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Fig. 1 The Bunaea alcinoe or cabbage tree emperor moth

Vibroacoustic Properties in Moth Wings

Some special scaled wings exhibit acoustic camouflaging properties. Modelling this effect helps to better understand the vibroacoustic phenomena at play.

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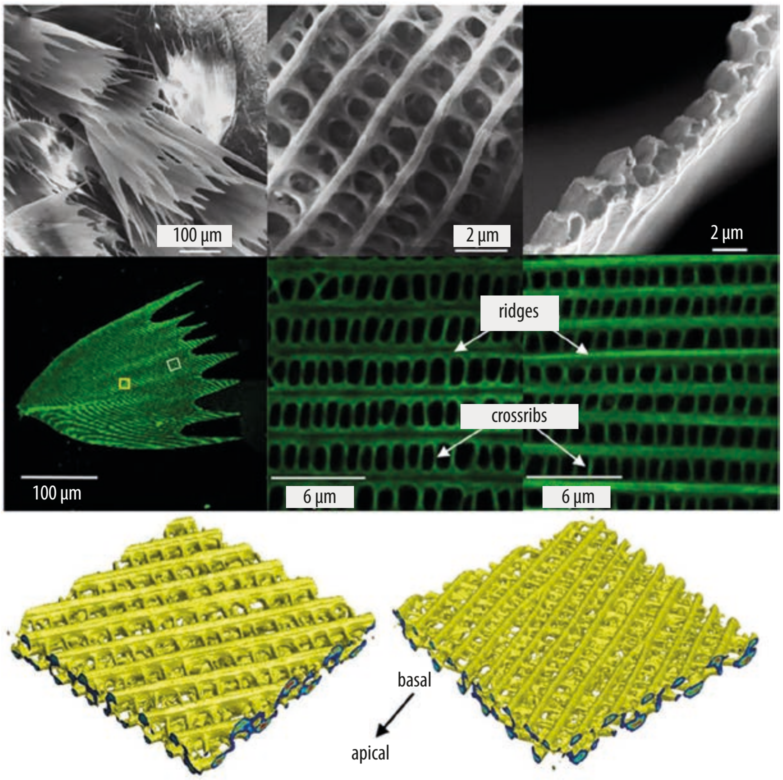
Have you ever looked at the ground or watched a tree branch or a leaf on a bush – and all of a sudden, it moves? Plenty of insects and arachnids camouflage themselves from predators by blending in with their surroundings. For instance, the orchid mantis has wings that look just like the delicate buds of an orchid flower; the Phasmatodea, also known as the "stick bug", has arms and legs that bear an uncanny resemblance to little brown twigs; and the Luna moth has fluorescent green wings that perfectly match bright leaves on a tree.

However, this type of visual camouflage is a moot point when trying to avoid one of the main predators of insects: Bats do not see with their eyes, but instead navigate and search for food using echolocation. So what is a bug to do? As it turns out, certain types of moths, like the Bunaea alcinoe (**Fig. 1**), also called the cabbage tree emperor moth, have scaled wings that provide acoustic camouflage, protecting them from bats' advanced sonar detection. Researchers from the University of Bristol used numerical modelling to study this wing scale phenomenon and see how we can potentially apply these acoustic camouflaging capabilities to other areas.

For over 65 million years, bats have sought out moths as a source of food. Some moths can detect the signals of approaching bats while others defend themselves with poison or clicking sounds that can startle the bats enough to fly away. The cabbage tree emperor moth is both deaf and nontoxic but it is not helpless. It simply relies on a more passive defense strategy: acoustic camouflage or cloaking.

But how do moths use acoustic camouflage to fend off bat attacks? To find out, we can take a closer look at their wings. Moth wings are solid, thin membranes made up of chitin, a long-chain polymer derived from glucose. Stiff wing veins hold these



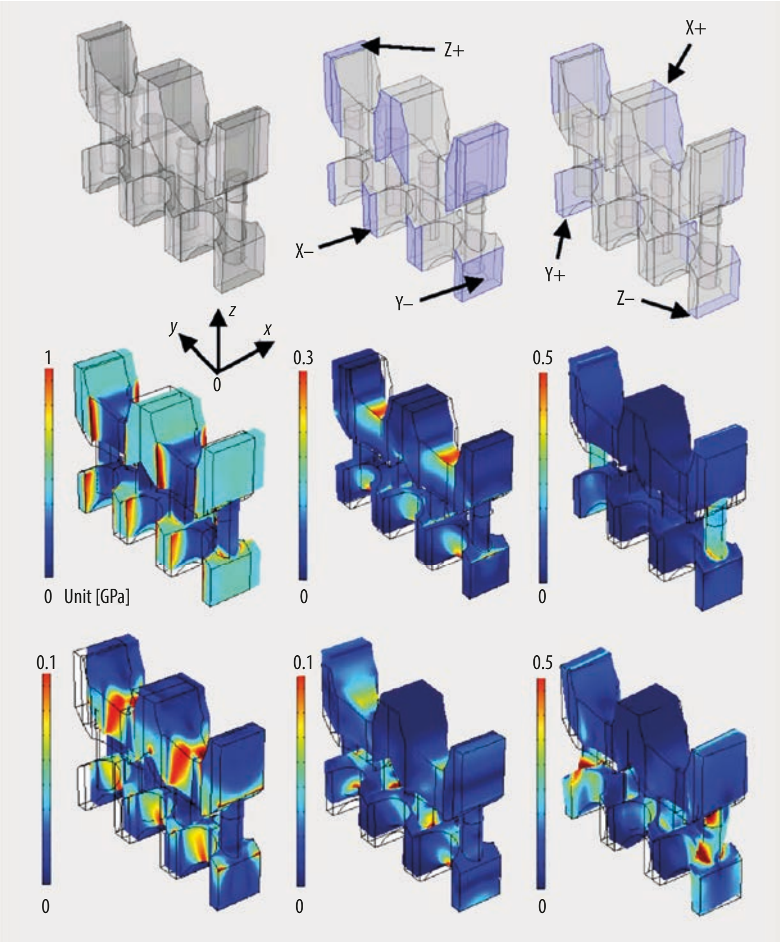
▶ **Fig. 2** SEM images of B. alcinoe scales (top row), confocal microscopy of the scale (middle row) and the top lamina (bottom row, left) and bottom lamina (right) with longitudinal ridges and cross-ribs

membranes in place (**Fig. 2**). Looking even closer, the upper and lower surfaces of the moth wing are covered in arrays of overlapping scales, like the tiles on a roof. Each scale is porous and of a complex structure. This highly sculptured scale structure stems from sophisticated evolutionary adaptations, analogous to the highly organized nanoscale photonic structures for visual signaling.

These wing scales are less than 0.25 mm long, making them smaller than one tenth of the wavelength that bats use for echolocation: the frequencies of the signals range from 11 to 212 kHz [1]. The University of Bristol researchers hypothesized that moth wings can be categorized as ultrathin absorbers with subwavelength thickness, acting as resonant absorbers. To investigate their hypothesis, the group sought to capture the governing physical phenomena of the wing scales and show that moth scales can achieve high absorption coefficients at resonance. To do so, they turned to numerical modelling.

Advanced Imaging Techniques Meet Numerical Simulation

The project started with a few moth pupae which were cultivated in the



▶ **Fig. 3** The parametrized single unit with different boundary conditions (top row) and the simulation results of stress distribution (middle row) and deformation (bottom row), each in the single unit under different boundary conditions lab until they reached maturity. Researchers collected samples of the moth wings which then underwent two types of advanced imaging techniques: scanning electron microscopy (SEM) and confocal microscopy. The SEM technique involved mounting sections of the moth wing to adhesive carbon tabs which were then coated with a thin layer of gold with a thickness of 5 nm. The scales were imaged under high-vacuum and variable-pressure modes and magnified to get a large, clear image. For the confocal microscopy process, the team immersed a single moth scale in glycerol and sealed it between two microscopy slides. Then they used autofluorescence to get ultraclear images.

Once the clear, high-quality images of the moth wings had been produced, the team was able to extract 3D data from the images into a 3D isosurface model. They saved this model in the STL format in the MATLAB® software and imported it into the COMSOL Multiphysics® simulation software with the LiveLink™ for MATLAB®. Using the COMSOL Multiphysics® model, the team identified the ideal unit cell of the moth wing scale and parameterized it to study the effective material properties (**Fig. 3**).

The next step consisted of performing a vibroacoustic analysis of the scale. The team used the Periodic boundary condition in COMSOL Multiphysics® to model the single unit cell instead of an entire scale array which saved computational effort and memory. The periodic boundary condition allowed expanding the structure into an array.

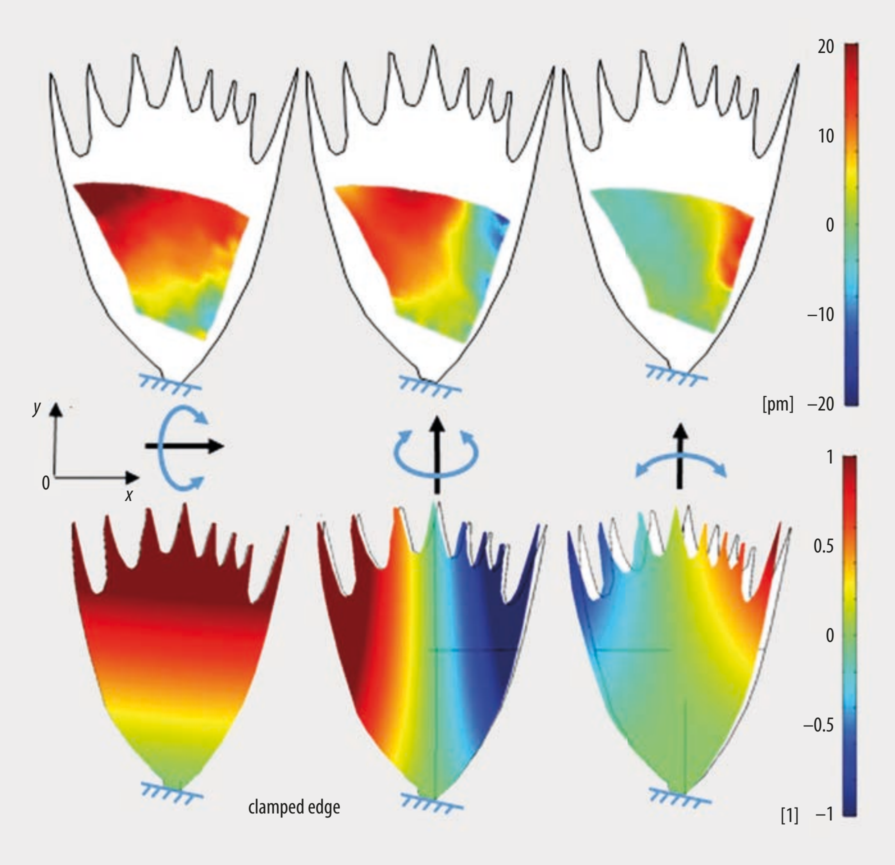


Fig. 4 Modelled and measured resonances of the moth scale: Scanning LDV results of the first three resonances of the scale (top row) vs. simulation of mode shape of a single scale with curvature radius of 700 µm (bottom row).

The team then modelled the scale vibrations at ultrasonic frequencies using a macroscale FEM model in COMSOL Multiphysics® allowing them to calculate the vibration of the scale. To understand how the ultrasonic wave is coupled with the scale structure they had to consider both acoustics and solid mechanics.

The team also built two models to analyze the damping effect of the moth scale and the ultrasonic properties of an entire moth wing made up of such scales. The former consisted of a single scale with one end fully clamped while the latter added Rayleigh damping to the material and was used to calculate the absorption coefficient of the scaled array.

Calculations vs. Measurements

In order to compare the calculated vibrations of the moth scale to their real-world behaviour, the team used a laser Doppler vibrometer (LDV) to characterize the vibrational behaviour of the single scale (**Fig. 4**). The LDV results showed good agreement with the calculated resonances for the first and third modes: they differed only by 2.9 % and 1.0 %, respectively. The calculated resonances were 28.4, 65.2, and 153.1 kHz compared to LDV results of 27.6, 90.8, and 152.3 kHz (**Fig. 5**). The simplified curvature of the moth scale might explain the 28 % deviation for the second mode. In addition, the perforation rate of the scale was modelled as constant when it actually varies and inconsistencies in the incident sound wave during the LDV measurements were neglected.

The calculated modes of the moth scale overlap and span the biosonar range used by bats for echolocation (typically 20 – 180 kHz). To crosscheck if this was just a coincidence, the analysis was repeated for a similar unit cell that mimics the structure of a butterfly wing scale.

While moths are nocturnal and often within bats' crosshairs, butterflies are active during the day and do not need protection. The modes at 88.4, 150.9, and 406.0 kHz fell outside of the bats' biosonar range supporting the theory that moths may have evolved to acoustically camouflage themselves from bats.

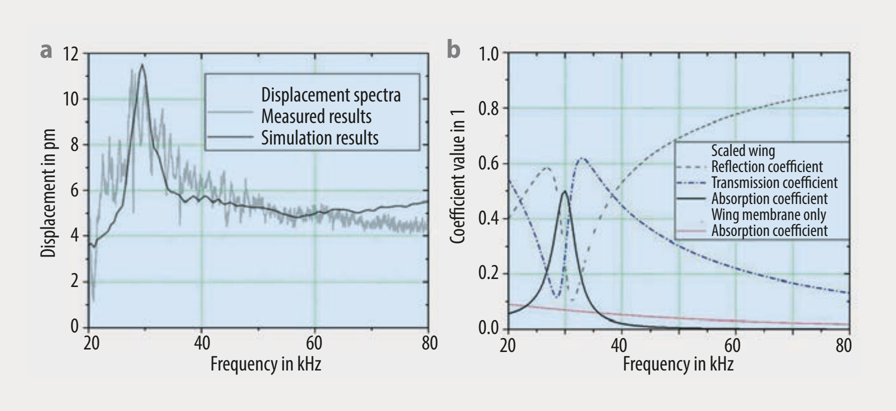


Fig. 5 Comparison between the modelled modes of a moth scale and the measured modes using a laser Doppler vibrometer

Acoustic Camouflage Reused

This research project marks the first effort to characterize the biomechanics and vibrational behaviour of moth scales, both numerically and experimentally. The results demonstrate that multiphysics modelling software helps to accurately capture moth scale behaviour, paving the way for further simulation-driven analysis. One future aim is to expand the current periodic model into a full three-dimensional model of an array of moth scales.

The research is also applicable beyond the animal kingdom. Being able to understand the vibroacoustic behaviour of moth scales allows developing macroscopic structures with the same acoustic camouflage capabilities. Possible applications include high-efficiency ultrasonic acoustic absorbers. It would be a big improvement for acoustic design if the thickness of a material would only be one hundredth of the wavelength it operates at.

In future, enhanced noise mitigation materials with acoustics camouflaging capabilities might be used in building design and defense technology.

[1] *G. Jones* and *M. Holderied*, Proc. R. Soc. B: Biological Sciences **274**, 905 (2007), DOI: 10.1098/rspb.2006.0200

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