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The use of ultrasound for determination of the thickness of glass panes of windows

A. Vladišauskas, L. Jakevičius, J. Butkus

Prof. K.Baršauskas Ultrasound Institute

Kaunas University of Technology

Introduction

Ultrasonic nondestructive measuring methods are widely used in quite different fields. One is determination of quality of filling of highly insulated noble gas filled glazing units [1]. How it was shown in [1], the thermal insulation of glazing units depends on the composition of the gas mixture inside a glazing unit. After the investigations [1, 2], it was revealed that the composition of the gas, filling the highly insulating glazing unit, may be determined by using the ultrasound measuring method. However, implementation of the ultrasound measuring method in practice meet some difficulties. Some of them are related to the possibility to get measurement information only from one side of the glazing unit [1, 2]. But most of them are related to the sound velocity measurement inside the glazing unit, which is a multi-layer structure, consisting from solids and gases. These difficulties appear because the sound velocity in the gas filling the glazing unit depends on its composition and temperature. So, the sound velocity may be determined only after the determination of the thickness of glass panes and the distance between the glass panes inside the glazing unit. So, first of all it is necessary to determine the thickness of the glass panes of glazing units. However, that is a problem, because the sound velocity in a glass pane is not exactly known in advance. It depends on composition of glass, its temperature and other factors. Since the direct contact to the glass panes of glazing units is possible only from outside, application of ultrasound methods are limited. Therefore, the aim of this investigation was to reveal the possibilities of ultrasound method for determination of the thickness of glass panes in situ, without necessity to unmount glazing units from their frames.

Theoretical investigation

The thickness of glass panes is expedient to determine by sounding them from outside and by receiving acoustical signals reflected from the inner surface of the glass pane. If the sound velocity in the glass pane is known, it is expedient to measure the thickness by sounding the glass pane perpendicularly [3]. In this case the times of propagation of acoustical signals in the glass media become twice longer. It allows to improve the resolution and accuracy of thickness measurements [3]. But, during measurements it is necessary that the received ultrasound signal do not overlap with the radiated signal. Therefore, it is necessary that the radiated acoustical signal would be sufficiently suppressed and its level in the receiving transducer must be considerably smaller than the level of the reflected measuring signal. So, it is necessary that the operational frequency of electroacoustical transducers would high enough, and the time of propagation of acoustical signal in the glass pane would be 3…5 times longer than the period of the carrier frequency of the measuring pulse. When sounding perpendicularly, the propagation time t of acoustical signal in the glass pane $t=2h/c$, where h is the thickness of the glass pane; c is the velocity of propagation of longitudinal waves in glass. Therefore, the period T of the carrier frequency $T=t/(3…5)=2h/(3…5)c$. So, the carrier frequency f of the measuring pulse is $f=1/T=(3…5)c/2h$. The carrier frequency of the measuring pulse must be selected depending on the thickness h of the glass pane. The frequencies of the measuring signal, when the velocity of acoustical signal in the glass pane is c=5770m/s [4] are given in the Table 1.

Table 1. **The dependence of the carrier frequency of measuring signal on the thickness of a glass pane**

Glass thickness [mm]	3	4	5	6	8	10	12	15	19	25
Carrier frequency, when $2h=3\lambda_{gl}$ [MHz]	2.89	2.17	1.73	1.44	1.08	0.87	0.72	0.58	0.46	0.35
Carrier frequency, when $2h=5\lambda_{gl}$ [MHz]	4.81	3.61	2.89	2.40	1.80	1.44	1.20	0.96	0.76	0.58

It should be noted that the accuracy of measurements is increased when the ratio of signal to noise is the same, but the frequency of a signal is higher [1,5]. On the other hand, the sound attenuation in gases increases roughly with the second power of frequency [1,5]. For that reason, when the frequency is increased, the signal to noise ratio becomes lower and the accuracy of measurements is decreased. The frequency of about 1MHz is a good compromise in our case

In accordance with the European Standard EN 572 [6, 7], the composition of the glass of the glass panes, which are produced by different producers, are quite different and the a acoustical properties are different too. So, when measuring the thickness of the glass panes by ultrasound, the propagation velocity of acoustical waves in the glass pane must be determined. In such a case angular piezoelectric transducers may be used [8]. Therefore, the possibilities and accuracy of glass thickness measurement and the presumptions for application of new measuring methods are developed.

The angular methods for introduction of ultrasound waves into the measuring object may be splitted into two groups:

- the methods, used until the first critical angle;
- the methods, which are used between the first and the second critical angles.

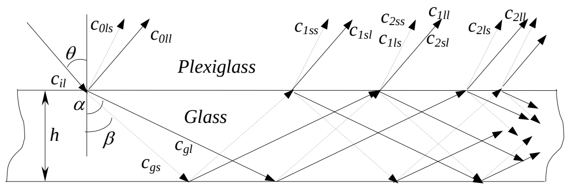

Fig.1. **The propagation of ultrasound waves in a glass pane**

In the first case two types of acoustical waves are transmitted to the measuring object: longitudinal waves and shear waves [8]. In the second case the shear waves are applied for measurement of the thickness. In our case the possibilities of application of longitudinal and shear waves will be analysed. Until the angle of incidence θ is less than the first critical angle, two ultrasound rays are generated in the medium under investigation (Fig.1). The first ray is the longitudinal wave and the second is the shear wave. The angles of propagation of these rays are the following: for longitudinal wave

$$\cos\alpha = \frac{h}{l_l}, \qquad (1)$$

and for shear wave

$$\cos\beta = \frac{h}{l_s}, \qquad (2)$$

where h is the thickness of the glass pane; l_l and l_s are the length of the path propagation of longitudinal and shear waves in the glass pane of respectively. The duration of time for one pitch and catch propagation of longitudinal waves in the glass pane

$$t_l = \frac{2l}{c_l} \qquad (3)$$

and for shear waves

$$t_s = \frac{2l_s}{c_s}. \qquad (4)$$

Taking into account Eq. 1 and 2 we obtain

$$t_l = \frac{2h}{c_l \cos\alpha}, \qquad (5)$$

and

$$t_s = \frac{2h}{c_s \cos\beta}, \qquad (6)$$

where c_{gl} and c_{gs} are the propagation velocities of longitudinal and shear waves in the glass medium.

According to the Snell's low for longitudinal and shear waves

$$\frac{\sin\theta}{\sin\alpha} = \frac{c_{pl}}{c_{gl}}, \qquad (7)$$

$$\frac{\sin\theta}{\sin\beta} = \frac{c_{pl}}{c_{gs}}, \qquad (8)$$

one can obtain the refractive angles in glass

$$\sin\alpha = \frac{c_{sl}}{c_{gl}}\sin\theta, \qquad (9)$$

$$\sin\beta = \frac{c_{gs}}{c_{pl}}\sin\theta, \qquad (10)$$

where c_{pl} is the propagation velocity of longitudinal waves in the prisms of transducers. If the velocity of longitudinal waves in the prism of the transducer (for plexiglass c_{pl}=2650 m/s) and velocities of longitudinal and shear waves in the glass medium are known (c_{gl}=5770m/s, c_{gs}=3390m/s) [4], the refractive angles are given by

$$\alpha = \arcsin\left(\frac{5770}{2650}\sin\theta\right), \qquad (11)$$

$$\beta = \arcsin\left(\frac{3390}{2650}\sin\theta\right). \qquad (12)$$

After the substitution Eq. 9 into Eq.5 and Eq.10 into Eq.6, the times of double propagation of longitudinal and shear waves, transmitted at the angle θ to the glass pane are

$$t_l = \frac{2h}{c_{gl}\cos\left[\arcsin\left(\frac{c_{gl}}{c_{pl}}\sin\theta\right)\right]}, \qquad (13)$$

$$t_s = \frac{2h}{c_s\cos\left[\arcsin\left(\frac{c_{gs}}{c_{pl}}\sin\theta\right)\right]}. \qquad (14)$$

By using algorithms (13) and (14), the times of propagation of longitudinal and of shear waves in the glass panes were calculated. The results of calculations, when the angle of incidence and the thickness of glass panes where changed in the range from 4 mm to 10 mm, are shown in Fig.2 and Fig.3. The incidence angle varies between θ=0° and the first critical angle. The results of calculation show, that the times of propagation of the shear waves are longer the analogous times for longitudinal waves. Therefore they are more is preferable for assurance of the accuracy.

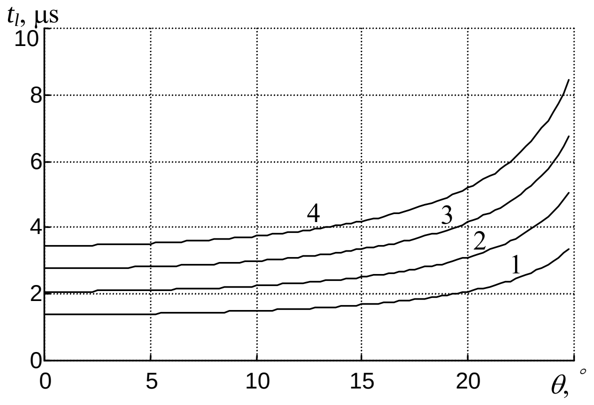

Fig.2. **The dependence of time propagation t_l of longitudinal waves in the glass pane on the angle of incidence θ, when the thickness of glass pane h is changed: 1-h=4mm, 2-6mm, 3-8mm, 4-10mm.**

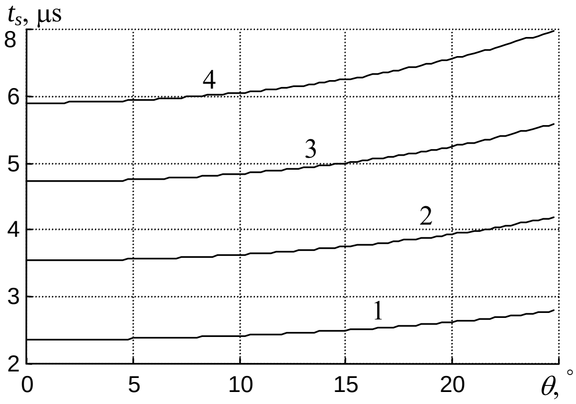

Fig.3. **The dependence of time propagation t_s of shear waves in the glass pane on the angle of incidence θ (θ is less than the first critical angle), when the thickness of glass pane h is changed: 1-h=4mm, 2-6mm, 3-8mm, 4-10mm**

After evaluation of the velocity of propagation of longitudinal and shear waves in the glass pane and the angle of incidence of acoustical waves to the glass surface it is possible to calculate the thickness of the glass pane:

$$h_l = 2t_l c_{gl} \cos\left[\arcsin\left(\frac{c_{gl}}{c_{pl}}\sin\theta\right)\right], \tag{15}$$

$$h_s = 2t_s c_{gs} \cos\left[\arcsin\left(\frac{c_{gs}}{c_{pl}}\sin\theta\right)\right]. \tag{16}$$

When the angle of incidence θ of acoustical wave is bigger than the first critical angle, only the shear waves are propagating in glass (Fig.4). Because the attenuation of acoustical waves in the glass media is insignificant, the multiple reflections between the glass surfaces occur.

Let us choose the system of co-ordinates in which the x axis is parallel to the glass surface. The radiating transducer is located at the point x_0 on the glass surface. The receiving transducer is moved along the x axis away from the radiating transducer. The acoustical signal, reflected from the bottom surface of the glass pane, at a separate points of x axis will be maximal. These points are

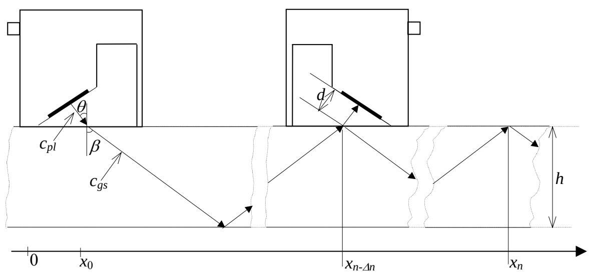

Fig.4. **The scheme of the shear wave propagation in the glass pane**

the points of multiple reflections of acoustical signals, which are labelled 1-x_1, 2-x_2 and so on. The times of propagation of acoustical signals from radiating transducer to the receiving transducer, located at corresponding points, will be labelled as t_1, t_2 and so on. Then from Fig.4 it is seen that

$$\sin\beta = \frac{\Delta x}{c_{gs}\left(t_n - t_{n-\Delta n}\right)}, \tag{17}$$

where $\Delta x = x_n - x_{n-\Delta n}$.

There n is the number of reflections of acoustical signal propagating from radiating transducer to the measuring point; Δn is the number of differences of reflections between two points chosen. Besides that, $n>k$. Then from Eq.17 and the Snell's low Eq.8 one can obtain the equation for determination of propagation velocity of the shear waves in the glass pane:

$$c_{gs} = \sqrt{\frac{c_{pl}\Delta x}{\left(t_n - t_{n-\Delta n}\right)\sin\theta}}. \tag{18}$$

In accordance with Fig.4

$$c_{gs}\left(t_n - t_{n-\Delta n}\right) = \sqrt{(\Delta x)^2 + (2h\Delta n)^2}, \tag{19}$$

and Eq.18, the thickness of the glass pane is given by

$$h = \frac{1}{2\Delta n}\sqrt{\Delta x\left[\frac{c_{pl}\left(t_n - t_{n-\Delta n}\right)}{\sin\theta} - \Delta x\right]}. \tag{20}$$

However, the algorithms which describe the velocity of propagation of acoustical waves (Eq.18) and the thickness of the glass pane (Eq.20) contain the velocity of propagation of acoustical signals in the prisms of ultrasound transducers. Because the prisms are produced of plexiglass, the influence of temperature is very important. Therefore, when seeking to ensure a high accuracy of measurements, the dependence of sound velocity $c_{pl}(T)$ in the prisms on temperature T and the temperature of prisms must be evaluated, when the algorithms (Eq.18) and (Eq.20) are used.

Trying to avoid this inconvenience, the variable c_{pl} is expedient to change by other parameter, which is minimally influenced by the temperature. In our case the middle length of ultrasound beam in the prisms of ultrasonic transducers satisfy these requirements best of all. This parameter for the selected pair of ultrasonic transducers is determined experimentally and is almost entirely independent on environmental conditions.

With the purpose to perform necessary replacement, the time during which the acoustical signal reflects *n* times may be expressed by equation

$$t_n = nt + \Delta t\ . \qquad (21)$$

Here *t* is the duration of the single reflection of acoustical signal in glass; Δt is the duration time of propagation of the acoustical signal in the prisms of the ultrasonic transducers.

After choosing of two points on the axis *x*, which are distant from each other by the Δ_n reflections, we obtain

$$\Delta t = \frac{nt_{n-\Delta n} - (n-\Delta n)t_n}{\Delta n}\ . \qquad (22)$$

Since

$$c_{pl} = \frac{2d}{\Delta t}\ , \qquad (23)$$

so, after the substitution of Eq.22 into Eq.23, one can obtain

$$c_{pl} = \frac{2d\Delta n}{nt_{n-\Delta n} - (n-\Delta n)t_n}\ . \qquad (24)$$

After the substitution of Eq.24 into Eqs.18 and 20, we obtain the expressions for determination of the shear wave velocity in the glass and the thickness of the glass pane:

$$c_{gs} = \sqrt{\frac{2d\Delta n\Delta x}{[nt_{n-\Delta n} - (n-\Delta n)t_n](t_n - t_{n-\Delta n})\sin\theta}}\ , \qquad (25)$$

$$h = \frac{1}{2\Delta n}\sqrt{\Delta x\left[\frac{2d\Delta n(t_n - t_{n-\Delta n})}{[nt_{n-\Delta n} - (n-\Delta n)t_n]\sin\theta} - \Delta x\right]}\ . \qquad (26)$$

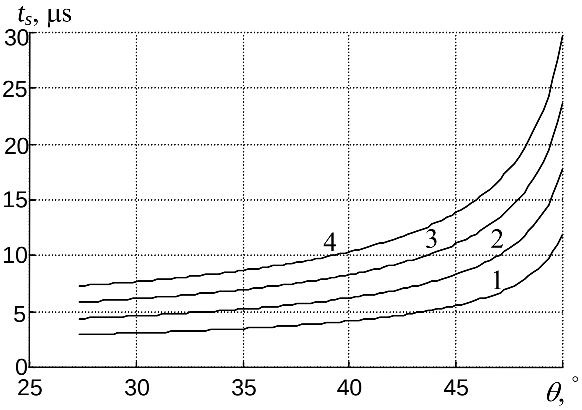

Fig.5. **The dependence of propagation the time t_s of shear waves in the glass pane on the angle of incidence θ (θ is between the first and second critical angles), when the thickness of glass pane *h* is changed: 1-*h*=4mm, 2-6mm, 3-8mm, 4-10mm**

Therefore, when calculating the velocity c_{gs} of propagation of shear waves in the glass and the thickness of the glass pane, using algorithms (Eqs.25 and 26), the middle length of ultrasound beam in the prisms of transducers and the angle θ of radiation of acoustical signal must be known in advance. Then it is sufficient to find the co-ordinates *x* of two pitch and catch propagation's and the times of propagation of acoustical signal to these points. The time of propagation of shear waves, when the incidence angle θ is between the first and second critical angle's, is shown in Fig.5. From Fig.5 one can see, that the propagation time of shear waves increased noticeably in comparison with Fig. 3. It allows to use lower frequency for measurement of the thickness of glass pane. Therefore, the same carrier frequency may be used for measurement of the thickness of glass panes as well as for measurement of the sound velocity inside the glazing unit.

Experimental investigation

Thickness measurement of glass pane was performed by using mechanical and ultrasonic measuring methods. For calibration of measuring instruments the thickness of the X-cut quartz plate was measured. It was selected due to high stability of ultrasound velocity (c_l=5720 m/s) in quartz plate [9]. So, the quartz plate was used as a test plate to check the incidence angle of the transducers and the accuracy of the time measuring instrument. The thickness of the glass pane specimens was from 4mm to 10mm. The measurement of the thickness was carried out mechanically (by micrometer) and also by ultrasound, when using the longitudinal and shear waves (Table 2). In the case of normal incidence the 5 MHz transducer was used. In the case of oblique incidence two different angles were selected. In the first case the small incidence angle (θ=3°) was used and 10 MHz double piezoelemet transducers were applied. At that case longitudinal and shear waves were received. In the second case the incidence angle θ was increased to the value more than the first critical angle and shear ultrasonic waves were received. At that case the refractive angle in the glass pane

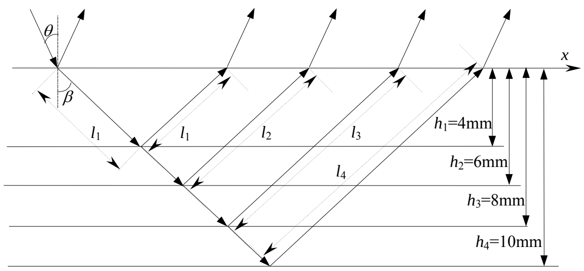

Fig.6. **Schematic diagram of the measurement of thickness of glass panes by the shear waves**

was β=54°. So, the carrier frequency of the shear wave electroacoustical transducers was decreased to 5 MHz. The diagram of the measuring principle when using the shear waves is shown in Fig.6. During the experiment, the thickness of the glass pane was calculated according to expression

$$h = \frac{v_{gs}t\cos\beta}{2}\ . \qquad (27)$$

How one can see from Table 2, the measured values of thickness of the glass panes, obtained by all methods used, were smaller than the nominal ones, but these values were in good agreement with the tolerances presented in the Standard EN 572-2 [7]. According to this Standard the tolerances of nominal thickness can vary from ±0.2mm for 4…6mm glass panes to ± 0.3mm for 8…10mm glass panes.

Table 2. **The values of glass pane thickness obtained using mechanical and ultrasonic measuring methods**

Material	Nominal thickness [mm]	Measured thickness [mm]			
		Mechanical method	Ultrasonic method		
			Longitudinal wave		Shear wave
			Normal incidence	Oblique incidence	Oblique incidence
Quartz	5.7	5.70	5.71	5.69	5.69
Glass	4.0	3.88	3.91	3.89	3.86
Glass	6.0	5.95	5.96	5.86	5.97
Glass	8.0	7.90	7.89	7.79	7.97
Glass	10.0	9.88	9.89	9.78	9.91

Conclusions

The results of investigation show that when the one side ultrasonic measuring methods are used for determination of thickness of the glass panes of windows, the longitudinal waves as well as the shear waves may be applied.

When measuring in the perpendicular direction, the longitudinal waves of 0.5…1MHz may be used for measurement of thickness of the glass pane as well as for the determination of composition of gas filling the glazing unit.

Using the angular excitation, when the angle of incidence changes from 0° to the first critical, the time of propagation of longitudinal waves is increased significantly in comparison with the perpendicular case. Besides that, the double piezoelement transducers may be used for measurement of thickness of glass panes. All these measures predetermine improvement of measurement accuracy.

When using the pitch and catch method for measurement of thickness of the glass panes as well as for measurement of propagation velocity of ultrasound signals in it, it is sufficient to determine the co-ordinates of pitch and catch points and the times of propagation of acoustical signals. Besides that, evaluation of the angle of radiation and the middle length of ultrasound beam in the prisms of ultrasonic transducers allows one to eliminate the influence of ambient temperature to the results of measurements.

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A. Vladišauskas, L. Jakevičius, J. Bukus

Ultragarso panaudojimas langų stiklų storiui matuoti

Reziumė

Tiriant langų stiklo paketus ultragarsiniu metodu, būtina nustatyti ir langų stiklų storį. Išnagrinėtos galimybės šiam tikslui taikyti vienpusius ultragarsinius matavimo metodus, kai stiklo lakšte sužadinamos išilginės ir skersinės ultragarso bangos. Sukurti nauji algoritmai skersinių bangų sklidimo greičiui stikle ir stiklo storiui apskaičiuoti. Algoritmai tinka, kai yra žinomas akustinių signalų kritimo į stiklo paviršių kampas, bet nežinomas ultragarso virpesių sklidimo stikle greitis. Skersinių akustinių bangų sklidimo greitį ir langų stiklo storį pasiūlyta matuoti naudojant daugkartinius akustinių signalų, sklindančių tarp skirtingų stiklo paviršiaus taškų, atspindžius. Tai leidžia eliminuoti signalų sklidimo laiko kampinių keitiklių prizmėse įtaką, dėl ko padidėja matavimo tikslumas. Pateikiami eksperimentinio tyrimo rezultatai.

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