Calibration Problem of AD5933 Device for Electromechanical Impedance Measurements

Tomasz Wandowski, Pawel Malinowski, Wieslaw Ostachowicz

CALIBRATION PROBLEM OF AD5933 DEVICE FOR ELECTROMECHANICAL IMPEDANCE MEASUREMENTS

Tomasz Wandowski[1], Pawel Malinowski[1], Wieslaw Ostachowicz[1,2]

[1] *Department of Mechanics of Intelligent Structures Institute of Fluid-Flow Machinery PAS, 80-231 Gdansk, Poland*

[2] *Faculty of Automotive and Construction Machinery, Warsaw University of Technology, 02-524 Warsaw, Poland*

tomaszw@imp.gda.pl

ABSTRACT

In this paper influence of incorrect calibration of AD5933 electrical impedance analyzer on errors in measurements was investigated. AD5933 is developed in the form of electronic integrated circuit by the Analog Devices. This device is very popular in the field of Structural Health Monitoring based on electromechanical impedance method. Electromechanical impedance method relies on measurements of electrical impedance of piezoelectric transducer bonded to the structure. Due to electromechanical coupling of piezoelectric transducer mechanical resonances of the structure can be seen in the electrical impedance characteristics of piezoelectric transducer. In order to properly measure electrical impedance mentioned devices must be calibrated using calibration resistor. In this research influence of wrongly selected calibration resistor value on the measurement results was interrogated. Measurements conducted with AD5933 were compared with measurements realized using professional electrical impedance analyzer HIOKI IM3570.

Research was related to simple supported beam made out of aluminium alloy with piezoelectric transducer in the form of disc. Measurements were taken for referential state as well as for few states with artificial introduced damage in the form of notch.

KEYWORDS : *E/M impedance, piezoelectric transducers, damage detection.*

INTRODUCTION

Electromechanical impedance method is based on measurements of electrical impedance of piezoelectric transducer bonded to the structure. Due to electromechanical coupling of piezoelectric transducer mechanical resonances of the structure can be seen in the electrical impedance characteristics of piezoelectric transducer. Damage existing in the structure is source of stiffness change and can be noticed in measured electrical impedance characteristics. In electromechanical impedance method actuation and sensing are done by the same piezoelectric transducer placed in predefined location. Very small value of loading is imposed on the specimen (low voltages on the transducer) and hence linear behavior of the structure is assured. Further information about high frequency impedance measurement can be found in [1].

Specific feature of most impedance analysers is the ability to give alternating voltage at the output with frequency over megahertz what makes them proper instrumentation for high frequency vibration analysis. Beginning of electromechanical impedance method is connected with paper published by Liang, Rogers and Sun [2]. Paper shows the essence of the method with usage of model of piezoelectric transducer bonded to 2 degree-of-freedom structure. Large amount of research in this field were done by Giurgiutiu [3]. In last few years, usage of integrated electric circuits in EMI, e. g. AD5933 – impedance analyzer, has been in the centre of interest of many scientists. This device is very popular in the field of Structural Health Monitoring based on electromechanical impedance method [4]-[7].

Critical problem related to this method is large temperature influence on electromechanical impedance measurements. Results of experimental study of this influence were presented for example in [8].

Research presented in this paper is related to calibration problem of AD5933. In this research influence of wrongly selected calibration resistor value on the measurement results was interrogated. Measurements conducted with AD5933 were compared with measurements realized using professional electrical impedance analyzer HIOKI IM3570. Research was related to simple supported beam made out of aluminium alloy with piezoelectric transducer in the form of disc. Measurements were taken for referential state as well as for few states with artificial introduced damage in the form of notch.

MEASUREMENT SET-UP

Measurement set-up consisted of HIOKI IM3570 impedance analyzer (Figure 1a) and evaluation board with AD5933 impedance analyzer (Figure 1b). Firstly mentioned is very precise and professional laboratory equipment that allow to measure electric parameters like: impedance, admittance, resistance, capacitance for wide frequency range 4Hz – 5 MHz. The second one is simply electronic chip developed by Analog Devices and allow to measure impedance for narrow frequency range from few hertz up to 100 kHz. Moreover AD5933 must be calibrated before measurements using calibration impedance. This is main drawback of this device. These two types of equipment differs also in price, second solution is very cheap.

All measurements during the research were conducted for one side clamped aluminium alloy beam with dimensions 270 mm x 30 mm x 3 mm. Beam was equipped with SONOX P5 piezoelectric disk with diameter 10 mm and thickness 0.5 mm (Figure 2). Piezoelectric transducer was placed on the top surface of the beam in the middle of its length.

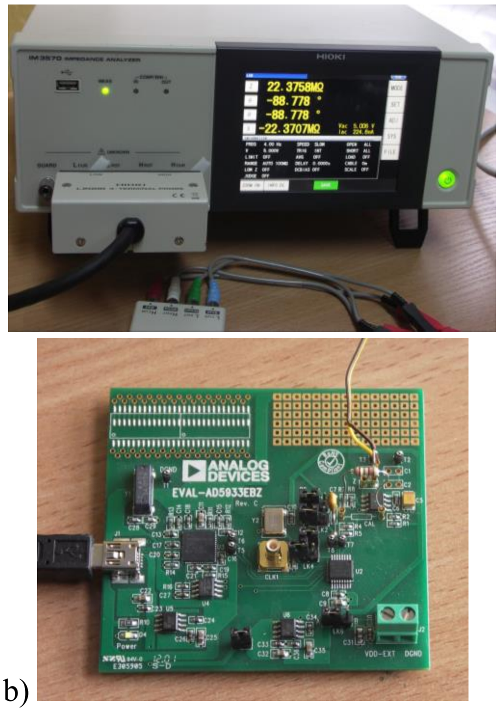
a)
b)


Figure 1: Impedance analyzers: a) HIOKI IM3570, b) evaluation board with AD5933.

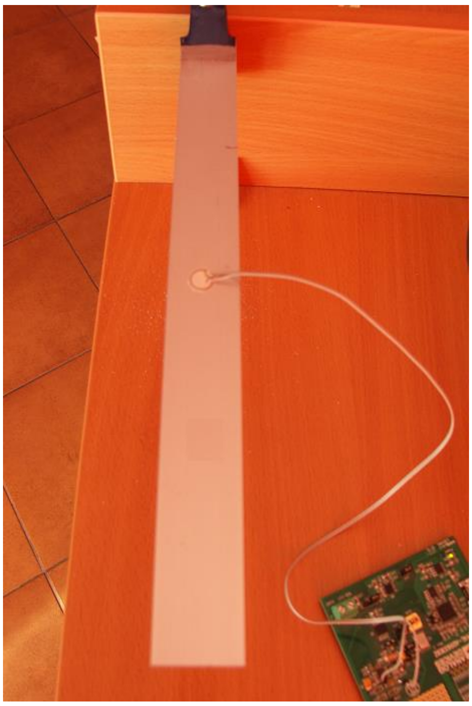


Figure 2: Object of investigations – aluminum alloy specimen.

CALIBRATION OF AD5933

As it was mentioned in previous section main drawback of AD5933 is necessary for its calibration using known impedance. According to the documentation [9] simplest way of calibration is utilization resistor with known resistance. Such a approach is appropriate for measurement for electronic elements like resistors with purely resistance characteristic. Changes of resistance with frequency and reactance values are negligible for such elements for frequency band till 100 kHz (maximal frequency of AD5933). For the measurements of capacitive elements measurements will be corrupted by errors due to its reactance that change with frequency while the AD5933 was calibrated for one calibration value of resistance. Piezoelectric transducer has capacitive character with dissipative resistance part. Preliminary results shown that it is possible to use calibration resistor in order to calibrate AD5933 for measurement of electric impedance of piezoelectric transducers. However value of calibration resistance should be appropriately selected in relation to electric impedance of piezoelectric transducers. At this stage it is necessary to utilize professional impedance analyzer like HIOKI IM3570 in order to measure electrical impedance of piezoelectric transducer in considered frequency range.

The aim of preliminary experiment was to test calibration using resistance for measurement of impedance of piezoelectric transducer in electromechanical impedance method. In this purpose piezoelectric transducer was attached to the aluminium beam described in previous section. In next step electrical impedance characteristic of transducer for frequency range: 5 kHz – 20 kHz with 30 Hz step was measured using HIOKI IM3570. Next measurements of the same characteristic using AD5933 calibrated using several different calibration resistor values was conducted. In Figure 3 impedance characteristics measured with AD5933 for different calibration resistor value was compared with impedance characteristic measured based on HIOKI IM3570. In order to improve of readability of results, measurements were divided into two sets: Figure 3a) and Figure 3b). Analysing these results it can be noticed that for certain values of calibration resistance (very low and very high) large errors in shape of characteristics occurs and impedance characteristic measured with AD5933 and HIOKI IM3570 differ strongly. After carefully analysis it was noticed that only certain sets of calibration resistance values allow to measure impedance characteristic which shape and trend are similar. Only one calibration resistance allow to measure impedance characteristic that is very similar to this measured by HIOKI IM3570 taking into account shape, trend and values.

Value of calibration resistance must be strictly related to the range of changes of impedance trend values measured for piezoelectric transducer. In this case values of impedance trend change from about 24 kΩ for frequency 5 kHz to 8 kΩ for frequency 20 kHz. If the calibration resistance values have much smaller or larger value than range 8 kΩ – 24 kΩ then measured impedance characteristic does not have similar shape, trend and values like for properly measured characteristic. For too large value of calibration resistance in comparison to the maximum impedance value impedance characteristics is not properly measured for higher frequencies. For too small values of calibration resistance impedance characteristic is not properly measured for low and high frequencies. In presented case the best results were obtained for calibration resistance 10 kΩ.

It should be underlined that even in this case values of impedance characteristic measured with AD5933 and HIOKI IM3570 are not the same. However it is not so important in the field of SHM based on electromechanical impedance method where repeatability of measurements of impedance characteristics is very important and shape of characteristic but not the accurate values of impedance. Moreover impedance peaks must be clearly seen in these characteristics.

In Figure 4 impedance characteristics were presented for measurements taken five times for the same piezoelectric transducer like in previous experiments. It can be clearly seen that characteristics are almost the same. No significant deviations of characteristics are visible.

In the next step different frequency band was selected for calibration testing. In this case frequency band from 19 kΩ – 28 kΩ was selected. At the beginning electrical impedance of transducer was measured using HIOKI impedance analyzer.

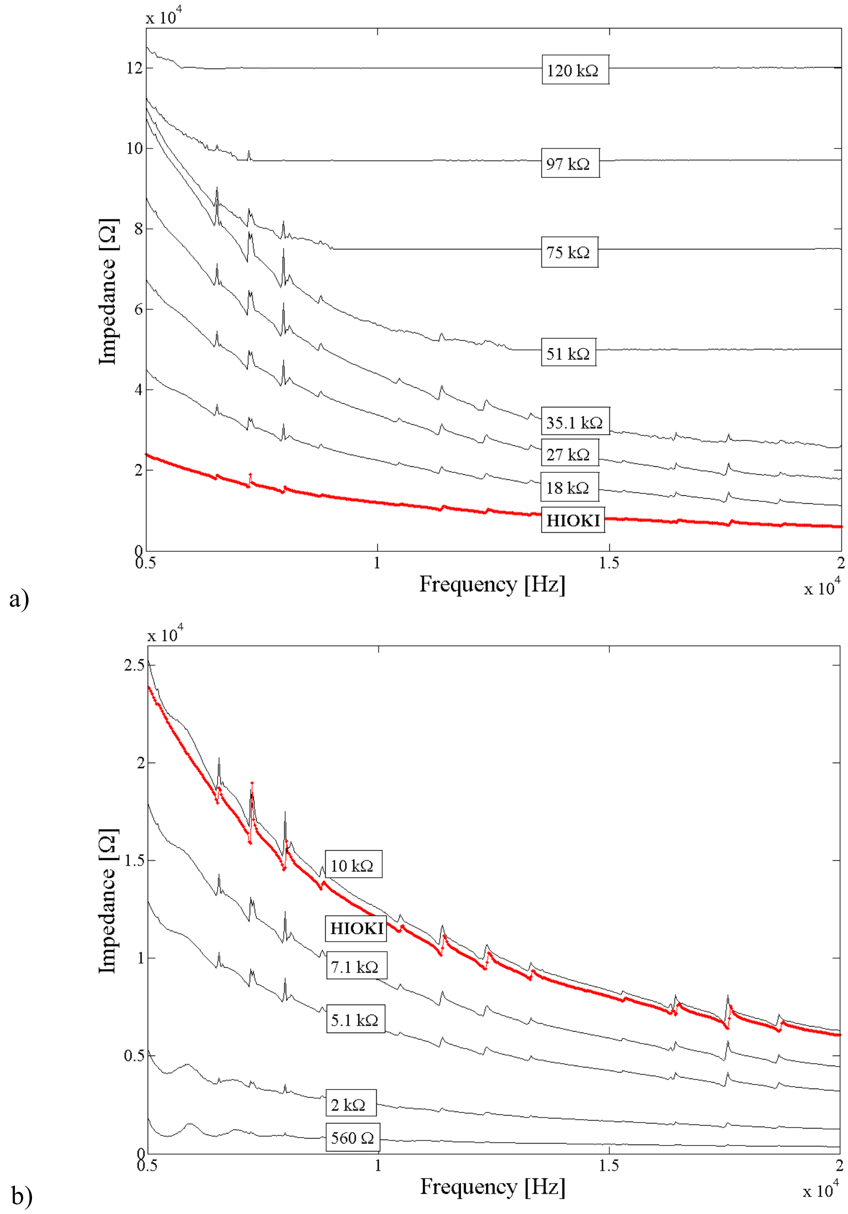


Figure 3: Influence of calibration resistor value on measurements of electrical impedance: a) too higher value of resistance, b) too small values of resistance.

Next few calibration resistance values were tested and the best one was selected, in this case it was 6 kΩ. Characteristics measured by HIOKI and AD5933 with calibration resistance 6 kΩ were presented in Figure 5. These characteristics are similar however differ a little bit taking into account its values. Small frequency shift can be also noticed however it was observed in all measurements done by AD 5933. It can be noticed that values of impedance measured by HIOKI change from 6.5 kΩ to about 5 kΩ.

In next step the influence of different calibrations of AD5933 on performance of electromechanical impedance method for damage detection was tested. In this case narrower frequency band was selected in order to reduce time of measurement what allow to reduce influence of temperature. The temperature problem will be analysed later in this paper. Narrow frequency band 20 kΩ – 21.2 kΩ was selected with frequency step 20 Hz. All measurements were next interpolated using spline in order to make the signals much smoother. After interpolation frequency step was equal to 1 Hz. It allow to detect very slightly frequency shift of impedance characteristics due to damage existence. Measurements were performed for one referential state and three damaged states and for three values of calibration resistance: 150 Ω (too low), 6 kΩ (appropriate) and 30 kΩ (too large). Damage was modeled as a through thickness notch 1 mm-wide and with length: 1 mm (N1), 3 mm (N2) and 5 mm (N3).

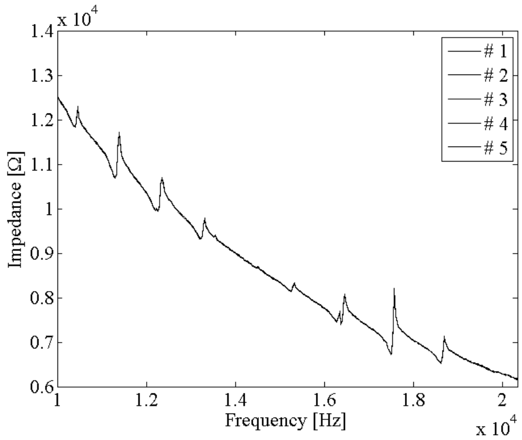


Figure 4: Repeatability of measurements using AD5933; #1–5 - five following measurements.

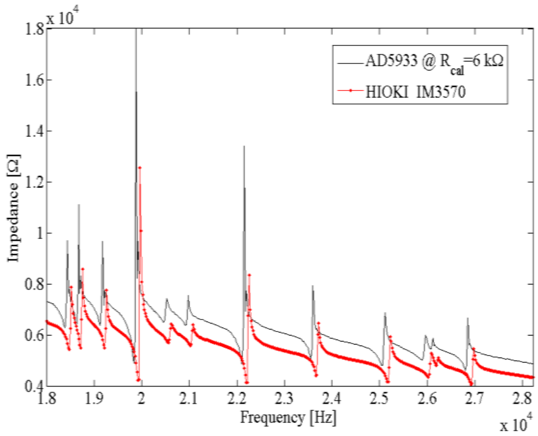


Figure 5: Comparison of measurements obtained for HIOKI IM3570 and AD5933 with calibrating resistor 6 kΩ.

Impedance characteristics were measured this time using only AD5933 and are presented in Figure 6 – Figure 8. The Figure 6 shows results for calibration resistance 6 kΩ. This resistance is appropriately selected. In the Figure 7 measurements results of electrical impedance were presented for calibration resistor 150 Ω which is too low. In this case many additional oscillations are clearly visible. Similar situation can be seen in Figure 8 where calibration resistance 30 kΩ used and this resistance was too high. It can be clearly visible that results obtained for not properly selected calibration resistance differ strongly for these obtained for its proper value. Analysing only Figure 6 frequency shift of signals for damaged case can be clearly visible.

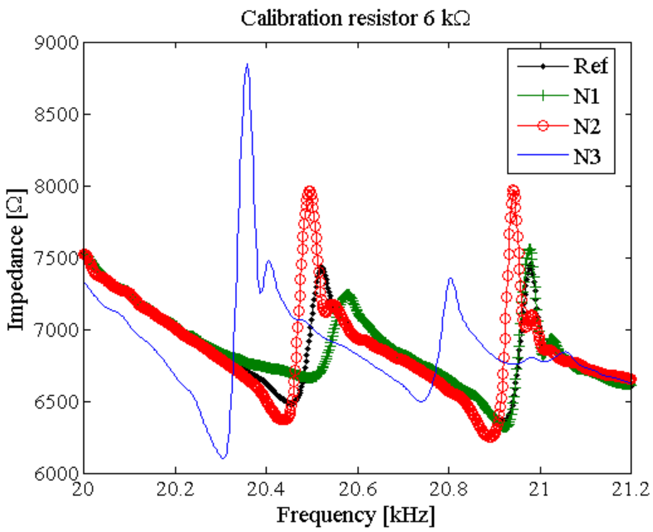


Figure 6: Electromechanical impedance measurements for: Ref1 – referential aluminium beam, N1 – beam with 1 mm long notch, N2 – beam with 3 mm long notch and N3 – beam with 5 mm long notch; appropriately chosen calibration resistor value.

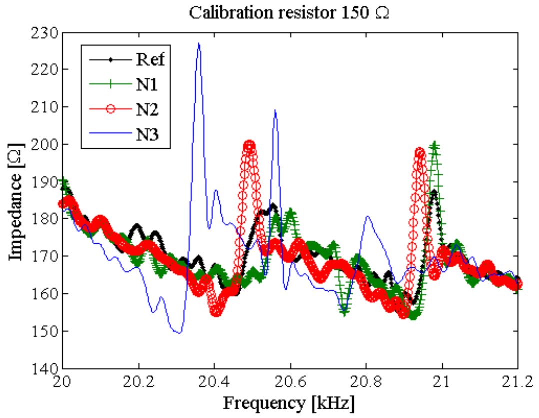


Figure 7: Electromechanical impedance measurements for: Ref1 – referential aluminium beam, N1 – beam with 1 mm long notch, N2 – beam with 3 mm long notch and N3 – beam with 5 mm long notch; too low calibration resistor value

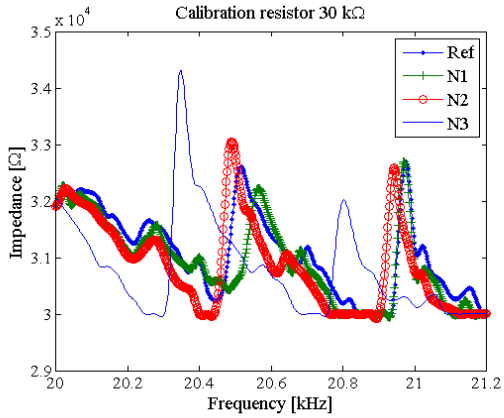


Figure 8: Electromechanical impedance measurements for: Ref1 – referential aluminium beam, N1 – beam with 1 mm long notch, N2 – beam with 3 mm long notch and N3 – beam with 5 mm long notch; too high calibration resistor value

In order to investigate the influence of calibration resistance on damage detection result using electromechanical impedance two damage indexes were proposed (1) – (2). First index is called RMSD, second MAPD and were proposed in [3].

$$DI1 = \sqrt{\sum_{i=1}^{n}\left(\frac{Z(i)_R - Z(i)_D}{Z(i)_R}\right)^2} \quad (1)$$

$$DI2 = \sum_{i=1}^{n}\left|\frac{Z(i)_R - Z(i)_D}{Z(i)_R}\right| \quad (2)$$

where: DI - damage index, $Z(i)_R$ - magnitude of impedance for referential case, $Z(i)_D$ - magnitude of impedance for damaged case.

In the first step these two indexes were calculated for undamaged beam impedance measurements and for two cases with not appropriately selected calibration resistance. That were the same signals presented above (Figure 7 and Figure 8). In both cases the reference with proper calibration was taken. Results were presented in Figure 9. Values of both type of damage indexes are higher for too high calibration resistance value.

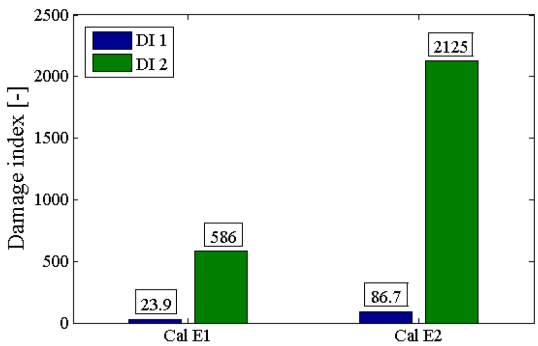


Figure 9: Damage indexes for wrongly calibration of AD5933 on damage indexes

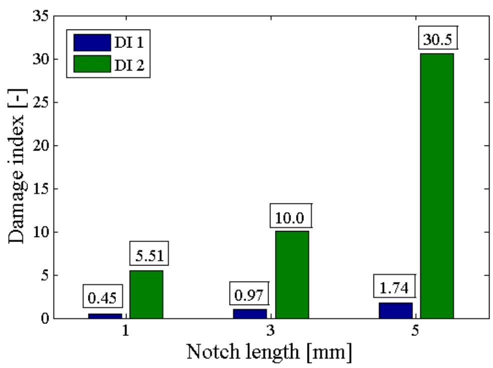


Figure 10: Damage indexes values for three cases of notch size: 1 mm, 3mm and 5 mm long

In next step both damage indexes were calculated for measurements with appropriately selected calibration resistance for referential state beam and for the beam with different damage severity. Damage was modeled as a through thickness notch 1 mm width and with length: 1 mm, 3 mm and 5 mm. Results for damage indexes calculated based on referential state measurements and damaged states were presented in Figure 10. After analysis of the results it can be noticed that both damage indexes monotonically grow with severity of the notch. Values of DI2 (MAPD) are higher than for DI1 (RMSD). In comparison with results presented in Figure 9 (for improper calibration) values of damage indexes are much smaller. It means that improper calibration had much larger influence on results than damage.

As it was previously mentioned changes of temperature have also strong influence on electromechanical impedance. In Figure 11 two impedance signals were presented taken for two temperatures. Measurements were performed for damaged beam with 5 mm long notch. In first case measurement was realized for temperature 20.1 °C and in the second for temperature 27.5 °C. It is clearly visible that with growing temperature signal shift to the left and its amplitude decreases. In Figure 12 damage indexes were presented which where calculated for referential signal taken in temperature 20.1 °C and for signals taken for few higher temperatures. Maximum temperature difference is 7.4 °C like between signals in Figure 11.

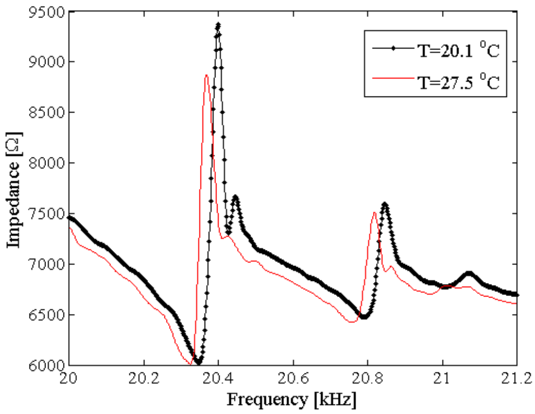


Figure 11: Influence on temperature on E/M impedance measurements (beam with 5 mm long notch)

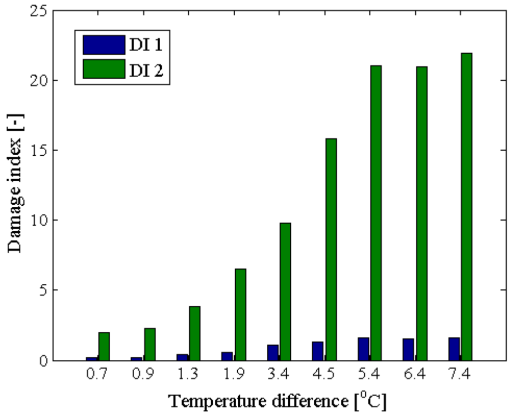


Figure 12: Influence on temperature on damage indexes values (beam with 5 mm long notch)

It can be seen that temperature change in the case of beam with 5 mm long notch caused large influence on damage index values. Damage index values achieve levels comparable with these obtained for different notch severity (Figure 10).

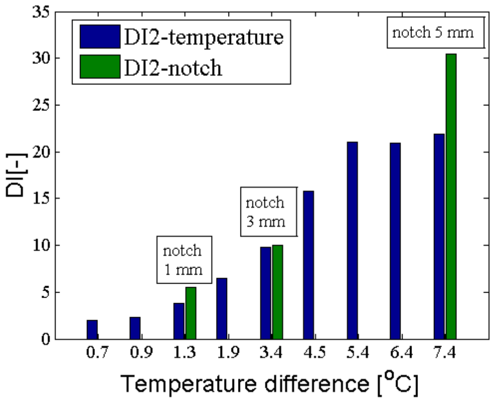


Figure 13: Comparison of second damage index DI2 values for different temperatures and damage severity (different baseline states for temperature and notch cases)

In Figure 13 values of damage index DI2 calculated for different temperature values and for three notch lengths were compared. In the case of damage index calculated for temperature changes a beam with 5 mm long notch at 20.1 °C was a reference. In the case of damage index calculated for different notch severity beam without notch was a reference (temperature was unknown for this analysis). For temperature change of 1.9 °C DI2 index value is higher than calculated for 1 mm long notch. For temperature change of 4.5 °C DI2 is higher than calculated for 3 mm long notch.

In case of 5mm long notch DI2 calculated for this state is higher than for largest temperature change. It should be emphasized that in this comparison different baseline states were taken as it was mentioned above. The same temperature changes can in different way change DI2 values for notch length 1 mm and 3 mm. However the aim of this comparison was to show how important is the influence of changing temperature on measurements. These results shown that influence of temperature needs to be compensated.

CONCLUSIONS

It can be concluded that electronic device AD5993 is an alternative solution for laboratory impedance analyzers like HIOKI IM3570. The first solution is much cheaper, has smaller dimensions and much smaller mass. However, has also some drawbacks: like limited frequency range till 100 kHz and most important the need of calibration. This paper shows that AD5933 can be properly calibrated for measurements of electromechanical impedance in SHM system using simple resistor. However in this purpose professional impedance analyzer is still needed in order to accurately measure impedance values and range of its changes. It means that during the development of SHM system based on AD5933 access to professional impedance analyzer is needed however after calibration system can work until frequency range is the same. It is only needed to use processional impedance analyzer at the prototyping stage of SHM system. Large cost of professional analyzer is balanced by low cost of SHM system based on AD5933.

It was shown that temperature changes have large influence on results of measurement. If these changes are very low it is still possible to detect damage however larger changes will cause false alarms due to damage index changes bring out by temperature changes.

ACKNOWLEDGMENTS

Tomasz Wandowski acknowledges the support provided by research project IUVENTUS Plus No. IP2011 058971 founded by Ministry of Science and Higher Education from the budget for science in years 2012-2013.

REFERENCES

[1] L. Callegaro: *The metrology of electrical impedance at high frequency: a review*, Meas. Sci. Technol. 20 (2009), 1-14.

[2] C. Liang, F. P. Sun, C. A. Rogers: *An impedance method for dynamic analysis of active material system*, Journal of Vibration and Acoustics 116 (1), p. 120 – 128,1994;

[3] V. Giurgiutiu: Structural Health Monitoring: with Piezoelectric Wafer Active Sensors. Elsevier, 2008.

[4] S. Park, C.-B. Yun, D.J. Inman: *Wireless Structural Health Monitoring Using an Active Sensing Node*, Steel Structures 6, 361-368, 2006.

[5] J. Min, S. Park, C.-B. Yun, B. Song: *Development of a low-cost multifunctional wireless impedance sensor node*, Smart Structures and Systems, Vol. 6(5-6), 689-709, 2010.

[6] S. Na, K.K. Lee: *A multi-sensing electromechanical impedance method for non-destructive evaluation of metallic structures*, Smart Materials and Structures 22, 095011 (8pp), 2013.

[7] F. G. Baptista, J. V. Filho, N. Oki, A. E. Turra, Jr. V. Lopes, D. J. Inman, *Versatile and Easy-to-Assemble Measurement System for Impedance-Based Structural Health Monitoring*, Proceedings of the 8th International Workshop on Structural Health Monitoring 2011

[8] F.G. Baptista, D.E. Budoya, V.A. Almeida, J.A. Ulson: *An Experimental Study on the Effect of Temperature on Piezoelectric Sensors for Impedance-Based Structural Health Monitoring*, Sensors 2014, 14, 1208-1227; doi:10.3390/s140101208

[9] Analog Devices: *AD5933 Datasheet*, Rev. E., www.analog.com