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Silent Owl Flight: Acoustic Wind Tunnel Measurements on Prepared Wings

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The wings and feathers of most genera of owls show unique properties that are held responsible for the silent flight of the owls. This ability to fly silently has long been of interest for engineers, with the aim to transfer the basic noise reducing mechanisms to technical applications such as blades of fans and propellers. The present paper describes acoustic and aerodynamic wind tunnel measurements on prepared bird wings of different species, among them two silently flying species of owls, the barn owl (*Tyto alba*) and the tawny owl (*Strix aluco*). The different wings are characterized in the study as technical airfoils in terms of their acoustic and aerodynamic performance. The experiments took place in an aeroacoustic open jet wind tunnel using microphone array measurement technique and deconvolution beamforming algorithms. Simultaneously to the acoustic measurements, the lift and drag forces of the wings were captured using a six-component-balance. This study, which is a complementary study to the approach of performing flyover measurements on flying birds, further confirms experimentally that the silent owl flight is a consequence of the special wing and plumage adaptations of the owls and not a consequence of their lower flight speed only.

I. Introduction

Owls are commonly known to fly very quietly. This silent flight is required to enable their survival regarding the hunting habits of the owl: The owl sits on a perch or flies very slowly and at a low altitude. When the owl aurally locates prey (e.g. mice and other small animals), it approaches silently and the prey does not hear the owl early enough to still have the time to escape. The silent flight therefore has two purposes: First, the owl's own noise must not disturb its ability to aurally locate the prey and second, the prey must not hear the owl's approach in time to escape. Non-silently flying birds of prey, on the other hand, visually spot their prey and fly very fast so that the prey simply has no time to escape due to the high speed of approach.

I.A. The Special Feather Adaptations of Owls

In order to pursuit this specially adapted hunting habit, owls have developed certain adaptations that are different from other birds of prey, making them unique among the birds. Besides differences in wing shape and wing loading, this is the special feather structure of the owls, which was subject to several biological studies in the past. An early investigation on the microstructure of the feathers of birds, including owls, was done by Mascha,[25] who describes the comb-like shape of the outer barbs of the owl's primary feathers as well as the very long and soft endings of the distal barbules, called pennula, that lead to the velvet-like surface of the feathers. He even assumes that the peculiarities of the owl feathers are sound muffling devices. More than 30 years later, Graham[15] designated the three mechanisms of the feathers and the plumage of owls that supposedly enable the silent flight: (1) a comb-like structure at the leading edge of the wings, (2) long and soft fringes at the trailing edge and (3) a soft, downy upper surface of the feathers. He assumed that the third mechanism either serves to muffle the small reverberations of sound or that it

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helps the further retardation of the boundary layer initiated by the comb-like leading edge. Sick[36] examined the microstructure of a variety of feathers of different bird species, stating that the soft consistence of the feathers of owls, as a result of the long, upward bent pennula, leads to a noise absorption during flight. Hertel[17] provided further information on the special properties of the owl feathers leading to the low noise generation, including detailed microscopy pictures of the hooks that form the leading edge comb and the inner and the outer vanes with the long, soft fringes. The most recent work on the feather structure of owls is the work by Bachmann.[2] He performed detailed anatomical, morphometrical and biomechanical measurements on the wings of barn owls (*Tyto alba*) and compared the results to those of the pigeon, representing the non-silently flying birds. Thereby, advanced measurement techniques like three-dimensional surface scans, three-dimensional digitizing and computed tomography scanners (to allow for the reconstruction of internal structures such as bones, skin and feather rachises) were used. Noticeable differences between the feather structure of both species were identified, including the longer pennula and lesser radiates of the feathers of the owl.

This short overview of biological studies of owls shows that these species are indeed different from other birds regarding their wings and feathers. The question that arises is whether the reported silent flight of owls results from these unique adaptations or from their low speed of flight compared to other birds of prey.

I.B. The Silent Flight of Owls

The silent flight of the owl as an inspiration for technical applications has been subject to scientific research for a long time. Inspired by a qualitative comparison of the flight noise of a "common" owl and a non-silently flying tawny fishing owl (*Ketupa flavipes*), Graham[15] studied the wings and feathers of owls. As a result he identified the above-mentioned three mechanisms that are held responsible for the low noise generation. Thorpe and Griffin[38] additionally noticed the lack of ultrasonic components in the flapping flight noise of owls. One of the most detailed studies regarding the silent owl flight was done by Kroeger et al.[21] and by Gruschka et al.,[16] where the aim was to use the knowledge of the quieting mechanisms of the owl for the development of future quiet aircraft. They conducted flyover measurements on a Florida barred owl (*Strix varia alleni*) during the phase of gliding flight in a reverberation chamber using a single condenser microphone. It was found that the noise spectrum of the owl is shifted strongly towards low frequencies well into the range where it cannot be heard by its prey.[21] Kroeger et al. further described the aerodynamic performance of the owls as being very poor (for example in terms of the lift-to-drag-ratio of the owl compared to that of an albatross). Additionally, wind tunnel tests were performed on two wings during which the flow field around the wing and the motions of the wing or single wing parts were observed. However, no acoustic wind tunnel measurements were done. Neuhaus et al.[29] compared the flight noise of tawny owls (*Strix aluco*) and mallard ducks (*Anas platyrhynchos*), although the measurements were conducted under completely different conditions. They performed flyover measurements using a single microphone and a frequency analyzer and found that the owl's flight noise during gliding flight has a low frequency character that the duck's has not. It shows a peak of the sound pressure level between 200 Hz and 700 Hz, and it is stated that this low frequency noise is below the hearing limit of the typical prey of the tawny owl. Neuhaus et al. also did flow visualization experiments in a wind tunnel and observed "a much higher degree of laminar flow" around the owl wing than around the duck wing. Another study on the silent flight of owls was done by Lilley[22] (with some aspects again revisited in a later airframe noise study[23]), who discusses Graham's mechanisms for the silent owl flight and concludes that these mechanisms lead to a major noise reduction above 2 kHz. Lilley developed a relatively simple noise prediction model for birds and small gliding aircraft. His model is derived from the fundamental theoretical work of Ffowcs Williams and Hall[11] for a flat, semi-infinite plate at zero incidence and consequently only considers trailing edge noise. The resulting model for the prediction of the gliding flight noise only contains two parameters, the mass of the bird or glider (as a measure for its lift in equilibrium flight) and its speed of flight. Other parameters, such as angle of attack or certain boundary layer parameters, are taken to affect the lift force and are hence accounted for. Lilley states that the model is not valid for owls due to the special features of their wings and feathers. Another important information given by Lilley[23] is that he holds the downy upper surface of the feathers (the third mechanism identified by Graham) responsible for the low noise generation of owls above 2 kHz.

Apart from the examinations of the flight noise produced by owls and birds in general, there exist several aerodynamic studies dealing with bird flight. This includes studies on birds flying in a wind tunnel, like those by Pennycuick,[30] Tucker and Parrott[39] and Brill et al.[5] Those investigations showed that aerodynamic measurements on birds in a wind tunnel are feasible and provide insight in the aerodynamics of birds. Besides measurements on living birds there are a number of aerodynamic wind tunnel studies on prepared bird wings. A basic theoretical work on the aerodynamics of bird wings, including the characterization of the wing data and the flight performance using the terminology of aviation aerodynamics as well as detailed descriptions of the procedure of wind tunnel measurements, was done by Nachtigall.[28] Withers[40] performed an aerodynamic study on eight bird wings and one single feather in a wind tunnel. Like Nachtigall, Withers also used the terminology of technical airfoils for the characterization of the aerodynamic properties of the prepared wings. No silently flying birds were examined in those experiments though. March et al.[24] conducted aerodynamic wind tunnel measurements on the prepared wings of a great horned owl (*Bubo virginianus*) as a representative for the silently flying owls and a red-tailed hawk (*Buteo jamaicensis*). Interestingly, they observed a strong twist of the highly elastic wings in the fluid flow and took this into account when discussing the aerodynamic performance. Additionally, they tried to model these aeroelastic effects with computational flow simulation tools. As opposed to the observations made by Kroeger et al. regarding the aerodynamic performance of owls, Klän et al.[19] examined an owl-based airfoil and argue that the surface structure of the owl wing may contribute to an increase of the aerodynamic performance of the wing by decreasing or suppressing the separation bubble or by stabilizing it.

These studies show that the acoustics and the aerodynamics of the silent owl flight are still of great interest for use in technical applications, especially against the background of rising requirements to further reduce airframe noise. Additionally, there exist only few publications that allow for a detailed comparison of the noise produced by gliding owls to that of other birds. The main reason is that it is very challenging to give experimental evidence for the lower flight noise generation. Basically, different approaches may be pursued to measure the noise generated by gliding owls compared to that generated by non-silently flying birds. These methods include

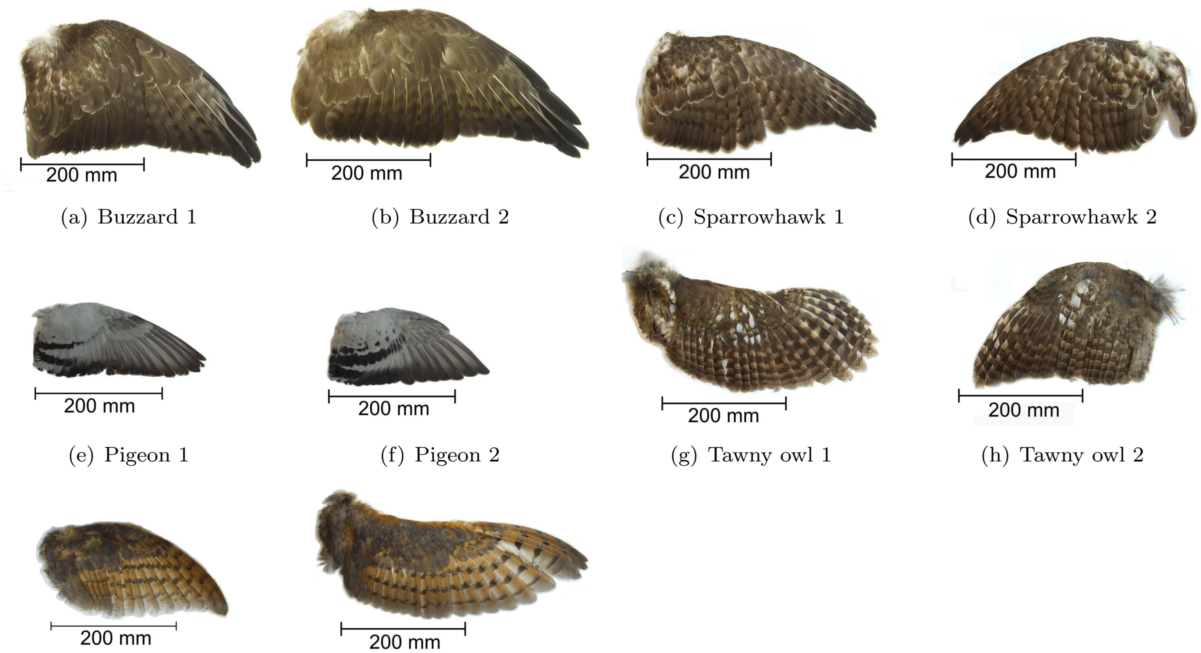
- measurements on flying birds and
- measurements on prepared birds or wings.

The first method was successfully realized as microphone array measurements in an outdoor environment on a common kestrel (*Falco tinnunculus*), a Harris hawk (*Parabuteo unicinctus*) and a barn owl by Sarradj et al.[34] Such experiments, however, are very sophisticated since (1) the birds have to be trained to fly along a desired trajectory, (2) measurements of both flight noise and trajectory have to be done without harming the birds or putting stress to the birds, (3) the gliding flight noise levels are very low, which requires a low background noise and a very sensitive measurement equipment and (4) large numbers of flyovers are necessary to achieve a sufficient statistical significance of the results. Additionally, it is very hard to compare the noise of different birds. In the end, the measured data from Sarradj et al. showed that the noise generated by the owl is significantly lower than that generated by the kestrel and the hawk in a frequency range above 1.6 kHz.

The second method, acoustic measurements on prepared wings, has the advantage that the experiments can be performed in an acoustically treated lab environment, as for example an aeroacoustic wind tunnel. Initially this approach seems to be more simple regarding both the setup and the reproducibility of the experiments. For such an experimental study the shape of the prepared wings plays a more important role. Due to the process of preparation it is not possible to obtain wings that have exactly the same properties as the wings of a living bird, and hence the prepared wings to be used have to be chosen carefully and their aerodynamic properties have to be considered at the same time.

The research presented in this paper focuses on the analysis of the silent flight of owls using the second method, experiments in an aeroacoustic wind tunnel. Preliminary results of such measurements on only two specimen are briefly described by the authors.[12] The aim of the present paper is the comparison of the noise generation at the wings of owls to that of birds that do not fly silently. The measurements were conducted in an aeroacoustic wind tunnel on prepared bird wings using microphone array measurement technique. Additionally, the aerodynamic performance of the wings is taken into account. The focus herein is on the gliding flight only, where the wing position is fixed without any flapping motions. Of course, the prepared wings behave different in a flow than wings of a living bird during flight, as their shape is not adjusted to the according flight situation and the instantaneous flow field. However, wind tunnel measurements, as opposed to experiments on flying birds, have the advantage of more repeatable measurement conditions independent of the behavior and training of a bird and the possible influence of the weather.

The remainder of this paper is organized as follows: First, the experimental setup is described. This includes the prepared bird wings available for this study, the aeroacoustic wind tunnel, the measurement



(a) Buzzard 1 (b) Buzzard 2 (c) Sparrowhawk 1 (d) Sparrowhawk 2 (e) Pigeon 1 (f) Pigeon 2 (g) Tawny owl 1 (h) Tawny owl 2 (i) Barn owl 1 (j) Barn owl 2

Figure 1. Bird wing specimen used for the present experiments

of the aerodynamic performance of the wings, the microphone array used for the acoustic measurements and the subsequent processing of the acoustic data. Then, the results of the aerodynamic and the acoustic measurements are presented and discussed.

II. Experimental Setup

II.A. Prepared Wings

The prepared wings of five different species were examined in the experiments described in the present paper, using two specimen from each species. The species included the tawny owl (*Strix aluco*) and the barn owl (*Tyto alba*) as representatives of the silently flying birds. In contrast, wings of the common buzzard (*Buteo buteo*), the eurasian sparrowhawk (*Accipiter nisus*) and the pigeon (*Columba livia*) represented the non-silently flying birds. Pigeons, although no birds of prey, are known as fast flyers and are thus included in the study. A photograph of each wing can be seen in Figure 1. The ten specimen were selected carefully out of a total set of 42 wings depending on suitability for the purpose of the experiments. The wings of both owl species, the buzzard wings and the sparrowhawk wings were provided by the *Senckenberg Naturhistorische Sammlungen Dresden*. The wings of the pigeon were provided by the *Institute for Biology II, Department of Zoology and Animal Physiology* of the *RWTH Aachen University*.

II.A.1. Description of the Prepared Wing Specimen

When using prepared wings for aeroacoustic and aerodynamic wind tunnel measurements, it is obvious that such specimen do not exactly represent the wings of living birds in gliding flight in their three-dimensional shape in every detail, but rather reduced models that can be used when the deviations from a real wing are considered. In the present case, the basic process of the preparation was the following: The wings were separated from the bodies and the muscle tissue was removed from the bones. The wings were then manually extended until they were sprawled out and finally they were dried. Some of the wings from Figure 1 are specimen that were not specially prepared for the purpose of this study, but were prepared at an unknown time in the past. It has to be kept in mind that differences in elasticity and tension of muscles and tendons between living and dead birds are generally unavoidable and remain a source of error.[10] As a result, the process of the preparation has an effect on aerodynamic parameters like the spanwise distribution of camber, thickness and twist[2] as well as on the aeroacoustic performance. As mentioned above, in contrast to the shape of the wings of a flying bird, which is actively adapted by the muscles as a response to changes in the flow field, the shape of the prepared wings cannot be changed actively. Additionally, the flexibility of the wing specimen, as opposed to rigid airfoil models, may also affect the aerodynamics and acoustics. However, if measurements on bird wings in a wind tunnel are desired, then the process of preparation is inevitable and its influence on the experimental results has to be discussed accordingly.

The three-dimensional shape of the examined wings was fixed in the present study due to the preparation. The wings were not swept during the measurements. The wing shape is assumed to correspond approximately to the shape of a wing during the gliding phase of the flight, and effects like natural twist or aerodynamically induced changes of the wing shape could not be accounted for. However, similar to the approach used by Lilley[22] for the development of his flight noise prediction model, the hypothesis is that the wing shape as well as possible imperfections of the wings – such as missing feathers – have an influence first and foremost on the aerodynamic performance of the bird, as they would in a living bird. In reverse, the aerodynamic parameters, if known, can then be included in the analysis to account for differences in wing shape.

As explained above, the selected specimen are the ones that were found to be best suited for the intended experiments despite some minor restrictions. These restrictions will be briefly discussed:

- Certain wings show small imperfections, for example the missing ninth and tenth primary feather of the second pigeon wing, Figure 1(f).
- The shape of some wings is somewhat flexed, for example the wings of the buzzard, Figure 1(a) and Figure 1(b). They may have been prepared in relation to the hunting behavior of the buzzard: To catch the prey, the bird maximizes its speed in a dive by bringing its wings closer to the body, still without any flapping of the wings. The shape of the prepared buzzard wings available for this study apparently resembles a condition where the bird starts this diving phase.
- Even the wings of one species may have a more or less different shape and wing area, as for example the two wings of the tawny owl, Figure 1(g) and Figure 1(h): While the first wing is fully extended and noticeable tip slots have been formed, the second wing is flexed to a certain degree.

II.A.2. Characterization of Prepared Wings using Airfoil Terminology

The geometry of the wings of the present study is described by the wing area A, the effective wing area A_{eff}, the wing halfspan h_s and the effective wing halfspan $h_{s,\mathrm{eff}}$, which were measured using a *Microscibe G2* three-dimensional digitizer. The effective wing area is the part of the complete wing area exposed to the flow during the measurements in the wind tunnel, in other words the area that solely contributes to the lift of the wings (in some publications also called the "wetted" area). The photographs in Figure 1 correspond to the (total) wing area A. Subsequently, the effective halfspan is the spanwise length of the wing measured from the point on the leading edge where the wing is exposed to the flow to the wing tip (the tip of the longest primary feather). In accordance to Withers,[40] the averaged chord length $\overline{c}_l$ is then defined as the ratio of effective wing area to effective halfspan,

$$\overline{c}_l = \frac{A_{\mathrm{eff}}}{h_{s,\mathrm{eff}}} \tag{1}$$

and the aspect ratio ar is defined as the ratio of effective wing area to the square of the effective halfspan:

$$ar = \frac{A_{\mathrm{eff}}}{h_{s,\mathrm{eff}}^2}. \tag{2}$$

Effective wing area A_{eff}, effective halfspan $h_{s,\mathrm{eff}}$, averaged chord length $\overline{c}_l$ and aspect ratio ar for each wing specimen examined in the present study are given in Table 1.

The angle of attack α of the wings in the flow was measured at mid-span, as proposed by Withers.[40] This was done when the wind tunnel fan was off, using an electronic water level held under the wing. Therefore, the measured angle is actually slightly smaller than the exact angle of attack at mid-span which is defined as the angle between the main flow direction and the chord (see Figure 2). It is known that the presence of a flow affects the effective angle of attack and the camber of a bird wing.[20] The angle of attack α is

Table 1. Data of the prepared bird wings

No	wing		side	A_{eff} [mm^2]	$h_{s,\mathrm{eff}}$ [mm]	$\overline{c}_l$ [mm]	ar	Figure
1	Common buzzard	*Buteo buteo*	right	48,417	381	127	0.33	1(a)
2	Common buzzard	*Buteo buteo*	right	46,187	384	120	0.31	1(b)
3	Eurasian sparrowhawk	*Accipiter nisus*	right	42,275	360	117	0.33	1(c)
4	Eurasian sparrowhawk	*Accipiter nisus*	left	36,535	355	103	0.29	1(d)
5	Pigeon	*Columba livia*	right	18,646	241	77	0.32	1(e)
6	Pigeon	*Columba livia*	right	17,388	228	76	0.33	1(f)
7	Tawny owl	*Strix aluco*	right	46,604	287	162	0.56	1(g)
8	Tawny owl	*Strix aluco*	left	38,229	320	120	0.37	1(h)
9	Barn owl	*Tyto alba*	right	27,810	285	98	0.34	1(i)
10	Barn owl	*Tyto alba*	right	44,811	334	134	0.40	1(j)

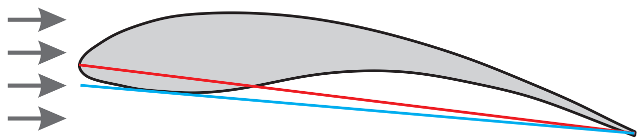


Figure 2. Measurement of the angle of attack at midspan, blue line along which the angle of attack was measured, red exact chord line (Note that the airfoil shown is not a biological profile, but a technical profile given for the purpose of illustration only.)

also expected to affect the noise generation in the flow, an assumption based on acoustic measurements on technical airfoils (as for example described by Hutcheson and Brooks[18]). The simplified procedure of measuring the angle at mid-span is therefore a limitation of this study, since spanwise variations of the angle of attack caused by flow-induced motions of the wing are not taken into account. A more exact method to measure the angle of attack and its spanwise distribution, like a three-dimensional scan of the wing shape, was not available. Additionally, the changes of the angle of attack due to the flow would have to be analyzed for each flow speed and the angle of attack would have to be readjusted accordingly. However, the purpose of this study is the comparison of the noise generation at the wings of silently flying birds to the noise generation at the wings of non-silently flying birds at comparable angles of attack. Therefore, special care has been taken to adjust the angle in a similar way for each prepared wing.

II.B. Wind Tunnel

The measurements took place in the aeroacoustic wind tunnel at the Brandenburg University of Technology Cottbus, which is an open jet wind tunnel. The circular nozzle used for the experiments has an exit diameter of 0.35 m, the maximum flow speed with this nozzle is approximately 25 m/s. The turbulence intensity in front of the nozzle and the corresponding velocity profile are given in Figure 3 for two flow speeds. It can be seen that the flow inside the core jet has a low turbulence intensity in the order of 0.2 % and less. The overall A-weighted sound pressure level of the wind tunnel background noise at 20 m/s is below 44 dB, measured at a distance of 1 m at 90° to the wind tunnel axis.

During acoustic measurements, the test section is surrounded by a cabin with sound absorbing sidewalls that provide full absorption for frequencies greater than 500 Hz. The side opposite to the wind tunnel nozzle is open. The cabin has a width of 1.55 m, a height of 1.5 m and a length (in streamwise direction) of 2 m. Figure 4 shows a schematic of the experimental setup. Additional information on the aeroacoustic wind tunnel are given by Sarradj et al.[32]

The dimensions of the wings (Table 1) are not negligible compared to the jet width, which leads to the effect of a partial blockage of the wind tunnel, especially at higher angles of attack. This blockage, which has an impact on the aerodynamic loading of the wings positioned in front of the nozzle, as well as the fact that the flow field around the wings changes in the spanwise and the chordwise direction due to the expanding jet width, are effects that usually require a correction of the angle of attack. Such a correction yields an effective angle of attack to account for differences between the flow field in the open jet compared to free flow conditions. Unfortunately, common correction procedures, like those proposed by Brooks et al.,[6,7] are more or less inapplicable to this study. The main reason is that the prepared wings are no ideal technical

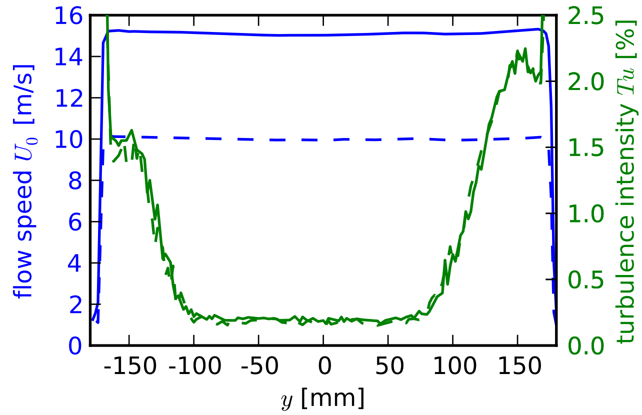


Figure 3. Velocity profile ( ) and turbulence intensity ( ) of the nozzle, measured along a horizontal line, U_0 = 15 m/s (solid lines), U_0 = 10 m/s (dashed lines)

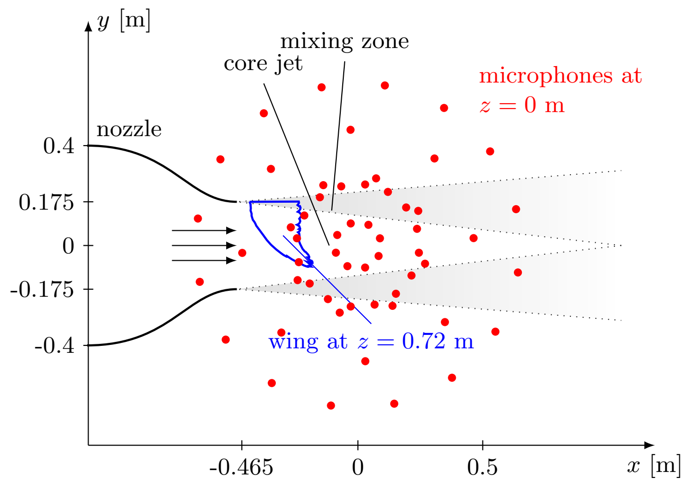


Figure 4. Schematic display of the measurement setup (top view). Note that only the effective "wetted" area of the wing is shown.

symmetrical airfoils, but cambered biological airfoils with complex shapes. Furthermore, the blockage of the nozzle changes due to the elasticity of the wings, while additionally each of the prepared bird wings is, at least to a certain degree, permeable to the air flow, which further reduces the effect of blockage compared to common technical airfoils. Therefore, as already mentioned in the last section, the geometric angles of attack are given for the purpose of comparison of different working points only.

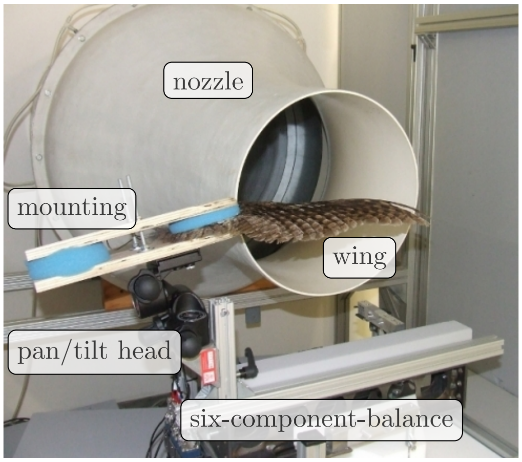
II.C. Aerodynamic Performance

A six-component-balance was used to measure the lift and drag forces F_L and F_D that act on the prepared wings as a measure of their aerodynamic performance. The balance consists of six single point load cells. The data were measured with a sample rate of 1 kHz using a National Instruments 24 Bit full-bridge analog input module and time averaged.

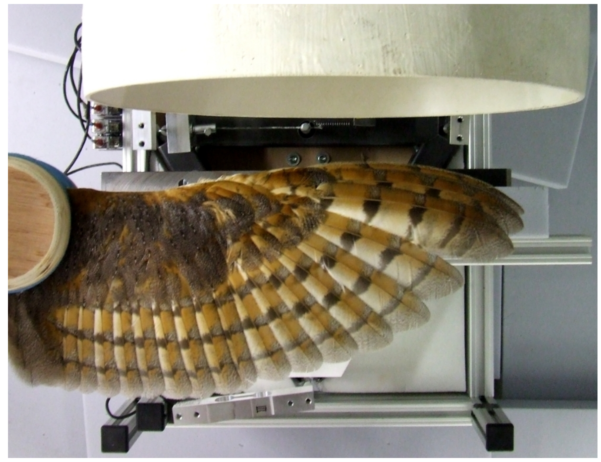
Since the position of the wings is fixed, the lift force is defined as the vertical force in the positive z-direction, perpendicular to the flow direction, and the drag force as the horizontal force in the positive x-direction, hence in the direction of the flow. The lift and drag coefficients C_L and C_D are then defined by:

$$C_L = \frac{2 \cdot F_L}{\rho \cdot U_0^2 \cdot A_{\text{eff}}} \qquad \text{and} \qquad C_D = \frac{2 \cdot F_D}{\rho \cdot U_0^2 \cdot A_{\text{eff}}}, \tag{3}$$

respectively. Herein, F_L and F_D are the measured lift and drag forces, U_0 is the flow speed and ρ is the fluid density.



(a) View from downstream (first tawny owl wing)



(b) Top view (second barn owl wing)

Figure 5. Photograph of the setup including the mounting specially designed to hold the fragile wings and to allow for the exact positioning of the wing in front of the nozzle.

The wings were attached to the balance with a mounting that allows for the adjustment of the angle of attack. The mounting was carefully designed and constructed to meet three requirements: First, no noise should be generated at the mounting, second, no aerodynamic effects should be caused by the mounting and third, the mounting had to tightly grip the wings without destroying the fragile bone- and feather-structure. Additionally, the prepared wing is bedded between two slices of soft polyurethane foam. Figure 5 shows a photograph of the setup, and especially the mounting, which is connected to a three-dimensionally adjustable pan/tilt head. The mounting was positioned out of the flow and the wings were hold in front of the nozzle at the height of its horizontal center plane.

II.D. Microphone Array and Data Processing

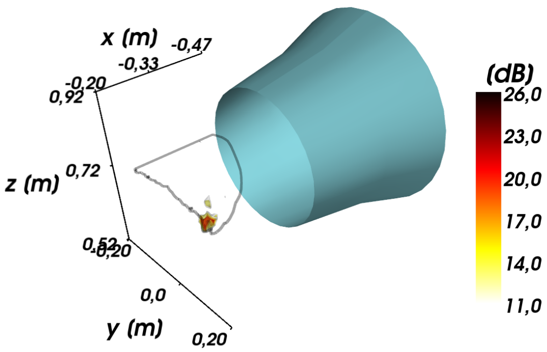
II.D.1. Beamforming Algorithms

The noise generated at the prepared wings propagated through the shear layers of the open jet and was measured with the microphone array positioned above the wings outside of the flow. In this study, no shear layer correction, like that published by Amiet[1] and Schlinker and Amiet,[35] was implemented. This is due to the fact that the exact geometry of the shear layer is not known and due to the relatively small flow speeds, resulting in only a minor effect of the refraction on the sound source localization and magnitude.

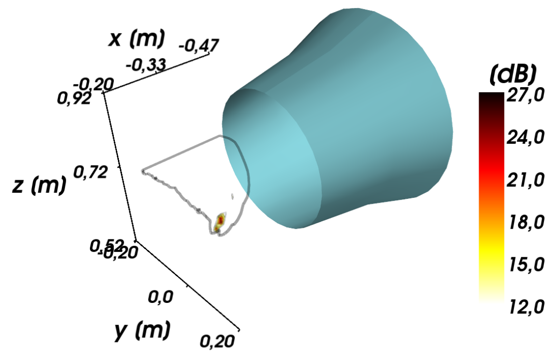
The planar microphone array that was used for the acoustic measurements consists of 56 microphones, the position of which can be seen in Figure 4. It was placed 0.72 m above the prepared wings. Using a 24 Bit National Instruments multichannel measurement system, the acoustic data were recorded with a sample frequency of 51.2 kHz and a total of 2,048,000 samples per channel, corresponding to a measurement duration of 40 s for each acoustic measurement. The sampled time data were Fast Fourier transformed with a Hanning window and 4,096 samples per block and 50 % overlap, resulting in a frequency line spacing of 12.5 Hz. For each block, the cross spectral matrix was calculated and the resulting 999 matrizes were averaged.

In a first step, a conventional delay-and-sum beamforming technique[27] was applied to the data, where the signals from each microphone are delayed appropriately, weighted and summed up to obtain maps of the local sound pressure contributions. Usually, these maps are two-dimensional representations of the sound pressure contributions located at the grid points of a two-dimensional mapping plane. In the present case, due to the fact that the prepared wings are not in one plane, the beamforming was applied to a fully three-dimensional source volume. Potential noise sources may be located at each grid point of a three-dimensional grid. Therefore, the three-dimensional beamforming provides a better depth resolution than conventional two-dimensional beamforming. The resulting "sound maps" are three-dimensional images of the sound sources. This method was, for example, successfully applied to the measurement of the flow-induced noise from high-speed trains by Brick et al.[4] and to airfoil leading edge noise measurements by Geyer et al.[14]

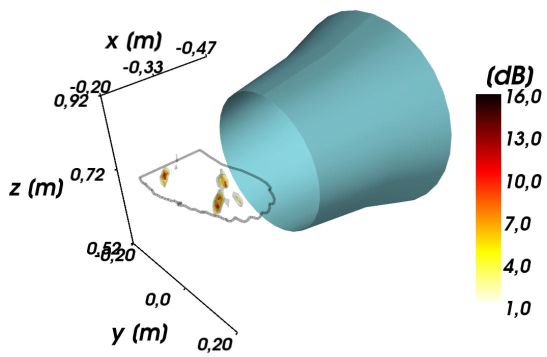
When three-dimensional beamforming is to be applied, a source grid with a noticeably increased number



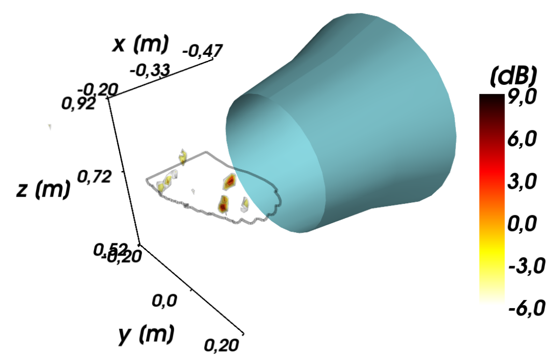
(a) Buzzard wing (Figure 1(a)), 4 kHz octave band



(b) Buzzard wing (Figure 1(a)), 8 kHz octave band



(c) Tawny owl wing (Figure 1(g)), 4 kHz octave band



(d) Tawny owl wing (Figure 1(g)), 8 kHz octave band

Figure 6. Three-dimensional CLEAN-SC sound maps, flow speed $U_0 \approx 12$ m/s

of grid points is necessary to obtain a sufficient resolution. In the present case, the grid had an extent of 0.5 m in the streamwise (x-) direction, 0.6 m in the lateral (y-) direction and 0.6 m in the vertical (z-) direction. With an increment of 0.01 m this lead to a total number of 189,771 grid points.

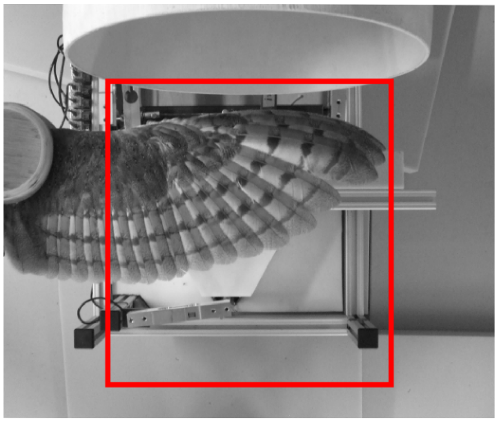
To further process the data and to remove the influence of side lobes, different deconvolution algorithms were considered, including

1. the DAMAS (Deconvolution Approach for the Mapping of Acoustic Sources) beamforming algorithm,[9] an algorithm that computes a theoretical point spread function between the points in the map and iteratively calculates the source strengths (thus removing the influence of side lobes),

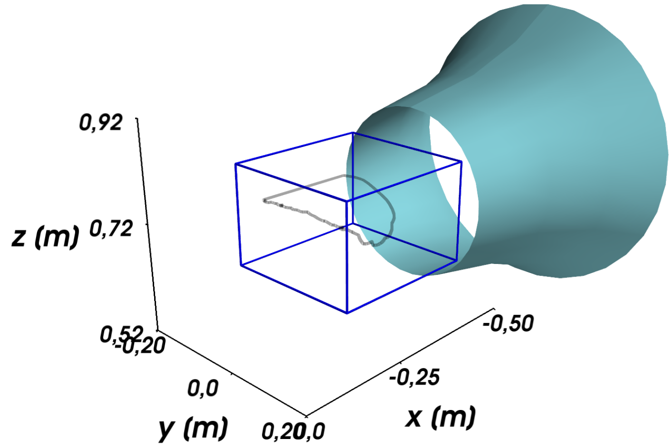
2. the CLEAN-SC beamforming algorithm[37] that uses the spatial coherence between points in the sound map instead of a theoretical point spread function and

3. the orthogonal beamforming (OB) algorithm[33] that performs an eigen-decomposition of the cross-spectral matrix to obtain a number of point sources smaller than the number of microphones.

The DAMAS algorithm iteratively solves a system of equations that contains as many equations as there are points in the grid by using a special Gauss-Seidel-technique. It is known to deliver reliable results in aeroacoustic testing, also at low frequencies. Unfortunately, due to the increased number of grid points necessary for three-dimensional beamforming, the DAMAS is computationally too expensive and hence, at this point in time, not feasible for the processing of the present data. The CLEAN-SC algorithm performs faster than the DAMAS. It is known to give good results at low and medium frequencies but, in some cases, was found to miss high frequency noise sources that are relatively weak.[13] This may be important for the present investigation because the noise sources located on the surface of wings of silently flying owls are expected to be relatively weak. The orthogonal beamforming method also performs faster than the DAMAS and tends to give reliable results over a large range of frequencies. At low frequencies, the noise source localization may be imprecise.



(a) Top view



(b) Schematic

Figure 7. Schematic of the volume used for the integration (0.30 m x 0.28 m x 0.28 m)

It was finally decided to use the CLEAN-SC algorithm for the processing of the acoustic data due to its overall good performance in the frequency range of interest. The main diagonal of the cross-spectral matrix was removed to eliminate the influence of channel self noise on the beamforming result.

Figure 6 shows three-dimensional sample sound maps, obtained for measurements at two specimen, a buzzard wing and a tawny owl wing. It is visible that the noise generated at the prepared wing of the buzzard exceeds the noise generated by the wing of the owl by about 10 dB in the 4 kHz octave band and about 18 dB in the 8 kHz octave band. The sound maps also show that the noise sources are positioned near the wing tip in case of the buzzard, while they are positioned on the wing surface in case of the tawny owl. This is in accordance to the results from flyover measurements.[34] Additional, weaker sources can also be found at the side of the wing near the position where the wings are mounted to the six-component-balance. It can be assumed that these sources are caused by the turbulent shear layer interacting with the wing. The amplitude of these weaker noise sources is noticeably smaller than that of the main sources.

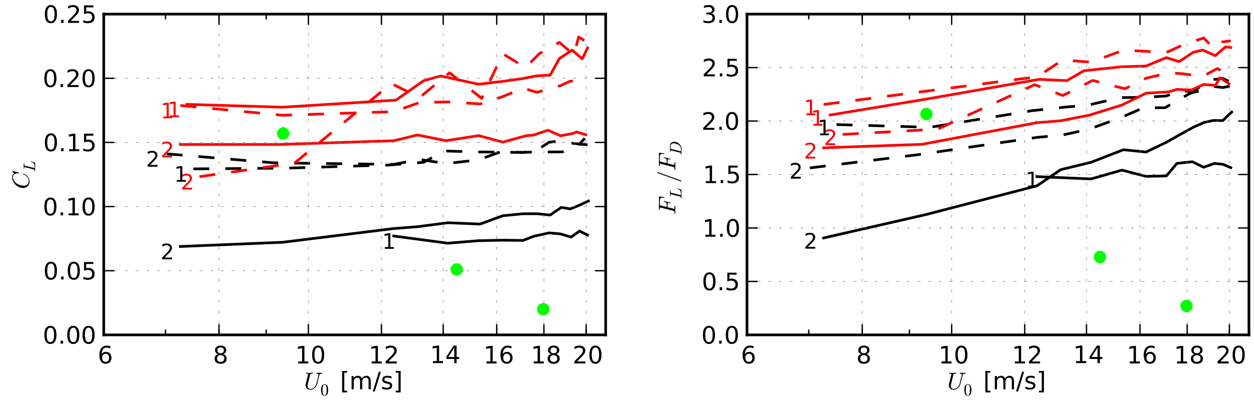
II.D.2. Sound Pressure Level Spectra

To obtain absolute sound pressure levels of the noise generated by the wing specimen, the resulting CLEAN-SC sound maps were integrated over a volume that contains the main wing area in front of the wind tunnel nozzle, but neither the nozzle itself nor the shear layers. At the position of the trailing edge of the first buzzard wing, which is the specimen with the largest streamwise extent, the shear layers have a distance of approximately 0.3 m. Thus the defined volume has a spanwise extent of only 0.28 m, to exclude the impingement of the shear layers on the wings, a vertical extent of 0.20 m and a streamwise extent of 0.30 m. It can be seen in Figure 7. Noise sources such as the weaker sources seen in Figures 6(c) and 6(d) are thus excluded from the integration.

The result of the integration is the contribution of the sound pressure that is generated within the chosen volume, measured in the array center. These results were then transferred to third octave band sound pressure levels (L_p), relative to $p_0 = 2 \cdot 10^{-5}$ Pa, with center frequencies between 630 Hz and 16 kHz. The lower frequency limit was chosen with respect to the limit of the measurement setup. For frequencies below the 630 Hz third octave band, the measured sound pressure level spectra suffered from the contamination with noise originating from standing waves in the measurement setup. The upper frequency limit was chosen due to the possible contribution of high frequency noise which is reflected at certain parts of the measurement setup.

III. Results and Discussion

Acoustic and aerodynamic measurements were conducted on the ten wings specified in Table 1 at three different angles of attack (0°, 8° and 16°) and 15 flow speeds between 5 m/s and 20 m/s. For the first



(a) Lift coefficient, $\alpha = 0°$

(b) Lift-to-drag-ratio, $\alpha = 0°$

Figure 8. Comparison of the lift and drag coefficients, angle of attack $\alpha = 0°$ (— buzzard, – – sparrowhawk, — tawny owl, – – barn owl, numbers indicate first and second specimen from each species, and ● great horned owl wing with data from March et al.[24])

buzzard wing, measurements were performed at flow speeds above 12 m/s only, for some other wings, additional measurements were performed at different angles of attack. This led to a total amount of raw acoustic data of more than 200 GByte. However, the present paper focuses on the results obtained at zero angle of attack since, as discussed in the previous section, non-zero angles lead to a more complex flow field around the wing and, in some cases, to a change of the wing shape.

As already mentioned above, owls do not fly very fast. According to Neuhaus et al.[29] the maximum speed of the tawny owl is only about 6 to 10 m/s (according to Mebs and Scherziger,[26] owls tend to fly even slower, with speeds in the range of 2.5 m/s to 7 m/s). The higher speeds are mainly given here to provide sufficient data for the non-silently flying birds of prey, which is in accordance to the approach by March et al.[24]

III.A. Aerodynamic Results

Prior to the presentation of the acoustic results, the results of the aerodynamic measurements on the wing specimen from Table 1 are presented since they will be used to normalize the measured acoustic data. Figures 8 shows the measured lift coefficient, calculated using Equation (3), and the lift-to-drag-ratio F_L/F_D as a function of the flow speed U_0 for 0° angle of attack. The aerodynamic data obtained for the two pigeon wings are not shown since the results were completely different for each wing and did not follow any physically reasonable trend.

At zero angle of attack the lift curves of the prepared wings remain nearly constant over the whole range of flow speeds, shown in Figure 8(a). The owl wings clearly produce the highest lift coefficient. It is approximately twice as high as the lift coefficient of the buzzard wings, which generate the smallest lift coefficient. The facts that the lift coefficient of both buzzard wings is comparatively small and that the second tawny owl wing generates less lift than the first specimen may also be influenced by the somewhat flexed shape of these wings. The according curves for the lift-to-drag-ratio of the prepared wings are given in Figure 8(b). On average, the wings of the tawny owl and the barn owl generate the highest lift-to-drag-ratio, while the buzzard wings generate the smallest lift-to-drag-ratio. It can be seen that the mean values increase with increasing flow speed. This increase, which corresponds to a decrease of the drag coefficients, is supposedly caused by changes of the (local) angle of attack, camber and wing area due to the flow induced bending of the wings, as is also reported in other wind tunnel studies on living birds or prepared wings.[24,31]

Included in Figure 8 are the data measured by March et al.[24] for the left wing of a great horned owl (*Bubo virginianus*) with a wing area of 126,000 mm^2. The data were obtained from diagrams that present the lift and drag coefficients as a function of angle of attack. The angles of attack adjusted by March et al. were not necessarily the same as in the present study, and additionally, the data was averaged. Therefore, the values shown in Figure 8 serve as an approximate means of comparison only. However, the lift and drag coefficients of the great horned owl's wing are comparable to the results of the bird wings used in this study. Interestingly, the values of the lift coefficient measured by March et al. strongly decrease with increasing

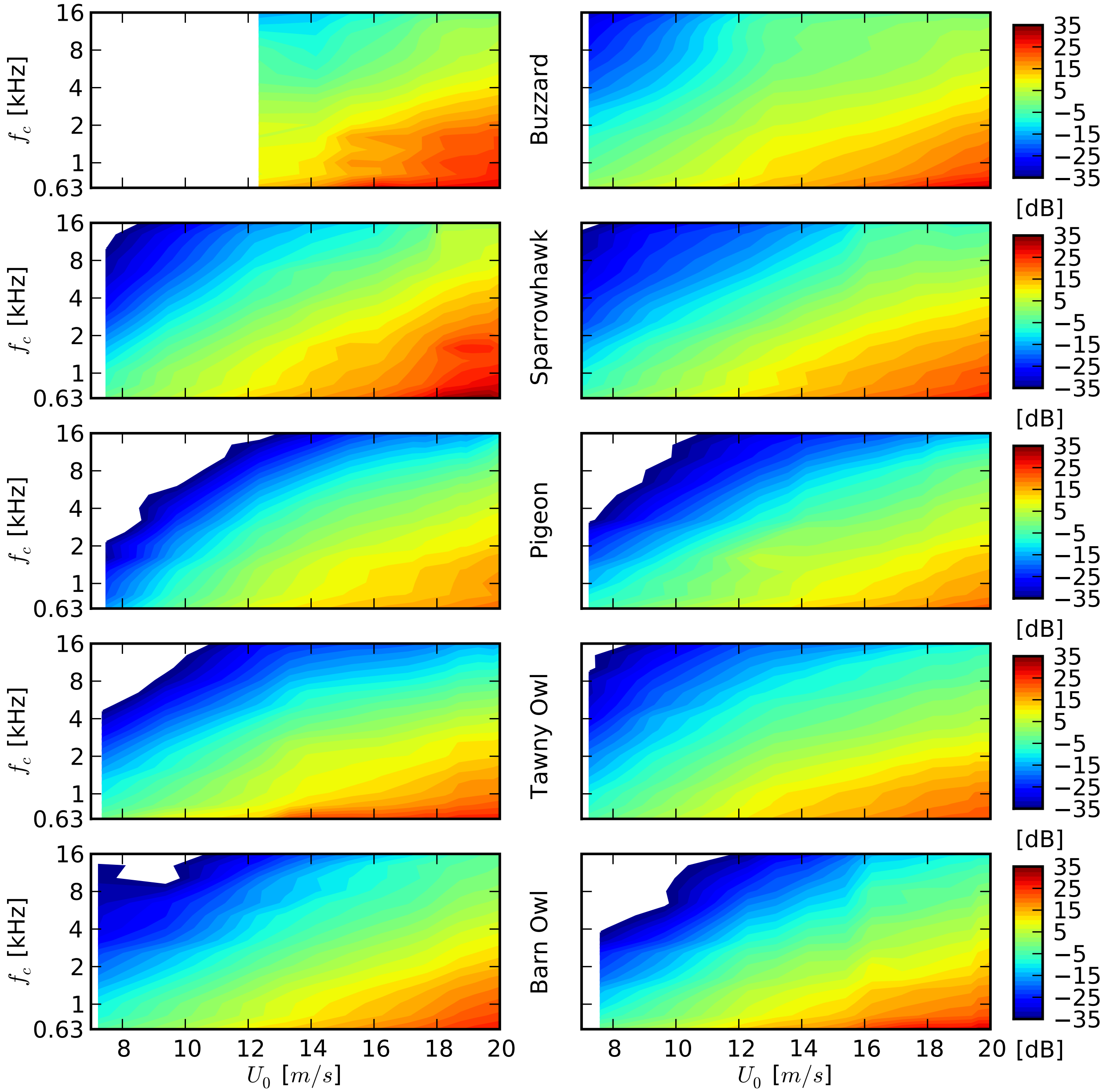


Figure 9. Power spectral density (re $4 \cdot 10^{-10}$ Pa^2/Hz) as a function of third octave band center frequency and flow speed, angle of attack $\alpha = 0°$, as measured in the sector presented in Figure 7 (left column: first specimen, right column: second specimen). Note that measurements of the noise generated by the first buzzard wing were performed at flow speeds above 12 m/s only.

flow speed.

It can be concluded from the results shown in Figure 8 that, on average, the owl wings examined generate a relatively high lift coefficient that exceeds the lift coefficient of the non-silently flying birds of prey.

III.B. Acoustic Results

In this section, the results from the acoustic measurements are presented and the usability of different scaling approaches is examined, including the use of the measured aerodynamic forces shown in the previous section. The noise generation of the prepared bird wings in the wind tunnel is a function of both frequency f and flow speed U_0. Figure 9 shows this dependence for zero angle of attack in the form of contour plots for the power spectral density measured at all ten specimen examined.

As one would expect, the figures illustrate that in general the noise generated at the prepared wings

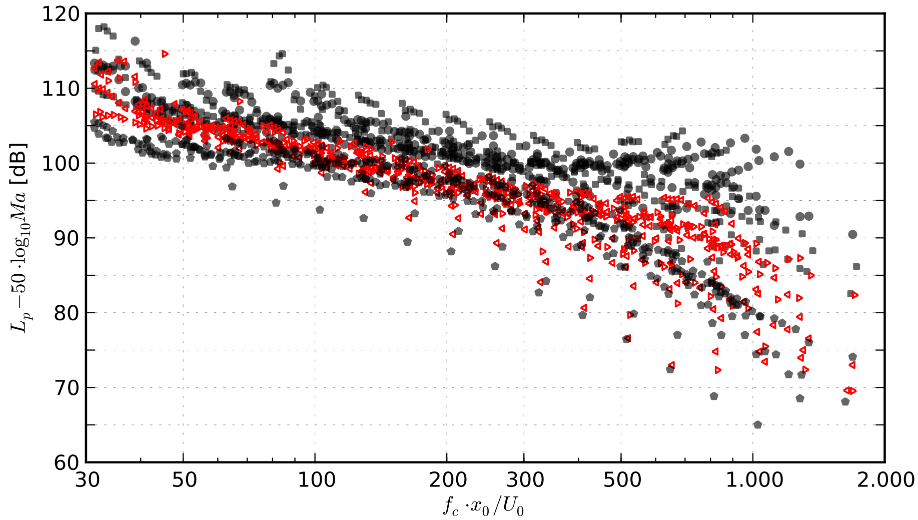


Figure 10. Comparison of the third octave band sound pressure levels, scaled with U_0^5, as a function of Strouhal number (based on an arbitrary dimension $x_0 = 1$ m), angle of attack $\alpha = 0°$ (● buzzard, ■ sparrowhawk, ⬟ pigeon, ▷ tawny owl, ◁ barn owl)

increases with increasing flow speed and with decreasing frequency. Regarding the maximum amplitude, it can be seen that the highest levels were measured for the second buzzard wing (30 dB) and the first sparrowhawk wing (34 dB), whereas the lowest maximum power spectral density levels were measured for both pigeon wings (21 dB and 22 dB). Still, it has to be kept in mind that the wings of the pigeon are also by far the smallest wings examined (see Table 1), and hence it does seem quite reasonable that they do not produce a very high total noise level. This circumstance will have to be considered in following scaling approaches. The second tawny owl wing also generated a relatively low maximum power spectral density level of 23 dB.

The dependence of the emitted noise on both frequency and flow speed is further examined as the third octave band sound pressure level spectra are plotted versus a Strouhal number $Sr = f_c \cdot x_0/U_0$, where f_c is the third octave band center frequency. Since no dimension of the wing lead to a better comparability of the results, x_0 is taken as an arbitrary dimension, which in the present case was chosen to be equal to 1 m. Additionally, the spectra are scaled with the 5th power of the Mach number $Ma = U_0/c$, with c being the speed of sound. This approach is commonly used for the scaling of edge noise[11] and was also applied to the results of the flyover measurements:[34]

$$L_{p,\text{scaled},1} = L_p - 10 \cdot \log_{10}(Ma)^5 \text{ dB}. \tag{4}$$

Figure 10 shows the resulting scaled third octave band sound pressure levels generated by the wings as a function of Strouhal number. In a first step, the results are given without consideration of aerodynamic performance or size of the wings. The scaling with $(Ma)^5$ leads to satisfying results. It can therefore be concluded that, although the noise sources may be located somewhere on the surface of the prepared wings, the aeroacoustic noise sources are essentially dipole (or "baffled" dipole[3]) in nature.

It can be seen from Figure 10 that the species that on average produce the highest noise levels are the buzzard and the sparrowhawk. The least noise is generated by the barn owl wings, the tawny owl wings and the pigeon wings. Again, the small size of the pigeon wings compared to the other wings has to be kept in mind. It is visible from Figure 10 that the difference between the noise generated by the buzzard wings and the sparrowhawk wings and that generated by the owl wings is noticeable, with a maximum noise reduction in the order of 20 dB at high Strouhal numbers.

Due to the limited frequency range of the acoustic measurements, it is not possible to draw conclusions on the noise generation at lower frequencies. A comparison between the examined bird wings and technical airfoils may allow for some further understanding. The spectral shape of noise generated by technical airfoils is characterized by a peak, whose frequency and magnitude depend on the dimensions of the airfoil, such as the chord length, and the flow speed (see for example the work of Brooks et al.[8]), and a decay towards lower and higher frequencies. No distinct peak is visible in the spectra shown in Figure 10, but only a noticeable decay with increasing Strouhal number. If it is assumed that such a peak also exists for biological wings

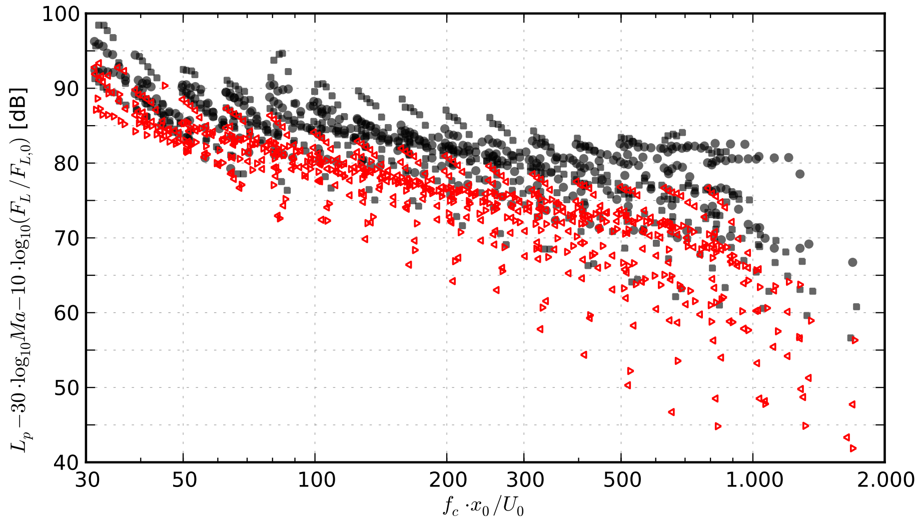


Figure 11. Comparison of the third octave band sound pressure levels, scaled according to Equation (5) using the measured lift forces F_L, as a function of Strouhal number (based on an arbitrary dimension $x_0 = 1$ m), angle of attack $\alpha = 0°$ (● buzzard, ■ sparrowhawk, ▷ tawny owl, ◁ barn owl))

(or, as in the present case, prepared biological wings), the spectra given in Figure 10 may implicate that the peak would be found at a frequency below the 630 Hz third octave band. This would be in accordance to the findings from Neuhaus et al.,[29] who state that the spectral peak in the gliding flight noise of the tawny owl lies between 200 Hz and 700 Hz. However, recent flyover noise measurements[34] showed that the flight noise of owls is significantly below that of non-silently flying birds in a frequency range above 1.6 kHz, and thus at frequencies that may well be detected in the present experiments. This observation is also in general agreement with the conclusion drawn by Lilley,[22] that the feather adaptations of the owl lead to a flight noise reduction in the frequency range above 2 kHz.

In order to allow for a better comparison of the noise generated by the wings from different species, and to account for differences in wing shape, the aerodynamic performance of the wings is included in the acoustic analysis. Following the model of Lilley,[22] the sound pressure levels are normalized in a first scaling approach by using the measured lift force F_L according to

$$L_{p,\text{scaled},2} = L_p - 10 \cdot \log_{10}(Ma)^3 \text{ dB} - 10 \cdot \log_{10}(F_L/F_{L,0}) \text{ dB}, \tag{5}$$

where $F_{L,0} = 1$ N. This approach was developed based on the fact that in equilibrium flight the weight of the bird is equal to the lift force, and the resulting sound pressure levels can be understood as the noise generated per unit lift force. Note that according to basic aerodynamic theory the lift force is proportional to the square of the flow speed, $F_L \propto U_0^2$, and hence the approach given by Equation 5 still includes a scaling with the 5th power of the flow speed.

The resulting scaled sound pressure levels are presented in Figure 11. The data for the two pigeon wings are not included due to the fact that the measured lift forces were found to be not usable. A comparison between the sound pressure levels given in Figure 11 and those from Figure 10 shows that now the trend is more obvious that the examined owl wings generate a lower noise level per unit lift force than the wings of the non-silently flying birds of prey. Again, the differences between the sound pressure level generated by the owls and those generated by the non-silently flying birds increase with increasing Strouhal number, which is in accordance to the findings from the flyover measurements.[34]

In a second scaling approach, the effective wing area will be included in addition to the lift force generated, and hence this approach uses the lift coefficient C_L as shown in Figure 8(a) according to

$$L_{p,\text{scaled},3} = L_p - 10 \cdot \log_{10}(Ma)^5 \text{ dB} - 10 \cdot \log_{10} C_L \text{ dB}. \tag{6}$$

Since the lift coefficient of a wing can be assumed to be a function of wing area, angle of attack and the spanwise distribution of camber and twist, this scaling approach indirectly considers these parameters. The resulting sound pressure levels of the wings from Table 1 are presented in Figure 12 as a function of Strouhal number (again, the data of the pigeon wings are not included).

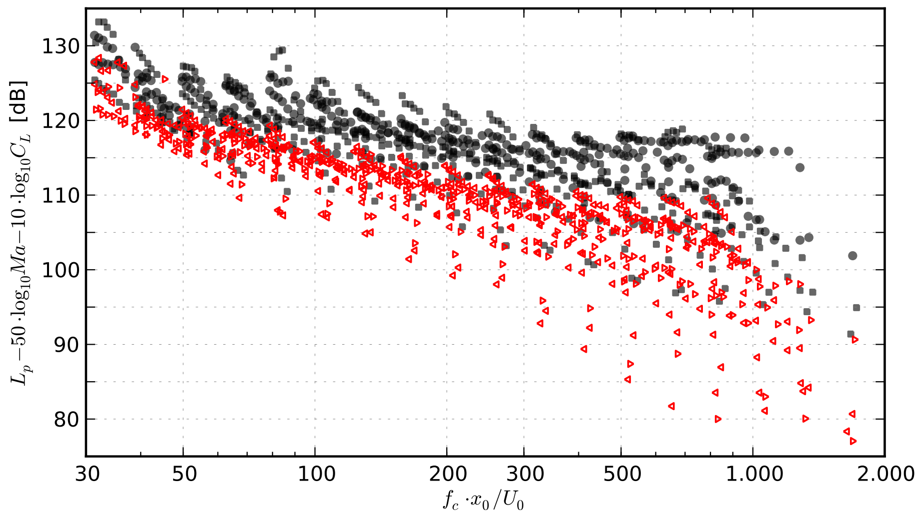


Figure 12. Comparison of the third octave band sound pressure levels, scaled according to Equation (6) using the measured lift coefficients C_L, as a function of Strouhal number (based on an arbitrary dimension $x_0 = 1$ m), angle of attack $\alpha = 0^\circ$ (● buzzard, ■ sparrowhawk, ▷ tawny owl, ◁ barn owl)

As in the previous figures, Figure 12 clearly shows that the scaled sound pressure levels measured at the wings of the owls are noticeably below those of the buzzard and the sparrowhawk. Since the presentation of the results in Figures 10 through 12 as a function of Strouhal number includes the dependence on flow speed U_0, the results confirm that the silent flight of the owls is indeed a result of their special plumage adaptations and not just a result of their lower speed of flight. The lower flight speed of the owl under natural conditions compared to the fast flight of the non-silently flying birds of prey only adds to the difference of the gliding flight noise emission.

IV. Conclusions

The silently flying species of owls have developed an adapted hunting system that combines a very good hearing to aurally locate the prey with distinct mechanisms of the wings and feathers that enable the nearly silent flight in order to not be heard by the prey.

This paper presents acoustic and aerodynamic results from wind tunnel experiments on prepared wings of five different species, including two silently flying owls. In order to examine the gliding flight noise of birds, these experiments are a complementary approach to flyover noise measurements, although the differences between the shape of a prepared wing and that of a living, gliding bird have to be kept in mind. The acoustic data were measured using a 56 channel microphone array and analyzed using a deconvolution beamforming algorithm applied to a three-dimensional source region. Sound pressure level spectra were then obtained through integration of the sound pressure contributions over a three-dimensional volume in the sound maps that only contains noise sources at the wing, but not the wind tunnel nozzle or the region where the wind tunnel shear layers interact with the wings. In order to account for differences in aerodynamic performance that may result from differences in the three-dimensional wing shape, different approaches are examined to normalize the sound pressure level spectra.

The observation of three-dimensional sound maps reveals that the locations of the noise sources are not necessarily the trailing edge or the wing tips. Although the study is limited concerning the shape and flexibility of the prepared wings available, the resulting sound pressure level spectra clearly confirm that the noise generated by the owl wings in gliding flight is significantly less than that generated at the wings of the non-silently flying birds of prey at the same flow speed, with differences between the third octave band sound pressure level spectra of the owl wings compared to those of the common buzzard in the order of 10 to 20 dB at high frequencies. Thus, the experimental results presented in this paper confirm that the silent flight of the owls is indeed a consequence of their special wing and feather adaptations and not only of their lower speed of flight, which is in accordance to the results from a recent flyover noise study.

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