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Non-destructive testing – Guided wave testing

Part 1: General guidance and principles

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Publishing and copyright information

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Contents

Summary of pages

This document comprises a front cover, an inside front cover, pages i to ii, pages 1 to 20, an inside back cover and a back cover.

Foreword

Publishing information

This British Standard is published by BSI and came into effect on 31 October 2011. It was prepared by Technical Committee WEE/46, *Non-destructive testing*. A list of organizations represented on this committee can be obtained on request to its secretary.

Information about this document

The purpose of this document is to define a standard for non-destructive testing (NDT) using guided stress waves.

Guided stress waves used for NDT are sonic or ultrasonic waves which travel along an object and are guided by its surfaces or shape, and whose wavelength is large compared to a characteristic dimension such as wall thickness. NDT using guided waves offers the possibility of performing rapid testing of 100% of the volume of the components in which they can travel and is therefore particularly suited to elongated objects such as pipes, tubes and rails. The nature of guided waves differs substantially from the ultrasonic waves used in conventional ultrasonic testing (UT), and therefore it is necessary to define guided wave testing (GWT) as a method in its own right and manage this branch of inspection under its own standard.

The standard has been written to incorporate flexibility to include different applications of guided waves, by separate parts of the standard, as the capability and needs arise.

Currently, BS 9690, *Non-destructive testing – Guided wave testing*, comprises the following parts.

Part 1: *General guidance and principles*.

Part 2: *Basic requirements for guided wave testing of pipes, pipelines and structural tubulars*.

However, it is anticipated that further parts of the standard will be introduced to cover the interpretation of measurements; the testing of advanced cases of pipes, pipelines and structural tubulars; and the application of GWT to other structures and components.

Presentational conventions

As a guide, this part of BS 9690 takes the form of guidance and recommendations. It should not be quoted as if it were a specification or a code of practice and claims of compliance cannot be made to it.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

1 Scope

This part of BS 9690 provides the general principles for guided wave testing.

The specific conditions of application and use of guided wave testing, which depend on the type of object tested, are described in documents which could include:

a) product standards;

b) specifications;

c) codes;

d) contractual documents;

e) written procedures.

Unless otherwise specified in the referencing documents the minimum recommendations of this standard are applicable.

This standard does not define:

1) extent of testing;

2) optimum test parameters for specific applications; or

3) acceptance criteria.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS EN 473, *Qualification and certification of NDT personnel – General principles*

BS EN 1330-2, *Non-destructive testing – Terminology – Part 2: Terms common to the non-destructive testing methods*

BS EN 1330-4, *Non-destructive testing – Terminology – Part 4: Terms used in ultrasonic testing*

3 Terms and definitions

For the purposes of this British Standard, the terms and definitions in BS EN 1330-2 and BS EN 1330-4 apply, together with the following.

3.1 axial direction

principal direction of propagation of the guided waves, particularly in a pipe where this is parallel to the pipe axis

3.2 axial length

length of a discontinuity in the axial direction normally parallel to the direction of propagation of the guided waves

3.3 call level [distance amplitude correction (DAC) or time-corrected gain (TCG)]

DAC curve or TCG threshold above which indications are required to be reported

3.4 circumferential direction
direction of propagation or displacement perpendicular to the axis and parallel to a tangent to the surface at any point

NOTE Applicable to objects of circular cross section, such as pipes.

3.5 circumferential order
number of vibration nodes of a guided wave mode around the circumference

NOTE Applicable to objects of circular cross section, such as pipes.

3.6 corrosion
deterioration of a material, usually a metal, that results from a chemical or electrochemical reaction with its environment

3.7 cross section
total area of the wave guide perpendicular to the direction of propagation

NOTE The amplitude of a reflection is assumed, typically as a first approximation, to be proportional to the CSC.

3.8 cross section change (CSC)
equivalent cross section change calculated, assuming that an indication is purely caused by a change in the cross section of the object

NOTE Also referred to as "estimated cross section loss" (ECL). It is given as a percentage of the nominal cross section. The amplitude of a reflection can also be affected by stiffness changes and the axial dimensions of a feature.

3.9 cut-off frequency of guided wave mode
frequency at which the energy velocity changes from non-zero to zero

NOTE The definition differs from the term "cut-off frequency" in BS EN 1330-4, which relates to limits of the bandwidth of an ultrasonic signal.

3.10 data capture range
distance over which data are gathered in a particular direction

NOTE This is not necessarily the same as the diagnostic range.

3.11 datum
reference point for reporting a test position and for correlating test results with actual position on the test object, normally a localized physical feature on, or in a fixed relationship to, the test object

NOTE In the case of a pipe this can be a weld, flange or any other suitable permanent feature. The distance from the datum to the test position is also reported.

3.12 dead zone
distance along the test length of object on either side of the test position, and equal to or slightly greater than the length of the transmitted pulse, where reflectors of interest cannot be detected

NOTE This definition differs from that in BS EN 1330-4, in which the term relates to distance from the scanning surface.

3.13 diagnostic range
axial length of the test object (excluding the dead zone), measured from the test position, for which the amplitude of the call level lies above the maximum usable sensitivity line

NOTE Also known as the "end of test".

3.14 dispersion
frequency dependence of the acoustic properties of a guided wave, such as velocity and attenuation

3.15 dispersion curve
graph of the variation of an acoustic property of a guided wave, for example the group velocity, as a function of frequency

NOTE Dispersion curves can be shown for any number of guided wave modes in the same graph.

3.16 energy velocity
velocity with which the energy of a guided wave signal propagates

NOTE See also "group velocity".

3.17 envelope (signal)
outline A-Scan trace bounding the oscillations in each pulse of ultrasound, obtained by a smoothing process

*NOTE See also "result trace" (**3.35**).*

3.18 feature
geometric change or addition to the uniform base material of the test object which does not constitute a discontinuity

3.19 focusing

3.19.1 focus
deliberate concentration of guided wave modes at a single circumferential and axial position

3.19.2 synthetic focus
post-processing of a recorded data set to concentrate guided wave modes at a single circumferential and axial position

3.20 guided wave (GW)
sonic or ultrasonic waves which travel along an object and are guided by its surfaces or shape, and whose wavelength is large compared to a characteristic dimension such as wall thickness

3.21 guided wave testing (GWT)
testing of a large volume of material from a test location utilizing the long distance propagation characteristics of guided waves

3.22 interpretation
process of identifying discontinuities from indications in the result trace and other displays

3.23 leakage
attenuation of the guided wave caused by the transmission of energy into a surrounding material

3.24 magnetostrictive transducer
transducer which generates and receives signals via the coupling of a changing electromagnetic field to an elastic strain field, using the magnetostrictive effect

NOTE This is best achieved using a specific magnetostrictive material in order to maximize the coupling behaviour.

3.25 maximum usable sensitivity line
line overlaid on the test data, which is a factor of 2 (6 dB) greater in value compared with the noise line at all points

NOTE This represents the lowest level at which responses may be reported without significant risk that they may arise from noise signals.

3.26 mode
specific kind of wave

NOTE Many kinds of guided waves are possible, and they are distinguished by reference to the nature of their displacements. Longitudinal modes have displacements predominantly in the axial direction; torsional modes have displacements in the circumferential direction. Axisymmetric (often simply called symmetric) modes have displacements which are uniform around the circumference; flexural modes have displacements which are not uniform around the circumference.

3.27 guided wave mode
distinct type of guided wave with a specific vibrational pattern

NOTE A variety of modes might exist in any given geometry of object. In the case of a pipe there are three families of modes: torsional, longitudinal and flexural. Each of these mode families has a particular vibrational behaviour, with the modes within a family being similar to each other.

3.28 nominal wall thickness
nominal reference wall thickness of the test object as per specification, not necessarily the actual wall thickness

3.29 noise line
line overlaid on the test data which describes the variation in noise amplitude along the test range, after removing the influence of high amplitude responses from pipe features or discontinuities

NOTE The basis for determination of the noise level (peak, root mean square, moving average, etc.) is stated in the report.

3.30 phase velocity
propagation velocity of a point of constant phase of a wave

NOTE This can be observed for example as the velocity of the crest of a wave. The phase velocity is equal to the group velocity in cases when there is no dispersion.

3.31 pitch-catch configuration
type of test in which pulses are emitted by one transducer device and reflections are received by another

3.32 primary mode
single mode which is generated selectively in the test object as the incident wave for the test

3.33 propagating mode
guided wave mode whose energy velocity is non-zero

3.34 pulse length
axial length of a transmitted pulse in the material under test

3.35 result trace
plot of the guided wave signal envelopes as a function of distance

NOTE This includes A-Scans, C-Scans, etc. In the case of a pipe, the result trace may include both symmetric and non-symmetric components.

3.36 reverberation
false echo caused by multiple reflections between discontinuities

3.37 screening
process of testing for the presence of and classifying discontinuities without claim of direct and accurate sizing

3.38 secondary mode
mode which is generated by mode conversion, in reflection or transmission, when the primary mode is incident at a feature or discontinuity

3.39 signal amplitude
maximum value of a signal, measured as the peak height on the result trace

NOTE This may be in arbitrary units and therefore needs to be referenced.

3.40 standard operating procedure (SOP)
equipment-specific operating procedure normally supplied by the GWT equipment manufacturer

3.41 stress wave
most general term for mechanical wave involving stress oscillations in a material

NOTE This includes infrasonic, sonic and ultrasonic waves, in solids, liquids and gases.

3.42 test object
fabrication or component along which the wave is guided

NOTE In the case of pipe testing, the object is the pipe.

3.43 test frequency
centre frequency of the tone burst pulse or signal transmitted by the transducer system for a particular test

3.44 test position (TP)
defined location relative to a known datum where the transducer device is placed

NOTE The test position is generally reported in terms of distance from a datum.

3.45 time-corrected gain
method of compensating for reduction in signal amplitude with increasing range from reflectors of equal area

NOTE This is achieved by increasing the system gain with distance so that the signals appear of equal amplitude.

3.46 time-trace
record of the unprocessed signals received by a transducer over a certain time interval

3.47 tone burst
pulse of extended duration designed to apply a controlled excitation to the transducer

3.48 transducer
device used to excite sonic or ultrasonic waves by converting electrical energy into mechanical energy, and vice-versa, which may consist of a number of individual active elements

NOTE This definition differs from the term "transducer" in BS EN 1330-4, which refers to the ultrasonic "probe".

3.49 waveguide
object along which a guided wave propagates

4 Qualification and certification of personnel

The test needs to be performed by personnel qualified in accordance with BS EN 473 or, by agreement between the inspector and the client, with any other equivalent standard in the industrial sector concerned.

GWT requires knowledge and skills which are very different from conventional ultrasonic testing (UT) or any other NDT method. It is therefore necessary that personnel are trained and qualified specifically for GWT. Furthermore, particular training and certifications might be needed for specific applications of GWT, and this will be specified as necessary in the other parts of this standard.

5 Information required prior to testing

Prior to testing the following information should be considered.

a) Purpose of testing.

b) Qualification and certification of personnel.

c) Material properties and geometry of the test object.

d) Environmental conditions and state of test object.

e) Accessibility of the surfaces of the test object.

f) Requirement for a written test procedure.

g) Any special requirements for preparation of the surface.

h) Type and thickness of and coatings or materials in contact with the test object.

i) Type and location of any supports.

j) Test sensitivity and method of setting up sensitivity.

k) Requirements for evaluation and recording level.

l) Acceptance criteria.

m) Extent of testing.

n) Requirements for a written test report.

6 Principles of GWT

6.1 General

GWT exploits mechanical stress waves which occupy the full thickness of the test object and which are guided along it. These waves can travel long distances, providing rapid, almost 100%, coverage. The usual inspection concept is comparable to a conventional ultrasonic pulse-echo test: a transducer injects a wave signal at a chosen location, and then receives echoes returning from any features or discontinuities. The arrival time of the echoes indicates the distance of these reflectors from the transducer. A single test can cover a large range, for example when testing pipelines it is normal to be able to test a length of 50 m or more.

Although the concept of the pulse-echo inspection used in GWT is simple, and analogous to that used in conventional bulk wave ultrasonic testing (UT), the underlying physics of the guided wave phenomena is more complex than for bulk waves, so the whole approach to the testing, the equipment, the procedures, and the training of operators, have all been developed as a separate, independent method of NDT.

At present the role of most guided wave testing is screening. The echoes returning from discontinuities and received by the instrumentation indicate their approximate size, but they do not give detailed quantitative information about their morphology. Therefore, the aim of the testing procedure is to use the guided wave measurements to identify (to call) any locations of concern, and then to follow up with conventional detailed inspection just at those locations. This provides rapid full coverage of the test object, combined with established detailed inspection at locations of concern.

6.2 The nature of guided waves

Guided waves are a class of sonic/ultrasonic waves whose propagation is guided by the shape or boundary of the test object. The geometry or boundary of the object guides the direction of the wave and the material properties and shape determine its speed, its stresses and its displacements. The fact that the guided waves are contained within the object (or waveguide) means that they can travel long distances without dissipating; this is a major attraction for NDT. The characteristics of the guided waves which can travel along a given waveguide are determined by the material and geometry of the waveguide; thus, the guided waves are properties of the object.

Guided stress waves can exist at any frequency. However, most guided wave testing is done in the low ultrasonic range of frequencies, between 20 kHz and 500 kHz. Guided waves can travel in any materials: solids, liquids or gases.

Guided waves can exist in many forms, or modes, within any chosen waveguide. There can be waves which are dominated by axial extensional motion (similar to ultrasonic compression waves), twisting motion, bending motion, or a combination of these, and additionally many other shapes of deformation. Furthermore, the propagation speeds of these waves vary with frequency. Therefore, it is critical to both understand and control selected guided waves in order to perform reliable GWT.

Generally, the guided wave modes can be divided into groups which share common characteristics in terms of mode-shape. Conventions for the naming of these groups have, for most basic objects, been defined. For example, guided waves in plates are named in the two groups: symmetric (“S”) and anti-symmetric (“A”), while guided waves in pipes are named in three groups: longitudinal (“L”), flexural (“F”) and torsional (“T”) (for “S” and “A” waves, see Lamb 1917 [1]; for “L”, “F” and “T” waves, see Silk and Bainton 1979 [2]).

The labelling of the specific modes within their groups is done using indices which indicate the order of the mode in each independent, finite dimension of the object. For example, for a plate the only finite dimension is the thickness; modes are therefore labelled by thickness order, for example S0 is the mode of the S group with 0 thickness order. For a pipe there is additionally the circumferential dimension, so, for example, the pipe mode L(0,1) is the mode of the L group which has zero wave cycles around its circumference (its displacements and stresses are uniform around the circumference) and is the first in the series of through-wall-thickness order.

6.3 Dispersion curves for the test object

A convenient means of presenting the properties of guided waves is the graphical display of lines known as the dispersion curves. Dispersion curves are calculated, using mathematical theory, for the chosen test object. Each curve represents the variation of a particular wave property (e.g. phase velocity, group velocity or attenuation) with frequency for each different guided wave mode which can travel in the object. The dispersion curves are different for each kind of object, and even for each dimension of a particular shape (for example, they differ for each size of a pipe). The effect of dispersion is to cause the transmitted guided wave pulse to spread out in time as it travels through the material, which reduces amplitude, reduces axial resolution and causes changes in the shape of the pulse even in the absence of discontinuities. The dispersion curves for any wave mode/test object combination allow these effects to be predicted and allow the selection of test conditions to minimize or avoid dispersive behaviour.

6.4 Selection of specific guided wave modes

The successful exploitation of guided waves for NDT requires attention to several important fundamental considerations.

a) Pure mode transmission. The established approach to GWT considers that it is vital to be able to generate just one pure guided wave mode in the test object; this will be referred to here as the ′primary mode′ of the test. Without specific care to do this, a large number of modes which are able to exist at the test frequency would be generated. These waves would all travel at different speeds, so creating a complicated signal which would be very difficult to interpret.

b) Dispersion. It is best to use modes and frequencies for which dispersion is minimal, so that the shape of the signal will not change as the wave propagates. The signals of dispersive waves tend to spread out as they travel which has the effect of reducing both the amplitude and the resolution.

c) Mode shape. If the interest is to find discontinuities which might be anywhere within the object, then it is important to choose a mode whose energy is distributed throughout the cross section.

d) Multiple mode reception. The reflected signals which are received at the transducer are generally a mixture of the primary mode and a number of other propagating modes which can exist in the object at the test frequency. These other modes, referred to as ′secondary modes′, are generated by mode conversion of the primary mode on interaction with features and discontinuities. The exact mixture of modes present in the reflected signal can enable some information to be determined about the geometric properties of the reflectors. It is therefore essential for the transduction system to be capable of detecting and recognizing both primary and selected secondary modes.

e) Direction selection. In most implementations guided wave testing is not carried out from the end of the object (waveguide). It is therefore possible for the guided wave modes to travel in more than one direction along the object. In order for the guided wave method to be successfully exploited for NDT it is necessary that one of the following is achieved:

Either the transduction system is designed such that it naturally sends and receives signals solely in a chosen direction. This is achieved, for example, using wedge-coupled guided wave transducers.

Or the transducer uses multiple signal paths such that the single-direction performance can be achieved by processing of the multiple signals. This is done, for example, by using two or more transducer rings when testing pipes.

The use of the signal processing approach is preferable if it is desired to test in more than one direction, because it allows multiple tests to be performed from the single transducer placement.

6.5 Methods of transduction of selected guided waves

There are three different types of transduction currently available to excite and receive guided waves in constructions and components:

a) piezo-electric transducers;

b) electromagnetic acoustic transducers (EMAT);

c) magnetostrictive transducers.

The selective use of a chosen mode is normally done by using an array of transducers applied to the available surface(s) of the object under test. The distribution of the transducers within the array, both in the axial and tangential directions, combined with the displacement and phasing of the individual transducers, determines the mode(s) which can be generated and received.

The quality of the selectivity which is achieved is critically important to GWT. If, for example, in the case of pipe testing, the transduction is not uniform in both amplitude and phase around the circumference, some proportions of the unwanted modes will be generated and received together with the intended signals.

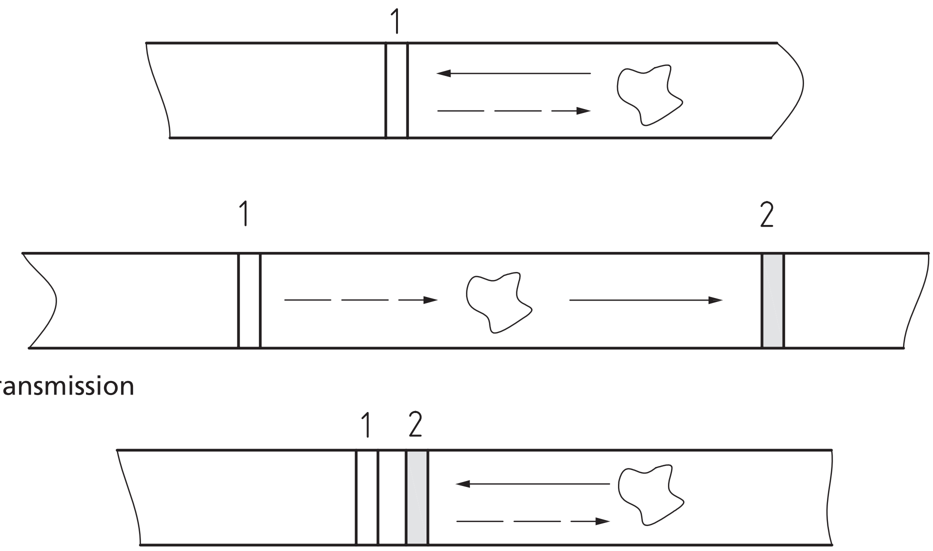
As well as the physical configuration of the transducers, it is also important to manage the shape of the electrical signal. It would not be sensible to use a short-time pulse, as is used typically for conventional ultrasonic testing, because such a pulse has a wide bandwidth and so accentuates any dispersion. Instead, a smoothly windowed tone burst is used, providing a compromise: the signal is reasonably short in time to aid resolution, yet still narrow-band in frequency, to minimize dispersion.

6.6 Test set-up

The most common set-up for GWT is pulse-echo.

Figure 1 shows the concept of the pulse-echo scheme. The chosen primary mode is generated by the transducer device, propagates along the test object, and is partially reflected from any location where there is a change of the cross section of the object. Such locations include benign features such as butt welds or supports, but also discontinuities such as patches of corrosion or cracks. The reflected primary and secondary signals return to the transducer where they are recorded.

Figure 1 **Schematic diagram of pulse-echo, pitch-catch and through transmission configurations**



a) Pulse-echo

b) Through-transmission

c) Pitch-catch

The major benefits of the pulse-echo set-up [Figure 1a)] are that only one position on the object (1) is required to mount the transducer device and the equipment requirements are minimal. However, the disadvantages are that attenuation cannot be measured directly and the dead zone and near field can be restrictive for inspections requiring coverage of areas close to the transducer position.

A second, less commonly-used alternative is the through transmission set-up [Figure 1b)]. In this case one transducer device (1) is used to send out signals and a second device (2), placed remotely from the first, is used to receive the directly transmitted signal. This technique may be used to accurately measure attenuation over a certain distance to correctly set DAC levels.

A third alternative, also less commonly-used, is the pitch-catch configuration [Figure 1c)]. In this case one transducer device (1) is used to send out signals and a second transducer device (2) is used to receive the reflected signals. This is conceptually similar to the pulse-echo set-up, except that it uses separate transducers for transmission and reception. Although more equipment and preparation are required for this configuration, pitch-catch data can give greater sensitivity as the high-amplitude excitation signals and very small returning echoes are separated within different transducers. Also, modal noise, as well as the dead zone and effects found when a transducer is next to a feature, can be reduced. Additionally, a transmission test can also be performed with the same set-up, which allows for the accurate measurement of the outgoing amplitude level. This enables a more accurate setting of the DAC level at the test position.

6.7 Reflection from features

It is essential to understand the nature of the reflection from features in order to assess the sensitivity of GWT.

When using guided waves, it is possible to find discontinuities whose depth is much smaller than a wavelength. However, the reflectivity of guided waves is governed by very different rules than those which are understood for bulk wave UT. The main determinants of the reflection are the extent of the indication in the three coordinate directions: lateral, depth and axial. The lateral and depth dimensions of an indication define its projection on the cross section of the waveguide; the area of this projection is the primary parameter governing the reflectivity. The axial dimension then influences this reflectivity by introducing the possibility of reverberations of the signal along the axial length, which can result in destructive or constructive interference.

Further details of the nature of the reflectivity, and how it is influenced by each of the dimensions, are given in Annex A.

6.8 Focusing

The capability to control a transducer device to function differently at different positions on the surface of an object enables the possibility of focusing the testing at a specific axial and lateral position on the object, thus enhancing sensitivity and spatial selectivity. The data collection process needs then to be repeated for each axial and lateral position of interest.

6.9 Synthetic focusing

As an alternative to testing using a specific pre-determined focal spot, synthetic focusing can be carried out by processing a collected set of multi-channel data. Such processing can be used to generate a map of reflection strength (as a colour or intensity) plotted on axes of axial location and lateral (circumferential in the case of pipeline inspection) location, similar in appearance to a conventional ultrasonic C-Scan image.

7 Equipment

7.1 General

Equipment should consist of:

a) a transduction system for the generation and reception of guided wave modes; and

b) a system for recording, processing and analysing the signal, capable of distinguishing at least one guided wave mode for the specific detection system.

7.2 Transducer

The transducer which is used to generate the incident signal has to be capable of generating the primary guided wave mode in isolation from other possible modes of the object.

The transducer which is used to receive signals has to be capable of separation of the individual guided wave modes which are of interest for the analysis and of the suppression of the undesired modes.

NOTE A transducer may consist of a considerable number of individual active elements in a specific arrangement.

7.3 Transmitter/receiver

The transmitter/receiver has to be suitable for the transducer to be used. In general, this means transmitter/receivers can only be used with transducers provided by the same GWT equipment manufacturer. Depending on the system used, the transmitter/receiver will have one or more channels capable of transmitting analogue signals to a transducer, and one or more capable of receiving them. These signals will usually be digitized and recorded for subsequent analysis.

7.4 Signal processing and analysis system

Raw data collected by the transmitter/receiver is very difficult to interpret, so that it needs to be processed appropriately prior to being viewed by the operator. This processing may be conducted on the transmitter/receiver unit itself, or on a separate personal or laptop computer, but the results have to be produced in a form which can be recorded reliably on a computer storage medium. The results have to be recorded in a form such that the features of the results can be correlated to physical locations on the test object.

8 Settings

In order to achieve the conditions described in **6.4**, equipment settings have to conform to the relevant standard operating procedures (SOP) for the equipment and application, where available.

The main parameters which govern the guided wave propagation are:

a) wave mode generated (e.g. S0, T(0,1) etc);

b) the test centre frequency;

c) the pulse bandwidth (determined by the excitation pulse duration and shape); and

d) the pulse repetition frequency.

The following general requirements have to be met.

1) Frequency and signal settings: the settings chosen to control the frequency and bandwidth of the signal have to be appropriate for specific guided wave modes which have been selected according to the object under test.

2) Pulse repetition frequency: the pulse repetition frequency has to be set sufficiently low to allow all signals to attenuate completely between subsequent pulses.

9 Summary

GWT is an effective means of examining large volumes of material from a limited number of test positions and provides a method of identifying areas for further more detailed investigation. It is particularly useful for the detection of in-service degradation which might occur at unpredictable locations, such as corrosion. However, there are substantial differences between guided wave testing and conventional UT, such that the user needs to be aware of the factors affecting the performance of the guided wave tests. The main factors are the existence of multiple wave modes, dispersive propagation and the dependence on the shape and thickness of the test object.

This part of BS 9690 has set out the background to this, has provided some explanation of the factors involved and has set out the principles required to achieve an adequate test. As explained in Clause **6**, the characteristics of guided waves are more complex than for the compression and shear bulk waves conventionally used for ultrasonic testing. Moreover, these characteristics are dependent on the geometry of the object under test, so that test parameters need to be tailored to the shape and size of the test object. Other parts of this standard will specify requirements for a number of common types of elongated components, pipes, tubes, plates, rails, etc., for which guided waves are applicable.

Part 2 specifies common requirements relevant to all applications of guided wave testing of pipes, pipelines and structural tubulars.

The additional parts (currently under preparation) specify detailed procedures, including precautions, for applying guided waves to specific geometries of component under certain circumstances.

When specifying the use of guided waves for NDT it is important to understand the nature of the information that such tests can provide. In particular, it is necessary to recognize that there is an inverse relationship between the volume of material which is tested from each location and the sensitivity and resolution attainable from the test. Therefore, a guided wave test will not be as sensitive as a local ultrasonic test. Further, the current applications are generally for screening purposes, such that definitive measurements, such as remaining wall thickness of a component, are not directly obtained and have to be determined by follow-up tests on regions identified as suspect. Guided wave tests should not be seen as a direct substitute for other non-destructive test methods which are able to examine each part of a component directly. Rather, they are an alternative means of gathering information about the general condition of a component when direct examination is not practical.

Annex A (informative) Theoretical basis for GWT of hollow cylindrical objects

A.1 General

This annex provides further background information concerning the theoretical basis for the specific case of GWT of hollow cylindrical objects.

A.2 Dispersion curves for the object

The primary method of presenting the properties of guided waves is the graphical display of lines known as the dispersion curves. Dispersion curves are calculated, using mathematical theory, for the chosen structure. Each curve represents a different guided wave “mode” which can travel in the structure. The dispersion curves are different for each kind of structure, and even for each dimension of a particular shape (for example, they differ for each size of pipe).

Figure A.1 shows the group velocity dispersion curves for a steel pipe with nominal 6 inch outer diameter (168.3 mm) and Schedule 40 (7.1 mm wall thickness). The group velocity is the speed of a wave packet, for example a tone burst or pulse, and is the important measure of speed in GWT.

Figure A.1 Group velocity dispersion curves for 6 inch Schedule 40 pipe

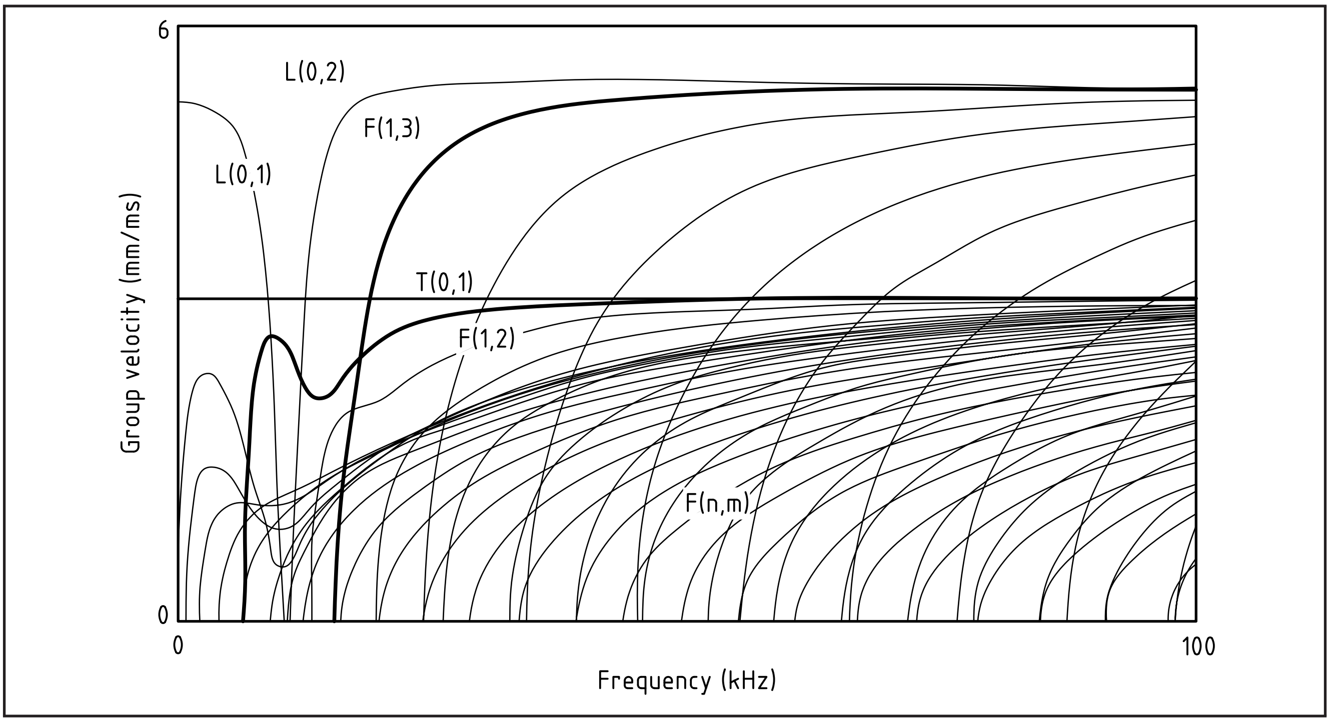
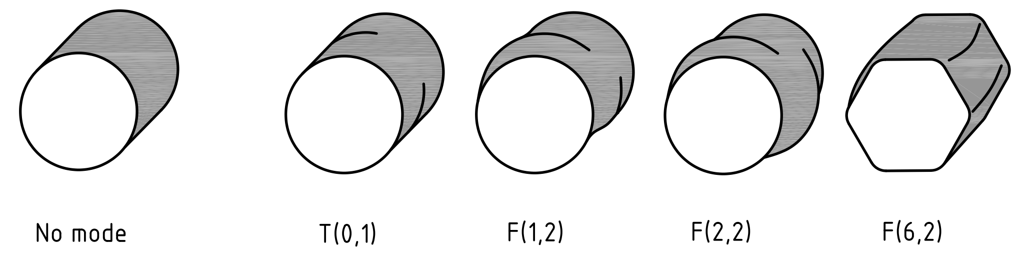


Figure A.1 shows that there are around 50 modes (50 curves) within the frequency range of 0 to 100 kHz. This means that many different guided wave modes can travel at any chosen frequency. Furthermore, the group velocity of the modes generally varies with the frequency; this is called dispersion: waves with such variation are said to be dispersive, and those whose speed does not vary with frequency are said to be non-dispersive.

The guided waves in a pipe can involve circumferential motion as well as axial motion. This results in multiple circumferential orders of modes in a pipe. Zero order modes have no variation of stress or displacement around the circumference; first order modes have one cycle of a sine wave around the circumference (this is, technically, the first harmonic order); the second order modes have two sine waves around the circumference; and so on. To help visualize this, Figure A.2 shows the displacement mode shapes of some example different circumferential orders.

Figure A.2 **Displacement mode shapes of modes with different circumferential orders**



A convention for the naming of guided waves in pipes and tubes is in common use in NDT. According to the displacement mode shapes, there are three families of modes:

a) torsional modes (T), which are zero order modes with displacements in the circumferential direction only (twisting motion);

b) longitudinal modes (L), which are zero order modes with displacements in the axial and radial directions only (extensional and breathing motion); and

c) flexural modes (F), which denotes all other higher order modes with, in general, displacements in all directions (bending motion).

The labelling of the specific modes (as in Figure A.1 and Figure A.2) uses two indices: the first index is the circumferential order; the second is a sequential counting number. For example, the fundamental torsional mode is called T(0,1).

A.3 Frequency scaling

The dispersion curves in Figure A.1 are for a 6 inch pipe, but they can also be used to assess the choice of mode and frequency for other sizes of pipes, by exploiting knowledge of the scaling characteristics. The relevant curves for a 3 inch pipe, for example, would look almost the same as those for the 6 inch pipe if the horizontal axis was re-labelled for the frequency range 0 kHz to 200 kHz. This means that, when plotting the group velocity dispersion curves as a function of the frequency-diameter product instead of frequency alone, the dispersion curves of the L(0,2) and the T(0,1) modes, and indeed the other important flexural modes used in GWT, all match reasonably well. In practice, this means that one set of dispersion curves is sufficient for a range of pipe sizes.

A.4 Methods of transduction of selected guided waves

The selective use of a chosen mode is normally achieved by using a transducer ring which controls the surface motion of the pipe around its entire circumference.

The use of controlled transduction around the circumference enables mode selection according to circumferential order. If identical transduction is applied at all positions around the circumference, then any wave motion which is excited in the pipe has to be axially symmetric in nature. In that case only modes which have circumferential order zero can be generated. Similarly, if all of the elements are sampled together in reception, then only the circumferential order zero modes which are propagating in the pipe can be received. In the dispersion curves in Figure A.1 it can be seen that at, for example 50 kHz, rejection of all modes which are not zero circumferential order leaves only the T(0,1), L(0,1) and L(0,2) modes.

A second means of selectivity is to employ transducers which operate in a chosen direction on the surface of the pipe. If the components of the transducer device are able to excite and receive selectively in either the circumferential direction (around the pipe) or the axial direction (along the pipe), then it is possible to select between the torsional T(0,1) mode and the L(0,1) and L(0,2) modes. The former has motion only in the circumferential direction whereas the latter have motion only in the axial and radial directions.

Finally, selectivity can be achieved by the use of transducer devices that control the motion along an axial length of the structure, which enables selectivity according to wavelength and also according to direction of propagation along the structure. Pipe testing instrumentation commonly uses multiple rows of the transducer elements to achieve this. Two rows of transducer elements are sufficient for selectivity between the L(0,1) and L(0,2) modes. Two rows are also sufficient for selectivity between the two different directions of travel. Addressing both of these multiple row considerations, it is found that inspection using the T(0,1) mode needs two rows of transducer elements, while inspection using the L(0,2) mode in practice needs four rows. For T(0,1), there is no need for mode rejection, so the two rows are only for the selection of direction. On the other hand, for L(0,2) it is necessary to reject the L(0,1) mode as well as select the direction, necessitating additional rows.

A.5 Reflection from features

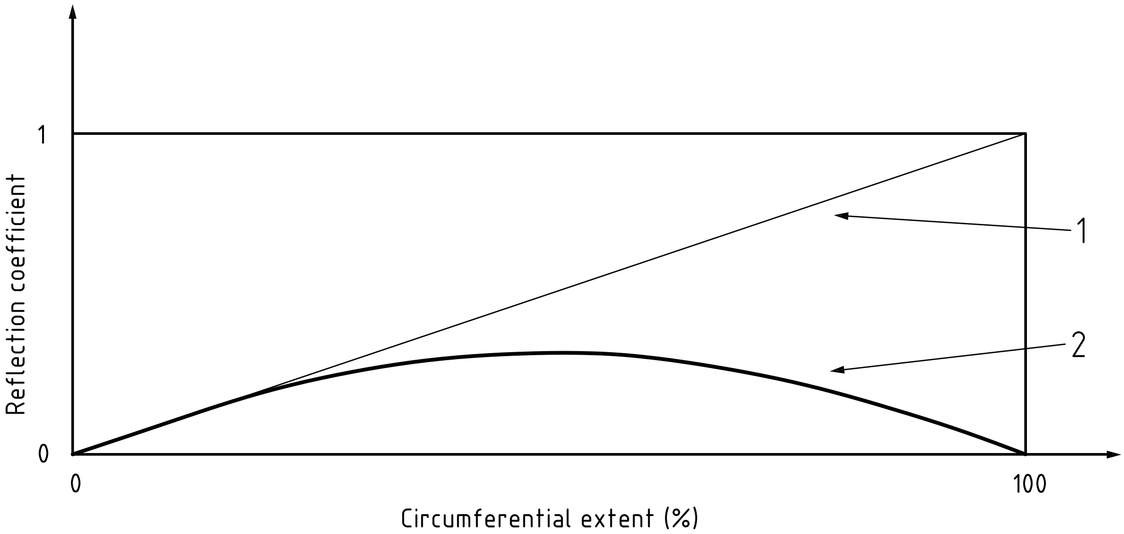
It is essential to understand the nature of the reflection from features in order to assess the sensitivity of GWT.

The reflectivity of guided waves is governed by very different rules than those which are understood for bulk waves UT. When using guided waves, it is possible to find discontinuities whose depth is much smaller than a wavelength. The main determinants of the reflection are the extent of the discontinuity (in the axial and circumferential directions) and its depth.

Figures A.3 to A.5 show the nature of the sensitivity of guided waves to loss of material, such as corrosion, in the wall of a pipe. Real corrosion normally occupies part of the circumference, part of the depth through the wall and part of the axial length, and can occur with any shape of profile. The figures show highly idealized examples, using the simplest shape of a straight-sided notch. Clearly this is not strictly representative of real defects, but nevertheless these simple cases show correctly the general nature of the reflection behaviour. The three figures show separately the sensitivity curves for each of the key dimensions of the notch. For further details of the nature of the reflection of guided waves from corrosion defects, see Demma et al 2004 [3].

Figure A.3 shows the reflection coefficient for the idealized case of a straight-sided notch which is all the way through the pipe wall, as a function of its length around the circumference. The incident wave is either of the symmetric modes, L(0,2) or T(0,1); the results for these two modes are almost identical. This result is also practically identical for any pipe size and any frequency within the typical ranges used in GWT. This shows that the reflection coefficient of the symmetric modes is directly proportional to the circumferential extent.

Figure A.3 **Typical reflection coefficients for a through-wall notch in a pipe versus the circumferential extent of the notch**



Key

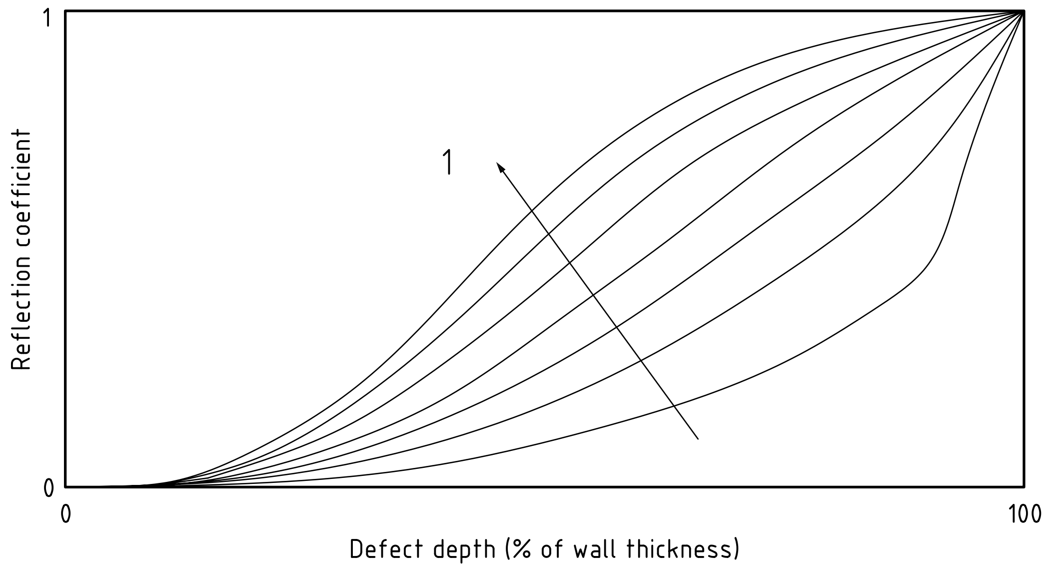
1 Symmetric mode

2 Flexural mode

NOTE The incident wave is symmetric (compression or shear). The figure shows the strength of the reflected symmetric wave and the reflected and mode-converted flexural wave.

Figure A.4 shows the reflection coefficient for the idealized case of an axially symmetric part-depth notch as a function of the depth. One of the symmetric modes, L(0,2) or T(0,1), is incident, and the figure shows the reflection of the same mode. In this case it can be seen that there is some frequency dependence, the sensitivity increasing with increasing frequency. There is also dependence on the pipe diameter and wall thickness (not shown here).

Figure A.4 **Typical reflection coefficients for a through-wall notch in a pipe versus the circumferential extent of the notch**



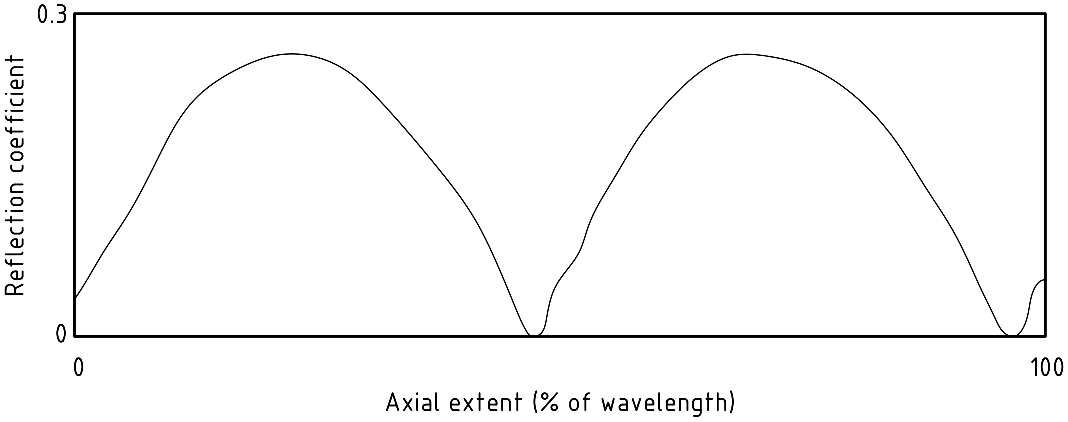
Key

1 Increasing frequency

NOTE The incident wave is symmetric (compression or shear); the figure shows the strength of the reflected symmetric wave for a range of frequencies. For simplicity, the figure shows the idealized case of a full-circumference (axially symmetric) notch.

The reflection coefficient curve for the third dimension of a notch, its axial length, is shown in Figure A.5. Again, one of the symmetric modes, L(0,2) or T(0,1), is incident, and the figure shows the reflection of the same mode. It can be seen that the reflection is sensitive to the axial length; indeed, the reflection is seen here to go to high values and zero values at particular lengths of the notch. This is because of constructive interference (high values) and destructive interference (zero values) between the reflection from the front of the notch and that from the back of the notch. The curve would compress or expand along the horizontal axis for other choices of frequency. But it needs to be emphasized again that this is an ideal case using model studies of perfectly rectangular notches and a specific single frequency. In practice, such strong variation does not arise because real corrosion patches are much less regular and real signals comprise multiple frequencies. Nevertheless, the interference phenomenon does occur to some extent, so the collection of results over a range of frequencies is an important measure to reduce the risk of it reducing the sensitivity of the test.

Figure A.5 **Typical reflection coefficients for a through-wall notch in a pipe versus the circumferential extent of the notch**



NOTE The incident wave is symmetric (compression or shear); the figure shows the strength of the reflected symmetric wave. For simplicity, the figure shows the idealized case of a full-circumference (axially symmetric) notch. It is important to note that this is an idealized straight-sided notch; the dip in the middle is not nearly so sharp in real cases when the shape is irregular (see text).

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