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

Aeroacoustic characterization of two pusher propellers in different configurations

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ABSTRACT

In this research, the effect of rotor to rotor interactions has been experimentally investigated. Pusher propeller configurations have been considered because of the several benefits offered over the traditional arrangements in the fields of civil aviation. For instance, the aircraft wing is no longer exposed to the swirling and turbulent slipstream and the position of the propellers considerably reduces the noise impact on the fuselage, yielding the potential of a low cabin noise level. However, in general, the exterior noise of pusher propellers is augmented by the interaction with impinging wakes and exhaust jets. To this purpose, an experimental study has been performed on different Unmanned Aerial Vehicles (UAVs) propellers considering that advances in inexpensive control systems and electronic devices have greatly promoted the development of UAV in a wide range of applications. The rotors investigated change in number of blades, pitch angles and loading conditions. The aim of the work is to investigate the noise field generated by the propellers in pusher configuration performing the measurements both for single rotor and considering the interaction between two co-rotating propellers having the same geometry to highlight the effect of the relative position on the noise produced. Three hub separation distances have been considered in order to find the optimized configuration in terms of acoustic impact. Tests have been performed in the Roma TRE semi-anechoic chamber of the Laboratory of Fluid Dynamics "G. Guj" on five UAV propeller models using three microphones properly positioned to cope with the supposed potential sound sources.

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Keywords: Noise, Propellers, Rotor interaction
I-INCE Classification of Subject Number: 10

1. INTRODUCTION

The sound field radiated by rotating systems such as propellers, fans and rotors, has a rich structure displaying a wide range of complex behaviour. This complexity makes the study of such systems both scientifically and technologically challenging. Moreover, advances in inexpensive control systems and electronic devices have greatly promoted the development of small Unmanned Aerial Vehicles (UAVs) in a wide range of applications. Because of their hovering ability such as vertical take-off and landing, and user-friendly flight controllability, the UAVs with rotary-wing system are very attractive to engineers. They offer promising solutions for varieties of civilian applications, such as package delivery, field sites surveillance, disease control, video taking, and personal entertainment. To provide sufficient thrust for small UAVs, multi-rotors are frequently used during various tasks. Though UAVs with multi-rotary-wing are promising for the civilian applications, technical improvements are highly needed to extend the operating time and reduce the aeroacoustic noise. The growing number of these vehicles has enhanced the efforts towards understanding and mitigating the noise produced and has been widely investigated in many researches. [1–3] Intaratep et al. [4] performed acoustic measurements on a commercial quad-copter. In their study the noise from one, two, and four propellers, was measured. They showed that the noise from a single propeller generated similar SPL at the first four BPF harmonics. Additionally, the propeller noise level did not follow a linear trend with the number of operational propellers. The non-linear trend was attributed to the small gaps between two propeller disks and the proximity between the propeller tip and the supporting arm. [4] The radiated noise from multiple propellers is also affected by the phase angle of each tonal source. Block [5, 6] measured the noise from two mechanically linked propellers. He found that the superposition of tones radiated from two propellers would generate a complex interference pattern. Sinibaldi and Marino [7] experimentally measured the aeroacoustic signatures of two UAV propellers, and found that while the optimized propeller is significantly lower than that of the conventional one at lower value of thrust, the noise of the two propellers would reach a same magnitude when the thrust increased to a higher value. Multi-rotors UAVs are commonly featured by even number of rotors that are designed into two sets with either clockwise or counter-clockwise rotations. Very few studies can be found in literature that examined the rotor-to-rotor interactions on the aerodynamic and aeroacoustic performance of UAVs. Except for Yoon et al. [8], who computationally analyzed the aerodynamics performance of multi-rotor flows in a quadcopter, and found that the rotor interaction has significant effects on the vertical forces of quadrotor systems in hover motion. And Intaratep et al. [4], who experimentally measured the acoustics level of Phantom II at static thrust conditions, found that there is a dramatically increase in acoustic broadband noise if increased the rotors from 2 to 4. Though those previous studies have uncovered some significant impacts of rotor interactions on the aerodynamic and aeroacoustic performance of small UAVs, researches are still needed to understand the underlying physics pertinent to multi-rotor interactions, and understand how the relative position of the rotors affect aeroacoustic noise. To this purpose, an experimental study has been performed to investigate the noise field generated by UAV propellers with different number of blades, pitch angles and loading conditions in pusher configuration. A pusher propeller offers several advantages over the traditional tractor arrangement and has become a viable option for the aircraft designer in recent years. In some cases, it is more efficient aerodynamically than a tractor propeller because of the lower velocity inflow from the upstream body but acoustically, pusher propellers produce more noise. In the present research, a twin counter clockwise propeller configuration has been analysed aiming to highlight the effect of the interaction on the noise produced. Results obtained for five different propeller geometries have been compared with the investigation made on a single propeller case. Different relative positions have been considered in order to find which configuration gives the best acoustic impact. Measurements have been performed in the Roma TRE semi-anechoic chamber of the Laboratory of Fluid Dynamics "G. Guj" on UAV propeller models using 3 microphones properly positioned to cope with the supposed potential sound sources.

2. EXPERIMENTAL SET-UP AND PROCEDURES

Tests have been carried out in the Laboratory of Fluid Dynamics "G. Guj" of Roma Tre University. Measurements have been performed in an acoustically treated chamber that measures 2 *m* x 4 *m* x 3 *m*. Chamber walls, except for the floor, are covered using soundabsorbent panels, 10 *cm* in length and backed with wooden insulation. This provides semianechoic conditions for frequencies above 500 *Hz*. Five propellers have been tested (Figure 1) changing the number of blades from 2 to 4 and investigating 3 values of the pitch angle for the three-bladed propeller. Some properties are reported in Table 1.


(a) P1 (b) P2 (c) P3 (d) P4 (e) P5

Figure 1: Tested propellers

Table 1: Tested Propellers.

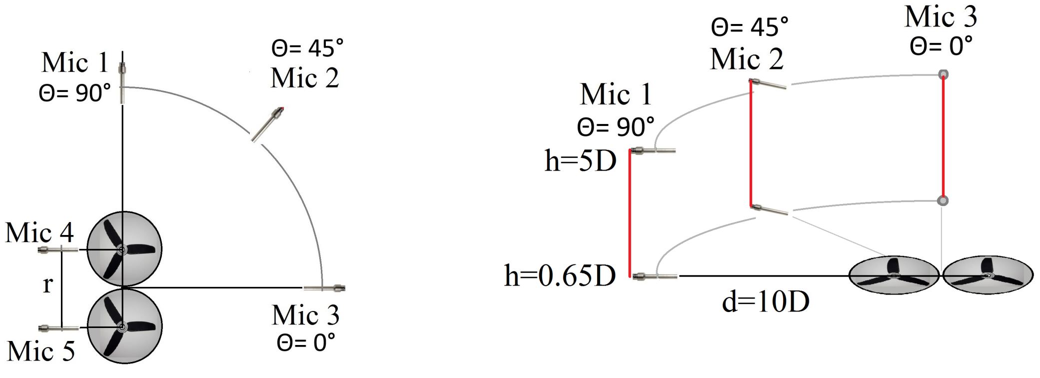
Propeller Name	Properties $diameter$X$pitch$X$n.blades$ [inch]
Propeller 1 (P1)	$3x3x3$
Propeller 2 (P2)	$3x4x3$
Propeller 3 (P3)	$3x5x3$
Propeller 4 (P4)	$3x3x2$
Propeller 5 (P5)	$3x3x4$

Experiments were performed on poly carbonate HQ Durable Prop propellers having a diameter of 7.6 cm, designed for counter clockwise rotation and driven by a GRAUPNER Speed 250 brushed motors. The motor was mounted onto a supporting structure covered with a soft porous material to reduce the scattered noise. Tests have been conducted measuring, at first, the noise generated by a single propeller and then, positioning a twin co-rotating propeller at three relative hub separation distances, r=1.2D, r=1.4D, r=1.6D.

Three rotational speeds of the motor have been considered. Three Microtech Gefell M360 microphones have been arranged as shown in Figure 2, at a distance from the propeller axes equal to 10D and at two altitudes from the propeller disk of h=0.65D and h=5D. Microphones were oriented orthogonal to the propeller axes, parallel to the plane disk. A short summary of the performed tests is reported in table 2. Two nearfield microphones are used in each test with the aim of monitoring the propeller rotational speed and the phase angle. Pressure fluctuations signals have been acquired for 10 s at the sampling frequency of 40 kHz using the software LabVIEW. The acquisition data unit used is a NI PXI-6143 (8 channel, 16 bit, 250 kS/s) with a controller NI PXIe-8840 Quad-Core model.

Table 2: Test Matrix.

Parameters	
Configuration	Single Propeller, Twin Propellers
Propeller	P1, P2, P3, P4, P5
Microphones position	θ = 0°, θ = 45°, θ = 90°
Microphones altitude	h=0.65D, h=5D
Hub separation distance	r=1.2D, r=1.4D, r=1.6D



(a) Microphones position

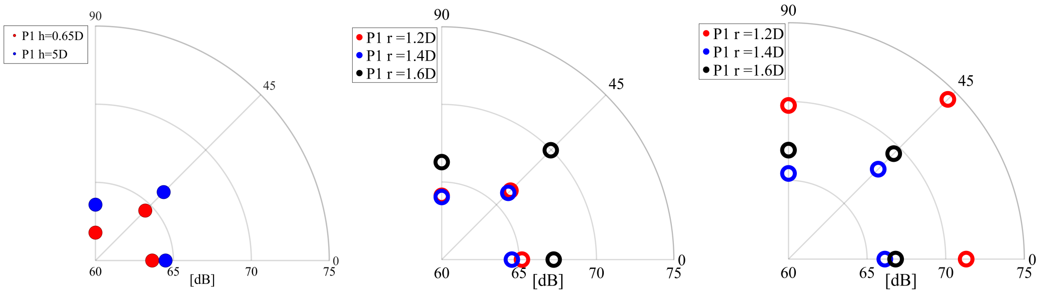
(b) Microphones altitude

Figure 2: Set up

3. RESULTS

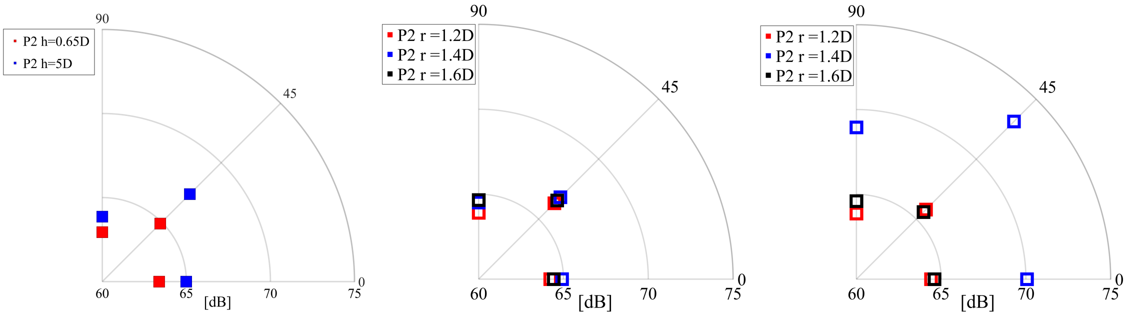
In the following pressure measurement results and comparisons are reported. Fgure 3, 4, 5, 6, 7 depict the OASPL distribution at d=10D from the center of the twin-rotor system. In each case, figure (a) reports the values at h=0.65D and h=5D in single propeller configuration while figure (b) and (c) exhibit the OASPL of the twin-propeller system as function of the hub separation distance respectively at h=0.65D and h=5D.

As the hub separation decreases, the gap between two propeller disks reduces. In one rotational period, the minimum distance between the blade tips on two propellers depends on the blade phase difference. Only when the blade phase difference is zero, it can reach the lowest value, which is equivalent to the disk gap between two propellers. In the current study, the relative blade phase angle was not locked. However, it has been



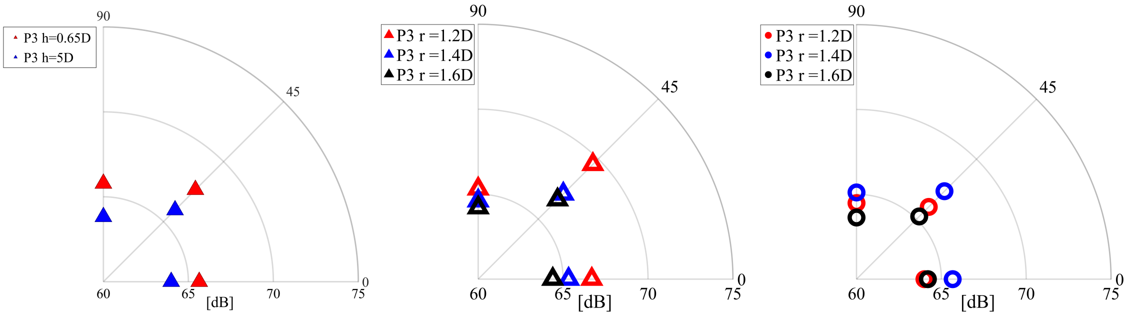
(a) (b) (c)

Figure 3: Effect of the relative hub separation distance on the OASPL. Propeller 1. (a) Single Propeller (b) Twin-propeller configuration. h=0.65D (c) Twin-propeller configuration. h=5D



(a) (b) (c)

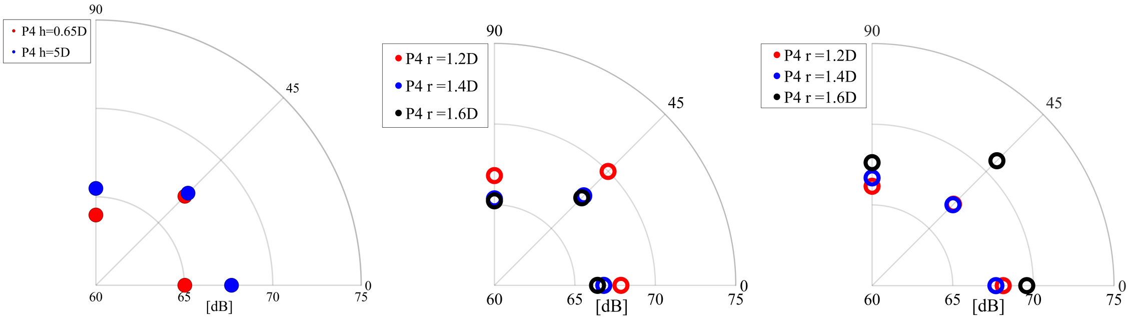
Figure 4: Effect of the relative hub separation distance on the OASPL. Propeller 2. (a) Single Propeller (b) Twin-propeller configuration. h=0.65D (c) Twin-propeller configuration. h=5D



(a) (b) (c)

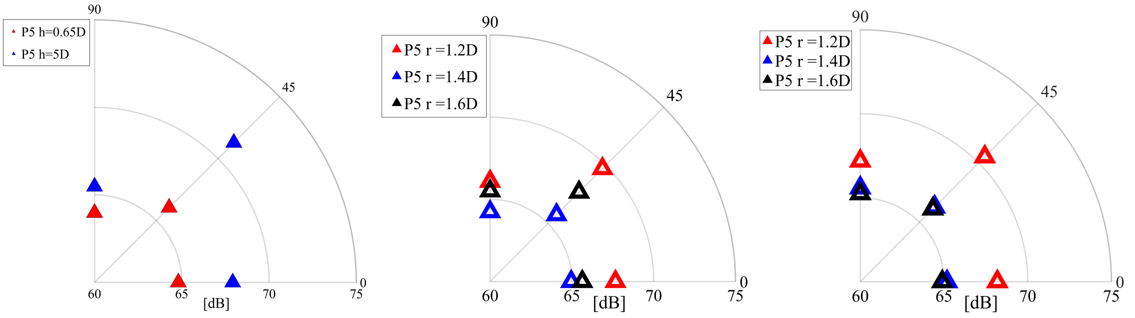
Figure 5: Effect of the relative hub separation distance on the OASPL. Propeller 3. (a) Single Propeller (b) Twin-propeller configuration. h=0.65D (c) Twin-propeller configuration. h=5D

verified that the aforementioned minimum value of the blade tip distance was rarely achieved. In single propeller configuration, for all the rotors except P3 the OASPL recorded increases proportionally with the distance from the blade disk. The propeller with the highest pitch angle (P3) shows the opposite behavior which is believed to be due to a quicker brake down of the propeller wake. In twin rotor configuration the propellers



(a) (b) (c)

Figure 6: Effect of the relative hub separation distance on the OASPL. Propeller 4. (a) Single Propeller (b) Twin-propeller configuration. h=0.65D (c) Twin-propeller configuration. h=5D



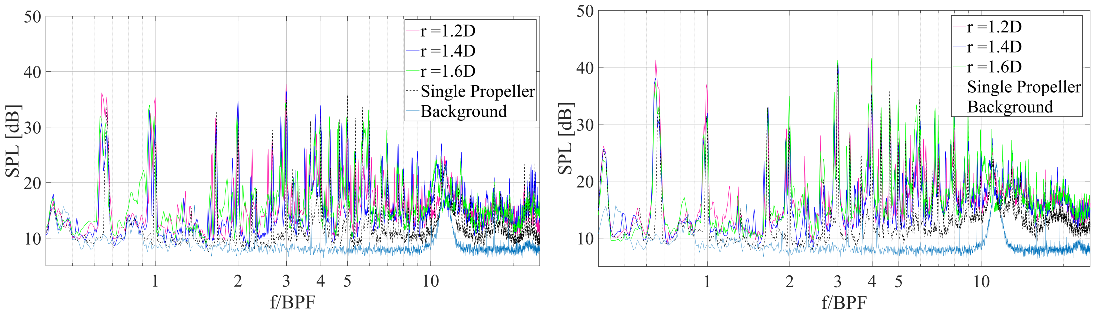
(a) (b) (c)

Figure 7: Effect of the relative hub separation distance on the OASPL. Propeller 5. (a) Single Propeller (b) Twin-propeller configuration. h=0.65D (c) Twin-propeller configuration. h=5D

exhibit different on-goings, at h=0.65D the measured OASPL of P3, P4, P5 is maximum when the separation distance is minimum while for P1 the highest values are registered for r=1.6D. In this position of the microphones OASPL of P2 are not influenced by the relative hub distance. At h=5D, for P1 higher OASPL are found comparing with the single propeller configuration reaching the maximum at r=1.2D. Noise due to P2 and P3 seems not to be influenced by the relative position of the rotors. For the two-bladed propeller (P4) the maximum OASPL is detected at r=1.6 D while remaining similar to single propeller configuration at the other two distances. Signals due to P5 show that increasing the hub separation the OASPL decreases. However, it is still unclear whether the noise increase is due to the enhancement in tonal noise, broadband noise, or both. Therefore, it is necessary to perform a sound spectrum analysis at various locations. For all configurations the sound pressure level (SPL) has been evaluated as a function of the blade passing frequency harmonics:

$$SPL = 10log\frac{PSD}{P_{\mathrm{ref}}^{2}} \tag{1}$$

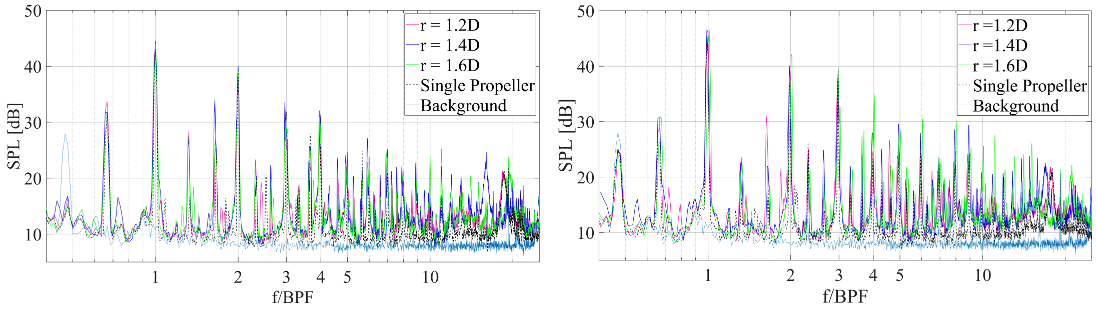
P_{ref} refers to the ambient pressure equal to $1.01x10^5$ Pa and a frequency of 1Hz has been considered as reference. Results for the microphone in $\theta = 0°$ position are reported in Figure 8, 9, 10, 11, 12, having considered the higher rotational speed.



(a) h=0.65D

(b) h=5D

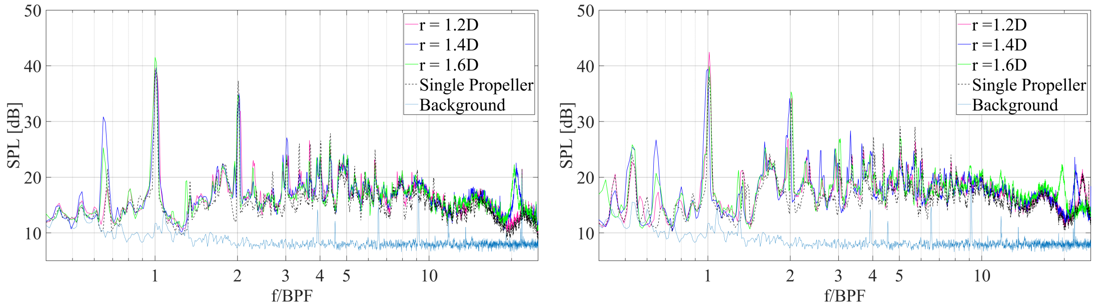
Figure 8: SPL. Microphone 3 ($\theta = 0°$). Propeller 1.



(a) h=0.65D

(b) h=5D

Figure 9: SPL. Microphone 3 ($\theta = 0°$). Propeller 2.



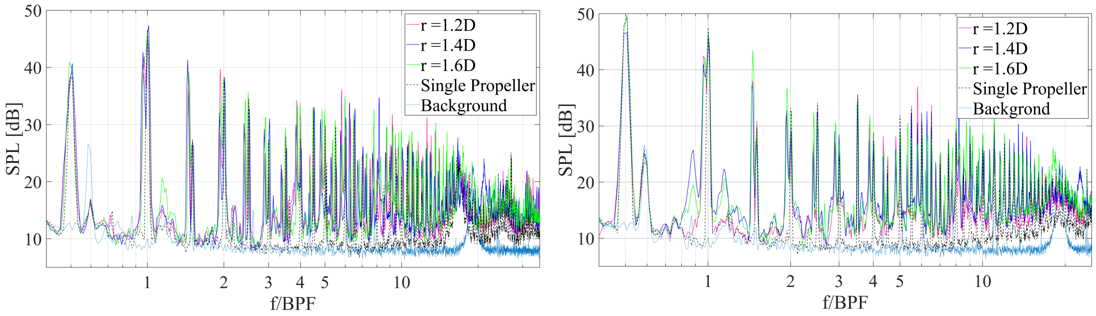
(a) h=0.65D

(b) h=5D

Figure 10: SPL. Microphone 3 ($\theta = 0°$). Propeller 3.

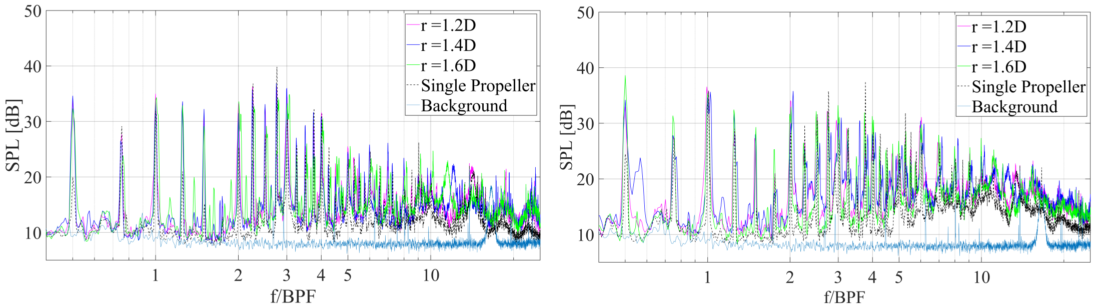
The dominant noise from a propeller in laminar inflow condition is governed by steady aerodynamics, is tonal and it generates discrete tones at the BPF harmonics. For incompressible flow condition, the tonal noise is dominated by the loading noise, which is directly associated with the dynamic loading of the rotor blade. Therefore, the augmentation of tonal noise is believed to be caused by the intensified thrust fluctuations. [9, 10]

In addition, comparing all the spectra, the broadband noises for the r = 1.2D were found to increase. Recalling the Lighthill's stress tensor, the broadband noise level is largely determined by the complex turbulent flow structures and shear layers, such as secondary flow distortions, blade trailing edge vortices, and tip vortices. Thus, the measured noises indicates that the flow could probably features with increased TKE level



(a) h=0.65D (b) h=5D

Figure 11: SPL. Microphone 3 ($\theta = 0°$). Propeller 4.



(a) h=0.65D (b) h=5D

Figure 12: SPL. Microphone 3 ($\theta = 0°$). Propeller 5.

and force fluctuations as function of the separation distance. However, each propeller acts as a tonal noise source with a fixed phased angle. The SPL is affected by the constructive and destructive interference of the tonal noise, which is specified by the blade phase difference [9]. Hence for a better understanding of the physics of the phenomena, a phase locked analysis is necessary.

4. CONCLUSIONS

An experimental study has been performed in the Roma TRE semi-anechoic chamber of the Laboratory of Fluid Dynamics "G. Guj" to investigate the effect of rotor to rotor interactions. Pusher propeller configurations of different Unmanned Aerial Vehicles (UAVs) propellers have been considered because of the several benefits offered over the traditional arrangements. The rotors investigated change in number of blades, pitch angles and rotational speeds [rpm]. This research has to be intended as a preliminary acoustic characterization aimed to investigate the noise field generated by the propellers in single rotor configuration and considering the interaction between two co-rotating propellers having the same geometry highlighting the effect of the relative position on the noise produced. Results show that the dual rotor system is only slightly influenced by the hub separation distance. This can be explained considering that the minimum distance between blade tips on two propellers and the disk gap will be equivalent only if the phase angles of two propellers are equal. As previously mentioned, coherently with the operating conditions of UAVs, the phase difference between two propellers was not maintained in the tests and the time-averaged distance between the blade tips was larger than the disk gap.

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