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Robust Piezo Impedance Magnitude Measurement Method

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Introduction

In SHM (structural health monitoring) applications PZT (lead zirconate titanate) impedance measurement is widely used for condition monitoring. PZT E/M (electro-mechanical) impedance can indicate defects on PZT host structure in early stage. Condition of the host structure can be derived from changes on PZT EMI spectrum. E/M impedance provides non-invasive measurement method, while response of the host structure is not modified by the sensor [1].

Electrical admittance Y(ω) 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) [2]

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

When comparing high-frequency local impedance against low-frequency global impedance, then high-frequency local impedance is more sensitive to damage in its initial stage. Because of this, E/M impedance method is more effective in SHM application than other more conventional methods [3].

Purpose of this research was to find the cheapest and most minimal setup needed for impedance magnitude measurement to find alternative to bulky and expensive industrial impedance analyzers or USB data acquisition boxes. Goal was to use simple off-the-shelf components and to keep design as simple as possible. Also avoiding computationally hard tasks like Fourier transform, would help save processing power and lower overall cost. Measurement time is critical factor. For example load changes on host structure (bridges, walls, windmills blades etc) can cause false measurement results. To minimize this measurement time should be as short as possible.

Previous works

[3] proposed low-cost impedance analyzer based on DAQ card. 10 MHz sample rate and 8 bit dynamic range was used for signal sampling. Digitally synthesized signals were used for active SHM. Results of linear chirp and frequency swept signal were compared by simulations and experiments. E/M impedance results were compared to HP4194A commercial impedance analyzer. Firstly free piezo was measured. After that an aluminum test panel with artificial damage (disbond, cracks and corrosion) was used. New impedance analyzer was proposed for aluminum disbond detection.

Work [4] described procedures for determination of frequency ranges where the PZT transducers are more sensitive for damage detection. Usually most sensitive frequency ranges are determined empirically. In this case tests were carried out on specimens with different sizes and good correlation between experimental and theoretical results was found.

In paper [5] results of using PZT transducers on surface of concrete were compared against embedded transducers. Comparison was made under different conditions, in different locations and extents. Results showed that embedded PZT transducers were more effective for identifying cracks in large-sized concrete structures.

[6] used E/M admittance signatures to model structural impedance. It described multiple –degrees-of-freedom system consisting of a number of one-degree-of-freedom elements with mass, spring and damper components. To solve unknown dynamic system, genetic algorithms were used. Genetic algorithms minimized an objective function. Effects of earthquake were simulated on two-storey concrete frame. Base vibrations hat simulate earthquake were applied to concrete frame. E/M admittance signatures were measured. Using genetic algorithm, the changes of the structural parameters were derived and analyzed. The results demonstrated that the appearance of damage leads to increase in damping and decrease in stiffness and mass at the driven point. Also results demonstrated that, created model was more sensitive to severe damage.

Paper [7] proposed “efficient and inexpensive methodology for electrical impedance measurement”. System consisted of National Instruments USB-6211 data acquisition box and a PC. Software was created using LabVIEW development tools. Results were compared against HP 4192A impedance analyzer.

In paper [8] a novel approach of excitation with chirp signal with simple time-domain analysis of response signal for such task was introduced and described with examples of measurement of the electro-mechanical impedance of piezosensors, in the frequency range of several hundred kilohertz. In one approach smoothed separately (by Savitzky-Golay filter) of excitation voltage and (current) response signals in a sliding window were found and their ratio was used for impedance module estimation, at corresponding time and frequency values. Alternative method for vector measurement of impedance spectra in time domain was also tested.

In papers [9, 10] interface for impedance spectroscopy measurements of piezo-sensors was developed, for a digital signal processor of Delfino series of Texas Instruments. DAC of the interface was based on a 16-bit PWM with extra 8-bit part of “high resolution” (of picoseconds), with external simple (3-rd order) analog filter. Internal 12-bit ADC is converting at rates of up to 10 MS/s with 2 simultaneous sample-and-holds. With few extra components, high-performance analog interface was” improvised” (developed and investigated) with a frequency range 10 kHz -400 kHz about 0,1% of the full scale resolution and repeatability of measurements.

Method

Proposed setup uses 4 main components microcontroller unit (MCU), waveform generator, amplifier and analog front end. Aim was to use as low cost and few parts as possible. Figure 1 describes method principle layout.

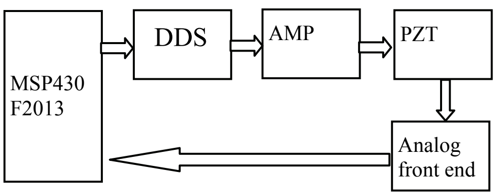

Fig. 1. Principle layout

Texas Instruments MSP430F2013 was chosen for MCU. MSP430F2013 is optimized for extended battery life in mobile measurement applications. It has five different power saving modes. Switch between low-power mode and operational-power mode takes less than 1µs. Architecture is based on 16 bit RISC CPU. Efficient code use is achieved by use of 16 bit registers and constant generators. MCU has built-in 16 bit timer and 10 I/O pins. It also has integrated 16 bit sigma/delta A/D converter and built-in communication capability using synchronous protocols (SPI and I2C). Proposed method SPI was used for waveform generator pre-programming and internal 16 bit A/D converter for signal sampling.

Analog Devices AD5932 waveform generator was used for excitation signal generation. The AD5932 is a pre-programmable waveform generator. Start frequency, frequency step, number of steps and time delay between frequencies are all pre-programmed. Generator uses internal logic to increment (or decrement) frequencies automatically step-by-step. Alternatively frequencies can be incremented on-by-one by toggling control pin. Programming is done over SPI interface using 16 bit words. Signal generation is started by only toggling control bin on generator. This saves MCU or DSP processing resources for other purposes and enables to use cheaper processing units. Signal changes frequencies phase-continuously, which enables easily to determine phase shifts. After finishing frequency sweep generator continues to generate last frequency until reset is done. AD5932 uses only 6.7 mA which enables to use it on mobile or low-power applications. In current solution use of AD5932 combined with MSP430F3013 enables to lower overall power consumption.

For excitation signal amplification simple OP-amp based wide-band amplifier was used. Excitation signal voltage was between +15 and -15 V.

Analog front end consists of full period rectifier and first order low pass filter. Rectifier design was based on LM318 operational amplifiers and diodes. Rectifier was designed and simulated using Texas Instruments TINA software package. Schematics was simulated on frequencies between 20-600 kHz. Fig. 2 and Fig. 3 describe analog front end schematics and simulation results.

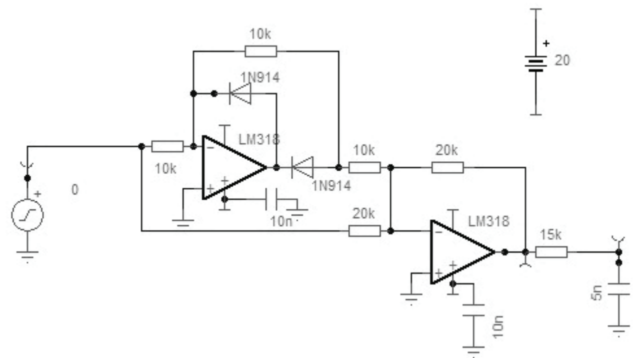

Fig. 2. Full period rectifier with low pass filter

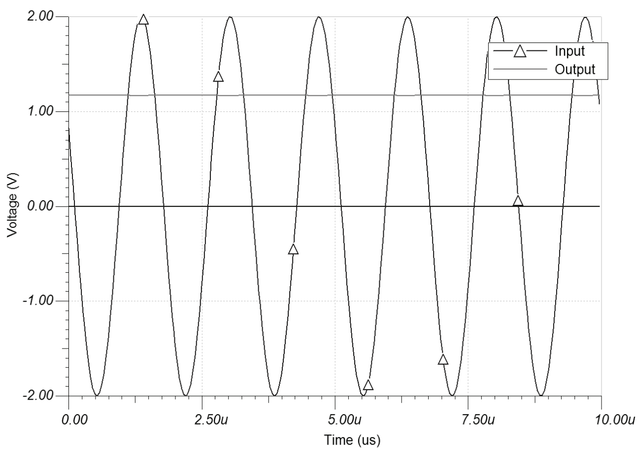

Fig. 3. Ti TINA simulation results at 600 kHz

Based on previous work [8] linear chirp signal was used for excitation

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

Excitation signal had frequency range 20kHz-600kHz and was 100 ms long. Impedance magnitude was calculated by dividing voltage magnitude with current magnitude. Because voltage (Vm Fig. 4) magnitude changes very little while measuring different PZT's, it could be used as constant vector. Based on this impedance magnitude can be calculated by only measuring current passing PZT. This lowers hardware requirements and cost of measurement system. It enables to use single analog input on MCU. Current was calculated by measuring voltage (Vp) on resistor (Zp on Fig. 4).

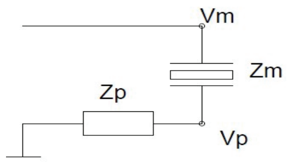

Fig. 4. Measurement scheme

Proposed method was tested using Ni USB-6529 DAQ, signal generator and assembled analog front end. 10 kHz sampling rate was used for signal sampling. Recorded signal was decimated to preserve memory. Results were recorded using Matlab based software.

Results

Measured results were compared against measurements made by made by commercial impedance analyzer type 6500B of Wayne Kerr. Piezos in two cases were measured. Firstly piezo was free in the air, secondly piezo was glued on 500x500 mm fiberglass plate.

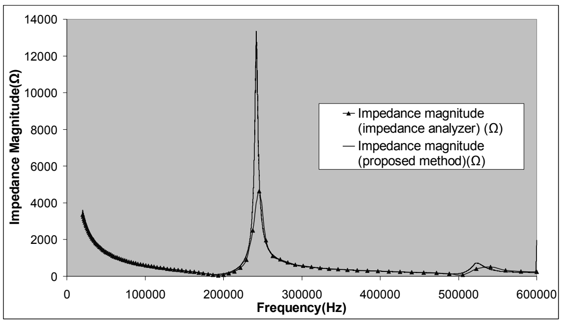

Fig. 5. Free piezo impedance magnitude

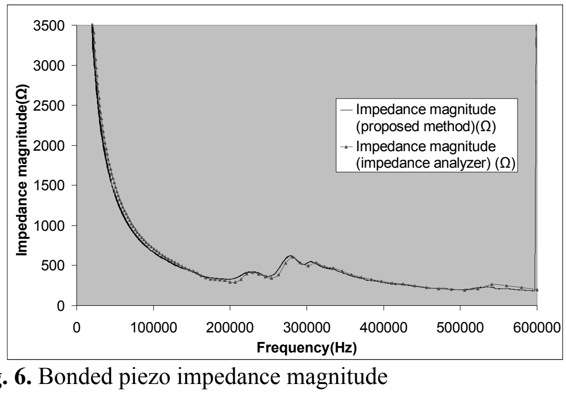

Fig. 6. Bonded piezo impedance magnitude

Measured results (Fig. 5 and 6) were very similar to measurements made using commercial impedance analyzer. Only by measuring free piezo, resonance frequency impedance values were much higher compared against commercial impedance analyzer. This effect can be caused by higher excitation signal voltage.

Overall cost of simulated hardware was around 50 Euros, without power supplies. Total power consumption of proposed system was below 3,5W. Most of the power was consumed by excitation amplifier. Low power consumption enables system to be used in wireless configuration. Because maximum power is only needed during 100ms bursts, system could spend extended periods of time in standby mode on battery power.

Conclusions

Proposed method has been studied and simulated. Also experimental results were measured. Method has high measurement speed, low price and low energy consumption compared against conventional methods. This makes it suitable for real-time on-site SHM application. Use of analog front end enables to use very low cost DSP or MCU. This makes it especially useful for application where great number of impedance spectrum measurement nodes are needed.

Future work

Future work should focus on impedance spectroscopy on even more extended frequency range. In some applications frequencies up to 2MHz are required. Also analog front end for impedance phase measurement should be developed. Depending on specific application impedance magnitude, phase or both are needed.

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T. Saar. Robust Piezo Impedance Magnitude Measurement Method // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 7(113). – P. 107–110.

Piezo impedance spectroscopy is widely used in structural health monitoring (SHM) applications. Purpose of the research was to find most robust and cheap method for impedance magnitude measurement. Proposed system consists of analog front end (AFE), signal synthesizer and microcontroller unit. AFE enables to use low sampling rate, while using high frequency excitation signal. Proposed system uses chirp excitation signal in 20kHz- 600kHz frequency range. Results were compared against measurements made with commercial impedance analyzer. Results show great potential for this method in SHM applications. Ill. 6, bibl. 10 (in English; abstracts in English and Lithuanian).

T. Saar. Pjezoelemento impedanso vertės matavimo metodas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 7(113). – P. 107–110.

Pjezo impedanso spektroskopija plačiai taikoma struktūrinei sveikatos stebėsenai. Siekiama rasti patikimą ir pigų metodą impedanso vertei nustatyti. Siūlomoji sistema sudaryta iš analoginės dalies, sintezatoriaus ir mikrovaldiklio. Sistemos matavimo rezultatai buvo palyginti su komerciniais matuokliais atlikto matavimo rezultatais. Gauti daug žadantys rezultatai. Il. 6, bibl. 10 (anglų kalba; santraukos anglų ir lietuvių k.).