

Advancing infrastructure sustainability

Professor Cliff Lissenden attempts to advance the early detection and analysis of microstructure defect progression which precedes macroscale damage in order to improve structural integrity



Could you begin by outlining the main objectives of your research group at Penn State?

The primary objective of our research group is to assess the integrity of structures in order to ensure safety, reduce life cycle cost, improve asset readiness and create an important paradigm shift in design. Structural integrity can be compromised by damage associated with fatigue, creep and corrosion, to give just a few examples. To meet this objective we develop and employ theoretical, numerical and experimental methods for the application of ultrasonic guided waves. Currently under investigation are systems involving structural health monitoring (SHM) using autonomous systems with stay-in-place sensors and nondestructive evaluation (NDE) using portable equipment.

You are currently conducting research on microstructural evolution. Could you elaborate on this work and explain why it is significant?

Conventional NDE and SHM methodologies are capable of detecting macroscale damage such as a fatigue crack. Different methodologies have different sensitivities and probability of detection for cracks on the millimetre-length scale. There are many cases where the time between when a crack is detectable and when it is of critical size (resulting in catastrophic fracture) is short. This means that there is insufficient time to effectively plan maintenance actions; thus, earlier indication of impending damage is extremely desirable. Our research aims to characterise the microstructure evolution that precedes macroscale damage. In the case of metal degradation due to cyclic loading, this is known as incipient fatigue

damage, and includes persistent slip bands and formation of dislocation substructures.

How important is it to embrace a multidisciplinary approach within your research?

Due to the nature of SHM, without a multidisciplinary approach it is only possible to solve part of the problem. The development of an SHM system for a particular structural arrangement is a multi-step process. First, the structure must be well understood and potential failure modes characterised. Secondly, the progression of damage that leads to failure is quantified. Thirdly, a sensory system is selected to measure some feature of the structure that can be correlated to damage accumulation. To actuate and receive ultrasonic guided waves, piezoelectric, magnetostrictive or electromagnetic transducers are commonly employed. The received signal is analysed in the time and frequency domains to determine physically-based correlation features.

There is a hierarchy for successful SHM: detection, location, classification and sizing. If each of these can be achieved, and provided the loading and operational conditions are known, the remaining lifespan can be estimated by the application of damage and fracture mechanics. Finally, for maintenance and operational decision making, it is important to know the reliability of the life estimate, which involves determination of the probability of detection and probabilistic modelling.

Has collaboration, on both a national and international level, been beneficial for your research?

The opportunities to interact, at international conferences and meetings, with colleagues from industry, government laboratories and other universities, have been extremely

beneficial to our research. Furthermore, the Ben Franklin Center of Excellence in Structural Health Monitoring now part of the Center for Acoustics and Vibration at Penn State, has been instrumental for initiating highly beneficial interactions and collaborations.

Given the enormity of the challenge to maintain the US's massive infrastructures, how confident are you that developing technologies will rise to the task?

Being an optimist, I'm confident that we will meet the grand challenge of infrastructure sustainability. I'm not sure what the solutions will look like yet, but I believe that scientists and engineers will meet the challenge as they have met others in the past. Of course, the crux of the problem is financial. Not only do the SHM systems need to be technically excellent, they need to be affordable.

Are you working on any other research projects at the moment, and what are your plans for the future?

We are currently developing methods to characterise the microstructural evolution of the nickel-base alloy 617, in a nondestructive way with nonlinear ultrasonic guided waves. This will be utilised for the characterisation of materials for the very high temperature reactor option of the next generation nuclear plant. That project is being extended to online condition monitoring (SHM) for light water reactors and the next-generation nuclear plant through the development of high temperature transducers. We are collaborating with Professor Bernhard Tittmann, who is part of our department at the University, on the high temperature piezoelectric transducers.

Nonlinear ultrasonics for infrastructure management

With their expertise in ultrasonic guided waves, **Penn State** engineers are tackling the enormous challenges of structural health monitoring in the US by driving innovation in engineering science and mechanics

CIVIL/INDUSTRIAL INFRASTRUCTURE right across the US is ageing; many public assets, such as road and rail networks, power stations and water supply plants, are decaying to such a degree that there are now concerns about their stability and ever-increasing maintenance costs. Authorities are faced with mounting pressure to manage or replace their assets but the rising costs are hampering progress. As if the ability to detect structural damage and repair or replace components is not challenging enough, the enormous number of existing structures to maintain exasperates the situation. Degradation, not identified prior to structural failure ultimately costs more financially, can have very negative effects on the environment and puts human lives at risk. In recent years, technology has developed to aid early detection, and Penn State is leading the way.

An ongoing research programme in the Department of Engineering Science and Mechanics is using novel autonomous sensory systems to address this national dilemma and is drawing on fundamental mechanics of materials to help understand the ways in which micro-level damage in materials evolves into macroscale damage, such as fatigue cracks. Thus, damage evolution can be diagnosed at a much earlier stage. To explore this concept, Principal Investigator Professor Cliff Lissenden and his team are using higher harmonics generated from ultrasonic guided waves and exploring their link to microstructure features whose evolution leads to damage. Whilst higher harmonic generation is not a new concept, its application to detect early indications of damage in the context of ultrasonic guided waves is relatively

unexplored. The intention of this research is to use interacting ultrasonic guided wave modes to identify material defects that would not be detected by linear ultrasonics. "It is conjectured that higher harmonic generation from two interacting guided wave modes enables *in situ* characterisation of microstructural evolution for reliable structural health monitoring (SHM)," observes Lissenden.

In describing how the 20th Century saw unprecedented construction and growth of power stations, civil infrastructure and the like, Lissenden explains that their design lifetime is nearly complete: "In the US, the American Society of Civil Engineers publicises the poor grades given to the condition of the civil infrastructure and estimated funds necessary to bring it to an acceptable level. These numbers are eye opening".

SHM is currently a passive measurement of vibration or strain which, unfortunately, is not very sensitive to the initiation of damage. The use of an active technique to monitor localised damage, such as ultrasonic guided waves, which must satisfy both the wave equation and the boundary conditions, will therefore improve SHM potential. And using higher harmonic generation will further perfect the operation. In employing higher harmonic methods designed by Lissenden and his group they will go a long way to refine the existing protocol.

NONLINEAR ULTRASONIC GUIDED WAVES

Because traditional damage monitoring, using SHM or nondestructive evaluation (NDE) falls short of detecting microstructural damage,

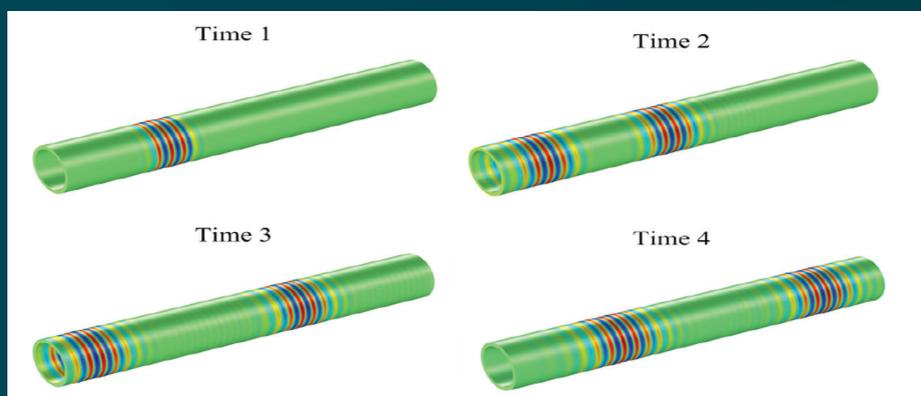
nonlinear ultrasonic guided wave (NUGW) technologies are being developed at Penn State.

NUGW employs features of received ultrasonic signals that are at a frequency different from the excitation frequency. Often these features occur at integer values of the excitation frequency and are known as higher harmonics. Typically, the ultrasonic waves are activated by piezoelectric or magnetostrictive transducers that convert an electrical signal into a mechanical pulse.

As NUGWs have the potential to detect incipient fatigue damage, more precise estimation of the remaining useful life of the structural system can be achieved through early diagnostics, enabling a shift from schedule-based maintenance to condition-based maintenance. This, in turn, will lead to better maintenance planning, asset operations and logistics, as well as reduced public health and safety risks.

Because microstructural features, including persistent slip bands and increased dislocation density, result in weakly nonlinear material behaviour, NUGW can offer valuable insights into the residual strength and remaining life of complex structures. "By triggering a purely sinusoidal waveform the material nonlinearity can be assessed by the distortion to the waveform that it creates, which becomes apparent through higher harmonic generation when transformed into the frequency domain," explains Lissenden. "Ultimately, these higher harmonics are sensitive to the microstructural evolution that precedes macroscale damage." It is not possible to gain this kind of insight using linear ultrasonic waves. Modelling the nonlinear interaction of ultrasonic guided wave modes is a critical step in the selection of guided wave modes and frequencies that generate usable higher harmonics. Higher harmonics with an amplitude that increases with propagation distance are sought. Development of actuators of primary wave modes and sensors of higher harmonics is another critical step.

The group is looking at how certain features of material microstructures including precipitate size and dislocation density, are linked and connected to higher harmonics. However, there are challenges with such research, including the



Snapshots of displacement field due to ultrasonic torsional wave propagation (mode T(0,2)) in a pipe obtained from finite element simulation of an interdigitated transducer.

The benefits will be especially valuable for nuclear and fossil fuel plants, turbines, aircraft and petrochemical plants that demand reliable estimates of remaining useful life

complexity of the evolution process in real materials. "We plan to partially circumvent this problem through control of the microstructure by selecting a material for which certain microstructural features are controllable and quantifiable by relatively simple means," elucidates Lissenden.

Waspaloy and Inconel 718 are two materials that meet their needs. Both are age hardenable nickel base superalloys known to perform well in extreme environments. The microstructure and deformation mechanisms are already well known, offering a solid foundation from which to investigate the link between microstructure and higher harmonic generation. Lissenden will be using thermal processing and mechanical loading to create different microstructures, and then metallography methods to characterise these microstructures in order to correlate them with higher harmonic generation from the nonlinear ultrasonics.

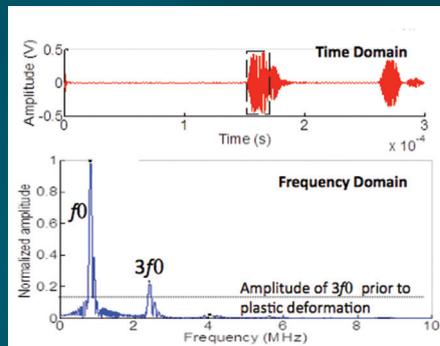
INVESTIGATING BROADER APPLICATIONS

There are a number of benefits this R&D will bring to engineering, including the ability to better assess beams, plates and shells, steel highway girders, pressure vessels, storage tanks, pipes and tubing. And research underway at other academic institutions is adding to the discourse, enhancing potential opportunities for sounder NDE methods for bridge cables and railroad tracks.

Lissenden's team is further exploring mode mixing and the relationship between

microstructure and harmonic generation. "Not all of our work is nonlinear ultrasonics," he explains. "We are also researching piezoelectric fibre composite multi-element strip transducers for actuating and receiving planar guided waves for SHM." They are also keen to learn more about ultrasonic guided waves for SHM of adhesively bonded joints in composite structures and this is the subject of their latest venture.

From the progress so far, the efforts at Penn State hold great promise for infrastructure managers; both technically and financially. Lissenden reiterates: "We anticipate this will have a tremendous economic effect on operators of a broad spectrum of structures and machines". In particular, the benefits will be especially valuable for nuclear and fossil fuel plants, turbines, aircraft and petrochemical plants that demand reliable estimates of remaining useful life. "Further, with more realistic estimates of actual operating conditions and an SHM system to detect and characterise damage, it becomes possible to reduce safety margins without compromising safe operations," concludes Lissenden. Already showing a number of promising developments, it is reasonable to expect that nonlinear ultrasonic guided wave technology will be transferred to other SHM applications in the near future and help to improve the safety of the infrastructure across the US.



Time and frequency domain responses for an aluminum alloy plate after plastic deformation, which shows the increase in the third harmonic.



Lissenden measuring a fatigue crack in aluminum plate, which was initiated at the centre hole, in order to correlate with Lamb wave data.

INTELLIGENCE

ADVANCING INFRASTRUCTURE SUSTAINABILITY WITH ULTRASONIC GUIDED WAVES

OBJECTIVES

- To advance structural health monitoring capabilities with ultrasonic guided waves to characterise damage in structures, with an emphasis on early detection of precursors to macroscale damage
- To advance theoretical modelling, computational simulation, transducer systems and data analysis methods in order to accurately and autonomously characterise the current condition of a structure, and then predict its remaining useful life

KEY COLLABORATORS

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