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A MULTIFUNCTIONAL DEVICE FOR MULTI-CHANNEL EMI AND GUIDED WAVE PROPAGATION MEASUREMENTS WITH PWAS

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ABSTRACT

This paper presents a multifunctional device enabling multichannel-measurements on piezoelectric elements and supports impedance and wave propagation measurements as well as the recording of additional information about environmental conditions within one experimental setup. This way of data acquisition enables the possibility of producing automated SHM systems according to the specific needs of the monitored structure including sensor assessment. A description of the hardware and software used in the process of data collection is presented and its applicability is demonstrated in some exemplary applications.

KEYWORDS : *Structural Health Monitoring, Measurement Device, Electro-Mechanical Impedance, Acousto-Ultrasonics, Signal Processing*

INTRODUCTION

In structural health monitoring (SHM) several steps like operational evaluation, data acquisition, feature selection and decision making are necessary for the detection, localization and quantification of defects as well as a possible prediction of remaining life time [1]. A promising research area in SHM applications uses a transducer network, consisting of piezo wafer active sensors (PWAS) for: guided wave inspection (GW), also called acousto-ultrasonics, and electro-mechanical impedance testing (EMI). For these two methods a variety of possible evaluation techniques and deployments are available (e.g. [1, 2, 3]). What is common for all applications is the need of taking a lot of data possibly using different configurations of the transducer network. For many guided wave approaches e.g. a round-robin procedure is necessary, where each transducer acts once as an actuator and all other transducers in turn as sensors. Commercially available equipment for data acquisition is often limited, because only one of the methods, GW or EMI, is supported. Moreover the bandwidth and the number of measurement channels are restricted, which makes data acquisition a time consuming task. Only with advanced data post-processing, fusion and condensation, these flaps can be corrected.

It has been shown that environmental conditions, such as temperature variations, play an important role, often making their recording and compensation mandatory [4]. Usually this is hardly possible with only one measurement device. To deal with the influence of environmental conditions, in many cases a series of baseline measurements are necessary to cover e.g. the whole temperature range for later comparison with current measurements.

To enable a convenient experimental investigation in a feasible short time, it is useful to combine these specific needs in one measurement device. This should make automated inquiry possible and needs to be affordable in price and portability. In this paper, the PZT Inspector, which is a multifunctional device enabling multichannel-measurements on piezoelectric elements, will be presented (Figure 2 a)). This integrated device supports impedance and wave propagation measurements as well as the recording of additional information about temperature within one experimental setup. It demonstrates the possibility of producing automated SHM systems according to the specific needs of the monitored structure. For example, this can include the combination of a guided wave approach for structural damage detection similar to [2], and an impedance based procedure for integrated check of the used transducers similar to [3]. Its requirements and specification are described in section 1. A description of the hardware and software used in the process of data collection is presented in section 2 and 3. Its applicability is shown in some exemplary applications, before stating the final conclusions.

1 REQUIREMENTS AND SPECIFICATION

During the development of the PZT Inspector several requirements are needed to be fulfilled. They arise from the specific needs apparent in SHM, as well as from disadvantages, present in former experiments. The PZT Inspector should:

- enable the data acquisition for a whole sensor network. As the number of implemented PWAS is quite diverse, a number of 32 PWAS channels (expandable) has been chosen, making the deployment for many investigations possible.
- support two different experimental operations - the measurement of the EMI and the excitation and sensing of guided waves, propagating through the monitored structure.
- be portable and able to be power-supplied by USB connection to ensure the deployment in any kind of environment when only a Laptop is available.
- enable temperature measurement during data acquisition.
- be a low cost device for experimental investigation in SHM.

For the realization of the different operations it is necessary to have a signal generator and a data acquisition device. Moreover some sort of data selection and channel switching is mandatory to secure mobility and price requirements. Four different modes of operation have been implemented: (1) Impedance mode, (2) Wave propagation mode, (3) Temperature measurement mode and (4) Halt mode.

The temperature measurement mode should work parallel to the other modes. When using the temperature mode, regardless what else is measured at the same time, the temperature is measured with the analog temperature sensors TMP37. The device will read the specified temperature channel, convert it to digital format and send it to the PC. This mode could be operated alone, or at the same time with the impedance mode or with the wave propagation mode. The halt mode secures minimal energy supply when no measurement takes place. This is specifically important to secure minimum energy consumption.

2 HARDWARE

The PZT Inspector, indicated as (1) in Figure 1, satisfies the specific requirements with the help of three hardware elements: control board, handyscope and HUB. The low lost control board (2) is used to switch between the abovementioned four operating modes. The handyscope (3) is a portable 50MS/s instrument from TiePie Engineering with two measuring channels and one output, which is used as signal generator and data acquisition device. The HUB (4) enables communication with the PC through one USB port.

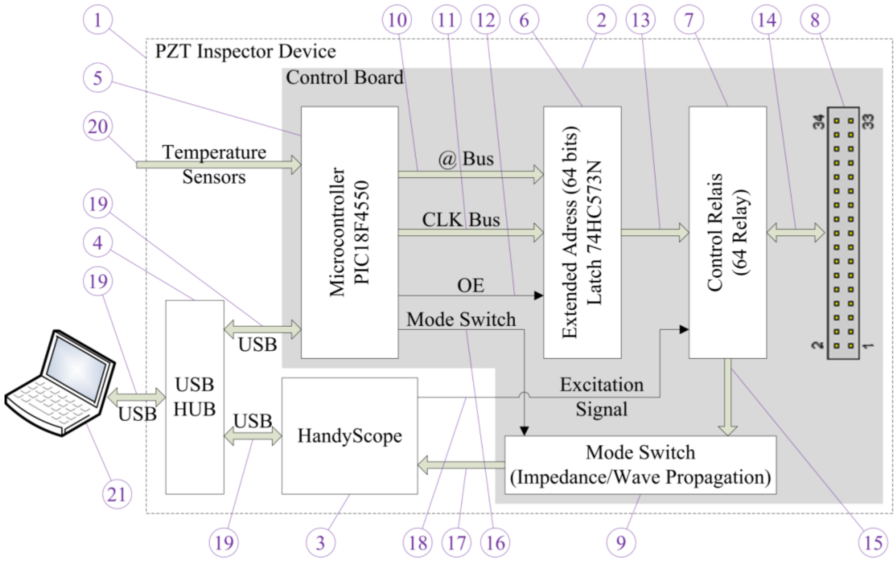

Figure 1: Structure of the PZT Inspector and the control board inside

The control board(2) consists of the following items:

- Microcontroller(5) from Microchip company, equipped with a specific firmware to handle USB communications and to respond to PC requests. The microcontroller enables the requested operating mode(s) on the board. In addition it handles temperature sensor signals, and analog to digital conversion.
- Extended address block(6), which consists of eight latches, and provides 64 internal memory bits. In addition to a clock input(11) that is used to load data from an address bus(10) into the latches internal memory, this block(6) has an “output-enable” gate called OE(12) that enables the stored memory values to appear on the outputs(13).
- Control relays(7), which consist of a set of identical 64 relays from Meder, type MS05-1A87-75D. 32 relays are used to deliver the excitation signal(18) generated by the handyscope(3) to the appropriate sensor. The other 32 relays are used to deliver the appropriate sensor signal to the handyscope input via the mode switch(9). The relays are switched on and off according to the values at the output of the extended address block.
- PCB Connector(8) with 34 pins. The first 32 pins are used to deliver signals from and to piezoelectric elements and the last two pins are connected together to the common ground line of all piezoelectric elements.
- Mode switch(9), which consists of two different relays from Meder, the first one is type MS05-1A87-75D, and the second one is type DIP05-1C90-51D. This block is used to switch the board between impedance and wave propagation modes.
- Address bus(10), which is an eight bit bus, used by the microcontroller(5) to provide input data for each latch in block(6).
- Clock bus(11), which is an eight lines bus, where each line is connected to the clock input of one latch in the address block(6). The microcontroller gives a clock signal on one line to load the current data, present at the address bus(10), to the appropriate latch. The microcontroller repeats the same process till all corrected data are loaded into the block(6).
- Output enable gate “OE”(12). All latches in the block(6) have an output enable gate. These are connected together and controlled by the microcontroller through OE. When the microcontroller loads all data to the latches memory inside the block(6). The OE is enabled and the stored data in the latches memory will be present at the output(13).
- Output bus(13), which is a 64 lines bus, and connects each memory bit in the block(6) to the appropriate relay coil. This enables controlling of all 64 relays together at the same time separately.

- Piezoelectric element lines(14) are represented by a 32 lines bus, which connects the output of each two different relays to one pin at the connector(8).
- Main signals bus(15) is used to receive the sensor signals between the mode switch block(9) and the relays block(7).
- Mode switch gate(16), used to deliver information, on which mode (wave propagation / EMI) should be active, from the microcontroller⑤ to the mode switch(9).
- Handyscope bus(17) is used to deliver signals between handyscope(3) and the mode switch block(9).
- Excitation signal connection(18) is used to deliver the excitation signal from the handyscope to the control relays block(7).
- USB bus(19), used for USB communication for both, handyscope and control board.
- Temperature sensors bus(20), used to power the temperature sensors, and as input for incoming temperature measurements.
- PC(21) with adequate hardware and suitable software to run the device.

2.1 Impedance Mode

Selecting the impedance mode drives the excitation signal from the handyscope output to the selected output port, which is one of the first 32 relays. The two input channels of the handyscope are connected in order to measure the sent excitation signal and the response of the excited PWAS that is passed back to the handyscope through the second 32 relays. The operating principle is similar to the measurement circuit proposed by Peairs [4]. A sketch is depicted in Figure 2 b). By recording the Voltages V_{in} and V_{out} provided that the ohmic resistance R is known, the electro-mechanical impedance can be calculated. For the PZT Inspector software the default excitation signal for the impedance method is a frequency sweep, where chirp rate, start and end frequency can be chosen. Since the handyscope has limited on-board memory, a wide frequency range can be scanned by splitting up the frequency range and automatic data fusion of the sampled measurements. Due to the high sampling rate of the handyscope (max. 50 MHz) also high frequency ranges can be investigated e.g. for sensor fault detection.

Figure 2: a) PZT Inspector, b) measurement circuit used for impedance measurements

2.2 Wave Propagation Mode

When the wave propagation mode is enabled, the board gates the excitation signal from handyscope output to the chosen actuator ($i \in 1 \dots 32$). Also the board drives the response signal from the chosen sensor ($j \neq i,\ j \in 1 \dots 32$) to the appropriate input in the handyscope. The device in general enables the use of a variety of excitation signal types. The accompanying software provides sinusoidal tonebursts from which carrier frequency and number of cycles as well as window type for windowing can be varied. In parallel, both modes support temperature measurements.

3 SOFTWARE

The PZT Inspector is provided with user-friendly software, developed in MATLAB®. For autonomous, case based measurements, a high amount of data has to be managed. Therefore a project oriented data management is placing and saving new measurements according to their measurement mode in a project folder.

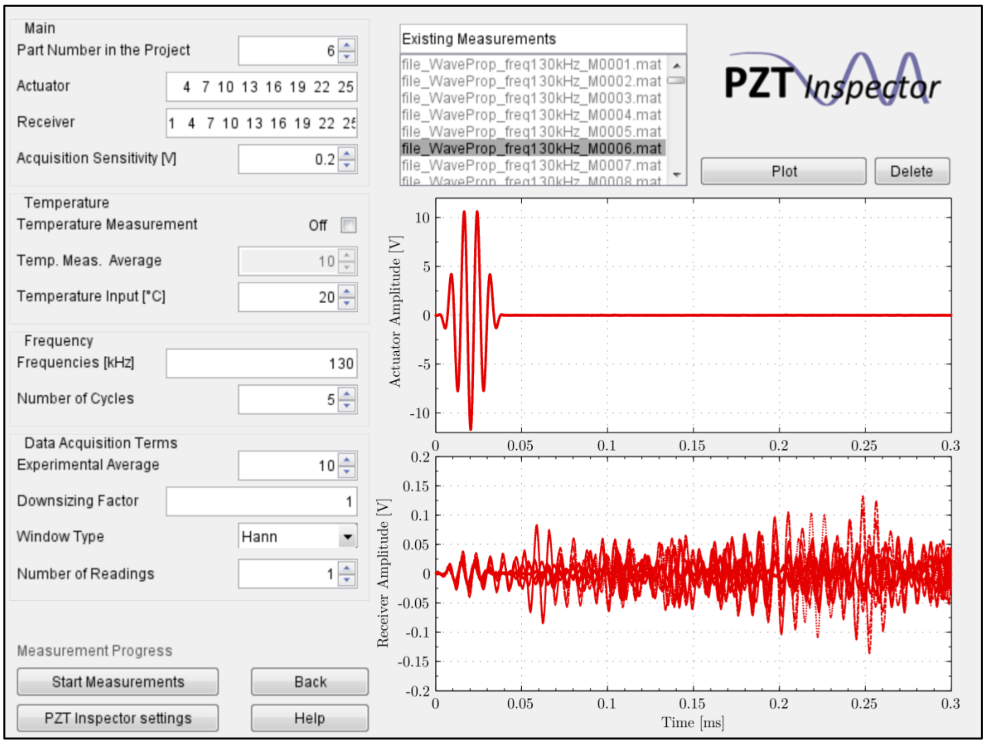

Figure 3: Graphical user interface for the operation of wave propagation measurements, excitation signal and receiving signals are displayed

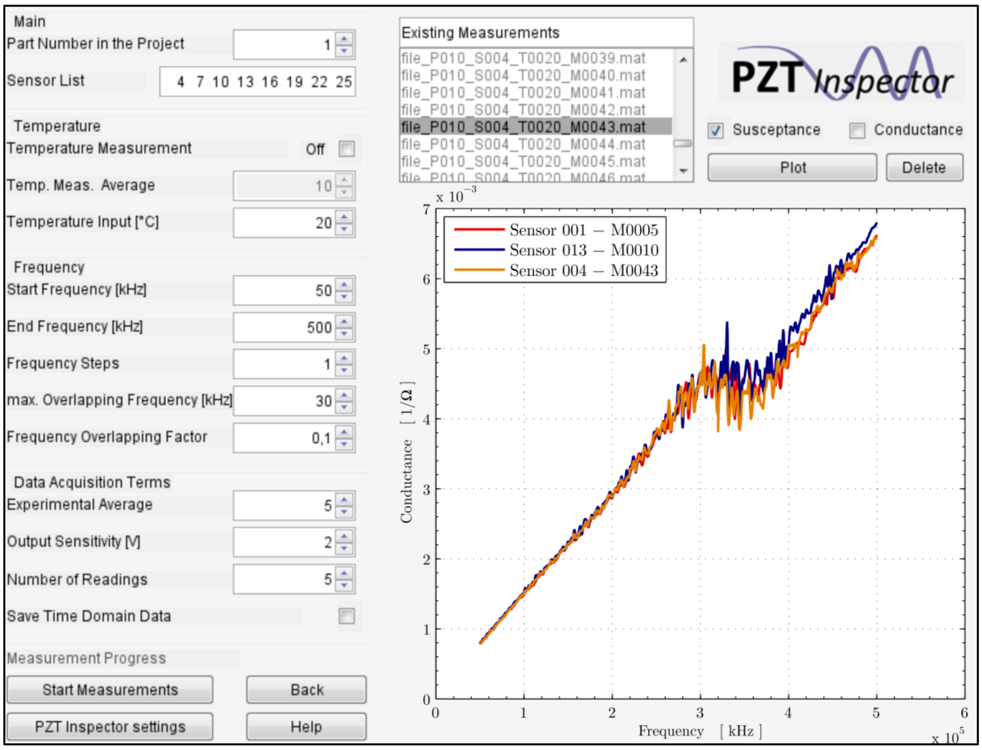

Figure 4: Graphical user interface for the operation of impedance measurements

Meaningful names make it easy to work with the recorded data. Moreover, it is necessary to enable intuitive handling. Therefore a graphical user interface enables the easy input of necessary parameters (e.g. mode, wave package parameters, sensor-actuator combinations, frequency range). For the visual check of the measurements the user interface provides a plot area. Data are saved within MATLAB format to enable easy manipulation for further data processing. The data acquisition windows of this graphical user interface for both operating modes are depicted in Figure 3 and Figure 4.

4 APPLICATIONS

4.1 Guided Waves Based Inspection

The PZT Inspector is used for continuous guided waves based inspection of an isotropic structure. The non-convex aluminium plate depicted in Figure 5 a) has a thickness of 1.5 mm and consists of 14 circular PWAS. By means of the proposed device it is possible to measure all transmitter-receiver pairs in a round-robin fashion without manual intervention. The time interval between two consecutive round-robin measurements has been defined by 30 minutes. A temperature sensor mounted on top of the plate measures the surface temperature.

This information is combined with the location of the PWAS and the sensor responses in a container file for further signal and image processing. The excitation signal is a Hann-windowed toneburst with five cycles at a carrier frequency of 380 kHz that enables an S_0-mode dominated experiment.

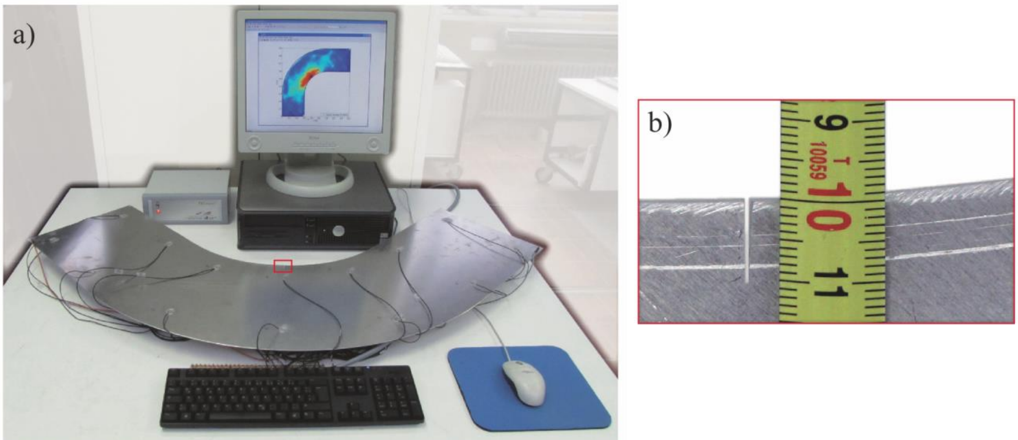

Figure 5: a) Experimental setup for guided waves based inspection, b) Artificial damage of 10 mm, inserted at the inner radius of the structure to simulate structural degradation similar to fatigue crack

The temperature effect has been excluded for the image processing part by selecting only those measurements that have temperature differences < 0.1°C. Otherwise coherent noise occurs in the sensor recordings, as e.g. shown in [5] so that damage localization based on differential processing can fail. An artificial crack with a size of 10 mm, shown in Figure 5 b), has been inserted at the inner radius of the structure to simulate structural degradation similar to a fatigue crack. The well-known delay-and-sum (DAS) method has been employed in the post processing to project the sensor signals on the plate's topology [2]. The imaging result is shown in Figure 6 a), where the highest intensity occurs exactly at the point where the damage has been introduced. By means of this result, it is demonstrated that the PZT Inspector can be used effectively for guided wave based damage localization in SHM applications.

On top of that, we are able to show the impact of a sensor failure with respect to the sensor signals by means of Figure 6 b). This example shows a partial and not a total sensor failure. A significant drop in sensor voltage occurs when the transducer is destroyed. This leads unavoidably to a false indication of structural damage and underlines the importance of monitoring the transducer functionality in SHM systems. The PZT Inspector is able to monitor the health status of the PWAS so that the latter false indications can be avoided. This represents an important step towards more reliable SHM systems.

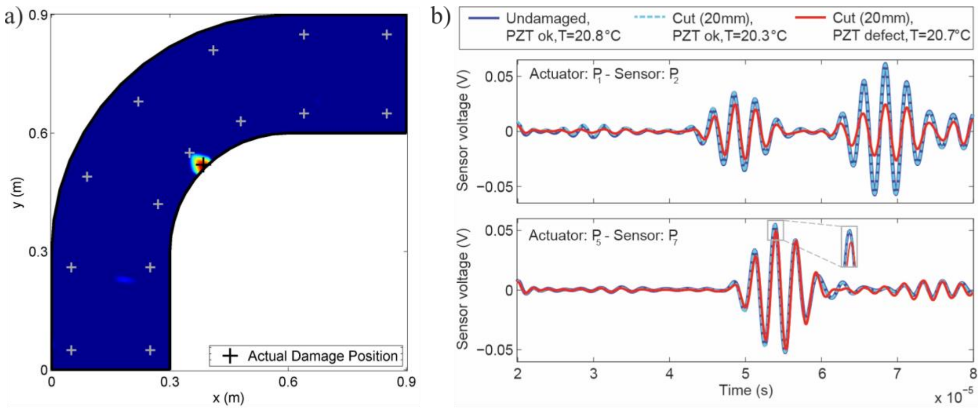

Figure 6: a) Imaging result, b) Wave propagation raw data

4.2 Electro-Mechanical Impedance Measurements for Check of PWAS

To show the applicability for EMI measurements different sensor faults for PWAS are demonstrated within a simple experimental setup. Nine PWAS of type PIC151 from PI Ceramic GmbH are bonded with Z70 superglue on a rectangular plate (400 mm x 400 mm) with a thickness of 1.5 mm. With the help of the PZT Inspector, in total more than 1800 EMI measurements have been taken to investigate the effect of different chemical and environmental treatments on the PWAS. The use of the PZT Inspector eases the experiments execution especially regarding consumed time. Three treatments and their influence on the EMI are shown here:

- Heat treatment (250°C – 10 minutes partial heat flux)
- Partial cut
- Treatment with chemical liquid (Dimethyl Formamide) to produce debonding

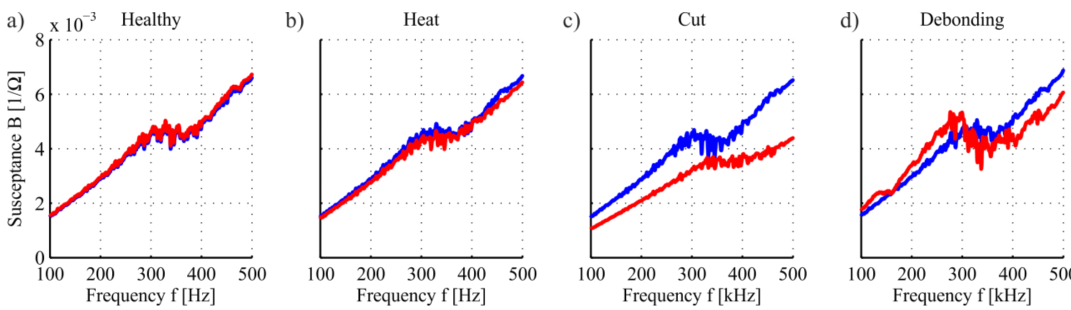

Figure 7: Susceptance spectra of bonded PWAS in different health conditions, a) Healthy, b) Heat, c) Cut, d) Debonding

The susceptance spectrum as imaginary part of the reciprocal of the impedance has shown to be a good parameter for monitoring the PWAS condition (e.g. [6], [3]). The raw susceptance spectra are shown in Figure 7. While the heat treatment shows negligible effect, the cut, as well as the chemical treatment, changed the susceptance spectrum. For the cut a decrease of susceptance slope is visible, whereas the general appearance is quite similar. For the debonded PWAS the susceptance slope is increasing only slightly, whereas the general appearance especially within the frequency range around 300 kHz changes significantly.

The implemented two modes of the PZT Inspector enable guided wave measurements along with the impedance measurements within the same experimental setup. These show a decrease of amplitude for the case of cut and an increased oscillating time for the case of debonding. Therefore, guided wave measurements confirm the results of **the** EMI measurements.

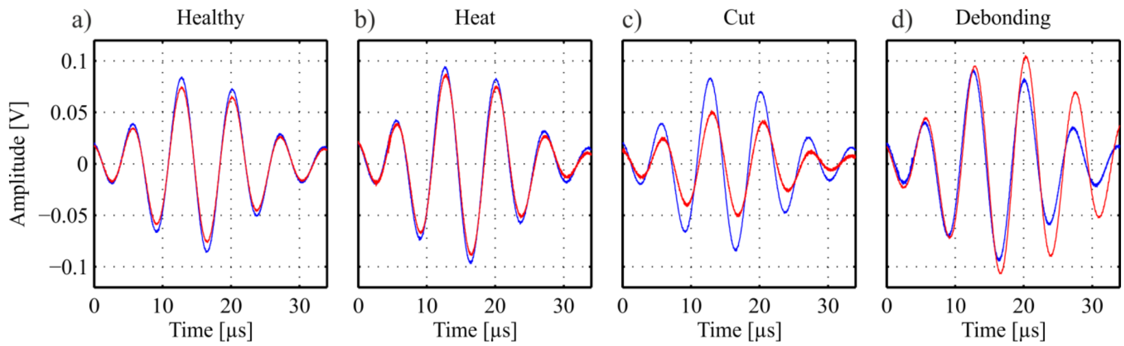

Figure 8: First wave package of guided wave measurements for different sensor faults, where the faulty PWAS was used as actuator, a) Healthy, b) Heat, c) Cut, d) Debonding, blue-baseline, red-damage

CONCLUSION

We have introduced a multifunctional device, called PZT Inspector, which enables multichannel-measurements on piezoelectric elements. The device supports impedance and wave propagation measurements and additional information about environmental conditions within one measurement setup. A description of the software and hardware used for data collection and management is presented. The smart hardware is implemented in a control board, which is described in detail. The software, especially the graphical user interface is shown. Two applications demonstrate the usability and the ease of measurement using the device. In the future the hardware could be improved to further decrease the cross-talking between the channels especially for open channels. To improve the applicability for operators without a huge knowledge in SHM data processing and evaluation, it would be very useful, to develop data evaluation modules, which are compatible with the software of the device. With these, operators will be able to conduct all necessary steps in real world applications within one system.

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