Digital Wideband Excitation Technique for Impedance-Based Structural Health Monitoring Systems

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Abstract—**With ever increasing complexity in new mechanical structures, as well as aging structures in operation, locating damage with structural health monitoring techniques is becoming increasingly important. Permanent deployment of structural health monitoring systems is limited by the availability of sensor technology. Previous efforts to miniaturize the hardware required for the impedance method of structural health monitoring resulted in prototypes reliant on a DAC for providing excitation to the structure of interest. In this paper, a new excitation technique using wideband digital signals is proposed to eliminate the power dissipated by a DAC in the system. An experiment is peformed to compare performance of the proposed technique and previous excitation techniques. Results are presented and reveal no loss in damage detection performance while reducing the power dissipation.**

I. INTRODUCTION

As current structures, such as bridges, buildings, and aerospace vehicles, are becoming more complex and larger, advance detection of structural damage is critical. A Structural Health Monitoring (SHM) system enables monitoring of the physical condition of structures and gathers information under various conditions to assist in detecting structural damage.

Impedance based detection is one of the most investigated SHM methods thanks to its potential low-cost implementation and relatively easy sensing technique [1]. Recent research presents a low cost implementation of the impedance based detection method by eliminating a bulky impedance analyzer from the SHM system [2]. Since the impedance based detection method utilizes certain materials that have capability of transforming electrical energy to mechanical energy and vice versa, it can employ Digital-to-Analog Converters (DAC) and Analog-to-Digital Converters (ADC) for actuating and sensing instead of using any expensive physical sensors.

Traditionally, a sinusoidal single tone has been used to excite the structure, and the response is measured over certain frequency range by incrementally increasing the frequency until the entire range is excited. This frequency sweeping can be time and power consuming, especially when taking into account the need to average out background noise. However, large allowance of clock drifting in cheap oscillators make the actual frequency of the excitation tone to shift more for longer excitation periods. Therefore, one has to consider how to compensate the clock drifting for accurate measurement, while also suppressing overall power dissipation.

We previously proposed an impulse-like excitation method utilizing sinc waves, which cover a wide frequency range from DC to very high frequencies depending on DAC speed [3]. Since sinc waveforms contain evenly spaced frequency tones within the target frequency range, the entire frequency range can be swept with a single sinc pulse. The excitation time is then also reduced, resulting in lower power dissipation and decreased clock drifting problems, though repetition is still necessary for higher noise immunity.

In this paper, we present a digital excitation technique utilizing wideband Pseudorandom Noise (PN) sequences to reduce further power dissipation by eliminating the usage of a DAC. Both the sinusoidal sweep and sinc wave methods require a DAC to produce the exact excitation waveform [3]. Note that the DAC is one of the power hungry components and consumes about 17% of the total power according to the measured data from our previous prototype [3].

II. ARCHITECTURE AND OPERATION

A. Overall Architecture

In general, SHM consists of three major functionalities that are signal generation, excitation, and sensing. Typically, a PZT (Lead Zirconate Titanate) piezoelectric ceramic is utilized for excitation in the impedance-based method [4]. PZT transforms electrical energy into physical force, and converts physical force back to electrical energy [5]. As shown in Figure 1, a PZT bonded to a structure reacts to a time varying voltage applied across two faces of the PZT, physically strains, and applies a force to the structure.

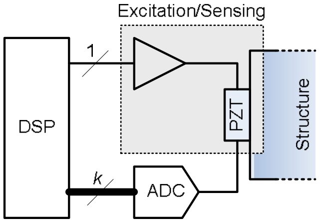

Figure 1 Simplified excitation and sensing block

Since the response of the PZT to a voltage input is the mechanical movement, the interaction between the PZT and the structure can be considered as periodic hammering on the surface of the structure. However, the reaction of the structure due to the PZT excitation can be either constructive or destructive depending on the mechanical characteristics of the structure and many external and internal factors, such as

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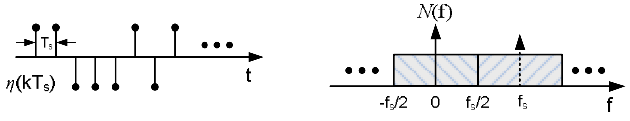
temperature, humidity, and environmental noise. In addition, the environmental conditions of the PZT can also be accounted into the factors affecting the interaction.

ADCs are normally utilized in the impedance-based detection method for recording the electrical response to the mechanical excitation since the mechanical response of the PZT, combined structural interaction, appears as electrical shapes, which is how the method is named as 'impedance-based'. Unlike the sinusoidal and the sinc wave excitations, the proposed method does not require DAC, which is normally located in between a digital signal processing (DSP) unit and an amplifier in Figure 1. The proposed excitation method does not rely on any specific signal shape, but on noise-like signal behavior whose signal shape is not predictable in theory. The excitation and sensing block is simplified in Figure 1 and will be covered in detail later. The absence of the DAC clearly has advantage over the previous methods in regard to the power dissipation.

B. *Digital Wideband Signal Generation*

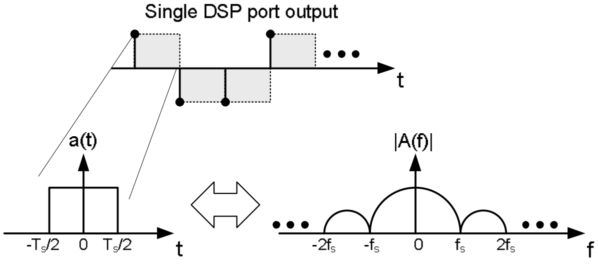
PN sequences are widely used in communication systems in order to widen the spectrums of data signals [6]. Let's assume a discrete-time noise signal $\eta(kT_s)$, where T_s is time space between two consecutive discrete signal points (a.k.a. sampling time), and k is a time index. The noise sequence occupies a bandwidth as wide as the sampling rate f_s, which equals $1/T_s$, around DC. Thus its spectrum $N(f)$ spreads from negative half of sampling rate to positive half of sampling rate and appears at every harmonic of f_s, as shown in Figure 2. The frequency resolution of the PN sequence is determined by the length of the PN sequence so that one can control the sweeping frequency resolution by adjusting the length of the PN sequence in a single trial.



(a) In time domain (b) In frequency domain

Figure 2 Discrete-time PN sequence

However, when a DSP outputs the noise sequence, it applies a zero-order hold to fill out the empty space between two consecutive discrete time points. The time-domain signal shape of the zero-order hold operation is rectangular so that its spectrum is known to have a shape of sinc function, as shown in Figure 3. Therefore, the higher frequency tones experience power decay.



$$a(t)=\begin{cases}1 & (-T_s/2<t\le T_s/2)\\ 0 & \text{elsewhere}\end{cases} \qquad A(f)=\mathrm{sinc}\left(\frac{f}{f_s}\right)$$

Figure 3 PN sequence at the output of DSP

The proposed method adopts a digital up-converting technique to address the power decay problem in higher frequencies. Since the digital PN sequence occupies limited bandwidth, the digital up-converting technique brings the baseband noise signal up to certain center frequency, which is determined by alternating digital sequence as depicted in Figure 4. The actual excitation signal to the structure is also illustrated in Figure 4.

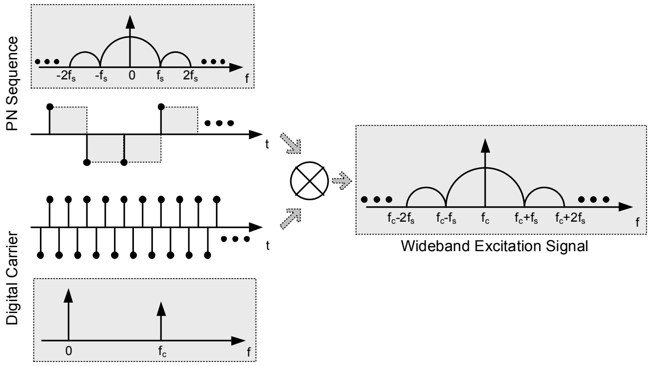


Figure 4 PN sequence upconversion and wideband excitation signal

C. *Excitation and Sensing*

Current systems apply the excitation signal directly to the PZT and sense the reaction of the PZT due to the excitation signal and structural interaction. Variations in impedance are observed by recording the voltage variation across a sensing resistor, which is connected to the PZT in series as described in Figure 5 (a) [1]. However, this formal sensing method with a sensing resistor does not linearly reflect the impedance variation of the PZT from the voltage variation across the sensing resistor due to a voltage dividing effect as seen in equation (1).

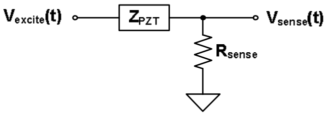
$$v_{sense}(t)=\frac{R_{sense}}{R_{sense}+Z_{PZT}}v_{excite}(t) \tag{1}$$

Z_{PZT} indicates the impedance of PZT. v_{excite} and v_{sense} are the output voltage from DSP and the input voltage to the ADC respectively. Though equation (1) becomes more linear to the variation of Z_{PZT} as Z_{PZT} is greater than R_{sense}, it reduces voltage gain from $v_{exicite}$ to v_{sense}, resulting in a system more sensitive to thermal noise.

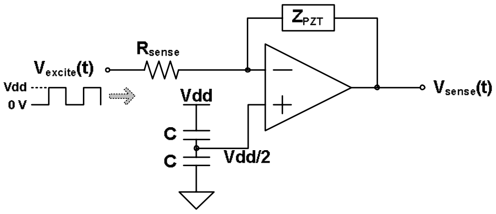
The improved excitation and sensing method is shown in Figure 5 (b). Since the generated wideband signal is digital and swings between ground to supply voltage (Vdd), it contains some DC offset that is about half of the supply voltage (Vdd/2). The DC offset cancellation is achieved by hooking up the positive input end to Vdd/2, so that the need of a comparator to convert uni-polar digital signal to bi-polar signal is eliminated. Note that bi-polar signaling does not contain DC power if the noise signal has zero mean. The configuration of the proposed excitation follows a conventional inverting OP-AMP stage to achieve a linear response to Z_{PZT}. Assuming high enough OP-AMP gain, the gain of the rational amplifier is defined as

$$v_{sense}(t)\approx-\frac{Z_{PZT}}{R_{sense}}v_{excite}(t) \tag{2}$$

Thus, the gain from v_{excite} to v_{sense} becomes simply negative Z_{PZT} when R_{sense} equals 1Ω, which is a highly linear response to the variation of Z_{PZT} and improves overall detection performance. Note that the value of R_{sense} should be appropriately adjusted according to the dynamic range of the ADC.



(a) Passive method



(b) Active method

Figure 5 Excitation and sensing methods

D. *Damage Detection Algorithm*

The traditional impedance-based detection method utilizes an impedance analyzer to measure electrical impedance variation as an indication of the damage on the structure. However, the impedance analyzer is very costly, large, and heavy, which makes this method unattractive for practical SHM systems. Thus, a low-cost impedance-based detection method, which is adapted in our application, was introduced for a compact SHM system implementation [1]. This detection algorithm discerns the ratio of the detection voltage (v_{sense}) to the excitation voltage (v_{excite}) at each frequency component being measured. As indicated in equation (2), the ratio of the two voltages estimates the impedance of the structure, the PZT, and the interaction between them. The detection voltage is digitized through the ADC and averaged for multiple periods to effectively mitigate the background noise. The averaged detection voltage undergoes a Fast Fourier Transform (FFT) for calculation of the ratio between the excitation signal and the detected signal in frequency domain at each frequency. This frequency component ratio is called an impedance signature.

Assuming that the structure is initially in a healthy condition, the first impedance signature is reserved for a reference named the baseline. As new measurements are generated, the impedance signature is updated accordingly and a comparison between the fresh impedance signature and the baseline generates a detection metric, which is an indicator revealing any damage to the structure. The detection metric used is a Root Mean Square Deviation (RMSD) between the real parts of the baseline and instantaneous impedance signature normalized to the mean of the absolute real baseline. The detection metric indicates how much the freshly measured impedance deviates from the reference called baseline. The expression of the detection metric is

$$RMSD = \frac{\sqrt{\dfrac{\sum_{m=1}^{M}\left(\mathrm{Re}\{Z_{baseline}(m)\} - \mathrm{Re}\{Z_{\mathrm{instantaneous}}(m)\}\right)^2}{M}}}{\dfrac{\sum_{m=1}^{M} abs\{\mathrm{Re}\{Z_{baseline}(m)\}\}}{M}} \qquad (3)$$

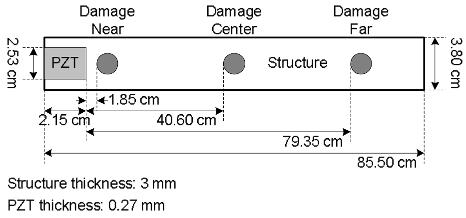
where $Z_{baseline}$ is the baseline, $Z_{instantaneous}$ is the instantaneous impedance signature, and M denotes the number of frequency components in the detection frequency range. Notice that only the real parts of the baseline and the instantaneous impedance signature are used to calculate RMSD because the real part is less vulnerable to temperature variations [4].

When the structure stays in a healthy state, the variation on the RMSD value will remain under a certain threshold level. Upon occurrence of damage on the structure, the fresh impedance signature diverges from the baseline. Therefore, the RMSD value increases, and the system indicates damage to an end user if the RMSD value exceeds the pre-determined threshold level.

III. PERFORMANCE ANALISYS

In order to verify and evaluate the operation of the proposed excitation technique, a set of measurements has been performed. Figure 6 (a) shows the test structure with a PZT bonded to one end. In the experimental setup, we simulated damage to the beam by applying two magnets to either side of the beam. Using magnets attracted through the beam thickness, the damage is non-permanent and repeatable. The magnets are applied in near, center, and far locations with respect to the PZT, and the exact damage locations, along with detail dimensions of the test structure, are illustrated in Figure 6 (b).

(a) Structure with a damage



(b) Test scenario and dimension

Figure 6 Test structure

The system used for evaluation is assembled from three TI boards, a TMS320C6713 DSP evaluation module (EVM), an ADS8364 ADC EVM, and a TLV5619 DAC EVM, for maximum flexibility in the development stage. Each EVM is stackable and connected via general purpose ports so that any required modification on the system is easily achievable. The evaluation system is shown in Figure 7.

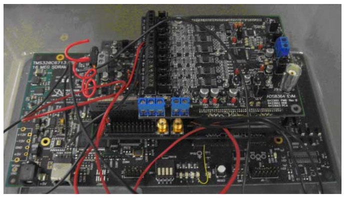


Figure 7 Evalutaion system

The impedance measurement frequency range is from 100 Hz to 100 KHz with a frequency step size of 10 Hz, and a HP 4194A impedance analyzer performs the impedance measurement of the PZT bonded to the structure. Measurements were taken on both the healthy and damaged structures with damage locations seen in Figure 6 (b). To alleviate noise effects, 35 measurements were taken, and the maximally occurring value was selected at each frequency through a histogram analysis. Values of resistance, the real parts of the measured impedance, at four different structural conditions are shown in Figure 8. After analysis, it is observed that the frequency range from 12 KHz to 20 KHz is highly sensitive to excitation, and damage at each of the locations alters the resistance at certain frequencies by arbitrary amounts.

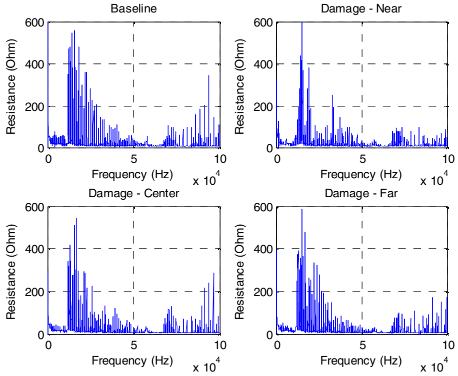


Figure 8 Measured impedance at different structural conditions

Based on this measured impedance, an experiment using the evaluation system shown in Figure 7 has been performed with the following specifications: The detection frequency range is from 12 KHz to 20 KHz, where the structure is highly sensitive to the excitation, and the frequency resolution within the detection frequency range is 125 Hz. The excitation digital wideband noise signal is produced by being up-converted at a center frequency of 16 KHz, and the signal is designed to occupy a 10 dB bandwidth within the measurement frequency range as shown in Figure 9. An Anritsu MS2665C performed spectrum analysis of the resulting digital wideband excitation signal.

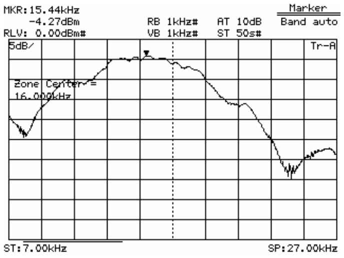


Figure 9 Digital wideband excitation signal in frequency domain

As summarized in Table 1, the comparison of the measured RMSD values for the digital wideband and sinc wave excitation methods clearly indicates that the proposed digital wideband excitation method reveals the structural defects to a higher degree. This increased performance is due to positive gain and the linear response to the variation of the PZT as discussed in Section II.C. One can notice that the RMSD values measured with the sinc wave excitation method are very small, so that quantization noise added by an ADC and the limited numbering resolution in a DSP can affect the detection performance.

TABLE I. DAMAGE DETECTION PERFORMANCE COMPARISON

Damage Location	**Proposed Digital Wideband**	**Sinc Wave**
None (Healthy)	104.36	0.0571
Near	1525.49	1.1267
Center	1150.59	0.9713
Far	911.61	0.9256

The most significant advantage of the proposed wideband excitation technique over the previous sinusoidal or sinc wave excitation methods is the power reduction due to the elimination of the DAC. This decrease in power is achieved without any degradation of performance. The power consumed by the DAC, which was 17% of the total power dissipation in our test setup shown in Figure 7 [3], can be completely removed. Also worth mentioning are two other affiliated advantages: lower hardware complexity and decreased memory requirement. A byproduct of using a digital excitation signal is that less memory is required as compared to sinc wave excitation. The sinc wave excitation method should store at least one period of the pre-calculated excitation signal in memory, and each excitation sample requires multiple bits as small as a resolution of the DAC to represent the exact signal voltage level. Furthermore, the reduced bus width, which is a result of not needing a DAC in the proposed wideband method, simplifies the system complexity in addition to the power benefits.

IV. SUMMARY AND CONCLUSION

We have presented a digital excitation technique utilizing wideband PN sequences to reduce power dissipation by eliminating the usage of a DAC. Compared to the impulse-like sinc wave excitation employed in our previous prototype, the proposed wideband excitation technique reduces the power dissipation by 17%. A noise-like digital random sequence, instead of a deterministic analog voltage waveform, is also advantageous in terms of memory requirements. By relaxing the memory requirements, we can obtain additional power savings by eliminating the memory access at excitation, as well as the reduced hardware complexity. The measurement results obtained from an evaluation system proved that the proposed digital wideband excitation technique provides an equivalent performance to the analog sinc wave excitation.

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