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Addressing the detection capability for scalable energy consumption using primary data acquisition system of embedded ultrasonic sensors in SHM

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Abstract—The long range inspection and long term monitoring of civil structures is a very important issue for structural integrity. Embedded ultrasonic active measurements can be a cost-effective and operator-friendly technique for damage/change detection system in infrastructure. For long term monitoring, the energy parameter should be calibrated to the required change detection capability. An experimental system was specially developed for these applications which allow transmitting, receiving and scaling the parameters of ultrasonic signals using a Labview application. In this paper, we related the first few steps in establishing an energy model that tune, the detection capacity to energy-related sensor parameter such as sample frequency. The primary objective is to apply the model to develop the wireless data acquisition equipment for embedded ultrasonic sensors. We show that for AR based detection feature, the signal sampling rate can be tuned close to the Nyquist frequency.

Index Terms—Data acquisition, Embedded ultrasonic sensor, Structural health monitoring, Feature, Concrete

I. INTRODUCTION

The smart sensing concept can be applied in civil engineering applications, to detect changes in the structure due to material degradation for extreme environmental and operational conditions [1]. However, it is difficult to find common instructions for the installation of the sensors on the surface or inside the structure [2] [3]. Nevertheless, some initial points are similar to the different fields and should be taken into account during the installation period. The first thing is the installation and stabilization of the sensors into or onto surface or inside the host material. Since, it is essential to ensure a good mechanical contact between the sensors and the material, while on the other hand, it is crucial to protect the sensors (like fiber optic sensor, ultrasonic sensor) mechanically [4]. In the case of a traditional sensor like strain gauge, it is hard to add an extra layer of protective cover without altering the sensor reaction. In this case, the sensor has to be glued or

embedded in the structure directly. For example, it is possible to glue a Fiber Bragg grating sensor with extra protective layer to the asphalt or to embed the sensor into a composite material [5]. Otherwise, the strain sensor can be first installed in a buffer material that is mechanically compatible with the surrounding material. After the sensor installation with all protection system, next step is data acquisition. The data acquisition system consists of sensors, data acquisition units (DAU), interrogators and a main computer which can work as a server. Sensors capture the signal either electrical or optical signal that is converted to digital numeric values which are processed by a computer. Signal processing and filtering might be needed, especially for electrical and optical sensors to allow for transmission and post-processing of the signal. There are different systems on the market required different components and multiple solutions. DAU systems are local servers located in approved locations on the structures, and sensors can be connected to them. Each DAU can be equipped with a time synchronization unit and may have some data processing and data storage facilities, if needed. Data acquisition mainly relies on the specific feature of the sensors and chooses to perform the detection of structural health. It also depends on the conditions where data are acquired and also on the architecture of each acquisition system. The data acquisition procedure is completed by change of the electrical signals received from each sensor into a readable mostly digitized format.

There are different challenges connected with the data acquisition system when monitoring a structural health, including the placement of the sensors, the acquired signal/data sampling rate and the number of active sensors to be processed [6]. All sensors on the structure need to be synchronized. The suitable data communication system needs to be selected. Typical SHM system has either the Wide Area Network (WAN) or Local Area Network (LAN) [7]. Large systems are operated with a backbone of fibre optic networks that allow for redundant systems with no data loss [8]. The typical schematic diagram of sensor's and synchronous data acquisition device are shown

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Fig. 1. Physical diagram of sensors and synchronous data acquisition device.

in Fig. 1.

The work presented in this article is a part of a collaborative European research project named Infrastar, receive grant from Marie skłodowska curie, and the objective is to deal with monitoring parameter such as load, temperature and strain measurements for fatigue safety assessment for bridges and wind turbines [9]. Especially, it relates the progress of developing new sensors and a primary data acquisition system for active sensor network, which is capable of detecting structural changes. With these progress model, we want to investigate the outline of this new data acquisition equipment in terms of detection capability and coupled parameters e.g., analog to digital converter (ADC) sample rate and resolution. Moreover, if the correlation between ADC sampling rate and feature detectability is well-known, then this knowledge can use to design improved data acquisition system that estimates the feature (change detection accuracy) and resolution (energy consumption) for a given environment of the ultrasonic active measurement system. This improved data acquisition system can be used for long term SHM system that balance the acquisition parameter related to energy consumption of the sensor network to the related feature accuracy; i.e. the time of active measurements and their ADC settings can be regulated by the acquisition system. The next parts of the paper is organized as follows. In Section II, we introduce the active sensing technology. This gives impression of benefit of using our new ultrasonic sensor. In this section we also present the new data acquisition system that has been used as a prototype and designed for some lab test. In Section III we describe our object (Reinforced concrete beam), experimental setup and analyze the obtained results. The last two paragraph concludes this paper and state our future aspects.

II. ACTIVE SENSING TECHNOLOGY

During decades, active sensing technology such as traditional ultrasonic pulse velocity (UPV) are widely used in civil engineering application to determine material properties as well as to detect defects and crack growth [8]. Traditional UPV shows a few significant disadvantages. The first one is the need of experienced technician, which is sometimes difficult

in practice. The high influence of environmental effects such as temperature, wind and soft material on surface leads to undesirable effects on the sensing accuracy. The sensors are intending for failures or impairment during practical field tests. Consequently, Bundesanstalt für Materialforschung und -prüfung (BAM) and Acoustic Control Systems ® in Moscow designed a new ultrasonic transducer, which can be permanently placed inside the reinforced concrete beam (component of the civil structure) [10] [11]. The main benefit of this sensor is its durability, high sensitivity on monitored certain areas of a structure with a minimum number of transducers.

Fig. 2. Sensor SO807' installed with plastic ring on the rebar.

A. New Ultrasonic Transducer

In our experiment, we use a new ultrasonic transducer “SO807”, which was developed by Russian company located in Moscow in coordination with and solely for BAM Germany [10]. The main part of SO807 transducer is a hollow piezo

Fig. 3. Diffuse ultrasonic signal and its frequency spectrum.

ceramic cylinder (Fig. 2). The primary advantages of this sensor is that it can be worked as a transmitter or receiver

and reciprocally [10]. The additional advantages of this sensor is it can be installed easily during the construction and after the construction (existing structures) also. Fig. 3 shows the amplitude and frequency spectrum of acquired signal from this transducer. The first significant peak frequency is at 55 kHz and the next at 67 kHz, short peaks visible around 50 and 85 kHz. In concrete, most common size of aggregate used is 20 mm, therefore a frequency of 62 kHz relates to a wavelength which is suitable for most aggregates [10]. It is essential to stabilize the position of sensors inside the structure for meaningful data acquisition. Therefore to ensure the sensors will be stable and keep their position during the construction, special plastic parts with different size parameters are printed using customized 3D printer in NeoStrain Fig. 2 company. With these plastic parts, 'SO807' can be easily fixed on the rebar Fig. 2.

B. Data acquisition system

For this novel ultrasonic sensor new data acquisition was designed [Fig. 4].

Fig. 4. Block diagram and component of the Data acquisition system (ultrasonic measurement system).

As 'SO807' can work as a transmitter and receiver at the same time, we can measure n couples of sensors ($(n + 1)$: number of sensors). The multiplexer can be connected to a local computer with an Ethernet cable and a DAQ which is connected to the local computer with a USB cable (for automatic switching between transducer). The measurement system Fig. 4 consists of a PC (application), a digital to analog converter (NI DAQ) with a resolution of 16 bits and

amplifier and pre-amplifier, to which ultrasonic sensors, can be connected via multiplexer. There is the 1st power amplifier (Tx), which amplifies the sine wave for the transmitter from 5V to 150V Fig. 6. The pre-amplifier (Rx) is designed for the analogue receiving signal if it has too low amplitude Fig. 5.

Fig. 5. Schematic of the two stage low noise preamplifier.

For ultrasonic transmission, we generate a signal (62 kHz) using NI 6361 DAQ. A power amplifier (± 80 V) was developed to amplify the signal as shown in Fig. 6. The two stage low noise preamplifier module connected with sensor was designed to receive the signal properly as indicated in Fig. 5. As indicated in Fig. 6, the power amplifier and preamplifier [Fig. 5] is designed using an amplifier IC [12]. We developed an amplifier circuit using a high voltage power operational amplifiers from APEX®. This low quiescent current MOSFET operational amplifier circuit with asymmetrical voltage supply is shown in Fig. 6. This amplifier circuit can operate from supplies around more than ± 150 V. The present system has an amplification of around 19 dB in a band within 1 Hz and 100 kHz. We have designed a printed circuit board with amplifier.

Fig. 6. Ultrasonic transmission amplifier schematic.

A Labview interface program was developed to control the setup and drive the cards. 'NeoStrain@US' is an new application written in LabVIEW to acquire the ultrasonic signal Fig. 7. This application can be install on any computer with Microsoft windows operating system. However, we can modify the configuration to measure the selected sensors or change the measurement parameters like the measure time interval, samples rate etc. The information such as waveform, current sensors being measured during the test shown on the software interface. With this system it is possible to work in pulse-echo and transmission mode. All the parameters can be defined independently for each active channels. The main menu of NeoStrain@US application is presented in Fig. 7. The ultrasonic signal can be generated through analog output (AO) channel of DAQ system, with introducing some parameters such as frequency, transmitting voltage and number of cycles. In the receiving mode, several parameters can be also selected for analog input (AI), for example, filters range, number of channels, number of samples etc. The signals were digitalized using the Nyquist criteria and it is possible to choose the number of samples, the sampling frequency, etc. The acquired files can be stored and read through majority of commercial software for post-processing purposes. The ultrasonic signals can be presented in time and frequency domains.

Fig. 7. Main menu of Labview application for ultrasonic inspection.

III. MEASUREMENT

A. Test Object

The goal of these measurement is to acquire ultrasonic data that can be used to developed new data acquisition system that relates ultrasonic feature with ADC resolution [6]. For this purpose, a $20 \times 20 \times 100$ cm reinforced concrete beam has been cast in the NeoStrain lab for preliminary tests of this novel ultrasonic transducers Fig. 8 and new data acquisition system. Rebar and formwork was manufactured for this meter size beam. Two ultrasonic transducers have been placed with rebar, before casting the beam. Load step were applied in one cycle up to a maximum load of 1 kN.

Fig. 8. Concrete beam and sensor position.

B. Test procedure

The test was performed for 45 minutes. This new data acquisition system used for transmission pulse successively to the transducer 1 (Tx), while the other waves passing through the structure to register in ultrasonic transducer 2 (Rx) receiver and store it in computer hard drive. Static test was performed to locate changes in the structure. For the static test, a load of 1 kN was applied in the middle of the beam at 19 minutes to 24 minutes to classify the load from environmental changes in the beam.

C. Overview of an ultrasonic propagation system configuration

Fig. 9 present the general overview of an ultrasonic measurement system configuration on a meter size concrete beam.. There are four main parts: the DAQ system, power amplifier, preamplifier, embedded transducers, and an application system. The attached transducer, which is embedded inside a concrete structure, is incorporated with the power amplifier and preamplifier to allow the ultrasonic propagation system to inspect large area of the structure. Moreover, the ultrasonic inspection system is operated by the specific application in the computer to perform the wave propagation process on the selected transducer placed in inspection area [13]. In ultrasonic transducer (Tx), the corresponding ultrasonic wave is generated and recorded by ultrasonic receiver (Rx), then digitized in the DAQ board and stored at the local SHM system through the USB communication [14]. The duration of signal 5 ms related to around 20 m of propagation for this mode, allowing many reflections to occur and creating as a diffuse wave [15]. Therefore, the duration of signal is effective to acquire most of the reverberating energy. This active acquisition procedure will stop till the predefined period. In the post processing, the two-dimensional spatial ultrasonic signals are further processed for damage/change evaluation purpose.

D. Detection

In order to illustrate the detection of changes in the meter size beam structure, one feature is computed from the time-

Fig. 9. Overview of an ultrasonic propagation system configuration.

domain signals collected from this beam by one pair of ultrasonic sensors during the experiment.

A simple but valuable methods to relate the structural changes, is calculating the autoregressive (AR) model coefficient between a predicted signal from initial measurement and all consecutive measurement under different operational effects. The AR model methods composed of using the parameters estimated from the baseline signal, and computing the experimental data obtained from the structure [16]. This AR model residual error can be written as:

$$\epsilon(t) = x(t) - \sum_{i=1}^n \alpha_i \bar{x}(t-i) + e_m \quad (1)$$

where $x(t)$ is the measured signal at discrete time index t , and $\bar{x}$ is the predicted signal value. The coefficients of the AR model parameter α_i . e_m is a noise that follows a normal distribution.

IV. RESULTS AND ANALYSIS

The value of acquiring good quality and compatible data is very important for long term monitoring. It is the first parameter we want to sort out, therefore first we investigate the optimal setting for acquiring good quality signal for our application. Hence, it seems hypothetical to go through the optimal settings for our signal, so it is better to understand whether our signal needs some requirements as we are acquiring it much more efficient way. As we know, the resolution, especially sampling rate, has an effect on acquired signal when they are digitalized. If sampling rate is too low, then acquired signal will be distorted and information (feature) will be lost. Nevertheless, if it (sampling rate) is high, then signal may contain high level of noise. And higher sampling rate will increase data size which need significant storage resource, more power and processing time. Therefore, optimal setting for our acquisition equipment is important for management of data. To validate this approach, we record the signal for the one pair of ultrasonic propagation with 14 bits of precision at a 2 MHz and 1 MHz sampling frequency. In post processing, we reduced the sample rate Fig. 10 and investigated the effect on AR coefficient result Fig. 11 a,b,c for given sensor pair. The AR coefficient increase up to a maximum value when the static load is applied in middle of the beam ($t = 21$ minutes). The AR coefficient can separate the load from the environmental effect Fig. 11. During these experiment in the lab, the value of the AR coefficient corresponded to maximum changes in the structure, which is relatively small since the

Fig. 10. Signal at given sampling frequency.

applied load was negligible compare to the strength of the beam. Also, It was found that, the signal sample rate of 1 MHz is suitable for our application but in certain situation we can tune the sampling frequency near to the Nyquist frequency, as long as that sufficient frequency components remain present in the under sampled signal. When the sample frequency is too low, however, the classification fails, as is the case for a sample frequency of 300 kHz. When sampling frequency is close (and under) the Nyquist frequency, the resolution seems to be influence (500 kHz) Fig. 11 c.

Fig. 11. Feature based change detection for a given sample frequency.

V. CONCLUSION

In this paper an experimental prototype system has been presented which allow implementing the diffuse ultrasonic technique for concrete structure. Some preliminary experimental results have been shown using the developed system. A test setup for ultrasonic inspection (record signals) has been used to detect structural changes that are representative for long term SHM application. Using these model, the influence of the sample frequency on the feature extracted from the ultrasonic signal has been investigated. Selecting an relevant sample

frequency and resolution, yields a damage/change detection which is comparable with traditional measurement systems.

VI. FUTURE WORK

In the future, we will use this knowledge to design wireless data acquisition equipment for active measurements, which can scale the energy based on requirements. Later, the effect of additional features (like Differential Curve Length, Normalized mean square error, etc.) from all transducer pairs will be investigated for the localization of operational changes (like cracks). Furthermore, digital noise reduction (with over sampled signals) can improve the detection capacity.

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