Measuring owl flight noise

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ABSTRACT

It is well known that most genera of owls are able to fly almost silently in order to hunt their prey. However, this knowledge is actually based on very few quantitative studies only. This is especially interesting regarding the fact that, against the background of increasing air traffic, the unique plumage adaptations of the owl responsible for the silent flight are the motivation behind various airframe noise reduction techniques such as serrations or porous trailing edges.

Both by reviewing existing data and by means of appropriate experiments, the paper will first illustrate the special feather adaptations of owls and will expand upon their contribution to the silent flight. Then, following a brief review of existing measurement data on the silent owl flight from past studies, the paper will focus on more recent measurements of the noise generated by gliding owls. Thereby, two different approaches were followed: First, outdoor measurements of the noise emitted by gliding owls were performed using microphone array technology and a high speed camera setup to capture the flight path of the birds. Second, indoor measurements in an aeroacoustic open jet wind tunnel revealed the noise generated by prepared wings as well as their aerodynamic performance in terms of lift and drag forces. In both cases, special attention was paid to the difference between the flight noise of the owl compared to the noise of other, non-silently flying birds.

Keywords: silent owl flight, airframe noise reduction, microphone array measurements, wind tunnel, porous media I-INCE Classification of Subjects Number(s): 51.4

1. INTRODUCTION

The silent flight of owls and, especially, the special adaptations of the owl wings and feathers that are held responsible for the low noise generation, serve as a motivation for engineers and researchers worldwide trying to transfer these techniques to technical airfoils by means of serrations, elasticity or passive porosity. This is not only true for a desired reduction of airframe noise due to increasing air traffic, but also for wind turbines, propellers and fans.

However, despite this increasing interest in the silent flight of owls, there exist only very few studies that contain experimental evidence for the low noise generation. The main reason for this sparsity of experimental studies on the silent flight is that, as opposed to aeroacoustic measurements on technical objects such as airfoils and aircraft models, measurements on living birds or even bird wings only are much more challenging.

Basically, two main facts are responsible for the silent flight. The first is the low speed of flight compared to other birds of prey, which is in the range from 2.5 m/s to 10 m/s only (1, 2). The second is the special quality of the feathers and wings of owls, which will be discussed in more detail in the following chapter. After this brief review of the special plumage properties, the present paper will show and discuss the results from existing experimental studies of the silent owl flight. Thereby, the focus is on the gliding phase of the flight only.

2. OWL PLUMAGE

One of the first studies of the microstructure of feathers was performed by Mascha in 1904 (3), which included feathers from different owl species such as barn owls (*Tyto alba*), eagle owls (*Bubo maximus*), a tropical offshoot of great-horned owls (*Bubo mexicanus*) and snowy owls (*Nyctea nivea*). The owl feathers

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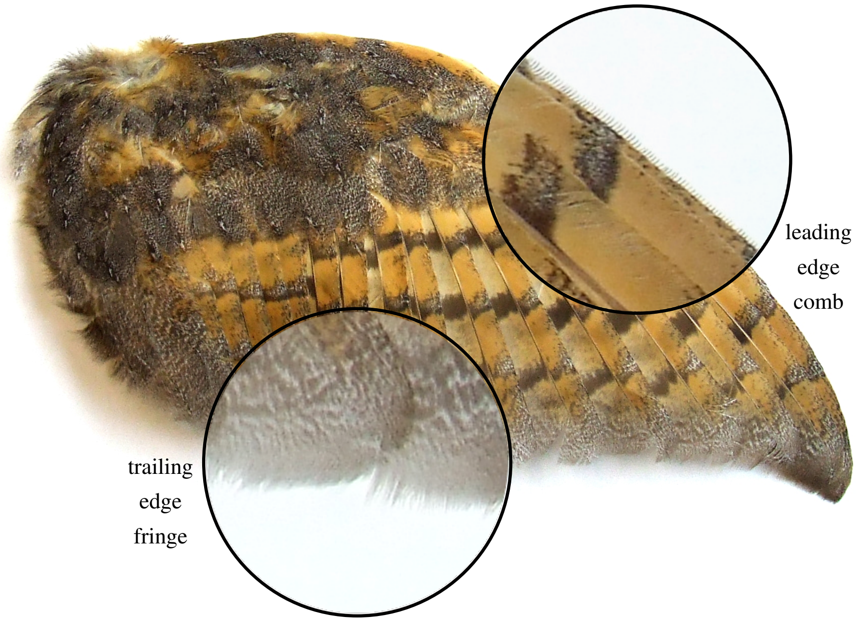


Figure 1 – Separated barn owl wing (*Tyto alba*)

were found to have several peculiarities that cannot be found on other birds. This includes an upward-bending of the outer branches on the feathers building the wing leading edge, resulting in a comblike structure (see Figure 1). Additionally, a very long and soft extension of the finest feather branches was observed, which gives the feather a velvety appearance and is responsible for the softness of the owl feathers. Mascha resumes that both peculiarities are adaptations responsible for the silent flight of the owl.

In 1934, Graham (4) identified the three feather adaptations that are held responsible for the silent owl flight: First, the *leading edge comb*, as observed by Mascha, second, the *trailing edge fringe*, formed by the branches of the vanes from the flight feathers (called barbs) and, third, the *downy upper surface*, formed by the long, soft extensions of the branches of the barbs that point towards the tip of the feather. Figure 1 shows a photograph of a barn owl wing, including close-ups of the leading edge comb and the trailing edge fringe.

Another detailed study of the fine structure of feathers was done by Sick (5), who partly revisits the work of Mascha. Sick concludes that the long extensions of the finest feather branches reduce the friction between overlapping feathers, leading to a reduction of noise. Regarding the serration of the leading edge he established the hypothesis that due to the serrations a part of the incoming air escapes, a part that would otherwise generate noise (at a rigid leading edge).

Further information on the feather structure of owls, including microscopy pictures of the leading edge comb and the trailing edge fringes were provided by Hertel (6).

The most comprehensive work on the plumage of barn owls, compared to those of pigeons, is the study of Bachmann (7) and Bachmann et al. (8), including the results of detailed anatomical, morphometrical and biomechanical measurements. Among other things, they provided detailed data on the three-dimensional shape of barn owl wings, such as the distribution of camber and thickness.

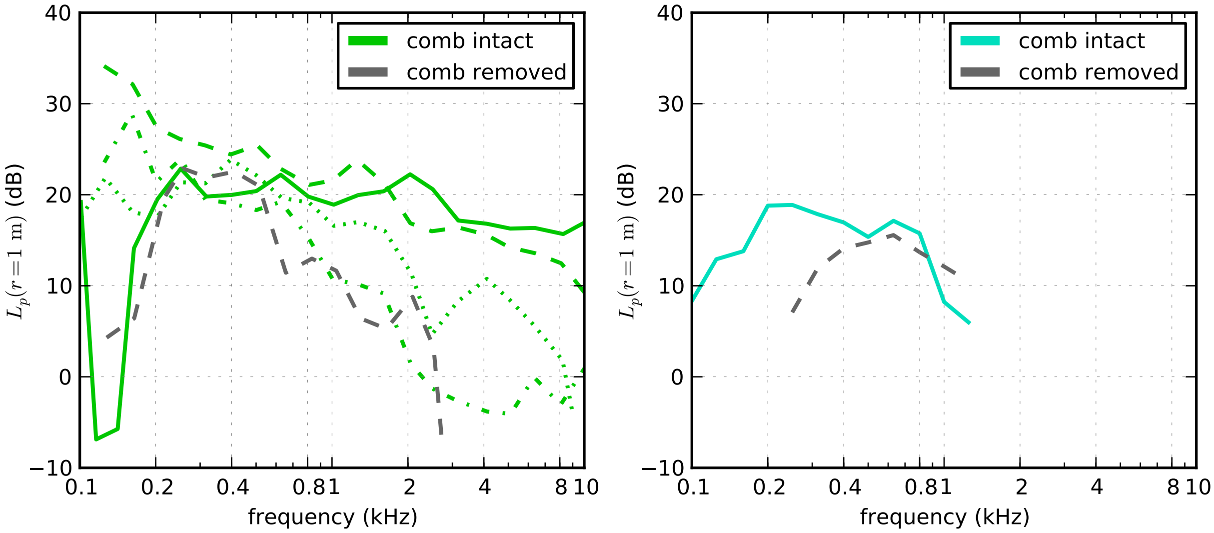
In the remainder of this section, information is presented for each of the three feather adaptations of the owl as identified by Graham: the leading edge comb, the trailing edge fringe and the downy upper wing surface.

2.1 Leading Edge Comb

Graham (4) assumes that the leading edge comb is designed to interact with fluctuations in the incoming air flow, which is done by reducing the local flow speed in front of the leading edge, thus affecting the local pressure gradient and resulting in a reduction of noise. Additionally, due to the fact that the single hooks are inclined upwards and towards the wing tip at a certain angle, Graham states that they serve to deflect the flow inside the boundary layer. This is assumed to lead to a further noise reduction, since the flow strikes the real leading edge at an angle smaller than the normal angle.

Hertel (6) describes the shape of the teeth from the leading edge comb and concludes that the comb must serve as a vortex generator. This presumably affects the boundary layer and prevents flow separation or other flow phenomena that are accompanied by a high noise radiation.

A very extensive study of the silent flight of owls, its causes and possible usability for silent aircraft, was done by Kroeger et al. (9) in 1971. Within the scope of this work, wind tunnel tests on owl wings as well



(a) Results from flyover measurements of Kroeger et al. (9) on a Florida barred owl (the data with the leading edge comb intact was derived from four individual measurements of the same bird)

(b) Results from flyover measurements of Neuhaus et al. (1) on a tawny owl

Figure 2 – Influence of the leading edge comb on the flight noise of owls

as indoor measurements on flying owls were performed. The wind tunnel tests included visual observations, the measurement of wing motions and flow visualization tests using a smoke generator. These tests were performed on two prepared wings, both coming from the same bird (the species is not denoted). Regarding the leading edge comb, Kroeger et al. found its function to be that of a vortex sheet generator that keeps the flow laminar and attached over the outboard half of the wing. The removing of the leading edge comb led to flow separation immediately aft of the leading edge. In order to investigate the effect of the leading edge comb on the flight noise of the owl, Kroeger et al. performed flyover measurements on a Florida barred owl (*Strix varia alleni*), with and without the leading edge comb removed. The experiments were conducted during three test series at different times in a reverberation chamber, using a single condenser microphone. Figure 2a shows spectra obtained for the same individual in different test series and hence at different times, with the leading edge comb intact and with the comb removed. Due to the relatively large variance of the results from the same owl with the leading edge comb intact, it is difficult to observe a distinguishable acoustic effect of the comb.

Anderson (10) revisited the data from Kroeger et al. and, in addition, examined the leading edge comb of a severed wing from a great horned owl (*Bubo virginianus*) using microphotography. He placed special emphasis on investigating the shape and orientation of the teeth. Anderson assumes that the reason why Kroegers experiments did not show a particular influence of the leading edge comb on the flight noise (Figure 2a) is the fact that the high gliding angle in Kroegers experiments did not correspond to the full aerodynamic capability of an owl wing.

Another important study on the silent flight of owls is the work of Neuhaus et al. (1) from 1973, who performed flyover measurements on a tawny owl (*Strix aluco*) with and without the leading edge comb. The results can be seen in Figure 2b (the results in the original manuscript are presented in a somewhat uncommon manner by giving the measured noise in scale divisions of the measurement instrument). The differences between both spectra are not very distinct, which is also due to the very small frequency range for which results are available and the fact that the data were obtained from only a single measurement each. Neuhaus et al. themselves state that the differences are below the accuracy of the measurements. However, the results possibly suggest that the leading edge comb leads to a noise reduction at low frequencies, approximately below 800 Hz. Additionally, Neuhaus et al. examined the flow structures around a wing with and without leading edge comb by performing flow visualization experiments in a wind tunnel. They observed a small zone of turbulent circulation near the comb and concluded that it may serve to reattach the flow.

When reviewing the above cited literature it can be concluded that the comblike structure at the leading edge of an owl wing seems to serve merely aerodynamic purposes. The few acoustic measurements available do not show a clear trend that the comb really helps to reduce the flight noise of the owl directly.

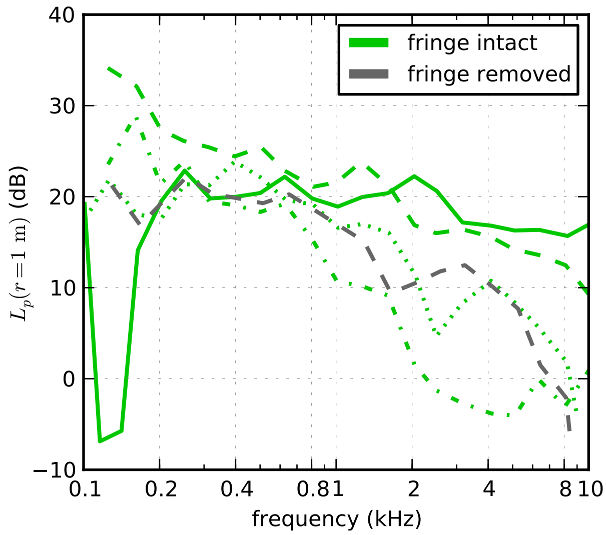


Figure 3 – Influence of the trailing edge fringe on the flight noise of owls, results from flyover measurements of Kroeger et al. (9) on a Florida barred owl (the data with the fringe intact was derived from four individual measurements of the same bird)

2.2 Trailing Edge Fringe

According to Graham (4), one possible purpose of the trailing edge fringe is that it allows for a partially mixing of the air streams flowing over both suction side and the pressure side of the wing upstream of the trailing edge. It is suggested that due to this mixing "the noise-producing vortices do not form". Moreover, Graham states that the fringe acts "as a damper" and prevents the fluttering of the trailing edges of the single feathers, especially during the up-stroke of the wings when the feathers separate.

Hertel (6) simply states that the fringe "damps the noise from the boundary layer".

According to Kroeger et al. (9), the influence of the trailing edge fringe, in combination with the soft feather structure of the owl in general, leads to a reduction in the velocity gradients at the trailing edge. Furthermore, since the wing surface including the fringes forms a compliant surface, the boundary layer turbulence spectrum is assumed to be shifted toward lower frequencies. The flyover measurements on a Florida barred owl also included measurements with the trailing edge fringe cut off. The results are shown in Figure 3. Again, the differences in the sound pressure levels between flyovers with and without trailing edge fringe are, if anything, very small only and even negligibe compared to the differences between single measurements on the same bird with intact fringes.

Lilley (11) states that the trailing edge fringe of the owl wing resembles a serrated or sawtoothed edge. Hence, due to the absence of a sharp trailing edge, owl flight noise may scale with the sixth power of the flow velocity instead of the fifth power, as expected for a solid edge. However, based on the data from Kroeger et al. Lilley notices that as a consequence of both the leading edge comb and the trailing edge fringe "the owl flies quietly but not silently". Additional modifications to the flight noise spectrum are necessary for the owl to not be heard by its prey, which is especially true for frequencies in the range from 2 kHz to 10 kHz.

More recently, Jaworski and Peake (12) showed that the velocity scaling of trailing edge noise in general is strongly influenced by both an elasticity and a porosity of the edge. As assumed by Lilley, they found that edge porosity changed the U^5 velocity scaling towards a U^6 behaviour. Jaworski and Peake argue that the increased velocity scaling exponent may lead to a noise reduction mainly at medium and high frequencies and that the poroelastic edge properties of an owl wing are responsible for a noise reduction approximately above 1.6 kHz. The validity of this theory is further assisted by a comparison that showed that the wing chord of a range of owl species, which are known as silent flyers, is larger than the wavelength of the lowest frequency of interest, which is a requirement for the proposed scaling with the sixth power of the flow velocity.

2.3 Downy Upper Surface

Compared to the first two mechanisms identified by Graham, relatively small empirical knowledge exists regarding the significance of the downy upper surface of the owls wings for the reduction of flight noise, although the pure existence and the possible function of the down is described in several studies.

Hertel (6) claims that the downy upper surface serves as a kind of cushioning and helps to prevent noise which is otherwise generated when the feathers slide over one another.

Table 1 – Specimen used for air flow resistance measurements.

Bird	binomial name	no. of prepared wings examined
Barn owl	*Tyto alba*	15
Tawny owl	*Strix aluco*	8
Long-eared owl	*Asio otus*	2
Common buzzard	*Buteo buteo*	9
Eurasian sparrowhawk	*Accipiter nisus*	2
Pigeon	*Columba livia*	5

Kroeger et al. (9) state that “a wing porosity exists which is a consequence of the soft feather structure”. They provide two possible functions of the downy surface: The first is that the downy surface allows the existence of a thin, uniform air film between the feathers, thus giving an evenly distributed porosity. The second possible function, assumed to be less important, is that the downy surface produces some kind of lubrication and hence enables a quiet motion of the sliding feathers, which is in agreement with the function assumed by Hertel.

The opinion put forward by Anderson (10) (in agreement with other authors) is that the light and downy consistency of the feathers forms a compliant surface that delays the transition of the boundary layer.

The notice that the feather surfaces show some kind of porosity due to the very long and soft extensions of the finest feather branches is also mentioned by Neuhaus et al. (1). Furthermore, it is noticed that for the tawny owl a larger part of the wing surface is covered by these downy feathers (about half the area) than it is for the mallard duck (*Anas platyrhynchos*), for which only one fourth to one third of the wing area is covered. They conclude that, in general, there is a clear trend that the feathers of owls are softer and more elastic and that their wing surface is porous.

Lilley (11) assumes that the downy surface damps the turbulence inside the boundary layer by acting as a compliant surface and that the small fibers of the down absorb the energy in the small turbulent eddies. Thus, it affects the high frequency portion of the flight noise spectrum, approximately above 2 kHz.

Chen et al. (13) tried to quantify the sound absorbing properties of owl plumage by measuring the sound absorption coefficient of the feathers of a common buzzard and an eagle owl, respectively, in an impedance tube. Although the approach of Chen et al. still leaves several open questions, the results indicate that the feathers of the owl have a higher sound absorption coefficient than those of the buzzard.

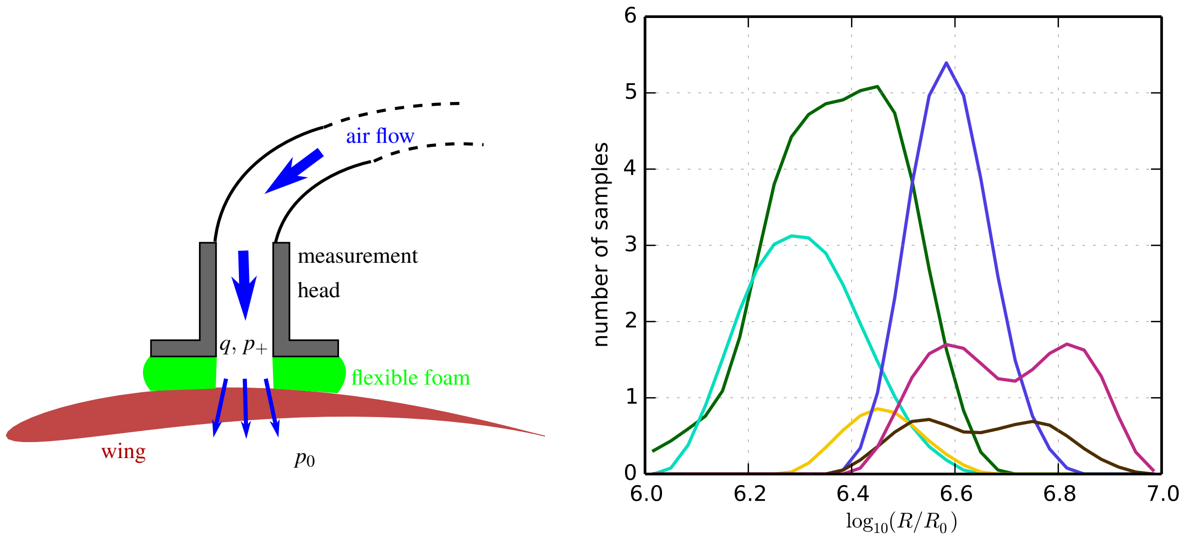
Although it is relatively easy to investigate the effect of both the leading edge comb and the trailing edge fringes by simply cutting them off, which has been done in some of the studies mentioned above, it is more challenging to quantify the difference between the downy feather surface of owls compared to that of non-silently flying birds, let alone to estimate its effect on the noise generation. In the present work, the contribution of the downy upper surface of the feathers on the noise reduction is assumed to be caused by its permeability. In order to describe this property using characteristic measures of homogeneous porous materials, the air flow resistance of a large set of prepared wings from both silently flying owls and from non-silently flying birds was measured, the latter group serving as a reference.

Measurement of the Plumage Air Flow Resistance

The air flow resistance measurements were performed on a total set of 41 wings, including wings from the barn owl (*Tyto alba*), the tawny owl (*Strix aluco*) and the long-eared owl (*Asio otus*), representing the silently-flying species, as well as wings from the buzzard (*Buteo buteo*), the sparrowhawk (*Accipiter nisus*) and the pigeon (*Columba livia*) as representatives of birds that do not fly silently. The wing specimen were not specially prepared for these measurements, but have been prepared at an earlier time. They were provided by the *Senckenberg Naturhistorische Sammlungen Dresden* and the *Institute for Biology 2, RWTH Aachen University*. An overview of all wings examined is given in Table 1.

The air flow resistance R of a homogeneous porous material describes the resistance of the material against a fluid flow through the porous sample and is hence a parameter inversely proportional to the permeability. It is usually measured according to ISO 9053 (14) by applying a pressure difference over a cylindrically shaped sample of the porous material and can then be calculated as the ratio of the static pressure difference Δp over the sample to the volume flow q through the sample:

$$R = \frac{\Delta p}{q} = \frac{p_+ - p_0}{q}, \tag{1}$$



(a) Schematic of the setup used for the measurement of the plumage air flow resistance R according to Equation (1).

(b) Results (barn owl, tawny owl, long-eared owl, common buzzard, eurasian sparrowhawk, pigeon).

Figure 4 – Plumage air flow resistance measurements.

where p_+ is the positive air pressure and p_0 is the ambient air pressure. Since the air flow resistance of the plumage should be measured in a nondestructive manner, it was not possible to obtain cylindrically-shaped samples with constant diameter and constant thickness as needed for a measurement according to ISO 9053. Rather, the air flow resistance had to be measured in situ. To this end, a special measuring head was constructed, designed to be gently pushed on the wing surface at a constant force. A very soft polyurethane foam, covered by an impermeable thin plastic film, was used to prevent air leakage between the measurement head and the wing surface. Figure 4a shows a schematic of the measurement setup. Apart from the measuring head, the measurements were in full agreement with ISO 9053.

For each wing specimen from Table 1, measurements were performed at eight positions distributed over the complete wing area to obtain a large statistical population. Thereby, it was assumed that the process of the preparation has no noticeable effect on the air flow resistance of the plumage. The results are shown in the histogram in Figure 4b, using $R_0 = 1$ Pa s/m^3 to normalize the measured data. The results confirm that, on average, the plumage of owls has a lower air flow resistance than the plumage of non-silently flying birds.

After this brief overview of the three feather adaptations identified by Graham (4) to be responsible for the silent flight of owls, the noise generated by gliding owls compared to that from non-silently flying birds will be investigated.

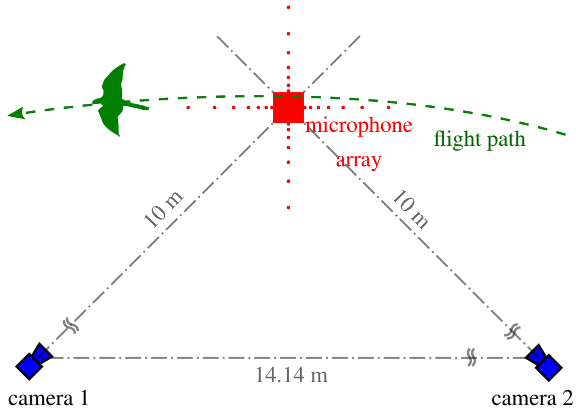
3. GLIDING FLIGHT NOISE MEASUREMENTS

In order to measure the gliding flight noise of birds, different possible approaches could basically be pursued. These include

1. flyover measurements, either outdoors in the natural habitat of the bird (which has the advantage that the bird can be expected to behave more or less naturally) or in an indoor environment (which most likely requires some sort of training for the bird) and
2. stationary measurements in an appropriate lab environment like a wind tunnel.

The latter could generally be performed on living birds that are flying in the air flow provided by the wind tunnel without changing their absolute position, or on prepared birds or even prepared wings only (which are those parts of a bird that are most likely the strongest contributors to the gliding flight noise). Of course, when the aim is to measure the gliding flight noise of owls, what makes each of these approaches even more challenging is the fact that the flight of the owl is supposedly silent. This means that high requirements have to be fulfilled regarding the measurement technique and the measurement environment. Additionally, the experiments should either be reproducible, as they would be when the second approach is chosen, or an appropriately large number of single measurements has to be performed in order to achieve some statistical significance.

In what follows, this paper will summarize and compare results from both approaches which were conducted by the authors.



(a) Schematic of the measurement setup.

(b) Photograph of the barn owl flying (from right to left) over the camouflaged microphone array.

Figure 5 – Flyover noise measurements.

3.1 Flyover Noise Measurements

The first published flyover noise measurements on owls were performed by Kroeger at al. (9) and Gruschka et al. (15). Some of the results are shown in Figure 2a and Figure 3. As previously reported, they examined the gliding flight noise of a Florida barred owl, aiming to derive design specifications for silent aircraft. The flyover measurements were performed in a reverberation chamber with a volume of 240 m^3 using a single condenser microphone. Unfortunately, no measurements were performed on non-silently flying birds of prey, and hence it is not possible to judge the noise reduction. However, the resulting sound pressure level spectra are indeed very low and confirm the often described low gliding flight noise of the owl.

The second set of experimental data on the flight noise from owls, that was also obtained from flyover noise measurements, was published by Neuhaus et al. (1). The results regarding the gliding flight noise are shown in Figure 2b. The measurements were performed on a tawny owl using a single microphone. As opposed to the approach from Kroeger et al., Neuhaus et al. also performed measurements on a non-silently flying bird, a mallard duck (*Anas platyrhynchos*). However, the experimental setup for the measurements differed for both birds. For example, the measurement of the noise from the ducks were performed outdoors, where the nearest distance between the bird and the microphone was visually estimated. The owls, on the other hand, were trained to fly along a more or less constant path inside a large reverberant room (a gymnasium). Thus, any accurate comparison between the gliding flight noise of the two different birds would probably lead to rather questionable results. Additionally, the resulting noise spectra were presented in an uncommon manner by giving the measured noise in scale divisions of the measurement instrument used. However, the results show that the maximum of the gliding flight noise of owls is in a low frequency range, approximately between 200 Hz and 800 Hz, while the maximum of the gliding flight noise of the ducks is in the range of medium to high frequencies approximately between 3 kHz and 5 kHz.

More recently, dedicated flyover measurements on both silently flying owls and, for means of comparison, non-silently flying birds of prey were performed by Sarradj et al. and are described in (16). The setup and results of these measurements will be summarized below.

3.1.1 Setup of Outdoor Flyover Measurements

The flyover noise measurements by Sarradj et al. took place in an outdoor wildlife park. Measurements were only performed under dry weather conditions and with wind speeds below 3 m/s. The temperature and wind speed were recorded using a portable weather station. The basic measurement procedure was that selected birds were brought to fly over a microphone array, preferably in gliding flight, by two falconers who worked with the same birds in daily flight shows. A two-camera-setup was used to capture the flight path of the birds. Figure 5 shows the basic experimental setup used for the measurements.

The 92-channel microphone array used for the measurements was positioned between the falconers on the ground and camouflaged using very thin, flow permeable fabric. The array consisted of a planar center array holding 64 flush-mounted 1/4 inch microphone capsules and additional 28 1/4 inch microphones, logarithmically spaced and attached to the center array via four linear extensions, as is visible from the schematic in Figure 5a. Thus the total aperture of the array was 3.5 m. The measurements were manually

Table 2 – Valid flyover noise measurements from (16).

Bird	binomial name	no. of valid flyovers	weight [kg]	mean flight speed [m/s]
Barn owl	*Tyto alba*	14	0.298	5.4
Common kestrel	*Falco tinnunculus*	31	0.198	5.2
Harris hawk	*Parabuteo unicinctus*	5	0.660	5.3

triggered and the data were recorded with a sample frequency of 61,440 Hz using a National Instruments 24 Bit multichannel measurement system. The data were then analyzed using a time-domain beamforming algorithm. In order to deliver optimum results in a desired frequency range from 500 Hz to 10 kHz, different subarrays (with smaller apertures for higher frequency ranges and the full aperture for low frequencies) as well as weighting factors were used in the processing of the results. Then, appropriate source powers were derived from the beamforming maps using the source power integration method (17) and third octave band sound pressure levels were calculated.

The trajectory of the birds was captured using two high-speed cameras, each positioned at a height of 1 m and an angle of 45° to the flight path, with the camera axes, perpendicular to each other, crossing at a point above the array center (see Figure 5a). The cameras were Gigabit Ethernet CCD monochrome cameras, recording 30 frames per second with a resolution of 640 × 480 pixels. From each of the two videos, the two-dimensional trajectory of the birds was calculated using a mathematical method to calculate the optical flow (18) that describes the apparent motion of objects from frame to frame in terms of speed vectors for each pixel. In order to identify the correct flight trajectory (and not some movements in the background or movements from the wings or tail of the bird), it was assumed that both direction and speed of the flight do not change rapidly between subsequent video frames for each camera. The resulting sequence of image coordinates was then smoothed using a fifth-order polynomial fit. Finally, the three-dimensional trajectory for each time step (corresponding to the frame rate) was calculated from these smoothed two-dimensional trajectories and the camera positions. The position of the bird between these time steps was estimated using a spline fit. Additionally, the mean flight speed was derived from the trajectories.

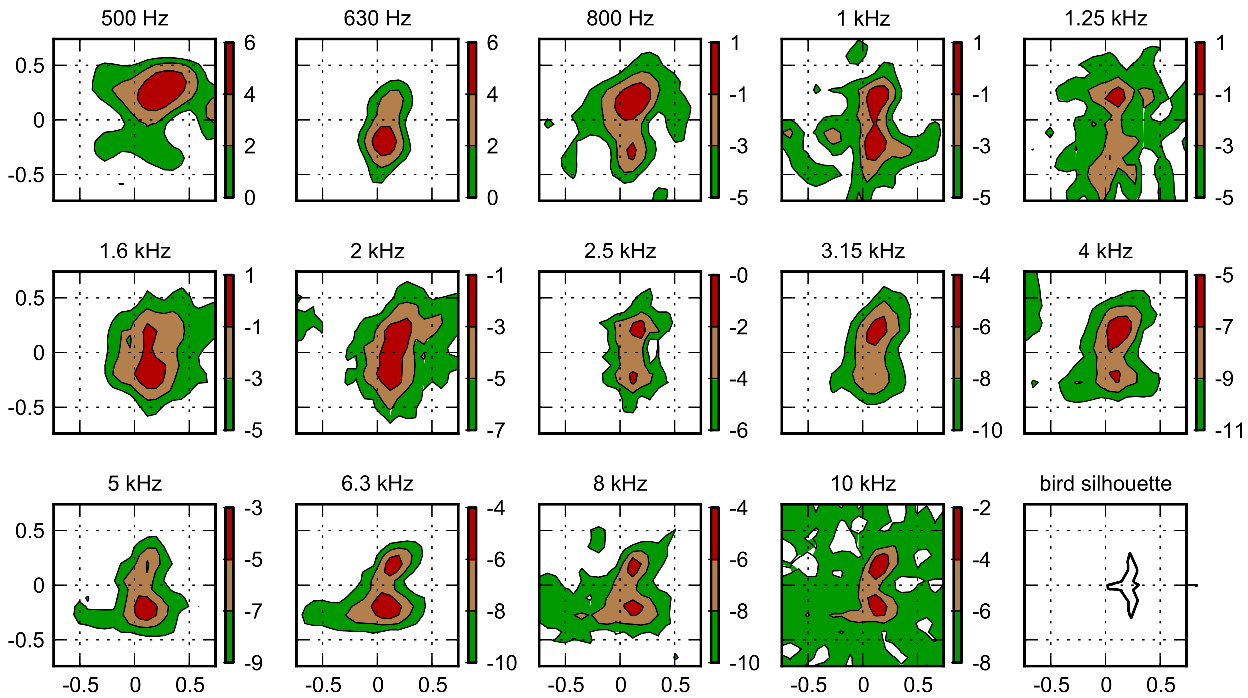
The flyover noise measurements were done on three days. In total, measurements were performed on two owl species, a barn owl and a male and a female Eurasian eagle owl (*Bubo bubo*), as well as on three non-silently flying birds, a common kestrel (*Falco tinnunculus*), a Harris hawk (*Parabuteo unicinctus*) and a Saker falcon (*Falco cherrug*). Each bird performed as much single flyovers as possible, mainly depending on endurance and the hunting desire of the individual bird. However, valid results were only obtained for three different birds, the common kestrel, the Harris hawk and the barn owl (see Table 2). This was either due to unwanted noise (for example when the bird was shrieking while flying over the microphone array) or to a deviation from the desired flight phase (when the bird was flapping instead of gliding) or a deviation from the desired flight path (when the bird was too far away from the microphone array). Interestingly, the mean flight speeds from the three birds are quite similar and within the natural flight speed range of a barn owl (1), although the kestrel and the hawk are able to fly considerably faster. However, due to the short distance between the two falconers (to ensure that the birds fly over the microphone array) the birds chose to not fly faster.

3.1.2 Results of Outdoor Flyover Measurements

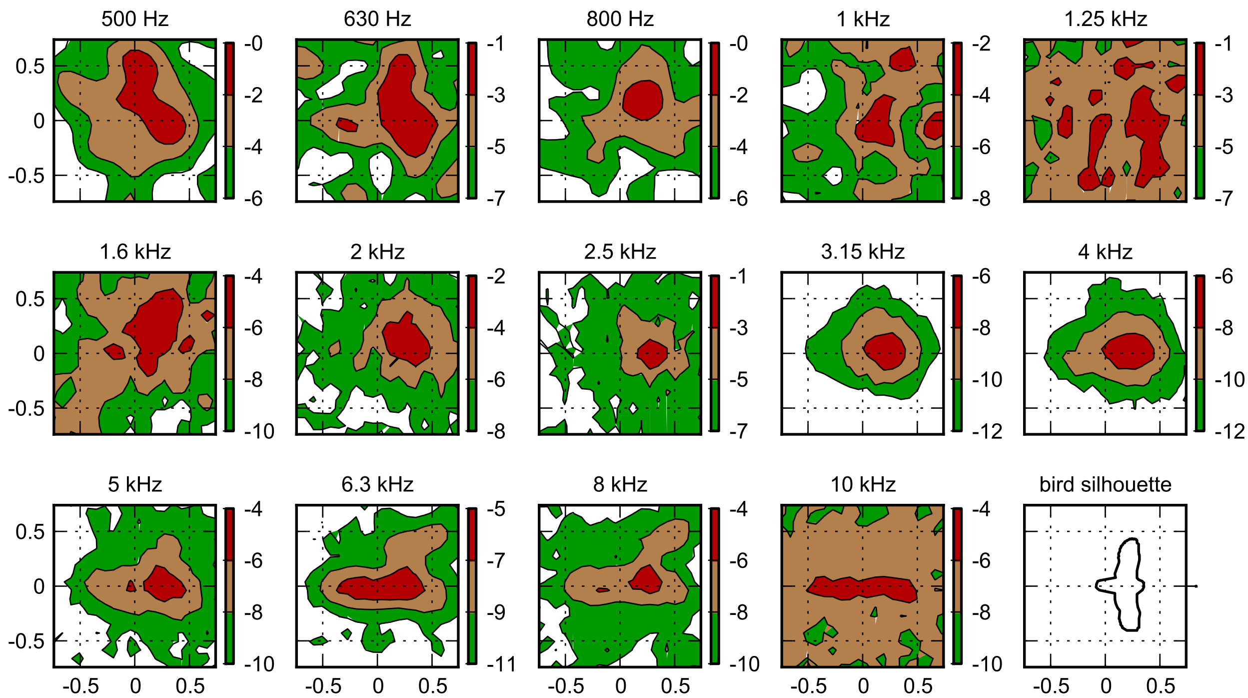
Figure 6 exemplarily shows beamforming sound maps for two individual flyovers, one for the common kestrel (Figure 6a) and one for the barn owl (Figure 6b). These maps were calculated for only a small fraction of the trajectory, when the birds were within a horizontal distance of 0.6 m from the array center axis. For example, for the common kestrel flyover shown in Figure 6a this resulted in a time period of only 0.15 s.

The sound maps for the common kestrel shown in Figure 6a, especially those at third octave bands with higher center frequencies (for example from 6.3 kHz to 10 kHz), indicate that the main noise sources are located at the wings. A more exact conclusion regarding the underlying noise source mechanism (such as trailing edge noise or wing tip noise) is not possible. In comparison, the sound maps obtained for the flight of the barn owl (Figure 6b) show no distinct sources at the wings.

Figure 7 shows the resulting third octave band sound pressure level spectra obtained for the three birds from Table 2. They are normalized to a distance of 1 m and scaled using the fifth power of the Mach number $Ma = U/c$, a theoretical approach common for the scaling of trailing edge noise (19). This approach was chosen simply due to the lack of a better hypothesis, but the noise source locations obtained for the kestrel from Figure 6a partially support this choice. It is visible from Figure 7 that in the low frequency range the flight



(a) Common kestrel (*Falco tinnunculus*).



(b) Barn owl (*Tyto alba*).

Figure 6 – Sample sound maps from the flyover measurements (16) in third octave bands.

noise from the different birds is not significantly different. However, for higher frequencies, approximately starting with the 1.6 kHz third octave band, the noise generated by the barn owl is below that generated by both the Harris hawk and the kestrel. This is in agreement with the conclusions drawn by Lilley (11), who states that the special feather adaptations of the owl lead to a major noise reduction in a frequency range above 2 kHz. Additionally, it can be observed that the slope of the spectra slightly differs between the owl and the non-silently flying birds: While the spectra of the latter decrease with about 10 dB per decade, the decrease of the barn owl spectrum is approximately 15 dB per decade. This difference in spectral shape indicates that the mechanisms responsible for the gliding flight noise generation are different, too. No peak is visible in the three spectra that would allow for further conclusions on the noise generation mechanisms. Under the

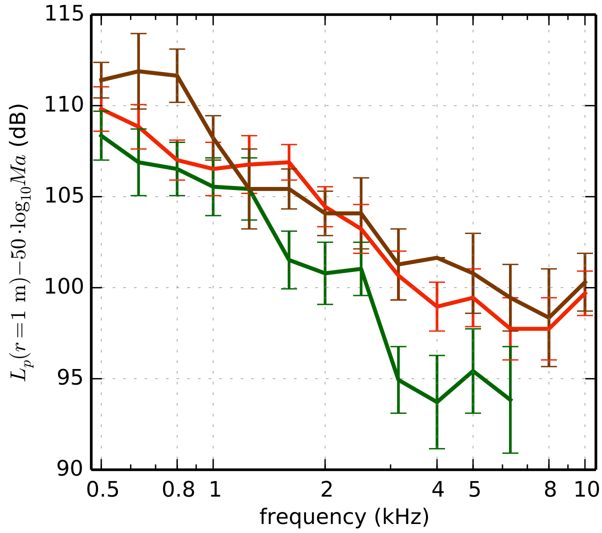


Figure 7 – Scaled third octave band sound pressure levels obtained from the flyover measurements presented in (16): ▬ barn owl, ▬ harris hawk, ▬ common kestrel.

assumption that edge noise is a dominant contributor to the gliding flight noise, a peak would be expected at lower frequencies (19, 20). In the present case, the detection of such a low frequency peak would require measurements with an even larger microphone array that has an increased aperture.

3.2 Wind Tunnel Measurements on Prepared Wings

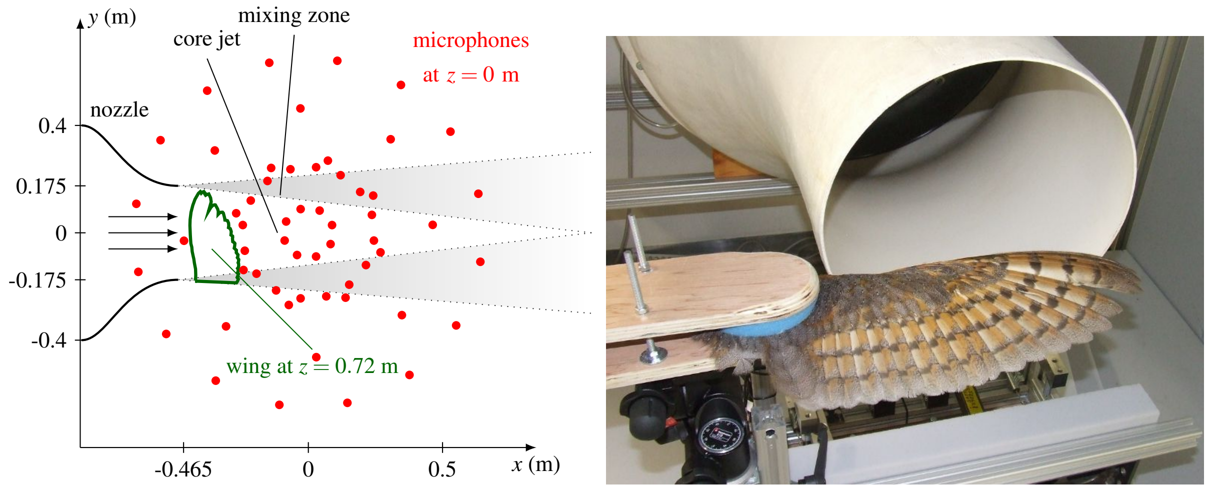
A second possible approach to experimentally determine the noise generated by gliding birds and an alternative to flyover measurements is to perform stationary measurements in a wind tunnel. One option that comes to mind is to measure the noise of living birds flying in the wind tunnel, with the bird remaining at virtually the same position. Such experiments are complex and expensive, as they would require a very large, preferably acoustically treated wind tunnel and a lot of training for the birds. Although similar studies have been done in the past (21, 22, 23), most were only aimed at measuring aerodynamic properties. In fact, the first acoustic measurements on a flying bird in a wind tunnel were performed only recently by Wei et al. (24). Their investigation consisted of microphone array measurements on a pigeon flying in gliding flight inside an anechoic open jet wind tunnel at a constant flow speed of 15 m/s. The planar 63-channel microphone array they used was positioned on the wind tunnel floor below the pigeon that was flying inside a cage fixed to the wind tunnel walls. Conventional delay-and-sum beamforming was used to analyze the results. The sound maps showed that the dominating noise source locations are the wing tips of the pigeon. Corresponding sound pressure level spectra were then obtained by integration over sectors that only contained the wing tips.

Due to the substantially lower effort and the better repeatability, wind tunnel studies on separated bird wings are more common. Existing wind tunnel measurements on separated wings are in most cases, however, purely aerodynamic investigations. Additionally, only few studies contain experiments on owl wings. The main disadvantage of such measurements compared to flyover measurements or wind tunnel measurements on flying birds, of course, is that the process of the preparation may have an effect on the wing shape and the wing elasticity. Thus, aerodynamic parameters like the distribution of camber, thickness and twist of a prepared wing are not necessarily the same as that of the wing from a living, gliding bird (25). Additionally, as opposed to the wing of a living bird, the shape of a severed wing cannot be actively adjusted during flight. Still, despite these disadvantages, the use of prepared wings in wind tunnel experiments is believed to provide valueable insights that otherwise would not be available.

One of the earliest wind tunnel studies is the work by Withers (26), who analyzed aerodynamic properties like lift and drag force and wing shape of several prepared bird wings. Thereby, Withers used the terminology of aviation aerodynamics, a method introduced by Nachtigall (27) to describe the aerodynamics of bird wings. No owl wings were studied in this work.

As shortly described in Section 2.1, Kroeger et al. (9) also performed wind tunnel measurements on a prepared wing of a "small owl" as part of their detailed study on silent flight. However, only the wing motions and the flow around the wing were investigated, but no acoustic measurements were performed.

Neuhaus et al. (1) also conducted flow visualization measurements on a prepared wing of a tawny owl and that of a mallard duck (see Section 2.1). Again, the focus of these experiments was to establish a general understanding on the qualitative effect of the special wing adaptations of the owl, especially the leading edge



(a) Schematic display of the measurement setup (top view). (b) Photograph.

Figure 8 – Setup of the measurements on prepared wings in the aeroacoustic wind tunnel.

comb, on the flow field and no acoustic measurements were performed.

Another aerodynamic wind tunnel study on prepared bird wings, including the wing of a great horned owl (*Bubo virginianus*), was conducted by March et al. (28). The aim of the study was to quantify the aerodynamic properties, like the lift and drag coefficients as a function of angle of attack, of bird wings under consideration that these biological wings can change their shape to adapt their morphology with respect to the desired flight regime. They noticed a significant deformation of the owl wing at high speeds and high angles of attack due to its aeroelasticity.

More recently, Winzen et al. (29) performed Particle Image Velocimetry measurements on a prepared barn owl wing to determine flow phenomena in the vicinity of the wing. They found that the flow over the wing was fully attached at lower angles of attack and higher Reynolds numbers, but was fully separated at higher angles of attack. No separation bubble was visible for the prepared wing, while such a bubble was found for an artificial three-dimensional wing based on the geometry of a real owl wing that was examined as a comparison.

The first wind tunnel study that focused on the noise generation of prepared wings was performed by Geyer et al. (30). They conducted microphone array measurements on prepared owl wings and compared the results to those obtained for non-silently flying birds. The two following sections will give a summary of the experimental setup and the results from these investigations.

3.2.1 Setup of Wind Tunnel Measurements

The experimental study described in (30) was performed in the small aeroacoustic open jet wind tunnel at the Brandenburg University of Technology. Regarding the intended measurements, the main advantage of this wind tunnel is that it has a very low background noise combined with a very low turbulence in the test section (31). For the experiments, a circular nozzle with a diameter of 0.35 m was used. With this nozzle, the maximum flow speed is about 25 m/s, the overall A-weighted sound pressure level measured at a distance of 1 m perpendicular to the nozzle axis is only 44 dB at 20 m/s and the turbulence intensity directly in front of the nozzle is in the order of 0.2 %. The test section is enclosed on three sides by sound absorbing walls providing full absorption for frequencies above 500 Hz.

The acoustic measurements were performed using a planar microphone array, consisting of 56 1/4 inch microphone capsules flush-mounted into a 1.5 m ×1.5 m aluminum plate, which was positioned out of the flow above the wings. The layout of the microphones can be seen in the schematic in Figure 8a. The data were recorded with a sampling frequency of 51.2 kHz, with a total number of 2,048,000 samples per channel, using a National Instruments 24 Bit multichannel measurement system and Fast Fourier Transformed using a Hanning window on 50 % overlapping blocks with a length of 4,096 samples each. The resulting cross spectra were then averaged to yield the cross spectral matrix. This matrix was then further processed using the CLEAN-SC algorithm (32), which was applied to a fully three-dimensional source grid. From the resulting three-dimensional beamforming sound maps, third octave band sound pressure levels with center frequencies from 630 Hz to 16 kHz were obtained by integrating the noise contribution over a chosen volume. This integration volume contains only noise sources generated by the wind tunnel core jet interacting with the wing, while unwanted noise sources, such as the wind tunnel nozzle or the region where the wind tunnel shear layers impinge on the wing surface, were excluded from the integration.

Simultaneously to the acoustic measurements, a six-component balance was used to capture the lift and drag forces acting on the wings. The data were recorded with a sampling frequency of 1 kHz using a National Instruments 24 Bit full-bridge analog input module. A photograph of the measurement setup is shown in Figure 8b.

In total, the noise generation of ten prepared wings, which were carefully selected from all available specimen listed in Table 1, was examined in this study. This included two wings from a tawny owl and two wings from a barn owl representing the silently flying owls as well as two wings of the common buzzard, two wings of the Eurasian sparrowhawk and two wings of the pigeon representing the non-silently fling birds. The wings were positioned in front of the nozzle by a special mounting that allowed for the adjustment of angle of attack and was itself positioned out of the flow (see Figure 8b). In agreement with the work of Withers (26), the angle of attack was measured approximately at midspan.

The selected specimen were the ones that were found to be best suited for the intended measurement of the gliding flight noise, although the deviations of a severed wing from the wing of an actively flying bird have to be kept in mind. The results may therefore be regarded as merely an estimate of the magnitude of the gliding flight noise generated by the wing of a flying bird.

3.2.2 Results of Wind Tunnel Measurements

Overall, measurements were conducted at 15 flow speeds between 5 m/s and 20 m/s at three geometrical angles of attack, 0°, 8° and 16°. However, in the remainder of this section results are presented for zero angle of attack only.

Figure 9a shows the resulting third octave band sound pressure levels as a function of the Strouhal number $f_c \cdot x_0/U_0$, where f_c is the third octave band center frequency, U_0 is the wind tunnel flow speed and x_0 = 1 m is an arbitrary distance. Thereby, a scaling approach was applied to take into account both the flow speed and, in a simple manner, the aerodynamic performance of each wing:

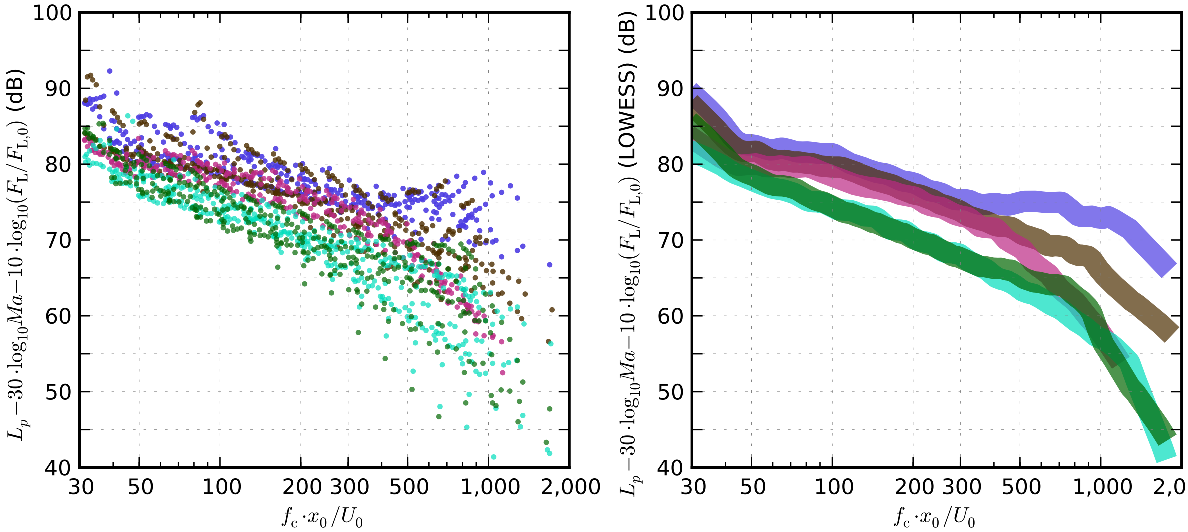
$$L_{p,\text{scaled}} = L_p - 10 \cdot \log_{10}(Ma)^3 - 10 \cdot \log_{10}\left(\frac{F_L}{F_{L,0}}\right) \text{ dB}. \tag{2}$$

In this equation, Ma is the flow Mach number and F_L is the measured lift force, which is normalized by $F_{L,0}$ = 1 N. This scaling approach thus takes into account the measured lift force as well as the third power of the Mach number. The resulting sound pressure level can be interpreted as the noise generated by each wing per unit lift force. Since the lift force itself is proportional to the square of the flow speed, the total velocity scaling corresponds to the theoretical U^5 scaling for edge noise of technical airfoils (19), typical for so-called "baffled dipoles" or "edge dipoles" (33). A higher exponent for the velocity would presumably lead to slightly better results for the wings of the owls (11, 12), however, to enable a direct comparison the same scaling was chosen for all wings.

Despite the scattering it can still be observed from Figure 9a that, on average, the noise generated by both owls is below that generated by the buzzard and the sparrowhawk. This is especially true for higher Strouhal numbers, since the differences in sound pressure level increase with increasing Strouhal number, which is in agreement with the theory by Lilley (11) and with the results from the flyover noise measurements presented in Section 3.1.2. Interestingly, the noise generated by the pigeon wings is noticeably less than that from the non-silently flying birds of prey and only slightly higher than that generated by the owl wings.

A basic confirmation of the present results is the fact that the noise of a pigeon flying in a wind tunnel measured by Wei at al. (24) showed good agreement with the present results for the two pigeon wings. At low and medium frequencies the sound pressure level spectra agree very well, while at high frequencies above 10 kHz the sound pressure levels from Wei et al. were below the ones shown in (30), with Wei et al. suggesting that the difference is due to the fact that the wing of the living pigeon effectively suppresses small scale turbulent flow, thus reducing high frequency noise. Another possible reason for the differences is that the spectra from Wei et al. were obtained by integrating over a sector in the sound maps that only contained the wing tip, while in the study by Geyer et al. the noise sources were integrated over the complete wing area. This hypothesis is supported by the fact that the sound maps presented in Wei et al. clearly show that noise from other parts of the wing, mainly the leading edge, become more and more important with increasing frequency.

To show the differences between the radiated noise from the owl wings compared to that from the non-silently flying birds more clearly, a LOWESS-algorithm (34) was applied to the data shown in Figure 9a. This algorithm is used for smoothing scatterplots by polynomial fits using weighted least squares, thus helping to make the visual information from a scatterplot better accessible. The resulting filtered sound pressure levels, still scaled using the third power of the flow Mach number and the lift force according to Equation (2), are shown in Figure 9b. The main outcome of the wind tunnel measurements on prepared wings is now better visible: On average, the wings from both the tawny owl and the barn owl generate less noise per unit lift force



(a) Scaled third octave band sound pressure levels.

(b) Scaled third octave band sound pressure levels, filtered with a LOWESS-filter.

Figure 9 – Results from the wind tunnel measurements on prepared bird wings as presented in (30): barn owl, tawny owl, common buzzard, eurasian sparrowhawk, pigeon.

than the wings from the buzzard, the sparrowhawk and the pigeon.

3.3 Discussion

The silent flight of owls is essentially caused by their low flight speed and their special plumage adaptations as identified by Graham (4). Both the results from the flyover noise measurements performed by Sarradj et al. (16) shown in Section 3.1 and the results from the wind tunnel measurements by Geyer et al. (30) shown in Section 3.2 give evidence that the gliding flight noise from owls is, on average, below that from other, non-silently flying birds even at the same speed of flight. If it is considered that non-silently flying birds of prey, such as the hawk, the kestrel and the buzzard, usually fly much faster than the owl, the noise reduction will be more pronounced.

However, the present results also show that the overall differences are, although significant, not very large. This is in agreement with the results from past studies, as for example Kroeger et al. (9) state that “the relative quietness of the owl flight appears to be rather a result of an appropriate noise energy distribution over the frequency spectrum rather than an overall low noise level”. It is therefore of importance to correctly interpret the measured data regarding the hunting habit of owls compared to non-silently flying birds of prey. Owls need to fly almost silently due to two reasons: (1) The owl has to be able to aurally locate its prey and, (2), typical prey, such as rats, mice, shrews, small birds and insects, shall not hear the owls approach early enough to be able to escape.

The first requirement is met since owls have a very good hearing ability (35, 36) due to such specifics as their asymmetrical external ears and the anatomy of their outer, middle and inner ear in general, which leads to the owls ability to effectively locate prey through hearing. Additionally, owls are able to detect even very small frequency differences and to discriminate frequencies by memory (37). In order to allow for conclusions regarding the second cause, it is reasonable to examine the hearing ability of small animals belonging to the typical prey of owls. As an example, Figure 10 shows corresponding hearing curves of a brown rat, a moth and a grasshopper, taken from the work of Neuhaus et al. (1). It is visible that the hearing of those animals is most sensitive at higher frequencies well above 2 kHz, and hence exactly in the range at which the noise reduction of the owl plumage is most effective. A noise reduction at lower frequencies is therefore not needed to secure the life habitat and the survival of owls, and hence it simply does not exist. In other words, the flight of the owl is just as quiet as necessary.

Another topic, which was purposely not subject to the present paper, but which should at least be mentioned when discussing the silent flight of owls is the noise generation during flapping flight. It seems reasonable, of course, to assume that owls also produce less noise than other birds during the flapping phase of the flight. Thorpe and Griffin (38) measured the high frequency noise generation of several owls, a scops owl (*Otus scops*), a little owl (*Athene noctua*), a tawny owl, a barn owl and a long-eared owl, in free flight using an “ultrasonic bat detector”. They found that in the examined frequency range above 15 kHz the wing beats of the

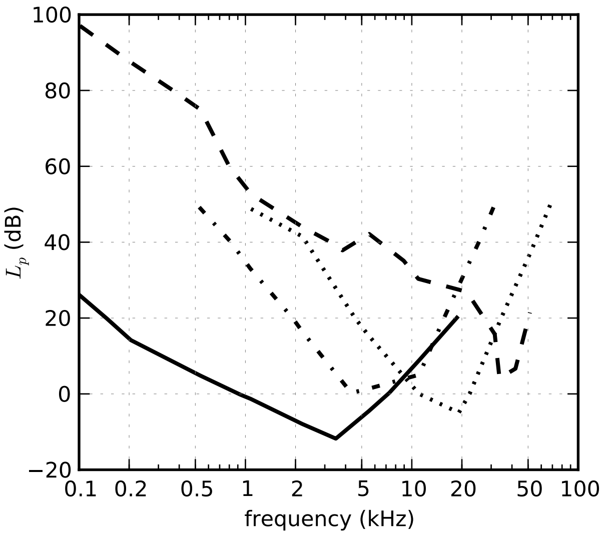


Figure 10 – Different hearing curves according to Neuhaus et al. (1), solid line: humans, dashed line: brown rat (*Rattus norvegicus*), dotted line: moth (*Eudocima tyrannus*), dot-and-dashed line: rice grasshopper (*Oxya japonica*).

owls did not generate any noise at all. However, besides this study there are currently no experimental data available for a larger frequency range that further quantify the silent flapping flight of the owl.

4. CONCLUSIONS

Owls are commonly known to fly almost silently, which serves as a motivation for many new techniques for the reduction of flow induced noise. The present paper examines the special adaptations of the owl plumage that are responsible for this silent flight – a comb-like structure at the leading edge of the wing, fringes at the trailing edge and a very soft and porous downy surface of the feathers.

After a brief overview on the single adaptations, two different approaches for the measurement of the gliding flight noise in comparison to the noise from non-silently flying birds are presented: The first are flyover noise measurements performed in an outdoor environment, which have the advantage that the birds are flying according to their natural behaviour. The downside of performing such measurements are the high requirements regarding the experimental setup and the fact that not only poor wheather conditions, but also the behaviour of the birds themselves, for example by shrieking or by flapping their wings, can have a negative effect on the feasibility of such an experimental investigation. The second are measurements on prepared bird wings in an aeroacoustic wind tunnel. The advantage of these measurements are the repeatability and the fact that the wind tunnel facility is especially suited for such measurements. The disadvantage, of course, is that a prepared wing is not identical to the wing of a living bird, and hence some deviations of the results can be expected.

The results of both experiments show that the owls generate less noise than the non-silently flying birds used in the studies. While there is almost no difference in the noise generation at low frequencies, the sound pressure level difference is significant at medium and high frequencies, which is in agreement with data from past studies. The comparisons take into account the flight speed by applying an edge noise scaling approach, thus showing that the silent flight of the owls indeed has to be a consequence of their special plumage adaptations and not just a consequence of their lower speed of flight.

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