ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2012. No. 7(123)
ELEKTRONIKA IR ELEKTROTECHNIKA

ELECTRONIC MEASUREMENTS

ELEKTRONINIAI MATAVIMAI

Modeling of Ultrasonic Measurement Systems with Waveguides

R. Kazys, E. Zukauskas, R. Rekuviene
Ultrasound Research Institute, Kaunas University of Technology,
Studentų str. 50, 51368 Kaunas, Lithuania, phone: +370 37 351162, fax. +370 37 451489, e-mail: ulab@.ktu.lt

crossref http://dx.doi.org/10.5755/j01.eee.123.7.2375

Introduction

Ultrasonic measurements are very popular techniques used for material characterization and non-destructive testing applications. One of the most popular is a pulse echo technique [1]. In specific cases of non-destructive testing applications, such as investigation of properties of hot fluids, hot or melted metals, measurements must be performed at a high pressure and/or at high temperatures [2]. However conventional ultrasonic transducers can't withstand high temperatures. In this case special high temperature transducers must be used or in order to protect conventional ultrasonic transducers from influence of a high temperature and avoid depolarization, measurements must be performed using special waveguides with a low thermal conductivity between the object under investigation and an ultrasonic transducer. On the other hand, presence of the ultrasonic waveguide has a significant influence on the transmission of the ultrasonic wave from ultrasonic transducer to the object under investigation [3]. It is very important to select a proper configuration of the waveguide [4]. In order to save materials and manufacturing time resources numerical modeling must be used.

Objective of this work was comparison of the two modeling techniques of the ultrasonic measuring systems with waveguides: 1D matrix technique and 2D finite element method.

Design of the ultrasonic systems with waveguides

The simplest geometrical shapes of ultrasonic waveguides are cylindrical and tapered waveguides. Numerical investigation of the propagation of the ultrasonic waves in a waveguide was carried out using ANSYS finite element code. To solve the transient wave equation implicit algorithm was used. Because object of the investigation possesses axial symmetry, the model was simplified using 2D axial symmetry approach. The simplified graphical representation of the finite element models of the cylindrical and tapered waveguides is presented in Fig. 1.

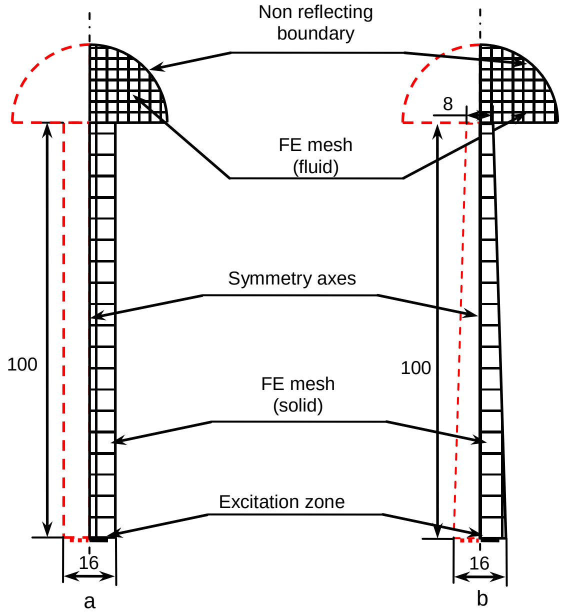

Fig. 1. Graphical representation of the finite element models of the cylindrical (a) and tapered (b) waveguides. (Dimensions are in millimeters)

The volume of the solid part of the model was meshed using PLANE42 elements, and the fluid was meshed using FLUID29 elements. In order to avoid unnecessary reflections of ultrasonic waves from edges of the fluid part, the non-reflecting boundary conditions were used (FLUID129 elements). Spatial resolution of the mesh in solid and fluid parts of the model is $\lambda/15$, where λ is the wavelength. A better refinement of the mesh is almost impossible due to limited computer resources. For excitation of the ultrasonic wave in the waveguide 3.5 MHz, the 2 period's Gaussian pulse was used. The time step duration is 14 ns.

One of the best materials for production of the ultrasonic waveguide is titanium. Titanium has a low thermal conductivity and can be used in high temperature conditions. The influence of the λ/4 matching layer between the waveguide and a liquid under investigation was evaluated as well and will be presented later. The matching layer is made from Duralco polymer.

The properties of the waveguide, matching layer materials and fluid used in the 2D and 1D investigations are presented in Table 1.

Table 1. Materials properties

	Longitudinal velocity, m/s	Shear velocity, m/s	Acoustic impedance for longitudinal wave, MRayl
Titanium (Grade 2)	5823	2933	26.7
Polymer (Duralco)	2615	1569	4.96
Water	1480	-	1.48

The normalized time diagram of the signal reflected from the waveguide - fluid interface and received in the zone of the ultrasonic transducer in a case of the cylindrical titanium waveguide is presented in Fig. 2.

The time diagram of the received signal shows that there are multiple waves traveling behind the wave of interest. Literature analysis reveals that the trailing waves occur due to reflections and mode conversions on the boundary of the waveguide [5, 6]. The delay time between the received trailing signals is proportional to the diameter of the waveguide [5, 7]. Such signals are unwanted due to the possibility of interference with signals used in measurements. The trailing waves can be suppressed using different configurations of the waveguide [8]. The most effective shape for suppressing trailing waves is the tapered waveguide (Fig. 1 (b)) [7].

The time diagram of the received signal in the case of the tapered waveguide is presented in Fig. 3. The time diagram shows that the tapered shape of the waveguide allows successfully suppress parasitic trailing waves and can be used for the ultrasonic measurements and non-destructive testing applications.

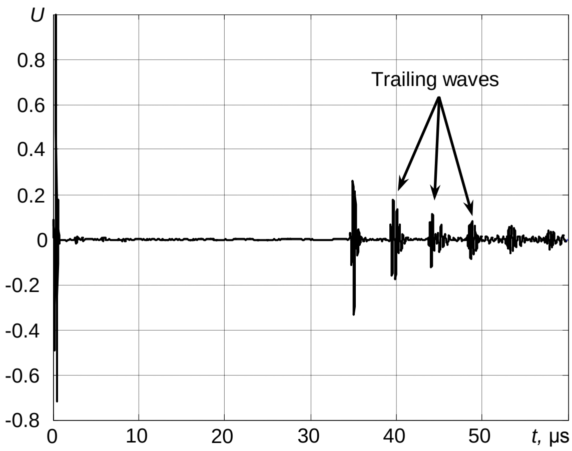

Fig. 2. Normalized time diagram of the received signal in a case of the cylindrical titanium waveguide

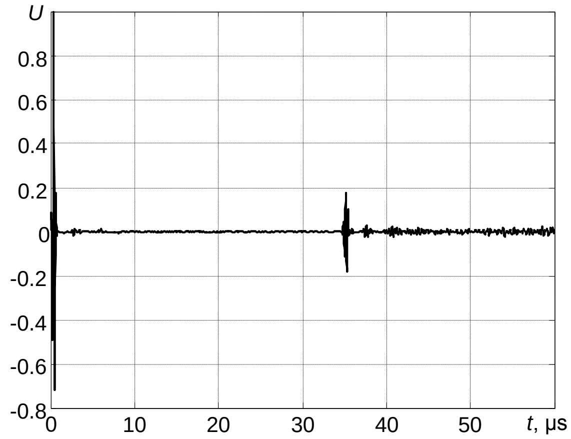

Fig. 3. Normalized time diagram of the received signal in a case of the tapered titanium waveguide

1D analytical model of measurement system

Graphical representation of the model of the multilayered ultrasonic measurement system is shown in Fig. 4.

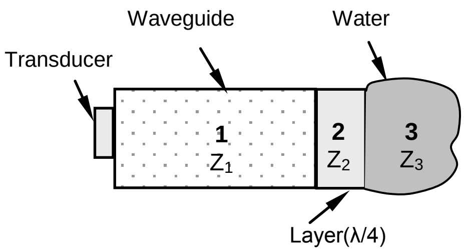

Fig. 4. Model of measurement system: 1 – waveguide; 2 – λ/4 matching layer; 3 – water

1D analysis of such multilayered structure is based on a matrix calculus. For example, the matrix equation of the λ/4 matching layer can be written as [9]

$$A = \begin{bmatrix} \mathrm{ch}\gamma l & A_0 Z_2 \mathrm{sh}\gamma l \\ \dfrac{\mathrm{sh}\gamma l}{A_0 Z_2} & \mathrm{ch}\gamma l \end{bmatrix}, \qquad (1)$$

where Z_2 is the acoustic impedance of the λ/4 matching layer, A_0 is the area of the layer

$$\gamma = \alpha(\omega) + j2\pi/\lambda\,, \qquad (2)$$

where $\alpha(\omega)$ is the attenuation coefficient of an ultrasonic wave, $\lambda = c/f$ is the wavelength, c is the phase velocity , l is the thickness of the layer, $\omega=2\pi f$.

The reflection and transfer coefficients of the ultrasonic longitudinal waves can be calculated using the following equations [9]:

$$R_{13}(\omega) = \frac{Z_{\mathrm{in}}(\omega) - Z_1}{Z_{\mathrm{in}}(\omega) + Z_1}\,, \qquad (3)$$

$$K_{13}(\omega) = \frac{2 Z_{\mathrm{in}}(\omega)}{Z_{\mathrm{in}}(\omega) + Z_1}\,, \qquad (4)$$

where Z_1 is the waveguides acoustic impedance, Z_{in} is the input acoustic impedance of the λ/4 layer, loaded by a liquid medium acoustic impedance of which is Z_3.

The input acoustic impedance Z_{in} is calculated (1) from the matrix coefficients $A_{ij}(\omega)$ using the following equation [9]

$$Z_{in}(\omega) = \frac{1}{A_0} \cdot \frac{A_{22}(\omega) Z_3 A_0 + A_{12}(\omega)}{A_{21}(\omega) Z_3 A_0 + A_{11}(\omega)}. \tag{5}$$

The calculations were carried for the titanium waveguide, while the λ/4 matching layer was made of the Duralco polymer (parameters are presented in Tab.1).

The results of calculations are presented in Fig. 5 and Fig. 6. Frequency characteristics are shown in figures, when the acoustic impedances of the liquid Z_3 are 1.48 MRayl, 1.94 MRayl and 2.25 MRayl. Please note that the frequency responses 1, 2 and 3 are obtained by the 1D analytical model, the response 4 - by the 2D finite element model.

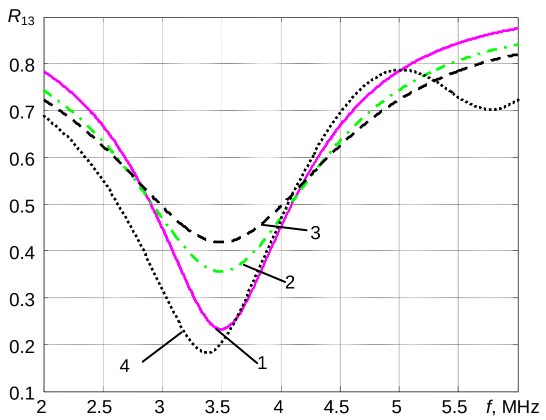

Fig. 5. Reflection coefficients R_{13} of the λ/4 layer versus frequency for different acoustic impedances of load: 1– 1.48 MRayl, 2 – 1.94 MRayl, 3 – 2.25MRayl. 4 – 1.48 MRayl from finite element modeling results

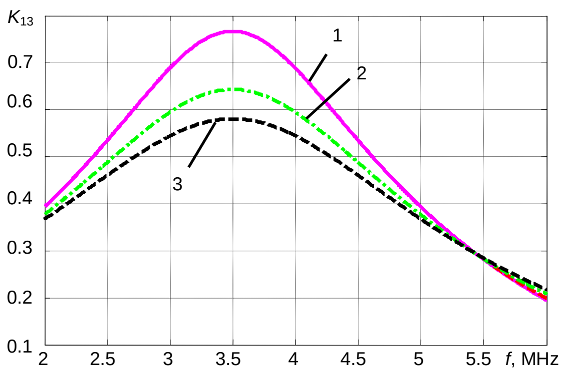

Fig. 6. Transfer coefficients K_{13} of the Ti-λ/4 versus frequency for different acoustic impedances of load: 1 – 1.48 MRayl, 2– 1.94 MRayl, 3 – 2.25 MRayl.

The minimum of the reflection coefficient is at the frequency f =3.5 MHz (Fig. 5.). It is essential to notice that when the acoustic impedance Z_3 is increasing, the reflection coefficient modulus $|R_{13}|$ increases also. It is clearly seen (curves 1 and 4) that 1D modeling results are very similar to the 2D modeling results.

The transfer coefficient maximum is obtained at the frequency f =3.5 MHz, e.g. when thickness of the matching layer l=λ/4. (Fig. 6). When the acoustic impedance Z_3 is increasing, the transfer coefficient modulus $|R_{13}|$ at this frequency decreases. The whole system transfer function with a multilayered piezoelectric transducer is shown in Fig. 7.

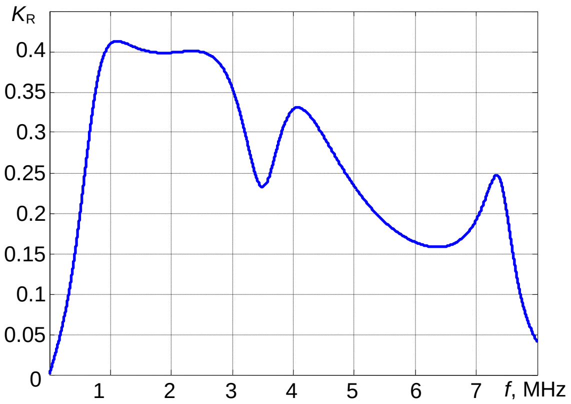

Fig. 7. Calculated transfer function K_R of the multilayered structure versus frequency

From the results presented in Fig. 7 follows that the frequency response of the ultrasonic transducer strongly affects the total systems frequency response, but still a clear minimum caused by the λ/4 matching layer is observed at the frequency f =3.5 MHz (Fig. 7).

2D finite element modeling of the transfer functions of waveguide with finite dimensions

Another question is the influence of the geometry and finite dimensions of the waveguide to the efficiency of the transmission of the ultrasonic wave between the ultrasonic transducer and the liquid under investigation in a presence of the waveguide between them. In order to achieve more efficient transmission of the ultrasonic wave through a waveguide - fluid interface λ/4 matching layers can be used. Finite element modeling of the titanium waveguide with 0.19 mm thickness polymer matching layer was carried out. Transfer functions in a pulse-echo mode obtained from the finite element modeling using Eq.6 are presented in Fig. 8. The transfer function is given by

$$K_{\mathrm{R}} = \frac{\mathrm{F}\left(u_{\mathrm{R}}(t) \cdot w(t)\right)}{\mathrm{F}\left(u_{\mathrm{Ex}}(t)\right)}, \tag{6}$$

where F denotes the Fourier transform, $u_{\mathrm{Ex}}(t)$ is the excitation signal, $u_{\mathrm{R}}(t)$ is the signal reflected from the waveguide - polymer interface and obtained in the zone of the ultrasonic transducer, $w(t)$ is the time window.

It is clearly seen, that in the case of the 2D finite element modeling the reflection coefficients are much smaller than in the case of 1D analytical modeling. This can be explained by energy losses due to the reflections and mode conversion on the boundaries of the waveguide. As well as in the case of 1D model, the transfer function of the waveguide with the λ/4 matching layer has a local minimum in 3.5 MHz frequency zone. The value of the transfer function in this frequency zone is approximately 4 times smaller than in the case of the waveguide without matching layer and of the transmission of the ultrasonic wave through waveguide - fluid interface will be more efficient. The transfer functions in the transmission mode calculated using (7) are shown in Fig. 9

$$K_{\mathrm{T}} = \frac{\mathrm{F}\left(u_{\mathrm{T}}(t)\cdot w(t)\right)}{\mathrm{F}\left(u_{\mathrm{Ex}}(t)\right)}, \qquad (7)$$

where $u_{\mathrm{T}}(t)$ is the signal obtained on the waveguide - polymer interface, F is the Fourier transform.

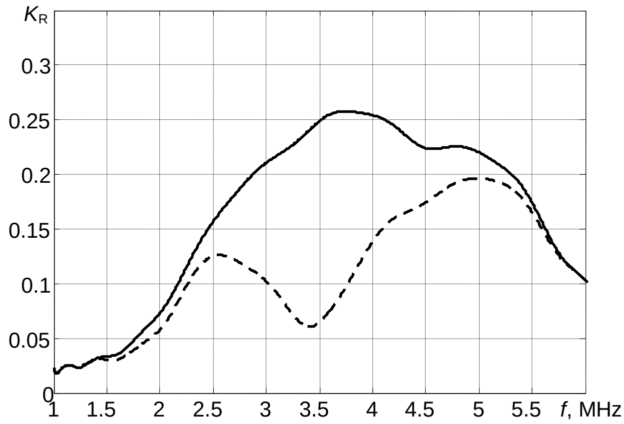

Fig. 8. Transfer functions K_R of the titanium waveguides without matching layer (solid line) and with λ/4 matching layer in the pulse – echo mode (dashed line)

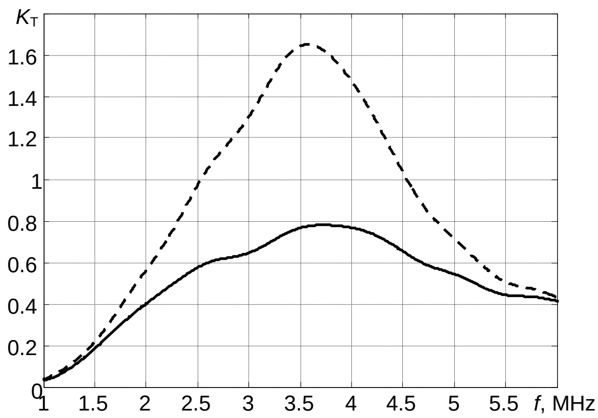

Fig. 9. Transfer functions K_T of the titanium waveguides without matching layer (solid line) and with λ/4 matching layer in the transmission mode (dashed line)

Conclusions

Using 1D matrix technique and 2D finite element method frequency characteristics of reflection and transmission coefficients were modeled and compared. There is a good coincidence of the modeling results between 1D and 2D models.

The transfer functions of the waveguide, taking finite geometry into account were calculated using a finite element technique. Transfer function coefficients obtained by the finite element technique are much smaller in comparison with 1D model. This can be explained by wave propagation phenomena in a finite dimension waveguide. These phenomena were not taken into account in the 1D analytical model.

References

1. **Cegla B.**, **Cawley P., Allin J., Davies J.** High temperature (>500^{0}C) wall thickness monitoring using dry–coupled ultrasonic waveguide transducers // Ultrasonics, Ferroelectrics and Frequency Control, 2011. – Vol. 58. – No. 1. – P. 156–167.
2. **Ono J., Whiteside B., Brown E.** Real–time process monitoring of micromoulding using integrated ultrasonic sensors // Transactions of the Institute of Measurement and Control, 2007. – Vol. 29. – No. 1. – P. 383–401.
3. **Jen C., Legoux J., Parent L**. Experimental evaluation of clad metallic buffer rods for high temperature ultrasonic measurements // NDT&E International, 2000. – Vol. 33. – No. 3. – P. 145–153.
4. **Liu Y., Lynnworth L., Zimmerman M.** Buffer waveguides for flow measurement in hot fluids // Proceedings of Ultrasonics International, 1998. – Vol. 36. – P. 305–315.
5. **Mason W. P., McSkimin H. J.** Attenuation and scattering of high frequency sound waves in metals and glasses // J. Acoust. Soc. Am., 1947. – Vol. 19. – No. 3. – P. 464–473.
6. **Thurston R. N.** Elastic waves in rods and clad rods // J. Acoust. Soc. Am., 1978. – Vol. 64. – No. 1. – P. 1–37.
7. **Jen C. K., Piche L., Bussiere J. F.** Long isotropic buffer rods // J. Acoust. Soc. Am., 1990. – Vol. 88. – No. 1. – P. 23–25.
8. **McSkimin H. J.** Measurement of ultrasonic wave velocities and elastic moduli for small solid specimens at high temperatures // J. Acoust. Soc. Am., 1958. – Vol. 31. – No. 3. P. 287–295.
9. **Домаркас В. И., Кажис Р. И. Ю**. Контрольно–измерительные пьезоелектрические преобразователи. – Вильнюс: Моксллас, 1975. – 41 с.

Received 2012 03 19
Accepted after revision 2012 05 15

R. Kazys, E. Zukauskas, R. Rekuviene. Modeling of Ultrasonic Measurement Systems with Waveguides // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 7(123). – P. 61–64.

The ultrasonic pulse-echo technique is used for non-intrusive process monitoring. The material properties must be investigated in very complicated conditions - high temperature and others. The special high temperature transducers or waveguides must be used to protect the transducer from the high temperature of the material. Objective of this work was comparison of the two modeling techniques of the ultrasonic waveguides for application of the ultrasonic measurements: 1D matrix technique and 2D finite element method. Ill. 9, bibl. 9, tabl. 1 (in English; abstracts in English and Lithuanian).

R. Kažys, E. Žukauskas, R. Rekuvienė. Ultragarso matavimo sistemų su bangolaidžiais modeliavimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 7(123). – P. 61–64.

Ultragarsiniai matavimo metodai plačiai taikomi šiuolaikinėje pramonėje, ypač kai matavimus reikia atlikti ekstremaliomis sąlygomis. Tam taikomi specialūs bangolaidžiai, apsaugantys keitiklio paviršių nuo aukštos temperatūros poveikio. Šio straipsnio tikslas – palyginti matavimo sistemos su bangolaidžiu 1D ir 2D modeliavimo metodus, įvertinti modeliavimo rezultatus. Il. 9, bibl. 9, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).