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Ultrasonic characterization of the PVC welded materials

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Abstract. Article refers to ultrasonic parameters identification and measures the relevant ultrasonic parameters in the detection of the integrity state of the welded materials pipe type from plastic PPR. To achieve the target values for acoustic parameters in case of ultrasonic wave propagation through studied samples literature review was performed first. There were identified the main elaboration processes of polyvinyl chloride, possible welding techniques, specific defects that may occur after joining processes as well as their ultrasound manifestation. There are presented the theoretical considerations regarding ultrasound propagation equations in samples in order to create theoretical model of the welded joint with related acoustic parameters. An experimental plan was then realized to determine the integrity state of the joined material on different welding regimes. It was also designed and realized a semi-automated ultrasonic control system A Scan type and B Scan type to simplify and streamline control operation. At the end, conclusions are taken regarding the quality of the joint of the plastic PPR pipe type samples by studying their acoustic parameters.

1. Introduction
Ultrasonic material testing is based on ultrasonic wave propagation in the examined piece and monitoring of the transmitted or reflected signal from a material discontinuity. Material examination can be performed manually or using semi-automated devices using different techniques like direct contact, without contact or immersion based on corresponding coupling methods. Ultrasonic parameters quantification is realized by ultrasonic wave introduction inside the probe with known characteristics like signal amplitude, frequency, speed and these characteristics evaluation after ultrasonic wave propagation inside material [13]. PVC welded materials quality is frequently qualitative and determined using the test for leakage at supra pressure [1]. This method indicates if the weld is sealed or not in the moment of the control but cannot anything about shape of the welded seam, degree of penetration, its dimension or material degradation because of overheating. Different theoretical studies refer to possible methods of material ultrasonic characterisation [2], while others methods focus on mathematical modelling methods of the material using ultrasonic evaluation methods [3].

2. Reference theoretical model
To realize a PVC material welding process optimization, the reference theoretical model of the joint without defect had to be known. This is necessary because each new result obtained by welding parameters variation has to be compared with etalon ultrasonic image of the joint without defect. Acoustic parameters experimentally observed were theoretically calculated using basic equations of the ultrasonic wave propagation. In this case, the determination of phase speed determination of the ultrasonic wave in the welded PVC probe.

Schematic of the control method used in specific material phase speed determination is presented in figure.1.

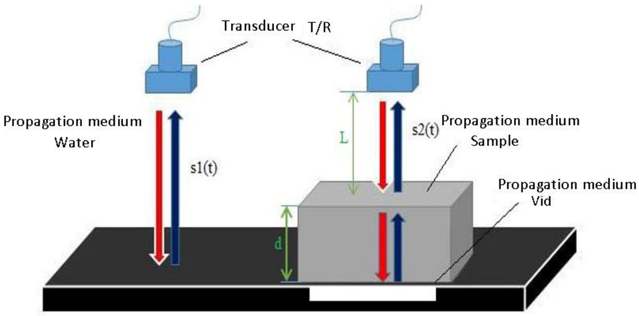

Figure 1. Scheme control system for ultrasonic speed determination.

The method consists in acquisition of three signals and then speed signal determination and/or material thickness [4]. Practical experiments consist in immersing of the tested probe in a dasher with liquid and an air layer (minimum 10 mm thickness) creation behind it. The technique assumes also three signal acquisition:

- a reference signal $s_1(t)$ for the working frequency without sample;
- a sample signal $s_2(t)$ reflected on the first probe interface;
- a signal s_3 (t) reflected on the interface between probe and vid.

The first signal describes acoustic field by the equation:

$$s_1(t) = R_{14} \cdot exp(\omega t - 2k_1(L+d)), \tag{1}$$

Where s(t) represents the acoustic field at the moment t in any point, R14 - reflex ion coefficient at the medium 1 (water) - medium 4 interface (stand), ω - wave pulsation (ω=2πf), t - time, k_1 - wave number ($k_1=\omega/c_1$), c_1 - ultrasonic wave phase speed determination in medium 1(water), (L+d) - distance up to probe.

The second signal s_2 (t) is described by the relation:

$$s_2(t) = R_{12} \cdot exp(\omega t - 2k_2 L) \tag{2}$$

The s_3 (t) signal that corresponds to medium 2 (probe) – medium 4 (vid) interface reflection, is a function of reflection coefficient on this interface that is the result of multiply of T_{12} and T_{21}:

$$s_3(t) = -T_{12}T_{21} \cdot exp(\omega t - 2k_2(L+d)) \tag{3}$$

Minus sign corresponds to ultimate interface in vid, reflection coefficient R_{23} = -1. This indicates a vibration string percussion to a perfect rigid wall that means a reflected phase change Φ = π. The transductor wave amplitude registration will be a function of bidirectional transmission coefficients at the 2-3 interfaces. The "flying" time of acoustic wave that corresponds to each echo will be t_1, t_2 and t_3 respective.

After simplifications and suitable arrangements, the following equation system is written:

$$\begin{cases} t_1 = \dfrac{2(L+d)}{c_1} \\ t_2 = \dfrac{2L}{c_1} \\ t_3 = \dfrac{2L}{c_1} + \dfrac{2d}{c_2} \end{cases} \tag{4}$$

Where: distances L and d are presented in the Figure. 1, c_1 and c_2 - phase speed in medium 1 (water) and 2 (probe).

To calculate the attenuation coefficient [5-8] the following equation is available:

$$A_i = A_0 exp(-\alpha x) \tag{5}$$

Where A_i is the theoretical wave amplitude at the interface situated inside the welded pipe, A_0 - incident wave amplitude in the reference point, x - distance between two measuring points, α - wave attenuation inside material.
The theoretical attenuation was calculated considering the wave propagation between probes there are not welded and measuring the amplitude loss in each two situations, according equation:

$$\alpha = 0{,}1151/c \cdot A_d \tag{6}$$

Where c is face speed in the considered medium [m/s], A_d - attenuation amplitude [dB/m].
According to experiments, figure 2 presents the Matlab amplitude theoretical distribution in the situation of ultrasonic wave distribution inside of the disc, considered homogenous and isotope.
The probe diameter is 80 mm, with the equivalent acoustic impedance equal to the PVC welded probe at the amplification of 20 dB. It is observed that the amplitude is uniform distributed starting from exterior to interior on concentrically izoamplitude circles. Because of complex phenomena linked to ultrasonic wave propagation in reality, those lines are disturbed. Also, because of the material, different phenomena are observed: local inhomogeneity, internal material diffusion because of PVC material viscous behaviour, wave diffraction on material discontinuity that have dimension close to half wave length of ultrasounds [9].

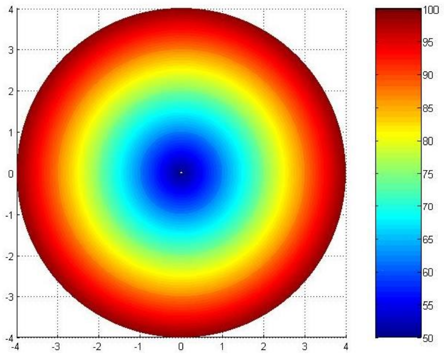

Figure 2. Izoamplitude surfaces modelled in Matlab software.

According to calculus, two closed values for theoretical attenuation α_1 and α_2 were obtained. Their weighted average, as a function of material participation at the welded piece, noted with α_{echi} is calculated according to relation:

$$\alpha_{echi} = d_1/(d_1 + d_2) \cdot \alpha_1 + d_2/(d_1 + d_2) \cdot \alpha_2 \tag{7}$$

Where d_k, k=1,2 represents the pipe thickness in m and α_k, k=1,2 are materials attenuations in [dB/m].
The difference between theoretical value and measured value for the equivalent attenuation can be written according the following equation:

$$E_{\alpha m} = \frac{\alpha_m - \alpha_{echi}}{\alpha_{echi}} \cdot 100\,[\%] \tag{8}$$

Where $E_{\alpha m}$ represents the error of the ultrasonic attenuation of the welded zone compared to theoretical attenuation, α_m is the real measured value of the attenuation [dB/m].

3. Results

The studied PVC samples consists in welded pipes with external heater element. Probe dimensions are: exterior diameter of the hub D_{hub} = 30 [mm] (hub thickness h_{hub} = 4.9 [mm]), exterior diameter of the pipe D_{pipe} = 20 [mm] (thickness of the interior pipe h_{pipe} = 3.7 [mm]).

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Twelve probes with different welding parameters were realized. Maximal and minimal limits were defined using values from bibliography [10], [12], presented in table 1.

Table 1. Welding parameters of the PVC pipes.

No. sample	**Temperature in [C◦]**	**Welding time in [s]**	**Force value in [N]**
1	200	8	30
2	200	8	50
3	200	12	30
4	200	12	50
5	250	8	30
6	250	8	50
7	250	12	30
8	250	12	50
9	300	8	30
10	300	8	50
11	300	12	30
12	300	12	50

The measuring of the acoustic parameters was done for each probe in six points at 60 º starting with 150 from the horizontal of the exterior element, table 2. A_1 and A_2 represent the amplitudes measured at line of welding joint and at the bottom of the sample.

Longitudinal waves frequency used in experiments are f_1 = 2 [MHz] and f_2 = 13 [MHz]. Comparing the two working sets of results it can be observed that the measures of the acoustic parameters are closer to theoretical model values for the frequency f_2 = 13 [MHz]. Based on measurements, the experimental attenuation coefficient for each probe was compared with calculated theoretical values according equation (8).

As can be observed, the minimal value of attenuation coefficient measured in the six points is for the probe no.8. Considering this results, this probe was than examined in 36 points along the circular perimeter. In each point, for each measure, the attenuation coefficient in [dB/MHz*cm] was determined. This parameter variation will offer important indications about welding zone homogeneity. Figure 4 presents this parameter evolution in polar coordination.

This diagram study offers information about amplitude variation of the attenuation coefficient which is about 2.4%.

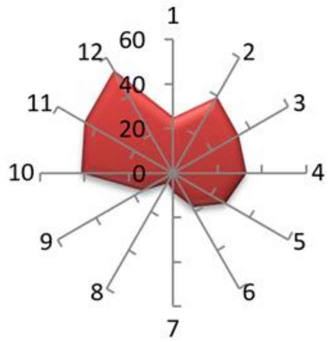

Figure 3. Deviation of attenuation coefficient.

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Table 2. Acoustic measured parameters.

No. sample	**Amplitude A_1**	**Amplitude A_2**	No. sample	**Amplitude A_1**	**Amplitude A_2**
1	67	54	4	49	56
	60	57		58	55
	17	68		30	63
	63	67		52	54
	43	64		37	60
	34	59		30	58
2	23	78	5	61	83
	41	64		36	26
	22	74		44	83
	27	69		40	29
	73	75		57	74
	44	60		39	65
3	57	62	6	40	67
	20	63		37	20
	57	65		85	82
	40	64		39	70
	47	68		50	27
	30	70		62	53
7	56	55	10	19	64
	55	66		23	63
	63	69		58	67
	54	60		30	65
	60	68		41	67
	58	67		51	66
8	83	64	11	42	35
	26	66		24	78
	82	68		41	64
	29	65		32	75
	74	60		27	42
	65	70		38	54
9	67	55	12	60	65
	20	63		17	50
	82	62		18	69
	70	58		45	56
	27	44		22	61
	53	61		15	65

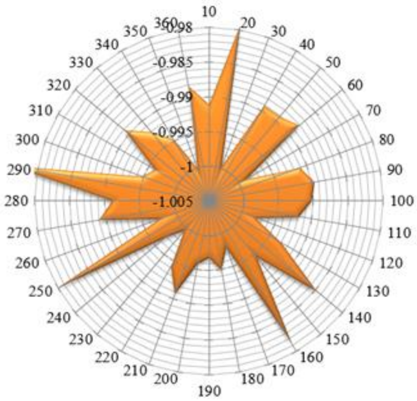

Figure 4. Variation for the attenuation coefficient in polar coordination.

This very small value shows that the PVC welding is uniform realized. On the semi-automated scanning device, in the A-SCAN and B-SCAN system, were realized six measuring of the probe no.8. A presentation of a B - Scan on automatized stand is presented in figure 5. Attenuation coefficient values were calculated in 36 points, with a 100 step. To establish the measuring reproducibility, the values were compared in order also to provide the stand feasibility.

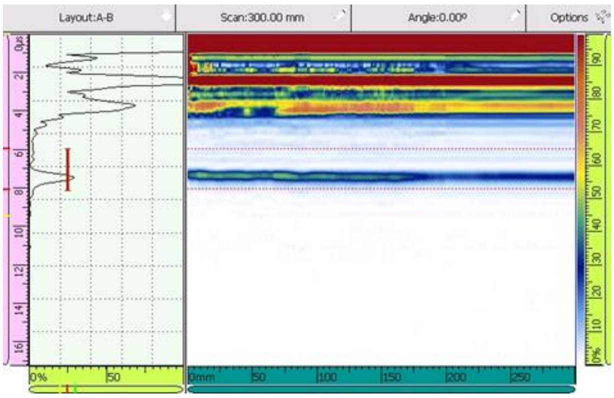

Figure 5. Variation of attenuation coefficient in polar coordination.

4. Conclusions

According to the study of the ultrasonic characterization for the welded PVC pipes, important conclusions can be done in order to provide information about welded quality zone. A complete mathematical and physical model was establishing from the theoretical and practical point of view. The technical methods for the initial determinations of the acoustic parameters of the probes were described. Wave propagation speed, acoustic impedance and attenuation coefficient were determined. For a group of products, welding quality measurement can by assured because of automated measuring device design.

The system can be adapted to different PVC welded pipes diameter with good results.

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