Estimation of the acoustic properties of moist sand

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Introduction

In the petro-chemical industry, a petroleum tank bottom is an object of ultrasonic non-destructive testing (NDT). The damage mechanisms associated with tanks are complex. They include under floor corrosion (may be reduced with cathodic protection and drainage), and internal corrosion (reducing bacteria with sulphate, temperature control). In the NDT the most actual is corrosion of floor plates [9,10]. The fracture of corrosion products is detected together with leaks which are active during the actual monitoring period. Various NDT methods for inspection of tanks, such penetrant, magnetic particle, radiographic testing, eddy current, thermal infrared, acoustic emission and also ultrasonic techniques are used [9,10].

The floor of an above ground storage tank is impossible to inspect using conventional methods in the filled tank; therefore the optimal choice is to use the ultrasonic guided waves technique. In order to improve efficiency of this technique, further investigation is necessary to determine the influence of the acoustic properties of the moist sand (pedestal of the tank) on propagation of the guided waves through the bottom plates of the tank.

The main objective of the presented research is to estimate the acoustic parameters of the moist sand such as ultrasound velocity, acoustic impedance and frequency dependent attenuation. In order to simplify analysis the diffraction effects will not be taken into account. The experimental technique used for estimation of the attenuation function and ultrasound velocity is based on the model identification approach and the time of flight measurements.

Estimation of the acoustic properties

The ultrasound signal losses are caused at least by two phenomena: absorption and scattering. Which one factor is dominant depends on the properties of a material and the frequency of an ultrasonic wave. Very often for analysis of ultrasonic wave propagation an attenuation function taking into account both phenomena is used. In this case it is necessary to determine the functional dependence of the attenuation versus frequency $\alpha(\omega)$. In the case of through transmission measurements this dependence can be estimated from the ratio of the frequency spectra magnitudes of the reference signal transmitted through the material with well known acoustic properties (for example distilled water) and the signal transmitted through the test medium [8].

The attenuation and corresponding transfer function are monotonous functions of a frequency, but due to various artefacts like a limited bandwidth and influence of noise the experimentally determined functions possess an oscillating character. Also, at some frequencies spectra of the received signals possess values close to zero; therefore division of these functions may give an undefined result. So, from the practical point of view it is better to use approximation of a frequency dependent attenuation presented in an analytical form. For this purpose various approximation laws of the attenuation can be used. As it was found in literature on acoustical oceanography, for seabed sand the best results are obtained using the power law approximation with n=1..2 [12]. In this case the frequency dependent attenuation can be expressed in dB by $\alpha(f)=\alpha_0\left(\dfrac{f}{f_0}\right)^n$, where α_0 is the attenuation coefficient in dB at the frequency f_0 [1,2,4,5,7]. The coefficients α_0 and n are defined by the properties of the material. For calculation of these coefficients in the case of the plane wave it was assumed that signals are affected only by attenuation and there is no dispersion of the phase velocity. In this case the inverse transfer function of the material under investigation becomes

$$H^{-1}{}_{att}(x,f)=\frac{U_0(f)}{U_1(f)}=K\cdot \mathrm{e}^{k\cdot x\cdot a_0\left(\frac{f}{f_0}\right)^n}, \qquad (1)$$

where $U_0(f)$ is the frequency spectra of the reference signal $U_0(f)=\left|\mathrm{FT}(u_0(t))\right|$ and $U_1(f)=\left|\mathrm{FT}(u_1(t))\right|$ is the signal transmitted through the moist sand**,** x is a thickness of the medium, k=0.115. Here K is the relation of the transmission coefficients at the boundaries of the matching layers of the transducers - distilled water and matching layers of the transducers- moist sand [2]:

$$K=\frac{T_{m.l.-H_2O}\cdot T_{H_2O-m.l.}}{T_{m.l.-sand}\cdot T_{sand-m.l.}}, \qquad (2)$$

where transmission coefficients are given by:

$$T_{m.l.-H_2O}=\frac{2\cdot Z_{H_2O}}{Z_{m.l.}+Z_{H_2O}},\ T_{H_2O-m.l.}=\frac{2\cdot Z_{m.l.}}{Z_{m.l.}+Z_{H_2O}},$$

$$T_{m.l.-sand}=\frac{2\cdot Z_{sand}}{Z_{m.l.}+Z_{sand}},\ T_{sand-m.l.}=\frac{2\cdot Z_{m.l.}}{Z_{sand}+Z_{m.l.}}.$$

Then assuming that the measurements were performed in the test medium at the known base distance x=x_0 between the transmitter and the receiver, the coefficients α_0 and n may be found from the values of the transfer function at the two different frequencies f_1, f_2 [14].

Substitution of these frequencies into Eq.1 leads to the system of two equations [3,14]:

$$\begin{cases} H_1 = H^{-1}{}_{att}\Big|_{\substack{x=x_0\\ f=f_1}} = K\cdot \mathrm{e}^{k\cdot x\cdot \alpha_0} \\ H_2 = H^{-1}{}_{att}\Big|_{\substack{x=x_0\\ f=f_2}} = K\cdot \mathrm{e}^{k\cdot x\cdot \alpha_0 \left(\frac{f_2}{f_1}\right)^n} \end{cases}, \qquad (3)$$

from which the coefficients α_0 and n can be found [8,14]:

$$\alpha_0(f_1) = \frac{\ln(K_0 \cdot H_1)}{x},$$

$$n = \frac{\ln\ln(K_0 \cdot H_2) - \ln\ln(K_0 \cdot H_1)}{\ln(f_2) - \ln(f_1)}. \qquad (4)$$

Such an approach was verified experimentally. As the investigation object the pressed moist sand with stabilized humidity and temperature was selected. The weight of sand was measured by a digital weighing-machine VLE-1kg4cl; the mass of the water in the sand mixture was evaluated by the steaming process. The mass quantity of the water component is 17.4%±0.03%, the mass quantity of the dry sand component (grains) is 82.6%±0.03%. The density of the moist sand ρ=1780kg/m^3±20kg/m^3 was calculated from the measured weight of the known volume. From literature analysis density of the ground sand and seabed sand is in the range from 1400kg/m^3 to 2030kg/m^3, the ultrasound velocity from 1480m/s to 1840m/s [11-15]. The average diameter of the sand grains was measured by the optical microscope MBS-9 and is in the range from 0.098mm to 0.658mm. It is less than wavelength (λ=1.306mm), therefore attenuation of the ultrasonic waves is caused due to the Releigh region of the scattering effect [16].

As it was mentioned it is necessary to find a most suitable approximation valid for description of the frequency dependent attenuation in the moist sand at the higher frequencies and extrapolate it to the low frequencies, which are under interest. Schematic presentation of the measurement equipment used for investigation of the attenuation function and ultrasound velocity measurement in the through transmission mode is given in Fig.1. The transducers were used with the 1MHz central frequency and the diameter 20mm. The distance between transducers x_0 was fixed and calibrated in the distilled water: x_0=10.91mm at the T=19.7°C. It was a direct contact between the transducers and the amount of the pressed moist sand. Data acquisition was performed by the HP54645A digital oscilloscope. The data were transferred to a personal computer via IEEE488 interface for a further analysis.

The time of flight estimation is one of the most essential procedures in ultrasonic measurements such as thickness measurements, determination of ultrasound velocity and attenuation, sizing of the defects in non-destructive testing and etc. (Fig.1). In simplest cases usually two signals are exploited. Depending on a measurement technique used, one of them is the excitation signal and the second one is the signal transmitted through the object under investigation. The time interval between these two signals is the physical quantity necessary to measure for estimation of the ultrasound velocity. There are many methods used for estimation of this time interval, but the most reliable and accurate are methods based on calculation of a cross-correlation function between these two signals. The excitation signal usually is used as a reference signal in a cross-correlation analysis. The instant of the best correlation in the time domain corresponds to the instance of the arrival time of the second signal.

The ultrasound velocity in the test sample at the central frequency of the transducer is calculated as:

$$c = \frac{x_0}{\Delta t} \qquad (5)$$

where x_0 is the distance between transducers (transmitter and receiver), Δt is the time delay between excitation and transited signal through the test material. This equation is based on the assumption that there is no geometrical increase of the wave path due to the scattering effect.

The windowed raw signals obtained using the described experimental set-up are presented in Fig.2 and Fig.3. It can be seen that transmitted through the moist sand signal is strongly attenuated (Fig.3). The signal transmitted through distilled water was used as the reference signal in the estimation of the frequency dependent attenuation function (Fig.2). Amplitude spectrum of the signal transmitted through distilled water $U_0(f)$ is presented in the Fig.4, and of the transmitted through the moist sand $U_1(f)$ in the Fig.5. Also in Fig.6 it is

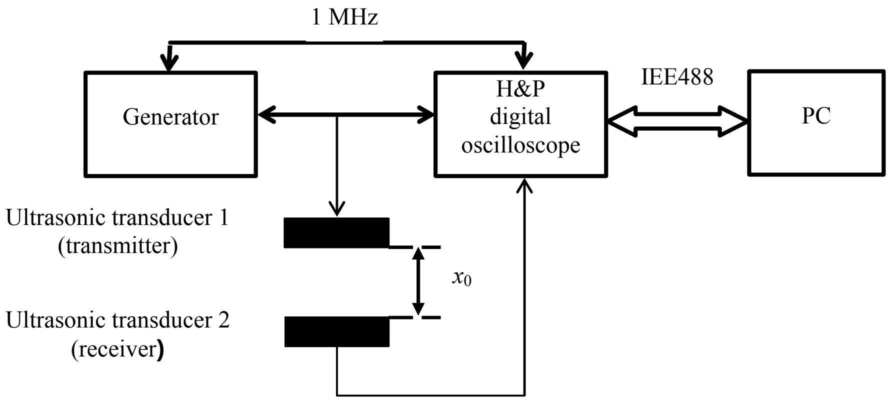

Fig.1. **Experimental set-up for measurement of the attenuation coefficient using through transmission technique**

possible to observe the above-mentioned oscillating character of the experimentally determined transfer function. The smooth approximating function found using the proposed approach is shown by the dashed line.

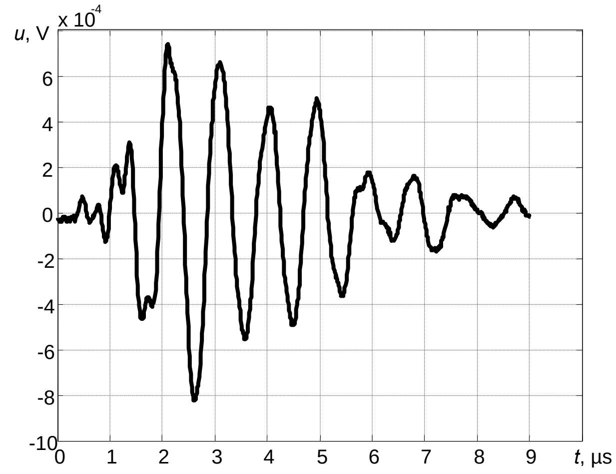

Fig.2. **Waveform of the signal transmitted through water**

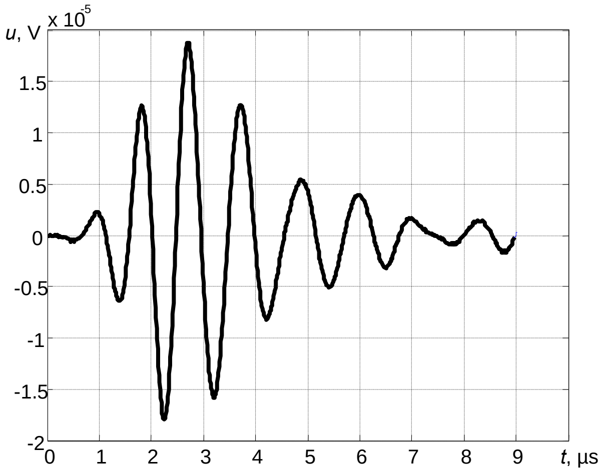

Fig.3. **Waveform of the signal transmitted through moist sand**

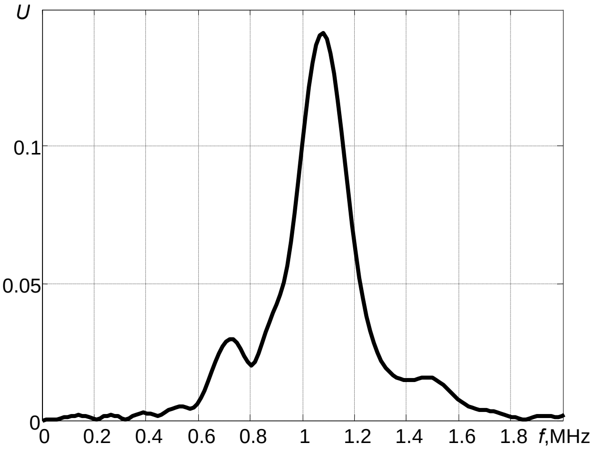

Fig.4. **Amplitude spectra of the signal transmitted through water**

The coefficients α_0 and n determined at the frequency f_0=1MHz according to the chosen approximation (f_1=0.89MHz, f_2=1.08MHz) are α_0=31.45dB/cm and n=1.97. The criteria of the reference frequency f_0 selection were described in the previous work [14]. From the described approximation, the attenuation at the lower frequencies could be evaluated also. The estimated frequency dependent attenuation function of ultrasonic waves in the moist sand is presented in Fig.7.

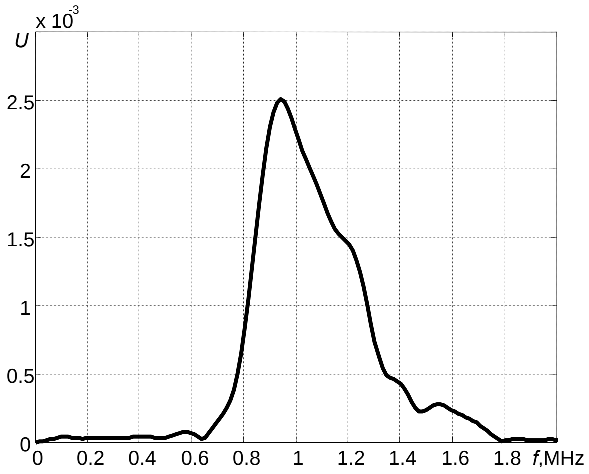

Fig.5. **Amplitude spectra of the signal transmitted through sand**

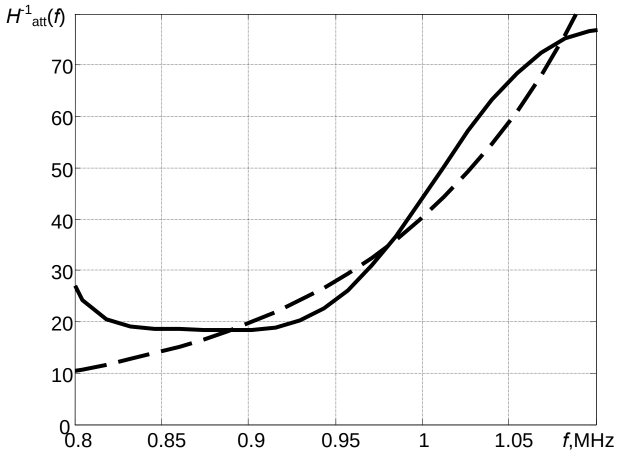

Fig.6. **Transfer functions of the moist sand in the through transmission mode: solid line-experimental results, dashed line- approximation** $K\cdot e^{k\cdot x\cdot\alpha_0\left(\frac{f}{f_0}\right)^n}$

For the investigated moist sand the estimated power of frequency dependent attenuation approximation n is close to the theoretical (n=2) in the case of the attenuation caused due to scattering [16]. The measured ultrasound velocity in the moist sand at the central frequency (1MHz) of the transducers is c=1306±10m/s. The similar results of the ultrasound velocity measurements in the water-saturated river sand were found in literature; however it was no information about the quantity of the water in the mixture and also density of the sand mixture [17]. Using the time causal form of the Kramers-Kronig relationship

[8], the calculated phase velocity dispersion is in the range from the 1265m/s to the 1306m/s in the frequency range (0.1..1)MHz.

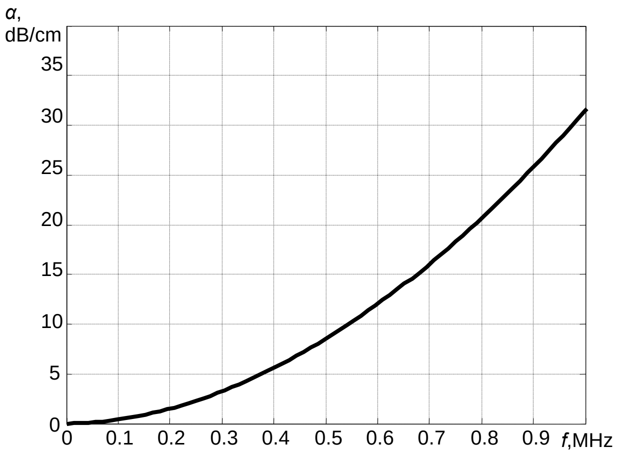

Fig.7. **Frequency dependent attenuation coefficient of ultrasonic waves in moist sand extrapolated from the measured transfer function**

Conclusions

The results presented are unique, because there is no information found in literature about the acoustic properties of the moist sand in a wide frequency range. The measured attenuation coefficient by the through transmission technique is α=31.45±0.3dB/cm at the 1MHz frequency with the power n=1.97, the measured ultrasound velocity c=1306±10m/s. The obtained results in the future investigation will be used as the initial data in the models of the petroleum tank inspect by guided waves.

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Drėgno smėlio akustinių savybių nustatymas

Reziumė

Atliekant metalinių konstrukcijų, turinčių sąlyčio su smėliu neardomosios kontrolės tyrimus, reikalinga informacija apie ultragarso bangų sklidimo metalo ir smėlio riboje dėsnius. Tam reikia ištirti smėlio akustines savybes.

Straipsnyje pateikti ultragarso greičio matavimo drėgname smėlyje eksperimentiniai rezultatai, taip pat nustatyta ultragarso bangų slopinimo dažninė priklausomybė atliekant perdavimo funkcijos aproksimaciją dažnio srityje. Esant 1 MHz dažniui nustatytas slopinimo koeficientas α=31,45±0,3 dB/cm ir ultragarso greitis 1306±10 m/s.

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