STRUCTURAL HEALTH MONITORING OF PIPES USING PERMANENTLY INSTALLED GUIDED WAVE SENSORS

by

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Declaration of Originality

The contents of this thesis are the results of work carried out independently by myself under the supervision of Professor Peter Cawley. Wherever work of others has been used throughout this thesis appropriate references are provided.
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Abstract

Low frequency ultrasonic torsional T(0,1) guided waves allow for the full volume of tens of meters of a pipe to be inspected from a single measurement position. Currently, these inspections are primarily carried out with detachable transducer rings and data collected is evaluated manually by the operator. Permanently installed guided wave sensors have been introduced by Guided Ultrasonics Ltd. in 2005 and since have been deployed on thousands of pipes. Measurements collected with these sensors are, in the current framework, evaluated in the same manual fashion as those obtained from detachable transducer rings. The contents of this thesis focus on the development and evaluation of a novel SHM procedure for guided waves in pipes utilising existing permanently attached transducer ring technology. This work can be subdivided into four main fields of investigation.

Firstly, a blind trial was conducted in order to test the sensitivity of a structural health monitoring (SHM) algorithm based on independent component analysis. It was found that compared to standard one-off inspections an improvement of approximately a factor of 5 could be obtained. Defects introduced on straight sections of a test pipe either before or after a 1.5D bend were identified with cross-sectional area losses between 0.5% and 1.5%. The sensitivity of the SHM algorithm to a defect located on a pipe bend was found to be significantly lower with a 3.5% cross-sectional area loss at the time of first detection.

The reduced sensitivity to the defect located on the pipe bend was investigated in the second part of this thesis utilising finite element (FE) simulations. It was shown that the sensitivity of guided wave inspections using the T(0,1) mode is highly dependent on the location of a defect both in circumferential and axial position, as well as the size of the bend itself. This sensitivity is proportional to the distribution of the squared von Mises stress across the structure. The results of this study allowed for the conclusion to be made that the reduced sensitivity during the blind trial was caused by the geometry of the inspected structure and the propagation of the T(0,1) wave mode rather than a shortcoming of the SHM algorithm.

The third main part of this thesis investigates the potential of using defect reflections obtained from FE simulations in combination with real measurements of a structure in a constant state.
in order to estimate the sensitivity of an installed SHM system. The validity of this method was verified by the use of measurements obtained from the blind trial setup. The growth patterns of the defects introduced into the pipe setup were replicated using FE simulations and superimposed onto measurements of the trial pipe in its baseline state. The applied SHM algorithm was found to have the same sensitivity to these synthetic datasets as to those containing the real defect growth.

The final part of this thesis discusses a novel temperature compensation approach developed for application to results obtained from the SHM procedure. It was found that, even if a stretch based temperature compensation algorithm is applied to guided wave measurements, temperature related variations in the coherent noise floor of the inspected measurements as well as frequency response changes in the signals transmitted by the transducer ring will continue to be present. A newly developed compensation procedure allows for these variations to be significantly reduced enabling lower rates of false calls as well as an improved probability of detection for small defects.
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Chapter 1

1 Introduction

1.1 Guided wave inspection

With millions of kilometres of pipeline in operation globally [1] and an additional eighty-four thousand planned or under construction as of 2017 [2] it is essential that these critical parts of infrastructure are regularly inspected. The failure of a pipeline and the subsequent loss of content could potentially cause prohibitive economic damage to the operator in the form of fines [3] as well as expenditure for clean-up operations not to mention long-lasting negative effects on the environment. Therefore it is in the utmost interest of the pipeline operator to ensure that locations of potential failure are identified reliably and as early as possible.

Compared to conventional non-destructive testing (NDT) techniques the use of guided waves gives the operator the ability to inspect large volumes of pipework from a single measurement location in a short amount of time [4][5][6]. For a straight pipe in good general condition, it is possible to cover distances of over 50 meters with just one measurement [7]. The speed at which a given section of a pipeline can be fully inspected is increased dramatically with the use of guided waves. Since the largest expenditure for most NDT inspections lies in personnel cost rather than the equipment used, more rapid inspections can greatly reduce the cost per distance of inspected pipeline. It is furthermore possible to inspect insulated pipes while only removing a small portion of the insulating material in the immediate vicinity of the measurement equipment mounted on the pipe. In contrast to this, most other inspection procedures require the complete removal of the pipe insulation and thus much higher costs are incurred by the operator. Other technologies which allow for full inspection coverage of a pipe such as the use of pigs are far more costly and require the shutdown of the pipe operation during inspection as well as special launch and recovery sites. Should the equipment get stuck in the pipe, retrieval of the pig will exacerbate the economic damage to the pipe operator dramatically. However, for very long runs pigs can be more economical as the cost of launch and retrieval of the equipment will be lower than the cost of periodic access to the pipe for guided wave inspections [8][9].
1 Introduction

For the inspection of a pipe using guided waves a ring of transducers is attached on the outside of the structure [10] which most commonly emits a low frequency (usually <100kHz) torsional (T(0,1)) wave pulse. Two parallel rows of transducers spaced a quarter wavelength apart allow for directional control of the emitted signal [11]. The walls of the pipe act as a one-dimensional waveguide enabling large propagation distances. Changes in the impedance of the pipe wall will cause part of the signal to be reflected back in the direction of the transducer ring [12][13][14]. These impedance changes are usually caused by a change in the wall thickness of the pipe such as a weld, a flange, a pipe support or a corrosion patch. It should be noted here that this is only valid for features with sharp transitions in wall thickness. Tapered defects with a gradual change over a length approaching the inspection wavelength become increasingly difficult to identify [12][15]. Axisymmetric pipe features will only reflect the incident symmetric T(0,1) mode. If the feature is not axisymmetric such as a typical corrosion patch, part of the signal will also mode convert upon reflection into flexural wave modes. The reflected signals are recorded by the same transducer ring which was used to induce the ultrasonic wave into the structure. This mode of operation is commonly referred to as pulse-echo. Other systems may also operate in a pitch-catch mode where signals reflected and transmitted by features are recorded by a second transducer ring which was not utilised for transduction. The amplitude of the reflection gives the operator the ability to estimate the cross-sectional area change due to a feature while the ratio of torsional and flexural waves in the reflected signal allows for the nature of the reflector to be determined [11]. With the known torsional wave speed in the pipe material, and the delay between sending of the signal and recording subsequent reflections, the distance from the transducer ring to a given feature can be estimated.

1.1.1 State of the industry

Guided wave inspection technology was developed at Imperial College London in the 1990s and subsequently licensed to Guided Ultrasonics Ltd. [16] (a spin-out company from Imperial College) and the TWI subsidiary Plant Integrity Ltd. [17]. In both cases, rings of piezoelectric transducers are used to introduce the T(0,1) signal into the pipe structure. US-based SWRI also independently developed a guided wave inspection system based on magnetostrictive transduction technology [18][19].
1.1.1.1 Inspections and data analysis

As of 2018, the vast majority of guided wave inspections in the NDT industry are carried out using deployable transducer rings. In order to assess the state of a pipe section, an inspector is required to be present at location to attach the inspection equipment to the pipe and carry out the measurement. After the data collection stage has been completed the inspector is required to manually analyse the measurement. Both these stages of the process are very time consuming especially in the case of infrastructure in remote locations.

An example result of such a measurement is shown in Figure 1.1. A high level of skill and experience is required of an operator in order to distinguish between benign reflections and parts of the signal caused by reflections from defects in the inspected pipe. The identification of damage becomes even more challenging if the pipe is in a poor general state, if the inspected section includes complex geometries such as pipe bends and T-pieces or if it is partially buried [20][21][22]. All of these examples require the inspector to have undergone additional training in order to successfully identify damage in the pipe structure due to having the potential of reducing the sensitivity of the inspection system and producing more complex signal traces.

![Figure 1.1 Example measurement of the defect-free pipe section as shown in Figure 4.1 a). Red traces denote the flexural wave reflections while black traces show the T(0,1) mode reflections. The measurement is plotted on a logarithmic scale.](image)

For an inspection of a straight pipe section a sensitivity between 3% and 5% of the cross-sectional area (CSA) can be expected to be detected reliably by a skilled operator [7][23][24], though this value can vary depending on the general state of the pipe and the location of the defect with respect to other features [23][20]. A defect located close to a butt weld or pipe supports can be
more challenging to identify as the reflections from the benign feature and those of the defect will be superimposed and thus the defect can be masked and fail to be detected. The use of flexural mode reflections in conjunction with the $T(0,1)$ mode will partly mitigate this effect.

Therefore it can be said that in its current state guided wave inspections provide a significant advantage over conventional inspection techniques but are limited by the complexity of the pipe structure and the human element.

1.1.1.2 Monitoring vs. one-off inspections

In order to improve the sensitivity of a guided wave system and reduce the risk of operator error, a move from one-off inspections with detachable rings to structural health monitoring using permanently attached sensors is of great interest [23]. Monitoring will make it possible for more frequent measurements to be collected allowing for defects to be detected earlier, with higher sensitivity and then tracked over the course of the pipe’s lifetime. The growth rate of defects can thus be better estimated and therefore the repair and replacement of pipe parts can be scheduled more economically making full use of the structure’s lifecycle.

1.1.2 Guided Ultrasonics Ltd.

This project was supported by Guided Ultrasonics Ltd. (GUL) as an industrial partner. GUL was founded by members of the Imperial College London NDT group in 1999. Over the past two decades, GUL has become a world-leading manufacturer of guided wave testing equipment and a provider of related training services. All guided wave measurements discussed in this thesis were collected using Guided Ultrasonics Ltd. equipment.

The GUL product range encompasses a number of different products for the inspection of pipes as well as rails. A small selection of these devices can be seen in Figure 1.2. a) shows a standard solid transducer ring used for the one-off inspection of pipes. b) shows a permanently installed ring (gPIMS) of the sort which was employed for most measurements used in the development of the structural health monitoring framework described in this work. The Wavemaker test instrument used in conjunction with most GUL transducer rings can be seen in Figure 1.2 c). Further equipment such as high temperature, inflatable, low profile and subsea rings as well as
rail inspection equipment is also available from Guided Ultrasonics Ltd. but has not been depicted here.

![Image of equipment]

*Figure 1.2. Sample selection of GUL equipment. a) Solid ring used for on/off inspections. b) gPIMS for permanent installation. c) Wavemaker test instrument.*

1.2 Permanently attached guided wave sensors

Permanently attached guided wave sensors were developed by Guided Ultrasonics Ltd. and have been commercially available from GUL since 2005 under the product name gPIMS. These transducer rings are fixed in position on a pipe indefinitely, therefore allowing for repeated measurements of exactly the same section of a pipe to be collected over an extended period of time.

1.2.1 Installation procedure

The layout of the two transducer rows in a gPIMS (see Figure 1.2) is very similar to that of a standard deployable ring. All the electronics and transducers of the ring are located on a flexible array and are covered in a polyurethane mould which acts as a protective cover from the environment. During installation, an adhesive is applied to each of the transducer elements and the ring is placed on the pipe. The gPIMS contains a screw mechanism which allows for the ring to be tightened around the pipe ensuring good contact of the transducers. Gaps between the polyurethane mould and the pipe are filled with an adhesive polyurethane sealant preventing water ingress over the lifetime of the gPIMS. A cable is run from the transducer ring to a connector box located in a conveniently accessible location. An example of this can be seen in Figure 1.3. To collect a measurement an operator is required to connect the Wavemaker measurement equipment to the connector box.
1.2.2 Current uses of gPIMS and future potential

Currently, gPIMS are mainly in use in locations which are hard to access such as road crossings and buried pipes in remote locations [23]. If such a pipe requires regular inspection it is not economically viable to excavate the pipe whenever a measurement has to be performed. Since a gPIMS is attached permanently to the pipe, it can be reburied or covered with insulation such that all further measurements will be performed from the above ground connector box as described in Section 1.2.1 using a Wavemaker test instrument (Figure 1.2 c)). As an example, this methodology is currently employed by BP [25] for the inspection of around 400 pipeline road crossings in Alaska alone.

The inspection of pipes using gPIMS as of 2018 are performed similarly to those using deployable rings. However, in the case of gPIMS, temperature effects are compensated by the application of a distance dependent signal stretch to a baseline measurement such that baseline subtraction can be performed. Data collection is performed manually as is the interpretation of the collected measurements. This manual approach does not take advantage of the full potential of having a permanently installed inspection system in place such as improving the sensitivity to defects, tracking the growth of damage and reducing operator workload and thus the potential for human error.

1.3 Structural health monitoring

Most NDT inspection techniques produce a snapshot of the health state of a structure which then has to be interpreted by a skilled operator. Signals produced by benign features have to be
differentiated from those originating at defects, and coherent as well as random noise can reduce the sensitivity of the measurement. For guided wave inspections, the identification of damage becomes more challenging with increasing geometric complexity of the investigated structure and the location of a defect with respect to benign features can have a detrimental effect on its visibility.

The next logical step in the development of guided wave NDT for pipes therefore lies in a move from single manual inspections to a structural health monitoring (SHM) framework. The advantage of SHM lies in its ability to detect changes in a structure over time rather than locating and identifying individual features. In a most basic sense, this is achieved by comparing subsequent measurements of the same structure. The presumption made in an SHM framework is that the only changes to a structure, and thus the only changes in its guided wave signature, will originate from the growth of defects while the underlying benign features are constant and unchanging.

This view is oversimplified and in reality, challenges arise from changes to the signals caused by a multitude of factors such as environmental condition changes, variations in the contents carried by a pipe as well as non-constant pipe support loading.

1.3.1 Environmental condition changes

The central challenges to the move from single NDT inspections to long-term structural health monitoring are the variations that the underlying structure and thus the collected signals experience over the course of its lifetime [26][27]; the most significant factor is temperature variation. Some of these changes are caused by natural cycles such as daily or seasonal effects, others originate from factors such as a change in the contents of the monitored pipeline. A shift in the pipe temperature will result in a change in the material properties of the pipe thus influencing the velocity of guided waves propagating in the specimen. Therefore two measurements collected from the same pipe section at different temperatures will not be identical.

Differences in the loading of a pipe may also influence the contact force between the inspected pipe and its supports affecting the reflections recorded from these features which can be
1 Introduction

significantly increased or reduced in amplitude. A number of other factors can impact the collected guided wave signals, such as changes in soil covering the pipe, wet or dry insulation, viscosity and temperature of pipe contents etc.

1.3.2 Baseline subtraction

The most basic approach to utilising repeated measurements of the same pipe section is the application of baseline subtraction (BS). As the name suggests, with this technique a baseline signal is collected at the beginning of the inspection period. The assumption is made that the specimen is in a defect-free condition at the beginning of the investigation. This baseline signal can then be subtracted from any subsequent collections in order to obtain a residual signal. For complex signals, such as obtained from a guided wave measurement, small variations in the conditions of the pipe, as discussed in Section 1.3.1, can cause changes in the reflections of the benign pipe structure such that the residual signals after BS subtraction are large enough to obscure small defect reflections [28]. In order to compensate for temperature effects before BS, various methodologies are available [23][29][30].

A procedure which allows for some temperature effects to be removed from residual signals is optimal baseline subtraction (OBS) [31][30][32]. To perform OBS a number of baseline signals are collected at different temperatures in an attempt to cover the full range of temperatures over which the specimen may vary during the monitoring phase. When subsequent measurements are collected the residual signal is produced by subtracting the baseline signal from the measurement at the most similar temperature or rather the baseline which produces the lowest RMS residual signal [30][33]. An obvious disadvantage of the OBS approach is the need for the baseline set to cover the full range of potential temperatures and the fact that other factors of the underlying changes in the signals such as support load changes cannot reliably be considered. OBS is currently employed by GUL instrumentation for measurements collected using gPIMS. To further improve the performance of this procedure a distance dependent stretch is applied to the baseline signals in order to reduce temperature effects. This procedure will be discussed in detail in Section 3.1 of this thesis.
1.4 Project objectives

The objective of this EngD project was the development of a structural health monitoring system using permanently installed guided wave sensors. The main focus here lay with the development and application of effective temperature compensation and signal processing approaches utilising data collected from a gPIMS supplied by this projects industrial sponsor Guided Ultrasonics Ltd. The target of the SHM system was the reduction of the minimum defect size detectable, the tracking of defect growth throughout the whole inspection period and partial automation of the detection system such that the workload of the user could be reduced significantly.

1.5 Thesis structure

This thesis is structured as follows. Chapter 2 describes the properties of guided ultrasonic waves in cylindrical structures as well as the finite element analysis theoretical background and how FE can be used to simulate the propagation of guided waves in pipes. In Chapter 3 the structural health monitoring method utilised throughout this thesis is presented and all the algorithms included in this procedure are described in detail. Chapter 4 focuses on the results obtained from a blind trial which was performed in order to assess the capabilities of the presented SHM procedure. During this blind trial, a reduced sensitivity of the SHM algorithm to defects located on a pipe bend was identified. Therefore the sensitivity of T(0,1) guided waves to defects on pipe bends was investigated using FE simulations and the results of this study are presented in Chapter 5. Chapter 6 describes a methodology which allows for the sensitivity of an installed SHM system to be determined prior to any defect growth as long as a set of baseline measurements has been collected in a constant state. The validity of this procedure was tested using results obtained from the blind trial presented in Chapter 4. In Chapter 7 a methodology is discussed which reduced the variations in the SHM algorithm results induced by environmental condition changes such as temperature fluctuations. This procedure allows for the sensitivity of the presented SHM algorithm to be improved and for its false call rate to be further reduced. Finally, Chapter 8 gives some concluding remarks on the work presented in this thesis and discusses potential areas of future work.
Chapter 2

2 Guided waves and FE modelling

This chapter will discuss the theoretical background of guided waves in hollow cylinders and the different wave modes propagating in such a geometry. Finite element analysis, the introduction of guided wave signals into the FE model of a pipe and the methodology of interpreting the signals recorded from the simulated geometry will be reviewed in the second half of this chapter.

2.1 Guided waves in pipes

The first theoretical investigations of guided waves in bars and rods date back to the late nineteenth century [34][35]. In the nineteen-twenties, the properties of sound waves propagating in hollow cylinders, such as pipes, were first described mathematically [36].

The propagation of guided waves in cylindrical geometries has received a lot of attention since the nineteen-nineties as it was, at this point, possible to first successfully realise their potential for the detection of defects in pipe structures. The application of guided wave inspections for pipes had been discussed since as early as the nineteen-seventies but was never successfully employed [37][38]. The delay between theoretical groundwork and the implementation of guided wave inspection can mainly be attributed to the challenges arising from the development of transduction technology allowing for the generation of only the desired inspection modes. The first guided wave systems for the long-range inspection of pipes utilised Lamb wave propagation. The ultrasonic signals were induced into the pipe via a ring of transducers. This system was developed by Alleyne et al. at the Imperial College NDE group in the early nineteen-nineties [39][10][40][4] and was first commercialised by the TWI subsidiary Plant Integrity Ltd. [17]. The Guided Ultrasonics Ltd. [16] pipe inspection system is based on torsional guided wave propagation [41] and so are the more recent implementations of the Plant Integrity Ltd. system.

2.1.1 Elastic waves in isotropic media

The propagation of bulk waves can be derived, as presented in this section, from Hooke’s law and Newton’s second law of motion [42]. For an elastic isotropic solid the following set of equations can be derived
\[ \varepsilon_{xx} = \frac{\partial u}{\partial x}, \quad \varepsilon_{yy} = \frac{\partial v}{\partial y}, \quad \varepsilon_{zz} = \frac{\partial w}{\partial z} \]

\[ \varepsilon_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}, \quad 2\ddot{\omega}_x = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}, \quad 2\ddot{\omega}_y = \frac{\partial v}{\partial z} - \frac{\partial w}{\partial x}, \quad 2\ddot{\omega}_z = \frac{\partial w}{\partial x} - \frac{\partial u}{\partial y} \]

(2.1)

where \(u, v\) and \(w\) are displacements along the corresponding Cartesian coordinates \(x, y\) and \(z\). \(\varepsilon_{xx}, \varepsilon_{yy}\) and \(\varepsilon_{zz}\) are the normal strains the components, while \(\varepsilon_{yz}, \varepsilon_{zx}\) and \(\varepsilon_{xy}\) correspond to the shear strains in the material. The final three components \(\ddot{\omega}_x, \ddot{\omega}_y\) and \(\ddot{\omega}_z\) do not relate to deformation of the material but rather represent the rotation of a rigid body.

From the generalised Hooke’s law [43] for an isotropic body, the following set of stress components can be obtained

\[ \sigma_{xx} = \lambda \Delta + 2\mu \varepsilon_{xx}, \quad \sigma_{yy} = \lambda \Delta + 2\mu \varepsilon_{yy}, \quad \sigma_{zz} = \lambda \Delta + 2\mu \varepsilon_{zz} \]

\[ \sigma_{yz} = \mu \varepsilon_{yz}, \quad \sigma_{zx} = \mu \varepsilon_{zx}, \quad \sigma_{xy} = \mu \varepsilon_{xy} \]

(2.2)

where \(\mu\) and \(\lambda\) are the Lamé’s constants [44] and the quantity \(\Delta\) denotes the dilation i.e. the change in volume of a unit cube and is defined as \(\Delta = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}\). From Newton’s second law of motion using the strain components defined in equation (2.1), it follows for displacements in each of the spatial dimensions that

\[ \rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} \]

\[ \rho \frac{\partial^2 v}{\partial t^2} = \frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} \]

\[ \rho \frac{\partial^2 w}{\partial t^2} = \frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} \]

(2.5)

By substituting the appropriate components from equations (2.1) and (2.2) into equations (2.3) they can be written in terms of the volumetric change and the material properties as

\[ \rho \frac{\partial^2 u}{\partial t^2} = (\lambda + \mu) \frac{\partial \Delta}{\partial x} + \mu \nabla^2 u \]

\[ \rho \frac{\partial^2 v}{\partial t^2} = (\lambda + \mu) \frac{\partial \Delta}{\partial y} + \mu \nabla^2 v \]

\[ \rho \frac{\partial^2 w}{\partial t^2} = (\lambda + \mu) \frac{\partial \Delta}{\partial z} + \mu \nabla^2 w \]

(2.4)
where the Laplacian $\nabla^2$ is defined as $\nabla^2 = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)$ and $t$ denotes time. By differentiating both sides of each equation in (2.4) in the respective dimension ($x$, $y$ and $z$) and summing the results the following wave equation can be obtained:

$$\frac{\partial^2 \Delta}{\partial t^2} = \frac{(\lambda + 2\mu)}{\rho} \nabla^2 \Delta$$  (2.5)

Equation (2.5) shows that a dilation in an elastic isotropic material medium propagates as a wave through the material with a velocity of $c_L = \sqrt{\frac{(\lambda+2\mu)}{\rho}}$. If the dilation of the material is equal to zero ($\Delta = 0$) the set of equations in (2.4) will simplify to:

$$\frac{\partial^2 u}{\partial t^2} = \frac{\mu}{\rho} \nabla^2 u$$  (2.6)

$$\frac{\partial^2 v}{\partial t^2} = \frac{\mu}{\rho} \nabla^2 v$$

$$\frac{\partial^2 w}{\partial t^2} = \frac{\mu}{\rho} \nabla^2 w$$

In this case for the propagation of an equivoluminal wave, the velocity is found to be given by $c_s = \sqrt{\frac{\mu}{\rho}}$. The wave equations derived in equations (2.5) and (2.6) define the two independently propagating wave modes in an unbound solid medium and are termed longitudinal (irrotational) and shear (equivoluminal) waves respectively.

2.1.2 Guided waves in hollow cylinders

The propagation of waves in a hollow cylinder was described by Gazis [45][46] and his derivation is followed in this section. For waves propagating along the axial direction in a hollow cylinder, the use of a cylindrical coordinate system is most appropriate. Thus $z$ is defined as the axial dimension, $r$ is the radial direction and $\phi$ is the circumferential coordinate. These three coordinates can be seen in Figure 2.1.
Equations (2.4) can also be written as a single equation in terms of the displacement vector $\mathbf{u}$ as

$$\mu \nabla^2 \mathbf{u} + (\lambda + \mu) \nabla \nabla \cdot \mathbf{u} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \quad (2.7)$$

The application of the Helmholtz decomposition [47] allows for equation (2.7) to be expressed in terms of a compressional/dilatational scalar potential $\Phi$ and an equivoluminal vector potential $\mathbf{H}$ such that

$$\mathbf{u} = \nabla \Phi + \nabla \times \mathbf{H} \quad (2.8)$$

where

$$\nabla \cdot \mathbf{H} = F(r, t) \quad (2.5)$$

for a function $F$ of both the radial coordinate vector $\mathbf{r}$ and the time $t$. By substitution of equations (2.8) and (2.9) in the equation of motion (2.7) the wave equations for both longitudinal and shear waves are found to be given as:

$$c_L^2 \nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial t^2} \quad (2.16)$$

$$c_S^2 \nabla^2 \mathbf{H} = \frac{\partial^2 \mathbf{H}}{\partial t^2}$$
with the longitudinal and shear wave velocities denoted by $c_L = \sqrt{\frac{(\lambda+2\mu)}{\rho}}$ and $c_S = \sqrt{\frac{\mu}{\rho}}$
respectively. Following the derivation of Gazis, the scalar potential $\Phi$ and the vector potential $H$ can take the form

$$
\begin{align*}
\Phi &= f(r) \cos n\phi \cos(\omega t + \xi z) \\
H_r &= g_r(r) \sin n\phi \sin(\omega t + \xi z) \\
H_\phi &= g_\phi(r) \cos n\phi \sin(\omega t + \xi z) \\
H_z &= g_3(r) \sin n\phi \cos(\omega t + \xi z)
\end{align*}
$$

where $\xi$ is the wavenumber. Substituting equations (2.11) in (2.10) yields

$$
\begin{align*}
\left(\frac{\nabla^2 + \omega^2}{c_L^2}\right)\Phi &= 0 \\
\left(\frac{\nabla^2 + \omega^2}{c_S^2}\right)H_z &= 0 \\
\left(\frac{\nabla^2 - 1}{r^2} + \frac{\omega^2}{c_S^2}\right)H_r - \left(\frac{2}{r^2}\right)\left(\frac{\partial H_\phi}{\partial \phi}\right) &= 0 \\
\left(\frac{\nabla^2 - 1}{r^2} + \frac{\omega^2}{c_S^2}\right)H_\phi + \left(\frac{2}{r^2}\right)\left(\frac{\partial H_r}{\partial \phi}\right) &= 0
\end{align*}
$$

This set of equations can be solved using Bessel functions and modified Bessel functions as described in [45]. This allows for a set of three equations for the displacement fields in the three cylindrical coordinate dimensions to be described in the form

$$
\begin{align*}
u_r &= \left( f' + \left(\frac{n}{r}\right)g_3 + \xi g_1 \right) \cos n\phi \cos(\omega t + \xi z) \\
u_\phi &= \left( -\left(\frac{n}{r}\right)f + \xi g_1 - g_3 \right) \sin n\phi \cos(\omega t + \xi z) \\
u_z &= \left( -\xi f - g_1' - (n + 1) \left(\frac{g_1}{r}\right) \right) \cos n\phi \sin(\omega t + \xi z)
\end{align*}
$$

where $g_1 = 0.5 \cdot (g_r - g_\phi)$ and $g_2 = 0.5 \cdot (g_r + g_\phi)$ and primes denote derivatives with respect to $r$. For the torsional modes of interest which only have displacements in the circumferential direction, it can be assumed that $f = g_1 = 0$ thus resulting in only the $u_\phi$ term of the set of equations in (2.13) being non-zero. The displacement field thus simplifies to (see [45])

$$
u_\phi = Ar \cdot \sin(\omega t + \xi z)$$

34
2.1.3 Different guided wave modes

Shear and compressional waves are the only two bulk waves propagating in a hollow cylinder geometry. Guided waves, which can exhibit displacement both transverse and parallel to the propagation direction, can be described as a combination of these two bulk wave modes and are divided into three different mode families travelling in the axial direction (see Figure 2.1) of the structure. These are the axisymmetric longitudinal and torsional modes and the non-axisymmetric flexural modes. By convention of Zemanek and Meitzler [48][49][37], the nomenclature used in this thesis for guided wave modes propagating in a pipe geometry is shown in Table 2.1.

<table>
<thead>
<tr>
<th>Torsional</th>
<th>Axisymmetric</th>
<th>T(0,m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>Axisymmetric</td>
<td>L(0,m)</td>
</tr>
<tr>
<td>Flexural</td>
<td>Non-axisymmetric</td>
<td>F(n,m)</td>
</tr>
</tbody>
</table>

*Table 2.1 Guided wave mode families propagating in hollow cylinders*

Here \( m = 1,2,3, \ldots \) denotes the mode and \( n = 1,2,3, \ldots \) denotes the mode circumferential order. The F(1,2) and F(2,2) flexural modes are torsional type waves as the majority of their displacement is in the circumferential direction while the F(1,3) and F(2,3) modes are longitudinal type waves due to most of their displacement being oriented in the axial direction of the pipe [41]. The phase and group velocities with respect to frequency for each mode can be plotted in a set of dispersion curves as shown in Figure 2.2 [50]. Here it can be seen that most of the guided wave modes present in a pipe are highly dispersive and therefore an excitation procedure is required which allows for good control over which modes are induced into the inspected structure [51][10][52]. As seen in Figure 2.2 the first order torsional wave mode T(0,1) in a hollow cylinder is non-dispersive, an advantageous property when used in guided wave inspection applications [41]. The transducers used for guided wave inspections of pipes operate in the low kilohertz regime (< 100kHz) below the cut-off frequency of the second and higher order torsional modes which will therefore not be excited in the inspected pipe. Early applications of guided wave inspections for pipes were based on the L(0,2) Lamb wave propagation as this mode is also close to non-dispersive over wide frequency ranges as seen in Figure 2.2. Both the T(0,1) and L(0,2) modes have displacements close to uniformity throughout the wall thickness.
of a hollow cylinder which allows for the detection of defects both on the inside and outside of a pipe. However, the T(0,1) mode has a number of advantages over the L(0,2) mode [41]. Firstly, due to the torsional mode being a pure shear wave it is not attenuated by liquid loading of inspected pipes or during subsea applications, unlike longitudinal L(0,2) signals [53][54][55][56]. It should however be noted here that highly viscous liquids will also attenuate the torsional T(0,1) mode. This effect though is usually negligible for applications of guided waves in the petrochemical industry. Secondly, although L(0,2) signals are slightly more sensitive to circumferential crack-like defects than torsional waves, L(0,2) based systems are unable to detect cracks orientated along the axial dimension of a pipe [14][57][58].

![Figure 2.2 Dispersion curves of phase velocity for an 8 inch schedule 40 carbon steel pipe](image)

The guided wave signal, propagating along the structure, will be partially reflected when encountering pipe features that cause a variation in the cross-sectional area of the pipe wall due to a change in the effective acoustic impedance of the structure [59][13][14]. These impedance changes can be caused by benign features such as pipe welds, flanges or t-pieces etc. Defects such as corrosion patches will also cause part of the signal to be reflected. Due to the symmetry of the T(0,1) mode, the reflected signals from axially symmetric features such as welds will experience no mode conversion, while the reflections from non-symmetric features such as defects will be partially converted to torsional type flexural waves (F(1,2) and F(2,2)). Since both of
these modes have propagation velocities close to that of the T(0,1) mode (see Figure 2.2) the
flexural and torsional signals reflected from a non-axisymmetric feature will arrive at
approximately the same time. The amplitude ratio of flexural and torsional modes reflected from
a feature is a function of the degree of asymmetry of the reflector and thus predictions about its
circumferential extent can be made [58].

For the successful application of guided waves for the inspection of a pipe it is necessary that
the number of modes propagating in the structure is limited, otherwise the interpretation of
recorded signals may become prohibitively complicated. To achieve optimal mode selection a
number of shear wave transducers are attached as a ring around the circumference of the pipe
at the same axial position [10][41]. By exciting all of the transducers simultaneously tangentially
it is possible to excite a pure torsional T(0,1) wave while also suppressing the generation of
flexural modes with an order of \( n < d \) where \( d \) is the number of transducers. The same
displacement can be achieved for an electromagnetic system with a driving coil circumferentially
wrapped around the outside of the pipe [60][18].

In order to control the direction of propagation of the introduced guided wave signal, a second
row of transducers is attached to the inspected pipe [11] with a distance of \( \frac{\lambda}{4} \) where \( \lambda \) is the
wavelength at a centre frequency of the signal pulse. By exciting the second row of transducers
with a phase delay of \( \frac{\pi}{2} \) the signals from the two rows will interfere constructively in the forward
propagation direction while interfering destructively for backwards travelling waves [11]. This
setup ensures that reflected signals recorded by the transducers are known to originate from
features located in the forward direction. It should be noted though that for practical guided
wave measurements these phase delays are added to the recorded signals in a post-processing
step rather than during data collection. This allows for forward and backward signals as well as
other propagating modes to be extracted from a single set of collections while using less
complicated electronics.

2.2 Finite element analysis

The propagation of ultrasonic waves in pipes with complex geometrical features such as bends,
butt welds, t-pieces and defects cannot easily be described analytically. Therefore numerical
models such as finite element analysis are utilised. By discretising the model in the time domain the propagation of guided waves can be described and a great deal of information about signal interaction with complex features can be gained. Some effects such as changes in the environmental operating conditions of the system cannot however be simulated to a satisfying degree.

2.2.1 Model setup

All finite element models of pipe geometries presented in this thesis were constructed using structured meshes utilising linear brick elements (C3D8R). For an 8 inch schedule 40 carbon steel pipe with a nominal wall thickness of 8.18\text{mm} and an outer diameter of 219.1\text{mm} a total of 4 elements were used in the radial direction and 300 elements around the pipe circumference. This gives an approximate element size of \( \Delta s = 2\text{mm} \) and thus the relation between element size and the wavelength of the signal of

\[
\Delta s = \frac{\lambda_{\text{min}}}{7}
\]

is satisfied \cite{ref} for an input signal pulse consisting of a multi-cycle Hanning window tone burst with a centre frequency of 25.5\text{kHz} where \( \lambda_{\text{min}} \) is the shortest wavelength in the model. As an example, for an 8 cycle tone burst, the minimum wavelength lies around 100\text{mm} and therefore this requirement is effortlessly satisfied. The time step of the FE simulations was chosen to be \( \Delta t = 0.2\mu s \) which lies below the minimum requirement of

\[
\Delta t = 0.8 \cdot \frac{\Delta s}{v_{\text{max}}}
\]

where \( v_{\text{max}} \) is the maximum wave velocity in the propagating in the FE model.

The time history outputs of the finite element models were recorded at a sampling frequency of 200\text{kHz}. It should be noted though that the size of some elements may vary around the target value of 2\text{mm} for some geometries such as bends or at the location of introduced defects. This however does not affect the performance of the FE models to a significant degree and the effect of these changes in element size is negligible in the case of the FE models presented in this thesis. An example cross-sectional view of such a pipe setup can be seen in Figure 2.3.
2.2.2 Introducing the T(0,1) mode

In order to introduce the desired pure T(0,1) mode into the FE model, a ring of excitation nodes is designated around the circumference of the pipe (Figure 2.4). These nodes can subsequently be displaced synchronously in the tangential direction thus generating a torsional wave in the model while no longitudinal or flexural modes are induced. For all models presented in this thesis no second ring of excitation nodes was used for directional control as described in section 2.1.3 since the same effect can be achieved by simply removing signals propagating in the undesired direction via a section of absorbing layers [62][63][64][65][66][67]. Absorbing layers can be generated by including a region in the FE model which has the same elastic properties as the rest of the model with the only difference that the damping of the material is slightly increased with distance. Due to the difference in impedance between the two materials a small and negligible amount of the incoming signal is reflected. With an absorbing layer of sufficient length and of ever increasing damping a signal entering this region will be slowly dissipated and thus effectively removed from the FE model.
2.2.3 Measuring signals and extracting modes

Signals propagating in the FE model of a pipe geometry are recorded by a ring of monitoring nodes on the surface of the pipe. At each of these points, the displacement in all three Cartesian dimensions is recorded. This allows for displacement in tangential direction at the monitoring nodes to be determined. By simply summing these tangential displacements the torsional T(0,1) mode can easily be extracted as described by Wilcox [68]. The first order flexural mode F(1,2) can be obtained from the same measurements by taking the angle in the circumferential direction of each of the monitor nodes into consideration. The procedure of extracting these two wave modes can be written as an equation in the form:

\[
T(0,1) = \sum_{i=1}^{N} u_i
\]

(2.17)

And

\[
F(1,2) = \sqrt{\left(\sum_{i=1}^{N} u_i \cos \phi_i\right)^2 + \left(\sum_{i=1}^{N} u_i \sin \phi_i\right)^2}
\]

(2.18)

where \(u_i\) and \(\phi_i\) denote the tangential displacement of the \(i^{th}\) monitor node and its circumferential position respectively. \(N\) is the total number of monitoring nodes at the given axial position. It should be noted that the flexural mode described in equation (2.18) is present in the form of a pair with each of its two constituents having zero displacement at one of the two principal axes.
2.2.4 Introduction of defects

Two distinct ways of introducing defects into FE models were utilised for the simulations described in this thesis. The first of these was the application of disconnecting elements of the FE model in order to simulate crack-like defects. This is a well-established approach and has seen wide application in numerical simulations for ultrasonic NDE applications [69][70]. The second defect type generated in FE applications was corrosion like damage. These defects were introduced by shifting the position of nodes to fit a target damage shape. This process will slightly alter the shape of some elements of the FE model which is acceptable as long as the elements are not too deformed and equations (2.15) and (2.16) still hold. A more detailed description of how the elements were deformed will be given in Section 6.2.2.

2.3 Conclusions

This chapter presented the derivation of shear and longitudinal bulk waves propagating in elastic isotropic media. From these results, the torsional guided wave mode T(0,1) propagating in a hollow cylinder geometry was derived. The properties of torsional, longitudinal and flexural wave modes propagating in such a geometry were discussed and their respective advantages and disadvantages for non-destructive evaluation applications for pipes were presented. It was shown that torsional T(0,1) guided waves are the most suitable for such inspections.

This chapter also presented the finite element simulation setup which will be used throughout this thesis. The limiting factors on maximum element size with respect to inspection frequency and the necessary time step length were discussed. Finally, two methods of introducing defects into FE models were presented by either disconnecting nodes or by deforming elements.
3 Structural health monitoring procedure

Chapter 3

3 Structural health monitoring procedure

The structural health monitoring procedure employed throughout this thesis on data collected from permanently installed guided wave sensors will be discussed in this chapter. This methodology was applied to measurements collected from the blind trial setup presented in Chapter 4 and the sensitivity estimation methodology of Chapter 6.

The health monitoring approach utilised throughout this thesis is based on previous work of Liu, Dobson et al. [71]. This SHM methodology showed very promising results when applied to artificial defect sets compared to the sensitivity of a more common baseline subtraction centred approach. The presented SHM procedure [71] can be subdivided into 3 different stages, the first being the application of a temperature compensation algorithm to the collected guided wave signals. The second stage is the use of independent component analysis (ICA), a statistical signal processing algorithm, enabling the decomposition of the dataset of guided wave collections into pairs of weighting functions and corresponding components. These pairs allow the location of features to be determined and the change in amplitude of these features over time to be determined. The third and final stage of the SHM procedure is the identification of those ICA component-weight pairs which correspond to the growth of actual damage rather than benign features or signal noise.

3.1 Environmental condition changes and compensation

A major challenge for all NDE monitoring applications is the effect of environmental condition changes on measurements collected from the same structure at different points in time. It is important to be aware of these effects when moving from a laboratory environment to on-site applications. It is not possible for a structure in industrial use to permanently be in a constant state. A great number of factors may influence the quality of a guided wave collection from a pipe section, such as changes in the temperature of the pipe itself or its contents, changes in the contents carried by the structure, wet or dry insulation etc. All these environmental variations will have unpredictable effects on the collected measurements making the application of simple
baseline subtraction or optimal baseline selection approaches infeasible \([72][33][73][29]\). It is therefore desired to remove as much of the effects of environmental condition changes as possible from the guided wave measurements prior to the application of further signal processing techniques.

3.1.1 Temperature changes

The most significant and prevalent environmental condition change is the effect of variations in a pipe’s temperature on the propagation properties of a guided wave signal. Changes in material temperature will cause the velocity of the torsional \(T(0,1)\) to be altered \([73][74]\) leading to a difference in the arrival time of echoes reflected from the same pipe feature. An example of two signals collected from the same structure at different temperatures can be seen in Figure 3.1. It is clearly visible that there exists a delay between the arrival time of reflections from the same pipe features since the velocity of the \(T(0,1)\) mode is increased at lower temperatures of the structure. It should also be noted that changes in the temperature of a pipe will not only change the arrival time of echoes but also cause changes in the interference of two signals reflected from features in close proximity. This effect can cause the amplitude of the reflected signal from some features to be dependent on the temperature of the inspected structure.

![Figure 3.1 a) Example signals collected at two different temperatures. b) Zoomed in view of the pipe cut end reflection at 4.5m. Measurements shown here were collected in the forward direction of the pipe shown in Figure 4.1 a).](image-url)

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3.1.2 Scale transform temperature compensation

The environmental variation compensation method of choice for the SHM approach presented in this chapter is the scale transform temperature compensation algorithm introduced by Harley et al. [75]. A change in the temperature of an inspected pipe will cause its material properties to be altered such that the velocity of the torsional T(0,1) mode in the structure will be affected. Assuming a uniform temperature distribution along the inspected section of the pipe, the baseline signal and the measured signal after a temperature shift can be expressed as \( x(t) \) and \( s(t) \) respectively. The variable \( \gamma \) will denote the factor by which the measured signal is stretched due to temperature compared to the baseline measurement. It should be noted here that a change in arrival time of a reflection from a feature increases linearly with distance from the transducer ring when comparing two measurements collected on the same structure at different temperatures.

During the process of temperature compensation, the stretch factor \( \gamma \) is not known. The aim of the compensation algorithm is thus to determine the best estimate \( \hat{\gamma} \) of the stretch factor by minimising the normalised square error between the baseline signal \( x(t) \) and the measured signal \( s(t) \) such that

\[
\hat{\gamma} = \arg\min_{\gamma} \int_{0}^{\infty} \left| \frac{x(t)}{\sigma_x} - \frac{s(\gamma t)}{\sigma_x / \sqrt{\gamma}} \right|^2 dt
\]

with the two signal energy normalisation factors for both \( x(t) \) and \( s(\gamma t) \) defined as

\[
\sigma_x^2 = \int_{0}^{\infty} |x(t)|^2 dt
\]

\[
\frac{\sigma_s^2}{\gamma} = \int_{0}^{\infty} |s(\gamma t)|^2 dt
\]

By binomial expansion of equation (3.1) the stretch factor estimate becomes

\[
\hat{\gamma} = \arg\min_{\gamma} \int_{0}^{\infty} \left| \frac{x(t)}{\sigma_x^2} + \frac{|s(\gamma t)|^2}{\sigma_s^2 / \gamma} - \frac{2x(t)s(\gamma t)}{\sigma_x \sigma_s / \sqrt{\gamma}} \right| dt
\]

\[
= \arg\max_{\gamma} \frac{\sqrt{\gamma}}{\sigma_x \sigma_s} \int_{0}^{\infty} x(t)s(\gamma t) dt = \arg\max_{\gamma} \frac{\sqrt{\gamma}}{\sigma_x \sigma_s} \Gamma_{xs}(\gamma)
\]
where \( F_{x_x}(\gamma) = \int_0^\infty x(t)s(\gamma t) \, dt \), a function of the stretch factor, is defined as the scale cross-correlation between the baseline signal and the measured signal.

The scale transform is defined as [76]

\[
\mathcal{G}\{x(t); c\} = X(c) = \int_0^\infty x(t)t^{-ic-0.5} \, dt
\]  

(5.4)

and its inverse

\[
\mathcal{G}^{-1}\{X(c); t\} = x(t) = \frac{1}{2\pi} \int_{-\infty}^\infty X(c)t^{ic-0.5} \, dc
\]  

(5.5)

Parseval’s theorem is satisfied by the scale transform and therefore the energy of the signal is conserved when it is transformed between the time and scale domain.

The application of a phase shift to a signal in the Fourier domain is an analogous operation to time-delowering a signal in the time domain. A phase shift to a signal in the scale domain will manifest as an energy conserving stretching of the signal in the original time domain [76] which is the desired effect of an algorithm compensating for temperature induced signal stretch such that [76]:

\[
\mathcal{G}\{\sqrt{\gamma}x(\gamma t); c\} = X(c)e^{-ic\ln(\gamma)}
\]  

(5.6)

During temperature compensation optimisation the process of applying the scale transform and its inverse operation to a signal has to be performed a large number of times. Therefore it was proposed by Harley et al. [75] to utilise the computationally more efficient fast Mellin transform[77][78][79]. The forward and reverse scale transforms can thus be defined in terms of the simple Fourier transform as:

\[
\mathcal{G}\{x(t); c\} = \mathcal{F}\{e^{0.5\tau}x(e^\tau); c\}
\]  

(5.7)

and

\[
\mathcal{G}^{-1}\{X(c); t\} = e^{-0.5\ln(t)}\mathcal{F}^{-1}\{X(c); \ln(t)\}
\]  

(5.8)

where \( t = e^\tau \). It can be shown that the scale cross-correlation can also be expressed in the form
3 Structural health monitoring procedure

\[ \mathcal{X}^{-1}\{X^*(c)S(c); \gamma\} = e^{-0.5\ln(\gamma)}\mathcal{F}^{-1}\{X^*(c)S(c); \ln(t)\} = \Gamma_s(\gamma) \]  

\((5.5)\)

and therefore equation (3.3) yields

\[ \hat{\gamma} = \arg\max_{\gamma} \frac{1}{\sigma_x \sigma_s} \mathcal{F}^{-1}\{X^*(c)S(c); \ln(\gamma)\} \]  

\((5.16)\)

This allows for the optimal stretch factor between signals \(x(t)\) and \(s(t)\) to be determined without the computationally very expensive process of actually stretching the signals in the time domain. Harley et al. showed that the application of scale transform based temperature compensation methods is computationally far superior to more conventional approaches such as optimal signal stretch [75][30].

3.2 Independent component analysis

The second stage of the structural health monitoring process introduced by Liu, Dobson et al. [71] and presented in this thesis is the application of the blind source separation (BSS) technique independent component analysis [80][81]. For the purpose of identifying changes in individual features in the inspected structure ICA is much better suited than other statistical methods such as principle component analysis (PCA) and singular value decomposition (SVD), as these maximise the variance of components resulting in inferior separation of features. ICA allows for a mixture of signals originating from different sources with unknown magnitudes to be separated into the previously unknown original source signals and their corresponding mixing parameters [82][83]. This can be expressed in the form

\[ x_i(t) = a_{i1}s_1(t) + a_{i2}s_2(t) + \cdots + a_{in}s_n(t) \]  

\((5.11)\)

where \(x_i(t)\) are the measured time signals recorded as a combination of the mixing parameters \(a_{ij}\) and the corresponding statistically independent source signals \(s_j\) for \(i, j = 1, \ldots, n\). In the case of applying this ICA algorithm to guided wave measurements, \(x_i(t)\) will be defined as the signals collected by the transducer ring attached to the pipe, the source signals \(s_j\), in an ideal case, are the signals reflected from a given feature in the pipe and \(a_{ij}\) are the weighting functions which contain information about the amplitude of a given feature over the course of the monitoring period.
For simplicity equation (3.11) can also be expressed in matrix form as

\[ x = \sum_{i=1}^{n} a_i s_i = As \]  \hspace{1cm} (5.12)

The goal of the ICA algorithm is the determination of the mixing matrix \( A \) such that it is possible to estimate the source signals \( s \) from its inverse as

\[ s = Wx = A^{-1}x \]  \hspace{1cm} (5.15)

For the estimation of the weighting matrix \( W \) and the source signals \( s \) the FastICA algorithm by Hyvärinen and Oja [84] was utilised. The FastICA approach approximates individual weighting vectors \( w \) iteratively in a number of steps by maximising the nongaussianity of \( w^T x \). When finding multiple weighting functions \( w_1, ..., w_n \) a decorrelation step has to be included in the ICA algorithm in order to prevent multiple components from converging towards the same result.

In order to illustrate the performance of the ICA algorithm, an example set of 100 measurements is shown in Figure 3.2. This set was artificially created from a single real guided wave signal collection. The maximum amplitude of the signals is randomly varied close to an amplitude of 100%. A different stretch factor was applied to each of the individual signals in order to simulate temperature effects. However, since the same underlying baseline collection was used for all 100 measurements the applied stretch was almost perfectly removed by the temperature compensation algorithm described in Section 3.1.2. A reflection from a pipe cut end can be seen at approximately 5 meters. At the 2.5m location a defect is grown artificially by superimposing a simple 8 cycle tone burst onto the baseline signals. The amplitude of this defect signal is zero for the first 20 measurements and then linearly increases to 0.1 over the next 80 collections. When applying the FastICA algorithm to this dataset, two component and weighting function pairs can be extracted. These are shown in Figure 3.2 b) and c). It can clearly be seen that c) corresponds to the baseline signal. The component incorporates the large reflector at 5m and the weighting function is stable close to 100% over the full dataset. Figure 3.2 b) on the other hand clearly displays a component at the 2.5m position (the location of the defect) and the corresponding weighting function is at 0% for the first 20 measurements and then linearly.
3 Structural health monitoring procedure

increases to 10% until the end of the dataset. These example results, therefore illustrate the expected performance of the FastICA algorithm when applied to a set of guided wave data. It should be noted here though, that for real collections with environmental condition changes affecting the arrival times of feature reflections, the coherent noise floor, the attenuation of the signals and other features, the FastICA algorithm will resolve the dataset into a much larger number of components such that no single baseline component will exist.

![Graphs showing amplitude as a function of distance and measurement number, with weights and components.](image)

*Figure 5.2 Example results of FastICA procedure. a) Dataset of 100 measurements with cut end reflection at approximately 5m and a defect growing at 2.5m. b) Component and weighting function of defect growth. c) Component and weighting function of baseline signal.*

3.3 Post-processing

After the application of both initial scale transform temperature compensation and the independent component analysis algorithm a large number of component and weighting function pairs are obtained. The final step of the SHM procedure, therefore, is the identification of those components and weighting functions which are related to the growth of real damage in the inspected structure rather than benign features or noise. The number of components obtained from the FastICA algorithm is largely dependent on the number of measurements in the dataset.
used during the analysis. It can be assumed though that this number will usually be higher than 50 for a dataset containing more than 100 individual guided wave measurements of a structure. Due to the possibility of operator error when dealing with repetitive large datasets, some post-processing steps are applied to the ICA outputs in order to reduce the quantity of components and weighting functions, which will have to be inspected manually by the operator, to a more manageable size. Two of these post-processing steps applied to the ICA algorithm results will be presented in the following subsections.

3.3.1 Temperature dependence

Even after the application of a temperature compensation procedure to the guided wave measurement set, prior to the use of the FastICA algorithm, weighting functions will still exhibit behaviour reflecting environmental condition changes. This effect can be seen in Figure 3.3 where both the weighting functions of a benign feature (Figure 3.3 b)) and that of a real defect (Figure 3.3 a)) are plotted and compared to the temperature of the inspected structure (Figure 3.3 c)) over the monitoring period. It is apparent that the weighting functions, which are used by the operator to determine whether an ICA component is related to damage growth or not, can be strongly correlated to the temperature trend of the investigated pipe section.

![Weights and Components](image)

*Figure 3.3 Residual temperature effects in ICA weighting functions even after initial temperature compensation. a) Defect component and weighting function. b) Component and weighting function of stable benign feature. c) Temperature of inspected structure.*
3 Structural health monitoring procedure

In order to remove temperature dependent benign components as shown in Figure 3.3 b) the correlation coefficients between all ICA weighting functions and the temperature history of the pipe are calculated and a threshold is applied such that components with correlation coefficients lying above the threshold are discarded, as they are assumed to be purely related to benign features undergoing temperature dependent amplitude variations and are therefore of no interest to the operator.

The temperature dependent amplitude variations of defect-related weighting functions can inhibit the identification of relevant components by the operator. This may cause a small delay between the onset of growth and initial identification of damage, especially in cases where damage growth might coincide with monotonic changes in the temperature of the inspected structure. It should be noted here though that all these effects are even more challenging to overcome when a one-off inspection approach is employed by the inspector.

In Chapter 7 a methodology is presented which allows for a significant amount of temperature related amplitude variations in ICA weighting functions to be removed. This procedure was shown to substantially improve the detection limit for small defects.

3.3.2 Mann-Kendall test

In this step of the post-processing of the ICA output components, the assumption is made that all weighting functions representing damage growth will exhibit monotonic growth over the time covered by the dataset of guided wave measurements. Benign features or components related to noise in the signals however will not show any monotonic behaviour, but will rather vary randomly or with respect to underlying environmental condition changes. In order to discard the stable feature components, which are of no interest to the operator, a test for monotonicity of the weighting functions will have to be applied. The algorithm utilised for the SHM procedure presented in this chapter is the Mann-Kendall (MK) test [85][86][87]. Given a set of \( n > 10 \) continuous data points the MK test is defined as [88]:

\[
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k)
\]  (5.14)
where the indicator function \( sgn(x_j - x_k) \) can have values 1, 0 or -1 depending on the sign of the term \( x_j - x_k \). \( sgn(x_j - x_k) \) thus is given as

\[
\begin{align*}
sgn(x_j - x_k) &= 1 \text{ if } x_j - x_k > 0 \\
sgn(x_j - x_k) &= 0 \text{ if } x_j - x_k = 0 \quad (5.15) \\
sgn(x_j - x_k) &= -1 \text{ if } x_j - x_k < 0
\end{align*}
\]

from the value \( S \) the MK test score \( Z \) can be calculated as

\[
Z = \frac{S - sgn(S)}{\sqrt{VAR(S)}} \quad (5.16)
\]

where \( VAR(S) \) is the variance of \( S \) defined as

\[
VAR(S) = \frac{1}{18}[n(n - 1)(2n + 5)] \quad (5.17)
\]

In order to determine if a given MK test score value signifies monotonic growth behaviour, the result can be compared to \( Z_{1-a/2} \) where \( a \) denotes the test significance such that the monotonic trend hypothesis is rejected if \( |Z| < Z_{1-a/2} \). The values of \( Z_{1-a/2} \) can be obtained from a standard cumulative normal distribution table [88].

After the application of the MK test, each weighting function has been assigned a test score value \( Z \). This allows for a threshold to be set, as described in the previous paragraph, such that all component weighting function pairs with MK scores lying below \( Z_{1-a/2} = 1.96 \) i.e. a certainty level above 95% that no monotonic trend is present, can be discarded. As an example, the weighting functions shown in Figure 3.2 a) and b) will result in MK scores of \( Z = 12.47 \) and \( Z = 1.32 \) respectively. Thus allowing the assumption to be made that growth is present in Figure 3.2 a) whereas no growth is present in Figure 3.2 b). These discarded components do not show sufficient monotonic growth behaviour and therefore do not have to be considered further by the operator as potential defects. It should be noted here that this threshold may differ for datasets collected from different structures as underlying environmental variations may influence the results of the MK test for benign features. A monotonic trend in the temperature of the inspected
3 Structural health monitoring procedure

pipe, for example, might cause the amplitude of a feature such as a weld to change monotonically in a given window of time. All weighting functions lying above the threshold of $Z_{1-\alpha/2}$ will be displayed to the operator, ordered by their MK score value in descending order such that those components most likely related to damage growth are emphasised.

3.3.3 Defect component selection

The final stage of the presented SHM procedure is the identification of damage relevant ICA components and weighting functions by the operator. At the current stage of the presented SHM methodology, this step is performed manually on the basis of selecting components which show well-defined features and have corresponding weighting functions which exhibit growth like behaviour independent of environmental condition changes of the underlying inspected structure.

3.4 Conclusions

In this chapter, the SHM methodology utilised throughout this thesis was presented. The SHM procedure can be subdivided into three main steps. Initially a scale transform based stretch algorithm is applied to a dataset consisting of guided wave measurements in order to reduce the impact of environmental condition changes on the collections. The second step is the use of the signal processing algorithm FastICA. This allows for the dataset to be decomposed into a number of statistically independent components each accompanied by a weighting function containing information about the evolution of the components amplitude over the monitoring period. The final step of the SHM procedure is the removal of component weighting function pairs strongly correlated to the temperature of the structure and those which exhibit no monotonic growth as measured by the Mann-Kendall test. This last step reduces the number of ICA components to a size easily manageable by a human operator responsible for the final selection of damage related signals.
Chapter 4

4 Blind trial validation of SHM procedure

Knowledge of the corrosion rate in plant and facilities is of increasing interest to operators, in order to manage actively corroding systems and to optimise inspection programs. Periodic ultrasonic measurements, either at points (if the wall loss of a component can be expected to be uniform) or by scanning areas [89], are being increasingly used for this application. An increasing number of continuous monitoring systems using permanently installed (fixed) monitoring sensors are entering the market, with very different properties. This chapter describes the results of an extended trial to evaluate the detection capabilities of a permanently installed guided wave monitoring system.

The current guided wave inspection procedure allows for defects to be identified with a sensitivity limit of approximately 3 to 5% cross-sectional area loss [7]. This is a value typically found in the field where it is a function of the general condition of the pipe, the presence of benign features and the location of defects e.g. corrosion on bends or at pipe supports etc. rather than a function of the instrumentation [20], [23].

Within the current framework of standard guided wave inspections, measurements are individually analysed by an inspector and defects are located manually. This approach can be very labour intensive and thus restricts the frequency with which a pipe section can be repeatedly inspected. Hence the next step in the development of monitoring systems is the move from individual inspections to an automated structural health monitoring (SHM) system. Permanently installed guided wave transducer rings can be adapted for this task by attaching electronics for regular, automatic data acquisition.

Permanently installed guided wave sensors are already used on pipework in areas which are difficult to reach, therefore the safety risks and the substantial economic cost of the site access during installation are only incurred once. An example of this would be buried pipes and road crossings. Currently, the data collection and evaluation using a permanently installed system is performed in the same way as for a conventional, one-off inspection, though the latest A-scan
signal may be compared with those obtained at an earlier stage. Variations in pipe temperature can be a complicating factor for long-term monitoring systems, as temperature affects the velocity of guided waves in a pipe and hence the arrival time of the reflected signals from particular features in the pipe system, including any defects present. This can reduce the effectiveness of some monitoring methods such as those utilising simple baseline subtraction. These environmental effects and approaches to reduce their influence on guided wave collections have been described in more detail in the previous chapter.

Recent work has shown that by using independent component analysis (ICA) more reliable results can be obtained from a set of guided wave measurements [71], [81]; this new approach as described in Chapter 3 was implemented in the analysis of the results presented in this chapter. This ICA based SHM system will allow for a reduction in the effects of variations in environmental and operational conditions, thus reducing the rate of false calls and improving the sensitivity of the system. It has been shown [71] that an increase in the frequency of collection for such a system is desired. The degree of automation achieved by using FastICA has the potential to greatly reduce the operator effort in dealing with a large number of guided wave measurements as it allows for the extraction of features and their variation over time from a set of guided wave measurements.

Since the guided wave inspection system covers a large volume of pipework from a single measurement position, permanently installed guided wave monitoring is likely to be particularly valuable for cases in which unexpected corrosion might develop rapidly in unpredictable locations, such as microbially influenced corrosion [90]. Hence usage of a single permanently installed guided wave sensor system would potentially enable early detection of this type of degradation anywhere within a long length of pipework.

A blind trial was carried out during which a number of defects were grown in a pipe section and guided wave measurements were collected at regular intervals allowing for the novel ICA based SHM procedure to be performed. The main aim of the trial exercise was to determine the detection sensitivity of the ICA based permanently installed monitoring system for the onset of new defects and the continued growth of defects already identified, i.e. the parameters of the smallest defect that can be detected by this system, and compare it to the standard guided wave.
4 Blind trial validation of SHM procedure

inspection approach. The performance of such an ICA based SHM system has not been evaluated before and its sensitivity is not yet known. Therefore the detection limit found during the trial provides information about the future potential of guided wave SHM for pipes.

The trial was conducted by three parties; The HOIS Joint Industrial Partnership [91] managed by ESR Technology [92], Guided Ultrasonics Ltd. [16] and the author based at the Imperial College London NDE group.

In the trial procedure section, the setup of the test pipe and the position of defects, as well as their mode and time of introduction, are discussed. The means of data transfer to the author and the SHM algorithm are presented. The results of the blind trial and the performance of the ICA algorithm are discussed in the results section. The final section of the chapter presents the conclusions obtained from the trial.

4.1 Trial procedure

A blind trial was conducted by ESR Technology in order to assess the sensitivity of an installed guided wave monitoring system. An I-shaped temperature controlled test pipe was set up into which a number of defects were introduced and grown in small steps. The separation of work between ESR Technology, Guided Ultrasonics Ltd. and the author at the Imperial College London NDE group allowed for full blindness of the trial and thus a reliable estimation of the sensitivity of the system was made possible.
4.1.1 General pipe setup

![Diagram of pipe setup and sensor ring]

*Figure 4.1 a) Geometry of the 8 inch schedule 40 test pipe. The 7 and 2 meter pipe sections are connected by a 1.5D bend. Introduced defects are highlighted and numbered in red. b) Example of a defect being introduced into the pipe. c) A gPIMS permanently attached transducer ring by Guided Ultrasonics Ltd.*

The trial described in this chapter was based on measurements collected using a Guided Ultrasonics Ltd. gPIMS [16] (see Figure 4.1 c)) sensor ring attached to an “L-pipe” component which is composed of a 7m straight section of 8 inch schedule 40 pipe with a 90° elbow (with a radius of 1.5D) and a further 2m straight section after the bend. In addition to the two elbow welds, a single weld was located on the longer straight section of pipe i.e. in the forward propagation direction. A schematic of the setup can be seen in Figure 4.1 a). The gPIMS unit was attached according to the standard installation procedure to the pipe with an epoxy adhesive that ensures good coupling between the structure and the transducers. Sealant was applied inside the outer rim of the gPIMS to minimise moisture ingress. The gPIMS acts as a transmitter/receiver inducing torsional T(0,1) guided wave signals into the pipe over a range of centre frequencies, spanning from 17kHz to 37kHz, via a ring of piezoelectric transducers. All results presented in this chapter were obtained from measurements utilising tone bursts with a centre frequency of 25.5kHz. Undesired flexural modes are suppressed by simultaneously exciting a signal from all transducers around the circumference of the ring [10]. It should be noted here that both torsional and first order flexural signals as well as all available measurement
frequencies were utilised for the initial detection of potential defects and the reduction of the probability of false calls during the blind trial. An example of this will be shown in Section 4.2.

The sensor ring was set to automatically collect data at uniform 30min intervals during the trial while simulated corrosion was progressively introduced by a grinding process at six different locations on the exterior surface of the pipe.

The times of the defect grinding exercises and the wall loss locations were not revealed to the author evaluating the trial data until after the trial had ended. The monitoring data was provided to the author in batches for analysis and the next batch was not handed over until the results of the analysis of the previous dataset had been reported.

The main aim of this independent blind trial was to evaluate the results in terms of the change in pipe wall cross-sectional area needed to give a detectable flaw response, as a function of location in the structure. The transducer ring was installed on the longer straight section of pipe, approximately 4.5m from the cut end of the structure as measured from the centre of the gPIMS.

As discussed in the previous chapter, a key challenge with any sort of permanently installed structural health monitoring approach is the influence of temperature variations on the sensitivity of the system. Therefore, testing the robustness of the system in temperature compensation was a crucial part of the trial. The inspected structure was heated by a 27m long trace heating cable (60W/m) helically wrapped around the circumference of the pipe, with a pitch of about 0.3m, attached using aluminium fixing tape. This setup can be seen in Figure 4.2. The pipe was covered with a 25mm thick jacketed thermal insulation. This reduces the heat loss of the pipe section to the environment and therefore ensuring a more uniform temperature distribution along the structure. Using the installed trace heating cable and the thermal insulation, the pipe temperature could be raised from ambient to circa 60°C in about 2 hours. The temperature of the pipe was controlled via a thermostat to cycle between ambient and 60°C.

After reaching the desired maximum temperature for the cycle the pipe was allowed to gradually cool back down to the ambient temperature before repeating the heating cycle. The temperature of the pipe was recorded during the trial via a thermocouple and supplied to the author along with the guided wave data. The temperature of the setup over the full trial period can be seen in Figure 3.3 c).
4.1.2 Defects

Six different positions along the pipe section were selected for the introduction of artificial defects. These locations were not revealed to the author prior to or during the trial. The defects had the axial positions of +3.46, +2.57, -1.95, -2.79, -3.16 and -3.94 m with respect to the centre of the gPIMS transducer ring (see Figure 4.1) with positive and negative signs denoting the forward and backward propagating direction respectively. It should be noted here that one of the defects was placed directly on the 1.5D bend while two further defects were situated beyond the pipe bend. One of these was located in close proximity to the second bend weld, a location which increases the difficulty of detection when operating in a standard guided wave single inspection framework.

Wall losses with roughly circular/elliptical area profiles were introduced at the six defect locations progressively by a manual grinding process. Each of these defects was introduced at different times during the trial. The subsequent growth stages of the six defects were achieved by increasing the wall loss in both depth at the damage location as well as the circumferential extent. As the pipe wall material was removed, the maximum defect depth was measured periodically until the pre-specified target depth had been achieved. The profile of the defects at each of its growth stages was recorded using a Creaform laser scan tool [93]. This allowed for the cross-sectional area loss for each of the six defects at every growth stage to be calculated with a high degree of accuracy. A plot of the growth of each of the introduced defects can be seen in Figure 4.3.
The timing of the grinding performed on the pipe was chosen to start immediately following the collection of a reading by the guided wave sensor unit, and was completed prior to the next data measurement. Hence none of the guided wave measurements collected corresponded to a partially completed defect enlargement stage. The trial plan contained the schedules for 10 stages of enlargement for each of the six defects. The number of stages was however extended for defect 4 (see Figure 4.1 a)) which was located on the pipe bend due to low sensitivity issues which will be further discussed in Chapter 5.

For each defect, an initial plan for its eventual maximum cross-sectional area, circumferential extent and wall loss was drawn up, based on the expected detectability of the defect by the monitoring system. This expected sensitivity was informed by the trial operator’s experience of standard guided wave inspection results. The general aim was to grow each defect such that the cross-sectional area loss at its final stage would be about twice that needed for its initial detection. There were however substantial uncertainties in this process, as the actual sensitivity of the guided wave structural health monitoring method was not known to ESR Technology accurately prior to the start of the trial.

![Graph showing growth pattern of all six defects introduced into the test pipe over the full trial period.](image)

**Figure 4.3** Growth pattern of all six defects introduced into the test pipe over the full trial period.

### 4.1.3 Data collection and data transfer

ESR Technology was responsible for the pipe setup, the introduction of defects, the process of the temperature control of the specimen as well as the operation of the permanently installed
4 Blind trial validation of SHM procedure

guided wave system. Measurements collected on the trial pipe were handed over by ESR Technology to Guided Ultrasonics Ltd. in small batches of data. GUL further assisted ESR Technology with the installation of the gPIMS transducer ring and the setting up of an optimal measurement practice. This included recommendations on the location of the sensor with respect to benign features, such as welds and the pipe bend, as well as assistance in the initial installation of the gPIMS which requires a certain level of experience.

The collected measurements were analysed, using the ICA based SHM algorithm, by the author at the Imperial College London NDE group which had no contact with ESR Technology over the duration of the trial. It should be noted, however, that the author did have knowledge of the basic setup of the trial pipe and its geometry. This reflects the information an operator can be expected to have with reasonable certainty when inspecting a pipe in field. The final manual stage of the SHM procedure was conducted by the author. Feedback on any potential defects and their location relative to the transducer ring was given to ESR Technology by the latter. As a result, ESR Technology was able to evaluate the performance of the SHM system and comment on its performance as an independent party.

Prior to the first defect introduction, the sensor setup was set to automatically record data at 30min intervals. During weekdays, the data logging was left on to run 24hrs per day. However, to keep data volumes within reasonable bounds, the collection was suspended during weekends, when no changes were made to the pipe in terms of active temperature variation, the introduction of new defects or the enlargement of defect already present in the pipe section. Data collected outside of working hours on weekdays were also not transmitted to the author for the same reason as stated above.

The trial duration was scheduled to be over a period of 40 days, with defect enlargements taking place at varying times during working days; on some days, no changes were planned to be introduced whereas on others there was to be more activity. To ensure full blindness for this trial, neither the author nor any employees of GUL were present at any stage during the defect introductions and enlargements. Also, no information was provided to the author regarding any of the plans for defect locations and their final extents.
In order to maintain the full blindness of the trial, it was important that no feedback on the results of the analysis was to be given to the author at any stage during the investigation. Following the handing over of a batch of data to the author, the next batch was not provided until the former had been analysed and the results reported to the trial controller. Only following receipt of this information was the next batch of data provided, with no feedback being given on the reported information of the last batch. This procedure ensured that it was not possible for the author to infer the early onset of a defect from the knowledge of its position obtained from a later batch with a more severe and therefore more visible defect reflection. Thus the true sensitivity of the SHM procedure could be established.

The data collected by the gPIMS guided wave sensor was divided into ten batches per week (twice daily); it is important to note that even with this small batch size, some data contained more than one defect growth increment. A typical batch consisted of approximately 12 measurements. The author analysed all of the data within each batch simultaneously and hence defect detection was reported in terms of its size at the end of the data batch in which it was reported. The reporting of results for each data batch also included the possible first detection of a new defect, with its location relative to the sensor ring, as well as any detected changes in previously reported defects.

Following completion of the trial, the author provided growth data for all defects as a function of date and time throughout the trial, as derived by the previously presented independent component analysis based SHM method [71].

4.2 SHM procedure

Measurements collected from the blind trial test pipe were investigated using the SHM procedure introduced by Liu, Dobson et al. [71] discussed in Chapter 2. All measurements collected during the trial were initially normalised to the reflection of the cut end in the straight section of the pipe (forward). The SHM process consisted of a scale transform stretch algorithm for the removal of environmental effects, a FastICA step which allows for the collected measurements to be decomposed into a number of components and weighting functions followed by a number of post-
processing stages. The final selection of damage relevant components was conducted manually by a human operator.

Chapter 3 already presented a number of example results from the FastICA algorithm for a dataset containing a slowly ramping defect indication; since defects were introduced by grinding away pipe material in a number of stages defects were not expected to smoothly grow over a longer period of time but rather to undergo a number of small step changes. Figure 4.4 thus shows three components and their corresponding weighting functions as obtained from a set of 20 guided wave measurements when applying the ICA based SHM algorithm. A defect reflection signal obtained from an FE model of a pipe was introduced into a random sample of 20 signals of the baseline measurements, collected on the setup shown in Figure 4.1, along the straight section of the pipe. There was no defect growth over the first 10 measurements, after which a 3% CSA defect was introduced at a distance of 3.5m from the transducer ring; the size of the defect stayed constant over the remaining 10 readings. The defect signal was generated as described in [71] which will be discussed further in Chapter 6; the amplitudes of the signals were normalised to the cut end reflection of the pipe located at 4.5m from the measurement position. In Figure 4.4 a) a defect component can be seen at 3.5m which is not present in the first 10 measurements and then grows from 0 to 3% between measurements 10 and 11. Figure 4.4 b) shows the ICA component corresponding to the baseline signal from the dataset. The weighting function shows that the amplitude is stable around 100% and the signal shows the clear reflection from the cut end at 4.5m. Finally, Figure 4.4 c) shows a noise component which can be identified by its undefined signal shape and the random but low amplitude variations seen in the weighting function. This example illustrates that the ICA algorithm allows for signals reflected from different sources in the pipe to be separated into individual component weighting function pairs in the presence of a step like defect growth pattern. Defects with a significant axial extent may be decomposed into multiple components by the FastICA algorithm. These can be combined into a single component and weighting function pair by multiplying the weights and components of both of the original ICA outputs of interest and summing the resultant time traces. Alternatively the number of output components of the FastICA algorithm can be restricted. This tends to contain extended defects into a single ICA component.
As described in the previous chapter, the last step of the SHM procedure, at this point, has to be performed manually. In order to increase the probability of detection for a small defect shortly after it has started to grow and, at the same time, reduce the probability of a false call, multiple different modes and frequencies were used during the analysis. An example of this can be seen in Figure 4.5 where the results of the early stages of defect 2 (see Figure 4.1) are shown. The defect is not detectable when only considering the 17KHz T(0,1) signals as shown in Figure 4.5 a). The defect is however visible when using T(0,1) data collected at a centre frequency of 25.5kHz (Figure 4.5 b)). In order to ensure that the onset of the damage growth in the 25.5kHz data is not caused by some measurement artefact or the presence of environmental condition changes, measurements at other frequencies and using modes other than the T(0,1) can be used. In this case, the growth of damage can also be observed in the flexural waves collected at 25.5kHz and the torsional mode with a centre frequency of 37kHz. Therefore, even though there might have been some ambiguity when only considering T(0,1) 25.5kHz signals, inspecting other modes...
and frequencies allows the operator to make a more informed decision and thus reducing the potential of false calls and increasing minimum detectable defect size of the SHM system.

Figure 4.5 Components and weighting functions of defect 2 at time of first call. Measurements collected using the torsional mode at a) 17kHz and b) 25.5kHz, c) flexural mode at 25.5kHz and d) torsional mode at 37kHz.

4.3 Results and discussion

After completion of the trial, the sensitivity of the SHM procedure to each of the introduced defects could be determined and the growth pattern observed from the ICA output could be compared to the expected growth as reported from the CSA loss measurements as recorded by ESR Technology.

4.3.1 Observed defect growth

Over the course of the trial, each new batch of guided wave measurements was evaluated and the appearance of any new defects, as well as the possible further growth of previously detected damage, was reported to the trial operator. Figure 4.6 shows the weighting functions and the corresponding components for each of the six defects that were identified by the author.
4 Blind trial validation of SHM procedure

The vertical blue lines in the component plots indicate the positions of the defects as measured on the pipe setup by the trial operator during their introduction. It should be noted here that defects 5 and 6 were both located past the pipe bend and therefore measuring the distance between the transducer ring and the damage location was not as trivial as for the defects placed in the straight pipe section. This most possibly led to the larger discrepancies between the position of the features in the ICA components and the defect locations as measured on the test pipe.

The vertical blue lines on the weighting function plots in Figure 4.6 indicate the time of the first introduction of wall loss for each of the six defects. It cannot be expected of the SHM algorithm to immediately identify the damage due to the small size of the batches submitted to the author during the trial and the fact that the first damage stage for most of the introduced defects was well below the expected sensitivity limit. Shown in red are the weighting functions for each of the damages at the point in time when they were first called by the author using the SHM algorithm. The last data point of the weighting function corresponds to the final measurement of the latest batch received by the author at the time of first call. Not all defects were called immediately by the author after showing monotonic growth as it had to be ensured that the ICA result truly represented defect growth rather than some residual environmental effect (as described in Chapter 7) in order to avoid a false call.

On the same plots shown in black are the weighting functions as obtained by using all available guided wave measurements after completion of the trial. Small variations between the two weights for each defect can be attributed to measurements from different temperature ranges being used in each case as well as the fact that at the time of first detection, fewer measurements were available, leading to a less effective decomposition of the data when applying the ICA algorithm.
Figure 4.6 Weighting functions and components for each of the 6 defects located in the test pipe. Defects a) and b) were found in the forward direction. Defects c), d), e) and f) were located in the backward direction of the pipe. Shown in red are the weighting functions at the time of first call. Plotted in black are the weighting functions obtained using all collected measurements with all defects grown to their final size. Vertical blue lines show the location as well as the time of introduction for each of the defects.

4.3.2 Accuracy of defect location and sensitivity

The axial locations first reported by the author during the trial were compared with their previously measured positions. The axial locations of the defects on and beyond the elbow were derived from their distance around the elbow extrados. For all defects, at the time of first
detection, the reported axial positions were sufficiently in agreement with the benchmark values to indicate unambiguously which defect had been detected (see Figure 4.6). The closest agreement was obtained for defects 1 and 3 on the longer straight pipe section, for which the differences were only 0.01 and 0.05m respectively. For defect 2, which was also on the longer straight, the difference was slightly higher at 0.13m. Defects 4 and 5 which were on or just beyond the elbow showed the largest differences of 0.14 and 0.15m respectively. However, for defect 6, which was positioned furthest past the elbow, the difference was only 0.06m.

The positions and differences given here were those obtained at the time of first detection of each of the six defects which were reported by the author to ESR Technology during the blind trial. The peak positions of some of the components seen in Figure 4.6 have slightly different values, as these were obtained by processing the full set of trial data; changes in the axial extent of defects and slight variations in the ICA algorithm output can impact the resulting component positions.

![Figure 4.7 Percentage of pipe wall cross-sectional area loss for each defect at the time of first detection as reported during the blind trial. Lower and upper bound of CSA values denote the minimum and maximum size of the defects within the data batch of first detection.](image)

As the author reported detection results for each batch of data as a whole, there were uncertainties in the exact defect dimensions required for detection, as each data batch may have
4 Blind trial validation of SHM procedure

...contained one or more defect enlargements. Hence the detection sensitivity limits for the trial are reported here in terms of the upper and lower bounds. The upper bound on the minimum detectable defect was taken to be the defect cross-sectional area loss at the end of the batch in which it was first reported. The lower bound on the minimum detectable defect was taken to be the defect CSA at the end of the last batch of data in which it had not been reported (i.e. the batch immediately prior to one in which it was detected). Figure 4.7 shows a plot of the CSA upper and lower bounds of the detection limit for each of the six defects detected in the pipe section during the trial.

For defects 1, 2 and 3, all located on the longer straight section where the sensor ring was positioned, the upper bound limits of the sensitivity were all found to lie between 0.8% and 1.3% CSA, while the lower bound values were between 0.6% and 0.7% CSA. For defect 4 (on the apex of the elbow and circumferentially positioned midway between the extrados and the intrados, see Figure 4.1), the lower and upper bound CSA values were 3.1% and 3.6% respectively. These values are significantly higher than for any of the other defects. This issue was subsequently investigated using 3-D finite element modelling techniques to study the detailed propagation of guided waves around a pipe elbow. The results of this investigation will be presented in Chapter 5 of this thesis. It was shown that the sensitivity to a defect at the $\phi = 90^\circ$ circumferential position halfway through a bend, is about 2.5 times lower compared to that obtained on a straight section of a pipe i.e. the low sensitivity to defect 4 was caused by the nature of the guided wave propagation along the bend rather than a failure of the ICA based SHM algorithm to identify the change.

In the standard guided wave inspection procedure the assumption is made that the defect detection sensitivity is reduced past complex pipe features such as bends. Pipe bends will cause mode conversions in the input torsional T(0,1) guided wave signal, resulting in reflections from features past the bend to increase in complexity and thus signal traces become more difficult to interpret reliably. Since two defects were introduced beyond the bend it was assumed, prior to the evaluation of the blind trial results, that the detection of these defects would be more challenging compared to the defects located in straight pipe sections before the 1.5D bend.
Defect 5 was positioned beyond the elbow from the sensor, immediately adjacent to the elbow weld, a position generally expected to reduce the detectability of a defect significantly. Hence, at the start of the trial, the planned final defect CSA for this defect was set to be larger compared to any of the other defects and, after the first stage of the defect introduction, it had already been enlarged to a CSA loss of 0.6%. However, this defect was reported by the author immediately after the analysis of the first batch of data that included the initial introduction of this discontinuity. Thus for defect 5, the lower bound of the detection sensitivity was found to be zero, while the upper bound was 0.6% CSA. These figures substantially exceeded expectations for a defect in such a location (adjacent to a weld, and beyond the elbow from the sensor).

Defect 6 was situated on the shorter straight pipe section, beyond the elbow from the sensor at some distance from the elbow weld. Its lower and upper bound of the detectable cross-sectional area losses were found to lie at 0.7% and 1.6% respectively, which were similar to the values found for defects 1, 2 and 3 placed on the straight pipe section containing the sensor ring. Hence for this defect, the presence of the elbow did not appear to have degraded the guided wave system detection sensitivity. These results show that comparing signals taken before, during and after the growth of these defects appears to reduce the effect of increased signal complexity in reflections from defects located after features.

4.4 Conclusion

The sensitivity of a new guided wave structural health monitoring methodology for pipes [71], based on an independent component analysis algorithm, was investigated via a blind trial. During the trial, defects were grown in a number of locations on a temperature controlled L-shaped test pipe section.

All six of the introduced defects were identified by the author, having no prior knowledge of times of defect introduction, location or growth pattern. At the same time, no false calls were made during the blind trial. This fact is of great value when moving from test trials towards field applications as a high false call rate can completely negate the sensitivity improvement of a monitoring procedure over single inspections when considering economic benefits to the pipeline operator. All defects placed on straight sections of the trial pipe were identified at cross-sectional
area losses between 0% and 1.5% which constitutes an improvement of a factor of approximately 5 over conventional one-off guided wave inspections. This increased sensitivity was also found for defects which were introduced into the structure past the 1.5D bend section. A single defect which was placed at the $\phi = 90^\circ$ circumferential position on the pipe elbow was only identified after it had grown to a cross-sectional area loss of about 3.5% and thus to a significantly larger extent than the defects in the straight pipe sections.

From the results presented in this chapter, it can be concluded that the guided wave SHM systems as introduced in Chapter 3 are an attractive monitoring tool for industrial applications.
Chapter 5

5 Reflection of torsional guided waves from defects in pipe bends

5.1 Introduction

As described in Chapter 4 of this thesis, during a conventional guided wave inspection the time trace recorded by the transducer ring will be evaluated manually by the operator. The minimum defect size to be found with this methodology in practical applications corresponds to approximately 5% cross-sectional area loss of the pipe wall [7]. This value can vary significantly depending on the position of the defect, the general condition of the inspected pipe and the presence of other pipe features [23]. Pipe bends pose further difficulties as they introduce mode conversion such that signals from beyond the bend are more complex in appearance thus making interpretation more challenging, thereby reducing detection sensitivity [20].

5.1.1 Challenges in detecting defects on pipe bends

During the blind trial presented in Chapter 4, it was found that sensitivity of the system to a defect located on the pipe bend was significantly reduced compared to defects placed in straight sections of the pipe, before as well as past the bend. The monitoring trial was performed on an 8 inch diameter schedule 40 carbon steel pipe containing a 90° 1.5D bend section as seen in Figure 4.1 a). The term 1.5D in this case refers to the ratio of the pipe diameter to the radius of the pipe bend. A number of defects were introduced into the setup and incrementally increased in size such that the sensitivity and validity of the new SHM method could be investigated. A total of five defects in the straight pipe sections before as well as past the bend could be identified. These defects were first detected at a cross-sectional area loss of between approximately 0.5 and 1.5%. A sixth defect, unlike the rest, was placed on the pipe bend roughly at the $\phi = 90^\circ$ circumferential position i.e. on top of the bend. An image of this defect can be seen in Figure 4.1 b). It was only possible to identify this defect after it had been grown to a cross-sectional area loss of 3.5% i.e. substantially more severe than the other defects. Even after the conclusion of this trial with the knowledge of the defect size and its position it was not
Reflection of torsional guided waves from defects in pipe bends

possible to identify the defect retrospectively from earlier measurements. In Figure 5.1 two collections of the trial pipe, one in its baseline state and another at the end of the trial, after all defects had been grown to their maximum extent, are shown. At this point defects 4 and 5 had cross-sectional area losses of approximately 3.5% and 8.2% respectively and both should be identifiable by manual inspection. The two defects were positioned sufficiently far from one another such that their reflections do not significantly overlap. This suggested that the reduced detectability of the defect located on the pipe bend is not related to a shortcoming of the applied SHM methodology but rather limited by the geometry of the pipe setup and the particular location of the defect.

![Figure 5.1 Comparison of a measurement collected at the beginning of the blind trial and at the end of the trial. Both collections obtained at the same temperature.](image)

In an initial finite element investigation, the reflections from a number of through thickness slits of different circumferential extent located at $\phi = 90^\circ$ circumferential position and an angular position of $\theta = 45^\circ$ along a 1.5D bend were compared to those obtained from defects of the same size positioned in a straight pipe section. It was found that the amplitude of the reflections from the defects located on the bend was reduced to 30-40% of that from defects on the straight pipe; these values correspond with the results obtained in the blind trial as presented in the previous chapter. This suggested that a more comprehensive study of the influence of defect position in a bend on the reflection obtained would be valuable. The results of this study will be presented in this chapter.
5 Reflection of torsional guided waves from defects in pipe bends

There has been little work published on the reflection from defects in pipe bends and on the influence of the precise position of the defect in the bend. The propagation of the L(0,2) mode [94], as well as its reflection from defects at various positions on pipe bends, has been investigated more than the T(0,1) mode [95][96]. It was found that the reflection from a crack at the bend intrados was significantly lower than that from a crack of the same size at the extrados of the bend. Qi et al. [97] studied T(0,1) mode reflections from axial defects at three different locations on a pipe bend, observing varying detectability with position. Jack et al. [98] investigated the reflections of L(0,2) and T(0,1) waves from circumferential defects at bend welds. Rose et al. [99] used flexural mode tuning to improve the detectability of defects on a pipe bend and investigated the reflection from defects located past the bend [100], while the scattering of the T(0,1) mode from junctions of straight pipe sections and bends was investigated by El Bakkali et al. [101]. The nature of modes in a bend [102][103][104] and mode conversion of guided waves travelling through bends have been studied extensively in the past decade using experimental as well as finite element approaches [105][106][20][107][108]. To the author’s knowledge, there has not been a systematic study of the sensitivity to defects as a function of their position along and around a pipe bend for the T(0,1) incident mode.

In this chapter the spatial variations in the sensitivity of guided wave inspections as a function of defect position around a bend and as a function of the bend radius is studied. The original motivation was to find an explanation for the results of the blind trial of Chapter 4, but it will also be a valuable tool in providing a more comprehensive understanding of the ability of a T(0,1) based guided wave inspections system to detect and size defects on pipe bends. To obtain a sensitivity map of a 1D pipe bend the torsional T(0,1) wave reflections from small defects located on the bend with varying circumferential and angular position were studied. The results were obtained from a numerical finite element model of a pipe section with a geometry similar to that employed in the blind trial as presented in Chapter 4 and shown in Figure 4.1 a).

This chapter is organized as follows. Section 5.2 specifies the properties of the finite element bend models used. This is followed by a description of the defects introduced into the model and the stress and displacement outputs generated by the analysis. In Section 5.3 the results from a study of reflections from crack-like defects at varying positions on the bend geometry is presented
5 Reflection of torsional guided waves from defects in pipe bends

and compared to the stress distribution in a bend of the same size. The correlation between the
two is discussed and the stress distributions in 2D, 3D, 5D, 7D and 20D bends are presented.
Next, in Section 5.3, the expected reflections from defects at specific areas of interest in bends
of different radii are compared and discussed. Section 5.4 presents the conclusions of the
investigation.

5.2 Pipe bend investigation

5.2.1 Finite element model setup

A 3D Finite Element model was constructed to investigate the behaviour of a torsional ultrasonic
guided wave propagating through a bend and reflecting from defects located on the pipe bend.
The mesh was generated using Abaqus CAE [109] and subsequently solved with Abaqus Explicit.
Defects, source nodes as well as monitoring nodes and elements were introduced via a MATLAB
[110] code; post-processing of the model was also carried out in MATLAB.

![Figure 5.2 a) Schematic of a 90° pipe bend. The radius of the pipe is denoted by r and the radius of the bend is
denoted by R. Monitoring elements were placed throughout the bend section. A ring of monitoring nodes is denoted
in red. Source nodes are highlighted in purple. b) View of the meshed bend consisting of 4 elements through the wall
thickness and 300 around the circumference. Element numbers in the axial direction vary with bend radius R. c)
For the investigation of the problem encountered in the blind trial as presented in Chapter 4, a model of an 8 inch diameter schedule 40 carbon steel pipe (wall thickness $8.18\text{mm}$, inner radius $101.37\text{mm}$ and outer radius $109.55\text{mm}$) containing a $90^\circ$ bend section was created. The model consisted of 3 distinct components; firstly a 2 meter long straight section into which the input signal would later be introduced, secondly a $90^\circ$ bend was connected to the previous section with a bend radius of either 1, 2, 3, 5, 7 or 20 times the outer diameter of the pipe and finally a further 1 meter length of straight pipe. The simplified geometry of the setup can be seen in Figure 5.2. Shown here is a 1D bend with a radius of $R = 219.1\text{mm}$. No further features such as welds connecting straight sections of the pipe to the bend were introduced as these were of no interest to this particular study.

The geometry was meshed with 300 8-node linear brick elements (C3D8R) around the circumference of the pipe and 4 elements through its thickness. The number of elements in the axial direction of the bend is dependent on the bend’s radius. A ring of 1500 source nodes was located at the beginning of the first straight pipe section i.e. at a distance of 2 meters from the start of the bend. The excitation signal was a 2 cycle Hanning windowed tone burst, with a centre frequency of $25.5\text{kHz}$. The signal was applied as circumferential displacements of the same amplitude to all source nodes around the pipe, therefore exciting a pure torsional $T(0,1)$ mode since the excitation frequency was well below the $T(0,2)$ mode cut off frequency. The model was set to a total run time of 2ms allowing the signal to propagate throughout the full length of the bend. Details about the element size requirements and the minimum time step can be found in Section 2.2.1. Further discussion about the extraction of the torsional and flexural modes will also be found in the same chapter.

The positions of elements on the bend are denoted as seen in Figure 5.2. The intrados of the bend lies at $\phi = 0^\circ, 360^\circ$, while the extrados of the pipe is at $\phi = 180^\circ$. The top and bottom of the pipe are located at the circumferential position of $\phi = 90^\circ$ and $\phi = 270^\circ$, respectively.

In order to investigate the relative reflection amplitudes from defects located at different positions on the bend, circumferential through thickness cracks were introduced in the finite
element model by disconnecting a small number of nodes. The cracks had a circumferential extent of \(7.2^\circ\), equivalent to a pipe wall cross-sectional area loss of 2\%. The crack position was varied in the circumferential direction in intervals of \(\phi = 5^\circ\) and in the angular direction in \(\theta = 2.25^\circ\) intervals. This resulted in a total of 1400 individual FE models to be solved. Signals reflected from these cracks were recorded by a ring of 300 monitor nodes located on the straight pipe section at a distance of 0.25 meters in front of the bend as seen in Figure 5.2. The displacement amplitude and the direction of the displacement recorded at the monitoring nodes enabled the extraction of the T(0,1) mode from the reflected signals using the procedure described by Lowe et al. [11]. Flexural modes contained in the reflected defect signals were not considered during the analysis presented in this chapter. The presence of the flexural modes can be attributed to the mode conversion of both the bend itself and the reflection from a part-circumferential crack. A baseline signal in the absence of any defects was also collected. The baseline signal was subtracted from all subsequent measurements in order to remove any minor reflections from the bend geometry itself as these are not related to the defects and therefore of no interest in this study. The maximum amplitude of the reflected T(0,1) mode for all introduced discontinuities could thus be plotted against their circumferential and angular position. In order to explain the resulting map of reflection amplitude with respect to defect location on the bend the von Mises stress distribution was investigated.

5.2.2 Stress monitoring

Stresses and displacements were monitored in each element on the surface of the bend section between \(0 \leq \phi < 180\), halving the number of monitoring points due to the symmetry of the setup along the plane of the bend. The stresses of each monitoring element reported in this chapter are the maximum stress values obtained from the models over the runtime of the FE simulations.

The Cauchy stress tensor \(\sigma\) [111] can be obtained from the solved FE model as Abaqus allows for the recording of all shear and normal stresses within an element of the model. The FE model and therefore the output Cauchy tensor are based in a Cartesian coordinate system and have to be rotated in the plane of the bend such that one dimension of the tensor can always be given as the axial direction of the pipe. To perform this operation the tensor has to be rotated
individuals at every monitoring element and for each time instant of the FE model. Thus the
rotated Cauchy stress tensor $\sigma'$ is obtained via the equation

$$
\sigma' = A \sigma A^T = \begin{bmatrix}
\sigma'_{xx} & \sigma'_{xy} & \sigma'_{xz} \\
\sigma'_{yx} & \sigma'_{yy} & \sigma'_{yz} \\
\sigma'_{zx} & \sigma'_{zy} & \sigma'_{zz}
\end{bmatrix}
$$

(5.1)

where $\sigma$ is the Cauchy stress Tensor given by its components

$$
\sigma = \begin{bmatrix}
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz}
\end{bmatrix}
$$

(5.2)

and $A$ is a 3-dimensional rotation matrix about the z-axis i.e. the axis perpendicular to the plane
of the bend

$$
A = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

(5.3)

with the angular position of the element at $\theta$ as shown in Fig. 2. The angle $\theta$ can easily be
calculated from the known coordinates of the monitoring elements and the rotation centre of the
bend using the equation

$$
\theta = \acos \left( \frac{\left| \begin{bmatrix} E_1 \\ R_2 \\ 0 \end{bmatrix} - \begin{bmatrix} R_1 \\ R_2 \\ 0 \end{bmatrix} \right|}{\sqrt{\left| \begin{bmatrix} E_1 \\ E_2 \\ 0 \end{bmatrix} - \begin{bmatrix} R_1 \\ R_2 \\ 0 \end{bmatrix} \right|}} \right)
$$

(5.4)

where $E = \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$ is the position vector of a monitoring element and $R = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \end{bmatrix}$ is the position vector
of the rotation centre of the bend. $\theta$ has a range of $0^\circ$ for the beginning of the bend to the
maximum value of $90^\circ$ at the end of the bend as seen in Figure 5.2.

The normal stress on a plane perpendicular to the pipe axis at each bend element of the FE
model is given by $\sigma'_{yy}$ in the rotated Cauchy stress tensor. In order to obtain a single stress value
at each of the monitoring elements, the von Mises stress $\sigma_v$ is calculated from $\sigma'$ using the
equation [112]

$$
\sigma_v = \sqrt{\frac{1}{2} \left[ (\sigma'_{xx} - \sigma'_{yy})^2 + (\sigma'_{yy} - \sigma'_{zz})^2 + (\sigma'_{zz} - \sigma'_{xx})^2 + 6(\sigma'_{xy}^2 + \sigma'_{yz}^2 + \sigma'_{zx}^2) \right]}
$$

(5.5)
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For the detectability of reflections from defects, the stresses across the surface of the crack have to be considered. In the case of a circumferential defect, these stresses are the direct and shear stresses in the axial direction. The distributions of these stresses across a 1D bend are shown in Figure 5.3. Equation (5.5) can be rewritten in a cylindrical coordinate system with the circumferential and radial directions denoted by the subscripts $\phi$ and $r$ respectively:

$$\sigma_v = \sqrt{\frac{1}{2} \left[ \left( \sigma'_{\phi \phi} - \sigma'_{yy} \right)^2 + \left( \sigma'_{yy} - \sigma'_{rr} \right)^2 + \left( \sigma'_{rr} - \sigma'_{\phi \phi} \right)^2 + 6 \left( \sigma'_{\phi y}^2 + \sigma'_{y r}^2 + \sigma'_{\phi r}^2 \right) \right]} \quad (5.6)$$

The squared maximum von Mises stress as observed in each monitoring element individually is thus plotted against its circumferential and angular position.

5.3 Results and discussion

5.3.1 Crack reflections and stress distribution

Figure 5.3 shows the maximum amplitude of the torsional T(0,1) mode reflected from circumferential through thickness cracks along a 1D bend. The reflection amplitudes are plotted against the circumferential and angular position of the centre of the crack. The plot was normalised to the amplitude of the reflections from cracks located at the beginning of the bend section i.e. with an angular position of $\theta = 0^\circ$. Therefore the amplitude scale is relative to the reflection expected from a $7.2^\circ$ crack located on a straight pipe. It can be seen in Figure 5.3 that the reflection amplitude is at a maximum for a crack located at a circumferential position of $\phi = 165^\circ$ and $\phi = 195^\circ$ with an angular position of $\theta = 67.5^\circ$. A local minimum can be observed at the angular position of $\theta = 60.75^\circ$ on the extrados of the pipe bend. The amplitude here is reduced by a factor of about 9.5 compared to the maximum reflection in the bend and 55% lower than a reflection from a crack of the same size in a straight pipe. The absolute minimum reflection in a 1D bend can be observed to originate from the defect located at the intrados of the pipe with an angular position of $\theta = 90^\circ$. 

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The distribution of the normal and shear stress in a 1D pipe bend can be seen in Figure 5.4. For both plots a) and b) the amplitude of the stresses was normalised to the shear stress value at the beginning of the bend i.e. 0° in angular position. This corresponds to the stresses in a straight pipe section generated by the incident torsional T(0,1) mode. There are no normal stresses present in the axial direction of the pipe at the beginning of the bend since the only wave propagating here is the pure T(0,1) mode. The amplitude of the normal stress increases due to mode conversion with the wave passing through the bend. The highest normal stresses can be found at the $\phi = 150^\circ$ and $\phi = 210^\circ$ circumferential location of the pipe at an angular position of $\theta = 65^\circ$, close to the extrados of the pipe. It should be noted though that the normal stress is zero on both the extrados and the intrados over the full length of the pipe bend. The shear stress in the pipe remains fairly uniform around its circumference at the beginning of the bend as expected from the T(0,1) input signal. Mode conversion along the bend causes a reduction in uniformity of the shear stress around the pipe circumference and a maximum stress concentration can be found on the extrados of the pipe at an angular position of $\theta = 80^\circ$. A local minimum in the shear stress distribution can be observed on the extrados of the pipe at an angular position of $\theta = 60^\circ$. Comparing the distribution of the normal and shear stresses with the map of the bend obtained from the crack study (Figure 5.3) a clear agreement in the location of distinct
features can be observed. The positions of the two maxima in Figure 5.3 match the two lobes seen in the distribution of the normal stress Figure 5.4 a). Similarly, the maximum observed on the extrados of the bend in the crack study at $\theta = 78.75^\circ$ is also found in the shear stress map of the bend as well as the local minimum on the extrados.

Figure 5.4 a) Distribution of normal stress in axial direction plotted against circumferential and angular position along a 1D bend. b) Shear stress distribution plotted against circumferential and angular position along a 1D bend. Both plots a) and b) normalised to the shear stress in a straight pipe.
5 Reflection of torsional guided waves from defects in pipe bends

It was observed that the shear as well as normal stress distribution along a 1D bend both show similarities in features with the circumferential crack study. It would, therefore, be convenient for further study to combine these into a single value and thus the distribution of the von Mises stress was investigated. The maximum of the squared von Mises stress \(\sigma_v^2\), calculated as described in Section 5.2.2, is plotted against the angular and circumferential position of the monitoring elements in Figure 5.5. The square of the Von Mises stress was used since reciprocity analysis [113] shows that the reflection from a defect is proportional to the product of stress and displacement, and displacement is also proportional to stress. Two maxima can clearly be identified at the \(\phi = 150^\circ\) and \(\phi = 210^\circ\) circumferential location with an angular position of \(\theta = 65^\circ\). A significant local minimum is located on the pipe extrados at an angular position of \(\theta = 60^\circ\). Areas of low stress can be found within the final parts of the bend on its intrados. There is a strong correlation between the crack reflection map seen in Figure 5.3 and the von Mises stress map of Figure 5.5, suggesting that the von Mises stress distribution is a satisfactory measure of relative reflections from cracks at different locations around a bend. It should be stressed though that this only applies to circumferential cracks which produce reflections due to both shear and normal stresses; axial cracks would not cause reflections from the normal stresses and therefore the correlation would break down. Corrosion defects produce reflections due to shear as well as the normal stresses and so the relative sensitivity to corrosion at different locations is likely to follow that of circumferential cracks presented here. As the crack study was extremely time intensive, for further bends with different radii only the von Mises stress distribution was investigated. Figure 5.5 also expands the investigation of the stresses in a pipe containing a 1D bend past the bend for an additional 0.7 meters. It can be seen here that the stress pattern observed on the 1D bend continues in the straight section but no maxima of equivalent amplitude compared to those on the bend could be observed. The wave past the bend is therefore much more uniform around the circumference of the pipe and no strong minima are present, suggesting that beyond the bend, defect detectability will not be a strong function of circumferential position.
Figure 5.5 Maximum squared von Mises stress $\sigma_2^2$ in a 1D bend section plotted against the angular and circumferential position of the monitoring elements. Von Mises stress also plotted for the first 0.7 meters past the bend. Amplitude normalised to the stress in a straight pipe section before the bend.

5.3.2 Influence of bend radius

The von Mises stress distributions along bends with varying radii are plotted in Figure 5.6 a)-d). As before all amplitudes of the von Mises stress were normalised to the stress at the beginning of the pipe bend, corresponding to the pure shear stresses generated by the incident torsional T(0,1) mode. Figure 5.6 a)-d) and Figure 5.5 were all plotted on the same amplitude scale in order to simplify the comparison of expected crack reflections between bends of different radii. In Figure 5.6 a) it can be seen that the von Mises stress in a 2D bend shows similar maxima close to the pipe extrados as observed before in the 1D bend result in Figure 5.5. These two lobes disappear with increasing bend radius and the maximum reflection is located on the extrados for bends with radii of 3D Figure 5.6 b), 5D Figure 5.6 c), 7D Figure 5.6 d) and 20D Figure 5.6 e). The strong local minimum found on the extrados of a 1D bend cannot be observed for any of the larger radii bends. Figure 5.6 c) also shows the von Mises stress for an additional 0.7 meters past the 5D bend. The stress distribution here shows a higher degree uniformity around the circumference of the pipe compared to the stresses past a 1D bend as previously seen in Figure 5.5.
Figure 5.6 Maximum squared von Mises stress $\sigma_v^2$ in a bend section plotted against the angular and circumferential position of the monitoring elements. Radii of bends plotted are a) 2D, b) 3D, c) 5D, d) 7D and e) 20D. For the 5D bend c) the stress distribution for the first 0.7 meters past the bend is also shown.

Figure 5.7 allows for a more direct comparison of the results obtained from the von Mises stress studies of the different bend radii. Plotted here in blue are the maxima of the von Mises stress observed on each bend. The highest von Mises stress could be observed on a 1D bend suggesting a defect at this location would yield the largest reflected signal. The maximum von Mises stresses $\sigma_v^2$ for the investigated bend radii are found to be 3.0 to 4.1 times higher compared to the stresses
in a straight pipe section. The minimum values of the von Mises stresses found in any element along the length of the bends are plotted in red. For each of the investigated bend radii, the lowest von Mises stress could be found at the intrados. Therefore the reflection from a circumferential crack at these minimum locations would be expected to yield a relative amplitude compared to a crack in a straight pipe of 27% for a 1D bend and approximately 10% for the bends with larger radii. Finally, the minimum von Mises stresses found along the extrados of the bends are plotted in green. Corrosion and erosion patches are particularly likely to form at the extrados of a bend where, in the worst case, the reflection amplitude is expected to be 60-90% for a 2D, 3D, 5D, 7D and 20D bend and 50% for a 1D bend relative to a straight pipe. For each minimum and maximum location obtained from the von Mises stress studies (Figure 5.5 and Figure 5.6) an FE model was used to determine the reflected amplitude of the T(0,1) mode from a circumferential through thickness crack. The size of the defects and the setup of the FE model was the same as used for the 1D bend crack study in Figure 5.3. The resulting relative amplitudes are plotted as crosses in Figure 5.7; there is generally good agreement between the predictions from the square von Mises stress $\sigma^2_v$ and the crack reflections. Figure 5.7 shows that an increase in the radius of the bend does not remove the strong variations in defect reflection amplitudes. These variations are probably caused by interference of the two wave modes propagating in the bend produced by an incoming torsional T(0,1) wave [20]. This phenomenon of natural focussing in pipe bends has been studied extensively by Rose et al.[100].
5.4 Conclusion

It was shown with a series of finite element models that the amplitude of the reflections of torsional guided waves from circumferential defects on a pipe bend are highly position dependent and that the degree of amplitude variation is a function of the bend radius. It was found that the largest reflections are obtained from defects located close to the bend extrados; these were shown to be up to 4 times higher compared to the reflections from a defect of the same size in a straight pipe section. The exact position of the maximum reflection was also found to be dependent on the bend radius. Areas of lowest detectability were located on the bend intrados for all investigated radii; for some radii, the reflection could be as low as 10% of that from the same defect in a straight pipe. The minimum reflections from defects located at the pipe extrados were shown to lie between 50% and 90% compared to a straight pipe defect, the lowest extrados sensitivity being on the smallest bend radius (1D) investigated.
Reflection of torsional guided waves from defects in pipe bends

The results of the Finite element study confirmed that the low reflection amplitude seen from a defect at a bend in an earlier study of a guided wave monitoring system was due to the location of the defect in the bend. This highlights a potential problem with guided wave inspection of bends unless the potential defect location is known in advance.

The results show that for circumferential cracks, the variation of the torsional guided wave inspection sensitivity around a bend follows the von Mises stress distribution. It is expected that a similar variation would be seen for small, roughly equiaxed corrosion defects, but the sensitivity to axial cracks would be very different as these do not affect the transmission of axial stresses. T(0,1) guided wave inspection is in general less sensitive to axial defects compared to defects which also exhibit some circumferential extent [70].
Chapter 6

6 Evaluating the performance of an installed SHM system

In this chapter, the potential of a procedure for the evaluation of the damage detection ability of a guided wave system will be discussed. Finite element models are a well-established method for simulation of guided wave reflections from discontinuities in a structure. The complex effects of environmental condition changes however cannot be generated reliably with numerical approaches. The methodology discussed in this chapter combines measurements collected on a real structure in an undamaged state undergoing environmental condition changes with defect reflections obtained from FE simulations. Using FE models to produce a large number of defect types and growth patterns allows for a large quantity of damage cases, unobtainable for experimental data, to be investigated while also making use of complex environmental effects collected on a real structure. This process was first proposed by Liu et al. [71] but was only applied to a very simple test pipe without any real damage growth. This chapter will utilise collections from the more complex blind trial test pipe (see Chapter 4) in order to determine how suitable this methodology can be for practical cases.

6.1 Introduction

Repeated access to a pipe section is highly costly and therefore there has been strong interest in advancing from the standard single inspection guided wave measurements to a structural health monitoring system permanently installed on site, thus allowing for the continuous collection and interpretation of data. It was shown in Chapter 4 of this thesis that such an SHM system based on an independent component analysis algorithm [82], [84] will allow for defects as small as 0.5-1% cross-sectional area loss to be identified [114] reliably. This corresponds to an improvement of the minimum detectable defect size by a factor of approximately 5 compared to standard single inspection investigations.

Knowledge of the damage detection ability of a health monitoring system is of great importance to an operator as it allows for an informed statement to be made about the maximum size of a defect that could be missed. For standard guided wave inspection the structure-specific minimum
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detectable defect size of the system is best estimated from the average noise level of a collection. This allows the operator to determine the detection threshold, which is usually set to be about twice the amplitude of the noise. This is not an appropriate approach for a health monitoring system as the smallest detectable defect signals can lie below the noise level of an individual measurement. This is due to the fact that a ICA based SHM system can decompose the noise and defects observed in a set of guided wave signals into different components, thus allowing for damage growth with reflection amplitudes lying below the noise floor to be revealed.

The determination of the damage detection ability of a health monitoring system has a multitude of challenges. Firstly, the probability of detection of the system is not solely governed by the equipment and the SHM procedure, but also by the general condition of the pipe, as well as the environmental changes it will undergo during monitoring. Secondly, the false alarm rate is also of great concern in monitoring applications as the costs of following up defect indications can be substantial. The receiver operating characteristic (ROC) curve [71] is a valuable performance metric as it plots the probability of detection against the probability of false alarm. Unfortunately, determining the ROC curve for an SHM system is even more difficult than for an NDT inspection system. This is due to the fact that the effect of environmental variations and potential transducer/instrumentation drift which may occur over an extended period, as well as the changes due to damage of different types and severity at different locations, must be evaluated. This would involve an impractical number of test structures in the operational environment, and an extensive programme of damage introduction over a long period of time. The environmental and operational conditions of the SHM system will also vary between different structures, thus causing results obtained from one inspected setup not necessarily being transferable to others.

Another approach is to simulate the received signal; modern computational resources mean that it is relatively straightforward to reliably predict the signature produced by damage in guided wave measurements, even when it has complex shape [59]. However, reliable prediction of signal changes due to environmental and other variability is much more difficult; on the other hand, obtaining experimental data with environmental variation on an undamaged structure is easy. Liu et al. [71] proposed a methodology of measuring data over multiple environmental cycles on
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an undamaged structure and synthetically adding damage to the resulting signals; this approach enables the addition of damage at different locations with different growth patterns, and the investigation of other practical parameters such as the extent of environmental changes, damage severity, frequency of readings, etc. They illustrated the approach on the guided wave monitoring of a single length of pipe in the laboratory with simple, flat-bottom hole defects.

The performance prediction methodology introduced by Liu et al. can potentially be of great value for any kind of SHM system which is expected to collect frequent data. Since the damage detection ability of an installed health monitoring system does not only depend on the measurement equipment used but also the general state of the inspected structure, its geometry and the extent of environmental variations, the minimum defect size detectable in practice is difficult to determine at the design stage, or even when the system is installed. By superimposing defect reflections obtained from FE simulations onto measurements collected from a monitored structure in a constant state it becomes possible to include environmental and other structure-specific effects in a synthetic monitoring data set; these complex effects could never be obtained by the use of FE analysis on its own. The synthetic dataset generated with this methodology can then subsequently be used to determine the damage detection ability of the SHM procedure of interest. Therefore, this novel approach will allow the operator of a given SHM system to make much more accurate predictions of the minimum defect size expected to be found reliably on the specific monitored structure or of the maximum defect size yet undetected. In this chapter, the results of an investigation of whether the use of simple defect geometries in FE simulations can satisfactorily predict the minimum defect size detectable by an installed structural health monitoring system will be presented. The measurements used in this investigation were those collected from the trial pipe described in Chapter 4. During the trial the dimensions of the introduced defect were recorded at each of their growth stages and a set of baseline readings were taken over multiple temperature cycles prior to the introduction of any of these defects. This therefore provided an ideal opportunity to validate the proposed performance prediction method [71] on a more complex pipe system with more realistic damage shapes and growth patterns, and this study is reported here.
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Section 6.2 describes the setup of the test pipe used to grow a number of corrosion-like defects as well as the setup of the FE models used to replicate these. In the same section the procedure of combining artificial defect reflections and real baseline data is discussed. Section 6.3 presents the results of the study and compares the damage detection ability of the processing scheme of real and artificial damage growth. Section 6.4 gives concluding remarks on the validity of the proposed procedure to estimate the damage detection ability of an SHM system.

6.2 Methodology

The measurements presented in this chapter were those collected on the temperature controlled test pipe section of Chapter 4. The gPIMS guided wave sensor was permanently attached onto an L-shaped pipe with an outer diameter of 8 inches. Two straight pipe sections of length 7 and 2 meters respectively were connected via a 1.5D 90° bend as seen in Figure 4.1 a).

A heating cable was helically wrapped around the outside of the pipe, allowing for its temperature to be controlled. The setup was cycled between room temperature and 60°C while measurements were collected. About 300 baseline measurements were taken at various temperatures during cycling and prior to any introduction of damage. Defects were introduced into the pipe at six different locations as indicated in Figure 4.1 a). Three defects were placed on the long straight pipe section onto which the gPIMS was attached. A single defect was introduced on top of the 1.5D bend approximately halfway along it, and two more damage sites were located past the bend. The defects were introduced into the setup by grinding away small amounts of material from the outside of the pipe using a diamond burr; no grinding was performed while a measurement was being collected. The size of each of the defects was increased in ten steps, after each of which precise measurements of its dimensions were taken; the cross-sectional area loss at each stage of the damage growth could thus be calculated. The work of this chapter will be focused on the growth of three out of the six defects; two on the longer of the two straight pipe sections (defects 1 and 2) and another close to a weld just past the pipe bend (defect 5). All three defects presented in this chapter were introduced at different times, i.e. the defects were grown to their 10th and final stage before damage at a different location was initiated. Since the defects were relatively small, they have little effect on the signal transmitted past them and incident on any features further down the pipe; therefore reflections from later
defects will not be significantly affected. However, a defect introduced between the monitoring ring and another defect will cause a change in the coherent noise floor past its location. This can affect the visibility of the later damage due to superposition of its reflection with the coherent noise.

FE models were created based on the measured dimensions of the defects during the growth process simulating the torsional T(0,1) guided wave reflections from these discontinuities. The predicted FE defect reflections could then be superimposed onto a number of damage free collections of the test pipe section at the same locations at which the real defects were later introduced. Datasets with the real and the artificial defect reflections were then investigated using an ICA based structural health monitoring algorithm such that the monitored growth for both cases could be compared. A flowchart of the procedure can be seen in Figure 6.1.
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Figure 6.1 Schematic of process of comparing real defect growth to artificial defect growth superimposed onto real data collections. Grey boxes indicate data. White boxes indicate operations on data.

6.2.1 Data collection

For the proposed procedure of superimposing simulated defect reflections and real guided wave measurements, a large number of collections from the test pipe setup are required. A non-dispersive torsional T(0,1) guided wave signal was excited by the transducer ring which works in pulse-echo mode. The Hanning windowed 8 cycle excitation signal used had a centre frequency of 25.5kHz. An example plot of such a measurement, collected in both directions from the transducer ring location can be seen in Figure 6.2. Due to the non-dispersive nature of the T(0,1) mode, all signals could be plotted in the spatial domain by simple conversion with the T(0,1) wave velocity in carbon steel. The signals are normalized to the cut end reflection of the straight pipe section (forward direction as determined by the sensor orientation). The reflection from the
cut end past the pipe bend is significantly reduced in amplitude and the mode conversions induced by the passing of the signal through the 1.5D bend cause severe distortions in the shape of the reflected wave packet. The reflection from the weld at a distance of approximately 2m from the transducer ring is highlighted in the plot. The pipe bend can be identified in the signal trace by the reflections from its two welds connecting it to the straight pipe sections, as seen in Figure 4.1 a) at approximately 2.5m and 3.2m from the measurement position.

![Graph showing A-scan on defect-free test pipe in forward and backward directions.]

*Figure 6.2 Example A-scan measured on the defect-free test pipe in the forward and backward directions.*

### 6.2.2 Artificial defects

With knowledge of the exact axial, circumferential and radial extent of the introduced defects, provided by ESR Technology, it was possible to replicate these using an FE model. This was achieved by first creating an undamaged mesh of the L-shaped pipe setup using Abaqus CAE [109]. The mesh was generated with 300 brick elements around the circumference of the pipe and 4 elements across the pipe wall thickness. The meshed geometry was exported to MATLAB in order to introduce defects of the same dimensions as those measured on the experimental setup over the course of the trial into the FE model. Using the measured dimensions of the real defects, ellipsoidal depressions were introduced into the pipe wall by compressing a number of elements of the FE mesh in the radial direction.

An ellipsoid of the correct defect dimensions (depth, circumferential and axial extent) was centred on the outer surface of the pipe wall in the desired damage location. Given the location $S$ of a surface node, with the centre of the defect ellipsoid $P$ the node position can be shifted in
the direction \( \vec{N} \) by a distance \( r \) to the point \( S' \). Thus the position \( S' \) as illustrated in Figure 6.3 is determined by the equation

\[
\left( \frac{S_x + rN_x}{a} \right)^2 + \left( \frac{S_y + rN_y}{b} \right)^2 + \left( \frac{S_z + rN_z}{c} \right)^2 - 1 = 0
\] (6.1)

\[\begin{align*}
\text{Defect profile} \\
\text{Inner surface} \\
\text{Outer surface}
\end{align*}\]

Figure 6.3 Illustration of the process of determining the shifted position of a surface node when introducing an ellipsoidal damage patch into the outer surface of a pipe. \( P \) denotes the centre of the defect ellipsoid, \( S \) and \( S' \) are the initial and target defect node positions respectively, \( r \) is the magnitude by which the node is shifted in the direction \( \vec{N} \).

The unit vector \( \vec{N} \) denotes the radial direction i.e. the vector points towards the central axis of the pipe. All surface nodes of the FE model lying within the volume of the ellipsoid are shifted in the radial direction by a distance \( r \) determined by Equation (6.2) when considering a defect located at any circumferential angle \( \varphi \).

\[
r^2 \left[ \frac{N_x^2 \sin^2 \varphi + N_y^2 \cos^2 \varphi + 2N_xN_y \sin \varphi \cos \varphi}{a^2} + \frac{N_x^2 \cos^2 \varphi + N_y^2 \sin^2 \varphi + 2N_xN_y \sin \varphi \cos \varphi}{b^2} + \frac{N_z^2}{c^2} \right] + \\
r \left[ \frac{2(S_xN_x \sin^2 \varphi + (S_xN_x + S_yN_y) \sin \varphi \cos \varphi + S_yN_y \cos^2 \varphi)}{a^2} \right. \\
+ \left. \frac{2(S_yN_y \sin^2 \varphi + (S_yN_y + S_zN_z) \sin \varphi \cos \varphi + S_zN_z \cos^2 \varphi)}{b^2} \right] + \\
+ \frac{2S_zN_z}{c^2} \right]
\] (6.2)
\[
\begin{aligned}
&S_x^2 \sin^2 \varphi + S_y^2 \cos^2 \varphi + 2S_x S_y \sin \varphi \cos \varphi \\
&\quad + S_x^2 \cos^2 \varphi + S_y^2 \sin^2 \varphi + 2S_x S_y \sin \varphi \cos \varphi + \frac{S_z^2}{c^2} \\
&\quad - 1 = 0
\end{aligned}
\]

\(S_x, S_y\) and \(S_z\) are the coordinate positions of the centre of the defect ellipsoid and the direction in which the surface nodes will be displaced is denoted by \(N_x, N_y\) and \(N_z\). For defects on straight sections of the pipe, the vector \(\vec{N}\) will be purely radial i.e. there will be no \(N_z\) component. The circumferential extent, the damage depth and the axial extent are given by the quantities \(a, 2b\) and \(2c\) respectively. For a defect located at the \(\phi = 90^\circ\) circumferential position Equation (6.2) simplifies to

\[
\begin{aligned}
&r^2 \left[ \frac{N_x^2}{a^2} + \frac{N_y^2}{b^2} + \frac{N_z^2}{c^2} \right] + r \left[ \frac{2S_x N_x}{a^2} + \frac{2S_y N_y}{b^2} + \frac{2S_z N_z}{c^2} \right] + \left[ \frac{S_x^2}{a^2} + \frac{S_y^2}{b^2} + \frac{S_z^2}{c^2} \right] - 1 = 0 \quad (6.5)
\end{aligned}
\]

Due to the structured nature of the mesh, all nodes directly below the displaced surface node are also shifted in order to keep the distribution of the mesh nodes throughout the thickness of the pipe wall as consistent as possible. The shifted distance of each of the non-surface nodes should therefore be reduced with respect to the depth of the node. In this particular case, for a total of 5 nodes over the thickness of the pipe wall this equates to a shifting distance of \(\frac{3r}{4}, \frac{2r}{4}\) and \(\frac{r}{4}\) decreasing for nodes closer to the central axis of the pipe. The nodes on the inner surface of the pipe were not shifted at all during this process in order not to generate a protrusion on the inside of the pipe. An illustration of this process can be seen in Figure 6.4 and Figure 6.5.
Figure 6.4 Illustration of the process of shifting node locations when introducing discontinuities in an FE model. View of a cut in the r-z plane. a) The node and element positions prior to damage introduction. b) Target aspect size highlighted in red, green arrows illustrate the position to which surface nodes will be shifted. c) Node positions after introduction of the discontinuity.
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Figure 6.5 Illustration of the process of shifting node locations when introducing discontinuities in an FE model. View of a cut in the r-ϕ plane. a) The node and element positions prior to damage introduction. b) Target defect size highlighted in red, green arrows illustrate the position to which surface nodes will be shifted. c) Node positions after introduction of the discontinuity.

Figure 6.6 shows a cut-away view of the mesh for defect 2 at its tenth and final growth stage. Individual FE models were generated for the 10 growth stages for each of the three investigated defects, yielding 30 models in total. The T(0,1) input signal was introduced into the FE model by displacing a ring of nodes on the surface of the pipe in the tangential direction. After introducing the desired defect shapes the models were solved in the time domain using the Abaqus explicit solver. This procedure has previously been reported in, for example [14], [58], [59]. A ring of monitor nodes was used to record displacements in all spatial dimensions. The T(0,1) mode was extracted by summing the tangential displacement of all the monitoring nodes, as discussed in [11] and Chapter 2.

The changing temperature of the pipe was not considered when using finite element simulations to generate defect reflections. This is reasonable as the reflection coefficient from a defect is
unlikely to be significantly affected by the small temperature-induced material property changes. However, the position of the defect reflections when superimposed onto the baseline data was determined by the temperature of each guided wave collection, as the temperature induced velocity changes do affect the arrival times. Possible changes to the phase of the induced signals were not considered, which could cause some variation between results of real defects and those replicated via FE simulations.

![Figure 6.4. Cut-away view of FE mesh used to replicate the final growth stage of defect 2.](image)

Reflections from defects in the straight pipe sections positioned before the bend were simulated by analysing the reflections in a straight pipe; since the T(0,1) mode is non-dispersive, the propagation distances are not relevant as a time delay can be added as required during the superposition process. However, when considering reflections from defects located past the bend, it was important to include the approximate bend geometry in the model as the signal incident on the defect is significantly affected by propagation round the bend, and the time delay induced by the bend is not as simple to determine as for a length of straight pipe.

Rather than exciting the guided wave signal at the ring position, the T(0,1) mode was induced at the cut end of the pipe. This meant that the wave travelled only in one direction from the excitation, therefore avoiding early reflections from the free end that would complicate the signal. In the physical setup, this is dealt with by exciting on two adjacent rings and phasing the inputs to give cancellation of the wave travelling in the unwanted direction [39]; this could have been implemented in the FE model but was an unnecessary complication. The phase delay between defect reflections recorded by the FE model and the test pipe section can easily be compensated

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for by shifting the signal in the time domain. Welds present in the trial pipe were neglected throughout the FE simulations as their influence on the defect reflections is minimal.

A torsional T(0,1) signal was introduced into the FE model by simultaneously displacing all the nodes in the excitation ring by the same amplitude in the circumferential direction, thus suppressing the generation of flexural wave modes [10]. The Hanning input signal had a centre frequency of 25.5 kHz and a pulse length of 8 cycles, identical to the input signal of the laboratory trial. Predicted reflections of the T(0,1) mode from the introduced defects were obtained by summing the circumferential displacements at a ring of monitoring nodes [11]. Using this setup, the reflections for each of the defects at each of their growth stages were recorded. An example plot of a number of reflected signals from defect 1 can be seen in Figure 6.7.

![Figure 6.7 Example reflections obtained from FE model of defects introduced into a straight pipe section. Five of the 10 stages of defect 1 are shown.](image)

6.2.3 Combining real and artificial data

The next stage of the investigation consisted of combining the baseline data collected from the physical pipe setup with the reflection signals obtained from the FE simulations of the damaged pipe. Measured and simulated time traces were combined by simply superimposing the FE time traces onto baseline measurements. The exact location of the defect reflections was adjusted for the temperature of the baseline measurement, ensuring correct positioning relative to other pipe
features and preventing misalignment after later temperature compensation of the signals. This was achieved by shifting the position of the simulated defect reflections in accordance with the temperature stretch factor of the respective baseline signal which was obtained as described in the following sub-section. The baseline measurements were chosen such that a range of temperatures, comparable to the measurements collected during the real defect growth, was covered. The same number of undamaged pipe measurements were chosen for the growth of the artificial defect as were collected during the growth of the real damage on the laboratory pipe setup; also the number of measurements at each growth stage of the defect was kept consistent between the real and simulated defect datasets, such that the performance of the SHM algorithm operating on both datasets could be compared directly.

6.2.4 Damage detection algorithm

For each of the three defects in the pipe setup investigated in this chapter, the SHM algorithm was applied to both the measurements of the real defect growth as well as the previously generated dataset containing the simulated defect growth superimposed onto defect-free measurements of the pipe. The first stage of the SHM algorithm consists of compensating each dataset for environmental variations by linearly stretching the signals to a baseline measurement by applying a scale transform based temperature compensation algorithm [75]. An ICA algorithm is subsequently used to reveal underlying changes in each of the temperature compensated datasets [114]. As described in Chapter 3 the ICA algorithm allows for a set of guided wave measurements to be decomposed into a number of weighting function and component pairs. Each of the obtained components corresponds to reflections from one or more features in the pipe. The corresponding weighting functions contain information about the change in the components reflection amplitude over the course of the dataset; a more detailed description of the SHM process is given in Chapter 3 of this thesis.

Temperature is the only environmental variable considered in this study and the associated blind trial [114]. This is generally considered to be the dominant environmental variable [32], [115] though load, for example, may be important in some instances [116], [117]. The influence of a large number of environmental effects can manifest as variations in the coherent noise floor, thus reducing the damage detection ability of a system. If the baseline data collected contains these
variations they will be included in the data to which the stretch and ICA methodology of Figure 6.1 is applied. Provided these environmental changes do not affect the defect reflection amplitude and arrival time more than the temperature of the structure, the simulation approach will also work and so could be used to evaluate the system performance. However, this has not been tested here since the blind trial only included temperature variations.

The temperature of a pipe in the field will generally not be as uniform as for the pipe setup used in this investigation. Non-uniform temperature distributions across the length of an inspected structure might affect the results of any SHM approach used. Provided that the baseline data includes these non-uniform temperature variations, the validation methodology will still work and it would be expected that the defect detection capability will be somewhat degraded. This cannot be verified using the trial data of [114] as the temperature was kept uniform over the full structure.

During the investigation presented in this chapter, the component and weighting function pairs corresponding to the growth of defects in the datasets were identified manually from the ICA results. The amplitude of the defect reflection over the course of the datasets obtained from the weighting functions, for both the simulated and real defect growth, could thus be compared to the actual cross-sectional area loss at each of the damage stages as measured during their introduction into the test pipe.

6.3 Results and discussion

The ICA based SHM methodology was applied to the datasets with real and artificial defect growth after each of the 10 growth stages for defects 1, 2 and 5, positioned as seen in Figure 4.1 a). For each of the defects two figures are plotted, the first of which shows the defect component at the time of first call i.e. when it was first detected during the blind trial [114]. The second plot presents the defect component and weight at its 10th and final growth stage. The weighting functions can be used to compare the defect growth patterns predicted from the real and synthetic datasets with each other and with the true defect growth.

Figure 6.8 shows the results obtained for defect 1, located on the longer straight section of the test pipe in the forward direction. The components shown in Figure 6.8 a) and b) for the first
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detection and final stages show that in both cases the defect was correctly located at a distance of 3.46m from the transducer ring, which is indicated by a vertical red line on the plots. In Figure 6.8 a) it can be seen that the defect growth pattern identified was similar for the real and simulated defect datasets, the growth at around measurement 50, being evident in both. The damage, in this case, was identified after it had been grown to its 4th stage corresponding to a cross-sectional area loss of 0.63%. The weighting functions obtained from both the simulated and measured data follow the true CSA level as determined from the defect dimensions. Deviations from the true defect size as well as variations in the defect amplitude during periods when its size was not changing can be attributed to the varying temperature of the pipe and imperfectly compensated environmental effects. An example of this can be seen in the weighting function in Figure 6.8 a) around measurement number 100. Here the baseline data onto which the simulated defect reflection was superimposed underwent a full temperature cycle. Figure 6.8 b) shows that both the simulated and real defect components follow the true defect size closely. For the two final growth stages, the weighting function obtained from the measured data underestimates the size of the defect slightly; this was because defect 2 was then also being introduced into the pipe, causing changes in the coherent noise at the location of defect 1 which destructively interferes with the defect reflection. This effect was not modelled in the simulations.

![Weighting functions for defect 1 a) at time of first detection after 4 growth stages and b) at its final size after 10 growth stages. The weighting function in black indicates the true damage size, blue shows the ICA weighting function using measured data and red the ICA weighting function using simulated data. The plotted components in a) and b) are those obtained from the real defect growth dataset. The position of the defect as measured on the pipe during the trial is indicated by a vertical red line.](image)

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The ICA results of defect 2, located on the straight section of the pipe in the forward direction, are shown in Figure 6.9. The components at both the time of first detection and the final growth stage indicate that the defect was identified at the correct distance of 2.57m from the transducer ring. The defect was first detected after 5 growth stages with a cross-sectional area loss of approximately 0.73% in the datasets of the real as well as simulated growth. The growth of the measured and simulated weighting functions are first evident around measurement number 90. In both cases, the weighting functions trace the true defect size well. Similar to the results for defect 1, the discrepancies between the expected and observed amplitude of the weighting functions can be attributed to imperfectly compensated temperature effects. Figure 6.9 b) shows the results of the SHM procedure after the defect had grown to its final size with a cross-sectional area loss of 1.8%. It can be seen that the weighting functions of both the simulated and measured data trace the true defect size well.

![Weighting functions](image)

*Figure 6.9 Weighting functions for defect 2 a) at time of first detection after 5 growth stages and b) at its final size after 10 growth stages. The weighting function in black indicates the true damage size, blue shows the ICA weighting function using measured data and red the ICA weighting function using simulated data. The plotted components in a) and b) are those obtained from the real defect growth dataset. The position of the defect as measured on the pipe during the trial is indicated by a vertical red line.*

The results of the last defect investigated in this chapter are shown in Figure 6.10 a) and b). Defect 5 was introduced into the test pipe close to a weld just after the 1.5D pipe bend. During the trial, it was initially expected that defects positioned past the pipe bend would be more challenging to identify and thus defect 5 was grown in larger increments and to a greater final size in comparison to the defects introduced before the bend. The defect was first detected during the trial after completing its first growth stage resulting in a cross-sectional area loss of 0.59%.
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Figure 6.10 a) shows the results of the ICA based SHM procedure at the time of first detection. A clear step in the weighting functions is visible around measurement number 50. Consistent with the results for defects 1 and 2, the weighting functions of both the simulated as well as the measured data trace the true defect size closely. Over the full 10 growth stages of the defect the weighting functions of both the simulated and measured datasets track the defect size well, as seen in Figure 6.10 b); it should be noted here that the weighting functions in Figure 6.10 a) and b) are plotted on different amplitude scales. Variations in the amplitude of the weight in Figure 6.10 b) with respect to temperature are not as prevalent as for the two previously presented defects; this can be attributed to the larger final size (8.27% CSA) of defect 5 diminishing the effect of temperature variations.

![Graphs showing weighting functions for defect 5](image)

*Figure 6.10 Weighting functions for defect 5 a) at time of first detection after the first growth stages and b) at its final size after 10 growth stages. The weighting function in black indicates the true damage size, blue shows the ICA weighting function using measured data and red the ICA weighting function using simulated data. The plotted components in a) and b) are those obtained from the real defect growth dataset. The position of the defect as measured on the pipe during the trial is indicated by a vertical red line.*

6.4 Conclusion

Validating the performance of guided wave SHM systems is vital if they are to be widely deployed; testing the damage detection ability of a system by introducing different types of damage at varying locations is very costly and cannot be performed on a system in operation. A performance validation methodology making use of large numbers of defect-free measurements of a system and superimposing defect reflections obtained from FE simulations has previously been proposed and shown to be successful on a rudimentary laboratory pipe setup.
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A blind trial was conducted in order to test the performance of guided wave structural health monitoring systems for pipes, results of which can be found in Chapter 4. A number of defects were introduced into a pipe setup including welds and a 90 degree bend. The setup underwent temperature cycling while measurements were collected and the locations, growth rates and dimensions of the defects were recorded. The measurements therefore provided an opportunity to investigate the accuracy of the proposed performance validation methodology on a representative pipe system.

The growth of three of the defects in the test pipe was replicated by superimposing synthetic defects, obtained from FE simulations of the damage, onto readings acquired during environmental cycling of the pipe prior to the introduction of any damage. This allowed for the generation of datasets with well-defined defect growth patterns at known locations while also retaining the effects of environmental variations of the structure on the signals which cannot be obtained from FE simulations. The datasets containing the simulated defect growth were processed with the same ICA based SHM procedure as used for the initial defect identification during the blind trial. The ICA procedure yields the estimated defect location and its growth as a function of time. Very good agreement was obtained between the results obtained using the purely experimental data collected during the blind trial and those obtained from the synthetic datasets, both corresponding well with the true defect growth. The results obtained during the investigation therefore validate the proposed performance prediction methodology.

The ability to validate the damage detection ability of an installed health monitoring system will be of significant value in the development of safety cases as it will be possible to establish whether a defect of a particular size, location and type would be detected by the setup. By combining measurements collected during environmental cycling of the system and simulated defect reflections obtained from FE studies, the minimum defect size detectable with the SHM system for a test structure can be determined. The presented methodology enables the operator to combine the ability of FE analysis to predict the signals reflected from a large number of different defect cases with the complex geometric and environmental effects specific to the particular pipe structure which cannot be effectively simulated. Although the results presented
in this chapter were obtained from a guided wave system for pipes, this methodology can be
utilised to predict the damage detection ability of any other SHM system.
Chapter 7

7 Improving temperature compensation and removal of residual noise

This chapter will discuss a novel approach which allows for the reduction of temperature dependent amplitude variations found in weighting functions obtained from the ICA based SHM algorithm when applied to guided wave signals. The presented methodology was first proposed by Dr Stefano Mariani, a postdoctoral researcher at Imperial College at the time of writing of this thesis. Dr Mariani and the author collaborated in testing and refining the presented procedure. The improvement in sensitivity and reduction of the false call rate that can be achieved with the application of this methodology by utilising the dataset of the previously presented blind trial was evaluated. It was found that this novel approach allows for the significant reduction of temperature induced frequency response changes and coherent noise variations commonly observed in guided wave inspection systems for pipes. The procedure has been patented under reference number 88096GB1 [118] and an additional journal article is in preparation by Mariani, Heinlein et al..

7.1 Introduction

When utilising permanently installed guided wave instrumentation for the purpose of structural health monitoring, it is inevitable that the system will undergo environmental condition changes over the monitoring period. These effects can originate from a multitude of sources such as load and pipe content changes, or variations in the temperature of the inspected structure. When applying the SHM algorithm presented in Chapter 3 it is aimed to remove the most predominant temperature effect, the change in the wave velocity within the material, by linearly stretching the collected signals, prior to the application of the ICA algorithm. However, it was observed during the blind trial evaluation of the SHM algorithm (Section 4.3.1) that, even after temperature compensation, a large number of the weighting functions obtained from the ICA stage of the procedure still exhibited behaviour strongly correlated to the temperature history of the test pipe setup. This effect can be observed in Figure 7.1 where a) shows the temperature
of the inspected structure over the course of the blind trial (Chapter 4) and b) shows a selection of weighting functions obtained after application of the ICA algorithm. It can be seen that a number of these follow the trend of the temperature while others show no temperature dependence.

![Graphs showing temperature and amplitude variations](image)

*Figure 5.1 a) Temperature of the structure inspected during the blind trial (Chapter 4); b) A selection of weighting functions obtained from the SHM algorithm applied to the full set of trial measurements. Similarity in the behaviour of the temperature and a number of the weighting functions can be observed.*

In this chapter, two different sources of this effect will be discussed. Firstly it was found that the variations in the coherent noise floor of the collected signals will exhibit behaviour closely correlated to the temperature changes in the inspected structure. Secondly, the temperature variations in the transducer ring will influence the frequency response of the system and thus the signal shape of the wave pulse propagating through the structure. This frequency response change will subsequently manifest as an amplitude variation in the weighting functions corresponding to benign feature reflections such as welds due to changes in the shape of the envelope and the phase of the signals excited by the transducer ring. It was found that the methodology presented in this chapter allows for the reduction of both of these effects and thus an improvement in sensitivity, as well as a reduction in the false call rate, can potentially be achieved.

### 7.1.1 Origins of coherent noise

Comparing a number of temperature compensated guided wave measurements, each collected at different temperatures, variations in the coherent noise floor of the signals can be observed. This
effect is highlighted in Figure 7.2. Here measurements from the blind trial pipe setup (shown in Chapter 4) covering a single temperature cycle are plotted. The colours of the graphs are given with respect to temperature such that measurements collected at the highest temperature (40°C) are plotted in yellow while those collected at the lowest temperature are plotted in black (14°C). When zooming into the noise floor it can be seen that there are clear variations in the coherent noise signals with respect to the temperature of the structure.

Figure 7.2 Figure colour coded from black (coldest) to yellow (hottest). a) Envelope of a set of measurements, obtained from the blind trial setup presented in Chapter 4, spanning the full temperature range after temperature stretch compensation has been applied. b) Zoomed in view of the noise floor. Amplitudes of coherent noise clearly temperature dependent.

This effect can be further illustrated when plotting the amplitude at a single location along the distance axis of the signals over the duration of the trial period. In this case, the coherent noise variation at the 4.25m and 3.60m positions (see Figure 7.2) was chosen. This is shown in Figure 7.3 where it can be clearly seen that the amplitude of the coherent noise at the 4.25m location shows a behaviour strongly correlated to the temperature of the inspected structure. It is important to note here though that the temperature correlation of the coherent noise floor is also dependent on the position along the pipe. While some locations show high temperature dependence, others might be inversely correlated to the temperature or show no temperature dependence at all. This effect is illustrated in Figure 7.3 when observing the behaviour of the coherent noise floor at the 3.60m position.
The existence of coherent noise in guided wave measurements can be attributed to the presence of modes, other than the torsional T(0,1), in the input signal. In order to excite a pure T(0,1) signal in a pipe, it is required that all transducer ring elements, located around the circumference of the pipe, induce the same signal with constant amplitude and phase. If a coupling imbalance exists between the individual transducer elements of the measurement ring the amplitude, and possibly the phase, of the excitation signals from the transducers will not be uniform and thus it is possible that a number of asymmetric modes, such as flexural waves (F(1,2), F(2,2), etc.) which were described in Chapter 2, will be generated alongside the desired torsional mode. Due to the coupling imbalance, the signals recorded by the transducer ring upon reception will also be influenced, further increasing this effect. These modes, if generated by the transducer ring itself, will travel along the pipe, reflect from features in the structure and subsequently interfere with T(0,1) reflections at the transducer location during the signal reception thus causing the amplitude of the measured torsional mode to be impacted by superposition of these multiple modes.

Another family of modes which are inadvertently generated by the transducer ring are circumferential modes. The circumferential modes are A0 and S0 like modes propagating around the pipe rather than in axial direction [119]. These modes will be generated even if no coupling imbalance exists in the sensor. However, if an imbalance exists the amplitude of these signals
will be increased. The received amplitude of these modes cannot be easily predicted as it is a function of the number of transducers in the ring as well as the wall thickness of the inspected pipe and thus the velocities of the generated circumferential modes. These modes are generated together with the T(0,1) signals since the transducers have displacements in the circumferential direction (tangential to the surface of the pipe and normal to the pipe axis). The presence of these circumferentially travelling waves can generate coherent noise in the recorded T(0,1) signals. Circumferential modes will propagate underneath the transducer ring around the pipe circumference. The repeated passing of these waves under the transducers will cause a signal to be recorded throughout the whole collection. These signals will subsequently interfere with T(0,1) signals reflected from features in the inspected structure, thus generating a coherent noise signal in the collected measurement. The presence of these circumferential signals can be inferred from the collected data due to the existence of coherent noise in collected signals located before any feature reflections. This noise thus cannot be attributed to signals propagating in the axial direction.

The origin of this coherent noise can easily be illustrated by using a finite element model of a simple straight pipe section containing a single weld. As described in Chapter 2 the torsional wave signal is usually induced by displacing a number of nodes located around the circumference of the pipe by the same amplitude in circumferential direction. By randomising the displacement amplitude of these source nodes within a certain limit it is possible to induce the effects discussed in the previous paragraphs. Shown in Figure 7.4 are the results of a finite element study of such a setup. The wave propagation was simulated on a short straight pipe section. A total of 26 excitation nodes were spaced evenly around the circumference of the pipe, thus simulating the individual elements of a transducer ring. The maximum amplitudes of the input signals for each transducer were set to a random value between 0.5 and 1.5 of the expected displacement. The distribution of these amplitude values can be seen in Figure 7.5. These finite element models were generated in MATLAB and the results were obtained from Pogo [120][121]. As expected this simulated variation in transducer coupling generates a coherent noise floor in the collected signals as shown in Figure 7.4.
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**Figure 7.4** a) Coherent noise simulated using FE analysis by changing amplitude balance of transducers. b) zoomed in view of the coherent noise floor highlighted by red area in a).

**Figure 7.5** Amplitude balance of simulated transducer ring used to obtain traces of the same colour in Figure 7.4. Transducers numbered on outside of plot. Radial position indicating amplitude of displacement when signal is introduced.

The coupling of individual transducers for a given inspection system will generally be dependent on the temperature of the inspected structure. This effect can be observed for both piezoelectric as well as electromagnetic based systems [122] and can be attributed to factors such as changes in the stiffness of the adhesive utilised to fix the transducer system in position. This temperature dependence will not be the same for all transducer elements and thus the relative balance of the
output amplitude will not be constant if environmental conditions change. This effect is most likely to be caused by the fact that the adhesive bond layer thickness will vary between individual transducers of the same ring after installation on a pipe. Therefore the transducers responses to temperature changes will not be identical. A similar effect can be observed in EMATs where temperature variations of the inspected structure will cause impedance changes in the transducer, as the conductivity of the coil, as well as that of the structure, will be affected, thus influencing the emitted signal. The coherent noise signal recorded by a given transducer system will thus be related to the temperature of the inspected structure.

7.1.2 Effect of coherent noise on ICA weighting functions

The ICA based SHM algorithm described in Chapter 3 allows for a large set of signals to be decomposed into a number of components containing information about the locations of features in the collected measurements and weighting functions giving information about the amplitudes of the components over the course of the dataset. Therefore, if temperature dependent coherent noise signals are present throughout the full length of the measurements, the variation in these signals will be incorporated in the output components of the ICA algorithm and thus may cause the weighting functions obtained from the ICA algorithm to show a certain degree of temperature dependence.

It was found that this temperature dependence of the weighting functions is influenced by the location of the feature (the position of the corresponding component) since the degree of variations in the coherent noise floor too are position dependent as it could be seen in the previous section (Figure 7.2 and Figure 7.3). An example of this behaviour is illustrated in three component and weighting function pairs shown in Figure 7.6 obtained from data collected over the full length of the blind trial. It can be seen that Figure 7.6 exhibits behaviour closely correlated to the temperature profile of the structure. This is illustrated in Figure 7.7 by plotting the temperature of the structure against the amplitude of the weighting function over the full blind trial period. It can therefore be assumed that the amplitude of the coherent noise is particularly influenced by temperature swings at this location. An increase in the variation of the amplitude at higher temperatures can be seen. This effect is most likely caused by an imperfect initial temperature stretch compensation.
Figure 7.6 ICA component and weighting function obtained from ICA based SHM algorithm applied to measurements collected from the blind trial setup presented in Chapter 4. Shown here a component related to temperature dependent variations in the coherent noise floor.

Figure 7.7 Temperature dependence of the component shown in Figure 5.6.

Figure 7.8 shows a component and weighting function of the same structure collected over the same period of time which does however not show any significant temperature dependence due to the coherent noise floor being consistent over time at this particular location. Scatter in the data of Figure 7.7 and Figure 7.8 can be attributed to random noise variations in the collected measurements. This is shown in Figure 7.9 by plotting the weighting function amplitude of the component against the temperature of the inspected structure.
Figure 7.8 ICA component and weighting function obtained from ICA based SHM algorithm applied to measurements collected from the blind trial setup presented in Chapter 4. Shown here a component related to coherent noise in the signal which is hardly influenced by temperature changes of the structure.

Figure 7.9 Temperature dependence of the component shown in Figure 7.8.

When using the ICA based SHM algorithm in order to identify the growth of damage it is necessary to define a call level for the obtained weighting functions. If the amplitude of the weighting function surpasses the call level the component can be classified as damage related. It follows that in order to reduce the number of false calls the call level has to lie above the temperature noise floor of the defect-free weighting function. Observing a component unrelated to any defect, such as shown in Figure 7.6, it can be assumed that the call level will have to be above the level of variability in order to ensure that changes in the components amplitude caused by temperature changes will not be misinterpreted as the onset of damage growth. This can be
best illustrated on the example of one of the defects which was grown in the structure during the blind trial. Figure 7.10 shows the component and weighting function related to the defect grown on the bend of the trial pipe (defect 4).

![Graphs showing amplitude and temperature variations](image)

*Figure 7.10 ICA component and weighting function obtained from ICA based SHM algorithm applied to measurements collected from the blind trial setup presented in Chapter 4. Shown here a defect component (defect 4) exhibiting temperature dependent amplitude variations.*

In Figure 7.11 the same weighting function as in Figure 7.10 is shown, however, the amplitude level was shifted such that all values are positive. This was done in order to ensure that temperature related fluctuations of the weighing function do not decrease the estimate of the defect size at the time of first call. A call level was added by setting it to the maximum amplitude of the weighting function prior to the introduction of the defect. It can be seen here that the call level is dominated by the presence of temperature related amplitude variations in the baseline data. It should also be noted that setting the call level just above these variations will cause the false call rate to be relatively high; in reality, the call level would most likely have to be set higher. Figure 7.11 can, however, be used to illustrate the large effect that temperature related amplitude variations have on the time of first call of a growing defect as the blue vertical line highlights the time of first introduction of the defect. The same component will be discussed again in the results section after the application of the proposed temperature dependent amplitude variation compensation.
Figure 7.11 Weighting function of a component related to a defect feature (defect 4). Horizontal black line signifies a simple call level (maximum amplitude of baseline). Vertical blue line is the time of first introduction of the defect.

When considering the three cases presented in this chapter (defect-free components with and without temperature dependence and damage component with temperature dependence) it becomes apparent that it would be beneficial to devise a methodology which allows for the effect of these temperature related coherent noise changes to be removed from the ICA output components and weighting function pairs. This will allow for the detectability of the growth of small defects in a pipe to be improved, as well as reduce the amplitude variations in components which are not related to damage and therefore decreasing the probability of false calls.

7.1.3 Temperature dependent frequency response changes

Changes in the temperature of the inspected structure and therefore in the attached sensor used to collect measurements will cause the frequency response of the transduction system (piezoelectric or EMAT based) to be influenced [122]. All such systems have resonances and therefore the amplitude and phase will be a function of the measurement frequency. A shift in the temperature of the system may cause the frequency response of the transducer ring to be altered and thus the induced and subsequently recorded signals will be influenced by changes in the temperature of the structure. If, for example, the resonance frequency approaches the inspection frequency the output signal of the measurement may be altered by an amount significant enough to deteriorate the performance of an SHM system.
The frequency response of a piezoelectric transducer based gPIMS system was investigated on a temperature controlled trial pipe as shown in Figure 7.12. The temperature of this system was varied over a much wider range compared to the previously discussed blind trial setup. As an example of this effect, the frequency response of a gPIMS sensor with respect to its temperature is shown in Figure 7.13. The transducer ring was installed on a temperature controlled straight pipe section and the frequency response was determined by investigation of the cut end reflection of the structure. The plots are coloured with respect to temperature, where measurements collected at the highest temperature (90°C) are yellow and collections at the lowest temperature (25°C) are shown in black. It can clearly be observed that the frequency response of the transducer ring is temperature dependent with higher frequencies for lower temperature. At room temperature, the resonance frequency is at approximately 26 kHz. This value is reduced to approximately 22 kHz for the transducer ring operating above 50°C. When the resonance frequency moves closer to the operating frequency of the system the signal induced into the structure will exhibit features such as an extended tail caused by ringing of the transducer ring.
Figure 7.13 Temperature dependent frequency response of a transducer ring. Figure colour coded by temperature. Measurements at room temperature shown in black. Measurement at 90°C shown in yellow.

The effect of this frequency response shift can clearly be observed in the changes of the cut end reflections of a straight pipe section. In the case of Figure 7.14 two signals collected at two different temperatures are shown. Both signals were excited at a centre frequency of 25.5 kHz. The two measurements clearly show a significant difference in the shape of the induced tone burst. This effect is best visible when observing the tail of the two signals where a measurement collected close to resonance will exhibit a prolonged ringing effect influencing the shape of the signal.

Figure 7.14 Two collections illustrating the effect of temperature changes on the transmitted signal shape. Figure showing the cut end reflection from a straight pipe section. Envelopes of the signals allow for better comparison of the signal shape.
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When applying the ICA base SHM algorithm to a dataset containing these frequency response effects, the components and the corresponding weighting functions obtained will exhibit temperature dependent amplitude variations. This effect could also be observed in the cut end reflections of the pipe used during the blind trial as presented in Chapter 4. An example of this can be seen in Figure 7.15. Shown here is the component and weighting function of a part of one of these cut end reflections. Clearly, the behaviour of the weighting functions is strongly correlated to the temperature of the sensor.

![Graphs showing amplitude variations and temperature over measurement number](image)

*Figure 7.15 ICA component and weighting function obtained from ICA based SHM algorithm applied to measurements collected from the blind trial setup presented in Chapter 4. Shown here a component related to temperature dependent variations shape of the transmitted signal as observed in the pipe cut end.*

These temperature related frequency response changes and the corresponding changes in the induced signal shape will influence the signal recorded by the transducer ring. It would therefore be desirable to eliminate these amplitude variations in the weighting functions obtained from the ICA based SHM approach in order to reduce the probability of sudden temperature changes being wrongly interpreted as the onset of damage growth.

7.2 Methodology

It was shown in the previous section, that even after the application of stretch based temperature compensation to a set of guided wave measurements, temperature dependent amplitude variations are found to still be present in the weighting functions obtained from the ICA based
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SHM algorithm. In this section, a new methodology, allowing for these temperature effects to be removed from guided wave data, is presented.

7.2.1 Amplitude compensation

For this novel methodology to be successfully implemented the ICA weighting functions obtained have to meet two basic requirements. Firstly, the temperature dependent coherent noise has to be consistent over time i.e. the temperature dependence cannot change within the window of time considered for compensation. Secondly, a number \( n \) of measurements have to be collected at the beginning of the dataset while no damage growth occurred in the structure. These \( n \) measurements, from this point on, will be referred to as “baseline measurements”.

It was observed in Figure 7.7 and Figure 7.9 that the first condition is met for measurements collected using a permanently installed gPIMS sensor for a structure undergoing multiple temperature cycles. Considering the data collected during the blind trial it is also known that a period of baseline signal collection existed, thus fulfilling the second requirement for the successful application of the amplitude compensation methodology. Therefore this section will illustrate the steps of the procedure using measurements collected during the blind trial. In this case, results related to defect 4, located on the bend of the structure, were used.

The first step of the procedure is the selection of the baseline dataset from the given weighting function. This is illustrated in Figure 7.16 where the original weighting function of the component related to defect 4 is plotted in black. The section of the weighting function used as the baseline data is plotted in green. It should be noted here that the baseline data covers measurements collected during the first full temperature cycle of the investigated structure (approximately from 14°C to 36°C). A small number of measurements at the start of the trial, collected at a stable temperature, were not included in the baseline dataset. No defects were introduced into the setup during this time period.
Figure 5.16 *Original weighting function of defect 4 of blind trial setup (Chapter 4) prior to amplitude compensation.*
*Baseline data highlighted in green.*

Given the weighting function of an ICA component, the data points associated with its baseline state can be plotted against the temperature history of the structure. It should be noted here that, in case of the temperature not being recorded during monitoring, the stretch factor applied during the initial temperature signal stretch also gives an appropriate scale against which the weighting function amplitude can be plotted. To obtain an estimate of the temperature dependence of the given weighting function a polynomial can be fitted to the scatter plot (weighting function amplitude against temperature). An example of this process is illustrated in Figure 7.17. Data points from the weighting function are plotted in black. The curve of best fit shown in red was obtained from a $3^{rd}$ order polynomial.
Figure 7.17 Plot of baseline data (Figure 7.16) against temperature of the structure at time of collection. 3rd order polynomial fit allows to estimate the relation of temperature to coherent noise variation at the component location.

This polynomial fit thus represents an estimate of the expected amplitude of the coherent noise with respect to temperature at a location given by the ICA component. Therefore, once this fit is obtained, and since the temperature of the structure or the stretch factor applied to the collections at the time of each subsequent measurement is known, it is possible to estimate the expected coherent noise contribution in the amplitude of the ICA weight for each data point by interpolation of the coherent noise fit function. This estimate of the expected coherent noise amplitude for the given ICA component can therefore be subtracted from the weighting function and thus its temperature dependent amplitude fluctuations in the baseline data points are significantly reduced. This process was applied to the data of Figure 7.16 and the results are shown in Figure 7.18. The compensated weighting function is shown in red while the compensated set of baseline measurements is shown in blue.
Figure 7.18 Original and compensated weighting functions of defect 4 of blind trial setup (Chapter 4) plotted in black and red respectively. Baseline data highlighted in green (before compensation) and blue (after compensation).

If the relation of the coherent noise amplitude to the temperature of the structure stays constant over the whole data set covered by the weighting function the presented approach will reduce these effects in the weight of components not related to actual damage growth. Thus the potential of making a false call by misinterpreting temperature induced changes as the onset of damage growth will be decreased.

If the inspected weighting function contains the growth of damage (starting after the baseline set of length $n$) the presented methodology will allow for improved detectability. As described in 7.1.1 the coherent noise floor is dependent on the transducer system rather than features in the structure. Thus it can be assumed that the relation of the coherent noise to the temperature of the structure at a location given by an ICA component is the same before and after damage was introduced. Therefore the fit obtained from the baseline data points can be utilised to reduce the temperature dependent variations in the weighting function after the defect has been introduced. Reducing these temperature effects will allow for the call level to be reduced (as false calls become less likely) and thus the probability of detection will be improved significantly.

It was shown in 7.1.3 that the effect of temperature related frequency response changes on the ICA weighting functions exhibits the same behaviour as that of the coherent noise. Therefore the same compensation approach can be applied to this additional temperature effect in order to reduce the false call rate and improve the probability of detection. The assumption is made
that these frequency response changes are consistent over time and over multiple temperature cycles. Thus the ICA weighting functions of feature components in the structure will exhibit clear temperature dependence which can subsequently be reduced by utilising the proposed methodology. The application of the compensation method will enable the improved detection of defects growing in close proximity to benign pipe features. These were previously obscured by the frequency response induced temperature dependent changes in recorded feature reflections. The methodology will further reduce the potential of false calls by decreasing fluctuations in the inspected ICA weighting functions.

### 7.3 Results and discussion

In this section, the results of employing the amplitude compensation method, as discussed in the previous section, will be presented. The procedure was applied to solve two distinct problems related to temperature variations. Firstly, the methodology was used to remove the coherent noise which can obscure defect growth observed in ICA weighting functions. Secondly, the effectiveness of the proposed method was tested for the removal of temperature dependent frequency response effects.

#### 7.3.1 Improving defect detection

The methodology was applied to measurements collected during the blind trial presented in Chapter 4. It can be shown that by removing the temperature dependent coherent noise in the ICA weighting functions, related to defect components, it is possible to improve the visibility of the damage growth steps and thus potentially improve the time of first detection and the sensitivity of an installed guide wave system. Components and weighting functions of all 6 defects are shown in Figure 7.19 a)-f). The performance of the applied methodology can be quantified by measuring the relative improvement in the peak to peak amplitude of the weighting function during the baseline collection period. While no significant improvement was achieved for defects 3 and 5 with a reduction in the peak to peak variation of 5% and 0% respectively, a decrease of 34%, 69%, 42% and 51% was obtained for defects 1, 2, 4 and 6. The weighting functions, in this case, are given as both pre and post application of the amplitude compensation process.
Figure 7.19 ICA components and weighting functions obtained from ICA based SHM algorithm applied to measurements collected from the blind trial setup presented in Chapter 4. a) defect 1, b) defect 2, c) defect 3, d) defect 4, e) defect 5 and f) defect 6. Original weighting functions shown in black and compensated weighting functions shown in red.

The improvement that can be achieved with the presented methodology is exemplified in Figure 7.19 d) showcasing the results of the ICA based SHM algorithm for defect 4. Here it can be seen that the original weighting function shows clear temperature dependence thus making the
7 Improving temperature compensation and removal of residual noise

identification of the damage growth harder to locate for the operator inspecting the ICA data, as discussed in Section 7.1.2. The compensated weighting function is much more stable during the baseline collection period and, unlike the original weight, does not show strong temperature dependent behaviour. The improvement in stability continues to be present even after the defect was introduced, thus allowing for the damage growth pattern to be more pronounced and easier to identify. The improvement in the time of first detection is illustrated in Figure 7.20 where the call levels for both original and compensated weighting functions are plotted (previously shown in Figure 7.11). The time of first call has been improved by the application of the amplitude compensation procedure such that the cross-sectional area loss, as measured on trial pipe, at first detection was reduced to 0.36% from 2.35%.

![Figure 7.20 Weighting function of a component related to a defect feature (defect 4). Horizontal lines signify a simple call level (maximum amplitude of baseline) for weighting function before (black) and after (red) compensation. Vertical blue line is the time of first introduction of the defect.](image)

It should be noted though that the proposed procedure does not necessarily improve any given weighting function. As an example of this Figure 7.19 e) shows the results of defect 5. From inspection of the original weighting function, it can be seen that the coherent noise at the defect location is not strongly related to the temperature of the structure. Therefore the application of the methodology does not further improve the sensitivity of the SHM algorithm.

Temperature related changes in the ICA weighting functions might cause sudden shifts in the structures environmental conditions to be misinterpreted as the onset of damage growth. The presented methodology will thus allow for the reduction of the false call rate by smoothing out
weighting functions of components that are unrelated to defects. An example of this is shown in Figure 7.21. Seen here is a component whose variations can be solely attributed to the changing temperature of the structure. It can be seen that after application of the proposed methodology the weighting function is much more stable and thus an inspector is less likely to make a false call. It should be noted however that not all temperature effects will be completely removed. In the case of Figure 7.21, a reduction in the peak to peak variation of 67% was achieved after the application of the amplitude compensation methodology.

![Figure 7.21 ICA component and weighting function obtained from ICA based SHM algorithm applied to measurements collected from the blind trial setup presented in Chapter 4. Shown here is a component related to temperature dependent variations in the coherent noise floor of the collected signals. Weighting functions shown before (black) and after (red) compensation.]

7.3.2 Compensating the effects of changes in frequency response

The methodology introduced in this chapter was applied to a set of measurements undergoing temperature dependent variations of the frequency response and thus changes to the signal transmitted by the transducer ring.

Figure 7.22 shows the weighting function of a component related to part of a cut end reflection of the blind trial pipe setup. It can be seen that the weighting function is clearly experiencing temperature dependent amplitude variations. By plotting the same weighting function, after the compensation algorithm presented in this chapter was applied, it can clearly be seen that the temperature dependence of the feature reflection is drastically reduced and a reduction in the peak to peak variation of 79% is achieved.
The presented procedure will therefore allow for the reduction in the presence of temperature dependent amplitude variations in weighting functions related to stable benign feature. Thus the false call rate should be decreased as the monotonic changes in weighting functions induced by temperature swings will not be present and therefore cannot be misidentified as the onset of damage growth.

7.4 Conclusion

In this chapter, a novel approach for the removal of temperature related coherent noise and frequency response changes was presented. The methodology was applied to results obtained from an independent component analysis based SHM algorithm for guided wave measurements of pipes. It should however be noted that this procedure is not limited to this very specific case, but can be utilised in a large variety of measurements dealing with environmentally induced variations consistent over extended periods of time.

Two conditions have to be met in order for the presented procedure to be applicable. Firstly, a set of baseline measurements, containing no damage growth at the location of the component of interest, have to be collected. Secondly, it has to be ensured, that for the timeframe of interest, temperature related variations in the signals are consistent.
It was shown in this chapter that it is possible to drastically reduce the coherent noise related variations in ICA weighting functions by application of the amplitude compensation methodology. Further results were presented indicating that the effects of temperature related frequency response changes of the inspection system and the corresponding differences in transmitted signals can be drastically reduced. For both cases, a potential reduction in false call rate and a subsequent improvement in the probability of detection for small defects could be seen. This can be quantified by the improvement of the peak to peak amplitude of the weighting functions. For defect components a reduction of 34% to 69% was obtained while some did not show any significant improvement as there was no temperature dependence to begin with. For components unrelated to damage features and those with variations induced by frequency response changes an improvement upwards of 65% could be observed.
Chapter 8

8 Conclusion

In this thesis, the results of an investigation of a structural health monitoring system for pipes based on the propagation of torsional guided waves were presented. The SHM procedure makes use of a statistical signal processing, independent component analysis, algorithm. The validity of this approach was verified during a blind trial operated by a fully independent third party. It was shown that the sensitivity of the SHM procedure allows for an improvement of a factor of approximately five compared to standard, one-off, guided wave inspections. While carrying out the blind trial it was found that the sensitivity of the gPIMS system to a defect located on a 1.5D bend was significantly reduced compared to flaws of similar size introduced on straight sections of the pipe. It was subsequently shown that this reduced sensitivity could be attributed to the propagation properties of the torsional guided wave mode around pipe bends rather than a lack in the performance of the SHM procedure.

Using results obtained from the blind trial study it could be shown that it is possible to predict the sensitivity of the employed SHM system by combining defect reflections obtained from FE simulations with real measurements collected from the structure of interest. Finally, a novel procedure was presented which allows for the temperature induced variations in the coherent noise floor of signals and effects related to changes of the systems frequency response to be removed. This enables a further improvement in the sensitivity of the SHM algorithm and subsequently the rate of false calls can be reduced.

The following subsections will further discuss the conclusions which can be drawn from the results presented in this thesis in more detail while the final section of this chapter will discuss areas of potential future work building on these results.

8.1 Blind trial validation of SHM procedure

A blind trial study was conducted in cooperation between the author, Guided Ultrasonics Ltd. and ESR Technology. During the trial, a total of six defects were introduced into an I-shaped pipe section of a total length of approximately 10m. These defects were gradually increased in
size such that the time of first call could be determined and thus the sensitivity of the ICA based SHM procedure be defined. It was shown to be possible to identify defects located within the straight sections of the pipe, either before or after the 1.5D bend, with a minimum size between 0.5% and 1.5% cross-sectional area loss. This is an improvement compared to one-off inspections using deployable transducer rings, which typically achieve a sensitivity between 3% and 5%, by a factor of approximately five. However, a single defect located at the $\phi = 90^\circ$ circumferential position halfway along the bend was only detected after it had already grown to a size of 3.5% cross-sectional area loss.

The blind trial showed that the independent component analysis based SHM procedure, initially proposed by Liu, Dobson et al. [71], has great potential for the monitoring of pipe systems.

8.2 Investigation of defect reflections on bends

Due to the low sensitivity to a defect located on the pipe bend during the blind trial, a study into the reflections of the torsional T(0,1) mode from discontinuities in pipe bends was conducted. This investigation was performed using numerical finite element simulations rather than an experimental trial setup. The reflection amplitudes from small circumferential cracks placed on a 1D pipe bend were compared to the stress distribution across the same, defect-free, structure during propagation of a guided wave signal. It was found that the amplitudes of the reflected T(0,1) signals were proportional to the square of the von Mises stress distribution across the bend. This relation was made use of in order to predict the sensitivity of a guided wave system to defects located on pipe bends of varying radii. It was shown that large discrepancies exist between the amplitudes of signals reflected from discontinuities of the same dimension depending on their circumferential and angular position along a pipe bend as well as the radius of the bend itself. Using the results obtained from this FE study it was possible to conclude that the reduced sensitivity which was observed for the defect located on the pipe bend during the blind trial could be attributed to the propagation of the T(0,1) mode around the bend geometry rather than a failure of the SHM procedure.
8.3 Predicting the sensitivity of an SHM system

By combing simulated defect reflection signals with guided wave measurements collected from a real pipe section Liu et al. [71] compared and evaluated the performances of a number of different SHM algorithms. This idea was utilised in order to formulate a procedure which allows for the prediction of the sensitivity of an SHM system installed on a structure which has not yet undergone any damage growth. Having knowledge of the sensitivity of a sensor mounted on a specific structure will allow for predictions to be made about the minimum defect size detectable as well as the maximum size of a potential defect which has so far gone undetected.

This methodology was validated by making use of measurements collected from the blind trial pipe setup. During this trial the dimensions for each of the introduced defects were precisely recorded by the trial operator ESR Technology. This allowed for these damages to be replicated using a simple FE model. Defect reflections obtained from these simulations were subsequently superimposed onto defect-free baseline measurements of the trial pipe. The SHM algorithm could thus be applied to this synthetic data set and the time of first detection for a growing defect could be determined. It was found that the SHM algorithm exhibited the same sensitivity to defects of the synthetic dataset compared to real defects grown in the trial pipe. Therefore it was confirmed that the proposed methodology will allow for the sensitivity of an installed SHM system to be determined prior to any actual defect growth.

8.4 Reducing environmentally induced amplitude variations

It was found during the blind trial that a large number of the weighting functions obtained from the ICA based SHM algorithm were strongly dependent on the temperature of the inspected structure. This temperature effect could not be completely removed by the application of a stretch based temperature compensation algorithm prior to the use of the independent component analysis. It was found that these variations can be attributed either to temperature dependent changes in the coherent noise floor of the signals or to frequency response related changes in the envelope shape and phase of the signals emitted by the transducer ring.

To combat this effect a new methodology was devised which allows for the influence of environmental variations to be drastically reduced. The procedure is based on two assumptions.
8 Conclusion

Firstly, a set of baseline measurements exists during which the structure underwent the full range of possible temperatures while no damage growth was occurring. Secondly, the relation of temperature to the coherent noise changes stays constant over the course of the data set.

In order to remove these temperature related changes found in ICA weighting functions, the data points of the baseline measurements are plotted against the temperature of the structure at the time of collection and a polynomial fit is applied. This fit can subsequently be used to estimate the coherent noise amplitude of the weighting function given the known temperature of the structure or the stretch factor applied at the time of collection. By removing these predicted coherent noise amplitude values from the data it is possible to reduce the temperature dependence of the output of the SHM algorithm. In the case of the blind trial measurements a reduction of up to 69% in the peak to peak variation of the defect weighting functions was achieved. The application of this procedure allows for the reduction in the false call rate as well as an improvement in the probability of detection of the SHM methodology presented in this thesis.

8.5 Further work

This thesis presented the successful implementation of an SHM procedure for guided waves in pipes. There are however a number of issues which could be addressed in future work on the subject.

Although the SHM algorithm already reduces the workload of the inspector significantly, a further reduction in the reliance on the operator would be desirable in the future. In the current form of the system the main task of the inspector is the identification of damage relevant ICA component and weighting function pairs which show behaviour associated with the growth of a defect. Further automation of the inspection process could be achieved by investigating the use of techniques such as machine learning in order to identify damage components. It should also be noted that in the current SHM framework not all knowledge of the structure available to the operator is used. While information about the temperature of the pipe is utilised, other factors, such as the location of benign features, are not incorporated in the automated steps of the SHM procedure but are rather taken into account by the operator during the manual stages of the
inspection process. Incorporating more a priori information about the structure in the SHM procedure will allow for the complexity of the work performed by the inspector to be further reduced.

The validity of the SHM procedure was shown during a blind trial exercise. It would however be of great interest to use the presented approach with guided wave sensors permanently installed on a pipe in operation in field. This would potentially address any issues which were not considered during the laboratory controlled trial. These could be effects such as challenges arising from suboptimal installation of the transducer ring, compensation for long term seasonal effects or changes in pipe contents, just to name a few.

Due to the promising results for a permanently installed guided wave structural health monitoring system the next step will be the commercial implementation of the presented procedure.
References


1998.


[22] E. Leinov, M. J. S. Lowe, and P. Cawley, “Investigation of guided wave propagation in


References


References


References


References


References


References


List of Publications


[P4] S. Mariani, S. Heinlein, and P. Cawley “Compensation for temperature dependent phase and velocity of guided wave signals in baseline subtraction for SHM”. To be submitted

[P5] S. Mariani, S. Heinlein, and P. Cawley “Improved baseline subtraction of guided wave signals in SHM via location specific temperature compensation”. To be submitted