High temperature performance of ultrasonic guided wave system for structural health monitoring of pipeline

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ABSTRACT

Power plant operators strive to maximise their operating efficiency and reduce plant emissions. This is achieved by increasing operating temperature of critical components such as pipework. These high temperature (HT) pipework are exposed to extreme operating conditions for prolonged periods and are known to suffer strength reduction due to thermal fatigue. They can develop cracks; which if undetected, can lead to catastrophic failures. This study investigates application of Ultrasonic Guided Wave (UGW) technique for in-service structural health monitoring of HT pipework. UGW uses arrays of piezoelectric transducers placed around the pipe and when excited produce a stress wave which propagates (tens of meters) along the path defined by the boundaries of the pipeline. The detection of defects is indicated by reflected ultrasound due to cross-section change. The technology is widely used for offline inspection to monitor corrosion type defects as is limited to operate at ambient temperatures. To enable SHM of HT pipework, a HT-UGW system was developed using HT transducers and collar for permanent attachment. Ultrasonic response of the HT transducer is highly sensitive to temperature variations and over time, which may lead to false alarms. Initially, a long term laboratory experiment was performed to evaluate effect of temperature on the system and its monitoring capabilities. The system showed a stable thermal response and could detect 2% cross-section change at HT. The system was then installed on a pipe operating at up to 200°C for over 1 year and the in-service UGW (T (0,1) wave mode in 40-60kHz range) data is analysed to investigate the effect of temperature loading and temperature over time on the system performance. The findings from this work increases confidence in UGW technique for HT-SHM and will contribute in the development of enhanced temperature compensation for improved defect detection under varying temperature ranges.

1. Introduction

The requirement for continuously assessing the integrity of critical structures has fostered research and development in the field of Structural Health Monitoring (SHM). SHM systems use sensors to repeatedly transmit excitation signal to the structure and receive response which is then analysed to detect presence of any defect and hence ensure their integrity.

In this study, UGW approach using piezoelectric transducer is being investigated for SHM of HT pipework. The pipework under inspection is excited with a high frequency ultrasonic signal using an array of piezoelectric transducers. This excitation signal produces stress waves which follow a path defined by the boundaries of the waveguide and are received either at the same transducer (pulse-echo)
or by another transducer (pitch-catch) placed on the wave guide. The change in received response from the structure allows early detection of defects. This information can be used for maintenance and operation of the structures, hence minimising the time they are out of service.

2. Defect detection using UGW system at high temperatures

For an SHM system, signal processing is a crucial part, with the objective of analysing the received signals to detect if the structure being monitored has developed a defect. Also, the information regarding the severity of the defect is desirable and can be used to plan maintenance and operation of the structure. A defect can be identified using subtraction approach where current signal is subtracted from a baseline recorded on the undamaged structure. To achieve a perfect subtraction, a stable baseline is required. However, temperature modifies the ultrasonic response of transducers and the mechanical properties of the waveguide which affect the stability of baseline.

2.1 Effect of temperature on ultrasonic guided waves

Temperature affects the UGW propagation mainly due to thermal expansion, which changes the propagation distance, density and thickness of the waveguide; and consequently, changes in ultrasonic wave velocities which are linked to materials elastic moduli. This results in time shifts in the ultrasonic signals leading to significant subtraction residual and hence affecting the defect detection capabilities. Apart from modifying the properties of the waveguide, temperature also affects the material properties of the ultrasonic transducer and their bonding to the waveguide. These transducers have an active piezoelectric material to convert electrical input to a mechanical excitation for the waveguide. The piezoelectric material properties are sensitive to temperature changes and can degrade over time. Long term thermal stability of the transducers is a major concern for this application.

The transducers used in this study use PZT-5A piezoelectric material with a Curie temperature (Tc) of ~350°C. To minimise the effect of thermal degradation of the piezoelectric material the experiments in this study were performed at temperatures not more than 1/2 Tc\cite{1}. Another study on thermal degradation and ageing of PZT material showed high degradation of its material properties with an increase in temperature but once the material was conditioned, the ageing rate was reduced to ~4% of the original\cite{2}. Another study\cite{3} showed that for a small temperature change of a few degrees, the effect on transducer performance has been shown to be significantly less than the effect on wave propagation on the waveguide.

2.2 Signal processing approach for defect detection at high temperature

There have been many investigations to address the issue of varying temperature for GW SHM. A previous study\cite{4} investigated the effect of temperature variation on lamb waves from ambient temperatures up to 70°C. The temperature effect was reported to be much more pronounced than the effect of a drilled damage (hole) with diameter of 1mm. Other temperature related studies\cite{5,6} addressed modelling of varying time-of-flight due to changing substrate elastic modulus and thermal expansion, and achieved a good agreement with experiments under mild thermal variations from 20 to 40°C. It has been suggested to use a ‘bank’ of baseline signals for various temperatures and picking a baseline signal which minimizes difference relative to the test signal for that temperature\cite{7}. This study evaluated these approaches for large temperature variations up to 150°C.

3. High temperature monitoring experiment

The experimental setup to evaluate the HT performance of the UGW transducer array for SHM is shown in Figure 1. A 6m long 4” Schedule 40 pipe specimen was used as a waveguide. Two rings of HT thickness shear type UGW transducers were mechanically attached near one end of the pipe with a HT collar. Two rings were required to control the directionality of the guided waves. Heating mats were
wrapped around either side of the collar array and powered by a Stork Cooperheat Heat Treatment Module\textsuperscript{[8]} to provide uniform heat exposure to all the transducers in the centre. A control thermocouple for the heating mats was attached in the middle of the two rings. Four other type-K thermocouples were attached in each quadrant of the collar array to measure the temperature distribution around the circumference of the transducer array. A Python based automated thermal test setup was developed for automated data acquisition. A Teletest focus GWT system\textsuperscript{[9]} was used as a pulser receiver for the transducer collar array.

![Diagram](https://example.com/diagram.png)

**Figure 1.** Test pipe specimen with heating mats for high temperature monitoring experiments

HT monitoring experiments were carried out to evaluate the performance of the transducer array at the target temperature. The Teletest GWT system provided the transducer array with a ten cycle hann window modulated sin wave of frequency 50 kHz. The excitation frequency was chosen to obtain maximum T (0,1) output. An automated test routine was established to continuously record the pitch-catch measurement from the transducer array along with its temperature.

![Diagram](https://example.com/diagram.png)

**Figure 2.** Schematic of the experimental setup and timeline for HT monitoring experiments

Baseline measurements were carried out for around ten days to capture data corresponding to ambient temperature conditions. The temperature of the transducer array was then increased to 150°C for extended periods of time to examine its thermal ageing stability. Thereafter, a saw cut defect of size 1% cross section area (CSA) was added 1 m away from the pipe end increased with increments of 1% to 4% CSA over a period of 4 weeks to simulate defect growth. The ultrasonic measurements were collected at the target temperature for each defect size. This data was used to analyse the defect sensitivity of the GWT system at the target temperature.

4. Results

4.1 Ultrasonic response with increasing temperatures

The response of the UGW system operating in pulse-echo mode was analysed for increasing temperatures from ambient up to the target temperature of 150°C. The signal amplitude and its time of arrival (TOA) increased with an increase in temperature (Figure 3b). This is a result of both the effect of temperature on the transducer array and on the waveguide. Since the length of the waveguide did not
have a uniform temperature distribution, it is difficult to analyse the contribution of waveguide alone on
the temperature response of the UGW system.

Figure 3. (a) Excitation signal and its frequency response and (b) change in response with temperature

The performance of the transducer array was examined by analysing the signal from a known feature
i.e. first reflection from the pipe end. The signal amplitude and the time of arrival showed a linear
response within a temperature range from 17 to 150°C (Figure 4). An increase of ~8dB in the signal to
noise ratio (SNR) of this signal was observed in this temperature range. A potential reason for this
increase in signal response could be the thermal expansion of the transducer frame providing additional
coupling force to the transducers. It can also be noted that the residual from the linear estimation of the
signal response increased near the target temperature. This variation is due to the on-off control of the
heating unit which was used to control the temperature of the transducer array and is investigated in
Section 4.2.

Figure 4. Relation between pipe end reflection (a) amplitude and (b) time of arrival with temperature

4.2 Ultrasonic response over time at high temperature

To evaluate the monitoring capabilities of the UGW system at the target temperature, the stability of the
ultrasonic response was investigated as a function of time and temperature. Once the temperature of the
transducer collar array reached the target temperature, it was maintained with an on-off control resulting
in a thermal cycle of 142±9°C with a period of ~4 hours.
The temperature recorded at the collar array and the SNR of the pipe end reflection are shown in Figure 5. The initial increase in the SNR of the pipe end reflection corresponds to the findings from Section 4.1. When the transducer array was subjected to thermal cycles at the target temperature the ultrasonic response varied in a similar fashion. Corresponding to this thermal cycle of ±9°C, the SNR varied by ±0.5dB and was stable over a period of 30 days. This dataset will be used as a baseline for HT defect detection study in Section 4.3.

4.3 Temperature compensation and defect detection

After the HT baseline measurements were collected, the defect detection capability of the HT-UGW system was investigated. A saw cut defect of size 1% CSA of the test pipe was introduced 1m away from the pipe end. The defect was gradually increased to a size of 4% CSA over a period of four weeks.

To evaluate the defect detection sensitivity of the system, the change in response with addition of defect was analysed. To allow direct comparison, a subset of the baseline dataset was selected using optimum baseline selection (OBS) method. Temperature compensation was performed to remove any variation in time of arrival and signal amplitude using the relations shown in Figure 4. The comparison of the defect signal and the corresponding baselines indicate the presence of the defect signal.

Although the response from the defect can be seen in Figure 6, it is comparable to the coherent noise level and can be masked. For this reason, signal subtraction is not feasible even after OBS and temperature compensation. This coherent noise is either caused by additional wave modes generated by the transducer or due to non-uniform temperature distribution along the length of the pipe.
This study evaluates an alternative approach for defect detection whereby, every new measurement is divided into windows of fixed length as shown in Figure 7. The size of these time windows is chosen after considering the effect of temperature on ultrasonic wave velocity. Each window of the new signal is then compared by the corresponding window of previous measurements.

Figure 7. Time signal analysis for defect detection using signal segmentation and comparison of response from known feature (pipe-end) and defect over monitoring time

Figure 7 shows the selected windows evaluated with this approach and the response from these windows over time as the defect size was gradually increased. An increasing trend in the response from the defect and corresponding decrease in the response from the pipe end reflection can be clearly observed. This change in signal response was significantly more than the variation within the baseline of ±0.5dB analysed in Section 4.2, indicating the presence of the defect.

5. System stability in service conditions

To evaluate the performance of the system in-service condition, the system was installed in a gas fired power station on a 4 inch Schedule 40 pipe connecting intermediate pressure (IP) economiser to IP drum line and the operational temperatures of up to 225°C. The sensor collar location is shown in Figure 8. An example of the recorded ultrasonic measurement is shown in Figure 9 where the T-Piece (TP) and bend weld (BW2) pipe features annotated in Figure 8 can be seen at a distance of 1m and 1.5m, respectively. In the backward direction, there was flange and another bend weld (BW1).

Figure 8. HT-UGW system installed on a streamline in a power plant
In this study, the ultrasonic response from the known TP and BW2 in forward direction have been analysed. The performance of the system was tested for a period of over 400 days. The operating temperature of the pipeline was measured at four locations around the circumference where the transducer array was installed. Temperature variation during the monitoring period is shown in Figure 10. This pipeline experienced thermal cycling during plant operation where the temperature varied between ambient (~70°C) to 180°C.

The pre-processing of the collected ultrasonic signals was carried out and a database was constructed using ultrasonic response, features from time and frequency domain and they were grouped in subsets for a temperature bins of 5°C. The ultrasonic signals shown in in Figure 11 are taken from the 100°C-105°C subset covering measurements from the first 100 days. A consistent ultrasonic response can be seen through the reflections from the TP feature at 1m.

To evaluate the stability of ultrasonic response during this monitoring period, root mean square (RMS) signal amplitude of the time window with reflection from the TP feature was analysed and is shown in Figure 11.
Figure 11. RMS feature with increasing temperature and over time (left) and subset of database with signal recorded between 100-105°C over time

The selected RMS feature is shown as a function of temperature and time. It can be noted that the feature increases with increase in temperature in a linear manner. This is due to the linear relation of ultrasonic amplitude with temperature as was shown in Figure 4(a). The variation of RMS feature indicates an increase in coherent noise at temperature close to 200°C. Another trend that can be seen is that the feature value gradually decreases over time and more significantly after 300 days. This resulted from the failure of some transducers over the period caused by thermal ageing and cyclic thermal loading.

6. Conclusions

High temperature performance of an UGW system was evaluated for SHM application for a target temperature of up to 150°C. The system showed a stable ultrasonic response over a HT monitoring period of three months. The system performance in terms of defect detection capability was analysed by adding a defect and gradually increasing its size over time. With appropriate signal processing and temperature compensation, the system’s capability for defect detection at HT was demonstrated. Further validation through in-service trials is required to fully demonstrate its SHM capabilities of the UGW system.

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References

[4] Lee BC, Staszewski WJ. Modelling of Lamb waves for damage detection in metallic structures:


