Ultrasonic Sensing: Fundamentals and Its Applications to Nondestructive Evaluation (a draft)

Ikuo Ihara

Nagaoka University of Technology

Abstract This chapter provides the fundamentals of ultrasonic sensing techniques that can be used in the various fields of engineering and science. It also includes some advanced techniques used for non-destructive evaluations. At first, basic characteristics of ultrasonic waves propagating in media are described briefly. Secondly, basic concepts for measuring ultrasonic waves are described with introductory subjects of ultrasonic transducers that generate and receive ultrasonic waves. Finally, specialized results demonstrating the capabilities of using a buffer rod sensor for ultrasonic monitoring at high temperatures are presented.

Keywords Ultrasonic Sensing, Transducers, Nondestructive Evaluation

1 Introduction

Ultrasonic sensing techniques have become mature and are widely used in the various fields of engineering and basic science. Actually, many types of conventional ultrasonic instruments, devices and sophisticated software are commercialized and used for both industrial and medical applications. One of advantages of ultrasonic sensing is its outstanding capability to probe inside objectives nondestructively because ultrasound can propagate through any kinds of media including solids, liquids and gases except vacua. In typical ultrasonic sensing the ultrasonic waves are travelling in a medium and often focused on evaluating objects so that a useful information on the interaction of ultrasonic energy with the objects are acquired as ultrasonic signals that are the wave forms variations with transit time. Such ultrasonic data provides the fundamental basis for describing the outputs of ultrasonic sensing and evaluating systems.

In this chapter the fundamentals of ultrasonic sensing techniques are described. What is ultrasound, how to produce and capture ultrasound, what kinds of methods and equipments can be used to measure ultrasound, and what kinds of information can be obtained from ultrasonic measurements? These questions are addressed in the following sections and the answers to the questions are briefly explained from the viewpoint of industrial applications. In addition, some specialized results using a buffer rod sensor that is an effective means for high temperature ultrasonic measurements are introduced to demonstrate its applicability for nondestrucive evaluations and monitoring. For further studies on ultrasonic sensing, it is recommended to refer to some books, [1]-[7] for basic theories of ultrasound propagations, [8]-[12] for transducers and instruments, and [13]-[23] for ultrasonic measurements, evaluations, applications and others.

2 Fundamentals of Ultrasound

2.1 Ultrasonic Waves in Media

It is known that frequency range of sound audible to humans is approximately 20 to 20,000 Hz (cycles per second). Ultrasound is simply sound that are above the frequency range of human hearing. When a disturbance occurs at a portion in an elastic medium, it propagates through the medium in a finite time as a mechanical sound wave by the vibrations of molecules, atoms or any particles present. Such mechanical waves are also called elastic waves. Ultrasound waves or ultrasonic waves are the terms used to describe elastic waves with frequency greater than 20,000 Hz and normally exist in solids, liquids, and gases. A simple illustration of the ultrasonic waves produced in a solid is shown in Fig. 1, where distortion caused depending on whether a force is applied normal or parallel to the surface at one end of the solid can result in producing compression or shear vibrations, respectively, so that two types of ultrasonic waves, i.e. longitudinal waves or transverse waves, propagate through the solid. The energy of the wave is also carried with it.

In a continuous medium, the behaviour of ultrasonic waves is closely related to a balance between the forces of inertia and of elastic deformation. An ultrasonic wave moves at a velocity (the wave velocity) that is determined by the material properties and shape of the medium, and occasionally the frequency. The ultrasonic wave imparts motion to the material when it propagates. This is referred to as particle motion, to distinguish it from the wave motion. This particle motion is usually specified as a particle velocity v. It is noted in ultrasonic measurements that the particle velocity is much smaller than wave velocity. Also, one can understand that no ultrasonic wave propagates in vacua because there are no particles that can vibrate in vacua.

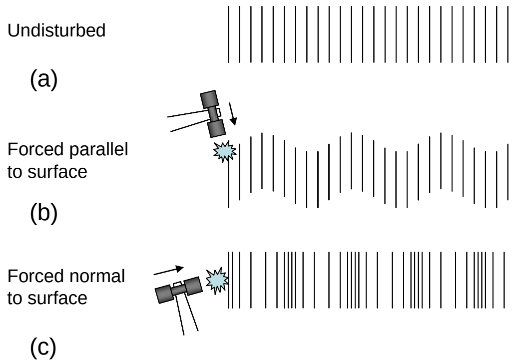


Fig. 1. Schematics of ultrasonic waves in a bulk specimen: (a)equilibrium state with no disturbance, (b)waves relating to shear (transverse) vibrations, (c)waves relating to longitudinal vibrations.

The balance between inertia and elasticity develops into a linear relationship between stress σ and particle velocity v, $\sigma = zv$. The proportional factor z is called the specific acoustic impedance of an ultrasonic wave [6][13]

$$z = \sigma/v = \rho c \qquad (1)$$

where, ρ is the density, and c is the wave velocity. The acoustic impedance characterizes the ability of a material to vibrate under an applied force and can be considered as the resistance of the material to the passage of ultrasonic waves. There is an analogy between impedance in electrical circuits and the acoustic impedance. The acoustic impedance is useful for treating the transmission of ultrasonic waves between two media, just like that the electrical impedance is effective to characterize a resistance in an alternating electric current circuit. For example, the transmission of an ultrasonic wave from one medium to another becomes maximum when the acoustic impedances of the two media are equal. The concept of using the acoustic impedance plays an important role in determining of acoustic transmission and reflection at a boundary of two media having different material properties and therefore, the acoustic impedance is an important parameter in designing ultrasonic sensors and sensing systems.

In Fig. 1, ultrasonic waves propagating across the material is simply shown in terms of the displacement of the layers from their equilibrium position and its amplitude. At a fixed position in the material, the displacement changes sinusoidally with time *t*, where the time required for the wave to propagate the distance between successive maxima is the period *T*. At any time, the amplitude of the displacement decreases periodically with increasing propagation distance because of its attenuation by the material. The distance between successive maxima in the amplitude variation is equal to the wavelength λ.

2.2 Features of Ultrasonic Waves

It is important to understand the behaviour and properties of ultrasonic waves in media, to design ultrasonic sensors and develop ultrasonic sensing systems. Some basic features of ultrasonic waves are introduced here.

Types of Wave (Modes of Propagation)

What types of ultrasonic waves can exist? The answer to this question can basically be given from solutions of the wave equations that predict wave behaviours by showing that material properties and body shape dictate the vibrational response to the applied forces that drive the wave motion. Details of wave types obtained by solving wave equations and their characteristics are shown in [1]-[7]. In short, there are two types of ultrasonic waves: bulk (fundamental) waves that propagate inside of an object, and guided waves that propagate near the surface or along the interface of an object [4]-[7].

Waves that propagate wholly inside an object, independent of its boundary and shape, are called bulk waves. Two types of bulk waves can exist in an isotropic medium: longitudinal (or dilatational, compression, primary), and shear (or distortional, transverse, secondary) waves as shown schematically in Fig. 1. As mentioned in Section 2.1, ultrasonic wave propagations are usually described in terms of the direction of particles motion in relation to the direction in which the wave propagates. The longitudinal waves can be defined on this basis as waves in which the particle motion is parallel to the direction of the wave propagation. The shear waves are defined as waves in which the particle motion is perpendicular to the direction of the propagation. Both waves can exist in solids because solids, unlike liquids and gasses, have rigidity that is a resistance to shear as well as compressive loads. However, the shear waves cannot exist in liquids and gasses because of no resistance to shear roads in such media.

When the influences of the boundaries or shape of an object are considered, other types of waves called the guided waves are produced. There are three types of guided waves depending on geometry of an object: surface acoustic waves (SAWs), plate waves, and rod waves.

SAWs are defined as waves that propagate along a free surface, with disturbance amplitude that decays exponentially with depth into the object. There are many kinds of SAWs such as Rayleigh, Scholte, Stoneley, and Love waves and the wave propagation characteristics of SAWs strongly depend on material properties, surface structure, and nature at the interface of the object. When an SAW propagates along a boundary between a semi-infinite solid and air, the wave is often called Rayleigh wave in which the particle motion is elliptical and the effective penetration depth is of the order of one wavelength. Among many types of SAWs, Rayleigh wave is the most common and well-known wave so that many researchers often call any SAWs Rayleigh wave.

When an ultrasonic wave propagates in a finite medium (like a plate), the wave is bounded within the medium and may resonate. Such waves in an object of finite size are called plate waves if the object has a multilayer structure, and called Lamb waves if it has a single layer. Also, when a force is applied to the end of a slender rod, an ultrasonic wave propagates axially along it. Wave propagations in rodlike structures such as a thin rod and hollow cylinders have been studied extensively. Further information on the guided waves and their characteristics can be obtained in Refs. [4]-[7], [20]. In general, the wave propagation characteristics of guided waves strongly depend on not only material properties but also the plate thickness, the rod diameter, and the frequency. The frequency dependence of the wave velocity of guided waves is called frequency dispersion. While the frequency dispersion often makes wave propagation behaviour complicated, it also provides unique materials evaluations using guided waves. It is noted that similar types of bulk and guided waves can exist for anisotropic materials and in general, their behaviours become much more complicated than those for isotropic materials [5]-[7].

Velocity

Ultrasonic velocity is probably the most important and widely used parameter in ultrasonic sensing applications. Each medium has its own value of the velocity that usually depends on not only propagation medium but also its geometrical shape and structure. The theoretical values can be obtained from wave equations and typically determined by the elastic properties and density of the medium. For example, the wave equations for an isotropic solid give the following simple formulae for the longitudinal and shear wave velocities

$$v_l = \sqrt{\frac{E}{\rho} \cdot \frac{1-\nu}{(1+\nu)(1-2\nu)}} \tag{2}$$

$$v_s = \sqrt{\frac{E}{\rho} \cdot \frac{1}{2(1+\nu)}} = \sqrt{\frac{G}{\rho}} \tag{3}$$

where, v_l and v_s are the longitudinal and shear wave velocities, respectively, E is Young's modulus, ν is Poisson's ratio, G is shear modulus and ρ is the density. For most of solid materials the longitudinal wave velocity is faster than the shear wave velocity because the shear modulus is lower than the Young's modulus. It is noted that Poisson's ratio is not a dominant factor affecting the velocities. As a rule of thumb, the velocity of the shear wave is roughly half the longitudinal wave. Although the velocities can be determined theoretically if material properties such as the elastic moduli and density are known precisely, these material properties are not always available for the determination because they change depending on mechanical processing and heat treatments. Therefore, it is important and necessary to make a calibration measurement for the velocities when one wants to know the correct values for velocities.

Attenuation

When an ultrasonic wave propagates through a medium, ultrasonic attenuation is caused by a loss of energy in the ultrasonic wave and other reasons. The attenuation can be seen as a reduction of amplitude of the wave. There are some factors affecting the amplitude and waveform of the ultrasonic wave, such as ultrasonic beam spreading, energy absorption, dispersion, nonlinearity, transmission at interfaces, scattering by inclusions and defects, Doppler effect and so on. To characterize the ultrasonic attenuation quantitatively, attenuation coefficient α is defined as follows

$$A = A_0 \cdot e^{-\alpha x} \qquad (4)$$

where A is the peak amplitude of the wave at propagation distance x, A_0 is the initial peak amplitude. The attenuation coefficient α is experimentally determined from the variation of the peak amplitude with the propagation distance, and it can be given in decibel per metre (dB/m) or in neper per metre (Np/m). In general, the attenuation coefficient highly depends on frequency. Since this frequency dependence reflects microstructures of materials, it can be used for characterizing microscopic material properties relating to chemical reactions and mechanical processes. Further information on the attenuation can be obtained in Refs. [7][9][10][12][13].

Wavelength

Wavelength λ is the distance over which one spatial cycle of the wave completes and the following expression can be given,

$$\lambda = v/f \qquad (5)$$

where v is the ultrasonic velocity and f is the frequency. Wavelength is a useful parameter in ultrasonic sensing and evaluations. In ultrasonic detection of a small object, the smallest size that can clearly be detected must be larger than half a wavelength at the operating frequency. If the critical size of an object to be detected is known, such prior information on size is helpful for selecting an appropriate frequency for measurements.

Reflection and Transmission

When an ultrasonic wave perpendicularly impinges on an interface between two media as shown in Fig.2, a part of the wave is reflected back to the medium 1 and the remainder is transmitted to the medium 2. The ratio of the amplitude of the reflected wave A_R to that of the incident wave A_I is called reflection coefficient R, and the ratio of the amplitude of the transmitted wave A_T to that of the A_I is called transmission coefficient T. Considering a balance of stresses and a continuity of velocities on both sides of the interface, the reflection and transmission coefficients, R and T can be given as follows

$$\boldsymbol{R} = \frac{\boldsymbol{A}_\mathrm{R}}{\boldsymbol{A}_\mathrm{I}} = \frac{\boldsymbol{z}_1 - \boldsymbol{z}_2}{\boldsymbol{z}_1 + \boldsymbol{z}_2} \tag{6}$$

$$\boldsymbol{T} = \frac{\boldsymbol{A}_\mathrm{T}}{\boldsymbol{A}_\mathrm{I}} = 2 \cdot \frac{\boldsymbol{z}_1}{\boldsymbol{z}_1 + \boldsymbol{z}_2} \tag{7}$$

where subscripts 1 and 2 refer to the medium 1 and 2, respectively, and z is the acoustic impedance defined as Eq. (1). It can be seen from these equations that the maximum transmission of ultrasonic wave occurs when the impedances of the two media are identical, and most of ultrasonic wave is reflected when the two media have very different impedances. The reflection and transmission at interface play an important role in designing ultrasonic sensing systems and understanding experimental results with the ultrasonic systems.

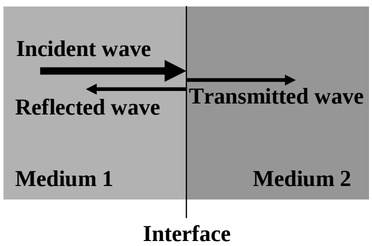


Fig. 2. Normal reflection and transmission at an interface between two media.

Refraction and Mode Conversion

When an ultrasonic wave obliquely impinges on an interface between two media as shown in Fig.3, several things happen depending on the incident angle of the wave as well as the material properties of the two media. One of important things is refraction in which a transmitted wave has a different angle from the incident. The refraction is basically caused by the velocity difference on either side of the interface. The refraction angle can be calculated from Snell's law [19] if the velocities of the two media and the incidence angle are known.

Another important phenomenon is mode conversion that is a generation of one type of wave from another type in refraction as shown in Fig. 3. For example, a longitudinal wave incident on an interface between liquid and solid is transmitted partially as a refracted longitudinal wave and partially as a mode converted shear wave in the solid. Mode conversion can also take place on reflection if the liquid shown in Fig. 3 is a solid. It is noted that any types of waves can be converted to another type, e.g. from a shear wave to a longitudinal wave, and from a longitudinal wave to a surface wave. The angles of reflection and/or refraction by mode conversion can be calculated from Snell's law.

Figure 4 shows a simulation result for refraction and mode conversion, calculated by a finite difference method. We can see that an incident plane wave (longitudinal wave) of 10º in water is refracted at the refraction angle of 43º in steel and simultaneously converted to shear wave at refraction angle of 22º.

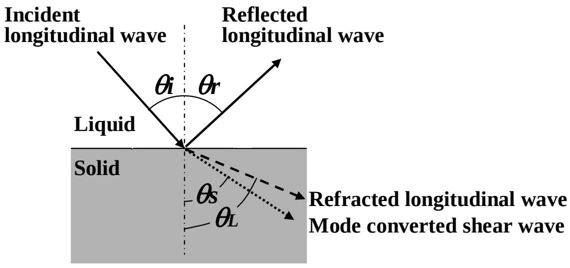


Fig. 3. Schematics of reflection, refraction and mode conversion at an oblique interface.

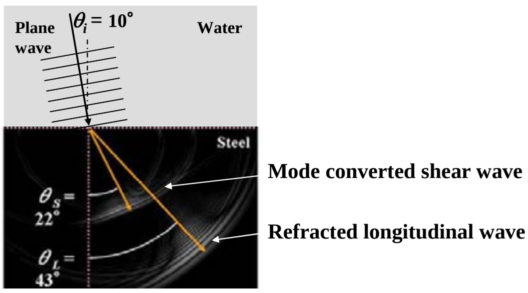


Fig. 4. A simulation result for refraction and mode conversion.

3 Measurement of Ultrasound

3.1 Generation and Detection of Ultrasonic Waves

Transducers

Ultrasonic sensors are often called transducers. The function of the transducers is to convert electrical energy into mechanical energy which directly corresponds to ultrasonic vibration, and vice versa. The most common way of generating and detecting ultrasonic waves utilizes the piezoelectric effect of a certain crystalline material such as quartz. Since the piezoelectric effect is reciprocal, it produces a deformation (a mechanical stress) in a piezoelectric material when an electrical voltage is applied across the material, and conversely, it produces an electrical voltage when a deformation (a mechanical stress) is applied to the material. Thus, the piezoelectric materials can be used for generating and detecting ultrasonic waves that are related to the mechanical stresses. Appropriate cuts and directions of quartz are utilized for two types of waves, longitudinal and shear, as shown in Fig. 5. Nowadays, many piezoelectric materials besides quartz are available, such as barium titanate ($BaTiO_3$), lead metaniobate ($PbNb_2O_3$) and lead zirconate titanate (PZT), etc. The size and shape of piezoelectric transducers have to be precisely designed depending on the desired frequency. For industrial applications, solid-state transducers are usually used, because of their robustness. A piezoelectric transducer consists of a piezoelectric element, electrical connections, backing materials, front layers and a casing. The typical construction is shown in Fig. 6. The front layer is to protect the piezoelectric element against external stresses and environmental influences, and also must function as an impedance matching layer with which the transfer of ultrasonic energy to the target medium is optimized. The backing material functions as a damping block that alters the resonance frequency of the piezoelectric element and deletes unwanted ultrasonic waves reflected from the back wall. The electrical line is connected AC or DC voltage supplies that are often operated at the resonant frequency of the piezoelectric element.

Depending on applications, other types of transducers can be available. Piezoelectric polymers that can exhibit the piezoelectric effect, often called PVDF (polyvinylidene fluoride), have some advantages owing to polymer characteristics such as its low acoustic impedance and softness. Magnetostriction effect that occurs in ferromagnetic materials is also utilized as transducers in industries.

It should be noted that the piezoelectric and magnetostrictive effects generally decrease with a rise in temperature and disappears at the Curie temperature. This is a crucial limitation in use of the ultrasonic transducers. When ultrasonic measurements are conducted at high temperatures near the Curie temperature, precautions are necessary so that the ultrasonic transducer does work properly. One of methods for high temperature measurements and its applications are presented in Section 4. It is also noted in the use of the transducers mentioned above that it is necessary to use some coupling medium for making an effective ultrasonic energy transmission between the transducer and specimen, as shown in Fig. 6. Gels, liquids or grease are often used as a coupling medium. It is extremely difficult to conduct the ultrasonic measurements without such coupling medium because of any air gap or large acoustic impedance between the transducer and specimen surface. This is another disadvantage of using contact-type transducers. Further information on transducers can be obtained in Refs. [10]-[13].

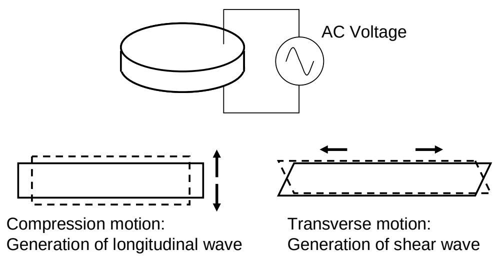


Fig. 5. Response of a piezoelectric plate to an alternating voltage.

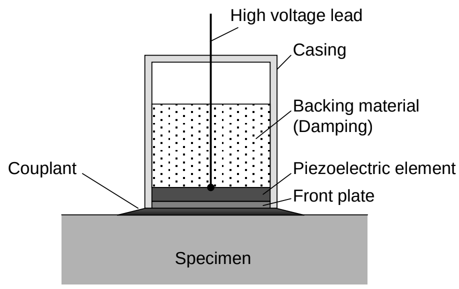


Fig. 6. Typical construction of a piezoelectric transducer and its use in measurement of a solid specimen.

Non-contact Techniques

Non-contact ultrasonic measurements are of great practical interests in the many fields of engineering. There are three kinds of non-contact methods for generation and detection of ultrasonic waves: optical method, electromagnetic method, and air-coupled method. Although each method has advantages and disadvantages, they have the potential to be powerful diagnostic tools for advanced ultrasonic sensing.

Optical methods for measuring ultrasonic waves are called laser-ultrasonics in which ultrasonic waves are generated and detected by using lasers. Laser generation of ultrasonic waves can be recognized as exciting the waves with an optical hammer. When a high energy pulsed laser beam is irradiated onto a specimen surface, an interaction of the laser beam with the specimen occurs in one or both of two distinct processes, thermoelastic and ablative. By controlling the laser irradiation conditions, it is possible to generate any types of ultrasonic waves such as longitudinal, shear and guided waves at a desired frequency. To detect ultrasonic waves, a laser beam is illuminated onto the specimen surface for the duration sufficiently long to capture the ultrasonic signal of interest. Ultrasonic waves are then detected by measuring surface displacements caused by ultrasonic disturbance, using an laser-assisted interferometer or other device. Mickelson, Confocal Fabry-Perot or Photorefractive Two-wave Mixing interferometers are often utilized. The ability of laser-ultrasonics to operate at large standoff distances provides big advantages in industrial applications such as materials process monitoring at high temperatures. Further information on laser ultrasonics can be obtained in Ref. [21].

Electromagnetic acoustic transducer (EMAT) is an alternative technique for generating and receiving ultrasonic waves, with which the ultrasonic measurements are conducted without any coupling medium between the transducer and specimen. The EMAT consists of a stack of coils and magnets to generate and receive ultrasonic waves in an electrically conductive material as shown in Fig. 7. When a coil that is placed near to the surface of a specimen is driven by a pulse current with a desired ultrasonic frequency, eddy currents will be induced by electromagnetic induction in near surface region of the specimen. Since a static magnetic field is present, the eddy currents will experience Lorentz forces F of the following form

$$F = J \times B \tag{8}$$

where J is the induced eddy currents and, B is the static magnetic field. Interactions of the Lorentz forces with the specimen produce high frequency vibrations resulting in generating ultrasonic waves. Since these processes are reciprocal, the same mechanisms work to allow the ultrasonic energy to be converted into electromagnetic energy, so that the EMAT works as a receiver as well as a generator. The EMAT eliminates the problems associated with the coupling medium because the electro-mechanical conversion takes place directly within the electromagnetic skin depth of the specimen surface. Thus, EMATs allow non-contact ultrasonic sensing for moving specimens, rough surfaces, in vacuum and also in hazardous locations. Further information on EMATs can be obtained in Refs. [22][23].

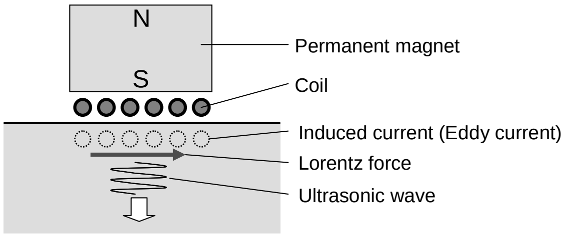


Fig. 7. Schematic of generation of an ultrasonic wave using an EMAT.

Another method for non-contact ultrasonic sensing is air-coupled ultrasonics. In air-coupled ultrasonics, air is used as a coupling medium between the transducer and specimen. Although air-coupling is very attractive, it has some difficulties because of high attenuation coefficient of air and high impedance mismatch between a transducer and air. To overcome such problem, a specially designed transducer with an optimal impedance matching layer is required for air-coupled ultrasonic measurements. Some piezoelectric-type air-coupled transducers have been commercialized and used for non-contact inspections. However, most of them have relatively low and narrow band frequency response with which it may not be sufficient to be used in a wide variety of applications. Recently, microelectromechanical systems (MEMS) technology has applied to ultrasonic sensors. A capacitive type air-coupled transducer, consisting of a metallized insulating polymer film placed upon a contoured conducting backplate, is developed using semiconductor manufacturing techniques [24]. This provides effective air-couple measurements with a higher and wider band frequency, in the range 100 kHz to 2 MHz. Utilizing such advantage, a novel noncontact method for characterizing surface roughness of materials by air-coupled ultrasound is developed [25].

3.2 Basics of Instrumentation

Figure 8 shows a block diagram of a basic construction of an ultrasonic measurement system used to generate and detect ultrasonic waves in a specimen. The synchronization generator gives trigger signals with high repetition rate (e.g. 1000 repetitions per second) to the pulse generator (pulser). Using these triggers, the pulser provides electrical voltage to the transducer so that the transducer generates ultrasonic waves at the same repetition rate. The reflected ultrasonic waves through the specimen are received by the same transducer and the resulting voltage of the received waves goes to the display through the amplifier. The computer is often used to analyze the acquired ultrasonic data.

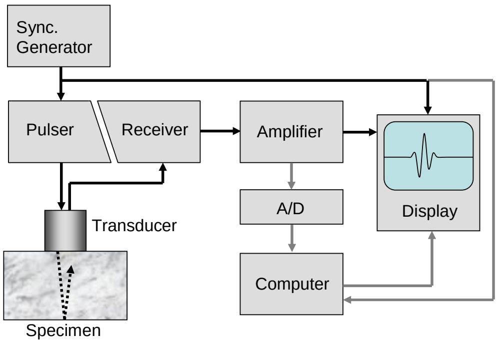


Fig. 8. Block diagram of a basic construction of an ultrasonic measurement system to generate and detect ultrasonic waves.

Figure 9 shows typical configurations for transducers used to launch and receive ultrasonic waves for ultrasonic measurements. Pulse-echo configuration with a single transducer shown in Fig. 9(a) is most commonly used to measure reflected waves from a flaw or the opposite side of the specimen. Through-transmission with a two transducers shown in Fig. 9(b) is probably the second most commonly used configuration. The third one is so-called pitch-catch configuration in which two transducers are placed on the same side of the specimen as shown in Fig. 9(c). This can be useful in the cases that the back wall is not parallel to the front wall or there is difficulty to use normal incidence ultrasonic beams.

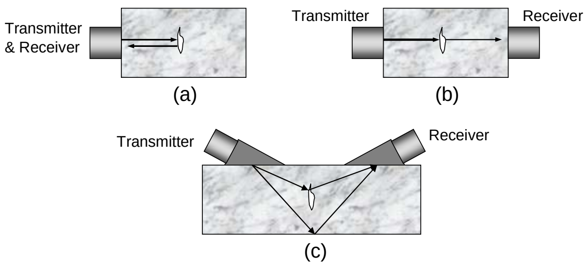


Fig. 9. Typical configurations of transducers used in ultrasonic measurements.

In general, an ultrasonic transducer operating at a high frequency radiates a narrow ultrasonic beam into a medium, which results in sensing over a narrow spatial region. To cover a wider region in ultrasonic sensing, scanning techniques are often used. Another powerful solution to probe a wide area is to use transducer arrays that are typically composed of number of individual transducer elements. A one-dimensional (linear) array or a two-dimensional array are commercialized and commonly used in the medical field for imaging. These transducer elements are arranged in certain patterns for the purpose of dynamic focusing or steering ultrasonic waves, using a beam forming effect based on wave interference. The elements configuration is designed to be able to form the desired beam shape and direction of ultrasonic wave. Phased-array transducers that provide a two-dimensional or a three-dimensional images in a medium are developed for performing a reliable flaw detection. Further information on the ultrasonic instrumentation can be obtained in Refs. [9][11]-[13].

A general scheme of ultrasonic based measurements and the related aspects are depicted in Fig. 10.

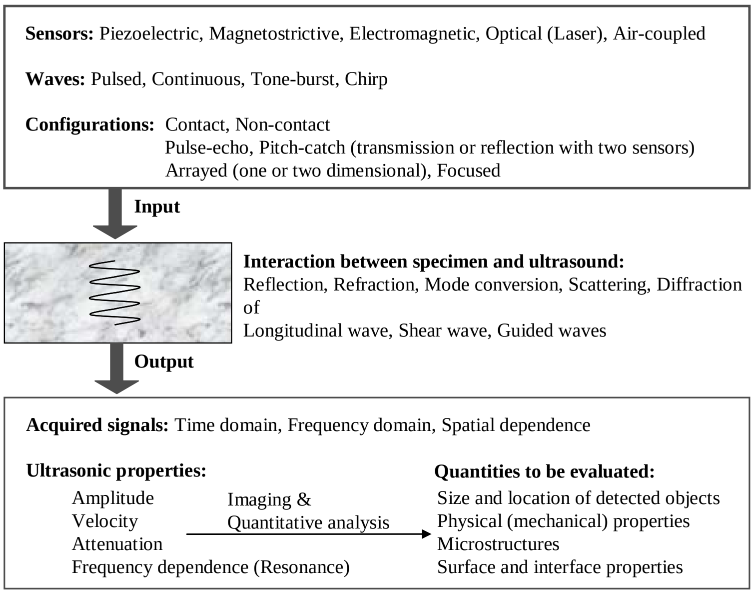


Fig. 10. General scheme of ultrasonic based measurements and evaluations.

4 Applications to Nondestructive Evaluation

Ultrasonic sensors have widely been used for numerous sensing applications in the fields of engineering, physics as well as medical science. Although the ultrasonic techniques have been applied to various nondestructive evaluations such as inspections of industrial structures, quantitative characterizations of materials and structural health monitoring [12]-[20], it is still required to develop new and more effective techniques that are applicable to advanced nondestructive evaluations. One of industrial demands is to realize ultrasonic in-line monitoring in a hazardous environment such as high temperatures. In this section, recent advances showing the capabilities of using buffer rod sensors as nondestructive tool for high temperature monitoring are presented.

Buffer Rod Sensors for High Temperature Monitoring

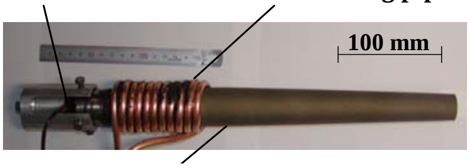
There are several ways for ultrasonic sensing at high temperatures: laser ultrasonics, EMATs, high temperature transducers and buffer rod method (known as delay-lines or waveguides). Since each technique has advantages and disadvantages, one has to select the appropriate technique to suit the objective depending on the application. Among the techniques, buffer rod method is a classical and still an attractive approach because of its simplicity and low cost. For high temperature applications of the buffer rod method, a long buffer rod is often employed as a waveguide. A conventional piezoelectric transducer is installed to the one end of the buffer rod and the other end is in contact with the material to be measured.

The difficulty in ultrasonic measurements using a buffer rod is, in most cases, caused by spurious echoes due to interference of mode converted waves, dispersion, and diffraction within the rod of finite diameter. These spurious echoes deteriorate the signal to noise ratio (SNR) because of their possible interference with desired signals to be measured. To overcome such difficulty, tapered and clad buffer rods are developed for various applications in materials evaluations and monitoring [26]-[31]. Fig. 11 shows the exterior of one of the developed buffer rod sensors, consisting of a tapered clad buffer rod, a cooling pipe and a conventional ultrasonic transducer (UT). The transducer end of the buffer rod is air cooled so that conventional room temperature UTs can be used while the other end (probing end) is in contact with a hot medium at 800ºC. Because of a taper shape of the buffer rod and a cladding layer of the outer surface, the buffer rod provides high performance pulse-echo measurements with high SNR at high temperatures. The length of the rod is possible to be up to 1000 mm.

Imaging using Focused Sensors

To provide high spatial resolution measurements, a spherical concave surface is machined at the probing end of the rod as shown in Fig. 12(a). This is expected to function as an acoustic lens for generating and receiving fo-

Ultrasonic transducer **Air cooling pipe**



Tapered clad buffer rod

Fig. 11. External view of a buffer rod sensor for high temperature use.

cused ultrasonic waves. Fig. 12(b) shows a contour plot of the acoustic field in the vicinity of a focal zone in molten aluminium at 800ºC, where the acoustic field is numerically examined by finite difference method [30]. We can see that the ultrasonic wave can be focused onto a small area comparable to a wavelength (460 μm) so that it is expected to make high resolution measurements using the focused buffer rod sensor. It is experimentally verified that the developed focused sensor can successfully detect alumina particles of about 160 μm suspended in molten aluminium [30]. Fig. 13 shows ultrasonic images obtained in molten zinc at 650ºC, by scanning of a focused buffer rod sensor [29]. This is probably the first ever image in a molten metal. Surprisingly, this kind of imaging is possible even using a long buffer rod of 1 m length. Fig. 14 shows the images obtained in water using a short rod of 75 mm and a long rod of about 1000 mm [28]. Although the resolution of the image using the long rod deteriorates because of an attenuation of higher frequency components of the guided wave in the rod, it can be seen that the ultrasonic wave can be focused onto a small spot of about one wavelength.

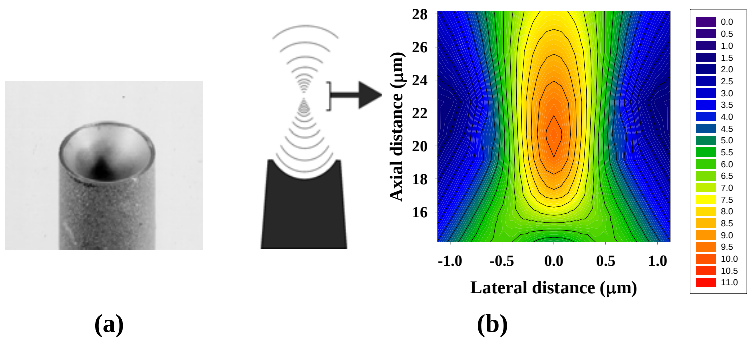


Fig. 12. (a) a concave acoustic lens fabricated at the probing end of a buffer rod sensor, (b) a simulation result of the sound field of focused ultrasonic wave at 10 MHz in molten aluminium [30].

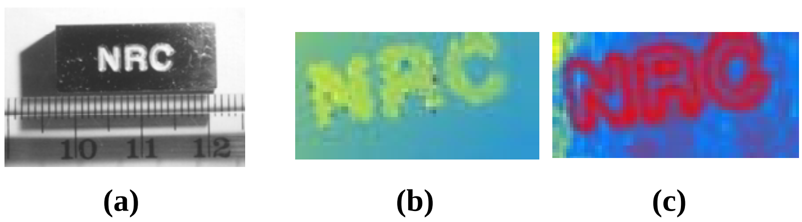


Fig. 13. Ultrasonic images in molten zinc at 800ºC: (a) specimen having the three letters NRC engraved on the surface, (b) by plotting the time delay of the echo, (c) by plotting the amplitude of the echo [29].

In-Situ Monitoring of Solid-Liquid Interface

Using the buffer rod sensor, an attempt has been made to monitor a solid-liquid interface of aluminium alloy during unidirectional solidification at 700ºC [31]. A solid-liquid interface of aluminium alloy is produced using a directional solidification furnace and then the interface behaviour is monitored during heating and cooling as shown in Fig. 15(a). Fig. 15(b) shows the location of the interface determined from the transit time of ultrasonic pulse echo. The growing rate of the solidification front is estimated to be 0.12 mm/s by time-differentiating the location. The amplitude change of the interface echo is also shown in Fig. 15(b). We can observe periodical

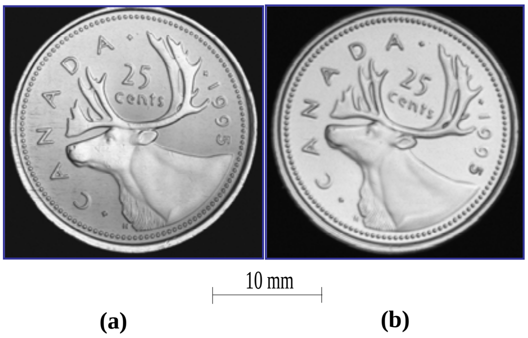


Fig. 14. Ultrasonic images of a Canadian quarter obtained using the (a) short and (b) long buffer rods with acoustic lens in water [28].

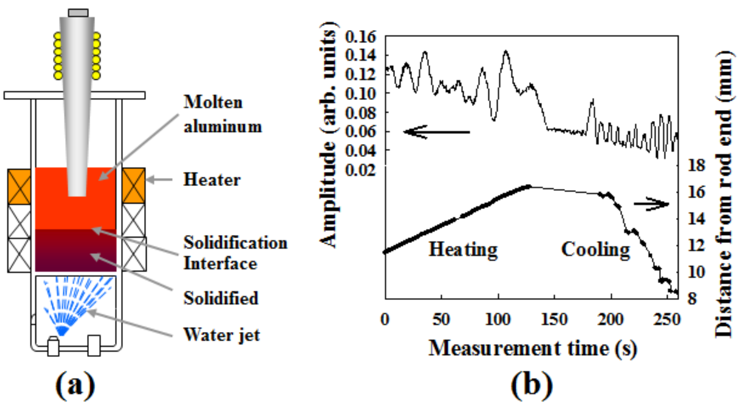


Fig. 15. (a) Schematic of experimental setup for ultrasonic monitoring of solid-liquid interface of aluminium alloy using a buffer rod sensor, (b) Monitoring result showing variations in amplitude and location of solid-liquid interface echo during heating and cooling [31].

oscillations in the amplitude during heating and cooling. It is tentatively considered that these oscillations are related to the feature of solidification instabilities such as variations in cellular structure and/or mushy zone consisting of solid and liquid phases.

Monitoring of Internal Temperature Distribution

In many fields of science and engineering, there are growing demands for measuring internal temperature distribution of heated materials. Recently, an ultrasonic method has been applied to internal temperature monitoring [32]. The principle of the method is based on temperature dependence of ultrasonic velocity in materials. A single side of a silicone rubber plate of 30 mm thickness is heated by contacting with a hot steel plate as shown in Fig. 16(a) and ultrasonic pulse-echo measurements are then performed during heating. A change in the transit time of ultrasonic wave in the heated rubber is monitored and used to determine the transient variation of internal temperature gradient in the rubber, where an inverse analysis is used to determine one-dimensional temperature gradient. Fig. 16(b) shows the internal temperature distributions in the silicone rubber and their variations with elapsed time. The temperature gradient determined ultrasonically agrees well with both obtained using commercial thermocouples installed in the rubber and estimated theoretically.

Thus, recent demonstrations shown in this section reveal that even a classical method such as a pulse-echo method using a buffer rod sensor has the high potential to be applicable to a novel sensing in an unexplored field.

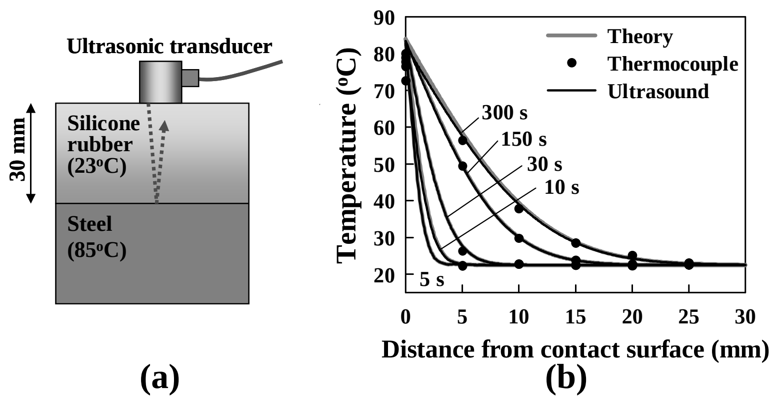


Fig. 16. (a) Schematic of ultrasonic temperature monitoring of a silicone rubber being heated, (b) Monitoring result showing internal temperature distributions in the silicone rubber and their variations with elapsed time [32].

5 Conclusion

In this chapter a brief overview of fundamentals in ultrasonic sensing is presented. Some advanced techniques and applications to nondestrucve evaluation are also introduced. The essentials of ultrasonic sensing are how to drive an ultrasonic wave into an object and how to capture the ultrasonic wave from the object. In addition, another essential is how to extract the information we want from the captured ultrasonic wave. To accomplish these and to create a useful sensing technique, it is indispensable to make an effective collaboration among researchers in different fields of engineering and science such as electrical, electronics, information, mechanical and materials. Actually, progress is being made in ultrasonic sensing technology, but, it should be noted that classical techniques and methods are still attractive and have the potential to create something new, as shown in the application of a buffer rod sensor.

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