forms (the propagation path of the wave is perpendicular to the surface of the object) is used throughout this thesis, where both the transducer and the investigated object are immersed in water. However, the multi-layered model derived in this thesis is valid for many configurations with normal incidence waveforms, and in Paper D, measurements using a through-transmission configuration with a hydrophone as the receiver is used, see Figure 2.4.

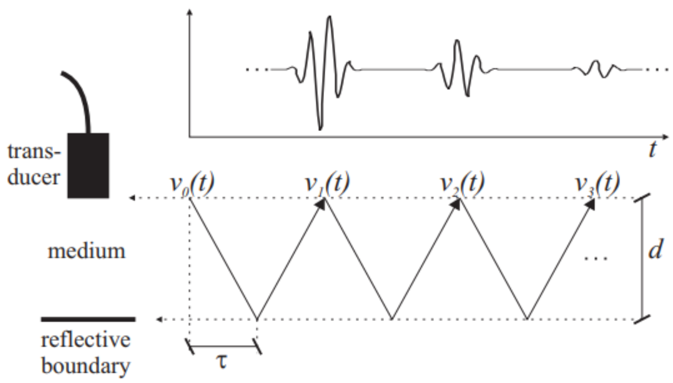

Figure 2.2: The figure shows a pulse-echo configuration at normal incidence using the same transducer as both transmitter and receiver. The notation d denotes the distance between the transducer and the reflective boundary and τ is the corresponding time-of-flight. The signal $v_0(t)$ is the unknown emitted signal from the transducer and the consecutive echoes $v_m(t)$ (solid line), for $m \geq 1$, add up to the received ultrasonic waveform available for analysis.

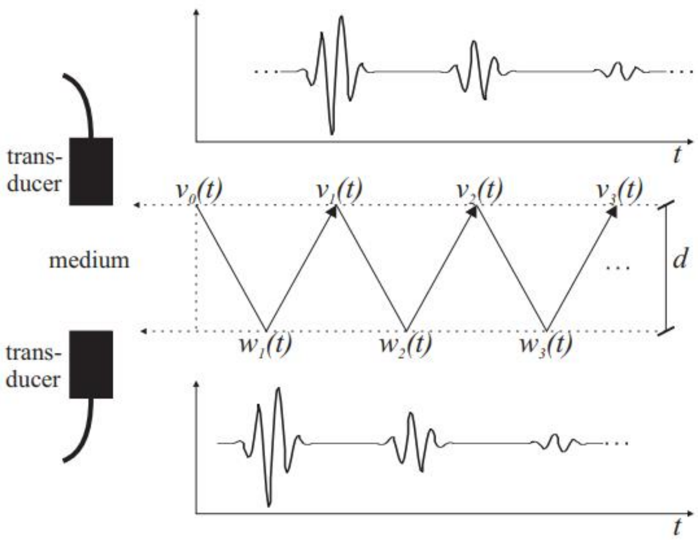

Figure 2.3: The figure shows a through-transmission configuration at normal incidence using one transducer as the transmitter and another transducer as the receiver. In this example, the transducer above is also in receiving mode, illustrating pulse-echo and through-transmission configuration used simultaneously.

The ultrasonic technique using through-transmission measurements, see Figures 2.3–2.4, is a method where the ultrasonic signal is transmitted by one transducer through the test object and received by another transducer or a hydrophone at the opposite side. This technique is especially useful for highly attenuating materials. However, through-transmission requires both sides of the test object to be accessible, and objects with inhomogeneities or large defects that give rise to strong reflections are difficult to examine. The technique implies alignment difficulties of the transducers and the reciprocity principle [11, 12] is not applicable, since the transmitter and receiver dynamics are different. Homogeneous objects without defects (fluids, gases, homogeneous solid materials) are appropriate to examine with through-transmission techniques because of the shorter propagation distance and hence the increased amplitude in the received signal. When using a hydrophone as the receiver, the spatial resolution is also increased due to the needle-type shape of the hydrophone, see Figure 2.4.

Pulse-echo and through-transmission setups can also be used simultaneously, with one transducer both emitting and receiving and another transducer on the opposite side of the object in the receiving mode, see Figure 2.3. These types of parallel measurements can provide additional information about the object. The main disadvantage with this method is the need of precise alignment of the sensors to assure that the two different measurements are obtained at the same location on the object. Another technique, which does not assume normal incidence waveforms is the angle-beam technique [13, 14]. The technique is applicable in through-transmission mode, pulse-echo mode or both. One application is to use an angle of incidence larger than the first critical angle, so that

2.3.2 Excitation of Signals - Choosing Transducer

The transducers used for the measurements throughout this study have been commercially available unfocused transducers. Transducers with a concave sensor surface are called focused transducers, which spatially focus the emitted sound field in a point at a distance from the transducer, see Figure 2.5.

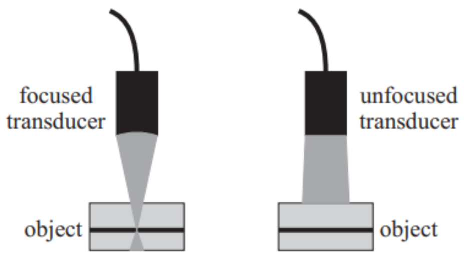

Figure 2.5: An example of the sound field from a focused and an unfocused ultrasonic transducer.

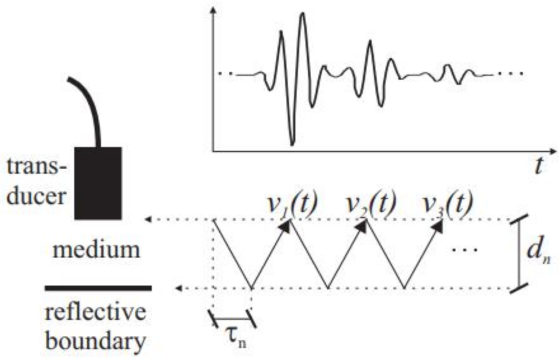

Figure 2.6: The figure shows an example of a pulse-echo configuration at normal incidence using the same transducer as both transmitter and receiver. The notation d_n denotes the shorter distance between the transducer and the reflective boundary and τ_n is the corresponding time-of-flight. The retrieved ultrasonic waveform available for analysis consists of partly overlapping echoes.

When the wave propagation distance decreases and the time-of-flight in a thin layer inside an object is shorter than the emitted signal's time support, the response signal will consist of overlapping waveforms, see Figure 2.6. Increasing the transducer frequency and decreasing the pulse width is the most common approach to prevent these overlaps. However, there are a number of situations when this approach is not an option (e.g., too short propagation distance, high-frequency attenuation and absorption, or hardware limitations). Hence, robust and accurate methods to handle situations with overlapping echoes are required, which is the focus of this thesis.

The unfocused ultrasonic transducers used in this thesis have center frequencies ranging from 5 MHz up to 20 MHz, and the media under investigation have layer(s) with thicknesses thin enough to produce overlapping signals.

both due to small layer thicknesses and reverberations. Accurate estimates of properties from within the material usually requires separated echoes, not achievable in these situations. This problem can be addressed in two ways: develop algorithms for separation of overlapping echoes, or model the waveform and reverberation directly, either by modeling the echoes or by modeling the underlying structure causing the reverberation. When there is some physical knowledge (number of layers, total thickness of the object, material properties of the media, etc.) the appropriate approach is to model the structure, but when no information of the material is available, modeling the waveform might be a better strategy. In Figure 1.1, the connection between the ultrasonic measurement and the material properties through a model and its parameters was presented. This connection can also be directly from measured waveforms to material properties without incorporating a model, usually the case when measurements resulting in separated echoes with high signal-to-noise ratio (SNR) are achievable and rapid estimates are required.

3.2 Acoustic Properties Inside Media

Throughout this thesis we assume plane acoustic waves, and that the incident angle of the wave propagation is perpendicular to planar surfaces (the wavefront is parallel with the surface of the object). This implies that the effect of mode conversion is decreased and the approximation that only longitudinal waves are present is justified [44]. Furthermore, we assume that linear acoustics apply, that is, the linear lossy wave equation, in the one-dimensional space, can be expressed as [45]

$$\frac{\partial^2}{\partial x^2} P(x,\omega) = -k^2(\omega) P(x,\omega), \tag{3.1}$$

where x is the spatial variable, ω is the angular frequency, $P(x,\omega)$ is the Fourier transform of the acoustic pressure, and $k(\omega)$ is the complex frequency dependent wave number. The solution to (3.1) in the positive x-direction, called the one-way wave equation [46], is given by

$$\begin{aligned} P(x,\omega) &= P(x_0,\omega) e^{-jk(\omega)(x-x_0)}, && (3.2) \\ &= P(x_0,\omega) e^{-j\frac{\omega}{c_p(\omega)}(x-x_0) - \alpha(\omega)(x-x_0)}, && (3.3) \end{aligned}$$

$$\frac{\partial^2}{\partial x^2} P(x,\omega) = -k^2(\omega) P(x,\omega), \tag{3.1}$$

where x is the spatial variable, ω is the angular frequency, $P(x,\omega)$ is the Fourier transform of the acoustic pressure, and $k(\omega)$ is the complex frequency dependent wave number. The solution to (3.1) in the positive x-direction, called the one-way wave equation [46], is given by

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where $j = \sqrt{-1}$, and $P(x_0,\omega)$ is the sound pressure at the initial location x_0.

The equality in (3.3) is found by using the complex frequency dependent wave number, defined as $k(\omega) = \omega/c_p(\omega) - j\alpha(\omega)$, where $c_p(\omega)$ is the frequency dependent phase velocity of the wave, and $\alpha(\omega)$ is the frequency dependent attenuation coefficient, expressed in nepers/m. The first part of the exponent in (3.3) is connected to the time-of-flight (phase delay) and the second part to the attenuation of the wave. The rate with which the amplitude of the wave is decreasing depends on the medium and on the frequencies of the wave. The attenuation can be described as the pressure change of a wave due to absorption, scattering, and diffraction. The absorption can be due to thermal losses or molecular changes, and is small in solids. The scattering effects are due to deflection of the sound waves by particles or inhomogeneities. In classical absorption theory the attenuation coefficient can be approximated to be proportional to the square of the sound frequency, $\alpha(\omega) = \alpha\omega^2$, where α is a scalar, which is often enough to capture the main characteristics of the observable attenuation. More sophisticated models of the attenuation are available [45], but in general, having a more complex model (also including diffraction, mode conversion, etc.) complicates the parameter estimation, due to a less numerically stable optimization algorithm.