

# Psychoacoustic analysis of contra-rotating propeller noise for Unmanned Aerial Vehicles

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Unmanned aerial vehicle (UAV) technologies are rapidly advancing due to the unlimited number of applications from parcel delivery to people transportation. As the UAV market expands, community noise impact will become a significant problem for public acceptance. Compact drone architectures based on contra-rotating propellers bring significant benefits in terms of aerodynamic performance and redundancy to ensure vehicle control in case of component failure. However, contra-rotating propellers are severely noisy if not designed appropriately. In the framework of a perception-influenced design approach, this paper investigates the optimal rotor spacing distance configuration to minimise noise annoyance. On the basis of a series of psychoacoustic metrics (i.e. loudness, fluctuation strength, roughness, sharpness and tonality) and psychoacoustic annoyance models, the optimal rotor axial separation distance (expressed as a function of propeller blade diameter) is at a range of 0.2 to 0.4. This paper also discusses the performance of currently available psychoacoustic models to predict propeller noise annoyance, and defines further work to develop a psychoacoustic annoyance model optimised for rotating systems.

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## 1 I. INTRODUCTION

2 New aviation markets, such as Urban Air Mobility (UAM) operations for passengers and drone  
3 operations for goods' deliveries and blue light services, are estimated to have a global potential of  
4 between \$132 and \$227 billion over the next 20 years (ATI, 2019). As the drone delivery market  
5 intensifies over the coming years, the payload requirement is predicted to increase by a factor of 50  
6 to 100, leading to further problems with their public acceptance; with noise becoming a primary  
7 focus. This increase in payload requirements can only be achieved with compact drone architectures  
8 such as co-axial or overlapping propellers. The use of contra-rotating propellers in Unmanned  
9 Aerial Vehicles (UAVs) has the benefit of increasing aerodynamic performance (Stract et al., 1981),  
10 reducing the UAV's plan size and adding redundancy in case of component failure (McKay et al.,  
11 2019).

12 However, the small tip-to-tip spacing between contra-rotating propellers results in a significant  
13 source of noise due to blade interaction effects (Tinney and Sirohi, 2018; Alexander et al., 2019).  
14 Extensive laboratory testing has found that in the frequency spectra of multi-rotor UAV there are  
15 significant sound levels at higher harmonics of the blade passage frequency, which seems to be  
16 caused by interaction noise from disturbed inflow due to other rotor blades or the fuselage  
17 (Magliozzi, 1991; Cabell et al., 2016; Torija et al., 2019). In an experimental investigation of static  
18 multi-rotor contra-rotating UAV propellers, McKay et al. (2019) observed that potential field  
19 interaction tones are about 20 dB higher than rotor alone tones at typical ground observer locations  
20 with a hovering UAV. This suggests that proper design of multi-rotor contra-rotating UAV  
21 propellers to minimise interaction between rotors can lead to significant reductions in noise  
22 emission.

23 The noise sources on a co-axial propeller system can be categorized into either rotor self-noise  
24 or interaction noise. Rotor self-noise is principally composed of tonal components and has

25 contributions due to the steady loading and aerofoil thickness, while the broadband component is  
26 relatively weak (Marte and Kurtz, 1970). An interaction source is generated when the spiraling wake  
27 and tip vortex from the upper propeller interacts with the lower propeller. At sufficiently small rotor  
28 separation distances, an additional interaction noise source is present arising from the interaction of  
29 the potential near field of each propeller with the other (Heff, 1990). A more recent study by  
30 Chaitanya et al. (2020) performed a detailed investigation on the sensitivity of the aerodynamic and  
31 aeroacoustic performance to the axial separation distance between a counter-rotating propeller  
32 configuration. An optimum separation distance to diameter ratio for maximum efficiency and  
33 minimum radiated noise was found to be at 0.25 based on overall sound power level. The reason  
34 behind this optimum is attributed to the balance between potential field interactions and tip-vortex  
35 interactions radiated from the contra-rotating configuration. The current paper extends their work  
36 to perform psychoacoustic optimization of contra-rotating propellers.

37 Anghinolfi et al. (2016) carried out a psychoacoustic optimization of blade spacing in subsonic,  
38 open, or nearly open axial-flow rotors. This optimization focused only on tonal noise and the  
39 objective function was based on the Tone-to-Noise Ratio (TNR) metric. They found optimal blade  
40 spacing for different numbers of blade rotors as a function of TNR and level of the highest tonal  
41 peak. However, these results do not have direct relation to loudness or other psychoacoustic  
42 features.

43 The perception-influenced design approach (Rizzi, 2016) aims to incorporate human response  
44 into the process of creating low-noise aircraft. Metrics that correlate well with human response to  
45 noise can potentially be incorporated into the aircraft design cycle to effectively reduce community  
46 noise impact (Krishnamurthy et al., 2018). Current noise certification metrics do not necessarily  
47 reflect the characteristics of noise signatures of unconventional aircraft designs (Rizzi, 2016;  
48 Christian and Cabell, 2017; Torija et al., 2019), and therefore may not be able to predict human

49 response. Torija et al. (2019) found that the Effective Perceived Noise Level (EPNL) is unable to  
50 account for the perceptual effect of series of complex tones spaced evenly across the frequency  
51 spectrum with relatively even sound levels, which is typical of multi-rotor vehicles (Cabell et al.,  
52 2016; Torija et al., 2019). Other metrics, such as the Sound Exposure Level (SEL), do not account  
53 for the effects of tonal noise, which is a major contributor towards the perceived annoyance due to  
54 aircraft noise (Angerer et al., 1991; Berckmans et al., 2008; More, 2011; White et al., 2017).  
55 Therefore, the use of current noise certification metrics for aircraft design might lead to suboptimal  
56 solutions.

57 Psychoacoustic metrics have been widely applied to improve the sound quality of different  
58 consumer products, especially in the automotive industry (Lyon, 2003). Psychoacoustic metrics,  
59 such as loudness, sharpness, tonality, roughness and fluctuation strength, are good indicators of how  
60 the human auditory system reacts to different features of acoustic stimuli (Zwicker and Fastl, 1999).  
61 Loudness measures the sensation of sound intensity. Sharpness and tonality describe the perceptual  
62 effects of spectral imbalance of the sound towards the high frequency region, and the presence of  
63 spectral irregularities or tones respectively. Fluctuation strength and roughness describe how slow  
64 and rapid fluctuations, respectively, of the sound level are perceived. The psychoacoustic metrics  
65 sharpness, tonality and fluctuation strength have been suggested as good indicators of rotorcraft  
66 noise annoyance (Krishnamurthy et al., 2018; Boucher et al., 2020). Investigating the performance  
67 of different psychoacoustic metrics to account for the perception of different aspects of aircraft  
68 noise, Barbot et al. (2008) found fluctuation strength as a good indicator of perceptual effects of  
69 turbulence and sharpness as a good indicator of the perceptual effects of high frequency noise.  
70 Torija et al. (2019) found that Aures/Terhardt tonality (Aures, 1985b) improves on the EPNL Tone  
71 Correction in terms of accounting for the presence of complex tones in aircraft noise.

72 Perception of mechanical sounds is a complex process due to the amount of noise features  
73 involved (e.g. tonal components, amplitude modulated sounds, etc.). To address this issue, Zwicker  
74 and Fastl (1999) proposed a model for combining several psychoacoustic metrics into one model to  
75 quantify annoyance (hereinafter called Zwicker's model for short). Using the Zwicker's  
76 psychoacoustic annoyance (PA) model, relative annoyance degrees of different noise samples can be  
77 estimated from measures of loudness, sharpness, fluctuation strength and roughness. However,  
78 Zwicker's PA model does not include a factor accounting for the influence of the tonality on noise  
79 annoyance. To improve accuracy in the estimation of relative annoyance degrees caused by several  
80 types of tonal/atonal noises, Di et al. (2016) carried out an update of Zwicker's PA model aiming at  
81 tonal noises. More (2011) developed a modified version of Zwicker's PA model based on the results  
82 of seven psychoacoustic tests for several aircraft sounds with varying psychoacoustic parameters.  
83 The modified PA model developed by More, which includes a term based on Aures/Terhardt  
84 tonality and loudness to account for the perceptual effect of tonal noise, was found able to  
85 accurately predict aircraft noise annoyance.

86 The aim of this paper is to perform a psychoacoustic analysis of a single static contra-rotating  
87 propeller mounted in an anechoic chamber. A set of psychoacoustic metrics are calculated for a  
88 series of far-field microphone measurements with different separation distance between the contra-  
89 rotating propellers. The contribution of each noise source component on the co-axial propeller  
90 under study is evaluated from a perceptual standpoint, using relevant psychoacoustic metrics.  
91 Working towards the development of a framework for the psychoacoustic optimisation of novel  
92 aerial vehicles, this paper investigates the optimal distance between contra-rotating propellers to  
93 minimise psychoacoustic impact. The performance of PA models to predict noise annoyance for  
94 propeller systems is evaluated and discussed. The main assumption in this paper is that PA models

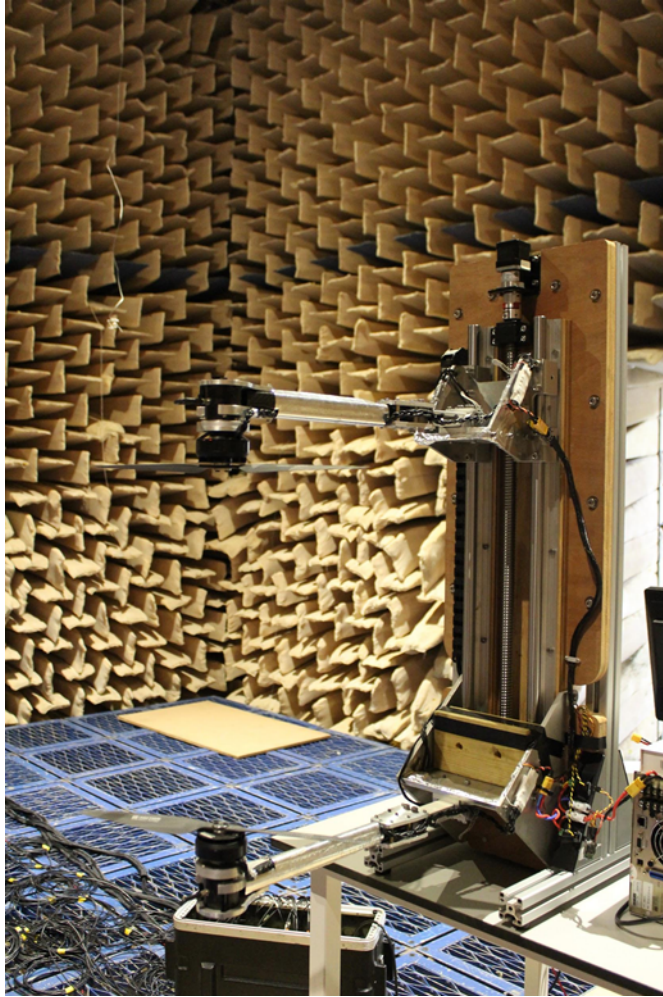
95 optimized for propeller noise annoyance can be used to inform propeller design for lower  
96 psychoacoustic impact.

97 This paper is structured as follows: Section II describes the experimental setup for acoustic  
98 measurements and the metrics for psychoacoustic analysis; Section III presents and discusses the  
99 experimental results and are followed by the main conclusions of this work in section IV.

## 100 II. EXPERIMENTAL AND PSYCHOACOUSTIC METHODS

### 101 A. Experimental set-up and procedure

102 The overlapping rotor test rig designed and manufactured at the University of Southampton  
103 consisted of two FOXTECH W61-35 brushless DC (BLDC) (16 poles) 700W motors mounted on a  
104 carbon fibre beam as shown in Fig. 1. A commercially available T-Motor 16 inch 5.4 inch rotor was  
105 used for this overlapping rotor propulsion system analysis. Two Hyperion HP-EM2-TACHBL  
106 sensors were used to measure the precise Rotations Per Minute (RPM). Two Maytech 40A-OPTO  
107 speed controllers were used to accurately control the BLDC motors. The overlapping rig allowed  
108 manipulation of the propulsion system in both rotor horizontal separation distance  $d/D$  (with  $D$  as  
109 the rotor diameter) and rotor axial separation distance  $z/D$ .  $z/D$  rotor separation was achieved by a  
110 custom linear actuator traversing the upper rotor. All of the tests for this study were achieved when  
111 the lower rotor plane was at least three rotor diameters away from the ground with anechoic wedges  
112 beneath. The selected lead screw and stepper motor configuration allows for  $z/D$  variations varying  
113 of 0.05 to 1. Sixteen  $z/D$  positions were tested: 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2, 0.25, 0.3,  
114 0.35, 0.4, 0.45, 0.5, 0.6, 0.8 and 1. The combined thrust of the dual-rotor propulsion system is varied  
115 from 2 to 20N in steps of 2N. Although 10 thrust settings were measured, the results shown in this  
116 paper refer to a thrust of 10 N (varying thrusts lead to changes in magnitudes, but do not alter the  
117 trends shown below). A detailed description of the rig is presented by Brazinskas (2019).



118

119 FIG. 1. (Color online). Photograph of overlapping propeller rig within the anechoic chamber of the  
120 Institute of Sound and Vibration Research at the University of Southampton.

### 121 **B. Far-field noise measurements**

122 The overlapping far-field noise measurements were carried out at the Institute of Sound and  
123 Vibration Research's open-jet wind tunnel facility. The overlapping rotor test rig was located within  
124 an anechoic chamber, of dimension  $8\text{ m} \times 8\text{ m} \times 8\text{ m}$  as shown in Fig. 1. The walls, acoustically  
125 treated with glass wool wedges, allow a cut-off frequency of 80 Hz.

126 Far-field noise measurements were made using 10,  $\frac{1}{2}$  in. condenser microphones (B&K type  
127 4189) located at a constant radial distance of 2.5 m from the centre of the propellers. These  
128 microphones were placed at emission angles of between 12 and 102 degrees measured relative to the

129 rotor axis. Measurements were carried out for 10 s duration at a sampling frequency of 50 kHz, and  
130 the noise spectra was calculated with a window size of 1024 data points corresponding to a  
131 frequency resolution of 48.83 Hz and a Bandwidth-Time (BT) product of about 500, which is  
132 sufficient to ensure negligible variance in the spectral estimated at this frequency resolution. Please  
133 note that the data analysed in this paper is same as the data presented in Chaitanya et al. (2020).

### 134 **C. Psychoacoustic data analysis**

135 Unlike physical quantities (e.g. sound pressure level), psychoacoustic metrics provide a linear  
136 representation of human hearing perception (HEAD Acoustics, 2018). Psychoacoustic metrics  
137 have been found to outperform conventional noise metrics (e.g. EPNL or SEL) in predicting noise  
138 annoyance of fixed-wing aircraft (Rizzi et al., 2016; Torija et al., 2019). Recently, several authors  
139 (Krishnamurthy et al., 2018; Boucher et al., 2020) have explored the potential of psychoacoustic  
140 metrics for the modelling of human annoyance to rotorcraft noise, and assessed the performance of  
141 each psychoacoustic metric to account for rotorcraft noise annoyance response.

142 The psychoacoustic metrics (including loudness in sone, sharpness in acum, fluctuation strength  
143 in vacil, roughness in asper, impulsiveness in IU, and tonality in TU) of all sound samples were  
144 calculated with ArtemiS software (HEAD acoustics GmbH). Loudness was calculated according to  
145 DIN 45631/A1 (2010), which is based on Zwicker loudness model and includes a modification for  
146 time varying signals. The calculation of sharpness was made according to the standard DIN 45692  
147 (2009). This sharpness method does not take into account the influence of absolute loudness on the  
148 sharpness perception. There are no standard methods for calculating roughness and fluctuation  
149 strength. These two metrics were calculated according to the hearing model given by Sottek (1993).  
150 Sottek's hearing model simulates the signal processing of human hearing and accounts for its  
151 limitations to track fast temporal changes within a critical band (Boucher et al., 2020). Tonality was  
152 calculated according to Aures/Terhardt tonality model (Aures, 1985b).



153 Three PA models were implemented to discuss their performance in assessing propeller  
154 noise annoyance. The Zwicker PA model, accounting for the relation between annoyance and  
155 hearing sensations loudness ( $N$ ), sharpness ( $S$ ), fluctuation strength ( $F$ ) and roughness ( $R$ ) is given  
156 by

$$157 \quad PA = N_5 \left( 1 + \sqrt{w_S^2 + w_{FR}^2} \right) \quad (1)$$

158 where

159  $N_5$  is the 5<sup>th</sup> percentile of the loudness (in sone)

$$160 \quad w_S = \{(S - 1.75) \cdot 0.25 \lg(N_5 + 10), S > 1.75; 0, S \leq 1.75\} \quad (2)$$

$$161 \quad W_{FR} = \frac{2.18}{N_5^{0.4}} (0.4F + 0.6R) \quad (3)$$

162 Note that although non specified by Zwicker in the original form of eq. 1, the 5<sup>th</sup> percentiles of  
163 sharpness, fluctuation strength and roughness metrics were used for calculating PA.

164 The use of 5<sup>th</sup> percentiles in psychoacoustic analysis is a standard approach widely accepted in  
165 the literature. However, these percentile values are dependent on the recording time and the  
166 fluctuation of the psychoacoustic parameter in question. This makes that the 5<sup>th</sup> percentile values  
167 for psychoacoustic metrics cannot be compared without appropriate background information. In  
168 this research, there is a steady sound pressure during the 10 s duration of each sound sample  
169 analysed. For instance, the 5<sup>th</sup> percentile and arithmetic mean of the loudness for the rotor spacing  
170  $z/D = 0.05$  at azimuthal angle = 12 degrees is 98.5 and 96.4 sones respectively. Therefore, the  
171 findings of this research can be argued to be non-dependent of the statistical parameters used to  
172 describe the psychoacoustic magnitudes. Furthermore, to avoid the transient effect of the digital  
173 filters (used for the computation of the psychoacoustic metrics evaluated) at the start of the audio

174 signal analysis, the first 0.5 s of the sound sample was ignored in the calculation of the 5<sup>th</sup> percentile  
175 of each psychoacoustic metric.

176 As described above, the Zwicker's PA model does not include a factor for accounting for  
177 the perceptual effects of tonal sounds. Di et al. (2016) derived a tonality factor (eq. 5) to develop a  
178 PA model able to account for the annoyance response of sounds with strong tonal components.  
179 The updated PA model developed by Di et al. (2016) ( $PA'$ ) is given by

$$180 \quad PA' = N_5 \left( 1 + \sqrt{w_S^2 + w_{FR}^2 + w_T^2} \right) \quad (4)$$

181 where

$$182 \quad w_T = \frac{6.41}{N_5^{0.52}} T \quad (5)$$

183 More (2011) developed a modified version of Zwicker PA model optimised to predict  
184 aircraft noise annoyance. The More's PA model ( $PA_{mod}$ ) is given by

$$185 \quad PA_{mod} = N_5 \left( 1 + \sqrt{\gamma_0 + \gamma_1 w_S^2 + \gamma_2 w_{FR}^2 + \gamma_3 w_T^2} \right) \quad (6)$$

186 where

$$187 \quad w_T^2 = [(1 - e^{-\gamma_4 N_5})^2 \cdot (1 - e^{-\gamma_5 T})^2] \quad (7)$$

188 The estimates for the More's PA model were optimised for aircraft noise on the basis of a  
189 series of psychoacoustic tests. The value of these estimates for eqs. 6 and 7, i.e.  $\gamma_0 = -0.16$ ,  $\gamma_1 =$   
190  $11.48$ ,  $\gamma_2 = 0.84$ ,  $\gamma_3 = 1.25$ ,  $\gamma_4 = 0.29$  and  $\gamma_5 = 5.49$ , show the significant emphasis of the  
191 More's PA model on sharpness and tonality. Note that 5<sup>th</sup> percentile of Aures/Terhardt tonality was  
192 used for calculating PA in Di et al.'s and More's models.

193           None of these PA models account for the impulsiveness of the audio signal. Although there  
194 is no agreement in the literature, some authors advise that the prevalence of annoyance due to  
195 rotorcraft is influenced by its impulsiveness (Mestre et al., 2017). The impulsiveness (measured in  
196 IU) of all sound samples were calculated using the Sottek's hearing model. This psychoacoustic  
197 metric accounts for the perception caused by short and sudden changes in sound pressure level  
198 (Boucher, et al., 2019). A full description of the calculation of the impulsiveness metrics and its  
199 computation in the Sottek's hearing model can be found at Sottek et al. (1995) and Sottek and  
200 Genuit (2005) respectively. McMullen (2014) suggested that a combination of different  
201 psychoacoustic metrics, including loudness, sharpness, tonality and impulsiveness might provide an  
202 accurate assessment of human response to helicopter noise. All this suggests that impulsiveness  
203 might need to be considered for developing a PA model for rotorcraft noise.

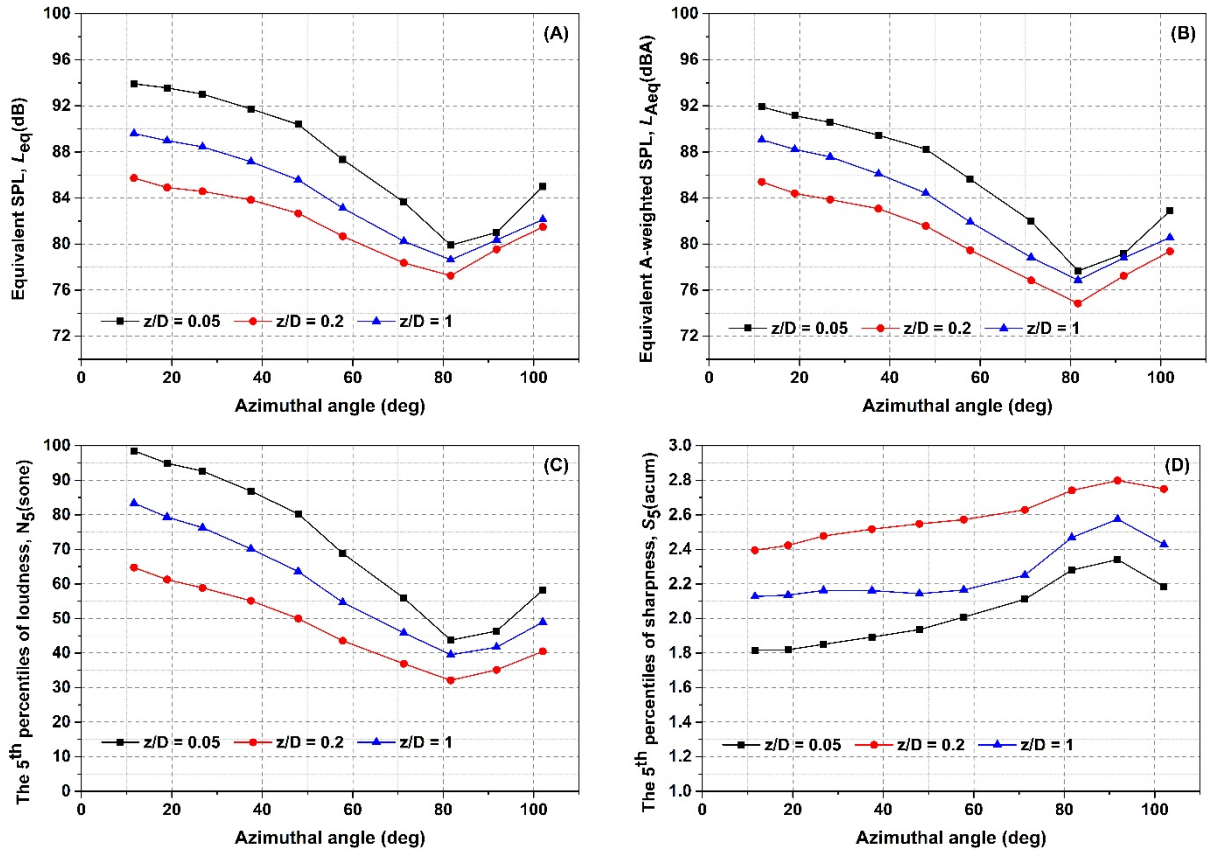
### 204 **III. RESULTS AND DISCUSSION**

#### 205 **A. Directivity and spectra patterns**

206           Figure 2 shows the 5<sup>th</sup> percentile of loudness (Fig. 2C) and sharpness (Fig. 2D) as a function of  
207 azimuthal angle (i.e. emission angles between 12 and 102 degrees measured relative to the rotor  
208 axis), for rotor spacings  $z/D=0.05$ ,  $0.2$  and  $1$  and a thrust setting of  $10$  N. Maximum noise emission  
209 (i.e. loudness) is found at the rotor axis. Loudness decreases with azimuthal angle, reaching  
210 minimum values at  $82$ - $92$  degrees (Fig. 2C). The same directivity pattern is observed for all rotor  
211 spacing evaluated. This is consistent with Chaitanya et al.'s (2020) previously observed optimum  
212 separation distance based on overall sound power level (see Figs. 2A and 2B for equivalent sound  
213 pressure level (SPL) and equivalent A-weighted SPL as a function of emission angle). Equivalent  
214 SPL, equivalent A-weighted SPL and loudness are lower at rotor spacing  $z/D=0.2$  than at rotor  
215 spacings  $z/D=0.05$  and  $z/D=1$ .

216 For all rotor spacings, maximum values of sharpness are observed at azimuthal angles of 82 to  
217 92 degrees (Fig. 2D). Sharpness at rotor spacing  $z/D=0.2$  is higher than sharpness at rotor spacings  
218  $z/D=0.05$  and  $z/D=1$ . Directivity patterns of loudness and sharpness metrics seem to be in line  
219 with the initial hypothesis that the highest contribution to measured sounds is the noise emission of  
220 potential field interaction tones. McKay et al. (2019) found that potential field interaction tones in  
221 co-axial propellers have a dipole directivity with a null at 90 degrees. In this research, the dip in the  
222 value of equivalent SPL, equivalent A-weighted SPL and loudness at about 82-92 degrees (as shown  
223 in Figs. 2A, 2B and 2C) can be attributable to a decline in the noise emission of potential field  
224 interaction tones. This slight shift in the dip of noise radiation from 90 degrees to 82 degrees may  
225 be due to the contribution of noise sources others than potential field interaction tones, and that in  
226 this research the azimuthal angles measured were related to the bottom propeller.  
227 The decline in amplitude of potential field interaction tones at about 82-92 degrees also leads to an  
228 important increase in the relative contribution of higher harmonics of the blade passage frequencies  
229 (BPFs) and high frequency broadband noise, which is accounted for by an increase of sharpness as  
230 shown in Fig. 2D.

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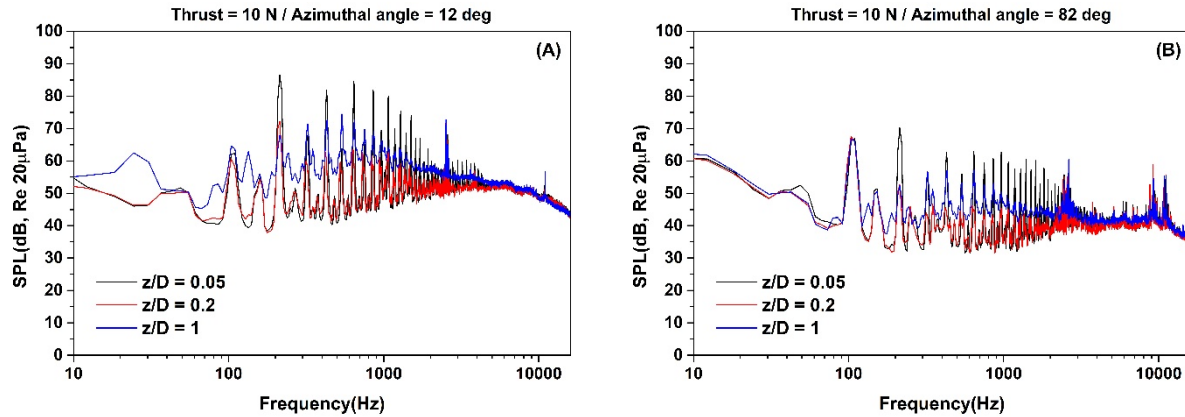
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234 FIG. 2. (Color online). The equivalent SPL (A), equivalent A-weighted SPL (B), and the 5<sup>th</sup>  
 235 percentiles of loudness (C) and sharpness (D) as a function of azimuthal angle, for a thrust setting of  
 236 10 N and for rotor spacings  $z/D=0.05, 0.2$  and 1.

237 To continue with the investigation of the individual noise sources in the contra-rotating  
 238 propeller under study, a narrow band frequency analysis was conducted. Figure 3 shows the narrow  
 239 band frequency spectra for the rotor spacings  $z/D=0.05, 0.2$  and 1 for azimuthal angles 12 deg (Fig.  
 240 3A) and 82 deg (Fig. 3B), and a thrust setting of 10 N. These two azimuthal angles allow the  
 241 comparison between the narrow band frequency spectra for high loudness (i.e. 12 deg) and high  
 242 sharpness (i.e. 82 deg).

243



244  
 245 FIG. 3. (Color online). Narrow band frequency spectra for the rotor spacings  $z/D=0.05$ , 0.2 and 1  
 246 for a thrust setting of 10 N, and for azimuthal angles 12 deg (A) and 82 deg (B).

247 As shown in Fig. 3, the noise signatures of the contra-rotating propeller measured are dominated  
 248 by tonal components distributed along the frequency spectrum (between 0.1 and 2 kHz). These  
 249 tonal components include potential field interaction tones at frequencies that are the summation of  
 250 rotor BPFs. An analysis carried out by McKay et al. (2019) and Chaitanya et al. (2020) demonstrated  
 251 that interaction tones are predominantly caused by potential field interactions, and therefore, they  
 252 decay rapidly with rotor spacing. This decay in amplitude of potential field interaction tones is  
 253 observed by comparing frequency spectra of rotor spacings  $z/D=0.05$  and 0.2. The decrease in  
 254 amplitude of potential field interaction tones as rotor spacing increases, leads to a sound signature  
 255 with higher relative contribution of high frequency components (broadband and tonal components  
 256 over 2 kHz). As the rotor spacing continues increasing, from  $z/D=0.05$  and 0.2 to  $z/D=1$ , the  
 257 contribution of broadband noise increases. This increase can be attributed to the enhanced  
 258 interaction between the turbulence generated by the upper propeller tip vortex and the lower  
 259 propeller as demonstrated by Chaitanya et al. (2020).

260 At an emission angle of 82 degrees, the amplitude of potential field interaction tones  
 261 significantly decays (especially for rotor spacing  $z/D=0.2$ ), due to their dipole directivity (as  
 262 described above). A decrease of about 20 dB is observed in the amplitude of potential field

263 interaction tones at 82 degrees compared to the amplitude at 12 degrees (see Fig. 3). For the specific  
264 case of rotor spacing  $z/D=0.05$  at 82 degrees, the amplitude of potential field interaction tones is of  
265 the same order of magnitude as the amplitude of BPF tones (Fig. 3B). This is due to both the dipole  
266 directivity of potential field interaction tones with a null at about 90 degrees and the maximum  
267 emission of BPF tones in the plane of the propeller (McKay et al., 2019). At an emission angle of 82  
268 degrees there is a reduction of high frequency broadband noise (compared to 12 degrees), and a  
269 series of tonal components of important magnitude are observed in the high frequency region, i.e. 2-  
270 12kHz. The precise reason for this behaviour is currently not known and more work is required to  
271 understand this phenomenon.

## 272 **B. Psychoacoustic metrics vs. rotor spacing**

273 To investigate the optimum rotor spacing configuration for the contra-rotating system under  
274 study, the value of the different psychoacoustic metrics described above in Section II.C has been  
275 calculated. The value of psychoacoustics metrics (5<sup>th</sup> percentile) as a function of rotor spacing at an  
276 azimuthal angle of 12 and 82 degrees is shown in Fig. 4. As described above (Section III.A), at 12  
277 and 82 degrees the contra-rotating system measured has the highest and lowest noise emission  
278 respectively.

279 As the rotor spacing increases, the amplitude of the potential field interaction tones distributed  
280 along the mid to high frequency regions decays significantly (see Fig. 3). Consequently, as shown in  
281 Fig. 4A, loudness decreases with an increase in rotor spacing, reaching the lowest values at the  
282 region  $z/D=0.2-0.4$  at 12 degrees and  $z/D=0.2-0.3$  at 82 degrees. This decay is more significant at  
283 12 degrees (about 30 sone reduction between rotor spacings  $z/D=0.05$  and 0.2) where the emission  
284 of potential field interaction tones is maximum, compared to 82 degrees (about 10 sone reduction  
285 between rotor spacings  $z/D=0.05$  and 0.2). At small rotor spacings, the decrease in loudness is due  
286 to a reduction in the potential field interactions between the two contra-rotating propellers. This

287 interaction noise is primarily tonal, and hence tonality drops significantly as rotor spacing increases  
288 (see Fig. 4B). These results are in line with existing literature (McKay et al., 2019; Chaitanya et al.,  
289 2020), where blade spacing optimization has been demonstrated to lead to important reductions in  
290 tonal noise (Anghinolfi et al., 2016). Figure 4B shows that, at 12 degrees, there is a significant drop  
291 in tonality at a rotor spacing  $z/D=0.35$ , to remain almost constant regardless rotor spacing onwards.  
292 At 82 degrees, this significant drop in tonality is found at a rotor spacing  $z/D=0.2$  (Fig. 4B). This  
293 might be due to the directivity characteristics of potential field interactions, as described in Section  
294 III.A. With higher amplitude of potential field interaction tones at emission angles about 0 degrees  
295 relative to the rotor axis, a greater rotor spacing is needed at 12 degrees for tonality to drop to  
296 minimum values (compared to 82 degrees). At both emission angles, 12 and 82 degrees the same  
297 minimum value of tonality is observed at a rotor spacing  $z/D=0.35$  (Fig. 4B).

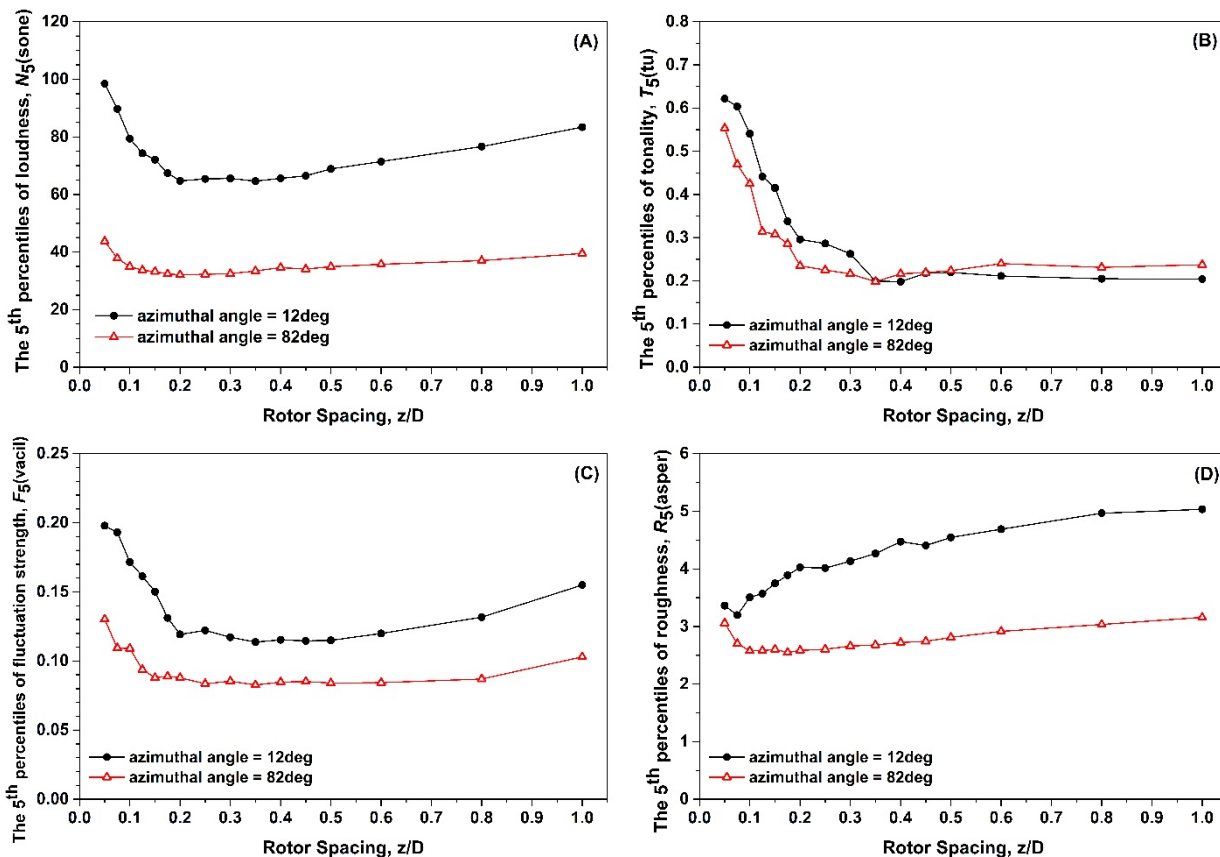
298 Fluctuation strength accounts for the low frequency amplitude modulation consequence of the  
299 closely spaced potential field interaction tones, as shown in Fig. 3. As rotor spacing increases  
300 beyond  $z/D=0.15-0.2$ , potential field interactions are reduced (i.e. amplitude of interaction tones  
301 decays), and consequently a significant drop in fluctuation strength is observed (Fig. 4C).

302 With increase in rotor separation distances, interaction noise between rotors increases due to  
303 enhanced turbulence-propeller interactions because of unsteadiness in the tip vortex as previously  
304 demonstrated by Chaitanya et al. (2020). This added turbulence-propeller interaction noise, which is  
305 tonal and broadband in nature (see Fig. 3), causes an increase of loudness after rotor spacing  
306  $z/D=0.4$  (Fig. 4A). Modulated broadband noise reaches higher roughness values than modulated  
307 discrete tones, and even unmodulated broadband noise attains considerable roughness values due to  
308 random envelope fluctuations (Daniel, 2008). Therefore, the increase in unsteady turbulence-  
309 propeller interaction noise as rotors are moved apart might explain the gradual growth of roughness  
310 shown in Fig. 4D. At 12 degrees, the highest emission of broadband noise due to unsteady



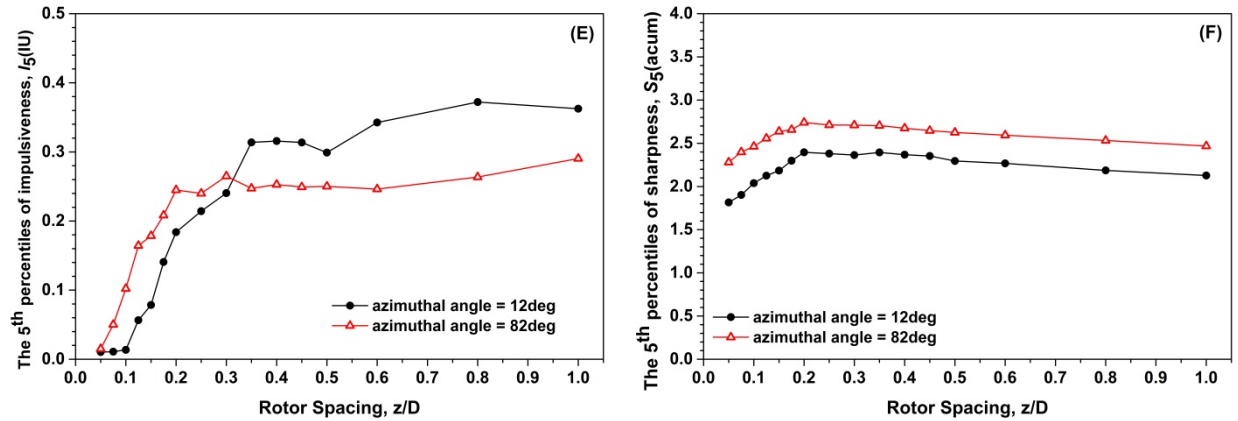
311 turbulence-propeller interaction noise leads to a higher rate of increase in roughness with rotor  
 312 spacing (as observed in Fig. 4D).

313 As seen in Fig. 4E, impulsiveness significantly increases as the rotor spacing grows. This is  
 314 observed for both azimuthal angles of highest and lowest noise emission, although the highest  
 315 values of impulsiveness are at 12 degrees. As discussed by Krishnamurthy et al. (2018),  
 316 impulsiveness and roughness metrics are strongly linked to each other. This is observed in this  
 317 paper by comparing Figs. 4D and 4E. Noise caused by enhanced turbulence-propeller interactions  
 318 is highly impulsive, and therefore, the added turbulence-propeller interaction noise as the contra-  
 319 rotating rotors move apart from each other leads to an increase in the impulsiveness metric. This  
 320 suggests that the impulsiveness metric should be considered, along with roughness, to account for  
 321 the perceptual response to propeller-turbulence interaction noise in the development of a PA model  
 322 for rotorcraft noise.



323

324



325

326 FIG. 4. (Color online). The 5th percentiles of loudness (A), tonality (B), fluctuation strength (C),  
 327 roughness (D), impulsiveness (E) and sharpness (F) as a function of rotor spacing at azimuthal  
 328 angle 12 deg and 82 deg, for a thrust setting of 10 N.

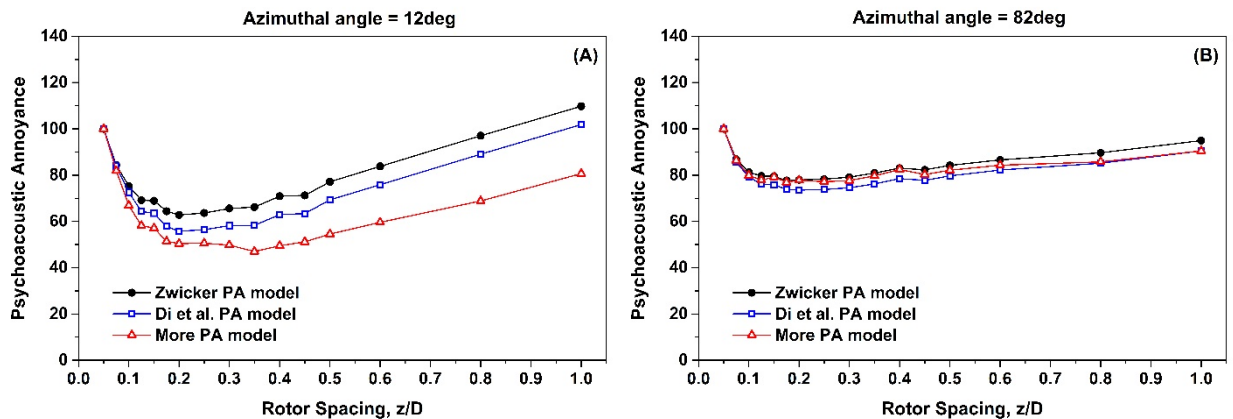
329

At rotor spacings in the region  $z/D=0.2-0.4$ , the contribution of potential field interaction tones  
 330 reaches a minimum. This leads to an increase in the relative contribution of high frequency tonal  
 331 and broadband components (i.e. shaper sounds). Therefore, at rotor spacings  $z/D=0.2-0.4$ , the  
 332 spectral centroid is located at a higher frequency (compared to audio signals of rotor spacings with  
 333 dominant potential field interaction tones), and therefore higher values of sharpness are observed  
 334 (Fig. 4F). The same pattern of sharpness as a function of rotor spacing is observed for both 12 and  
 335 82 degrees, although sharpness values are higher at 82 degrees due to the lowest emission of  
 336 potential field interaction tones at these emission angles. Cabell et al. (2016) found important  
 337 emissions of high frequency tones between 3.5 and 5 kHz for a series of multi-copters driven by  
 338 brushless DC motors. The noise generated by brushless DC motors is primarily due to both force  
 339 pulses as the magnets and armature interact and forces caused by phase changes in the motor drive  
 340 signal (Brackley and Pollock, 2000). Alexander et al. (2019) observed high frequency humps in a  
 341 series of multi-copters measured at hover configuration. Although the authors state this noise being  
 342 broadband in nature, its origin is still under investigation.

343 **C. Models for psychoacoustic annoyance**

344 To identify the optimal rotor spacing configuration for the contra-rotating propeller under  
345 evaluation, PA as a function of rotor spacing has been calculated according to PA models developed  
346 by Zwicker and Fastl (1999), Di et al. (2016) and More (2011). As shown in Fig. 5, as expected from  
347 the value of the psychoacoustic metrics analysed in section III.B, the lowest values of PA are found  
348 for rotor spacing in the range of  $z/D=0.2-0.4$  for both 12 and 82 degrees.

349 At 12 degrees, i.e. the emission angle with the highest amplitude of potential field interaction  
350 tones, three main results are observed in Fig. 5A: (i) A significant decay in PA is observed at the  
351 optimal rotor spacing area, compared to rotor spacings below  $z/D=0.2$  and above  $z/D=0.4$ . (ii) As  
352 rotor interaction noise at this rotor spacing is tonal in nature (i.e. potential field interaction tones),  
353 Di et al.'s PA model and especially More's PA model (both of which include a tonal factor) lead to  
354 lower psychoacoustic annoyance at optimal rotor spacing than Zwicker's PA model. (iii) While  
355 Zwicker's and Di et al.'s PA models give the minimum value of psychoacoustic annoyance at rotor  
356 spacing  $z/D=0.2$ , the lowest psychoacoustic annoyance according to More's PA model is at  
357  $z/D=0.35$ . This seems to be due to the higher contribution of the tonal factor in the PA model  
358 developed by More (see Fig. 6).



359

360 FIG. 5. (Color online). Psychoacoustic annoyance (PA) calculated with Zwicker's, Di et al.'s and  
361 More's PA models as a function of rotor spacing, for azimuthal angle 12 deg (A) and 82 deg (B) with  
362 a thrust setting of 10 N. Normalised to PA = 100 at  $z/d=0.05$ .

363 At 82 degrees, i.e. the emission angle with the lowest amplitude of potential field interaction  
364 tones, it is observed that the three models implemented give similar values of PA (Fig. 5B). The PA  
365 model developed by Di et al. (2016) gives the lowest values of PA among the three models used.  
366 The values of PA calculated according to the model developed by More are higher than the values  
367 calculated with Di et al.'s PA model for the rotor spacing range  $z/D=0.15-0.6$ . This seems to be  
368 due to the higher contribution of the sharpness factor in the PA model developed by More (see Fig.  
369 4F for sharpness vs. rotor spacing). At this emission angle, the range of variation of PA as a  
370 function of rotor spacing is significantly more reduced than at an emission angle of 12 degrees. This  
371 finding suggests that a suboptimal rotor spacing between contra-rotating propellers can lead to a  
372 significant increase in PA at emission angles in line to the rotor axis. These emission angles are  
373 typical for an observer on the ground interacting with a hovering contra-rotating UAV.

374 Zwicker's and Di et al.'s PA models (Zwicker and Fastl, 1999; Di et al., 2016) were derived for a  
375 series of mechanical sounds, and More (2011) modified Zwicker's PA model to account for  
376 characteristics of fixed-wing aircraft noise. However, none of these PA models have been optimised  
377 for propeller noise, and therefore might not be able to account for the complex perceptual  
378 interactions between individual noise sources (e.g. tonal components, roughness due to interactions  
379 between closely spaced tones, broadband noise in high frequency region due to unsteadiness in the  
380 wake, propeller-turbulence interaction noise, etc.). This might lead to important uncertainty in the  
381 prediction of PA with current models available. Furthermore, in the three PA models implemented  
382 in this work, loudness is included as a first order term, and the other psychoacoustic metrics are just  
383 second order factors. For this reason, the calculations of PA with these psychoacoustic models are

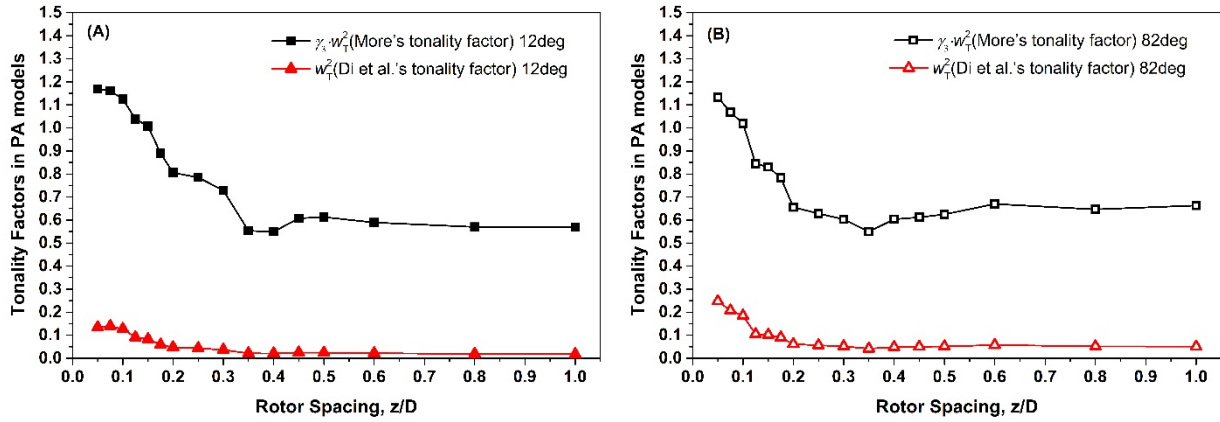
384 mainly driven by loudness, and the contribution of other psychoacoustic factors is quite reduced.  
385 Sharpness has been found to be an important contributor to aircraft noise annoyance (Torija et al.,  
386 2019). Sharpness, tonality and fluctuation strength were found to be important predictors of  
387 annoyance for rotorcraft-like sounds (Krishnamurthy et al., 2018; Boucher et al., 2020). Roughness  
388 has been found, for instance, an important factor to describing sound quality of electric motors  
389 (Mosquera-Sanchez et al., 2014; Ercan, 2019). The relative contribution of psychoacoustic features  
390 to annoyance for propeller noise is unknown. A process of listening tests and optimization of  
391 coefficients for psychoacoustic terms in PA models, similar to the one carried out by More (2011)  
392 for fixed-wing aircraft, is needed for propeller noise.

393 A recent study carried out by Gwak et al. (2020) has investigated the relationship between  
394 psychoacoustic metrics and the annoyance reported for a range of hovering UAVs of varying size.  
395 The authors found that the annoyance reported for medium and large drones is driven by loudness,  
396 sharpness and fluctuation strength; they also found that the annoyance reported for small drones  
397 cannot be explained by the three psychoacoustic metrics above, but tonality might play an important  
398 role. Based on the  $\beta$ -coefficients of a linear regression model of the annoyance for medium and  
399 large drones developed by Gwak et al. (2020, pp. 13), reported annoyance is mainly driven by  
400 loudness ( $\beta = 0.908$ ) and sharpness ( $\beta = 0.102$ ) and fluctuation strength ( $\beta = 0.268$ ) are second  
401 order contributors. Further, the standardised  $\beta$ -coefficients of the linear regression model indicate  
402 that an increase of 0.516 loudness units (i.e. sones) is needed to increase the annoyance in 1 unit<sup>1</sup>,  
403 while an increase of 9.902 sharpness units (i.e. acum) is needed for an increase in 1 unit of  
404 annoyance. Using the results of Gwak et al. (2020), the increase in the contribution of sharpness  
405 (relative to loudness) needed in order for it to dominate the psychoacoustic annoyance calculation is  
406 unrealistic. Based on this, one could argue that the optimal rotor spacing, in terms of

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<sup>1</sup> Note that annoyance in Gwak et al. (2020) is assessed using a 11-point scale.

407 psychoacoustic annoyance, suggested in this paper is not subjected to specific models but a more  
 408 general finding.



409  
 410 FIG. 6. (Color online). Di et al.'s tonality factor ( $w_T^2$ ) and More's tonality factor ( $\gamma_3 w_T^2$ ) in PA models  
 411 as a function of rotor spacing, for azimuthal angle 12 deg (A) and 82 deg (B) with a thrust setting of  
 412 10 N.

413 Although the perceived roughness and impulsiveness might be a factor due to unsteady  
 414 turbulence-propeller interaction noise, annoyance might be assumed to be primarily driven by  
 415 perceived tonality in the region of optimal rotor spacing as shown in Figs. 4B and 5 (i.e. sound is  
 416 eminently tonal in nature in this region due to the contribution of potential field interaction tones).  
 417 Several studies on a variety of noise sources, such as mechanical ventilation systems (Lee, 2016) and  
 418 aircraft noise (More and Davies, 2010) have suggested a combination of loudness and tonality  
 419 factors in multiple linear regression models as an accurate approach to predict annoyance. As seen  
 420 in Fig. 6, both the tonality factors derived by Di et al. (2016) and More (2011) (accounting for the  
 421 combined effect of loudness and tonality) suggest the optimal rotor spacing at  $z/D \geq 0.35$  (note that  
 422 the minimum value of both tonality factors is at  $z/D = 0.35$ ). Figure 6 shows the Di et al.'s tonality  
 423 factor squared (eq. 5), and More's tonality factor squared (eq. 7) multiplied by  $\gamma_3 = 1.25$  (to account  
 424 for the total contribution of tonality in More's PA model). This figure also shows that More's

425 tonality factor emphasises more the contribution of tonality in the PA model than Di et al.'s. The  
426 value of both tonality factors as a function of rotor spacing demonstrates that More's factor is more  
427 sensitive to variations in tonality, and therefore would lead to higher variation in PA for the same  
428 changes in tonality.

429 Future work for the development of PA models for propellers, and especially contra-rotating  
430 multiple blade propellers, will need to focus on psychoacoustic features such as perceived  
431 impulsiveness caused by propeller-turbulence interaction, and perceived roughness and perceived  
432 tonality of multiple tone complexes. Perceived roughness of superpositioned multiple pure tones  
433 (see Fig. 3) differs from perceived roughness of amplitude modulated tones, even with similar  
434 modulation strengths (Terhardt, 1974; Aures, 1985a). Perakis et al. (2013) found that the modulation  
435 index of an amplitude modulated tone must be lowered by  $2/3$  to be perceived as equally rough as a  
436 pair of superpositioned tones. This perceptual phenomenon should be taken into account when  
437 deriving a fluctuation strength/roughness function accounting for the perceptual interaction effect  
438 of closely spaced multiple tones. The perceived tonal strength of mechanical sounds containing  
439 series of harmonic or inharmonic complex tones can adversely influence the perception of these  
440 sounds (Lee et al., 2005). The prediction of annoyance from sounds containing multiple tone  
441 complexes requires not only accounting for the tonality of the most prevailing tone and signal  
442 loudness, but also the frequencies and the structure of the other tones in the noise signal (Lee and  
443 Wang, 2020). Aures/Terhardt tonality model (Aures, 1985b) accounts for the presence of complex  
444 tones. However, Lee et al. (2005) found that Aures/Terhardt tonality model overestimates  
445 perceived tonality of complex tones. These authors modified Aures/Terhardt tonality with a factor  
446 accounting for the differences in tonality perception between harmonic complexes and single tones,  
447 and concluded that the perceived tonality of multiple tone complexes is a function of the pitch  
448 strength of the harmonic components. Therefore, pitch perception models, such as Terhardt's

449 virtual pitch model (Terhardt et al., 1982a;b) should be taken into account when deriving a function  
450 accounting for the perceived tonality of complex tones in propeller noise.

#### 451 **IV. CONCLUSION**

452 This paper presents the results of a psychoacoustic analysis carried out to investigate the optimal  
453 distance between contra-rotating propellers to minimise noise annoyance. On the basis of  
454 psychoacoustic annoyance, calculated with models available in the literature, it can be concluded that  
455 the optimal rotor axial separation distance for the contra-rotating propellers under study is at a range  
456 of  $z/D=0.2-0.4$ , instead of previously observed  $z/D=0.25$  by Chaitanya et al. (2020) on the basis of  
457 overall sound power level. Similar optimal rotor spacing is found for azimuthal angles of maximum  
458 and minimum emission of potential field interaction tones, which are the highest contributors to the  
459 contra-rotating propellers sounds measured. These results are consistent with the rotor spacing with  
460 maximum aerodynamic efficiency for this contra-rotating system, measured at  $z/D = 0.3$  by  
461 Chaitanya et al. (2020). Although the Aures/Terhardt tonality metric and More's and Di et al.'s  
462 tonality factors suggest an optimal rotor spacing at  $z/D \geq 0.35$ , the psychoacoustic annoyance as  
463 calculated with the three models implemented in this work significantly increases for rotor spacings  
464 over  $z/D = 0.4$ . Furthermore, a rotor separation over  $z/D = 0.4$  might be more impractical from a  
465 construction perspective.

466 Below the optimal rotor spacing, the noise generation is dominated by potential field  
467 interactions between the two contra-rotating rotors, which is consistent with previous observations  
468 (McKay et al., 2019; Chaitanya et al., 2020). As the rotor spacing increases towards the optimum,  
469 the magnitude of these potential field interactions lessens significantly, and therefore a decrease in  
470 loudness is observed. As this source of noise is tonal in nature, tonality also drops significantly at the  
471 optimum rotor spacing. This decrease in tonality, and especially loudness, lead to a minimum in  
472 psychoacoustic annoyance. Fluctuation strength accounts for the slow amplitude modulation due to



473 closely spaced potential field interaction tones, and therefore drops importantly as the amplitude of  
474 these interaction tones decays.

475 With increased rotor separation distances after optimum, interaction noise between contra-  
476 rotating rotors increases due to enhance turbulence-propeller interactions, and this leads to an  
477 increase in loudness. Furthermore, as this is unsteady broadband noise in nature, roughness and  
478 impulsiveness increase when rotors move apart. This suggests that the perceptual effect of  
479 propeller-turbulence interaction noise could be accounted for by roughness and/or impulsiveness  
480 metrics.

481 A special case takes place when calculating sharpness as a function of rotor spacing. Sharpness  
482 reaches the highest values at the optimal rotor spacing region. As potential field interaction tones,  
483 distributed evenly along low-to-mid frequencies, decays significantly at the optimal rotor separation  
484 distance, the centroid of the spectrum moves towards the high frequency region (i.e. the relative  
485 contribution of high frequency tonal and broadband noise increases). Under these conditions of  
486 more dominant high frequency noise components, the values of sharpness are consequently higher.

487 The approach described in this paper, based on psychoacoustic methods available in the  
488 literature, provides a more sophisticated and comprehensive analysis than traditional sound power  
489 level analyses to inform the optimal design of rotating systems for lowest noise annoyance.  
490 Compared to sound power level based assessments, the proposed method is able to account for the  
491 key psychoacoustic features highly correlated to noise perception (e.g. tonality, roughness).  
492 Appropriately accounting for the perceptual effects of key psychoacoustic factors is crucial for the  
493 optimisation of designs for lower noise impact on potential exposed communities. As observed in  
494 this paper, minor deviations from the optimal design (in terms of rotor spacing) of contra-rotating  
495 propellers can lead to substantial increase in noise annoyance at emission angles typical for an  
496 observer on the ground interacting with a hovering UAV.

497 The three models implemented in this research gives the minimum psychoacoustic annoyance at  
498 similar rotor spacings. Despite differences in tonality, these models are mainly driven by loudness.  
499 Analysing findings of recent literature, the increase in the contribution (relative to loudness) of some  
500 secondary factors (e.g. sharpness) required to become dominant for psychoacoustic annoyance  
501 might be unrealistic. Based on the above, it could be argued that other psychoacoustic annoyance  
502 models might also lead to the same conclusion in terms of optimum rotor spacing, and therefore,  
503 the results of this paper are more general and no specific to the three annoyance models  
504 implemented. However, this cannot be demonstrated without extensive testing, as it is uncertain  
505 whether these psychoacoustic annoyance models provide an accurate picture of actual noise  
506 perception for propeller noise (and specifically contra-rotating rotor noise). The relative  
507 contribution to noise annoyance of different key psychoacoustic features in a variety of rotor noise  
508 must be investigated to derive psychoacoustic annoyance models optimised for rotating systems.

509 Further work is recommended to aid the design of rotating systems for lowest noise impact: (1)  
510 additional noise testing should be carried out to gather a comprehensive database with sound  
511 samples of different blade geometries, thrust settings, emission angles and single vs. coaxial  
512 propellers; (2) further analyses will include other psychoacoustic factors, such as impulsiveness,  
513 relative approach and additional tonality models; and (3) extensive subjective testing should be  
514 conducted to identify the psychoacoustic factors mainly driving rotor noise annoyance, refine or  
515 compute coefficients accounting for their relative contribution to noise annoyance, and thus,  
516 develop psychoacoustic annoyance models for rotor noise.

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