MEASUREMENT OF CHANGE OF ULTRASONIC WAVES PHASE DUE TO PRESENCE OF LIQUID ON REFLECTIVE SURFACE

Rustam Ravshanovich Jabbarov

Abstract: The uncertainty of the measurement method of phase shift for ultrasonic wave, reflected from solid (fused silica)-investigated liquid (distilled water and Tung oil) by impedance method is evaluated.

Keywords: phase shift, uncertainty, measurement, combined, standard, ultrasound, impedance, fused silica.

1. Problem setting

As it has been first shown by Stokes [1], conventional ultrasonic methods are unsuitable for measurement of dynamic shift of viscosity and elasticity because in a viscoelastic liquid pure shear vibrations totally disappear already at distances of a few micrometers from the converter, stimulating them. However, using indirect acoustic methods it is possible to measure both dynamic shear viscosity and elasticity [2]. On megahertz frequencies, impedance method is the most appropriate for this purpose in which these values are determined by measuring reflection coefficient r and phase shift $\vartheta$ of transverse acoustic wave as a result of its repeated reflection from interface of solid (e.g., fused silica)—investigated liquid (next for short – the phase shift of $\vartheta$ wave). Degree of reliability and validity of obtained results and judgments, based on them, is expressed by their uncertainty estimates.

2. Relevance

To study the mechanisms inside and intermolecular interactions in viscous liquids, particularly vegetable oils, measurement of reflection coefficient r and phase shift $\vartheta$ of the wave is of great interest. Index of reliability and validity of obtained results and judgments based on them is expressed by their uncertainty estimates. It is not difficult to see the interest of the world of science to this subject, hence its relevance according to numerous international scientific symposia, conferences and seminars, as well as publications in scientific and technical journals on estimation of measurement uncertainty is present.

3. Purpose of the work

Purpose of the work is the development of scientific and methodological basis of analysis of the evaluation of uncertainty in measurement of phase shift of $\vartheta$ wave by the impedance method.

4. Summary of basic material

Phase shift measurement of $\vartheta$ wave is carried out in the frequency range 10-150 MHz, using installation [3], based on the impedance method. Installation has two channels - work and reference channels, acoustic cells, which are made in the form of identical rectangular blocks of fused quartz of identical size with ends, beveled at angle 82°40′.

Phase shift $\vartheta$ is measured by compensation of working and reference ECHO-signals, which is achieved, if the signals are equal in amplitude and phase shifted to 180°. In the process of measuring, compensation was performed with an attenuator and a variable delay line. Long lines are used as variable delay lines and totalizers, ensuring running (without reflection) electromagnetic waves. This made it possible to avoid the use of radio-electronic circuits, providing additional frequencies and phase distortions and also enhanced the accuracy of measurement of phase shift of $\vartheta$ wave.

Phase shift of $\vartheta$ waves is calculated by the formula

$$\vartheta = \frac{360}{(2m-1)\cdot c} \cdot f \cdot (L_0 - L)$$

where $f$ is the ultrasound frequency, Hz;

$L_0$ is the initial length of the variable delay line where compensation of working and reference ECHO-signals has been reached before applying investigated liquid on working surface of acoustic cell of installation working channel, m;

$L$ is the length of variable delay line where compensation of working and reference ECHO-signals has been reached after putting the researched liquid on the working surface of acoustic cell of installation working channel, m;

$m$ is the serial number of reflections (ECHO);

$c = 2.15 \cdot 10^8$ is the electromagnetic wave velocity in variable delay line, m/s;

We conducted experimental research of veg-
etable (Tung) oil after calibration of measuring equipment (instruments) [3]. For this procedure, as a liquid, it was necessary to choose a fluid with constant dynamic shear elasticity and viscosity, i.e. not relaxed in the investigated frequency range and with the lowest static viscosity. Invariable dynamic shear elasticity and viscosity are necessary to facilitate comparison of measurement results with theoretical calculations, small static viscosity - to determine resolution of the installation. We chose distilled water as such liquid. From (1) it follows that uncertainty of measurement of values \( f, L_0 \) and \( L \) are the main potential sources of uncertainty of measurement result of phase shift of \( \theta \) wave. Results \((n=5)\) of multiple measurements of these values for distilled water are listed in table 2.1, and for Tung oil - in table 2.

* \( \bar{f} \) and \( \Delta L \) - Accordingly, average arithmetic values and standard uncertainties of input values \( f \) and \( \Delta L \).

It is supposed that five independent series of simultaneous observations of these two input values \( f \) and \( \Delta L \) (table.1 and 2) are obtained in the same conditions. Here, average arithmetic of observations \( \bar{f}, \Delta L \) are given and experimental standard deviations \( u_f(\bar{f}) \) and \( u_{\Delta L}(\Delta L) \) of these averages, calculated from equations (2) [4].

\[
S(\bar{f}) = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (\bar{f}_i - \bar{f})^2},
\]

where \( n \) – is the number of observations, \( \bar{f}_i, \Delta L_i, \bar{f}, \Delta L \) - are average arithmetic values of \( f \) and \( \Delta L \).

**5. Procedure of evaluation of measurement uncertainty**

The result of measurement, described by nonlinear function (1), is assessed using either linearization method or reduction method, depending on presence or absence of correlation between uncertainties of measurements of input values \( f, \Delta L, c \). Therefore, we primarily defined correlation coefficients between them and checked their relevance by Student’s t-test [5].

Our assessments both of distilled water, and Tung oil, showed no significance of the correlation coefficients between input values \( f, \Delta L \) and \( c \).

Linearization method, however, as it is known, is allowed, if it is possible to ignore remainder term \( R \), in expansion of function in Taylor series, evaluated by equation (3)

\[
R = \frac{1}{2} \sum_{j} \frac{\partial^2 \theta}{\partial f^2}(\Delta f)(\Delta L) \,
\]

where \( \Delta f \) and \( \Delta L \) are maximum deviations of \( i \) result of observation of secondary argument values

| Table 1 – The results of measurements of values \( f, \Delta L=L_0-L \) and \( \theta \) for distilled water \( M \) |
|---|---|---|---|---|---|---|---|
| Row number | Frequency \( f, \) MHz | 11,4 | 29,1 | 50,0 | 72,1 | 88,3 | 111,0 | 128,0 | 148,0 |
| Phase shift of \( \theta \) shift, \( \circ \) | 1 | 0,725 | 0,906 | 1,340 | 1,425 | 1,597 | 1,821 | 2,015 | 2,181 |

| Table 2 – The results of measurements of values \( f, \Delta L=L_0-L \) and \( \theta \) for Tung oil |
|---|---|---|---|---|---|---|---|
| Row number | Frequency \( f, \) MHz | 11,4 | 29,1 | 50,0 | 72,1 | 88,3 | 111,0 | 128,0 | 148,0 |
| \( \Delta L=L_0-L \), m | 1 | 2,99 | 1,87 | 1,02 | 0,6 | 0,52 | 0,51 | 0,42 | 0,3 |
| Phase shift of \( \theta \) shift, \( \circ \) | 1 | 11,415 | 18,223 | 17,079 | 14,487 | 15,377 | 18,958 | 18,003 | 14,869 |
Applying (3) to measuring model (1) we get
\[
R = 360 \cdot k \cdot \Delta f \cdot \Delta L / c
\]  
(4)

Remainder term R, as it is known, is ignored, if in equation is performed
\[
R < 0.8u_c(\theta)
\]  
(5)

where \(u_c(\theta)\) — is combined standard uncertainty of measurement of phase shift of \(\theta\) wave.

Our assessments showed execution of these conditions (see table 1). Therefore, for evaluation of indirectly measured value \(\theta\) and its accuracy characteristics, the linearization method is used and values are obtained, given in table 1 and 2.

Evaluation of \(\theta\) measurement result is obtained by substitution into the equation (model) of measurement (1) (the average arithmetic values) of input values \(f\) and \(L\).

The results of the study show (see table 1) that phase shift \(\theta\), in the investigated range of frequencies continues to change, i.e. the relaxation process continues in the liquid when it is effected by dynamic shear stresses

Formula (6) for assessment of combined standard uncertainty and \(u_c(\theta)\) phase shift measurement of \(\theta\) wave, obtained by applying equation (7) [4] to model (1), taking into account smallness of evaluation of value uncertainty of electromagnetic wave velocity in variable delay line \(c\), is as it follows

\[
u_u(\theta) = \sqrt{\left(u_c(f)\right)^2 + \left(u_c(L)\right)^2}
\]  
(6)

\[
u_u(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_j}\right)^2 u^2(x_i) + \sum_{i=1}^{N} \sum_{j=1}^{N} \left(\frac{\partial f}{\partial x_i}\right) \left(\frac{\partial f}{\partial x_j}\right) u(x_i)x_j}
\]  
(7)

where

\[
c_1 = \frac{\partial \theta}{\partial f} = \frac{360}{(2m-1) \cdot c}
\]

\[
c_2 = \frac{\partial \theta}{\partial \Delta L} = \frac{360}{(2m-1) \cdot f}
\]

— is the sensitivity coefficient of evaluation of phase shift of \(\theta\) wave to change of values \(f\) and \(\Delta L\), accordingly;

\(u_c(f)\) and \(u_c(L)\) — are the combined standard uncertainties of values \(f\) and \(\Delta L\) evaluation, accordingly;

Uncertainty, defined by not excluded systematic error in measurement of the amplitude of the oscilloscope, is evaluated by type B and makes up to no more than 6%.

Combined standard uncertainty \(u_c(\theta)\) of angle measurement of phase shift \(\theta\) in the examined frequency range is not more than 1.5%.

### 6. Conclusion

1. Using of the linearization method for evaluation of phase shift of \(\theta\) wave and its accuracy characteristics is justified.

2. Values of phase shift angle of \(\theta\) acoustic wave, reflected from fused silica-distilled water interface with increasing frequency from 10 до 150 MHz, increases from 0,61 to 2,3 ...о, i.e. 3.9 times.

3. Results of measurement of \(f\) and \(\Delta L\) values mutually are not correlated.

4. Equations for estimating of measurement of combined standard uncertainty of phase shift angle \(\theta\) acoustic wave are obtained and measurements uncertainties are evaluated.

5. Results of the study of phase shift angle change of \(\theta\) reflected ultrasonic shear wave from solid-Tung oil interface at temperature of 20°C in the frequency range 10-150 MHz showed that in the investigated range of frequencies it continues to change, i.e. relaxation process that occurs in the studied fluid because of impacts on it if dynamic shear stress, continues.

6. Uncertainty of measurement of length change \((\Delta L)\) of variable delay lines makes the greatest contribution to combined standard uncertainty of measurement of phase change,

7. Combined standard uncertainty of phase angle \(\theta\) measurement method, implemented by installation [3], is no more than 1,4%.

### 7. References


Data of authors:

Rustam Ravshanovich Jabbarov
Place of work - «VRZ STANDART» LLC, Director.
Postal address: 107. Mustakillik Street Tashkent, The Republic of Uzbekistan, 100077
Tel. +998974205506.
E-mail: vrz.standart@mail.ru