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POTENTIALS FOR ACOUSTIC OPTIMIZATION OF ELECTRIC AERIAL VEHICLES

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Summary

Various configurations of electric aerial vehicles (e.g. electric vertical takeoff and landing systems - eVTOLs) for use cases like transportation of people and goods are currently being developed. These systems are based on distributed electric propulsion and thus have multiple rotors across the aircraft. However, these create loud and annoying noise, which is mainly caused by the rotors. This leads to problems regarding acceptance and obstructs market success. A framework for systematic acoustic optimization of electric aerial vehicles at early development stages is proposed in this paper. A classification of system levels of electric propulsion systems is developed. It focuses on rotor configurations and is detailed with characteristics of emerging electric aerial vehicles. Four system levels are identified. Based on that, a survey on noise reduction approaches for each system level is done. The survey is complemented with approaches from other domains like general aviation, helicopters and cars. Merging classification with survey, enables to rate characteristics of the identified system levels regarding acoustics and uncovers open research topics.

Keywords

Rotor Acoustics; Noise Reduction Technologies; Psychoacoustics; Distributed Electric Propulsion

1. INTRODUCTION

Aerial vehicles based on distributed electric propulsion (DEP) have gained great interest. Development of aerial vehicles for search and rescue missions [1], surveillance missions [2], transportation of parcels [3], or people [4] and medical aid [5] takes place. Multiple rotors are applied, which often create loud and annoying [6] noise, mainly caused by rotors [7]. The noise emissions however prevent acceptance of emerging electric aerial vehicles. Reduction of CO_2 and NOx emissions as well as noise emission of aerial vehicles by 65 % are goal of the European Comission for 2050 [8].

This paper contributes to the acoustic optimization of electric aerial vehicles at early development stages. A framework for systematic acoustic optimization is proposed:

- A classification of electric propulsion systems at aerial vehicles is presented. Four system levels, see Fig. 1, are identified: 1. blade design, 2. rotor configuration, 3. rotor integration, 4. overall vehicle design. Characteristics of each system level of emerging concepts are highlighted.
- Based on the classification, a survey on noise reduction approaches for acoustic optimization, including approaches from other domains is created. Noise emitted into the environment is focused.
- A comparison of the characteristics of the system levels and the survey uncovers open research topics and allows to identify acoustic measures applied at emerging concepts.

The paper is structured as follows. First, an introduction to acoustics of aerial vehicles is given, including psychoacoustic perception of rotor noise. Second, the classification of electric rotorsystems and its characteristics are presented. Third, the survey on noise reduction technologies is shown, assigning measures to the earlier defined system levels. Finally, improvement of acoustics at each system level and across system levels is discussed. Moreover, assessment of noise reduction capability of emerging concepts, rating of acoustic measures and valuable rotor sound using psychoacoustics are discussed. Open research topics are outlined.

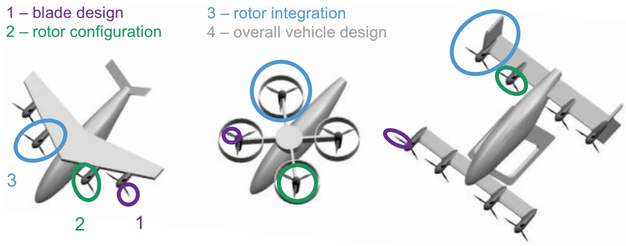

FIGURE 1. Classification of rotors of electric propulsion systems into four system levels, presented at three different aerial vehicles.

2. ACOUSTICS OF AERIAL VEHICLES

An introdcution to acoustics of aerial vehicles, definition of rotors, rotor acoustics and psychoacoustic perception of rotor noise is presented in the following.

2.1. Noise Sources of Aerial Vehicles

The acoustic signature of an aerial vehicle highly depends on its configuration and propulsion system. According to [9], the primary source of noise is the propulsion system, divided into engines with rotor and turbo-engines. At aerial vehicles with rotors, the rotors themselfs are according to [10] the primary source of aerodynamic noise. Main aircraft noise sources were identified by [11] for a conventional aircraft[1]: Airframe noise sources, lift and control surfaces, engine noise sources, interaction and installation effects. Even though these sources are derived from conventional systems, not including electric systems, measures concerning e.g. the airframe, might be transferable. Distributed

[1] single-aisle, tube-and-wing, medium-range transport aircraft

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eletcric propulsion (DEP) and revolutions per minute (RPM) control [12] are applied at electric aerial vehicles. It is often suspected, that electric propulsion systems allow reduced noise. Results by [13] support this. However, assessments by [14] indicate, that single electric engine aircraft produces higher noise annoyance compared to a single engine piston aircraft.

2.2. Definition Rotor

The terms rotor, propeller and fan are historically defined. Since emerging aerial vehicles apply multiple rotorsystems based on various historical definitions, the available terms are utilised diverse in current literature. Therefore a short historic overview is given in the following, completed with definitions used for this paper. The term propeller is used by [9], [10] to describe systems generating thrust in forward flight. Regarding classic engines, the term propeller is connected to turboprop engines (examples see [15]), too. The term rotor is used for helicopter systems providing vertical takeoff and landing capability by [10]. It is also used in combination with the term stator in the context of classic engines [9], [15]. The term rotor is moreover connected to so called open rotor concepts. An example of an open rotor concept is the open rotor counterrotating turbofan [15]. Sometimes the blades of a quadrocopter are described as propellers while the system is called to have four rotors, like done by [16]. The term proprotor is applied for aerial vehicles with tiltable structures, which enable rotating blades to be used for lift and forward flight, like [17]. Since this paper is focusing on emerging aerial vehicles using distributed electric propulsion, the terms *rotor* and *rotorsystem* are used as umbrella terms for historically distinguished propellers, proprotors, fans and rotors. In case a specific term is used in literature and is correctly used according to historic definition, it is also used in this paper (like "propeller" at the nose of a propeller aircraft).

2.3. Rotor Acoustics

Acoustic measures for electric rotorsystems, with rotors being the dominant noise source, in close proximity to humans have not been focused in the past. An introduction to rotor acoustics, focusing on aerodynamic noise transmitted into the environment, is given in the following. Aerodynamic noise is described by [10] as result of relative motion between a solid body and surrounding medium. An overview of aerodynmaic noise, including noise sources of propellers, rotors and fans, is given by [10], see Fig. 2. Most important noises generated by rotating blades on propellers are according to [9] rotational noise and vortex noise. Rotational noise [9], mostly the prevailing source, results due to rotating blades exciting air in the disc periodically, characterized by a discrete frequency spectrum harmonically related to the blade passage frequency (BPF):

$$f_1 = B \cdot \frac{n_P}{60} \tag{1}$$

with B - number of blades and n_P - rotational speed [1/min]. It contains loading noise, which is associated with production of thrust and thickness noise, caused by symmetrical volume displacement of air in the disc due to the finite thickness of the blade [9]. Three categories of noise are present at coaxial rotors [18]: Thickness noise, loading noise and high-speed impulsive (HSI) noise. Loading noise contains blade vortex interaction (BVI) noise, which occurs when tip vortices interact with a rotor blade [18]. High-speed impulsive (HSI) noise occurs at high speeds where transonic flow and shocks can form on the blade [18]. Vortex noise is based on unsteady random disturbances at blades and has as broadband noise a wide range above 1000 Hz [9]. [19] distinguishes between rotor and propeller noise components for auralization purposes. Emerging concepts apply mixtures of classic rotor and propellers for vertical takeoff and landing capability.

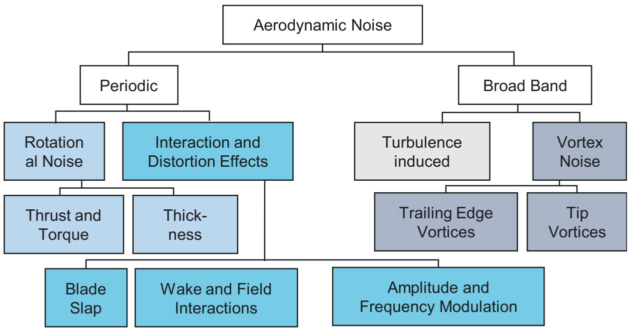

FIGURE 2. Aerodynamic noise sources adapted from [10].

Important noise components, transmitted into the environment, are shown in Fig. 3 for a single rotor in horizontal position. It can be observed, that the position of a rotor (horizontal or vertical) highlights different noise components for a observer at the ground. Fig. 4 presents frequency spectrum of ambient noise and rotor noise (symmetric blades X106 with a radius of 106 mm at 3000 rpm), measured at a hover-test-bench[2] at three microphone positions. The typical BPF, which belongs to the rotational noise, is marked with a blue f_1. The BPF is strongest in the rotor plane at microphone 1, while higher harmonics and broadband noise are strongest at microphone 3. This corresponds with earlier described theory. Since emerging aerial vehicles applying multiple rotors are going to operate in close proximity of humans, the reduction of SPL, but even more the quality of sound is significant. It can be determined using psychoacoustic sound quality metrics. These metrics are loudness [sone], roughness [asper], sharpness [acum], critical band rate [bark] and tonality [tu] [22] and provide a basis for annoyance models. Psychoacoustic metrics are applied extensively in automotive engineering, however only few studies are available for aviation, especially for electric propulsion systems.

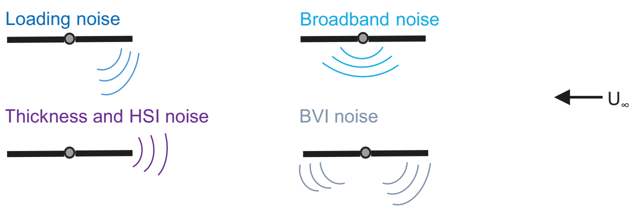

FIGURE 3. Important noise components for a single rotor in horizontal position, adapted from [20].

Annoyance aspects of aircraft sound, focusing on turbofan engines, were assessed using loudness, tonality and sharpness by [23]. Roughness was left out, since it is not as strong an annoyance factor as it is for aerial vehicles driven

[2] Details see [21]. Hover-test-bench is based on a propulsion system of the type DJI 4114. Walls of the hover-test-bench are covered with acoustic foam.

by rotors. The rotor noise presented in Fig. 4, has highest sharpness[3] in the rotor plane (microphone 1) and increase in loudness from microphone 1 to 3. Further analysis are required to detail psychoacoustic rating of rotor sound. Sound of electric ground vehicles is designed using existing sounds of auxiliary units and coordination of the various components, what creates a harmonic sound image of the full vehicle [24]. [25] found a systematic difference between the annoyance response generated by the noise of an aerial vehicle and ground vehicle. Still, sound design principles of electric ground vehicles could be used as first steps for optimization of electric aerial vehicles. Moreover [26] found, that acoustic properties, for example the impulsiveness of sound and nonacoustic parameters, like age or fear, are important factors of rotor noise annoyance [26]. Optimization of rotor acoustics considering psychoacoustics is recommended by [27], [28], to give hints to the acceptance of noise by the public [29].

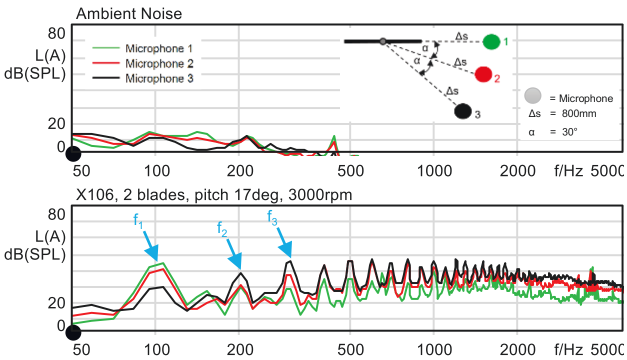

FIGURE 4. Frequency spectra of ambient noise and rotor noise.

3. CLASSIFICATION OF SYSTEM LEVELS OF ELECTRIC PROPULSION SYSTEMS

Emerging aerial vehicles applying electric propulsion are not yet fully understood regarding their acoustic signatures and optimization potential. Since noise is mainly caused by rotors [7], the electric propulsions system, in particular the rotor, has to be optimized. Acoustic interaction effects with the whole aerial vehicle should be considered as well. Building silent electric aerial vehicles in future can be supported by a structured approach. Therefore a classification of aerial vehicles focusing on the electric propulsion systems is required. The classification serves as a basis for a structured approach to optimize acoustics. During early development stages, when only digital mock ups of aerial vehicles are available, a classification combined with acoustic measures allows to prevent decisions leading to poor acoustics. Moreover measures for good acoustic performance can be fed into the development process without generating additional costs and weight at later development stages.
In the past, classifications were done, however neither looking at the propulsion system in detail nor at the environment of rotors. Five categories are e.g. distinguished by [30] focusing on the whole aircraft[4]. Main aircraft noise sources have been published by [11], however for conventional propulsion systems, not considering electric propulsion systems.
A classification of system levels considering details of the rotor itself and its environment is proposed in the following. The electric propulsion system is focused and connected with its surrounding parts. This allows to considers every acoustic measure possible to create optimal acoustic signatures. Four main system levels are identified:

1. Blade design,
2. rotor configuration (e.g. number of blades),
3. rotor integration (e.g. ducted or open rotor),
4. overall vehicle design.

The system levels are shown in Fig. 1 for three different examples of aerial vehicles. It can be observed, that the three examples show different features e.g. at system level 3 (rotor integration): A ducted rotor has potential for acoustic optimization (Fig. 1, middle), compared to an open rotor configuration (Fig. 1, left and right), which directly transmits its noise into the surrounding air. However thrust generation and the additional weight of the duct would have to be considered. Applying a classification complemented with acoustic measures and knowledge about penalties like additional weight, in early development stages, benefits silent and sustainable aerial vehicles.
To detail, which designs are conceivable for each system levels, an analysis of emerging electric aerial vehicles is done as a first step. Published photographes and data are used. The designs found for each system level, are structured applying geometric characteristics as decisive criterion. Geometric characteristics are reasonable, since they have direct impact on the displacement of air and thus on acoustics. Using a structure based on characteristics enables to assess acoustic behaviour and thus identify parameters benefitting acoustics. The results are presented in the following.
In chapter 4, a literature survey is done, explaining acoustic behaviour of the here derived characteristics. This shows to what extent acoustic measures are already applied at emerging aerial vehicles. Moreover possibilities for acoustic optimization of an aerial vehicle can be assessed and the acoustic performance of an aerial vehicle can be roughly determined.

3.1. System Level 1: Blade Design

Blade design has an impact on acoustics and efficiency, since it is the primary source of noise generation of the rotorsystem. Six different blade types have been found at emerging aerial vehicles. Fig. 5 shows an abstract summary of these types in 2D.

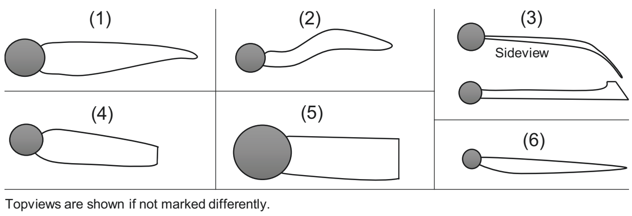

FIGURE 5. Characteristics of blade designs, found on emerging aerial vehicles.

[3] Calculations done with Headacoustics. Sharpness in [acum], Loudness in [soneGF] DIN 45631.

[4] Tilt-Body, Tilt Rotor and Tilt Wing, Rotor → Wings, different Lift/Propulsion, Tilt Blade and Tip-Path-Plane

First, blades with high pitch, twist and rounded curves are used, which narrow in direction of the blade tip (1). Blades were found at ducted rotors, that are formed along a z-structure, and remind of ”blue edge blades” applied at classic helicopters for improved acoustics (2). Special formed blades, like a drooping blade tip or squared geometries, are applied, too (3). Blades with small, angular blade tips and bended contours can be found (4). Wide, angular tips aligned with the duct conture with relatively short length are used for ducted cases often (5). Blades like (1) do not often occur in ducted configuration. Long and narrow blades with small tips and low twist are visible, too (6). These blade designs include features made for noise reduction. Especially designs like (2) and (3) are discussed in detail in chapter 4.1.

3.2. System Level 2: Rotor Configuration

The cofiguration of a rotorsystem influences acoustics and efficiency due to operational parameters as well displacement of air. Variance of rotor configuration on emerging concepts was found, see Fig. 6.

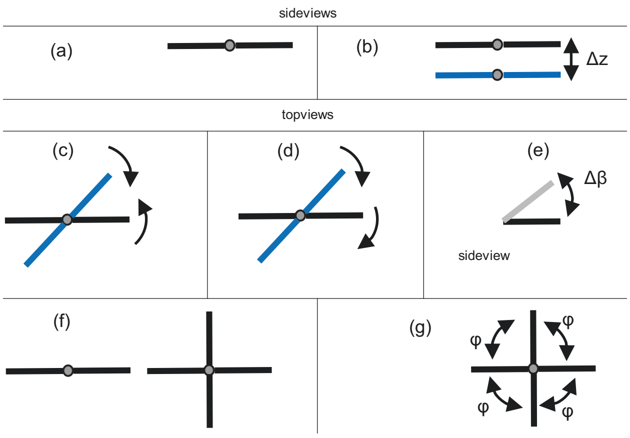

FIGURE 6. Characteristics of rotor configurations, found on emerging aerial vehicles.

Rotors are designed as single rotors (a) and stacked configurations, like coaxial rotors (b). Coaxial rotors are mostly positioned centered above each other. Blades often show sign of counterrotating configurations for coaxial rotors (c). Besides corotating rotors (d), active blade control via blade pitch is applied on emerging concepts (e). The number of blades on each rotor is varied from two to six, for most configurations (f). Higher numbers are applied at ducted rotors. Blades are distributed equally (g). No obvious difference in rotor configuration considering systems for lift or cruise only were found. Analysis and current assessments of these aspects are discussed in detail in chapter 4.2, highlighting influence on acoustics.

3.3. System Level 3: Rotor Integration

The environment of a rotor determines acoustic behaviour by its characteristics, due to interaction with the airflow of the rotor. It is identified, that the direct environment of a rotor at emerging concepts can be divided in open, ducted and other geometries. Open rotor environments apply no or only few components next to the rotor. Ducted rotors purposely apply geometry close to the rotor. Fig. 7 shows ducted single and coaxial rotors configurations found on emerging concepts. Rotors are also built into fuselages. Some aerial vehicles are using open or ducted rotors only. Mixed configurations are visible as well.

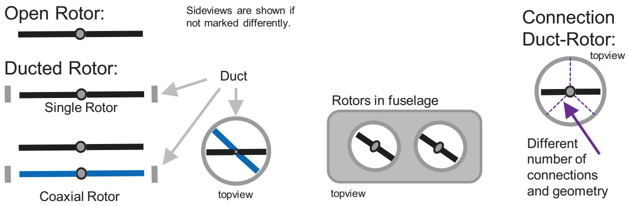

FIGURE 7. Characteristics of rotor integration (1): Direct rotor environment. Open rotor vs. ducted rotor(s).

The position of a rotor at an aerial vehicle contains further geometric environments next to the rotors, influencing efficiency and acoustics. Fig. 8 presents a selection of positions and environments found at emerging aerial vehicles.

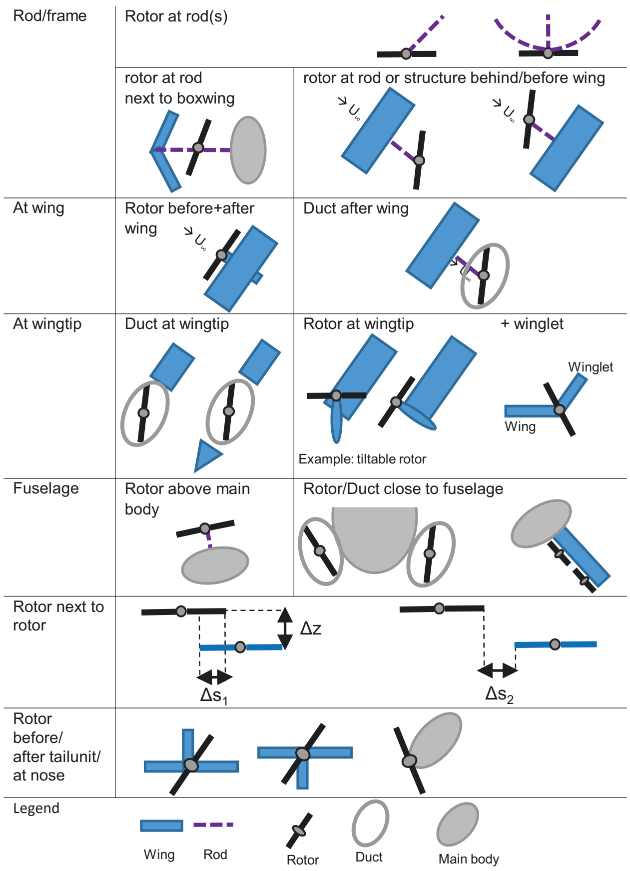

FIGURE 8. Catgeorization of rotor integration (2): Rotor locations at rods, wings et al.

Rotors are applied at classic components of aerial vehicles, like wings, fuselages or tail units, at any position conceivable. Rods and frames, sometimes in combination with wings are often used to mount a rotor to an aerial vehicle. Distances between rotors show huge variance on aerial vehicles in all directions of space. Distances as small as just preventing collission between rotors to huge distances close to the vehicle length can be seen. Overlapping configurations can be found as well. Influence of these topics on acoustics, as well as the current state of the art are discussed in chapter 4.3.

3.4. System Level 4: Overall Vehicle Design

Overall vehicle design is important to optimize acoustics, since structures can shield noise or change the overall acoustic signature by influencing the airflow. Fig. 9 presents eight categories of overall vehicle designs showing differences in geometry and thus presumably acoustic behaviour.

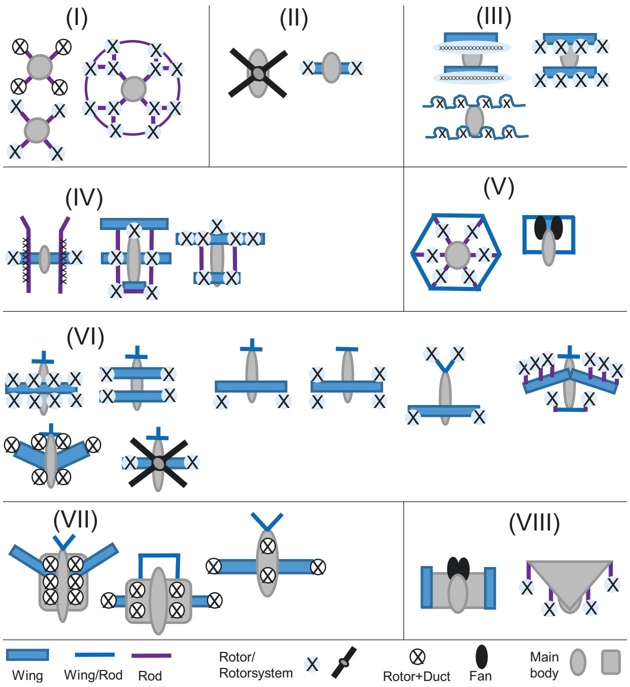

FIGURE 9. Characteristics of overall vehicle designs as schematic top views (presence of rotorsystems is marked, not orientation of rotorsystems).

Quadcopter and multicopter designs are applied with centered payload and rotors fixed at rods (I). Designs reminding of classic helicopters, sometimes using two rotors can be seen (II). Applications with two wings or one wing and a large tailplane with multiple rotors in front of each wing/tailplane are emerging, as well as channel wings (III). Some concepts are based on conventional aircraft designs combined with rods to mount multiple rotors on (IV). Other concepts use boxwing and add rotor or fans at rods or the fuselage (V). Rotors can be seen at wings and empennage of conventional looking aerial vehicles (VI). Large, flat fuselages for rotor integration are added to conventional configurations with wing and empennage (VII), reminding of Hybrid Wing Bodies (HWB) and Blended Wing Bodies (BWB). Variance also occurs for the number of rotors and the blade length. Electric helicopters with only one rotor with large blades to concepts applying close to twenty rotors with smaller blades are emerging. Details of acoustic influence are discussed in chapter 4.4.

4. NOISE REDUCTION TECHNOLOGIES AND OPTIMIZATION OF ROTOR ACOUSTICS

System levels of electric propulsion systems at aerial vehicles have been presented in chapter 3. In the following, a survey on noise reduction technologies and acoustic design approaches is done. Those are assigned to the corresponding system level and presented in the following.

4.1. System Level 1: Blade Design

Approaches to optimize acoustics of system level 1 (blade design), see Fig. 10 are presented in the following. Abstract sketches of discussed changes are shown applied at a symmetric, rectangular blade in Fig. 11 (1).

FIGURE 10. System level 1: blade design.

4.1.1. Overall Blade Geometry

Important parameters for blade design are global parameters (radius, tip Mach number, number of bades), blade layout (distribution of profile depth, twist, sweep, geometry of blade tip) and profiling (radial distribution of profiles) [31]. The parameters blade tip (chapter 4.1.2) and blade radius, which is directly connected with the number of blades (chapter 4.2.1) have influence on acoustics. Increase of blade radius, combined with reduced rpm leads to acoustic benefits, however cost and weight increase [32]. Blade twist did not significantly affect thickness and loading noise of a coaxial rotor in calculations done by [33]. The analysis was done in simulation for blades with a radius of 0.76 m, which allows however no general statement. A prominent example of blades reducing noise generated from blade-vortex interactions (”blue edge blades”), applies a double swept configuration [34], see Fig. 11 (2). Reduction of rotor noise of 4-7 dB was shown [35]. Swept blades reduce according to [36] aerodynamic losses and additional noise, due to phase lag of sound signatures and thus limiting increase of higher harmonic noise levels. Sweep becomes effective for noise reduction at high-speed cruise, due to relatively high Mach numbers at blade sections [37]. Further analysis are required to connect geometric parameters of blades with acoustic behaviour.

4.1.2. Shape of Blade Tip

This chapter focuses on blade tip shapes improving acoustics. A review of helicopter blade tip shapes by [38] showed a wide variety of explored concepts, however no consensus regarding the ’best design’ exists. Three types of blade tip designs are mostly used depending on the country, see Fig. 11 (2) [38]: USA uses the sheared-swept tip or swept-tapered-anhedral tip, Europe uses the parabolic tip and UK the BERP[5] tip [38]. A swept tip shows a reduced tendency for a shock to develop [38].
Drooping blade tips, see Fig. 11 (3), can according to [39] reduce the approach noise by moving tip vortices away from the following blade and thus reducing blade vortex interactions. Potential of ”winglets” at blades analyzed by [40], led to overall higher noise emmission compared to an equal blade without winglet, while sharpness decreased, which increases subjective tolerability. Experimental results by [7], [41] appear promising to improve acoustics due to

[5] British Experimental Rotor Programme (BERP)

assymetric blade tip design. Those variations of blade tips did not uniformly lead to acoustic optimization, however potential regarding psychoacoustics seems to exist. Designs to split tip vortex to reduce rotor noise have been tried, however with limited performance potential [38]. Easier potential lies according to [38] in low volume tips and low tip speed. The influence of tip speed is discussed in detail in chapter 4.2.1

4.1.3. Serrations

Noise reduction due to serrations at leading or trailing edges of blades is discussed in literature. Fig. 11 (4) shows serrations (left) and anti-phase noise redcution concepts with trailing edges waves by [7], [41] (right), designed for noise reduction. Leading edge serrations can according to [42] be sawtooth serratios, sinusoidal serrations or changes of chord triangularly or sinusoidally in spanwise direction, inspired by whales [43], [44], see Fig. 11 (5). Noise reduction emerges due to the interaction of the boundary layer flow with the edge [45]. Positive changes in acoustics due to serrations were found by [46] for axial fans, [47] at high serration amplitudes and [45] at reduced far-field high frequency broadband noise. Reduced noise at low to mid frequencies was found by [48], high frequencies however increased. Negative effects on efficiency were found by [46], especially for serrations at the blade tip, see Fig. 11 (4). Potential for acoustic optimization due to serrations was found, however deterioration at certain frequencys and deterioration of efficiency was also observed. Application of serrations should be done carefully.

4.1.4. Bio Inspired

Analysis of blade geometries and surfaces inspired by nature are researched for acoustic optimization of blades, see Fig. 11 (5). Numerical investigations of owl wings by [49] and wind tunnel measurements by [50] indicate, that structures of owl wings at leading and trailing edge, as well as soft, porous upper surfaces optimize acoustics. Treatments replicating effects of owls, see Fig. 11 (6), provided up to 10 dB broadband attenuation of trailing edge noise [51]. Application on rotor blades however was not done. Blades designed like a maple seed and the wing planform of a cicada were experimentally tested for hover flight condition by [52]. Equal thrust at equal power input and reduced noise by up to 4 dB were found. Slower rotational speed was observed and smaller wake regions were generated [52]. Blades inspired by maple seeds attained higher reduction of turbulent trailing edge noise compared to serrated trailing edge blades with no efficiency decrease [53]. Studies analyzing bio inspired blade geometries are conducted, however applications at rotating blades do not show high maturity.

4.1.5. Material and Surface Properties

Material and surface properties have influence on acoustics and efficiency. A change of helicopter broadband noise because of surface roughness during ice accretion was observed by [54]. High frequency broadband noise increased with surface roughness heights. A comparison of blades made from different material was done by [55]. Since no comparable weight and geometries were used, the resulting quieter carbon fiber blades cannot be deduced as general results. Further analysis regarding surfaces and material properties are necessary to derive universal statements.

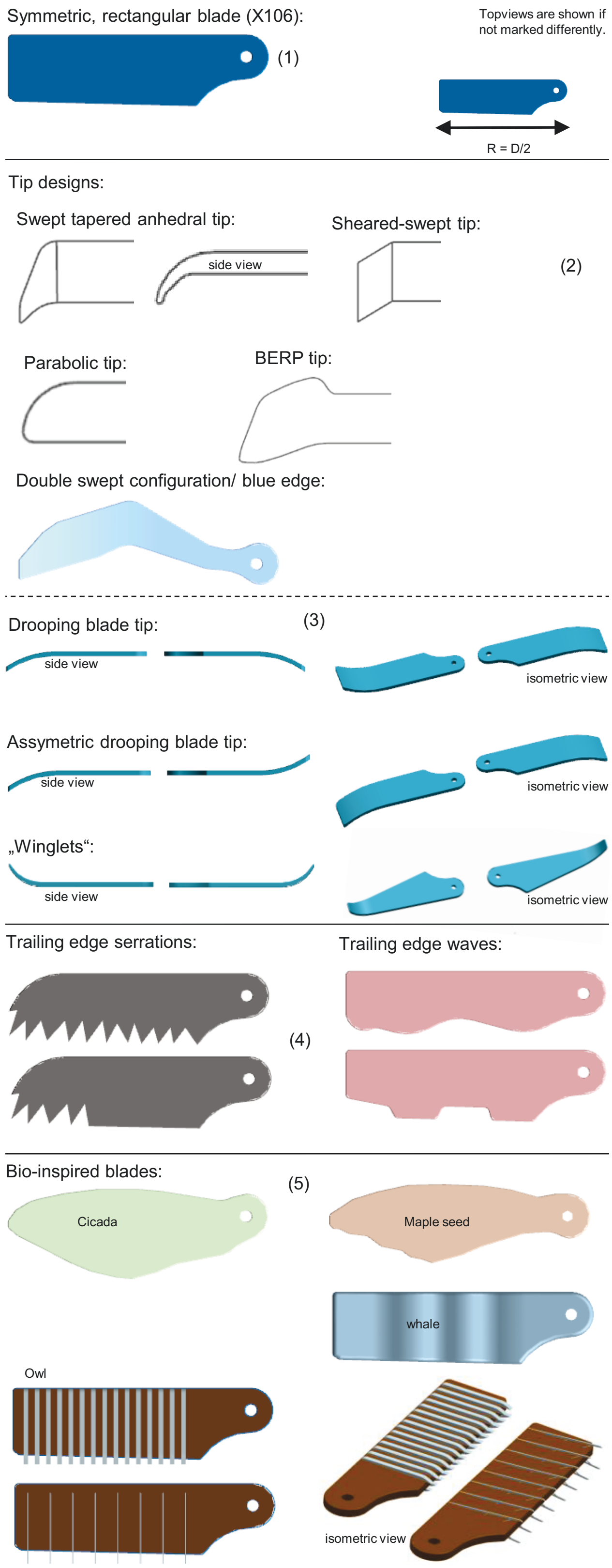

FIGURE 11. Sketches of changes in blade geometry for acoustic optimization.

4.2. System Level 2: Rotor Configuration

Approaches to optimize acoustics of system level 2 (rotor configuration), see Fig. 12, are presented in the following.

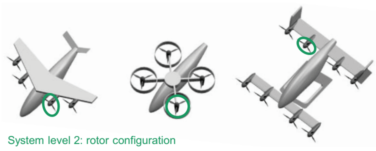

FIGURE 12. System level 2: rotor configuration.

4.2.1. Number of Blades and Rotational Speed / Tip Speed

Acoustics can be influenced by the number of blades, see Fig. 13 (left) at a rotor as well as tip speed. Increasing the number of blades decreases acoustic signature [56], [57]. Reduced SPL with increased number of blades at same thrust, was shown by [59], [55]. Increasing the number of blades, however increases weight [39]. BPF and higher harmonics are changed due to increased number of blades. An increased number of blades allows lower rotational numbers at same thrust. Like [58] states, multi-blade configurations applied at helicopter tail rotors, lead to low noise power emission due to reduced tangential velocity of blade tip. Drop in efficiency however was found by [60]. If the number of blades is fixed, noise reduction can be done by reducing rpm [56], [61] and thus tip speed [36], [57], [39]. Blade tip speed V_{tip} describes the velocity of the blade tip relative to the air [9]:

$$V_{tip} = \sqrt{V^2 + (\omega R)^2} \qquad (2)$$

with V - flight speed, ω - angular velocity, R - blade radius.

4.2.2. Distribution of Blades

Another approach to optimise acoustics with a fixed number of blades is to change the angles between the blades, so called uneven blade spacing (UBS), see Fig. 13. Applying UBS at a rotor redistributes the tonal content across the audible spectrum and thus reduces annoyance [62]. Reduction of SPL and improvement in sound quality due to UBS and low rotor tip speeds were presented by [62]. Unevenly distributed rotor blades are applied at the Fenestron ®. Dominant shrill noise related to the BPF and corresponding harmonics are modulated [29]. However for application at aerial vehicles, it has to be considered, that additional effort and weight may be neccessary for UBS due to balancing.

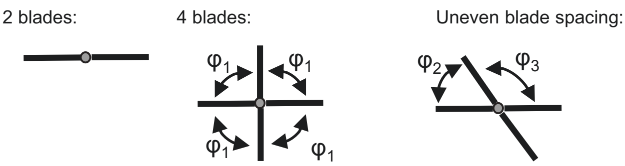

FIGURE 13. Optimizing acoustics by increasing the number of blades and the distribution of blades.

4.2.3. Design of Rotor Planes (Single/Coaxial)

Single rotors as well as coaxial rotors, can be found at emerging aerial vehicles. Coaxial rotors have advantages regarding building space, since additional thrust can be generated with only few additional space. Comparisons of the acoustic signature and efficiency of single and coaxial rotors are discussed in detail in literature. A 2-bladed coaxial rotor requires according to [63] less power than a 4-bladed rotor of the same solidity and more than 2-bladed rotors of the same solidity [33]:

$$\sigma = \frac{b \cdot c}{\pi \cdot R} \qquad (3)$$

with b - number of blades, c - blade chord and R - blade radius. Coaxial rotors have according to [36] similar dominating noise source mechanisms and radiation characteristics as a single rotor in disturbed inflow. According to [33], the peak thickness and loading noise levels of a hovering coaxial rotor occur in the plane of the rotor. A coaxial rotor is noisier than a equivalent single rotor according to [64], [33]. Extensive research has been done regarding the optimal distance between coaxial rotor Δz, see Fig. 14. Analysis done by [33] support the conclusion of [63] that for the axial separation $\frac{\Delta z}{D} > 0.05$ little effect on performance occurs. [65] found this for $\frac{\Delta z}{D} > 0.15$. Optimum distance at $\frac{\Delta z}{D} = 0.13$ was found in [21]. The bottom rotor experiences steeper wake velocity gradients, which results in the amplification of higher harmonic noise levels [36]. Positive influence on acoustics by increasing the axial separation was found by [36], [53], [64].

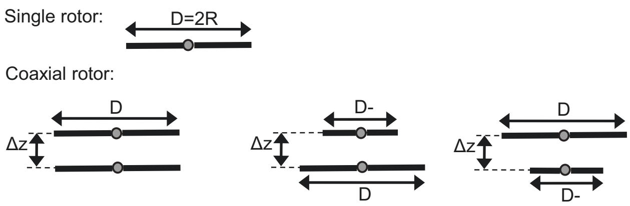

FIGURE 14. Parameters of single and coaxial rotors.

4.2.4. Active Blade Control

Another measure for optimization of acoustics are active blade control systems. Higher Harmonic Control (HHC) [66] and individual blade control (IBC), have been applied on helicopters for simultaneous reduction of noise and vibration [39]. 1-2 degree of blade pitch can influence rotor behaviour significantly [39]. However these systems add weight and components. Changes of the blade pitch influence acoustics, like shown by [45]. Greater broadband and tonal noise is generated by small rotating blades at low Reynolds numbers, when increasing the pitch angle due to increased interaction of flow [45]. Moreover active modification of airfoil geometry is applied at helicopter blades. However the typical sizes of control systems and actuators are not suitable for smaller blades [67]. Systems have been applied at large helicopter rotorsystems, however required space and weight is questionable for smaller rotors.

4.2.5. Phase Control and Sense of Rotation

Options for acoustic optimization based on sense of rotation and phase control are presented in the following. Direction of rotation is discussed in literature for coaxial rotors and

side-by-side rotors. So called synchrophasing of propellers is applied at propeller aircrafts to minimise noise and vibration in aircraft cabins by synchronising rotors and maintaining phase angles [68], [69]. However active systems like synchrophasing lead to additional complexity, costs and weight depending on required actuators [68]. The influence of different synchrophase angles can be determined using propeller signature prediction by [70], which predicts harmonic noise from the vector sum of the contributions [68]. Noise reduction potential of synchrophasing is dependent on the number of rotors [68], since reduced number of rotors reduces available phase angle combinations [71].
Phase Control for DEP as an advancement of conventional synchrophasing was presented by [72], controller design by [73]. Rotors were positioned side-by-side, corotating, see Fig. 15 and counterrotating rotors were analyzed. Modification of the overall directivity of the BPF noise was presented. Larger benefits were found for higher number of rotors and all rotors rotating in the same direction. Phase control at coaxial rotors is illustrated in Fig. 15. It was tested by [64], however no positive effect on acoustics occured.

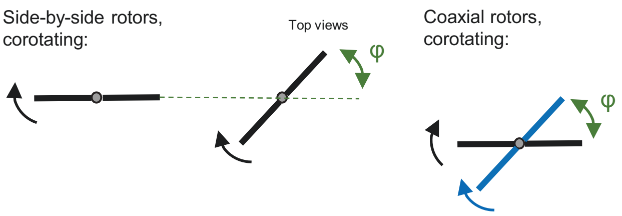

FIGURE 15. Phase control for DEP of side-by-side rotors and coaxial rotors. Example shows corotating states.

Different statements can be found in literature regarding sense of rotation. Corotating rotors could according to [68] lead to assymetry of noise and vibration patterns. However corotating side-by-side rotors can better be optimized regarding acoustics as per [72]. However [74] found, that counter-rotating options appear best in terms of acoustics. Detailed studies concerning the changes in acoustic signature including psychoacoustics on phase control are not available.

4.2.6. Electric Motor Noise

Besides rotor noise, the acoustic signature of electric motors is also new to aerial vehicles. Anaylsis of rotors by [75] showed, that motor noise peaks exist in direction normal to the motor-rotor-axis. Adding blades to the motor resulted in additional BPF tones and higher harmonics and increase of broadband noise across the spectrum [75]. Important to know is, to which extent electric motor noise contributes to the acoustic signature. Experimental results by [76] note, that electric motor noise does not substantially contribute to noise signature. According to [28] however, electric machinery noise e.g. from motors, generators, converters has major impact on acoustics signature of propulsion systems. No clear answer can been found in literature.

4.3. System Level 3: Rotor Integration

Rotors at aerial vehicles are facing different environments. The analysis done in chapter 3.3 identified that open and ducted environments exist, as well as geometries of the aerial vehicle itself (rods, frames, wings, main bodies, ducts and empennages). Approaches to optimize acoustics of system level 3 (Rotor Integration), see Fig. 16 are presented in the following.

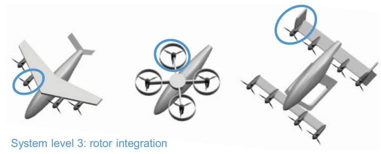

FIGURE 16. System level 3: Rotor Integration.

4.3.1. Ducted Rotors

Ducted or also called shrouded rotors are used for various reasons. They provide better crash worthiness and safety [77] compared to open rotorsystems. Experimental proof of improved overall efficiency has been shown in the past [78]. According to [78] ducts can potentially dampen the noise signature of the rotor. Acoustic masking effects especially in the rotor plane are known from tail rotors [58]. A negative effect due to increased blade tip clearance on broadband noise level and efficiency was found by [79]. [77] found no influence of ducts on SPL, however higher tonal content for cases with higher vortex core/duct interactions. Active acoustic measures at ducts are not visible at emerging concepts of electric aerial vehicles. However transfer of acoustic measures of other disciplines could be analyzed. One example are measures applied at charge air ducts of classic engines and turbochargers, like resonators, reinforcement structures or absorption measures, see [22]. Chevron designs, see Fig. 17, are used on jets to reduce noise by shielding through altering the location of jet noise sources [80]. Rotors integrated in wings, fuselage or empennage have been identified in chapter 3.3. Analysis on major turbulence phenomena of such configurations, however no acoustic analysis, can be found in [81].

FIGURE 17. Open rotor (left) in comparison to a ducted rotor (middle) and ducts with "Chevron" designs applied.

4.3.2. Rods, Wings and Empennage

Rotors are positioned at various structures at an aerial vehicle. Objects can occur in the in- or outflow of a wake generated by a rotor. Noise reflection towards the ground should be avoided, as well as interaction between wakes and structural elements [82].
Objects in the outflow of a rotor are discussed in the following. Increase of noise when a wake interacts with a surface was found by [83]. An assymetric wake results when positioning the rod in the outflow [84]. Experimental results by [60] suggest thin rods for best performance. A tractor configuration, see Fig. 18, is often used at aerial vehicles. Increase in SPL was found by [85] for an open rotor engine in front of a wing. Increase in broadband noise, however

little change in harmonic noise results, since pressure fluctuations at the wing due to the rotating wake are less powerful than steady pressure loads of the propeller [86]. Streamwise position has little effects on noise according to [86] and efficiency [87], see Fig. 18, Δx. According to [88] however close placement of the rotor at the wing (0.17 D) translates into larger airframe drag. Harmonic noise increases, when positoning the wing vertically away from the propeller axis, see Fig. 18, Δz [86], however drag increases [87]. Spanwise position, see y-Position Fig. 18, is insignificant regarding efficiency at conventional positions [87].

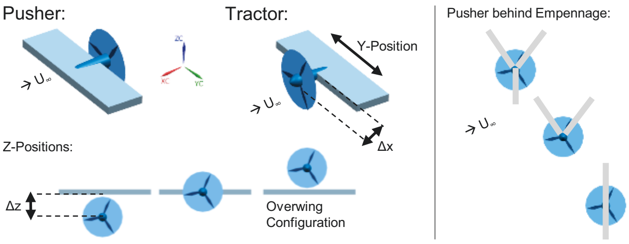

FIGURE 18. Positions of rotors at wings. Configurations based on [89].

Objects in the inflow of a rotor are discussed in the following. Undisturbed, uniform and axis-symmetric inflow is desireable for noise reduction [82]. Obstacles in the rotor inflow lead to additional unsteady blade forces and thus noise generation [36]. A pusher propellers behind empennages, see Fig. 18 has strong effect on noise above the first few harmonics of BPF due to interaction of empennage wakes with the propeller and thus unsteady blade loads on the propeller [90]. Increase of distance between propeller and empennage decreases noise [90]. Y-tail and V-tail noise decrease in the plane of the propeller while I-tail noise is uniform in all directions [90].
Considering these information, objects have neither positiv effect on acoustic in the inflow nor the outflow of a rotor. Few information is available that rates both cases. [84] found higher SPL at higher harmonics, when positioning a rod in the inflow. Distances between rotor and object are suggested to be large by multiple studies. Potential for acoustic optimization is given by so called overwing configurations. Shielding effects of this position are discussed in chapter 4.4.1.

4.3.3. Distance between Rotors

The analysis done in chapter 3.3 identified huge variety of applied rotor distances at emerging concepts. Experimental tests of two identical rotors side by side, see Fig. 19, rotating in opposite direction were done by [91]. Small distances between rotor axis Δa_1 of minimum 2.1 R showed worse rotor performance, compared to 2.4 R, presumably due to inter-rotor wake interaction. [92] did not find acoustic effects when changing Δa_1. However SPL of counterrotating systems was higher than of corotating ones. Experimental results of overlapping rotors about Δa_2 by [60], [93] suggest that efficiency decreases with overlap compared to two isolated rotors. However [93] found increase in efficiency for partial overlapping at $0 < \frac{\Delta a_2}{D} < 1$. Examples of overlapping rotors at aerial vehicles are shown in [94], [95]. For $\Delta a_2 = D$, coaxial rotorsystems arises, see chapter 4.2.3.

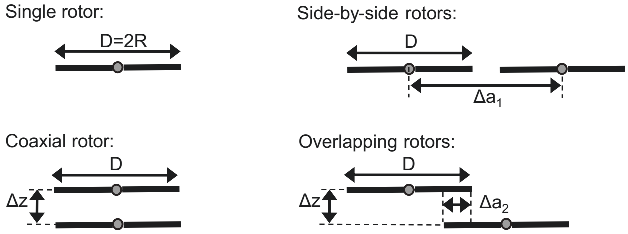

FIGURE 19. Parameters of rotor positioning.

Variations in blade radii and axial separation are parameters for acoustic design of coaxial rotors. Different recommendations regarding blade radii at coaxial rotor exist, see Fig. 14. According to [60] a coaxial rotor configuration should have a ”slightly smaller diameter” at the bottom rotor (contraction of flow) and ”slightly higher pitch angle” (operation in accelerated flow) at the bottom rotor. However calculations done by [33] confirm the findings in [96], that a reduction in top rotor radius of roughly 10 % over the bootom radius can reduce required power, while not influencing thickness and loading noise significantly.

4.4. System Level 4: Overall Vehicle Design

Approaches to optimize acoustics of system level 4 (overall vehicle design), see Fig. 20 are presented in the following. This includes shielding effects, number of rotors, distances between rotors as well as material selection.

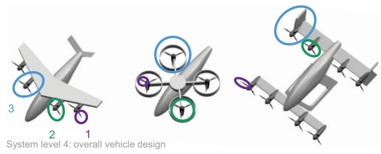

FIGURE 20. System level 4: overall vehicle design.

4.4.1. Shielding

Optimization of the acoustic signature through shielding effects has been investigated for channel-wings, tail configurations and unconventional aircraft configurations, see Fig. 21. According to [82], the integration of propulsion systems should be optimized according to noise shielding effects. Exemplary, low noise aircraft concepts are shown in [11]. These concepts apply motors mostly above wings, empennages or structures. Blended Wing Body configurations (BWB) and Hybrid Wing Body Configuratiosn (HWB) are discussed regarding improvements on acoustics and efficiency, see [97]. Unconventional aircraft configurations[6] show shielding levels down to 30 dB [98]. Maximum shielding efficiency at a BWB would intuitively be given at an engine position away from the edges of the airframe [99], see Δx, Fig. 21. However engine location has to be upstream the BWB trailing edge to avoid servere interference with high speed flows at cruise [99]. Shielding benefits at positions upstream the trailing edge (1-2.5 D) were presented by [85], [100] at BWBs and HWBs.
Comparisons of a conventional tail, T-tail or U-tail, see Fig. 21, by [85] showed that positioning engines at a U-tail leads to noise reduction.
Vertical tails, see BWB in Fig. 21, provide a clear shielding

[6] DLR Low Noise Aircraft (LNA), NASA Hybrid Wing Body Configuration (HWB), UCAV configuration (DLR F17E)

benefit torwards the sideline, however increase noise below aircraft sligthly [100].
Moreover, wings can be used and designed for shielding effects. Shielding levels increase when a sound is positioned close to the mid-chord of the airfoil [101]. Channel wings are used for acoustic optimization. Design parameters, see Fig. 21 were analyzed by [102]. Axial position Δx of the propeller has hardly any impact on propeller efficiency, however a front position reduces lift/drag significantly [102]. Overall efficiency is almost not influenced by channel depth Δz_c, axial propeller position and clearance between wing and propeller Δb, what allows to find an optimum position regarding acoustics without restrictions regarding efficiency [102].

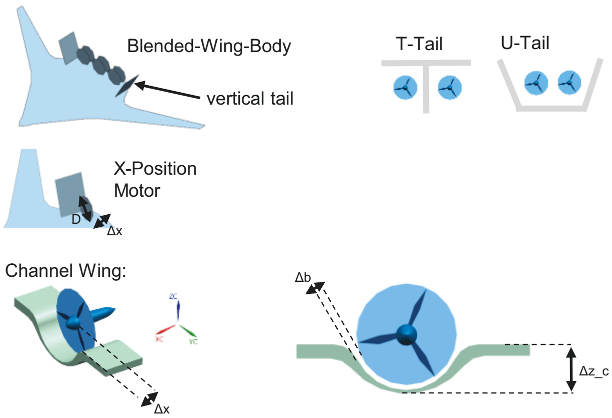

FIGURE 21. Noise reduction due shielding effects.

4.4.2. Number of Rotors

Influence of the number of rotors on acoustics is discussed in the following. According to [14] overall SPL can be reduced increasing the number of electric engines and reducing maximum tip Mach number. However [6] found that annoyance increases with increasing number of propellers. Annoyance did not vary significantly with the relative rpm between propellers. Therefore potential benefits of a spread frequency approaches for reduced annoyance might be limited [6]. Different numbers of rotors analyzed by [76], showed nearly identical acoustic characteristics. Changes of direction of rotation and rotor location also showed invariant spectra [76]. However [103] found, that broadband noise increases significantly with number of rotors. Negative influence on acoustics due to increased number of rotors has been found, however no clear statement can derived from literature.

4.4.3. Materials and Porous Treatment

Reduction of noise due to porous material is discussed in literature. Porous treatment at trailing edges by [104] and acoustic lining inserted flush with elevon and airframe surface by [85] indicates potential for noise reduction. [105] found best results of porous covers to minimize flow noise of landing gears, in materials highly permeable to air. Metamaterials, composites scaled smaller than a wavelength, for noise reduction due to absorbtion are discussed in [106], [107]. Potentials for applications involving moving fluids are still undisclosed [106], however basic effectiveness for low-frequency noise transmission has been shown [107]. Influence on weight, size and aerodynmics is open [106]. Moreover light-weight composite materials providing high acoustic transmission loss for airframe fabrication are discussed in [108].

4.4.4. Operations

Another potential for acoustic optimization is the design of operations. To reduce annoyance of aerial vehicles applying rotors, a combination of low noise designs and operations has to be done [61]. Low-noise operations can according to [28] be achieved throught low-speed approaches, since noise sources strongly correlate with flight velocity. Low noise operations have been implemented for classic helicopters.

5. DISCUSSION

A framework for systematic acoustic optimization of electric aerial vehicles has been presented in this paper by identification of system levels (chapter 3) complemented with a survey on acoustic measures (chapter 4). In this paper a literature survey has been used to describe the acoustic infuence of each system level. This however does not cover all characteristics found on emerging concepts as well as arising penalties, like additional weight. Further analysis are necessary to add those information.
Chapter 5.1 compares the acoustic potentials of each system level with the characteristics found at emerging aerial vehicles. Three cases are identified: First, acoustic measures are found in literature, that are applied at emerging concepts (e.g. drooping blade tips). Second, characteristics are found at emerging concepts, that have not been addressed in literature (e.g. ducts at the bottom rotor of a coaxial rotorsystem), which indicates open research topics. Third, acoustic measures are found in literature, that are not yet applied at emerging concepts. For those, further research and development is required. Acoustic optimization based on system levels, overall noise reduction capability of emerging concepts, rating of acoustic measures and creation of valuable rotor sound using psychoacoustics are discussed in the following.

5.1. Acoustic Optimization at each System Level

System level 1 (blade design): Blade geometries applying a double swept configuration ((2) in Fig. 5) or drooping blade tip ((3) in Fig. 5) can be observed on emerging concepts and have potential for noise reduction as analyzed in chapter 4. However additional noise reduction concepts, like bio inspired blades or serrations, are discussed in literature, that could be considered for application at emerging aerial vehicles. The characteristics shown in Fig. 5 are thus enlarged by the blade designs found in chapter 4. Further analysis are required to connect geometric parameters of blades with acoustic behaviour. Moreover profound psychoacoustic analyses are missing.
System level 2 (rotor configuration): Some acoustic measures described in chapter 4, are visible at emerging concepts (e.g. increased number of blades, active blade control). To some extent, parameters for acoustic improvement of rotor configurations are already known (e.g. distances at coaxial rotors). However open topics exist. Additional potentials are discussed in literature, like unequal distribution of blades. Those characteristics thus have to be added to system level 2. Well known parameters, like increased number of blades, reduced rotational speed and tip speed should further on be investigated concerning psychoacoustics. Further research on phase control, variance in rotor

radii at coaxial rotors, unequal blade spacing, sense of rotation and electric motor noise is needed. Optimal configurations do not seem to be found yet.
System level 3 (rotor integration): Acoustic measures for positions of rotors at wings are available for conventional configurations and might be transferable. Acoustic measures for trivial cases like one rod in the outflow are also available. Emerging concepts however apply much more complex designs, see Fig. 8. It is known from literature, that acoustics deteriorate due to interaction of rotor wakes with rods and wings. However only little is known, how those should be designed to lessen acoustic consequences. Design of the integration environment focusing on acoustics first is often not done due to more pressing issues like weight. Ducted electric rotors, especially ducts at the bottom rotor of a coaxial rotorsystem or rotors integrated into a fuselage, have not yet been discussed in literature. Also ideal distances between rotors regarding psychoacoustics are open.
System level 4 (overall vehicle design): The literature survey allows to rate the characteristics of overall vehicle designs derived in Fig. 9. Characteristics (VII) and (VIII) remind of HWB and BWB concepts, which are known for acoustic benefits due to shielding abilities. Same applies for channel wing configurations ((III) in Fig. 9). Acoustic rating of increased number of rotors is contradictory in literature, especially when considering psychoacoustics. Moreover it is open, how multiple rotors should be positioned considering shielding effetcs.

5.2. Assessment of Overall Noise Reduction Capability of Emerging Concepts

Comparing emerging aerial vehicles (chapter 3) with acoustic measures (chapter 4), leads to the conclusion, that further acoustic optimization of electric aerial vehicles is possible. Shielding capabilities seem to be often not considered at emerging concepts with high numbers of rotors and rods. However, reasons exist for not creating ideal acoustic conditions, when designing an electric aerial vehicle. Contradictions with building space, efficiency, weight or structural requirements can occur. Changing systems for improved acoustic behaviour can lead to conflicting measures [56] and penalties. An overview, regarding cost, weight, structural reliability and performance is given by [32]. Increasing number of blades, variable pitch or unequal blade spacing for example lead to increased costs [32]. Adding further experimental analysis of acoustic measures and resulting penalties to each system level, can introduce acoustic optimization during early digital development steps at digital mock ups.

5.3. Acoustic Optimization across System Levels

It stands out, that measures optimizing acoustics presented in chapter 4 often focus on single aspects of one system level only. Combinations of measures are proposed by [39] (rotor tip speed, blade geometry, HHC), [67] (serrations, porous material, geometry changes), [36] (reduced tip-speed, increased number of blades, ducts, uneven blade spacing), [57] (reduced tip speed, increased number of blades). This indicates, that interplay of acoustic measures is possible. To what degree single improvements of acoustics can be summed up when applying more than one measure at an aerial vehicle is not known. Investigations focusing on acoustic optimization across system levels, like interaction of increased number of blades and ducts are required.

5.4. Rating of Acoustic Measures and System Levels

Huge differences regarding blade sizes, configurations of aerial vehicles, placement of microphones and used facilities (e.g. anechoic chamber) have been found in the studies cited in chapter 4. Therefore no rating of the effectiveness of an acoustic measure compared to another is inferable. Analyses of acoustic measures under defined boundary conditions are required to enable rating.
Measures for acoustic optimization for each system level have been presented in chapter 4. Open however is the question, which system level contributes how much to acoustic optimization. Experiments by [27] for example indicate, that blade geometry (system level 1) has much larger effect on acoustics than supporting structures (system level 3, rotor integration). Knowledge about the potential of each system level regarding acoustics, efficiency and adjacent topics, would allow to decide, where to invest for good acoustics during early development stages.

5.5. Valuable Rotor Sound using Psychoacoustic Designs

The survey done in chapter 4 showed, that only few studies are available that focus on psychoacoustics in the context of electric rotors. Strikingly, nearly all studies have analyzed reduction of SPL only. Psychoacoustic optimization has huge potential, especially if noise cannot be prevented in the first place or weakened with secondary measures like for example porous materials. Positive, valuable rotor sound should be considered in future analyses.

6. Conclusion

A framework for systematic optimization of electric aerial vehicles at early development stages has been presented combining a classification of system levels of electric propulsion systems with a literature survey on acoustic measures. The classification of system levels of electric propulsion systems focuses on rotor configurations and contains four system levels: 1. blade design (e.g. bio-inspired blades), 2. rotor configuration (e.g. number of blades), 3. rotor integration (e.g. ducted or open rotors), 4. overall vehicle design (e.g. shielding effects). Characteristics and integration environment of emerging concepts have been included. The literature survey on noise reduction approaches for electric aerial vehicles includes approaches from other domains aligned with the earlier identified system levels.
Merging the identified system levels with the literature survey on acoustic measures identified, that acoustic measures are applied at emerging concepts, however additional ones are discussed in literature. It results, that acoustic improvement of electric aerial vehicles is possible.

Open research topics have been identified for each system level. Comprehensive analysis of acoustic measures regarding not only SPL but psychoacoustics, like sharpness as well, are required. Knowledge regarding acoustic optimization across system levels, like interaction of increased number of blades with ducts, is missing. Currently no rating of acoustic measures is possible, since large differences in boundary conditions, like microphone placement, exist.

Analysis with defined and unifrom boundary conditions could solve this. Adding further experimental analysis of acoustic measures and resulting penalties to each system level, would allow to introduce acoustic optimization during early development steps at digital mock ups. Complementation of the framework with this knowledge has potential to enable the design of silent and sustainable aerial vehicles.

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