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Vibroacoustic Modulation of Wideband Vibrations and Its Possible Application for Windmill Blade Diagnostics

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Abstract**—**Wind turbine has become one of the most popular energy production methods. However, failure of blades and maintenance costs evolve into significant issues in the wind power industry, so it is essential to detect the initial blade defects to avoid the collapse of the blades and structure. This paper aims to apply modulation of high-frequency blade vibrations by low-frequency blade rotation, which is close to the known Vibro-Acoustic Modulation (VAM) method. The high-frequency wideband blade vibration is produced by the interaction of the surface blades with the environment air turbulence, and the low-frequency modulation is produced by alternating bending stress due to gravity. The low-frequency load of rotational wind turbine blades ranges between 0.2-0.4 Hz and can reach up to 2 Hz for strong wind. The main difference between this study and previous ones on VAM methods is the use of a wideband vibration signal from the blade's natural vibrations. Different features of the VAM are considered using a simple model of breathing crack. This model considers the simple mechanical oscillator, where the parameters of the oscillator are varied due to low-frequency blade rotation. During the blade's operation, the internal stress caused by the weight of the blade modifies the crack's elasticity and damping. The laboratory experiment using steel samples demonstrates the possibility of VAM using a probe wideband noise signal. A cycle load with a small amplitude was used as a pump wave to damage the tested sample, and a small transducer generated a wideband probe wave. The received signal demodulation was conducted using the Detecting of Envelope Modulation on Noise (DEMON) approach. In addition, the experimental results were compared with the modulation index (MI) technique regarding the harmonic pump wave. The wideband and traditional VAM methods demonstrated similar sensitivity for earlier detection of invisible cracks. Importantly, employing a wideband probe signal with the DEMON approach speeds up and simplifies testing since it eliminates the need to conduct tests repeatedly for various harmonic probe frequencies and to adjust the probe frequency.

Keywords**—**Damage detection, turbine blades, Vibro-Acoustic Structural Health Monitoring, SHM, Detecting of Envelope Modulation on Noise.

I. INTRODUCTION

ONE of the most common energy generation technologies is the wind turbine. However, wind turbines operate in the most extreme environment to convert mechanical energy into electrical energy, exposing them to damage. The part of a wind turbine that is exposed to the pressure of the harsh environment is blades, which play a significant role in generating energy. Therefore, this imposes damage detection and structural health monitoring (SHM) methods to extend their service life and save costs. A considerable literatures and books have grown up for developing the SHM method [1]-[4]. The Vibro-Acoustic SHM method, that analyzes features extracted from the blade’s structural vibrations, is one of these methods. The formation of the damaged could be indicated by changes in the frequency response, vibration amplitude, and mode shapes, etc. [4]-[6]. However, all vibro-acoustic SHM methods are based on comparing the structural vibration for damaged and undamaged structures, which limits the functional applications of these methods.

Nonlinear Vibro-Acoustic SHM (NVA SHM) methods are more sensitive to the cracks and damage present. They do not require comparison with the data from undamaged structures. Historically, the first applications of nonlinear acoustic (NA) techniques for material characterization used measurements of the second and higher harmonics generated by the nonlinear distortion of a primarily sinusoidal acoustic wave propagating in a medium with defects. The first tests of this method were made as early as 1979 in wave propagation experiments [7], [8]. A large spectrum of NA effects is used in different NVA NDE and SHM techniques. Several thousand papers have been published on this matter; book [9] and reviews [10]-[15] give a state of the art in this area.

One of the most classical nonlinear techniques is VAM, which is based on the modulation of high-frequency (probe waves) by low-frequency vibrations (pump waves). In some papers, it is called Nonlinear Wave Modulation Spectroscopy (NWMS) [16]. The wind turbine produces periodical changes in the loads due to the blade rotation, and this low-frequency load can be used as the pump wave for modulation of the high-frequency probe wave. The papers [17] and [18] investigated this method in experiments with actual wind turbine blades. In this test, the high-frequency probe signal radiation and reception were conducted using micro fiber composite (MFC) transducers, and the probe signal frequencies were 5-10 kHz. The modulation of this signal was observed in the rotation frequency 3.1 Hz and its harmonics. However, the suggested approach is not practical for real operational SHM because it requires special emitters installed on blades.

In this paper, we consider the more straightforward way of

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VAM SHM using the modulation of the blade's natural vibration by the loads produced by the blade's rotation. The main distinction from the previous investigation of VAM methods is the broad spectrum of the blade's natural vibrations. Thus, the modulation of the wideband probe signal by the low-frequency vibration can be considered. For this purpose, we have developed a model that predicts the features of the probe wave modulation in the rotating blades. This model is based on previous experimental and theoretical studies that described variations in the resonance frequencies [19]-[21] and damping [22] of the blade with breathing cracks under periodic blade loading. The currently developed model considers the modulation of the harmonic probe wave, and we plan to extend it to analyze wideband noise probe wave in the future. The laboratory VAM experimental outcome for applying the wideband probe wave with a low-frequency pump wave is also presented. The pump wave modulation was analyzed using the algorithm for Detecting Envelope Modulation on Noise (DEMON), initially developed for underwater acoustic submarine detection [23].

II. VAM MODEL OF BREATHING CRACK

The previous theoretical model of VAM attributed the modulation to the nonlinear constitutive relation caused by a defect [24].

We consider a cracked media model different from that previously used. The oscillator parameters fluctuate due to low-frequency blade rotation in this model, which considers the linear excitation of the mechanical oscillator (see Fig. 1). When the blade rotates, the weight of the blade creates internal stress that changes the crack's elasticity and damping. These effects were modeled in [19]-[22]. The developed model can predict the complicated dependencies of the resonant frequency shift, their amplitude dependencies, and the loss on the applied loading. Our model only considers the smallest resonant frequencies and loss fluctuations that a linear dependence on the loads can modulate. It can detect smaller cracks that were assessed in [19]-[22].

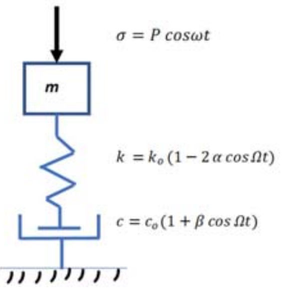


Fig. 1 The model of the mechanical oscillator, the stiffness $k(t)$, and damping $(c(t))$ are modulated by the rotational load.

The VAM model can be explained by the following model:

$$m\ddot{q} + c\dot{q} + kq = -\sigma(t) \tag{1}$$

where m is the mass, q denotes the crack response to the applied force σ, k is the crack model stiffness, and c is the attenuation coefficient.

This model considers the application of the probe wave near the resonance frequency $\sigma = \cos\omega t$. Thus, (1) can be written in the following form:

$$m\ddot{q} + c\dot{q} + kq = \cos\omega t \tag{2}$$

The solution can be presented in the form

$$q = A\cos(\omega t - \varphi) \tag{3}$$

The amplitude and phase are $A = \frac{P}{\sqrt{(\omega_o^2-\omega^2)^2+(c\omega)^2}}$, and $\tan\varphi = \frac{c\omega}{\omega_o^2-\omega}$ where the resonance frequency is $\omega_0 = \sqrt{\frac{k}{m}}$. These parameters depend on the frequency ω, the resonance frequency ω_o, and attenuation coefficient c.

The pump wave changes resonance frequency and attenuation.

$$\omega_o = \widetilde{\omega}_o(1-\alpha\cos\Omega t) \tag{4}$$

$$c = c_o(1+\beta\cos\Omega t) \tag{5}$$

where α and β << 1. Nonlinear parameters α and β reveal resonance frequency shift and attenuation changes because of the pump wave's influence. Therefore, we consider very low values for these parameters; for instance, in Fig. 3, computations were done with α and β = 0.001. It means that the developed model can describe the very low level on the nonlinearity in the damage initiation phase when cracks not yet propagate. For modelling we will use the resonance frequencies obtained in the publication [19] and shown in Fig. 2. The presence of the breathing crack decreases the resonance frequency from 52.246 Hz to 47.093 Hz, which is about 5%. In our computation of VAM by using a developed model, we employ the same resonance frequency (50 Hz) and nonlinear frequency shift parameter $\alpha \sim 0.1\%$, which is viewed as small cracks.

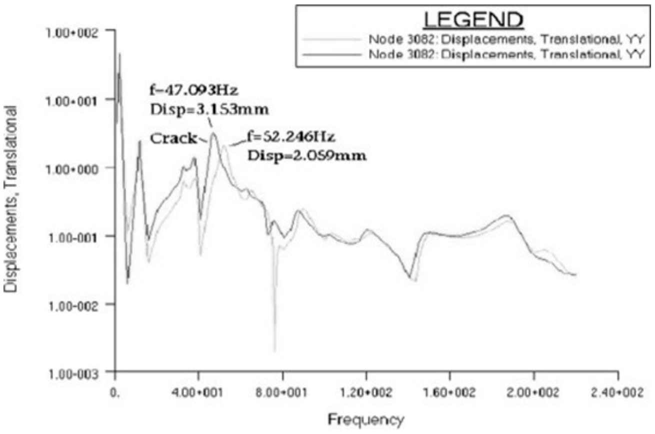
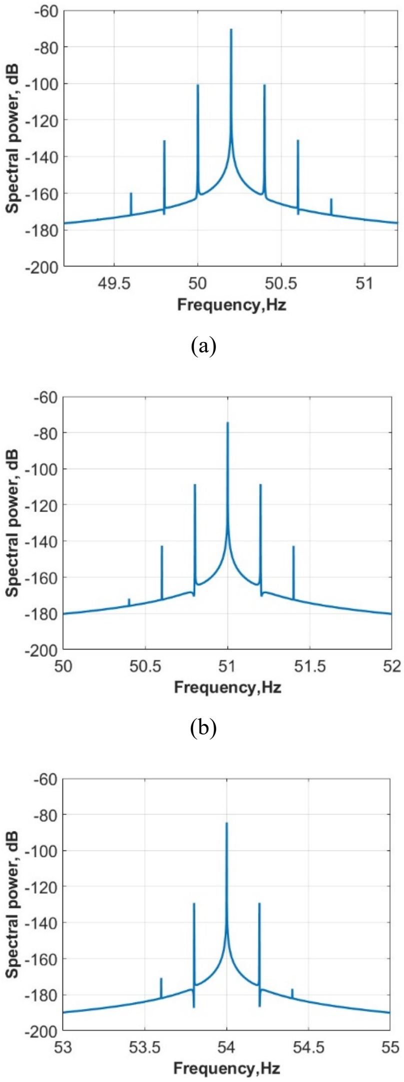


Fig. 2 The blade displacement magnitude vs. frequency plot at point 1 for the damaged blade (Black) and for the undamaged blade (Gray) [20]

Fig. 3 represents the spectra of the model calculated using the following parameters and values: $\tilde{\omega}_o = 2\pi F_o$; $\Omega = 2\pi F$; c_o=10; α and β = 0.001; $\omega = 2f\pi$ where $f = 50.2, 51, 54$ Hz and $F = 0.2$Hz (12 rpm for typical windmill).



(a)

(b)

(c)

Fig. 3 VAM spectra result by the proposed model for different probe frequencies: (a) $f = 50.2\ Hz$, (b) $f = 51\ Hz$, (c) $f = 54\ Hz$ Movement of the excitation frequency out of the resonance decreases the MI

III. EXPERIMENTAL SETUP WITH WIDEBAND MODULATION SIGNAL

The laboratory experimental research for observation of the wideband VAM application for crack detection was conducted using the setup that was described in [25]. Instead of using a sinusoidal signal, a wideband noise signal is used in this experiment.

The sample utilized in the experiment was a 254 mm A36 bar with a cross-section of 25.4 × 3.175 mm. A central hole with a diameter of 6.35 mm was created to control the location of the expected fatigue crack. Two piezoelectric disks were attached to the sample to transmit and receive the signal, and the sample was installed in the material test system (MTS). Fig. 4 shows the experiment setup.

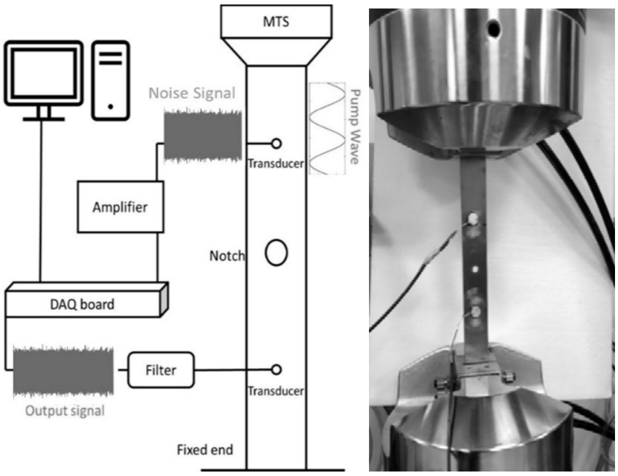


Fig. 4 The experimental setup for VAM with wideband probe wave

Two scenarios were performed on the sample, evaluating, and damaging the sample until the sample became a complete break. Cycle tensile loads are set using the MTS with a goal setpoint of 10.5 kN and an amplitude of 10 kN.

During the VAM evaluation, the MTS used to excite the sample using the frequency of 10 Hz with an amplitude of 0.5 KN as pumping waves, and the wideband noise signal was sent by one of the piezoelectric discs into the sample. For the pump wave excitation, we used NIUSB 6361 data acquisition (DAQ) board and its signal was 50 times amplified by a piezo driver power amplifier. Hence, the interaction between the noise signal and pump wave occurs with the presence of the defect at the notch location. The modulated signal received by the other piezoelectric disc was sent to the bandpass filter with a frequency range of 110-220 kHz, which was received by the DAQ board. Finally, the spectral modulated signal is analyzed by the computer.

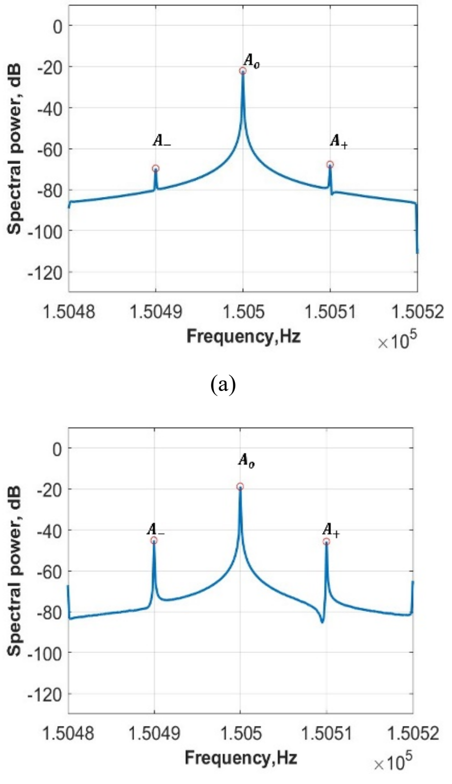
IV. LABORATORY TEST RESULT

First, we started to assess the steel sample fatigue life with the well-known VAM method using a sinusoidal probe and pump waves. In this test, the modulation of the high-frequency probe wave by the low-frequency pump wave was observed, and Fig. 5 presents the observed spectra for a different number of load cycles. The probe frequency of $f = 150.5$ kHz and the pump frequency of $F = 10$ Hz were applied.

The MI usually characterizes the level of the nonlinearity in VAM according to:

$$MI = \frac{A_{-}+A_{+}}{2} - A_o$$

where A_0 is the received spectral component of the pump wave in dB (Fig. 5), A_+ and A_- are side band components.



(a)

(b)

Fig. 5 Modulated signal spectra for the probe wave of 150. 5kHz: (a) at the 5000 cycles load; (b) at the 48004 cycles load

The MI was typically estimated using the level of probe frequency and two side components having frequencies. The load cycles are utilized to normalize representative results of the MI, which had a varying number of cycles to failure, and this number of normalized load cycles may be regarded as the sample lifetime, as represented in Fig. 6. With increasing cyclic load, the MI measurement plot begins to show a slight rise. When damage occurs in the samples, the line starts to trend. Finally, due to a fracture, the two sidebands become prominent, as shown in Fig. 5 (b), demonstrating that the MI increases until the end of the measurement.

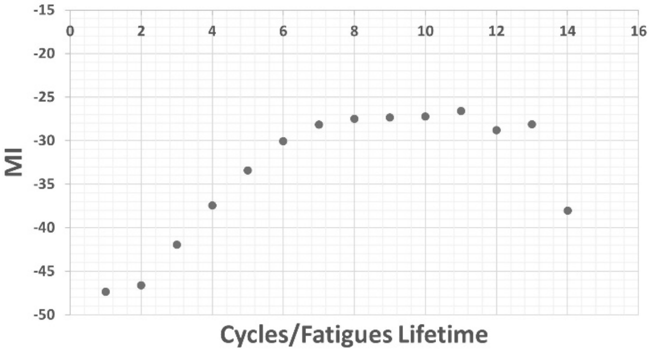


Fig. 6 MI versus the number of cycles ratio for average frequencies

In the experiment for investigation of the VAM with a wideband probe signal, the probe wave was excited by the noise signal in the frequency band $150-200$ kHz. There are no apparent sideband components in the spectra of the modulated signal, and the classical MI method does not work here. The DEMON technique presented in [23] was applied to demodulate the wideband signal. This technique was widely used for submarine detection, and the DEMON calculation method is in Fig. 7.

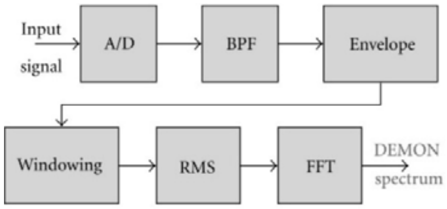
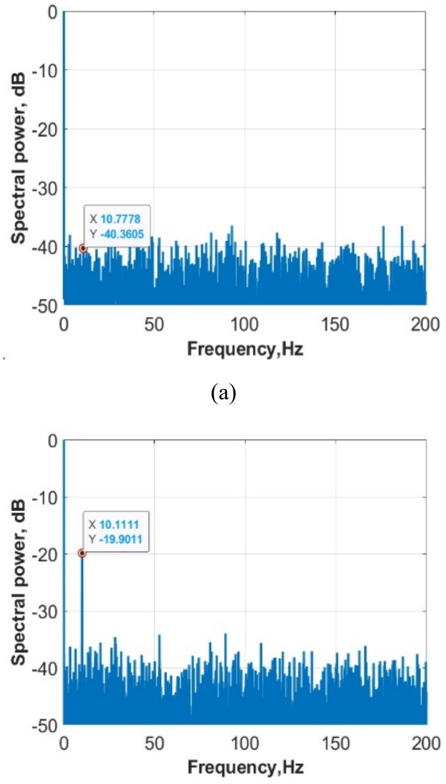


Fig. 7 DEMON calculation process [23]

The DEMON method was applied to the signals recorded on the steel sample using VAM wideband noise signals. Examples of the signal spectra are presented in Fig 8. The 10 Hz modulation frequency value displayed in the figure increases when the cycle numbers increase, and these spectra are shown for different numbers of cycles of loading. The DEMON result revealed in the diagram illustrates two stages of the sample lifetime. In the first stage, there is no damage to the sample. In the second stage, the damage is invisible, but the high level of the 10 Hz component indicates the presence of a crack.



(a)

(b)

Fig. 8 DEMON spectra in the frequency window of 200 Hz for the steel sample in different cycles load: (a) a) 5000 cycles load, (b) 48004 cycles load

In Fig. 9, the level of the DEMON component is presented versus the normalized number of cycles. This normalized load cycle number can be viewed as the sample lifetime.

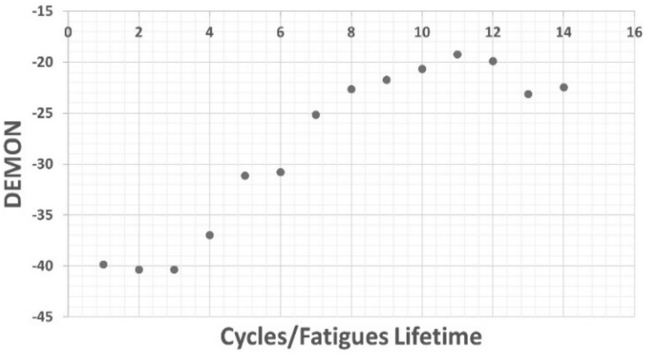


Fig. 9 Steel fatigue life assessment using the DEMON of a 10 Hz component versus the normalized number of cycles load

The comparison of the plots in Figs. 6 and 9 shows that both methods have the same sensitivity to crack detection. The wideband signal method is easier for real windmill blade SHM because it does not need a probe wave emitter that sends out sinusoidal waves.

V. Conclusion

The windmill blades are the primary concern regarding blade damage. In this paper, wideband frequency VAM for the SHM of the windmill blades is suggested. The modulation of the wideband frequency noise vibration in the wind turbine blades is caused by the blade's loading during their rotation. This technique's realization requires installing wireless accelerometers on the blades. One of the possible systems for this purpose could be the sensor produced by eolofix sensor technology. These flexible sensors have a thickness of under 2 mm and there is no need for external wiring on the blade. These sensors collect energy from the sun and use a rechargeable energy storage system. The measured data are sent to a base station in the tower or nacelle of the turbine using wireless communication. Triaxial MEMS accelerometers, which have a measuring range of 16 g and a sensitivity lower than 0.49 mg, with 1 g =.81 m/s^2 equal to the acceleration due to gravity, were employed in the wireless prototype sensor. The sampling rate for the data recorded was up to 833 Hz [26]. In addition, the developed model allows for the detection of sinusoidal pump wave modulation by the loads produced by the blade rotation. Extending the analysis of the wideband noise wave is planned in the nearest future.

The laboratory experiment demonstrated the possibility of VAM with wideband probe waves.

The presented methods could be used to extend the current method based on blade vibro-acoustic signatures [26]. This extension of the current technique does not require any additional equipment.

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