R&D: Ultrasonic Technology / Fingerprint Recognition

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# Description of software for measurement of time of flight, phase velocity, dispersion, attenuation of sound and impedance of materials.

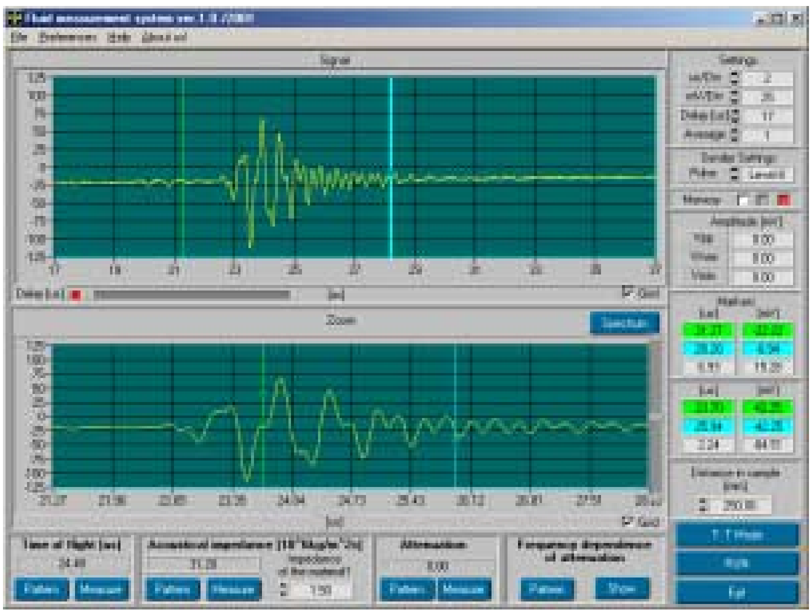
This software package allows to measure time of flight, sound velocity, attenuation and frequency dependence of attenuation, dispersion, phase velocity and impedance (density) of any material. The software uses ultrasonic pulses and is based on comparison of pulses achieved with reference and measured medium.

For each measurement it is necessary to choose reference signal and compare it with the signal, coming from the measured medium (reflected or transmitted through it). This allows to use this software with almost any kind of samples, containments etc. For people using this software it is necessary to have some knowledge about such kind of measurements, physics of ultrasounds etc. This software package gives them very good tool for such measurements.

## I. Introduction to the work with the software

### *First step*

Reference signal should be prepared, the best way to do it is to use pure (distilled) water. Using markers in the upper window most important part of the signal should be chosen. In the bottom window signal between markers from the upper window can be seen - magnified. See picture 1.



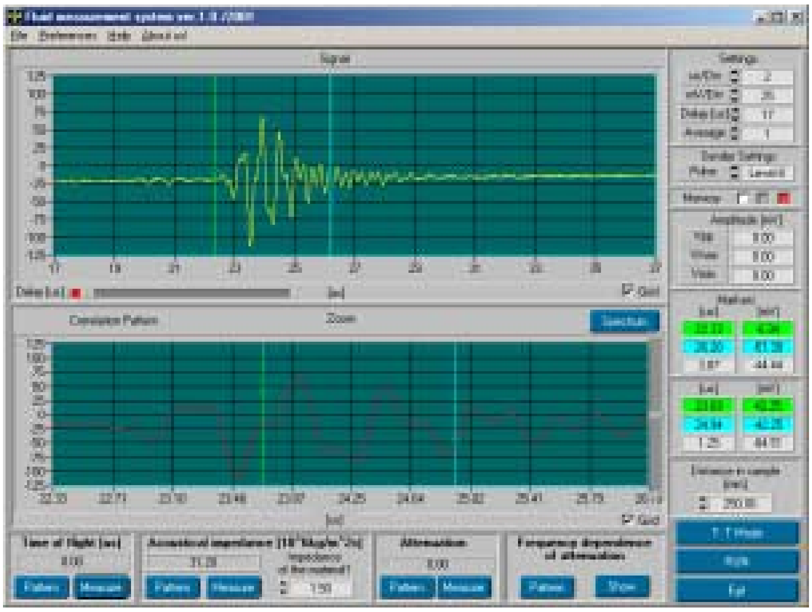
Picture 1.

## *Second step*

Button “Pattern” should be used. After pressing this button, chosen signal appears in bottom screen in white color together with information: "Correlation pattern". It means this signal from this moment will be “reference signal”. See picture 2.

Picture 2.

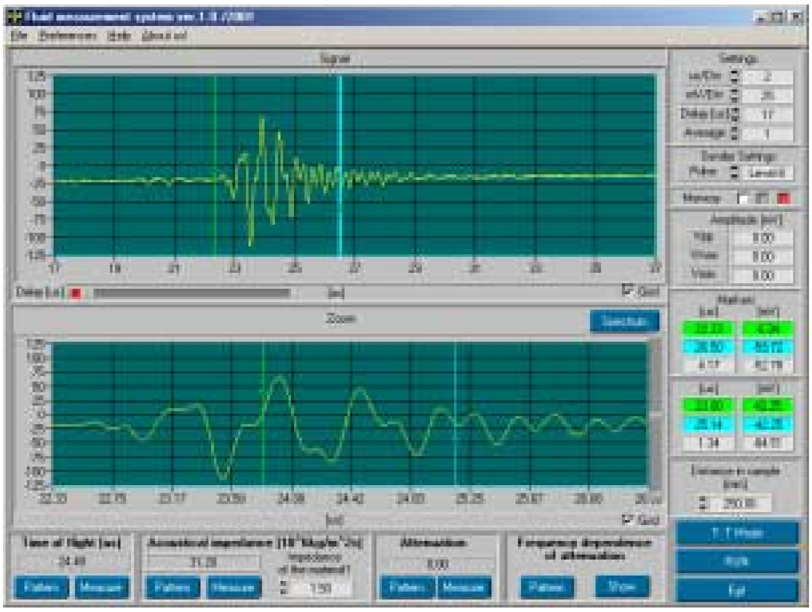
From this moment key called "Measure" should be used – all subsequent operations will use signal stored before (pattern) as reference for comparison with actually measured signal. See picture 3. For time of flight measurement the display will show 0 – nothing changed.



Picture 3.

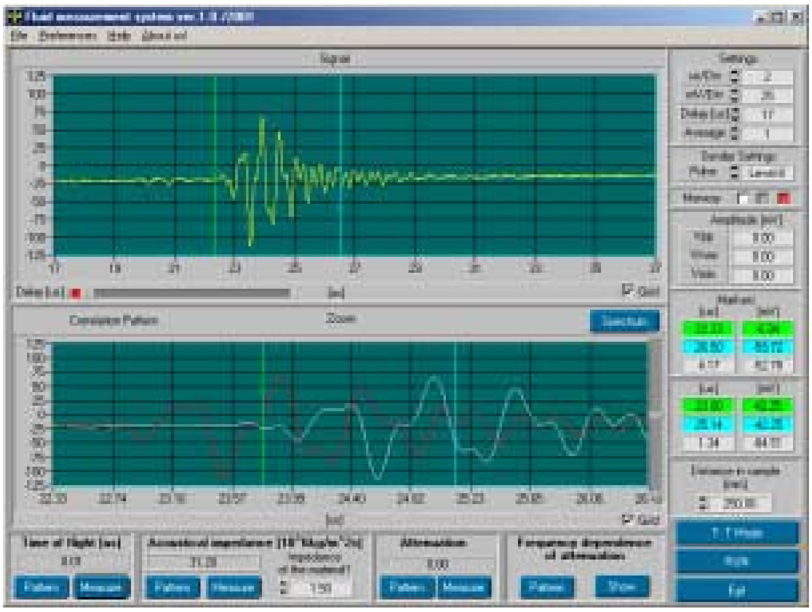
## Third step

In this moment we have to repeat operations described in the first step. In upper window we choose - using markers the most important part of signal we are getting from measured medium. In the bottom window we can see only signal between markers from the upper window. See picture 4. Pay attention on marker position (it is changed now). It means now we have another signal (with time offset for example).



Picture 4.

In this moment we have all information which is necessary for calculation of time of flight (and another functions too), and then the button “Measure” should be used (see picture 5). On the bottom window we can see two earlier prepared signals (white – reference signal; red - measure signal) in this case we receive result different from zero.



Picture 5

## II. The time of flight and sound velocity measurement method.

In most cases we can assume, that the signal will change after propagation - simple geometrical comparison of signals won't work properly. This is the reason, why we are using following algorithm for comparison of two signals with different time of flight:

a) FFT with Hamming window is made.
b) In frequency domain, frequency with maximum amplitude is chosen and using relatively sharp windowing only this frequency and frequencies from its neighborhood are taken.
c) Inverse FFT is done.
d) Center point of achieved signal is taken as time mark, telling us the moment of "coming" of this signal.

Time of flight can be measured from zero point (start of pulse) or from the time of "coming" of another signal, stored as pattern – as described above.

If the path length is known, it is possible to calculate the sound velocity in the measured material, using comparison with reference fluid – for example water.

If the experimental setup have a containment with measured fluid, where only a part of the sound propagation path is in the measured fluid, we can wrote following formula:

$$T=T_1+T_2$$

Where $T_1$ is time of propagation outside of measured fluid and $T_2$ in this medium. We can measure time of flight in the whole system (T) filled with water ($T_W$, that has velocity $C_W$), or measured fluid $T_X$ (velocity $C_X$). If we know the path length (L) in measured fluid, we can calculate the velocity of sound in this medium:

$$T_{2w}=L/C_W$$
$$T_1=T_W-T_{2W}$$

This ($T_1$) can be obtained after measurement with water, and this measurement must be done only from time to time, since parameters of system doesn't change quickly.

$$C_X \text{ (sound velocity in measured medium)} = L/(T_X-T_1)$$

The user of the software must know the path length (L), and choose appropriate signals (not only direct transmission must be chosen, but also multiple reflections for example).

## III. Theoretical basis of material impedance measurement method

The measurement of impedance of an unknown medium can be based on evaluation of the wave, reflected on the interface of this medium with another medium (i.e. wall of solid material - in most cases), eventually transmitted wave too, and comparison with reflection from another medium with known impedance.

Meanings of used variables:

***Z*** - impedance of medium (unit is $Ns/m^3$)
***R*** - the relation of reflected and transmitted wave (their intensities)
ρ - density of material ($g/cm^3$)
c – sound velocity (m/s)
$I_R$ - intensity of reflected wave
$I_t$ - intensity of transmitted wave

Geometrical representation:

| Material 1 (i.e. solid wall) | | Material 2 (measured medium, water or air) |
|---|---|---|
| $Z_1=\rho_1 c_1$ | \| | $Z_2=\rho_2 c_2$ |
| Incident wave with intensity I ⟶ | \| | Transmitted wave with intensity $I_T$ ⟶ |
| Reflected wave with Intensity $I_R$ ⟵ | \| | |

In most cases we are only able to measure the reflected wave and not the transmitted (this will be disturbed during propagation in unknown medium). This is the reason, why it is normally necessary to know the impedance of the solid wall. But it is also possible to measure it using air as reference medium (material 2). In this case the measurement would need following steps:

1) Measurement of reflection from the solid wall in contact with air - result is the intensity of incoming wave. If we know the impedance of the wall material, this measurement is not necessary – the intensity can be calculated from the measurement made in the second step.
2) Measurement of reflection from solid wall in contact with reference fluid with known impedance (for example water) – this is only necessary for obtaining value of wall material impedance. If we know this parameter, we can calculate R for water and do not need the measurement with air (we are able to calculate the intensity of incoming wave).
3) Measurement of signal reflected from measured fluid.

If the setup doesn't change, measurements from steps 1 and 2 must be done only from time to time (relatively seldom). The formulas used here are as follow:

$$R=I_R/I_T= (Z_2-Z_1)/(Z_2+Z_1)$$

$$I = I_R + I_T = const$$

I is the same in each case - with any material, because it depends only on used transducer and pulser, and can be also directly measured in comparison with air (which has almost 0 impedance and thus 100% reflection – $I_T \approx 0$) or calculated if we know both impedances ($Z_2$ and $Z_1$ – this is the case, if we know the impedance of the wall material and are using known fluid, for example water).

$$I = I_R + I_R/R \text{ (if we know R and } I_R)$$

We can measure $I_R$ (reflected wave) or $I_T$ (transmitted) wave. If we know only $I_R$, and the intensity of the incoming wave I, we can calculate R:

$$R = I_R/(I - I_R)$$

After comparison with another substance we are able to calculate the impedance of the measured substance:

$$Z_1 = Z_2(1-R)/(1+R)$$

$$Z_2 = Z_1(R+1)/(1-R)$$

The first equation is necessary to calculate the impedance of wall material (assuming, that $Z_2$ is the impedance of known material – i.e. water) and the second for calculation of impedance of measured material ($Z_1$ is impedance of wall material).

In the case of impedance measurement only with reflected signal it is not necessary to measure the signal using FFT filtration, because it doesn't change the shape (only in special cases, that are not realistic here). But this is also not worse, if we do it.

If we know the impedance and sound velocity of a material, we are able to calculate the density ($\rho = c/Z$).

## IV. Description of method for measurement of phase velocity, dispersion and attenuation of sound

### A. Introduction

The idea of the measurement is based on sending and receiving signals through measured medium. This operation is repeated many times, after some time period or after some changes was made (different material, temperature etc.). Each received signal can be described by[1] $g_n(t)$ where n=1,2,...N. Each signal can be also described using its Fourier transform:

$$\tilde{g}_n(f) = \int_{-\infty}^{\infty} g_n(t) \cdot e^{-i2\pi ft} dt \qquad (1a)$$

after inverse Fourier transform is applied, signal can be restored from his spectrum

$$\tilde{g}_n(f) \quad g_n(t) = \int_{-\infty}^{\infty} \tilde{g}_n(f) \cdot e^{i2\pi ft} df \qquad (1b)$$

The distribution of harmonics of this spectrum shows the transfer function of the whole unit, where $\tilde{e}(f)$ is the function of electronics (generator, transducer, amplifier...), wave propagation $\tilde{p}(f)$, including diffraction effects $\tilde{p}_d(f)$ and influence of the medium $\tilde{o}(f)$.

$$g_n(f) = \tilde{e}(f)\tilde{p}_d(f)\tilde{o}_n(f) \qquad \textbf{(2)}$$

In evaluation of material properties the most interesting thing are changes of medium properties $\tilde{o}_n(f)$. Thus it is necessary to design the system in the way, that all other elements are negligible (at least in frequency region of interest). This means, that it is necessary to use:

a – broadband devices (capable of transmitting and receiving short pulses),
b – transducer with small or controlled diffraction effects.

In all cases of relative measurements, where measured signal is compared with reference (index zero), it is allowed to assume, that the characteristic of electronics $\tilde{e}(f)$ and geometry of the system $\tilde{p}(f)$ do not change. Thus:

$$\tilde{\varsigma}(f) = \frac{\tilde{o}_n}{\tilde{o}_0} \approx \frac{\tilde{g}_n}{\tilde{g}_0} \qquad \textbf{(3)}$$

[1] Formulas are given for continuous variable *t*, but in computing we are using discrete variable *iT*, where *T* is the sampling period.

## B. Measurement with changing distance:

Measurements made in two distances $z_1$ and $z_2$

$$s_{z1}(t) = \int_{-\infty}^{\infty} \tilde{g}_{z1}(f) \cdot e^{i2\pi ft} df \quad \textbf{(4a)}$$

$$g_{z2}(t) = \int_{-\infty}^{\infty} \tilde{g}_{z2}(f) \cdot e^{i2\pi ft} df = \int_{-\infty}^{\infty} \tilde{g}_{z1}(f) \cdot \tilde{\varsigma}(f) \cdot e^{i2\pi ft} df \quad \textbf{(4b)}$$

Compound factor responsible for propagation

$$\tilde{\varsigma}(f) \approx \frac{\tilde{g}_{z2}}{\tilde{g}_{z1}} \quad \textbf{(5)}$$

we are writing it as

$$\tilde{\varsigma}(f) = e^{i2\pi f\beta(f)(z_2 - z_1)}$$

where $\beta(f) = -s(f) + i\alpha(f)/2\pi f$ ,

$s(f) = \dfrac{1}{c(f)}$ - slowness

$\alpha(f)$ - attenuation coefficient.

For the case without attenuation and dispersion

$$g_{z2}(t) = \int_{-\infty}^{\infty} \tilde{g}_{z1}(f) \cdot e^{-i2\pi fs\cdot(z_2 - z_1)} \cdot e^{i2\pi ft} df \quad \textbf{(6a)}$$

We are writing it as the superposition of propagating waves

$$g_{z2}(t) = \int_{-\infty}^{\infty} \tilde{g}_{z1}(f) e^{i2\pi f[t - s\cdot(z_2 - z_1)]} df \quad \textbf{(6b)}$$

Careful comparison of this both formulas allows to see, that propagation of wave packet can be treated as a superposition of harmonic waves with different slowness (6b). From (6a) follows, that with the distance compound amplitudes of harmonics are changing:

$$\tilde{g}_{z2}(f) = \tilde{g}_{z1}(f) \cdot e^{-i2\pi fs\cdot(z_2 - z_1)}$$

Imaginary part of the coefficient $\beta(f)$ is responsible for attenuation. Inclusion of this effect for chosen harmonics allows us to write compound amplitude after propagation:

$$\tilde{g}_{z2}(f) = \tilde{g}_{z1}(f) e^{-\alpha(f)\cdot(z_2 - z_1)} e^{-i2\pi f[s(f)\cdot(z_2 - z_1)]}$$

Calculation of compound coefficient $\beta(f)$ is possible after logarithm of formula (5)

$$\alpha(f) = \ln \frac{|\tilde{g}_{z2}(f)|}{|\tilde{g}_{z1}(f)|} / (z_2 - z_1) \qquad \textbf{(7)}$$

where

$$\tilde{g}_{z1}(f) = |\tilde{g}_{z1}(f)| e^{i\varphi_{z1}(f)}$$

$$\tilde{g}_{z2}(f) = |\tilde{g}_{z2}(f)| e^{i\varphi_{z2}(f)}$$

Difference of compound amplitudes

$$\varphi_{z2}(f) - \varphi_{z1}(f) = -2\pi f s(f) \cdot (z_2 - z_1)]$$

In large distances this difference changes quickly with frequency and if it is larger than $2\pi$ we get non continuous phase readings. In this moment, for the purpose of doing the phase continuous, it is necessary to be able to estimate the properties of the medium and try to make a model, that follows the reality. To calculate the dispersion we describe slowness as containing two parts – constant and changing:

$$s(f) = s_0 + \Delta s(f)$$

$$\tilde{g}_{z2}(f) = \tilde{g}_{z1}(f) e^{-i2\pi f s_0 \cdot (z_2 - z_1)} e^{-\alpha(f)\cdot(z_2 - z_1)} e^{-i2\pi f \Delta s(f)\cdot(z_2 - z_1)}$$

where first two parts are describing the propagation in a medium without dispersion (see (6)). Phase velocity is calculated from phase difference:

$$\varphi_{z2}(f) - \varphi_{z1}(f) + 2\pi f s_0(f) \cdot (z_2 - z_1) = 2\pi f \Delta s(f) \cdot (z_2 - z_1),$$

and from this equation

$$\Delta s(f) = \frac{\varphi_{z2}(f) - \varphi_{z1}(f)}{2\pi f \cdot (z_2 - z_1)} + s_0 \qquad \textbf{(8)}$$

The calculation of attenuation using this method gives realistic results in the central region of transfer bandwidth, under the condition, that propagation is going only in one mode (only one path). If many paths are existing, interference effects occur, that are causing waves in the attenuation diagram. The existence of such effects can be shown after measurements for some distances and comparison of results. In the border region of transfer function noise occurs, resulting from division of two small noise functions.

## C. Measurement with changing medium parameters.

We are going back to describing individual measurements using $g_n(t)$ and reference signal with $g_0(t)$. For relative measurements it is necessary to store reference measurement, made with known medium. For water solutions the best way could be to use water as reference medium. Treating attenuation of water as negligible and taking slowness $s_0$ of water as reference, for calculation of attenuation and dispersion of measured medium we can use modified formulas (7) and (8):

$$\alpha_n(f) = \ln \frac{|\tilde{g}_n(f)|}{|\tilde{g}_0(f)|} / z \qquad \textbf{(9)}$$

$$\Delta s(f) = \frac{\varphi_n(f) - \varphi_0(f)}{2\pi f \cdot (z_2 - z_1)} \qquad \textbf{(10)}$$

Similar formulas can be used for calculating changes of attenuation and dispersion of medium. As reference one of the previous done measurements can be taken.