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by Prashita Saxena

PEER EVALUATION FORM:

S.No.	Name (Entry Number)	Marks for effort (out of 5)
1.	Arsh Saiyad (2020BB10009)	5
2.	Darpit Rangari (2020BB10044)	5
3.	Kabeer Singh (2020BB10022)	5
4.	Prashita Saxena (2020BB10038)	5
5.	Sarthak Singh Chauhan (2020BB10050)	5

CLL231 Mini Project

WHY ARE OWL WINGS SO QUIET?

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Submitted On:

18th March 2022

Index

Abstract

This paper aims to solve the decades-old enigma of silent owl flight. Owls have been known to fly silently at high speeds, even the larger species like Barn Owl or the Great Horned Owl. While other birds produce much noise, owls have been found to be dormant to flight noise production. Various morphological factors like serrations of the leading edge, fringes, and a velvety surface are known to contribute to noise reduction. Apart from these features, the paper discusses the evolution and selection pressures leading to silent flight in owls. The serrations help in restricting vortex formation thus lowering the turbulent noise, and the velvety surface aims to provide a cushioning surface, further reducing the noise. Further, pennula, which are hair-like extensions, also aid in silent flight. We look over experiments deducing important conclusions about their flight. Apart from the morphology, silent owl flight can also be attributed to a fluid mechanical point of view. The Lighthill equation introduces us to aerodynamic noise, which when extrapolated to further studies, establishes the idea of owl wings as a quadrupole source which had been discussed further in this paper. Apart from these features, the paper discusses the evolution and selection pressures leading to silent flight in owls.

Introduction

Owls have been known to fly silently for ages. The silent flight helps owls catch their prey and helps them fly in almost absolute silence. This feature also helps the owl in tracking and hearing prey. Being a nocturnal predator, this adaptation of the owl aids it in catching prey by muting frequencies near the range at which rodent hearing starts.
As an intuitive trend, we can expect larger and faster birds to make louder noises due to increased noise due to air turbulence. However, in owls, we observe even the largest owl species as the Barn owl flies virtually silently. Certain characteristics possessed by owls help them achieve this.
Currently, there are two ways to understand owl flight: an engineering perspective constructed by the fluid mechanical equations and wind tunnel experiments & a biological perspective based on anatomy, morphology, genomics, and evolution. A truly integrated architecture will probably require both.
The serrations on the leading edge help break the wind flow down to reduce the noise generated by turbulence. This, further cushioned by the velvety texture of the wings, and the soft fringe on the wings trailing edge help dampen the airflow, streamline it, and absorb the sound produced. Another reason for the birds (or, airplanes) being louder is due to the rigidity, and impermeability of the wings. The wings of the owl, on the other hand, are significantly porous and elastic in comparison. In addition, wind tunnel experiments have also been performed to understand the right porous material for the reduction of noise. Our study attempts to draw out specific characteristics of an owl that makes the other birds appear much noisier in comparison to it.

Timeline of studies conducted

Scientists	**Conclusion**
Mascha	Talked about serrations on the edges of the owl wings being a long-known fact. He talked about the velvet-like surface and the pennula as a source of the soft surface of the wing of owls.
Graham	Added the third adaptation of the owls as trailing-edge fringes. He correlated the flight of airplanes and owls.
Sick	Gave quantitative information for the three feather adaptations. Also compared different owl species
Gruschka et al	Studied the noise production of a gliding barred owl (*Strix varia*), and studied the effects of leading-edge serrations on flight noise. Studied airframe noise mechanism.
Arndtl et al	Studied acoustic and aerodynamic characteristics of rotors with respect to leading-edge serrations and concluded

Schwind & Allen	Investigate the surface flow on an aerofoil with and without serrated edges. Studied effects of serrations on airflow for Low and High Reynolds number
Tawny owl- Neuhaus et al	Demonstrated a clear increase in noise production after removal of serrations from flapping flight.
Hersh et al[7]	Performed experiments on a NACA-0012 airfoil, attaching serrations at its leading edges. Concluded that serrations reduced broadband noise.
Lilley	Proposed a theoretical model of noise production. Concluded that far-field noise was dominated by sound scattered by the wing's trailing edge. Compared leading-edge serrations to co-rotating vortex shedders.
Liu et al	Studied the physical configuration of an owl wing. Reported that the owl wing was a single layer of primary feathers. The camber at 0.4 spanwise positions was about 0.05.

Mechanisms of noise generation

Origin of Turbulent noise:

By rearranging the components in the Navier-Stokes Equation (Conservation of Momentum Equation) and transforming them into a waveform of an equation simply in terms of the density (x,t) driven by the fluid stress in the turbulent zone, Lighthill established the idea of aerodynamic noise. Aerodynamic noise is generated in low-Mach Number flows due to the conversion of hydrodynamic kinetic energy (Rotational) in confined turbulent zones.

The following is the Lighthill Equation:

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

Derivation - In the first place, the Navier-Stokes equation is used to carry out this derivation.

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \nabla \cdot \sigma,$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = -\nabla p + \nabla \cdot \sigma.$$

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \nabla \cdot \left[\nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) - \nabla \cdot \sigma + \nabla p - c_0^2 \nabla \rho\right],$$

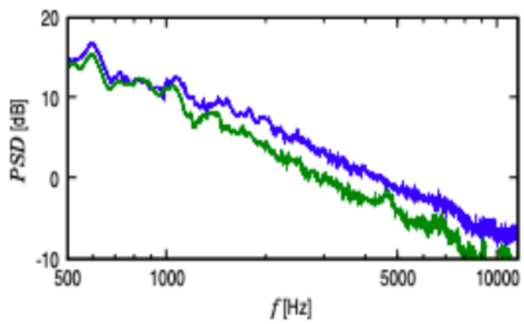
$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = (\nabla \otimes \nabla) : \left[\rho \mathbf{v} \otimes \mathbf{v} - \sigma + (p - c_0^2 \rho) \mathbb{I} \right],$$

$$T_{ij} = \rho v_i v_j - \sigma_{ij} + (p - c_0^2 \rho) \delta_{ij},$$

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \nabla^2 \rho = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}, \quad (*)$$

T_{ij} is the well-known Light-Hill Tensor. T_{ij} is usually approximated using the Reynolds Stress $u_i u_j$ in low Mach-Number flows, where u is the flow velocity and c_o is the speed of sound in the medium. A turbulent eddy is thought of as being equivalent to a point quadrupole source for flows with a speed less than a threshold. This causes density fluctuation (i.e. noise), which is now given by:

$$\rho'(\mathrm{x}, t) = \frac{1}{4\pi c_0^2 |\mathrm{x}|} \frac{\partial^2}{\partial x_i \partial x_j} \int T_{ij}(\mathrm{y}, t - |\mathrm{x}|/c_0)\, \mathrm{d}^3\mathrm{y}.$$



The density fluctuation scales with the 4th power of the Mach number, as Lighthill shows directly from the above equation (m). Given that the observation position appears in the time argument of the quadrupole thanks to the assumption of perfect source compactness, this scaling is made up of two factors of m from the quadrupole term and another factor of m from each of the two spatial derivatives.

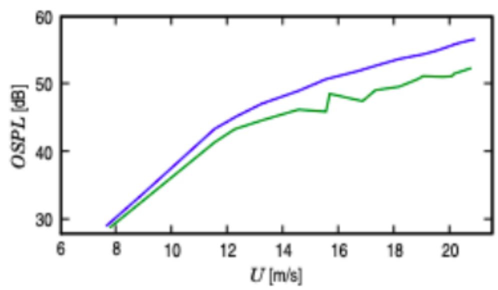
Sarradj and coworkers conducted a comparative study of the Barn Owl, European Kestrel, and Harris Hawk. Barn owl noise was 4 dB lower than the other two at frequencies above the 1.6 kHz third-octave band, according to the findings. Additionally, Sarradj conducted an indoor research measurement investigation on prepared wings. They discovered that owls made less noise per unit of lift force than non-silent species.

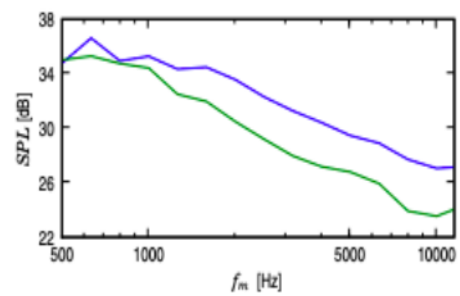
They also compared 7 wings from four distinct species, two of quiet flyers and two of non-silent flyers, in an experiment. The left wings of the Eurasian Sparrowhawk and Tawny Owl were compared because they have similar effective areas (wing area in front of the nozzle). The tests were carried out at three distinct angles of attack, namely 0°, 8°, and 16°, and at 14 different flow speeds ranging from 7 to 20 m/s.

The following were the outcomes:

1. The sparrowhawk (blue) had a higher power spectral density than the Tawny Owl (green)

2. At all frequencies, the sound pressure level (SPL) generated by the sparrowhawk (blue) was higher than that of the Tawny Owl (green).

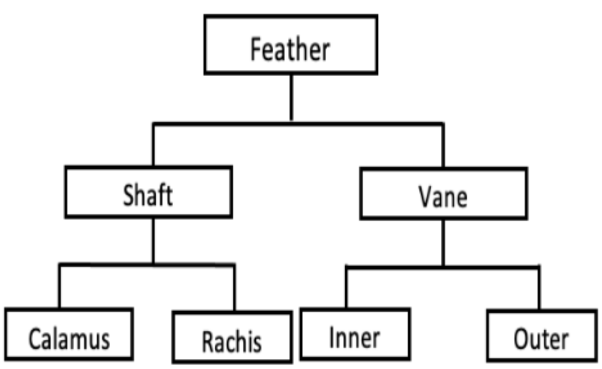


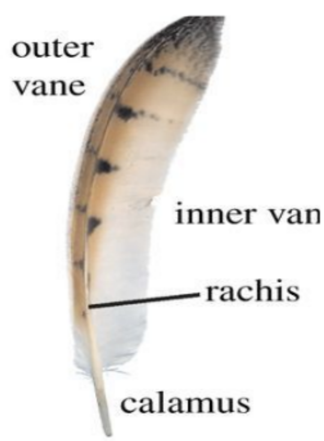


3. Sparrowhawk had a higher overall sound pressure level than a tawny owl in a 3rd-octave band with center level frequencies between 800 Hz and 16 kHz.

Wing and Feather Morphology

Bird wings are formed by forelimbs and feathers. Of these, there are two major groups of flight feathers- Primaries and Secondaries. They are attached to the skeletal muscles and their covering. A wing is characterized by its chord length, wingspan, wing area, thickness and camber.





The vane comprises barbs having barbules or radiates. The posterior (proximal) barbules are called bow radiates, and the anterior (distal) barbules are hook radiates. Anterior barbules also have hooklets. Hair-like extensions at the end of radiates are called pennula.
Wing Chord: The end-to-end length between the leading and trailing edge of the wing.
Wing Span: The end-to-end length between the rightmost and leftmost tip of the wings of an owl.
Wing Area: Wing area is the area enclosed by the wing when it is completely stretched.
Camber: Camber is the deviation of the center of geometry of the owl with respect to the horizontal chord between the leading and trailing edge of the wing. In the above image, it is the chord along the vertical axis.
Aspect Ratio: Wingspan divided by mean chord length.
Wing Loading: Wing loading is defined as the weight of an owl acting per unit area of owl wings.

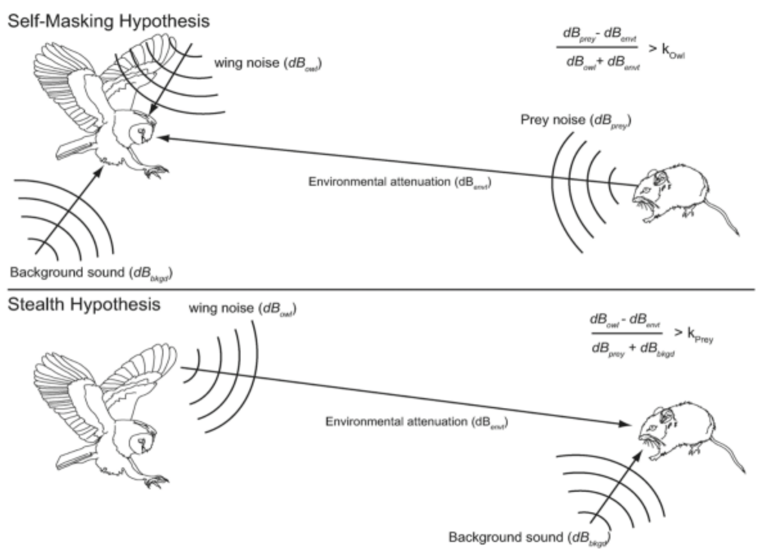
Survival pressures leading to silent features of owl flight

There are mainly two hypotheses for the evolution of sound dampening features in owls:

1. Owls have a low hearing threshold. A low hearing threshold means that owls can detect soft sounds. This detection enables them to trace the distance and the direction in which their prey is and finally earn it as a meal. While taking a flight towards prey, if their wings make noise then, they will get confused by the superposition of sound by prey and sound by their wings(since they have a low hearing threshold) which will lead them in the wrong direction. So, silent flight helps them hunt in silence and without confusion. This particular hypothesis is known as the "***prey detection hypothesis***" or "***self masking hypothesis***".
2. Owls having silent flight do not allow their prey to escape when they approach them since their prey will most likely not hear them till they are significantly close. This hypothesis is known as the "***stealthy hunting hypothesis***".

Following this precedence, Le Piane detected the above-mentioned hypotheses on the basis of serrations and fringes in owls having dietary differences and nocturnal/diurnal behavior.

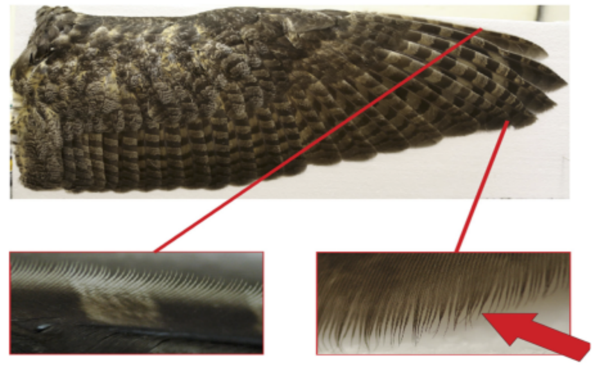
In 1934, Graham[1] stated that serrations on leading-edge, fringes on trailing edge and velvet surface on wings lead to a silent flight of an owl. It has been found that wider serrations on the



leading edge led to more noise reduction due to more vortex shedding.

Le Piane[2] concluded:

1. The nocturnal owls hunting at night are found to have wider serrations producing less noise because auditory cues are important at night when compared to the diurnal owls. This conclusion supports Hypothesis 1 stated above.
2. The owls hunt on fish and insects that make noise found to have narrower or no serrations at all. While owls hunting on quieter animals were found to have wider serrations making less noise. This conclusion supports Hypothesis 2 stated above.



Close-up images of a Great Horned Owl's Wing On the left you can see the leading-edge comb; it's this width that Le Piane measured for her study. On the right, is the trailing-edge fringe. Diagram: Krista Le Piane.

Lower wing loading leads to lower speed flights

The reason wings flap at all is to generate thrust: lacking separate power plants, such as propellers or jet engines, bird (and bat) wings must do it all," says Spedding. Birds propel themselves forward by accelerating air backward using their wings.

There are two aspects that are to be considered during the flight of any object: Lift and Drag acting on the object.

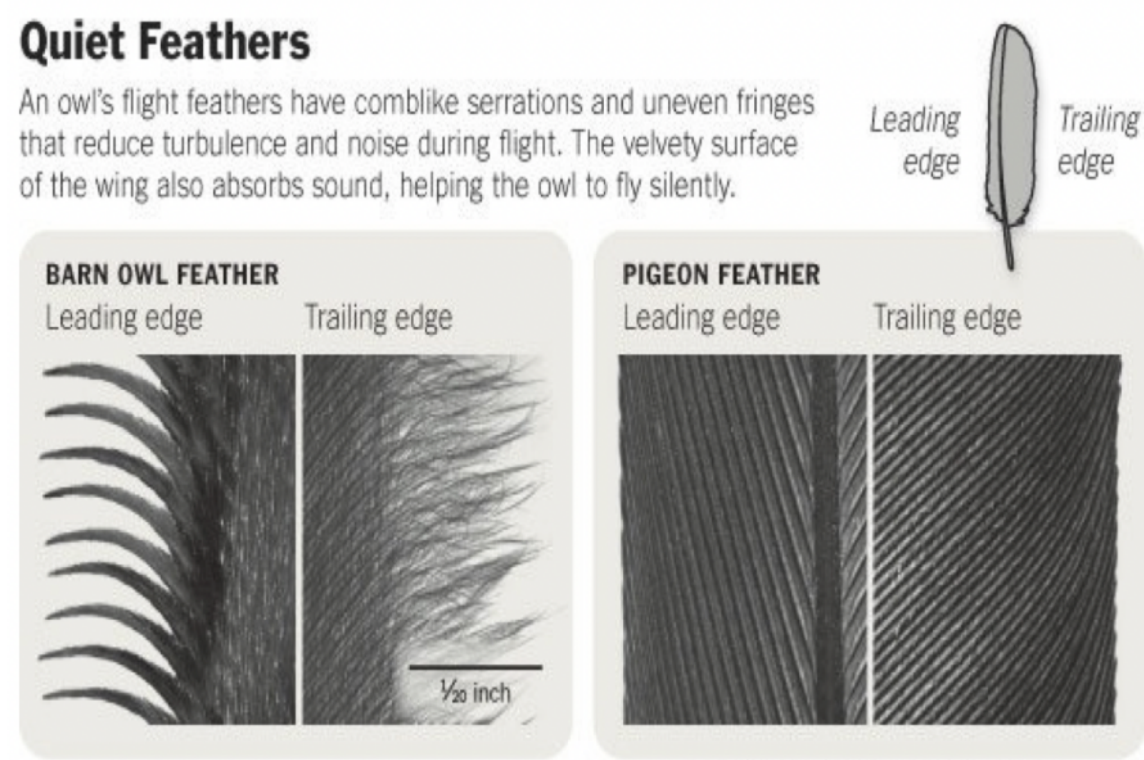
Lift is basically the pressure acting on the wing in an upward direction. Suppose a particular object with a wing is flying at a certain height in a particular fluid medium, so basically lift acting on the object is only dependent on the difference in fluid flow velocity between the upper side of the wing and the lower side of the wing in accordance to Bernoulli's Theorem.

Drag is basically the resistance offered by a fluid medium to an object while flying. So, for an efficient flight, we need as little drag as possible while as much as possible lift.

Wing loading is basically the weight of an object acting per unit area of the wing of an object. If we have a lower wing loading that is acting downwards then objects have to generate a lower lift. Lower lift means there is less difference between fluid flow velocity at the upper and lower surface of the wing.

This difference in fluid flow velocity at the upper and lower surface is directly proportional to the velocity of the object which is flying. According to the wing loading on an object's wing, the object has to generate the velocity in order to get the lift needed. So, lower wing loading means lower lift for the flight which means objects can fly at lower speeds to generate sufficient lift needed.

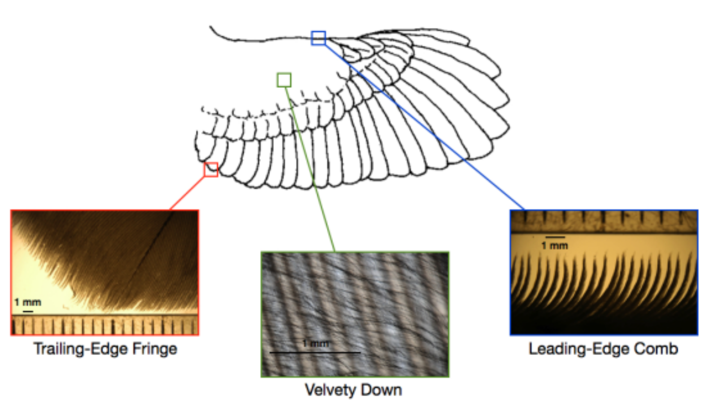
That is why lower wing loading in an owl's wing leads them to fly at lower speeds means there has to be lower thrust generated for flight implying lower flapping.



Comparison of Owl Feather and Pigeon Feather showing the difference between both wings. The owl feather has a specially designed very fine leading edge comb and trailing edge fringe whereas the pigeon feather has very common and conventional feathers.

In 1934, Graham observed three morphological features in owl's wings that help in silent flight. These 3 features were namely:

1. Serrations
2. Fringes
3. Velvets



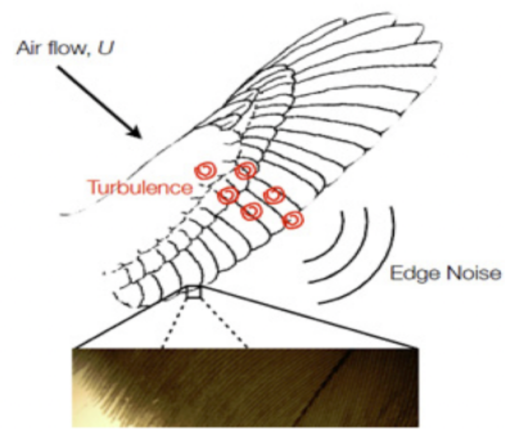
Serrations

Serrations on the outer vane of feathers are comb-like hooks. Serrations that run along the leading edge of the wings are known as leading-edge serrations. Serrations affect the aerodynamic performance of wings and minimize noise, according to several trials conducted in various research. They have an impact on the airflow near the leading edge.

The formation of serrations has been discovered to vary depending on the species' lifestyle. Serrations, for example, were found to be more developed in nocturnal species like barn owls and eagle owls than in diurnal species like snowy owls.

It's crucial to comprehend the structure of serrations in order to fully comprehend how they aid in noise reduction. A first-order approximation is a rough three-dimensional model of serrations, but a second-order approximation is a more thorough model that takes into consideration minor variations such as tilting and twisting with the position of wings. The first-order approximation of a barn owl serration reveals that the serration bends towards the flight direction, tilts upwards, and twists to form a 90-degree angle with the free stream wind. There is definitive quantitative research on second-order approximation, but it has been discovered that second-order approximation with wing tilting and twisting aids in noise reduction and efficient flight.
These aerodynamic facts are useful in the real world.

The turbulent boundary layer creates a vortex when air flows across a structural element. This area is located around the trailing edge of the wings of birds.

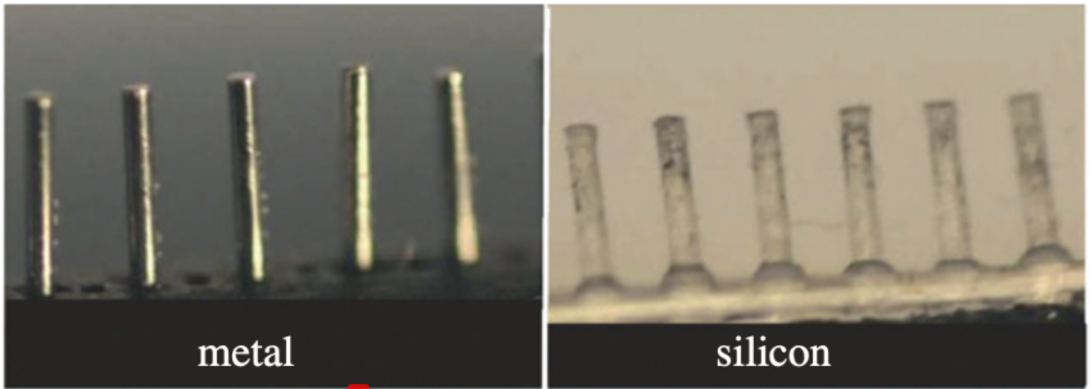


Turbulence in Owl Feather

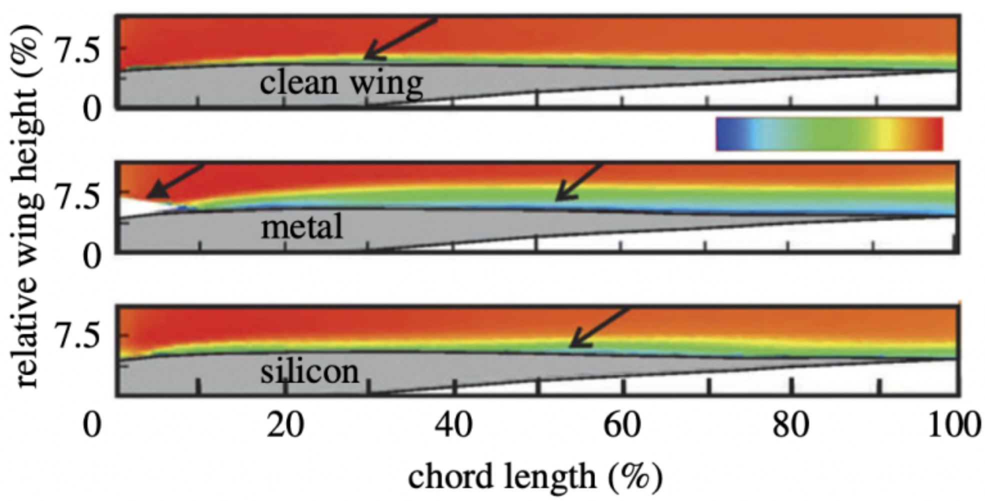
Owl Feather Turbulence

Vortex shedding occurs here, in which vortices are shed alternately from one side to the other, resulting in alternating low-pressure zones. In his investigation, Nakashima[8] found that variations in vorticity were one of the main sources of noise. These unstable vortices are controlled and inhibited by the serrations.

The serrations break down the air rushing over the wing foil into micro-turbulences, which reduces the noise produced by wings that lack this characteristic. The "wing graph" was introduced in Shinkansen trains as a result of this characteristic.
An experiment was carried out on models with artificial serrations constructed of silicon and metals. They were able to replicate the static flight of a serrated wing and discovered that serrations made of silicon reduce the turbulent boundary layer more than serrations made of metals.



The two different types of artificial serrations are used.

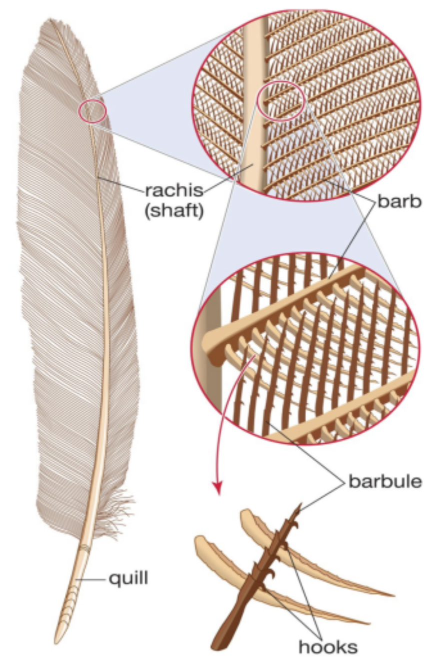


Measured Flow Field.
The inset shows the velocity scale *(u/u1, u1= freestream velocity)* ranging from 0 (blue) to 1 (red)

In the wake of the serrated case, vortices vanished faster. Liang et al. investigated the impact of saw teeth on fan noise reduction. While the fan rotated, several types of sawtooth-shaped leading edges were analyzed acoustically. The non-smooth forms prevented the creation of an off-body vortex, which is created by a turbulent boundary layer on the vane surface, according to the experiments.

Fringes

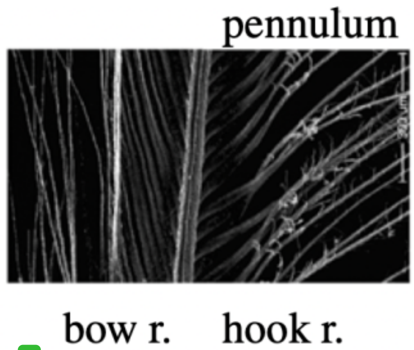
The ends of owls' feathers are fringed rather than smooth, unlike those of other birds. Barb tips have fringes, which are separated by a drop of hooklets at the hook radiates, resulting in barb ends that are disconnected. The thickness of the feathers at the fringes' ends also decreases as a result of this. The radiates also have a tendency to bend towards the barb shafts, assisting in the creation of the fringes. In one feather, as well as among several feathers in one wing, the fringes are of various sizes and orientations.



They blend into the grooves formed by the two barb shafts that are adjacent to each other in adjoining feathers. When the fringes are static, they do not line with the barb next to it; yet, when they are in motion, they mix strongly in the grooves. This interconnectedness prevents adjacent feathers from becoming separated, as well as allowing the creation of a single trailing edge behind the wing (and not several edges behind one wing). As a result of the lower number of edges, the number of noise sources is likewise reduced. This is because, in aeroacoustics, the trailing edges are a primary source of the noise.

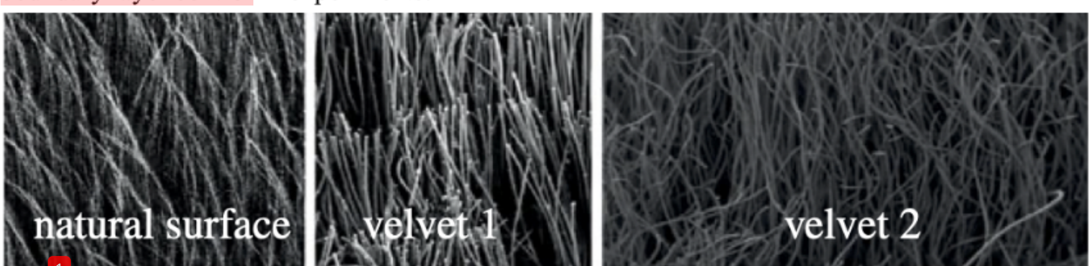
Velvets

The pennula, the filamentous distal end of the cell, creates the velvet-like surface.
The outer vane's peninsulas were usually shorter than the inner vane's. Up to four adjoining barb shafts were overlapping on the peninsula.
Different surface texture features were identified in covered and uncovered sections of the outer vane. In comparison to covered parts, uncovered areas exhibited a lower density of pennula, a lower porosity surface, and bigger pennula angulations, resulting in a thinner structure.
The surface of owl wings becomes exceedingly fluffy and porous due to the length and a vast number of pennula. The velvet-like dorsal surface of the inner vane may act as a method to reduce friction when the wing scrapes against each other while flapping, or it may affect the wing's aerodynamic behavior (or both).

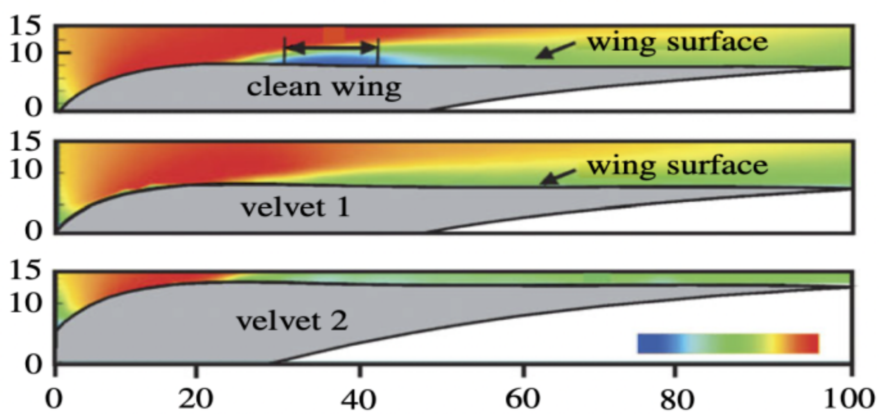


Close-up view on a feather vane

Klan, Winzen, and others discovered that velvet-like surfaces reduced flow separation and permitted boundary layer control in experiments.



The natural surface, and the artificial structures velvet 1 and velvet 2. The surface of velvet 1 was chosen to mimic the natural surface as much as possible with respect to the softness, length of hairs and density of hairs. Velvet 2 possessed longer hairs.



On Y-axis: %height On X-axis:%chord length

Measured fluid flow

The inset shows the velocity scale ($u/u1$) ranging from -0.2 (blue) to 1.2 (red)

(u1 is free to stream velocity)

The arrow points to the upper wing surface

Thus, it was concluded that velvet texture also helps in increasing the aerodynamic performance of wings, hence reducing the noise. Apart from that, when wings flap, these velvet-forming feathers(pennula) help reduce friction when the feathers rub on each other while flapping.

Wind Tunnel Experiment

A few attempts were made to investigate owl plumage and discover the explanation for the owls' quiet flight. The University of Cottbus conducts a specific experiment known as the wind tunnel experiment. It's a wind tunnel that's open to the public. The setup's measurements are as follows:

Circular Nozzle Diameter: 0.35m
25 m/s Average Flow Velocity
At 20 m/s, the turbulence intensity in front of the nozzle is 0.3 percent.

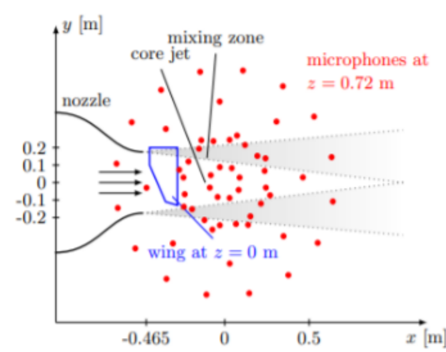
A cabin shreds the part in front of the nozzle. Porous materials are used to seal the cabin's perimeter. This is done to create a "semi-anechoic" acoustic environment, which is mostly for frequencies above 500 Hz.

The owl wings are attached to a six-component balance on a specific piece of equipment. It sits immediately on top of the nozzle. This is constructed in such a way that it may be adjusted to fit various wing structures. Furthermore, two essential considerations were made, the first of which was that no aeroacoustic effects should occur at the mounting. This is done to avoid the results from being skewed.

The owl's wings, which are fixed on the six-component balance, must be mounted in such a way that neither the wings nor the bones are injured. This is a representation of the measurement setup.

The acoustic measurements are taken with a 56-channel microphone that is placed 0.72m above the ground (shown in the display of the setup). The orthogonal beamforming algorithm is the algorithm that was used to process the data.

With the help of the six component balance, the lift and drag forces generated throughout the experiment are measured. The projected area is the area directly in front of the wing's nozzle. The average chord length is denoted by the letter C. The effective wing area is denoted by the letter S. h refers to the distance between the arm bone (at the mounting) and the wingtip. As a result, we arrive at the formula:



$$C = h/S$$

The measurements in this experiment were taken at various angles on the mounting, as well as at varying flow speeds. A delay and sum beamforming approach was used to generate the sound maps. The experiment was carried out on two wings, the sparrowhawk wing and the owl wing, with the following results:

Conclusion

Solving the age-old mystery of the silent flight of owls, this study discusses the various adaptations made by the wings of the owl, and the mechanism of its flight. Theoretically, the biological adaptations in the structure of the wings, namely, the comb, serrations, and velvety texture, have been discussed. The mechanism of flight also provides explanations based on fluid mechanics talking about the suppression of noise caused by turbulent air- as explained by inhibition of vortex formation due to fringes, and the Navier-Stokes equation. Experimental measurements of the noise generation as measured by Sarradj and coworkers have also been explained. Lastly, the paper talks about the Wind Tunnel experiments carried out to check for the right porosity and elasticity required for noise reduction. By bringing out contrasts in the flight of the owl, and the other birds (as well as airplanes), this paper aims not only at elucidating the reasons for the silent flight of owls but also at bringing out the reason for the increased noise production by other birds and airplanes.

Future Research Scope

While progress has been made towards determining the reasons for the silent flight morphologically, the efforts made in bringing out the explanation in terms of Physics have been convergent but not conclusive. The extremely silent flight of the owl makes it impossible for even sensitive microphones to record and measure the noise, making noise measurements extremely difficult.
Hence, a challenge for the future would be to develop a mechanism for the absolute measurement of noise production during owl flight.

To make progress, biology and aeroacoustic communities data and tools are necessary along with designing and testing modular owl wings. Understanding owl flight, bringing out phylogenetic comparisons for understanding the flight of owls other than the Barn owl, and making geometric measurements is essential for applying the owl flight model in industrial automation. As a technical advancement, micro-aerial vehicles need to be optimized to operate at lower Reynolds numbers and on ventilators and fans.

Acknowledgments

We would like to extend our sincere gratitude to Prof. Somnath Ghosh, without whose tutelage and interactive sessions, this study would not have been possible. We would also like to thank him for his pragmatic teaching methodology which has often helped us relate the most complex of problems to daily practical problems- an approach that has made fluid mechanics extremely riveting for us. Lastly, we would also like to thank all of our professors that have helped us in developing a strong foundation and aided us in understanding the concepts necessary for furnishing this report.

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