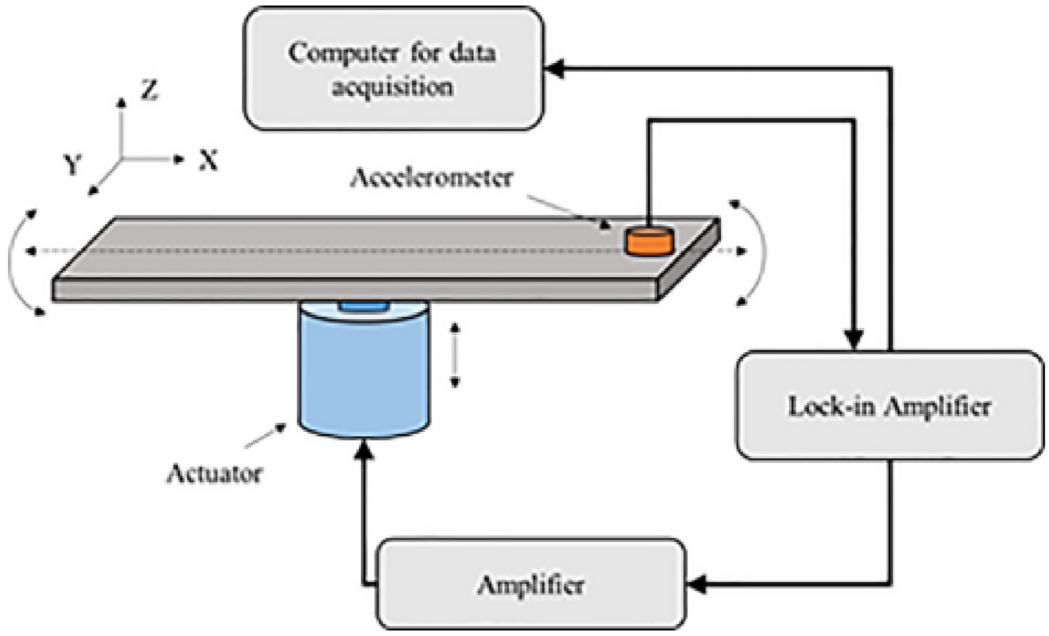
Jin, Jiang, Weilun Xi, Jacques Riviere, and Parisa Shokouhi. "Single-impact nonlinear resonant acoustic spectroscopy for monitoring the progressive alkali–silica reaction in concrete." *Journal of Nondestructive Evaluation* 38, no. 3 (2019): 1-15.

Nonlinear Resonance Approaches: Methods/Instrumentations

Input: Lock-in >Amplifier>Actuator

Output: Accelerometer>Conditioner>Lock-in

use of Lock-in on source and measurement sides offers high sensitivity both in terms of amplitude and frequency



Chakrapani, Sunil Kishore, and Daniel J. Barnard. "Determination of acoustic nonlinearity parameter (β) using nonlinear resonance ultrasound spectroscopy: Theory and experiment." *The Journal of the Acoustical Society of America* 141, no. 2 (2017): 919-928.

Nonlinear Resonance Approaches: Methods/Instrumentations

Input: Wfm Generator>Amplifier>Transducer

Output: Transducers>A/D Converter

Shear mode transducer – sensitive to sliding contacts

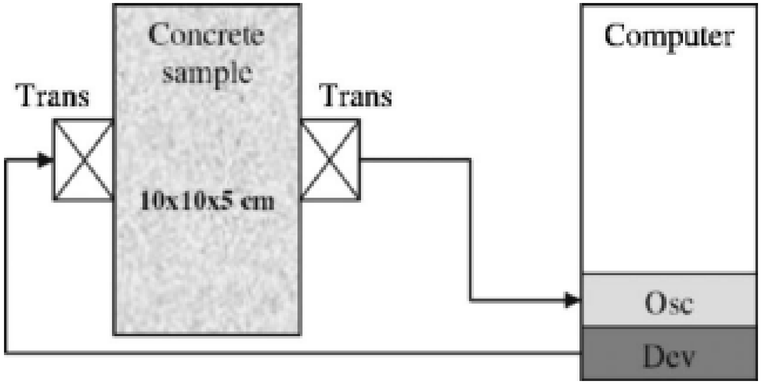


Fig. 2. Scheme of the NRUS experiment. Osc: A/D converter; Dev: high voltage ultrasonic device; Trans: Panametrics transducers (V1012 for P modes and V1548 for S modes).

Payan, C., V. Garnier, J. Moysan, and P. A. Johnson. "Applying nonlinear resonant ultrasound spectroscopy to improving thermal damage assessment in concrete." *The Journal of the Acoustical Society of America* 121, no. 4 (2007): EL125-EL130.

Nonlinear Resonance Approaches:
Examples of Applications and Results - ASR in Concrete

Cement and Concrete Research 40 (2010) 914–923

Contents lists available at ScienceDirect

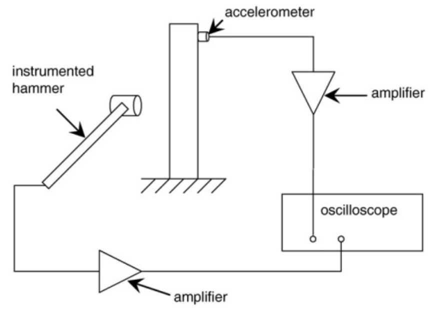
Cement and Concrete Research

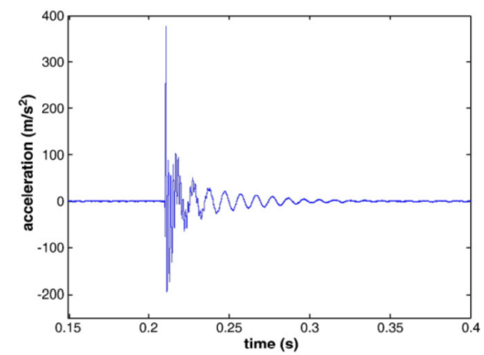
journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Rapid evaluation of alkali–silica reactivity of aggregates using a nonlinear resonance spectroscopy technique

Jun Chen [a], Amal R. Jayapalan [a], Jin-Yeon Kim [a], Kimberly E. Kurtis [a,*], Laurence J. Jacobs [a,b]

[a] School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA
[b] GWW School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA





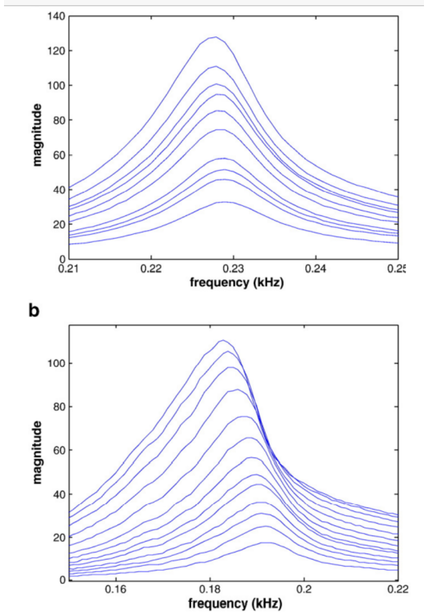


Fig. 4. (a) Resonance of intact mortar sample with increasing impact energy. (b) Resonance of damaged mortar sample with increasing impact energy.

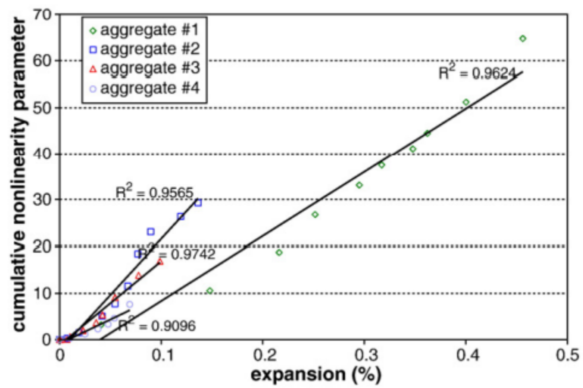


Fig. 13. Correlation between cumulative nonlinearity parameters and AMBT expansion.

- NIRAS used to evaluate ASR response of aggregates
- Cumulative Nonlinearity Parameter differentiates aggregate ASR reactivity early in exposures to moisture that is not identified by expansion measurements

Nonlinear Resonance Approaches: Examples of Applications and Results – Beta by NRUS

Determination of acoustic nonlinearity parameter (β) using nonlinear resonance ultrasound spectroscopy: Theory and experiment

The Journal of the Acoustical Society of America 141, 919 (2017); https://doi.org/10.1121/1.4976057

Sunil Kishore Chakrapani[a)] *and* Daniel J. Barnard

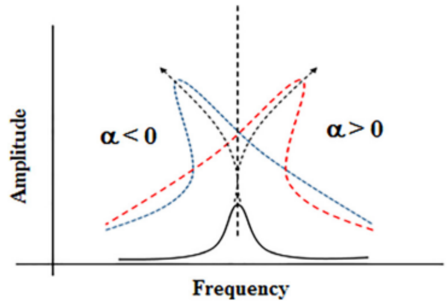


TABLE II. The linear parameters extracted from experimental results.

Material	Linear frequency (Hz)	Density (Kg/m^3)	ν (Poisson's ratio)	C_{11} (GPa)
Al 1100	1271	2710	0.33	110.5
Pyrex	1231	2230	0.2	76.2
Cu 101	833	8960	0.33	180
CFRP 0°	950	1580	0.28	132
CFRP 90°	204	1580	0.013	6.08
CFRP 45°	265	1580	0.133	10.33

- Chakrapani demonstrated that the α from NRUS could be used to determine C111, and with published values of C11 for a range of materials, calculated β
- Demonstrate further that the sign of β could be determined by the slope of the frequency shift

TABLE III. Nonlinear parameters α, β, and C_{111} obtained using the inversion procedure.

Material	Nonlinearity parameters α	Experimental values C_{111}	β	Reference C_{111}	Reference β
Al 1100	-1.83×10^{15}	-8.35 ± 0.96	5.61 ± 0.17	-10.76	5–17[a]
Pyrex	3.55×10^{14}	-0.97 ± 0.11	-1.6 ± 0.17	3.96	−8.77[b]
Cu 101	-9.78×10^{14}	-16.18 ± 0.37	6 ± 0.22	-15	4–9[c]
CFRP 0°	-4.44×10^{15}	-42.81 ± 0.55	29.5 ± 0.48	-48.84	35[d]
CFRP 90°	-8.23×10^{13}	-0.87 ± 0.024	11.3 ± 0.39	-3.08	17.5[d]
CFRP 45°	-7.85×10^{13}	-1.03 ± 0.035	7 ± 0.52	NA	NA

Nonlinear Resonance Approaches:
Examples of Applications and Results – Bolt Torque

Probing Interface Elastic Nonlinearity Applying Nonlinear Resonance Ultrasound Spectroscopy: The Case of Screw Tightness-of-fit

Jacques Rivière,* Guillaume Renaud, Sylvain Haupert, Maryline Talmant, and Pascal Laugier
UPMC Univ Paris 06, CNRS UMR 7623,
Laboratoire d'Imagerie Paramétrique,
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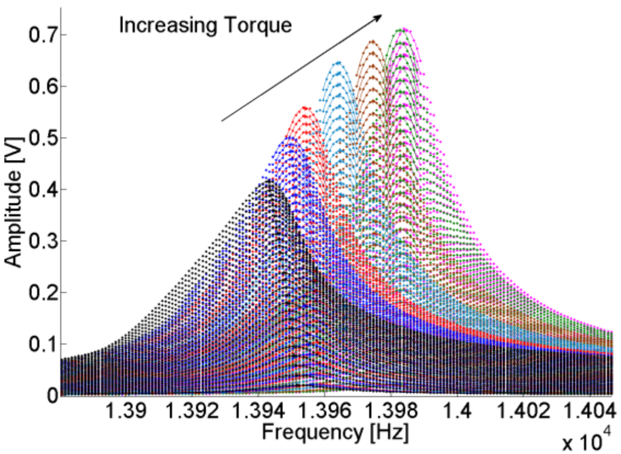
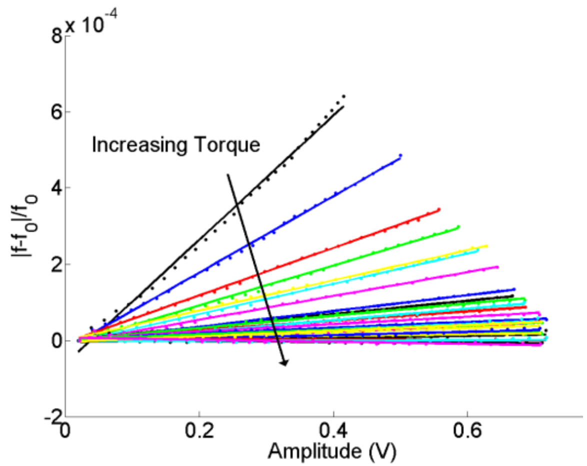
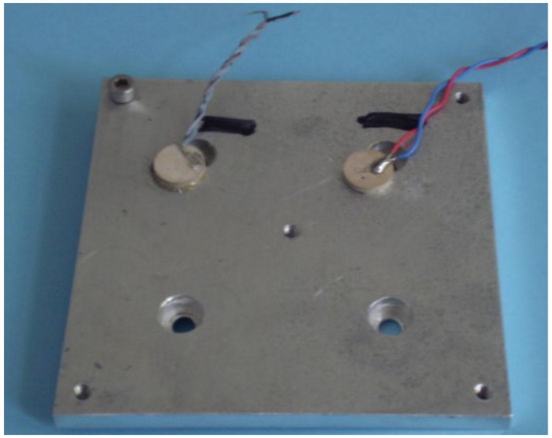
Paul A. Johnson†
Los Alamos National Laboratory, NM, USA







- Bolt in upper left corner is tightened to 7 different torque values
  - Note: this is a single plate, not two plates bolted together
- Frequency shift (proportional to nonlinearity parameter α) increased to higher frequencies with each increasing torque increment
- The shifts to higher frequencies is analogous to strain hardening

Riviere, Jacques, Guillaume Renaud, Sylvain Haupert, Maryline Talmant, Pascal Laugier, and Paul A. Johnson. "Probing interface elastic nonlinearity applying nonlinear resonance ultrasound spectroscopy: The case of screw tightness-of-fit." *Journal of Applied Physics* 107 (2010): 124901.

Nonlinear Resonance Approaches:
Examples of Applications and Results – Bovine Bone

Nonlinear resonant ultrasound spectroscopy (NRUS) applied to damage assessment in bone

Marie Muller, Alexander Sutin, Robert Guyer, et al.

Citation: The Journal of the Acoustical Society of America **118**, 3946 (2005); doi: 10.1121/1.2126917

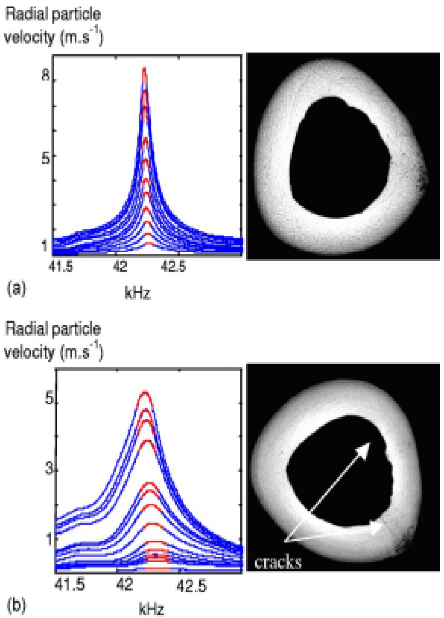


FIG. 5. (Color online) Example of resonance curves for damage steps 0 and 9. The radial velocity measured close to the top of sample B1 is plotted as a function of frequency. Top: damage step 0, Bottom: damage step 9.

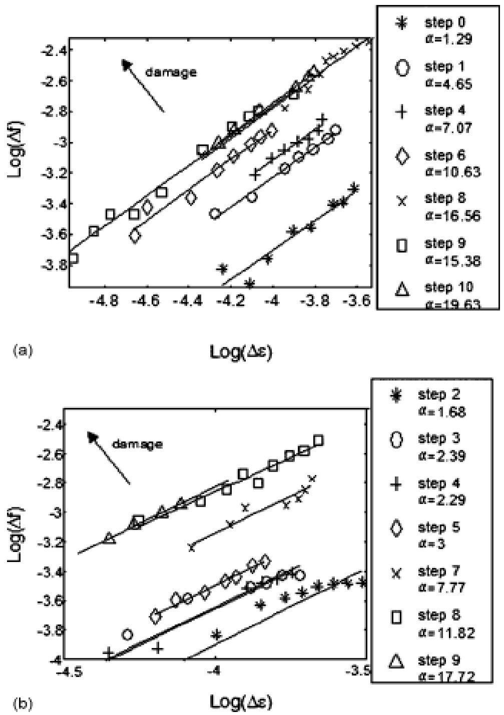
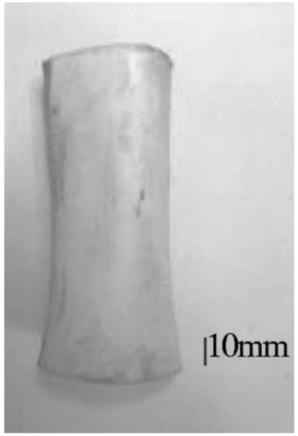


FIG. 6. Resonance frequency shift as a function of strain in log-log space. As damage increases, the curves are translated towards the top of the space, reflecting an increasing nonlinear parameter.



- Axial Compression Fatigue used to introduce damage (stage 0-10)
- Progressive damage resulted in increasing ΔF (related to nonlinearity parameter)

Nonlinear Resonance Approaches:
Examples of Applications and Results – Composites

Appl Compos Mater (2008) 15:115–126
DOI 10.1007/s10443-008-9061-7

Detecting Damage in Composite Material Using Nonlinear Elastic Wave Spectroscopy Methods

Michele Meo • Umberto Polimeno • Giuseppe Zumpano

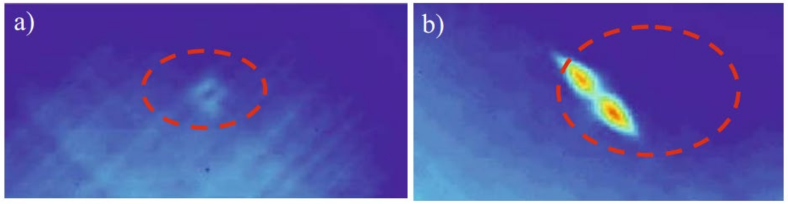


Fig. 5 Thermography images—**a** front face, **b** back-plate

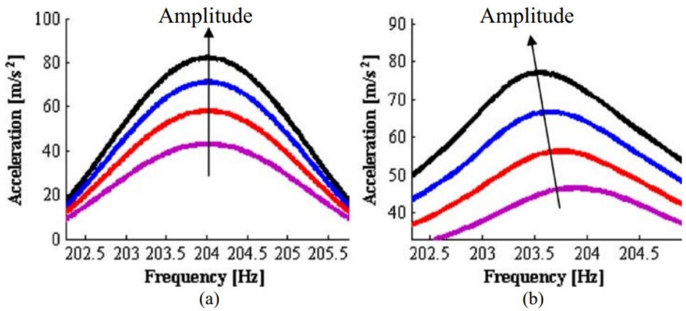


Fig. 6 Resonance curve: **a** undamaged sample, **b** damaged sample

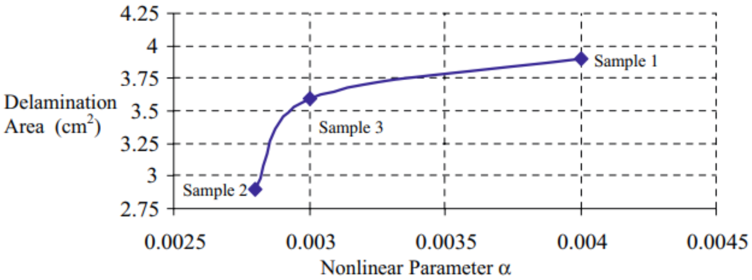


Fig. 9 Delamination area vs. non linear parameter α

- Damage by low velocity impact (BVID impact damage)
- NRUS used and demonstrated that increasing damage area (measured by thermographic methods) increased measured nonlinearity parameter

Nonlinear Resonance Approaches: Examples of Applications and Results – Concrete

Applying nonlinear resonant ultrasound spectroscopy to improving thermal damage assessment in concrete

C. Payan, V. Garnier, J. Moysan, et al.

Citation: The Journal of the Acoustical Society of America **121**, EL125 (2007); doi: 10.1121/1.2710745

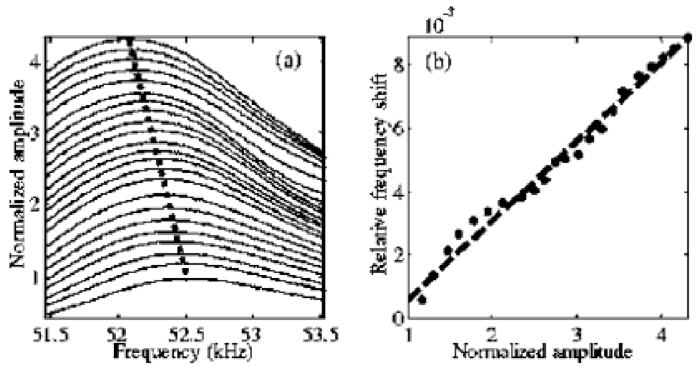
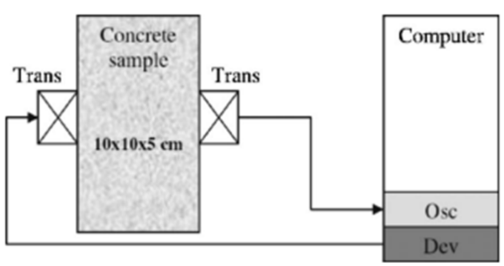
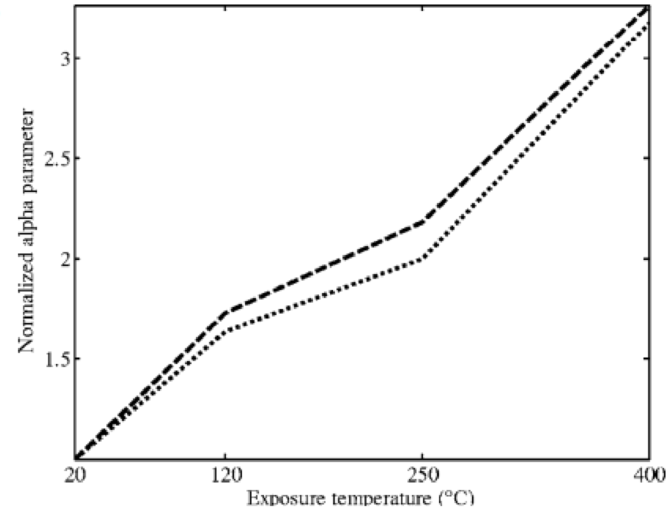


Fig. 5. 250 °C damaged sample frequency shift (a) and extraction of α parameter (b) in shear mode.





- Damage by high temperature exposure
- Shear Mode NRUS showed increased nonlinearity parameter vs temperature

Nonlinear Resonance Approaches: Examples of Applications and Results – Concrete

Quantitative linear and nonlinear resonance inspection techniques and analysis for material characterization: Application to concrete thermal damage

C. Payan, T. J. Ulrich, P. Y. Le Bas, et al.

Citation: The Journal of the Acoustical Society of America **136**, 537 (2014); doi: 10.1121/1.4887451

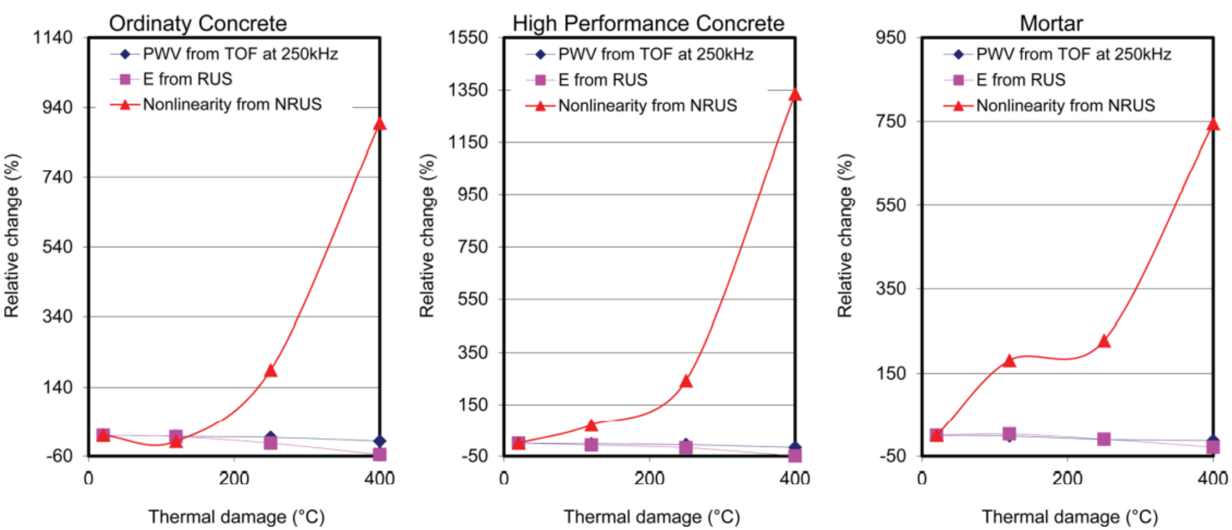


FIG. 14. (Color online) Sensitivity study. PWV is the Pulse Wave Velocity evaluated from time of flight measurements.

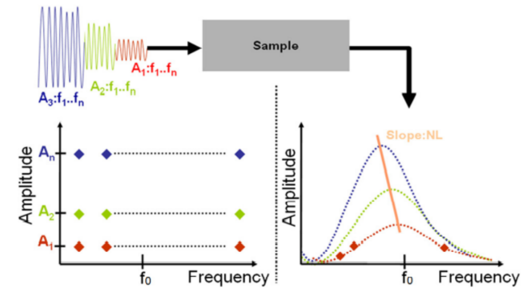


FIG. 7. (Color online) Data acquisition procedure. (left) Generation. (right) Reception.

- Damage by high temperature exposure
- NRUS nonlinearity Parameter showed much greater change with increasing thermal exposure compared to modulus measurement (E) from RUS and Pulse Wave Velocity measurements

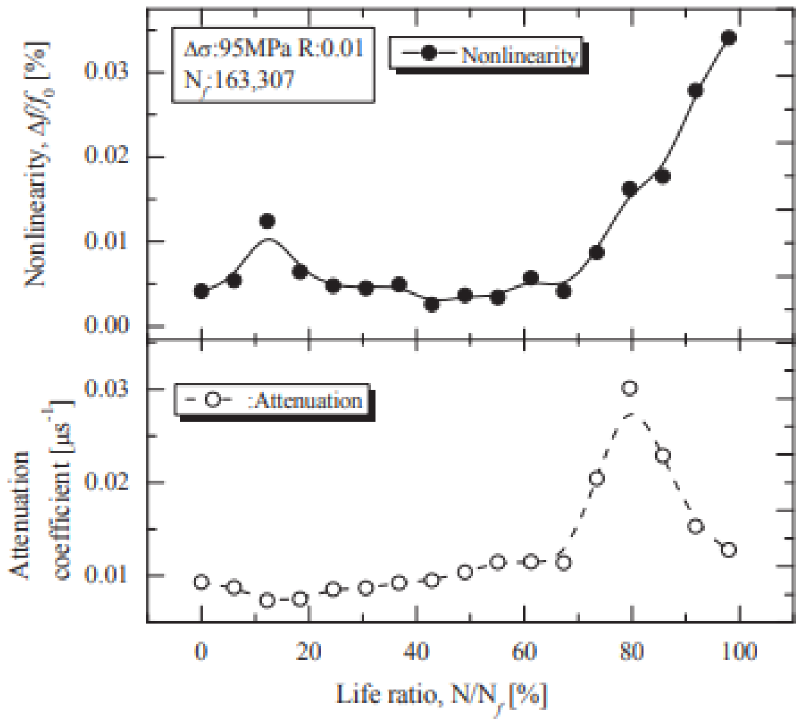
Nonlinear Resonance Approaches: Examples of Applications and Results – Copper

AIP Conference Proceedings

Nonlinear Resonant Ultrasound Spectroscopy (NRUS) applied to fatigue damage evaluation in a pure copper

Toshihiro Ohtani and Yutaka Ishii

Citation: AIP Conf. Proc. **1474**, 203 (2012); doi: 10.1063/1.4749331



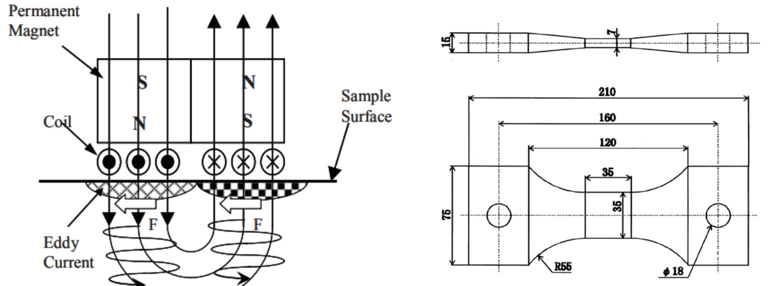


FIGURE 1. Structure of the shear wave EMAT.

- Tension fatigue damage in pure copper flat dog bone sample to failure
- Used EMAT to drive and sense resonance changes (EMAR)
- Nonlinearity parameter tracked fatigue damage to failure

Nonlinear Resonance Approaches:
Examples of Applications and Results – Cracks in RPV Steel

NONLINEAR PARAMETERS FOR A DIAGNOSIS OF MICRO-SCALE CRACKS USING A NONLINEAR RESONANT ULTRASOUND SPECTROSCOPY (NRUS)

AIP Conference Proceedings **1211**, 1439 (2010); https://doi.org/10.1063/1.3362237

Yong-Moo Cheong[a], M. K. Alam[a], *and* CheolGi Kim[b]

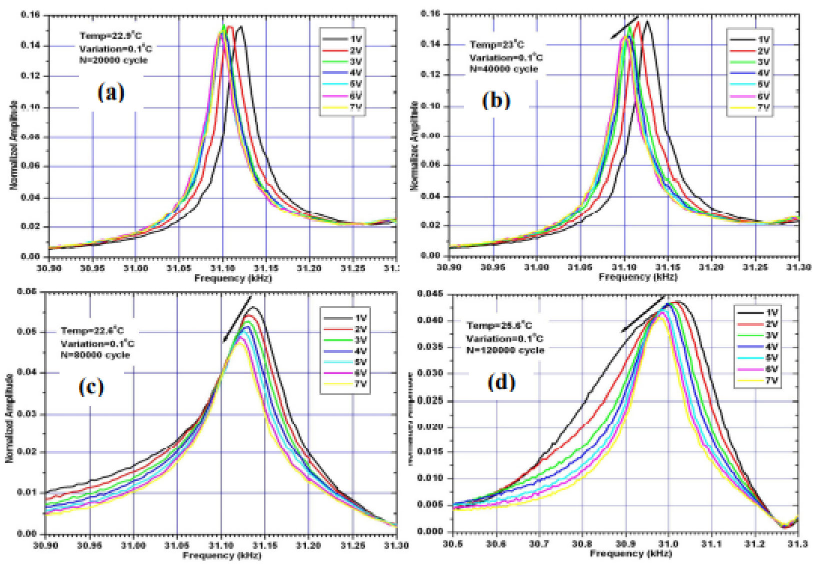


FIGURE 4. Normalized resonance pattern of CT specimen with a number of fatigue cycles (a) N = 20000, (b) N = 40000, (c) N = 80000 and (d) N = 120000.

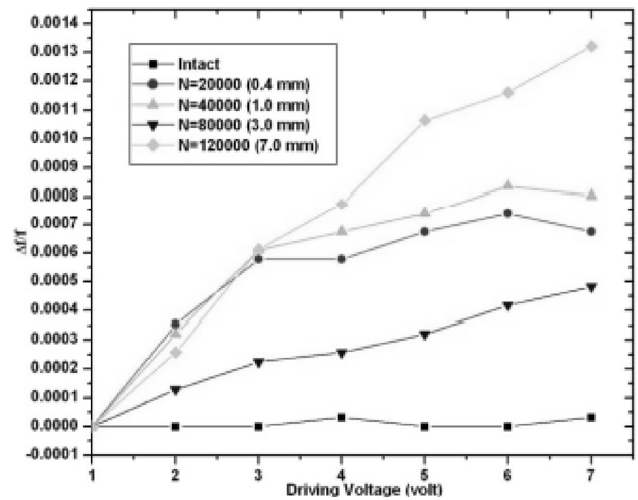


FIGURE 7. Frequency shift vs. driving voltage.

- Microcracks generated in low carbon steel CT specimens (RPV steel) in fatigue
- Rate of change of nonlinearity parameter increased with increasing fatigue cycles

Nonlinear Resonance Approaches: Examples of Applications and Results – Creep

Noncontact nonlinear resonant ultrasound spectroscopy to evaluate creep damage in an austenitic stainless steel

Cite as: AIP Conference Proceedings 1511, 1227 (2013); https://doi.org/10.1063/1.4789183
Published Online: 24 January 2013

T. Ohtani, Y. Kusanagi and Y. Ishii

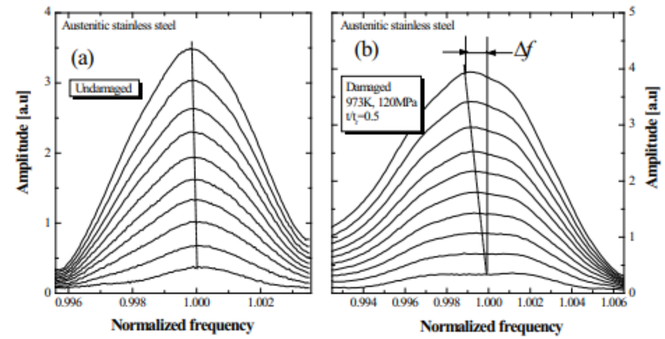


FIGURE 1. NRUS measurements from (a) intact and (a) creep damaged (973K, 120MPa) in austenitic stainless steels (at the fifth resonant mode round 1.5 MHz).

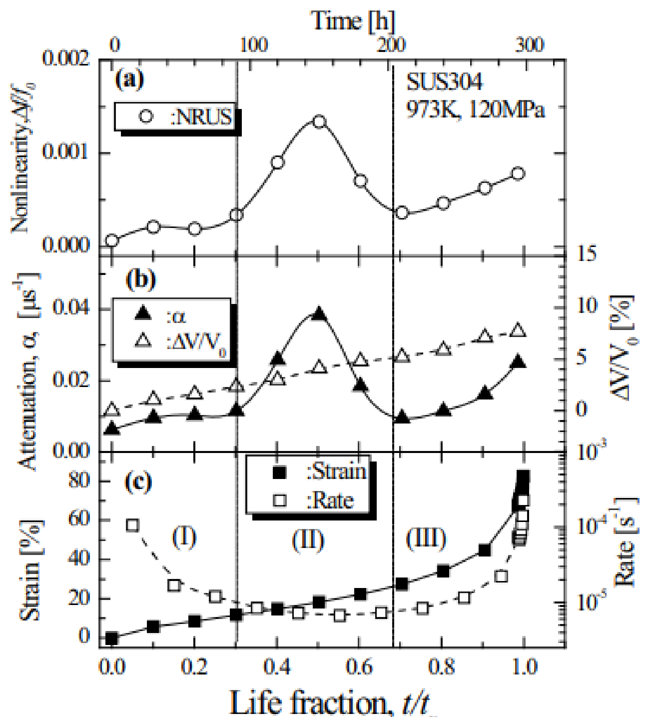


FIGURE 3. The relationship between the nonlinearity, $\Delta f/f_0$, the attenuation coefficient, α, relative velocity, $\Delta V/V_0$, in the 5th resonant mode (around 1.5MHz), the creep strain, and the strain rate, and life fraction, t/t_r, during creep (973K, 120MPa)

- Creep damaged sample at 973°K, stress of 120MPa in air (intermittent creep)
- Used EMAT to drive and sense resonance changes (EMAR)
- Changes in nonlinearity (x3) and attenuation (x5) peaked about mid-life
- Authors attribute peak (and after peak decrease) to dislocation mobility, corroborated by TEM results

Nonlinear Resonance Approaches:
Examples of Applications and Results – Dislocations

Ultrasonics 96 (2019) 220–223

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Short communication

Multiscale model to study dislocation dynamics in nonlinear resonance spectroscopy of crystalline solids

Sunil Kishore Chakrapani

Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI, USA

- Expanding on models by Cantrell and Zhang et al, Chakrapani coupled dislocation dynamics to bulk nonlinear response using a nonlinear beam vibration model.
- The ΔF in a NRUS measurement can then include the dislocation contribution and the lattice contribution
- Modeled effect of the contributions in both SHG and NRUS approaches

Table 1
Description and value of various parameters used in the model.

Symbol	Description	Value (units)
L_d	Dislocation loop length	0.27 (μm)
G	Shear modulus	81 (GPa)
b	Burger's vector	0.3 (nm)
μ_ψ	2nd order Huang's constants	273 (GPa)
ν_ψ	3rd order Huang's constants	−3040 (GPa)
σ_{PN}	Pierle's-Nabarro stress	0.11 (MPa)
R	Schmid factor	0.3
B	Positive constant for increasing loop length	100
Λ	Dislocation density	10^{12} (m^{-2})
α	Constant whose values is between 1 and 0.5	0.5
Ω	Shear to longitudinal strain constant	10
λ	Positive constant for increasing loop length	15e-6
σ_1	Initial stress	0.2 (MPa)
	NRS model parameters	
γ	Linear damping parameter ($2 * \omega * \eta$)	4.739
η	Linear loss factor	0.0025
p	Vibration mode shape	–
L	Length of the sample	152.4 mm
h	Thickness of the sample	6.35 mm
ω	Linear angular frequency of sample	947.9 Hz
f	External forcing frequency	Variable
F	External forcing amplitude	Variable
ς_p	Detuning parameter at peak amplitude	–

Nonlinear Resonance Approaches:
Examples of Applications and Results – Dislocations *Cont'd*

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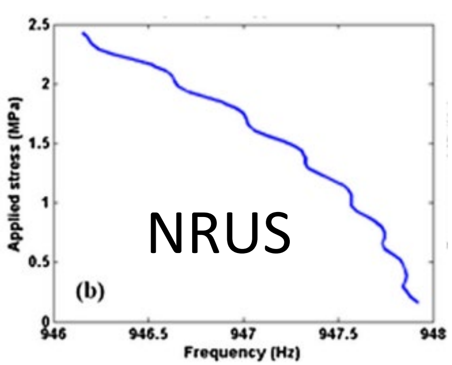
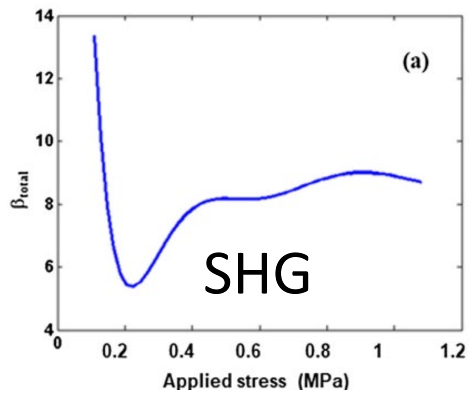
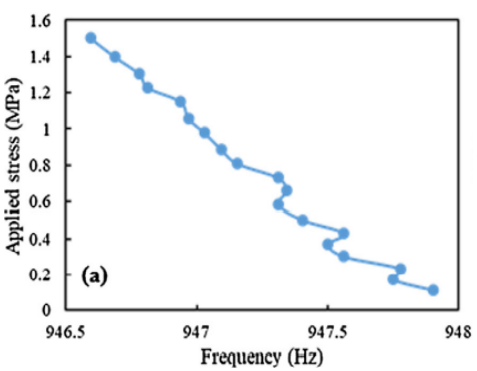
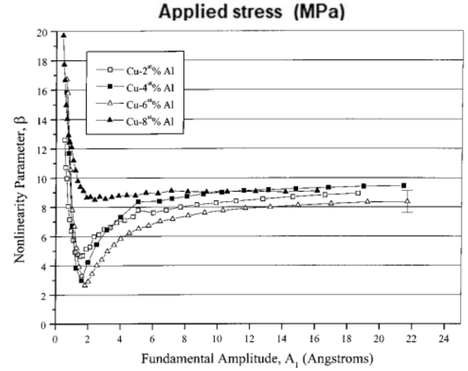


Model





Expt



- Model and experiment for NRUS showed VG agreement with inputs for cold drawn steel
- Model for SHG* of cold drawn steel showed qualitative agreement with Barnard's experimental data on Copper-Al alloys

* Second Harmonic Generation

Nonlinear Resonance Approaches: Examples of Applications and Results – Microstructure

Investigation of the relationship between classical and nonclassical ultrasound nonlinearity parameters and microstructural mechanisms in metals

Katherine Marie Scott Levy, Jin-Yeon Kim and Laurence J. Jacobs

Citation: The Journal of the Acoustical Society of America **148**, 2429 (2020); doi: 10.1121/10.0002360

TABLE I. Sample dimensions for NRUS and SHG specimens, SHG technique used for each material, and longitudinal mode of vibration.

Material	NRUS Specimen Dimensions (mm)	SHG Specimen Dimensions (mm)	SHG Technique	Mode of Vibration
304 SS	10 × 10 × 100	152. × 50.8 × 12.7	Rayleigh wave	2
316L SS	5 × 5 × 50	152. × 50.8 × 12.7	Rayleigh wave	1
Fe-1.0% Cu alloy	5 × 5 × 50	150 × 32 × 9	Longitudinal wave	1
17-4 PH	10 × 10 × 100	230 × 38 × 19	Rayleigh wave	2
9% Cr ferritic steel	5 × 5 × 50	203.2 × 45.72 × 12.7	Rayleigh wave	1

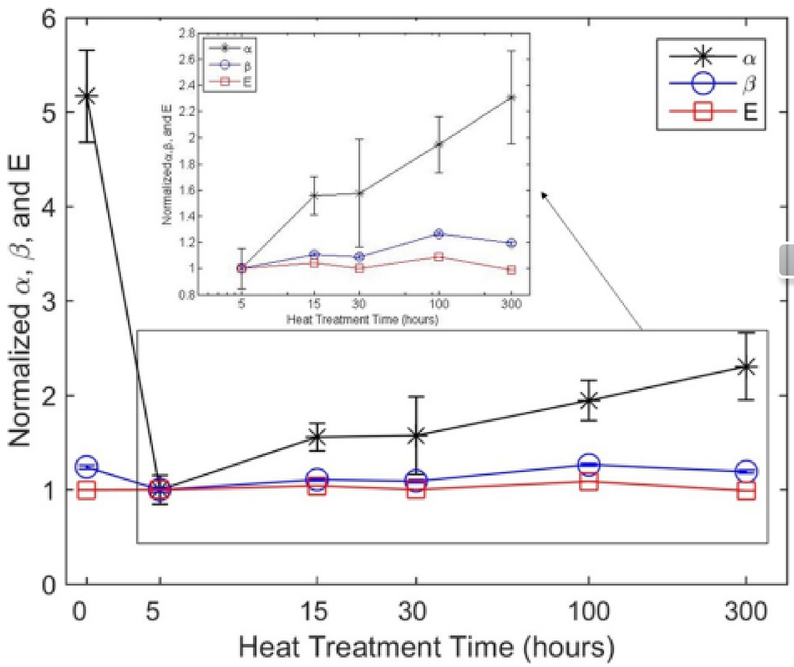


FIG. 5. (Color online) Comparison of α, β, (Scott *et al.*, 2018) and E results for Fe-1% Cu specimens, where inset figure clarifies the behavior from 5 h heat treatment time to 300 h heat treatment time.

- Investigated β, α and E (Young's mod.) changes for precipitate growth in and along the grain boundaries, dislocations, and precipitate pinned dislocations in ferrous alloys
- In Fe-1% Cu, decrease in β and α, followed by increase, is consistent with nucleation and growth, respectively, of copper precipitates, corroborated by small angle neutron scattering measurements

Nonlinear Resonance Approaches:
Examples of Applications and Results – Microstructure *Cont'd*

Investigation of the relationship between classical and nonclassical ultrasound nonlinearity parameters and microstructural mechanisms in metals

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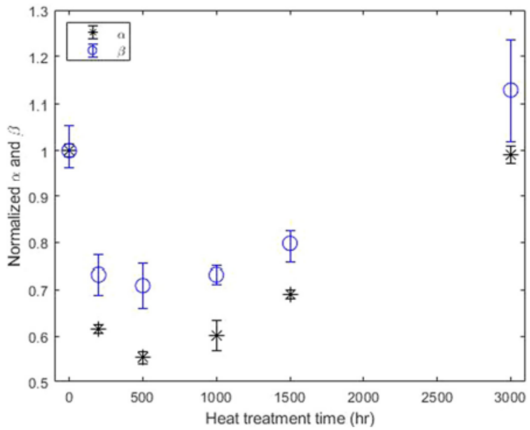

FIG. 7. (Color online) Comparison of β and α results for 9% Cr ferritic steel specimens (Fahse *et al.*, 2020; Marino *et al.*, 2016).

TABLE II. Summary of β and α response to microstructural mechanisms.

		β			α	
Material	Microstructural Mechanism		Response/Description			Response/Description
304 SS	Growth of precipitates along grain boundaries	↑ 25%	Interaction of carbide with the grain boundary		↑ 43%	Contact/friction between carbide and grain boundary
316L SS	Removal dislocations from cold working	↓ 20%	$\Delta\beta \propto \Lambda$		↓ 44%	Reduced contact from dislocations
Fe-1.0% Cu	Nucleation of precipitates	↓ 25%	Cu atoms to Cu precipitates		↓ 400%	Precipitate nucleation
	Precipitate pinned dislocations	↑ then ↓ 27%	Growth of radii then loss of coherency	$\Delta\beta \propto r^4$	↑ 95%	Growth in contact area between precipitate and matrix
17-4 PH	Precipitate pinned dislocations	↓ 50%	Increase # density	$\Delta\beta \propto N^{-1/3}$	↑ 150%	Growth in contact area as # increases
9% Cr ferritic steel	Dislocation Density decrease	↓ 30%	Competing effects	$\Delta\beta \propto \Lambda$	↓ 55%	Reduced contact from dislocations
	Growth of precipitate radius	↑ 60%		$\Delta\beta \propto r^4$	↑ 80%	Growth in contact area

- In Fe-9% Cr steel, an initial decrease in β and α is related to falling dislocation density and precipitate nucleation, then an increase due to continued growth of precipitates
- Table provides estimates of changes in β and α, for various mechanisms in materials evaluated. In general, NRUS (α) shows higher change/sensitivity

Nonlinear Resonance Approaches:
Examples of Applications and Results – Slow Dynamics

PHYSICAL REVIEW E **70**, 015602(R) (2004)

Strain-induced kinetics of intergrain defects as the mechanism of slow dynamics in the nonlinear resonant response of humid sandstone bars

Oleksiv O. Vakhnenko,[1] Vvacheslav O. Vakhnenko,[2] Thomas J. Shankland,[3] and James A. Ten Cate[3]

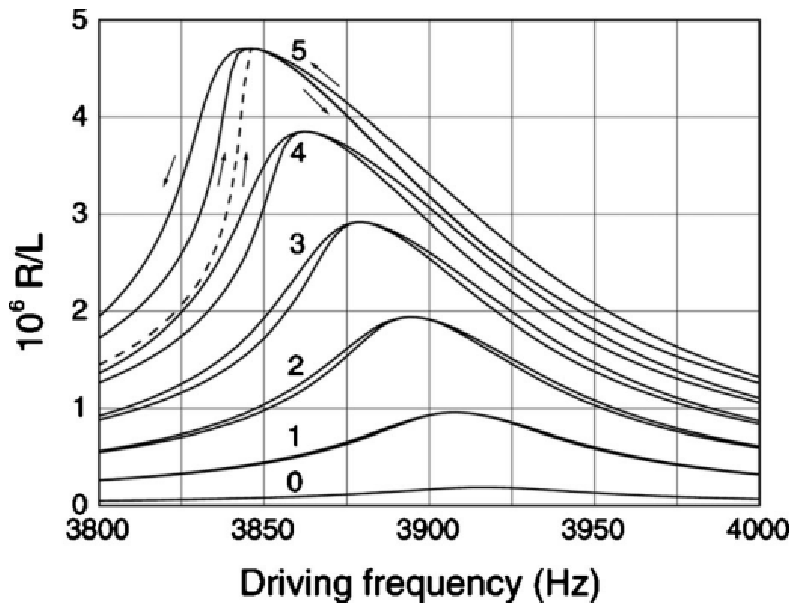

FIG. 1. Resonance curves $j=0,1,2,3,4,5$ at successively higher driving amplitudes $D_j=3.8(j+0.2\delta_{j0})10^{-8}L$. The time to sweep back and forth within the frequency interval 3700–4100 Hz is chosen to be 120 s.

- Materials subject to high excitations can become “conditioned”, where it may take seconds to minutes to recover.
- Can manifest as hysteretic behavior
- The recovery time depends on the nature of the material and the severity of the conditioning (amplitude and dwell time)

Nonlinear Resonance Approaches: Examples of Applications and Results – Stress Corr. Cracking

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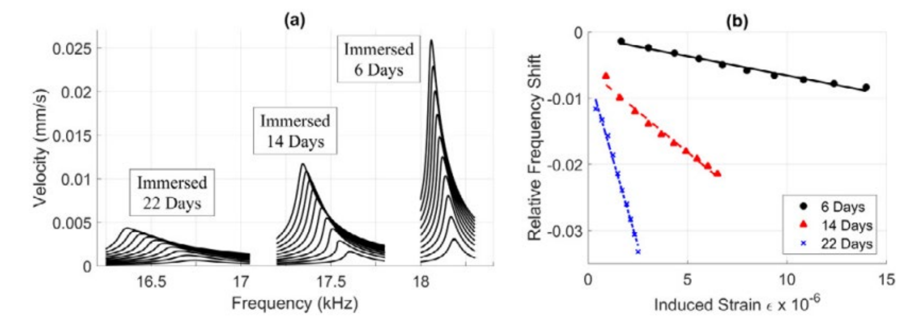
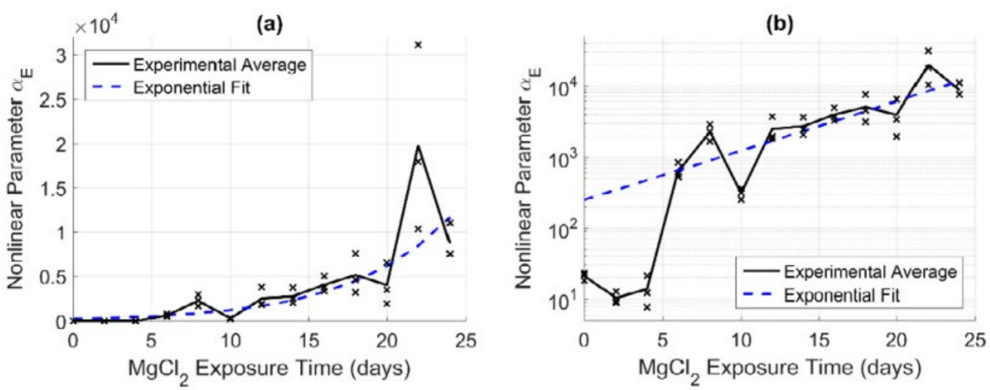
Nonlinear resonant ultrasound spectroscopy of stress corrosion cracking in stainless steel rods

Stephen M. Hogg[a], Brian E. Anderson[a,*], Pierre-Yves Le Bas[b], Marcel C. Remillieux[c]





- Weld and HAZ created by welding two 0.5”dia. x 2.5” long 304L rods together end to end
- 12 Stainless steel rods exposed in a 42% MgCl/Water solution at 80C
- Rods removed from solution after a period of exposure and tested with NRUS
- NRUS nonlinear parameter, α, increased with increased exposure to MgCl/water solution

Nonlinear Resonance Ultrasound Spectroscopy Summary

- Although only is use a dozen or so years, many successful applications have been identified

- NRUS would never likely be considered an NDE technique
  - Sample sizes, geometries and the equipment involved will relegate this approach to laboratories, not field work
  - The approach interrogates bulk properties/conditions, not isolated defects

- However, NRUS had demonstrated capabilities in materials characterization that are quite remarkable for its simplicity

- Low cost of particular setups make adding to laboratory economical
  - CNDE system: lock-in ($5k), magnetostrictive actuator ($0.8K), old stereo amplifier (<$50), accelerometer and conditioner ($0.7K)

Questions?