IDENTIFICATION OF INHOMOGENEOUS COVER LAYER BY NON-CONTACT ULTRASONIC METHOD – STUDIES FOR MODEL MATERIALS

CARACTÉRISATION DE L'ENROBAGE EN BÉTON PAR ONDES ULTRASONORES AVEC CAPTEURS SANS CONTACT – ÉTUDE SUR MATÉRIAUX MODÈLES

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ABSTRACT

The paper is devoted to validation of the method of identification of inhomogeneous cover layer of materials. The identification procedure applies non-contact ultrasonic technique of surface waves with air as the coupling medium and optimisation method which searches the best fit of the Thomson-Haskell model of surface waves in layered medium to experimental data. Within the work the experimental studies were performed for two material systems: PMM (cover layer) over aluminium and the concrete class C8 (cover layer) over the concrete class C20. The thickness of the cover layer was from few millimetres to few centimetres. The experiments were performed over frequency range from 40 to 250kHz. The cover layer mimics the degraded layer of structural materials. The identification procedure uses dispersion curves of pseudo-Rayleigh waves and the identified parameters are thickness of the cover layer and velocities of the shear waves in the materials of layers.

Keywords: *Concrete, surface waves, cover layer, inhomogeneity, dispersion, inversion, non-contact measurements, NDT*

1. INTRODUCTION

For the materials of concrete building structures which are exposed to harmful interactions with environment with strong changes in humidity and temperature (in particular in the case of negative temperatures) or interaction with chemicals or biological species a degradation of materials starts from their surface and penetrates into their body. In the surface layer (cover layer) concrete may change its structure and/or properties, in particular it usually increases porosity and permeability and decreses the strenght and stifness. The changes in properties of cover layer have direct influence on accelerated degradation of the body of concrete (including reinforcement) and as the result a drop of durability of a structure.

The evaluation of properties of concrete, including the presence of changes in the cover layer, can be based on non-destructive methods, e.g. ultrasonic techniques [2,5], and in most cases for this purpose the contact techniques are used. The techniques need application of a coupling medium (usually fluid) in order to adjust acoustic coupling between the materials and transducers. The coupling fluid however in the case of concrete is absorbed into the material and as the result it causes nonstationarity of ultrasonic signals during the tests. The phenomenon is particularly visible when the cover of concrete is degraded and its porosity assumes higher values. Thus, it is reasonable to use in diagnosis of concrete (e.g. evaluation of strength and parameters determining durability such as porosity or permeability) some non-contact methods, [1,6,7].

In this work the evaluation of identification method of inhomogeneous cover layer of materials with help of non-contact ultrasonic surface waves method is performed. The experimental ultrasonic studies use air as the coupling medium and are focused on determination of dispersion of surface waves in inhomogeneous layered model materials. The application of the Thomson-Haskell model and optimization have allowed to determine selected parameters of the studied system. The comparison of results of identification with data obtained through independent tests have allowed to evaluate effectiveness of the developed method. The tests were performed for two groups of model materials: the layered system of PMM over aluminium and different systems of inhomogeneous concrete.

2. EXPERIMENTAL SYSTEM, TESTED MATERIALS

We apply ultrasonic non-contact method of transmission of surface waves. The experimental studies have been done using the measurement system (a robot) the idea of which was presented in [1, 6]. The system is equipped with two non-contact ultrasonic transducers, an arbitrary signal generator, oscilloscope, a system of automatic positioning of transducers with respect to the studied material, and a computer with appropriate software for signal acquisition and processing. The measurement apparatus and the concept of wave process used in the studies are shown in Fig. 1. The transmitting transducer (T) can be solely rotated while the receiving transducer (R) can be rotated as well as displaced along the surface of studied material. One of the significant stage of the measurement procedure constitutes the proper orientation of the transducers with respect to the surface of the tested material (Fig. 1b) to ensure the angles which are slightly larger than the second critical angle α_c for the case of wave transmission from air to the material. According to the Snell's law the angle is (1):

$$\alpha_c = \arcsin \frac{V_{Air}}{V_S} \qquad (1)$$

Where: V_{Air} and V_S are velocities of longitudinal waves in air and shear wave in the studied solid material.

The positioning of the transmitter and receiver at the angle is the condition for the generation and reception of surface waves, Fig. 1b. The longitudinal surface waves in the presented studies were introduced into materials under angles from 6^o to 12^o, depending on the properties of the tested materials. For each test the initial position of the receiver was the closest to the transmitter and than it moves away.

The elementary spatial step (Δx) and the total displacement of the receiver (L) are established by the operator and for the presented case were Δx = 5mm and L=185mm, respectively. The transmitter was excited by the linear chirp (the frequency modulated sinusoidal signal). The leaky wave from the tested materials are acquired by the receiver, the signals are converted to digital form and correlated with the signal which is used to excite the transmitter. The final result is obtained using 10 times averaging. The frequency range of excitation which was used amounted from 40 kHz to 250kHz while the central frequencies of the applied transducers (Ultran Group) were 50, 100 and 200 kHz. For each sample three tests along parallel profiles (pathways) distant 35mm from each other were done. The number of acquisitions for a profile amounts 37.

The experiments were performed for two groups of model two layered materials: the system PMM (cover layer with thickness 5.5mm) glued to aluminium (base with thickness 100mm) and the concrete class C8 (cover layer with thickness 10 or 20mm) and the concrete class C20 (base with thickness 105 and 95mm), see Fig. 2. The samples of concrete were made by moulding the wet cover concrete on the wet base concrete and vibration compacting. The layers of PMM and concrete class C8 represent the degraded cover layer of structural materials. The parameters characterizing properties of the component materials are gathered in Table 1 (the columns – data measured directly). In the case of concrete the density was determined by indepen-

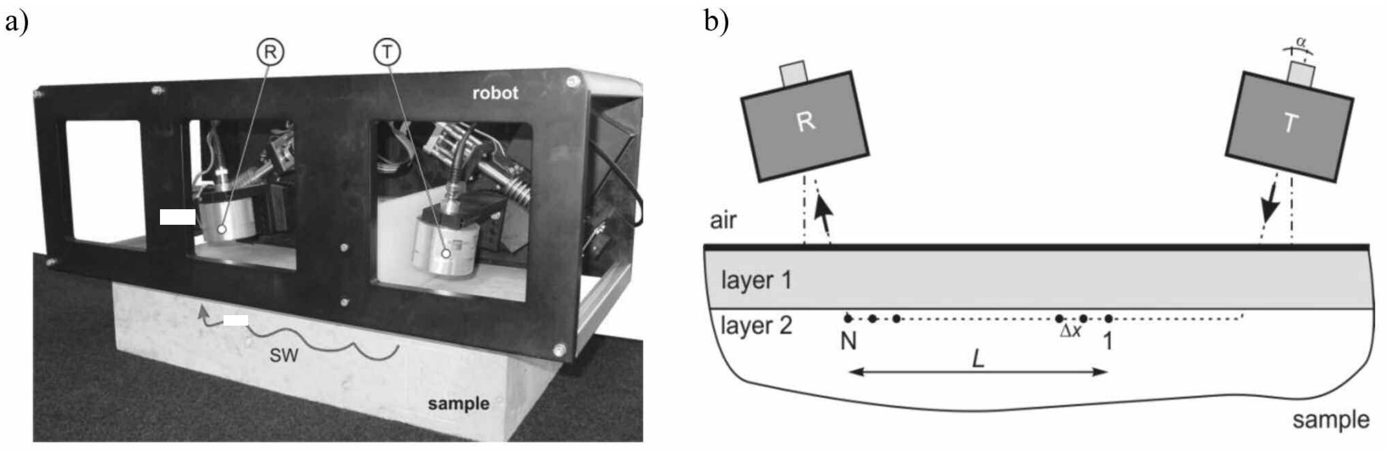

Figure 1. The experimental system (robot) for studies of surface waves (a) and the idea of wave propagation process in the material (b); T- transmitter, R- receiver, SW-surface wave.

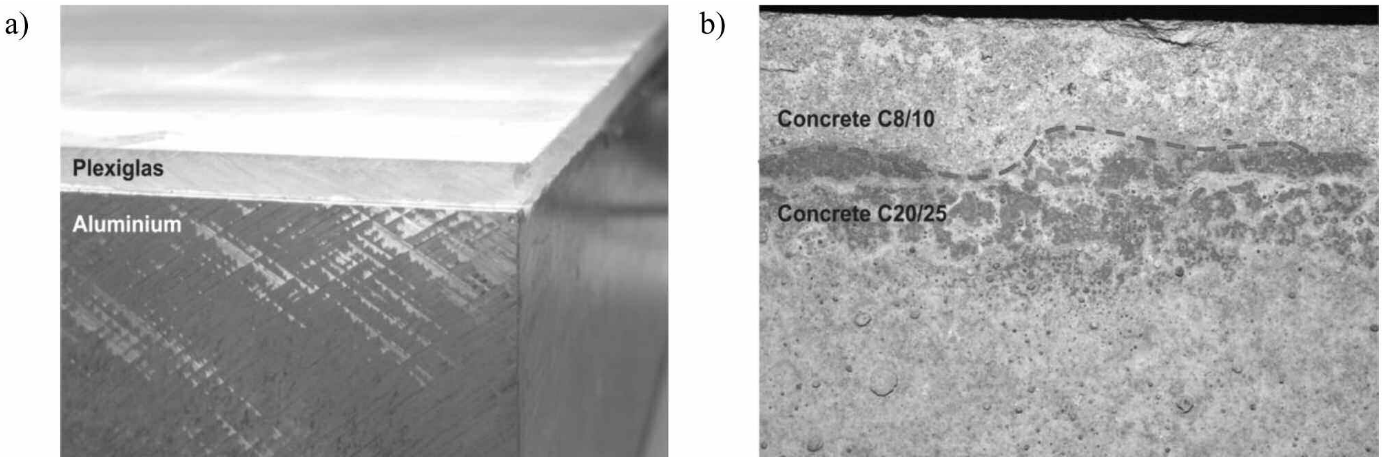

Figure 2. The samples of studied materials: the system PMM (cover) over aluminium (a) and two layer concrete of class C8 (cover) over C20 (b).

dent evaluation of mass and volume of the materials while the velocities of longitudinal and shear waves were found by the contact transmission methods using transducers with central frequencies 0.5MHz (Panametrics V318 for the longitudinal waves and V151 for the shear waves), the pulser/receiver PR5058 (Panametrics) and oscilloscope WJ324A (LeCroy). The silicone protective membranes (for longitudinal waves) or special coupling liquid (for shear waves) were used to improve the energy transmission. In the case of PMM over aluminium the wave velocities were found by the echo method.

3. MODEL, SIGNAL PROCESSING AND IDENTIFICATION PROCEDURE

The physical model used to derive dispersion characteristics of the surface waves for the considered layered materials, which is necessary for the developed identification technique, is based on the Thomson-Haskell model [8]. The model relates dispersion characteristics of different wave modes of pseudo - Rayleigh waves with mechanical properties and thickness of layers. The model assumes jump of mechanical properties at joints of layers and infinite half space of the most remote material from the surface. The solution of the dispersion equation requires finding of multiple roots of the homogeneous algebraic equation as the functions of frequency (or wavelength) of the waves and is realized by a numerical technique. In the case of using solely the fundamental wave mode, as is in the proposed procedure, the wave mode which has the lowest velocity is taken into account.

The signals registered for a single profile are processed with the Slant Stack transformation leading to maps of wave surface velocity as the functions of frequency as it shows in Fig. 3. The extraction of the maximum values on the maps (white dotted lines) gives the dispersion curves of the fundamental mode. The data constitute the input data for the solution of inverse problem leading to identification of parameters, [4].

The algorithm of solution of the inverse problem uses as the objective function the minimization of the least square error function of the wave velocity (the difference between the velocity determined from experiment and predicted by the model) for the trustworthy range of frequency. The range and number of data within the range was determined based on the experience with the applied technique. The minimization procedure uses hybrid optimization methods which combine global and local techniques [5]. The software performs the optimisation multiple times with different starting points selected randomly and leading to

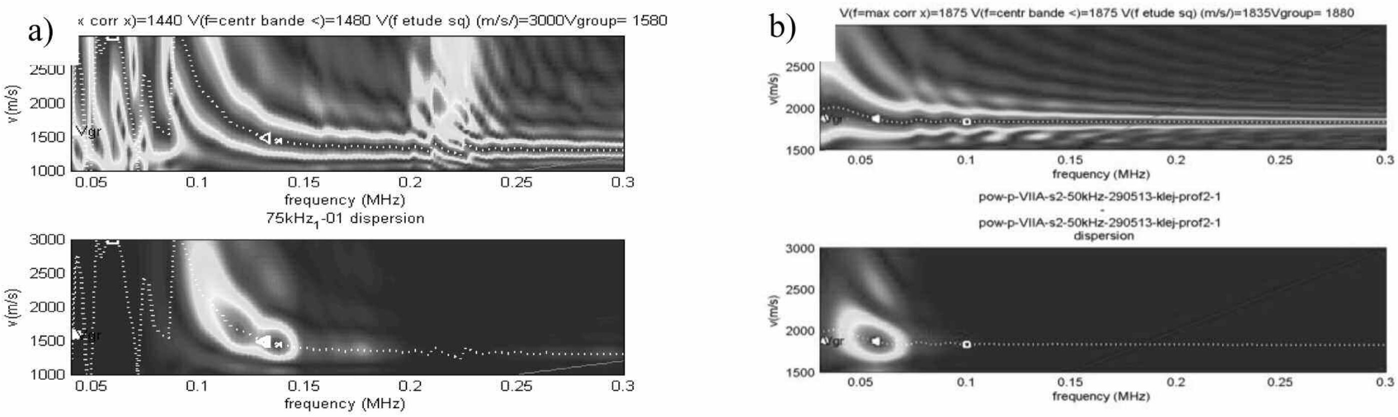

Figure 3. The dispersion curves of surface waves determined for: (a) the systems PMM-aluminium and (b) the layered concrete C8-C20 (the cover layer with thickness 10mm).

different levels of quality of fitting. The software was written in Matlab environment.

4. RESULTS

The parameters which were assumed as unknown were velocities of shear waves in the two layered systems and thickness of the cover layer. The other parameters (input data): densities and velocities of longitudinal waves in the materials were assumed as known and the values determined from the independent direct tests were used (see Table 1). In Fig. 4 the numerical results of the solution of the inverse problems for the systems: PMM-aluminium (a, b), and concrete class C8-C20 with thickness of the cover layer ~10mm (c, d) and ~20mm (e, f) are presented. The red curves in Fig.4a,c,e represent experimental data while the black curves refer to model predictions for the best fit. The results obtained for the system PMM-aluminium are slightly better than for the concrete systems. The discrepancies observed for concrete may result from the fact that in the physical system properties of concrete at the joints between layers may change continually as the result of mutual penetration of the materials during samples formation while the model assumes sharp changes. Moreover, as it is seen in Fig. 2b the surface between the layers is not perfectly flat as it is for the PMM-aluminium system. Figures 4b,d,f show distributions of the shear wave velocity V_S as the functions of depth measured from the surface and determined for a set of the best fits along with the averaged values and standard deviations. The coordinates corresponding to the jump of the averaged shear wave velocity is assumed as the thickness of the cover layer. The thickness determined for the PMM-aluminium system was ~ 5.9mm (std 1.21%) (Fig. 4b), for the concrete with thin cover (Sample10) it was ~11.1mm (std 8.5%) (Fig. 4d), and for the thick cover (Sample20) it was~20.9mm (std 10.5%) (Fig. 4f). The **Table 1** compares the results obtained by inversion and measured directly. The difference between the directly measured thickness of the layered systems and the one identified with the considered non-contact technique was for the PMM–aluminium system ~0.4mm (~7.3%), for the concrete with thin cover (Sample10) ~1.1mm (~9%), and for the concrete with thick cover (Sample20) ~1.1mm (~5.3%). Thus, the results give approximate values of the cover with the precision better than 10%.

The difference between the shear wave velocities identified by the non-contact method of surface waves and measured directly amounts for the PMM and aluminum ~73m/s, and ~61m/s, respectively, for the system characterized as Sample10 and concrete C8 and C20 it is ~83m/s, and ~395m/s, respectively, and for system Sample20 and concrete C8 and C20 it is ~98m/s and ~243m/s. The highest differences were noticed for concrete class C20.

The shear wave velocities determined for concrete by indirect non-contact method of surface waves are lower than the values measured directly by contact method. The potential sources of discrepancies are inhomogeneity within layers, measurement errors related to problems with contact for direct technique, and limitations of the applied model of layered material which assumes a single layer over an infinite half space. In Fig. 5 the comparison of the least square error functions of the solution of the inverse problem normalized with respect to the average velocity of surface waves for a set of the best iterations of the procedure for all the studied systems are presented. The range of the error functions for the systems PMM-aluminium, concrete Sample10 and concrete Sample20 are: 0.91÷1.07%, 0.74÷0.92%, and 0.97÷1.32%.

5. SUMMARY

The paper presents efforts undertaken in order to evaluate the effectiveness of identification of cover layer of model materials with help of non-contact surface wave method and inversion procedure. The experimental tests were performed for two-layered systems PMM-aluminium and inhomogeneous concrete C8-C20 with the thickness of

Layers	Input data		Data determined directly				Results of identification		Relative difference [%]	
	ρ [kg/m3]	V_L [m/s]	ρ [kg/m3]	V_L [m/s]	V_S [m/s]	Layer thickness [mm]	V_S [m/s]	Layer thickness [mm]	**$\Delta V_S/V_S$**	**$\Delta L_t/L$**
PMM	1200	2700	1180	2700	1370	5.5	**1393**	**5.9**	**1.6**	**7.3**
Aluminum	2800	6400	2800	6420	3104	100	**3165**	**-**	**1.96**	**-**
Sample10 C8	2000	3100	1995	3112	1945	12.2	**1862**	**11.1**	**4.3**	**9**
Sample10 C20	2400	4850	2364	4842	2924	105	**2529**	**-**	**13.5**	**-**
Sample20 C8	2100	3000	2095	3024	1937	22	**1839**	**20.9**	**5**	**5.3**
Sample20 C20	2400	4860	2379	4859	2880	95	**2637**	**-**	**8.5**	**-**

V_L the velocity of longitudinal wave, V_S the velocity of shear wave.

Table 1: Properties of studied materials and results of identification.

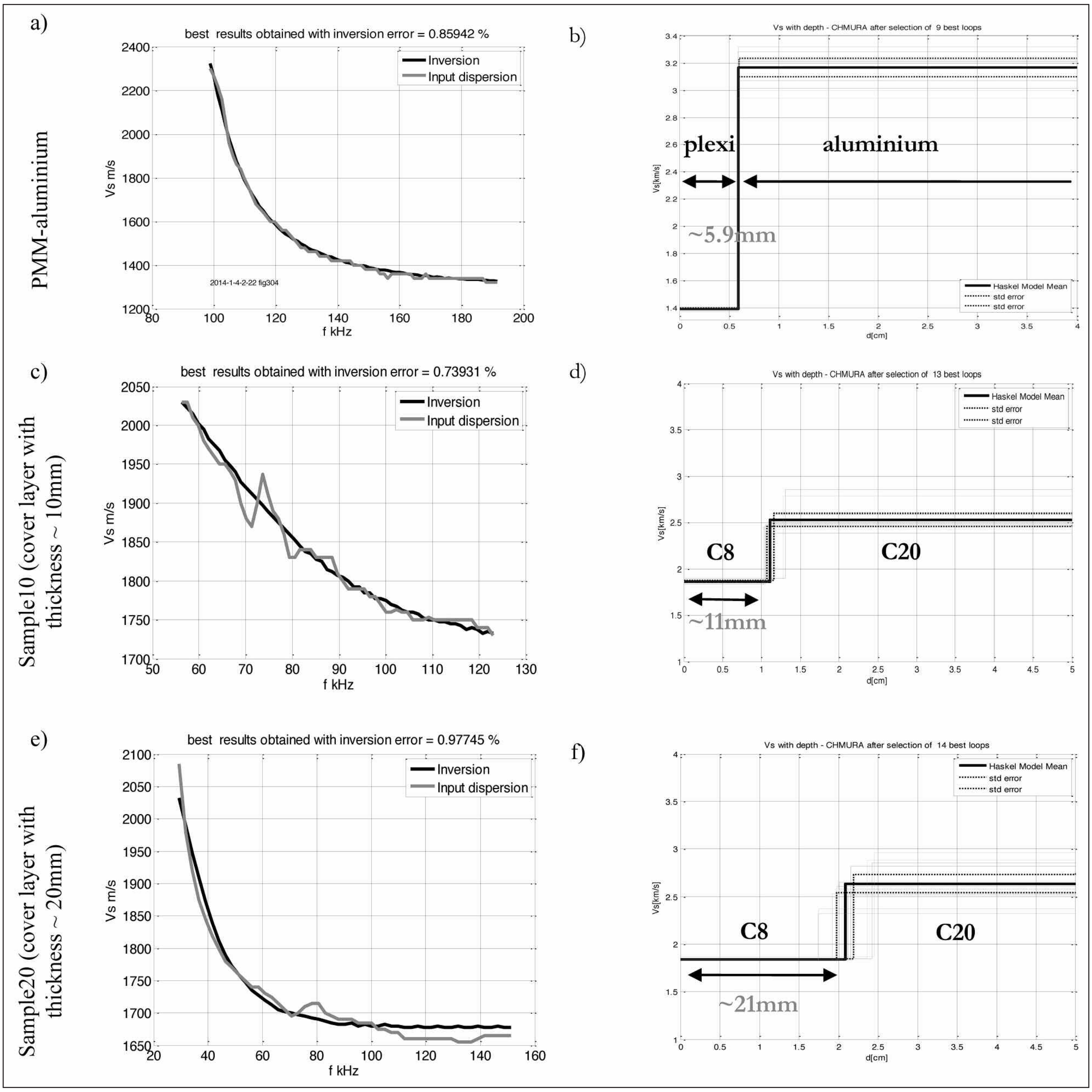

Figure 4. Comparison of dispersion curves obtained from experiments and as the result of the best inversion (left column) and distributions of the shear wave velocity VS as the functions of depth (right column) determined for the systems: PMM-aluminium (a,b), concrete C8-C20 with the cover 10mm (c,d) and with the cover 20mm (e,f).

cover equal to 10 and 20mm. The thickness of the cover layer and the shear wave velocities for both materials of layers were found using the Thomson-Haskell model and optimization technique implemented in Matlab environment.

The obtained results confirm efficiency of the proposed identification method for the inhomogeneous materials with relatively sharp changes of material properties of the single cover layer. The differences of thickness and shear wave velocity determined directly and by numerical identification were from 5 to 9% and from 2% to 13.5%, respectively. The results may support application of the technique in engineering diagnostics. One should add that the results are obtained for the case when the list of input parameters includes densities and velocities of the longitudinal waves for all the materials of layers. In the case when the list of input parameters must be limited, the inversion procedure may have more problems with unique finding of parameters and longer time of calculation should be expected. Further studies of the factor are planned in the future. Also the evaluation of the discussed method in field conditions should be performed, particularly in the case when limited knowledge concerning number of layers and real properties of the materials of the system is available.

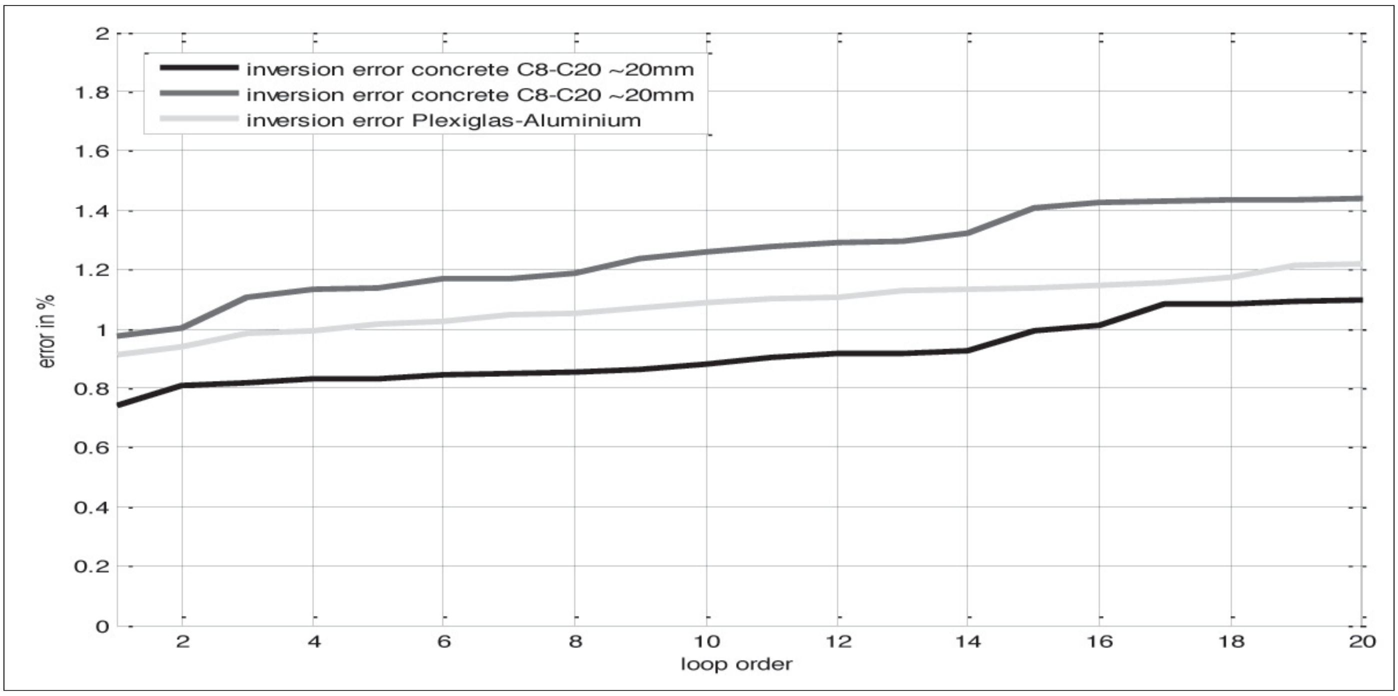

Figure 5. Comparison of the inversion errors for the 20 best inversions.

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