MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Validation of Optoacoustic Propeller Noise Examinations

Konrad Oeckel, Dr. Sven Angermann, Dr. Andreas Frahm[1]
University Of Applied Sciences Wildau
Hochschulring 1
15745 Wildau
Germany

Sebastian Kümmritz, Michael Kerscher, Gunnar Heilmann[2]
gfai tech GmbH
Volmerstraße 3
12489 Berlin
Germany

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 a comparative acoustic examination of UAV propellers was conducted. The integration of spaced microphone arrays ("Acoustic Cameras") in conjunction with a rotational beamforming filter provided an outstanding insight to the aero-acoustic sound sources on fast rotating propeller blades.

This paper introduces several validation approaches to the results of the aforementioned investigation presented at last year's Internoise. That includes inter alia a precise observation of the natural blade oscillation with a high speed camera and the inspection of dynamic unbalances of the propeller blades. Falsifying impacts were identified and evaluated in additional measurements, like noise levels, sound power and source localization with the Acoustic Camera. The findings of this validation prove that optoacoustic examinations achieve comparable and reproducible results which may play an important role in the prospective design of aircraft propulsion systems.

Keywords: UAV propeller noise, sound source localization, rotational beamforming
I-INCE Classification of Subject Number: 13

[1] konrad.oeckel@th-wildau.de; sven.angermann@th-wildau.de; andreas.frahm@th-wildau.de
[2] kuemmritz@gfaitech.de; kerscher@gfaitech.de; heilmann@gfaitech.de

1 Introduction

Unmanned aviation has already become part of our everyday lives. In 2017, the number of commercial drones sold worldwide exceeded 3.5 million - and rising [11]. As a consequence thereof the noise pollution caused by UAVs increases particularly in suburban areas [3]. Accordingly, their acoustic optimization have to be addressed in the near future. The majority of UAVs are driven by electric propulsion. The overall noise is thus mainly emitted by the propellers, which must therefore be the focus of the research. Several approaches to reduce that noises were provided in the past, e.g. the roughening of the blade surface or the usage of proplets[3].

For the first time, a comparative acoustic examination of UAV propellers was presented as part of the Internoise 2018. The impact of proplets could be visualized by using spaced microphone arrays ("Acoustic Cameras"). The sound sources of fast-rotating propellers were redissolved to the still-standing blade by applying a rotational beamforming filter. Corroborated by standardized sound power level determination and psycho-acoustic assessments, valuable insights of the acoustic behavior of the test propellers were gained (see ref. [9]). Inter alia high-frequency oscillations were assumed that cause virtual thickening of the blades. In addition, imbalances were visible due to uneven allocation of the sound energy at the tips.

Based on the results obtained, this paper introduces several approaches to validate and verify the provided conclusions. For this purpose, the established propeller configurations are analyzed again and extended by an additional test piece. Dynamic unbalances of the propeller blades as well as falsifying impacts of the test bed and the measuring environment are determined. A visual inspection of the assumed blade oscillation is realized with the aid of a high speed camera. By including a propeller thrust determination, the properties of the blade tip configurations can therefore be represented more comprehensively.

2 Test Propellers

The test propellers (see figure 1) were designed at the University Of Applied Sciences Wildau as part of [1] and [10]. They 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

Figure 1: Reference propeller

[3]blade tip device that lower the tip vortex

The 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.

In [9], a reference propeller with conventional wing tips as well as a propeller with proplets were subject to investigate. For the present examination, an additional half height proplet configuration is taken into consideration. Table 1 and figure 2 hereafter specifies the geometric characteristics of the blade tips.

Table 1: Geometric properties of the test propellers' blade tips

	reference	**proplet 50 %**	**proplet 100 %**
type	conventional tip	blended proplet	blended proplet
height	0 mm	1.1" / 27.94 mm	0.55" / 13.97 mm
cant angle	0°	90°	90°
sweep	0 mm	0 mm	0 mm

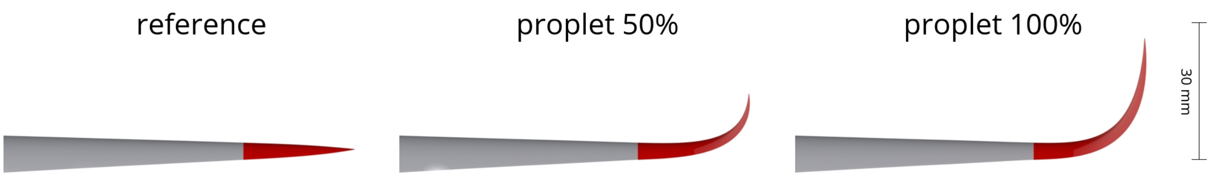

Figure 2: comparism of tip configurations

3 Summary of Previous Examinations

Widespread acoustical investigations of the reference propeller and the full height proplet propeller were conducted in [9]. All information given here refer to the set rotational speed of 3,000 rpm which is equivalent to the flight state climbing.

3.1 Sound Power Level and Psychoacoustics

To ensure quantifiable comparability of the test propellers' acoustic properties, the sound power level according to [5] as well as perceptional parameters loudness and sharpness were determined. The latter are described in [4] and [6]. The results are listed in table 2.

Table 2: Results of the determination of sound power level and psycho-acoustic parameters

	reference	**proplet 100 %**
sound power level	94 dB	96.1 dB
loudness	78.1 sone	82.5 sone
sharpness	2.76 acum	2.21 acum

According to this, the proplet propeller produces a higher acoustic power and perceived loudness. As opposed to this, the sound seems less sharp and more comfortable to the human ear, which coincides with the impression that all colleagues present during the measurement had. This conjuncture is further supported by the frequency responses in figure 3.

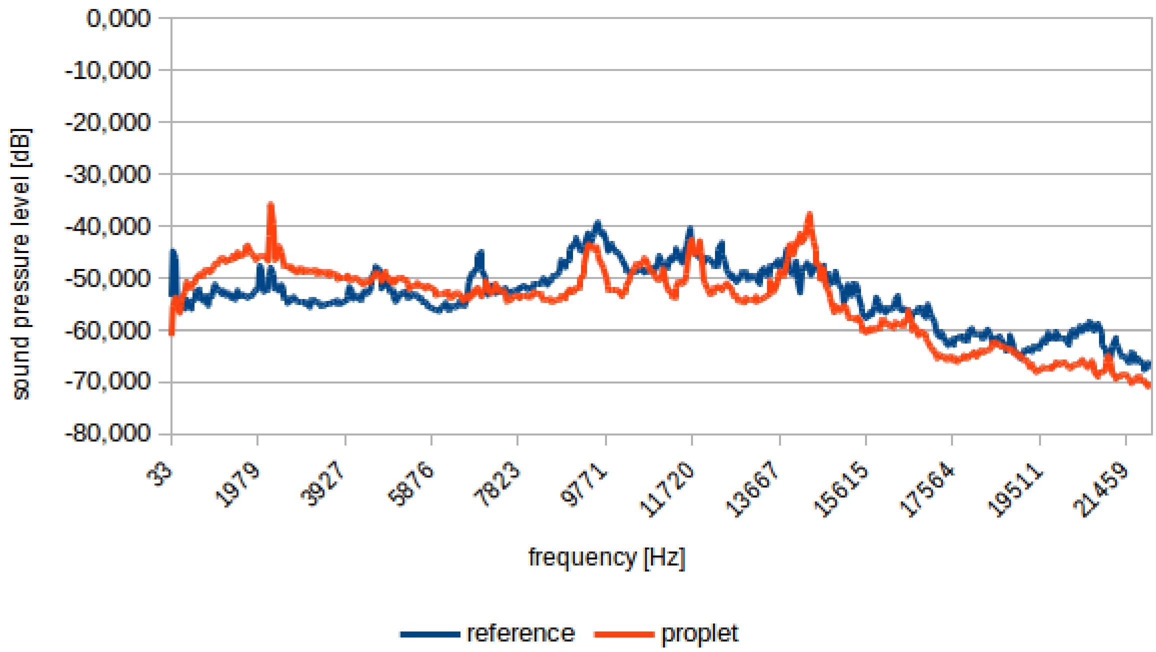

Figure 3: Frequency response analysis (linear depiction)

Obviously, the proplet propeller has significantly higher levels in the mid frequency range, which affects the overall sound event most. In the treble frequencies higher than 8 kHz, the frequency levels of the proplet propeller are about 8 dB lower in many cases. These frequency bands are occasionally determining for the subjective perception of a sound event. The frequency responses seem thus plausible regarding the determined loudness and sharpness.

3.2 Acoustic Camera

To understand the noise emission along the propeller blades, an Acoustic Camera was integrated in the test series. This measurement system realizes precise localization of sound sources. By applying 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 [2], [7] and [8].

According to the previous results, the sound events at several third octave bands were analyzed. This is exemplified by the images hereafter.

Figure 4 shows the impact of the thickness of the propeller blades. 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 is more at the tip of the blade, which implies a blade oscillation induced by the proplets. Since it is a folding propeller with a free hinge at the propeller attachment, there is no braking effect on the vibration.

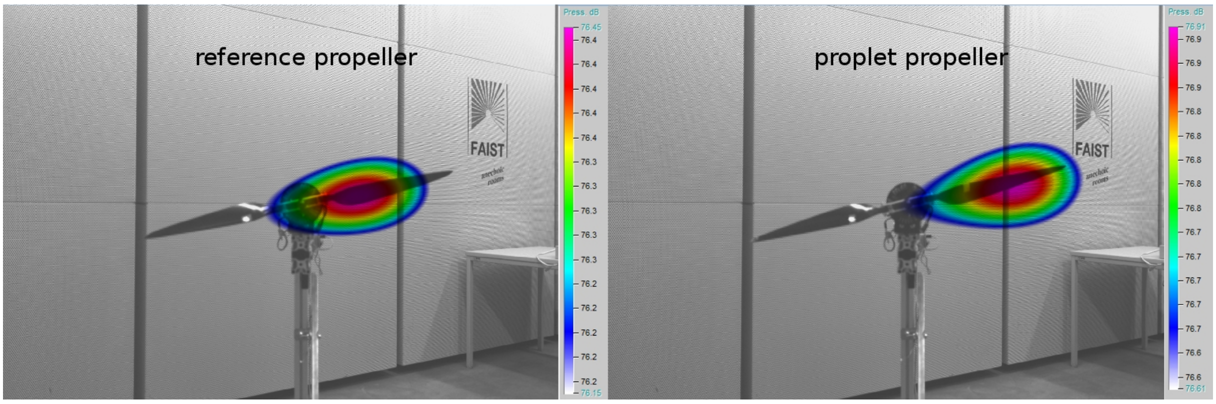

Figure 4: Acoustic images of both propellers at 800 Hz third octave band

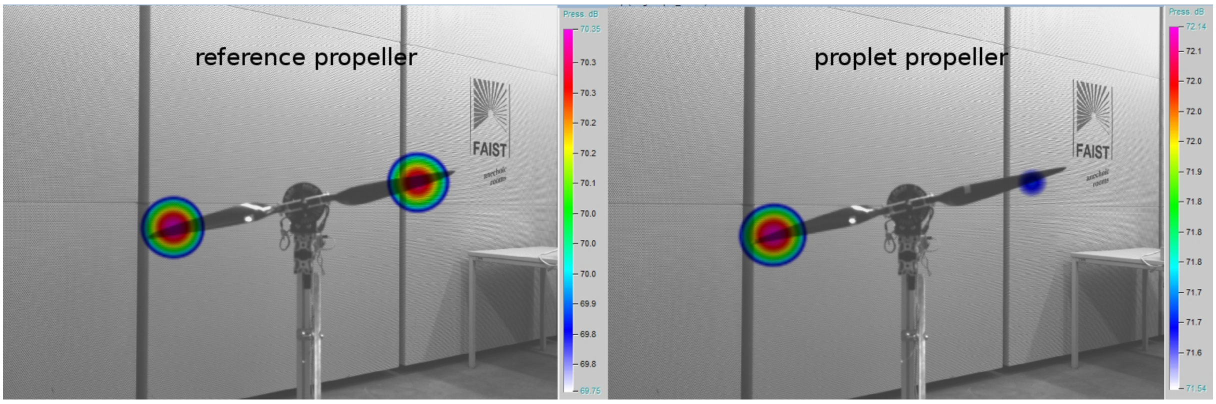

Figure 5: Acoustic images of both propellers at 1,600 Hz third octave band

While the reference propeller's sound levels in the frequency band at Figure 5 are evenly spread at the blade tips, the energy of proplet propeller is concentrated on the left tip. Reason for this could be a weight inequality of that left blade, which therefore aerodynamically and acoustically dominates and induces the higher level.

3.3 Conclusions

The investigations in [9] determine the impact of different designs of the blade tips. By attaching proplets to the propeller, the overall sound power and the loudness increases admittedly. However, the sharpness and the perceptive annoyance decreases as well. The images generated by using an Acoustic Camera thus could reveal possible reasons for that acoustic behavior. The explanatory approaches are now subject to verify.

4 Conventional Acoustic Analysis

To gain a more profound insight to the acoustic effect of the proplets, a half height proplet is integrated in the measurement series. As exposed in section 2, the geometric properties of all investigated propellers are identical. The only difference is the height of the proplet, which is exactly half the size (13.97 mm) of the initial proplet propeller.

Since a blade oscillation caused by the proplets was assumed, it is also advisable to review the full height proplet propeller with fixed blades. Thereby it should be possible to eliminate the missing breaking effect of the free hinge at the propeller's root.

To ensure comparability, all measurement circumstances correspond to the previous examinations. That includes i.e. the test bench, measuring system and location.

4.1 Thrust, Loudness and Sharpness

According to the results in section 3, the first step is the determination of standardized psycho-acoustic parameters. Since the sound power level is adequately represented by the loudness, it is not necessary to measure it again. On the other hand, an additional static thrust determination was conducted to assess the aerodynamic properties of the propellers. These results are listed in table 3 as well.

Table 3: Results of the determination of static thrust and psycho-acoustic parameters

	reference	**proplet 50 %**	**proplet 100 %**	**proplet 100 % fixed**
static tthrust	31.5 N	31.9 N	32.1 N	31.4 N
loudness	76.4 sone	75.1 sone	79.5 sone	82.2 sone
sharpness	2.92 acum	2.68 acum	2.71 acum	2.95 acum

The new propeller equipped with half height proplets seems to be the most promising test piece as it has the lowest loudness and sharpness. It generates notably more static thrust than the reference piece. The parameters determined for reference propeller and full height proplet propeller correspond to the previous findings. However, the results of the fixed blade propeller are out of the ordinary. The thrust generation as well as loudness and sharpness are measurable worse as against the propeller with loose blades. Reason for this might be a slightly varying angle of incidence. Since it is not possible to set that angle precisely, this configuration is not subject to further investigation in this paper.

4.2 Frequency Responses

The recorded noises are subdivided into 1,024 frequency fractions by using FFT[4]. For an easier analysis of the treble frequency range, a linear depiction of the X-Axis is used.

Figure 6 reveals several similarities as well as differences between the examined propellers. The harmonic peaks are congruent, which seems plausible since the rotational speed was always the same. However, the levels of the full height proplet propeller are usually highest. The frequency response of the half height proplet propeller approaches to the reference piece. It is even lower in the overall level-determining mid frequency range. Furthermore, a widespread peak between about 9,000 and 11,000 Hz in the response of the reference propeller is apparent. This abnormalcy may be the reason for the higher sharpness of this propeller.

[4]Fast Fourier Transformation

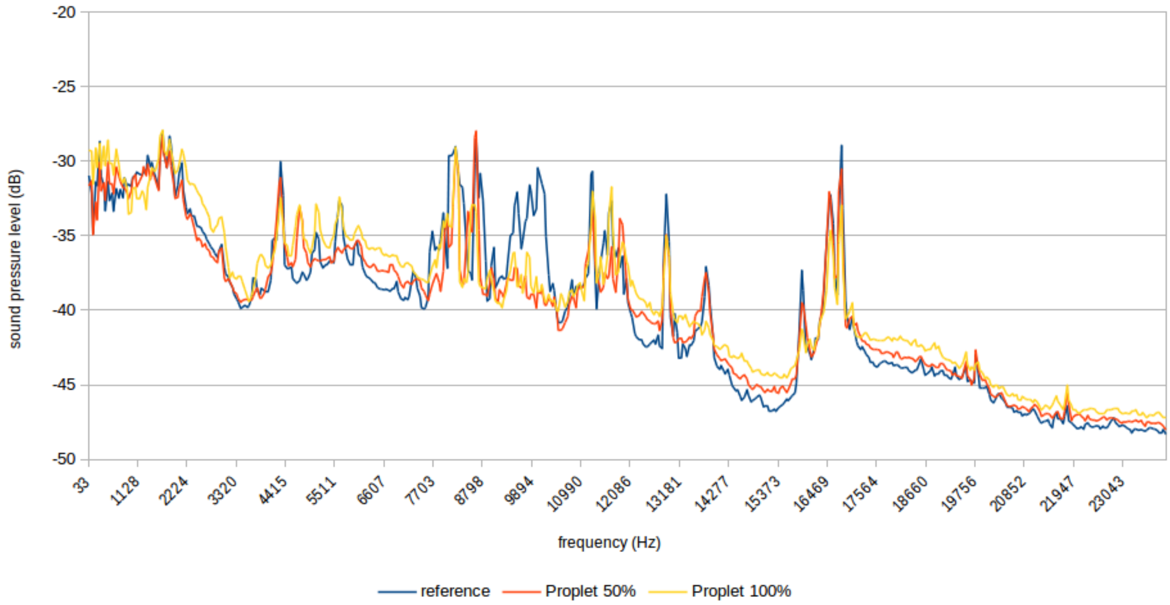

Figure 6: Frequency response analysis (linear depiction)

5 Acoustic Camera

The integration of the Acoustic Camera into the measuring is advisable in order to take a closer look particularly at the mid frequency ranges. For a description of the principle of operation, the measuring environment and also the test bench, see [9].

5.1 Reproducibility

To ensure evaluability of the acoustic images, similar characteristic properties have to be apparent. Figure 7 exemplary shows the reference propeller at the 800 Hz third octave band, comparing the previous measurement with the current one. As the images are congruent, reproducibility is given.

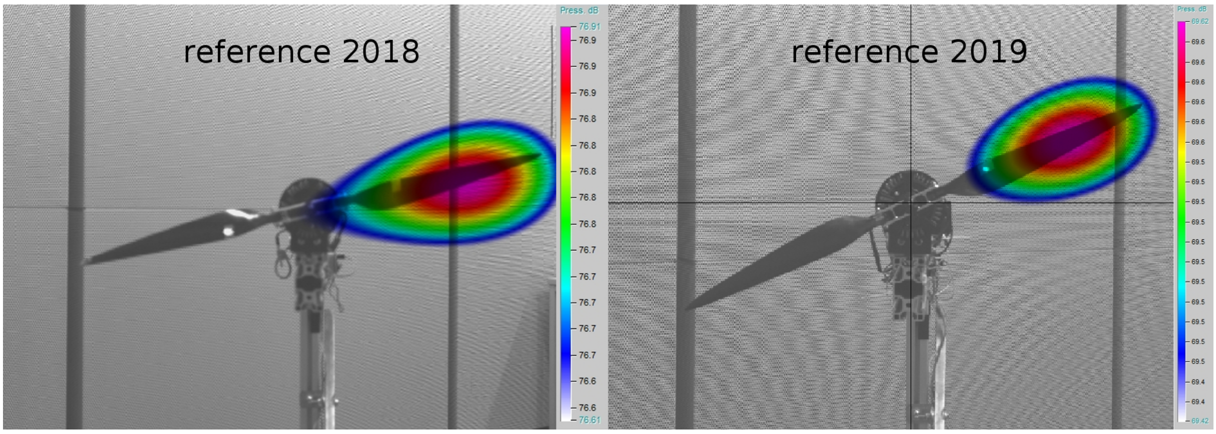

Figure 7: Acoustic images of reference propeller at 800 Hz third octave band - 2018 vs. 2019

5.2 Results

According to the previous results, the appropriate frequency ranges have to be analyzed in order to review the effects of the proplets. The impact of the blade thickness can be seen in Figure 8.

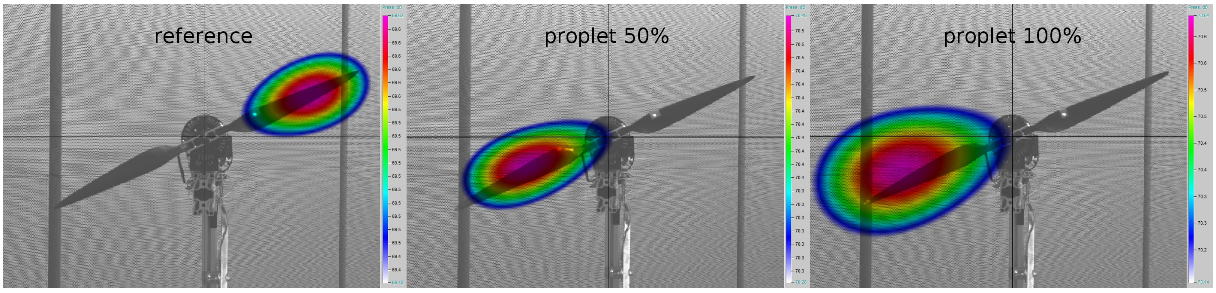

Figure 8: Acoustic images of the propellers at 800 Hz third octave band

The levels of the sound events correspond to the findings in the section 4. While the reference propeller's right blade is dominant, it is the opposite with the other test pieces. The center of the sound sources is expected to be at the thickest point of the blade, approximately at the transition of the root to the blade. This pertains most for the half height proplet propeller. This contradicts the assumption in section 3.2, that proplets induce a high frequency oscillation, which leads to a virtual thickening of the blades.

In addition to that, figure 9 shows the impact of the blade tip stroke in the 1,600 Hz mid frequency third octave band.

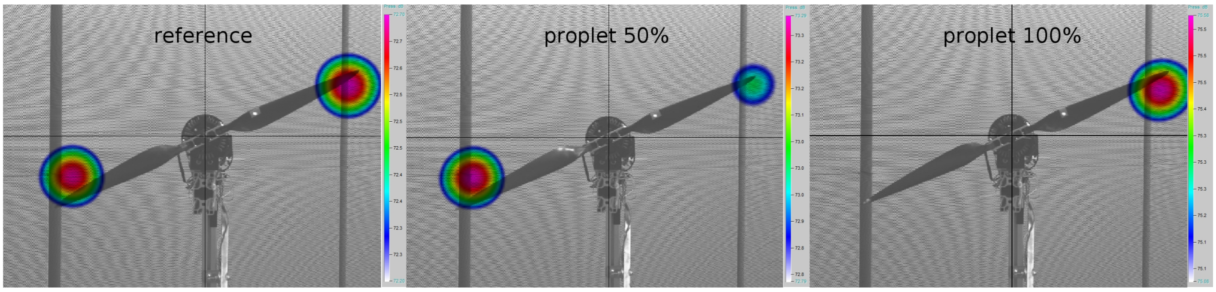

Figure 9: Acoustic images of the propellers at 1,600 Hz third octave band

According to the previous results, the sound energy of the reference propeller is almost evenly spread at the tips. On the other hand, both proplet equipped propellers show a dominant blade, whereas the full height proplet is affected most. In section 3.2 it was assumed that dynamical unbalances caused this behavior. However, it seems possible that the proplets on the dominant blade produce dead wake themselves, wherefore the effect is weaker at the half height proplet propeller.

6 Validation

6.1 Dynamic Imbalance

In sections 3.2 and 5.2, a dynamic imbalance of the propeller blades was assumed. During the production process, the blades were statical balanced, i.e. they were weighed to 1/10 g. However, for the dynamical balance, the center of gravity is crucial. For this reason, its position was determined for each blade used in this measurement. Therefore, the propeller blade was balanced on a needle and then a perpendicular was dropped through its attachment. The distance between needle and perpendicular represents the center of gravity of the blade.

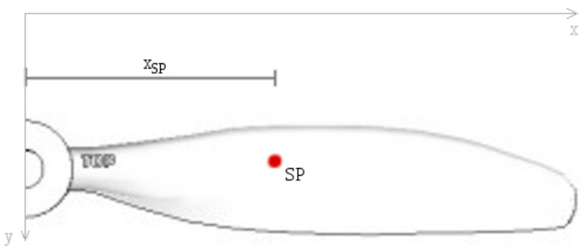

Figure 10: Position of the center of gravity on the propeller blade

Since the mass of the propeller blades is not more than 35 g, a shift of the center of gravity by only 1 mm can already effect a noticeable imbalance. The results listed in table 4 show different positions of the center of gravity on the blades.

Table 4: Results of the determination of static thrust and psycho-acoustic parameters

	reference	**proplet 50 %**	**proplet 100 %**
CoG blade 1	83.76 mm	83.61 mm	83.46 mm
CoG blade 2	83.89 mm	83.28 mm	82.55 mm
difference	0.13 mm	0.33 mm	0.91 mm

These results show an effect of the height of the proplet to the center of gravity, as the reference propeller without proplets has the lowest difference. This corroborates with the assumption that the dynamic imbalance may be the cause for the unequal spread of the sound energy at the blade tips. However, it is not a counterproof that the proplets themselves induce that behavior aerodynamically. Further measurement series are therefore required.

6.2 Blade Oscillation

Since the assumed blade oscillations are not visible to the naked eye, a high speed camera was implemented into the measuring. It was positioned perpendicular to the propeller's rotational plane. The recording speed was set to 6,000 frames per second. From the resulting slow motion picture a snapshot at the apex of the rotation could be extracted. Now the propeller chord of each single image was traced. Finally, it was possible to determine the angle of deflection between the extrema. Figure 11 provides an overview of the results.

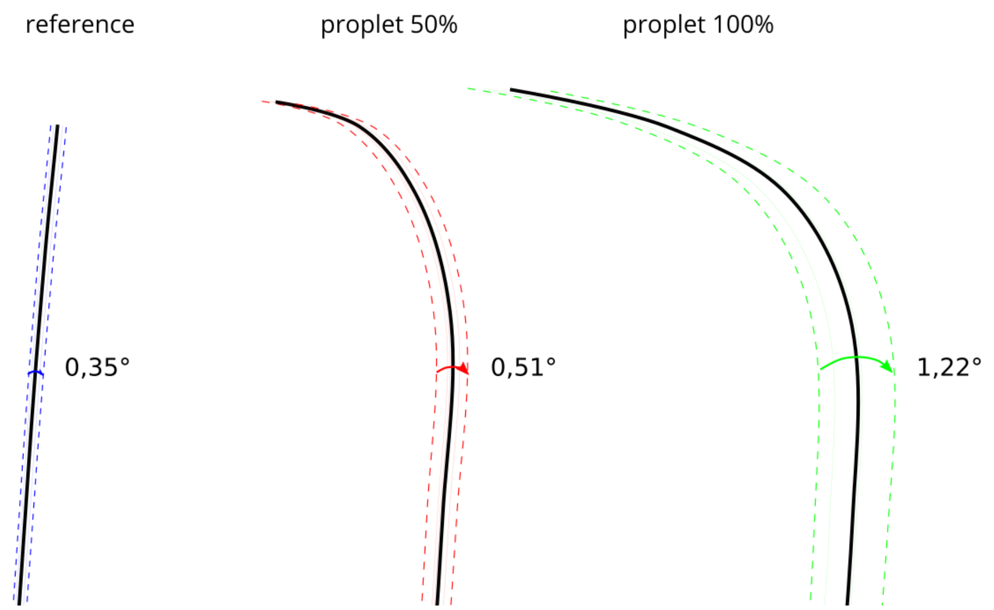

Figure 11: Comparison of the propeller's angles of deflection

Again, the impact of the proplets to the deflection of the propeller blades becomes obvious. This suggests that the assumed vibration of the blades actually occur and are caused by the proplets. According to that, the high speed recordings indicate a virtual thickening of the blades, which seems plausible to the previous findings. A reason for the higher levels in the mid frequency ranges of the proplet propellers could be determined.

6.3 Falsifying Impact of the Test Bench

The accurate knowledge of acoustic interferences is necessary for examinations such as the presented. For this reason, the test bench itself needs to be assessed. It is made of aluminum sections, which is why natural oscillation is possible. To detect its impact on the above-mentioned measurements, acoustic images were made from a side view point at the same operational state (see figure 12).

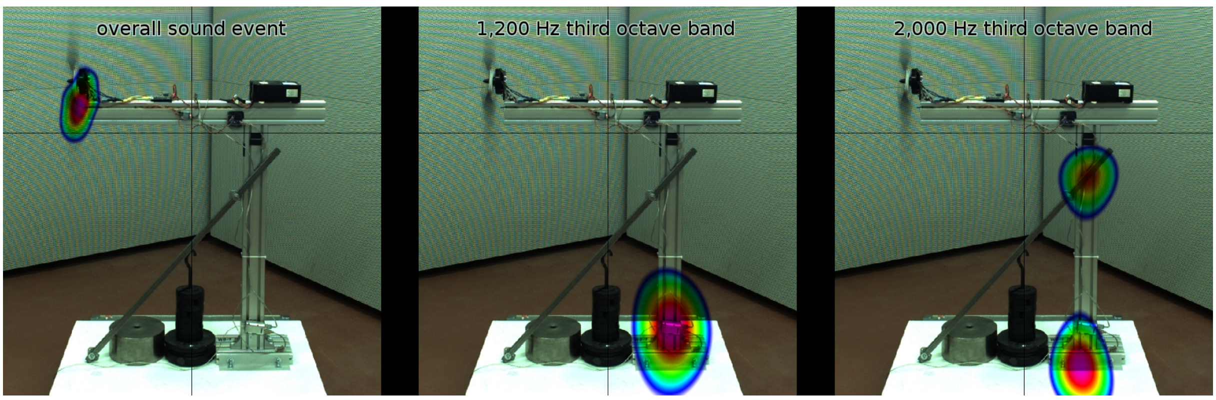

Figure 12: Acoustic images of the test bench - overall sound event; 1,200 Hz & 2,000 Hz third octave bands

The acoustic images reveal the main sound source at the front face of the test bench. This seems plausible since the downdraft induced by the propeller's thrust generation hits that part without deflection. Thus, it is required to perform constructive adjustments to the holding fixture.

Furthermore, additional sound sources can be seen in the 1,200 Hz and 2,000 Hz third octave band. Their positions are remarkable due to the fact that the beam has no structural manipulations (drillings, fittings, etc.) at this point. Therefore, several means of damping should be considered at those locations.

7 Conclusions

The introduced examinations provides several approaches to verify the results of the optoacousic noise measuring with spaced microphone arrays. The images created by using the Acoustic Camera prove outstanding applicability to analyze the noise emission of fast rotating objects. Many of the findings could be confirmed by additional measurements.

Furthermore, the impact of proplets on the noise emission of a propeller could be validated more accurately. Although the proplets reduce the sharpness and increase the perceptive acceptance of the propeller sound, negative impacts can not be denied. These include particularly the resulting vibration and the acoustic dominance of one of the blades. Moreover, inaccuracies in production as well as the in measuring circumstances were detected. Nevertheless, a promising configuration was found with the half height proplet propeller. Further investigation and optimization in manufacturing could even increase its positive impact.

8 Acknowledgements

The authors would like to thank Prof. Dr. Peter Blaschke and his team from the machine dynamics research group at the University for Applied Sciences for providing the acoustic measurement cabin. We also would like to thank Dr. Martin Burger and Prof. Dr. Sigurd Schrader from the laser and photonics research group for the training with the high speed camera. Furthermore we mention the support of Fabian Quaeck and David Rieck from the department of aeronautical engineering in Wildau with the construction of the test bench.

References

[1] S. Angermann, *Investigations of Propeller Optimization by using Proplets*, PhD thesis, Università degli studi di Roma "Tor Vergata", Italy, 2016.

[2] S. Bradley, M. Kerscher, and T. Mikkelsen, *Use of the Acoustic Camera to accuratelty localise wind turbine noise sources and determine their Doppler shift*, in 7th International Conference on Wind Turbine Noise, Rotterdam, 2-5 May 2017, 2015.

[3] A. Christian and R. Cabell, *Initial Investigation into the Psychoacoustic Properties of Small Unmanned Aerial System Noise*, tech. rep., NASA Langley Research Center, 2017.

[4] *DIN 45631/A1:2010-03 - Acoustics - Calculation of loudness level and loudness from the sound spectrum - Zwicker method - Amendment 1: Calculation of the loudness of time-variant sound*, March 2010.

[5] *DIN EN ISO 3747:2011 - Acoustics - Determination of sound power levels and sound energy levels of noise sources using sound pressure - Engineering/survey methods for use in situ in a reverberant environment*, March 2011.

[6] *DIN EN ISO 45692:2009 - Acoustics - Measurement technique for the simulation of the auditory sensation of sharpness*, August 2009.

[7] M. Kerscher, G. Heilmann, C. Puhle, C. Friebe, and R. Krause, *Sound Source Localization on a Fast Rotating Fan Using Rotational Beamforming*, in Inter Noise, 46th International Congress and Exposition on Noise Control Engineering, Hong Kong, 27-30 Aug. 2017, 2017.

[8] M. Kerscher, B. Vonrhein, G. Heilmann, S. Barré, and P. Weigel, *Measurement and Visualization of Room Impulse Responses with Spherical Microphone Arrays*, in Tonmeistertagung 2016, Cologne, 17-20 November 2016, 2016.

[9] K. Oeckel, J. Heimann, M. Kerscher, S. Angermann, G. Heilmann, and W. Ruther-Kindel, *Comparative Acoustic Examination of UAV Propellers*, in Inter Noise, 47th International Congress and Exposition on Noise Control Engineering, Chicago, 26-29 Aug. 2018, 2018.

[10] F. Quaeck, *Auslegung eines höhentauglichen Antriebes für das unbemannte Luftfahrtsystem ATISS*, Master's thesis, University of Applied Sciences Wildau, Germany, 2016.

[11] statista.com, *Anzahl der verkauften kommerziellen drohnen weltweit*. https://de.statista.com/statistik/daten/studie/660240/umfrage/anzahl-der-verkauften-kommerziellen-drohnen-weltweit/, 2018. assessed: 31.03.2018.