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Influence of delamination and temperature conditions on electromechanical impedance

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Abstract

This paper focuses on damage detection in composite materials under temperature influence. Damage detection was based on electromechanical impedance method (EMI). This method uses a piezoelectric transducer to excite the structure and sense the response. Frequency spectra of electrical quantities are registered. Damage presence or external factors influence the shape of these spectra. In this paper result of detection and localization of artificially initiated delaminations in carbon fibre reinforced polymer CFRP samples are presented. Delamination causes frequency shift of certain resonance frequencies visible in resistance characteristic. In this paper temperature effects on EMI method are investigated. The problem of temperature influence and its compensation is addressed. An algorithm is proposed in order to compensate the temperature induced effects. Results show that temperature change causes frequency shifts. Moreover this frequency shifts are not constant, therefore the compensation needs to be performed in narrow frequency bands. Results shown that application of temperature compensation algorithm improved EMI method sensitivity to damage. Moreover results show that sensitivity to damage depends on frequency range.

1 INTRODUCTION

One of the obstacles for wide application of electromechanical impedance (EMI) method is the sensitivity to changing ambient temperature [1-5]. In the real part of impedance one observes horizontal shift in the whole frequency band and vertical shift especially for low frequency band [2],[6]. With the increasing temperature one observes leftward horizontal shift and reduction of amplitudes. The imaginary part of admittance shifts upward with the increasing temperature [7]. To overcome temperature influence temperature compensation algorithms are sought for. In [8] authors proposed effective frequency shift to achieve maximum correlation between baseline signal and compensated signal. In research reported in [2] data normalization technique based on Kernel Principal Component Analysis improved damage delectability under varying temperature. In [4] it was suggested that temperature influence is strongly frequency dependent. Authors proposed algorithm for temperature compensation based on cross-correlation and CC index. However they did not applied their methodology for damage detection. In research reported here a horizontal and vertical compensation was proposed and applied for damage detection in CFRP sample with delamination.

2 EXPERIMENTAL APPROACH

The EMI specra were registred with HIOKI IM3570 impedance analyzer that allow to perform measurements of electrical quantities in 4 Hz – 5 MHz frequency range. Measurements were performed with a piezoelectric disc transducer that was bonded on investigated sample. The disc had 10 mm diameter and 0.5 mm thickness, and was manufactured by NOLIAC (NCE51 material). The investigated sample was made of CFRP based on pre–pregs GG204P IMP503 42 (balanced fiber Plain 3K fabric). The sample had dimensions 200 mm x 600 mm x 3.5 mm with 8 layers.

3 TEMPERATURE INFLUENCE

During this research serial resistance of electromechanical impedance were registered. Initial reference measurement was taken in the laboratory condition at 23.5^{o}C. Measurements for other temperatures were taken outdoors. Seven resonant peaks visible at 23.5^{o}C were selected and traced for lower temperatures. In Table 1 frequency shifts for the temperature drop were compared. Frequency shift increases with temperature drop and with the peak frequency increase. These results agree with conclusion given in paper [4].

	Frequency peak at 23.5^{o}C [kHz]						
	5.921	7.350	7.892	11.390	13.070	17.171	17.970
ΔT [^{o}C]				Δf [Hz]			
6.7	9	11	9	21	20	39	41
7.7	10	12	16	23	33	49	53
9.3	12	16	19	36	40	69	69
13.2	19	29	37	47	87	104	132
14.5	20	32	40	60	89	119	146

Table 1: Frequency shift Δf of resonant peaks caused by temerature drop ΔT

The observed frequency shift needs to be removed from EMI spectra in order to avoid false system alarms not related to damage. The starting point for the research were studied reported in [4] and [8]. Approach presented in these papers are based on temperature influenced signal shift in order to maximize correlation with signal at baseline temperature. This is achieved by utilization of CC index:

$$CC = \sum_{i=1}^{n} \frac{\left[Rs(i)_X - \overline{Rs}_X \right] \left[Rs(i)_Y - \overline{Rs}_Y \right]}{\sigma_X \sigma_Y} \tag{1}$$

where: Rs(i)x is the i-th sample of serial resistance in signal at baseline temperature, Rs(i)y is the i-th sample of serial resistance in temperature influenced signal, dash above symbol represents the mean value, σ is the standard deviation.

As it was already presented, the frequency shift is strongly frequency dependent, here for CFRP sample resistance signal can be only temperature compensated for narrow frequency band. The whole frequency band (1 kHz – 20 kHz) was divided into five subbands (1–4.8 kHz, 4.8–8.6 kHz, 8.6–12.4 kHz, 12.4–16.2 kHz, 16.2–20 kHz). For each frequency sub-band temperature compensation is performed in order to maximize correlation with the baseline measurement at 23.5^{o}C. Results of the temperature compensation for resistance are presented in Fig. 1.

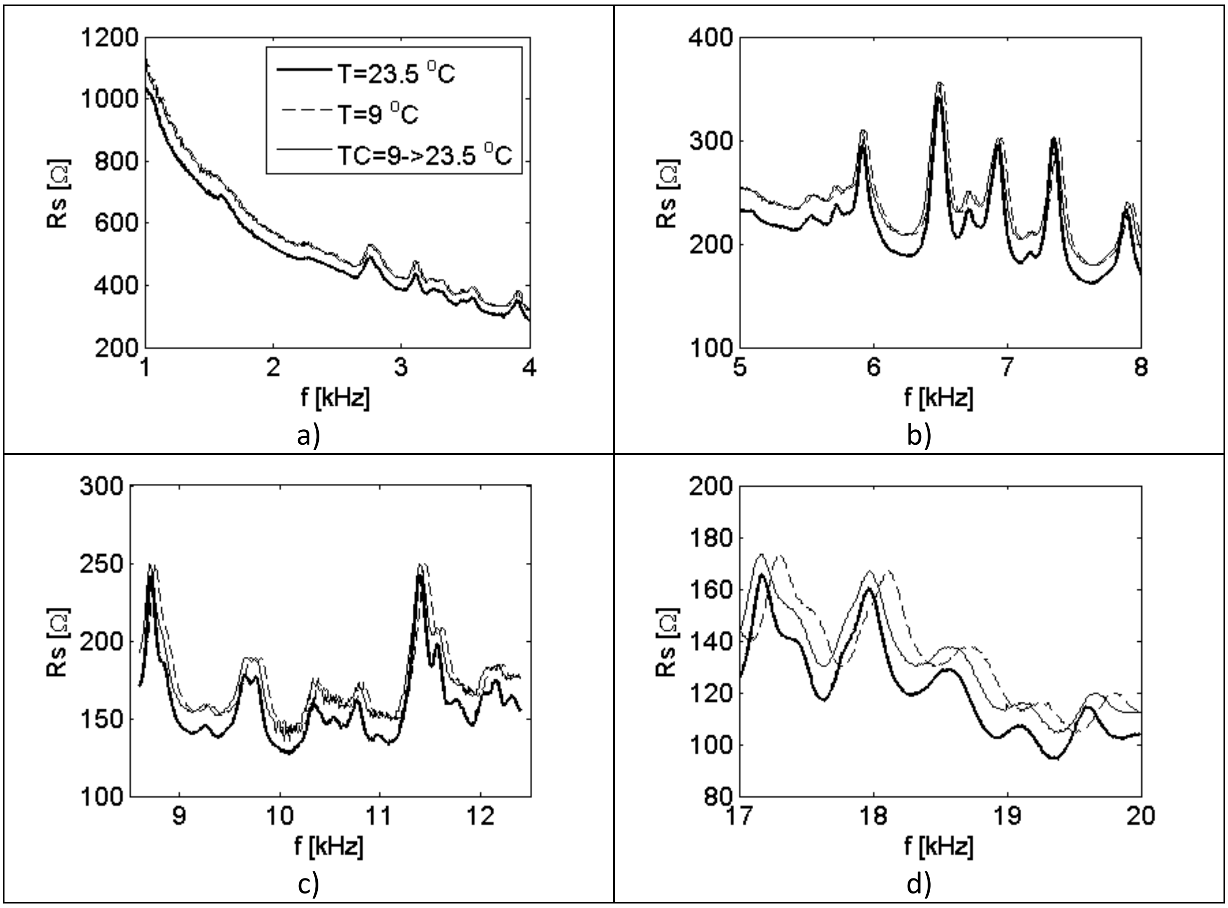
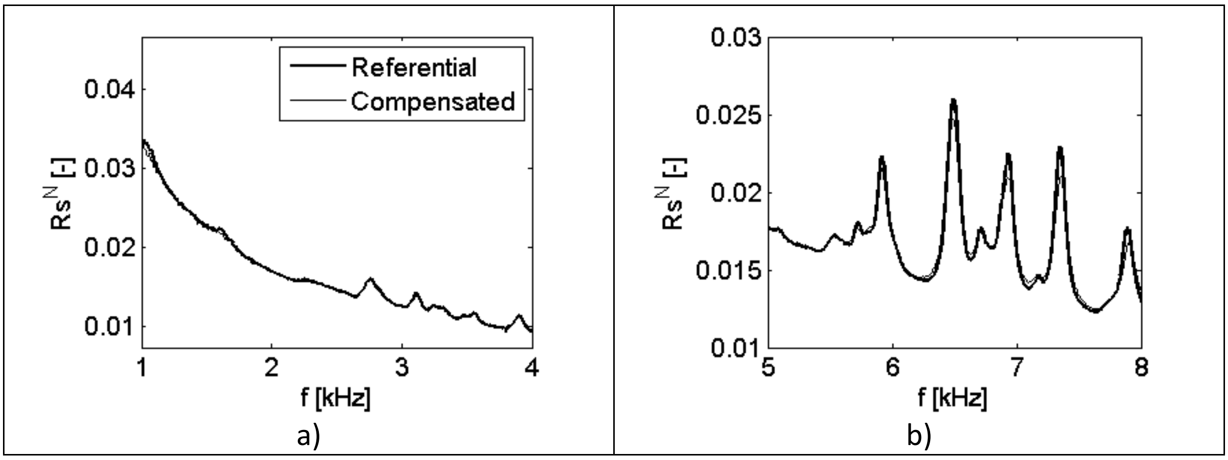


Figure 1: Results of temperature compensation (horizontal shift) using cross-correlation, frequency range: a) 1–4 kHz, b) 5–8 kHz, c) 8.5 –12.5 kHz, d) 17–20 kHz



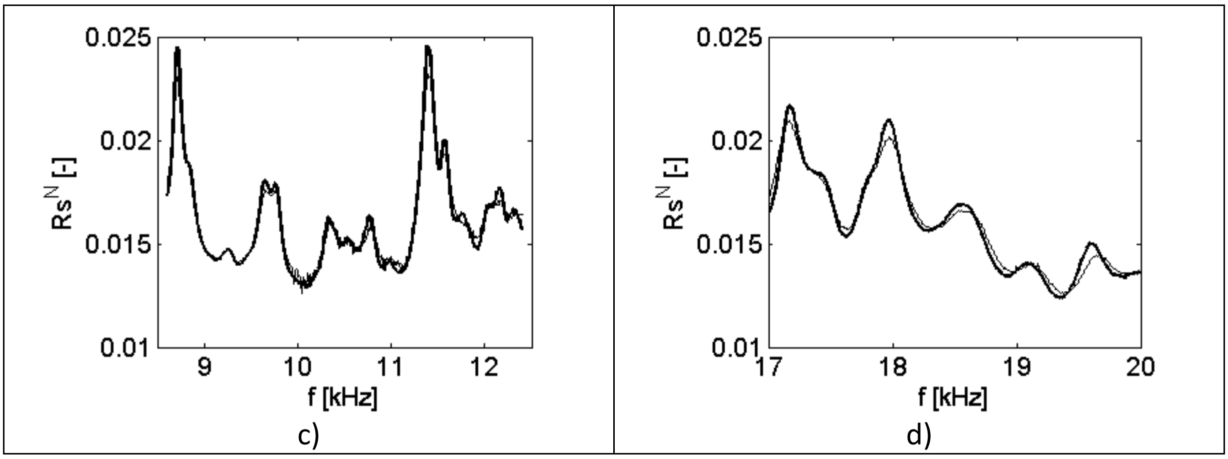


Figure 2: Results of temperature compensation (vertical shift) using normalization with RMS value, frequency range: a) 1–4 kHz, b) 5–8 kHz, c) 8.5 –12.5 kHz, d) 17–20 kHz

Frequency bands in Fig. 1 were limited for better figure resolution. In the case of the lowest frequency band (Fig. 1a) there is almost no frequency shift and as consequence spectrum for T=9^{o}C and compensated spectrum (TC) are covered. Results of compensation are visible for higher frequency bands (Fig. 1b–d). After compensation, TC is very similar to baseline. For highest subband (Fig. 1d) it can be noticed that not all peaks are compensated. Peak for frequency around 19.5 kHz is still a little bit shifted to the right in relation to the peak for baseline. This is due to frequency dependent signal shift caused by temperature. After temperature compensation still vertical shift can be noticed. In order to compensate vertical shift RMS value was used:

$$Rs(i)_X^N = \frac{Rs(i)_X}{RMS(Rs_X)} \tag{2}$$

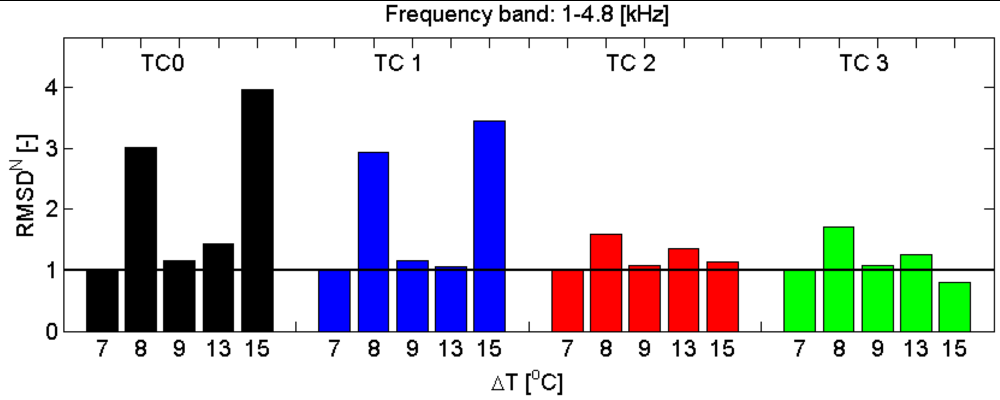
where RMS is defined as follows:

$$RMS(Rs_X) = \sqrt{\sum_{i=1}^{n} [Rs(i)_X]^2} \tag{3}$$

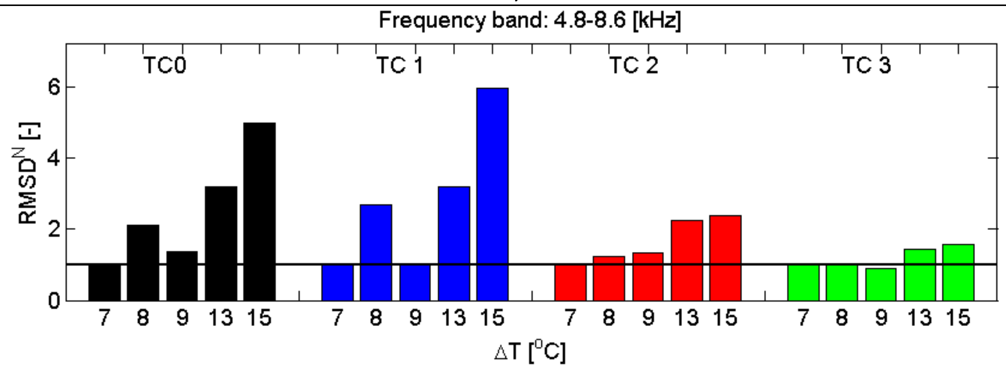
After such signal normalization vertical shift is reduced. In the Fig. 2 comparison of baseline and signals compensated by CC index and RMS (Compensated) are presented. In the case for lowest frequency band Fig. 2a signals are almost identical. In the case of next two frequency subbands with higher frequencies Fig. 2b and 2c small differences exist near maxima of peaks. The worst situation is for the last subband, but vertical shift was strongly reduced in comparison to situation presented in Fig. 2d. Compensated signal can be further used for comparison with baseline signal in order to perform damage detection process. In this research popular RMSD index was used.

Before the proposed approach was used for damage detection, it was tested for temperature compensation. The RMSD index compared the baseline (at 23.5^{o}C) and spectrum after temperature compensation (Fig. 3). In the Fig. 3a)-e) results for five frequency sub-bands are presented. In each plot four groups of results are presented. In each group results were normalized. Zeroth group (TC0) presents RMSD without temperature compensation. The first group (TC 1) shows RMSD index after CC compensation. Second group (TC 2) shows RMSD index after RMS compensation (2).The third group (TC 3) shows results after compensation using CC and RMS.

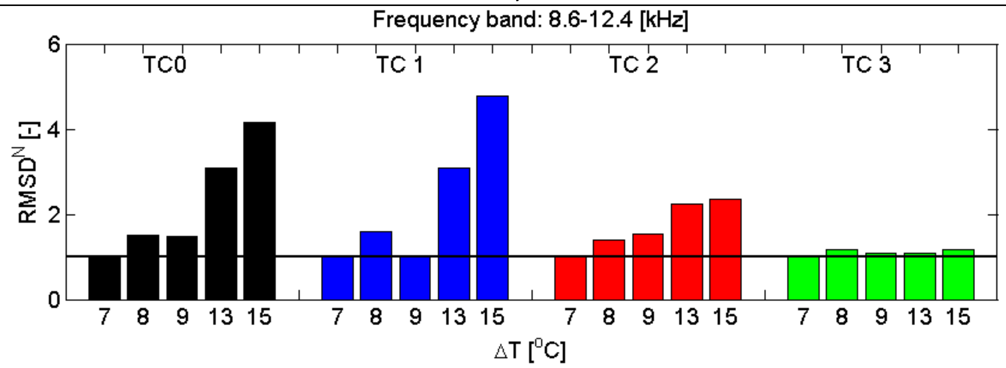
After compensation using cross-correlation (TC 1) spectra are correlated however vertical shift still exists that makes RMSD index high. After normalization using RMS value (TC 2) values of RMSD indexes were reduced in comparison for the case without compensation. In the last case (TC3) the best results were achieved. Only in the case of 1–4.8 kHz band results of compensation TC 3 differ not much from results for TC 2 (Fig. 3a). For the rest cases values of RMSD are much more reduced in comparison to other groups, especially for frequency bands 4.8–8.6 kHz (Fig. 3b) and 8.6–12.4 kHz (Fig. 3c) where RMSD values for TC 3 group are reduced and equalized.



a)



b)



c)

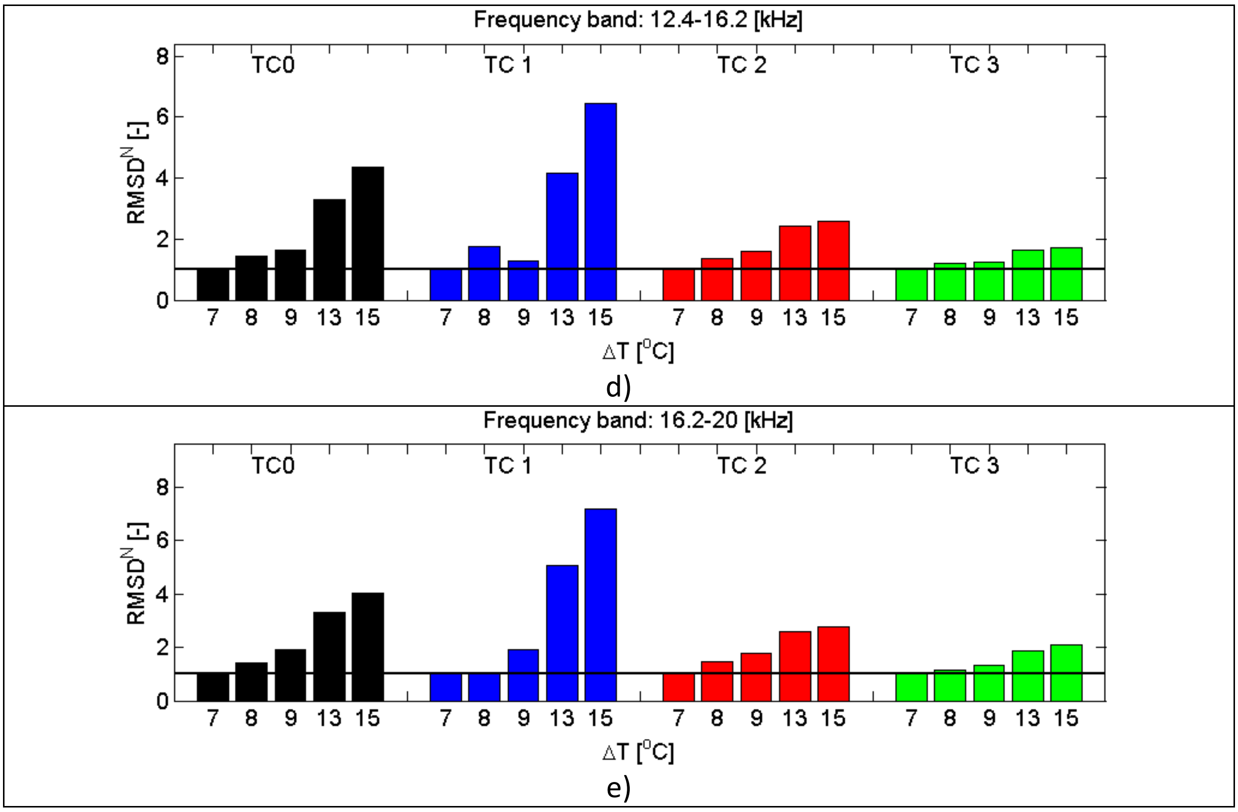


Figure 3: Influence of temperature compensation on RMDS index for different frequency subbands: a) 1–4.8 kHz, b) 4.8–8.6 kHz, c) 8.6–12.4 kHz, d) 12.4–16.2 kHz, e) 16.2–20 kHz.

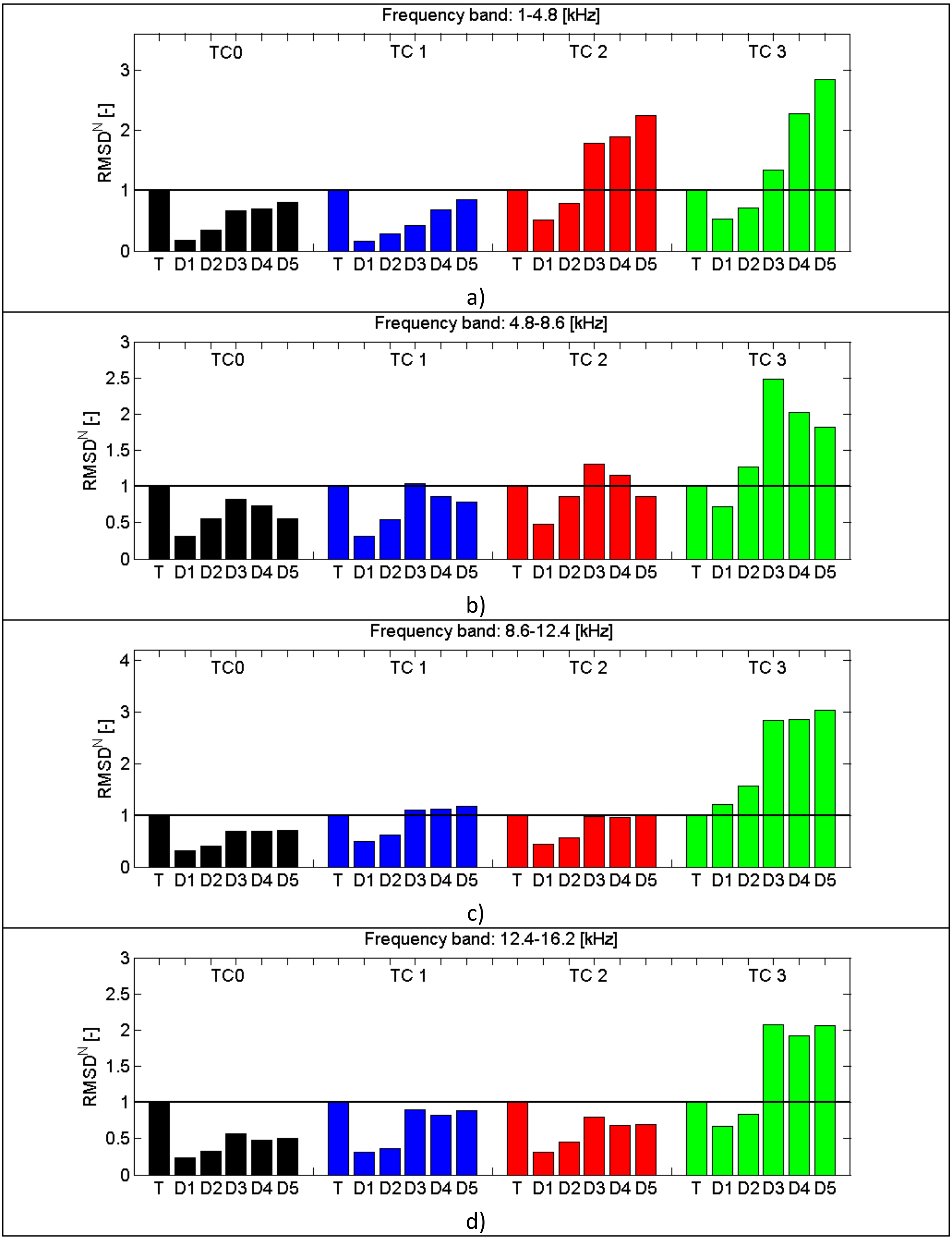
4 DAMAGE DETECTION

In next step proposed approach for temperature compensation was utilized for damage detection. Baseline signal for referential sample (damage free) was taken at 23.5^{o}C and for 4.5^{o}C (damage free). Next, five signals for different damage sizes were taken at 23.5^{o}C. Damage was in the form of artificially made delamination. In order to characterize extent of delamination length and width were measured (Table 2). Length was measured along the longer edge of the sample (600 mm) where delamination was initiated. Width of delamination was measure along shorter edge.

Case #	L [mm]	W [mm]
D1	10	5
D2	35	10
D3	70	25
D4	100	40
D5	130	60

Table 2: Dimensions of artificially made delamination in the first CFRP sample.-

Results of damage are gathered in Fig. 4. As before, the results are divided in four groups (TC0, TC1, TC2, TC3). Results are also divided for the same five frequency sub-bands. Case denoted as T shows RMSD value for comparison of damage free signals taken at 23.5^{o}C and 4.5^{o}C. Cases D1–D5 show values of RMSD index for damage cases listed in table 2.


Frequency band: 1-4.8 [kHz]
TC0
TC 1
TC 2
TC 3
RMSD^N [-]
0
1
2
3
T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5
a)
Frequency band: 4.8-8.6 [kHz]
TC0
TC 1
TC 2
TC 3
RMSD^N [-]
0
0.5
1
1.5
2
2.5
3
T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5
b)
Frequency band: 8.6-12.4 [kHz]
TC0
TC 1
TC 2
TC 3
RMSD^N [-]
0
1
2
3
4
T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5
c)
Frequency band: 12.4-16.2 [kHz]
TC0
TC 1
TC 2
TC 3
RMSD^N [-]
0
0.5
1
1.5
2
2.5
3
T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5 T D1 D2 D3 D4 D5
d)

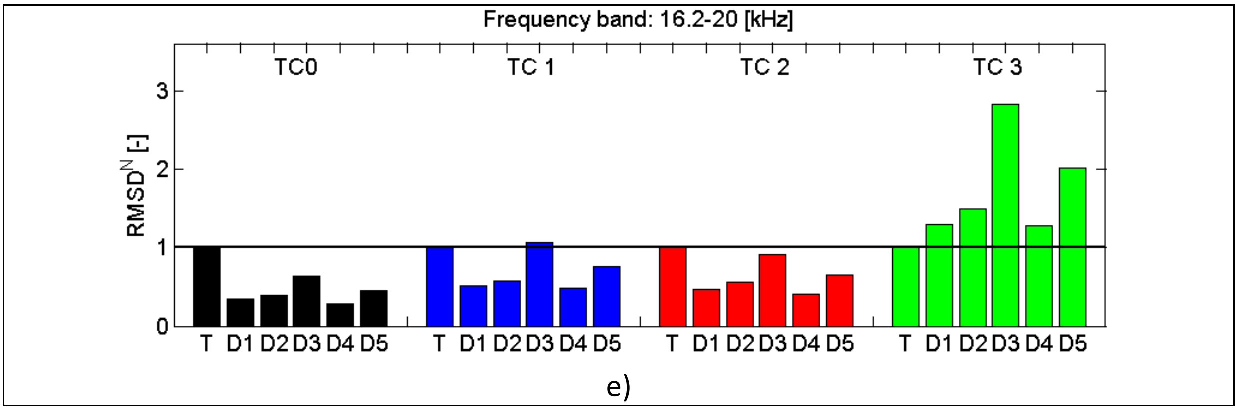


Figure 4: Influence of temperature compensation on RMDS index values for different sample state, for different frequency sub-bands: a) 1–4.8 kHz, b) 4.8–8.6 kHz, c) 8.6–12.4 kHz, d) 12.4–16.2 kHz, e) 16.2–20 kHz.

In all frequency subbands for TC0 the RMSD index for temperature difference (T) is always higher than for damage cases (D1–D5). Damage cannot be detected in such conditions. Using first level comensation (TC1) it can be seen that delamination presence can be detected for some cases. RMSD values are larger than for T case: D3 (Fig. 4b), D3–D5 (Fig. 4c), D3 (Fig. 4e). After using only RMS value (TC2) it can be noticed that delaminations: D3–D5 can be detected for frequency band 1–4.8 kHz (Fig. 4a) and D3–D4 for 4.8-8.6 kHz (Fig. 4b). After the full proposed temperature compensation with CC and RMS (TC 3) the results are even more improved. Smallest delamination D1 can be detected in the frequency sub-bands: 8.6–12.4 kHz (Fig. 4c) and 16.2–20 kHz (Fig. 4e). Delamination D2 can be detected in the frequency sub-bands: 4.8–8.6 kHz (Fig. 4b), 8.6–12.4 kHz (Fig. 4c), 16.2–20 kHz (Fig. 4e). D3–D5 cases were detected in all frequency subbands.

The best sensitivity to delaminations after temperature compensation based on proposed approach can be observed for frequency subbands: 8.6–12.4 kHz and 16.2–20 kHz. In these cases all delamination extents are detected. It should be noticed that values of RMSD index are not strictly related to delamination extent. It can be clearly see in Fig. 4e). Similar fact was reported in [9].

9 CONCLUSIONS

A detailed analysis of influence of changing temperature on measurements of resistance in EMI method was presented. This analysis was performed for composite CFRP sample. Temperature change causes frequency shift of resistance signals and this frequency shift increases with frequency. For this reason compensation need to be performed in narrow frequency bands. Improved method for compensation of temperature influence was proposed. This is two step method based on compensation of horizontal shift using CC and compensation of vertical shift using signal normalisation with RMS value. The proposed comensation method was tested for damage detection process. For the purpose of damage detection RMSD index was used. Obtained Results showed that application of temperature compensation algorithm improved EMI method sensitivity to damage. Before introducing the temperature compensation, damage index for delaminations had much smaller values than for temperature change. Moreover, experimental results show that sensitivity to damage in the form of delamination depends on frequency range.

ACKNOWLEDGMENTS

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