# Ultrasonic method of materials characterization for recognition buried objects

**Vjera Krstelj*, Josip Stepanič Jr., Damir Markučič**

**Department of Quality,*
*Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb,*
*I. Lučića 5, HR-10000 Zagreb, Croatia*
*T: (++385 1) 6168 497, 6168 430, F: (++385 1) 6118710, 6157 129,*
*E: vjera.krstelj@fsb.hr, josip.j.stepanic@fsb.hr, damir.markucic@fsb.hr*

## 1.Introduction

### 1.1. Materials characterization using ultrasound

Among the ultrasound based NDT methods and techniques, some are used for materials characterization. In a typical situation, some of the measurable properties of a tested object's material are used as a data set for characterization. The basis of measurements are properties of an ultrasonic pulse that can propagate through the object. In order to obtain intense enough registered ultrasonic pulse, one should have relatively low transfer losses and relatively high signal to noise ration in the system. In order to obtain large enough extractability of information about the tested object material, one should know the changes in the pulse that occur during its propagation [1]. Information about the tested object material, gained through signal processing, contains, e.g. values of the elastic constants and pulse attenuation coefficients, as well as other quantities that could not be so straightforwardly related to the ultrasound propagation properties [2]. In the context of the characterization, usually there was no differentiation among various object's parts, based on differences in their properties. As will be shown later, one may obtain different results depending on whether the object bulk or surface response is used in characterization.

Starting from the achieved level in ultrasonic based materials characterization, the approach is further being developed for the purpose of unknown, buried objects' material type determination [2-5]. Appropriate transfer of the ultrasound pulse is essential for the ultrasound based materials characterization. In the appropriate setup, the ultrasonic pulse transfer is realized as the pulse's propagation from the transducer to the buried object to be characterized, and back to transducer again. The signal received is a complex combination of characteristics of both the transfer entity and the characterized object. If one does not know quantitatively how much a transfer entity influences the ultrasonic pulse propagation, the possibility of the buried object characterization is drastically lowered. Therefore, the transfer entity influence on the ultrasonic pulse should be known in order to enable one to use the ultrasound for buried object materials characterization. That influence could be modeled and the object containing transfer medium appropriately designed. Following this line of thought, the ultrasound could not be used in the characterization if it propagates through a bulk of the buried object's material, because then the object's structure and shape would affect the pulse properties. Because of the facts presented, the ultrasonic pulse should propagate through a characterized transfer entity, and be influenced only by the surface of the buried object to be characterized.

### 1.2. Mine facts

Among the variety of possible applications, the target area of application is humanitarian demining. The humanitarian demining is a set of operations conducted in order to decontaminate mine contaminated regions [6].

During the last decade the Southeastern Europe became affected with landmines. Particularly, in Croatia, present estimate is that mine affected regions contain around 1 million of landmines, around 60% of which are of antipersonnel type [7, 8]. Several types of antipersonnel landmines (APL) are shown in Fig. 1. As APL PROM 1 has metal body, it is usually detected using metal detectors, so application of ultrasound to APLD is developed presumably for blasting mines. APL PMA 3 is separated from others because its plastic body is covered with a rubber cover, what differentiate it from PMA 1, PMA 2 and VS 50 that have uncovered plastic body.

Humanitarian demining is nowadays rather slow and dangerous process. APLD is time-consuming operation causing most of the humanitarian demining casualties. Therefore, the humanitarian demining detection equipment improvement is a permanent task while humanitarian demining lasts.

There are several landmines detection methods used for APLD: hand-prodding, metal detection, ground penetrating radar and usage of specially trained dogs [9]. The ultrasound based methods are not regularly applied [9-12].

Many times in the clearance of various mine affected regions a mechanical demining was used. As it is shown in practice, mechanical demining is relatively efficient procedure for the agricultural terrain and homogeneous soil composition fields. In a number of situations, where terrain has been impenetrable for machines, the demining was done manually. However, the manual demining is a very risky task, and is accompanied with a large number of victims among the professionals. Additionally, among used APLD methods, some are fast, efficient and relatively safe, but are not applicable in all the conditions in mine affected areas. Some of the APLD methods are applicable in all conditions, but are time-consuming, expensive and dangerous for deminers. Basis for humanitarian demining quality criteria are UN requirements that require, e.g. the clearance level of at least 99,6 % and the possibility to locate small APL down to size of 4 cm buried in soil or grass at a depth of 10 - 20 cm depending on the terrain [6]. The probability of detection and reliability are some of the characteristics used in quantitative evaluation of a detection method quality. However, in the humanitarian demining detection methods and demining procedures they are not adequately adopted [12, 13].

In the following section of this article we briefly present promising ultrasound applications in APLD. In the second section the analysis of the factors influencing the ultrasonic propagation in the geometry used is given. The third section contains a preliminary and exemplary experimental set-up for materials characterization and measured results. They are discussed in the fourth section. Finally, the conclusions are given.

Fig. 1**. Some of the types of APL found in the region of Southeastern Europe. From left to right PMA 1, PMA 2, PROM 1, VS 50 and PMA 3. The APL PROM 1 is of bouncing fragmentation type, while other APL are of blasting type**

## 2. Ultrasound and the improved APLD method

The applications of ultrasound to improve APLD could be divided into two generations.

In the first generation there are systems for buried object characterization using ultrasonic waves propagation through a soil containing tested objects. Because of that, the registered ultrasonic pulse was modified significantly by the soil properties, its composition and microstructure [14, 15]. Somewhat similar approach has been very fruitful when large enough wavelengths were used so that soil's microstructure influenced wave propagation in a precisely predictable way [16]. Generally, in the range of ultrasonic wavelengths it was not possible to separate soil induced modifications of a signal from the part that contained information about the buried object. In other words, the first generation systems have a relatively low probability of detection and relatively low a reliability level. The final answer to the applicability of the first generation of ultrasound based APLD methods in humanitarian demining could be given only after analysis of their results combined with the appropriate signal processing.

Based on the results of controlled testings conducted in field conditions using the first generation ultrasound equipment, several new approaches were formulated. In these approaches influences of the existing soil varieties have been lowered drastically.

In the second generation there are systems like Surface Waves for Obstacle Detection (SWOD) [16, 17], and systems exploiting sensor fusion in which the ultrasound is included, that will be described in detail elsewhere [5]. In the SWOD it is shown that, after starting from the selective sensitivity of surface waves on local non-homogeneities, one can formulate the shallow objects localization process that is applicable in the realistic mine affected soil conditions.

Our approach, formulated previously as the OCULAR (object classification by ultrasound for landmines reveal) method [3], is a particular realization of the ultrasound based method for buried objects materials characterization that falls into this category. Other examples are found in the existing literature [18-20]. One does not accompany the second generation systems with the probability of detection, because the detection occurs during the mechanical contact that precedes the complete second generation system characteristics usage. The essential parameter describing these systems is the false alarm rate.

In that way, the emphasis in development of detection equipment is put both on the detection quality and on the confirmation property of the sensor, what was recently shown to be rather important for the field work [21].

In the case of the OCULAR system the method advantage is the sensitivity of ultrasound signal dependence on the properties of material it may pass through. The OCULAR method and similar methods solve the problem of the unknown transfer entity explicit influence through formation of a direct contact between the unknown object and the transfer entity. Then the registered pulse's properties are rather sensible to the characteristics of the contact region. This is not a disadvantage because the contact region characteristics are determined partially with the tested object material properties [2, 22]. Hence, the contact region represents a channel for putting the tested object *fingerprint* into the ultrasound pulse.

## 3. Mathematical formulation of the problem

The collection of the objects that could be found in the soil varies from natural objects of various shapes (e.g. stones, roots) to artificial, non-purposely or purposely buried objects (e.g. bricks, cans, pipelines, landmines). Although their dimensions vary, we consider here the objects with characteristic dimensions of the order of several centimeters. Much larger objects could be characterized by other methods (e.g. ground penetrating radar), while much smaller objects are usually unimportant for the characterization considered here. The materials characterization is easier in the case of isotropic materials, what will be assumed throughout this paper.

The unknown, buried objects could be rocks, wooden objects, polymeric objects and metallic objects. The magnitudes of mechanical characteristics, here especially important elastic constants, may for various materials differ by several orders. In order to understand more precisely influence of the tested object composition and structure on the final ultrasound pulse properties we shall use representative geometry, thus simplifying the results' interpretation [2]. For a particular geometry in this paper we take a slab of a large enough lateral dimensions (Fig. 2). The boundary conditions include the transfer of the ultrasound from some material in the contact with the slab. Also it is assumed that the slab surfaces are free from stresses. Initially, there are no ultrasound pulses propagating in the slab. This problem is easily formulated mathematically with the solution expressible in the closed form. However, the solution's form is rather complex and non-transparent, therefore usually a direct numerical modeling of the ultrasonic pulse propagation is more suitable.

If the ultrasonic pulse representative length is $l$, and

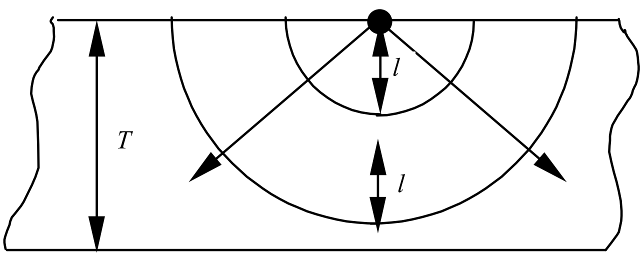


Fig. 2. **Slab as the representation of the tested buried object in the local probing configuration. The half-circles represent the regions traversed by generated ultrasonic pulse in two different moments. Here *T* is the slab thickness, and l is the characteristic ultrasonic pulse length.**

the duration $t_p$, then the described shape simplification is applicable when the slab thickness $T$, satisfies

$$T > t_p \max\{v\}/2\,. \tag{1}$$

Here $v$ denotes the group speed of the particular ultrasonic pulse in the tested sample material and $\max\{v\}$ its predicted maximal value for a type of materials that are expected to be possibly found. That way, the characterization is to be performed on some randomly chosen, relatively small part of the surface and close enough to the subsurface region of the unknown, buried object. A consequence is that the tested sample material homogeneity is artificially enhanced with the possible deviation of the values obtained from the whole sample average value. This occurs because all the non-homogeneities shown on the distances much larger than $T$ are not observable. Therefore, the characteristics of the probed region may not represent fully the material taken as a whole.

The precise description of propagation of generated ultrasound pulse in an isotropic and homogeneous material of known characteristics is given with the wave equation in the range of linear elasticity, combined with the appropriate initial and boundary conditions [1]. The general solution of the problem of ultrasound propagation in the slab is a rather complex combination of normal modes that represents retarded travelling waves in lateral directions. Boundary conditions include the given deformation field of the incoming ultrasonic pulse and are a consequence of the dynamics of the contact region. Precise description of the contact region between the transfer object and the tested sample is by no means a trivial problem. The contact is, at least partially, the adhesive phase, during which the boundary conditions are easily written in terms of the equal values of projections of the strain tensor $\sigma_{ij}$ on the local normal axis [1, 22]. The setting of boundary conditions requires knowledge of contact region surface roughness [4]. Initial condition for the contact region is expressed in its initial curvatures.

## 4. Measurements

Despite of reduction of complexity of the tested object shape, described in the previous section, there are different parameters influence of which should be determined. For the moment, therefore, it is opportune to present a toy model that is idealized interpolation between the detection systems from the first and the second generation.

The experimental set-up consists of an ultrasonic transducer coupled to a digital oscilloscope [2]. The experiment is performed using immersion pulse-echo technique (Fig.3). A measured variable was the amplitude of the registered pulse that was reflected from the upper side of a known specimen. Samples, were all of the same dimensions and surface roughness' up to the preparation tolerance (Fig.4). Along with these parameters, the distances between the transducer and specimens were always equal to the transducer near field length. The registered amplitude is influenced by the ultrasonic attenuation coefficient in water $\alpha$. An acoustic impedance of the sample is expressed through the amplitude reflection factor $r$ for a water-sample interface. The factor $r$ is the only quantity through which a sample material enters into the description. Hence, this is an example of one-parameter materials characterization using ultrasound. Although in this measurement samples of same dimensions, surface waviness and roughness were used, there could be some weakening of these requirements [23]. For example, sample's lateral dimensions are unimportant as long as they are larger than some dimension defined by the ultrasonic beam after propagation of a known distance in water, as it was assumed in Eq.1. In the experiment described one had $T = 0{,}025$ m, $t_p \approx 2{,}75$ µs and $\max\{v\} = v_L^{(1)} = 6460$ m·s$^{-1}$. In this case it was not just that Eq.1 was satisfied, but also the end of the first echo reflected by the front boundary of the specimen was registered before the beginning of the signal reflected by the specimen back wall boundary.

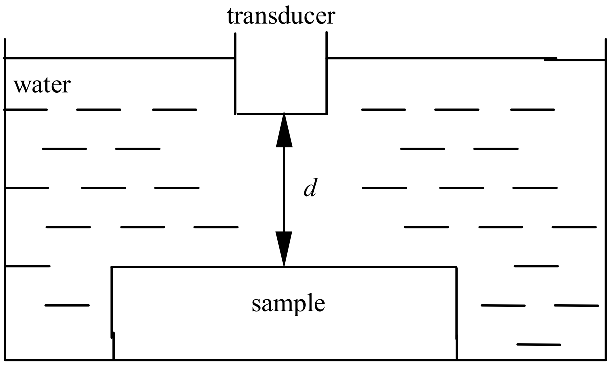


Fig. 3. **Sketch of the experiment**

As additional weakening, one could have relatively small incident angle of the ultrasound beam on water-specimen interface. The surface roughness does not influence the registered signal intensity significantly if it is within an appropriate interval [4].

The relationship between the registered amplitude $A_r$, the initial amplitude $A_i$ and the amplitude reflection factor $r$ for the water-specimen interface is

$$\ln\frac{A_r}{A_i} = \ln|r| - \alpha d\,, \qquad (2)$$

where $\alpha$ is the attenuation coefficient for ultrasound in water and $d$ is the distance between the ultrasonic transducer and the specimen boundary, Fig. 3. If Eq.2 is used to determine $r$, then one should measure $A_r/A_i$ and know $\alpha$ and $d$. For this case, when the transducer of frequency 2 MHz was used, one had $\alpha = 0{,}004$·m$^{-1}$ and $d = 0{,}032$ m, which corresponds to the focal distance of the transducer.

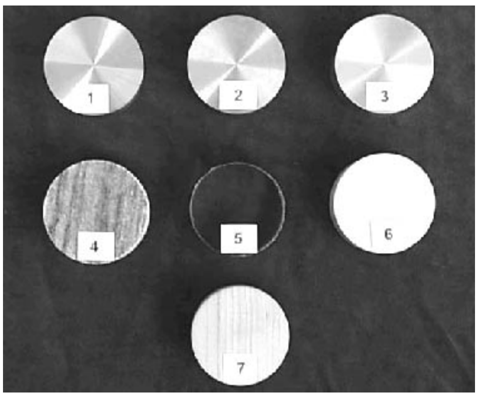


Fig. 4. **Some of the types of APL found in the region of Southeastern Europe. From left to right PMA 1, PMA 2, PROM 1, VS 50 and PMA 3. The APL PROM 1 is of bouncing fragmentation type, while other APL are of blasting type**

Furthermore, one can calculate the acoustic impedance of the tested sample, $Z_t$, using relation

$$r = \frac{Z_t - Z_w}{Z_t + Z_w}\,, \qquad (3)$$

valid for normal incidence of ultrasound on the water-sample interface, where $Z_w = 1{,}48\cdot10^6$ kg·m$^{-2}$·s$^{-1}$ is the acoustic impedance of water under standard conditions in our laboratory. If $r$ is calculated using Eq.2, then one loses the sign in Eq.3, i.e. only the absolute values of left and right sides in Eq.3 are left. We calculated $r$ from the known acoustic impedances, and compared it qualitatively with the registered amplitudes in Table 1.

Table 1. **Measured ratios of amplitudes, calculated reflection factors and acoustic impedances for tested samples. Here Δ is additional gain given for enabling easier on-line operator performed analysis**

| Sample | $\ln[(A_r+\Delta)/A_i]$ | $r$ | $Z_t$, $10^6$ kg·m$^{-2}$·s$^{-1}$ | |
|---|---|---|---|---|
| | | | $>Z_w$ | $<Z_w$ |
| 1 | 1,51 | 0,969 | 46,3 | 0,022 |
| 2 | 1,53 | 0,964 | 40,1 | 0,025 |
| 3 | 1,22 | 0,921 | 18,1 | 0,055 |
| 4 | 1,25 | 0,917 | 17,1 | 0,058 |
| 5 | 1,22 | 0,887 | 12,4 | 0,080 |
| 6 | 0,59 | 0,622 | 3,35 | 0,30 |
| 7 | 0,32 | 0,396 | 2,03 | 0,49 |

From the data presented in Table 1 follows that there are some well differentiated regions as well as some samples that can not be reliably differentiated on the basis of the measurement performed. This is generally the case for relatively very similar and relatively very non-similar materials, i.e. those for which $r \cong 1$ and $r \ll 1$, respectively. That can be seen from the ratio of the standard deviation$\sigma_r$, for $Z_t$ and $Z_t$:

$$\frac{\sigma_t}{Z_t} = \frac{2\sigma_r}{1-r^2}\,, \qquad (4)$$

what diverges for $|r| \to 1$. That is in the case when the sample material acoustically is very different from water. From Eq.2 one has $\sigma_r = r\sigma(A_r)/A_r$, where $\sigma(A_r)$ is the standard deviation of the reflected amplitude. Solely from Eq.2÷4 one could conclude that in the parametric region of acoustically similar materials, when $r \cong 0$, there would be no strong requirements imposed on the experimental precision. However, the effects of noise that were not taken into account would in that region become important. Therefore, the strongest requirements for experimental precision comes both from $r \cong 0$ and $r \cong 1$ regions. Hence, this method is suitable for materials which are acoustically relatively similar to that of the transfer entity.

The occurrence of two possible values of the acoustic impedance of the tested sample, determined by one measurement, is consequence of the symmetry of the absolute values of in Eq.3 due $Z_w \leftrightarrow Z_t$ change. This means that one cannot generally obtain a unique characterization of the tested sample, no matter how precise the measurements are. However, here this is possible, having in mind the relatively low acoustic impedance of water. The parameter used for characterization of objects induced classification of the set of objects. Other parameters could cause different classifications. The combination of several, suitably set, parameters could enable one to differentiate each object from others. The disrepancies shown in Table 1 points to the existence of "hidden" factors that were not taken into account.

For more complete differentiation one needs more than one parameter to be measured. Many of the previously mentioned factors, like contacts, boundaries and transients, are not important in this experiment, as a consequence of the fluid being the transfer entity. However, some of the transfer entity characteristics enter the final expressions. This means that fluids having different acoustic impedances could be more suitable for materials characterization of some samples. Water could be, in this simple experiment, thought of as both the idealized homogeneous soil, and the idealized transfer entity.

## 5. Summary and conclusions

The principle of the materials characterization using ultrasound, concentrated on the surface properties, is discussed. The possibility of material characterization using local surface and subsurface properties depends highly on the detailed understanding of complex combination of transient, mutually dependent processes. There is a need for further, more detailed experiments and numerical simulations in order to formulate precisely the set of relevant boundary conditions applicable for various possible contact regions. An important point in the analysis is the description of a mechanical contact established. In the method discussed the formation of the contact region enables transfer of characteristics about the buried object with a high enough resolution to a neighboring objects, particularly the one that is used for controlled propagation of ultrasound pulses between a transducer and a contact region.

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V. Krstelj, J. Jr. Stepanič, D. Markučič

**Užkastų objektų atpažinimas, naudojant ultragarsinį medžiagų charakterizavimą**

Straipsnyje analizuojama galimybė panaudoti ultragarsą charakterizuojant užkastus objektus, ypač ieškant užkastų minų. Keli kokybiškai skirtingi ultragarsiniai metodai yra išnagrinėti bei pateiktas vieno iš jų modeliavimas. Atlikti eksperimentai su dirbtiniais objektais ir aptartos, naudojant metodą objektą charakterizuoti, galimybės.

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