SHM ultrasound system for damage detection in composite material

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Abstract

The structures made of composite material show two well-known difficulties for monitoring systems using ultrasonic waves. The first one is the need of a signal of such power that it can excite properly the piezoelectric transducer stuck on composite material. In fact, the composite material shows high mechanical resistance and high acoustic impedance. This paper shows two ways to increase the power given to piezoelectric transducers for ultrasound tests: to increase the current and/or the voltage applied to the transducers. The second difficulty is the need of high sensitivity electronic systems due to the high power loss that ultrasonic waves suffer when they are propagating on a structure of composite material. The paper introduces the acquisition of signals from piezoelectric transducers arranged on composite material during the test set. The tests summarized in the paper quantify the attenuation of ultrasonic waves with the distance in composite material structures.

1. Introduction

Composite material is the term that defines the combination of two or more materials to obtain a new material with improved features. Hence, there is a wide range of composite materials that can be found in many applications as aviation, aerospace or railway applications. The health of structures in such applications must be taken into account and regularly analyzed to avoid accidents [1-3]. Structural Health Monitoring (SHM) systems carry out non-destructive tests on many types of structures to analyze their damage level due to impacts, fatigue or aging, for example [4]. Since some of the structures under test with SHM systems are made of composite material, SHM systems must deal with composite material. Usually, SHM systems spread Lamb waves along the structure and, according to the processing of the signals received in some specific point(s), the flaws and/or damage in the material are identified [5]. However, the internal structure and features of the composite material, i.e., its hardness, dispersion, high attenuation in some propagation directions,… make the issue of SHM systems applied to composite materials a hot research topic [6,7].

There are some models to define the electric performance of a piezoelectric piece of material [8-11]. Usually, the piezoelectric transducer utilized in SHM systems is glued
to the structure under test and, therefore, the model that defines the mechanical performance is modified. The resultant model of adding the circuit to generate the excitation signal to the piezoelectric transducer is very complex. However, there are some clear features to take into account. From the electrical point of view, the model includes a component with inductive impedance, and it means a higher power requirement when the frequency increases. Composite material also shows high acoustic impedance. In addition, the propagation of acoustic waves is not uniform in all directions and, as a result, some propagation preferential directions can be defined. The frequency response of the composite material is like a narrow band-pass filter. Additionally, the frequency response of the output amplifier of the SHM system must be taken into account. It usually is like a low-pass filter with a cut-off frequency of a few kHz.

As a summary, it is necessary to apply high excitation power level to piezoelectric transducers on composite material samples. The power level must be increased when the operation frequency increases.

There are two ways to boost the power in the transducers: to increase the current provided by the signal generator or to increase the voltage of the generator. Section 2 describes the instrumentation and materials for the tests. Section 3 shows the setup and discusses the results of the analysis of the increase of current with a signal generator. Section 4 describes the setup and discusses the results of the options considered for voltage boost in piezoelectric transducers. As a final point, Section 5 summarizes the conclusions.

2. SHM ultrasound system

The two ways to obtain more power in the transducers were considered to carry out the SHM tests on the composite material sample. Two SHM ultrasound systems (SHMUS) with all the capabilities to perform ultrasonic tests on structures autonomously were used in the tests. The first one is PAMELA III [12], a SHMUS that generates and acquires signals through 12 channels. The second one is PAMELA IV [13], the SHMUS that integrates the electronic circuitry to control simultaneously up to 18 signal generation/acquisition channels (Figure 1). A set of new signal generators that provides higher power level than regular SHM systems is included in the new design of PAMELA.

The signals generated in the SHMUS are applied to the piezoelectric transducers stuck on the structure. The transducers convert the signals into ultrasonic waves that propagate along the structure. Any damage in the structure will change the shape of the ultrasonic waves that are converted into electronic signals with the transducers. PAMELA acquires these signals to analyze the structure.
Two types of signals are considered in the tests: sinusoidal waveform (see Figure 2) and Hanning-windowed sinusoidal waveform (see Figure 3). The figures show the signals used in the test in both time and frequency domain. Even though the amplitude in time domain is smaller for the windowed waveform, the energy for the Hanning-windowed sinusoidal waveform is better focused around the oscillation frequency.

The piezoelectric transducer SMD07T02R412WL from STEMiNC [14] is included in the tests. Its main features are summarized in Table 1.
Figure 3. Oscilloscope screen capture for the Hanning-windowed sinusoidal wave form generated at 300 kHz with PAMELA IV applied to composite material in time and frequency domain.

<table>
<thead>
<tr>
<th>Mode vibration</th>
<th>Radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric material</td>
<td>SM412</td>
</tr>
<tr>
<td>Dimensions</td>
<td>7mm diameter x 0.2mm thickness</td>
</tr>
<tr>
<td>Resonance frequency</td>
<td>300 KHz±10 KHz</td>
</tr>
<tr>
<td>Electromechanical coupling coefficient</td>
<td>≥55%</td>
</tr>
<tr>
<td>Resonant impedance</td>
<td>≤10.0 Ω</td>
</tr>
<tr>
<td>Static capacitance</td>
<td>3000pF±15%@1kHz</td>
</tr>
<tr>
<td>Test condition:</td>
<td>23±3°C 40~70% R.H. LCR meter at 1KHz 1Vrms</td>
</tr>
</tbody>
</table>

3. Increase of the current signal generator

The first tests are carried out with the set-up in Figure 4, which includes a structure made of composite material, an oscilloscope, a piezoelectric transducer and a SHMUS. Excitation signals for the piezoelectric transducers are generated with the mentioned two SHMUS and at different frequencies. PAMELA III includes regular operational amplifiers at the output stage. PAMELA IV includes a more suitable design of the output stage for piezoelectric transducers.

Figure 5 shows the signal generated and the signal acquired in the test set-up shown in Figure 4. As it can be seen, the first one’s amplitude is 40 V and the second one’s amplitude is 28.38 mV.

Figure 6 summarizes the results (peak-to-peak voltage value) measured in the oscilloscope at different frequencies with the two SHMUS considered in the tests.
The regular operational amplifiers at the output stage cannot manage the power requirement at higher frequencies due to the inductive load effect of the piezoelectric transducer. As a result, the amplitude of the voltage provided by PAMELA III decreases when the frequency increases. On the other hand, the specific design of the output stage of PAMELA IV can handle such voltage requirement and shows an acceptable decrease with the frequency of the voltage applied to the transducer. It is important to be sure that the power applied to the piezoelectric transducers in the frequency range of interest is enough for the purposes of the SHM tests.
4. Increase the voltage amplitude of the signal generator

The goal of the tests is to check the viability of increasing the amplitude, consequently the power level, of the surface waves throughout the composite material sample with just one SHMUS. There are two ways to achieve it: apply the output of the SHMUS to an array of close piezoelectric transducers, or apply the sum of several output signals to a unique transducer.

Figure 7 shows the two set-ups considered to check the both ways to increase the applied power. The output signal of each channel in the first set-up is applied to each one of the piezoelectric transducers of the array, which are placed in a line. This way, the acoustic power given by each channel is summed in the direction perpendicular to the positioning line of the transducers. In the second set-up, the voltages are summed before the electric signal is applied to the unique transducer. The breaking voltage of the transducer is taken into account not to apply higher voltage to the component.

Figure 7. Set-up #1 (left) to test the increase of the amplitude of the acoustic wave when using three piezoelectric transducers and Set-up #2 (right) to increase the voltage applied to a unique piezoelectric transducer.
The tests consist of performing the SHM tests as listed in Table 2. The distance between the piezoelectric transducers in the array, i.e., A, B and C transducers, is set at 9 mm. The distance between the acoustic wave emitter(s) and the closest receiver (node D) is set at 40 cm. The furthest receiver (node E) is placed at 80 cm from the emitter(s). The excitation signal generated in PAMELA is a sine wave that lasts 3.5 cycles, whose frequency is 300,000 Hz, and the amplitude 48 V per channel. PAMELA acquires signals at 60 Msps per channel.

The composite sample is an anisotropic material that provides privileged directions for the propagation of acoustic waves. However, to get away from the best case in composite material, the direction of wave propagation considered in the tests is not the privileged one.

<table>
<thead>
<tr>
<th>LABEL</th>
<th>TX channel</th>
<th>TX (PZT)</th>
<th>RX channel</th>
<th>RX (PZT)</th>
<th>Set-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONE SINGLE</td>
<td>2</td>
<td>B</td>
<td>4, 5</td>
<td>D, E</td>
<td>1</td>
</tr>
<tr>
<td>TWO SINGLE</td>
<td>1, 2</td>
<td>A, B</td>
<td>4, 5</td>
<td>D, E</td>
<td>1</td>
</tr>
<tr>
<td>THREE SINGLE</td>
<td>1, 2, 3</td>
<td>A, B, C</td>
<td>4, 5</td>
<td>D, E</td>
<td>1</td>
</tr>
<tr>
<td>ONE DOUBLE</td>
<td>1, 2</td>
<td>B</td>
<td>4, 5</td>
<td>D, E</td>
<td>2</td>
</tr>
<tr>
<td>TWO DOUBLE</td>
<td>1, 2, 3, 4</td>
<td>B, C</td>
<td>5, 6</td>
<td>D, E</td>
<td>1</td>
</tr>
<tr>
<td>ONE TRIPLE</td>
<td>1, 2, 3</td>
<td>B</td>
<td>4, 5</td>
<td>D, E</td>
<td>2</td>
</tr>
</tbody>
</table>

For instance, some of the results for the test named one double are shown in Figure 8. The voltage amplitude generated and applied to the piezoelectric transducer is increased. If the amplitude in Figure 5 is compared to the one in Figure 8, the amplitude increase in the excitation voltage applied to the piezoelectric transducer turns into proportional amplitude increase of the voltage acquired from the transducer. More specifically, when one double type of test is considered, 74.37 V are generated in the SHMUS to apply to the emitter transducer and 51.74 mV are acquired from the receiver transducer.

![Figure 8. Generated (yellow) and acquisition (green) signals in the oscilloscope case one double.](image-url)
Figure 9 summarizes the results of the tests for the sample made of composite material. The set of figures focuses on the representative part of the acquired signals, similar to the green signal in Figure 8. Two or three signals are included in each figure for convenience. The figures on the left correspond to the signal received at 40 cm. The figures on the right correspond to the signal received at 80 cm.

Figure 9. Results of the tests for the composite material sample. The following excitation situations are considered: One single, Two single, Three single, One double, Two double, and One triple. The figures on the left show the signals received at 40 cm for some situations. The figures on the right show the signals received at 80 cm.

Figure 9(a) and Figure 9(b) demonstrate that the signal received in the transducer is almost the same at 40 cm and 80 cm distance when the output power in three channels is applied to a unique transducer or to a set of three transducers.
Figure 9(c) and Figure 9(d) show the way the amplitude of the received signal increases when the power transmitted through one, two and three channels is applied to one, two and three transducers. As shown, the more power applied the merrier.

Figure 9(e) and Figure 9(f) show the way the amplitude of the received signal increases when the power transmitted through one, two and three channels is applied to a unique transducer. As shown, the more power applied the merrier.

When Figure 9(c-f) are compared, it can be seen that operating with more transducers to apply power to the sample material provides slightly better results in the receiver transducers at 40 cm and 80 cm.

Figure 9(g) and Figure 9(h) demonstrate that the power transmitted through four channels is applied to two transducers provides bigger amplitude in reception when compared to the power transmitted through three channels is applied to three transducers.

5. Conclusions

The paper shows and discusses the results of the SHM tests performed on composite material. It demonstrates that PAMELA SHM™ carries out SHM tests on composite material samples satisfactorily, i.e., the amplitude of the generated signal that is applied to piezoelectric transducers keeps constant with the frequency.

The multiple differential isolated output channel feature of PAMELA eases the combination of more than one channel to apply it to more than one transducer. This way, voltage high amplitudes can be applied to the transducers. All the voltage values applied to each piezoelectric transducer in the tests were below the breaking voltage of the transducers.

It was shown that applying three channels in phase to a unique transducer and applying those channels to three close transducers placed in a line provide similar results in the receiver transducers placed at 40 cm and 80 cm along the perpendicular line.

The feature of PAMELA SHM™ that gives the chance to apply different generated signals (same amplitude and frequency, but different phase) to transducers eases the beamforming SHM test technique. This way, the energy provided by the SHMUS is focused in one specific direction upon our needs. This is a future work line.

As a summary, the paper shows that the high amplitude generated and applied to transducers as well as the high reception sensitivity of PAMELA SHM™ gives the chance to operate on composite material.
References