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Fast Impedance Spectroscopy of Piezosensors for Structural Health Monitoring

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Introduction

Electromechanical impedance measurement by electro-impedance spectroscopy (EIS) of piezoelectric transducers (based on lead zirconate titanate, PZT) is widely used in health monitoring of composite structures, primarily for near-sensor monitoring of the structure and for checking quality of sensors and bonding of sensors to the surface of the material. Reasonable frequency range for testing of structures and sensors is often determined by experimental results. In the impedance-based method, multiple frequency ranges with multiple peaks could be used. A frequency range higher than 200 kHz is found to be favorable for local sensing, while frequencies lower than 70 kHz cover larger sensing areas. Typically the frequency range of 30 kHz to up to 400 kHz is used. For higher frequencies, the wavelength of the excitation is small, and sensitive enough to detect small changes in the structures. For higher frequencies the sensing region of the PZT is limited to an area near to the PZT sensor/actuator. Typically the real part of electric impedance is more reactive to damage or changes in the structure's integrity than the imaginary part. Temperature changes, among all other ambient conditions, significantly affect the electric impedance signatures measured by a PZT [1].

Paper [2] summarizes the description of the modified electromechanical impedance model, for parametric studies for impedance-based sensor diagnostics. Paper [3] describes, how a PZT patch is surface bonded to the structure to be monitored and its corresponding electro-mechanical admittance signature is used for damage detection. Among other features and defects cracks and even multiple cracks in the material under test can be found by impedance measurements [4].

By measuring electrical impedance over certain frequency range one can make conclusions about quality of the bond. If bond between piezoelectric device and material is week then sharp resonance peaks can be seen on impedance-frequency plot. But if bond is strong then impedance curve is much smoother, peaks of resonance frequencies are lower and sometimes resonance frequencies are even shifted along frequency axis. [1, 5]

Electrical admittance Y(ω) (inverse function of the electrical impedance) of the piezoelectric transducer (PZT) is a combined function of the mechanical impedance of the PZT actuator $Z_a(\omega)$ and that of the host structure Z(ω) [6]:

$$Y(\omega) = i \cdot \omega \cdot a\left(\bar{\varepsilon}_{33}^{\ T} - \frac{Z(\omega)}{Z(\omega) + Z_a(\omega)} d_{3x}^2 \hat{Y}_{xx}^{\ E}\right). \quad (1)$$

For carrying out measurements in the research phase commercial impedance analyzer instruments (like HP4194A) could be used. Alternative is to use special impedance measurement chip-based solutions (like AD5933-1 MSPS, 12 Bit impedance converter network analyzer) [7]. Unfortunately such chips are limited by accuracy (resolution) or frequency range and can measure one frequency at a time, making the impedance measurements slow and so fast changes could not be monitored.

Also a good solution is to make special (preferably wireless) embedded measurement nodes, like [8] with dedicated analog front-end and digital signal processor (DSP).

Measurement setup

For described experiments a following setup has been used. Measurement system is PC-based (with Matlab tools and interfaces), using of National Instruments' USB-6259, a USB high-speed M Series multifunction data acquisition (DAQ) module optimized for accuracy at fast sampling. This unit contains multiplexed analog-to-digital converter (ADC) and digital-to-analog converter (DAC), with 1,25Ms/S speed and 16-bit resolution. A signal conditioning analog front end is containing a power driver with Ku=3 voltage amplification and a voltage divider (1:3) to measure excitation voltage Uexc (to ±30V) is on the PZT circuit and shunt resistor R=70Ω for current sensing in a PZT (Iz signal) (Fig. 1). Generation of various waveforms (sine-waves and their combinations) and also data acquisition and processing, is carried out by the PC software, according to the selected algorithms. PZTs (of Noliac - www.noliac.dk) – 3 pieces- are fixed to a glass fiber composite material 500x500x4 mm) by special glue (Fig. 2), plus fourth PZT sensor has been measured in the air.

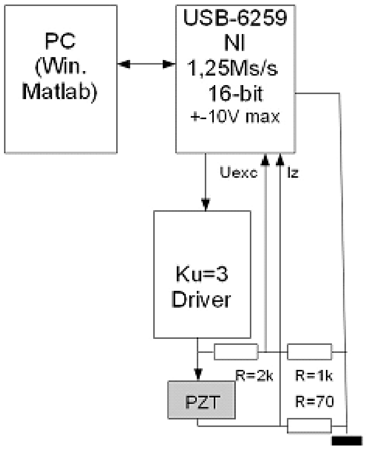


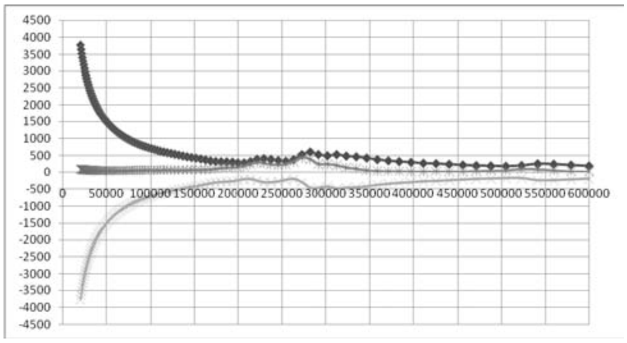
Fig. 1. Measurement setup (block diagram)

Fig. 2. Measurement setup

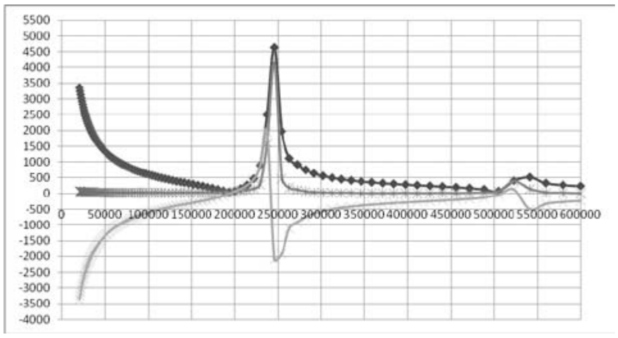
General approach to tried algorithms

General idea of the algorithms is generation of sinewave(s), one frequency at a time (discrete scanning or linear chirp) or simultanous multi-frequency voltage for excitation and measurement of the voltage drop of the current on the shunt resistor and then calculation of the complex impedance by Discrete Fourier Transform (DFT), taking into account the transfer coefficients of the measurement setup and subtracting the shunt resistor real value of the total complex impedance of the measured circuit, for PZT complex impedance. In some case DFT is reasonable to implement as Fast Fourier Transform (FFT). In current setup for reference (excitation) value one analog measurement channel is used, to get synchronous samples for excitation(Uexc) and current channels (Iz).

Voltage range of ±10V of ADC and DAC has been used, to ±30 V excitation (peak-to-peak). Actually amplitudes of about 30% of the full scale has been used. Sample rate has been 1.25 Ms/s for DAC and 500 kS/s for each ADC channel in current experiments. As used USB-6259 has multiplexed input with one ADC, the (phase shift between two “synchronous” ADC channels, corresponding to half of the ADC sampling period time delay has been corrected for current frequencies. Frequency range has been about from 10-300 kHz (or more) with frequency step (and resolution) of 5 kHz. The results of the PZT (labeled as “S3”) measurements are presented and described below. For reference, the impedance of PZT sensors has been measured by commercial Precision Impedance Analyzer 6500B of Wayne Kerr- look to Fig 3, a) -PZT “S3” and for comparison PZT in the air (PZT Sx) –b). Here and on next figures- highest line shows the module of the impedance, next line- real part and lowest part -the imaginary part of the measured complex impedance.



a)



b)

Fig. 3. Bonded (S3): a – vs. free(Sx); b – PZT impedance

Algorithms and measurement results

The following excitation signals and processing algorithms were tried:

1) Frequency scanning (one frequency at a time, 0,5s measurement per frequency, complex DFT realized as convolution or dot-product by reference (excitation frequency) sine- and cosine-waves (Fig. 4).

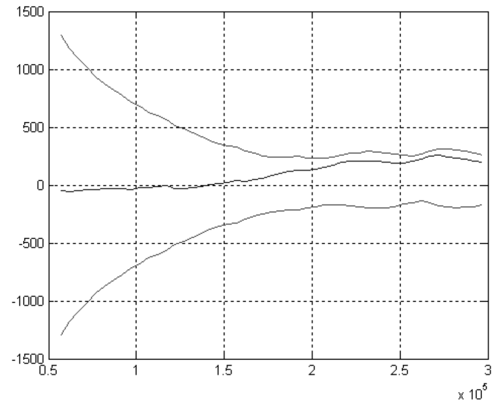
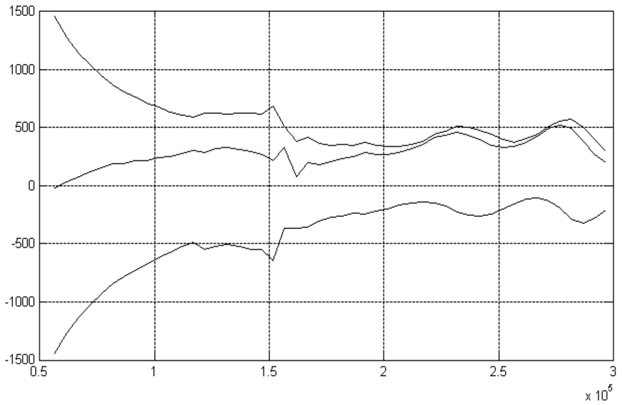
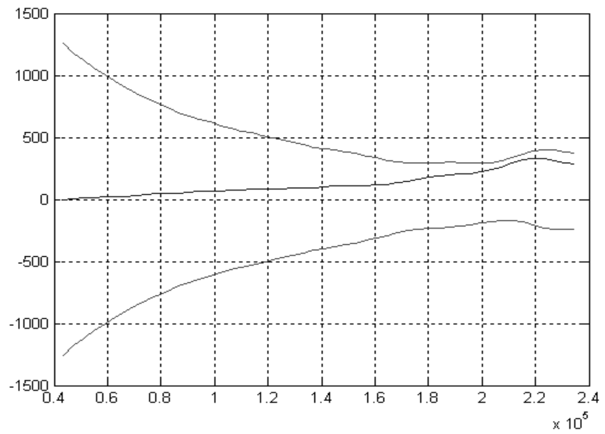


Fig. 4. PZT (S3) impedance for frequency scanning method

2) Multi-frequency: simultaneous multi-frequency excitation and DFT calculation (Fig. 5 a). Frequency values were shifted by 2 kHz from the 5 kHz grid, to have more realistic results (Fig. 5 b).



a)



b)

Fig. 5. PZT (S3) impedance of simultaneous multi-frequency method (a) measured by using of 5 kHz frequency grid, in (b) the used frequencies has been shifted by 2 kHz.from the 5 kHz grid

3) Multi-frequency excitation with FFT analysis. Initially here the idea was to use a regular (linear) FFT frequency grid for excitation and analysis frequencies. The results had clear artifacts, probably simultaneous ultrasound waves of integer frequency ratios cause interactions and disturbances to each other. The method was modified- resolution of FFT has been 4 times increased (so to 1.25 kHz) and used excitation (and analysis) frequencies have been shifted by this 1.25 kHz discrete value (¼ of initial grid resolution value), giving quite reasonable results (Fig. 6). In spite of using 4 times “oversampling” of FFT this method is still computationally very efficient, compared with all other methods. Furthermore, the averaging of FFT results over sequence (as FFT is a linear transform) of time windows (frames) can be turned into accumulating of the received sequential time-buffer segments into one accumulated buffer of (“4x”) FFT-size and then performing FFT only once.

4) Chirp signal: for chirp signal the frequency changes linearly over time period T. It can be expressed as

$$V(t) = \sin(2\pi(f_1 t + \frac{(f_2 - f_1)t^2}{2T})\,. \qquad (2)$$

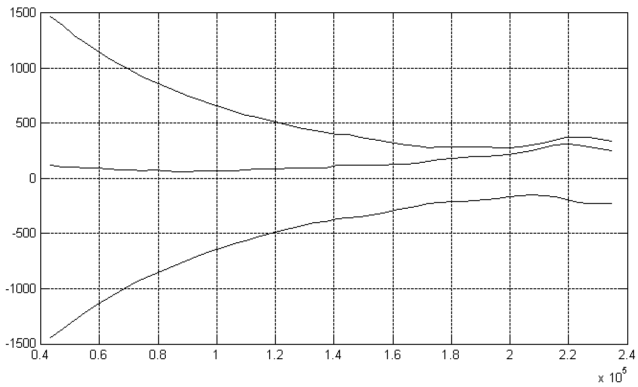


Fig. 6. PZT (S3) impedance obtained by the □ido f simultaneous multi-frequency method, by using 4x FFT and ¼ shift of frequency values

In general terms, ignoring specific applications and practical aspects the chirp signal clearly offers optimal features for use in dynamic process [9]. Excitation signal with frequency range 20kHz-600kHz has been generated. Pulse width from 0,8 -80 ms was tested. Longer pulse width resulted more accurate impedance plot. Figure 7 shows 80 ms chirp pulse result. In current example the impedance is calculated by using of FFTs of excitation voltage and current signals.

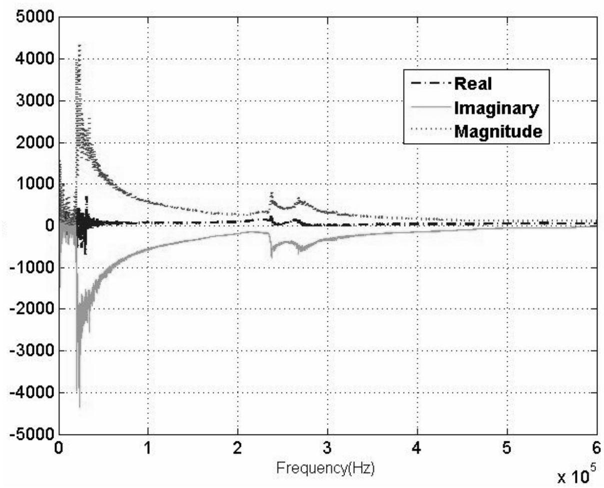


Fig. 7. PZT (S3) impedance obtained by the aid of a chirp (80ms) signal

Also works [10–12] offer interesting approaches for using of chirp signals for spectral impedance measurements, and can be further investigated. Trying of “signum chirp” signals to simplify the solution did not give good results in these experiments.

Conclusions

Using of multi-frequency and chirp signals shows a great potential in using of EIS in piezo-sensor based embedded SHM solutions by making the solutions cheaper and more easily operating in real-time.

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Electroimpedance spectroscopy (EIS) of piezoelectric transducers (PZT) is used in structural health monitoring (SHM) of composites and for checking quality of PZT and bondings. Measurements have to be precise, as small changes in real or imaginary parts of the impedance can indicate early changes in the structure or in the sensor. EIS methods, by one frequency at a time, are time and energy consuming, limiting such approach for embedded systems. Alternative faster methods of EIS are suggested here and tested in an PC-based experimental setup, with a composite plate and PZTs. Usage of simultaneous multi-frequency or wide-band excitation signals like chirps have been studied and compared. Ill. 7, bibl. 12 (in English; abstracts in English, Russian and Lithuanian).

О. Мяртенс, Т. Саар, М. Мин, Р. Ланд, М. Рейдла. Быстрая спектроскопия импеданса пьезоэлектрических сенсоров для структурного мониторинга здоровья // Электроника и электротехника. – Каунас: Технология, 2010. – № 7(103). – С. 31–34.

Элекроимпедансная спектроскопия (ЭИС) пьезоэлектрических сенсоров используется для мониторинга структурального здоровья композитных материалов, сенсоров и их крепления. Измерения должны быть прецизионными, так как малые изменения комплексного импеданса могут предсказать ранние изменения структуры или сенсора. Методы ЭИС, при которых измерения проводятся по одной частоте одновременно, требуют много времени и энергии, ограничивая таким образом их применение в строенных системах. Альтернативные быстрые методы ЭИС предложены и испытаны здесь. Рассмотрены методы с использованием многочастотного (мультисинус) или широкополосного (например „чирп“) сигнала возбуждения. Ил. 7, библ. 12 (на английском языке; рефераты на английском, русском и литовском яз.).

O. Märtens, T. Saar, M. Min, R. Land, M. Reidla. Sveikatos struktūrinės stebėsenos pjezoelektrinių jutiklių apkrovos analizė // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 7(103). – P. 31–34.

Šiandieninei sveikatos stebėsenai turi būti naudojamos labai didelio tikslumo medžiagos ir įvairūs jutikliai. Šiuo atveju tikslinga naudoti pjezojutiklius. Išnagrinėti daugiadažniai ir plačiajuosčiai signalų atvaizdavimo metodai ir pasiūlyti originalūs pjezojutikliai, kurie gerokai sumažina sveikatos tyrimų trukmę ir leidžia optimizuoti sistemų struktūrą. Il. 7, bibl. 12 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).