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Nonlinear Acoustics for Crack Detection in Aluminium Plates – Wireless and Mobile Platform Based on a Smartphone

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Abstract

The paper demonstrates a mobile and wireless smartphone platform that can be used for damage detection. This platform consists of sensors, electronics, Android-based software and a smartphone that is used for control, communication, data storage, damage detection analysis and the presentation of damage detection results. The method used for crack detection is based on nonlinear acoustics that utilizes vibro-acoustic wave modulations. The application of the smart damage detection platform is demonstrated in undamaged and cracked aluminium plates. The results demonstrate damage detection capability of the mobile smartphone-based system.

1. INTRODUCTION

Many engineering structures and rotating machines need to be monitored to prevent potential catastrophic failures. This process relies on periodic or online inspections that require measurements and data analysis. Often measurements are performed using sensors that are permanently attached to monitored structures/machines. Recent years have seen a number of mobile and wireless sensor platforms for structural damage detection [1-4]. The development of mobile telecommunication technologies – together with wireless sensor platforms - has opened new opportunities for structural health monitoring and condition monitoring. Modern smartphones are equipped with a variety of sensors - such as GPS, accelerometers, gyroscope or light and proximity sensors) – that can be used for monitoring of different parameters. Application examples relevant to structural dynamics include: measurements of accelerations [5] and displacements [6]. Smartphones also offer: large computational and programmable power (dual-core CPUs clocked at GHz frequencies and minimum one GB of RAM), flash memories for data storage (tens of GBs), high battery capacity (hours of constant usage), connectivity (via USB) and wireless connection via Bluetooth or to a local area network. This functionality is important for Structural Health Monitoring (SHM). Application examples that utilize

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smartphones for damage and fault detection are still limited. The majority of these examples demonstrate software capability for data analysis and storage in condition monitoring applications. Two interesting smart device concepts – mainly for civil engineering SHM applications - have been presented in [7] and [8]. The former proposes to use acceleration data and the well-known peak-peaking method [9] for the estimation of natural frequencies. The latter demonstrates measurements of inclination and acceleration, claiming that both parameters could be used for SHM applications.

The paper demonstrates a mobile and wireless smartphone platform that can be used for damage detection. This platform consists of sensors, electronics, Android-based software and a smartphone that is used for control, communication, data storage, damage detection analysis and the presentation of damage detection results, as described in Section 2. The application of this smart damage detection platform is demonstrated in Section 3 using an example of crack detection in an aluminium plate. The method used for crack detection is based on nonlinear acoustics. Non-linear vibro-acoustic modulations - produced by crack-wave interactions - are used in this application. Finally, the paper is concluded in Section 4.

2. NONLINEAR ACOUSTICS

Various ultrasonic methods have been developed for damage detection for the last few decades. Nonlinear acoustics uses different nonlinear phenomena that can be observed in propagating ultrasonic waves. Analysis of higher ultrasonic harmonics is the most commonly used technique in material testing investigations. Ultrasonic/acoustic wave interactions with material imperfections and contact-type interfaces are less common in engineering applications but also researched extensively. These interactions can be attributed to various contact phenomena related to elastic (e.g. local bi-linear stiffness or clapping) and dissipative (e.g. hysteresis or nonlinear thermo-elastic coupling) nonlinearities, as reviewed in [10]. It is widely acknowledged that acoustic damage-related nonlinearities can be used for structural health monitoring applications. Various damage detection methods have been developed over the last twenty years. The work presented in this paper uses combined vibro-acoustic interactions of vibration and ultrasonic response fields [11-18]. These interactions result nonlinear wave modulations in the presence of damage. When the method is used for damage detection, monitored structures are excited simultaneously with low-frequency harmonic vibration (f_L) and high-frequency harmonic ultrasound (f_H). Modal frequencies corresponding to structural resonances can be used for the low-frequency excitation. The high-frequency ultrasonic wave – selected arbitrarily - is used as a probing wave to detect possible structural damage. When monitored structures are intact or undamaged, the probing wave is unchanged. However, when structures are cracked the high-frequency ultrasonic wave is modulated by the low-frequency vibration flexural wave. Often power the response spectra are used to observe modulation sidebands around the probing carrier wave. The intensity of modulation is then used for damage detection. This modulation intensity strongly relates to damage severity, i.e. the number of sidebands and their amplitudes increase with the severity of damage. The nonlinear vibro-acoustic modulation technique has been used successfully for crack detection in metals [11-15] and impact damage detection in composites [16-18]. This method has been selected for the mobile wireless sensor platform mainly due to its relative implementation simplicity.

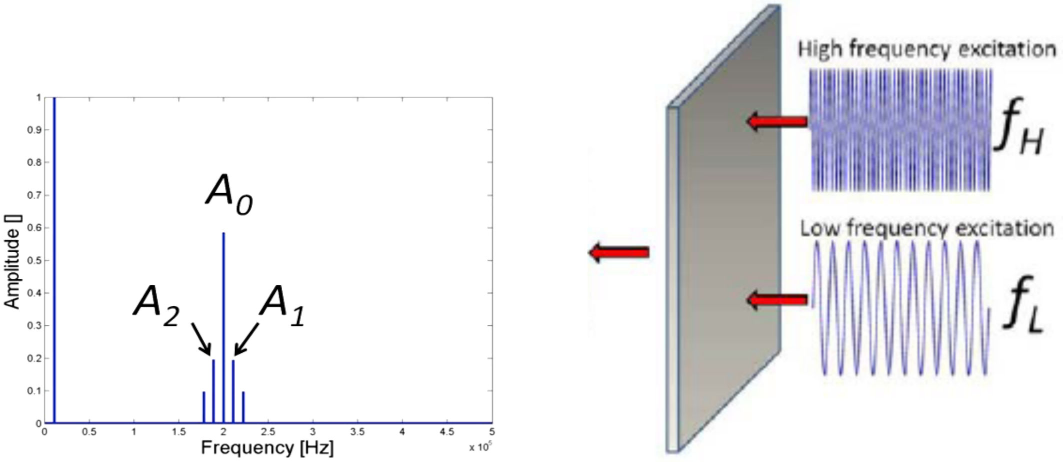

Figure 1. Example illustrating the nonlinear vibro-acoustic wave modulation technique. Modulation sidebands (e.g. A_1 and A_2) can be observed around the A_0 high-frequency ultrasonic component due to structural damage.

3. SIGNAL DEMODULATION

When the nonlinear vibro-acoustic modulation technique is used for damage detection the ultrasonic wave is modulated by the vibration flexural wave, as described in Section 2. Various methods can be used to analyse signal modulations. The work presented in this paper utilizes the synchronous demodulation procedure. This section briefly describes the method.

The high-frequency ultrasonic wave is the carrier and the low-frequency vibration wave is the modulating component. The synchronous demodulation procedure extracts the modulating component from the modulated response wave. This process – known as signal demodulation - shifts the information on modulations from high-frequencies (modulated response carrier) to low-frequencies (modulating wave). As a consequence, the method can be easily implemented using analog signal processing and off-shelf electronic components. Also, when the demodulated signal needs to be analysed relatively low sampling frequencies and small memories are required for analog-to-digital conversion and data storage, respectively.

The modulated signal $u_s(t)$ can be expressed as

$$u_s(t) = U_s[1 + m(t)]\cos(\omega_0 t + \varphi_0) \tag{1}$$

where m(t) is the amplitude modulating signal, ω_0 is the carrier frequency, φ_0 is the phase and U_s is the constant amplitude component. When the synchronous demodulation is used the modulated signal is multiplied by the generated signal $u_g(t)$ that is defined as

$$u_g(t) = U_g\cos(\omega_0 t + \Psi_0), \tag{2}$$

where Ψ_0 is the phase and U_g is the constant amplitude component. Equation (2) shows that the frequency of the generated signal is equal to the frequency of the carrier signal. Thus the result of the multiplication contains the low-frequency demodulated part $u_O(t)$ that can be expressed as

$$u_0(t) = \frac{1}{2} U_s U_g \mathrm{m(t)} \cos\left(\varphi_0 - \Psi_0\right) \tag{3}$$

The higher-frequency component can be easily filtered out. It is clear that the efficiency of demodulation is optimal when phases of the signals $u_s(t)$ and $u_g(t)$ are the same. The so-called Phase Locked Loop (PLL) is used in order to generate the signal $u_g(t)$ electronically. The frequency of the signal that outputs the PLL is the same as the frequency of the input signal but its phase is shifted by 90°. Thus an additional element – that shifts the phase – needs to be used. Fig. 2 presents a block diagram of the demodulator used.

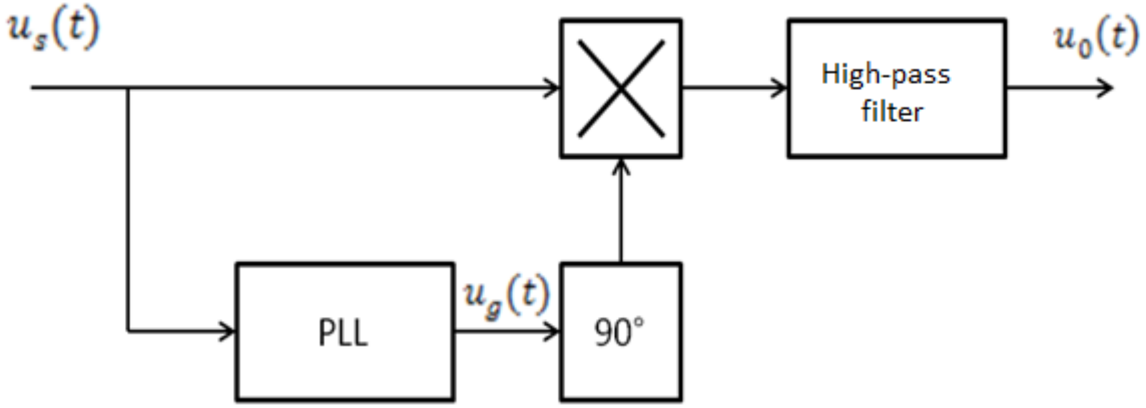

Figure 2. Block diagram of the demodulator used.

An electronic circuit was built to perform the demodulation task. The circuit used the LM565, MC1496 and OPA604AP electronic elements for phase looping (PLL task), multiplication and pre-amplification, respectively. The latter element was also used for active filtering. The entire circuit was powered from a 12 V DC battery.

4. DATA ACQUISITION, PROCESSING AND DISPLAY SYSTEM

A separate data acquisition and processing system was designed and built to: (1) acquire modulated analog signal responses; (2) transfer analog responses to the digital domain; (4) store the digitized data; (5) analyse the data and (6) present damage detection results. An electronic circuit was built to perform the first two tasks. A smartphone was used to perform the remaining tasks. A *HTC One* mobile phone - with the *Android* operational system - was used as a smartphone. Data analysis involved the calculation of the Fast Fourier transform. The smartphone was also used to control the computing system and to transfer the data to a PC for further analysis, if necessary. The smartphone was receiving the digitized data and sending control commands to a microcontroller through the JY MCU v1.05 Bluetooth communication module. Fig. 3 shows a schematic diagram of the data acquisition and processing system used.

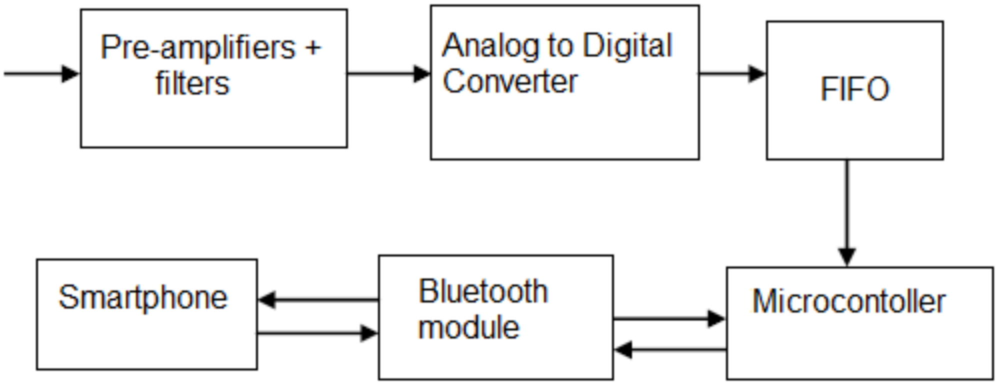

Figure 4. Schematic diagram of the data acquisition and processing system used.

A signal from a receiving ultrasonic transducer was firstly amplified and filtered using the OPA604AP cascade-connected operational amplifiers. The filtered signal was sampled by the TDA8703 fast 8-bit resolution Analog-to-Digital (A/D) converter. Then the digitized (but still relatively high-frequency) data were saved temporarily in the IDT7204 4-kB First-In-First-Out (FIFO) memory element. When the measurement process was completed the data were transferred further through the serial RS-232 communication to the ATmega8L microcontroller. The sampling frequency - which controlled the A/D converter and the FIFO memory - was generated by a microcontroller.

A small *Sparkfun COM-10917* transducer was used to excite monitored structures modally. This surface transducer was similar to a speaker. However, instead of a cone, a coil was attached to a pad that transferred vibration to a surface of monitored structures. When this solution was employed an audio output signal from a smartphone could be used to generate a low-frequency excitation signal that was driving the surface transducer.

A *SUNNY-ELECTRONICS* 40-ST-16 and (40-SR-16) air-coupled transducers were used for high-frequency ultrasonic wave generation and sensing, respectively. These types of transducers are widely used in automotive applications for parking systems. The major advantage of this transducer is that it requires relatively low-voltage signals for excitation. The resonance frequency of the transducers was equal to 40 kHz. A separate signal generator was designed and built to provide a high-frequency signal for the generating ultrasonic transducer. The design of the signal generator was based on a B-class push-pull amplifier concept. The SG3525A PWM controller was used to adjust the excitation frequency and properly charge the MOSFET's (IRF510) gates. A transformer at the output stage of the signal generator was not needed to be used to supply a signal to the air-coupled transducer.

All purpose-built electronic elements of the system, i.e. signal generator, demodulator and data acquisition system, were powered from 12 V DC batteries. All electronic elements were connected using high quality shielded BNC cables to reduce undesired noise signals.

A special (software) front-end – illustrated in Fig. 5 - was designed and programmed for the operation of the entire mobile wireless sensor platform. This front-end allowed for the selection of all relevant parameters (e.g. excitation frequencies, sampling frequency) and operational commands (e.g. data acquisition, display).

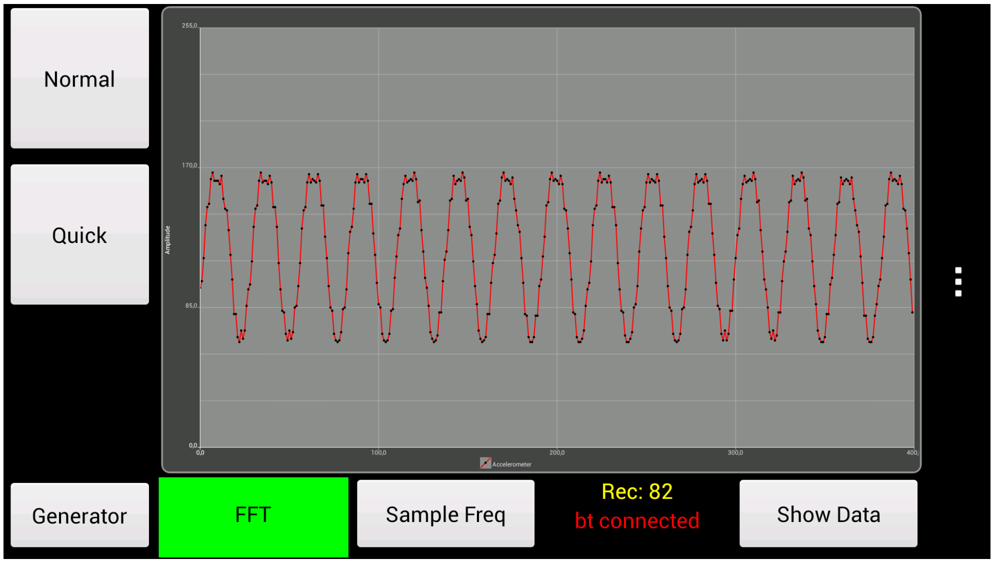

Figure 5. Smartphone front-end designed for the operation of the mobile wireless sensor platform.

5. DAMAGE DETECTION DEMONSTRATION

The performance of the mobile wireless sensor platform was tested using damage detection example based on the nonlinear acoustics method described in Section 2. Fig. 6. gives a schematic diagram of the experimental set-up used.

The specimen used for damaged detection was a cantilever 150 × 400 × 2 mm aluminium plate. Fatigue testing was used to introduce a 73 mm crack to the middle of the plate. The surface transducer was attached to the plate by a metal clamp.

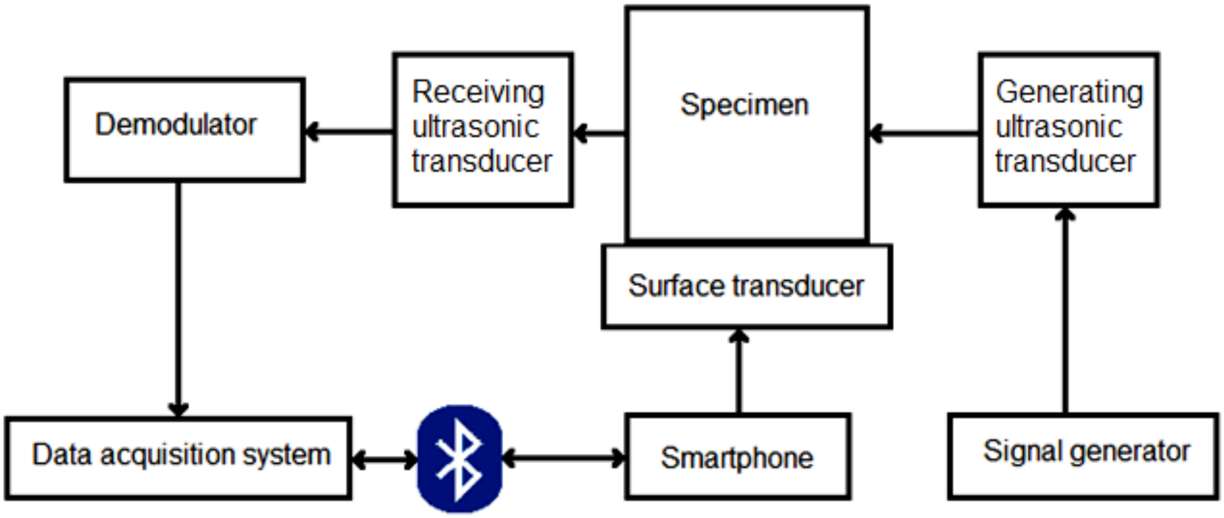

Figure 6. Schematic diagram of the experiment set-up used to demonstrate the performance of the mobile wireless sensor platform

A square audio wave of 230 Hz was generated by the smartphone for low-frequency vibration excitation. This signal was used to drive the surface transducer. A sine wave of 40 kHz was generated by the purpose-built generator for high-frequency ultrasonic excitation. This signal was driving the air-coupled ultrasonic generating transducer. The vibration and ultrasonic excitations were introduced to the plate simultaneously. The response signal was captured by the receiving air-coupled ultrasonic transducer and demodulated. The natural frequency of the demodulator's PLL was adjusted to be close to 40 kHz. The demodulated signal was digitally sampled. The sampling frequency was equal to 5 kHz. The acquisition system was capturing 4096 samples of data. Ten data sequences were captured and averaged. The averaged signal was processed using the FFT. Finally, the power spectrum was calculated. Fig. 7 gives the result displaying clearly the 230 Hz spectral component that corresponds to the modulation frequency resulting from the nonlinear crack-wave interaction.

6. CONCLUSIONS

A mobile wireless sensor platform was designed and built for damage detection application. This platform was operated by a smartphone. The performance of the system was demonstrated using the example crack detection in an aluminium plate. Nonlinear vibro-acoustic wave modulations were used for crack detection.

The results show that the designed system has a potential for damage detection applications. A fatigue crack was clearly detected using the nonlinear acoustic technique. The system was operated wirelessly by a smartphone. A further work is required to demonstrate potential applications.

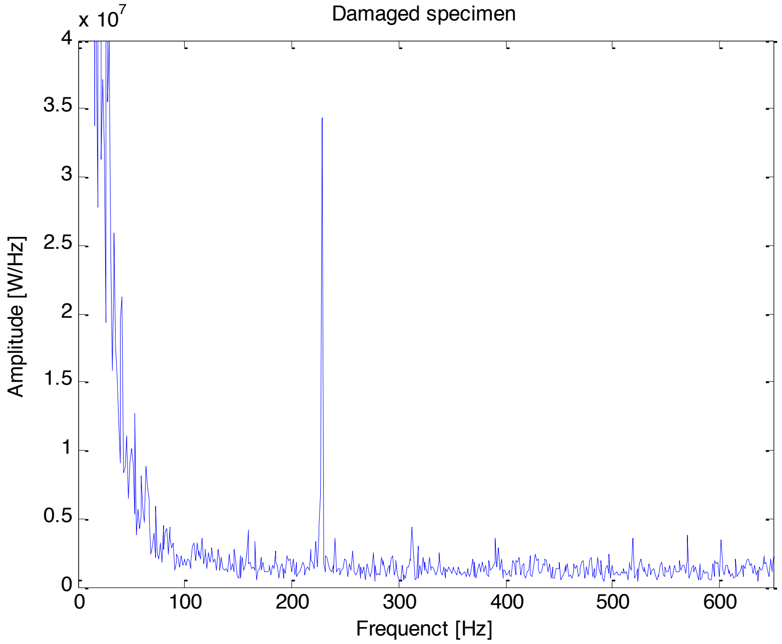

Figure 7. Average power spectrum displaying the modulation frequency resulting from the nonlinear crack-wave interaction.

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