Real-Time Monitoring of Burning Buildings

A different approach…

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Topics

- Background and Development
  - Contributions/Milestones 2001-present
- Shift in focus
  - Collapse → Stability

- Theory of Stability Monitoring Approach
- Monitoring Technique Development
- Frequency Based Stability Indicator
- Field Test Results

- Practical Applications and Tasks

Background and Development

- Original grant (Sept 2000) funded to pursue acoustic based tracking of firefighters during operations
- Vibration-based approach proposed (Jan 2001) to NIST
- First field demonstration of fire-induced vibration monitoring (Phoenix, AZ March 2001)
- First field demonstration of correlation between fire-induced vibrations and impending collapse (Kinston, NC August 2001)
- Wide range of full-scale burn tests conducted on wood, steel and masonry structures (2002-2005)
- Stability based indicators proposed (August 2005)

Contributions/Milestones 2001-present

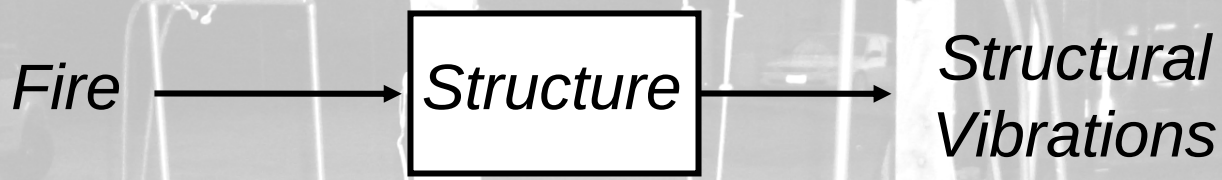
- Development of
  - fire-induced vibration based approach
- Demonstration
  - that fire excites measurable structural responses in burning buildings
  - that fire-induced vibrations contain important information on the changing conditions in a burning building
- (Ongoing) Development of
  - a practical field monitoring technique
  - of cost-efficient and reliable fire-sensors
  - a Systems Based Theory that describes observed behavior during burn
  - real-time monitoring tools and visual indicators of changing conditions during burn

Shift in focus

- Originally focused on *collapse monitoring and prediction*
- Currently focused on *stability based monitoring*
  - opens up a wider range of applications
    - burning structures (i.e. not limited to buildings)
    - damaged structures (i.e. not limited to fire)

Theory of Stability Monitoring Approach

Systems Model



Traditional Systems Theory predicts behavior based on "inputs and outputs" and the ratio of these

Transfer Function Analysis (TFA)

- Defined as

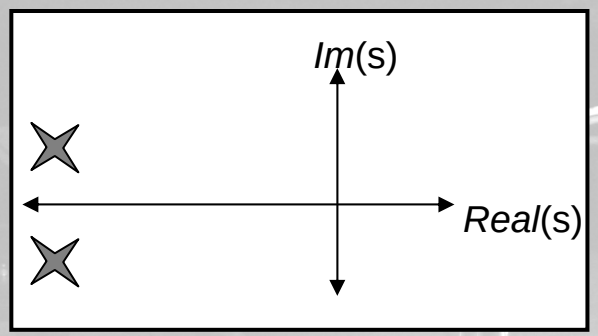
$$H(s) = \frac{Output(s)}{Input(s)} = \frac{N(s)}{D(s)}$$

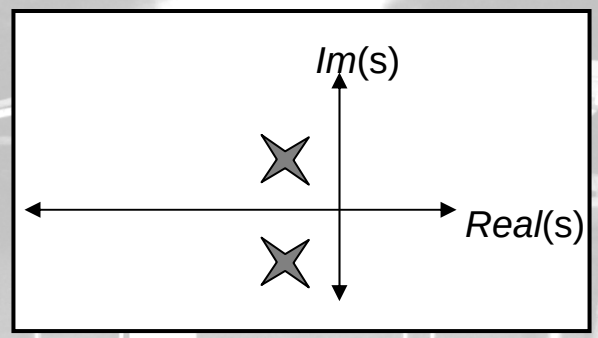
- The poles (roots) of the dominator $D(s) = 0$ provide all the information we need about a system's behavior and relative stability
- What would these poles look like in the field?
  - How do poles relate to measured responses?
  - Can you extract poles from measured responses?

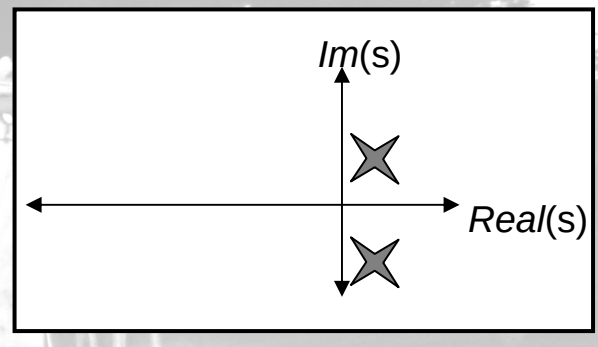
Principles of Stability Theory

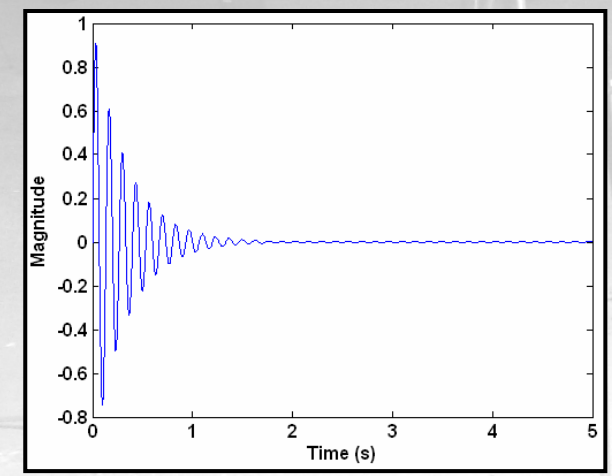
Poles and Stable Behavior

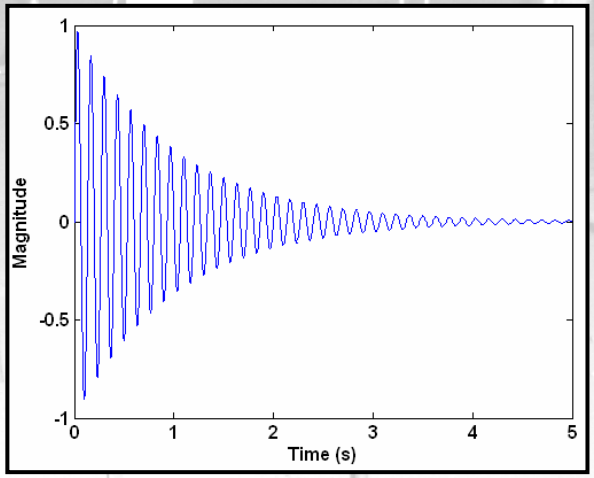
Poles contain information on frequency and damping

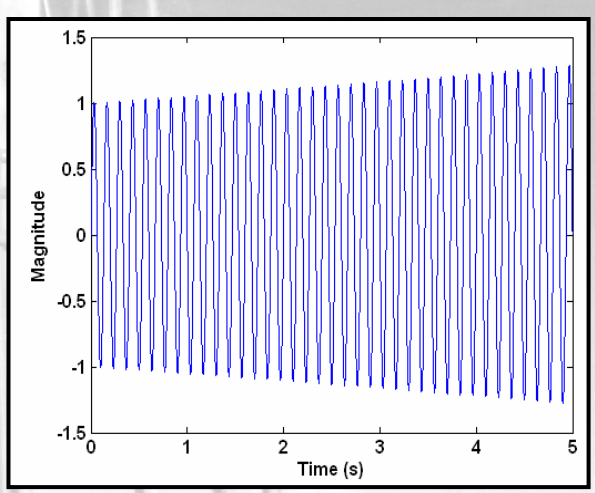






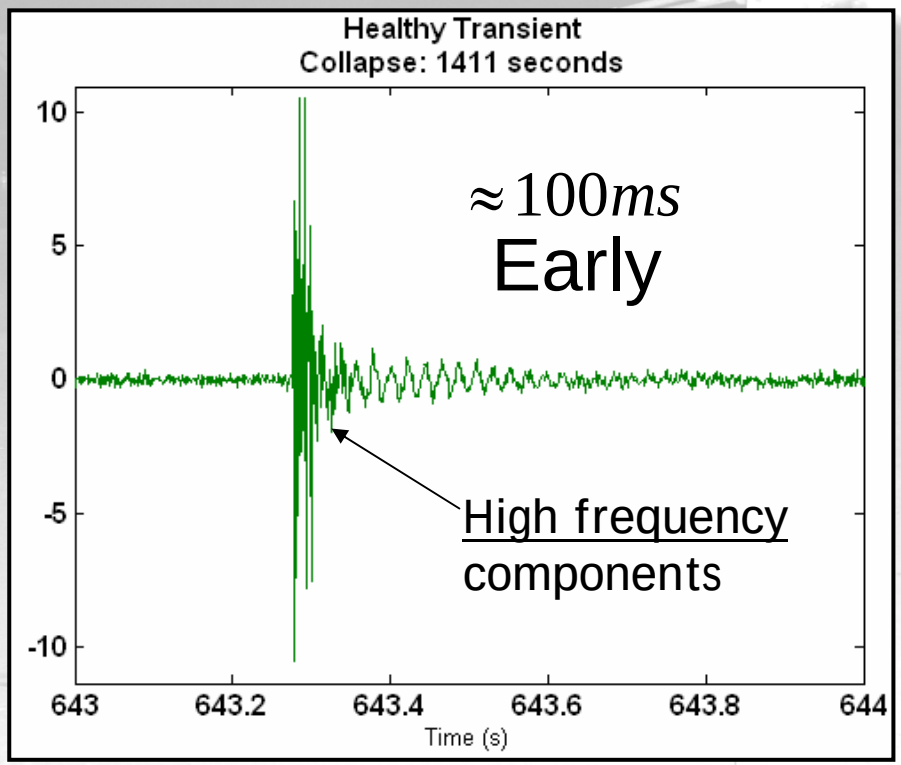


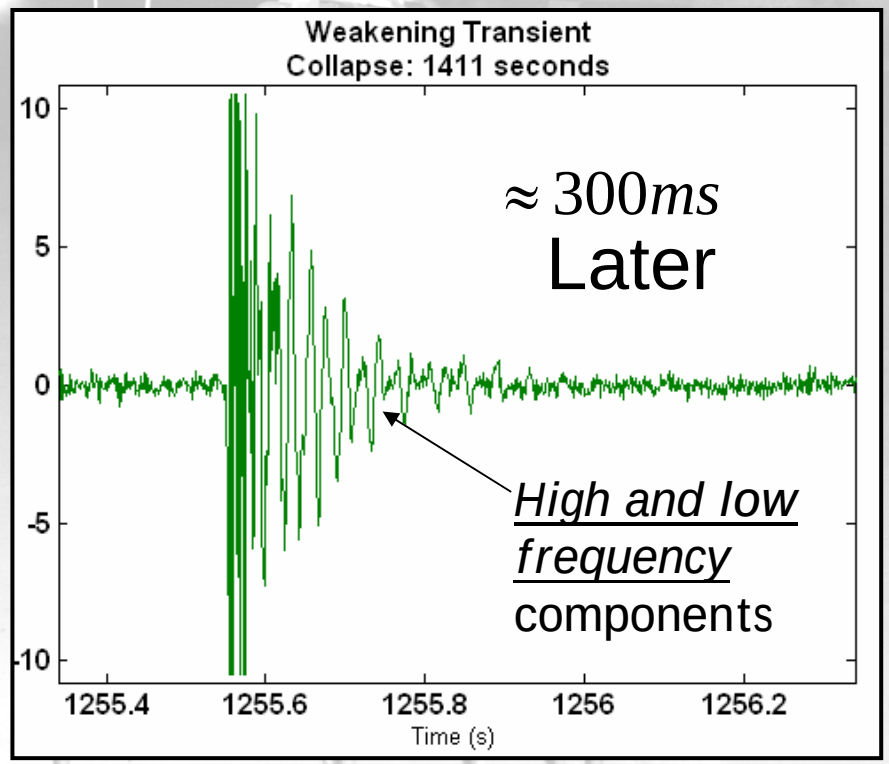




Sample Field Data

- As burning continues, the transients take longer to return to original levels





Stability and Energy Absorption

- As a structure burns, its ability to absorb impacts (and return to its original position) diminishes
- The time it takes a structure to "recover" from an "impact" is a direct indicator of its growing instability

Healthy Structure

Damaged Structure

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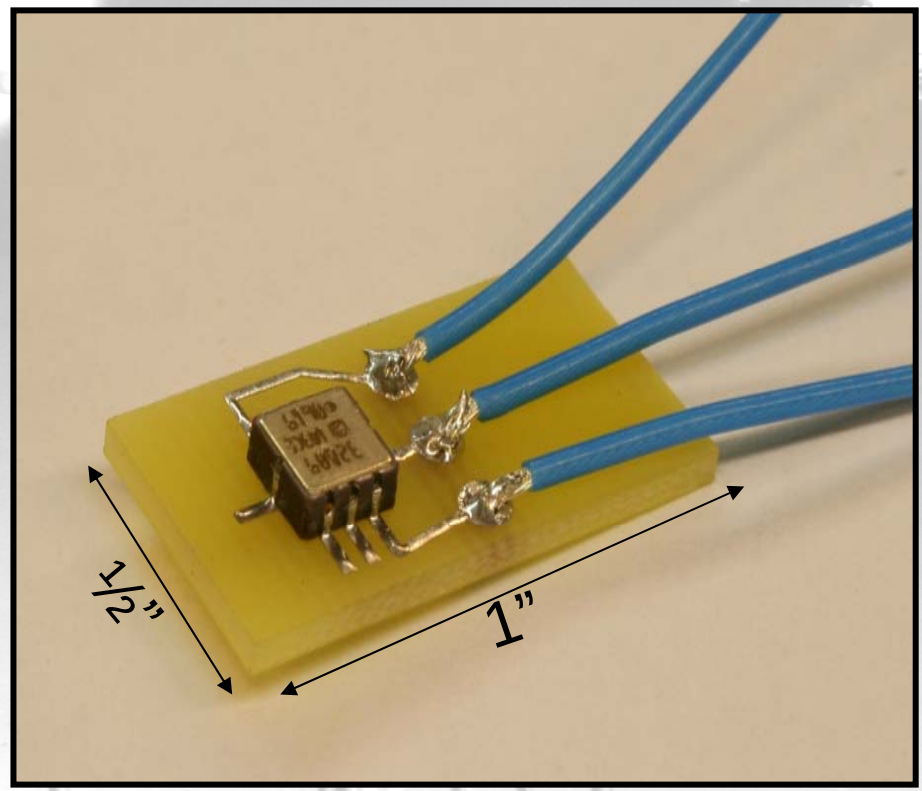
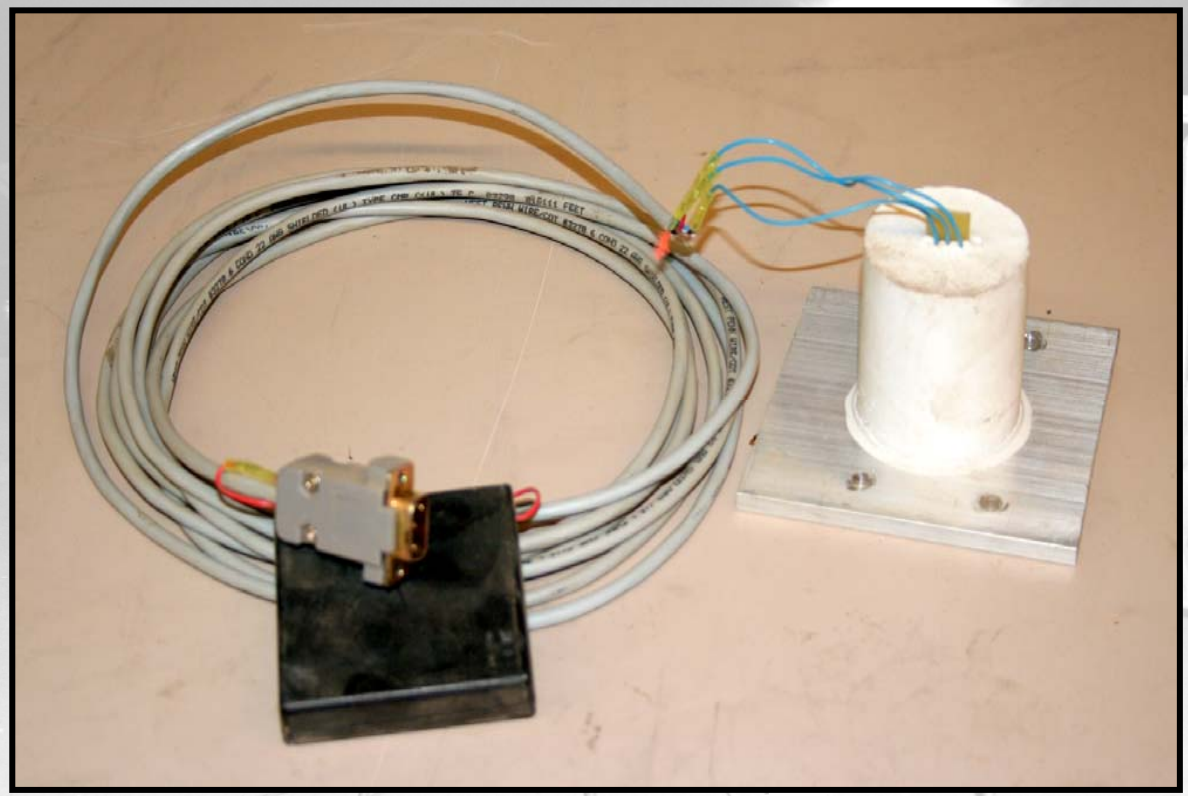
NIST

Monitoring Technique Development

- Fire-Sensor Development
  - MEM Accelerometer
  - Cost
    - $12 (Analog Devices)
    - Down from $1500
    - Down from $250
  - Sensitivity
    - 1 V/g
    - Down from 10V/g
    - Up from 0.5V/g
  - Frequency Response
    - >300 Hz
    - Consistent with previous sensors



New Fire-Sensor Design

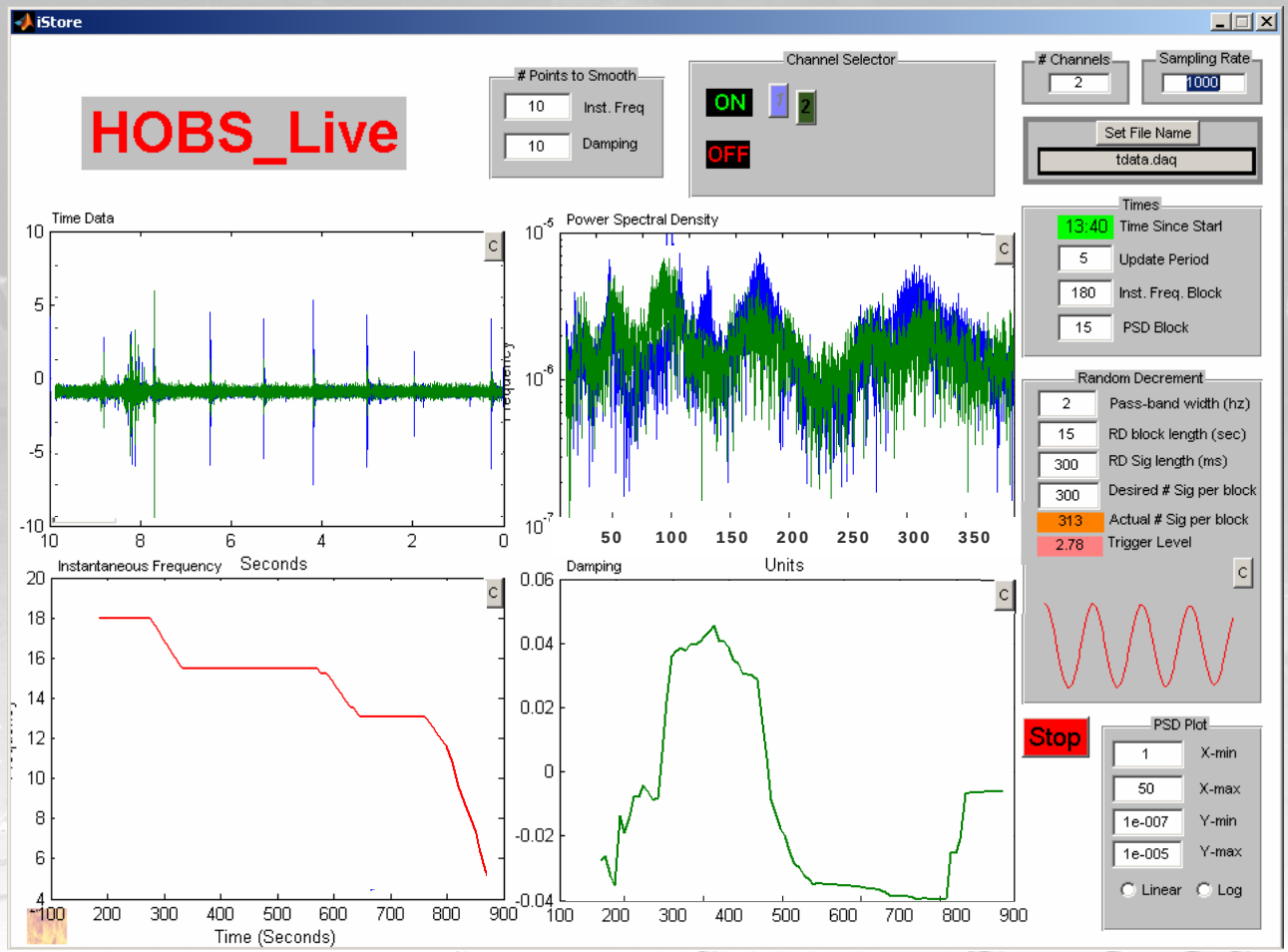


Castable thermal ceramic (AREMCO Ceramacast 645N)

- Protection to 1000ºF (exact rating TBD)

Attached to mounting plate with Cotronics Thermal Adhesive (Resbond 989)

Real-Time Monitoring Tool (HOBS)



Frequency-based Indicator

- All structures are described by this set of equations

$$M\ddot{\underset{\sim}{x}} + C\dot{\underset{\sim}{x}} + K\underset{\sim}{x} = \underset{\sim}{f}(t)$$

$$let\ \underset{\sim}{x} = A\underset{\sim}{q}:$$

$$A^T MA\ddot{\underset{\sim}{q}} + A^T CA\dot{\underset{\sim}{q}} + A^T KA\underset{\sim}{q} = A^T \underset{\sim}{f}(t)$$

$$where\ A^T MA = [I],\ A^T CA = \begin{bmatrix} \ddots & \cdots & 0 \\ \vdots & 2\xi_i\omega_i & \vdots \\ 0 & \cdots & \ddots \end{bmatrix},\ A^T KA = \begin{bmatrix} \ddots & \cdots & 0 \\ \vdots & \omega_i^{\,2} & \vdots \\ 0 & \cdots & \ddots \end{bmatrix}$$

Frequency-based Indicator

$$A^T K A = \begin{bmatrix} \ddots & \cdots & 0 \\ \vdots & \omega_i^{\,2} & \vdots \\ 0 & \cdots & \ddots \end{bmatrix} = \textit{strength}$$

- As a structure burns, dominant frequencies "fall" and the time "to return" lengthens
- These properties define the "poles" of the system
- Techniques to extract dominant *frequency* components from measured responses are being evaluated
- Techniques to extract *damping* will be developed

"Falling" Frequency Trends

- Do structural resonances really decrease as damage progresses?
- Can we demonstrate this without "fancy" analyses?

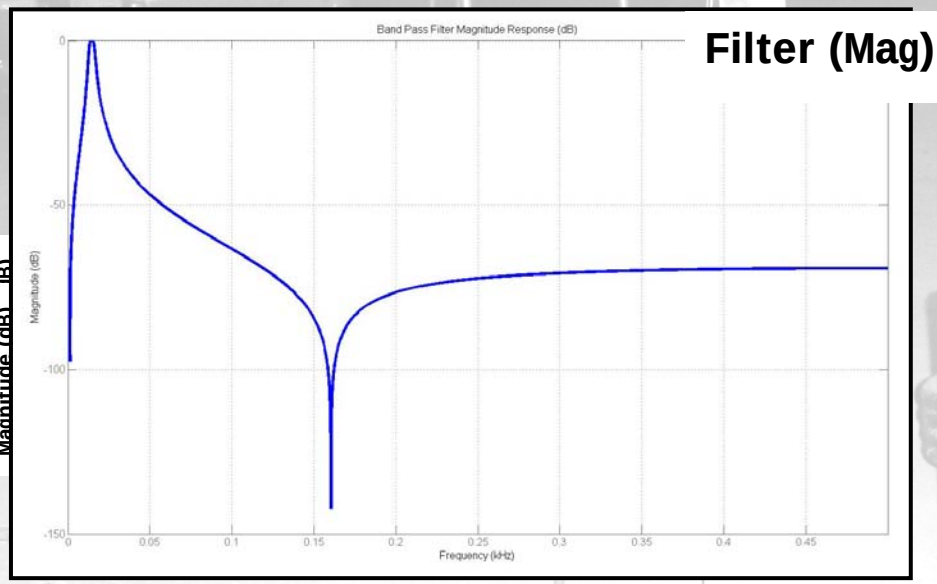
Yes

  - Design a series of (narrow-band) band-pass filters and look for frequency tracks

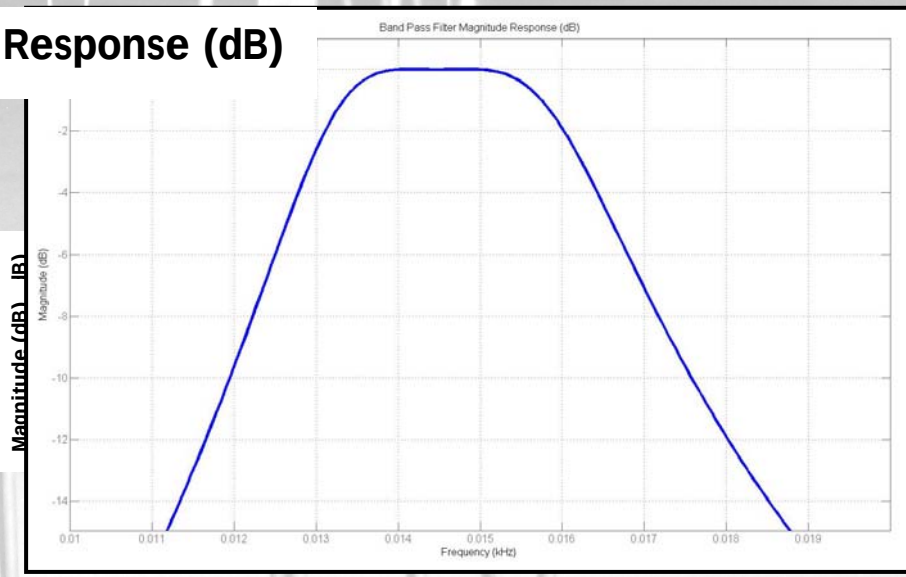
Sample Filter Characteristics

- Second-order Elliptical band-pass filters
- Narrow (0.5 Hz) pass band

Filter (Mag) Response (dB)

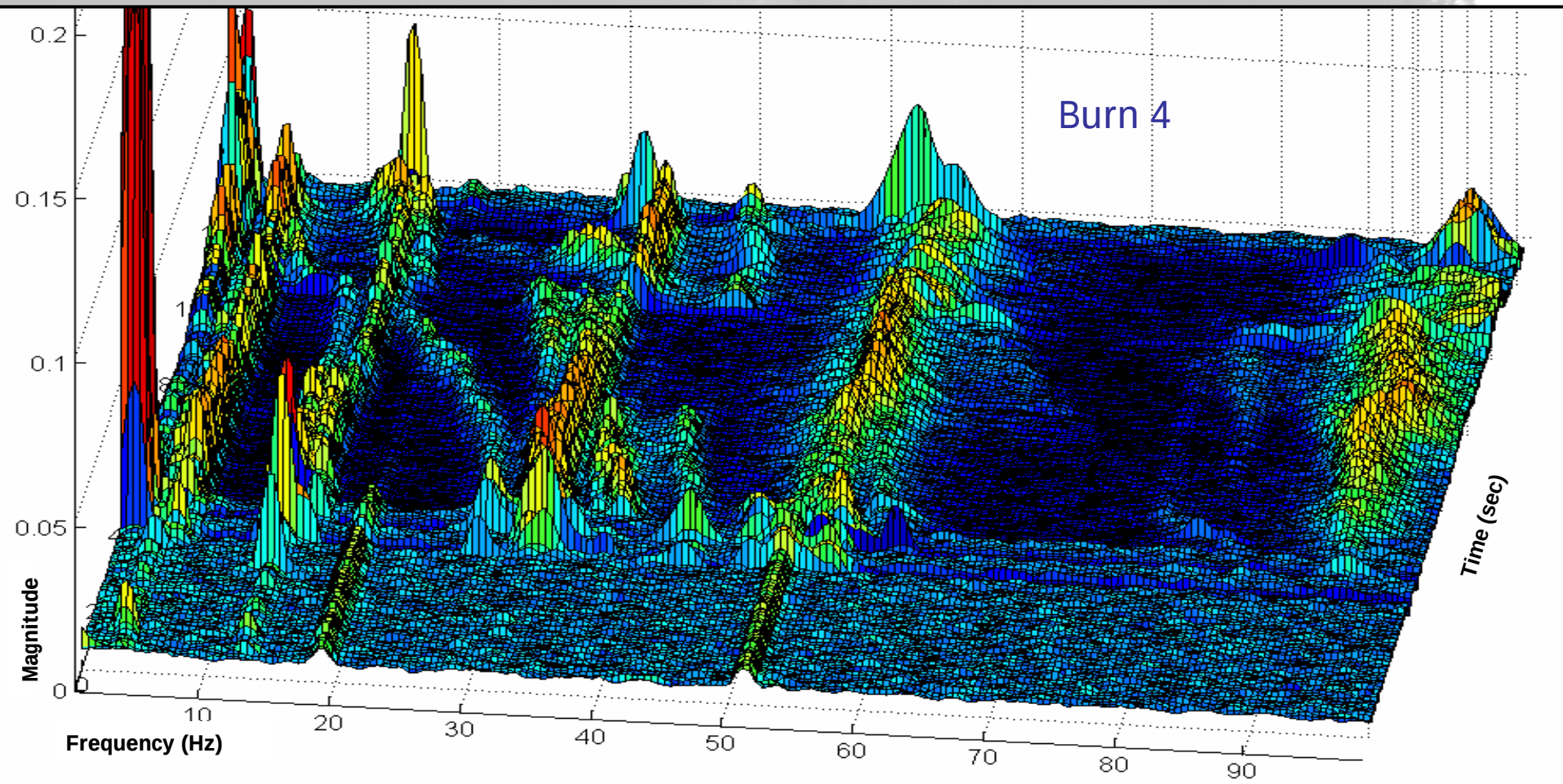


Frequency (Hz)

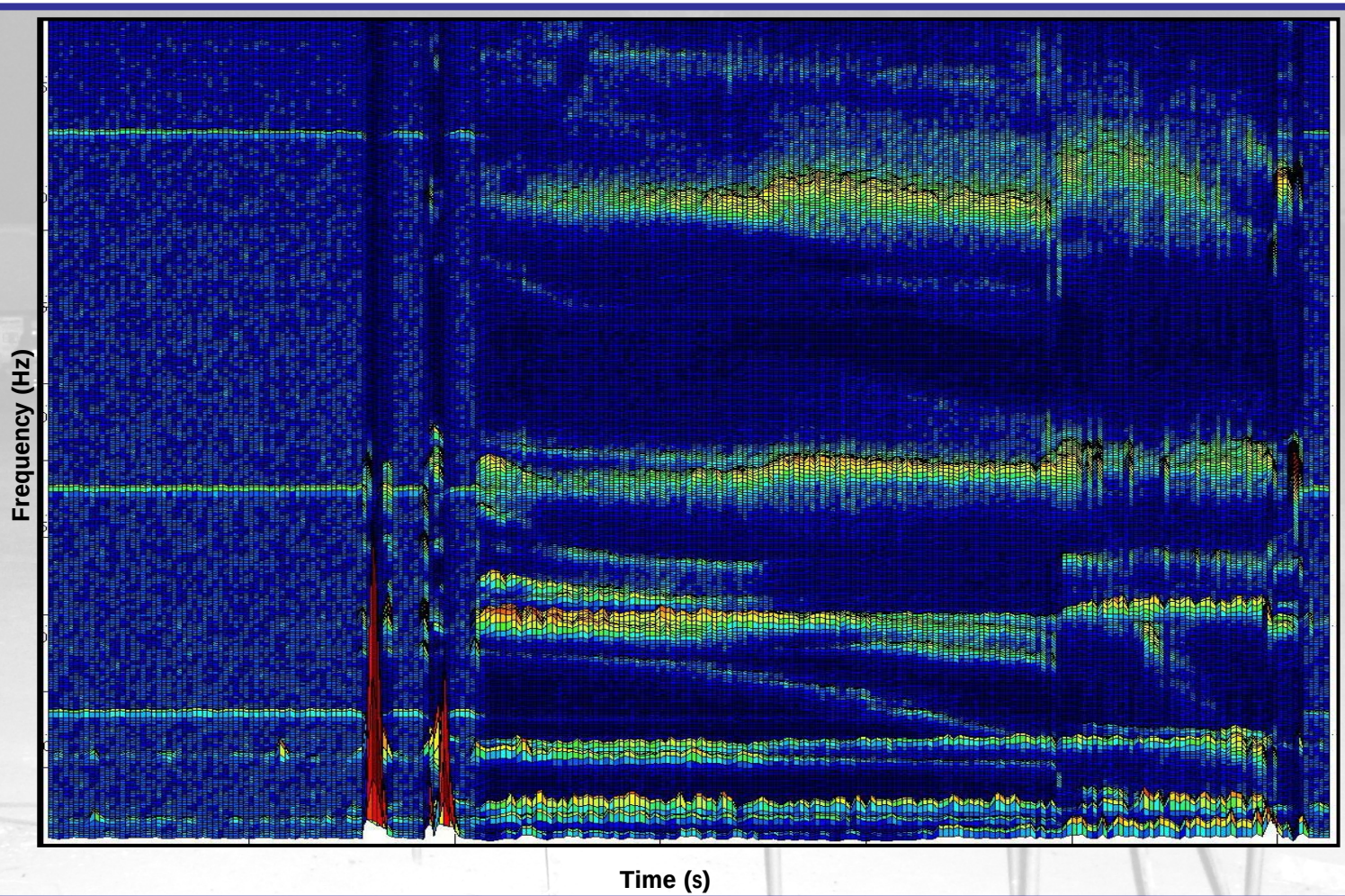


Frequency (Hz)

Normalized Power Spectrum



Normalized Power Spectrum



Frequency Tracking Algorithms

- Investigating three methods

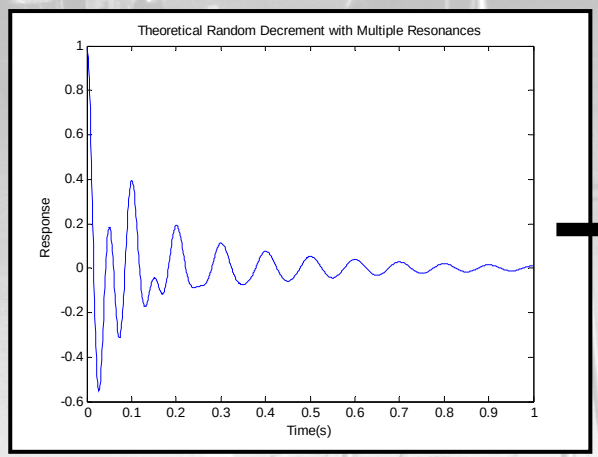
  1) Wavelet Transform Decomposition

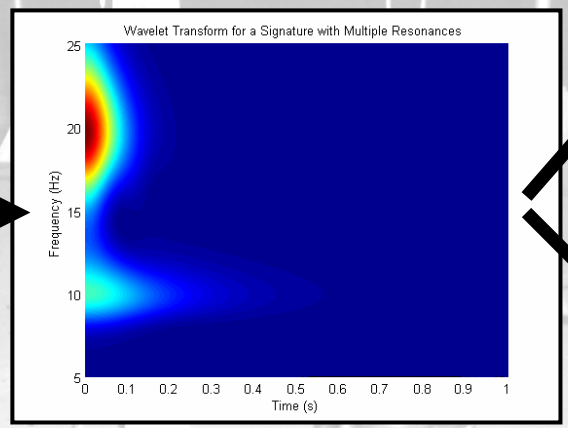
  2) Empirical Mode Decomposition

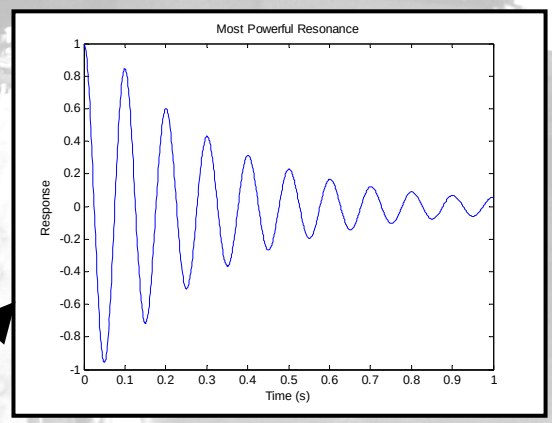
  3) Instantaneous Frequency

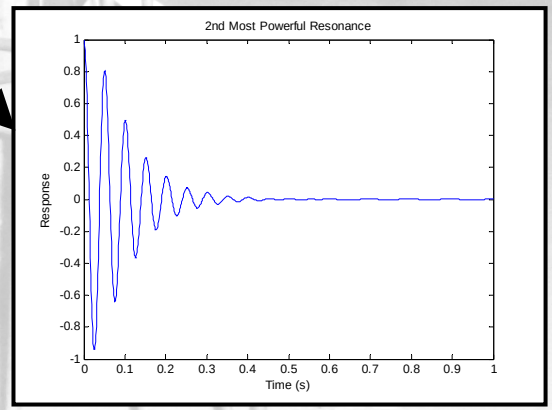
Wavelet Transform Freq Decomposition

$$W(a,t) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(\tau)\psi^* \left(\frac{t-\tau}{a} \right) d\tau$$

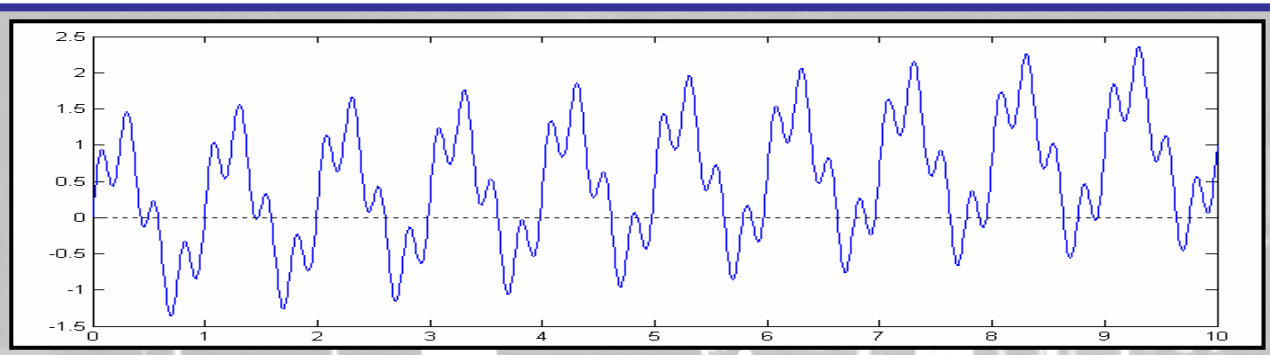








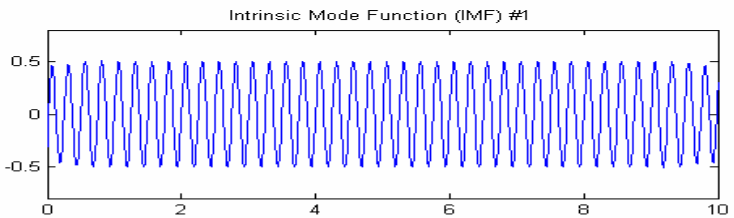
Empirical Mode Decomposition

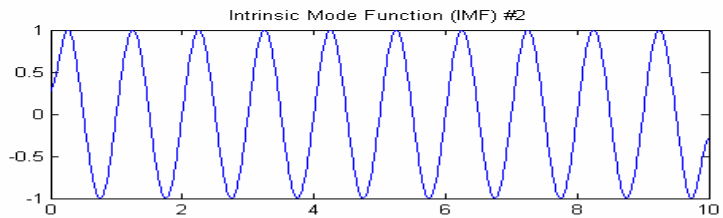


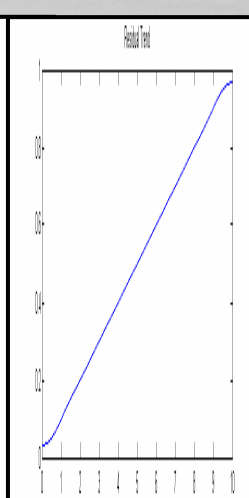
x1(t) = 0.5*sin(8*pi*t)

x2(t) = sin(2*pi*t)

x3(t) = t/10







Instantaneous Attributes of Analytic Signal

$$X(t) = x(t) + j\tilde{x}(t) = A(t)e^{j\varphi(t)}$$

- Instantaneous Magnitude

$$A(t) = \sqrt{x(t)^2 + \tilde{x}(t)^2}$$

- Instantaneous Frequency

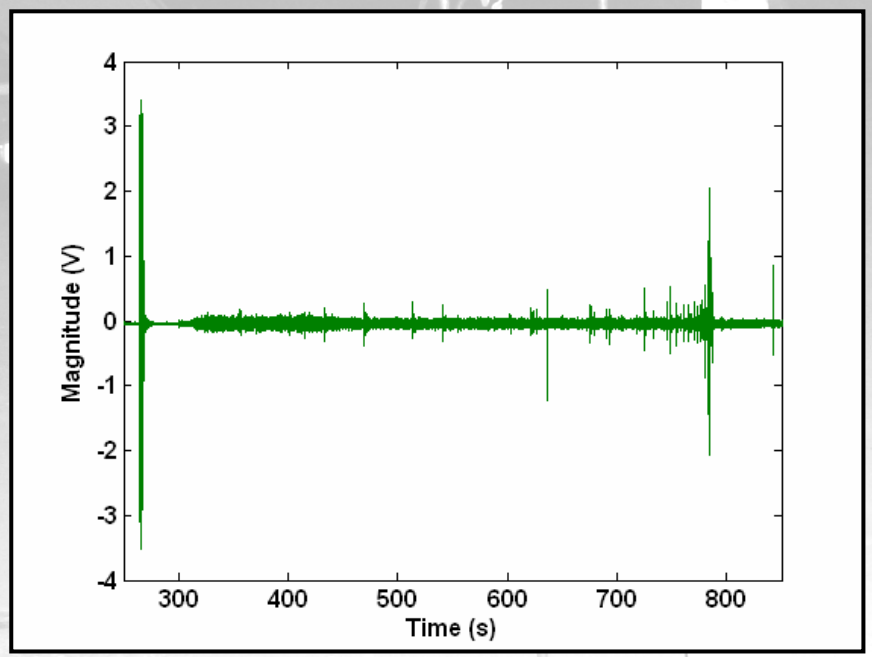
$$\omega_{inst} = \frac{d\varphi(t)}{dt} = \frac{d}{dt}\left[\tan^{-1}\left(\frac{\tilde{x}(t)}{x(t)}\right)\right]$$

Frame Burns

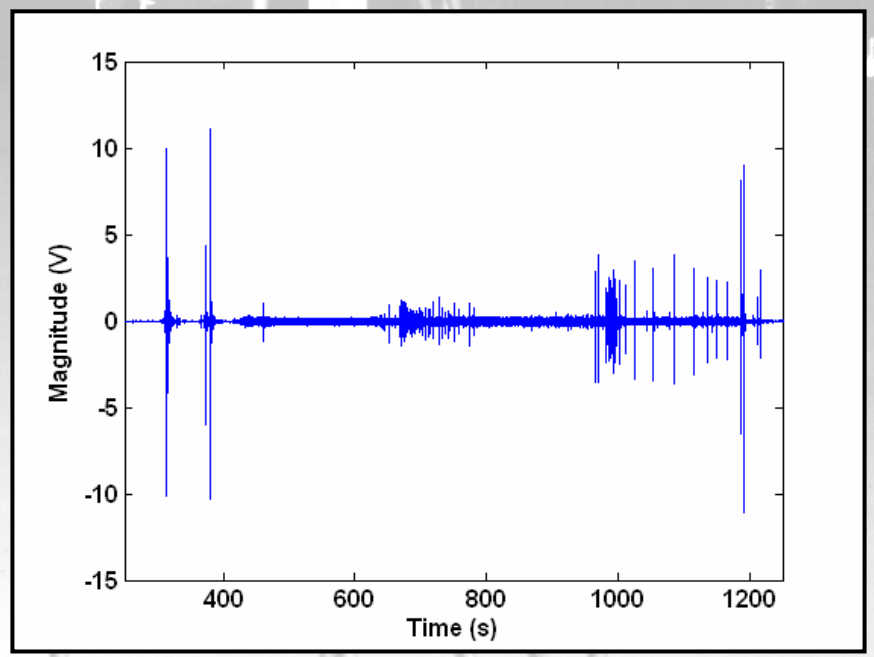
- Objective: to correlate trends with visual evidence
- Concentrated loads
- Torches provide controlled flame impingement
- Tested different accelerometers and burn conditions

Frame Burn Time Histories

Simple Frame (F3)
Channel 1

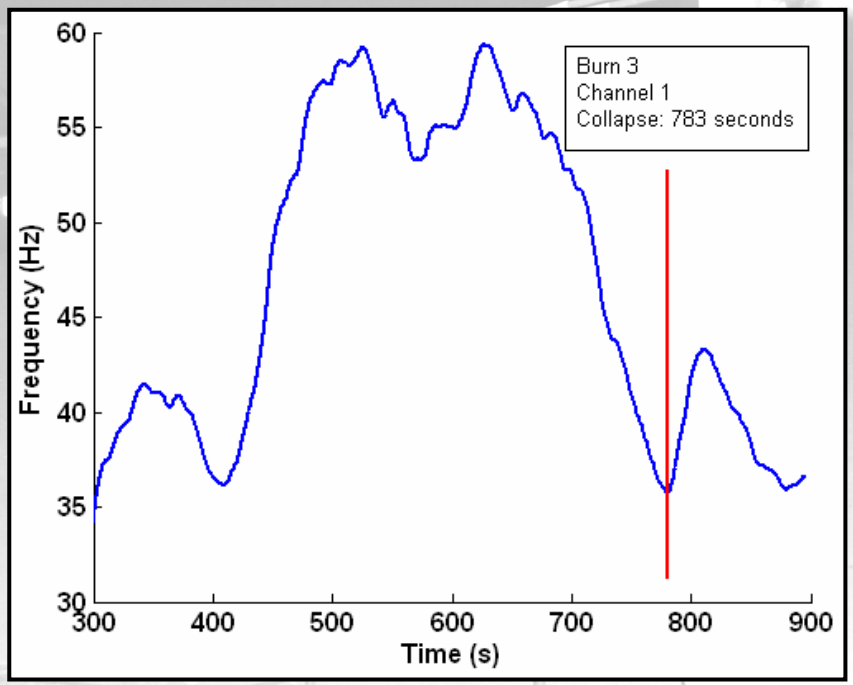


Simple Frame (F4)
Channel 0

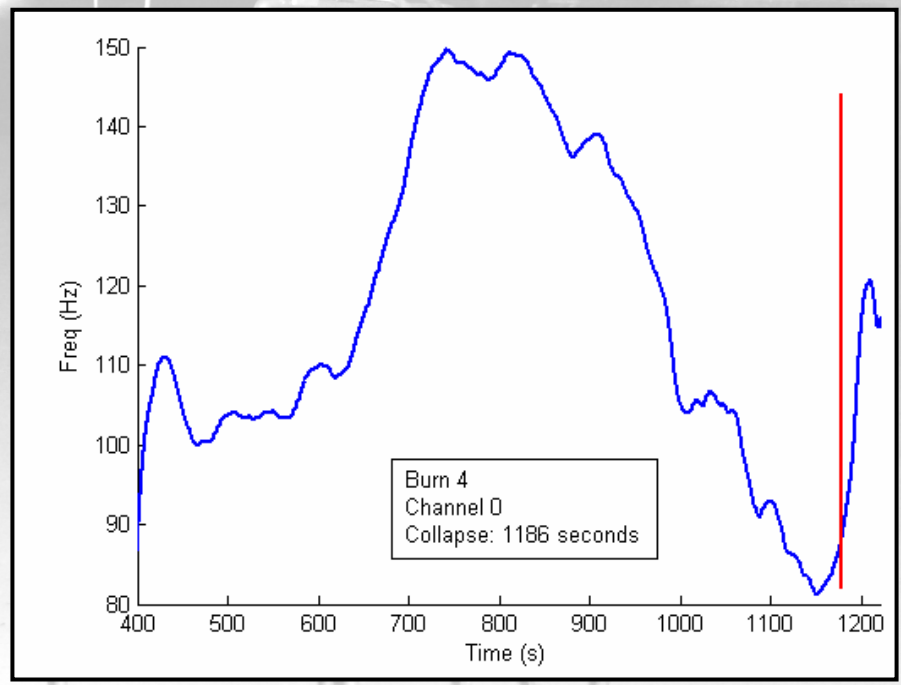


Frame Burn Instantaneous Frequency

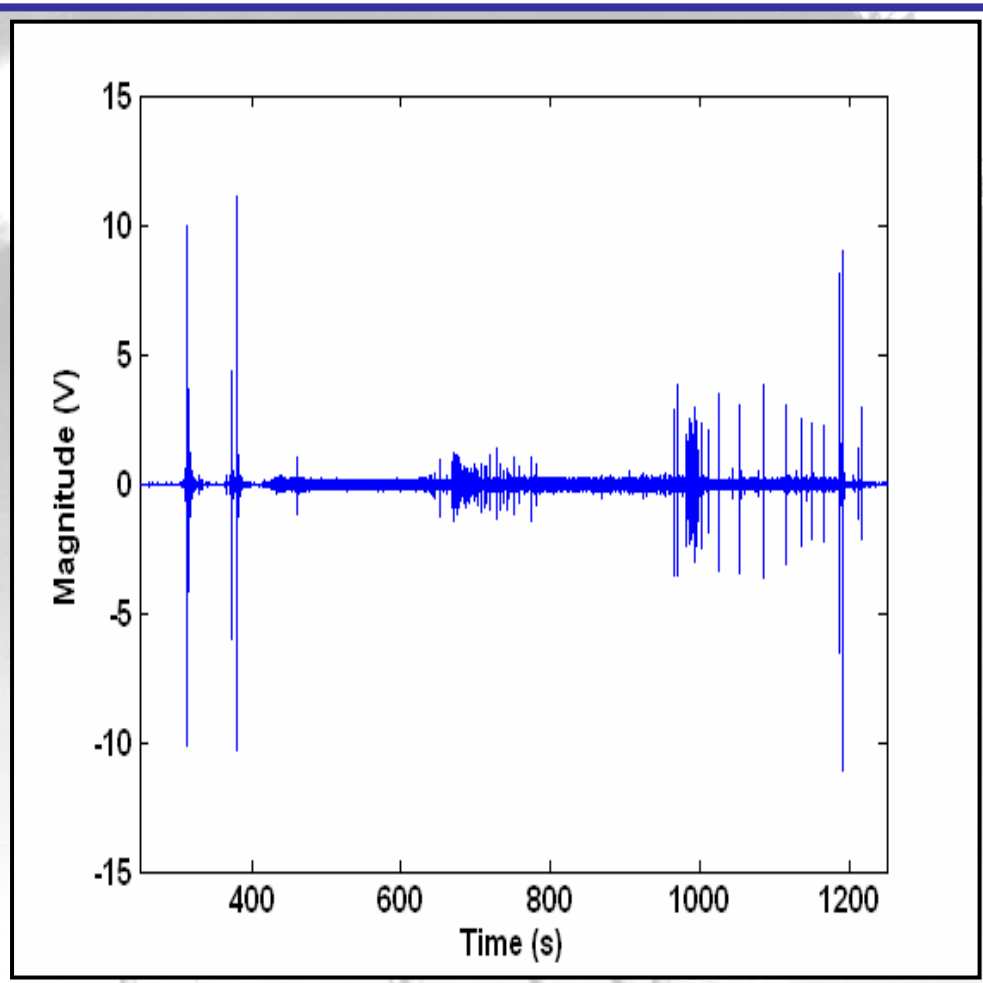
Simple Frame (F3)



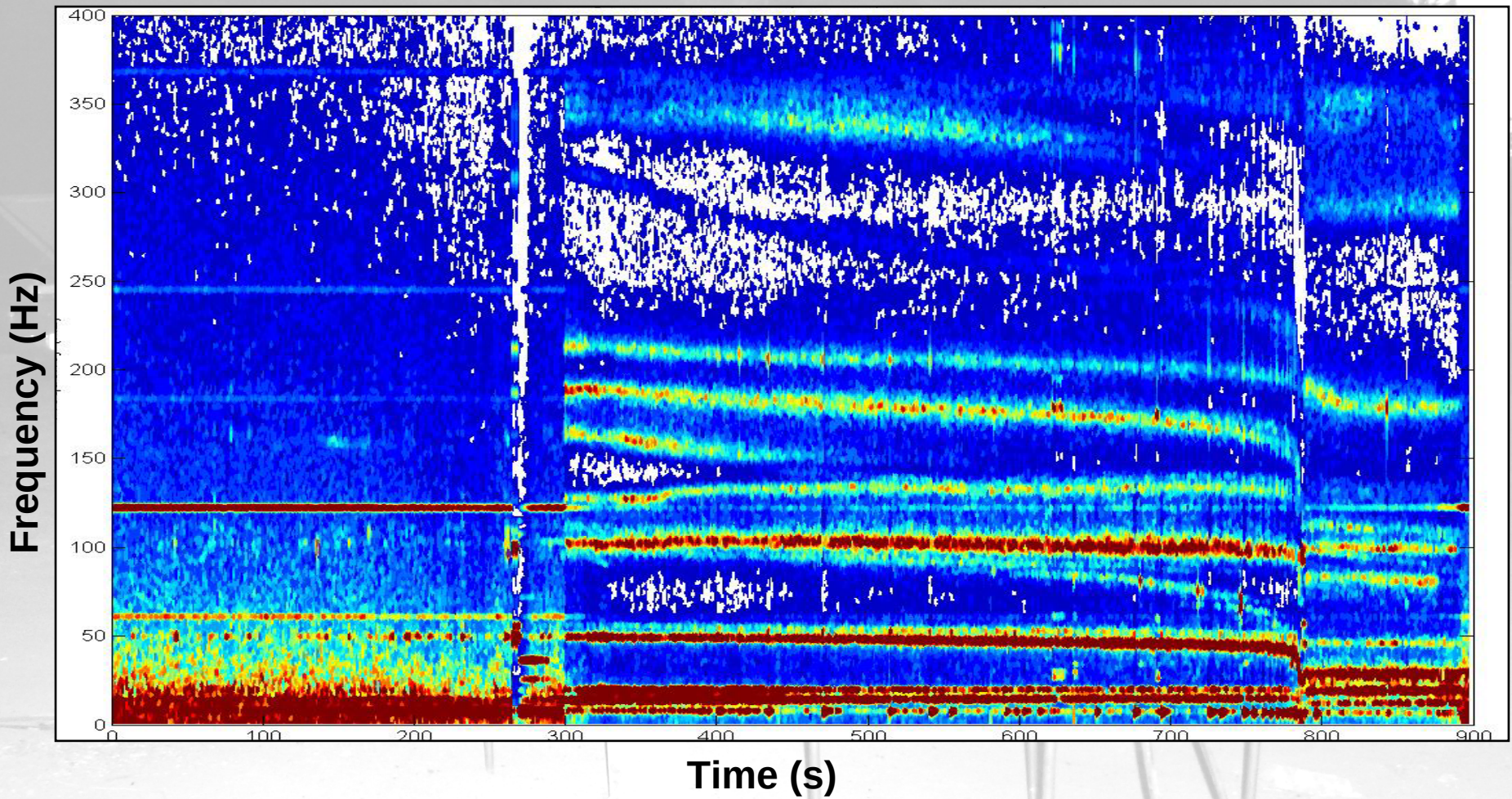
Simple Frame (F4)



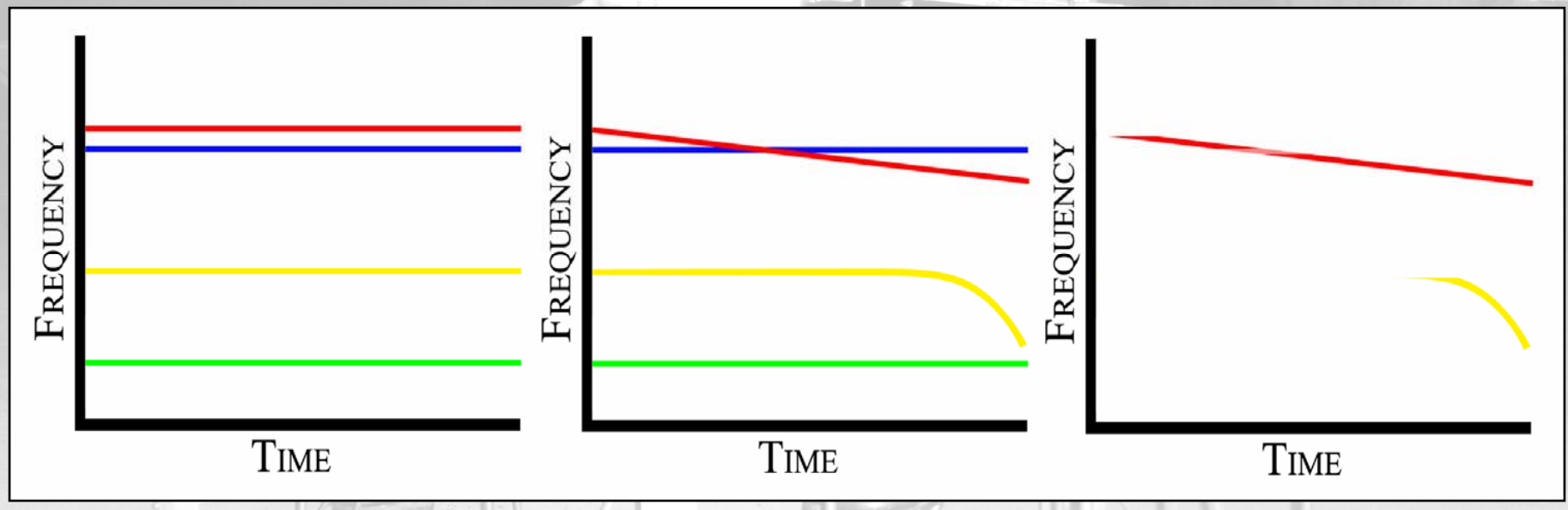
Frame Burn – Audible Indicator



Normalized Power Spectrum



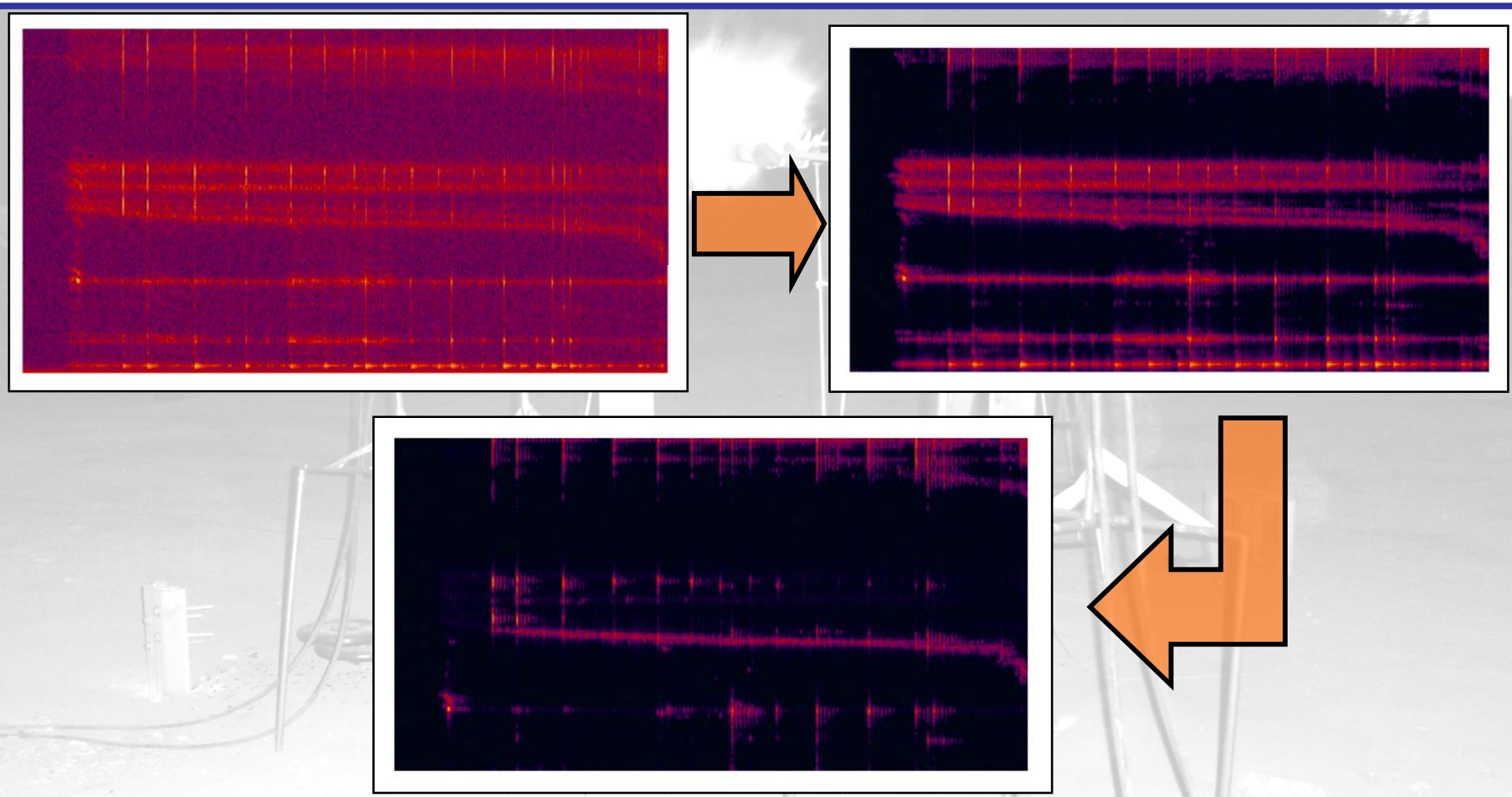
Extracting the Audible Indicator



Healthy fingerprint

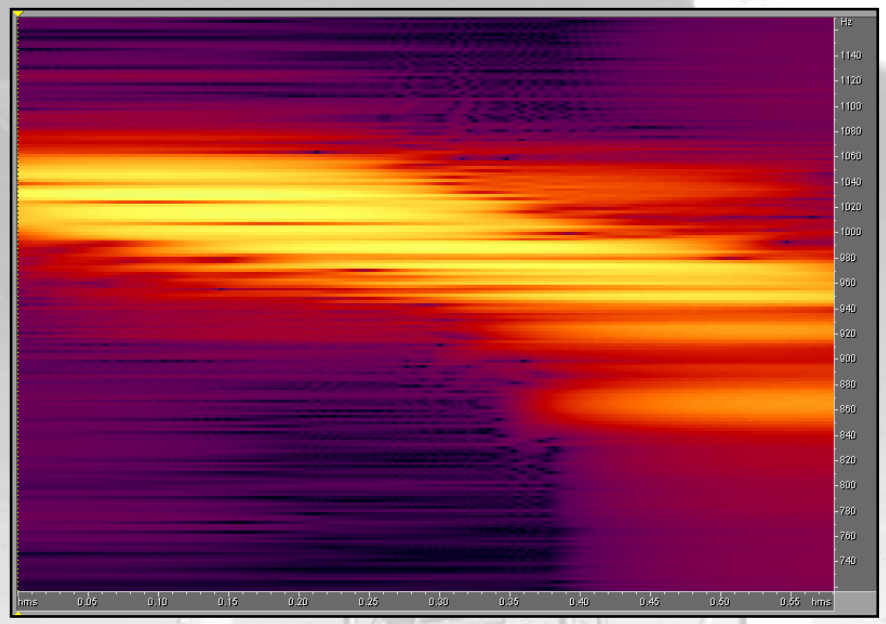
Damaged fingerprint

Noise Removal

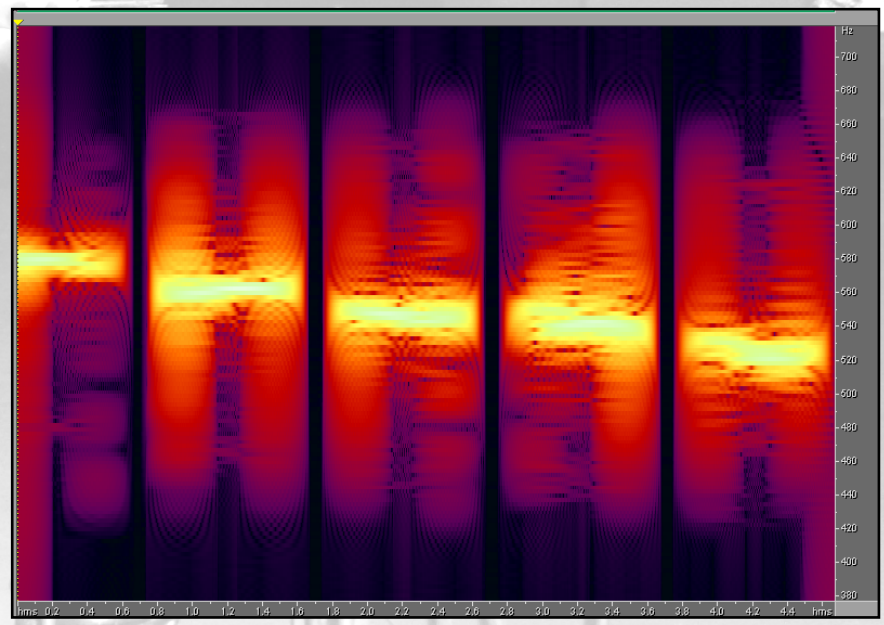


Audible Indicator

Structural spectrum is shifted into the audible range

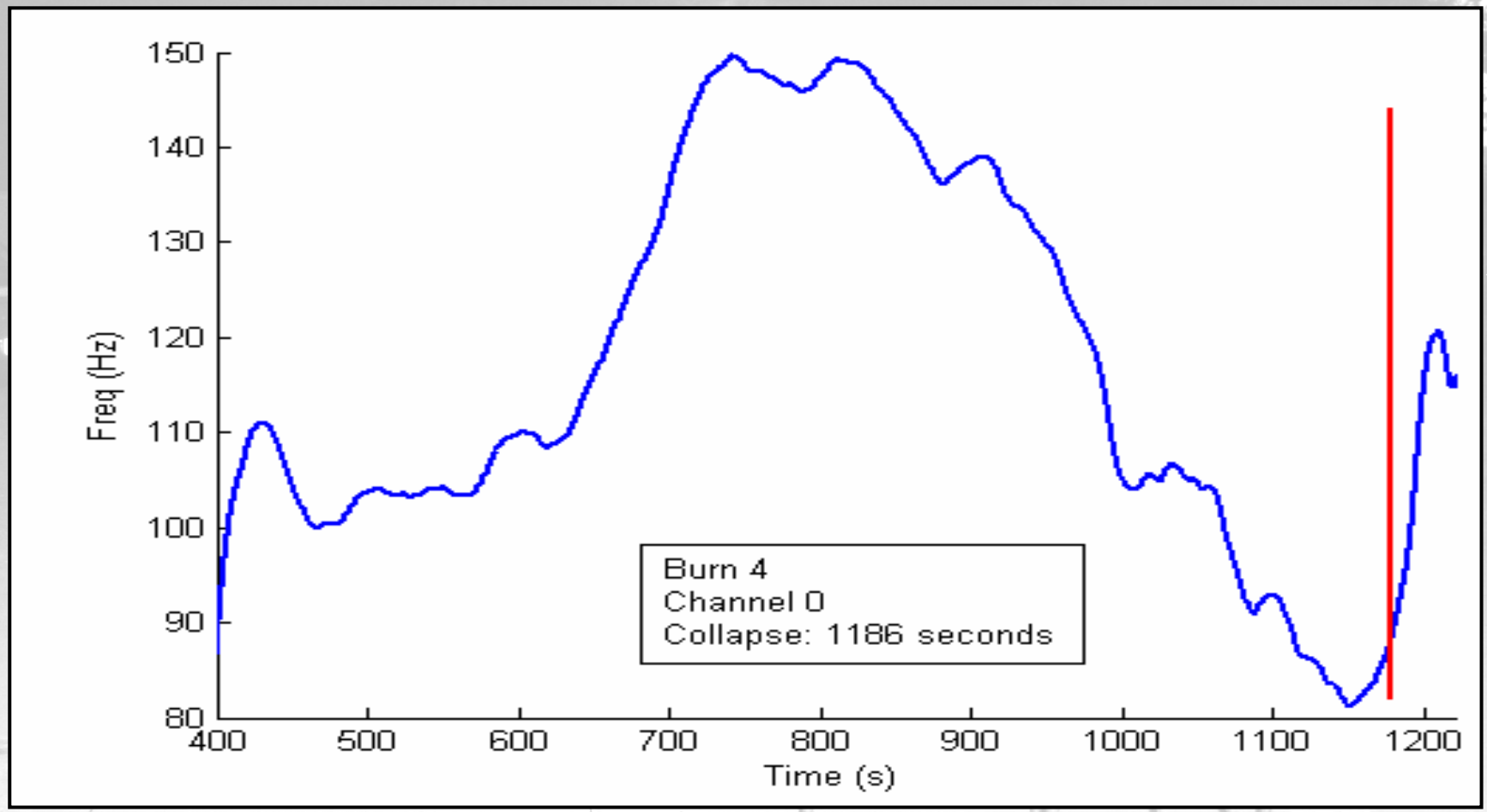


Continuous sliding pitch



Discrete frequency blocks (chords)

Visual (IF) Indicator



Comparison to Full-Scale Structure

Isbell Junior High School

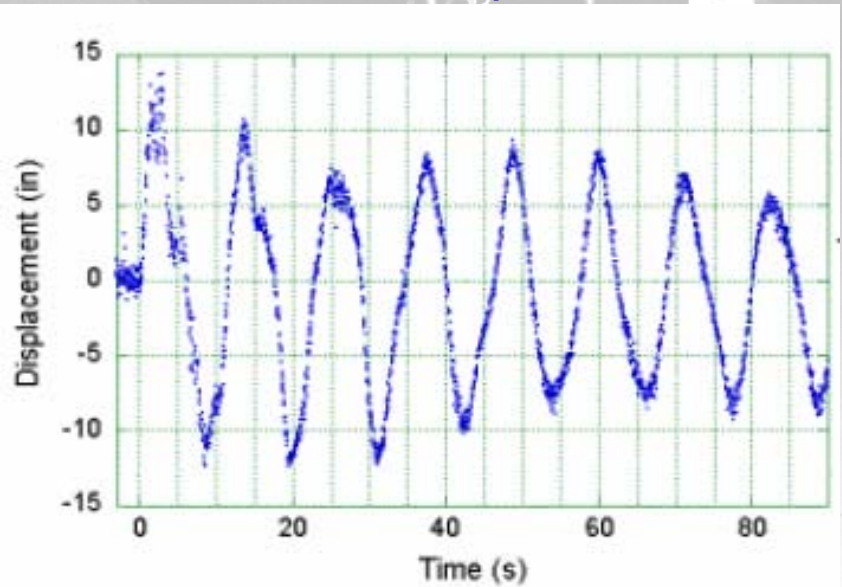
Transient Correlation – (?)

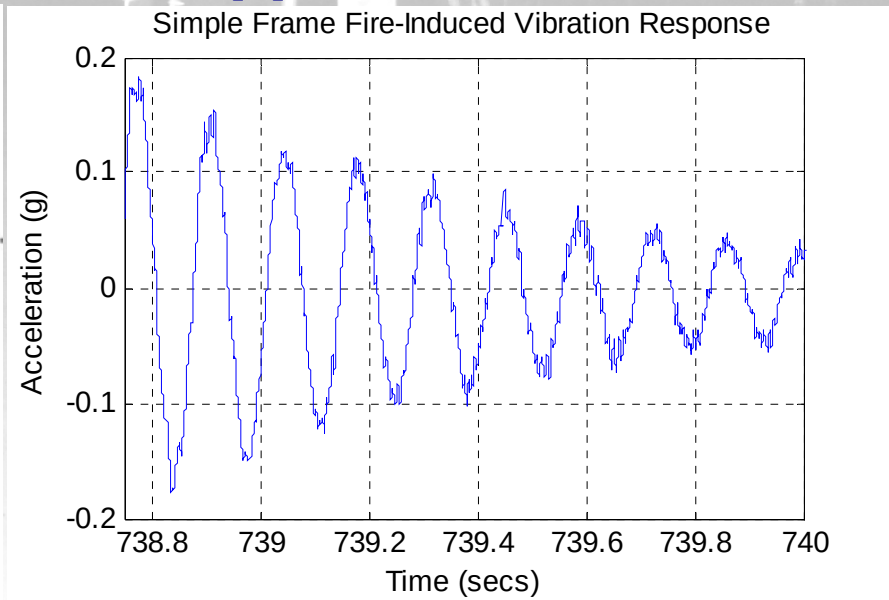
Practical Applications - Tasks

- Firefighter Training
  - Develop curriculum materials including classroom (workbooks) and field exercises
  - Working with LA County FD
- Special Operations Command (SOC)
  - Designing field demonstration tests for stability monitoring during field operations
  - Wireless sensor/receiver for individual/local monitoring as soldiers move through structure
  - Tests planned at Fort Bragg, NC

WTC 2 Displacement Record Analysis

- A Moiré analysis of video acquired from WTC 2 has resulted in a series of displacement records presented in Ref [1]. The analysis was based on a geometric decomposition of moiré patterns that amplified the actual motion, and a sample record taken from Ref [1].





1. K. Butler, et.al, "Moire Analysis of Primary Frequencies and Time-Dependent Oscillation Amplitude Following the Aircraft Impact for WTC 2," NIST NCSTAR 1-5, Appendix K, pp.915-954.

Thank You

- Questions?