Evaluation of the long-term stability of guided wave EMAT transducers for SHM applications

Balint Herdovics¹, Dr Frederic Cegla²
1 Research Assistant - Imperial College, UK, balint.herdovics13@imperial.ac.uk
2 Senior Lecturer - Imperial College, UK, f.cegla@imperial.ac.uk

Abstract

Long-term monitoring of structures can highly improve defect detection capabilities when compared to standalone inspections (1). However, for long-term monitoring applications it is essential that the ultrasonic transducers and signal acquisition systems are capable of transmitting and receiving signals with high repeatability.

It has been postulated that Electromagnetic Acoustic Transducers (EMATs) have better repeatability, as they do not require mechanical coupling to operate (2,3). Rather than taking this for granted it is important to experimentally verify the temperature dependence and long-term stability of the EMAT transducer output.

The authors have previously developed an EMAT transducer for pipe monitoring which can generate and receive torsional guided waves with high Signal-to-Noise ratio (>40dB) (3). The long-term performance of these transducers was investigated, focusing on applications where repeated temperature cycling is to be expected.

It has been experimentally measured that the EMAT’s complex excitation mechanism is affected by the temperature, resulting in a temperature dependent wave excitation. Furthermore, long-term changes in amplitude (~8%) and phase (~25°) have been observed. The key factors which influence the long-term stability performance of EMATs (focusing mainly on the guided wave applications) will be summarized.

1. Introduction

Traditional non-destructive testing (NDT) of structures is carried out as a one-off inspection, when trained personnel access the plant and perform a standalone measurement. In some cases, the plant can be located in hazardous or remote locations; hence, access costs can be larger than the cost associated with the measurement itself.

Structural Health Monitoring (SHM) is a popular alternative, which utilizes permanently installed transducers for automatic measurements (1). Access to the structure is gained only once when the transducers are installed permanently, the measurements are performed automatically, and are transmitted to the operator. The result is a decrease in manual labour costs and increased safety for the human workforce. This SHM approach is becoming popular due to the advances and decrease in cost of electronics, and battery operated measurement systems.

Several benefits are available for Structural Health Monitoring systems. For example, more frequent measurements can be performed, which increases the damage detection capabilities. Also, as the transducers are permanently installed, the installation dependent uncertainties influence all acquired data to the same extent and they can often be eliminated if relative measurements are performed.

The ultimate goal of the monitoring method is to detect and monitor the severity of defects in the structure from the changes in the acquired signals.
However, signal processing techniques are required to evaluate the large datasets, and estimate the change in structure from the monitored ultrasonic signals. Several signal processing techniques exist. The most common being the baseline subtraction method. The reading signals are compared to the baseline signal, and the difference between the two highlights the effect of structure changes. Before performing the baseline subtraction a temperature compensation method is essential (not detailed in this paper) so that differences in propagation speed due to temperature variations are compensated first.

2. Detailed aims of work

In order to reliably monitor a structure it is essential, that reliable and stable transducers (and signal acquisition systems) are used for the signal acquisition. Any instability in the transducer can change the acquired signal, which then can be misinterpreted as a defect in the structure. Therefore it is required that stable transducers are used for Structural Health Monitoring applications.

The long-term stability of bonded ultrasonic transducers has been investigated previously. It was reported, that piezoelectric transducers might not perform as desired for long durations (2). The degradation of the bonded transducers have been investigated, and it was found that temperature cycling can alter the performance of such systems (3).

Electromagnetic Acoustic Transducers (EMATs) do not require bonding, therefore they potentially could be more stable. However, just because their excitation mechanism is contactless this does not necessarily mean that they are stable as well. It is therefore required that the long-term stability of EMATs is evaluated. In this paper the main focus is on the stability of low-frequency torsional guided wave EMATs which operate on carbon steel pipes.

Compared to bulk wave EMATs, the operational frequency is magnitudes lower, hence, the factors influencing the excitation and reception mechanism might differ from bulk-wave EMATs.

For this particular transducer the centre frequency of the excitation is chosen to be 27 kHz. So far limited literature is available on the long-term stability of these low frequency EMATs.

3. Torsional guided wave EMAT

The authors have previously developed a torsional guided wave EMAT, which can generate and receive ultrasonic signals with high Signal-to-Noise Ratio (SNR), and is able to operate at high temperatures (>200 °C) (4). The EMAT operates via the Lorentz force mechanism, hence the excitation force is generated from the interaction of the static magnetic field of permanent magnets and the induced eddy current. Figure 1 shows a manufactured transducer ring on a 3 inch NPS mild steel pipe.
Each EMAT ring consists of a flexible Printed Circuit Board (PCB) with 6 coils, and 12 cubic magnets placed onto the elongated sections of each coil. This is then supported by metal ribs which are rigid in the axial direction but allow the transducer to bend around the pipe. The whole assembly is moulded into a silicone casing for easier handling. The EMAT measurement system consists of two transmitting rings (for directional control), and one receiving ring placed 40 cm away from the transmitters (see Figure 2).

The 40 cm axial separation was chosen so that the incident wave can be observed (this is made possible by a special cross-talk reduction system (5)). The transducer has been installed onto the pipe in December of 2016, and measurements have been collected since then. Electric pipe heaters were installed inside the pipe, which was exposed to many (90+) heating cycles with various peak temperatures (30°C, 50°C, 80°C). The effect of the temperature change on the acquired ultrasonic wave, and its compensation has been previously presented by the authors (6). However, for the evaluation of non-reversible long-term effects the room temperature signals are compared. Figure 3 shows two (room temperature) signals acquired in 2017 one in January and the other in December. It can be observed, that the two signals correlate well. By visually observing the time signals, only really small changes can be noted on the incident wave, and almost no change at the coherent noise part.
4. Investigation of EMAT stability

The presented signals show good agreement, but are not completely identical. For improved sensitivity to small defects it is beneficial to have the highest available stability. The factors affecting the long-term stability of the system must be investigated.

2.1 Effect of long-term degradation of array transducers (in general)

Before evaluating the stability it is necessary to investigate what the possible effect of any change/degradation in the transducer is. The torsional guided wave EMAT consists of a 12 patch excitation array (transmitter and receiver).

In the first scenario, it is investigated when the performance of each excitation patch changes by the same amount. The change (magnitude or phase of the excitation signal) will then alter the excited wave-packet and the acquired signal with the same magnitude and phase.

In case the phase of the excitation changes, the phase of the ultrasonic wave’s carrier sine wave will change, but the envelope of the signal remains unchanged. Whereas, in case the magnitude of the excitation changes, the acquired signal is simply going to be a scaled version of the original signal. Any change caused by the transducer performance is not ideal. However, if the amplitude of the reading signal changes, it can be compensated if a reference wave-packet is available for scaling the signal. Similarly, the authors think that in case the phase of the wave-packet changes it can be compensated if the incident (direct) wave-packet is observed (6).
Larger problems can occur, when each individual excitation patch in the array change by a different amount. In this case the transmitted wave-packet is not the scaled or phase altered version of the baseline signal. Rather, the non-uniform change in the excitation will result in other modes propagating in the structure. These modes can easily be dispersive, hence increase the coherent noise level. This is then practically impossible to compensate for.

2.2 Evaluation of the EMAT long-term stability

The stability of the low-frequency guided wave EMAT system is evaluated experimentally solely by analysing the ultrasonic signals. The incident wave of the ultrasonic signal is windowed and its long-term performance is recorded. This indicator highlights the changes, which affect all excitation patches. Secondly, the coherent noise levels are evaluated as well. As the non-uniform changes generate waves with dispersive modes the coherent noise might change. Due to the propagation properties of these modes it can be expected that the majority of change in the coherent noise will occur at the early arrival times (which is associated with the near field).

The near field with the distance less than a meter that corresponds to 0.4-0.6 milliseconds in Figure 3 is evaluated separately from the far field (any later reflection).

2.3 Results

The acquired signals (shown in Figure 3) indicate that the GW EMAT can operate reliably for a long time, and despite the repeated thermal exposures the signal changes only slightly. When investigating the performance of the incident wave it was found that most of the change was observed at the first heating cycle. The amplitude dropped by 6.68%, and the phase of the wave packet changed by 16.03° after the first heating cycle. However, after the following 94 heating cycles the signal amplitude changed only an additional 0.88 %, and a 7.16° additional phase shift was observed. It was also observed, that the coherent noise level did not change notably during the heating cycles.

The part of the signal (from 0.4 to 1.4 milliseconds) between the arrival of the incident wave and the pipe end reflection is the coherent noise of the signal. It has been observed that the average change on the coherent noise was 0.41% (relative to the signal amplitude) up to the first heating cycle. The coherent noise change have increased by an additional 0.09% up to 0.5% in the following heating cycles.

As the first heating cycle changed the performance of the investigated EMAT system slightly, its long-term stability itself is considered as fair. However, a practical improved could be to set the baseline to be the signal which is measured after the first heating cycle, hence reducing the instabilities of the system. With this practical solution, the EMAT torsional guided wave system is considered as stable. Any defect with small reflection coefficient (1-3 %) would be picked up.

In addition to presenting these results in details at the conference, results from currently ongoing measurements will be presented as well.

2.4 Future work
Small, but not negligible changes have been observed in the long-term performance of the torsional guided wave EMAT system. The majority of the performance changes were observed at the first heating cycle. The transducer is considered as stable for the following time period. The cause of these changes should be addressed in order to further improve the monitoring capabilities of the system.

Electromagnetic Acoustic Transducers generate the ultrasonic wave via complex excitation mechanisms. Parts in the excitation mechanisms needs to be investigated separately so that the cause of the instability can be identified. For this, new measurements need to be performed. Furthermore, numerous reasons exist which could potentially lead to a drift in the signal. It is possible, that the strength of the permanent magnets decreases over time. This is certainly the case when they are exposed to temperatures higher than their rated operating temperature. For the Lorentz force transducers it is then expected to change only the magnitude of the acquired signal.

Any change in the input current will change the excitation as well. Instabilities of the eddy current could be measured when the input current of the transducer and its complex impedance is monitored. Any change of the eddy current would be picked up in these monitored quantities.

The permanent magnets (depending on the carbon steel alloy) can magnetize the pipe which might influence the excitation. Its effect on the wave excitation should be addressed as well. The stability relies on the mechanical position of the excitation patches. In case the position of these patches is not fixed the generated ultrasound can also change.

5. Conclusion

This paper reports a study of the long-term stability of a torsional guided wave EMAT. The EMAT (see Figure 1) which was designed and manufactured by the authors. This EMAT was tested on a 3-inch carbon steel pipe and was exposed to 94 heating cycles while signals have been collected regularly. It was found that over the whole period (more than a year) the signals have changed by 7.56% in amplitude and 23.19° in phase. This would be deemed not very stable however, it was noted that most of the change (6.68% amp, 16.03° phase) occurred after the first heating cycle and must have to do with some sort of settling phenomenon. For the rest of the monitored period (90+ cycles and 11 months) the system was stable (to 0.88% in amplitude). It is expected, that with monitoring after the first heating cycles defects of 1-3% could be detected. Future work will need to focus on explaining why the phase changed considerably after the first heating cycle.
References:


