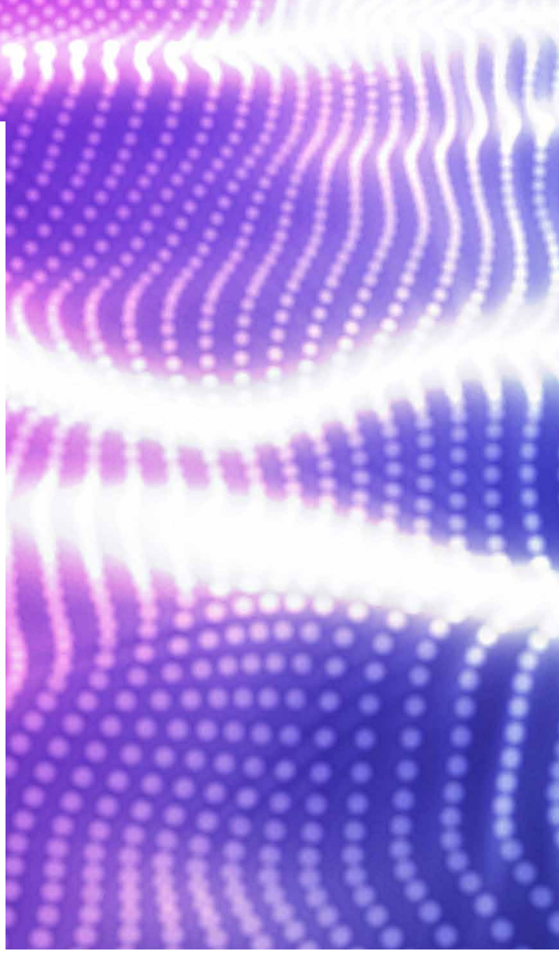
Using Noise to Control Micromechanical & Macromechanical Systems

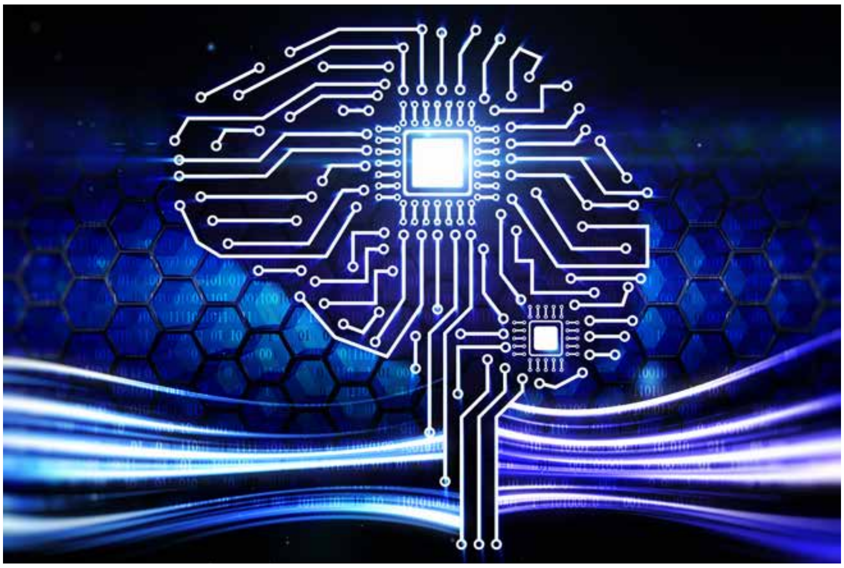
Professor Balakumar Balachandran

Scientia



USING NOISE TO CONTROL MICROMECHANICAL & MACROMECHANICAL SYSTEMS

Micromechanical oscillators are components of many electronic systems that keep track of signal processing and ensure data is moved around without becoming jumbled up. **Professor Balachandran** and his team at the University of Maryland are exploring how noise can be used to control certain phenomena within arrays of these tiny mechanical oscillators, to change their behaviour and make them operate better than before. Their studies also have important ramifications for macro-scale mechanical systems.

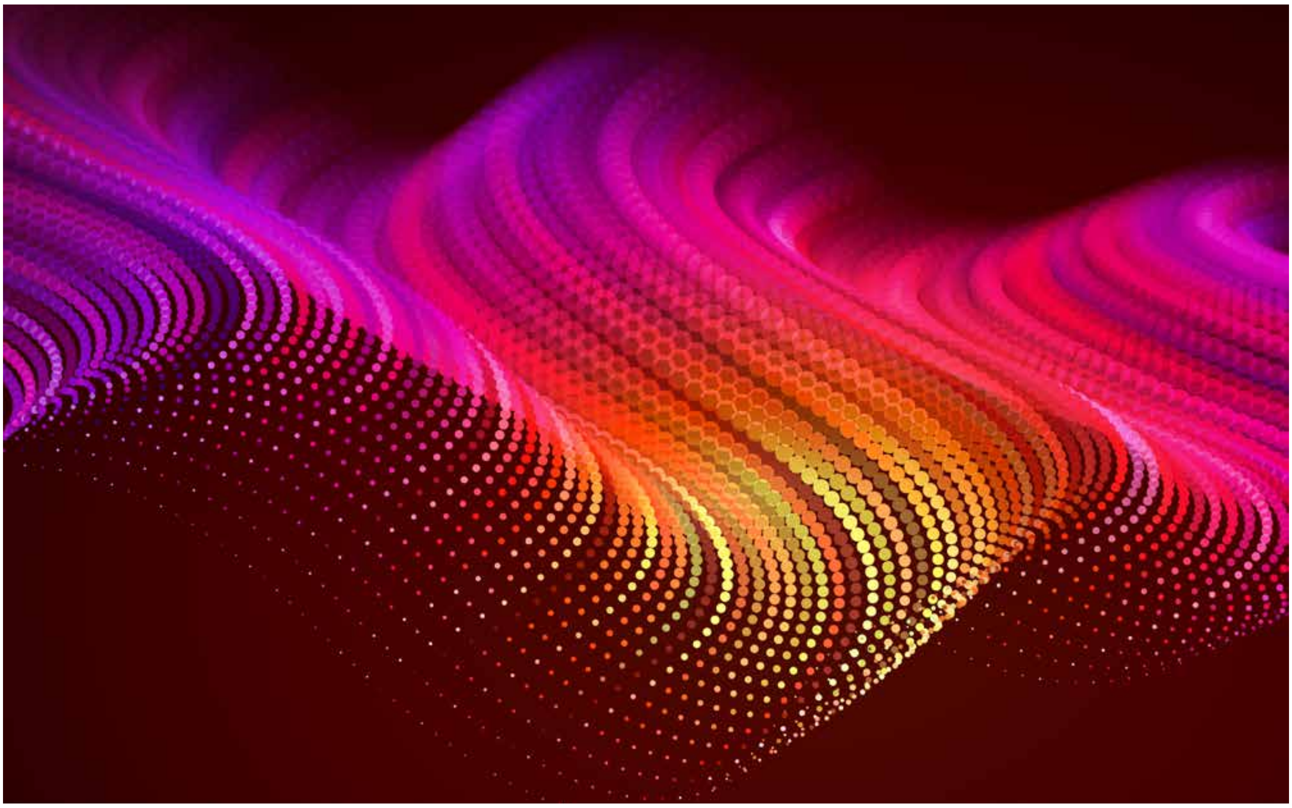


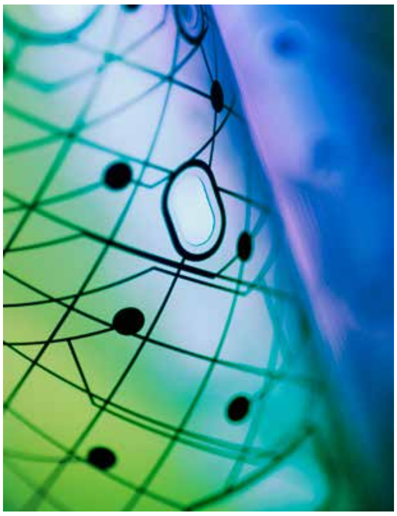
At very small scales – those smaller than a millionth of a metre – strange effects and phenomena can be observed in dynamic systems. These effects are usually not observed at larger scales, or are so tiny that they become swamped by everything else taking place. Some of these effects appear random in their cause, but can be attributed to fabrication flaws in the very small components of a system. Sometimes, vibrations caused by thermal sources can cause these components to start exhibiting unexpected activity (heat, at the smallest scales, is after all just vibrations of atoms and molecules).

However, for the design of systems that have very small components – for example, integrated circuits – a better understanding of these strange phenomena is needed. This is true not only so that people can know how the system will behave, but also because these phenomena could potentially be used to control micromechanical systems and make them perform in entirely new and better ways.

One type of system that has components small enough for these effects to take place is a micromechanical oscillator array. Micromechanical oscillators are tiny devices that generate electrical or optical signals with very accurate frequencies. Effectively, they act as miniature clocks within more complex systems, and these systems can be used to carry out a number of different functions. Quartz crystals used to be the standard for generating regular frequency signals within a system, but they are sensitive to impacts and can easily be disabled or made inaccurate. In the last decade, more robust oscillators have been fabricated from different materials and have more sophisticated designs. Much of the early work in this area was funded by DARPA, the US Defence Advanced Research Projects Agency.

One of the most important of these oscillators is timekeeping, in order to keep track of signal processing within the circuitry and ensure that data is moved around without becoming jumbled up. In effect, these oscillators provide a heartbeat for the rest of the electronic system. Where multiple timing signals are required, a number of oscillators are often placed together in orderly arrays. At the University of Maryland, Professor Balachandran and his research team have been working for several years to understand the effects of noise and vibration on the behaviour of oscillator arrays across different length scales. Impressively, the team has figured out new ways to control these effects.





The Bizarre World of Intrinsic Localised Modes

Intrinsic Localised Modes (ILMs) are a phenomenon that takes place in these arrays of oscillators, where energy accumulates in a spatial region or wave within the system. Usually, this localisation occurs at a single location and holds position, which is different from what would be expected in a classical wave system – normally the energy is dissipated away from local sources and the wave travels through the system. For this reason, ILMs are also sometimes called breathers as they 'breathe' in and out, usually holding steady at one location. However, under certain conditions, they can also move through an oscillator array without dispersing the wave energy – a phenomenon with many potential applications if it can be controlled.

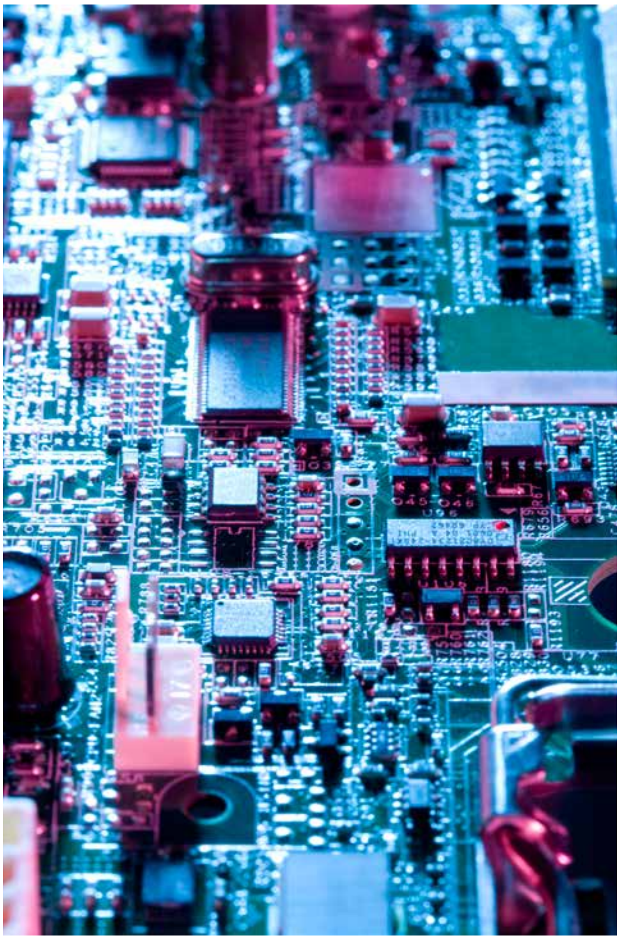
The reason that ILMs exist in oscillator arrays and other similar systems is difficult to pin down and still a topic of many research investigations. Originally, they were thought to result from random noise within the oscillator system, but this was shown to be impossible. However, Professor Balachandran and his colleagues have shown that with sufficiently high intensity noise of the correct type and frequency content, ILMs can be variously generated, enhanced or suppressed throughout an oscillator array. Developing this ability to control ILMs is important, as it might give rise to new and useful behaviour within the array.

Noisy Oscillations – Better than the Normal Kind?

This control is achieved by adding noise to the baseline signal controlling the array, with the effect of this depending on the strength of the noise in relation to the baseline signal. What Professor Balachandran and his team have found is that it is possible to make ILMs occur at specific, controlled locations within in the oscillator arrays, and also to make them last longer than they normally would.

In addition to this, the team has explored the effects of signal noise on the creation and destruction of a specific type of ILM, within arrays of oscillating cantilevers that are coupled to one another. These cantilevers, which are beam oscillators held at only one end by a coupling rod, were vibrated from side to side, while the team measured their responses by using strain gauges. When they added noise to a harmonic input with a certain vibration frequency, an intrinsic localised mode (ILM) was generated. The team found that in the absence of noise, no ILM was present in the system. They also found that when noise was added to a system where an ILM existed, it destroyed the ILM.

The frequency and strength of the signal driving an array of coupled oscillators appear to be two important factors in the creation of ILMs. The strength of the noise signal is also vital in terms of its influence on the ILMs. However, the relationships that exist between all these factors are not yet properly understood. In order to investigate further, Professor Balachandran and his colleagues have developed a macro-scale mechanical system that mimics arrays of tiny oscillators by using cantilever oscillators, enabling them to control the frequency content and level of noise added to the system.



Useful Noise

There are multiple applications for this work ranging across a number of fields, beyond engineering. One of these is artificial intelligence, where adding noise to the input signals of artificial neurons can enhance and improve the signal-processing performance of the system. It seems strange that adding random fluctuations to the input signal would result in better and more stable pattern recognition within an artificial neural network, but researchers have validated this mathematically.

Without noise in an artificial neuron's signal, it tends to become stuck in one of the two possible states (active or inactive). With too much noise, the neuron fires randomly and provides a meaningless output. But with the right amount of noise added to its input signal, the artificial neuron becomes much more capable of swinging between these two states when it needs to, with a greatly reduced background signal. This makes it more responsive to changes in this signal and improves pattern recognition.

The mathematics explaining this and other effects within an array of oscillators is quite complicated, but at its core, it is based on the Fokker-Planck equation. This equation describes how the velocity of a particle or an object will change over time, when it is subjected to drag (dissipation) and random forces. The Fokker-Planck equation is a partial differential equation, meaning that it combines values of parameters with the rates of change of those parameters. This makes the equation exceedingly difficult or impossible to solve for nonlinear systems, except under special circumstances.

When there is no solution to a specific mathematical equation, researchers normally rely on simulation methods to approximate variations of the value over small distances. This is a bit like splitting a simulated volume up into lots of small boxes, and calculating the change to the values in each box over small time steps. With the Fokker-Planck equation, this approach allows the particle movement to be changed from a continuous smooth curve to a series of tiny steps. If the steps are small enough, then this gives the same appearance as a smooth slope when viewed from a distance.

For simulations of coupled oscillating systems, the Fokker-Planck equation demonstrates what is seen in reality – that the oscillating system tends to become stuck in specific patterns. Adding noise to the equation, as in real life, shows that the system is much more capable of switching between states and therefore responding in a much more sensitive manner to external stimuli. This finding has relevance for sensors and signal processing, and has even helped to explain a number of observed biological phenomena, such as the foraging behaviour of animals.

The challenge is to figure out the best possible way to apply noise within a coupled oscillatory system, in order to maximise the benefits of this effect. Professor Balachandran and his team have explored this with their mechanical cantilever oscillator array device, which allows them to alter the frequency of the harmonic signal and the relative strength of the noise added. The cantilever, if left to itself, tends to switch back and forth regularly and repeatedly between the two states without any variation. When the team adds noise, the cantilever tends to stabilise around an equilibrium or fixed point, oscillating much less than before.

Further Work

What Professor Balachandran and his team have found is that this noise can be used to steer the performance of an oscillating system towards a desired dynamic state. The earliest observations of this were found in microscopic systems, but the results of Professor Balachandran's research have enabled this phenomenon to be translated into macroscopic systems. This is an important point, as it implies that we may be able to gain better control over complex oscillating systems and enhance their performance. However, there is still much work to be done in this area.

Professor Balachandran and his team have developed an analytical-numerical framework that enables them to study the effect of noise on the dynamics of coupled oscillating systems. Along with the mechanical system they have constructed, this will allow the team to explore various arrangements of the system, vibration, and noise. They will also be investigating ways to scale up some of the phenomena observed in arrays of microscopic oscillators, to see if they can be induced in macroscopic systems. One future study of interest to them is a rotor system whose dynamics they expect to influence by injecting noise into the drive torque.

In addition, the team plans to develop an experimental prototype containing other types of oscillators, and to experiment with more sophisticated models of coupled oscillating arrays. This will allow them to gain a better understanding of how real-life coupled oscillatory systems such as artificial intelligence designs could be improved, and even controlled.

Meet the researcher

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Professor Balakumar Balachandran received his PhD in Engineering Mechanics from Virginia Tech, USA. Since 1993, he has worked at the University of Maryland, where he is currently a Minta Martin Professor of Engineering and the Chair of the Department of Mechanical Engineering. He is a Fellow of ASME (American Society of Mechanical Engineers) and AIAA (American Institute of Aeronautics and Astronautics) and is also a member of several other societies. His research interests include nonlinear phenomena, dynamics and vibrations. Much of his work has focused and is focused on nonlinear phenomena, dynamics of nonlinear systems, and control mechanisms for nonlinear systems. His team's recent work has included efforts to use nonlinear phenomena for the benefit of system control. Professor Balachandran has published over 90 journal articles and a number of textbooks and book chapters related to nonlinear dynamics and vibrations. He serves as the Technical Editor for the *ASME Journal of Computational and Nonlinear Dynamics*, a Contributing Editor of the *International Journal of Non-Linear Mechanics*, and is on the editorial boards of several journals including *Acta Mechanica Sinica*, the *Journal of Vibration and Control*, and the *International Journal of Dynamics and Control*.

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