Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Ultrasonic structural health monitoring – current applications and potential

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Abstract—**The trend to the application of structural health monitoring (SHM) as an alternative to periodic nondestructive evaluation (NDE) is discussed and examples are referenced of the use of both ultrasonic guided waves and bulk waves. Dealing with the volumes of data generated to produce useful information is a significant issue and fruitful areas for future research are given.**

Keywords—SHM, NDT, Guided Waves, Bulk Waves

I. Introduction

There is growing interest in moving from periodic inspection (NDT) to quasi-continuous monitoring (SHM). Unless the probable damage locations are precisely defined and identified in advance, or the degradation will affect a large area so a few sample points are sufficient to give a reliable estimate of its severity, then successful SHM requires an area monitoring capability; it is unlikely to be practical to cover the structure with point sensors so a method that gives significant area coverage per sensor is needed. Ultrasonic guided waves are particularly attractive in SHM because of their ability to give large area coverage from a limited number of transducers.

If the probable position of a defect is known, or if degradation is expected to be relatively uniform so a small number of sample points is sufficient to assess the overall structural integrity then local, essentially point monitoring, techniques are attractive. In principle it is possible to convert conventional ultrasonic NDT methods to SHM by fixing them permanently to the structure and attaching the instrumentation required for the test, together with communications hardware. However, routine NDT is usually applied at shutdowns under ambient conditions, whereas a permanently installed system has to survive the operational environment.

This paper discusses both guided wave and bulk wave applications and indicates fruitful areas for research. It is based on a recent overview paper [1] looking at progress with SHM technology and the barriers to its implementation.

II. Guided Waves

There are many guided wave modes that can propagate in a given structure and the key to successful applications is to manage this complexity, typically by exciting only one mode in a controlled direction [2]. Guided wave inspection has found most application in essentially one-dimensional structures such as pipes and rail [3]. It has been particularly commercially successful on pipes in the oil and gas industry, usually using a torsional wave at low ultrasonic frequencies (<100 kHz) which travels along the axis of the pipe using the walls as a waveguide. The wave has full volumetric coverage and very low attenuation in steel, making it especially suited for long range screening applications; a single sensor system can routinely inspect more than 50m of pipe from a single location [4]. This coverage comes at the cost of lower sensitivity, with commercial guided wave systems typically sensitive to changes in cross section of around five percent and above in a single inspection [5]. This type of sensor is therefore usually used in conjunction with another localized, high accuracy technique such as ultrasonic thickness gauging [6] to do follow-up inspections of the areas the guided wave sensor has identified as suspect.

Permanently installed guided wave sensors were originally deployed to reduce the access cost of repeated inspection but an improvement in detection sensitivity is also obtained [5]. For example, guided wave NDT of pipelines using the fundamental torsional T(0,1) mode has been shown to reliably detect large corrosion-like defects which result in 5% cross-sectional area (CSA) loss.

The detection sensitivity in monitoring is a function of the stability of the signals received in the absence of any damage growth and a great deal of research has been done on the compensation of the effects of temperature and other factors on the signals. Most compensation schemes cover the whole signal via, for example, stretching to compensate for velocity changes with temperature, or overall phase changes [7, 8]. Permanent installation and frequent data collection coupled with these compensation methods enables the reliable detection of smaller corrosion patches of the order of 0.5-1% CSA loss [9]. However, recent work has shown that these 'global' schemes can be supplemented by additional, point-by-point compensation to take account of changes in attenuation or the mix of modes generated with temperature. This can give a substantial further improvement in performance to better than 0.5% cross section loss [10].

The successful applications on pipe and rail are on relatively simple, essentially one-dimensional structures with few complicating features. This means that there is no attenuation due to beam spreading, the attenuation due to scattering from features is modest and the received signals usually have clear reflections from features such as welds that do not overlap which greatly simplifies interpretation. There has also been a great deal of interest in applications to 2D structures such as airframes. Here there are multiple reflections from the relatively closely spaced ribs and stiffeners that greatly complicate the received signals and reduce the feasible test range; Dalton et al [11] showed that testing over distances greater than 1m was unlikely to be feasible at the >100kHz frequencies required for adequate spatial resolution in these structures. Many schemes have been proposed for imaging damage growth using measurements from sparse sensor arrays e.g. [7, 8, 12, 13] but they have not been applied in commercial settings.

Chang and an associated spinout company from Stanford University [14] have pioneered a sparse array of piezoelectric sensors mounted on a flexible printed circuit board to form a ‘smart layer’ that can either be embedded in composite materials or surface mounted on any structure [15, 16]. This is connected to instrumentation that can transmit the data either wirelessly or via wired connections to an analysis centre where bespoke software assesses whether any damage is present and its severity. It was originally developed for aerospace applications but multiple potential applications have been proposed [14]. However, these are mainly at the trial rather than routine industrial deployment stage.

III. Bulk Waves

Converting ultrasonic NDT equipment to SHM applications is relatively straightforward, the main challenges being simple, reliable attachment of the transducer to the test structure and ensuring that the system will withstand the operational environment. With guided wave systems it is sometimes possible to locate the transduction system away from the harshest environment, but this is les easy with local, bulk wave testing. An intrinsically safe, permanently installed thickness monitoring system capable of operating at up to 6000C has been developed [17] and has been very successful with over 20,000 installations at ~200 sites worldwide, mainly in the oil and gas industry [18]; these have generated over 20 million thickness readings transmitted via a wireless mesh system. An alternative electromagnetic acoustic transducer (EMAT) that operates at lower temperatures, is easier to install and will take measurements through coatings such as fusion bonded epoxy paint has also been developed [19]. Systems involving bonded transducers are also available [20, 21]. Permanently installed ultrasonic systems for monitoring the growth of known cracks are also available [22, 23].

IV. Dealing with Data

In most conventional inspection, the data interpretation is done directly by the trained technician operator so those responsible for the integrity management of the structure are only alerted when there is an abnormality. In contrast, SHM data is generated automatically, it is typically much more frequent than NDT inspections (eg daily rather than annual) and is transmitted direct to the structure operator. As the number of monitoring locations on a structure or plant increases, this data stream can become unmanageable unless some automatic pre-processing is applied. When the thickness monitoring system [81] [82] was first deployed at 100s of locations on a plant, operators described the experience of frequent, multi-point data as being like 'drinking from a hosepipe'. This can be mitigated by presenting information from multiple sensors together, colour coding those with anomalous behaviour that need to be followed up. However, in larger installations it will be attractive to investigate automatic diagnostics, perhaps via machine learning; this is an attractive area for future research.

There is an increasing number of applications of both guided wave and bulk wave structural health monitoring and there is increasing industrial interest in the methods. Key research areas for the future are:

- Transducers that will withstand harsh operational environments and are simple to deploy;
- Signal processing methods that will reliably compensate readings for environmental changes and will enable significant structural change to be flagged automatically without operators needing to view large volumes of data;
- Further improvements in electronics, communications and power sources to increase system life;
- Developing business cases to identify the economic benefits of SHM deployments.

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