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Comparative Acoustic Examination of UAV Propellers

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Abstract

The reduction of aircraft noise is one of the major challenges of the aviation industry. This also concerns unmanned aerial vehicles (UAVs), since they will play an increasingly important role in everyday life. In the context of the presented project the energetic potentials of winglets at propeller tips ("proplets") were investigated in order to increase the aerodynamic efficiency and decrease the noise emission of propellers. Therefore it was necessary to determine the acoustic effects of the attached proplets.

This paper compares the noise emission of a reference propeller with a proplet-equipped propeller for the first time. Except for the tips, they were identically designed. The acoustic power level of both propellers was determined and the results are assessed psycho-acoustically. Additionally an examination of the test pieces with a spaced microphone array ("Acoustic Camera") was conducted to visualize the localization of sound sources on the propellers. A rotational beamforming filter using a virtual array rotation was applied to precisely identify the positions of the rotating aero-acoustic sources. The results of the investigation provide an insight to the noise-reducing potential of using winglets in propeller design.

Keywords: propeller noise, winglets, proplets, propeller design, sound source localization, rotational beamforming

1 Introduction

Unmanned aviation started an unprecedented triumph in the past years. The number of commercial drones sold worldwide already exceeded overall 3.5 million in 2017 [11]. Additionally industrial applications are also progressing such as *amazon.com* is testing mail delivery drones in the United Kingdom. In this context, a recently published NASA study [4] found a significant aversion of the US population to UAV[3] noise even if it is in the same intensity as e.g. road traffic noise.

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Both for multicopters and fixed-wing UAVs, the main part of the noise is emitted by the propellers. Accordingly, an acoustic optimization must begin at this point in order to increase public acceptance of unmanned aircraft.

In the recent past, various approaches were provided to lower the above-mentioned noises: roughening the blade surface, using winglets/proplets or fringing the trailing edge of the blade. Thus far, no comparison of one of those potential improvements has been conducted yet. Therefore, for the first time, this paper introduces a comparative acoustic examination of a proplet-equipped propeller to a reference propeller. Both are, except for the tips, identically designed. They were manufactured at the *University of Applied Sciences Wildau*, Germany, to be part of the propulsion system of a conventional fixed-wing UAV to perform measurement flights in high altitudes.

A sound power level determination and psycho-acoustic assessments identify the effect of those proplets with conventional and proven methods. For a more comprehensive insight to the noise emission of the propeller, it is necessary to localize the sound sources along the blade accurately. For this purpose, this paper introduces a comparison of the propellers using so-called acoustic cameras. This spaced microphone arrays have been providing outstanding results with precise sound source localization for many years. At the Internoise 2017, a novel algorithm was introduced that provides the possibility of redissolving fast-rotating objects. This rotational beamforming filter uses virtual array rotation and solves the above-named issues (see ref. [8]).

2 Test propellers

The test propellers (see figure 1) were designed at the *University Of Applied Sciences Wildau* as part of the PhD thesis of Sven Angermann [2] and the master thesis of Fabian Quaeck [10]. Both are folding propellers for a conventional fixed-wing unmanned aircraft with a maximum take-off weight of 25 kg. The operating ranges of the propulsion system are altitudes of approximately 5,000 m. All characteristic values coincide:

- diameter: 22" / 558.8 mm
- propeller pitch: 19" / 482.6 mm
- number of blades: 2

Both test pieces were manufactured in negative form way of construction using carbon wet in wet lamination. Since only 10 % at the tips of the negative molds differ, the airfoils along the blades of both propellers are the same. For this reason, parameters such as camber and thickness, which affect the propeller noise, are also identical. The efficiency of the propeller geometries was validated by a series of CFD-simulations. In addition, the dimensions of the proplet were determined:

- type: blended proplet
- height: 1" / 25 mm
- cant angle: 90° / Sweep: 0

Figure 1: Reference propeller and proplet-propeller

In order to verify the simulation results, both test pieces - the reference propeller as well as the proplet propeller - were examined on a test bench for electric propulsion systems. Contrary the hypothesis that proplets have a positive effect on the aerodynamics of a propeller, these trials reveal marginally worse thrust characteristics of the respective propeller.

Beside the slightly poorer aerodynamic properties of the proplet propeller, a subjectively more pleasant sound of this propeller could be felt during the test bench trials. This gave rise to the idea of subjecting both propellers to an high-precision acoustic examination.

3 Acoustic Power Level

The first step of the comparative acoustic examination is the determination of the sound power level of the test propellers according to the enveloping surface method, which is described in [6]. The measuring surface covers a hemisphere around the propeller with five metering points in a defined distance of 40° (see figure 2), which prevents the fifth metering point from the high air mass flow directly behind the propeller. The radius of the hemisphere was set to 1.50 m.

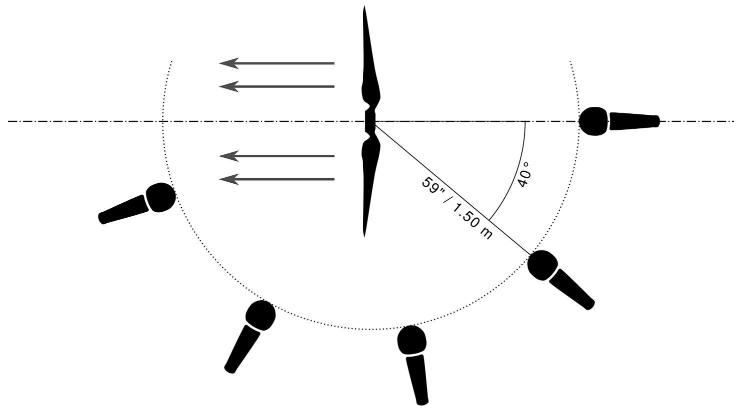

Figure 2: Positioning of the metering points

The measurement was executed in the main laboratory area of the department of aeronautical engineering at the *Technical University of Applied Sciences Wildau*. To calculate the sound power level from the sound pressure levels that were recorded at the above-mentioned metering points, it is necessary to eliminate the impact of local ambient noises and the measuring environment. Since it is not possible to determine the reverberation time of the measuring location, an estimation according to the test standard applies. This method uses the location's mean sound absorption coefficient to calculate the sound absorption capacity and subsequently the associated correction factor (see table 1).

Table 1: Acoustical properties of the measuring location and correction factors

measuring location			
mean sound absorption coefficient	$\overline{\alpha_S}$	[-]	0.2
sound absorption capacity	A	[m²]	68.73
correction factor - ambient noises	K_{1A}	[dB]	0
correction factor - measuring environment	K_{2A}	[m³]	2.6

According to the test standard, the sound power levels for both propellers can be calculated at five predefined operating states (see table 2).

Table 2: Calculated sound levels

	reference propeller					**proplet propeller**				
Rotational speed (rpm)	2,500	3,000	3,500	4,000	4,500	2,500	3,000	3,500	4,000	4,500
Average SPL (dB)	83.6	85.1	88.7	91.3	93	84.4	87.2	89.2	92.3	95.3
Measuring surface SPL	81	82.5	86.1	88.7	90.3	81.8	84.6	86.6	89.7	92.7
Sound power level (dB)	92.5	94	97.6	100	102	93.3	96.1	98.1	101	104

Although the difference of the detected sound power levels never exceeds 2 dB, the noise emission of the proplet propeller is evidently higher. A linear correlation of the calculated levels as a function of the rotational speed of the propellers can be seen from the visual exposition of the measurement results (see figure 3). Since the operational speed of the propellers was almost completely covered, the proplet propeller's acoustic properties compared to the reference propeller are not be expected to alter at other states.

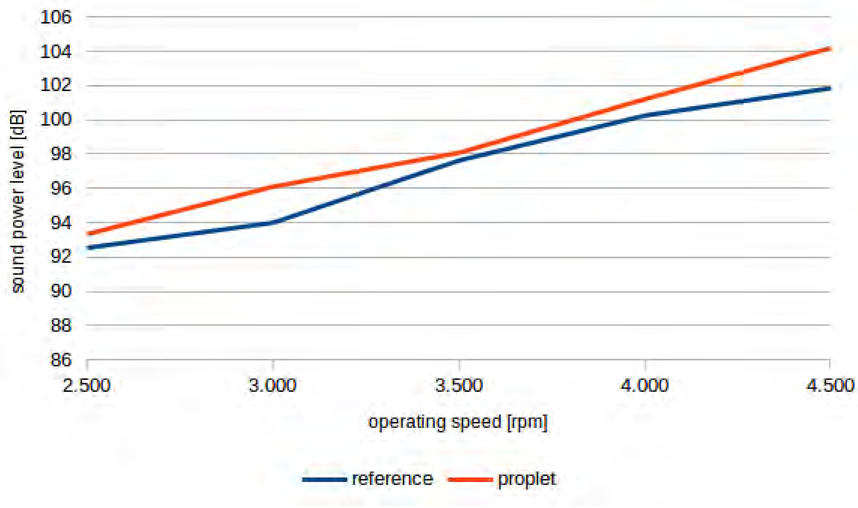

Figure 3: Comparison of the sound power levels of both propellers at each operating state

Contrary the prognosis, the proplets have a negative impact to the overall noise emission of the propellers. This result coincides with the findings of the aerodynamic examinations in [2].

4 Psychoacoustics

Since the sound of the proplet propeller was consistently perceived as subjectively less disturbing during the aerodynamic surveys, a psycho-acoustic analysis of the emitted noises is appropriate. For this reason, the propeller noises were recorded during the determination of the sound power levels in order to visualize the acoustic differences between both test pieces.

4.1 Frequency response

From the recorded data, a spectrogram can be generated for each test piece (see figure 4). These show a broad band noise with single harmonic peaks according to the rotational speed (3,000 rpm).

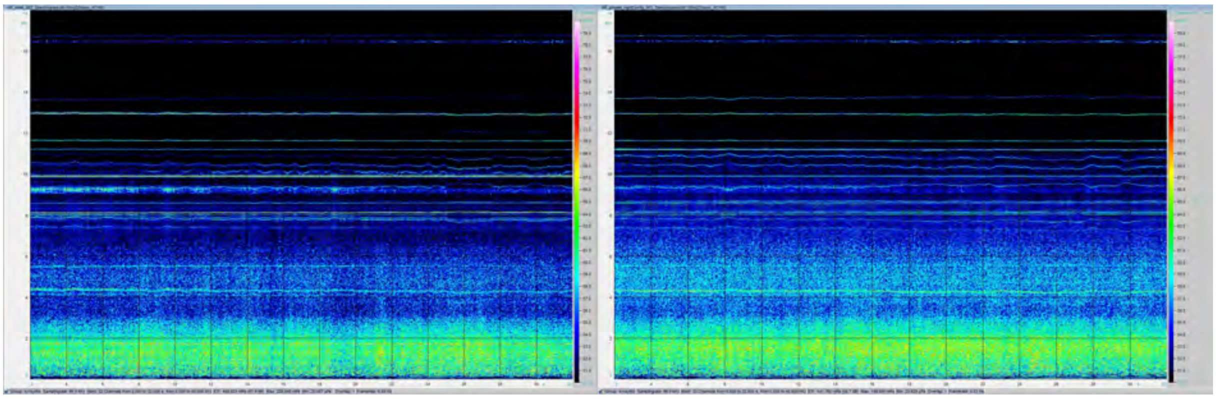

Figure 4: Spectrograms of the recorded noises; left: reference propeller; right: proplet propeller

According to the *equal loudness contours* [5] and the *loudness discomfort level* [1], which were determined through various empirical surveys, the frequency responses of the propeller noises have to be considered. By using FFT[4], the recorded noises are subdivided into 1,024 frequency fractions (see figure 5). For an easier examination of the treble frequency range, a linear depiction of the X-Axis is used.

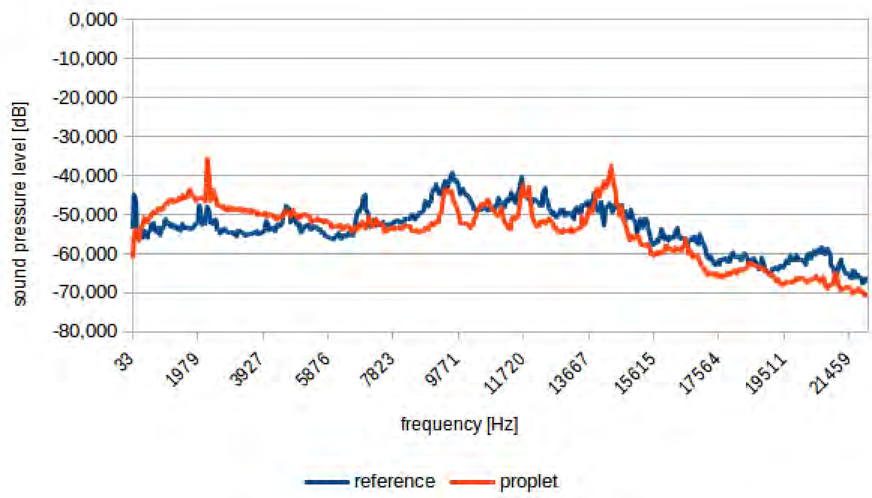

Figure 5: Frequency response analysis for both propellers at 3,000 rpm

Obvious differences in the spectra of both propellers appear. The proplet propeller has significantly higher levels in the mid frequency range, which influences the overall sound event most. This seems plausible concerning the obtained results of section 3 and the aerodynamic examination. In the treble frequencies higher than 8 kHz, the frequency levels of the proplet propeller are up to 8 dB lower in many cases. These frequency bands are occasionally determining for the subjective perception of a sound event, since the loudness discomfort level significantly decreases in this range.

[4] Fast Fourier Transformation

4.2 Sharpness

In order to validate these findings, it is appropriate to determine the sharpness of the recorded noises. This parameter was described in [7] and has proven itself for the subjective assessment of acoustic patterns.

- sharpness reference propeller: 2.76 acum
- sharpness proplet propeller: 2.21 acum

The psycho-acoustic analysis of the propeller noises confirms the above-mentioned subjective perceptions. Although the proplet propeller produces a higher overall sound level, its sound is less sharp and more comfortable to the human ear.

5 Acoustic Camera

To understand the noise emission along the propeller blades, a more accurate examination is recommended. For this purpose, an Acoustic Camera was integrated in the test series. This measurement system realizes precise localization of sound sources. By using a rotational beamforming filter, it is possible to redissolve the high rotational speed of the test pieces. The algorithm and functional principle were described in [3], [8] and [9].

5.1 Test bench

A propeller test bench (see figure 6) hat to be set up to perform the acoustic camera measurements. Since no further aerodynamic examination was necessary, a minimal setting (motor, controller, battery) could be used. A simple LabVIEW program was written for the controller so that the required rotational speed could be set exactly.

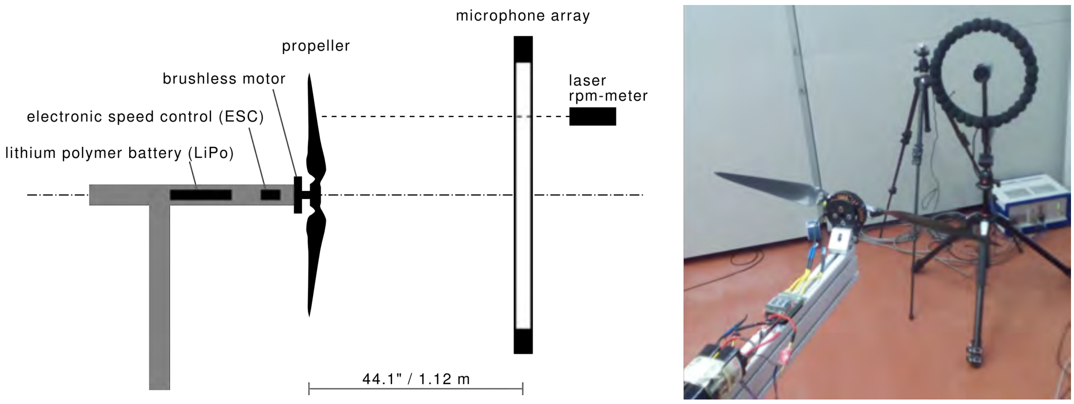

Figure 6: Test bed for examining propeller noises with the Acoustic Camera

For proper usage of the rotational beamforming filter, concentric and parallel positioning of the array to the test piece is urgently needed. This requirement was realized by stepwise trigonometrical alignment. Furthermore, the rotational speed of the propeller must be accurately recorded at all times. For this reason, a laser rpm-meter was taken into the measuring, thus, a reflecting strip had to be attached on the propellers.

In order to prevent the measurement from environmental noise, the low-reflection acoustic measuring cabin of the laboratory of machine dynamics at the *University of Applied Sciences Wildau* was chosen as measurement location. The propeller noises were recorded 24 bit quantized with a sample rate of 96 kHz. The software used for recording and analysis was Noise Image 4.9.

5.2 Results

After applying the rotational beamforming filter to the recorded data, it is possible to generate an acoustic photo of the propeller. Now the sound sources could be visualized along the stationary blade. According to the results in section 4, a third octave band analysis is recommended to determine the sound events throughout the frequency range, starting with the 1,600 Hz band (see figure 7).

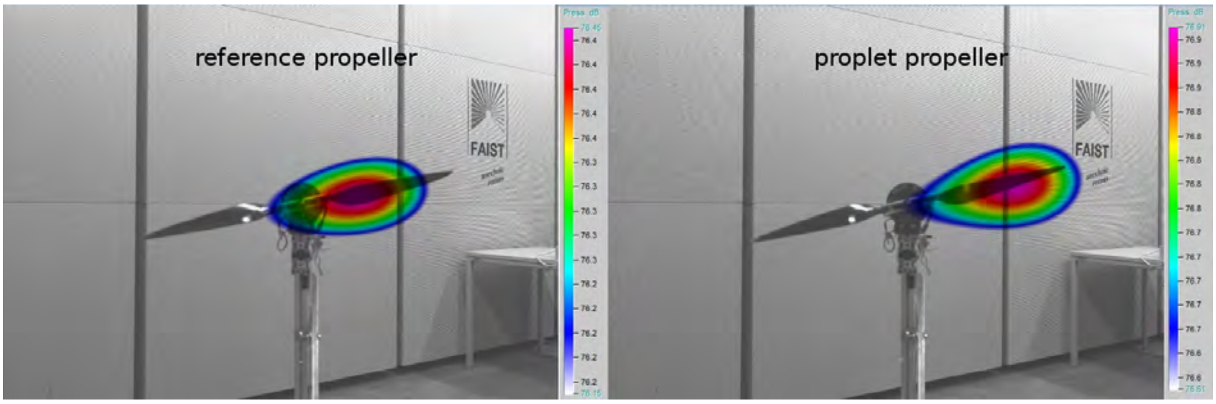

Figure 7: Acoustic images of both propellers at 1,600 Hz third octave band

These acoustic images show the impact of the thickness of the propeller blades. The levels of the sound sources correspond to the findings in the previous sections. The center of the sound event on the reference propeller is located as the thickest point of the blade, as expected. The source of the proplet propeller, however, is more at the tip of the blade. This implies a blade oscillation induced by the proplets that increases the virtual thickness of the appropriate airfoil. Since it is a folding propeller with a free hinge at the propeller attachment, there is no braking effect on the vibration.

Another characteristic can be seen in the 3,000 Hz band in figure 8:

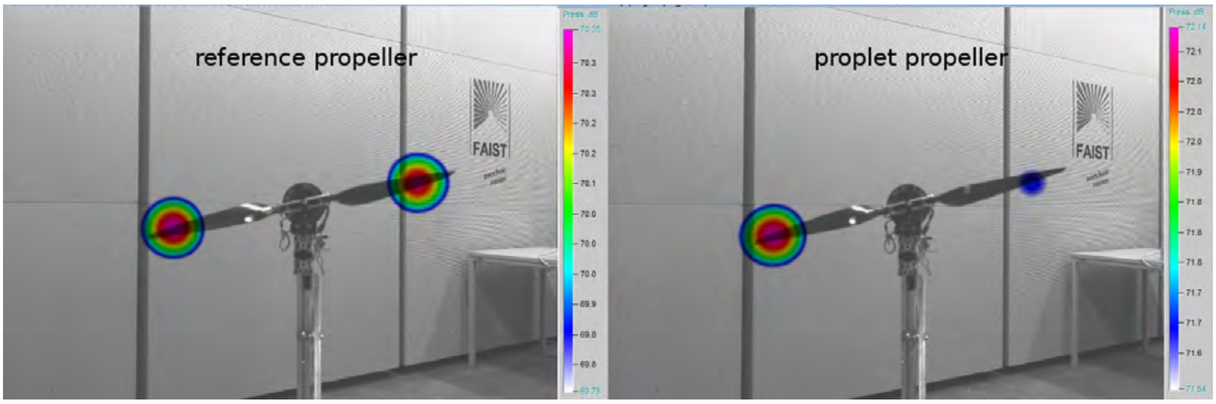

Figure 8: Acoustic images of both propellers at 3,000 Hz third octave band

While the reference piece's sound levels in that frequency band are evenly spread at the blade tips, the proplet propeller's energy is concentrated on the left tip. Reason for this could be a minimum weight inequality of that left blade, which therefore aerodynamically and acoustically dominates and induces the higher level. However the right blade seems to strike in dead wake and has less overall influence.

Further effects of the proplets can be seen in the 8,000 Hz band (see figure 9):

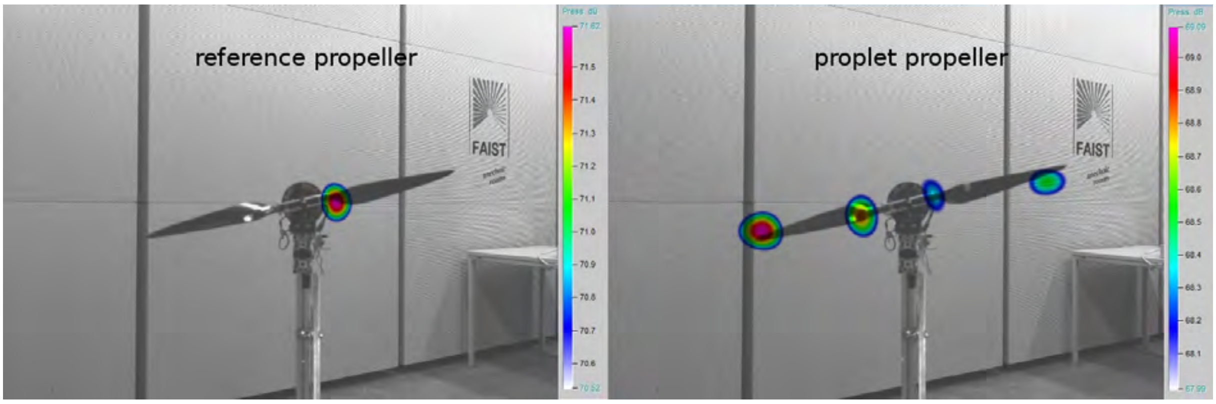

Figure 9: Acoustic images of both propellers at 8,000 Hz third octave band

The sound energy of the reference piece concentrates on one single point at the trailing edge of the blade root. Since the angle of attack is maximum at this point, this could indicate a stall at this location. The acoustic image of the proplet propeller shows attenuated effects at the roots but also the blade tip stroke, as expected in high frequency ranges. Again, the left blade seems to be dominant. Nevertheless, the sound energy at this propeller is better spread and the overall level is lower.

6 Conclusions

The introduced examination proves outstanding applicability of the Acoustic Camera to analyze the noise emission of UAV propellers. As well as the rotational beamforming filter provides a valuable insight to the acoustic behavior along the rotor blades, this measuring method is also usable for more powerful propulsions such as Turboprop engines.

Additionally, the impact of proplets on the noise emission of a propeller could be verified. As they reduce the sharpness of the sound event and lower the level of high frequency ranges, they might be a promising option to increase the public acceptance of UAVs in the future. Nevertheless, some disadvantages were uncovered that have to be corrected in order to reason their usage. For example, alternative proplet designs should be tested to validate the results. In addition, the balance of the blades should be analyzed to obtain clarification about the unsymmetrical noise emission of the proplet propeller.

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