Some recent advances of ultrasonic diagnostic methods applied to materials and structures (including biological ones)

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Abstract—This paper gives an overview of some recent advances of ultrasonic methods applied to materials and structures (including biological ones), exploring the broad applications of these emerging inspection technologies to civil engineering and medicine. In confirmation of this trend, some results of an experimental research carried out involving both destructive and non-destructive testing methods for the evaluation of structural performance of existing reinforced concrete (RC) structures are discussed in terms of reliability. As a result, Ultrasonic testing can usefully supplement coring thus permitting less expensive and more representative evaluation of the concrete strength throughout the whole structure under examination.

Keywords—diagnostics, nondestructive test, structural performance, ultrasound, medicine, ultrasonic method.

I. INTRODUCTION

Ultrasonic method is a form of Non-Destructive Testing performed in Engineering for the inspection without damaging the parts or components and for the characterization of materials. The advantages of this method include flexibility, low cost, in-line operation, and providing data in both signal and image formats for further analysis. In Engineering, ultrasonic testing is often performed on steel and other metals and alloys, on concrete, wood, plastics, ceramics and composites. The main applications in Medicine are diagnostics and therapy of conditions/diseases involving most organs of the body.

Since the 1940s ultrasonic test instruments have been employed to detect hidden cracks, voids, porosity, and other internal discontinuities as well as to measure thickness and analyze material properties. The main advantages are: high sensitivity in detecting small flaws; ease of performance; greater accuracy than other nondestructive methods in determining the depth of internal flaws. The main disadvantages are: variability due to operator-dependency; technical limitations regarding rough, irregular, very small, thin or not homogeneous parts; need for surface preparation by cleaning and removing loose scale, paint, etc. (although paint that is properly bonded to a surface does not need to be removed).

Many international standards covering ultrasonic testing methods in Engineering are published by ISO (International Organization for Standardization) and by CEN (European Committee for Standardization). A standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose.

Some of the latest standards are:

• ISO 17405:2014, Non-destructive testing -- Ultrasonic testing -- Technique of testing claddings produced by welding, rolling and explosion
• ISO 12715:2014, Non-destructive testing -- Ultrasonic testing -- Reference blocks and test procedures for the characterization of contact probe sound beams
• ISO 16809:2012, Non-destructive testing -- Ultrasonic thickness measurement
• ISO 16810:2012, Non-destructive testing -- Ultrasonic testing -- General principles
• ISO 16811:2012, Non-destructive testing -- Ultrasonic testing -- Sensitivity and range setting
• ISO 16826:2012, Non-destructive testing -- Ultrasonic testing -- Examination for discontinuities perpendicular to the surface
• ISO 16827:2012, Non-destructive testing -- Ultrasonic testing -- Characterization and sizing of discontinuities.
• ISO 16831:2012 , Non-destructive testing -- Ultrasonic testing - Characterization and verification of ultrasonic thickness measuring equipment.

In 1942, Floyd Firestone [1] patented an instrument he called the Supersonic Reflectoscope, which is generally regarded as the first practical commercial ultrasonic flaw detector that uses the pulse/echo technique commonly employed today. It led to the development of many commercial instruments that were introduced in the following years.

“My invention pertains to a device for detecting the...
presence of inhomogeneities of density or elasticity in materials. .......My device may also be used for the measurement of the dimensions of objects, and is particularly useful in those cases where one of the faces to which the measurement extends is inaccessible. .......The general principle of my device consists in the sending of high frequency vibrations into the part to be inspected, and the determination of the time intervals of arrival of the direct and reflected vibrations at one or more stations on the surface of the part....”.

This pioneer patent has been cited in about 111 other patents.

In the late 1940s, researchers in Japan pioneered the use of ultrasonic testing in medical diagnostics using early B-scan equipment that provided a two-dimensional profile image of tissue layers. By the 1960s, early versions of medical scanners were introduced to diagnose tumors, gallstones, and similar conditions.

The latest advances in ultrasonic instruments have been based on the digital signal processing techniques and the inexpensive microprocessors that became available from the 1980 onwards. This has led to the latest generation of miniaturized, highly reliable portable instruments and on-line inspection systems for flaw detection, thickness gaging, and acoustic imaging.

The aim of this paper is to give an overview of some advanced ultrasonic diagnostic methods applied to materials and structures (including biological ones), exploring the broad applications of these emerging inspection technologies to civil engineering and medicine. In confirmation of this trend, some results of an experimental research carried out involving both destructive and non-destructive testing methods for the evaluation of structural performance of existing reinforced concrete (RC) structures are discussed in terms of reliability.

II. ADVANCES OF ULTRASOUNDS IN MEDICINE

The introduction of ultrasonic methods in Medicine in the late ‘60s is one of the most important innovations of the last decades.

Most UltraSound (US) machines include a transducer array, a beam-former, a processor, and a display, and use electroacoustic transducers, which convert electrical energy into mechanical energy and vice versa. The beam-former sets the phase delay and amplitude of each transducer element to enable dynamic focusing and beam steering. Where appropriate, a lens is mounted on the transducer array to focus the transmitted pulses and received echoes. In operation, the transducer array directs a number of pulses towards the anatomical area of a patient to be imaged, and after a variable propagation delay receives echoes that are reflected back by the patient’s anatomical structures.

The ultrasound beam is attenuated by the organs and tissues (absorption), and this phenomenon increases with the viscosity and density of the biological structures as well as with the frequency of the ultrasound. Thus, the higher the frequency of ultrasound, the better is the resolution attained; however, the penetration of the ultrasound into the body will be less, and deep structures will be poorly investigated. In practice, different ranges of frequency are used for examination of different parts of the body: 3–5 MHz for abdominal areas, 5–10 MHz for small and superficial parts and 10–30 MHz for the skin or the eyes. The received signal can then be presented on a display for immediate examination or recorded for a later review. Moreover, computerized image processing may improve image quality.

In medical practice, the most used modalities of signal display are three: M-mode, which shows the ranges of targets along one scan line versus time; B-mode, which provides a cross-sectional image of the body, built up by sweeping a beam sideways through a chosen scan plane; and Doppler ultrasound, which is used to study blood flow as scattering blood cells move towards or away from the probe producing the Doppler effect.[2-4]

The Doppler effect can be employed to study the movement of blood, and consequently to perform a detailed functional assessment of the cardiovascular system as well as evaluation of inflammatory disorders (i.e. intestinal US for inflammatory bowel disease). The injection of intravenous contrast agents, microbubbles, improves the visibility of small vessels with color Doppler; therefore, contrast agents allow a more detailed image of the vascularity of organs (which in some cases is an expression of inflammation) or tumours.

A novel processing modality, three-dimensional imaging, has been recently patented by Angelsen and Johansen [5] in order to allow a better representation of anatomic structures during placement of devices in the heart, guidance of electrophysiology ablation, or guidance in minimal invasive surgery.

Biologic advantages of ultrasounds are ease of use and lack of radiation exposure and carcinogenic properties; disadvantages are the operator-dependency effectiveness and - even if rare- the risk of heating, cavitation and direct damage of cells and organs.

Ultrasounds can be used either for diagnostic and interventional/therapeutic purposes, with appropriate devices and in support of invasive and surgical procedures to increase efficacy and reduce complications (i.e. placement of intravascular catheters, performance of biopsy).

Regarding diagnostics, US devices are increasingly used as a non-invasive imaging tool to evaluate anatomy and detect a wide range of diseases and conditions in all age groups: every anatomical system and apparatus can be studied, and US-based functional studies have greatly reduced the use of radiations and invasive procedures. The size, shape, echo pattern, vascularity and position of organs and other structures can be demonstrated.

Thanks to their biological safety, low cost, lack of radiation exposure and carcinogen properties, US are currently adopted in prenatal medicine, childhood and adulthood. Ultrasound probes can be applied over the skin (transcutaneously) or
internally (i.e. transesophageal, rectal, vaginal US) for a better representation of internal organs.

The main structures which can be evaluated are listed by site in Table 1. A typical ultrasound image of the heart, often referred to simply as echocardiogram, is reported in Fig.1.

Table 1: Main sites and organs which can be evaluated by ultrasounds.

<table>
<thead>
<tr>
<th>Head</th>
<th>Brain hemorrhage, infarctions, edema, congenital abnormalities (in small infants through bone openings: fontanellae); eye; salivary glands</th>
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<tbody>
<tr>
<td>Neck</td>
<td>Thyroid and parathyroid glands, lymph nodes, abscesses, vessels</td>
</tr>
<tr>
<td>Chest</td>
<td>Chest wall, pleura, lung (peripheral areas), mediastinum, heart and great vessels</td>
</tr>
<tr>
<td>Abdomen and pelvis</td>
<td>Gastrointestinal system (intestine, liver, gallbladder, pancreas), genito-urinary apparatus (kidneys, ureters, bladder, uterus, salpinges, ovaries, prostate), spleen, adrenal glands, fluidcontaining structures (cysts, cancer), great vessels and lymph nodes</td>
</tr>
<tr>
<td>Scrotum</td>
<td>Testicles, tumors, hernias</td>
</tr>
<tr>
<td>Extremities</td>
<td>Joints, muscles and connective tissue, vessels</td>
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Fig.1 A Typical echocardiogram

Regarding procedures and therapeutic use, US can be employed directly (i.e. breaking of stones) or indirectly (i.e. US-guided procedures, release of drugs)[6]. A list of diagnostic and therapeutic procedures is shown in Table 2.

The evaluation and management of normal and problem pregnancy is one of the most important advances achieved by ultrasounds in the last decades. US enables the detection of the number of the fetuses, position, organ development and congenital abnormalities, placenta, umbilical cord blood flow. In recent years interventional US is being increasingly used for diagnostic and therapeutic procedures, including fetal noninvasive surgery. In particular, amniocentesis and chorionic villus sampling allow the detection of genetic abnormalities; amnioreduction and amnioinfusion are used to increase or decrease the volume of the amniotic fluid when alterations in its production occur; fetal blood sampling and intrauterine fetal transfusion allow the detection and treatment of blood disorders.

Regarding other recent applications, a patent by Palmeri and al. [7] introduced a method to evaluate liver stiffness (expression of fibrosis and cirrhosis) by means of shear waves which are emitted and detected by an ultrasound transducer, thus limiting the need for liver biopsy - a procedure which could be associated with significant risk of bleeding, particularly among patients at high risk (i.e. liver cirrhosis).

Table 2: diagnostic and therapeutic procedures performed with ultrasounds

<table>
<thead>
<tr>
<th>Diagnostic procedures</th>
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<tr>
<td>• Ultrasound-guided aspiration of fluid from organs and cysts/lesions</td>
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<tr>
<td>• Tissue sampling with needles (biopsy)</td>
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<tr>
<td>• Staging of internal cancer by endoscopic US (esophagus, prostate, rectum)</td>
</tr>
<tr>
<td>• Evaluation of liver stiffness (fibrosis, cirrhosis)</td>
</tr>
<tr>
<td>• Pregnancy (fetal development, placenta, umbilical cord flow)</td>
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</table>

<table>
<thead>
<tr>
<th>Therapeutic procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Drainage of fluid collections (abscesses, cysts) by needle or catheter</td>
</tr>
<tr>
<td>• Injection of drugs/electrodes into cancer masses or cysts</td>
</tr>
<tr>
<td>• Breaking of urinary stones (Extra-corporeal shock wave lithotripsy)</td>
</tr>
<tr>
<td>• Pain relief (carpal tunnel syndrome, chronic low back pain, shoulder pain)</td>
</tr>
<tr>
<td>• High intensity focused ultrasound</td>
</tr>
<tr>
<td>• Drug delivery</td>
</tr>
<tr>
<td>• Pregnancy-related procedures</td>
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</tbody>
</table>

In 2011, Lau et al. patented a method for delivering high intensity focused ultrasound (HIFU) energy to a treatment site internal to a patient's body with the purpose of providing therapeutic treatment of internal pathological conditions, such as cancer [8,9]. At focal intensities 4-5 orders of magnitude
greater than diagnostic ultrasound (typically about 0.1 W/cm2), HIFU (typically about 1000-10,000 W/cm2) can induce lesions or tissue necrosis at a small location deep in tissue while leaving tissue between the ultrasound source and focus unharmed. Tissue necrosis is a result of focal temperatures typically exceeding 70°C.

Special transducers designed for high power ultrasound application are employed. Self focusing piezoceramic bowls made of low loss PZT (Lead Zirconate Titanate) or piezocomposite are widely used. A more expensive and technically more complex alternative is the use of phased array transducers composed of many single elements.

Another promising application of HIFU is drug delivery: in order to locally enhance the drug concentration in vivo in tumors, a drug can be administered either encapsulated in liposomic or other carrier bubbles intravenously. Once the tumor is sonicated, the bubbles are destroyed and the drug is released locally to the tumor. The resulting scenario is a local enhancement of the drug concentration in the focal area of the ultrasound beam. A wide spectrum of research has been conducted demonstrating proof of the concepts of the feasibility and effectiveness of this approach in vitro and in animal studies in vivo [10].

III. ADVANCES OF ULTRASONIC METHODS APPLIED TO MATERIALS AND STRUCTURES

The directly measured quantities, ultrasonic velocity and attenuation, are required for the ultrasonic non-destructive technique of material characterization.

The ultrasonic velocity is related to density and elastic constants, such as tensile modulus, shear modulus, flexural modulus, bulk modulus, Young’s modulus, Poisson’s ratio, Lamé constants. The knowledge of elastic properties is basic to understand and predicting the behavior of engineering materials.

Based on velocity and attenuation measurement microstructure and morphology (such as mean grain size, grain size distribution, texture, anisotropy, density variations, etc.) and diffuse discontinuity (such as microcracking, microporosity, fiber breakage, impact damage, creep damage etc.) can be characterized. Ultrasonic assessments of mechanical properties (such as tensile strength, shear strength, yield strength, hardness, fracture toughness, fatigue resistance etc.) are indirect and depend on empirical correlations.

Ultrasonic tests are currently employed for advanced structural ceramics, for evaluating bond performance in adhesive bonding and for composites laminates. See, for example, [11-13].

Nowadays, ultrasonic testing also provides the detection of rebar corrosion. Corrosion of RC structures has become a big problem worldwide due very high repair costs. Recently, the ultrasonic guided wave (UGW) technique is adopted to monitor the RC corrosion damage evolution process [18]. The corrosion experiment shows that the first wave peak value can describe the whole process of steel rebar corrosion.

A. Application of Ultrasonic Pulse Velocity (UPV) test to concrete structures

The UPV test is performed by using a sending transducer that sends an ultrasonic pulse to generate a stress wave in a concrete specimen and uses a receiving transducer to receive the wave.

By knowing the distance and time, the UPV in the specimen can be calculated. As pointed out by many researchers, the value of the UPV is affected by numerous factors, including the properties and proportion of the constituent materials, aggregate content and types, age of the concrete, presence of microcracks, water content, stresses in the concrete specimen, surface condition, temperature of the concrete, path length, shape and size of the specimen, presence of reinforcement, and so on.
The test equipment shown in Fig.2 consists of a pulse generator, a pair of transducers (transmitter and receiver), an amplifier, a time measuring circuit, a time display unit, connecting cables and material of coupling.

The test is performed generating a series of pulses by means of a dedicated generator. A timing circuit is used to measure the travel time of the pulse, which is subsequently reported on the display unit. The presence of low density, or cracked, concrete increases the travel time and consequently causes a decrease in the pulse velocity. Performing tests at various locations, lower quality concrete or damage zone can be detected.

It is possible to make measurements of pulse velocity by placing the two transducers on opposite faces (direct transmission), on adjacent faces (semi-direct transmission), on the same face (indirect or surface transmission) of a concrete structure or specimen (Fig.3).

According to the scientific literature in the field of ultrasonic investigations, there are numerous experimental formulations able to correlate the concrete compressive strength $f_{ck}$ with the measurement of the non-destructive parameter of the ultrasonic pulse velocity. Therefore, to limit the uncertainty of this method, three of the most reliable correlations proposed by Qasrawi [19] (Eq.A in Fig.3), Giannini et al. [20] (Eq.B in Fig.3), and Bilgehan and Turgut [21] (Eq.C in Fig.3) can be taken into account.

In order to evaluate the accuracy of these formulations, UPVs have been calculated in 16 locations by UPV test, as reported in [22],[23].

Then the estimated compressive strengths according to Eq. A, Eq. B and Eq. C, respectively, have been compared with the effective compressive strengths determined by Destructive Tests (DTs) on samples extracted in adjacent locations. To compare prediction performance of the formulations, Root Mean Square Error (RMSE) has been calculated. All the comparisons are shown in Fig.3.

<table>
<thead>
<tr>
<th>Ultrasonic Pulse velocity [m/s]</th>
<th>Quality of Concrete</th>
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<tbody>
<tr>
<td>$&gt; 4500$</td>
<td>Excellent</td>
</tr>
<tr>
<td>3500 to 4500</td>
<td>Good</td>
</tr>
<tr>
<td>3000 to 3500</td>
<td>Doubtful</td>
</tr>
<tr>
<td>2000 to 3000</td>
<td>Poor</td>
</tr>
<tr>
<td>$&lt; 2000$</td>
<td>Very poor</td>
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</table>

Table 3. Quality of concrete as a function of the ultrasonic pulse velocity
values using different formulations

By comparing all the correlation curves and the effective strength curve (fc), it can be observed a good approximation even if the most reliable correlation is related to Eq.B

IV. CONCLUSION

Ultrasonic methods represent a form of nondestructive testing and characterization of materials and structures used in engineering, including aerospace, automotive and other transportation sectors. The advantages of these methods include flexibility, low cost, in-line operation, and providing data in both signal and image formats for further analysis.

To explore the possibilities of the application of these emerging inspection technologies, the topic of the evaluation of structural performance of existing RC-structures is considered in this work. Since these structures were built according to the standards and materials which were quite different to those available today, procedures and methods able to cover lack of data about mechanical material properties and reinforcement detailing are required. This issue seems more relevant when seismic zones are concerned and structural strengthening needs to prevent failures occurred due to earthquakes. Recent seismic codes give relevance to procedure and methods to establish the performance levels of existing structures. To this end detailed inspections and tests on materials are required. In RC structures, the compressive strength of concrete has a crucial role on the seismic performance and is usually difficult and expensive to estimate. According to various international codes, estimation of the in-situ strength has to be mainly based on cores drilled from the structure.

However, Non-Destructive Tests (NDTs) can effectively supplement coring thus permitting less expensive and more representative evaluation of the concrete properties throughout the whole structure under examination. The critical step is to establish reliable relationships between NDT results and actual concrete strength. The experimental research suggests correlating safely in most codes the results of in-situ NDTs carried out at selected locations with the strength of corresponding cores. As a consequence, NDTs can strongly reduce the total amount of coring needed to evaluate the concrete strength in the entire structure.

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REFERENCES