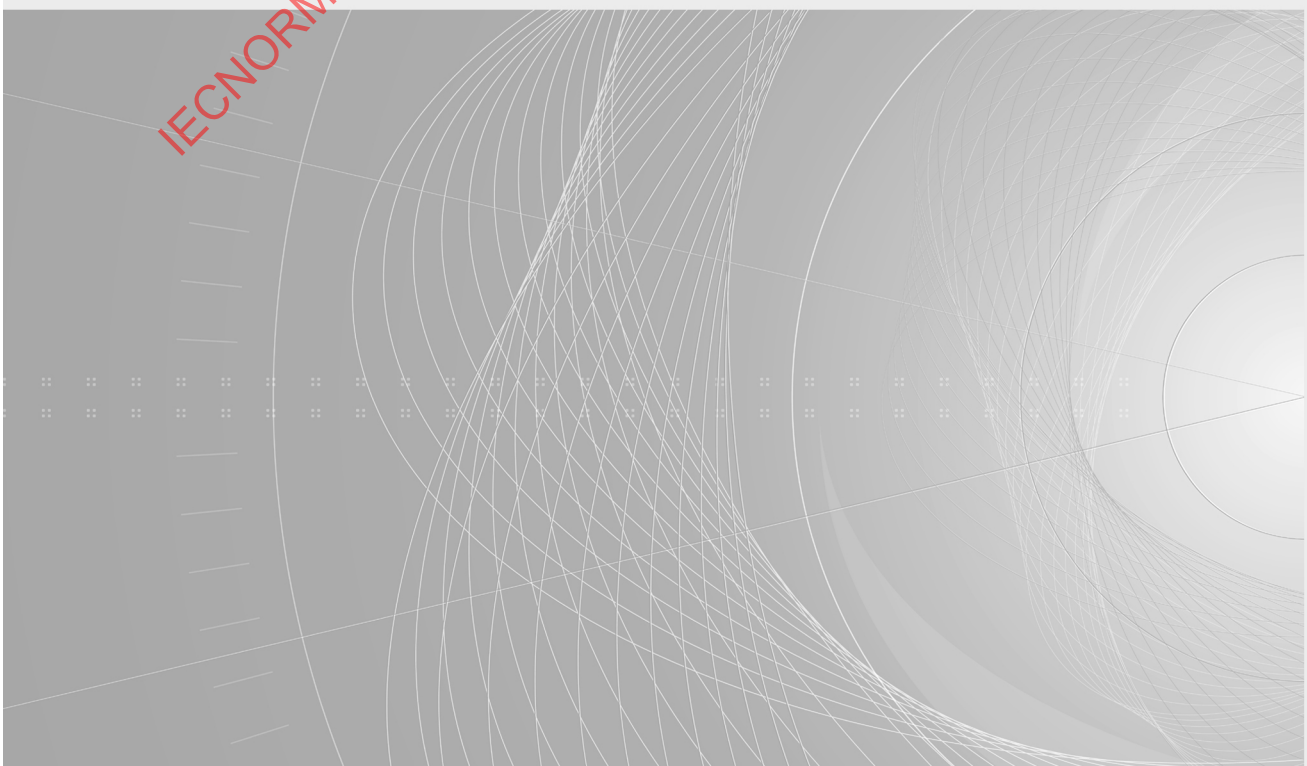
IEC TS 63081

Edition 1.0 2019-12

TECHNICAL SPECIFICATION

colour inside

Ultrasonics – Methods for the characterization of the ultrasonic properties of materials



IEC TS 63081:2019-12(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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Ultrasonics – Methods for the characterization of the ultrasonic properties of materials

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 17.140.50

ISBN 978-2-8322-7643-3

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ULTRASONICS – METHODS FOR THE CHARACTERIZATION OF THE ULTRASONIC PROPERTIES OF MATERIALS

FOREWORD

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- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards

IEC TS 63081, which is a Technical Specification, has been prepared by IEC technical committee 87: Ultrasonics

The text of this Technical Specification is based on the following documents:

DTS	Report on voting
87/718/DTS	87/725/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

Words in **bold** in the text are defined in Clause 3. Symbols and formulae are in *Times New Roman + Italic*.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

Many ultrasonic measurement standards contain requirements for the properties of acoustic materials to be used to construct the measurement equipment relied upon within those documents. The following are examples of such standards.

- IEC 61161 specifies amplitude reflection factor and acoustic energy absorption for reflecting targets and absorbing targets and specifies amplitude transmission coefficient for anti-streaming foils.
- IEC 61391-1 discusses reflection coefficient.
- IEC 61689 defines echo reduction and specifies limits upon its values. The terms reflection loss and transmission loss are also used, and values specified.
- IEC TS 62306 specifies transmission loss and reflection amplitude reduction.
- IEC 62359 specifies reflection coefficient and absorption.
- IEC 60601-2-37 specifies reflectance and absorption coefficient.

As the list above suggests, a wide range of terms is used to specify the properties of an acoustic material, and these terms are not used consistently across IEC documents. Furthermore, there is a degree of duplication with multiple names for the same quantity. This is further confused since there is no document within the IEC ultrasonics portfolio that defines the methods by which those properties are measured.

This document seeks to address the shortcomings by providing:

- a clear unambiguous definition of the key quantities of interest during materials characterization;
- a discussion of similar terms and how they may relate to the key quantities;
- recommended experimental methods for determining the values of key quantities.

ULTRASONICS – METHODS FOR THE CHARACTERIZATION OF THE ULTRASONIC PROPERTIES OF MATERIALS

1 Scope

This document:

- defines key quantities relevant to ultrasonic materials characterization;
- specifies methods for direct measurement of many key ultrasonic materials parameters.

This document is applicable to all measurements of properties of passive acoustic materials under drive conditions that are not subject to nonlinear acoustic propagation. Whilst there are materials properties that may be of interest in a nonlinear drive regime, these are currently outside the scope of this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
absorption per unit length
α
component of the attenuation coefficient (IEC 60050-801:1994, 801-23-35) that does not arise from scattering and is due only to absorption of acoustic energy within the sample

$$\alpha = \alpha_0 \left| f^y \right| \tag{1}$$

where

α_0 is the absorption constant (dB/(MHz^y m));

f is the frequency in MHz;

y is the frequency exponent (in general not an integer).

Note 1 to entry: For absorption, y = 2 for water, and in general y is between 1 and 2 for fluids, soft tissues and tissue mimicking materials.

Note 2 to entry: **Absorption per unit length** is expressed in units of decibel per metre (dB/m).

3.2
amplitude reflection coefficient
R_p
ratio of the pressure amplitude of an acoustic wave reflected from an interface separating two media to the pressure amplitude of a plane wave incident on that interface

$$R_p = \frac{p_r}{p_i} \tag{2}$$

where

p_r is the pressure amplitude of the reflected longitudinal wave, at the reflection angle θ_r;

p_i is the pressure amplitude of the incident longitudinal wave, at the incident angle θ_i

Note 1 to entry: Care should be taken with the term reflection coefficient as both amplitude and intensity forms appear in common scientific parlance. This can be particularly problematic when equations involve reflection coefficient terms, since both are dimensionless, but one varies as the square of the other. Intensity forms of reflection coefficient are more common in optics.

Note 2 to entry: In general, the equation shown can apply to reflections of different types, each at different reflection angles but all governed by Snell's law.

Note 3 to entry: **Amplitude reflection coefficient** is dimensionless as it is a ratio of quantities. It does not require the use of a calibrated receiver since measurements are relative in nature.

3.3
amplitude transmission coefficient
T_p
ratio of the pressure amplitude of an acoustic wave transmitted through an interface separating two media, to the pressure amplitude of a plane wave incident on that interface

$$T_p = \frac{p_t}{p_i} \tag{3}$$

where

p_t is the pressure amplitude of the transmitted longitudinal wave;

p_i is the pressure amplitude of the incident longitudinal wave

Note 1 to entry: Care should be taken with the term transmission coefficient as both amplitude and intensity forms appear in common scientific parlance. This can be particularly problematic when equations involve transmission coefficient terms, since both are dimensionless, but one varies as the square of the other. Intensity forms of transmission coefficient are more common in optics.

Note 2 to entry: In general, the equation shown can apply to transmissions of different types. For example, a longitudinal wave incident from fluid to solid at an angle will generate two transmitted waves at non-normal incidence, a shear wave and a longitudinal wave, each at different refraction angles. Each of the transmitted waves is governed by Snell's law.

Note 3 to entry: **Amplitude transmission coefficient** is dimensionless as it is a ratio of quantities. It does not require the use of a calibrated receiver since measurements are relative in nature.

3.4
backscatter coefficient
η
differential scattering cross-section per unit volume as a function of frequency for a scattering angle of 180°

Note 1 to entry: **Backscatter coefficient** is expressed in units of one per second per steradian (s^{-1} Sr^{-1}).

3.5
density
mass density
ρ
at a given point within a three-dimensional domain of quasi-infinitesimal volume dV, scalar quantity equal to the mass dm within the domain divided by the volume dV

$$\rho = \mathrm{d}m/\mathrm{d}V$$

Note 1 to entry: **Mass density** is an intensive quantity describing a local property of a substance.

Note 2 to entry: The concept of **mass density** may also be applied to the mass m in a domain D with a volume V, leading to the average **density** $\rho_{\mathrm{av}} = \frac{m}{V} = \frac{1}{V}\int_D \rho \mathrm{d}v$.

Note 3 to entry: **Mass density** is expressed in units of kilogram per metre cubed (kg/m^3).

[SOURCE: IEC 60050-113:2011, 113-03-07]

3.6
echo reduction
ER
reduction in pressure amplitude of an ultrasonic plane wave resulting from its reflection from an interface between two media

$$\begin{aligned} ER &= -20 \log_{10}\left(\frac{p_{\mathrm{r}}}{p_{\mathrm{i}}}\right) \mathrm{dB} \\ &= -20 \log_{10}\left(R_p\right) \mathrm{dB} \end{aligned} \tag{4}$$

where

p_{r} is the pressure amplitude of the reflected longitudinal wave;

p_{i} is the pressure amplitude of the incident longitudinal wave

Note 1 to entry: In general, the reflected waves are governed by elastic Snell's laws and the reduction in pressure amplitude is a function of the angle of the incidence of the plane-wave on the surface.

Note 2 to entry: **Echo reduction** is expressed in decibels (dB).

3.7
group velocity
v_{g}
velocity in the direction of propagation of a characteristic feature of the envelope of a pulse

Note 1 to entry: **Group velocity** is commonly defined in terms of angular frequency ω and wavenumber k as $v_{\mathrm{g}} = \frac{\mathrm{d}\omega}{\mathrm{d}k}$ and differs from **phase velocity** only in a dispersive medium.

Note 2 to entry: **Group velocity** is ordinarily the velocity of propagation of the energy associated with the disturbance.

Note 3 to entry: **Group velocity** is expressed in units of metre per second (m/s).

[SOURCE: IEC 60050-801:1994, 801-23-21, modified – In the definition, "non-sinusoidal disturbance" has been replaced by "pulse".]

3.8
insertion loss
IL
reduction in pressure amplitude of an ultrasonic plane wave resulting from the insertion of a sample in the acoustic path

$$IL = -20 \log_{10}\left(\frac{p_s}{p_{ns}}\right) \text{dB} \quad (5)$$

where

p_s is the amplitude of the received pressure wave with the sample in the path (with sample);

p_{ns} is the amplitude of the received pressure wave without the sample in the path (no sample)

Note 1 to entry: Care should be taken as **insertion loss** is sometimes incorrectly labelled transmission loss. However, transmission loss is a more general term describing loss of signal between a source and a receiver. IEC 60050-801:1994, 801-23-39 defines transmission loss as "reduction in sound pressure level between two designated locations in a sound transmission system, one location often being at a reference distance from the source". As such it can include contributions from the directivity functions of both source and receiver as well as acoustic spreading. These are functions of the experimental configuration and not the material under investigation.

Note 2 to entry: **Insertion loss** is expressed in decibels (dB).

3.9
longitudinal wave speed
c_L
magnitude of the velocity of a free progressive longitudinal wave

Note 1 to entry: **Longitudinal wave speed** is expressed in units of metre per second (m/s).

3.10
phase velocity
v_p
velocity in the direction of propagation of a surface of constant phase

Note 1 to entry: **Phase velocity** is commonly defined as $v_p = \frac{\omega}{k}$ where ω is the angular frequency and k is the wave number.

Note 2 to entry: **Phase velocity** is expressed in units of metre per second (m/s).

[SOURCE: IEC 60050-801:1994, 801-23-20]

4 List of symbols

A	toneburst amplitude in single sample absorption coefficient measurements
A_n, A_m	amplitude of nth and mth echoes in single sample absorption coefficient measurements
A_0	area of a transducer aperture
B	bandwidth of time delay spectrometry (TDS) tracking filter
c_{CF}	**longitudinal wave speed** in the coupling fluid
c_L	**longitudinal wave speed**
e_{CFM}	excitation signal used with compensated frequency modulation (CFM)
E_{CFM}	spectral modulus of CFM signal
ER	**echo reduction**

f	frequency
F	focal length of a transducer
H_s	frequency spectrum of transducer used in calculation of CFM signal
IL	**insertion loss**
k	wave number
$p(x,t)$	pressure signal as a function of time, measured at position x
$P(x,f)$	Fourier transform of $p(x,t)$
p_i	pressure amplitude of the incident longitudinal wave
p_{ns}	amplitude of the received pressure wave without the sample in the path
p_r	pressure amplitude of the reflected longitudinal wave
$\hat{p}_r$	pressure amplitude of the reflected longitudinal wave, corrected for imperfect reflector
p_s	amplitude of the received pressure wave with the sample in the path
p_t	pressure amplitude of the transmitted longitudinal wave
$q(x,t)$	pressure signal as a function of time after delay applied, measured at position x
$Q(x,f)$	Fourier transform of $q(x,t)$
R_p	**amplitude reflection coefficient**
t	time
S	sweep rate of TDS source signal
T_p	**amplitude transmission coefficient**
x	distance/position
y	frequency exponent of **absorption per unit length**
Z	acoustic impedance
v_g	**group velocity**
v_p	**phase velocity**
α	**absorption per unit length**
Δx	thickness (either of sample or vessel wall)
Δt	change in time
$\Delta\varphi$	change in phase
η	**backscatter coefficient**
φ	phase
ρ	**density**
τ	time delay
ω	angular frequency

5 Overview

5.1 General principles

It is important when measuring materials characteristics that the equipment set-up environment and method have as little effect on the results as possible. Clause 5 discusses some of the set-up issues and items to be noted when performing these measurements.

The application of a consistent and well understood protocol is the key to deriving meaningful measurements that are reproducible and transportable. Controlling as much of the test environment as possible, from temperature to sample preparation and conditioning, has an important impact on the measurement quality and confidence.

Having water-filled tanks where the temperature can be controlled and measured to the desired accuracy is important. Similarly, other aspects of the water quality employed for the measurements (dissolved gas content and conductivity) may be important subject to the applied technique.

In addition, measurements should be repeated at different conditions (distance, orientation driving signal) depending on the property to be measured, in order to understand and minimize set-up and instrumentation effects. To this end, once the type of measurement has been selected for the particular parameter, sources of uncertainty should be investigated and quantified [1]. Type A uncertainties can be quantified by repeating measurements and building up an appropriate uncertainty budget. Type B sources of uncertainty will require modelling or parallel/confirmatory validation studies.

5.2 Sample preparation

5.2.1 Fluid samples

When working with fluids, immersing the test transducers in the fluid is ideal. However, practically fluids often need to be housed within a container which is immersed within a test tank. Such containers are typically either rigid walled vessels (such as a parallel walled cell culture flasks) or have an acoustically thin membrane at either end of the acoustic path through the material.

Rigid-walled vessels are likely to have the benefit that they have parallel walls, and therefore maintain a uniform thickness of sample. However, the material used to construct the walls of the flask is likely to be acoustically mismatched to water, leading to significant reflections at the interfaces. Additionally, they can exhibit acoustic absorption and dispersion.

Whilst membranes may be thin relative to the acoustic wavelength, their influence on the determination of ultrasonic power as part of the radiation force balance measurement is well documented [2],[3], and such effects need to be avoided. Care should also be taken to avoid expansion of the membrane during the process of filling the measurement vessel with the fluid under test. Particularly if the vessel is surrounded by air during filling, membranes can expand to a convex shape and thus the vessel might become an acoustic lens which further perturbs the measurement. It is best practice to use flat restraining plates in contact with the membrane to minimize expansion during filling.

Given the possible artefacts introduced by a measurement vessel, measurements should be conducted in a manner that separates the properties of the fluid under test from those of the vessel containing it. A description of methods to accomplish this is given in Clause 6.

When testing fluids, the sample ideally needs to be degassed to a constant level. During sample preparation, it is easy to introduce air into the sample when pouring the liquid. Care should be taken to minimize this; however, it is likely that gas will still be introduced particularly for viscous liquids. Therefore, once the sample is prepared, it may be useful to degas the sample with agitation in a vacuum chamber jar to allow any entrapped gasses to be liberated.

5.2.2 Solid samples

Many solid samples will require machining to yield a sample of the appropriate dimension. In these cases, the material finish should be smooth relative to the smallest wavelength in the ultrasonic signal being used to interrogate the material. Where this involves polishing, sanding or similar techniques, any debris/residue from the machining process should be removed prior to characterization.

Some solid samples, such as resin systems, start in a fluid form. In these cases, the comments raised in 5.2.1 with regard to the avoidance of trapped air are equally valid. If the resin system contains high- and/or low-density fillers, these can have the tendency to slump or float during cure. This should be avoided by rotating the sample during cure to ensure a uniform distribution of filler.

5.2.3 Sample geometry

A sample the thickness of which is such that the transit time of the acoustic signal is larger than the duration of the signal of interrogation is preferable for some measurements such as attenuation characterization. However, there may be cases (e.g. very high attenuation materials) where this is not practical. Thin samples should be mounted in a fixture to prevent possible lens effects from loose materials or effects from drum skin fixtures. Very thick samples may be needed for some material characterization measurements including:

- measurement of absorption coefficient in very low loss materials;
- measurement of the velocity or speed of sound of a sample within a water bath, whose longitudinal velocity is similar to that of water.

In both these cases, a propagation distance of many wavelengths inside the material under test is needed to ensure a measurable change in the quantity being evaluated.

The sample should have lateral extents such that the wave diffracted around the edge of the sample can easily be time resolved from the direct wave passing directly through the sample. Careful consideration of the lateral dimensions of the container should be employed as this may dictate the lowest frequencies which can be used for characterization and also influence the positioning of the container within the acoustic field.

It is recommended that samples are prepared with parallel sides. A constant thickness greatly facilitates measurement of those quantities involving a distance dependence (such as absorption coefficient). It also helps to minimize experimental error due to mis-alignment since refraction effects are equal magnitude and opposite direction at the front and rear surfaces of a parallel-sided sample. Consideration of parallel surfaces is particularly important when measuring fluid samples within a measurement cell (container) that has a flexible membrane at one end or at both ends. Overfilling of the measurement vessel can result in a convex surface on the end membrane and this can cause lens effects. When parallel-sided samples are not used, testing in several orientations should be performed to gain an average measurement.

5.2.4 Sample stabilization

The measurement of samples immersed in a fluid medium is common. When a sample is immersed in fluid, there is the possibility of:

- absorption of the fluid medium by the sample;
- micro air-bubbles being trapped on the surface of the sample;
- a temperature differential between the sample and the immersing fluid.

All of these phenomena can result in an inaccuracy when quantifying the properties of the sample. The sample should be immersed in the fluid medium prior to measurement to ensure it has opportunity to normalize to its surroundings. An immersion period of 1 h is often sufficient but this may vary from sample to sample and thus the investigator should determine an appropriate stabilization period.

NOTE Speed of sound or phase velocities in materials are temperature dependent and arrival time of a pulse or toneburst can be measured very accurately, for example, using an oscilloscope. By immersing the test container in a fluid of different temperature, the arrival time of the ultrasound excitation at the receiver can be monitored and will shift in time as the specimen gradually becomes thermally equilibrated. This provides the investigator with information on when thermal equilibrium has been achieved.

5.3 Source and receiver transducers

When conducting materials characterization experiments there are often advantages to be gained by using large area receivers, both in terms of maximizing signal-to-noise ratio and by reducing the effects of diffractive loss. This contrasts with normal practice for acoustic output measurements where smaller receivers are preferred due to the minimization of directivity and spatial averaging effects. A general expression for the diffraction loss between a circular source and circular receiver is available [4] and the geometry is as shown in Figure 1. If both transducers have the same diameter, a simpler single-integral solution for the diffraction loss exists [5]. It has also been shown that use of very large receivers in materials characterizations measurements results in a procedure that is free from diffractive loss artefacts [6]. Correction for diffractive artefacts should be applied to all materials characterization measurements, particularly for measurements of attenuation of low loss media where there is a large mismatch in speed of sound between the test specimen and the water used as a reference medium.

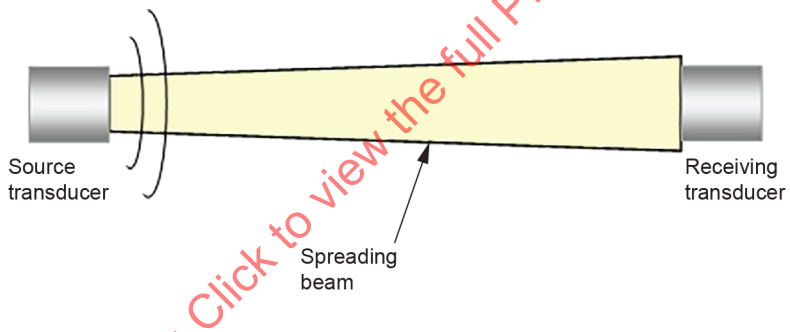


Figure 1 – Schematic showing diffractive spreading between source and receiving transducers

Diffractive spreading as a function of distance or at a specific distance can be determined by measuring the spectrum of the signal received from a transmitter and receiver at the selected distance(s) and dividing it by the spectrum of the signal measured when the transmitter and receiver are in close proximity in a medium with negligible absorption (water). If there is non-negligible absorption in the medium, the measurement should be corrected for it.

5.4 Transmission versus reflection measurements

Materials characterization has been conducted in a variety of different ways. Some methods employ reflected signals only [6],[7],[8], whilst others are based solely on the transmission of ultrasound through a sample [9],[10], [11]. There are yet further methods that incorporate both reflected and transmitted signals [12],[13],[14]. Choice of characterization technique may be influenced by the properties of the material being measured and/or the limitations of the sample geometry and orientation. The following factors should be considered.

- Any measurement method that relies upon the rear surface reflection requires the acoustic sample to have travelled across the thickness of the sample twice. For very high attenuation materials, this may introduce signal amplitude losses that exceed the dynamic range of the system. Therefore, transmission methods (with only a single transit across the sample) may be preferable.

- Reflection methods of determining absorption often rely upon theoretical values of **amplitude transmission coefficient**. These are frequently derived from calculations of characteristic acoustic impedances of the media involved, which in turn are based upon experimentally determined values for **density** and **longitudinal wave speed**. This extended chain of calculations can lead to accumulation of uncertainty at each stage.
- Methods combining reflected and transmitted signals offer the possibility to measure the thickness of the sample ultrasonically. This eliminates the need to independently measure the thickness of the sample (which can be difficult with compliant, gel or fluid samples).

5.5 Transducer excitation signal

5.5.1 Frequency dependence of quantities

Many of the quantities defined in this document may vary with frequency, although some ceramic and metallic media may have properties that are constant over a broad range of frequencies. Other materials (e.g. visco-elastic polymers) may exhibit significant variation in their properties as a function of both temperature and frequency. Typically the modulus of elasticity of these materials will be complex-valued and frequency dependent. Complex-valued elastic moduli introduce to the description loss mechanisms which leads to ultrasonic absorption. From causality considerations it follows that there is also dispersion in the material's **phase velocity** [15], [16], [17], [18], [19]. Therefore, the user should consider whether measurements of material properties at a single frequency are adequate or whether measurements are needed at multiple frequencies.

No single type of transducer excitation signal will be optimum for every measurement. Consequently, it will be necessary to establish a compromise between multiple considerations, some of which may be mutually incompatible. When selecting a transducer signal, the user should consider the following:

- whether measurements are needed at just one frequency or over a range of frequencies;
- how much attenuation the signal is likely to experience;
- how much dispersion the signal is likely to experience;
- whether the data analysis technique is predicated upon achievable pre-conditions (e.g. the ability to temporally resolve incident and reflected signals);
- how rapidly the measurement can be conducted;
- The availability of necessary equipment (e.g. specialist source transducers, receivers or instrumentation).

5.5.2 CW and quasi-CW methods

When a transducer is driven with a continuous wave (CW) sinusoidal excitation, its output will be mono-harmonic provided that:

- the transmission system does not introduce any harmonic distortion;
- the source pressure radiated by the transducer is below the threshold of nonlinearity of the medium.

This permits high energy levels to be input to the material sample and is thus a useful technique for high attenuation materials as it offers the potential for high signal-to-noise ratio. Furthermore, even if the material is dispersive, because the source signal contains only one frequency, the variation of sound speed as a function of frequency cannot normally be determined without changing transducers. However, care should be taken to ensure that energy levels are not so high as to generate any heating of the specimens and therefore a change in its temperature or that of the water bath.

In practice, CW excitation leads to standing wave fields within the measurement tank and there is no ability to temporally separate directly incident signal from those reflected from the structures of the measurement tank. Whilst applying anechoic coatings (e.g. absorbing tiles) to reflective surfaces can reduce this effect, it is preferable to use a transducer excitation that is intrinsically time limited. A toneburst signal provides the high energy benefits of a CW signal, whilst also having limited time duration to permit identification and rejection of unwanted reflection artefacts.

Care should be taken to ensure that the transducer has reached a steady-state, and thus a quasi-CW, condition. Many transducers take a few cycles to ring-up and ring-down (see for example the tonebursts in Figure 8). The varying amplitude within the first-two and last-two cycles may introduce measurement inaccuracy. Therefore, measurements should only be made during the constant envelope portion of the signal (cycles 3 to 6 in Figure 8). Extending the length of the toneburst may be used to increase the usable, constant amplitude portion of the signal. However, this can only be done if the dimensions of the sample are such that there is adequate temporal separation of multiple echoes within the sample and between the sample and the transducer.

Quasi-CW signals can also be used to determine the frequency dependence of a material's characteristics if the centre frequency of the toneburst can be altered. This can be undertaken by manually adjusting the operating frequency of the source signal generator, but this is very time consuming and automated adjustment (via computer control) is recommended. Care should also be taken to ensure that the acquisition record length is also adjusted as a function of frequency. As frequency increases, the duration of a fixed cycle count toneburst will decrease. It is therefore possible that the transducer ring-down section will start to appear within the acquired signal window and this may lead to measurement errors.

5.5.3 Frequency modulated pulses and time delay spectrometry

5.5.3.1 General

When measurements are required over a broad spectral range, frequency modulated pulses (sometimes called swept sinusoids or chirps) or time delay spectrometry may be suitable.

Frequency modulation in its simplest form involves a signal the instantaneous frequency of which varies linearly from a lower to an upper frequency. This is a linearly frequency modulated (LFM) signal. The sweep rate may be nonlinear and exponentially swept sinusoids are common. The amplitude of the instantaneous frequency component need not be constant. This can be used to provide a broader bandwidth acoustic signal [20],[21] by driving a transducer with a signal that is an inverse of its frequency response. These are often referred to as compensated frequency modulated (CFM) signals.

5.5.3.2 Time delay spectrometry (TDS)

Time delay spectrometry (TDS) measures the frequency response of a system by applying a swept frequency acoustic source and using a tracking receiver to select only those through-transmission signals that have the desired time delay corresponding to the ultrasound transit time directly from the transmitter to the receiver (Figure 2). This system can be used to provide broadband measurements of complex hydrophone sensitivity as well as frequency-dependent acoustic characterization of materials (attenuation, **group velocity** and **phase velocity**).

In this technique, a transducer is driven with an LFM signal. As a result, at a particular time the received frequency differs from the transmitted frequency by the TDS offset frequency $\Delta f = S\,\tau$, where S is the TDS sweep rate (e.g. in MHz/s) and τ is the ultrasonic transit (delay) time between the transmitter and receiver. The receiver circuitry incorporates a "tracking filter" that tracks the transmitted frequency with an appropriate pre-set time delay. Stray signals (such as reflections from walls of a water tank and sample fixture diffractions) with other than the desired path length (and therefore time delay) are blocked by this tracking filter. The width of the tracking filter's time acceptance window (Δt) is determined by the quotient of the resolution bandwidth setting of the tracking filter (B) and S, $\Delta t = B/S$. Because the receiver uses such a narrow band tracking

filter, considerable improvement in signal-to-noise ratio (SNR) is realized compared to pulsed techniques. Furthermore, because the system uses a swept-frequency source, considerable improvement in measurement bandwidth can be realized compared with pulsed techniques.

TDS techniques have been used extensively for the calibration of ultrasonic hydrophones and transducers [22],[23],[24],[25],[26],[27] and for frequency-dependent attenuation and sound speed measurements[14],[28].

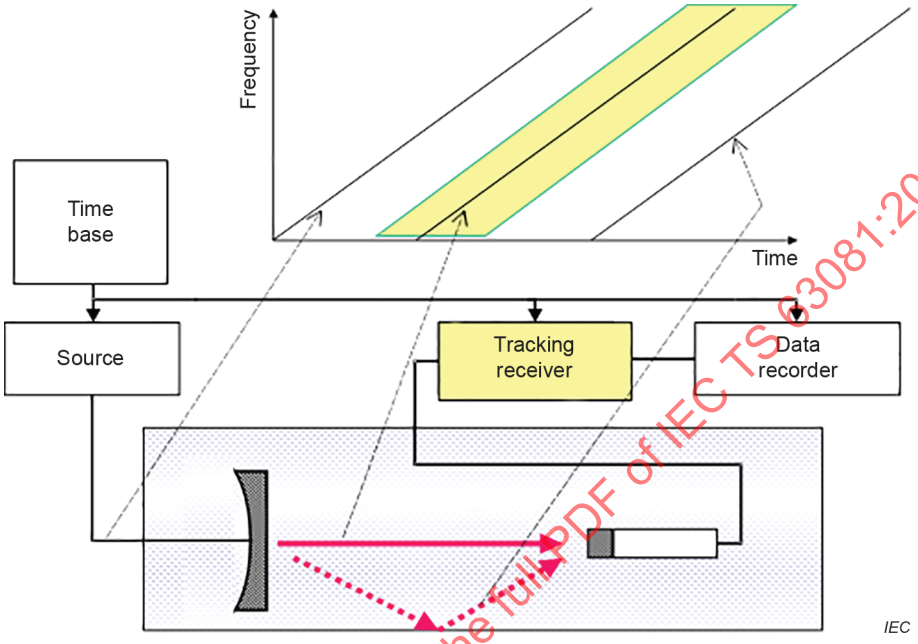


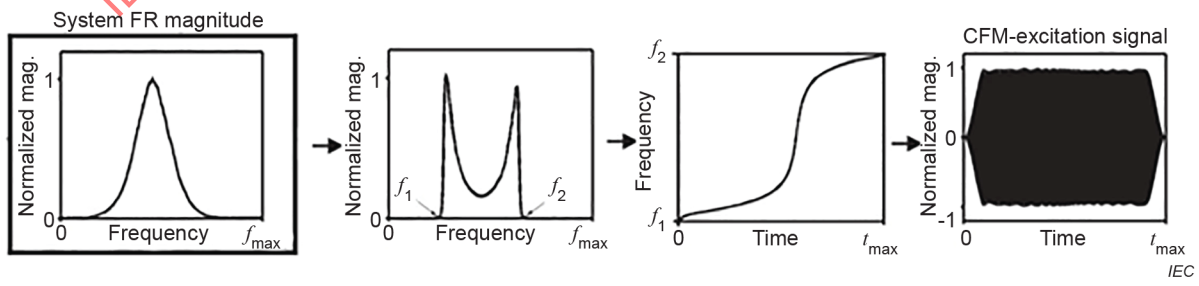
Figure 2 – Illustration of a typical TDS system

5.5.3.3 Compensated frequency modulation (CFM)

The use of compensated frequency modulated (CFM) signals within ultrasound measurements [21],[29] provides the ability to compensate for intrinsic nonlinearities it contains (e.g. the system frequency response). With the appropriate signal processing it also provides the ability to isolate and discard distorted components of a measured signal.

The basis consists in constructing a waveform in the time domain from information previously known or experimentally obtained about the system frequency response.

Figure 3 was extracted and adapted from [29], and summarizes the signal construction method.



FR frequency response

Figure 3 – Development and signal processing for a compensated frequency modulated signal

In the context of CFM pulses, the term system frequency response (FR) includes all amplifiers and filters within the transmit signal chain in addition to the intrinsic frequency response of any source transducer. This system FR needs to be either determined experimentally or arbitrarily defined. The system FR is band-limited, which defines the bandwidth for the final signal, and then pseudo-inverted. For a given frequency spectrum H_s, the excitation spectrum is defined as its band-limited inverse $E_{CFM} = |H_s|^{-1}$. The group delay function $\tau(f)$ is calculated from the magnitude of the pseudo-inverted frequency spectrum by

$$\tau(f) = \int_{f_1}^{f_2} C \cdot \left| E_{CFM}(f') \right|^2 \mathrm{d}f' \tag{6}$$

where f_1 and f_2 are the upper and lower frequencies of the band limit, respectively, and C is the ratio of the signal duration to the signal spectral energy. The phase Φ_{CFM} for the CFM signal is then calculated as

$$\Phi_{CFM}(f) = -2\pi \int_{f_1}^{f_2} \tau(f') \mathrm{d}f' . \tag{7}$$

Finally, the excitation signal in the time domain $e_{CFM}(t)$ is defined by

$$e_{CFM}(t) = \mathcal{F}^{-1}\left\{ \left| E_{CFM}(f) \right| \mathrm{e}^{\left| j\Phi_{CFM}(f) \right|} \right\} \tag{8}$$

where $\mathcal{F}^{-1}$ is the inverse Fourier Transform and $j = \sqrt{-1}$. The excitation signal can be used to interrogate a system or material and the received signal is compressed by cross-correlation with the excitation signal or deconvolution in the frequency domain, as described in detail within [21],[29].

If no restriction is placed on the time duration of the signal, there is no limit to the amount of energy that could be used to interrogate material samples; note that this does not require high instantaneous amplitude anywhere in the excitation signal. This ensures that the likelihood of cavitation and/or nonlinear propagation effects can be dramatically reduced or even completely suppressed.

5.5.4 Impulse methods

Impulse drive signals are widely used in non-destructive evaluation (NDT) and can be simply generated with a pulser and transducer; typically, an impulse excitation is much shorter than the impulse response of the transducer. A temporally short signal has a very wide spectral bandwidth and thus a single, rapid, measurement can be used to interrogate a material over a wide range of frequencies. Limited temporal duration also permits the use of windowing techniques to isolate discrete portions of a time waveform for subsequent analysis. Examples of measurement methods that may benefit from this are to be found with the multiple echoes of a single sample attenuation method in 8.1 and the incident and reflected signal measured with a membrane hydrophone in 9.1.

For the propagation of a short-duration pulse, the various frequency components have different attenuation coefficients, and potentially phase velocities due to dispersion. This means that the pulse shape can change significantly with propagation distance and methods for measuring attenuation through the derivation of a pulse amplitude or speed of sound through a specific arrival time, are no longer appropriate. An example of the change in pulse shape can be seen in Figure 4. From Figure 4 it is clear that employing simple threshold crossing methods to

evaluate transit time during wave speed measurement will be inadequate in dispersive media. This is discussed further in Clause 7. Instead, spectral analysis needs to be used to determine the intrinsic properties of the test material as a function of frequency. Such methods can particularly provide an efficient way of quantifying the variation in **phase velocity** as a function of frequency [10], [30] even up to 60 MHz [31].

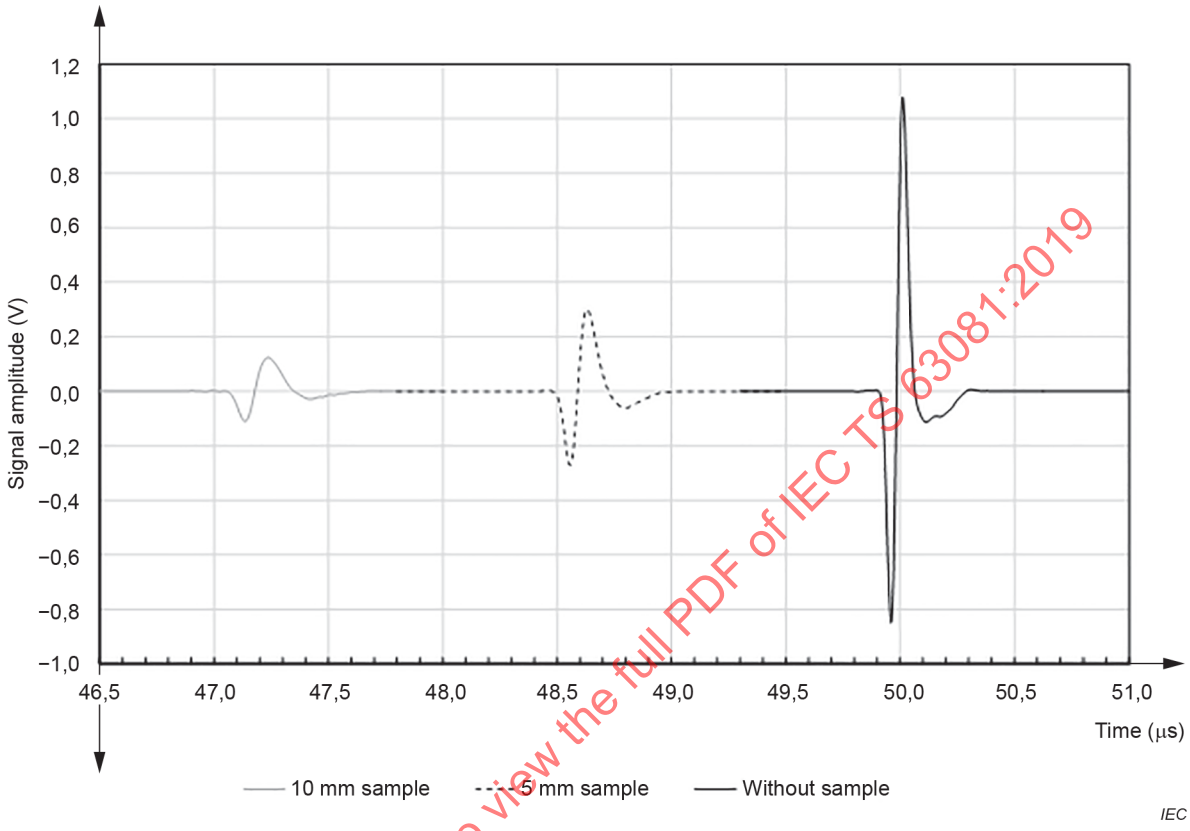


Figure 4 – Pulse dispersion in absorbing media

6 Insertion loss measurement

Insertion loss (IL) measurements are conceptually some of the simplest materials characterization measurements that can be made. An ultrasonic source and receiver are aligned to maximize the signal present at the receiver and a signal is recorded; this signal permits p_{ns} in 3.8 to be evaluated. A sample is then placed between the source and the receiver and a second waveform is recorded; p_s in 3.8 is evaluated from this second waveform and thereby IL can be calculated.

NOTE 1 IL measurement is not equivalent to an absorption measurement since it makes no attempt to evaluate or correct for any loss incurred due to reflection at the water-sample interfaces (for immersion testing) or for loss occurring at the first interface (for direct contact pulse-echo testing).

As discussed in 5.2.1, when a measurement vessel is used to hold fluid samples, the procedure should be amended to correct for its influence. If the material properties of the acoustic window of the container have been previously characterized and it has been shown that the impact is negligible, then it is possible to ignore the effects of propagation through the walls of the vessel.

The **amplitude transmission coefficient** across a layer has been derived analytically [32]. For normal incident sound originating in a fluid (medium 1), propagating across a layer (medium 2) and radiating out into a terminating fluid (medium 3), the plane-wave **amplitude transmission coefficient** can be expressed as

$$T_{\mathrm{p}} = \frac{4\, Z_3\, Z_2}{(Z_3 - Z_2)(Z_2 - Z_1)\, e^{ik_2\Delta x} + (Z_3 + Z_2)(Z_2 + Z_1)\, e^{-ik_2\Delta x}} \tag{9}$$

where

Z_1, Z_2, Z_3 are the characteristic acoustic impedances of media 1, 2, and 3 of the sample, respectively;

k_2 is the wave number in the medium of the layer;

Δx is the thickness of the container wall.

This expression can then be used at the front and rear surfaces of the measurement container to correct p_{ns} to establish the pressure amplitude that would be experienced as a result of propagation through both container acoustic windows.

NOTE 2 This method assumes non-absorbing frequency-independent properties of the materials and only considers normal incidence of sound upon the acoustic windows of the container. This may lead to errors in the assessment of the effect of the vessel on the measurement.

An alternative method to correct for the properties of the acoustic windows of the container is to undertake a slight modification to the basic **insertion loss** measurement procedure. Initially the measurement container is filled with water and the ultrasonic source and receiver are aligned to maximize the signal present at the receiver. The signal through the measurement cell is recorded as p_{ns}. The measurement vessel is then filled with the fluid to be tested and once re-alignment is complete p_{s} is recorded.

NOTE 3 Using this measurement protocol with a water-filled container, a normally small correction will need to be employed that takes account of the difference in the acoustic impedance of water and the specimen under test as this will influence transmission across the container acoustic windows.

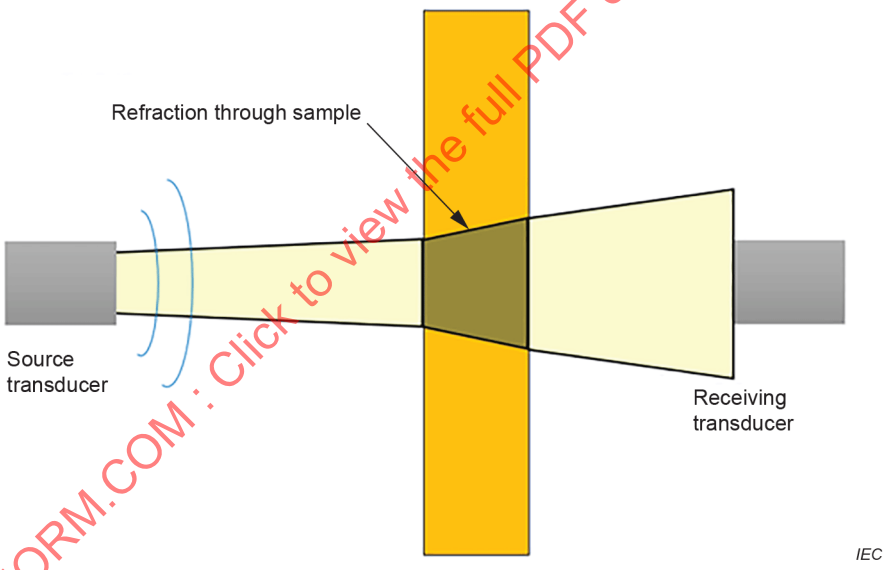
To minimize experimental uncertainty, the following issues should be considered, and appropriate remedial action taken.

- Sample orientation
  - Oblique incidence onto the sample surface can lead to mode conversion and two waves emerging from the rear surface of the sample which may then interfere with each other at the position of the receiver. The sample should be placed such that it is orthogonal to the acoustic axis of the source such that the ultrasound is normally incident upon the surface of the material.

    NOTE 4 One way of doing this is to observe the pulse-echo response of the transmitting transducer generated from the reflection from the front container acoustic window, and altering the orientation of the container (tilt and rotation) in order to maximize this signal. Doing the same with the second container interface may provide qualitative information about the parallelism of the two container acoustic windows.
  - Oblique incidence will also lead to a diagonal path through the sample and an increase of effective path length through the material.
- Type of source signal
  - Source signals that are temporally localized (such as pulses or tonebursts) permit the use of time-gating techniques. This enables unwanted artefacts such as reflections from experimental fixtures, or diffraction from the edge of the sample, to be excluded.
  - Tonebursts have most of their energy at one frequency. This is likely to be consistent with the narrowband approximation of 5.1.7.1 of [33] and [34]. Pressure can therefore be simply determined from Equation (4) of [33].
- Diffraction around sample

  - When inserted into the ultrasonic field, the sample should be placed in a manner that minimizes the effects of diffraction as waves travel around the edge of the sample. In practice, this can be achieved by placing the sample as close as experimentally possible to the
    i) transmitter since this is the part of the acoustic field that is most collimated and thus acoustic pressure amplitudes at the edge of the beam will be minimized, or
    ii) receiver since this ensures that any waves diffracting around the edge of the samples have to diffract through a large angle to reach the receiver.
  - The sample needs to be larger than the lateral extent of ultrasonic beam. Ideally the sample dimensions should be at least double the −40 dB beam width of the source.

- Diffractive beam spreading
  - The diffractive spreading of the beam from the source transducer, as illustrated in Figure 1, can often be exaggerated if the sample has a different wave speed to the surrounding medium. As is shown in Figure 5, refraction occurs at the sample's front and rear surfaces. In comparison to Figure 1, the beam area at the receiving transducer is increased and thus the pressure amplitude will be reduced due to the combined effects of diffraction and refraction. This effect produces a contribution to **insertion loss** that is in addition to any absorption within the material and any reflection that may occur at surfaces of the sample. Measurements should be conducted in a manner that either corrects for diffractive beam spreading [35], [36], or is insensitive to it [6]. These effects are particularly important when the intrinsic attenuation in the material is low.



NOTE The diagram shows the effect on the acoustic field at the position of the receiving transducer of inserting a layer of material in which the speed of sound is higher than in the water immersion medium.

Figure 5 – The additional diffractive spreading encountered in through transmission measurements

7 Longitudinal wave speed measurements

7.1 General

Evaluation of **longitudinal wave speed** involves the determination of the time taken for an ultrasonic wave to travel a known distance through a material. The wave speed is therefore determined by

$$c_{\mathrm{L}} = \frac{\Delta x}{\Delta t} \tag{10}$$

where Δt is the time taken for the wave to traverse the sample, and Δx is the thickness of the sample. For elastic media, c_{L} is typically constant as a function of frequency. However, many materials are visco-elastic and exhibit dispersion. Consequently, wave speed should be evaluated as a function of frequency since both attenuation or absorption and **phase velocity** are functions of frequency.

As discussed in 5.5.4, the shape of any broadband signal will alter as a function of propagation distance through a dispersive and absorbing material. It is therefore not appropriate to determine Δt from simple threshold-crossing time-of-flight methods. Instead a frequency-dependent method should be used. For any given frequency, f, the relationship between a time shift Δt and a phase shift $\Delta\varphi$ is

$$\Delta t = \frac{\Delta\varphi}{2\pi f} \tag{11}$$

Subclauses 7.2 and 7.3 employ the phase of spectral data to evaluate time shift. However, these subclauses also cater for the situation when dispersive media are characterized with a narrowband signal (e.g. 5.5.2) when changes of waveform shape should be negligible.

7.2 Transducers immersed within fluid material

Consider source and receiving transducers that are both immersed within the fluid medium to be characterized (as shown in Figure 6). If the separation of the two transducers is altered from position x_1 to x_2 then there will be a time delay between the signals recorded on the receive transducer at each position. This is the geometry considered in [9] and summarized here.

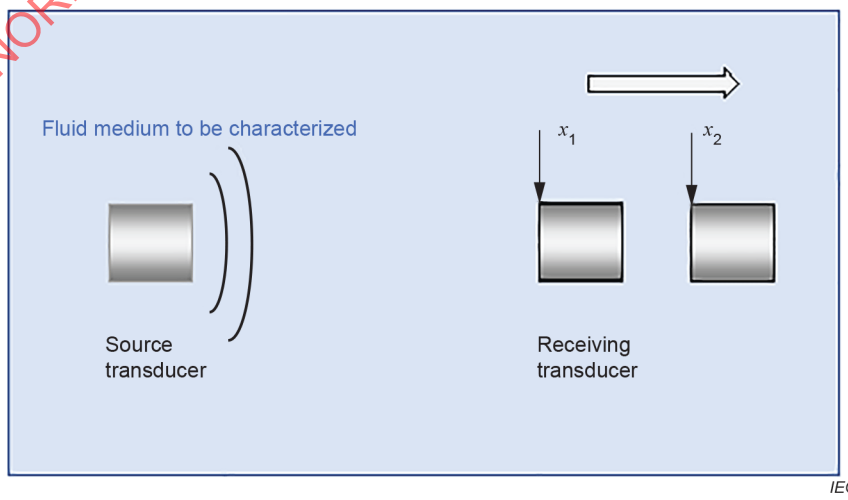


Figure 6 – Source and receiving transducers immersed in a fluid medium to be characterized

The frequency-dependent **longitudinal wave speed** can be determined as

$$c_{\mathrm{L}}(f) = \frac{2\pi f}{\Delta\varphi}(x_2 - x_1)\,. \tag{12}$$

However, this equation requires the determination of the absolute phase shift between the two measurement positions. Spectral phase has a period of 2π and thus there is an ambiguity in phase whenever the propagation distance is greater than one wavelength at the frequency of interest. This can be resolved by using the method proposed by Peters and Petit [9] and summarized here.

The signal on the receiving transducer should be recorded at the two positions, $p(x_1,t)$ and $p(x_2,t)$, and a cross-correlation between them should be performed. There will be a peak in the cross-correlation function and the time at which this occurs is the mean time delay, τ, between the two signals.

The delay, τ, should then be subtracted from $p(x_2,t)$ to ensure that it overlaps with $p(x_1,t)$. The newly shifted signal $q(x_2,t)$ is given by

$$q(x_2,t) = p(x_2,t-\tau) \tag{13}$$

The operation above ensures that any phase shift between signals $p(x_1,t)$ and $q(x_2,t)$ is between $-\pi$ and $+\pi$ and thereby the ambiguity in the determination of spectral phase is avoided. The Fourier transforms of $p(x_1,t)$ and $q(x_2,t)$ are defined as $P(x_1,f)$ and $Q(x_2,f)$ and therefore the phase shift can be determined from

$$\Delta\varphi(f) = \arg\left[Q(x_2,f)\right] - \arg\left[P(x_1,f)\right]. \tag{14}$$

For non-dispersive media $\Delta\varphi(f)$ should be a constant but will show variation in materials where dispersion exists. From this the frequency-dependent time shift, $\Delta t(f)$, which accounts for the delay between the two signals, τ, is given by

$$\Delta t(f) = \frac{\Delta\varphi(f)}{2\pi f} + \tau\,. \tag{15}$$

Finally, the frequency-dependent **longitudinal wave speed** in the sample is calculated with

$$c_{\mathrm{L}}(f) = \frac{(x_2 - x_1)}{\Delta t(f)}\,. \tag{16}$$

7.3 Transducers and sample immersed in a coupling fluid

When characterizing solid materials, or fluids constrained within a measurement cell or container, the experimental configuration shown in Figure 7 is commonly encountered. This method is sometimes called the through-transmission substitution technique and the measurement procedure follows that of an **insertion loss** measurement. Consequently, consideration of issues such as sample orientation, diffraction and corrections for reflections and transmissions through boundaries [10],[19],[30],[36] as described in Clause 6 is required.

NOTE 1 Sample orientation is especially important for material samples capable of supporting shear waves. Non-normal incidence of an ultrasonic signal on the surface of such materials will result in mode conversion at the interface. Whilst this can be exploited as a means of measuring shear wave velocity [9],[37],[38], small mis-alignments may result in superposition of longitudinal and shear modes transmitted through the sample. This in turn will lead to inaccuracy.

Initially the signal on the receiving transducer should be recorded without the sample in place; this is the reference signal $p_{ns}(t)$. The sample is then inserted between the source and receiver and signal $p_s(t)$ is recorded. In this configuration, a path length of Δx (corresponding to the thickness of the sample) of the fluid medium has been replaced by the sample. The time shift, Δt, that this introduces will therefore be a function of both the wave speed in the coupling fluid, c_{CF}, and the wave speed in the sample being characterized and is given by

$$\Delta t = \Delta x \left(\frac{1}{c_L} - \frac{1}{c_{CF}} \right). \tag{17}$$

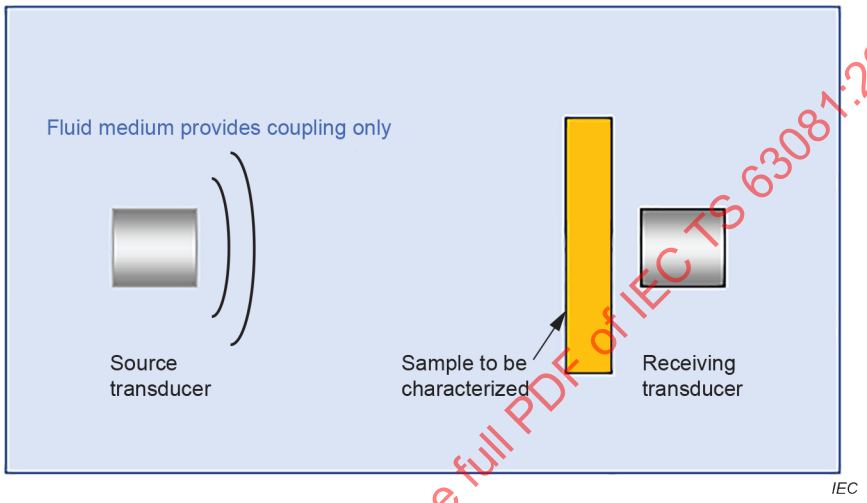


Figure 7 – Source, receiver and sample all immersed in a coupling fluid

The value of c_{CF} can be calculated using the method described in 7.2.

NOTE 2 The wave speed of pure water has been well-characterized. If pure water is used as the coupling medium it may be sufficient to measure the temperature of the water and then determine the wave speed according to the polynomial provided by Bilaniuk and Wong [39].

For dispersive materials it will be more relevant to determine the frequency-dependent longitudinal **phase velocity**. Therefore, the frequency-dependent time shift, $\Delta t(f)$, should first be determined by the method outlined in 7.2. This should then be incorporated in a re-arranged version of Equation (16) to obtain the frequency-dependent **longitudinal wave speed**:

$$c_L(f) = \frac{\Delta x}{\Delta t(f) + \dfrac{\Delta x}{c_{CF}}}. \tag{18}$$

8 Absorption coefficient measurements

8.1 Single sample through transmission method

When a sample with low absorption (e.g. a metal) is subject to pulse-echo ultrasound, it may be possible for multiple echoes to propagate within the material and still have an amplitude that is above the noise floor of the measurement equipment. In this case, it is possible to evaluate attenuation by comparing the amplitude of the rear surface reflection from two of these echoes. The mth and nth echoes will have amplitudes A_m and A_n, respectively. The **absorption per unit length** of the sample can be evaluated with

$$\alpha = \frac{20 \log_{10} \frac{A_m}{A_n} \text{dB}}{2\,(n-m)\,\Delta x} \tag{19}$$

where Δx is the thickness of the sample. Whenever measurements of this type are made, Δx should be large enough that each echo can be temporally separated from adjacent echoes (see Figure 8) and the rear interface should be a near-perfect reflector (e.g. steel-air interface).

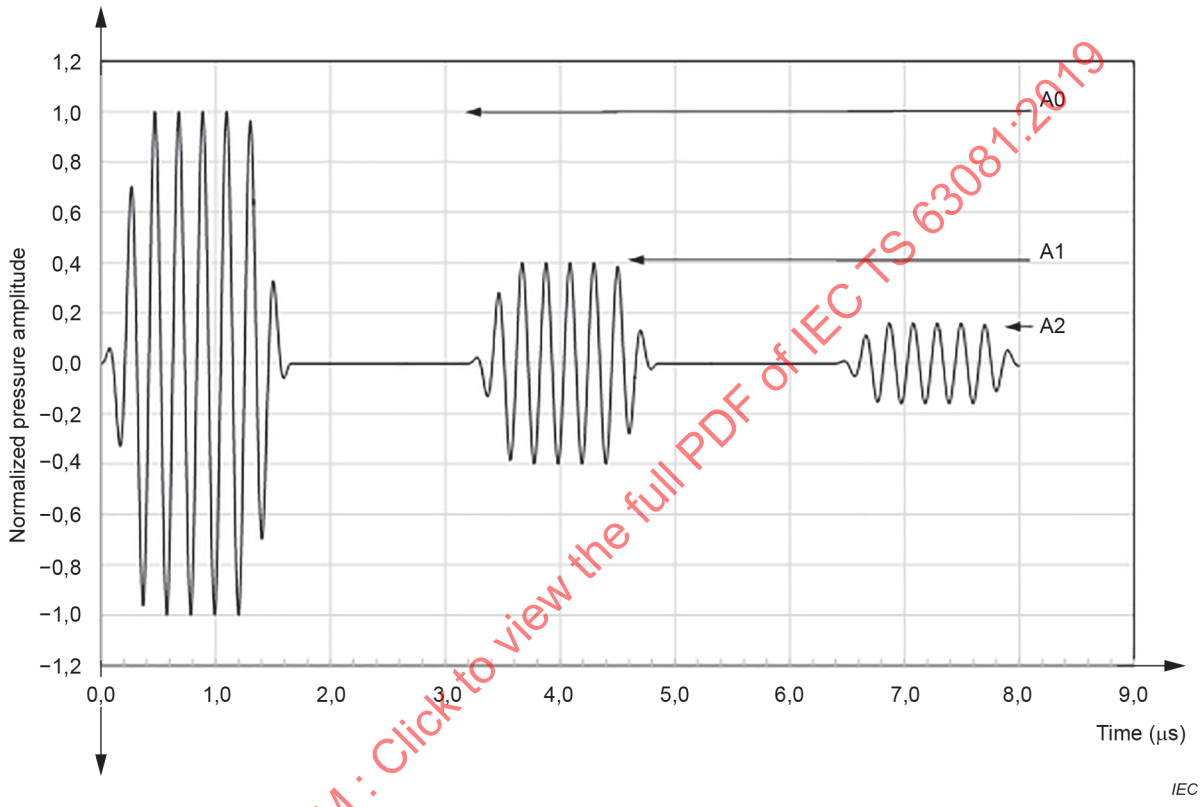


Figure 8 – Multiple echoes that are clearly separated in time

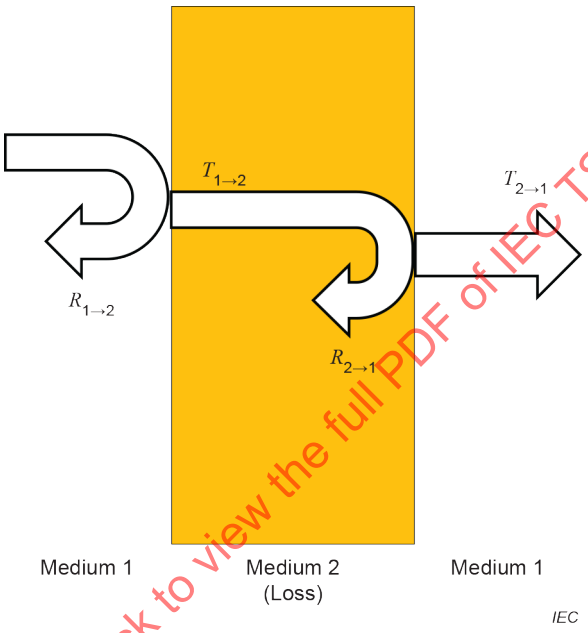
If toneburst methods are used, then A_m and A_n can simply be determined from the envelope of the echoes within the time signal as is shown in Figure 8. This can then be repeated with a range of different frequency tonebursts to determine the frequency-dependent absorption. Care is needed when selecting toneburst length, particularly at lower frequencies (and hence longer wavelengths), to ensure that there is no overlap of adjacent echoes.

If impulse source signals are used then, as shown in Figure 4, there may be pulse shape change arising from dispersive propagation and it will not be appropriate to simply determine the amplitudes of the pulses from the time domain signal. In this case, it is necessary to use windowing techniques to isolate each echo-pulse from the surrounding time trace. Fourier transform methods should then be used to derive the spectral amplitude as a function of frequency for each echo. These spectral amplitudes are then used in Equation (19).

The major limitation of single sample methods is that they are prone to errors arising from beam diffraction artefacts as discussed in Clause 6, particularly for low loss materials. This has been studied [40] and the authors concluded that many of these limitations can also be overcome using the double sample method described in 8.2.

8.2 Double sample through transmission method

For samples with high absorption, a single propagation across the thickness of the sample may attenuate the ultrasonic amplitude so much, that the multiple-echo method above is not an option. In these situations, it may only be possible to measure the signal on the far side of the sample (in a manner similar to a single **insertion loss** measurement). However, as can be seen in Figure 9, an ultrasonic signal that has made a single transit of a sample will have been subject to both reflection and transmission phenomena at each interface. Within this figure R and T represent amplitude reflection coefficient and amplitude transmission coefficient, respectively, and the subscripts indicate passage from one medium to another; for example, $R_{1\to2}$ indicates the amplitude reflection coefficient incurred as a wave propagates from medium 1 to medium 2. These reflection phenomena will introduce reflection artefacts, which means that the measured **insertion loss** is greater than the contribution due to absorption alone.



Key

R amplitude reflection coefficient

T amplitude transmission coefficient

Figure 9 – Multiple reflection and transmission phenomena occurring at the surfaces of a sample

To overcome this limitation, two samples of the same material, but of different thicknesses, should be prepared, where Δx is the difference in thickness of the two samples. Each sample should be thick enough to introduce a measurable IL at all frequencies of interest, but not be so thick that there is not transmitted signal content at the highest frequency of interest. For low loss samples (such as tissue mimic materials) this may necessitate a sample that is up to 50 mm thick, whereas for highly attenuating materials, samples may only be a few millimetres thick. The two samples are subject to the same reflection and transmission phenomena at each interface. Therefore, the only difference between the two IL measurements will be due to a distance of Δx in water being replaced with the material of the sample. The **absorption per unit length** of the material can be calculated by

$$\alpha(f) = \frac{IL_{\text{thick}}(f) - IL_{\text{thin}}(f)}{\Delta x} \tag{20}$$

where IL_{thick} and IL_{thin} are the values of **insertion loss** of the thicker sample and thinner sample, respectively.

NOTE When deriving the absorption or attenuation coefficient of a material using the through-transmission substitution technique, measurements need to be corrected for the attenuation of water as positioning the specimen between the transducer and the receiver displaces a water path equal to the sample thickness. Due to the quadratic dependence of water attenuation on frequency, this correction becomes increasingly more significant at higher frequencies, particularly above 5 MHz.

9 Echo reduction (ER) measurement

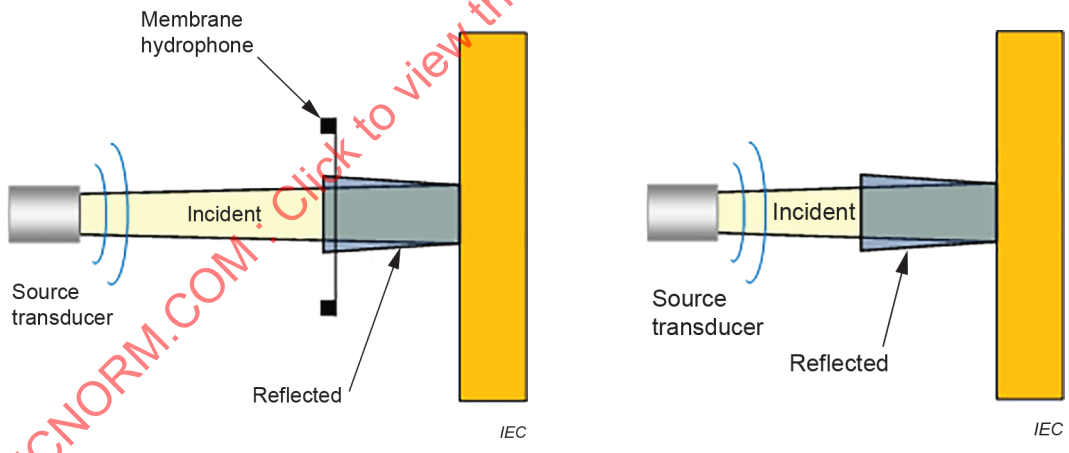
9.1 Normal incidence

The **echo reduction** of a material can be measured by determining the amplitude of the acoustic reflection from the interface between the test-material and the surrounding medium relative to a reflector of known properties (herein termed the reference reflector). The reference reflector is commonly a polished stainless-steel block providing a close approximation to a perfect reflector possessing an **amplitude reflection coefficient** of unity. However, it is still necessary to correct for the error introduced by this approximation and the process is discussed in detail further below in Clause 9.

When undertaking measurements relative to the reference reflector made from a material such as stainless steel, care should be taken to ensure the reference block is sufficiently thick such that the reflection from the rear (steel-water) interface does not interfere with the desired reflection from the front (water-steel) interface.

NOTE 1 Details of the minimum reference reflector thickness will depend on the excitation of the transducer, i.e. pulsed or tone burst, as well as the frequencies of interest, but this will typically require a reference block thickness greater than 25 mm.

The reference block should also be of sufficient lateral dimensions to ensure that the effect of diffraction at the sample periphery is negligible.



a) with membrane hydrophone **b) without membrane hydrophone**

Subfigure a) shows the transmitting transducer, the acoustic sensor (membrane hydrophone) and the reflecting surface under test; subfigure b) is an alternative configuration where the pulse-echo response of the transducer is used, with no membrane hydrophone interposed.

Figure 10 – Schematic presentation of a measurement set-up used to determine the echo reduction of a test material

Figure 10 illustrates the measurement set-up used. Ultrasound generated by the source travels through the semi-acoustically transparent receiver (the membrane hydrophone) which is used to detect the acoustic echo from the surface of the material under test. The receiver is aligned for maximum signal on the transducer beam alignment axis and is positioned in the transducer far field. The reflector is positioned as close to the hydrophone as possible, and its surfaces are aligned to be perpendicular to the transducer beam-alignment axis. This is obtained by altering the tilt and rotation of the sample to ensure maximization of the reflection echo detected by the hydrophone.

NOTE 2 As in other places within this document, it is assumed that the material under test is parallel-sided, with lateral dimensions sufficiently large to negate the effects of diffraction from the sample periphery.

For measurement of the reflected amplitude, the reflecting surface of the test sample is moved to a position where the signal detected is unambiguously from the front surface of the material and is not contaminated by other reflections.

NOTE 3 This can be tested by observing the effects of moving the reflector along the axis, and of tilting and rotating the reflector, using an oscilloscope to identify and measure the appropriate acoustic signals.

After measuring the pressure amplitude of the reflection back to the hydrophone (p_r), the test sample is removed and replaced by the reference reflector.

NOTE 4 As the **echo reduction** measurement is relative, it does not actually require a calibrated hydrophone. Here, pressures are used in the analysis, although measured voltages are equally applicable.

The reference reflector is then moved along the beam alignment axis until the reflecting surface is at the same location used for the test sample.

NOTE 5 This can be done by observing the arrival times of the two acoustic waveforms using an oscilloscope, to ensure that they arrive at the receiver at the same time. This is more difficult when the test surface is not planar (flat) but is structured (for example containing reflecting pyramids to scatter the incident ultrasound), when a judgement is made as to when the two acoustic waveforms best overlap.

Once positioned and aligned for maximum signal, the amplitude of the reference signal is acquired (p_i). It should be noted that this reference signal is smaller in amplitude than would be achieved from a perfect reflector because the reflector has a reflection coefficient that is not unity. For reflection of longitudinal waves occurring at the planar interface between two media, the **amplitude reflection coefficient** R_p can be calculated

$$R_p = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{21}$$

where Z denotes the characteristic acoustic impedance (calculated from the product of **density** and **longitudinal wave speed**) and the subscripts 1 and 2 denote the media 1 and 2 as shown on the left-hand side of Figure 9.

Density and **longitudinal wave speed** may vary slightly with the material specification. However, typically, the longitudinal speed of sound for stainless steel is 5 980 ms^{-1} and **density** is 7 861 kg m^{-3} (for stainless steel 302). Thus, for a stainless-steel reflector immersed in water at 20 °C, R_p has a value of 0,938 9. The reflected pressure amplitude (p_r) can be adjusted to account for the imperfect reflection according to

$$\hat{p}_r(f) = p_r(f) \cdot R_{p,\text{reflector}} \tag{22}$$

and thus, **echo reduction** (ER) is calculated with

$$ER = -20 \log_{10}\left(\frac{p_r}{\hat{p}_r}\right) \text{dB}. \tag{23}$$