BS ISO 18211:2016

BSI Standards Publication

Non-destructive testing — Long-range inspection of above-ground pipelines and plant piping using guided wave testing with axial propagation

bsi.

National foreword

This British Standard is the UK implementation of ISO 18211:2016.

During the development of this standard, the UK Committee voted against its approval as an International Standard. The UK Committee is of the opinion that the National Standard BS 9690 has a more detailed approach to the subject, including the requirement for information to be provided by the client (e.g. plant owner) to the inspector.

The UK Committee is of the opinion that there could be more information about data quality and interpretation in ISO 18211 and that the test procedure could detail engagement with the client to ensure appropriate deployment.

BS 9690 has been developed for a wide audience with the intention that interested parties such as plant operators can use the BS standard as performance criteria when issuing Guided wave testing (GWT) contracts. GWT is different from all other methods of Nondestructive testing (NDT) including Ultrasonic testing, and BS 9690 has been developed to highlight and explain many new concepts and requirements which are associated with it.

The UK participation in its preparation was entrusted to Technical Committee WEE/46, Non-destructive testing.

A list of organizations represented on this committee can be obtained on request to its secretary.

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

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

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INTERNATIONAL STANDARD

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Non-destructive testing — Long-range inspection of above-ground pipelines and plant piping using guided wave testing with axial propagation

Essais non destructifs — Vérification à large échelle des réseaux de canalisations hors sol et de la tuyauterie d'usine utilisant un essai d'onde guidée à propagation axiale

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is IIW, *International Institute of Welding*, Commission V.

Requests for official interpretations of any aspect of this International Standard should be directed to the ISO Central Secretariat, who will forward them to the IIW Secretariat for an official response.

Non-destructive testing — Long-range inspection of above-ground pipelines and plant piping using guided wave testing with axial propagation

1 Scope

This International Standard specifies a method for long-range testing of carbon and low-alloy steel above-ground pipelines and plant piping using guided ultrasonic waves with axial propagation applied on the entire circumferential pipe section, in order to detect corrosion or erosion damage.

The guided wave testing (GWT) method allows for fast inspection of above-ground pipelines, plant piping and cased road crossings, giving a qualitative screening and localization of probable corroded and eroded areas. GWT is typically performed on operating piping systems.

This International Standard is applicable to the following types of pipes:

a) above-ground painted pipelines;

b) above-ground insulated pipelines;

c) painted plant piping;

d) insulated plant piping.

NOTE Pipe sections within road crossings with external casings (without bitumen or plastic coating) are a special case of buried pipe where there is no soil pressure on the OD of the pipe. This International Standard applies to these cased road crossings.

Other types of pipes not included in the above list need dedicated approaches due to increased complexity.

2 Normative references

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

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

3 Terms and definitions

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

3.1
axial direction
direction along the main axis of the pipe

3.2
circumferential direction
direction around the circumference of the pipe

3.3
total pipe wall cross-section
TCS
area between the inner and outer diameters of the pipe in a plane perpendicular to the pipe axis

3.4
cross-section change
equivalent cross-section change calculated assuming that an indication is purely caused by a change in the cross-section of the pipe wall

3.5
datum point
reference point for reporting a *test position* (3.16) and for correlating test results with the corresponding position on the test object

3.6
dead zone
length of pipe on either side of the *test position* (3.16) where reflectors of interest cannot be detected because they are covered by the transmitted pulse

3.7
flexural mode
non-symmetric bending type mode of guided wave propagation in pipes, with particle displacements in axial, circumferential and radial directions

3.8
focus
concentration of guided waves at a single axial and circumferential position, achieved either by hardware settings or by post-processing of a recorded set of signals (synthetic focus)

3.9
geometric feature
pipeline feature (e.g. weld, support, flange, bend, etc.) causing the reflection of guided waves because of a *cross-section change* (3.4) or other acoustic impedance variation

3.10
guided wave mode
distinct type of guided wave with a specific vibration pattern

3.11
longitudinal mode
symmetric compression type mode of guided wave propagation in pipes, with particle displacements predominantly in the *axial direction* (3.1)

3.12
primary mode
guided wave mode (3.10) which is chosen for the incident wave

3.13
probe ring
circumferential component, containing transducer elements with direct contact to the pipe

3.14
secondary mode
guided wave mode (3.10) which is different from the *primary mode* (3.12) and is generated by mode conversion at pipe features or discontinuities

3.15
test frequency
centre frequency of the pulses transmitted by the *probe ring* (3.13)

3.16
test position
axial position on the pipe where the *probe ring* (3.13) is placed

3.17
test range
distance between the *test position* (3.16) and the furthest position for which the minimum acceptable sensitivity of the reference signal is achieved, in each direction (positive or negative)

3.18
torsional mode
symmetric twisting type mode of guided wave propagation in pipes, with particle displacements in the *circumferential direction* (3.2)

4 Test personnel

The personnel performing ultrasonic guided wave testing shall be qualified in accordance with ISO 9712 or with any another equivalent standard of the relevant industrial sector.

Training in the use of the specific equipment is required because there are significant differences between the available systems and diagnostic approaches.

5 General

Ultrasonic guided wave testing (GWT) uses elastic waves which are guided along the pipe wall and can travel long distances, thus providing rapid near complete coverage of the volume of the pipe wall.

The typical test setup is comparable to conventional ultrasonic pulse-echo testing: an ultrasonic instrument forces transducers in the probe ring to generate ultrasonic waves in the pipe wall which are reflected by discontinuities and received by the same probe ring. The time-of-flight of the received signal indicates the distance between the discontinuities and the probe ring. A single test with guided waves can cover a length of pipe of tens of meters.

Within this International Standard, GWT is performed as a screening method. The reflections returning from discontinuities and received by the ultrasonic instrument indicate the position of the discontinuity. However, they do not give detailed quantitative information about its morphology. Therefore, GWT is used to indicate any locations which need to be followed up with complementary detailed inspection. More information on the nature of guided waves is given in Annex A.

Within this International Standard, GWT typically uses a frequency range between 20 kHz and 500 kHz. If the performance of the test has been shown to have equal or better sensitivity to that obtained with the frequency range specified above, a frequency lower than 20 kHz can be used for GWT.

The successful application of guided ultrasonic waves requires the following:

a) selective pure mode transmission and reception;

b) wave modes which are non-dispersive in the frequency range used;

c) coverage of the full cross section of the pipe wall;

d) signals coming from each direction shall be distinguished.

The amplitude of a reflected ultrasonic guided wave signal from a discontinuity varies in a complex manner that depends on many factors such as test frequency, guided wave mode and the specific morphology of the discontinuity. It is often possible to correlate the size of the reflected signal with the overall cross-section change in the pipe wall resulting from wall loss, meaning that GWT can qualitatively group discontinuities into different severity groups such as indications of low, medium and high concern. However, usually the parameter of interest when testing piping systems with wall loss is the remaining wall thickness in areas with discontinuities, which GWT cannot accurately provide (see Annex A for more information).

It is recommended to perform ultrasonic guided wave testing using a range of frequencies to improve the accuracy of the test. Also, GWT ultrasonic instruments often employ advanced approaches like focusing or synthetic focusing to improve the sensitivity and discontinuity sizing ability of GWT. The use of these is not specified in this International Standard, but background information is provided in Annex A.

6 Factors influencing GWT performance

6.1 External diameter

The sensitivity of GWT depends on the cross-section change. The absolute cross-section change in a pipe due to corrosion or erosion loss is measured in the units of area and depends on both the depth and the circumferential extent of the discontinuity. GWT is sensitive to a minimum per cent of cross-sectional loss, which is a function of both the absolute cross-section change and the pipe geometry. As an example, a discontinuity in a small diameter pipe may represent a large per cent change in cross section that is easily detectable using GWT, but the same discontinuity in a large diameter pipe may represent a small cross-section change that cannot be detected using GWT. Because of this effective decrease in sensitivity as pipe diameter increases, testing of pipes larger than DN 600 (24 inches in diameter) can miss significant isolated corrosion pits, so it is recommended that complementary NDT methods are used. When testing pipes where the known damage mechanisms result in larger cross-section changes rather than isolated pitting, GWT is still recommended for rapid testing of pipes with diameters larger than DN 600 (24 inches in diameter).

6.2 Pipeline geometry

The complexity of the pipe geometry can limit guided wave propagation. Below are summarized the effects of some common pipe features which can be present in the pipes listed in Clause 1.

a) It is not possible to test beyond flanged joints or any breaks of the pipe because the guided waves cannot propagate across them.

b) It is not permitted to test beyond an elbow fitting; instead, the tool shall be moved to a test position on the other side of the bend. Testing beyond “pulled” bends, where a straight length of pipe is formed into a curve of radius equal to five or more times the pipe diameter is permitted.

c) It is permitted to test beyond a branch or a tee only if the diameter of the branch is no greater than ½ the diameter of the pipe being tested. This restriction is to avoid problems with distortion of the forward travelling guided wave by interactions with the branch.

d) It is not permitted to test beyond a support if the amplitude of reflection from it is higher than 6 dB below the weld DAC curve. This restriction is to avoid problems of the distortion of the forward travelling guided wave by interactions with the support.

6.3 Test range

The test range depends on many factors which are summarized below. In general, the test range is limited by the signal-to-noise ratio (SNR) of the test data (see Clause 9, item e).

a) Geometrical features on the pipe attenuate and/or distort guided wave modes reducing test range.

b) The type of coating on the pipe can have a large effect on test range. Typically, insulation materials like calcium silicate do not affect test range appreciably, but coatings like bitumen drastically reduce test range by attenuating guided wave signals.

c) This International Standard only applies to above-ground pipe, but buried pipe where there is soil in contact with the pipe surface or pipe coating is a more difficult GWT application due to high attenuation and low signal to noise.

d) The substance contained in the pipe affects test range and it is a complex function depending on the specific substance, ID corrosion products and the specific guided wave mode being used.

e) The presence of welds in the pipe causes reflections thereby attenuating the guided wave signal.

6.4 Road crossing

If performing GWT on a pipe passing through a road crossing with an external casing, achievement of the test for the length of the crossing shall be proven by the test range including a reflection from a geometrical feature (normally a weld) beyond the crossing or a reflection from a geometrical feature (normally a weld) inside the crossing that is identifiable from both sides of the crossing.

7 Test equipment

7.1 General

The test equipment consists of the following:

a) an ultrasonic instrument to generate and receive pulses in the frequency range from 20 kHz to 500 kHz;

b) a probe ring carrying transducers for the generation of guided wave modes;

c) a probe ring carrying transducers for the reception of reflected guided waves; it can be the same probe ring used for generating guided wave modes;

d) an electronic system for recording, processing and analysing the reflected signals.

7.2 Probe ring

The transmitting probe ring shall be capable of generating the primary guided wave mode in isolation from other possible modes of the pipe. If more than one wave mode is used, they should be used separately to improve the reliability of the inspection.

The receiving probe ring shall be capable of separating the individual guided wave modes which are of interest for the analysis and to suppress the undesired modes (see Annex A for more information).

There are three different types of transducers currently available to generate and receive guided ultrasonic waves in pipes:

— piezoelectric transducers;

— electromagnetic acoustic transducers (EMAT);

— magnetostrictive transducers.

These types of transducers are deployed on a probe ring which is placed around the pipe.

7.3 Signal processing and analysis system

The signal processing and analysis system shall produce its results in a form which can be recorded reliably on a computer storage medium.

The results which are recorded shall be in a form such that the features in the results can be correlated to physical locations on the piping system.

7.4 Periodic verification of equipment performance

The equipment shall be verified periodically, at intervals of no more than 12 months, to check its proper functioning and performance, and any faults found shall be corrected.

This verification shall be performed in accordance with a dedicated written procedure following the manufacturer's instructions.

7.5 Instrument settings

If no relevant standards for instrument settings are available, the following minimum requirements shall be met.

a) **Frequency and signal settings**

   The settings which control the frequency and bandwidth of the signal shall be chosen to be appropriate for specific relevant guided wave modes which have been selected according to the inspection procedure to be used for the pipe under test.

b) **Pulse repetition frequency**

   The pulse repetition frequency shall be set sufficiently low as to allow all signals to attenuate completely between subsequent pulses.

8 Test procedure

GWT shall be performed according to a written test procedure, which shall include at least the following:

a) a reference to this International Standard, i.e. ISO 18211;

b) background information (including standards, restrictions, safety requirements, etc.);

c) personnel qualification;

d) a description of the pipe to be tested;

e) range of the test;

f) access and environmental conditions;

g) surface preparation;

h) equipment used;

i) equipment parameters and functional testing;

j) parameters for data collection;

k) parameters for evaluation of results;

l) complementary non-destructive testing;

m) reporting requirements;

n) recording of deviations from the procedure.

9 Requirements for test data quality

The minimum requirements to assure the quality of the test data are as follows.

a) Before testing, the whole combined test system shall be checked according to the specifications provided by the manufacturer. If the GWT instrument performs self-checks, then the results of these shall be stored with the recorded data. Any equipment deviations from allowed specification shall be rectified before starting the test.

b) The tolerance of range setting shall be agreed upon between the parties (due to the long wavelength used for GWT the tolerance on distance measurement is not likely to be better than ±100 mm).

c) The probe ring coupling to the pipe surface shall be checked according to the procedures and thresholds provided by the manufacturer. If the coupling is found not to meet the required specification, then the surface preparation shall be improved, the probe ring re-applied and the data re-sampled.

d) If the equipment permits an absolute amplitude calibration, then it shall be used. Otherwise, calibration of sensitivity, using knowledge of a well-characterized reflector, such as a girth weld, shall be used. The calibration shall also include distance amplitude correction (DAC) or time corrected gain (TCG), in order to compensate the calibration for axial position within the range of the test. DAC and TCG are to be understood conceptually in the same manner as is established for conventional UT testing; a DAC provides a constant level of sensitivity as a function of range, allowing reflections at varying ranges to be compared in a consistent manner to a known reference level. The calibration shall be set according to the instructions provided by the manufacturer of the GWT equipment.

e) The signal-to-noise ratio shall be estimated according to the procedure provided by the manufacturer. For adequate interpretation of the test data, the signal-to-noise ratio shall be greater than 6 dB; small amplitude signals below this value cannot be interpreted reliably and will lead to noise signals being reported as discontinuities. The signal-to-noise ratio is used to determine the range of the test (see 6.3 for more information on test range).

10 Testing

10.1 Preparation of the test object

10.1.1 Surface temperature

The surface temperature of the pipe shall be within the operating range of the test equipment used.

10.1.2 Removal of insulation

Testing on insulated pipes requires the removal of circular bands of insulation at all the points where the probe ring shall be positioned and for a length that is sufficient to allow the fixing of the probe ring directly on to the pipe surface.

10.1.3 Wall thickness assessment

Metal loss at the probe ring location affects the test performance of GWT. Visual testing and ultrasonic testing shall be performed to assess the presence of external or internal metal loss. If metal loss is detected, it is recommended that the probe ring is attached to an alternative location. The wall thickness values shall be recorded.

GWT does not provide inspection coverage in the dead zone. One way of providing 100 % pipe inspection coverage is to perform more than one guided wave test on a piping system where there is sufficient overlap between tests to provide inspection coverage in all dead zones. If the dead zone is not inspected with GWT using another test location and if the dead zone is to be tested, ultrasonic testing (or an alternative method) shall be used.

10.1.4 Surface preparation

Testing on well-adhered painted surfaces is normally satisfactory. Loose or flaking paint, superficial corrosion products and other coatings shall be removed at the test location prior to attaching the probe ring if required to achieve the data quality set out in Clause 9, item e).

10.2 Probe ring test position

In a typical piping system, it is normal to require many different probe ring test positions to provide full inspection coverage of the entire piping system. The choice of these locations for the probe ring is critical in order to provide adequate inspection of the entire piping system (see 6.2 for more information). The position(s) of the probe ring on the piping system shall be recorded with reference to a known physical datum or on a piping drawing to allow repeatability.

10.3 Data collection

Data shall be collected according to the instructions provided by the equipment manufacturer and to a dedicated procedure. This procedure shall include instruction on the following:

a) ensuring proper probe ring coupling to the pipe surface;

b) ensuring proper electrical connection between system components;

c) setting test equipment parameters;

d) setting test equipment range;

e) setting test equipment sensitivity;

f) verifying data quality.

10.4 Reporting sensitivity

Prior to GWT data interpretation, DAC or TCG curves shall be applied to establish sensitivity using the requirements in Clause 9, item d. In practice, it is typically not possible to perform an absolute amplitude calibration of the GWT test equipment.

A pipe end with a machined surface normal to the pipe axis represents an ideal 100 % reflector of GWT sound energy and it is ideal to establish a DAC. However, when performing GWT, it is also not typical to have such a pipe end available. Note that the bevelled end of a pipe before welding is not the same as a machined surface normal to the pipe axis and it is not recommended to use to establish a DAC.

When inspecting operating piping systems, it is typical to use the reflections from girth welds to establish the DAC sensitivity level. However, there is natural variability in the geometry of girth welds, which leads to some variability in sensitivity level. For most pipe schedules used in typical industrial applications, girth welds reflect 20 % of the guided wave sound intensity. For pipe schedules with thickness in excess of 13 mm, the relative percentage of weld reinforcement compared to pipe thickness changes and the girth welds will reflect a different percentage of guided wave sound intensity. When performing GWT screening inspections on piping systems, it is typically sufficient to use the value of 20 % for girth weld reflections. If more accuracy is required, then other techniques are required. Note that flanges are not the same as a pipe end with a machined surface normal to the pipe axis due to the geometry differences, and do not strictly reflect 100 % of the guided wave sound intensity.

A machined surface normal to the pipe axis reflects 100 % sound intensity, which is typically defined as 0 dB. Therefore, a girth weld that reflects 20 % sound intensity is equivalent to −14 dB and a discontinuity that reflects 5 % is equivalent to −26 dB.

10.5 Data interpretation

A call level shall be established that has the same shape as the DAC and is above the usable signal-to-noise level as described in Clause 9. The call level is to be agreed upon between the contracting parties or shall be determined using an appropriate procedure as supplied by the equipment manufacturer. All signals higher in amplitude than the call level shall be subjected to the interpretation procedure. Responses lower in amplitude than the call level can be evaluated if the signal-to-noise ratio meets the requirements in Clause 9. All relevant signals shall be recorded on the test report. In the absence of agreement between contracting parties or equipment manufacturer's guidelines, the call level shall be set to the equivalent of a discontinuity that reflects 5 % of the guided wave sound intensity or −26 dB below the reflection from a machined surface normal to the pipe axis. The call level shall be included in the test report.

10.6 Detection sensitivity

The test sensitivity is a function of many variables and depends on the following:

a) the test equipment, including the ultrasonic instrument and the probe ring;

b) the specific guided wave mode;

c) the diameter of the pipe being tested; the same isolated wall loss discontinuity that is detected in a small diameter pipe may not be detected in a larger diameter pipe;

d) the type of discontinuity in the pipe, as the guided wave reflection coefficient will not be equal for all wall loss discontinuities (see Annex A for more information).

The instructions provided by the equipment manufacturer shall be used for any assessment of sensitivity.

10.7 Visual confirmation

All indications from the GWT test shall be confirmed visually whenever possible. Where possible, the locations of geometric features shall be identified visually and their positions shall be measured and compared with the GWT results.

11 Complementary NDT to support the GWT

The GWT method provides rapid screening of the complete volume of the entire pipe, from which indications are called. However, it does not provide direct characterization of the indications. It also does not provide screening results for certain locations where clear GWT signals cannot be obtained; these include the material adjacent to large reflectors such as flanges, valves, and branches, and short sections between closely spaced major features where it is not possible to achieve sufficient access.

Therefore, complementary testing using other methods and applied according to their relevant standards, shall be used to

— perform follow up inspection of all indications that have been identified by GWT, and

— perform inspection of local areas which cannot be tested by GWT, but nevertheless are required to be inspected by the test program.

Complementary NDT is necessary to give a complete evaluation of the pipe and it is considered to be an essential part of the inspection.

12 Test report

At the end of the inspection, a test report shall be compiled to document the results of all GWT and complementary NDT performed. The final test report shall include the following:

a) date and place of test;

b) identification of client;

c) identification of pipeline;

d) section of pipeline tested;

e) pipe diameter and thickness;

f) test conditions and any variation during the test;

g) part of the pipe tested;

h) test technique;

i) test equipment;

j) guided wave modes and test frequencies used;

k) probe ring position relative to the datum;

l) size of the dead zone;

m) length of pipe tested and any areas which cannot be tested;

n) distance-amplitude-correction curve (DAC), relative to a known geometrical feature (i.e. a weld);

o) call level (all echoes above the call level shall be identified and interpreted);

p) schematic indication of the features identified;

q) indication of the loss of cross section and, when possible, circumferential extent and angular position of possible discontinuities;

r) identification of company who conducted the test;

s) reference to test procedure;

t) reference to contractual documents, standards, etc.;

u) name, qualification and signature of the operator who conducted the test.

Annex A
(informative)

Selection of guided wave modes

A.1 Physics of guided waves

Guided waves are waves whose propagation is guided by a structural shape. In general, guided waves may exist in structured shapes of any materials (solid, liquid, gas) and at any frequency. The guided waves used for the GWT of pipes are stress waves which are guided in the solid material of the wall of the pipe.

The shape and material properties determine the direction, speed and distributions of stresses and displacements of the wave. The guiding effect enables propagation for long distances with minimal dissipation. The guided waves are properties of the structure; only the guided waves which are able to exist in a given structure can be considered for possible exploitation.

Guided waves can exist in many forms ("modes") within any chosen structure. Some are dominated by axial extensional motion (similar to UT compression waves), some by twisting motion, some by bending motion, and so on. Furthermore, in general, the speeds of these waves vary with frequency, i.e. they are dispersive. Therefore, it is critical to both understand and control selected guided waves in order to perform reliable tests.

A.2 Dispersion curves and mode shapes

The primary information to present the properties of guided waves for any particular structure is the dispersion curves, which show the speed of each guided wave mode versus the frequency. These are calculated using mathematical theory. There is a separate dispersion curve for each mode and the dispersion curves are different for each size of a pipe.

The other key descriptor of the guided waves is their mode shapes. These are the physical shapes of their displacements, describing the form of motion: extensional, torsional, flexural, etc. Guided waves in pipes are named conventionally in three groups: longitudinal ("L"), flexural ("F") and torsional ("T").

A.3 Selection of specific guided wave modes

Guided wave behaviour is complex and it is important to understand that the successful development of the GWT method requires a commitment to a careful test strategy. The elements of the test strategy are as follows.

a) **Pure mode transmission**

Without careful control, there are many modes which will travel in a structure concurrently and at different speeds. GWT uses careful choice of transducers, probe ring and signals to generate just one pure guided wave mode in the structure, named as the "primary mode" of the test. This is the reason why GWT uses a complex ring of transducers around a pipe, with tone burst signals. Furthermore, GWT transducer systems are designed to perform separate tests in the two directions along the pipe from the test position (separate upstream and downstream propagation).

b) **Dispersion**

GWT uses modes and frequencies such that the shape of the guided wave signal does not change significantly as the wave propagates. Without proper choice of modes and frequencies, the guided wave signal can spread out temporally and spatially making interpretation of guided wave reflections from discontinuities difficult.

c) **Mode shape**

GWT uses modes which are sensitive to the expected discontinuities in pipes; specifically, the GWT of pipes uses modes which reflect with significant amplitude from defects on either the internal or external wall.

d) **Multiple mode reception**

The reflected signals which are received at the probe ring are generally a mixture of the primary mode and a number of other propagating modes which can exist in the structure at the test frequency and which are generated by mode conversion when the primary mode reflects from a discontinuity. GWT detects the reflected primary mode and normally also a selected mode converted wave, named the "secondary wave". Processing of both the primary and the secondary wave is used to enhance the interpretation of the reflecting features.

The quality of the performance of the equipment and the care of the user are critically important to achieve the requirements listed above.

A.4 Reflection of guided waves from discontinuities

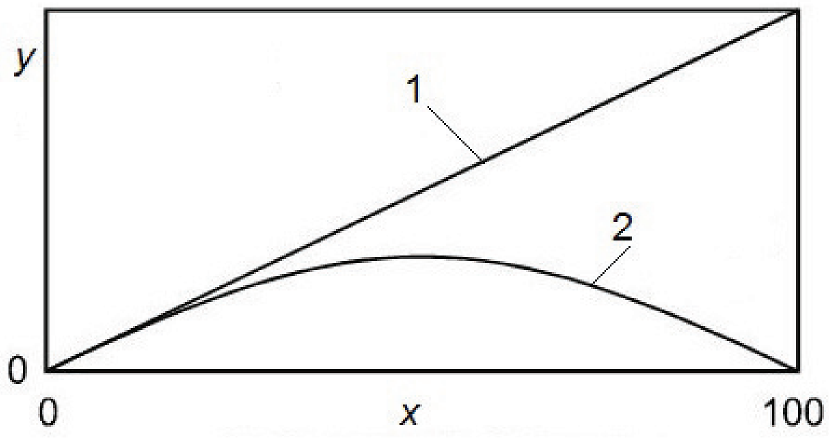
The reflectivity of guided waves from discontinuities requires a different understanding than that for conventional bulk wave UT. Unlike bulk wave UT, guided waves can reflect significantly from discontinuities whose depth is much smaller than the wavelength. The main determinants of the reflection are the extent of the discontinuity in the circumferential, axial and depth directions.

Discontinuities caused by corrosion are variable and typically unknown in shape, so reflectivity of guided waves is strictly a complex multi-parameter relationship. However, the key influences are the three discontinuity dimensions as stated above. Furthermore, the nature of the reflection relationship can be modelled by considering these three dimensions; that is to say by considering the reflection from straight-sided notches with a range of widths, depths and lengths. Figure A.1, Figure A.2 and Figure A.3 shows, in schematic form, the reflectivity from notches according to these three dimensions. Further details of the nature of the reflection of guided waves from corrosion defects are given in Reference [1].

Figure A.1 shows the reflection versus the circumferential extent of a notch. The incident wave is the primary mode (longitudinal or torsional); the figure shows the reflection coefficient for the same primary mode and also the mode-converted secondary wave (flexural). This figure shows that the reflection coefficient is proportional in simple linear manner to the circumferential length of the notch for longitudinal and shear modes.

Figure A.2 shows the reflection versus the depth of a notch. The incident and reflected waves are the primary mode (longitudinal or torsional). This figure shows that the reflection coefficient is not linear, but has increasing sensitivity with depth of the notch. This curve is different for different parameters of the test: in general, its sensitivity is increased by increasing the frequency and is also affected by pipe diameter and wall thickness.

Figure A.3 shows the reflection versus the axial length of the notch. Again, the incident and reflected waves are the primary mode (longitudinal or torsional). However, there is a significant variation of the reflection according to the axial length of the notch and this can be understood simplistically as interference between reflections from the near and far ends of the notch. In practice, such extreme variation in reflection does not occur because real discontinuities are not straight-sided and regular in shape. Also, in practice, the axial lengths corresponding to the maxima and minima of this curve depend on the test frequency, so testing at a range of frequencies avoids the nulls in reflected waves.



Key

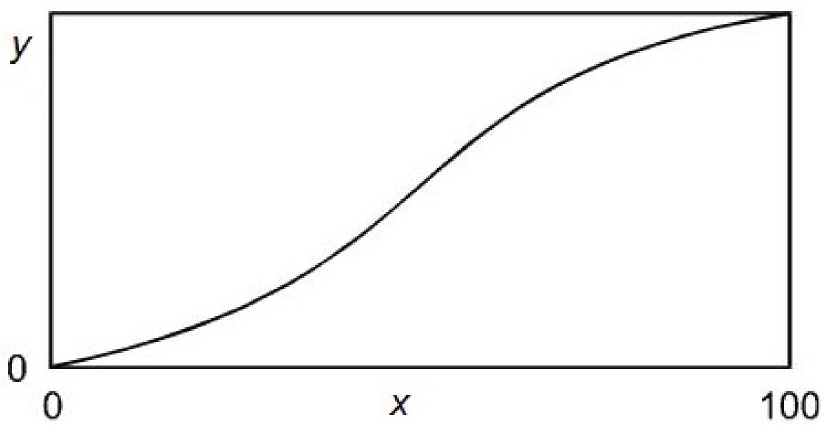
1 longitudinal or shear mode

2 flexural mode

x circumferential extent (%)

y reflection coefficient (linear scale)

Figure A.1 — Schematic illustration of reflection coefficient for longitudinal or torsional mode incident at a straight-sided notch — Circumferential extent

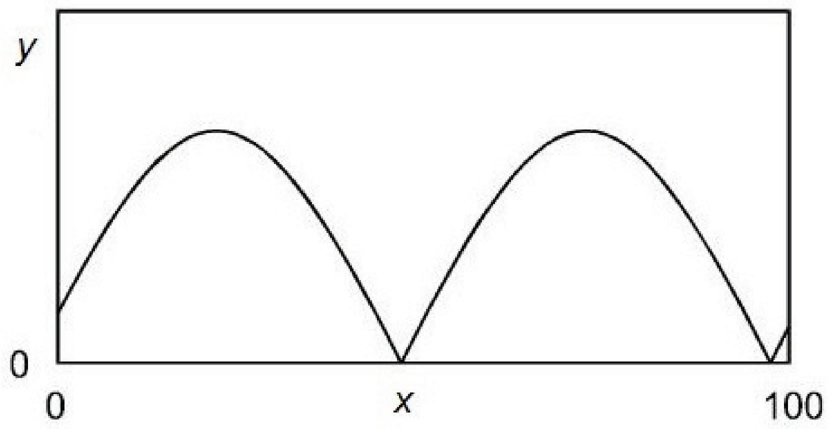


Key

x depth through wall (%)

y reflection coefficient (linear scale)

Figure A.2 — Schematic illustration of reflection coefficient for longitudinal or torsional mode incident at a straight-sided notch — Depth



Key

x axial extent relative to wavelength (%)

y reflection coefficient (linear scale)

NOTE Such extremes are not seen in practice; see text.

Figure A.3 — Schematic illustration of reflection coefficient for longitudinal or torsional mode incident at a straight-sided notch — Axial extent

A.5 Focusing of guided waves

In addition to the selection of modes described in A.3, it is also possible to focus the testing at specific axial and lateral positions on the structure, thus enhancing sensitivity and spatial selectivity. This is possible because the transducers surround the circumference of the pipe and so can be used to focus in a similar way to a phased array. The focusing can be achieved either by hardware delays or by post-processing signals recorded separately from multiple channels. In the latter case, the processing can then be repeated systematically to focus on all axial and circumferential locations along the test length and so produce a map of reflection responses.

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