Bridge Structural Health Monitoring Using Nonlinear Vibro-Acoustic Method

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Outline

1. What are Nonlinear NDE/SHM methods and why are they extra sensitive to damage detection?
2. A few examples of NA NDE/SHM applications for concrete and bridges.
3. Nonlinear Impulse Resonant Acoustic Spectroscopy (NIRAS) method.
4. Application of bridge vehicle/train vibrations to the extraction of nonlinear properties. DEMON applications.
5. Sensor Technology and Apply Research (STAR) center experience and equipment.

Structural Health Monitoring versus Nondestructive Testing and Evaluation

Structural health monitoring (SHM) refers to the process of implementing a damage detection and characterization strategy **for engineering structures**. The SHM process involves the observation of a system over time using periodically sampled response measurements from an array of sensors (often inertial accelerometers), the extraction of damage-sensitive features from these measurements.(Wikipedia}

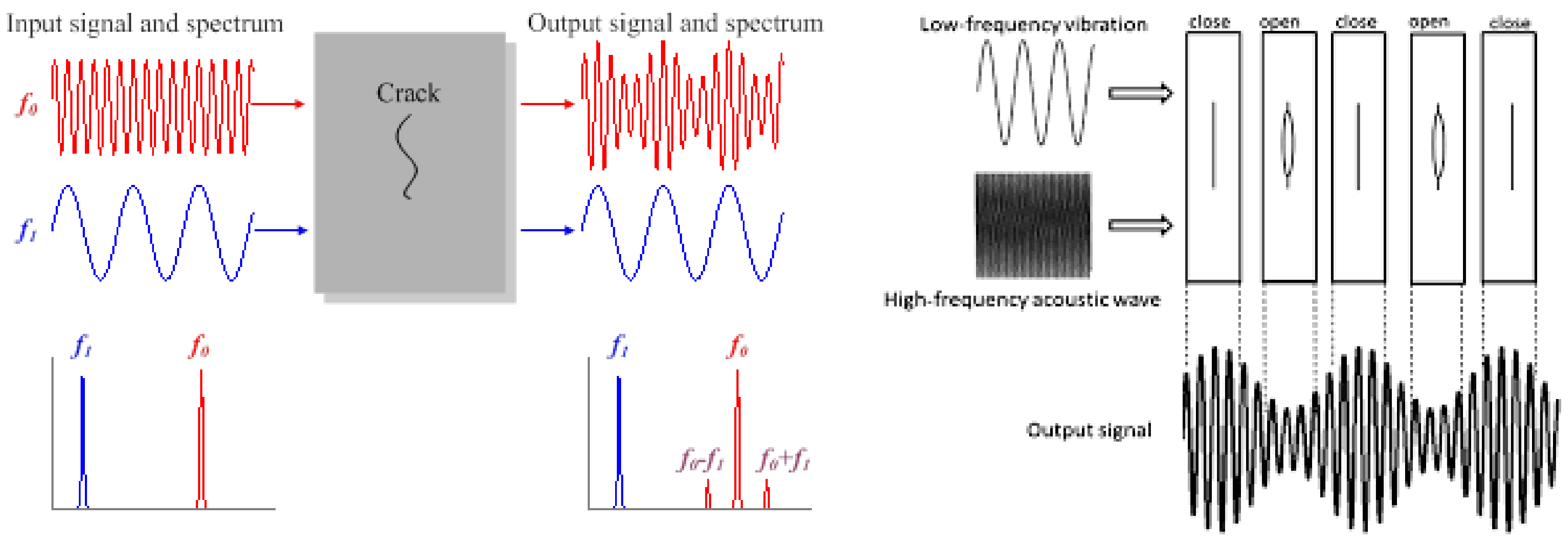
Vibration based SHM techniques rely on that structural damage or condition change significantly alters the structural properties, such as stiffness, mass and damping, which in turn changes the structural vibration properties extracted from the measured data.

(Li, J. and Hao, H., 2016. A review of recent research advances on structural health monitoring in Western Australia. *Struct Monit Maint*, *3*(1), pp.33-49.)

Nondestructive testing (**NDT**) is a wide group of analysis techniques used in science and technology industry to evaluate **the properties of a material, component** or system without causing damage. The terms **nondestructive examination** (**NDE**), **nondestructive inspection** (**NDI**), and **nondestructive evaluation** (**NDE**) are also commonly used to describe this technology. (Wikipedia}

Vibro-acoustic modulation

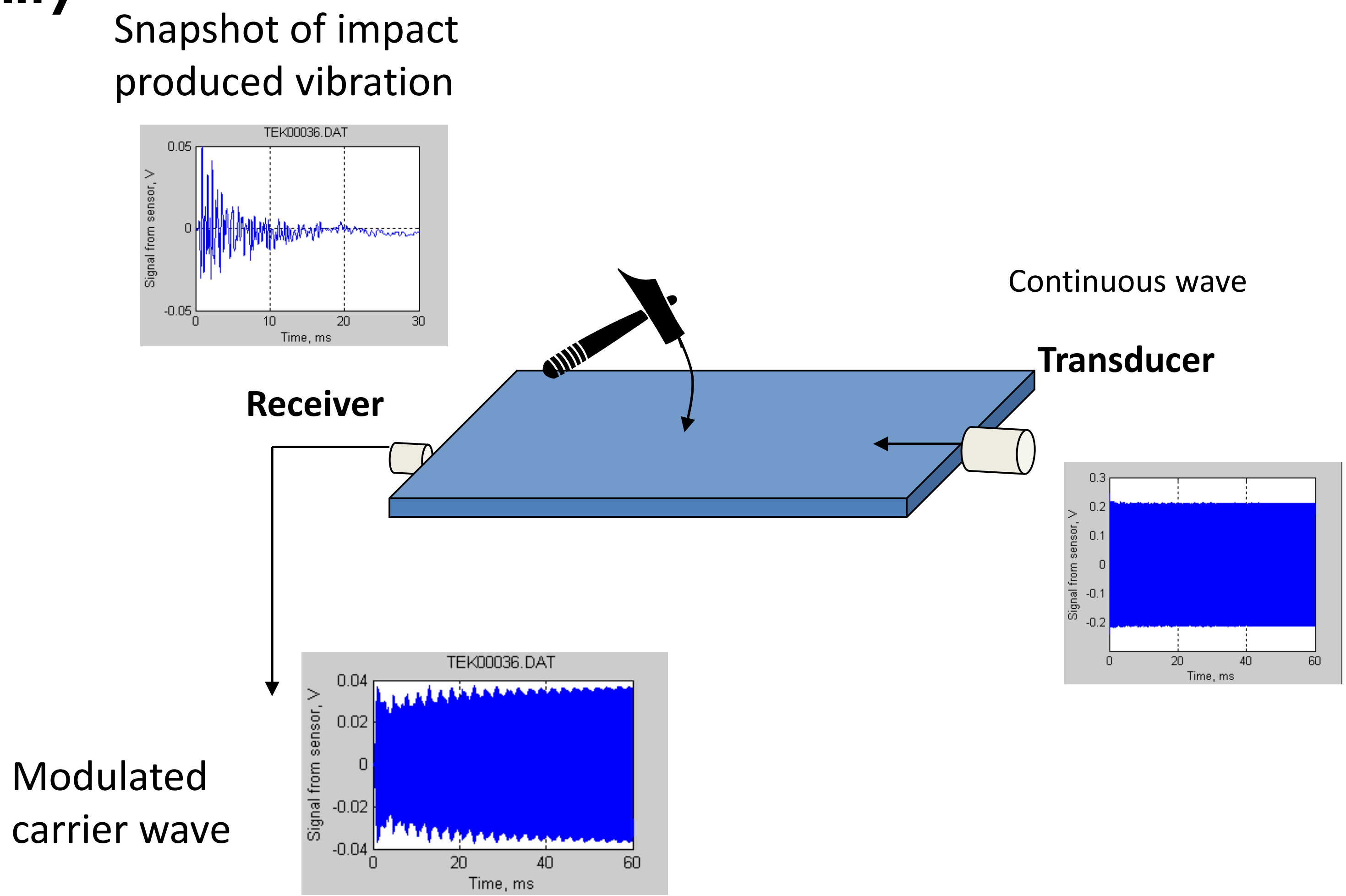
Simplified explanation



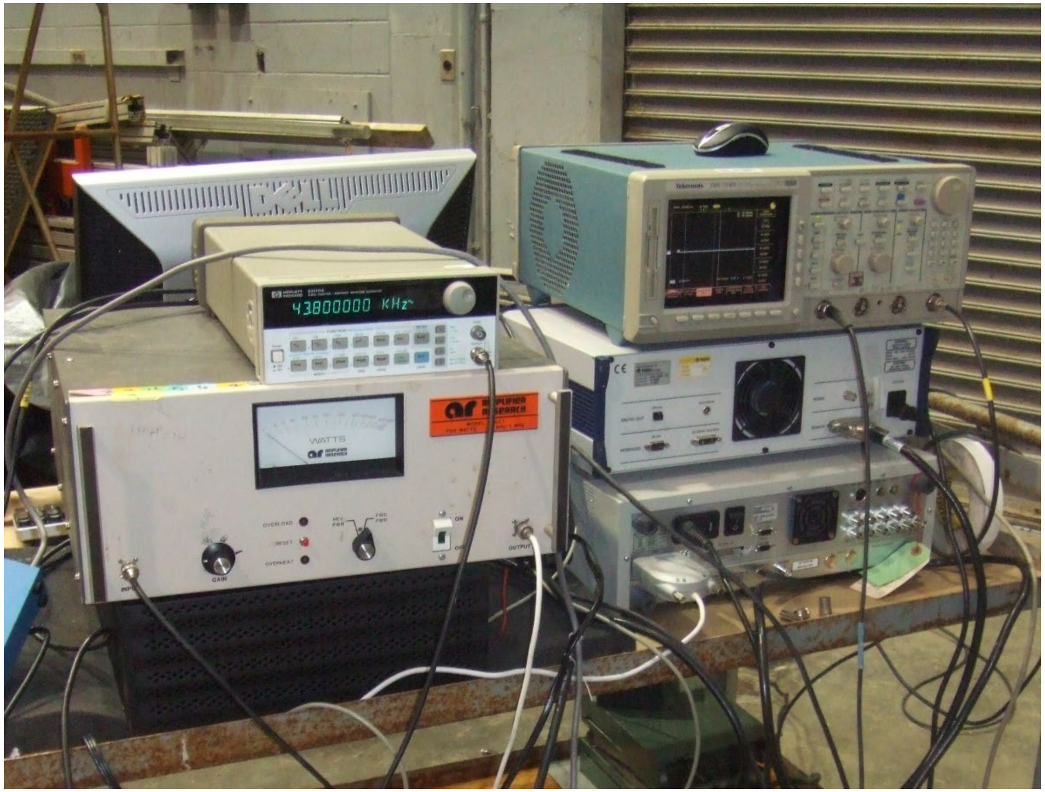
This effect is one of the most popular effect used in Nonlinear Acoustic NDE

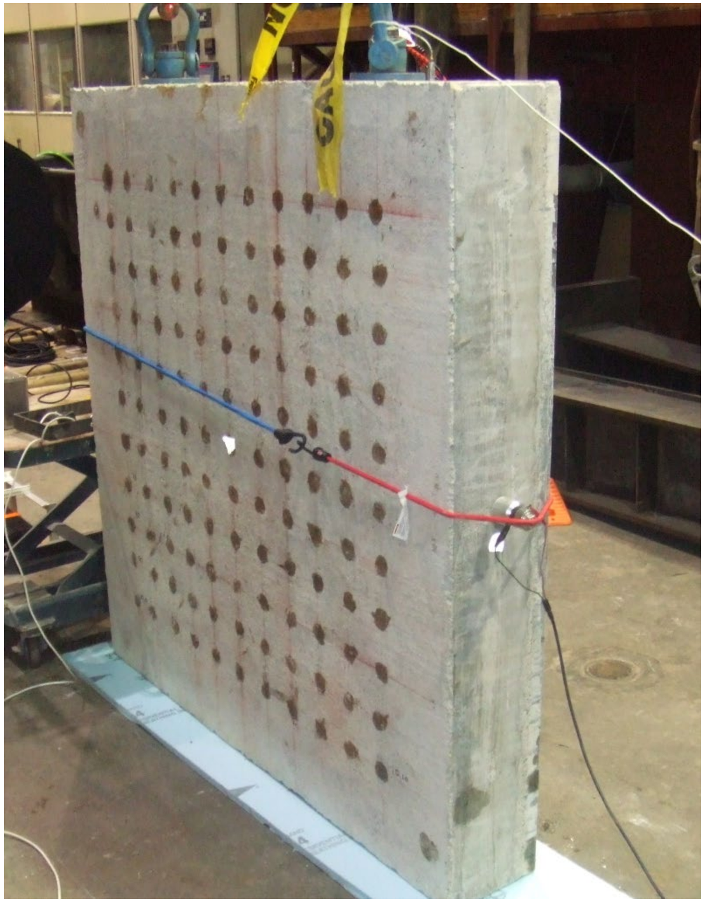
Nonlinear Acoustic NDE of Concrete

Tests were conducted at U.S. Army Corps of Engineers facility



Pictures of Experimental Setup

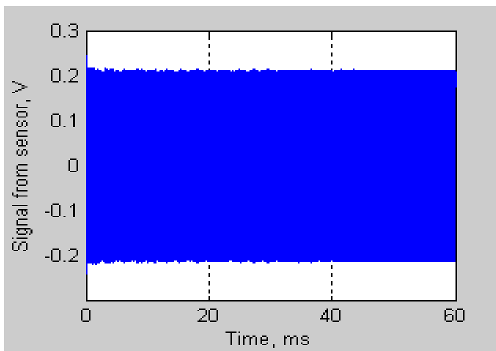
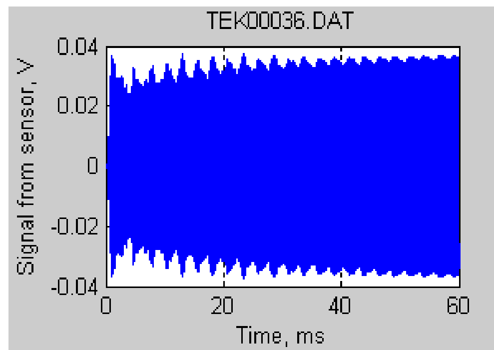
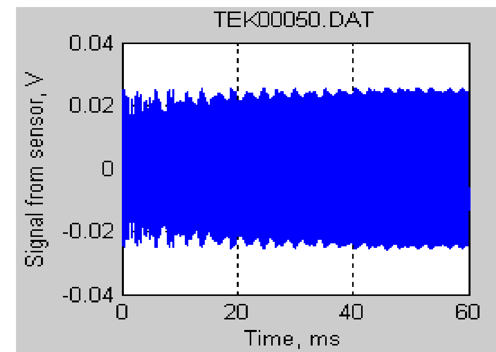
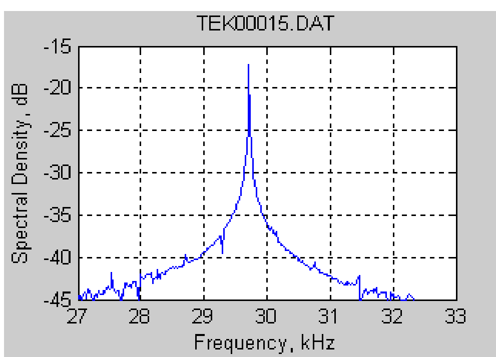
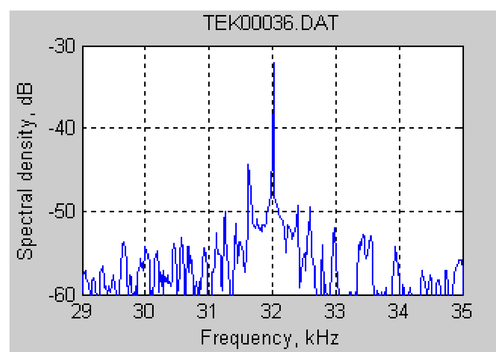
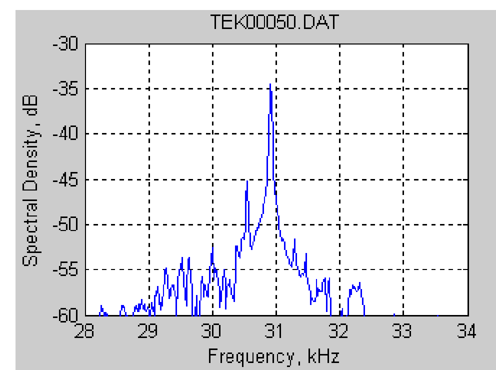




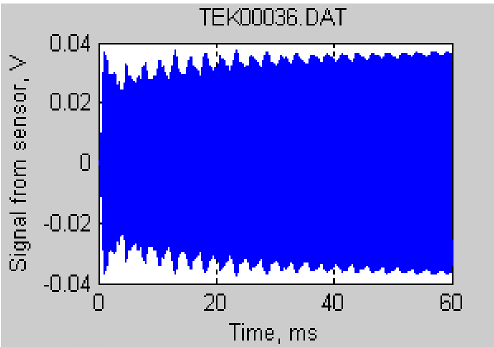
Concrete slab side size 56"

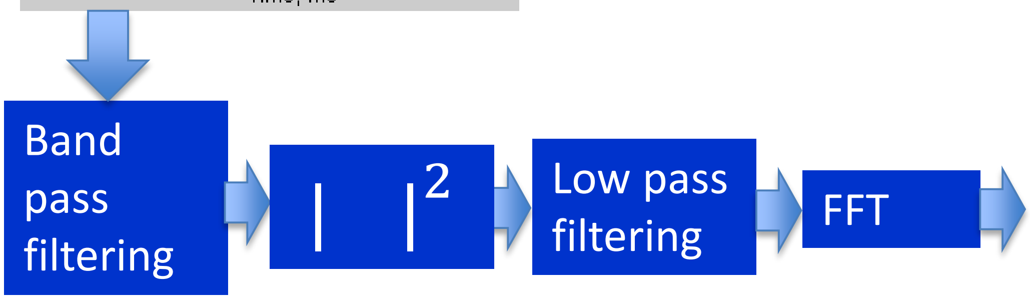
Comparison of modulation for three tested slabs

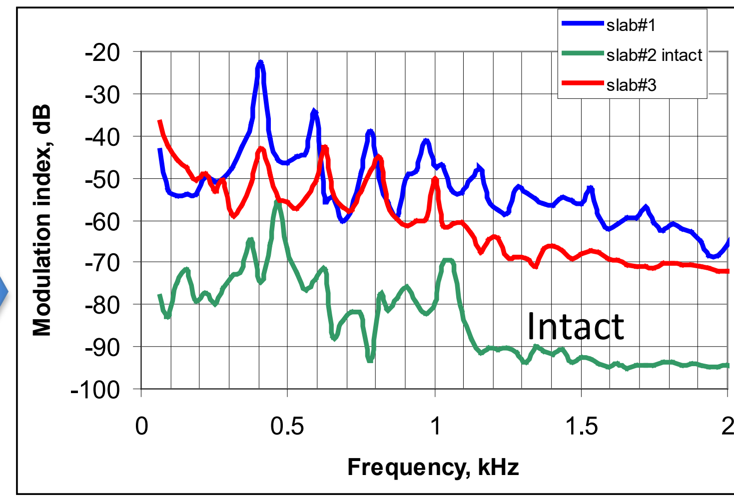
Ultrasonic frequencies ~30 and 50 kHz

	Intact slab CCS-4	Slab UCSGUHPC-10	Slab UCSGUHPC-6
Waveform			
Spectra around carrier frequency			

Demodulation processing in vibro-modulation method

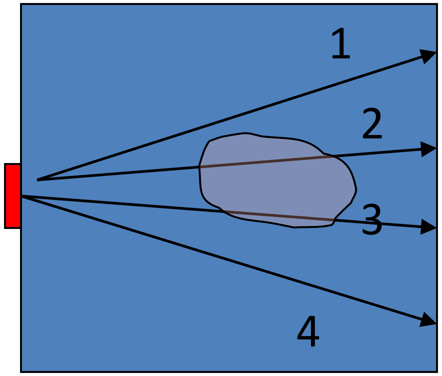






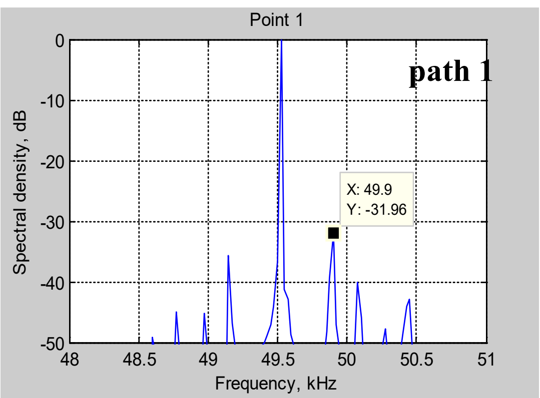
	Slab #1	Slab#2	Slab#3
Modulation Index, dB	31.6	0	20.9
Increasing of Modulation index in comparison with intact slab	1457	1	122

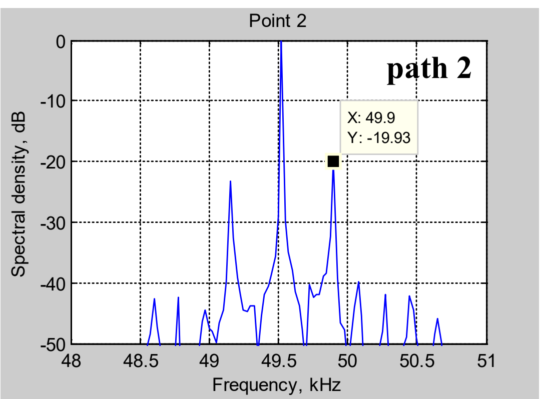
Modulation for various acoustic paths

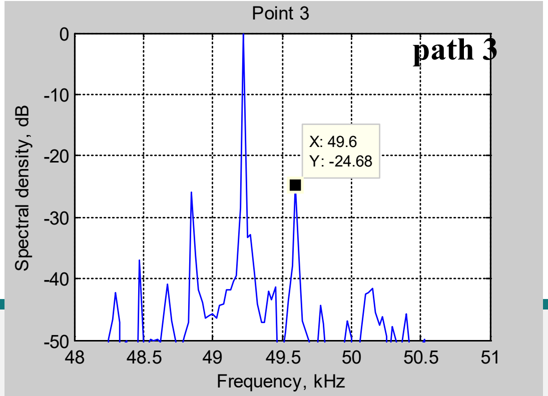


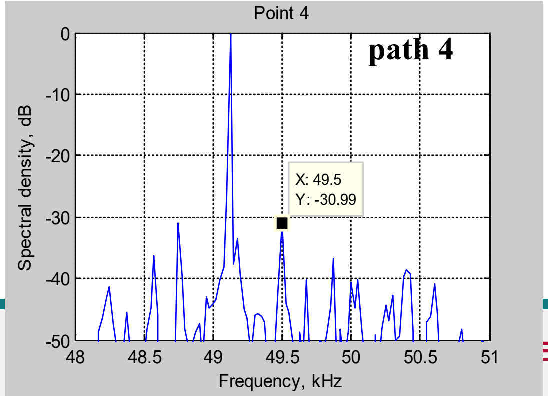
Modulation for the path passing area with cracks

Less modulation for the path without cracks

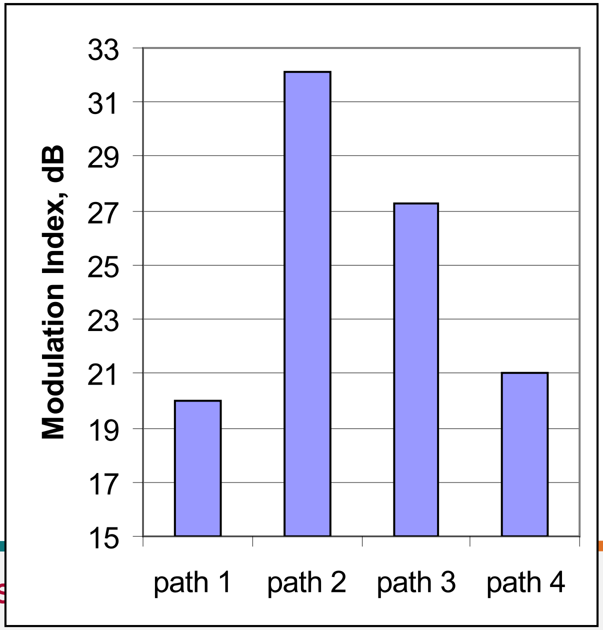




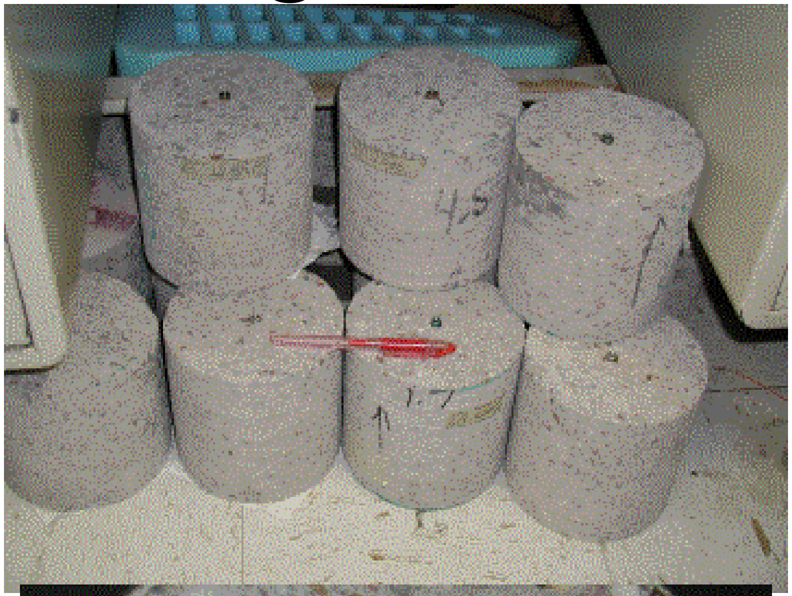


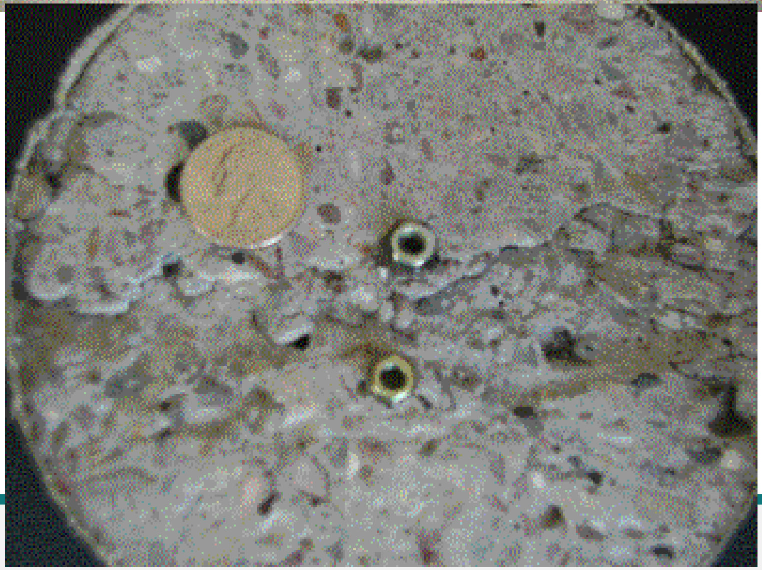


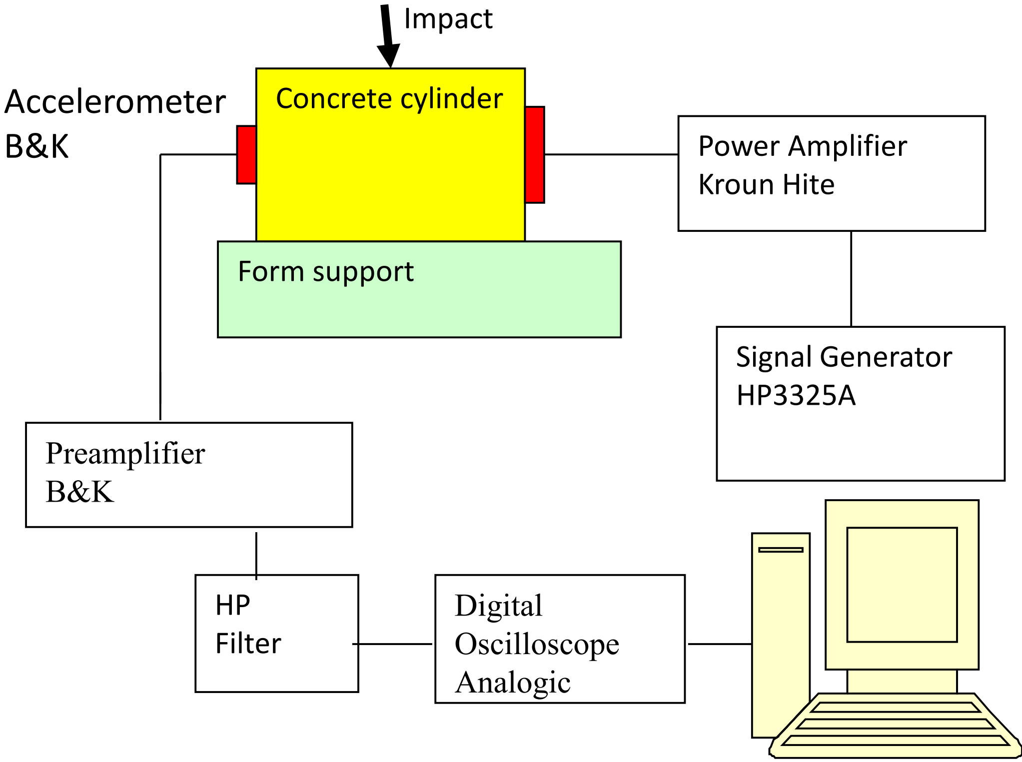
Modulation index



Vibro-Modulation test of Explosion Damaged Concrete

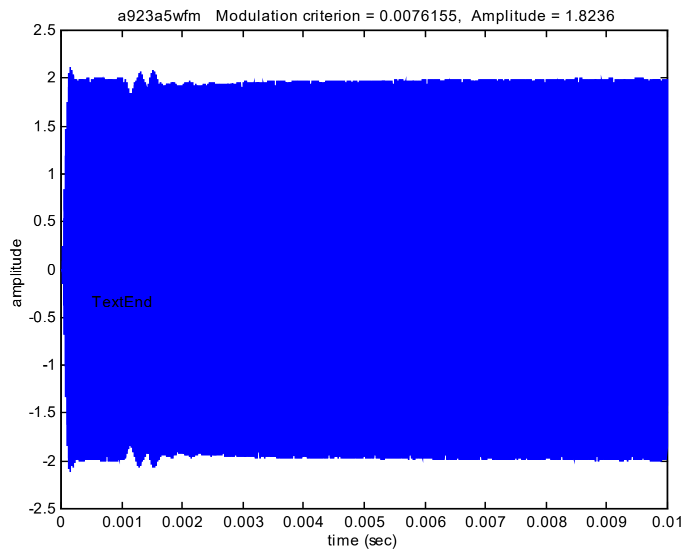




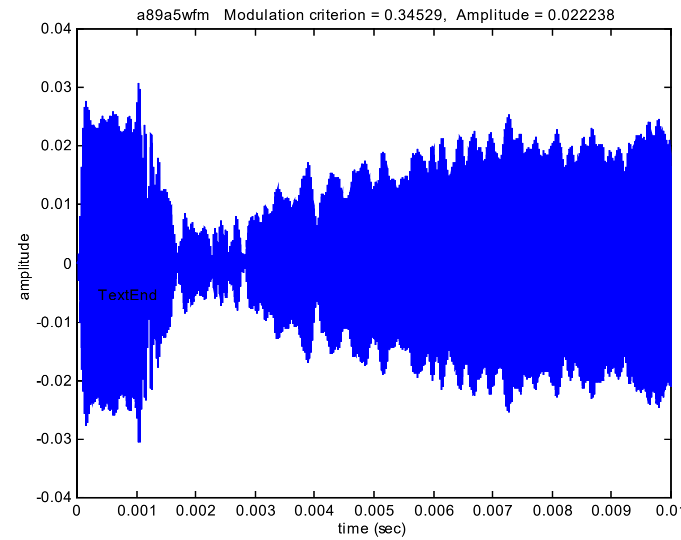


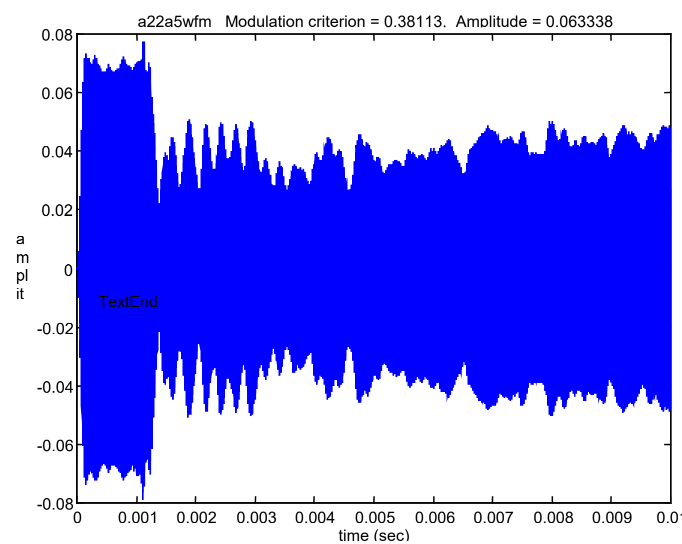
Snap Shots of High Frequency Signals

Undamaged Concrete Far from explosion

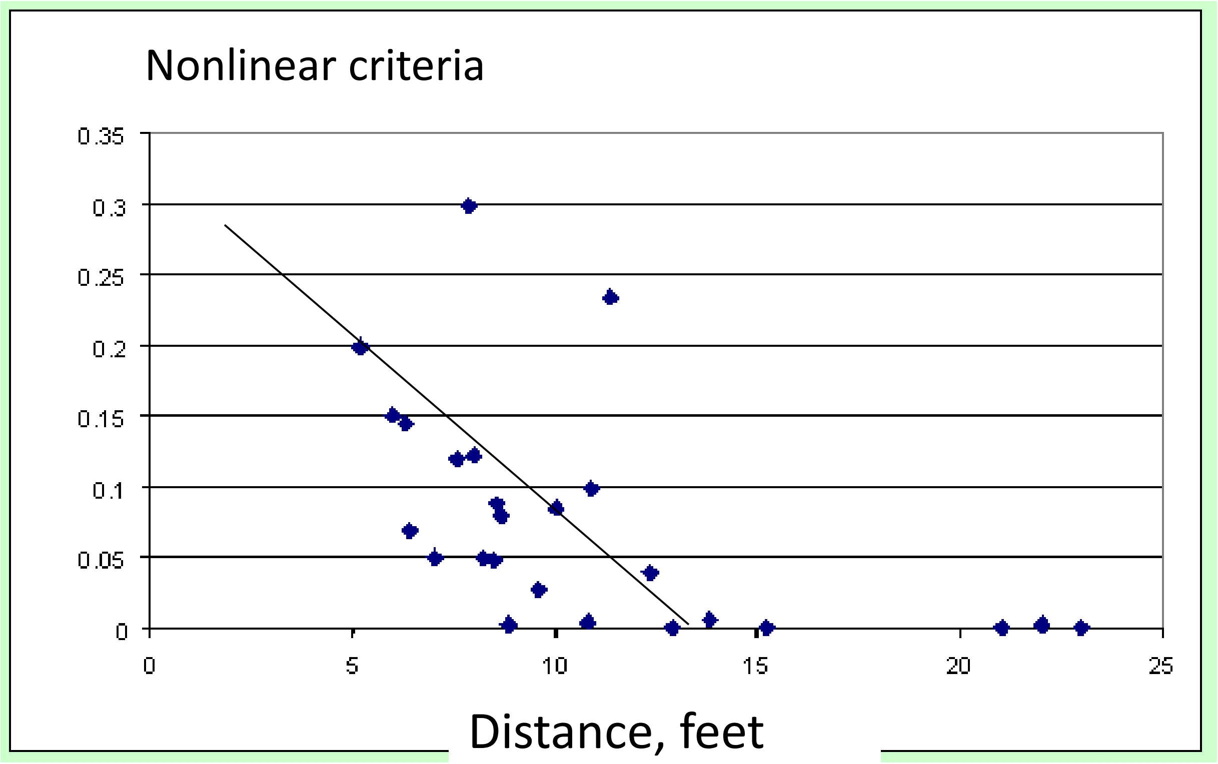


Damaged Concrete closer to explosion





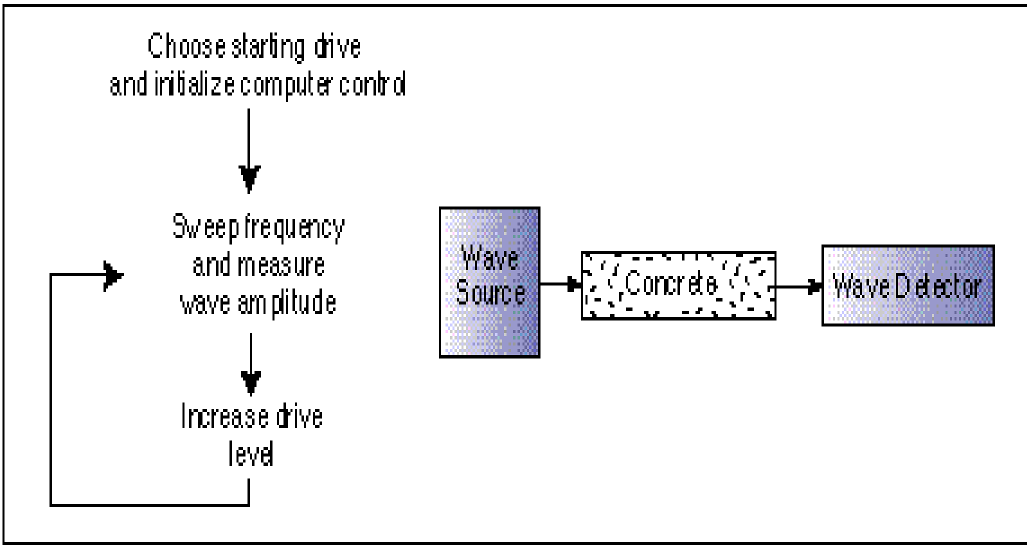
Dependence of Nonlinear Damage Criteria on Distance from Explosion

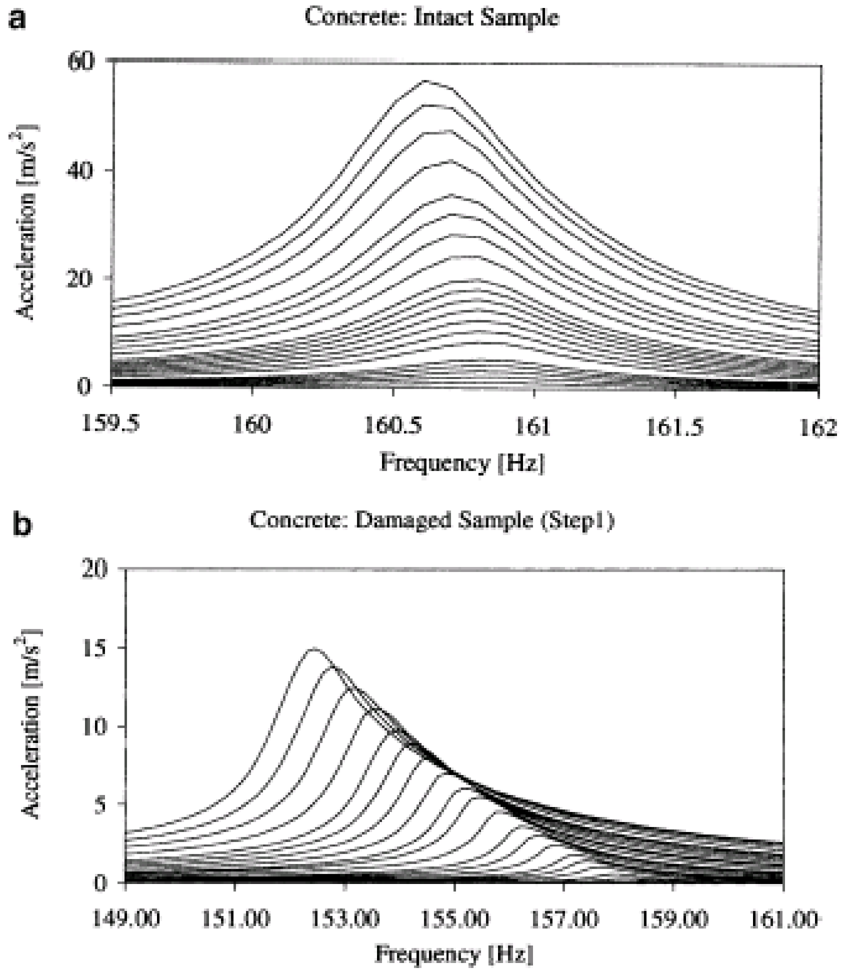


Nonlinear diagnostics provide the means to study varying quantities of damage

Nonlinear Resonant Ultrasound Spectroscopy (NRUS)

Measurement of a resonance curves function of the applied dynamic excitation





Nonlinear Criteria:

Amplitude dependable resonance frequency shift

Amplitude dependable attenuation

Comparison of Linear and Nonlinear NDE progressive damage induced by cyclic loading

K. Van Den Abeele, J. De Visscher / Cement and Concrete Research 30 (2000) 1453-1464

Nonlinear parameters:

Amplitude dependent frequency shift and attenuation

Linear parameters:

Sound speed variation and attenuation.

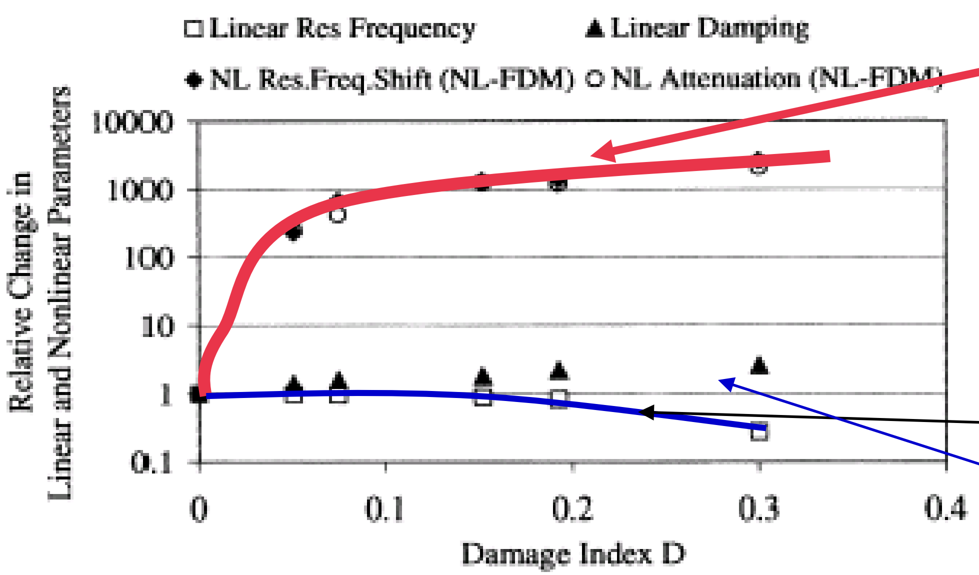


Fig. 14. Relative changes of the linear and nonlinear characteristics derived from SIMONRAS analysis of an RC beam as function of damage due to consecutive loading steps.

List of NA NDE/SHM (~10,000 papers)

Resonances of the whole structure. Nonlinear Elastic Wave Spectroscopy (NEWS)	Nonlinear Imaging Damage localization
•High Harmonic Generation and its modification (Phase Inversion, Scaling Substraction) •Nonlinear Resonant Ultrasound Spectroscopy (NRUS) •Amplitude Dependent Internal Friction •Multifrequency interaction •Nonlinear Wave Modulation Spectroscopy (NWMS) or Vibro Acoustic Modulation (VAM) •Slow Dynamics Diagnostics (SDD) •Nonlinear Reverberation Spectroscopy (NRS) or Nonlinear Impact Resonance Acoustic Spectroscopy (NRAS) •Bi Spectral and High Order Statistic Analysis •Subharmonic and Ultraharmonic Methods	•Nonlinear Time Reversal Acoustics (NTRA) or TR NEWS •Nonlinear Harmonic Imaging •Nonlinear Local Resonances method •Nonlinear Acoustic Tomography •Pulse Modification of Vibro- Acoustic Modulation (VAM) •Nonlinear Guided Wave Imaging and Tomography •Subharmonic and Ultraharmonic imaging •Fundamental wave amplitude difference imaging •Nonlinear Structural Intensity imaging

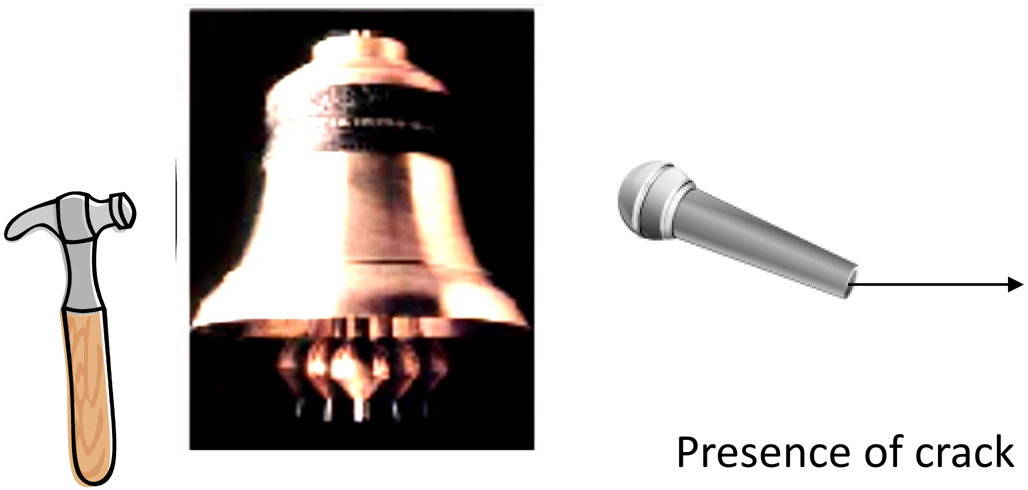
List of NA NDE/SHN (~10,000 papers)

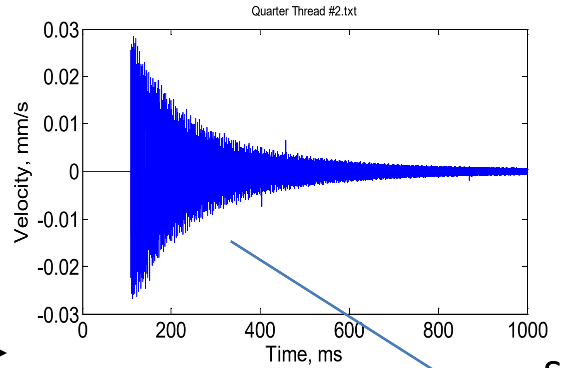
Resonances of the whole structure. Nonlinear Elastic Wave Spectroscopy (NEWS)	**Nonlinear Imaging Damage localization**
•High Harmonic Generation and its modification (Phase Inversion, Scaling Substraction) **•Nonlinear Resonant Ultrasound Spectroscopy (NRUS)** •Amplitude Dependent Internal Friction •Multifrequency interaction **•Nonlinear Wave Modulation Spectroscopy (NWMS) or Vibro Acoustic Modulation (VAM)** •Slow Dynamics Diagnostics (SDD) **•Nonlinear Reverberation Spectroscopy (NRS) or Nonlinear Impact Resonance Acoustic Spectroscopy (NRAS)** •Bi Spectral and High Order Statistic Analysis •Subharmonic and Ultraharmonic Methods	•Nonlinear Time Reversal Acoustics (NTRA) or TR NEWS •Nonlinear Harmonic Imaging •Nonlinear Local Resonances method •Nonlinear Acoustic Tomography •Pulse Modification of Vibro- Acoustic Modulation (VAM) •Nonlinear Guided Wave Imaging and Tomography •Subharmonic and Ultraharmonic imaging •Fundamental wave amplitude difference imaging •Nonlinear Structural Intensity imaging

Impulse Resonant Acoustic Spectroscopy (IRAS)

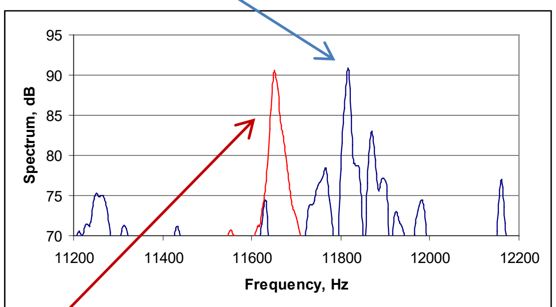
Recorded signal

Intact bell



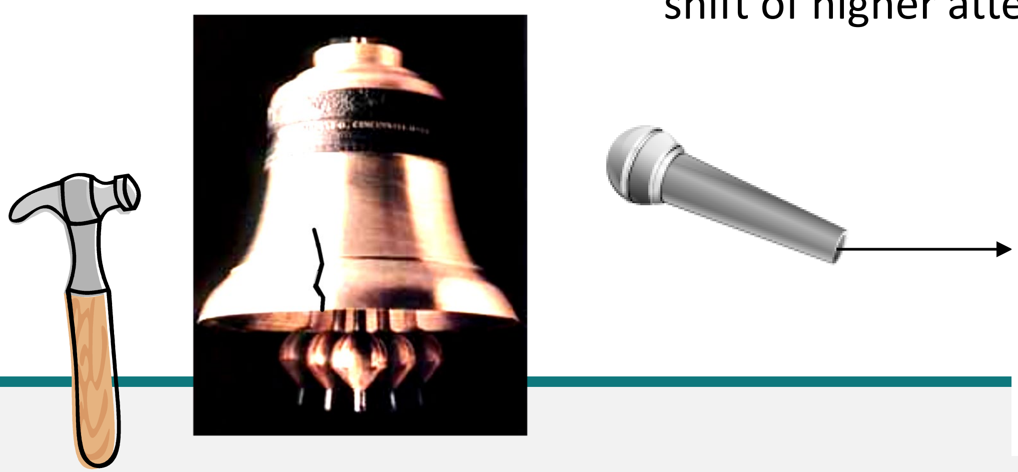


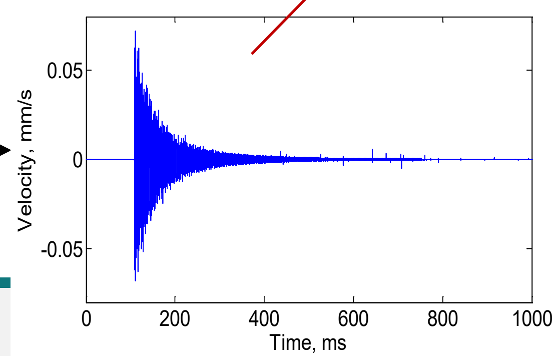
Spectra



Presence of crack leads to the resonance frequency shift of higher attenuation

Cracked bell



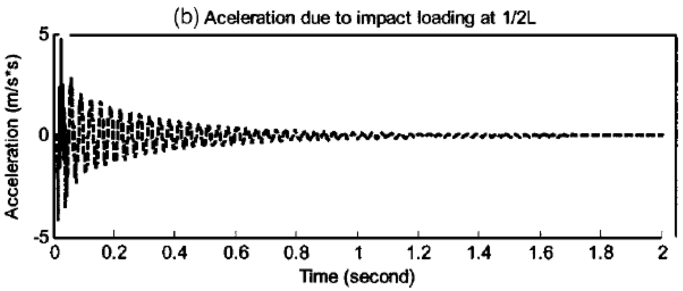


IRAS application for bridge damage detection

Example

Law, S.S. and Zhu, X.Q., 2005. Nonlinear characteristics of damaged concrete structures under vehicular load. *Journal of structural engineering*, *131*(8), pp.1277-1285.

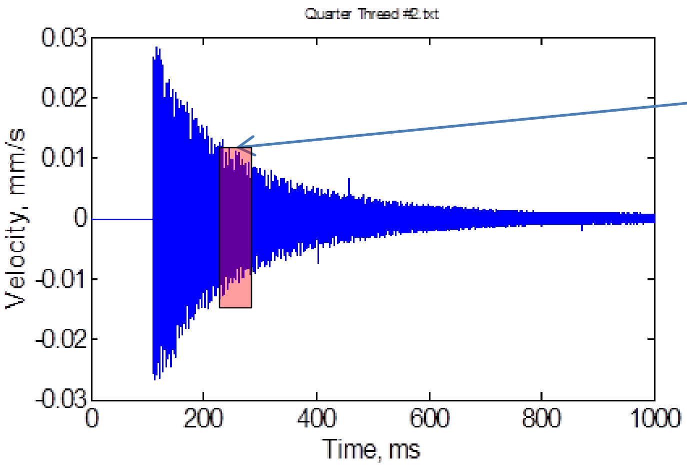
Test of a tee-section reinforced concrete beam of 5 m length, with a 4.8 m simply supported span, The impact excitation was applied using a 12 lbs model 5803A sledge hammer.



Mode number	No damage, frequency, Hz	Small damage, frequency, Hz	Large damage, frequency, Hz
1	30.7	27	25.7
2	100.9	94.4	88.8
3	168.3	158.4	154.4

Nonlinear IRAS

One of the simplest Nonlinear Acoustic SHM methods. Required equipment: accelerometer/ microphone and hammer.

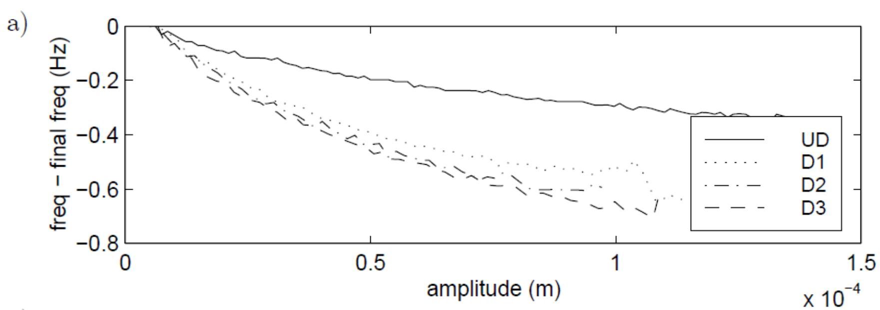


Short time window measurements of frequency and amplitude slope allow finding the amplitude dependable frequency shift and amplitude dependable attenuation by simple means.

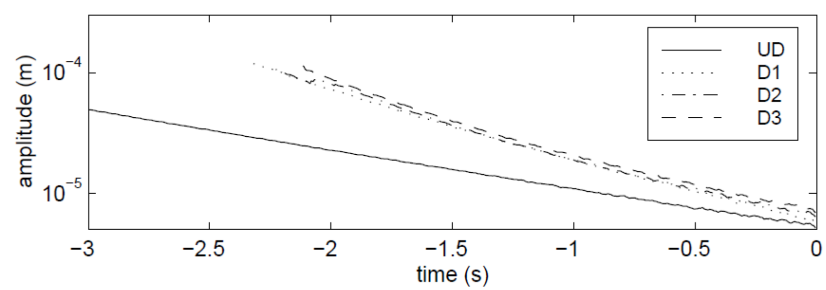
Example of the Nonlinear RUS: Using Non-Linear Vibration Techniques to Detect Damage in Concrete Bridges 2001. Ph.D. Thesis. University of Bristol

Experiments were performed on four 1.8 m long beams. The beams were 200 mm deep and 140 mm wide The fundamental frequency was 120 Hz. A loading rig was used to damage the beams.

Amplitude dependable frequency shift



Amplitude dependable attenuation



How to extract nonlinear effects directly from bridge vibration signal

No additional equipment is required

Modulation of High frequency spectral part by low frequency part can be used for **Vibro Acoustic modulation** methods

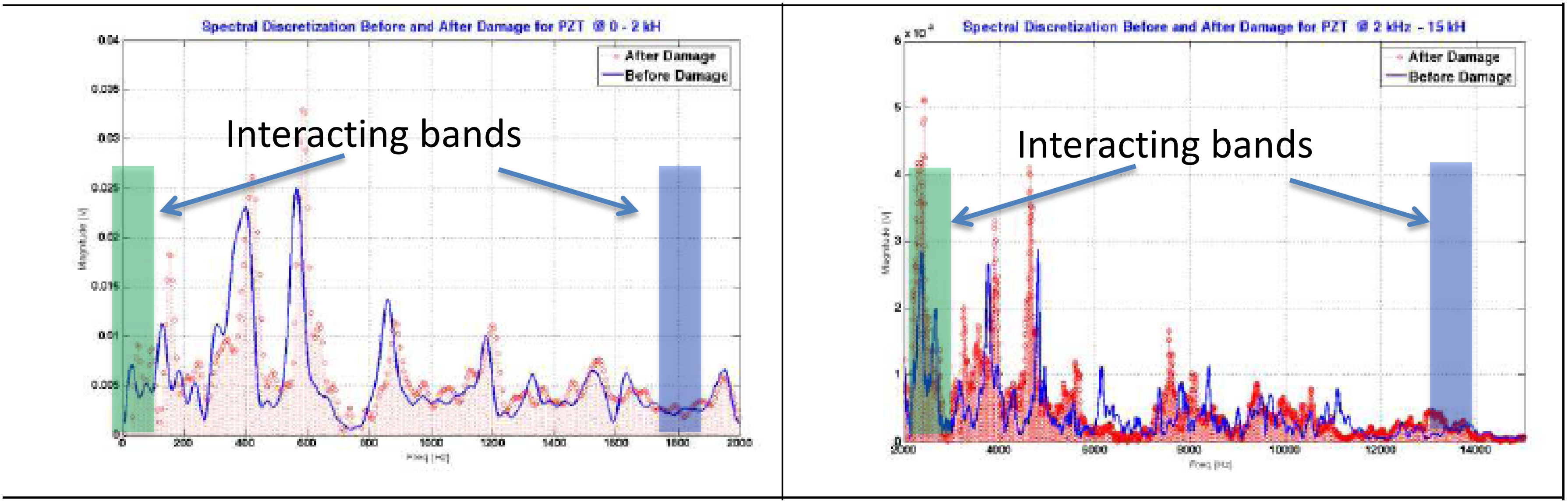
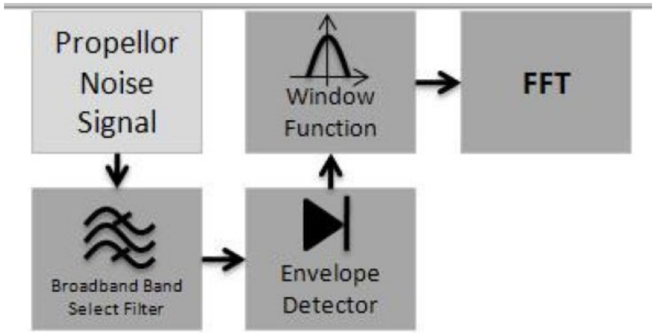


Figure – 7: Spectral Profile before damage and Spectral Harmonics after damage

Belisario-Briceno, A., Zedek, S.F., Camps, T., François, R., Escriba, C. and Fourniols, J.Y., 2014, July. SHM based on modal analysis: accelerometer and piezoelectric transducers instrumentation for civil engineering in heterogeneous structures. EWSHM - 7th European Workshop on Structural Health Monitoring, IFFSTTAR, Inria, Université de Nantes, Jul 2014, Nantes, France

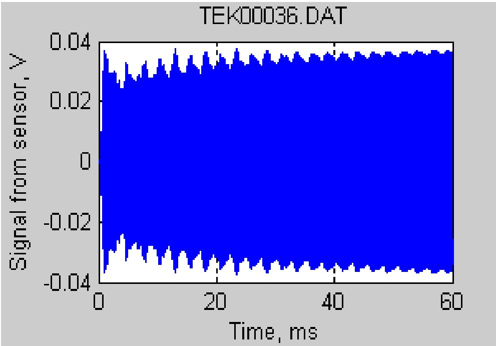
DEMON application for Nonlinear Vibro/acoustic SHM and for Nuclear war prevention

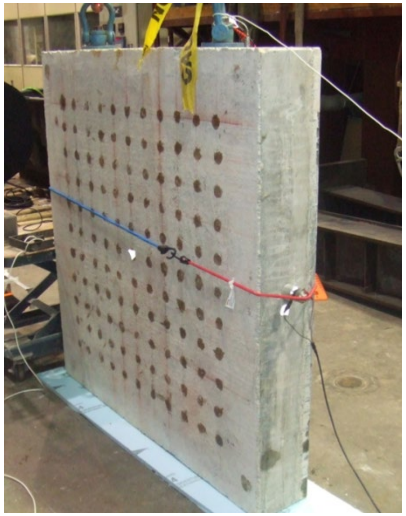
DEMON processing (**DEtection** of **Modulation On Noise**) is a technique employed by submariners to **detect** the presence of propeller craft. It uses the FFT of the **envelope** of band pass filtered sonar signals to emphasize the **modulation** in time of the pressure signal.



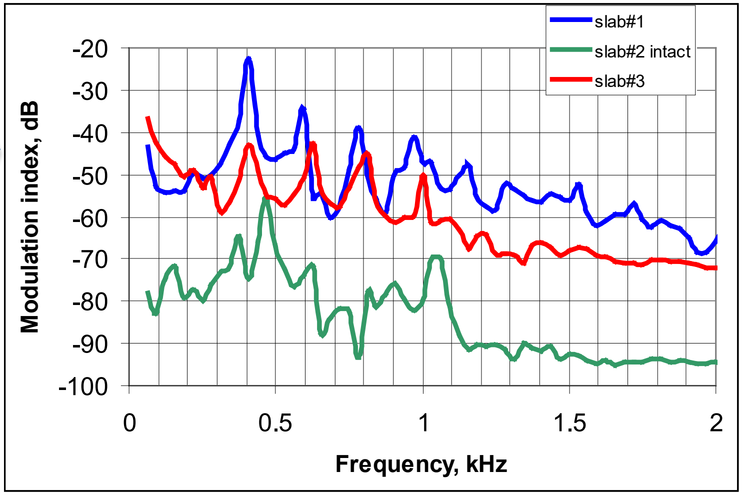
Coates, R, 2001, *Active and Passive Naval Sonar*, The Sonar Course, Seiche Pty Ltd, United Kingdom

Demodulation processing in vibro-modulation method



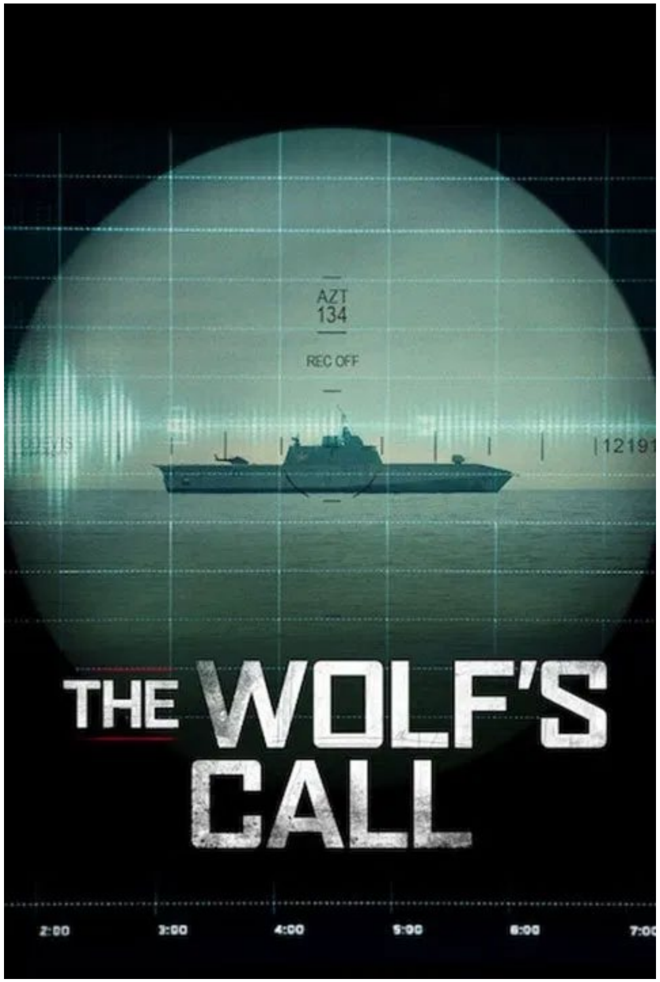


Band pass filtering → $| \quad |^2$ → Low pass filtering → FFT →



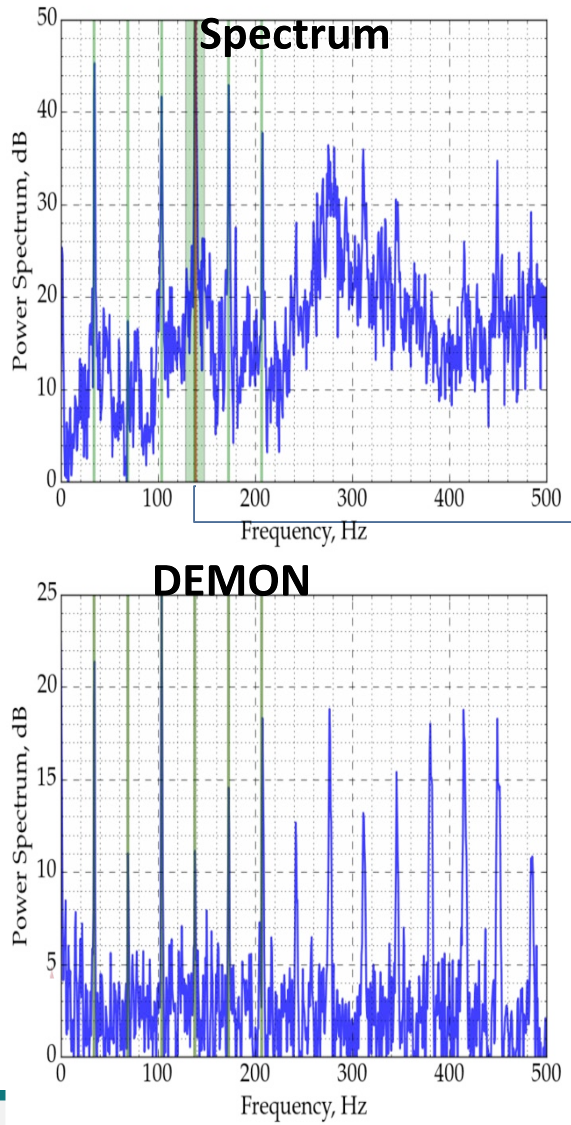
DEMON process that was applied for submarine classification and can be applied for Nonlinear SHM without any additional equipment

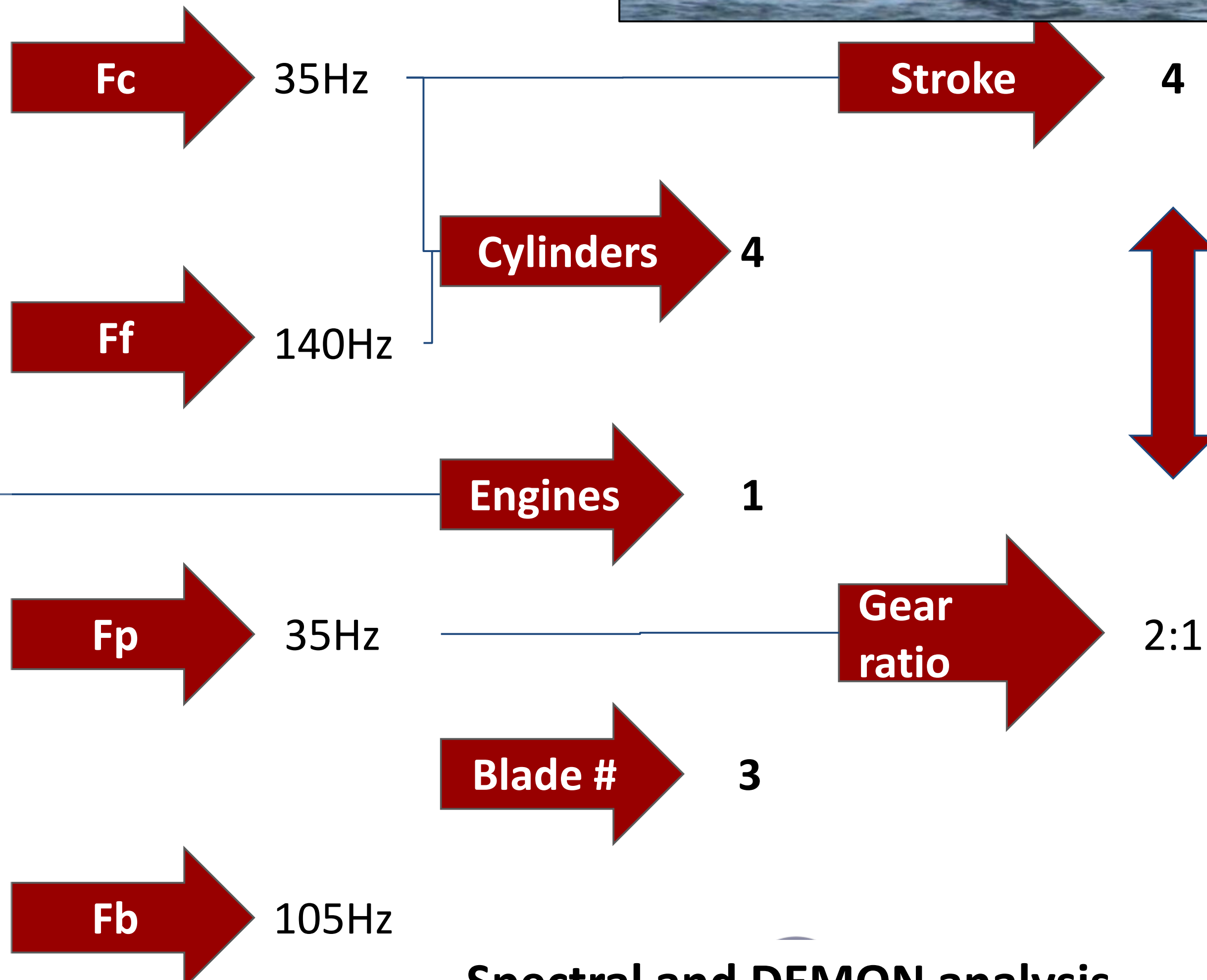
DEMON application for nuclear war prevention in the movie the Wolf's Call (Netflix 2019)



The main character in this movie is a sonar officer whose "golden ears" can distinguish virtually any vessel based on its acoustic signature. He used DEMON that allows finding that a submarine firing a missile leading to WW3 was not really a modern Russian sub, but an old Russian sub purchased by jihadists.

Boat signal processing at Stevens STAR center





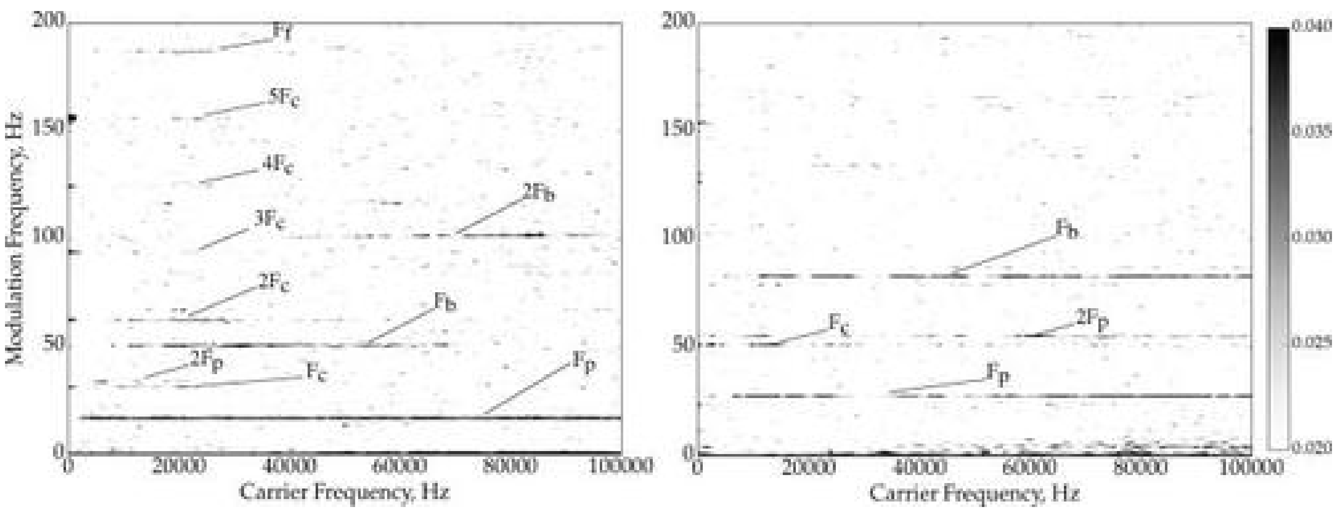
Spectral and DEMON analysis allowed boat detection and classification

DEMON extension - Cyclic Modulation Spectrum

This algorithm demodulates various frequency components in the recorded wide band signal and allows finding high frequency bands having maximal modulation.

Can be applied for optimization of vibro-modulation method.

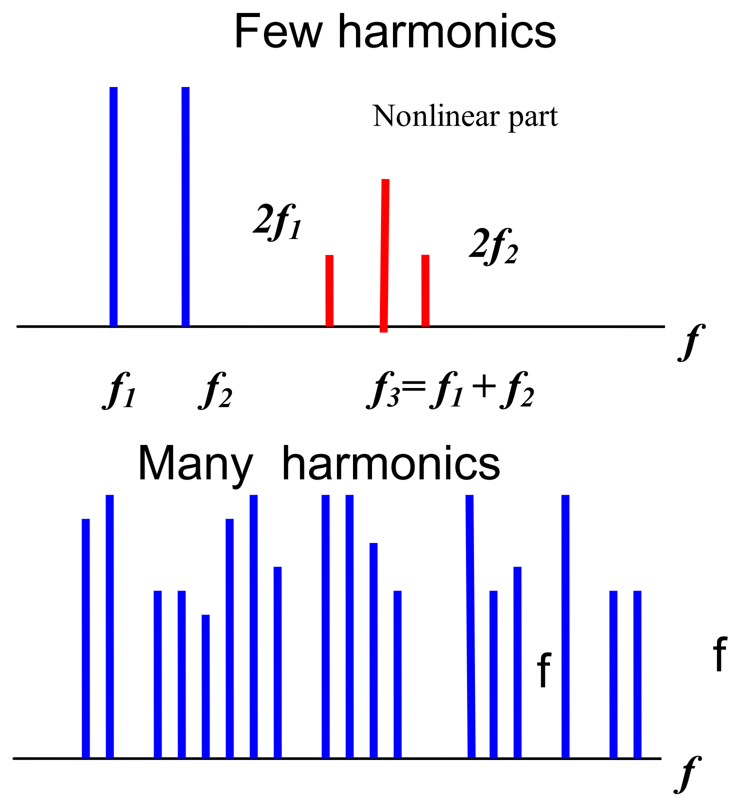
Pollara, A., Sutin, A. and Salloum, H., 2017. Modulation of high frequency noise by engine tones of small boats. The Journal of the Acoustical Society of America, 142(1), pp.EL30-EL34.



CMS of the Panga traveling at 8 kts (left) and 21 kts (right). F_p, F_b, F_c, and F_f, and their harmonics are marked where they occur.

Bi Spectral and High Order Statistic Analysis in Structural Health Monitoring

Workers rappel down the side of the Brooklyn Bridge to install highly sensitive accelerometers to measure vibrations

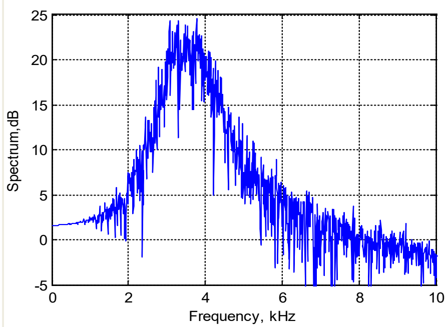
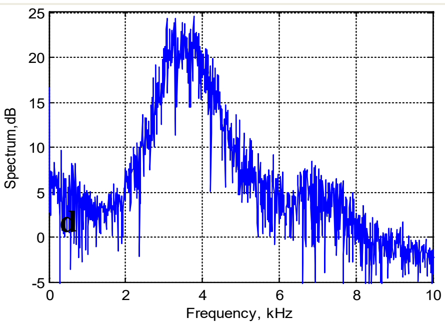
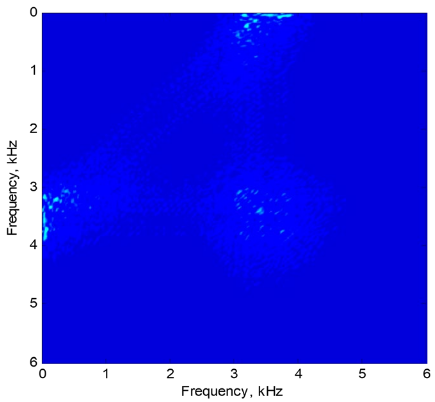
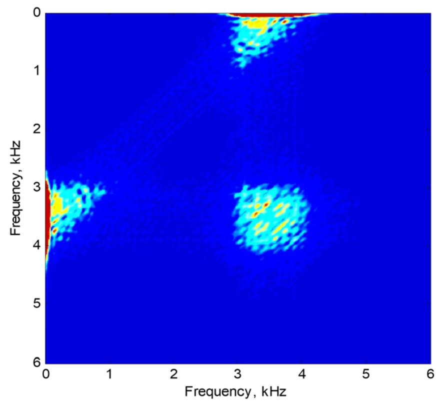


$$E_{xxx}(f_1, f_2) \quad = X(f_1)^* X(f_2)^* X(f_1 + f_2)$$

E is the mathematical expectation, *X* is Fourier transform, * complex conjugative. The bispectrum analyzes the interaction between frequencies f_1, f_2 and $f_1 + f_2$

Simple simulation of bi spectral analysis

For a random signal ***X(t)*** in the frequency band 2-3 kHz (max ***X=1***) the nonlinear effects were simulated by $Y=X+0.1X^2$

	$Y=X$	$Y=X+0.1X^2$
Spectrum		
Bi Spectrum		

Example of bi-spectral analysis application

Pazdera, L., Smutny, J. and Topolar, L., 2011, June. Applying High Order Statistics Analysis at Non Destructive Evaluation of Concrete Tiles. In *49th International Scientific Conference* (p. 309).
Test results for a flawless concrete roof tile and for a roof tile containing simulated defect, intentionally created crack.

George, D., Hunter, N., Farrar, C. and Deen, R., 2000, February. Identifying damage sensitive features using nonlinear time-series and bispectral analysis.
In *Proceedings of the 18th International Modal Analysis Conference* (pp. 1796-1802).

The data are from the UC-Irvine bridge column tests 36-in-dia (91-cm-dia) columns. , 136 “ length.
17 columns were tested (11 damaged), 40 accelerometers and APS electromagnetic sensor for vibration excitation.

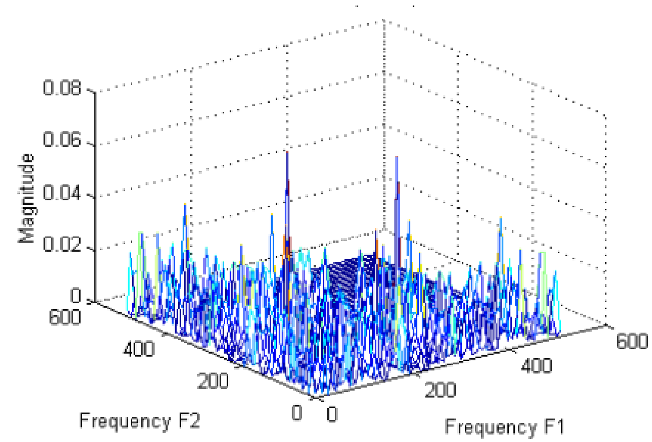


Fig. 5 Bicoherence function obtained from accelerometer 1 data measured on the undamaged column.

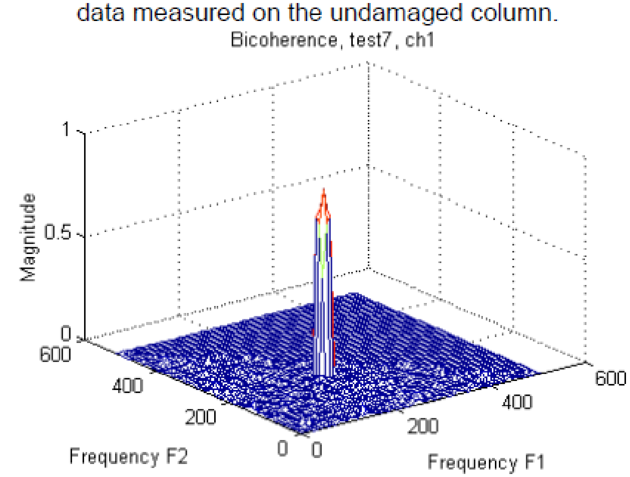
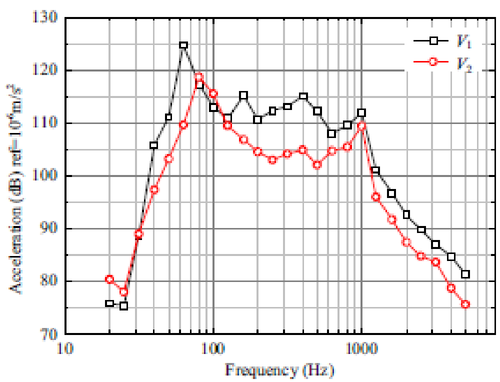


Fig. 6 Bicoherence function obtained from accelerometer 1 data after the shotcrete column had been cycled to the first yield level (Test 7).

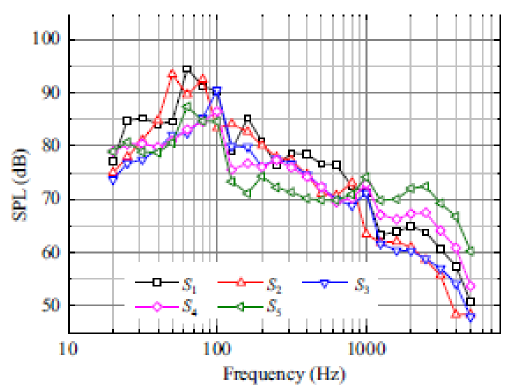
Possible applications of bridge sound recording

Bridge borne noise is produced by bridge vibration and nonlinear properties of audio noise reflect nonlinear vibration properties that can be used for SHM

Acceleration



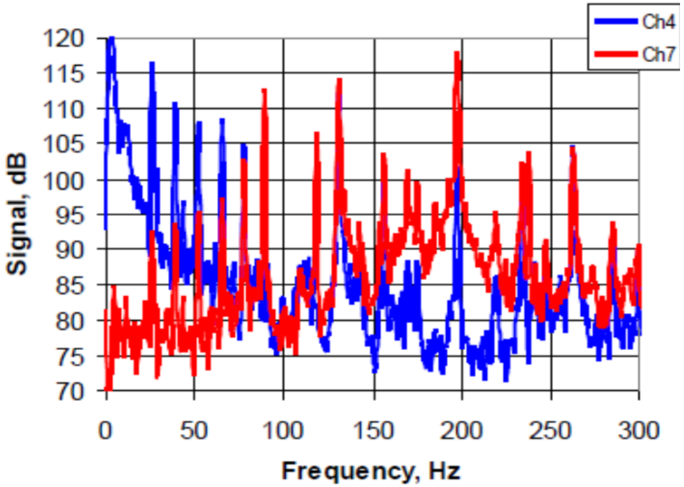
Sound



Li, X., Yang, D., Chen, G., Li, Y. and Zhang, X., 2016. Review of recent progress in studies on noise emanating from rail transit bridges. Journal of Modern Transportation, 24(4), pp.237-250.

Stevens acoustic and vibration sensors and signal analysis for low flying aircraft detection

Comparison of the spectrograms recorded by the microphone **(blue)** and by the geophone **(red)** for the Ultralight flight

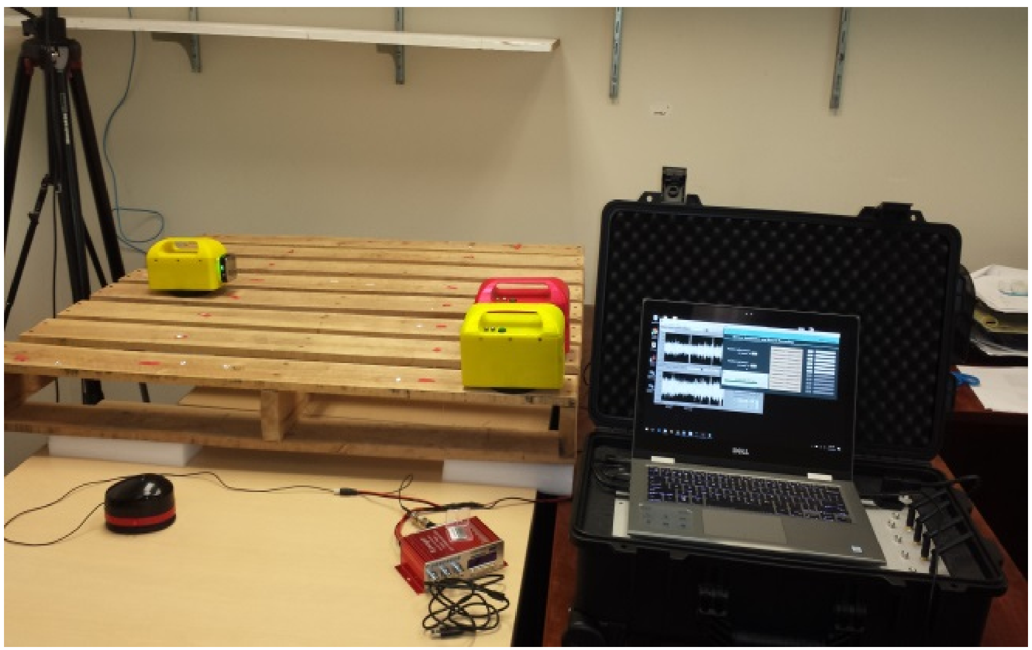


Sedunov, A., Salloum, H., Sutin, A. and Sedunov, N., 2018, October. Long-term testing of acoustic system for tracking low-flying aircraft. In 2018 IEEE International Symposium on Technologies for Homeland Security (HST) (pp. 1-6). IEEE.

Stevens acoustic and vibration sensors and signal analysis

Prototypes for detection of wood boring insects in Wooden Packing Materials (for Customs Border Protection) in trees (for USDA).

We built wireless vibration sensors with coupling provided by the sensor weight. No clamping is required.



Small recording systems included accelerometers and microphones for cancellation of external sounds.

Conclusions

Nonlinear acoustic NDE/STM were suggested 25-30 years ago. They have high sensitivity for detects but are complicated and not simple to use.

We described here the simplest NA SHM methods that do not require complicated equipment: just vibration sensors and a hammer.

Impulse Resonant Acoustic Spectroscopy (IRAS) and NIRAS are the simplest active methods with a hammer. Many studies were conducted here but they did not reach transition to practice.

Analysis of nonlinear effects in vehicle/train excited vibration is a prospective method. This analysis can be done for previously recorded bridge vibration signals. Some research was conducted using bi spectral analysis but was not applied is practice. DEMON was not used here and its application may be beneficial.

Sounds generated by bridges have chance to be used for Nonlinear acoustic SHM.

The STAR center at Stevens has experience and algorithms for Nonlinear SHM. We have equipment that can be used for bridge diagnostics.