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A BIOINSPIRED MECHANICAL MODEL OF THE ULTRASONIC CLICKS PRODUCED BY ERMINE MOTHS

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Summary A recently discovered sound production system (Aeroelastic Tymbal) located at the base of the hindwings of ermine moths produces bursts of ultrasonic clicks. The sound is produced when a ridge area on the aeroelastic tymbal buckles. The resultant sound has similar characteristics to that produced by the tiger moth, which in a certain genus is capable of jamming a bat biosonar. The biomechanical function of the aeroelastic tymbal is idealised by a simplified one-dimensional compliant mechanism, and the stability of the structure is evaluated using the modified Riks method. The purpose of this research is to take inspiration from evolved biological structures found in insects, for the development of adaptive and well-behaved non-linear structures.

A tymbal organ, which is a well known sound production system found in cicadas [1], and also present in different moth species [1, 2], allows the production of sounds for social communication or defence purposes. A moth's tymbal organ consists of a cuticular membrane typically located at the tegula, thorax (muscular actuated tymbals) or wings (aeroelastic tymbal), and produces a high-frequency clicking sound when it buckles. Also, the tymbal's membrane can present a striated band on one side, leading to the production of bursts of ultrasonic clicks when buckled. It has previously been observed that ermine moths (*Yponomeuta*) continuously produce two sets of ultrasonic clicks while flying, and such sound production occurs during the rotational stages of the stroke cycle [3]. Furthermore, it is suggested that this species mimics the sound produced by toxic tiger moths; thus, warning their predators (bats) of potential danger. Experimental approaches such as the use of high-speed cameras have provided evidence on how a tymbal organ buckles [4]. However, far too little attention has been paid to the structural mechanics associated with such phenomena. An objective of this study is to investigate the aeroelastic tymbal actuation mechanism among ermine moths. The function is modelled using a one-dimensional compliant mechanism, analysed using the finite element method. This project provides an important opportunity to explore the feasibility of bio-inspired adaptive or morphing structures.

The aeroelastic tymbal is distinguished as a clear patch (due to the absence of scales) at the base of the hindwing (Figure 1A), located between the cubital (Cu) and postcubital (pCu) veins. A micro-computed tomography (micro-CT) shown in Figure 1B indicates the venation and parts of the aeroelastic tymbal. Individual ridges forming the striated band alongside the pCu vein are referred to as "microtymbals", the rest of the translucent patch is called the "window". Throughout the pCu axis, the membrane is folded through a steep angle, and this region is called the "wall". A set of micromanipulators on an ablated hindwing, and a bat detector (to detect ultrasound signals), allowed the identification of two conditions for the sound production. Folding and unfolding the crease along the pCu vein axis was found as the triggering mechanism. Both, the initial and buckled states are shown in Figure 1C, and the latter is characterised by the birefringence of the wing's membrane.

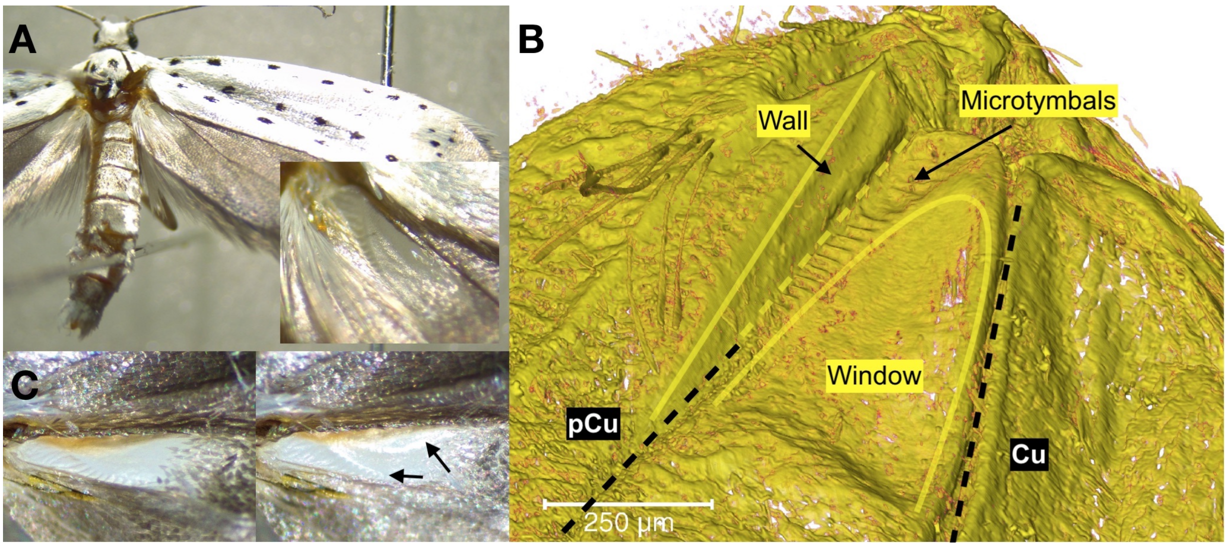

Figure 1: A. Ermine moth (*Y. malinellus*), with an enlarged image of the aeroelastic tymbal. B. Dorsal view of a micro-CT of the base of the hindwing (the yellow dotted line along the pCu indicates a folding region, also known as the claval furrow). C. Initial and buckled states of the aeroelastic tymbal (birefringance is indicated).

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From the micro-CT it can be observed that the tymbal is not a flat structure but a doubly curved membrane. The membrane's thickness was found to be less at the interface between the microtymbals and the window. Inspired from how the aeroelastic tymbal works, a simplified approach is undertaken. Taking a chordwise cross-section of the tymbal, the system can be represented by a curved compliant mechanism (Figure 2A). The stability response is then evaluated using the modified Riks method in the Abaqus commercial software package. Three design parameters (w_t/w_w: tymbal-to-window width ratio, t_t/t_{int}: tymbal-to-interface thickness ratio and the κ: tymbal's curvature), and the material properties (E: modulus of elasticity and v: Poisson's ratio) are considered, while the structure is simply actuated by a transverse force at the flexure hinge. Assuming the boundary condition (BC) at the Cu vein position is clamped and the BC at the pCu is simply-supported, the t_t/t_{int} ratio is the parameter driving the stability of the structure; which can be tuned to obtain a bistable or monostable behaviour. Assuming an even tymbal thickness, and a width ratio bounded to the tymbal-to-window dimensions, the tymbal response is characterised in terms of the thickness ratio. As a result, the Force-Displacement diagram in Figure 2B demonstrates that when a critical thickness value (t_{crit}) is achieved, the system behaves as a bistable structure.

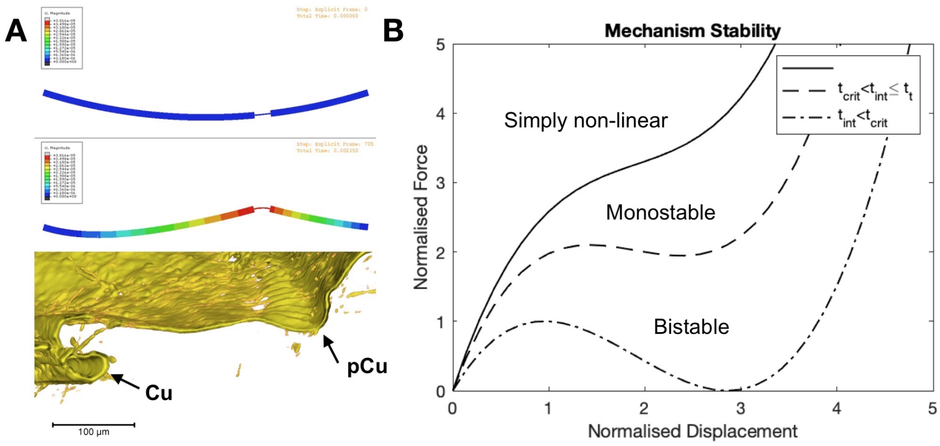

Figure 2: A. Compliant mechanism model taken from a cross-section of the aeroelastic tymbal. B. Force-displacement diagram of the stability behaviour of the compliant mechanism.

To gain insight into the acoustic response, a modal analysis is performed to obtain the fundamental frequency of the structure. This value can be tuned by modifying the elastic modulus to match the peak frequency obtained in acoustic recordings. The κ parameter determines the depth of the mechanism, controlling the maximum deflection attained from the initial to the secondary stable position. The transverse deflection of the structure is averaged and together with the resonant frequency, the sound pressure level can be calculated from a closed-form structural-acoustic model such as the baffled-piston [5], assuming the window as the sound radiator. However, this is only a representative result as the actual dynamic and acoustic response are influenced by the tymbal membrane's mass and the combined spanwise and chordwise constraints; added to the consideration that the baffled-piston model is a non conservative approach as it assumes an infinite baffle boundary.

CONCLUSIONS

The function of the aeroelastic tymbal was studied experimentally. Taking inspiration from this system, a curved compliant mechanism from a chordwise cross-section was designed. The stability, dynamics and acoustics of the one-dimensional structure were approached successfully to the extent of the assumptions. Further studies are undergoing on the design of a 2D shell structure to better address the function of the aeroelastic tymbal. This would improve the understading of the structural and acoustic response towards the design of larger scale adaptive structures.

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