Non-Invasive Monitoring Strategies for Engineering Structures using Guided Waves

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Abstract. Ultrasonic waves can propagate for long distances with a low loss of intensity in a variety of engineering structures with plate-like or prismatic geometries, because these geometries cause the structures to act as acoustic waveguides. These Ultrasonic Guided Waves (UGWs) can be manipulated to allow rapid structural evaluation that is non-destructive and non-disruptive. Discontinuities in a waveguide’s cross-section, such as ancillary structural features or structural flaws, cause ultrasonic guided waves to be partially scattered. The response of the UGWs to various structural features can be used to discriminate and characterise flaws through a variety of inspection and monitoring techniques. As the devices used generally require only limited access to a structure’s surface and work over a long range, they have the potential to screen the volume of a structure that is both large in scale and with regions inaccessible to other inspection methods.

Of particular relevance is the ability to detect time dependent changes to a structure’s condition through its service life, caused by corrosion, fatigue or SCC. This strategy may be implemented using permanently mounted sensors which are interrogated frequently. This allows statistical methods to detect trends in condition of the structure which are not detectable by a one-off large area screening test. To achieve this careful control is required of the stability of the test system and external factors, such as temperature and humidity, which influence the test results.

The work presented covers a range of UGW technique developments for inspection and monitoring for a range of engineering applications, including strategies for control of the test system and external influences. These applications include the structural evaluation of oil and gas pipelines, aircraft components, storage tanks, ship hulls and bridges, although many of the developments presented have scope for wider application.
Guided wave testing

Guided wave testing is now an established method for testing of pipes and pipelines, principally for corrosion. A number of standards are available for the application of these tests [1-5] and other documents are under preparation by bodies such as NACE and ASME. Guided wave ultrasonic testing has some unique features which make it highly suitable for examining long lengths of pipe. The ability of the low frequency ultrasound to travel along the pipe wall from a tool mounted on the pipe allows 100% examination of the test length and the sensitivity of guided waves to metal loss makes them ideally suited for the detection of corrosion. The principle is shown in Figure 1. The equipment for guided wave testing usually consists of three main parts; a bracelet tool containing transducers that is attached around the pipe at the test location, a specialised low frequency flaw detector and a software suite which both controls the data gathering process and allows the display and analysis of data. The main elements of the system may be seen in Figure 2.

![Figure 1. Principle of guided wave inspection for a pipe. A bracelet tool around the circumference sends a circular wave front that interrogates the whole volume of the pipe wall. It is reflected from the end. Changes in section due to corrosion or cracking are detected.](image)

![Figure 2. Teletest® guided wave test system; Transducer bracelet, multi-channel flaw detector and software](image)

The rapid long-range test capability makes guided wave testing an ideal screening tool. The identification of the presence of discontinuities and the ability to locate them along the pipe allows localised follow up inspections to be carried out at the appropriate locations. This is straightforward when the pipe is readily accessible, as for insulated pipe in process plant, but becomes more difficult when the affected section is buried or in a
cased section under a road, railroad or river. Further, where pipelines are buried the access costs to the site and for excavation are significant. This has led to the concept of monitoring using sensor tools permanently attached to the pipe surface. Once installed, the electronics unit may be attached via an above ground connector and a test performed. This is shown in Figure 3.

![Permanently mounted guided wave tool.](image)

**Strategy for monitoring**

In many instances the permanently installed tools have been used in the same manner as the single-shot tests. The electronics unit is connected up at infrequent intervals and a set of data collected. However, the availability of the sensor on the pipe at all times opens up a range of other options which allow a greater level of sensitivity to be achieved plus the ability to detect time-dependent changes in the condition of the component. This has great advantages for pipeline monitoring as it is the gradual degradation of the pipe with time, usually owing to corrosion, that is the cause of ultimate concern. Features that are not changing (growing) with time are not usually an issue. A useful strategy is to compare the test data gathered at a specific time with a baseline, taken with the pipe under a known condition. Repeated data sets may also be compared to establish trends. Under normal circumstances degradation rates are well controlled; significant corrosion may take years to develop, so that it may be possible to collect the necessary data sets by repeated visits to the test site by a technician. Data may only be required to be gathered once a week or once a month. However, in the long term it is more cost effective and reliable for the test system to be automated and mounted in a suitable enclosure by the test object. Data may then be stored and downloaded at convenient intervals.

A monitoring protocol therefore requires that data are gathered regularly and that the conditions under which they are collected are stable. For the monitoring program to be successful, differences detected must be related to a change in the condition of the pipe, rather than drift or uncertainty in the monitoring system itself. The availability of a permanently installed tool reduces the variability associated with repeatedly mounting and dismounting the transducers. However, environmental conditions, such as temperature and humidity, will cause small variations and these must be accounted for if sensitivity to real degradation is to be maintained.
There are a number of factors which need to be addressed when planning a monitoring exercise:

- The area to be monitored. This might be straightforward in the case of a pipeline, but may require more consideration for other types of construction.
- Sensor design and placement.
- The likely degradation mechanisms and the anticipated rate of degradation. This affects the frequency of data gathering and also the sensitivity required.
- Means of checking system health.
- Format of reporting.

These are illustrated below by means of a number of examples of the development of monitoring protocols and procedures for a variety of constructions.

**Development of monitoring procedures**

**Fatigue cracks**

A good illustration of the ability of a monitoring procedure to achieve high sensitivities is provided by the results of an experiment to monitor the growth of a fatigue crack in an aluminium plate. This represented an aerospace component; part of the structure of a wing.

The expectation for one-off guided wave tests is that they can detect around 5% cross-section loss [6]. Fatigue cracking is a cumulative process which occurs under cyclic loading, with crack growth rate increasing exponentially with loading cycles under constant loading conditions according to the Paris law [7]. Eventually, the presence of the growing crack reduces the load bearing section of the component to the extent that it will fail catastrophically under normal service loads. The consequence is that it is vital to detect any such crack at an early stage, before the growth rate has accelerated significantly. This means that, to be useful, the monitoring method has to have a better detection threshold than for a single one-off test. The purpose of the experiment was to determine the effectiveness of the guided wave tests to detect crack growth and to determine the sensitivity achievable. Figure 4 shows the experimental set up. The crack was initiated from a starter notch underneath the actuator. The only accessible position to mount the transducers on the aircraft was at the corner of the specimen, so this arrangement was chosen for the test.

![Fatigue test on aerospace component showing the transducers (circled). The crack was initiated at the waisted area under the actuator.](image)

Figure 5 shows the results of the fatigue test. It may be seen that the level of deviation of the signal from the starting condition increases with the data collection number.
(which is proportional to the number of fatigue cycles). The plot shows that for the first 12 tests there is hardly any change in the signal. This region suggests that over that number of fatigue cycles there was either no crack growth or it was not detected. From the 13th test onwards there is a significant continued upward trend in the degree of differences between the signals. While this is not monotonic, the general trend is clear. The crack extension from the starter notch at the end of the test, i.e. at test 55, was 5mm. In the figure both green and red columns may be seen. The red columns indicate the results recorded when the crack had been detected by dye penetrant inspection. This occurred at test 25. Before this, however, a significant upward trend in the deviation of the signals from the starting condition may be seen. This indicates that the crack was detected by the ultrasonic system before it could be observed by the dye penetrant tests. This suggests that the crack was detected at less than 1mm deep. Given the 300mm wide specimen at that point, this suggests that the sensitivity for detection was less than 0.5% of the cross-section, compared with the expected 5% for a one-off test. This result strongly suggests that the method of using guided waves is suitable for monitoring fatigue sensitive components.

Fig 5. Progressive increase in the amount of deviation of the signals from the starting condition of the region containing the fatigue crack in the aluminum plate shown in Figure 4.

This work was extended to larger steel fabrications. The example studied was the cruciform welds in the deck of a box girder bridge where site welded transverse seams intersected with shop-made longitudinal seams in pre-fabricated sections. The operator had concerns about fatigue cracks initiating at these locations and required a means of monitoring them. Figure 6 shows the view of the underside of the bridge deck from inside the box girder. The presence of longitudinal stiffeners, ‘V’ stiffeners under the deck and flat stiffeners on the floor, made the test geometry more complicated. Laboratory experiments were carried out on 3m by 3m plates 10mm thick, the same as the bridge deck, each containing a cruciform weld. Four plates were made. Two had no stiffeners; one had flat stiffeners and one ‘V’ stiffeners. A slitting disc on a specially made profile cutter was used to simulate the growth of a fatigue crack at the cruciform joint. The experimental set up is shown in Figure 7. Three guided wave transducers were placed on each plate. The arrangement is shown in the figure. They were placed so they would not pick up the directly reflected signals from the notch. An automated test system was set up using a Teletest® flaw detector with a multiplexer, so that data could be captured sequentially on a continuous basis from all four plates.
Initially a series of baseline data was captured for each plate. Subsequent data sets were compared with these. It was known that temperature fluctuations affect the velocity and amplitude of the ultrasonic signals [8], so that the baseline was captured over a 14 day period before the monitoring stage commenced. This was to allow data to be collected at a variety of temperatures (the tests were running on a 24 hour basis) for later comparison with the monitoring data. Data were gathered from all four plates over a 19 day period, during which time the signals were compared with the relevant baseline. It was established that the signals to be compared needed to be collected at temperatures within 1 degree Celsius of each other to obtain a valid comparison. One of the flat plates was kept as a control. This had no notch cut in it, so that ideally there should be no changes in the signals over the monitoring period once the temperature effect had been taken into account. The other 3 plates had notches cut progressively at intervals over the 19 day period according to the profiles shown in Figure 8. The results for the control plate and the plate with the ‘V’ stiffeners are shown in Figure 9. It may be seen that on the control there is a random low-level variation of the signals during the monitoring period. While steps have been taken to minimize the effects of temperature, there are obviously other factors which are causing small changes to the signals. It is known that humidity also affects this and ways are being investigated into means of reducing this. In Figure 9 the results of the ‘V’ stiffener plate are also shown. The results from the control are also plotted for comparison. It may be seen that, before the introduction of the notch, the level of random variations are comparable for the two plates, suggesting that this level is the inherent ‘noise’ in the system. However, once the notch was cut into the plate the level of changes from the baseline increase dramatically. At 2mm deep there is still some overlap with the magnitude of the random variations, suggesting that this depth is at the limit of detection, but as the notch depth was
increased there were clear differences between the level of variation and the expected level of background ‘noise’. Therefore, above 2mm it was clearly possible to detect the notch and to determine that it was growing. Note that the notch was only taken to 8mm deep in this specimen.

![Fig 8. Successive notch profiles](image)

**Fig 8.** Successive notch profiles

**Fig 9.** Results of the monitoring exercise. Left, signal variation from the control plate over the 19-day monitoring period. Right, Signal variation before the introduction of the notch and as the notch was grown on plate with ‘V’ trough stiffeners. The variations from the control are also shown for comparative purposes.

**Corrosion**

One area where the long-term guided wave monitoring method has considerable advantages is that of detection of corrosion in the floor of hydrocarbon storage tanks. The technique, which has been under development at TWI for a number of years, involves the use of low frequency ultrasound to examine the whole of the tank floor from a number of permanently attached sensors around the perimeter on the outside. The long distance propagation characteristics of the ultrasonic waves used allow signals from one side of the tank to be picked up by sensors on the other side. The circular geometry of these tanks allows a tomographic method to be used to reconstruct an image of the tank floor from the transmitted ultrasonic signals. The image is formed by collecting information at many angular positions around the circumference of the tank. Figure 10 shows the concept. A number of sensors are placed around the edge of the tank floor. The transmitted signal from a single transducer is captured by a number of similar sensors on the opposite side of the tank. This process is repeated for each sensor transmitting. The data from all these tests are summed to produce the image. By taking readings from the sensors regularly, long term trends in the condition of the floor can be determined. In this way, short term variations, for example from temperature fluctuations or changes in the fill levels in the tank, can be separated from changes in the physical condition of the floor. In this way, tanks needing priority attention may be identified and the more rigorous internal examinations may be concentrated on these. Figure 11 shows images produced from the guided wave data on a 4m (13ft) diameter tank. The circular area of the tank is imaged. In the one example an image is produced of a single hole, inserted to represent metal loss. In the other, there are 3 holes. All are plotted in their correct location. Again, these images are produced by a
baseline subtraction approach. The variation of the blue colour of the background is caused by the same effects as the background variations in the data in Figure 9. These are the ripples of the baseline. However, it may be seen that the holes are of significantly greater amplitude and detection is clear. The 20mm diameter hole is 0.0025% of the area examined.

Conclusions

- Guided wave based techniques have great potential for structural monitoring.
- Sensor design has to be carefully chosen for both the correct ultrasonic parameters and for longevity.
- Frequent gathering and trending of data is critical
- Temperature measurement and control is vital.
- Detection performance for corrosion and cracking is within industrial requirements.

Fig 10. Typical ‘fan beam’ data collection - one transmitter, many receivers. Left, schematic of transducer arrangement; Right, an FEA image of wave propagation across a circular tank floor.

Fig 11. Images of a 4m diameter tank floor; Left, one 70mm diameter hole, Right, two 70mm and one 20mm holes

References