EFFECT OF MATERIAL STRUCTURE ON WAVE PROPAGATION IN NON-CONTACT ULTRASOUND IDENTIFICATION OF WASTE PLASTICS

R. ILARIONOV*, M. KOLEVA**, N. SHOPOV***, I. SIMEONOV*, D. DEMIREVA****

**Department of Computer Systems and Technologies, Technical University of Gabrovo, Bulgaria*
***Department of Chemistry and Ecology, Technical University of Gabrovo, Bulgaria*
****Department of Automatics, Information and Control Technique, University of Food Technologies – Plovdiv, Bulgaria,*
***** Department of Physics, Technical University of Gabrovo, Bulgaria*

SUMMARY: Ultrasonic testing (UT) has been practiced for many decades. It is now well-established that in solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. In air, sound travels by the compression and rarefaction of air molecules in the direction of travel. However, in solids, molecules can support vibrations in other directions, hence, a number of different types of sound waves are possible. Waves can be characterized in space by oscillatory patterns that are capable of maintaining their shape and propagating in a stable manner. The propagation of waves is often described in terms of what are called "wave modes." Longitudinal and transverse (shear) waves are most often used in ultrasonic inspection. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible.

This paper describes the behaviour of sound and waves' propagation in bulk and porous waste plastics during non-contact ultrasonic identification. Influence of materials thickness on the sound propagation is also investigated.

1. INTRODUCTION

It is now well-established that if ultrasound can be propagated in a given medium then significant information about that medium can be deciphered [M. C. Bhardwaj, J. Neeson, G. Stead, Introduction to Contact-Free Ultrasonic Characterization and Analysis of Consolidated Materials, NDTnet, Vol.5, N6, 2000]. Ultrasonic testing (UT) has been practiced for many decades. It is now well-known that in solids, waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves [http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/Introduction/ futuredirection.htm].

In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation. Since compressional and dilational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compression waves can be generated in liquids, as well as in solids because the energy travels through the atomic structure by a series of compressions and expansion (rarefaction) movements. In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves. The propagation of waves is often described in terms of what are called “wave modes”. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing and inspection. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible. Some of these wave modes such as Rayleigh and Lamb waves are also useful for ultrasonic inspection.

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for material characterization, flaw detection/evaluation, dimensional measurements and more [J. L. Rose, J. B. Nestleworth, K. Balasubramaniam, Ultrasonics, 1988, Vol.26, pp. 124-131]. A typical pulse/echo inspection configuration as illustrated below (Fig.1) will be used to illustrate the general inspection principle.

The ultrasound non-contact testing method is the technological application of the echo phenomenon [TEC EUROLAB, Testing and Consulting, teceurolab.com]. The echo results from the reflection of sound waves from that bounce against the surface of an obstacle and come back to the listener ear. Ultrasonic waves can be sent to the material to be tested; once there, the waves spread with the same generator frequency and with the speed depending on the material crossed. When the beam meets the obstacle, it is reflected, absorbed, diverted or broken according to the common rules of all wave propagation phenomena. The reflected waves have the same frequency as the incident waves, but are out of phase to them, also according to the distance covered, that is to the distance from the transducer to the different points of the obstacle surface. The same happens to broken waves. The energy absorbed from the non-uniformity area of the material hit by incidence waves makes that area to vibrate generating variously out-of-phase waves with a frequency typical for it. As a matter of fact, the signal coming back to the transducer is very complex because it results from the sum of many waves with the same frequency but out of phase, and of other waves with different frequency and out of phase as well. This signal contains all information about the dimension, geometry and nature of obstacle hit by the incident ultrasound beam. Due to the piezoelectric physical phenomenon, when the wave reflected or emitted by the obstacle comes back to the transducer, it gives an electric signal which, if suitably amplified and filtered, can be viewed on the oscilloscope monitor, fitted in any ultrasound detecting instrument.

In that way ultrasonic non-destructive evaluation utilizes information from different data acquisition and signal features domains for complete material characterization and analysis in a variety of different materials and structures, so the recognition of the examined materials can be realized in real time (“on-line”) [James P. Wolfe, Imaging Phonons: Acoustic Wave Propagation in Solids, Cambridge University Press, 09/2005, 428 pages]. This procedure forms an extremely versatile data acquisition protocol, followed by detailed analysis through a signal processing technology, pattern recognition and/or artificial intelligence implementation practice.

2. EXPERIMENTAL SET

The aim of this work is to investigate the influence of the thickness of the sample on the propagation of the ultrasound wave, which gives a possibility for identification of waste plastics with different thicknesses. The following materials had been investigated: polystyrene (PS), polyvinyl chloride (PVC) and low-density polyethylene (LDPE). For the purposes of the experiment rectangular samples with sizes 110x100 mm and thicknesses as follows: PS – 4 mm, PVC – 6 mm, LDPE – 0.5 mm had been used. For determination of the influence of the thickness on the behaviour of the material upon ultrasound action, for every kind of plastics we used combinations of one, two and three samples with indicated sizes, so the following thicknesses had been investigates: PS – 4, 8 and 12 mm, PVC – 6, 12 and 18 mm and LDPE – 0.5, 1.0 and 1.5 mm.

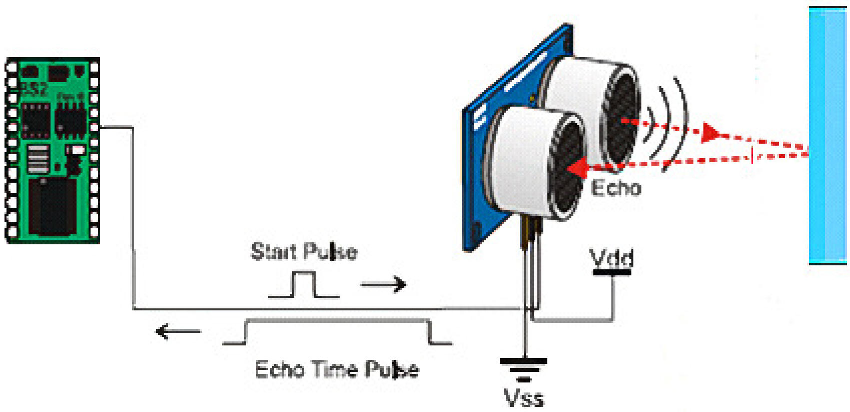

Figure 1. Experimental set-up scheme, used for material characterization.

Ultrasonic Testing (UT) method is used according to the sound echolocation principle, based on the effect of the reflection of the sound waves from the investigated material. In that way distinguishing features of the investigated plastic materials had been determined. Their identification by type and thickness is being done after an analysis in the time and frequency range of the discrete signal, reflected from the material.

The signal coming back to the transducer is very complex because it results from the sum of many waves with the same frequency but out of phase, and of other waves with different frequency and out of phase as well. Depending on the situation along the direction of the propagation of the acoustic wave, its characteristic parameters are being modified. In that way the ultrasound signal carries information about the characteristics of the medium between the transmitter and the receiver [Baltes, H., W. Göpel, J. Hesse. Sensors Update. Volume 3. Sensor Technology-Applications-Markets. Weinheim-Berlin-New York-Chichester- Brisbane-Singapore-Toronto, Wiley-VCH Verlag GmbH, 1998]. For investigation of the upper cited materials 213 measurements with distance between the transmitter and the receiver of 50 cm had been done.

On Figure 1 is shown the experimental set-up scheme, used for material characterisation. It is designed to generate an ultrasonic signal which is spread in the medium and to receive the reflected wave, converts it into an electrical signal and amplify it to a level suitable for processing.

The module consists of three blocks. Block generator is designed to generate an analogue signal for excitation of the transmitter. Sensor block, consisting of two piezoelements -

transmitter and receiver has been used. The third block is a precision high-frequency amplifier designed to amplify the signal, received from the receiver.

The experiments are realized in off-line mode with two types of air ultrasonic sensors:

- UST40T/UST40R (Nippon Ceramic Company) with follow parameters: centre frequency 40 kHz, total beam angle at 6 dB (55,0°);

- 125SR250B with follow parameters: centre frequency 125 kHz, total beam angle at 3 dB (10,0°).

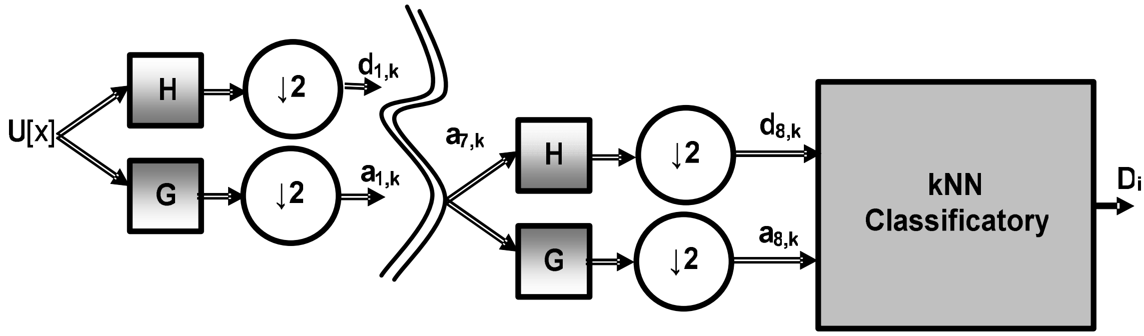

Figure 2. Block scheme of kNN classificatory with wavelet forming of signs.

A piezoelectric transmitter generates a packet of ultrasound pulses into the material. When they are reflected from it under the form of an echo-signal. The last is returning back toward the receiver and is detected by it. The reflected signal is amplified, detected and is applied on the input of the oscilloscope.

The information is systemized using the second method of discreet wavelet transformation for signal spectral analyses, know as Mallat's algorithm [Chau F-T.,Y. Liang, J.Gao, X-G. Shao, Chemometrics From Basics to Wavelet Transform John Wiley & Sons, Inc., Hoboken, New Jersey. 2004]. The generation of symptoms' spaces by wavelets is performed by special software on the basis of Matlab program media [Smolencev N. N., Wavelet theory basis. Wavelets in MATLAB, DMK Press, Moscow, 2005].

On the Figure 2 is shown the algorithm of Mallat for fast wavelet transformation by means of which the approximating and detailing coefficients are being received. The same are used as sighs for classification. The chosen classifier, working by the method of "k-closest neighbours" accounting for the Euclidian distance to the three closest neighbour clusters is also shown on the same figure.

Three of the most common waste plastics types – bulk and porous – with various thickness were experimentally tested: polyethylene (PE), polystyrene (PS) and polyvinyl-chloride (PVC).

The questions for synthesizing of symptoms space at automatic classification of plastics by using of orthogonal wavelet basis functions for synthesis of symptoms are analyzed.

3. RESULTS AND ANALYSIS

Through the program product MATLAB the approximation and detailing coefficients of the realizations of the training excerpts (150 numbers) at levels from $m=1$ to $m=8$ by application of DWT with orthogonal wavelets of Haar, Dobeshi, Conflets and Simlet are obtained. During that treatment when the level $m=8$ is reached, the sign space of 10 approximating and 10 detailing coefficients is formed. The results after the wavelet transformation (wavelet spectrum), put together with the reflected signal for the investigated material, are shown on the Figure 3 (a, b, c), respectively for LDPE (a), PS (b) and PVC(c).

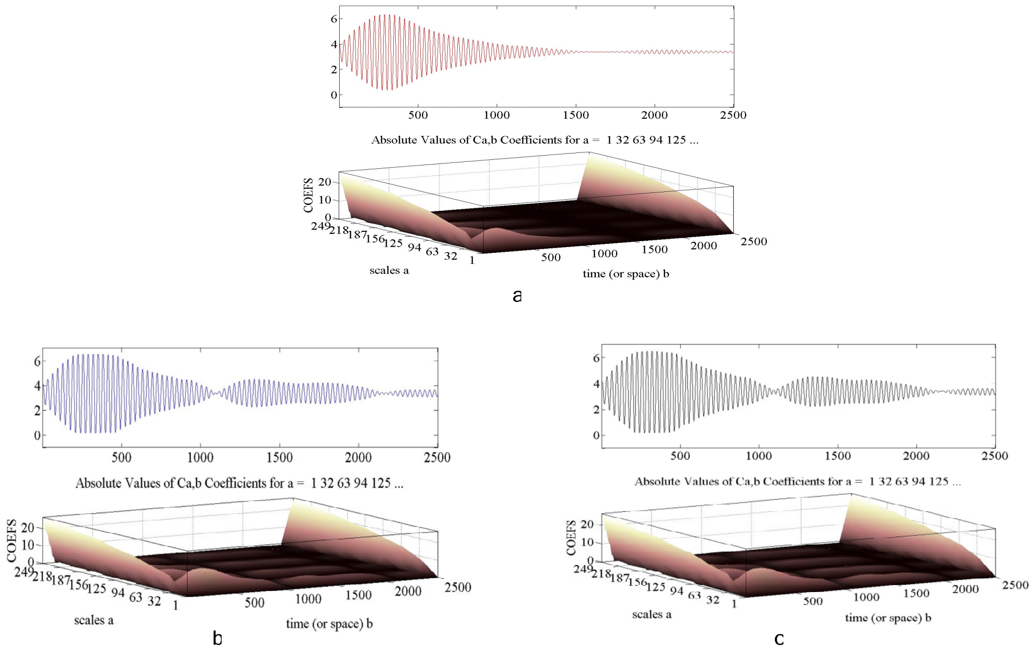

Figure 3. Wavelet spectrum for samples of three investigated types of plastics, put together with the reflected signal for the investigated material: *a) LDPE;b) PS; c) PVC.*

The obtained coefficients had being investigated in qualities of sighs for recognition (classification). On Figures 4-9 are shown the approximating and detailing coefficients after fast discrete wavelet transformation (DWT) at level $m = 8$ with wavelet of Haar, with which the best results for LDPE, PS1 and PVC with three thicknesses examined had been obtained. As it is seen, from the received 10 signs (coefficients) the biggest distinguishing exists in the seventh and eighth features.

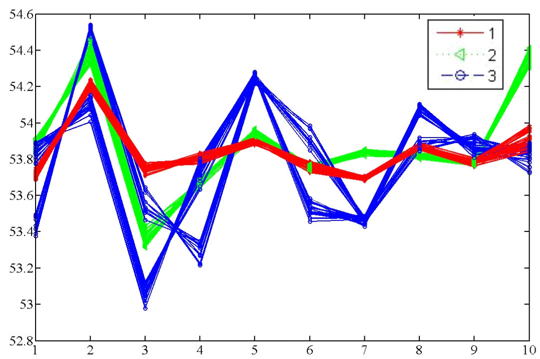

Figure 4. Approximating coefficients of LDPE with three thicknesses obtained at m=8 level after DWT with Haar wavelet.

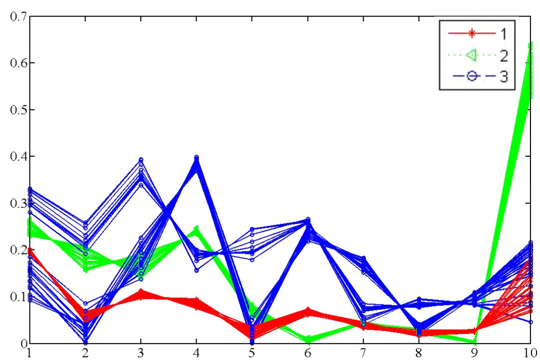

Figure 5. Detailing coefficients of LDPE with three thicknesses obtained at m=8 level after DWT with Haar wavelet.

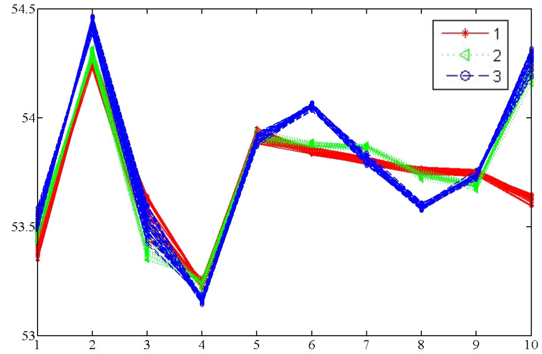

Figure 6. Approximating coefficients of PDI with three thicknesses obtained at m=8 level after DWT with Haar wavelet.

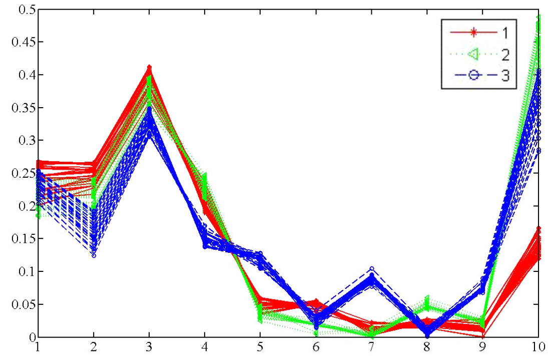

Figure 7. Detailing coefficients of PSI with three thicknesses obtained at m=8 level after DWT with Haar wavelet.

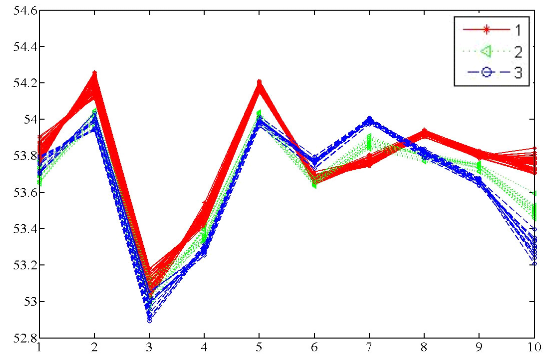

Figure 8. Approximating coefficients of PVC with three thicknesses obtained at m=8 level after DWT with Haar wavelet.

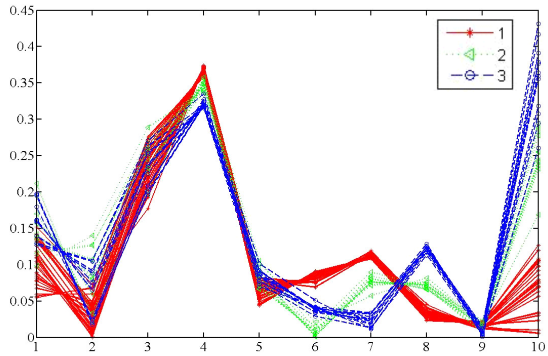

Figure 9. Detailing coefficients of PVC with three thicknesses obtained at m=8 level after DWT with Haar wavelet.

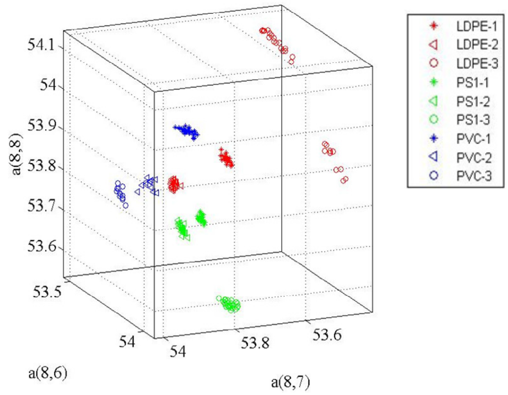

Figure 10. Clusters of approximating coefficients obtained after DWT with Haar's wavelet for the investigated materials with three thicknesses.

On the basis of received features nine clusters are defined, corresponding to the materials for recognition and their thicknesses. They are shown on the figures 10 and 11. It is seen from these figures, that there is not overlapping, but a clear distinguishing between the separate cluster zones exists, which in practice is a premise for a zero error. In that way the separate cluster zones can be recognized by type and thickness.

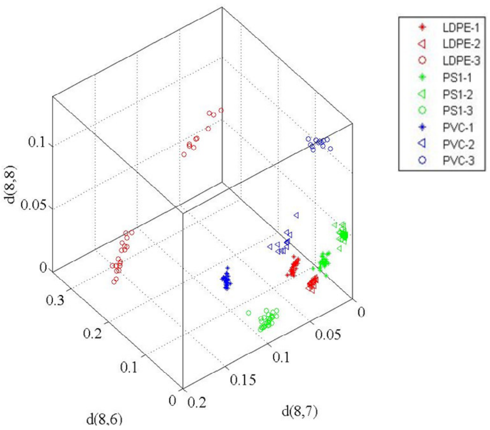

Figure 11. Clusters of detailing coefficients obtained after DWT with Haar's wavelet for the investigated materials with three thicknesses.

In the Table 1 the results by classification of the validation set with volume of 140 realizations (different from these included in the testing excerpt) are generalized. It is seen there that with the used classificatory working with three features, the error is equal to zero and all performed measurements are taken to the corresponding clusters. On this basis one can make a system for recognition of different materials.

The shown experimental data and these from the wavelet analysis categorically proof that the behaviour of the every investigated types of plastics during ultrasound action is different. According to M. C. Bhardwaj, J. Neeson and G. Stead, propagation of ultrasound waves in a given material depends on the chemical structure, type and parameters of the crystal lattice and so on. In the concrete case probably this is due to the mechanism of the propagation of waves, determined from the differences of their composition, structure of the macromolecules and presence of different by organization super molecule structures. Thee type and quantity of the last by great degree depends on the degree of crystalline of the polymer, the degree of orientation (the method of preparation).

Table 1. Results obtained for the classification of the validation set (140 samples) with wavelet "Haar", level $m = 8$ of features $a_{8,k}$ k=6, 7, 8;

Material		**Classified by the classifier, number**										**Errors**	
		LDPE -1	**LDPE -2**	**LDPE -3**	**PS1-1**	**PS1-2**	**PS1-3**	**PVC-1**	**PVC-2**	**PVC-3**	**Total**	**Real**	**Main**
Class	m_{ik}	m_{i1}	m_{i2}	m_{i3}	m_{i4}	m_{i5}	m_{i6}	m_{i7}	m_{i8}	m_{i9}	**Number**	g_i,%	e_i,%
LDPE-1	m_{1k}	16	0	0	0	0	0	0	0	0	16	0	0
LDPE-2	m_{2k}	0	12	0	0	0	0	0	0	0	12	0	0
LDPE-3	m_{3k}	0	0	20	0	0	0	0	0	0	20	0	0
PS1-1	m_{4k}	0	0	0	18	0	0	0	0	0	18	0	0

PS1-2	m_{5k}	0	0	0	0	20	0	0	0	0	20	0	0
PS1-3	m_{6k}	0	0	0	0	0	14	0	0	0	14	0	0
PVC-1	m_{7k}	0	0	0	0	0	0	21	0	0	21	0	0
PVC-2	m_{8k}	0	0	0	0	0	0	0	9	0	9	0	0
PVC-3	m_{9k}	0	0	0	0	0	0	0	0	10	10	0	0
Total	number	16	12	20	18	20	14	21	9	10	140	**General error** **E_0=0%**	

It is seen from the shown graphic interpretations, that in the case the propagation of the ultrasound wave is also influenced from the thickness of the sample. That permits identification of the material not only by type, but also by its thickness.

As a hole, the results obtained from the validation set, shown on the Tables 1 and 2, leads us to draw the conclusion, that the method of ultrasound testing is extremely sensitive in the identification of plastics with different thicknesses (0 % error). This makes it suitable for creating devices for identification of waste plastics in the systems for separation of mixed wastes with a purpose of their recycling.

Table 2. Results obtained for the classification of the validation set (213 samples) with wavelet of “Haar”, at level $m = 8$ of features $a_{8,k}$ k= 6,7,8;

Material		**Classified by the classifier, number**										**Errors**	
		LDPE -1	**LDPE -2**	**LDPE -3**	**PS1-1**	**PS1-2**	**PS1-3**	**PVC-1**	**PVC-2**	**PVC-3**	**Total**	**Real**	**Main**
Class	**m_{ik}**	**m_{i1}**	**m_{i2}**	**m_{i3}**	**m_{i4}**	**m_{i5}**	**m_{i6}**	**m_{i7}**	**m_{i8}**	**m_{i9}**	**Number**	**g_i,%**	**e_i,%**
LDPE-1	m_{1k}	26	0	0	0	0	0	0	0	0	26	0	0
LDPE-2	m_{2k}	0	24	0	0	0	0	0	0	0	24	0	0
LDPE-3	m_{3k}	0	0	28	0	0	0	0	0	0	28	0	0
PS1-1	m_{4k}	0	0	0	27	0	0	0	0	0	27	0	0
PS1-2	m_{5k}	0	0	0	0	27	0	0	0	0	27	0	0
PS1-3	m_{6k}	0	0	0	0	0	27	0	0	0	27	0	0
PVC-1	m_{7k}	0	0	0	0	0	0	30	0	0	30	0	0
PVC-2	m_{8k}	0	0	0	0	0	0	0	12	0	12	0	0
PVC-3	m_{9k}	0	0	0	0	0	0	0	0	12	12	0	0
Total	number	26	24	28	27	27	27	30	12	12	213	**General error** **E_0=0%**	

4. CONCLUSIONS

On the base of experimental results it was concluded that:

- Upon ultrasound action the behaviour of the investigated types of plastics (for the three investigated plastics) is different, due to the differences in the chemical composition, structure of the macromolecules and the presence of different by organization super molecule structures;
- The propagation of the ultrasound wave in the investigated materials is influenced from the thickness of the material, which makes possible identification and distribution of the material from the same type of plastics also by thickness.
- The method of ultrasound testing is extremely sensitive in the identification of plastics with different thicknesses; with the used methods for non-contact and fast receiving of information and the fast wavelet transformation it is possible the recognition of the examined materials to be realized in real time (“on-line”).

ACKNOWLEDGEMENTS

This study was carried out in the framework of the DRNF 02/9 project titled "Design and development of a device for non-contact ultrasonic investigation of materials aimed at embedding in automated manufacture systems ", financed by the National Science Fund of the Bulgarian Ministry of Education, Youth and Science.

REFERENCES

M.C.Bhardwaj, J. Neeson, G.Stead, Introduction to Contact-Free Ultrasonic Characterization and Analysis of Consolidated Materials, *NDTnet*, Vol.5, N6, 2000.

Future Direction of Ultrasonic Inspection, http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/Introduction/futuredirection.htm

J.L.Rose, J.B.Nestleworth, K.Balasubramaniam, Ultrasonics, 1988, Vol.26, pp. 124-131.

TEC EUROLAB, Testing and Consulting, teceurolab.com.

James P.Wolfe, Imaging Phonons: Acoustic Wave Propagation in Solids, *Cambridge University Press*, 09/2005, 428 pages.

Baltes, H., W. Göpel, J. Hesse. Sensors Update. Volume 3. Sensor Technology-Applications-Markets. Weinheim-Berlin-New York-Chichester- Brisbane-Singapore-Toronto, *Wiley-VCH Verlag GmbH*, 1998

Smolencev N. N., Wavelet theory basis. Wavelets in MATLAB, *DMK Press, Moscow*, 2005.

Chau F-T.,Y. Liang, J.Gao, X-G. Shao, Chemometrics From Basics to Wavelet Transform, *John Wiley & Sons, Inc.*, Hoboken, New Jersey. 2004