VIBRO-ACOUSTIC MODULATION AS A BASELINE-FREE STRUCTURAL
HEALTH MONITORING TECHNIQUE

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VIBRO-ACOUSTIC MODULATION AS A BASELINE-FREE STRUCTURAL HEALTH MONITORING TECHNIQUE

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ABSTRACT

VIBRO-ACOUSTIC MODULATION AS A BASELINE-FREE STRUCTURAL HEALTH MONITORING TECHNIQUE

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Structural health monitoring (SHM) methods are being explored as techniques to assess the integrity of mechanical, civil, and aerospace structures. Most of these methods detect or quantify damage by comparing current structural state measurements to stored baseline measurements collected from an undamaged structure. These baseline dependent methods assume that measured signals will not change when exposed to varying environmental and usage conditions. To avoid limitations of this assumption, baseline-free techniques such as vibro-acoustic modulation (VAM) are being explored.

VAM is a nonlinear vibration technique in which the structure of interest is excited using a combination of specific frequencies and the response recorded. The VAM technique assumes that an undamaged structure can be represented by a linear system while the representation of a damaged structure must include
nonlinearity. A nonlinearity is assumed to result in the generation of sideband responses.

To demonstrate the use of VAM to detect fatigue cracking, experimental testing has been performed on existing damaged and undamaged specimens, as well as on fatigue specimens where cracks have been initiated and grown. Initial testing of the damaged and undamaged specimens provides validation for using VAM as a baseline-free SHM technique. Subsequent measurements during fatigue testing confirm this result. Two rectangular coupons were fatigue cycled to initiate and grow cracks. The VAM method detected cracks at 6.42 percent and 12.24 percent damaged cross-sectional area. Potential advantages and limitation of the use of VAM for fatigue crack detection are discussed, and recommendations for additional research efforts to improve or refine the technique are given.
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CHAPTER I
INTRODUCTION

Structural health monitoring (SHM) methods are being explored as techniques to assess the integrity of mechanical, civil, and aerospace structures. Most of these methods detect or quantify damage by comparing current structural state measurements to baseline measurements collected when the structure is in the “pristine” or “undamaged” state. These baseline dependent methods assume that measured signals will not change when the structure is exposed to varying environmental and usage conditions, which in general is not true. To avoid erroneous conclusions based on drift and other variations in the baseline measurement, baseline-free techniques such as vibro-acoustic modulation (VAM) are being explored. A literature review was performed highlights the limitations of various current SHM techniques and to assess the potential use of VAM as a baseline-free technique. Results from the literature review are summarized in Chapter II.

VAM is a nonlinear vibration technique in which the structure of interest is excited using a combination of specific frequencies and the response recorded. The VAM technique assumes that an undamaged structure can be represented by a linear system while the representation of a damaged structure must include nonlinearity. A nonlinearity is assumed to result in the generation of
sideband responses. To utilize VAM for SHM, a fundamental understanding of the technique is required. Chapter III reviews the underlying theory of the VAM technique and includes example simulations to illustrate its use for damage detection.

To demonstrate the use of VAM to detect fatigue cracking, experimental testing has been performed on existing damaged and undamaged specimens, as well as on fatigue specimens where cracks are initiated and grown. Chapter IV discusses the specimens and equipment utilized for this testing and outlines the testing procedures. Initial testing of the damaged and undamaged specimens provides validation of VAM as a baseline free SHM technique as shown by Klepka et al. (Klepka 2012), Parsons et al. (Parsons 2006), Dutta et al. (Dutta 2009), and Hu et al. (Hu 2010). Subsequent measurements during fatigue testing confirm this result and highlight some of the issues associated with the technique. Experimental test results, and a discussion of their significance, are presented in Chapter V.

Lastly, Chapter VI presents conclusions and recommendations based on these research efforts. Potential advantages and limitations of the use of VAM for fatigue crack detection are included. Recommendations are given for additional research efforts to refine the technique and to address some of the identified limitations.
CHAPTER II
LITERATURE REVIEW

Based on a review of published literature, this chapter provides a brief description of structural health monitoring and discusses typical crack detection techniques. Many of these techniques are not well suited for aerospace environments and often require the use of baseline measurements. Vibro-acoustic modulation is introduced as a baseline-free technique for monitoring aircraft structures.

Structural Health Monitoring

Structural Health Monitoring (SHM) is the process of assessing the integrity of a civil, mechanical, or aerospace structure to better understand the current state and remaining capability of the structure (Raghavan 2007). This research focuses on SHM techniques applicable to aerospace structures. Military aircraft are being utilized well beyond their initial design lives (Giurgiutiu 2002) and, as a result, can require frequent inspection and significant maintenance. SHM techniques are being developed to reduce cost, increase availability, and maintain the safety of air vehicle structures. Eliminating unnecessary structural inspections offers the potential to reduce costs and increase availability. Providing a better understanding of the
current operational state of the structure can also reduce the probability of catastrophic failures (Hamey 2004).

In general, SHM is accomplished as follows. The structure under investigation is excited using actuators (active SHM) or operational loading (passive SHM). The response to the excitation is sensed at various locations throughout the structure. The response signals (and possibly the excitation signal) are collected and processed, and based on the processed data, the state of the structure is diagnosed. SHM evolved from the field of Non-Destructive Evaluation (NDE). SHM and NDE utilize similar methods and techniques, with several notable differences. Unlike NDE, SHM systems typically utilize sensors which are permanently bonded to the structure of interest. Therefore, the SHM sensors are exposed to the environments in which the aircraft is flown and laboratory calibration of the sensors, commonly performed for NDE sensors, is not possible.

**SHM Methods for Crack Detection**

This research focuses on SHM techniques for aerospace structures. Fatigue cracking is one of the primary damage types limiting the life of aircraft structures (Sohn 2003); therefore, the development of SHM techniques for fatigue crack detection is of interest. Various SHM methods can be employed for crack detection, with many of these techniques utilizing bonded piezoelectric sensors (Yu 2009). Among other benefits (high frequency bandwidth, low power requirements, low profile and volume, etc.), piezoelectric sensors offer unique capabilities in that the sensors can be utilized to both actuate a structure and sense the structural response. Piezoelectric sensors can be used for multiple SHM crack detection
modalities, including acoustic emission, electro-mechanical impedance, and ultrasonic guided wave techniques. A brief discussion of these techniques, and the capabilities and limitations of each follows.

Acoustic emission (AE) methods measure the mechanical stress waves that result when strain energy is released due to micro-structural changes (e.g. cracking) in a material (Wevers 1997). The ultrasonic stress waves propagate through the structural component and are sensed by AE sensors. The AE sensors are typically broadband piezoelectric sensors which are coupled to the surface of the structural component using grease couplant, epoxy-based adhesive, or bolts. The AE method is a passive technique where the sensors “listen” to the structure continuously during operation. Measured data is often difficult to interpret due to the presence of ultrasonic energy with similar frequencies to those emitted by the release of strain energy. Such difficulties can be exacerbated in aerospace environments involving extreme vibration and noise variations. In these environments, events such as surface fretting can create ultrasonic waves which mimic crack propagation. The AE method has found common use as an inspection method for pipelines, pressure vessels, and similar applications, where pressure sensitive structural components can be monitored without the presence of significant environmental noise (Aljets 2012).

The electro-mechanical impedance (EMI) method measures the combined electrical and structural impedance of a structure. Electrical impedance is the ratio of voltage to current in an alternating current circuit. When a piezoelectric sensor is bonded to a structure, the measured electrical impedance of the sensor is affected
by the mechanical state of the host structure through the piezoelectric effect. This is an active technique where a single sensor is used to excite the structure and record the response. The measured EMI has a unique frequency response depending on the particular sensor circuits utilized and the structure to which the sensors are attached. When damage or other mechanical changes are present in the region near an attached sensor, peak frequency shifts, peak splitting, and the presence of new harmonics can be detected in the response (Giurgiutiu 2005). Unfortunately, similar variations in the response may occur due to changes in the sensors or other electrical components or circuitry. In addition, sensors typically need to be located relatively close to the damage and may have inadequate sensitivity for certain geometries (e.g. for structures that are thicker and stiffer than typical aircraft skin structure (Lopes 2000)).

Another SHM technique which has received considerable attention in the literature is the propagation of ultrasonic guided waves (GW) in a structure. These waves can be “guided” along or between the free surfaces of a structure. There are three primary GW methods which have been explored for SHM (Yu 2009): (1) pulse-echo methods; (2) pitch-catch methods; and, (3) phased array methods. The unique operation of each of these methods is discussed below.

The pulse-echo method is similar to conventional radar. A single piezoelectric sensor is used as an excitation source for a period of time to excite or “pulse” the structure. Circular sensors are often utilized such that waves propagate outward in a circular wave front from the center of the sensor (Yu 2008). Once the excitation ends, the sensor then switches to a receiving mode to record any “echo” of
the emitted waves. This method can vary in accuracy depending on the thickness of
the structure and the location of the sensors with respect to the damage. Damage
far from the sensor is difficult to detect due to signal attenuation as the waves
propagate. Damage too close to the sensors can be missed due to echoes of the
emitted waves occurring prior to the end of the excitation pulse. Changes in
structural thickness can also cause issues, particularly with regards to damage
localization, since the speed of the propagating waves can change with thickness.

The pitch-catch method is similar to the pulse-echo method, but utilizes a
pair of sensors instead of a single sensor. One piezoelectric sensor is used for
excitation to “pitch” waves and a second sensor, at a different location, is used as the
receiving sensor to “catch” the waves. Unlike the pulse-echo method, the pitch-
catch method can detect damage close to the sensors. However, the pitch-catch
method requires that the damage lie within (or at least relatively close to) the direct
propagation path between the two sensors. The method requires more sensors
than the pulse-echo method.

The phased array method uses multiple sensors to alleviate some of the
constraints of both the pulse-echo and pitch-catch methods. A collection of circular
sensors is typically utilized such that waves propagate outward in circular wave
fronts from the center of the sensors (Yu 2008). By adjusting the excitation signal
phasing between sensors, beam forming techniques can be utilized to direct energy
in particular directions. Once the excitation ends, the sensors can then be switched
to a receiving mode to record any “echo” of the emitted waves. Directing energy in a
particular direction can help overcome the signal attenuation issues of the pulse-
echo method and the pitch-catch constraint that damage must lay within the direct
propagation path between a pair of sensors. However, the method requires the use
of multiple sensors, precise control of the excitation phasing of the sensors is
necessary, and near-field damage cannot be detected.

The GW techniques, and many other potential SHM crack detection

...
techniques which do not require any previously known damage state and which are less sensitive to changes in boundary, loading, and environmental conditions.

Several baseline-free SHM techniques which have been proposed are discussed below.

A baseline-free SHM technique proposed by Sohn (Sohn 2011) utilizes two bonded piezoelectric sensors co-located on either side of a plate specimen as shown in Figure 1. In this configuration, the sensors are used to measure pitch-catch GWs actuated at different locations on the plate. Due to the co-located nature of the sensors, the measured responses from both sides of the structure can be subtracted from each other to yield only the mode conversions that occur along GW paths. Mode conversions, which involve the transformation of deformation waves from primary compression (P waves) to shear waves (S waves), or vice versa, occur when waves are propagated through discontinuities or damage in the structure, or interact with geometric features.

![Figure 1: Co-located Bonded Piezoelectric Sensors (Sohn 2011)](image)

Because this approach relies only on a direct comparison between two sensors bonded to the structure, it eliminates any need for previously collected reference waveforms or baselines. Disadvantages of this method include the need
to have two co-located piezoelectric sensors and the need to have a structure be of uniform local thickness. These two requirements present problems as locations of interest typically exist in complex aerospace structural components with variable thickness and for which access to both sides of the structure is often difficult. Issues with this approach can also arise if the structure is not at a constant temperature, particularly if thermal gradients exist along the length between the collocated actuation and receiving sensors.

Another baseline-free SHM technique was proposed by Lee, *et al.* (Lee 2012) and utilizes GW imaging via adaptive source removal. The technique uses a piezoelectric sensor as an internal source location waveform transmitter specific to the region being monitored. Transmitted waveforms are recorded around the area of interest, allowing for a multidirectional history of waveform transmission. This history allows the user to monitor scattering that occurs when waves interact with flaws. Figure 2 shows the conceptual set-up of this method, with waveforms recorded at the external receivers using a laser vibrometer for convenient measurement at the boundaries of the monitored region.

![Figure 2: Set-Up Utilized for GW Imaging via Adaptive Source Removal (Lee 2012)](image-url)
Lee’s method processes collected waveforms from each of the receiving points to create a history of time-of-arrival signatures for each of the transmitted waveforms. With knowledge of the first arrival waveform, the scattered wave component of each collection can be extracted after necessary time-shifting and scaling is performed. Time-shifting and amplitude scaling are required due to waveform signal attenuation and changes in waveform shapes due to surface medium thickness changes. Figure 3 shows reported results from this experiment. The plot on the left illustrates the image generated for the source location while the plot on the right illustrates the image generated when waveforms were scattered from a steel cylinder bonded to the surface of the structure.

Figure 3: Source (a) and Scatter (b) Location Images from Adaptive Source Imaging (Lee 2012)

This imaging technique requires collecting a relatively large amount of data, but does not require baseline measurements and is insensitive to temperature changes provided the structure remains at some constant temperature. However, difficulties may arise if significant reflections occur at geometric edges. The results presented above were generated using a 2.4 m × 1.5 m × 3.18 mm aluminum sheet
where edge-influenced reflections were not a concern. Scattering from geometrical features would almost certainly occur with the complex geometries of most aerospace structures. In addition, the use of a laser vibrometer would be impractical for most aerospace applications and replacing the vibrometer with multiple sensors around the boundary of the monitored region may introduce other issues.

Vibro-Acoustic Modulation

To overcome some of the limitations of existing baseline-free techniques, vibro-acoustic modulation (VAM) has received interest in recent years. Similar to the other baseline-free methods discussed above, VAM can be accomplished using bonded piezoelectric sensors. VAM consists of the applying a lower frequency “pumping” excitation signal and a higher frequency “probing” excitation signal into the host structure (Yoder 2010). Structures that are healthy will return a response with energy only at the pumping and probing frequencies. However, in the presence of damage, additional nonlinear components are created due to nonlinear effects leading to mixing of the two input signals. For example, the presence of a crack creating differing stiffness characteristics in the opening and closing halves of a vibration cycle, producing a more complex vibratory response than that observed in a crack-free component.

Key to the VAM method is the creation of energy at new frequencies not present in the pump or probe signals; the energy at the new frequencies can be measured when damage is present. These new frequencies, referred to as
sidebands, occur at values which are a function of the pumping and probing frequency values:

\[ \omega_{1\text{st sideband}} = \omega_{\text{probe}} \pm 1 \cdot \omega_{\text{pump}} \]  
\[ \omega_{2\text{nd sideband}} = \omega_{\text{probe}} \pm 2 \cdot \omega_{\text{pump}} \]  
\[ \omega_{i\text{th sideband}} = \omega_{\text{probe}} \pm i \cdot \omega_{\text{pump}} \] 

The sideband amplitude decreases as a function of the sideband order (e.g. 1, 2, ..., \(i\)). Figure 4 shows a spectral response of the peak probing frequency and the resultant sidebands as presented by Zacharias, et al. (Zacharias 2009). Here the probing frequency is 49 kHz and the pumping frequency is 270 Hz. The lower and upper sidebands can be seen at frequencies equal to the probing frequency plus or minus one, two, three, and four times the pumping frequency.

Figure 4: Example of Sidebands Generated in the Presence of Damage (Zacharias 2009)

Selection of the pumping and probing combinations is typically performed based upon the harmonic response of the structure of interest. Figure 4 shows
results for fixed pumping and probing frequencies. For use as a SHM technique, Yoder, et al. (Yoder 2010) suggested that the fixed frequencies could limit the potential to modulate sidebands in the presence of damage and investigated the sensitivity and robustness of using swept probing frequencies. For their research, probing signals were swept from 20-40 kHz with pumping signals at less than 1 kHz. The pumping and probing signals were generated using bonded piezoelectric disk actuators, with accelerometers used to collect responses. The modulating effects of crack interaction with the input signals resulted in the presence of sidebands around the main peak of the ultrasonic probing frequency (Duffour 2006).

The previously discussed baseline-free techniques demonstrated damage detection using large sheets of plate material and may be highly sensitive to geometry changes or boundary conditions. VAM offers the potential to alleviate such concerns and has been demonstrated on composite plates (Ekimov 1999), water pipes (Donskoy 2001), and cantilever beams (Donskoy 2001) where crack damage was present and also propagated. More recent studies of VAM as a SHM technique have focused on similar structures. For example, Yoder, et al. (Yoder 2010) used a cantilever beam where crack growth was completed on a small scale, Klepka, et al. (Klepka 2012) used a previously cracked aluminum plate, and Aymerich, et al. (Aymerich 2009) used previously undamaged composite plates. This research further investigates the use of VAM as a SHM technique for complex aerospace structures.
CHAPTER III
THEORY

The previous chapter introduced VAM as a nonlinear vibration technique which as a baseline-free SHM method. To apply VAM to the complex aerospace structures of interest, a detailed understanding of the theory is required. The first part of this chapter describes the basic theory behind the VAM technique. The technique is based on the generation of sidebands in the frequency domain. For SHM, metrics must be created which can detect or quantify fatigue cracks based on the presence of sidebands. Various damage metrics have been proposed, as discussed at the end of this chapter.

Nonlinear Vibrations

Recall, VAM is a nonlinear vibration method which utilizes excitation based on a sum of a lower frequency sinusoid and a higher frequency sinusoid. When an excitation is applied to a structure containing damage, a predictable response is observed. The history of nonlinear vibrations traces back to the Luxembourg-Gorky effect (Zaitsev 2002) first observed at Eindhoven, Netherlands in 1933. Here, powerful transmitted signals from radio stations in Luxembourg and Gorky, Russia (USSR) were observed at modulated frequencies. This cross modulation was a direct result of frequency dependent variations in energy absorption in ionospheric
plasma under the presence of both broadcast signals. The stronger transmitted signal perturbs and influences electrons in atmospheric molecules which influences wave velocity. This wave velocity influence results in the amplitude modulation from the stronger signal present, resulting in creation of different frequency combinations (Tellegen 1933; Ginzburg 1948). This phenomenon is based upon the effects of reactive, rather than dissipative, nonlinearities (Zaitsev 2002).

To illustrate the phenomenon of modulation due to a nonlinearity, a mathematical model was developed and implemented using MATLAB. The model input is the sum of the sinusoidal signals. The pumping signal, \( x_{\text{pump}} \), and probing signal, \( x_{\text{probe}} \), are represented as sinusoidal signals:

\[
\begin{align*}
    x_{\text{pump}}(t) &= \sin (2\pi f_{\text{pump}}(t)) \\
    x_{\text{probe}}(t) &= \sin (2\pi f_{\text{probe}}(t))
\end{align*}
\]

where \( f_{\text{pump}} \) and \( f_{\text{probe}} \) represent the pumping and probing frequencies in Hz and \( t \) represents time in seconds. The signal out of the nonlinear model is:

\[
x_{\text{total}} = a_1 x_{\text{pump}} + a_2 x_{\text{probe}} + a_3 x_{\text{pump}} \cdot x_{\text{probe}}
\]

where \( a_1 \) and \( a_2 \) define the amplitudes of the pumping and probing signals, respectively. The nonlinearity is created by including the product of the pumping and probing signals, scaled by \( a_3 \). When \( a_3 \) is set to zero in the model, the system is linear, producing an output with only the pumping and probing components. A non-zero value of \( a_3 \) results in a nonlinear system.

Figure 5 shows the time and frequency domain response for a linear system with a 5 kHz pumping signal (amplitude of 1.0) and a 50 kHz probing signal.
(amplitude of .5). As seen in the Figure 5(b), the frequency content in dominated by peaks at the pumping and probing frequencies. Figure 6 shows results for a system with multiplicative nonlinearity $a_3$, of 0.95. Comparing Figures 5(a) and 6(a), the time domain responses are very similar. However, in the frequency domain (Figures 5(b) and 6(b)), sidebands are clearly visible for the nonlinear system. These sidebands occur at the expected frequencies of $f_{\text{probe}} \pm f_{\text{pump}}$ (at 45 kHz and 55 kHz for this example). Although this is only a mathematical model, it provides a clear graphical representation of the relationships among pumping, probing, and modulated frequencies.

![Figure 5: Linear System Response in (a) Time and (b) Frequency Domains](image)
A fundamental understanding of the physics behind the nonlinear vibration phenomenon in solids is not well understood (Parsons 2006). However, many researchers have described and modeled potential processes (Morris 1979; Donsokoy 1998; Haller 2007). Various nonlinear mechanisms exist in solids and typically are characterized as either elastic or dissipative. Klepka, et al. (Klepka 2012) described and summarized many of these mechanisms. They classified the mechanisms based on whether the mechanisms occurred at the atomic, mesoscopic, or macroscopic scales and as a function of strain. Table 1 shows the various mechanisms identified. Compounding contributions from each of the different mechanisms may be difficult to separate in experimental collections (Zaitsev 2005). In addition, compounding nonlinear effects from surface-to-surface bonding and other tangible interfaces could mask sidebands indicative of damage.

**Figure 6: Nonlinear System Response in (a) Time and (b) Frequency Domains**

(a) 
(b)
Table 1: Nonlinear Mechanisms in Solid Materials (Klepka 2012)

<table>
<thead>
<tr>
<th>Material Scale</th>
<th>Strain Level</th>
<th>Non Linear Mechanism</th>
<th>Nonlinearity Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic</td>
<td>$10^{-10}$ to $10^{-8}$</td>
<td>Intrinsic elastic nonlinearity due to anharmonicity of interatomic potential</td>
<td>Elastic</td>
</tr>
<tr>
<td>Mesoscopic</td>
<td>$&lt; 10^{-8}$</td>
<td>Non-friction and non-hysteretic dissipation locally enhanced by thermoelastic coupling</td>
<td>Dissipation</td>
</tr>
<tr>
<td>Macroscopic</td>
<td>$&gt; 10^{-6}$</td>
<td>Hysteresis in stress-strain amplitude dependent dissipation</td>
<td>Elastic</td>
</tr>
<tr>
<td></td>
<td>$10^{-5}$ to $10^{-3}$</td>
<td>Friction, adhesion hysteresis</td>
<td>Dissipation</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$ to $10^{-2}$</td>
<td>Crack-induced nonlinearity, variation in elastic moduli</td>
<td>Elastic</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$ to $10^{-2}$</td>
<td>Local stiffness reduction leading to natural frequency shift</td>
<td>Dissipation</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}$ to $10^{-2}$</td>
<td>Bilinear stiffness (closing-opening crack)</td>
<td>Dissipation</td>
</tr>
</tbody>
</table>

For the current research, the nonlinear mechanism is assumed to be dominated by a bilinear stiffness change under excitation. Nonlinear effects for this mechanism occur during the opening and closing of the faces of so-called “breathing” cracks (El Arem 2012; Sinou 2008). The opening of the crack under tensile loading and the closing of the crack under compressive loading causes a local change in stiffness near the damaged region and can be modeled as a bilinear oscillator (Klepka 2012; Douka 2005). The variation in local stiffness in the crack region determines the nonlinear contribution to the lower pumping and upper probing frequencies. As shown in the next section, this results in the presence of sidebands at specific combinations of the pumping and probing frequencies.

A Newtonian mechanics model was developed to illustrate the nonlinear response of a bilinear oscillator system. As shown in Figure 7, this undamped single
The single degree-of-freedom model utilizes two different spring stiffness to account for when the crack is open or closed. The basic equation of motion for this system is:

\[ m \ddot{u} + k(u)u = F(t) \]  \hspace{1cm} (7)

where:

\[ k(u) = \begin{cases} 
  k_{\text{open}} = k_1 & \text{if } u(t) \geq 0 \\
  k_{\text{closed}} = k_1 + k_2 & \text{if } u(t) < 0 
\end{cases} \]  \hspace{1cm} (8)

\( F(t) \) is a forcing function, \( k_1 = 88,200 \frac{N}{m}, k_2 = 1800 \frac{N}{m}, m = 10 kg \). As shown in Eqn. 8, the stiffness changes instantaneously when the position of the cart passes through zero. For actual systems, the literature indicates that the transition between the two states does not occur instantaneously, but rather in a more gradual manner (Douka 2005; Rytter 1993). The forcing function is a combination of sinusoidal signals at the pumping and probing frequencies with the addition of a moderate level of random noise.

Figure 7: Single Degree-of-Freedom Bilinear Oscillator System

Figure 8 shows time and frequency domain responses for a simulation using a 1.0 Hz pumping signal and a 6.5 Hz probing signal with no nonlinearities introduced (i.e. \( k_{\text{open}} = k_{\text{closed}} \)). The time domain response shows a representative time period after steady-state response has been achieved. As expected, the frequency response around the probe frequency shows only the probe frequency.
with no indication of sideband frequencies. The effects of the random noise can be seen in both the time and frequency domain responses, especially when compared to Figures 5 and 6. Figure 9 shows similar time and frequency domain responses for a system with a 2 percent change in stiffness between the open and closed crack states (i.e. \( k_{\text{open}} = 0.98k_{\text{closed}} \)). The time domain response of the nonlinear system looks quite similar to the response from the linear system and is dominated by the pumping and probing frequencies. However, when observed in the frequency domain, the first-order sidebands at 5.5 Hz and 7.5 Hz are clearly visible.

**Figure 8: Linear System Response in (a) Time and (b) Frequency Domains**

**Figure 9: Nonlinear System Response in (a) Time and (b) Frequency Domains**
Obviously, the dynamics of typical aerospace structures are much more complex than the simple model presented here to illustrate the concept behind vibro-acoustic modulation. Furthermore, the demonstrations provide idealistic representations of undamaged responses that are unlikely to occur in practice. Influences such as noise and temperature variations may affect relative amplitudes of the lower and upper sidebands, or eliminate one or both of the sidebands that have been shown to be dependent on the underlying vibration magnitude of the system (Dutta 2009). The following section discusses techniques for detecting and quantifying damage based on the presence and relative strength of frequency sidebands.

**Damage Detection & Quantification**

In the literature, experimental observation of sidebands has been reported and used for crack detection. Methods used to detect damage include measuring sideband amplitude (Parsons 2006, Dutta 2009), normalizing sideband response to probing frequency response (Klepka 2012; Duffour 2006; Hu 2010), normalizing sideband response between undamaged and damaged measurements (Zaitsev 2005), or comparing undamaged and damaged spectral shapes between collections (Duffour 2006). Of these methods, the last two utilize formulations that compare current measurements to prior measurements of an undamaged structure. Since the objective of this research is the development of a baseline-free approach, only those approaches which do not rely on previously collected signals will be considered. Of the remaining baseline-free methods, measuring the generated sideband amplitudes is the most commonly used.
Sideband amplitude response has been shown to be heavily dependent on the system excitation (Duffour 2006; Parsons 2006; Zaitsev 2005; Dutta 2009). Furthermore, sideband amplitude has been shown to be influenced by boundary conditions. In one experiment, the torque on bolts fixing a cantilevered plate was increased and the observed sideband response subsequently decreased (Polimeno 2008). In another experiment, oil was applied to crack interfaces of a torsional rod (Ekimov 1999). Observed sideband amplitudes decreased five to six dB. These observations, where the global or local stiffness was changed, validate the theory that breathing crack nonlinearity dominates the sideband generation. In addition, Dutta, et al. (Dutta 2009) observed decreases in sideband amplitude as fatigue cracks grew well past initiation. This observation could potentially be explained by the increasing dominance of global stiffness reductions as cracks grow to large lengths as compared to the significance of breathing cracks at smaller crack lengths.

This research focuses on the use of piezoelectric generated excitation for crack detection. Some of the damage detection techniques discussed above have been demonstrated using amplified signals sent to bonded piezoelectric sensors for excitation at the pumping and probing frequencies (Duffour 2006; Klepka 2012; Dutta 2009). However, only a few researchers have attempted to use damage metrics for crack length estimation (Duffour 2006; Dutta 2009). The influence of structural configuration, excitation voltage, boundary conditions, and crack geometry are not thoroughly addressed here and remain as obstacles to fielding SHM applications using nonlinear acoustics.
CHAPTER IV
EXPERIMENTAL TESTING

Initial testing was performed on healthy and cracked specimens to assess the applicability of VAM techniques and to study the repeatability of measured values. Subsequent testing was performed on two fatigue specimens where cracks were initiated and grown to different final lengths. Details on the specimens, equipment, and procedures used for these tests are given below. Results from the experimental testing are presented and discussed in the following chapter.

**Damaged and Undamaged Specimens**

Initial testing was performed on a healthy and a cracked specimen to verify that no sidebands existed in an undamaged case, but sidebands did exist when damage was present. These tests used two identical 7075-T7351 aluminum dogbone specimens, one of which had been previously fatigue cracked to a total length of 1.50 inches (38.1 mm) roughly centered about the gage section starter hole. The basic layout of the tensile dogbone specimens is shown in Figure 10.
Three piezoelectric sensors were bonded to the surface of the specimen to excite the pumping and probing frequencies and to measure the response. As shown in the figure, a 1.61 inch (41 mm) diameter piezoelectric was used to excite the structure at a specific pumping frequency. The largest piezoelectric sensor was used to apply the pumping signal for greater energy transfer to the structure. One 0.39 inch (10 mm) diameter piezoelectric was used to apply the probing signal and a second 0.39 inch (10 mm) diameter piezoelectric was used to record the response. All of the piezoelectric sensors were 0.010 inch (0.25 mm) thick and were bonded to the specimens using aircraft grade Hysol 9394 adhesive with a seven day room temperature (70°F) cure. The bonded piezoelectric sensors on each specimen were assumed to behave similarly, although it is recognized that inherent bondline variation existed between the two specimens. Because the pumping and probing sensors were bonded to the specimen for previous unrelated tests, optimized sensor placement was not possible.

The experimental setup for the damaged and undamaged specimen tests consisted of a National Instruments (NI) 1042 PXI chassis equipped with Labview.
2010 Data Acquisition (DAQ) software. The NI PXI 1042 chassis utilized a NI PXI 12-bit 5105, 8-channel DAQ digitizer card with only one channel needed for data collection. Two external Agilent 33220A function generators were remotely accessed using the Labview DAQ software to generate pumping and probing signals at selected frequencies. Figure 11 shows the experimental equipment.

![Figure 11: Equipment Utilized for Experimental Testing](image)

Pumping and probing excitation amplitudes were limited to a maximum of ±10 V based on the capabilities of the external function generators. Excitation amplitude influences the sideband response amplitude, so sidebands may prove more difficult to observe at lower excitation voltages. Previous researchers have used excitation values up to ±20 V (Klepka 2012; Aymerich 2010; Hu 2010); however, the lower excitation voltages simplified the experimental setup necessary for these studies.

For each collection, the pumping and probing piezoelectrics were actuated for a period of 1.5 seconds prior to recording the response. This delay was chosen
to allow adequate time for the response signal to achieve steady-state conditions prior to collection as confirmed by visual inspection. After reaching steady-state conditions, the DAQ system collected the response at the sensing piezoelectric for 0.25 seconds at 1 MHz sample rate. Although relatively low compared to the 10 MHz capability of the DAQ, the 1 MHz sample rate should be more than sufficient to avoid any potential aliasing effects at the frequencies of interest.

Measurements were collected with the damaged and undamaged specimens aligned vertically in a tabletop vise such that probing sensor was toward the top of specimen. The specimens were centered in the vise with the bottom 1.5 inches of the specimen clamped, and similar grip turns were utilized for each test. Nearly identical conditions were utilized for each specimen to alleviate any issues with boundary conditions affecting sideband generation. Collections were completed at an ambient laboratory temperature of 70°F.

Since the objective of this comparison was to confirm the absence of sidebands when healthy and the existence of sidebands in the presence of damage, collections were made over a range of pumping and probing frequencies. The pumping frequency was varied from 5 kHz to 10 kHz in steps of 0.5 kHz and the probing frequency was varied from 90 kHz to 100 kHz in steps of 1.0 kHz. These ranges were based on prior testing of similar specimens. Results from the damaged and undamaged comparison are presented and discussed in the following chapter.

Additional testing was performed using the damaged specimen to study the repeatability of measured values. Investigations performed after the initial damaged and undamaged specimen testing indicated that larger sideband
amplitudes were observed at slightly higher pumping frequencies. As a result, the repeatability testing used pumping frequencies ranging from 10 kHz to 20 kHz in steps of 1.0 kHz and the same probing frequencies ranging from 90 kHz to 100 kHz in steps of 1.0 kHz. Results from the repeatability testing are also included in the following chapter.

**Fatigue Specimens**

Subsequent testing was performed using two fatigue specimens where cracks were initiated and grown to increasing lengths while a sequence of VAM measurements were recorded. The tensile coupons used for the experimental fatigue testing had a cross section similar to the specimens used for the damaged/undamaged comparison. The specimens were made from 7075-T7351 aluminum with dimensions of 12.0 inch (305 mm) by 3.0 inch (76.2 mm) by 0.25 inch (6.35 mm) thick. A 1.61 inch (41 mm) diameter actuator was used for the pumping signal, a 0.39 inch (10 mm) diameter actuator was used for the probing signal, and a 0.39 inch (10 mm) diameter sensor was used to collect the response. As shown in the Figure 12, the nearest edges of all of the sensors were located 2.5 inches from the center of the specimen. Similar to the undamaged versus damaged comparison, the specimens included a 0.125 inch (3.18 mm) diameter starter hole. Furthermore, 0.025 inch (0.64 mm) notches were cut in the transverse loading direction of the hole to further increase the stress concentration. Figure 12 shows the layout of the fatigue specimens.
The same measurement system utilized for the damaged and undamaged specimens (see Figure 11) was utilized for the fatigue specimens. Pumping and probing excitation amplitudes again were limited to a maximum of ±10 V based on the capabilities of the external function generators. For each collection, the pumping and probing actuators were excited for a period of 1.5 seconds to achieve steady-state conditions. The response at the sensing piezoelectric was recorded at 1 MHz for 0.25 seconds.

For the fatigue specimens, collections were completed at various cyclic intervals with measurements taken with the specimens resting on foam blocks. The foam blocks created repeatable boundary conditions for each measurement. As shown in Figure 13, measurements were collected with 0.50 inch (12.7 mm) of each end of the specimen resting on the foam blocks. Collections were completed at an ambient laboratory temperature of 70°F.
Mechanical loading of the fatigue specimens was performed using a MTS Corporation 55 kip hydraulic test frame as shown in Figure 14. Fatigue specimens were cycled at a rate of 5 Hz. A maximum load of 13 kip was applied with a stress ratio of 0.1. The 13 kip maximum load was determined based on a 2000 μstrain limit of the piezoelectric sensor material. This determination considered the material properties of 7075-T7351 aluminum, the theoretical stress concentration values, and assumptions considering sensor bondline strain shear lag. Under the 13 kip cyclic load, strains at the piezoelectrics were calculated to be around 1700 μstrain. In actuality, the strain values seen by the sensors would be less than 1700 μstrain due to shear lag in the bondline. Thus, overstraining the piezoelectrics was not a concern during the fatigue testing.
Collection intervals for the fatigue testing varied for each specimen, based upon insight gained during the testing. Prior to cycling the first fatigue specimen, twelve individual collections were measured. These collections were obtained to help determine if there were any significant changes in response after initial loading of the specimen to 13 kip (e.g. possibly due to microcracking in the piezoelectric sensors or bondlines). Furthermore, a thirteenth collection was completed after 1000 cycles, followed by a fourteenth collection the following morning prior to any additional cycling. The purpose of these collections was to identify any potential issues that could affect measurements taken over multiple days. Similar collections were completed after 2000, 3000, and 4000 cycles, with three sequential collections taken after each interval and another three collections prior to resuming cycling the following day. Minimal day-to-day variability was observed, so this process was not repeated after 4000 cycles. Additional sets of three sequential collections were taken at 5000 cycles and at 5000 cycle intervals thereafter.
For the second fatigue specimen, 20 individual pre-cycle collections were measured. Once cycling commenced, three sequential collections were typically taken at 1000 cycle intervals. This interval was chosen to provide additional pre-damage collections, as well as to provide further insight into the stability of collections over time. After 12,000 cycles, a drop in the calculated damage metrics was observed. An additional twelve measurements were taken at this point, for a total of fifteen collections, to ensure that the drop did not result due to hardware issues. Discussion of the damage metric drop will be discussed later in this document.

Based on the results from the damage and undamaged specimens, the pumping and probing frequency ranges utilized for the repeatability tests were also utilized for the fatigue specimens. The pumping frequency was varied from 10 kHz to 20 kHz in steps of 1.0 kHz and the probing frequency was varied from 90 kHz to 100 kHz in steps of 1.0 kHz. Results from the fatigue testing are given in the following chapter, along with a discussion on the development of a damage metric for the detection of fatigue cracks.
CHAPTER V
RESULTS AND DISCUSSION

This chapter presents results from experimental testing of damaged and undamaged specimens, including repeatability testing, and fatigue specimens. A discussion on the significance of the various results is included.

Damaged and Undamaged Specimen Results

The primary objective of the undamaged and damaged specimen testing was to demonstrate the absence of sidebands in a healthy case, and the existence of sidebands in the damaged case. Using the collection procedures outlined in the previous chapter, data was collected at 121 pump and probe frequency combinations (11 pumping frequencies × 11 probing frequencies). For many combinations, sidebands were not readily visible. However, for other combinations sidebands were easily detectable. Figure 15 shows the frequency spectrum of the undamaged and damaged specimens using a pumping frequency of 100 kHz and a probing frequency of 10 kHz. Given the largest magnitude responses over all 121 combinations a normalization factor was applied making the largest magnitude equal to zero dB. Here, the pumping frequency has the largest response, and thus the probing frequency is not shown to be at 0 dB. This particular combination of frequencies was chosen to highlight the appearance of sidebands in the damaged specimen. Although both the lower and upper sidebands were observed, the upper
sideband amplitude is almost 10 dB higher than the lower sideband amplitude. It should also be noted that the results from the undamaged specimen appeared to have significantly more noise than the damaged specimen, as illustrated by the frequency content away from the probe and sideband frequencies.

![Figure 15: Undamaged (a) versus Damaged (b) Sideband Comparison](image)

A second objective of the damaged and undamaged specimen testing was to verify the stability and repeatability of the measured responses. For the repeatability studies, a single pumping frequency was chosen. Previous researchers (Yoder 2010) have suggested that selecting a pumping frequency near a structural resonance increases the vibratory displacements of the structure and increases the possibility of sideband generation due to nonlinearity. The process used to select the pumping frequency is discussed below.

As outlined in the previous chapter, collections were recorded from the damaged specimen at pumping frequencies ranging from 10 kHz to 20 kHz in steps of 1.0 kHz and probing frequencies ranging from 90 kHz to 100 kHz in steps of 1.0 kHz. At each pump and probe frequency combination, the spectral amplitude at the
pumping frequency was measured. Figure 16 shows pumping peak response amplitude for each of the eleven probing frequencies. The figure illustrates that varying the probing frequency had little effect on the overall response for each pumping frequency used. Furthermore, the figure shows that the highest resonant response measured occurred at 13 kHz. Thus, a pumping frequency of 13 kHz was chosen for the repeatability studies using the damaged specimen.

![Figure 16: Pumping Amplitude Response Using Damaged Specimen](image)

To quantify the stability of the measured responses, five sequential collections were taken on the damaged specimen and analyzed in the frequency domain. The amplitudes at the lower and upper sidebands, pumping, and probing frequencies, as well as the amplitude and standard deviation of the noise, were compared between the five collections. Table 2 shows the standard deviation (in dB) between each of these quantities for all five sequential collections using the selected 13 kHz pumping frequency and across all eleven probing frequencies ranging from 90 kHz to 100 kHz in steps of 1.0 kHz.
Table 2: Repeatability of Test Results Across Five Collections

<table>
<thead>
<tr>
<th></th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Sideband</td>
<td>0.76 dB</td>
</tr>
<tr>
<td>Upper Sideband</td>
<td>0.70 dB</td>
</tr>
<tr>
<td>Pumping Peak</td>
<td>0.03 dB</td>
</tr>
<tr>
<td>Probing Peak</td>
<td>0.50 dB</td>
</tr>
<tr>
<td>Mean Noise Floor</td>
<td>0.03 dB</td>
</tr>
</tbody>
</table>

From the Table 2, it can be seen that the largest standard deviation values were seen for the lower and upper sideband amplitudes. The lowest standard deviation responses were seen in the pumping peak response and the mean noise floor response. The standard deviation responses of the lower and upper sidebands and the mean noise floor are of particular interest for the subsequent use in the formulation of the damage metric used during fatigue testing. These responses indicate that there is little to no changes between the five sequential measurements. These results indicate that damage metrics using these values will likely remain stable over sequential measurements.

**Fatigue Specimen Results**

For the fatigue tests, a damage metric (DM) was defined to help detect fatigue cracking. The DM was calculated as the average of the lower and upper sideband amplitudes, in dB, normalized to the noise floor. Equation 9 shows this formulation, where $A_L$ and $A_U$ are the lower and upper sideband amplitudes and $A_N$ is the mean response of the noise floor. Normalizing the sidebands relative to the noise floor allowed for positive DM values to be calculated from the inherently negative dB values.
Sideband amplitudes were obtained by analyzing responses in the frequency domain. When measuring the amplitudes, the peak response often occurred at frequencies which differed slightly from those expected. Based on the 1 MHz sample rate and 250,000 input samples, the frequency data had a resolution of 4.0 Hz. Peaks were observed at as many of four bins, or 16 Hz, lower or higher than expected. As a result, a frequency range of five bins, or 20 Hz, on either side of the expected value was searched. To compute the mean response of the noise, a 10 kHz range was defined based on the particular pump/probe frequency combination of interest. The upper frequency limit of the range was defined as the probe frequency minus three times the pump frequency, with the lower frequency limit starting 10 kHz below this value.

As an example, Figure 17 shows the frequency response of the undamaged specimen, from the damaged/undamaged comparisons, using a 100 kHz probing and 10 kHz pumping frequency. The probing frequency peak can be observed at 100 kHz. As shown in the figure, the lower limit for the noise floor calculations would be 60 kHz with the upper limit at 70 kHz. Using a range well below the probing frequency helps to eliminate the possibility of computing DM values which might be adversely affected by the probing frequency response.
Figure 17: Example Frequency Response Showing Parameters used for DM Calculation

Within the same 10 kHz range used to calculate the amplitude of the noise, the standard deviation of the noise was also computed. The standard deviation of the noise was used to define a threshold value that the DM must exceed for crack detection. For these studies, the threshold was set at three times the standard deviation, since 99.7% of the noise should occur at values below this threshold. Thus, crack detection was noted when the DM (the average of the two sideband amplitudes) is statistically significant compared to the noise.

Similar to the repeatability studies performed on the damage specimen, single pumping frequencies were chosen for examining the fatigue test results. Using the process described above for the damaged specimen test, a pumping frequency of 14 kHz was selected for Fatigue Test 1 and a 20 kHz pumping frequency was selected for Fatigue Test 2. Differences between the selected pumping frequencies between the “identical” specimens are attributed to minute differences in specimen geometry, sensor performance, and sensor bonding. The
probing frequency was similarly varied from 90 kHz to 100 kHz in steps of 1.0 kHz for the fatigue tests. A range of probing frequencies was utilized since the selection of a single probing frequency was difficult to determine at the inception of an experiment and the damage and undamaged specimen testing indicated that utilizing a range of frequencies increased the likelihood of sideband generation. In practice, future refinement of VAM for fatigue crack detection could utilize a swept frequency response that would include all structural resonances across the frequency range tested. However, it is acknowledged that, by averaging across frequencies that do not generate sidebands in the presence of damage, the computed DM value will consequently be lowered.

For both fatigue test specimens, calculated DM values were plotted versus the percentage of the specimen cross section that is cracked. Due to the stress concentrations created by the hole and notches, cracks generally initiated on both sides of the hole. Plotting DM values as a function of percentage cracked area provided a reasonable approach for quantifying the effects of multiple cracks, and enabled the cracked area to be compared to the area at which fast fracture would occur. It is recognized that this form of crack length quantification may not be applicable to more complex geometries where determining the cross section area may be much more difficult due to varying crack growth directions. Figure 18 shows results from Fatigue Test 1 and Figure 19 shows results from Fatigue Test 2. The lines in these plots show DM threshold values which were independently calculated for each collection point.
In both tests, the DM values remained well below the threshold early in the tests before any significant damage occurred. The DM values from initial collections remained steady around a mean value of 6.5 dB for Fatigue Test 1 and 8.5 dB for
Fatigue Test 2. Recall that the DM values have non-zero starting values based on the formulation used for the calculations. Future enhancements might include reformulating the DM calculations such that values are closer to zero prior to any cracking. During the experiment, the DM values crossed the thresholds at a cracked area of approximately 6.42 percent for Fatigue Test 1 and approximately 12.24 percent for Fatigue Test 2. Although the cracked area percentages may seem relatively large, these values were still well below the cracked area at which fast fracture would occur. Results from AFGROW (a linear elastic fracture mechanics code) analyses predicted that fast fracture would not occur until a cracked area of 64.25 percent was reached. For both tests, the maximum DM values were around 21, but occurred at different crack areas. Additional refinements would be recommended to improve the consistency of the VAM crack detection approach so that damage would be detected at similar crack areas and the DM values would map more consistently to crack area. One possible refinement would be to establish improved techniques for selecting probing frequencies to avoid averaging results which do not contribute to the DM values, but which dilute the significance of results at key probing frequencies.

Fatigue Test 1 included results at much larger crack areas than Fatigue Test 2. In Figure 18, the results from Fatigue Test 1 show that the DM values began to decrease after a cracked area of 30 percent and subsequently fell back below the DM threshold value. This decrease in DM values when large cracks are present was also observed by Dutta, et al. (Dutta 2009) who noted decreases in sideband voltages after cracks grew well past their initial lengths. As shown previously, the sideband
amplitudes are a function of the pumping and probing frequencies. For Fatigue Test 1, the decrease in DM values was attributed to changes in the frequency response of the specimen due to the large structural damage that was present. This behavior highlights one potential issue with using the current VAM approach to estimate crack length (or crack area). As such, the VAM method may prove more applicable as a damage detection method.

Fatigue Test 2 included a much larger number of “pre-damage” measurements than Fatigue Test 1. However, even with the increased number of collections, the collection-to-collection variability did not change significantly. Although not intuitively seen from Fatigue Test 2, there was a sharp decrease in DM values between 12,000 and 13,000 cycles. This decrease warranted additional collection points as described in the Experimental Testing section. Up to 12,000 cycles, the DM values were clustered at approximately 11.5 dB, but subsequently decreased to around 8.0 dB. The decrease in the DM values was believed to be due to an unknown change in one or more of the piezoelectric sensors. If the decrease resulted due to intermittent connections between the DAQ and sensors, one might assume that additional decreases or increases would be observed later in the testing. However, no further decreases or increases were seen for the remainder of the testing. It should be noted that, although the DM values decreased, no significant changes occurred in the amplitude or standard deviation of the noise. Further testing is required to better understand this behavior.
CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Most current SHM techniques perform damage detection using baseline measurements. However, the performance of these techniques can degrade if measured signals vary over time due to environmental exposure or usage rather than damage. This research investigated the validity of using vibro-acoustic modulation (VAM) as a baseline-free SHM technique. The VAM technique assumes that the response of a structure is linear and that any damage creates nonlinearities. For example, fatigue cracks can cause small changes in stiffness as the cracks open and close. These nonlinearities result in the generation of sideband responses when a structure is excited using a combination of specific frequencies.

Initial experimental testing was performed using existing damaged and undamaged specimens. This testing demonstrated the validity of VAM for fatigue crack detection and showed that the process was stable and repeatable. Subsequent testing of fatigue test specimens confirmed this finding. A damage metric (DM), and corresponding threshold value, were defined to detect cracking. Cracks were only detected at fairly large sizes, but still well below the point at which fast fracture might be expected to occur.
The formulated DM used for these studies averaged responses across all collected probing frequencies. This approach eliminated difficulties with selection of a specific probing frequency or frequencies, but may limit the crack detection capabilities by diluting the responses from key frequencies. It is recommended that additional studies be performed to determine if an optimal probing frequency, or set of probing frequencies, can be defined to maximize the crack detection capabilities. In addition, these investigations were performed under controlled environmental conditions and with significant attention given to the boundary conditions. Testing in varying environments and under varying boundary conditions is suggested.

Lastly, only limited testing was performed during this research. Additional testing of multiple specimens is highly recommended. This testing should include blind fatigue tests, where VAM is used to predict crack detection without any prior knowledge of the fatigue behavior or actual crack sizes. Performing additional tests, across the range of anticipated conditions, will develop the experience needed to apply VAM technologies in fielded SHM applications and provide further insight into potential shortfalls of the method.
WORKS CITED


