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Multi-parametric approach for assessment of deterioration in construction materials using ultrasonic surface waves

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As opposed to single-parametric ultrasonic pulse velocity measurements, a multi-parametric approach is proposed for assessment of the condition of constructional materials and early stages of its degradation. The method is based on acquisition of ultrasonic signals by stepwise profiling of the material surface at several frequencies in the range from 80 to 300 kHz. The analysis of the obtained 2D spatio-temporal waveform profiles allows us to extract case-specific parameters and features informative of deterioration. The parameters include group and phase velocities of head and surface Rayleigh waves, damping and dispersion of signals, frequency slope of attenuation, intensity distribution parameters in the spatio-temporal waveform profiles processed as images. Sensitivity of the method was confirmed in three use cases, including: a) surface quality in frost resistant concrete with rubber admixtures during freeze-thaw cycles; b) local structural deteriorations in refractory concrete subjected to high temperature; c) appearance of porosity in pultruded composite profiles due to inappropriate curing regimes.

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I. INTRODUCTION

Deterioration of structural materials leads to a decrease in their performance and quality that can be due to technological defects and the exposure to harsh environment. Non-destructive monitoring of the material's condition can help predicting the real strength and longevity. Routinely, the condition of construction materials is examined utilizing a single parameter like pulse velocity calculated from time-of-flight [1]. Although this parameter correlates with the strength of some materials like concretes [2], it is often not sufficient to identify the early stage of degradation and quantify its progressing. Particularly, it relates to concretes in the open air, where periodical freeze and thaw initiates deterioration expanding from the surface by depth with time [3]. In pultruded composite profiles, occasional non-even curing results in a partial loss of strength and some aside effects like porosity and delamination. Ultrasonic scanning in A- and C-modes is effective for damage detection [4], but it doesn't allow quantification of the accumulation of microstructural defects and characterization of the material properties.

A multi-parametric approach is proposed based on the surface transmission profiling at several frequencies in the range between 100 and 300 kHz. Analysis of thus obtained spatio-temporal waveform profiles at a dual-frequency acquisition was implemented in an experimental bone ultrasonometer[5,6] that helped discrimination of the early osteoporosis stage. The aim of this study was to demonstrate the sensitivity of the similar approach in assessment of the material deterioration in a range of constructional materials, including concretes and composites.

2. METHODOLOGY

The method is based on the step-by-step acquisition of ultrasonic signals along a profiling line on the surface of an examined object and analysis of 2D waveform profiles that are digital matrices formed by the plurality of consequently recorded signals. It is achieved by movement of the receiving transducer along a line on the surface in relation to the immovable emitter. At each scanning step, ultrasonic signals are obtained at several frequencies, at least two, during the same acquisition. The scan-obtained 2D profiles of ultrasonic waveforms show ultrasound propagation time on the x axis, where the y axis represents the distance coordinate and brightness codes the signal's amplitude (Figure 1). The matrices processing included the following steps: frequency filtering, equalization, averaging and parameter calculation. Complex analysis of the spatio-temporal waveform profiles allows calculation of the following deterioration informative parameters: a) group and phase velocities of head and surface Rayleigh waves - the indicators of stiffness and strength of the material; b) the ratio of signal intensities at higher and lower frequencies indicative of the deterioration process expanding by the depth due to the dependency of the propagation depth of Rayleigh waves on the wavelength; c) signal dispersion parameters due to increased scattering on micro-and macro- defects; d) morphologic parameters of the spatio-temporal waveform profiles processed as images, where the brightness distribution indicates the deterioration process.

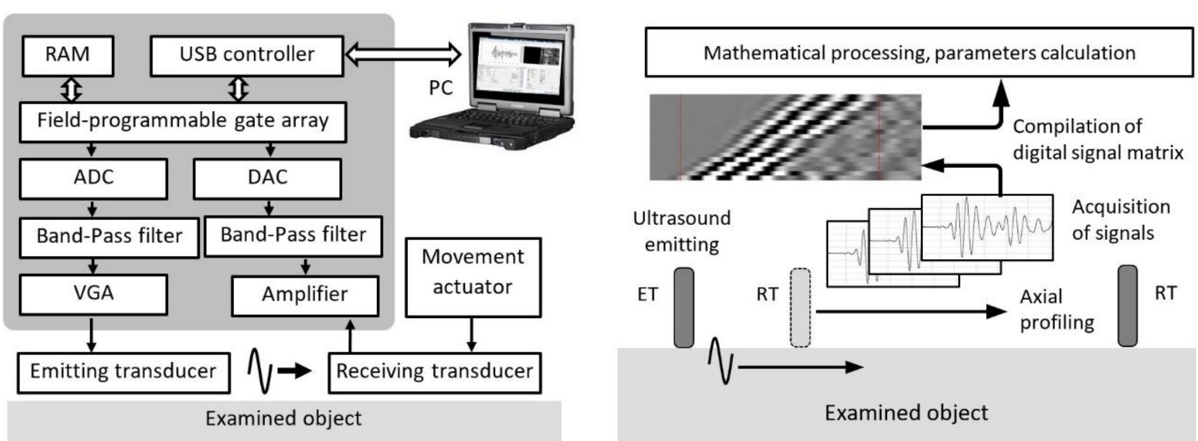

Figure 1. Diagrams of ultrasonic setup (left) and data acquisition (right).

3. RESULTS AND DISCUSSION

Three use cases were tried in which the deterioration of the material was caused by temperature effects: 1) frost resistant concrete; 2) refractory concrete and 3) pultruded composite profiles after curing.

Use case 1: frost resistant concrete. The aim of the study conducted at the Riga Technical University was to improve the frost resistance of concrete by inclusion of rubber particles (30 kg/m^3) and BASF microspheres (2 kg/m^3) into the composition in order to mitigate temperature deformation. Typical ready-mix concrete compositions of the strength class C 35/45 with locally available coarse aggregates, local quarry washed sand and a superplasticizer provided the workability and a low water-cement ratio. Frost resistance was tested in accordance with CEN /TS 12390-9 slab method, which included 56 cycles freezing cycle in 3 % sodium chloride solution. Surface scaling (the mass of delaminated material) was determined after a series of freezing cycles after 7, 14, 28 and 56 freeze/thaw cycles.

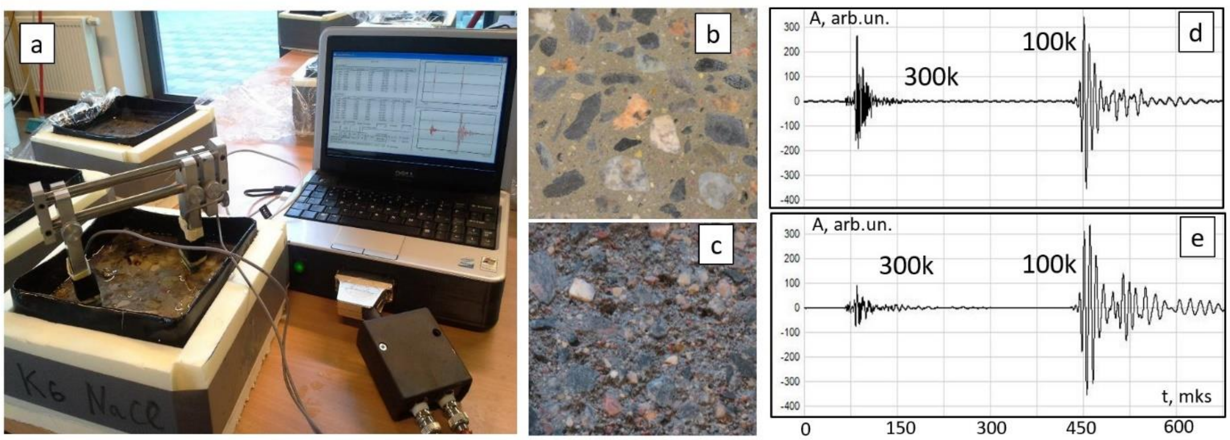

Figure 2. Testing of frost-resistant concrete: general view of experiment (a); examples of resisted (b) and damaged (c) surface layers of concrete specimens after freeze-thaw cycles; d and e – examples of raw signals at 300 and 100 kHz at the same amplification before and after freeze/thaw cycles.

Ultrasonic testing was done in parallel to scaling tests (Figure 2). The surface profiling was carried out at two frequencies, 100 and 300 kHz to obtain signals of Rayleigh wave at two wavelengths with different effective penetration depths. Deterioration of the surface layer in the reference group of specimens started right after the first series of freeze/thaw cycles. After 56 cycles, scaling reached there 1200 g/m^2 in average, while in the specimens with rubber and BASF additives, the surface layer remained visually intact and average scaling didn’t exceed 25 g/m^2. The deterioration of the surface layer and its expansion in depth were manifested in the following consequent changes: 1) a decrease of the 300 kHz signal and a lowering of the 300/100 kHz signals ratio; 2) complete disappearance of the 300 kHz signal below the noise level and a lowering of 100 kHz signal; 3) complete damping of the both 300 and 100 kHz signals at severe destruction of the surface layer with multiple surface cracks. The integrals of the signals amplitudes at 300 and 100 kHz and its ratios were found to be indicative of degradation stages of the surface layer. In frost resistant specimens, this ratio remained almost the same, whilst in the reference specimens it decreased manifold just after first 7 freezing cycles.

Use case 2: refractory concrete. A research conducted at the Vilnius Gediminus Technical University on medium-cement refractory concretes is aimed at finding of a right composition, comprising microsilica, mullite filler, deflocculant and fibers in order to provide the best fire resistance and durability. Ultrasonic testing is considered to assess the dynamics, location and severity of destructive changes after the exposure to high temperatures. To estimate the sensitivity of the method, a cubic specimen of refractory concrete sized 20x20x20 cm heat-treated in the oven with a spatial temperature gradient from 250 to 900 ^{0}C was examined. 2D waveform profiles at 300 kHz were recorded in 5 lines on the facets of the cube according to the temperature gradient as shown in Figure 3.

The 2D waveform profiles shown on the right side of Figure 3 demonstrated a high degree of compliance to the high temperature effect manifested in: a) a gradual decrease of group velocity of the wave packet related to the slow-type surface Rayleigh wave; b) a gradual dispersion of the ultrasonic pulse by the time scale; c) an increase of attenuation. These manifestations are explained by a sequential accumulation of microstructural defects in the material not observable with the naked eye.

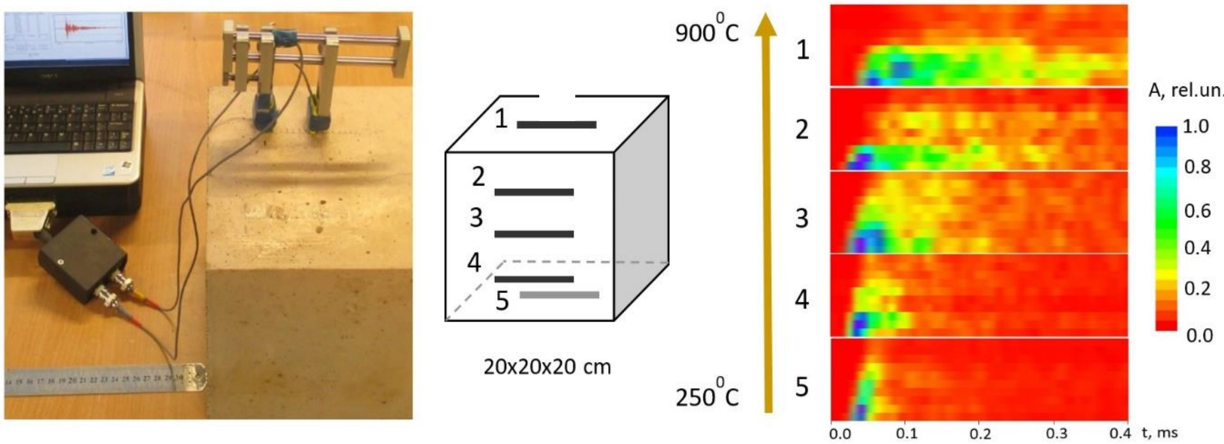

Figure 3. Testing of refractory concrete: general view of experiment; profiling lines 1-5 on concrete cube's surface and 2D waveform profiles at 300 kHz arranged in order according to lines 1-5 and temperature gradient.

Use case 3: pultruded composite profiles. Defects in pultrusion composite profiles such as increased porosity and delamination typically occur due to inappropriate curing regimen of polymer matrix. Optimization of curing regimens, specifically using numerical simulations of the process [7], requires feedback with the manufacturing process. Such feedback can be provided by an ultrasonic testing modality sensitive to appearance of tiny internal defects in a part of the cross-section and to changes of the matrix properties. Besides, this modality should be potentially applicable in the industrial environment.

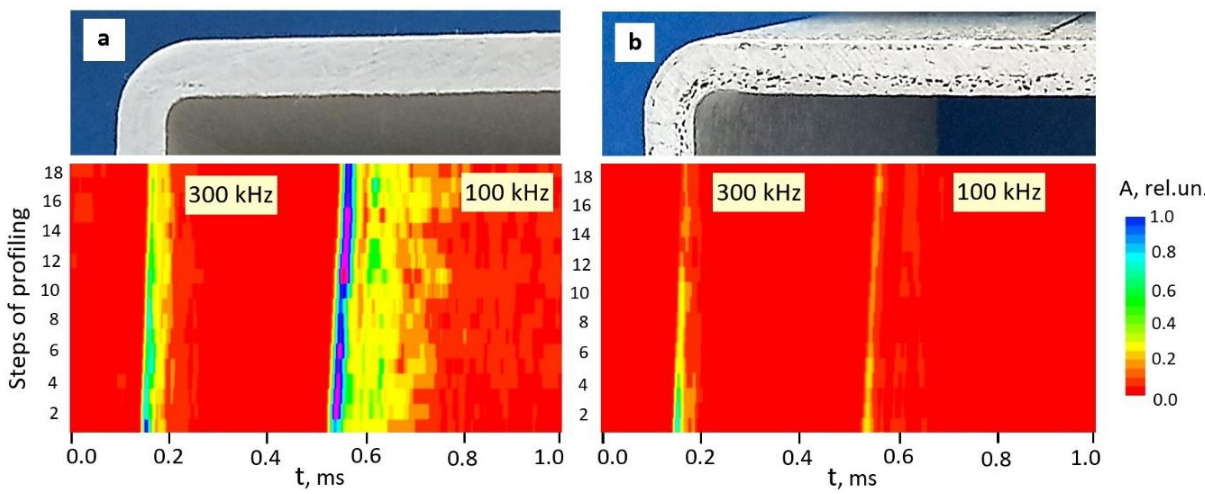

Figure 4. Testing of pultruded composite profiles: fragments of cross-section and 2D waveform profiles at 300 and 100 kHz in healthy (a) and defective (b) specimens.

2D waveform profiles at 300 and 100 kHz were compared in fragments of healthy and defective (porous) pultruded composite profiles presented by the manufacturing company Compor Ltd. (Salaspils, Latvia) (Figure 4). The main difference between these conditions was a dramatic decrease of the signals' intensity along the specimens. A stronger relative decline was observed at 100 kHz. This can be explained by the fact that the voids causing ultrasonic scattering were located at the far bottom surface of the profile and affected the surface wave with a larger wavelength at a relatively higher degree.

4. CONCLUSION

The selected use cases demonstrated sensitivity and potential efficacy of the multi-parametric approach based on 2D waveform profiles obtained by surface profiling for assessment of different features of deterioration processes in construction materials. The 2D waveform profiles by themselves can serve as imaging “footprints” of a certain material and its condition. Parameters derived from the 2D profiles such as group and phase velocities of surface wave, attenuation and dispersion, as well as parameters based on the images analysis using pattern recognition approaches, can be specified and quantified for particular applications.

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