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Early Warning Capabilities for Firefighters: Testing of Collapse Prediction Technologies

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Early Warning Capabilities For Firefighters: Testing of Collapse Prediction Technologies

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Notice

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Final Report

Fire Induced Vibration Monitoring for Building Collapse

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1 Executive Summary

A field-based monitoring technique that utilizes measurements of fire-induced vibration was developed and first demonstrated under a previously funded research effort. This report details the findings of the ensuing 3-year endeavor in which significant improvements were made to both field-test and analysis procedures. A real-time monitoring tool has been developed and numerous full-scale burn tests on a variety of structures have been completed. A significant contribution of the research stems from the use of system stability theory to aid in the interpretation of the field measurements. The techniques described in this report can be used to monitor burning structures and to provide visual indicators that track changes in structural stability.

2 Acknowledgements

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3 Background

Structural health monitoring has been largely promoted as a means for assessing the condition of buildings and other critical structures in the aftermath of significant events. Support for installation of real-time monitoring devices and systems, however, continues to lag due in part to the absence of clear and convincing benefits to owners and to the structures themselves. A case can be made that a fresh approach, or application, may be needed to bolster the case for real-time structural health monitoring.

Firefighting operations and the accompanying risks are typically scrutinized and reviewed anytime loss of life results. In recent history, no single event has drawn more attention to the technology and methodology of modern firefighting technique than has the collapse of the World Trade Center Towers. The collapse of those structures and the corresponding loss of life reveled a vulnerability in the absence of real-time health monitoring that may have informed firefighters of the weakening structural conditions around them.

Under a previous research effort funded by the Building and Fire Research Laboratory and the National Institute of Standards of Technology (BFRL/NIST), a new methodology and application for health monitoring was introduced. The major findings of that initial effort including a description of the approach and of its application to firefighting operations are provided in Ref [1].

3.1 Report Overview

The following presents a brief overview of the monitoring technique and provides a stability based context for interpreting the measured responses acquired from burning structures. The results of the current 3-year research effort are reported herein with the intent of providing the reader with a sense of the application and potential for the new technology. Numerous field investigations have been completed over the duration of the current grant, and not every field measurement will be presented. Instead, the collective experience and knowledge gained from these tests along with the most promising analytical techniques and stability indicators are discussed.

The first demonstration of fire-induced vibration based health monitoring is presented in Section 3.2, followed by a conceptual description of the vibration based monitoring of structures. A description of the research objectives is provided in Section 4, and progress made since the initial development (Ref [1]) of the fire-sensor technology is discussed in Section 5. The application of a time averaging scheme for the purpose of stability based analyses and the adaptation of that technique to the monitoring of burning structures is presented in Section 6. The development of a real-time field monitoring tool and the various stability indicators employed are described in Section 7. Particular attention is directed toward estimating damping and dominant frequency in Section 7.5. The application of the real-time monitoring tool is described in Section 8 and sample measured responses and corresponding stability indices for burn tests conducted on simple frame and large wood frame structures are also presented. Section 9 relates the loss of structural stiffness during burns to changes in the frequency of building response. The report concludes in Section 10 with a discussion of the implications for practical field monitoring techniques that eventually may mitigate the risk of injury during firefighting operations.

3.2 Fire-Induced Vibration Based Health Monitoring

Fire-induced vibration based health monitoring was first demonstrated in tests conducted on a single-family wood frame structure in Kinston, North Carolina (August 2001). In those tests, a heating oil tank was mounted on the roof of the structure in an effort to induce roof collapse during burn. The objective of that test was to evaluate the possibility of measuring fire-induced vibrations in a burning structure that correlated with weakening conditions leading to a significant collapse event. As detailed in Ref [1], those tests demonstrated for the first time, that fire was capable of exciting dynamic structural vibration responses that provided real-time indication of impending collapse. Figure 1 shows a picture of the building on fire with a 250 gal heating oil tank mounted on the roof (top) and a sample of fire-induced responses (bottom) acquired during the test.

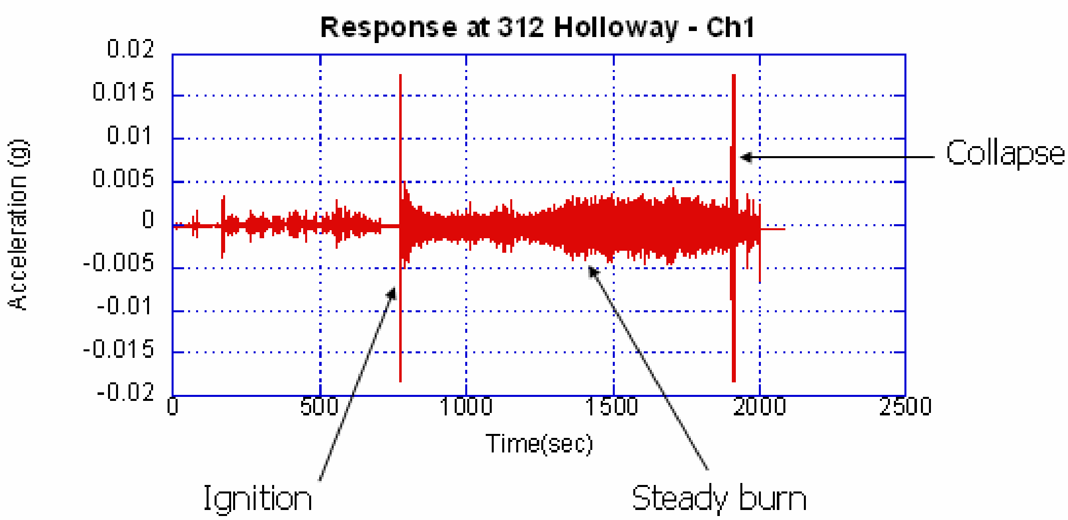


Figure 1 - Fire-induced monitoring of a wood frame structure.

The measured response was acquired on the exterior wall (left most wall as shown in Figure 1) and captures ignition, steady burn and collapse of the tank through the roof. The measured behavior was analyzed after the test, and a response index (shown in Figure 2) based on response variance was developed.

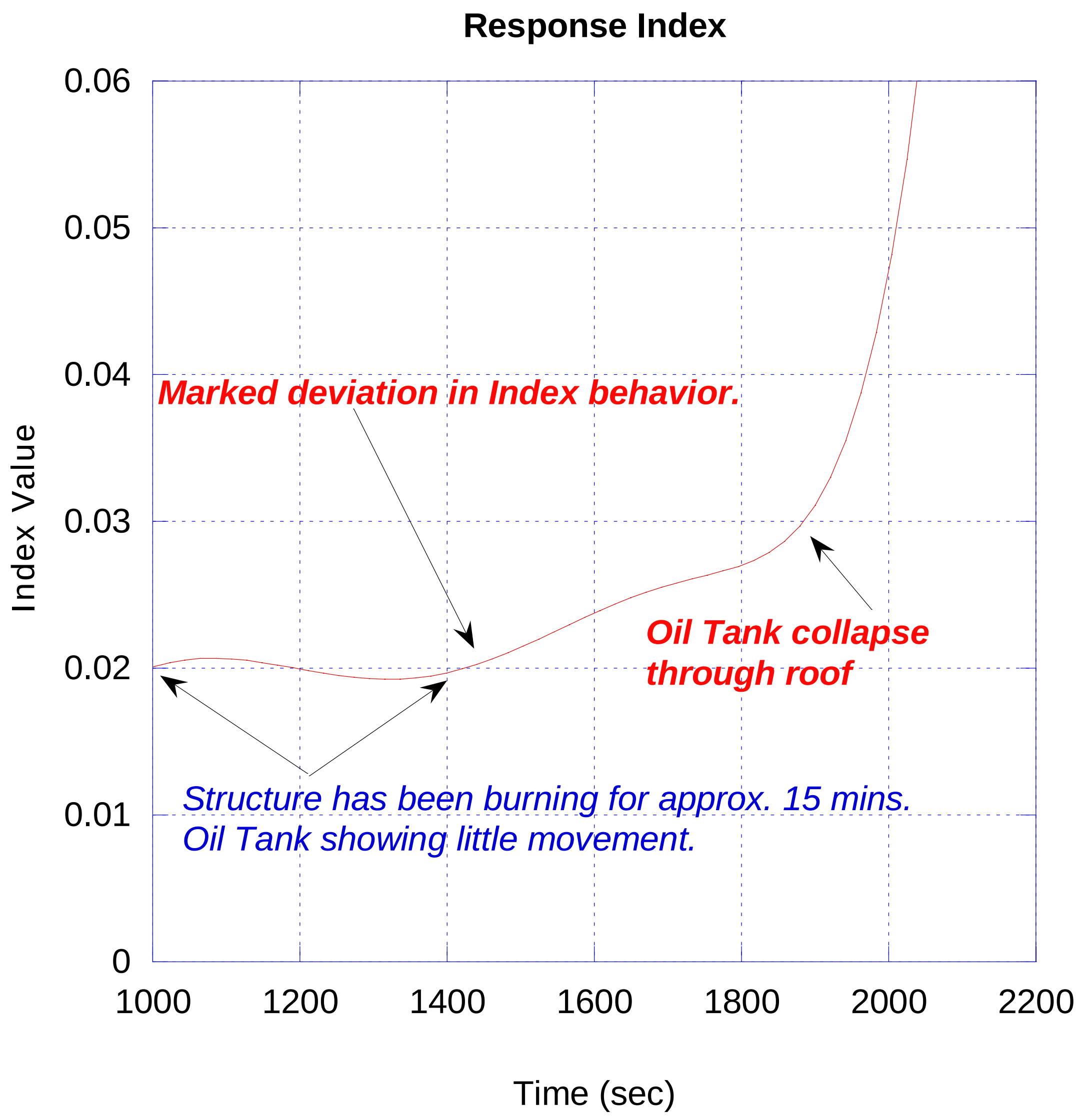


Figure 2 - Collapse index behavior for a burning wood frame structure.

The behavior of the index correlates well with visual evidence obtained during the burn, which clearly shows when the oil tank collapsed through the roof. The marked deviation after 1400 sec occurs approximately 8 minutes prior to collapse and provides a measure of early warning.

3.3 Vibration Based Monitoring – A Conceptual Overview

For the purposes of illustration, consider the signal shown in Figure 3. The signal is not an actual field measurement, but was constructed in a manner consistent with observed responses from a burning structure both prior to and after ignition at $t=0$ seconds. The response is random-like and does not indicate significant deviations in amplitude or character after ignition. The signal exhibits “healthy” fire-induced behavior in the sense that the structure is not in danger of imminent collapse (since the response after ignition does not appear to differ with the pre-ignition response).

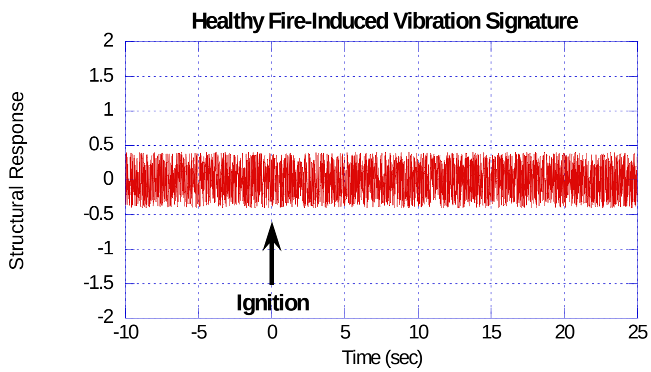


Figure 3 - Sample (idealized) fire-induced vibration response.

The signals in Figure 4 (variations of the signal in Figure 3) illustrate the occurrence of a fire-induced event near 5 seconds and the structure’s probable response to that event. In Figure 4 (left), the response appears to be (largely) unaffected by the event, indicating that no significant structural change has occurred. On the other hand, Figure 4 (right) indicates growing response behavior following the event that could be indicative of weakening structural conditions.

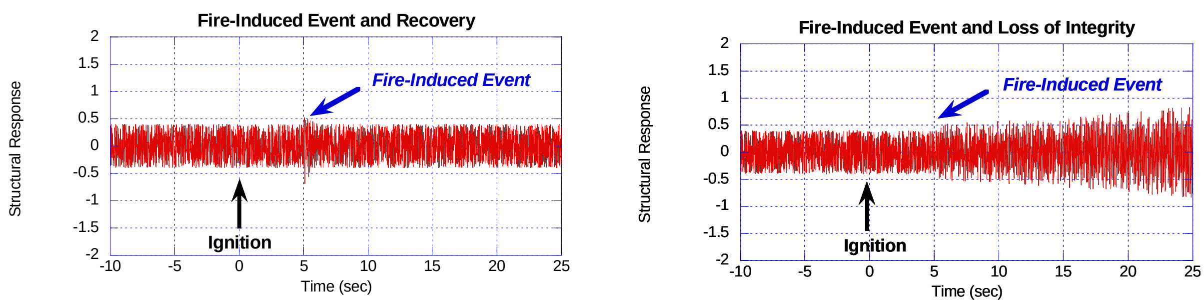


Figure 4 - Fire-induced response in a healthy (left) and weakening (right) structure

Interpretation of these types of signals in the context of collapse monitoring is complicated by the random nature of the response, and the fact that collapse mechanisms may result in low-level responses that grow undetected or are masked by the ambient noise in the burning structure. An analysis technique is needed that can transform fire-induced vibration measurements of the type illustrated in Figure 4 into signatures that are readily associated with structural stability. The simplest of these signatures is the transient sinusoidal response.

It is well known that a mechanical system subjected to a sudden impact or impulse load, will produce a transient response of the type indicated in Figure 5 (left). In the context of a burning structure, a suddenly applied impact load may be associated with the progressive failure of a main (load carrying) structural member or connection. In addition, many of the firefighting operations in the field (e.g. roof venting) induce impact type loads on a structure. These loads typically result in responses that are characterized by a sudden deviation from pre-impact levels, a dominant oscillation, and a decaying amplitude that ultimately returns to pre-impact levels. Mechanical systems that exhibit this type of behavior are said to be stable.

If such an analysis technique were available, transient signatures (i.e. signals) could be derived from measured responses to provide indications of changes in structural stability. For example, if a signature of the type shown in Figure 5 (left) were obtained from a burning structure, the decay rate would reflect the structure's ability to dissipate energy, and the return to pre-event response levels after a short time would reflect the continuing stability in the structure. If, on the other hand, a signature of the type shown in Figure 5 (right) were obtained from a burning structure, the slower decay rate would reflect the structure's inability to "quickly" dissipate energy within the weakening structure.

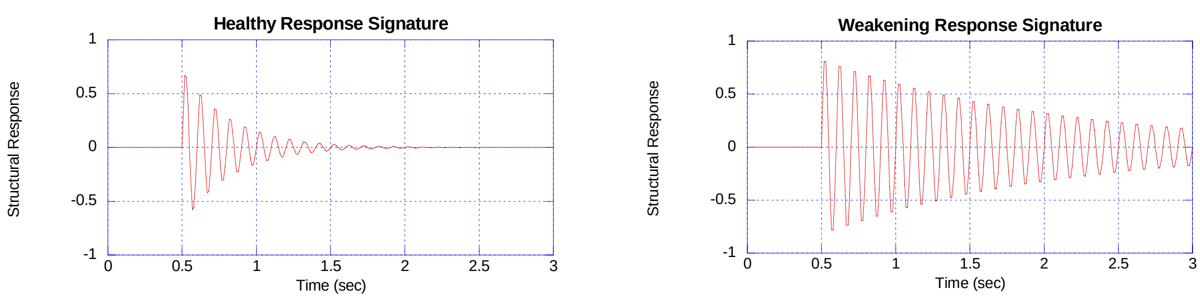


Figure 5 - Sample transient signatures for healthy (left) and weakening (right) burning structures.

4 Research Objectives

Original research objectives for the completed program are listed below.

- To develop improved field test procedures and instrumentation for measuring fire-induced vibrations during burn tests
- To investigate apparent relationships between fire-induced responses and indications of impending collapse
- To investigate advanced analytical techniques that extract structural stability parameters which may indicate impending collapse
- To develop collaborative relationships with local and national fire departments that allow participation in field training exercises suitable for structural monitoring for collapse

What follows is a description of the various tasks completed in order to achieve the listed objectives. Section 5 and Section 6 of the report detail the advancements in fire-sensor technology and address the signal requirements and characteristics for fire-induced vibration monitoring. Section 7 describes the current state of analytical techniques and insights related to the analysis of measured fire-induced responses and corresponding index behavior interpreted in the context of weakening structural stability. The relationships developed with local and national fire departments are described throughout the report in the context of the various burn tests conducted. The report concludes with a summary of findings and provides a discussion of the potential significance and contributions of the ongoing research effort.

5 Fire-Sensor Technology Development

The development of the original fire-sensor is detailed in Ref [1], and was based in part on the expected low-level, random-like character of fire-induced vibration responses. Based on extensive experience with field testing on large concrete structures (including dams and bridges), the original fire-sensor utilized servo-force balance accelerometers that provided sensitivity on the order of 10v/g. The devices were current output based and allowed extra long cabling to be used without significant signal loss or reduced sensitivity. Elaborate installation and thermal protection procedures were developed to ensure that the fire-sensor could survive full-scale burn tests on actual structures.

A key component of the installation procedure was the recognition that mounting on the exterior surfaces (i.e. walls) of the structure provided adequate signal quality for monitoring purposes. It was further realized that the exterior skin of the structure along with placement away from door and window openings significantly lowered requirements for thermal protection. As a result, a series of tests were conducted in which a new fire-sensor design was evaluated. A complete listing of all the tests conducted under the current grant is provided in Table 1.

Table 1 - Description of Burn Tests Conducted

Structure Type	Location, Date	Description	Number
Wood frame	Camarillo, Ca – July 2003	Mrs. O'Leary's Barn	1
Wood frame	Camarillo, Ca – May 2004	Single family home	1
Simple frame	Pomona, Ca – August 2004	Steel column, wood cross beam	2
Wood frame, stucco exterior	Fillmore, Ca – April 2005	Classroom structure	1
Simple frame	Pomona, Ca – June/July 2005	Steel and wood columns, wood cross beam	10
Wood frame	Pomona, Ca – July 2005	Single room structure	1
Wood frame, stucco exterior	Santa Paula, Ca – July 2005	Classroom structure	1

5.1 Improved Fire-Sensor Design – Performance Criteria

A replica of Mrs. O'Leary's barn, thought to have played a significant role in the Great Chicago Fire of 1871, was constructed by the Discovery Channel and burned as part of a reenactment of the events that led up to the fire. A picture of the barn along with construction drawings (as built dimensions were 20' wide, 14' maximum height, and 16' deep) is shown in Figure 6. At the invitation of the producer in charge of the documentary, the barn was instrumented with fire-sensors for the purpose of gathering structural response information on the barn and evaluating new fire-sensor designs and configurations. The burn was conducted at the Ventura County Fire Training Facility in Camarillo, California in July 2003. Four sensors were installed around the exterior of the barn including two original fire-sensors, Sunstrand Q-Flex Accelerometers (QA), and two newly developed **M**icro**E**lectro**M**echanical (MEM) fire-sensors. A main objective was to evaluate the performance of the MEM sensor design against the QA sensors that have been in use since March 2001.

Figure 6 - Replica of Mrs. O'Leary's barn and drawings.

A segment of the measured fire-induced vibration response acquired during the test is shown in Figure 7 (top). The portion of the response prior to the time at which the barn door slams shut reflects a "steady burn" condition inside the barn. Once the barn door slams shut, however, response levels clearly increase reflecting the changes in fire dynamics within the barn. These changes, observable within the barn during the test, created a furious burn environment.

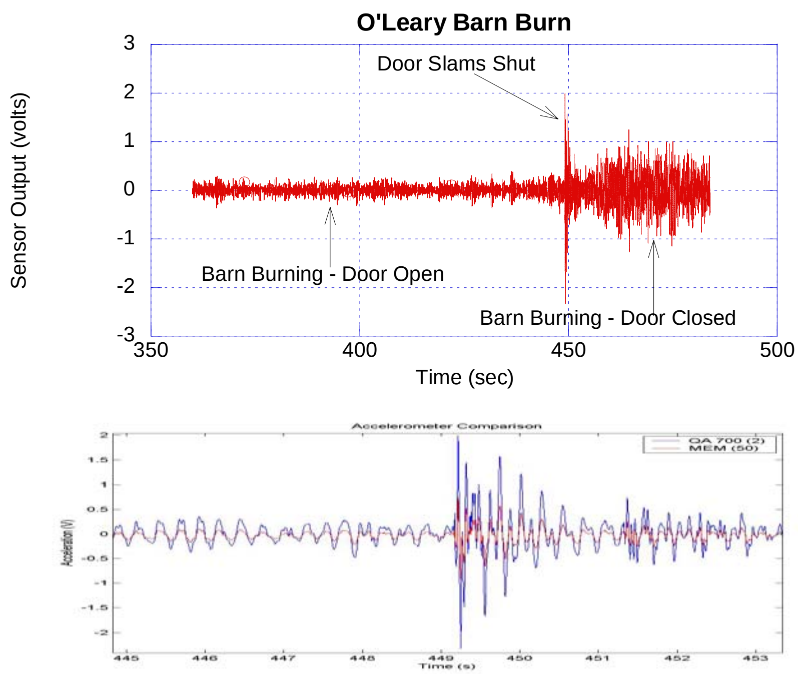


Figure 7 - Sample fire-induced vibration responses acquired during the O'Leary barn tests.

Figure 7 (bottom) provides a comparison of responses acquired using an original fire-induced vibration sensor (blue curve) and the new MEM based sensor (red curve). The top signal in Figure 7 demonstrates the MEM sensor's ability to track changing conditions in the barn as they occurred during the burn.

The initial portion of the response (refer to the top signal in Figure 7) corresponds to the early portions of the burn and what can be characterized as a "steady but random response." Close inspection of the time response beyond 400 seconds reveals the presence of multiple short duration transients leading to a large spike (or, transient) near 450 seconds that corresponds to the barn door slamming shut. A comparison of the QA and MEM sensor at the time of the large spike is shown in Figure 7 (bottom). Immediately after the barn door is shut, fire-induced vibration levels in the barn increase significantly. The responses shown in Figure 7 (along with other measurements not shown here) have been correlated and synchronized with video of the burn. The video provides clear evidence of the changing fire dynamics inside the barn that led to the door slamming shut against an upper doorstop, which produced the large transient response near 450 seconds.

Fire conditions encountered during the burning of the O'Leary barn were extreme due in part to the type of construction and the 20 mph wind conditions introduced for this test (to simulate weather conditions that night in 1871). Nonetheless, the test was instrumental in developing an improved understanding of the requirements for a new sensor design.

The MEM sensor reduces the cost by 75% (as compared to the cost of the original QA sensor), and appears to provide adequate resolution and accuracy for the application.

5.2 Sensitivity and Thermal Protection Requirements

An important consideration for the development of a fire-sensor is the minimum sensitivity needed to capture the induced responses. Since the sensor is required to detect low-level vibrations induced early in the burn, as well as the large transient response levels encountered as collapse nears, sensor sensitivity and gain selection are important design considerations. Previous experience has shown that sensitivities on the order of 10V/g along with amplifier gains ranging from 2 to 60 can provide adequate signal-to-noise content throughout a typical burn period leading to structural collapse. The comparisons of the MEM and QA sensor signals acquired during the barn tests suggest the lower sensitivity (of the MEM sensor, on the order of 0.67V/g) produces adequate signal content. It is expected that amplifier gains for the lower sensitivity MEM sensor would stay within the 2 to 60 range.

Thermal protection requirements for the sensor were originally based on the expectation that the sensors would be installed inside a burning structure where temperatures could reach 1500 degrees Fahrenheit. However, it has since been shown that sensors can be placed at remote locations around the exterior of the structure where direct fire impingement does not occur.

Pictures of the fire-sensor housing, the MEM based sensor, and cabling are shown in Figure 8. The housing was manufactured by Thermal Ceramics Inc. and designed to provide protection up to 1200 degrees Fahrenheit. The fire protection material is encased in a metal housing and welded to an attachment plate to facilitate installation. The MEM based sensor is shown in Figure 8 inside the housing. The sensor cable exits the box through an opening that requires fire protection during use. The main components of the MEM sensor include the button battery (top left corner), the MEM accelerometer (bottom center), a power switch (bottom left corner), and the signal cable (right side, red and white wires). When assembled, a layer of fire protection blanket is placed over the sensor board to provide additional thermal protection as well as shock resistance in the event of direct impact (during installation or burn).

Figure 8 - New fire-sensor housing and MEM based design.

Additional testing of the fire housing's ability to withstand elevated temperatures and direct fire impingement was carried out during training exercises with the Ventura County Fire Department in May 2004. Figure 9 shows pictures of a wood frame house (top), a fire sensor mounted to the exterior siding (middle), and view of the back of the house (bottom) during burn. The roof was loaded with approximately 300 pounds of sand bags in an effort to encourage collapse of the main roof members during burn.

These tests were primarily designed to evaluate the thermal protection of the sensor housing and of the cable sleeves (shown in red with aluminum tape Figure 9). Based on the performance of the sensor during these tests, improvements to both the housing and cable protection systems were made.

Figure 9 - Fire sensor evaluation tests.

5.3 Installation / Attachment Procedures

It should be noted that the attachment procedures developed are intended to aid in the conduct of field tests in support of the current research effort. It is anticipated that alternate procedures will be required for real-time and practical monitoring during firefighting operations.

The original attachment procedures described in Ref [1] were fairly elaborate and required drilling, installation of anchors and bolts, as well as thermal blankets and aluminum tape. A typical installation lasted about 30–45 minutes depending upon site conditions and the installer's own experience. Part of the rationale for using bolts to attach the sensor stemmed from the desire to secure the sensor firmly against the structure's exterior. This technique is consistent with mounting procedures employed on large civil structures for long term monitoring purposes. In those applications, sensors are bolted or adhered (e.g. epoxy mounted) to the structure. In the current application of fire-induced vibration monitoring, however, the sensors need only to be firmly attached to the surface in order to detect low level vibrations and to avoid being "knocked off" in event of light impacts from falling debris.

A measure of success has been achieved with magnetically attached sensors to the exterior of the building. The procedure requires a steel plate to be attached at the location on the exterior where the sensor is to be placed. The plate may be simply nailed or screwed directly to the exterior surface. Magnets are then used to place the sensor onto the plate. While the magnets result in a gap between the sensor housing and the exterior surface, testing has not revealed degraded signal behavior during monitoring. Since the sensor housing provides adequate thermal protection for most applications, the installation procedure is greatly simplified and a typical installation can be completed in less than 10 minutes.

6 Stability Based Analysis Techniques

Fire-induced vibration responses acquired during burn tests on both wood and steel frame structures exhibit random and transient characteristics. As discussed above, decaying transient behavior can be interpreted as indicating stable behavior, and growing transient response is more often associated with weakening conditions (see Figure 5). An analysis technique is required that is capable of extracting transient behavior from measured fire-induced vibration responses and that can create, in effect, a second series of "measurements" from the burning building which can be interpreted in the context of stability.

In order to illustrate that transient behavior can be captured during burn; a sample measurement acquired during a control burn of a strip mall store in Woodbridge, Virginia that took place in May 2001 is shown in Figure 10. During that test, fire sensors were placed at the front and at the back of the store (rectangular floor plan), and the roof was loaded with 5800 lbs to encourage roof collapse. Monitoring began at 120 seconds before ignition and continued through the collapse of the roof at 426 seconds.

Figure 10 shows the data retrieved from the accelerometer nearest the collapse. The extracted segments at 205 and 370 seconds illustrate transients due to fire-induced events. Indeed, each spike observed in the measured vibrations (Figure 10a) correlates with a response transient of this nature.

As collapse nears, observed changes in transient characteristics include: increased magnitude of response (from 0.006g to 0.0015g), shallower exponential slope, and a decrease in high frequency components. In order to quantify these changes, statistical and frequency distribution analyses were performed. Yet, the results provided little more than indication of the growing magnitude of the system response leading to collapse.

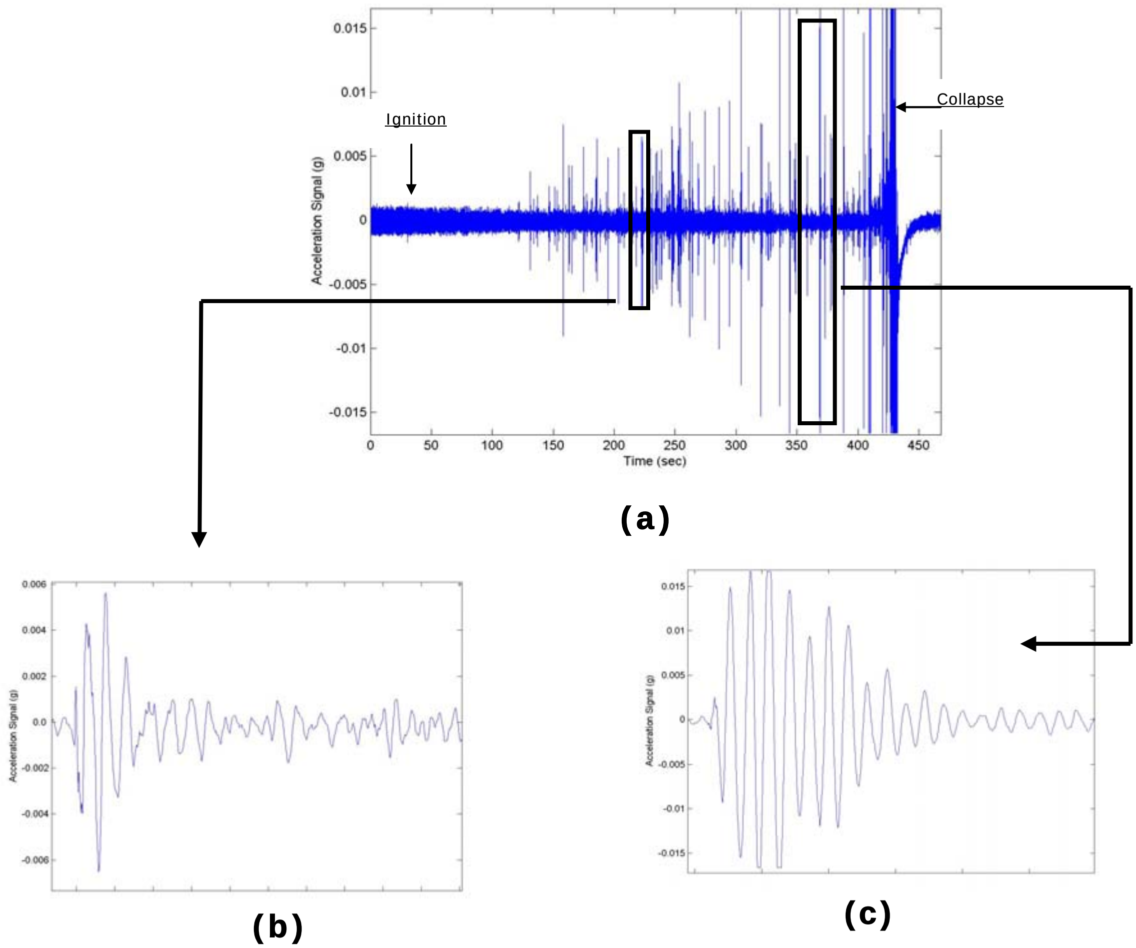


Figure 10 - (a) Acceleration response at the front of the strip mall store with extracted transients at (b) 205 and (c) 370 seconds. Changes in the transient character indicate the structure's weakened state approaching collapse.

6.1 Random Decrement Analysis

In order to extract fundamental information about the structure from obtained data, the Random Decrement technique was adapted. Random Decrement signatures computed throughout the measured data constitute an entirely new data set tracking the system's behavior from ignition to collapse.

Random Decrement (RD) is a time-domain analysis method developed in the 1960's by Henry Cole at NASA to study flutter effects on airplane wings, particularly relating to structural degradation [[2],[3]]. The method involves extraction of transients of a specified length, τ, within the data set that cross a pre-selected trigger value. These extracted segments are then averaged to produce a RD signature representing the free response of the system to a non-zero initial condition equal to the trigger value, X_s [[4],[5]]. Both damping and frequency information, obtained from the produced signatures, can then be used to asses the structure's stability.

The signature, $\delta(t)$, is represented mathematically as follows [6]:

$$\delta(t) = \frac{1}{N}\sum_{i=1}^{N} x_i(t_i + \tau)$$

where

N is the number of segments extracted

$x_i(t_i) = X_s$ is the trigger value

τ is the signature length

The slope, $dx_i(t_i)/dt$, is assumed to alternate with every averaged segment in this analysis.

Much literature currently exists that discusses the application and validity of the RD technique, mainly to bridges and offshore oil platforms [[5]-[7]]. Collectively, the sources define a set of assumptions that must be validated to deem the RD results significant:

1. The impacting force is zero-mean and Gaussian.
2. The system response is zero-mean and Gaussian.
3. The system is linear and time-invariant.
4. Signature characteristics are independent of X_s.
5. The length of data is sufficient to provide > 400 segments averaged per signature.

For the measured fire-induced vibration response shown in Figure 10, the assumption of linear time-invariance (3 above) does not strictly apply due to the changing nature of the system's behavior as it burns. However, if RD signatures were computed over sufficiently short time blocks in the measured response, an approximation of time-invariance might be made. Still, some error would persist, particularly nearing collapse.

The primary consequence of the response's time-varying nature is a signature dependence on trigger level, X_s, which violates assumption 4. Typically, the trigger level is chosen as a multiple of the standard deviation in the data set, however in a time-varying system, the standard deviation will also vary with time [[4],[8]]. Since the trigger is no longer uniform over the full data set, resulting signatures cannot be meaningfully compared. A better approach involves comparing results over a range of trigger values and searching for consistency in RD signature trends across the different trigger levels. As a result, the RD technique was adapted for the fire response data to include several computed signatures per data set calculated over specified time blocks, and multiple trigger levels.

Implementing a RD analysis based on shortened block times may cause the number of averaged segments to fall below the suggested value of 400 [[5],[6]]. Indeed, for a data block 60 seconds long, only 150-200 segments might be available to produce a RD signature. Nonetheless, consistency in signatures across multiple trigger levels can be used to evaluate the effect of fewer than suggested averages.

6.2 Adapting RD Analysis to Fire-Induced Vibrations

Adapting the Random Decrement analysis requirements to fire-induced vibration measurements would appear to be problematic. The basic theory of Random Decrement analysis imposes the assumption that the burning structure exhibits single degree of freedom behavior and can be modeled as a single lumped mass, massless spring and viscous damper. The responses from an actual burning structure, however, often exhibit multiple frequency content behavior that reflects the (nonlinear and time varying) changes in mass and stiffness properties of the burning structure.

A large amount of field work has led to the creation of a database of measured fire-induced vibration responses. The experience gained in the field, coupled with the careful review of this database, provides practical insights that allow an informed interpretation of the RD analysis to be made. Specifically, since the rate of change of many stability indicators appears to be relatively slow, some measure of time invariance may be assumed. Furthermore, the relative magnitudes of the stability indicators derived from RD analysis appear consistent with values reported from healthy, stable structures. Perhaps most compelling, however, is that the trends and relative changes in the various indices are consistent with (video) recorded observational evidence of collapse behavior.

The result of these experimental and observational correlations strongly suggests that, although burning structures may not adhere to the strict assumptions of Random Decrement analysis, their behavior is sufficiently modal in nature (that is, the behavior can be described by a few dominant frequency components) that interpretation in the terms of structural stability can still be made.

Anticipating that RD analysis could provide a series of transient signatures that may be used to develop stability indicators for real-time monitoring, a tool was developed and evaluated during burn tests of simple frame as well as large wood frame structures. This tool is described in the following section, and its application to full-scale burning structures is also discussed.

7 The Health Of Burning Structures (HOBS) Panel

HOBS is a real-time monitoring tool that provides researchers with the ability to acquire and analyze fire-induced vibration measurements in the field. Analysts may use HOBS to track a series of indicators that can be interpreted in the context of structural stability. HOBS acquires data via a National Instruments PCMIA data acquisition card (installed in a laptop) and provides a series of visual and numeric indicators for tracking changing conditions during burn. A sample image of the HOBS front panel at the conclusion of a burn test on a simple frame is shown in Figure 11.

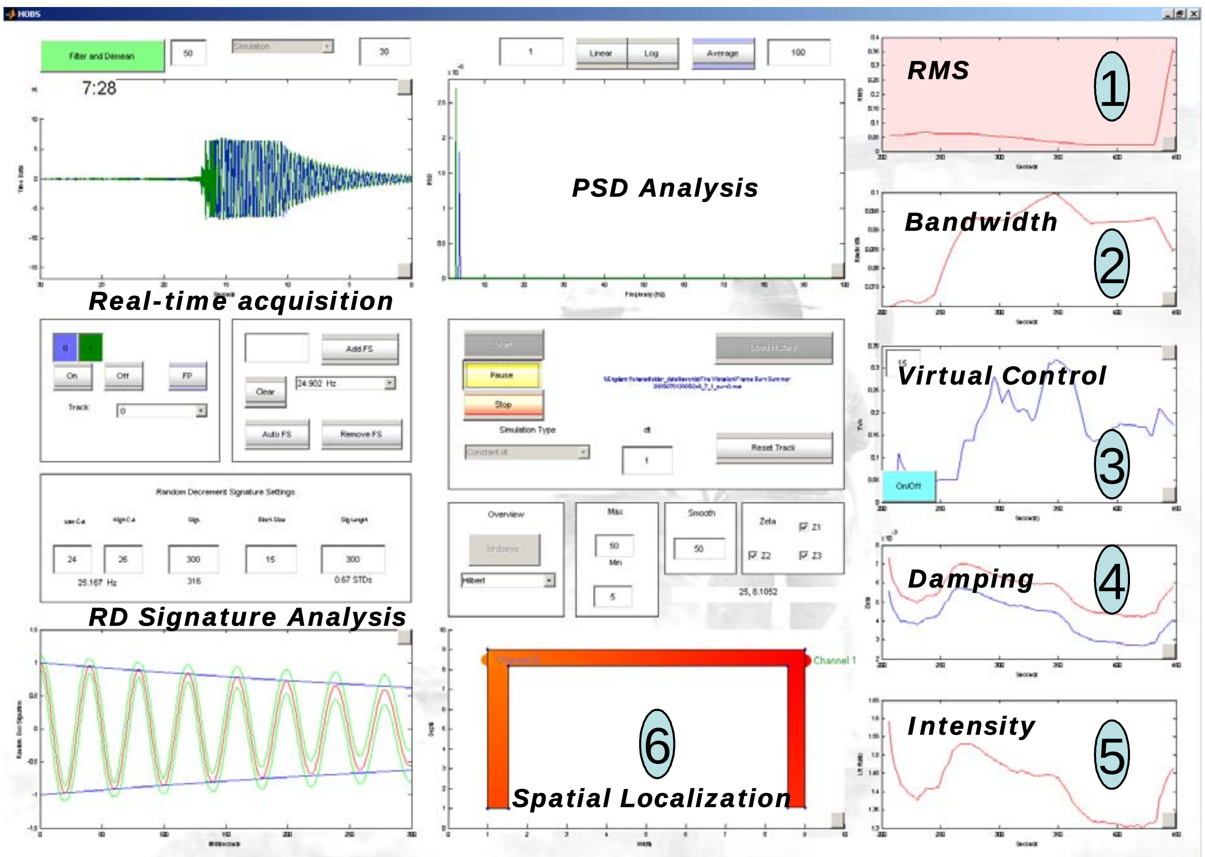


Figure 11 – Image of HOBS panel during simple frame burn.

In a typical HOBS application, fire-induced vibrations are acquired and analyzed (using power spectral density (PSD) analysis) in order to identify dominant frequency components. This initial analysis is important since it aids researchers in their identification of dominant structural response behavior. An added benefit is the ability to use PSD analysis to identify the presence of steady-state excitation sources in the measured responses. Behavior associated with steady-state excitation complicates the various HOBS indicator analyses (since they are mostly based on transient behavior), and appear as narrow-band, sharp resonant peaks that typically result from generators or fire truck engines idling on-site. Researchers can set appropriate filter parameters to mitigate this problem and enable HOBS to track dominant structural responses during burn.

7.1 HOBS Analysis Tree Structure

The current HOBS analysis tree structure is shown in Figure 12. A typical HOBS analysis begins with the acquisition of the fire-sensor response signals and the identification of dominant frequency components. Filtering is performed in order to maximize signal-to-noise ratios and to remove steady-state responses associated with operating equipment that can obscure stability indicators and their interpretation. These filtered responses form the basis for subsequent analyses (each analysis is indicated inside the rectangular boxes) that ultimately produce the various stability indicators (indicated in red). HOBS has the ability to produce multiple versions of the same indicator, thereby providing a measure of verification or enhanced confidence in the result.

Transforming the measured fire-induced vibrations (as shown in the upper left window in HOBS) to corresponding Random Decrement signatures (as shown in the lower left window in HOBS) is a key step in producing stability indicators that track changing conditions during burn. Other analyses, including frequency distribution, power spectral density, RMS and tuned vibration absorption can be performed on both filtered and non-filtered responses. A description of the indicators shown in the HOBS panel in Figure 11 (identified as 1-6) follows.

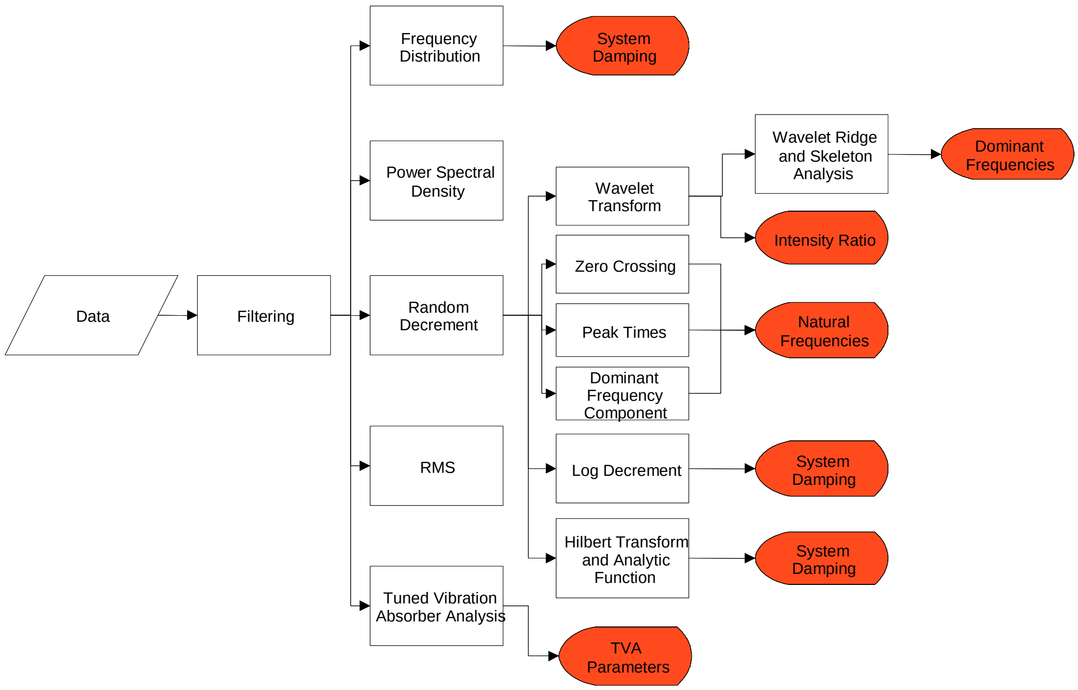


Figure 12 – HOBS analysis flowchart.

7.2 Root Mean Square (RMS) 1

A Root Mean Square analysis is applied to measured responses according to

$$x_{rms}(t) = \sqrt{\frac{\sum_{j=0}^{N} x(j)^2}{N}}$$

where

$x_{rms}(t)$ is the root mean square value at time t

$x(j)$ is the jth time instant of the response

N is the number of time instances in x

In general, the magnitude of the RMS index will increase as the structure becomes less stable. Large changes in the index indicate changes in structural stability, whereas flat regions are indicative of sustained stability. While the absolute value of this indicator will be dependent upon the sensitivity of the sensor, structural stability may still be tracked through relative trends. The RMS index is a suitable indicator for severe changes in response magnitude that may be associated with the weakening of main load carrying members in the burning structure. However, a sustained RMS index level may mask changing conditions within the structure that could ultimately lead to collapse.

7.3 Bandwidth 2

A Signal Bandwidth based index is derived from the measured responses and represents the spreading of the frequency content (or, bandwidth) in the burning structure. The index is interpreted in the context of a model of the structure that assumes the presence of only a few dominant frequency components early in the burn. As the structure is allowed to burn, additional frequency components begin to appear in the measured responses that are associated with sub-system or component behavior within the structure. The spreading of the frequency content, or bandwidth, is used as an indicator of weakening conditions.

The Signal Bandwidth index is defined as

$$B(t) = \sqrt{\int_{-\infty}^{\infty} (f - f_m)^2 |X(f)|^2 df}$$

where:

$B(t)$ is the frequency bandwidth of the signal at time t

$X(f)$ is the Fourier Transform of the signal

f is the frequency of the signal in Hz

f_m is the averaged frequency of the signal in Hz

This index is considered, as in the case of the RMS based index, to be a reasonable indicator in the presence of severe damage or loss of stability. Depending upon the spectral content, computation of averaged frequency, f_m, may bias the indicator somewhat, and suffers from poor signal-to-noise ratios in the measured responses. Filtering can be employed to remove unwanted noise, however, stability behavior associated with frequency components outside the filter band may be lost.

7.4 Virtual Control Indices 3

Virtual control indices are a class of indices under investigation that attempt to “control” the response of a burning structure in a virtual sense. These indices stem from the following question:

“What if a controller could be attached to the burning structure for the purpose of maintaining or even minimizing the structure’s response levels?”

Virtual controllers are attached to simplified models that represent the burning structure while the control parameters are continually adjusted to maintain or minimize measured response levels. As the burning structure is monitored, control parameters form an index that reflects the increasing difficulty of the controller to perform as response levels grow or significant loss of structural stability occurs. The presumption is that as it becomes more difficult to maintain acceptable response levels, the corresponding structure's stability decreases. Any number of controllers may be examined, however perhaps the simplest (passive) controller is derived from tuned vibration absorption (TVA) theory, used to determined the TVA index.

The TVA based index mimics the presence of a vibration absorption system attached to the burning structure that attempts to minimize the measured vibration responses during burn. This index reflects the effort required to keep measured responses from the burning structure below a certain threshold. A lumped model is shown in Figure 13 that describes this analysis approach.

The model in Figure 13 (left) is based on the Random Decrement signature behavior obtained from HOBS. For signatures that exhibit single dominant frequency behavior, a single degree of freedom lumped element model can represent the Random Decrement response behavior of the burning structure. This model is then used to calculate the source excitation, x, (or base motion) that is required to produce the measured Random Decrement behavior, Y_1. As the structure continues to burn and the magnitude of the Random Decrement response increases, the model will predict a corresponding growth in the source excitation or base motion. The source excitation signals computed using this model, are then utilized in the following analysis.

Tuned vibration absorbers can be attached to the structural model to absorb the growing source excitation associated with a weakening structure, as shown in Figure 13 (right). The absorbers must be tuned to the dominant frequency components observed in the measured Random Decrement response of the main system (M_s) in order to achieve the desired attenuation. The analysis is conducted using the computed source excitation (from the model in Figure 13 (left) without the absorbers) applied to the model with absorbers to compute the response Y_2. If the absorbers function properly, significant attenuation of the response of M_s will be achieved.

A sample response comparison that indicates the potential effectiveness of this type of index is shown in Figure 14. A noisy (judged to be poor in quality) Random Decrement response (blue) and the response of the main mass in the presence of just one tuned absorber (red) are depicted. The response with the single absorber is significantly reduced in magnitude and indicates that effective tuning has been achieved.

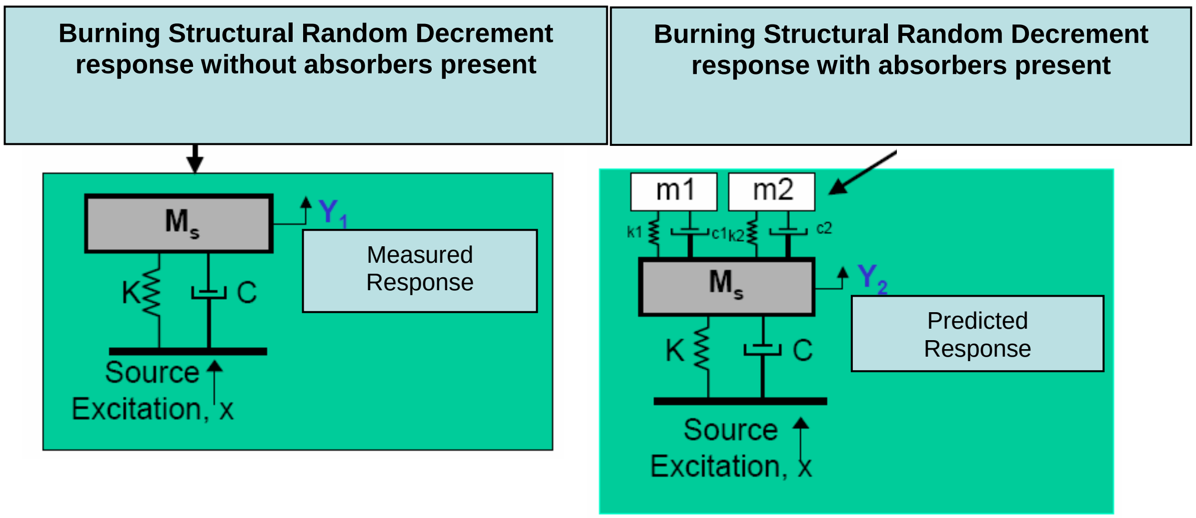


Figure 13 - Vibration absorption model.

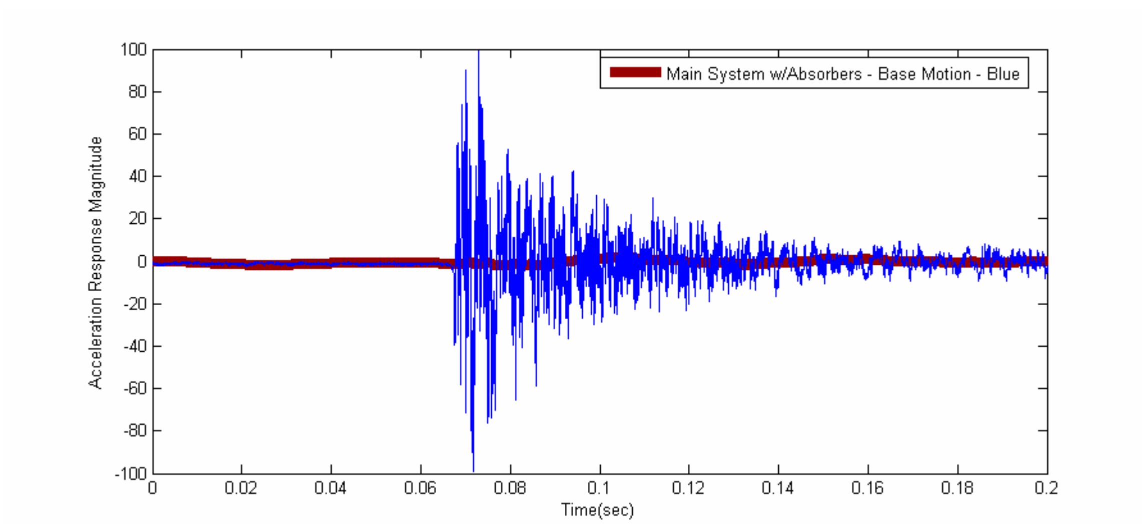


Figure 14 - Influence of absorbers on response magnitude.

The TVA index can be defined as a combination of analysis parameters such as

- the mass ratio (defined as the ratio of the absorber mass to the main system mass),
- the absorber damping values assumed in the analysis,
- and of the response ratio (defined as the ratio of the derived Random Decrement response to the computed response magnitude with absorbers present).

A growing TVA index value corresponds to declining absorber performance indicative of growing instability in the burning structure.

Traditional applications of tuned vibration absorbers (also referred to as Tuned Mass Dampers) are typically limited to those instances where undesired, dominant sinusoidal behavior exists. However, in the current application, responses derived from measured fire-induced vibrations may, or may not, contain dominant resonant (or sinusoidal) behavior.

The PI of this research project has direct experience with the application of tuned vibration absorbers in which TVAs have been successfully introduced in shock environments exhibiting multiple and unwanted resonances. The following comment, taken from Ref [9], offers an independent opinion.

> "In fact it has been shown that on certain kinds of structures a single tuned damper can contribute significant damping to several different modes distributed over a significant frequency band."

Studies are underway to further evaluate the best practice for implementing this and other virtual control indices within HOBS (based on preliminary results that suggest these indices can provide reasonable tracking of structural stability during burn).

7.5 Damping 4

Much of the reported literature in damage detection research on civil structures points to a weak correlation between damage and changes in both resonant frequency and damping. In the context of stability monitoring, however, the product of these variables is usually considered a key parameter in tracking stability. The problem has been that reliable estimates of how damping and resonant frequency change over time have been difficult to measure using traditional analysis techniques. The observational evidence that burning structures exhibit relatively slow varying behavior provides enhanced confidence in the use of the Random Decrement analysis.

A variety of methodologies provide damping estimates based on the decaying transient behavior from Random Decrement signatures. The algorithms, each of which is described below, include:

- Log decrement analysis
- Envelope analysis
- Wavelet Transform analysis

Log decrement analysis is perhaps the most common technique described in textbooks on Mechanical Vibrations for determining damping from transient behavior. In this technique, damping (denoted by zeta, ζ) is directly related to the ratio of two neighboring peaks according to

$$\zeta = \frac{1}{2\pi} \ln\left(\frac{x_1}{x_2}\right)$$

where x_1 and x_2 are the response levels associated with two neighboring peaks in the decaying transient. Resulting damping estimates may vary depending upon which neighboring peaks are selected, and cannot be relied upon to provide a consistent index that tracks changing conditions within the structure if the Random Decrement signature exhibits multiple frequency components.

Envelope analysis is performed using the Hilbert transform to create an analytical or complex representation of the Random Decrement response. If the Random Decrement response can be expressed as

$$RDS(t) = e^{-\zeta\omega_n t} \sin(\omega_n t)$$

the corresponding complex representation becomes

$$z(t) = e^{-\zeta\omega_n t} \sin(\omega_n t) + je^{-\zeta\omega_n t} \cos(\omega_n t)$$

whose magnitude is easily determined to be $|z(t)| = e^{-\zeta\omega_n t}$.

This relationship can be used to produce an envelope of the Random Decrement as shown in Figure 15 (blue curve). HOBS compares the envelope to the signal and computes a standard deviation of the signature (green signal in Figure 15) to provide an estimate of the confidence in this result.

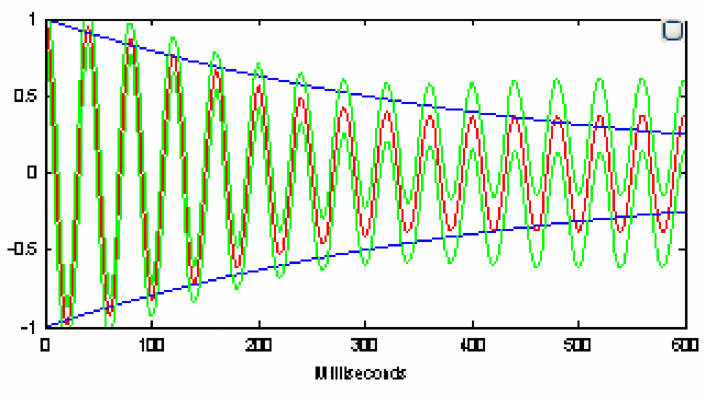


Figure 15 - Random decrement signature with enveloping function and standard deviation, normalized.

Problems arise, however, when the Random Decrement signature does not appear as in Figure 15, and instead appears more like the signature in Figure 16.

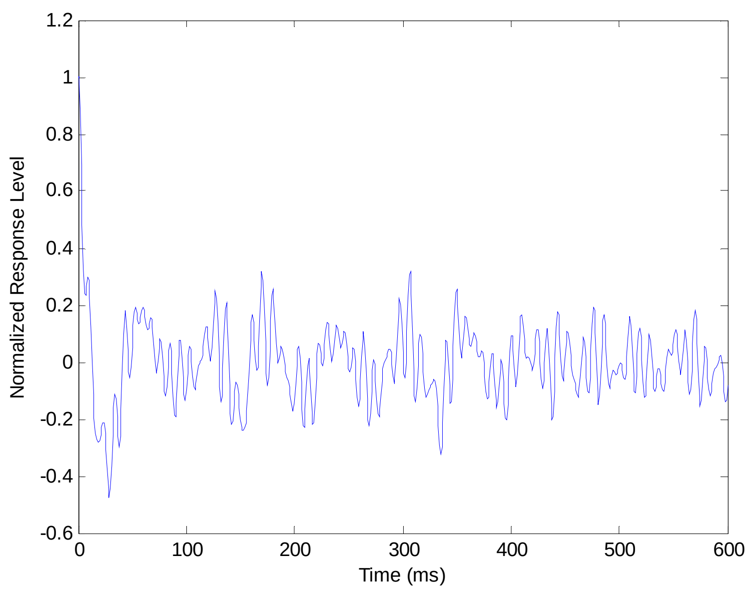


Figure 16 – Signature acquired from Fillmore High School burn utilizing Random Decrement analysis with no applied bandpass filtering and the removal of 60 Hz noise

7.5.1 Wavelet Transform Analysis

The Random Decrement signature shown in Figure 16 is not uncommon in the field. The typical signature, even with careful bandpass filtering of the measured fire-induced vibrations, may still exhibit multiple frequency behavior within the filter passband. Attempts to apply log decrement or even envelope analysis techniques to this type of signal will result in large uncertainties in damping estimates. An approach is required that is able to decompose the Random Decrement signature into its dominant frequency components. Wavelet transform analysis can be used effectively in this case.

The wavelet transform of a signal, $x(t)$, is the convolution of the signal with a parent wavelet, $g(t)$, according to the equation

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

where, a, τ are scaling and translation factors, respectively. Although not entirely correct, one may interpret the scale factor in terms of frequency, and the translation factor provides the time varying nature of the wavelet coefficients, $W(a,t)$, which are complex. The coefficients represent the similarity of the wavelet at a given scale and time, (a,t), to the signal at that time, t, thereby localizing a signal in both frequency and time.

Different wavelets are available for a variety of analysis applications, and the Morlet wavelet,

$$g(t) = e^{j\omega_n t} e^{-t^2/2} = e^{-t^2/2}\left(\cos(\omega_n t) + j\sin(\omega_n t)\right)$$

is particularly well suited for harmonic analysis applications. Since in the current application, the intent is to obtain the wavelet transform of Random Decrement signatures (as in Figure 16), the Morlet wavelet is a reasonable function with which to perform the convolution. The complex exponential at the beginning of this function serves to window this harmonic component in order to restrict the wavelet in time, providing a consistent function with which to convolve the Random Decrement signatures.

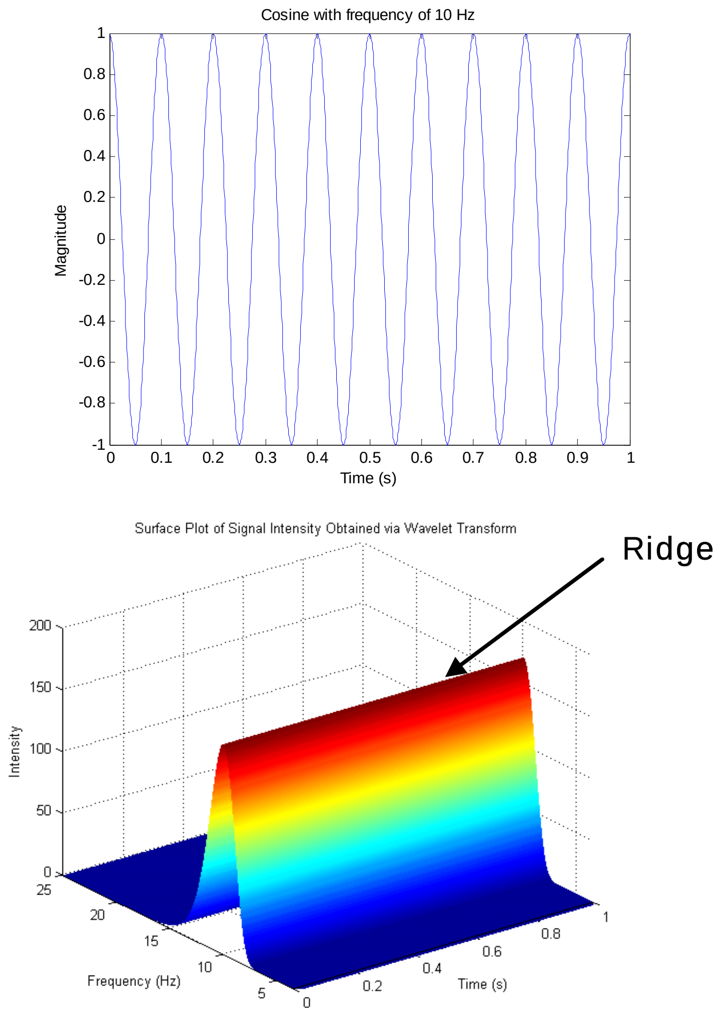


Figure 17 – Theoretical Random Decrement signature (top) and surface plot of wavelet intensity (bottom).

Figure 17 shows a sample cosine function with a frequency of 10 Hz (top) and a surface plot of $|W(a,t)|^2$ for the signal (bottom). $|W(a,t)|^2$ represents the intensity contained in the signal as a function of frequency and time. A Ridge is defined along a frequency where the maximum intensity values occur, as indicated in Figure 17 (bottom). The wavelet coefficients corresponding to the Ridge can be extracted to yield a (complex) wavelet skeleton. The real and imaginary parts of the skeleton approximate the signal at the instantaneous frequency that the Ridge follows, and also approximates the complex representation of the signal (described above). In this example, a single skeleton would be extracted from the analysis since only one dominant frequency exists in the signal.

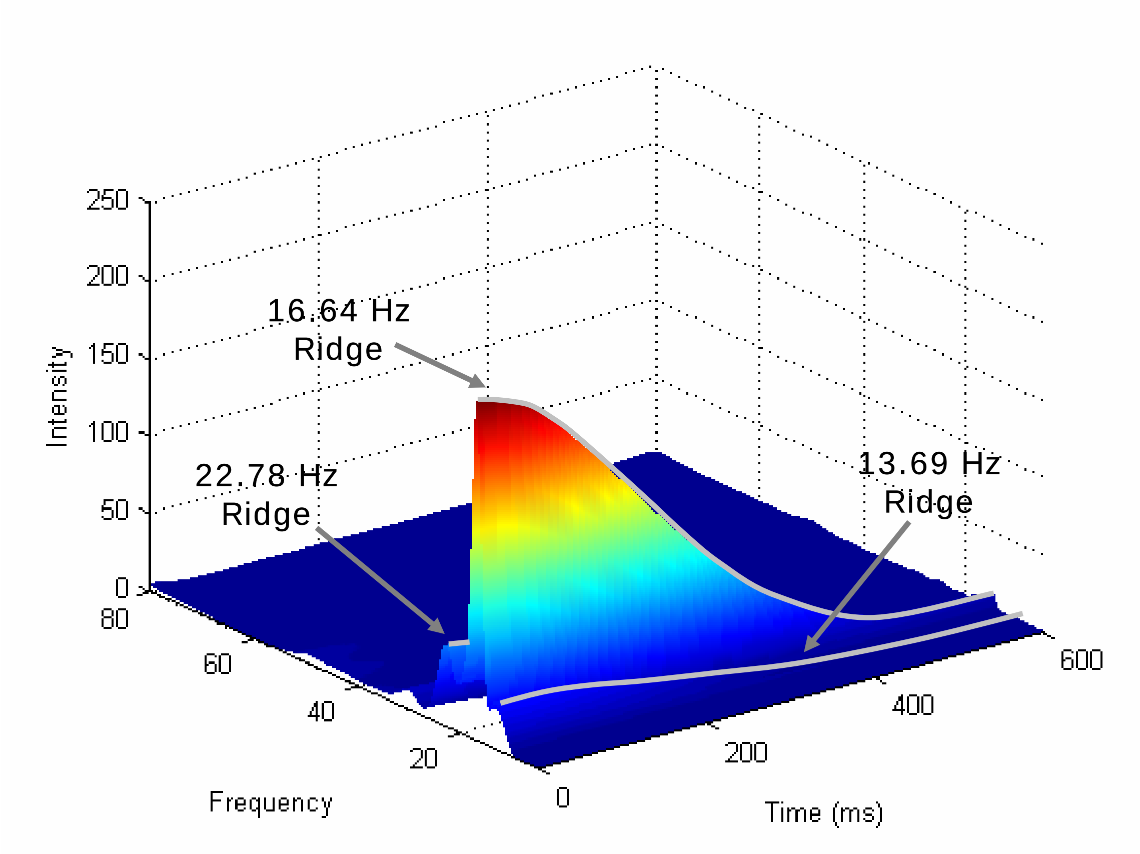


Figure 18 – Surface plot of the wavelet intensity of the signature shown in Figure 16. Ridges indicated in light gray

A wavelet transform analysis of the signature in Figure 16 produced the surface plot shown in Figure 18. Multiple frequency components in the signature are observed in the result, and the 3 most dominant have been identified. Instead of using the absolute maximum intensity to isolate a single Ridge, multiple Ridges can be identified by finding the local maxima over the entire surface plot of $|W(a,t)|^2$. These maxima are determined by summing the intensity across time according to the equation:

$$P(f) = \sum_{t=0}^{T} |W(a_f, t)|^2$$

where:

$P(f)$ is the total intensity of the signal at each frequency , f
T is the total time over which the signal was acquired
a_f is the scale factor corresponding to each frequency

The $P(f)$ plot generated from the wavelet intensity of the signature shown in Figure 16 that highlights the three most dominant peaks is shown in Figure 19. The summation is performed even though the response of the structure is not time invariant due to the slowly varying frequency content in each random decrement signature.

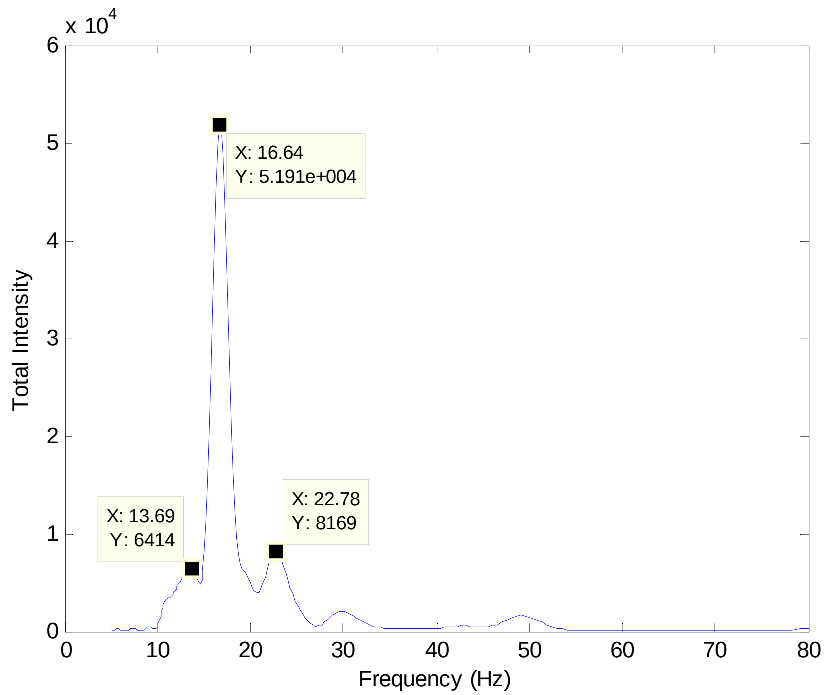


Figure 19 – The total intensity, *P(f),* of the signature shown in Figure 16.

After the dominant frequencies are determined, the Ridges at these frequencies are extracted. An example of successful ridge identification may be seen in Figure 18 in which the three most dominant ridges, found using $P(f)$, are indicated across time. The skeleton of each of these ridges can be extracted to provide the dominant components in the Random Decrement signature. For the signature shown in Figure 16, the skeletons associated with the three most dominant Ridges, are shown in Figure 20.

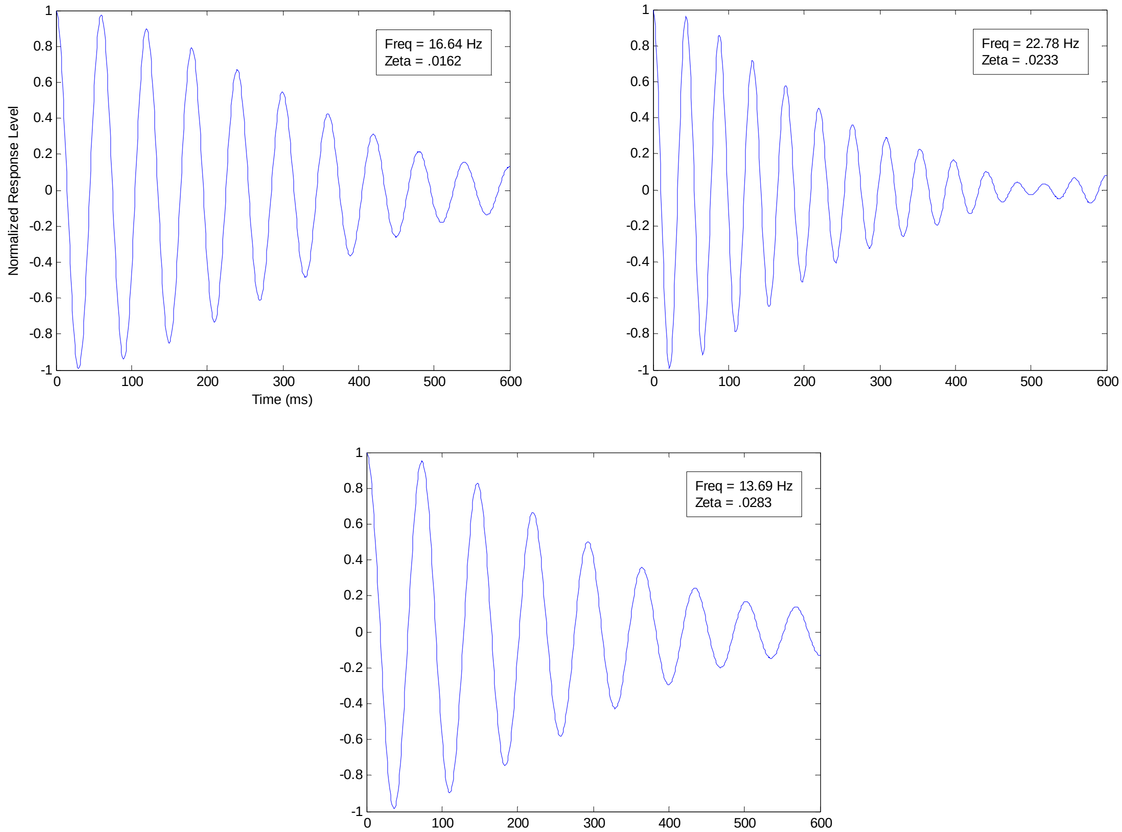


Figure 20 – The skeletons associated with the 1st, 2nd, and 3rd most dominant ridges generated from the signature in Figure 16.

(top left, top right, and bottom respectively)

The value of instantaneous frequency can be combined with the decay rate ($\zeta\omega_n$) derived from the Hilbert Transform or log decrement of the skeletons in order to provide a damping estimate for each dominant frequency component in the signal.

7.6 Intensity 5

The intensity of a Random Decrement response, $|W(a,t)|^2$, can be divided into two parts associated with the front and back portions along the time axis. The ratio of the intensity of the front portion to the intensity of the back portion can be used to indicate relative changes in a structure's stability in a manner not too dissimilar from damping. For example, Random Decrement signatures obtained from healthy, stable structures will decay rapidly with time and the corresponding ratio of intensities (front to back) will be greater than unity. As the structure weakens, and the Random Decrement signature exhibits almost no decay, the ratio of intensities (front to back) will decrease and approach unity, as is the case in Figure 17. In the unlikely event that the Random Decrement signature obtained from a burning structure exhibited a growing trend, the ratio of intensities would be less than 1.0, and would indicate (severe) instability.

7.7 Spatial Localization 6

Spatial localization in HOBS is achieved by selecting one or more of the stability indicators to produce a color contour of the type shown in Figure 21. Shown is an outline of a structure (the outline corresponds to the structure at Fillmore High School, discussed below) and the colored dots represent the fire-sensor locations around the perimeter of the structure. The color of each dot corresponds to varying index levels for each fire-sensor. In the example shown the color is based on RMS index values. A dark blue dot (Channel 6) indicates that sensor is no longer active, a light blue dot indicates a fairly low index value (Channels 0-2), and a dark red dot (Channel 5) indicates extremely high index values. This “birdseye” view of the burning structure is updated at pre-selected time intervals and provides a spatial overview of relative changes in stability.

At the time corresponding to Figure 21 the structure was near collapse and the region most afflicted was the upper right corner. In a relative sense, the structure appears least stable in the upper right corner, and in fact, collapse occurred in this area shortly after this time.

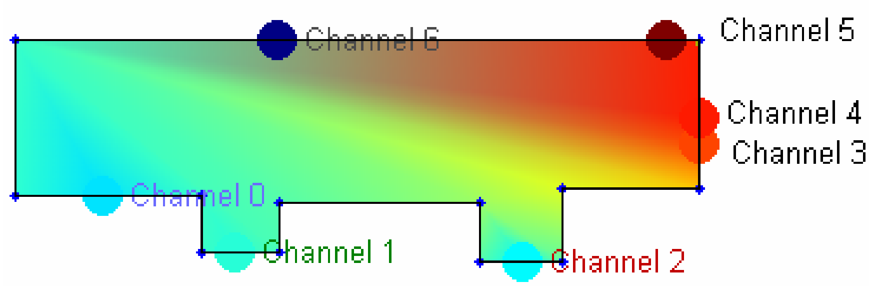


Figure 21 – Localization or RMS indicator during Fillmore Burn

This feature has the potential to provide quick and accurate information to firefighters during operations. As regions change colors from blue to red, relative stability can be assessed and this information can be used to enhance firefighter safety.

8 Application of HOBS to Burning Structures

HOBS has been applied to a series of full-scale burn tests on simple frame structures and on two large wood frame structures. Sample results acquired from each type of structure are presented here. Implications for future research and the development of a practical structural stability monitoring system for firefighting operations are also discussed.

8.1 Simple Frame Burns

A series of simple frames were constructed for the purpose of evaluating HOBS in the field. Simple frames consisting of two vertical columns and a single cross beam (header) were built at the Los Angeles County Fire Training Facility in Pomona, California with burn tests conducted during June and July, 2005. A total of ten frames were constructed with the first three frames consisting of steel columns and a wood cross beam, and the remaining seven frames constructed using wood columns and wood cross beams. Each frame was designed to produce a single, dominant collapse event involving the fracture of the cross beam, without damaging the vertical columns. To encourage this collapse event, the center of each cross beam was pre-loaded at center span (weights ranging from 100 lbs to 375 lbs).

Fire was applied through the use of a flame impingement device consisting of four torches, each fueled by a 5 gallon propane tank. Control valves were used to regulate the line pressure and the size of the flame. Stands made of copper tubing facilitated the positioning of the torches at the desired locations along the cross beam. A picture of one of the wood column/cross beam simple frames along with the torch system is shown in Figure 22. Two fire-sensors are shown attached at the upper end of each supporting column, and the metal hardware connecting the cross beam to the column supports is also shown. To obtain distinct indicators of impending collapse, the connections were designed to prevent a failure scenario in which nails are “pulled out” as the cross beam weakens.

Figure 22 - Simple frame burn test.

A sample of the fire-induced vibration response acquired during the frame burn test is shown in Figure 23. The response is similar in character to many of the previous field measurements taken on larger wood frame and steel frame structures, and this similarity provided confidence in the design of the experiment to provide realistic response behavior. The signal is characterized by a series of transient events leading to collapse near 430 seconds. A close up of the response between 130 seconds and 200 seconds in Figure 24 provides an indication of the changes leading to collapse.

Evaluating the changing structural conditions in the frame from the response indicated in Figure 23 can be achieved by examining the magnitudes of the recovery response portions of the signal. While the trends in recovery response magnitude may be a possible indication of relative stability, a better picture of the changing conditions emerges if comparisons of the recovery response levels can be made throughout the response. For the frame burn response shown in Figure 24, there exists a measurable difference in the magnitude associated with the 1st Recovery as compared to the larger response magnitude of the 2nd Recovery. Further examination of the recovery response levels beyond 200 seconds (not shown here) indicated levels remained consistent in magnitude throughout the remaining duration of this test.

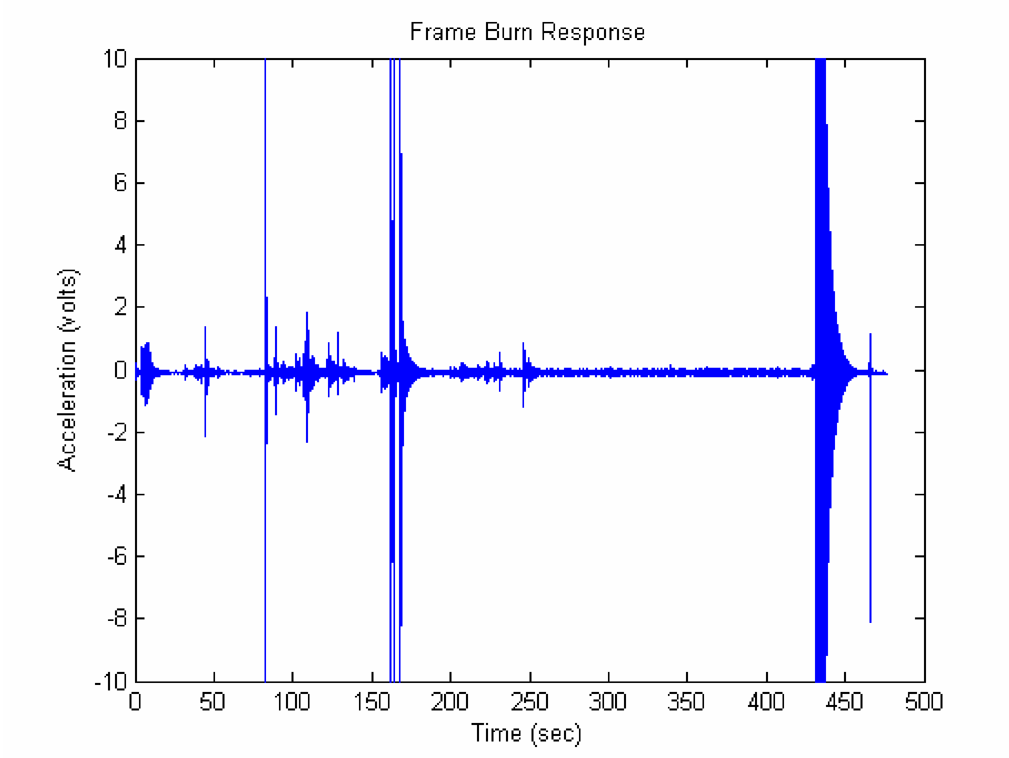


Figure 23 – Vibration response data for simple frame burn.

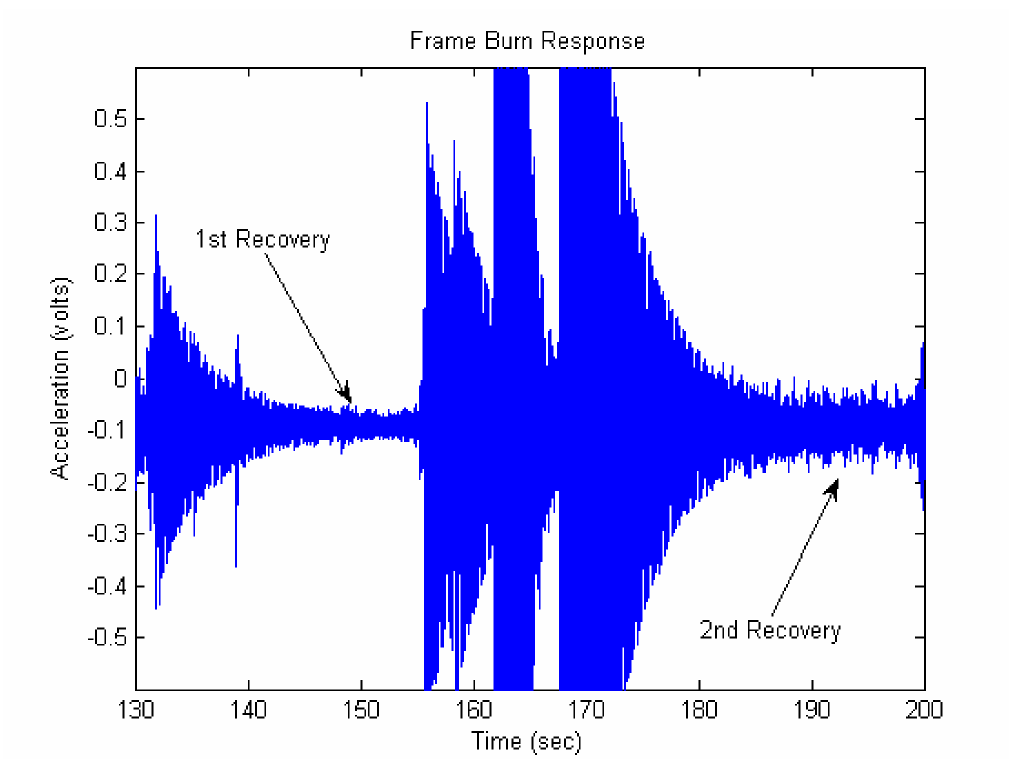


Figure 24 – Changing response levels between 130 and 200 seconds.

The difference in recovery magnitudes (1st compared to the 2nd in Figure 24) may indicate an irreversible change in the structure has occurred. On the other hand, since the recovery levels beyond 200 seconds remained fairly consistent, this can not be relied upon as the sole measure of changing conditions in the structure.

HOBS can be effectively used, however, to monitor a variety of indices during burn that collectively may provide a clearer picture of actual changes occurring in the structure. For example, the indices shown in Figure 25 are damping based, obtained using the log decrement (red) and enveloping analysis (blue) of the Random Decrement signatures. Ignoring the difference in index magnitude, both damping indices indicate similar trends that are consistent with impending collapse behavior. The dramatic drop in damping beyond (approximately) 270 seconds reflects a change in structural stability that is not readily observed from the measured response signals in Figure 23. The trend in damping index is thought to be consistent with the swelling that occurs in the connections during the early portion of the burn. As the frame heats up, the connections swell and the resulting friction likely contributes to elevated damping values. Near 270 seconds, however, a significant drop in the damping value occurs that indicates an irreversible change in the frame's ability to dissipate energy. This drop is followed by a steady, but slow decline in damping. As collapse nears, damping appears to increase, however, this increase is believed to be associated with the relative increase in friction at the connections associated with the failure mechanism at collapse. At collapse, the cross beam rotates about the connection furthest from the fracture point, and the relative motion during collapse contributes to the sudden increase in damping.

Another HOBS index is shown in Figure 26 and is based on the intensity ratio derived from the wavelet analysis of the Random Decrement signatures. The intensity index shows a similar drop in value near 270 seconds as observed in the damping indices, leveling off near 1.5 as collapse occurs. The similarity in the character and trends in both damping and intensity indices provide added confidence in the performance of HOBS and in its ability to track changing conditions during the burn.

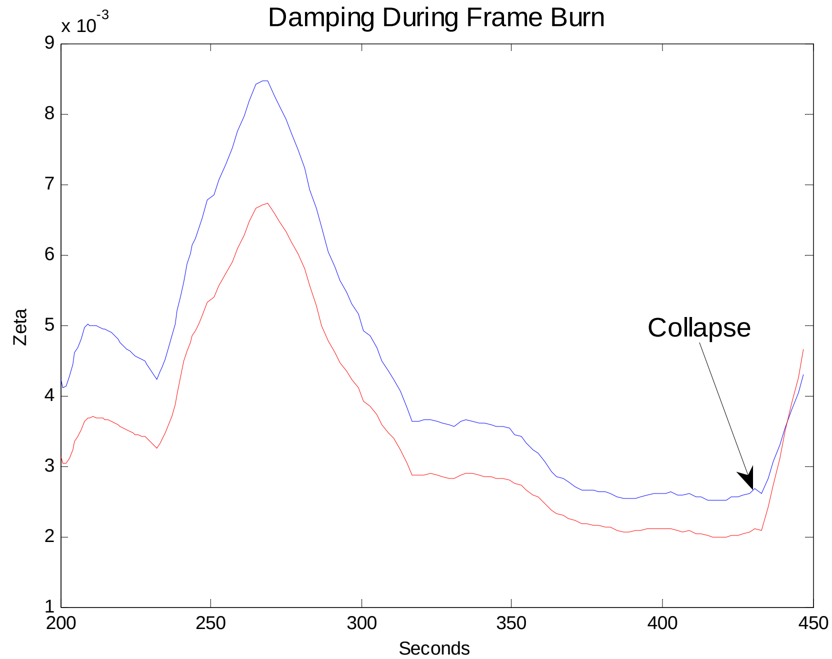


Figure 25 – Damping index during simple frame burn.

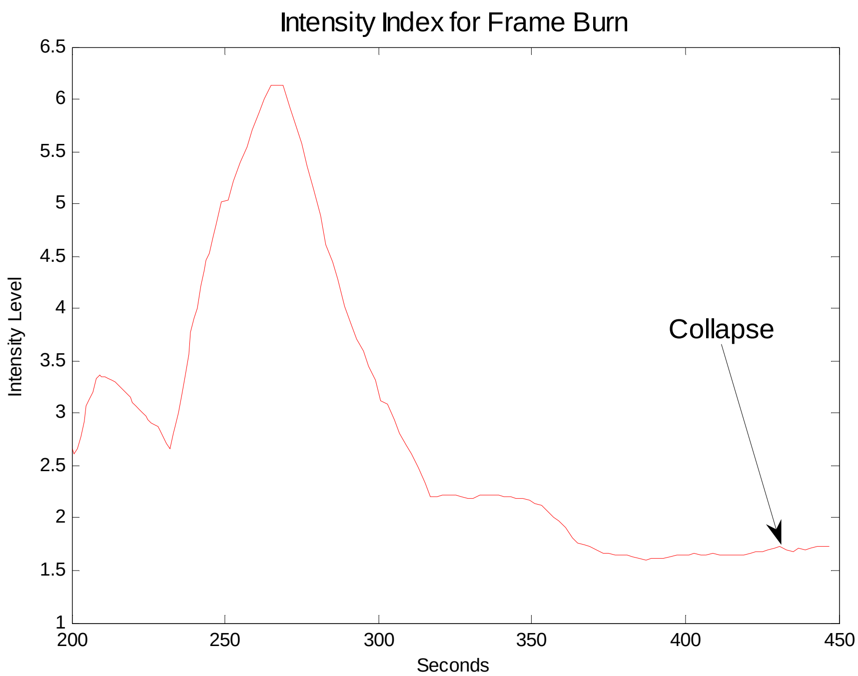


Figure 26 – Intensity index for simple frame burn.

8.2 Fillmore High School Burn Tests

Full-scale burn tests were conducted on a classroom structure at Fillmore High School located in Fillmore, California in April, 2005. Figure 27 and Figure 28 provide pictures of the building as well as of the roof loading mechanism. The structure was approximately 35 ft wide and 165 ft long and constructed using wood frame members covered with a stucco and brick veneer. The purpose of this test was to induce multiple collapses in the structure while monitoring fire-induced responses at locations around the perimeter of the building (see measurement layout in Figure 27). Anticipated collapse events included the collapse of the cantilevered overhang along the east side of the building and the collapse of two locations on the roof loaded with approximately 1200 lbs. Roof loading was achieved using five 30 gal steel trash cans filled with sand.

Pictures of the sensors installed on the cantilevered overhang (Ch5) and at one location along the west side (Ch2) are shown in Figure 29. MEM based fire sensors were installed at all measurement locations, and one of the QA fire sensors (Ch4) was installed adjacent to a MEM sensor (Ch3) on the south wall of the classroom. The QA sensor provided a signal that was used to evaluate the quality and content of the MEM sensor's signal, and to assess the MEM sensor's suitability for this application. Figure 30 shows the south wall and roof loaded during burn and a picture of the collapsed cantilevered overhang is shown in Figure 31. Fire-induced responses were acquired for slightly more than 80 minutes.

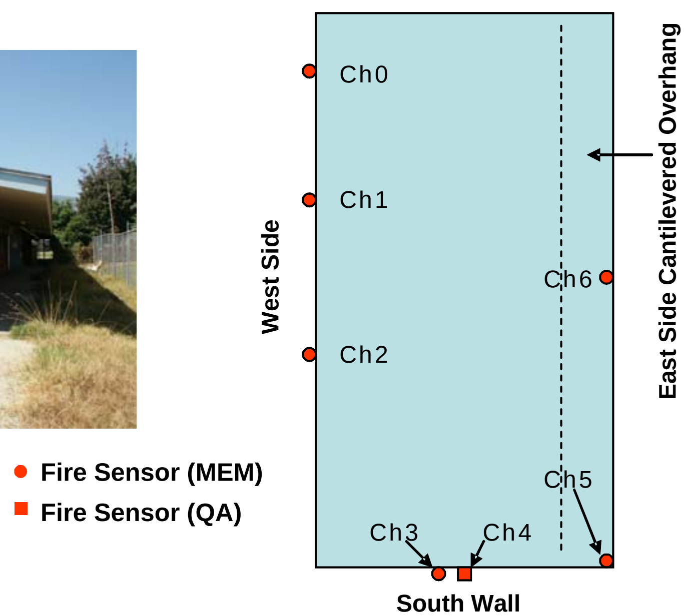


Figure 27 – South wall and measurement layout of Fillmore High School classroom building.

Figure 28 - West side of building (top left), view along east side corridor (top right), and installation of steel cans filled with sand simulating roof load of 1200 lbs (bottom).

Figure 29 – Fire sensors installed on cantilevered overhang (top left), on south wall (top right), and west side (bottom).

Figure 30 – Conditions over south wall during burn.

Figure 31 – Collapsed cantilevered overhang along east side of building.

8.2.1 Sample Measured Responses

Samples of measured fire-induced responses acquired during the burn tests at Fillmore High School are shown in Figure 33. The top response was acquired on the west side of the building and the bottom response was taken at the south wall. Both responses were acquired using the MEM fire-sensor and timing signals were used to synchronize the responses with video acquired during the burn. Actual time of ignition was not clearly identified (due to a delayed confirmation at ignition), however, the first visible smoke was observed 150 seconds after the start (at t=0 sec) of data acquisition. Both signals clearly indicate the collapse of the east side cantilevered overhang near 700 seconds. These high quality data sets are representative of the data acquired from all sensors.

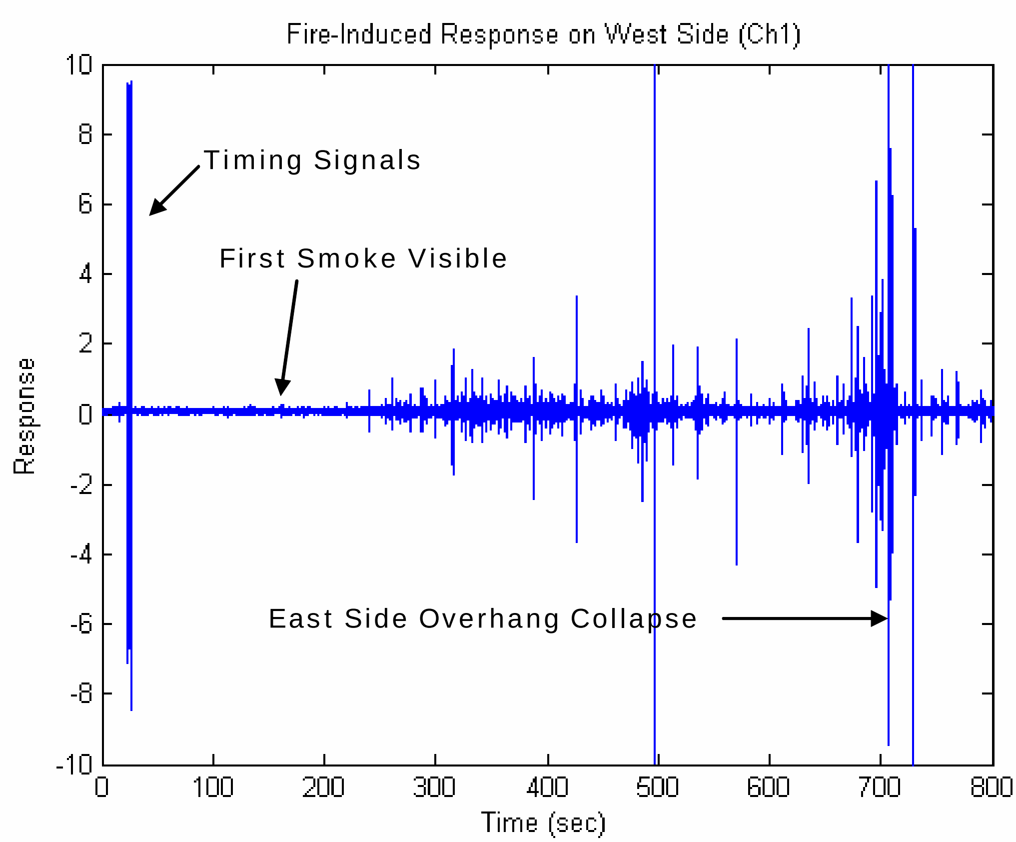


Figure 32 – Measured fire-induced response on the west side of Fillmore High School.

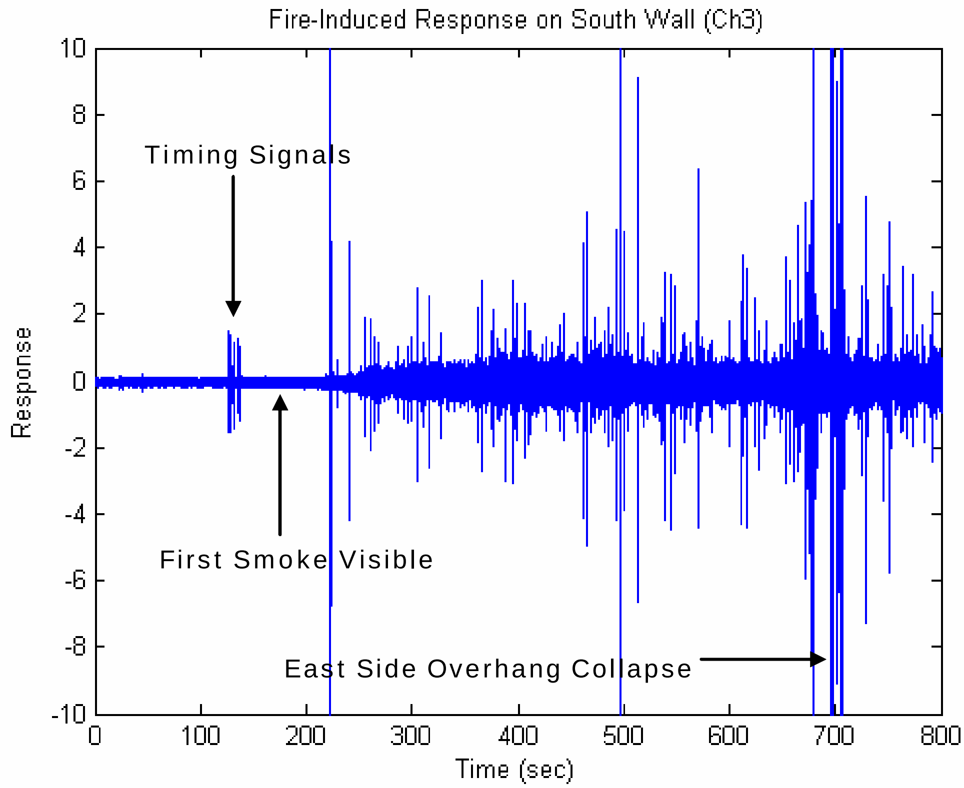


Figure 33 – Measured fire-induced response on the south wall of Fillmore High School.

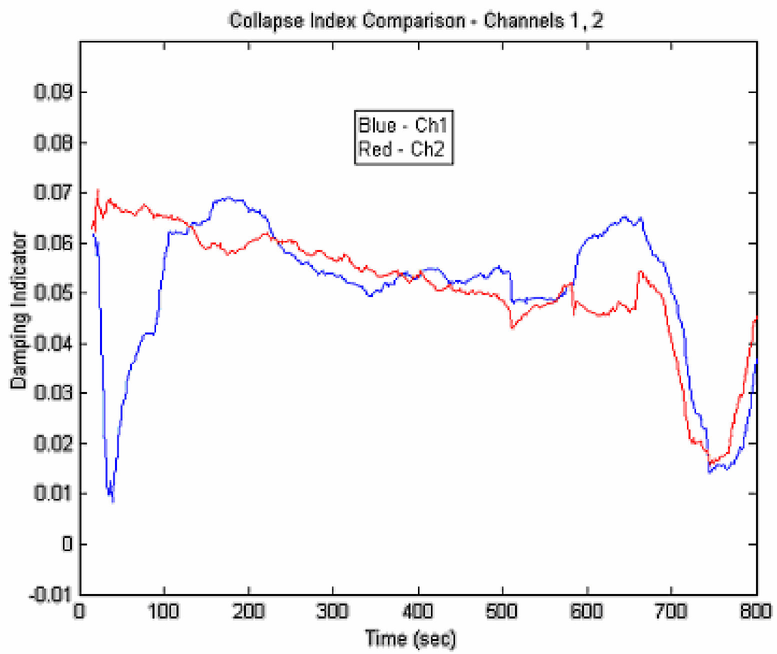
8.3 Damping based collapse indicator behavior

HOBS was used to produce damping indicators using the Random Decrement signatures extracted from the measured responses at each location on the structure. The spatial distribution of the fire-sensors around the classroom structure provided an opportunity to examine the ability of HOBS to discriminate relative stability changes as a function of sensor placement. The damping based indices associated with the responses at locations 1 through 5 (see Figure 27) are shown in Figure 34.

The consistency in the damping indicators suggests the following.

- Indicators associated with the sensors closest to the main collapse event seem to contain more frequent and larger variations in response compared to indicators obtained from sensors mounted farther away from the collapse event. This suggests a spatial dependency associated with the collapse indicators that may be used to identify weakening areas in the building.

- The magnitudes of the damping indicators prior to ignition are consistent with values reported in the literature from ambient surveys of large civil structures. As the structure weakens, damping values approach zero.
- Based on the timing of the observed collapse of the east side overhang, measurable changes in the collapse indicators are seen (approximately) 2 minutes prior to the collapse.



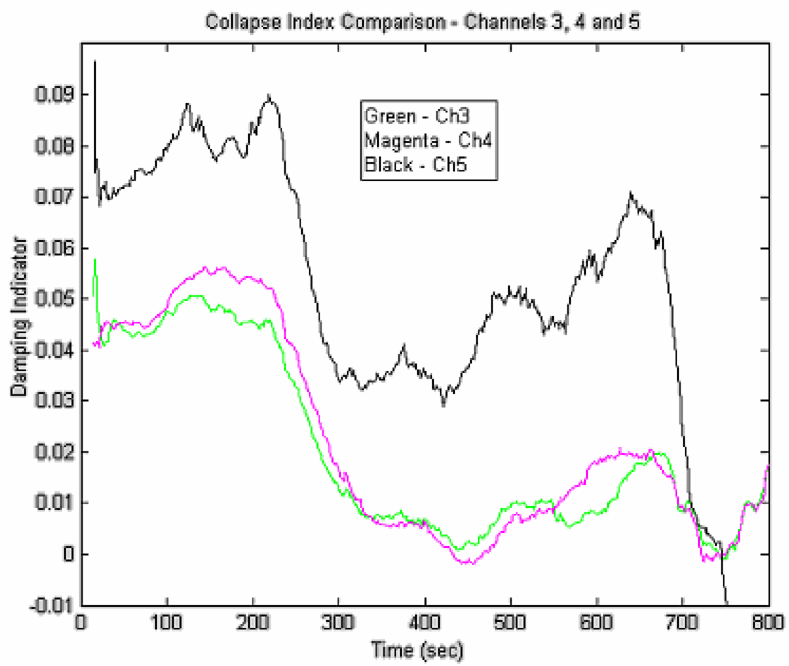


Figure 34 – Damping based collapse indicator response behavior.

8.4 Isbell Junior High School Burn Tests

HOBS was used during the burn test conducted at Isbell Junior High School (Santa Paula, CA) in July, 2005 on a structure similar to that tested at Fillmore High School. The structure was approximately 35 ft wide, 165 ft long, and constructed using wood frame members covered by a stucco exterior. The purpose of this test was to capture the collapse of the cantilevered overhang in the structure while monitoring fire-induced responses at locations around the perimeter of the building (see measurement layout in Figure 35). Unlike the tests at Fillmore High School, the roof was not pre-loaded to induce additional collapse events and only MEM sensors were used.

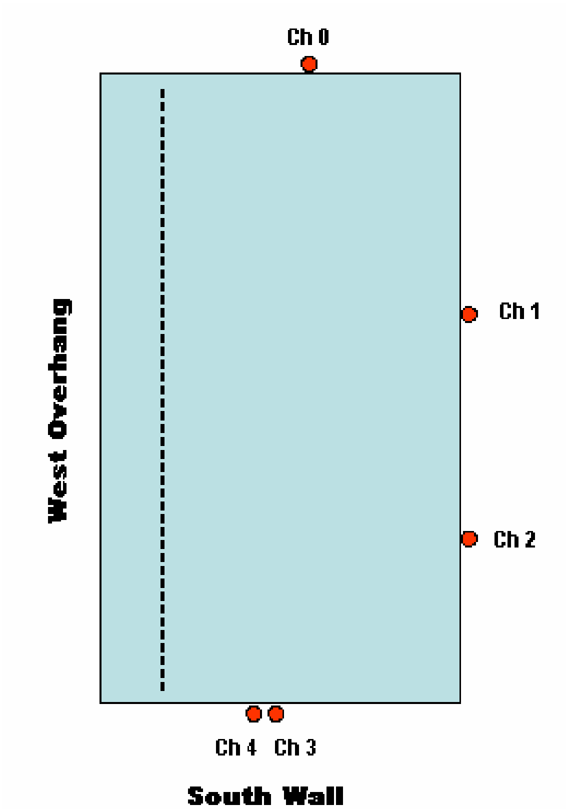


Figure 35 – Accelerometer layout for Santa Paula Burn.

A picture of the classroom structure during burn and a sample of the measured response behavior acquire during the test is shown in Figure 36.

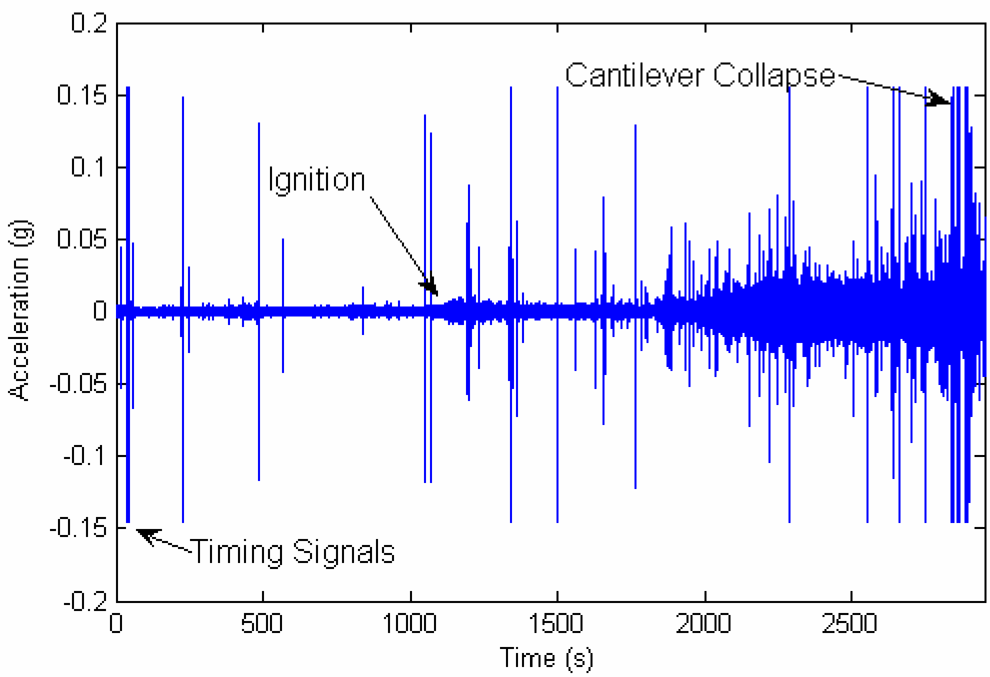


Figure 36 – Isbell Junior High School during burn and fire induced vibration response from accel 2.

During the tests at Isbell Junior High School, data acquisition was interrupted at 2434 seconds due to an accelerometer cable that caught fire. Acquisition was resumed by disconnecting the cable from the signal conditioning hardware. As a result of this, the data set was concatenated and the signal shown in Figure 36 is one of the concatenated signals from the test. In spite of this interruption, the character of the measured response is quite similar to that observed during the Fillmore High School burn tests and is considered to be of high quality.

The damping indicator generated using HOBS on the concatenated data set is shown in Figure 37. The damping trend is similar to that observed during the Fillmore tests where a dramatic decrease in damping is followed by relatively steady behavior with a smaller drop in damping just prior to roof collapse 2765 seconds. As observed during the simple frame tests, damping can increase during actual collapse due to the added friction of the movement across connections.

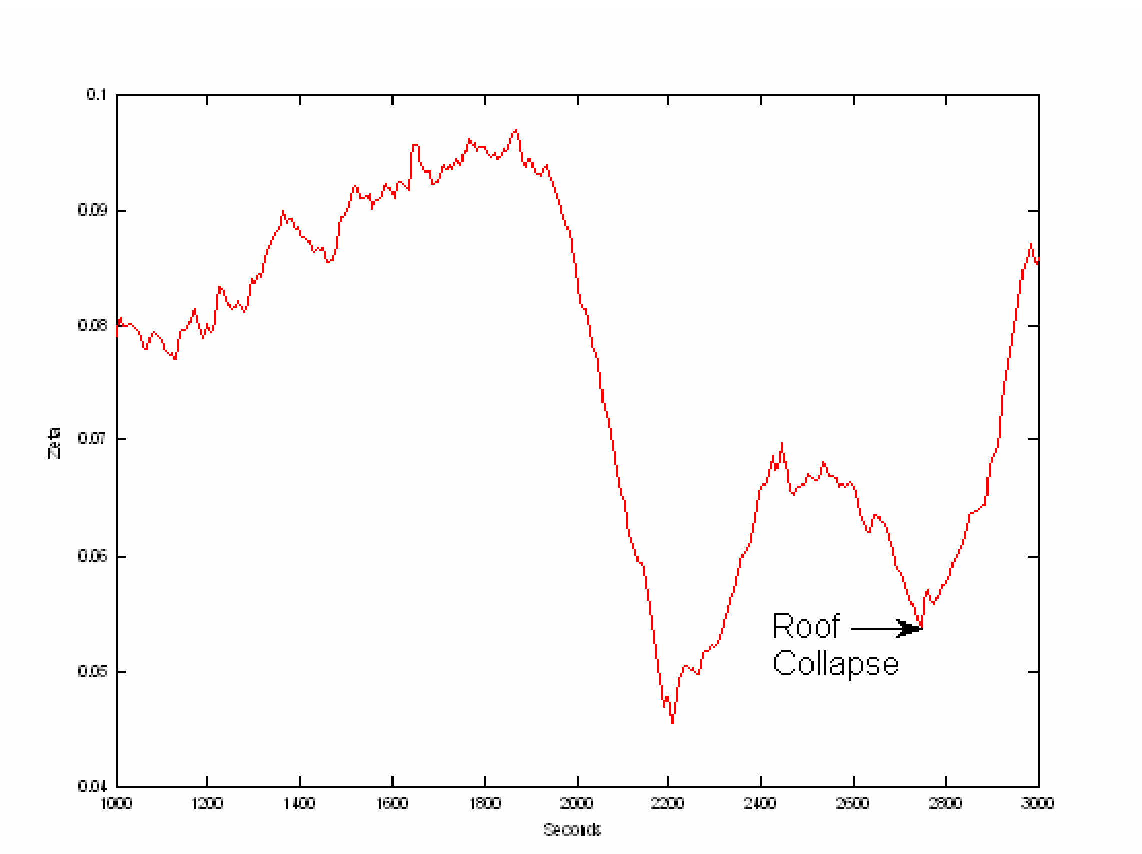


Figure 37 – Damping indicator for Santa Paula burn.

9 Tracking Loss of Stiffness in Burning Structures

Researchers have long held the idea that damaged structures should exhibit reduced stiffness. In the context of a dynamic response, this reduction in stiffness should manifest in terms of lower resonant frequency behavior. There exists very little in the literature, however, that directly illustrates this relationship based on field measured responses.

An analysis of the measured fire-induced vibration responses from the Fillmore High and Isbell Junior High School tests was performed with the objective of extracting instantaneous frequency behavior. The analysis procedure relies on the creation of a complex response based on the measured signal, $x(t)$, defined as

$$w(t) = x(t) + jHT(x(t))$$

where $x(t)$ is the measured response and $HT(x(t))$ is the Hilbert Transform of this response.

The expression for the complex signal can be re-written using polar notation

$$w(t) = Mag_{Inst}(t)e^{jPhase_{Inst}(t)}$$

where $Mag_{Inst}(t) = \sqrt{\left(x(t)^2 + (HT(x(t)))^2\right)}$, and $Phase_{Inst}(t) = Tan^{-1}\left({HT(x(t))} \big/ {x(t)} \right)$.

The instantaneous frequency response can then be computed as the rate of change with respect to time of the phase response as

$$Freq_{Inst}(t) = {d(Phase_{Inst}(t))} \big/ {dt}$$

to produce an indicator that tracks the change in frequency behavior as the structure burns.

Results from this analysis for the Fillmore High and Isbell Junior High School tests are shown in Figure 38 and Figure 39 respectively. Shown in each plot is instantaneous frequency as a function of time throughout each burn. The significance of these results lies in the remarkably smooth and decreasing trends in frequency and in their correlation with the known collapse events. Increases in frequency are normally associated with stiffening structural behavior, and this type of behavior could be associated with temporary swelling and increased friction at critical connections within the structure. As the structure continues to burn and weakening conditions develop, the structure softens in a manner consistent with the decreasing frequency behavior. The measurable decrease (in percent) of instantaneous frequency in each case is quite large.

These results are believed to be the first of this kind reported in the literature, and represent a significant contribution to the understanding and correlation of measured fire-induced responses to loss of stability in burning structures.

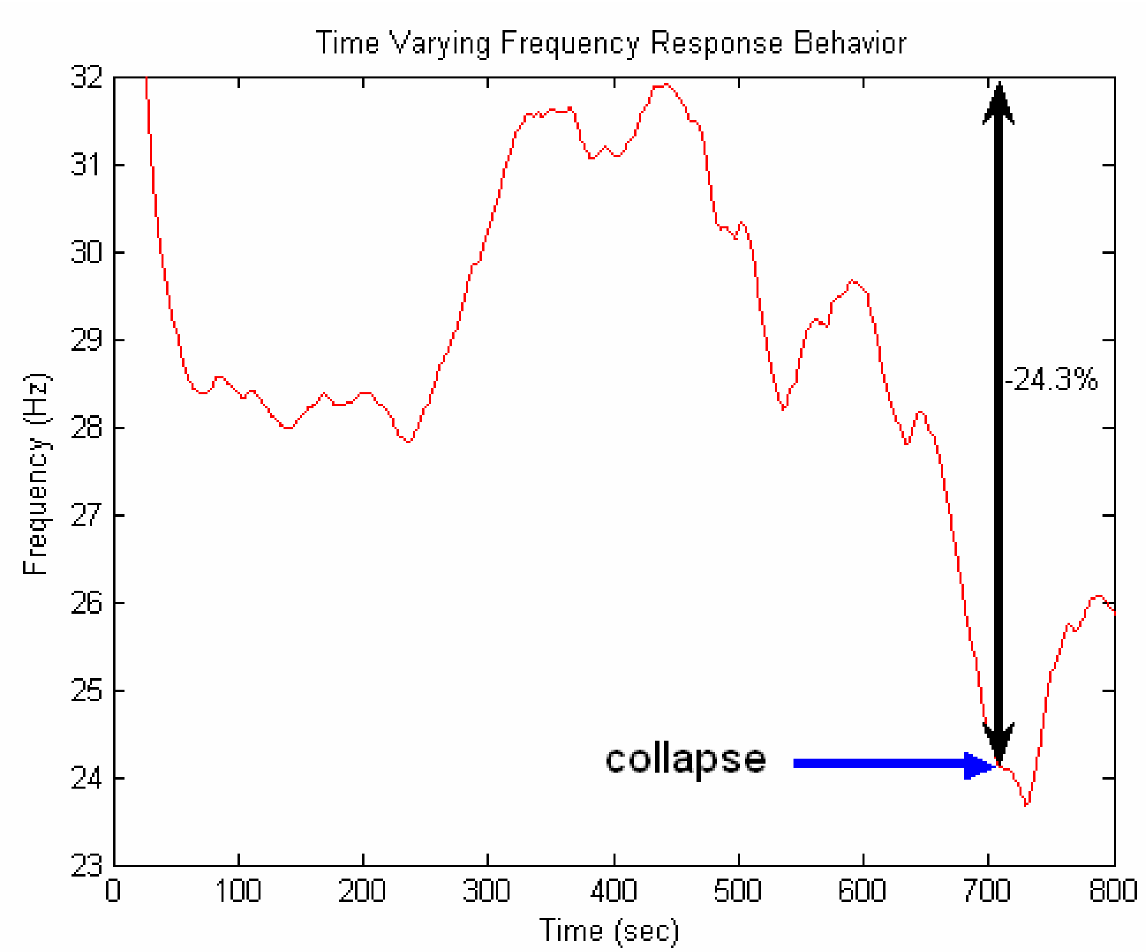


Figure 38 – Instantaneous frequency behavior for Fillmore High School burn

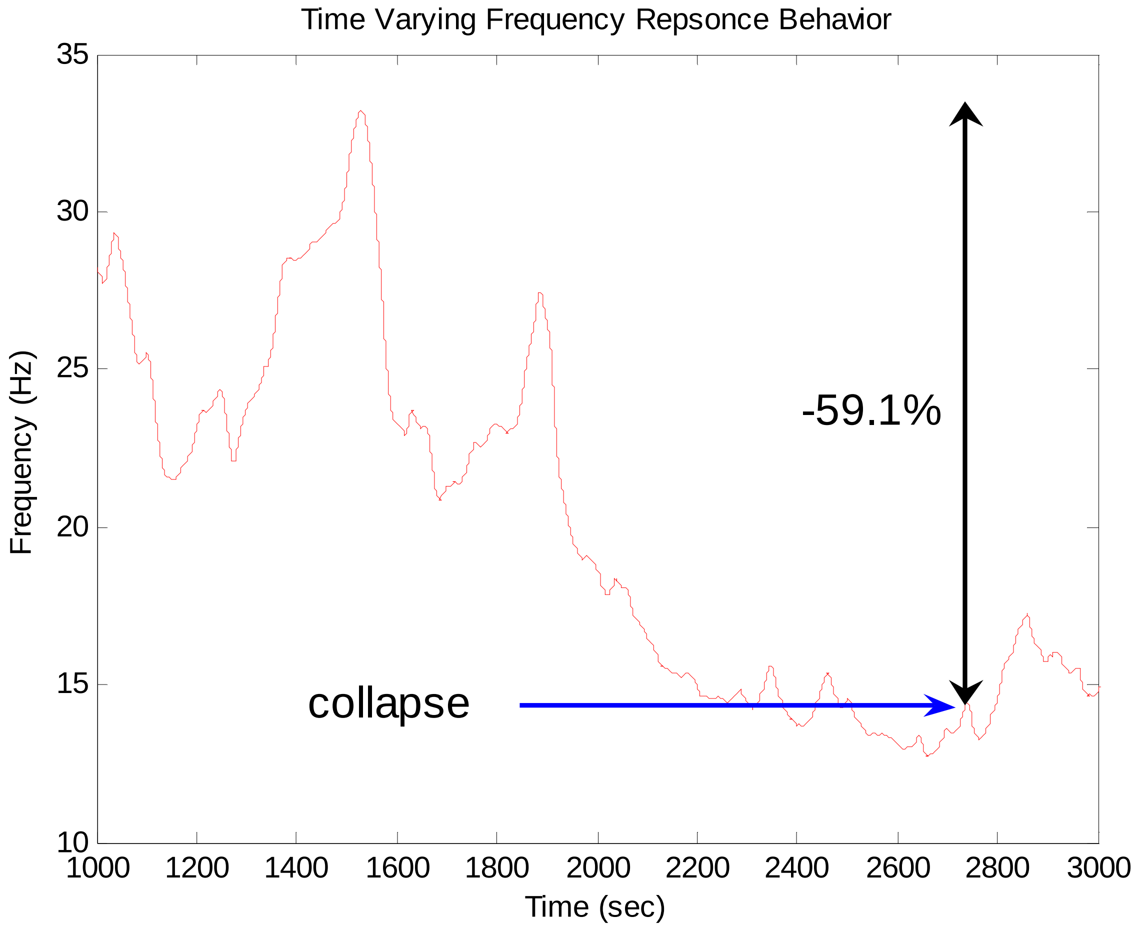


Figure 39 – Instantaneous frequency behavior for Isbell Junior High burn

10 Implications for Future Work

The significance of the results and findings described in this report suggest that a practical monitoring technique could be developed for firefighting operations in the field. The promise of HOBS for aiding in the acquisition and analysis of fire-induced vibration responses to provide information not currently available to firefighters is quite high. There is little doubt that the measured responses acquired from burning structures contain information that can be related to changes in structural stability, and what remains is the development of practical indicators and visualization tools.

The demonstrated trends in damping and instantaneous frequency associated with burning structures and the mechanisms leading to collapse suggest that system stability theory may be applicable to fire-induced behavior. Specifically, the product of damping and instantaneous frequency forms what is referred to as the pole of a system and can be used to track stability in a manner described in texts of analysis and design of control systems. This will aid the development of virtual control indices and in the interpretation of the observed changes during burn.

Future efforts should be focused on

- continued fire-sensor development to ensure the highest quality in field measurements,
- on the development of stability based indicators insensitive to the presence of multiple frequency components,
- and on the development of simple representations indicative of the changing conditions in the burning structure.

If successful, an important contribution to the Fire Service and to their safety will result.

11 References

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