Sensor Mimics Nature to Detect Dangerous Structural Cracks

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As the world's infrastructure ages, future inspections and assessments need new methods to predict and assess structural conditions. Using geometrical patterns appearing in nature, researchers developed a new type of ultrasound sensor that will hopefully lead to improvements in our ability to detect cracks in safety critical structures such as aircraft engines and nuclear plants as well as bridges and other critical infrastructure.

In 2007, the Interstate I-35W Mississippi River Bridge in Minneapolis collapsed into the river, killing 13 and injuring 121 others. (photo courtesy of Federal Emergency Management Agency (FEMA)/ U.S. Fire Administration (USFA))

The research team developing this technology is part of the Centre for Ultrasonic Engineering at the University of Strathclyde based in Glasgow in the UK. This centre has more than 30 years of experience in designing and building ultrasonic transducers; the most common type of sensor used to non-destructively test safety critical components.

The United States' infrastructure is structurally deficient. Until funding toward maintaining and enhancing infrastructure is implemented, the state of the nation's infrastructure will continue to decline due to the ongoing threat of terrorism and other natural occurrences.

In 2013, more than 64,000 bridges in the United States were evaluated and deemed structurally deficient, indicated by deterioration to one or more major components. [1] Implementing sensor technology that assesses structural cracks in infrastructure allows problems to be quickly identified and addressed and public safety measures implemented before bigger issues arise.

Many naturally occurring objects look incredibly complex but are often built recursively from a simple shape. The geometry of the materials used inside an ultrasonic transducer play a key role in its operating characteristics; so by taking inspiration from nature, it should be possible to radically affect the performance of these sensors. Nature's users of ultrasound technology – bats, insects, dolphins and so forth – can outperform the man-made equivalents and part of this advantage stems from the complexity of the designs they use.

Ultrasonic transducers operate by converting an electrical signal into a mechanical vibration (transmission mode). This vibration then traverses the medium of interest and is collected by the transducer (reception mode) and converted back into an electrical signal. This signal undergoes some post-processing to extract the encoded information and generates an image of the medium. To maximise their sensitivity, these transducers operate at their resonant frequency, which is determined by the type of material they are composed of and the length scale of this material.

When operating in transmission mode you can think of the transducer as a musical instrument. Commercial transducers typically have a single length scale of material and so operate at a single frequency. This restricts the types of signals they can transmit and receive; think of a musical instrument that can only play one note. To extend the range of frequencies the transducer can operate at is then obvious – the device needs to have a range of resonating components. Each one would have a different length and would therefore resonate at a different frequency; this is the fundamental basis upon which all musical instruments rely. It is clear from observing nature's ultrasound experts that they emit complex signals (called chirps) that span a wide range of frequencies and this somehow enables them to image objects at a far greater resolution than any man-made equivalents.

We see other objects in nature with components spanning a range of length scales; think of snowflakes, ferns and cauliflowers. Such structures have been studied for many years using the mathematics of fractals, which generates methods for studying the dynamics of such structures. The researchers at Strathclyde used cutting edge mathematical techniques to create the world's first fractal ultrasound transducer (based on a Sierpinksi gasket). At the moment the investigation has all been theoretical but the results just published [2] confirm the potential of the idea and a program to manufacture these devices is underway.

The work is timely as the traditional restrictions on what could be manufactured have been swept aside by the advent of 3D printing and other additive manufacturing methodologies. It is fair to say that part of the reason that commercial transducers are based on a single length scale (their internal structure looks like a chess board) is due to manufacturing constraints. Now that we are being freed from these constraints the designs of the future are only limited by our imagination. The hope is that these new transducers will be able to detect defects at a much earlier stage in their development. So this device could not only improve safety but also save a great deal of money, as early detection means inspections don't have to be carried out as often.

References:

[1] State bridge inspection data, structurally deficient ratings. (2013). Governing Data.

[2] Algehyne, E.A. & Mulholland, A.J. (2015). A finite element approach to modelling fractal ultrasonic transducers. *IMA Journal of Applied Mathematics.*

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