

## Optimization of polypropylene pipe wall thickness measurement by pulse ultrasonic method

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### Abstract

The analysis of optimization questions of the piezoelectric transducer for the polypropylene pipe wall thickness measurement is given. Theoretically and experimentally the maximum of the transducer sensitivity is obtained when the protector (acoustic delay layer) is produced from anti-friction material caprolone with graphite (caprolone+C).

**Keywords:** ultrasonic non-destructive testing, plastic pipes production, propylene pipes

### Introduction

The problems of the certification and the quality parameters correspondence to the EU's strict standards often arise while implementing the new technologies in Lithuanian industry and producing the competitiveness of the product in the EU. This work is devoted for the large-diameter polypropylene pipe wall thickness measurement testing during the production. The ultrasonic pulse method is usual by for this purpose used. In specific cases there is a need for new solutions in spite of the ultrasonic methods development and high level of practical use. In this case, there is a need to control the large-diameter (thickness from 40cm to 100 cm) thin-walled (wall thickness from 3mm to 6 mm) propylene pipe manufacturing process at the temperature of (40...60) °C. This requires high-precision measurement of a thickness that could be achieved by increasing the frequency of the used ultrasonic signals. However, polypropylene, as well as all plastics, is characterized by the increased ultrasonic wave attenuation, exponentially increasing with the frequency. The low acoustic impedance is also characteristic to polypropylene; and it would not allow the use of the standard measuring instruments and stimulates the search for the optimal solutions.

### Theoretical research

The broadband piezoelectric transducers with the acoustic delay layer are used to measure small thickness by the pulse ultrasonic method. The most appropriate is to measure the product wall thickness through pipe wall from inner side, since the polypropylene a pipe during manufacturing process (Fig. 1a) is formed on the steel cylinder (Fig. 1b). In this way the ultrasonic signal propagates in the triple mechanical system; its summarized scheme is shown in Fig. 2. The layers in the simplified scheme can be assumed as a flat, whereas the piezoelectric transducer diameter  $d \ll D$ , where  $D$  is the diameter of a polypropylene pipe.

Acoustic signal in the most common case is defined as a pressure function

$$p(t) = P(t)\cos(\omega t), \quad (1)$$

where  $P(t)$  is the amplitude time function,  $\omega = 2\pi f$ ,  $f$  is the frequency.



a



b

Fig. 1. a – the section of polypropylene pipe (with a cut fragment), b – the steel cylinder for a formed polypropylene pipe.

An acoustic signal is decreasing during propagation in the carrier with the acoustic impedance  $Z = \rho c$ , where  $\rho$  is the density of the carrier,  $c$  is the velocity of the inner sound. When the ultrasonic wave is flat and incidents perpendicularly to the surface its amplitude is given by

$$A_x = A_0 e^{-\alpha x}, \quad (2)$$

where  $x$  is the distance,  $A_0$  is the pressure amplitude value on the surface layer ( $x = 0$ ),  $\alpha$  – attenuation coefficient, described as

$$\alpha = \frac{\ln(\frac{P}{P_0})}{x} \text{ [Np/m]}. \quad (3)$$

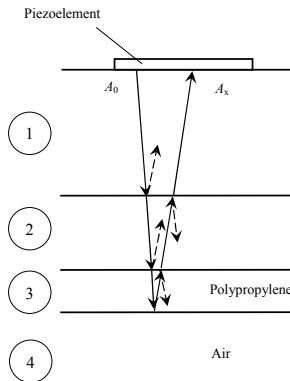


Fig. 2. Ultrasound propagation in the triple mechanical system: 1 - the acoustic delay layer of piezotransducer, 2 - steel pipe wall, 3 - the polypropylene pipe wall, 4 - air.

Having assessed the acoustic signal propagation through the layers  $n, n + 1$  limit, the ratio as

$$D_{n,n+1} = \frac{2Z_{n+1}}{Z_n + Z_{n+1}} = \frac{2\rho_{n+1}c_{n+1}}{\rho_n c_n + \rho_{n+1}c_{n+1}}, \quad (4)$$

the relative decrease in the signal amplitude on the road piezoelement-third layer-bottom piezoelement is equal to

$$\frac{A_x}{A_0} = D_{1,2} D_{2,3} R_{3,4} D_{3,2} D_{2,1} e^{-2\alpha_1 d_1} e^{-2\alpha_2 d_2} e^{-2\alpha_3 d_3}, \quad (5)$$

where  $Z_n$  and  $Z_{n+1}$  are the acoustic impedances of adjacent layers;  $\rho_n$  and  $\rho_{n+1}$  are their densities,  $c_n$  and  $c_{n+1}$  are the sound phase velocities in them;  $d_1, d_2,$  and  $d_3$  are the thicknesses of the 1st, the 2nd, and the 3rd layers;  $\alpha_1, \alpha_2$  and  $\alpha_3$  are the sound attenuation coefficients in the corresponding layers,  $R = (Z_n - Z_{n+1}) / (Z_n + Z_{n+1})$  is the reflection coefficient from the third layer of the bottom line.

Since the 3rd layer from the bottom contacts air and  $Z_{n+1} \ll Z_n$ , so  $R \approx 1$ .

Then

$$\frac{A_x}{A_0} = D_{1,2} D_{2,3} D_{3,2} D_{2,1} e^{-2(\alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3)}. \quad (6)$$

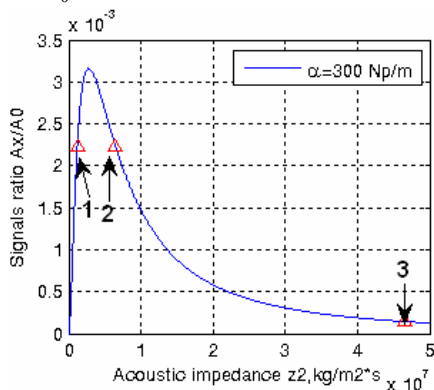


Fig. 3. Signals ratio dependence on the acoustic impedance of the triple system of the ultrasonic transducer

The calculated theoretical dependence  $(A_x/A_0)(Z_2)$  when the 1st carrier is plexiglas ( $Z_1 = 0,322 \cdot 10^7 \text{ kg/(m}^2\text{s)}$ ) and the 3rd carrier is polypropylene ( $Z_3 = 0,183 \cdot 10^7 \text{ kg/(m}^2\text{s)}$ ) has shown that the acoustic pressure transmission coefficient of the steel pipe ( $Z_2 = 4,66 \cdot 10^7 \text{ kg/(m}^2\text{s)}$ ) is  $\approx 10$  times lower (Fig. 3, point 3) than the  $(A_x/A_0)_{\max} = 3,3 \cdot 10^7$ . Experimentally measured plexiglas and polypropylene attenuation coefficient values for the frequency  $f = 2,5 \text{ MHz}$  have been used for the calculation.

It is clear that a polypropylene pipe wall thickness  $d_3$  measurement through the steel pipe wall is not optimal, so in order to increase the measurement sensitivity it is appropriate to use a special acoustic delay layer with an acoustic impedance in marked borders of point 1 and 2, i.e.,  $0,15 \cdot 10^7 < Z_2 < 0,6 \cdot 10^7 \text{ kg/(m}^2\text{s)}$ . In this case, the 2nd intermediate layer is also the protector which protects piezoelement against mechanical wear, scrolling measured the polypropylene pipe surface through it. Therefore, in selection of the material not only to the acoustic properties, but also to the anti-friction must be taken into consideration.

Fig. 4 shows the theoretical acoustic signal relative reduction dependence on the intermediate layer thickness  $d_2$  for different materials, characterized by a low acoustic impedance with the resistance to abrasion (caprolone, caprolone + C, teflon).

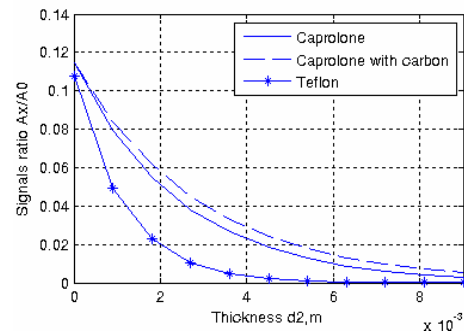


Fig. 4. Signals ratio dependence on the thickness  $d_2$  of the triple acoustic system

The low acoustic impedance and the thickness are the acoustic requirements for the intermediate second layer (Fig. 3 and 4). So in order to fulfill this task it required to make a hole in a steel cylinder for the embedding of the protector. This required to investigate the double acoustic system where the first layer (protector) has an anti-friction material of  $d_1$  layer thickness; the second layer is of polypropylene. The results of the theoretical calculations for the double acoustic system are shown in Fig. 5 and 6.

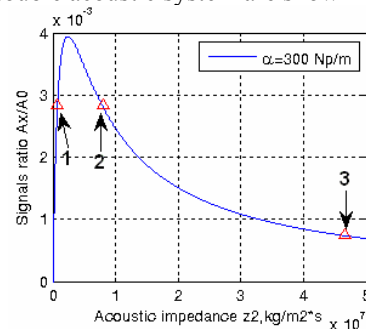


Fig. 5. Signals ratio dependence on the acoustic impedance of the double acoustic system

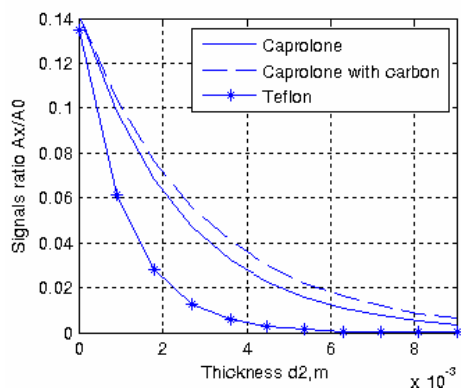


Fig. 6. Signals ratio dependence on the thickness of the second layer thickness  $d_2$

According to the theoretical calculations, the maximum measurement sensitivity is obtained using the double layer acoustic system with caprolone + C.

### Experimental investigation

The investigations were carried out by the ultrasonic digital flow detector described in [1, 2]. The acoustic properties of the test material (polypropylene), as well anti-friction polymers were investigated there also. The experimental measurement results are presented in Table 1.

Experimentally it was found that the attenuation of 5 MHz frequency signal in polypropylene is 5 to 8 times higher than the attenuation of 2.5 MHz signal, so all investigations were performed with 2.5 MHz transducers. The measurements were carried out without changing the piezoelectric transducer excitation conditions.

Table 1. The experimentally measured and calculated acoustic parameters of the polymeric materials ( $f=2,5$  MHz)

Material	Sound velocity $c$ , m/s	Density $\rho$ , kg/m <sup>3</sup>	Acoustic impedance $Z$ , (kg/m <sup>2</sup> s)	Attenuation coefficient $\alpha$ , Np/m
Plexiglas	2730	1180	$0,322 \cdot 10^7$	35
Teflon	1350	2200	$0,297 \cdot 10^7$	434
Caprolone	2158	1160	$0,250 \cdot 10^7$	204
Caprolone+C	2368	1160	$0,275 \cdot 10^7$	173
Polypropylene	2083	880	$0,183 \cdot 10^7$	243

The temperature dependence of the polymer materials acoustic properties have been investigated in order to evaluate the real production conditions (environmental temperature in the measurement range ( $T= 40...60$ )<sup>0</sup>C) (Fig. 7).

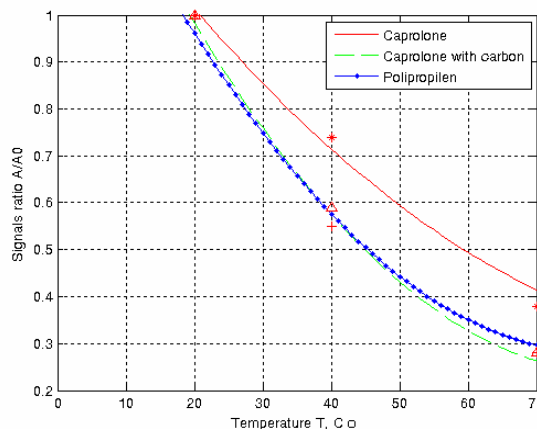


Fig.7. Signals ratio dependence on the temperature of the investigated materials

The transducers with the acoustic delay line of different thicknesses from the caprolone with carbon impurity (aprolone+C) have been produced. The Gaussian shape acoustic signal of  $\approx 2.5$  MHz frequency was emitted after the excitation. The piezoelectric transducer acoustic delay line thickness  $d_2 = 20$  mm ensures temporary separation of the received signals not only from the acoustic delay line outer surface, but also from the acoustic delay line end from the probe excitation signal according to the experimental signal images (Fig. 8) obtained by measuring 3.3 mm thick polypropylene pipe wall by 2.5MHz transducers. Fig. 8a shows the delayed pulse that is the signal of the second reflection from the acoustic delay layer and that does not influence the measurement of thin pipe wall thickness.

The optimized structure of the specialized piezoelectric transducer adapted to the polystyrene pipe wall thickness measurement has been developed according to the experimental results (Fig. 9). The mechanical damper of the piezoelement is made of the epoxy resin and the tungsten powder mixture by the volumetric ratio 1:1. The protector is made from the caprolone+C with its working surface of the cylindrical profile and has a curvature radius equal to the polypropylene pipe inner diameter radius.

### Conclusions

The piezoelectric transducers of the special design with anti-friction protector, having the low acoustic impedance, the low damping of the ultrasonic signals and a cylindrical active surface are required for the measurement of the polypropylene pipe thin wall thickness during the production process. According to the theoretical calculations and experimental investigation caprolone+C is the most optimal material for the piezoelectric transducer delay layer, which is used as a protector.

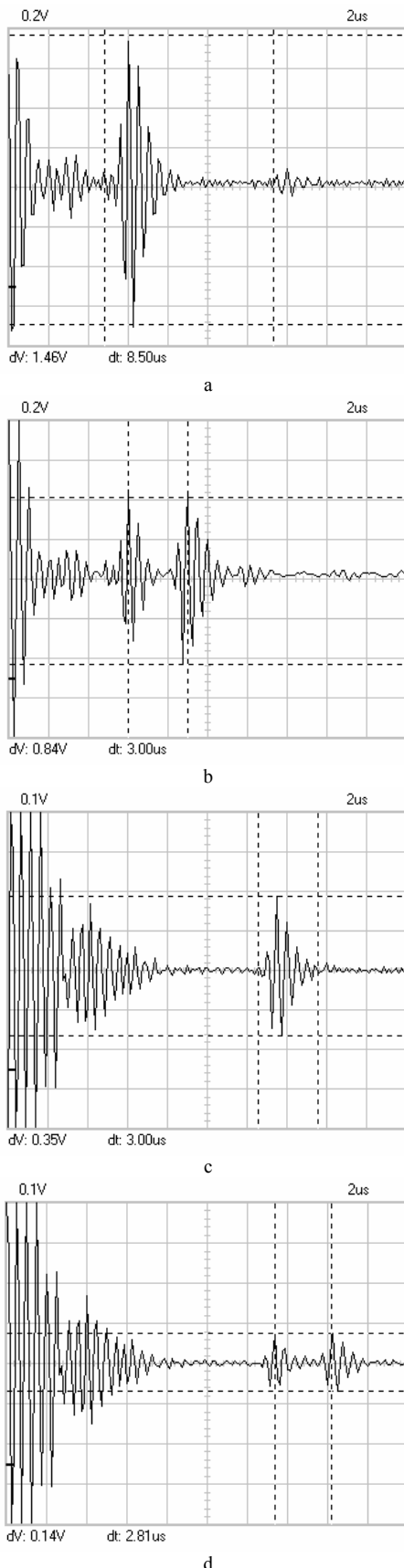


Fig. 8. Ultrasonic signals of 2.5 MHz frequency obtained by the transducers with the acoustic delay line length of 10 mm (a, b) and 20 mm (c, d). The acoustic delayer has no contact with the explored polypropylene pipe wall; only a signal reflected from acoustic delay line end is observed (a and c). Fig. b and d show the signals of 3.3 mm thick polypropylene pipe wall during the thickness measurement.

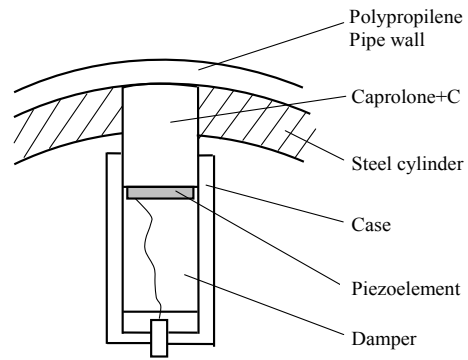


Fig. 9. The construction of piezoelectric transducer

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Polipropileno vamzdžių sienelės storio matavimo ultragarsiniu impulsiniu metodu optimizavimo tyrimai

Summary

Nagrinėjamas pjezoelektrinių keitiklių, skirtų polipropileno vamzdžių sienelės storiui matuoti, parametru optimizavimas. Teoriškai ir eksperimentiškai nustatyta, kad didžiausias pjezoelektrinio keitiklio jautrumas gaunamas naudojant vėlinimo (apsauginį) sluoksnį iš antifriccinės medžiagos – kaprolono su grafito priemaiša.

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