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Vibro-Acoustic Amplitude and Frequency Modulations during Fatigue Damage Evolution

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Abstract. Vibro-Acoustic Modulation method (VAM) utilizes effect of the nonlinear interaction between higher frequency ultrasonic wave (carrier signal) and much lower frequency structural vibration (modulating signal). This interaction is taken place at the nonlinear interfaces (cracks, bolted connections, delaminations, etc.) manifesting itself in the spectrum as side-band components around the carrier. There are numerous studies applying VAM for nondestructive testing and structural health monitoring. Most of them utilize resonance structural bending vibrations as the modulating signal and measure a ratio of sideband to carrier spectral components defined as Modulation Index (MI). The present VAM study utilizes in-plane non-resonance very low frequency (10 Hz) tensile oscillations for monitoring fatigue and stress-corrosion damage evolution in steel. Experiments consistently demonstrated significant increase in MI during 70% – 80% of the fatigue life. Additionally, newly developed algorithm separates Amplitude and Frequency Modulations during the damage evolution demonstrating FM dominance at initial micro-crack growth stages and transition to AM dominance during macro-crack formation.

INTRODUCTION

Fatigue failure is one of the most common failure modes of structural components. Fatigue cracking, which arises from cycling loads that are well below the yield stress, causes up to 90% failures of in-service metallic structures [1]. Therefore, integrity of a structure depends on the detection of fatigue crack in early stages, and inability to detect fatigue cracks in appropriate time results in a brittle-like failure which can be sudden with delayed or no damage warning. The fatigue life of a component can be stated as the number of stress cycles that can be applied to a structure prior to failure. Fatigue failure occurs in three stages – crack initiation; incremental crack propagation; and rapid fracture. Thus, continuous monitoring of fatigue crack growth and predication of remaining life-cycle are vital to prevent rapid rupture of the structural component.

To prevent a possible brittle, unexpected failure of a structure, inspections of their components play a key role in identifying and assessing their condition. Being aware of the presence of micro-cracks would allow the timely maintenance of the structure and provide input data for estimation of its remaining life. To that end, many non-destructive evaluation (NDE) methods have been implemented in the past to allow the inspections to be as accurate and efficient as possible. Unfortunately, few NDE techniques can practically monitor the damage accumulation at micro-scale [2].

Several non-destructive testing (NDT) methods have been used to detect crack formation such as acoustic emission (AE), Eddy current (EC) and ultrasonic (UT) techniques. Acoustic emission technique monitors elastic stress waves generated by crack initiation and propagation in the material [3]. This technique has been used for detecting and localizing of fatigue cracks [4, 5]. The main drawback of this technique is that the recorded signals may be contaminated with high level of environmental noise which makes it impossible to distinguish between structural and ambient noise waves. Eddy current technique is also used to detect fatigue cracks specifically for surface or near-surface cracks [6, 7]. Eddy Current should be used on conductive materials and is not suitable for large area monitoring since it works on nearby conductive surface and needs to scan all the surface which takes a long time [8]. Linear ultrasonic techniques utilize the linear effects of reflection and attenuation of the elastic waves by structural inhomogeneity to detect a fatigue crack [9-12]. While the linear ultrasonic techniques are effective in the detection of macro cracks [13], they cannot be used to identify micro-cracks because micro-cracks are significantly smaller in size than the wavelength used by such methods. In contrast, the non-linear response of inspected materials is quite sensitive to micro-cracks and can be used to identify small imperfections [14-19]. The nonlinear ultrasonic techniques are based

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on various material and structural nonlinear behavior, e.g. generation of harmonics of ultrasonic wave and modulation of high-frequency ultrasound by low-frequency vibration. These effects are mainly caused by the local vibration of micro-cracks, which produces a clapping motion and frictional contact between damage surfaces.

Among the nonlinear acoustic NDE methods, a cost-effective and practical method to measure material nonlinearities is the Vibro-Modulation Technique (VMT) which does not need the expensive hardware components required for the conventional non-linear methods [14, 20]. Specifically, the Vibro-Acoustic Modulation (VAM) method is used to overcome the deficiencies of other non-linear methods. This technique makes use of the dependence of level of nonlinearity to the density or severity of the defect and effectively distinguishes intact and damaged samples [14]. This approach detects material defects by monitoring the modulation components generated by the interaction between probing (high-frequency ultrasound, ω) and pumping (low-frequency vibration, Ω) signals in the presence of a crack which reveals itself in the nonlinear behavior of material [21]. Nonlinear behavior of material is present as the modulation components in sidebands of probing frequency, as opposed to linear system response of intact system without indication of any sidebands.

Most of the reported VAM studies correlate flaw presence and its growth with the increase in the Modulation Index (MI), defined in the spectral domain, as the ratio of the side-band spectral components at frequencies $\omega\pm\Omega$ to the amplitude of the probing frequency. This approach does not distinguish between two kinds of modulation: frequency and amplitude modulation, FM and AM, respectively. The Hilbert Transform and its modifications, [22], are routinely used to extract the instantaneous amplitude and phase/frequency where dominant amplitude modulation for visible cracks is reported [23, 24]. The new proposed algorithm [25] is used in this research for separating the amplitude and frequency modulated components of the received signal.

In this study, comprehensive experimental studies are carried out to investigate the modulation index dependence of different fatigue stress levels. The MI evolution during the fatigue test is investigated for different steel types in detail. In addition to the initially proposed plan, we also developed and methodically tested a new Amplitude and Frequency modulation (AM/FM) separation algorithm specifically tailored to VAM crack detection. This provides further understanding of modulation type in fatigue loading.

METHODOLOGY

In this investigation, VAM technique is used to acquire Modulation Index (MI) as a damage indicator for the tested specimens. The preliminary goal in this method is to apply a high frequency signal (carrier signal) and a low frequency signal (modulating signal) to the specimen and analyze the output modulated signal in the power spectrum for damage detection. The process starts with sending a carrier signal, ω, to the specimen via attached piezoelectric transducer (Tx). Low load fatigue vibration is utilized as a source for modulating frequency, Ω, input in the background. The initial settings such as the required frequency and sampling rate are set as inputs in the LabVIEW F-scan software. Once the initial setup is completed, the generated signal is sent to the amplifier via Data Acquisition board to reach the desired amplitude. The amplified signal is then sent to the specimen. Receiving the output signal takes place via the other attached transducer (Rx). The output signal is then sent to the computer via DAQ to be evaluated in the LabVIEW. The modulated signal arises from nonlinear interaction of carrier and modulating signals due to micro/meso-scale cracks as illustrated in Figure 1. In the presence of damage in the specimen, the output modulated signal contains side bands around the carrier in its power spectrum which is used for MI calculation (Equation 1). It is well-known that presence of damage in the specimen provides the nonlinear response whereas the frequency response of an intact system is linear.

$$MI = 20\log_{10}\frac{A_{-}+A_{+}}{A_1} \qquad (1)$$

A_{-} and A_{+} are the corresponding amplitudes for the sidebands, $\omega\pm\Omega$. On the other hand, A_1 is the amplitude of the carrier signal, ω.

In this study, corresponding MI for a 5kHz range is measured and averaged at each measurement cycle. The trend of the MI during the fatigue life of the specimen is monitored to catch the crack identification moment.

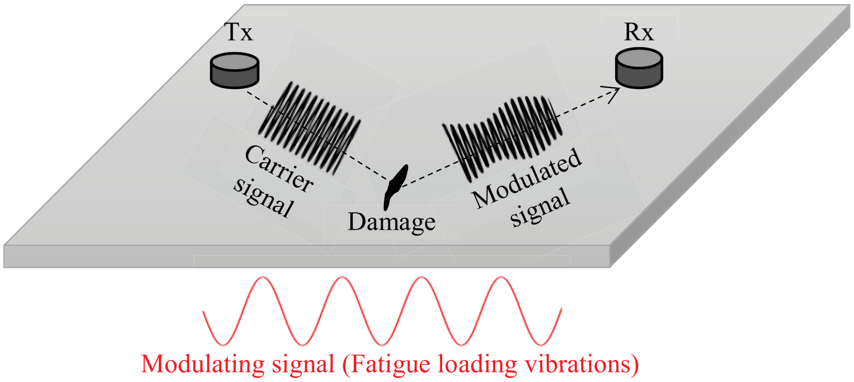
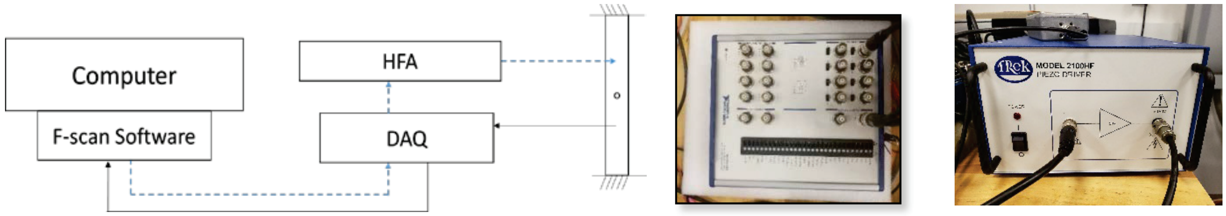


FIGURE 1. Presence of Non-Modulated Carrier in Addition to Modulated Signal in Received Signal

EXPERIMENTAL SETUP

The applied VAM technique in this study consists of a computer with a LabVIEW F-scan software that generates the carrier signal. This occurs via Data Acquisition board (DAQ) and the high frequency amplifier that are connected to the computer as shown in the Figure 2 (a). The amplified high frequency signal is introduced to the sample by the transmitter transducer (Tx). The received modulated signal will be transmitted to the DAQ via the receiver sensor (Rx). The typical specimens under tests are 1” by 10” rectangular bars of 1/8” thickness and 1/4” diameter center-notch.



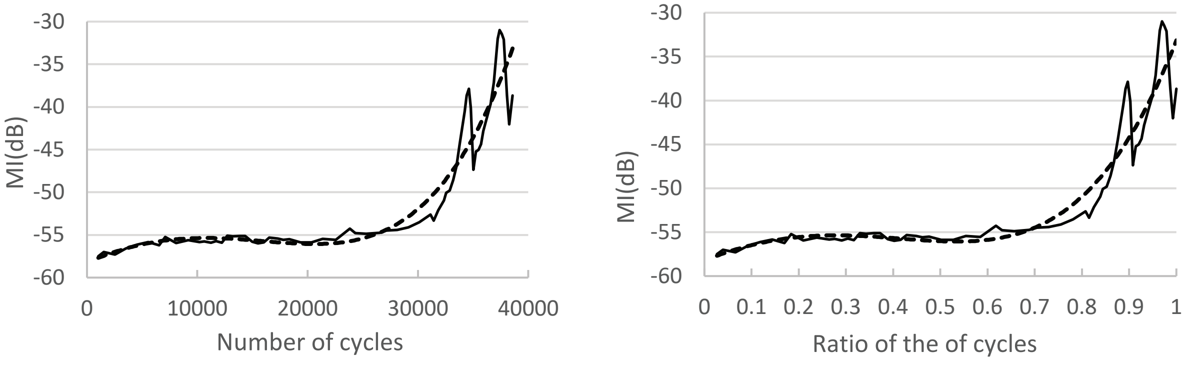
(a) (b) (c)

FIGURE 2. VAM technique equipment (a) Connection diagram (b) Data Acquisition board (c) Amplifier

Fatigue tests were conducted using an 810 MTS test frame connected to a digital data acquisition and processing station. The specimens were mounted parallel to the applied load. A 10 Hz tension only low-load fatigue cycling was used for the measurement purposes. The applied tension load during the initial tests are 20kN maximum and 0kN minimum. Later on during the parametric study, different stress levels were also applied to the specimens.

RESULTS AND DISCUSSION

The primary target of these set of tests was to improve the applicability of the VAM technique for material degradation assessment in different steel samples used for the civil infrastructure specifically steel bridges. Thus the experimental setup containing VAM equipment, fatigue machine and its digitizer were assembled to conduct fatigue tests. The initial tests were accomplished on steel ASTM A108. The results of the preliminary successful test are revealed in Figure 3. As shown in the corresponding graphs of the sample with approximately 38000 life-cycle, the averaged MI was constant until around 30000 cycle and then it started to increase significantly. To clarify the relation of the steep slope initiation to the total life of the specimen, Figure 3(a) is normalized to the fatigue life time which shows the start of the steep slope at around 78 % of the life of the specimen.



(a) (b)

FIGURE 3. Preliminary results of the VAM technique on ASTM 108 samples (a) Trend of the Modulation Index (MI) vs the number of cycles until failure (b) Trend of MI vs Normalized number of life cycles

From the graph shown in Figure 4, the results of the four following tests with the same stress level and condition, we can see that the steep slope starts from 70 to 80 % of the life of the specimen.

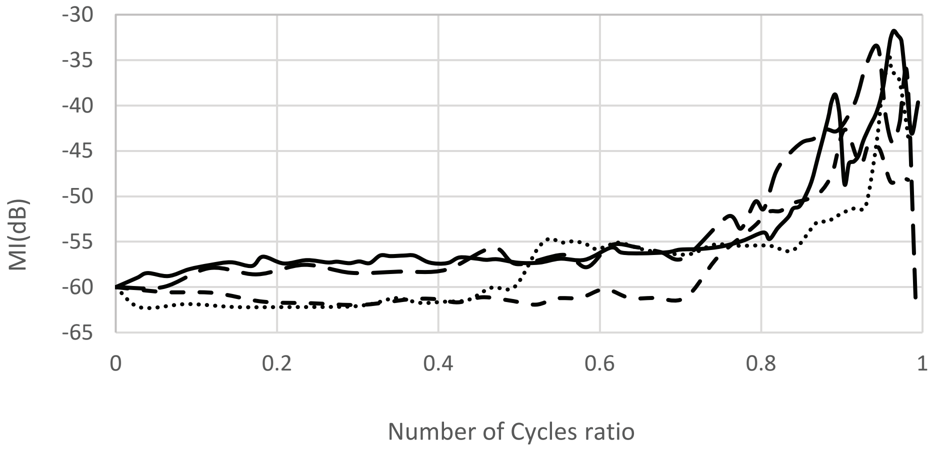
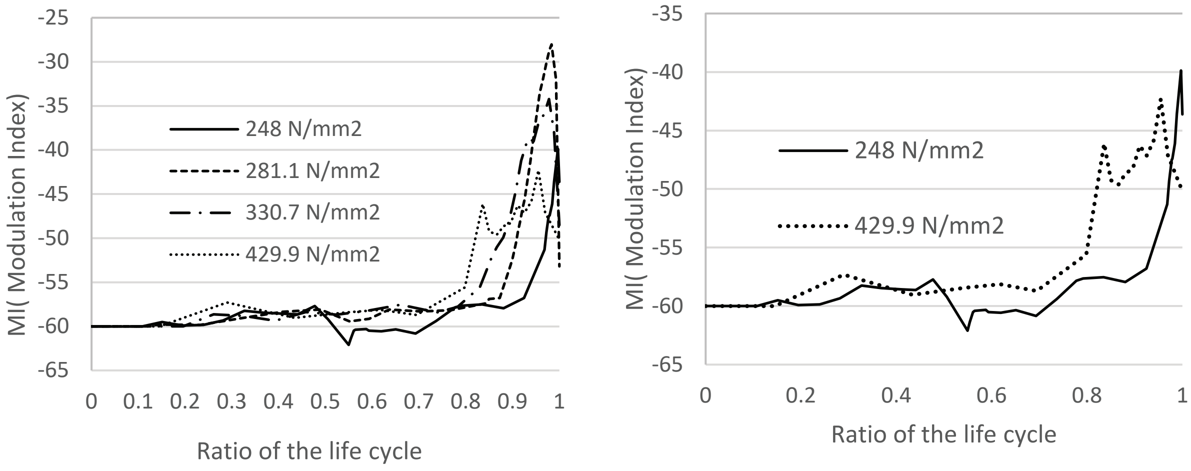


FIGURE 4. MI evolution of 4 tension only test with similar fatigue stress levels

Thereafter, the conventional steel material for bridges (ASTM A36) was utilized to prepare center-notched rectangular samples for the fatigue tests.

Variation in stress level

The effect of different stress levels on changes in the averaged MI was investigated and is shown in Figure 5. From this data, it can be seen that changing stress levels for the same test types does not significantly alter the initiation of steep slope during the life of the specimen. Comparison of the beginning of the steep slope in the highest and the lowest stress levels shows that the lower stress level will result in a delay in the failure prediction around 10% of the life of the specimen. However, higher fatigue life time in the lower stress level compensates for this delay in prediction and saves time for the maintenance (Figure 5 (b)).

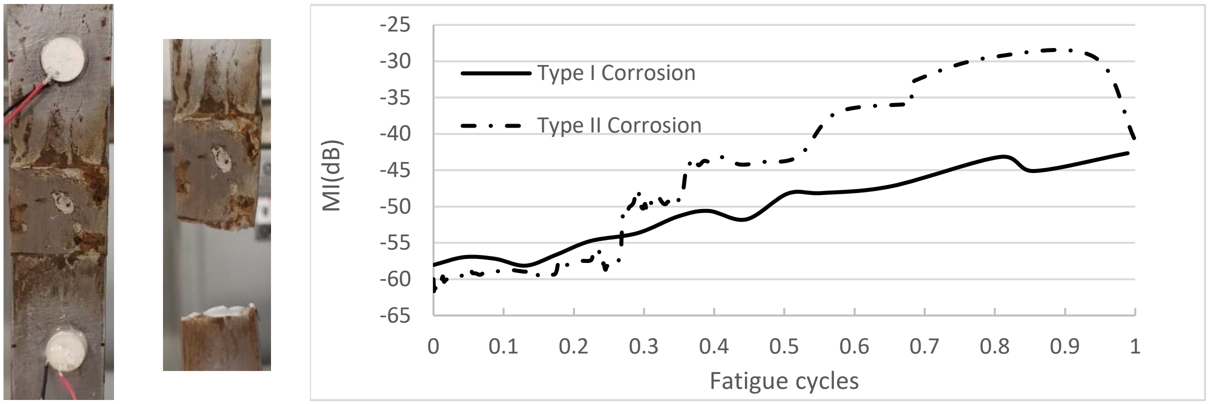


(a) (b)

FIGURE 5. Trend of the modulation index vs the specimen`s life ratio until failure- effect of stress level variation(a) in four stress levels (b) in maximum and minimum stress levels

Corrosion effect

In this study, the proposed NDT approach is tested at corroded samples. Samples are corroded within an accelerated test.in which they undergo cyclical wetting and drying process. The first cycle is a 5% saline solution spray for one hour. The following cycle is an hour of heat (produced by heat lamps to approximately 100 F) and UV irradiation to dry the specimens. These two cycles rotate one after another for 16 hours, producing 8 wetting and 8 drying cycles. Two different types of samples regarding the corrosion depth are created: type I is under exposure for two weeks and type II is under exposure for four weeks. The sample is covered with tape except for the middle part where the crack is intended to occur.



(a) (b)

FIGURE 6. Corroded samples test results, (a) corroded sample type II specimen and fractured (b) MI evolution in two type corroded specimens

It is observed that corroded samples differ from typical samples tested before in the modulation index progress during the fatigue life of the specimen. The steep slope is not observed. Instead a rather gradual increase of MI over the cycle number is observed. The normalized MI-cycle number curves of type I and type II corroded samples are cross-plotted in Figure 6(b) steady (maybe even linear) increase of MI over the cycle number for corroded samples might be advantageous in respect to life cycle analysis and residual life time prediction. More tests should be conducted on the corroded samples to have a thorough understanding of the damage indication by the VAM in fatigue loading.

Modulation type investigation

The output modulated signal is processed to get its amplitude and frequency modulated components. A fatigue test was performed to observe the AM and FM dynamics during the test of a steel bar. The IQHS algorithm which is proposed as an alternative to Hilbert Transform for demodulation of systems under fatigue loading is used to process the received signals. The IQHS algorithm is based on multiplication of received modulated signal and carrier signal. The received modulated signal multiplication by the in-phase, cos(ωt), and quadrature, sin(ωt), carrier signals produce AM and FM spectral component amplitudes [25]. The results in Figure 7 reveals that the initial damage produces primarily FM modulation which is taken over by AM modulation as visible contact-type defect has developed. It may be concluded that the crack initiation and incremental crack propagation stages of fatigue failure may exhibit primarily frequency modulation as compared to amplitude modulation from contact interfaces in macro crack formation.

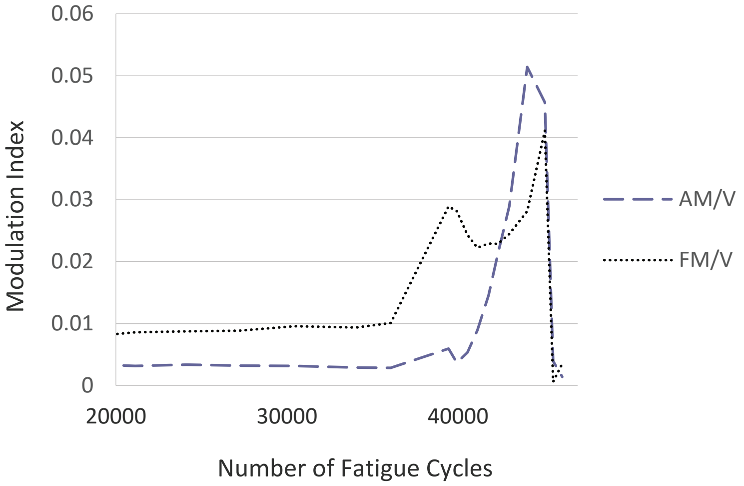


FIGURE 7. AM/FM separation

CONCLUSION

In this study VAM technique has been introduced as an NDT method to be applicable in critical steel bridge components. Therefore, several fatigue tension only tests have been conducted on two types of steel material. As a result of these tests for the typical test specimens under similar condition, 20 to 30 percent in advance prediction of crack existence prior to failure was proved. Moreover, variation in stress levels were tested and 10 % tolerance was notified for the delay in the lower stress level prediction. In addition to that the effect of corrosion as a common issue in steel bridge components were studied. In contrast to earlier findings, the corresponding results showed that the MI evolution in the corroded samples do not comply with the warning of the crack existence at 70 to 80 percent of the fatigue life time. The investigation showed that a gradual increase in the MI during the life of the corroded specimens can contribute in a different way to the life cycle analysis. Demodulation of output signal shows preliminary frequency modulation dominance in micro-crack initiation and growth compared to prevalent amplitude modulation in contact-type macro-crack formation. These findings contribute in several ways to the application of this approach and paved the way for more research in this area for different samples with different geometries both in small and large scales.

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