Noise from unmanned aerial vehicle contra-rotating propellers

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Abstract. This paper presents an analysis of the noise produced by contra-rotating propeller systems used on small unmanned aerial vehicles. Selected results from an extensive experimental campaign are presented. In these experiments a commercially available contra-rotating propeller with 2- and 3-blade props was statically tested in a large anechoic chamber. It was observed that the noise spectrum contained a large number of tones which occurred at the sum of integer multiples of the blade passing frequency of each propeller. These tones exhibit some interesting features including: the amplitude of the interaction tones decays rapidly with increasing propeller spacing; tones for which the azimuthal mode number is equal to zero generally have a dipole like radiation pattern radiating strongly along the propeller axis. This is in contrast to the tones at the blade-passing frequency which radiate strongly in the plane of the propeller. A simple theoretical model for predicting the tones produced by the contra-rotating propeller is presented and is used to explain some of the observed phenomena.

1. Introduction
This paper concerns the noise produced by the contra-rotating propeller systems used on small unmanned aerial vehicles (UAVs) such as quadcopters. These contra-rotating propellers consist of two coaxial propellers that rotate in opposite directions with the axis of the propeller generally aligned vertically, or close to vertical. A significant amount of research has been conducted investigating the noise from large horizontal axis contra-rotating propellers which are being considered as propulsors for large passenger aircraft because of their significantly better fuel efficiency compared to conventional turbofan engines [1]. The vertical axis contra-rotating propeller systems used on small UAVs may also provide good efficiency for some modes of operation relative to single propellers but also have several other advantages which include: a reduced planform area, redundancy in case of a propeller failure and a reduction in net torque imparted to the airframe. In this paper, which is an extension of a previous paper by the authors [2], a simple theoretical model is presented for predicting the interaction tones produced by these propellers. The experimental method is then described and results from the experimental study are presented and discussed. In particular, the effect of blade number, propeller spacing and propeller diameter on the radiated noise field is investigated. The theoretical model is used to explain some of the observed phenomena.

2. Theory
In this section a theoretical model is presented for calculating the interaction tones produced by the contra-rotating propeller in hover. These tones are produced by the unsteady loading on the blades of each propeller due to their interaction with the unsteady flow from the adjacent propeller. The model is based on the frequency domain formulation first presented by Hanson [4] with slight modifications so
that the formulae are valid for static hover with the blades modelled as being chordwise compact and straight. The model predicts the radiated acoustic pressure from one propeller which has $B$ evenly spaced blades. The acoustic pressure produced by the unsteady loading on the $b^{th}$ propeller blade is modelled as being equal to that produced by an unsteady line force, $F^{(b)}(r, \tau)$ (with units of N.m$^{-1}$), which varies with time, $\tau$, and radius $r$. The line force has axial component, $F^a\phi^{(b)}$, and tangential component, $F^\phi\phi^{(b)}$. The radial component is neglected. The line force rotates at speed $\Omega$ rad/s and is located in the $x = 0$ plane at azimuthal angle $\phi = \Omega \tau + \phi_0$, where $\phi_0$ is the azimuthal angle of the line force at $\tau = 0$. The line force is located between the blade hub and tip which are, respectively, located at $r = r_{hub}$ and $r = r_{tip}$.

The adjacent propeller has $B_a$ evenly spaced blades and counter-rotates at speed $\Omega_a$ rad/s. The reference blade passes a blade on the adjacent propeller at times $\tau = \frac{2\pi n}{B_a(\Omega + \Omega_a)}$, $n \in \mathbb{Z}$. (1)

Thus, if the unsteady flow field produced by each blade on the adjacent propeller is identical then the force acting on the reference propeller blade due to its interaction with the unsteady flow field of the adjacent propeller is periodic with period $T_F = 2\pi/B_a(\Omega_a + \Omega)$, and can thus be expressed as a Fourier series

$$F^{(b)}(r, \tau) = \sum_{k=-\infty}^{\infty} F^{(0)}_k(r) \exp\{i k B_a(\Omega_a + \Omega) \tau\},$$

(2)

where $F^{(0)}_k(r)$ is the amplitude of the $k^{th}$ Fourier harmonic of the force produced by the reference blade which has axial and tangential components, $F^a_{x,k}(r)$ and $F^\phi_{\phi,k}(r)$. Note that the $k = 0$ harmonic corresponds to the steady loading exerted by the reference blade on the air.

At time $\tau = 0$, the $b^{th}$ blade is located at azimuthal angle $\phi_0 = 2\pi b/B$ and the reference blade corresponds to $b = 0$. Thus the force exerted on the $b^{th}$ blade is related to that on the reference blade by

$$F^{(b)}(r, \tau) = F^{(0)}\left(r, \tau + \frac{2\pi b}{B(\Omega(\Omega_a + \Omega))}\right).$$

(3)

The far-field acoustic pressure, $p(x, t)$, at fixed location $x$ and time $t$ produced by the propeller is given by

$$p(x, t) = \frac{1}{4\pi c_0} \sum_B \sum_{b=-\infty}^{\infty} \int_{r_{hub}}^{r_{tip}} \left[\frac{F^{(0)}_k R}{R(1-M_R)}\right]_{t=t-R/c_0} \, dr,$$

(4)

(see ref. [3], eq. 49) where $c_0$ is the speed of sound in the ambient fluid, $M_R$ is the Mach number of the source location relative to the observer and the terms in the integrand appearing in the square brackets are evaluated at source time $\tau = t - R/c_0$, where $R$ is the distance between the source and observer positions and $\vec{R}$ is the unit vector pointing from the source to the observer location. The observer is located a distance $R_o$ from the origin of the coordinate system along polar angle $\theta$ (measured from the propeller axis) and azimuthal angle $\phi$ (the angle through which the blade rotates).

Making use of eqs. (3) and (4) and following the procedure described in ref. [3], the following expression can be derived for the far-field acoustic pressure

$$p(x, t) \approx \frac{B}{4\pi R_o c_0} \sum_{k=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \exp\left\{i \omega_{m,k} \left(t - \frac{R_a}{c_0}\right) - i v \left(\phi - \frac{\pi}{2}\right)\right\} I_{m,k},$$

(5)

where $v = dB - kB_a$ is the azimuthal mode number, $\omega_{m,k} = kB_a\Omega_a + m B \Omega$ is the tone frequency (in rad.s$^{-1}$) and

$$I_{m,k} = \int_{r_{hub}}^{r_{tip}} J_v\left(\frac{\omega_{m,k} \sin \theta}{c_0}\right) \left[\frac{F^{(0)}_{m,k} \omega_{m,k}}{c_0} \cos \theta - F^{(b)}_{\phi,k} v \right] \, dr.$$

(6)

For an observer on axis at $\theta = 0$, the Bessel function is equal to zero except when $v = 0$ (which, for a contra-rotating propeller configuration with 2 blade propellers top and bottom, occurs when $m = k$) for which the Bessel function has a value of 1. This yields $\omega_{m,k} = kB(\Omega_a + \Omega)$ and

$$p(x, t) \approx \frac{B}{4\pi R_o c_0} \sum_{k=-\infty}^{\infty} \exp\left\{i \omega_{m,k} \left(t - \frac{R_a}{c_0}\right)\right\} \hat{P}_{x,k},$$

(7)

where

$$\hat{P}_{x,k} = \int_{r_{hub}}^{r_{tip}} F^{(0)}_{x,k} \, dr.$$

(8)
Eq. (5) shows that the spectrum produced by the contra-rotating propeller will contain a series of tones at the sum and difference of the blade passing frequency of each propeller. It has been shown that for horizontal-axis contra-rotating propellers that, because of the behavior of the Bessel function term which appears in the integral of eq. (6), difference tones do not radiate efficiently. Eq. (7) shows that on the propeller axis, because only tones for which the azimuthal mode order $\nu = 0$ exist, the spectrum should (in theory) consist of a number of evenly spaced tones. This suggests that the acoustic pressure measured on-axis should consist of a series of identical impulses generated as each propeller blade interacts with the unsteady flow caused by the adjacent propeller. These impulses are periodic on axis, because the distance between a source on the blade and the observer and the relative velocity of this source is the same for each interaction and thus the acoustic pressure is periodic just like the blade loading. For observer locations away from the propeller axis, because the distance and relative velocity of a source on the propeller axis varies for each interaction, the acoustic pressure is not necessarily periodic.

3. Experimental method

Experiments were conducted for a large number of contra-rotating propeller configurations. These configurations used commercially available single propellers with 15” and 12” diameter propellers with 2 blades and a 12” diameter propeller with 3 blades. The motor used for this testing was a brushless DC coaxial rotor motor which was based on the design of a T-Motor MN501 motor and is shown in Figure 1. This type of motor configuration was chosen as it is a practical motor design that does not have an obstruction between the propeller - which allowed small propeller spacings to be investigated. The motor was controlled by two T-Motor Alpha electronic speed controllers powered by direct current power supplies. A single-axis Honeywell Model 151 S-type load cell was positioned directly underneath the motor to measure thrust as shown in figure 1 (left). The total electric power supplied to the motors during testing was also recorded. The testing was performed in the University of Auckland’s anechoic chamber, which has internal dimensions of 6.2 m × 6.2 m × 6.2 m and has a cut off frequency below 80 Hz. Acoustic measurements were taken with 11 G.R.A.S 46AE 1/2” microphone & preamplifier sets connected to National Instrument NI9234 modules in an NI cDAQ-9178 chassis. Microphones were positioned every 15° from a polar angle of 0° (directly above the propeller) to 150° on a C-shaped frame, as shown in Figure 1 (right). Measurements were not made close to a polar angle of 180° because these positions were in the direct flow from the propeller and measurements were contaminated by wind noise. All acoustic data was corrected to 1.5 m assuming spherical spreading. Acoustic measurements were taken over 30 s and saved as narrowband sound pressure levels for each polar angle. Most reflective surfaces were covered with a 10 mm acoustic absorber to minimise reflections. All acoustic data were acquired at 51.2 kHz and were processed to determine the power spectral density using Welch’s method with a Hanning window and a frequency resolution of 1 Hz.

Figure 1. Contra-rotating motor with 15” propellers spaced 48 mm apart. The motor was mounted on a load cell in the University of Auckland’s anechoic chamber (left). Microphone array around contra-rotating propeller test rig (right).
Detailed tests investigating the effect of propeller speed were conducted for nine different propeller configurations with between 100 and 169 experiments conducted at different propeller speeds for each configuration. The effect of a cropped top and bottom propeller was investigated using 4 different contra-rotating propeller configurations for the two-blade 15” and 12” diameter propellers. These tests were repeated for two different propeller spacings (17 mm and 48 mm). The effect of blade number was investigated using the 12” diameter, 3-blade propeller on top and a 12” diameter 2-blade propeller on the bottom which was compared with results from the various two-blade configurations. The effect of propeller spacing was investigated in detail for the two configurations using 2-blade propellers (the first configuration used a 15” diameter propeller top and bottom and the second used a 15” diameter propeller on top and with a 12” diameter propeller on the bottom). Propeller spacings from 15 mm to 70 mm at 2 mm increments were tested.

4. Results

The sound pressure level spectrum measured on-axis produced by a contra-rotating propeller configuration with two 15” diameter, 2-blade propellers spaced at 17 mm producing a total of 19 N of thrust is shown in figure 2. The measured spectrum is shown in blue. Rotor-alone and interaction tones are identified by the annotations which show the BPF harmonic of the top and bottom propellers. For example, \(\{2,1\}\) corresponds to the interaction tone at a frequency equal to the sum of 2 times the top propeller BPF and 1 times the bottom propeller BPF. The energy contained within a single tone “haystack” in the measured spectrum was defined as the total sound energy in the haystack which was more than 6 dB above the broadband noise level. The processed tonal sound pressure levels for significant tones below 2500 Hz are plotted in orange in figure 2.

The on-axis result is important for these vertical axis propellers as it represents the case for the UAV flying directly overhead. As measurements were not available for an observer position directly beneath the propeller, we have selected the position directly above the propeller. Inspection of eqs. (12-15) shows that the amplitude of the interaction tones at 0° and 180° should be identical. In accordance with the results expected from the theoretical analysis we see that the sound pressure level spectrum is dominated by tones for which the azimuthal mode order, \(\nu\), is equal to zero. The amplitude of the first eight tones is relatively high, but the amplitude of tones at higher frequencies decreases rapidly with increasing frequency indicating that the loading on the blades is relatively impulsive for this particular case. The spectrum contains much lower amplitude rotor-alone tones (at integer multiples of the BPF of each propeller) and interaction tones with non-zero azimuthal mode orders which theoretically should not occur, but might be partially explained by the microphone being slightly off-axis or the BPF tones being produced by some other mechanism such as periodic unsteady blade motion, caused by the brushless DC motor, or unsteady loading due to an inflow distortion.

The spectrum produced by the configuration with the 3-blade propeller on top and the 2-blade propeller on the bottom showed similar characteristics. However, for this configuration only two significant tones (the \(\{3,2\}\) and \(\{6,4\}\) tones) with zero azimuthal mode order were present in the spectrum below the sharp roll-off at 2500 Hz. This reduced the overall sound pressure level on-axis for this design. This result shows how careful blade number selection can be used to reduce the on-axis noise produced by such contra-rotating propeller systems.

Figure 3 shows the polar directivity of the first rotor alone tones of the top (\(\{1,0\}\)) and bottom (\(\{0,1\}\)) propellers, four interaction tones (\(\{1,1\},\ {2,2\},\ {3,3\},\ {4,3\}\)) and the overall broadband noise level produced by the contra-rotating propeller system considered in figure 2. For this case the rotor-alone tone from the top propeller is significantly louder because of the higher rotational speed of this propeller and the corresponding higher loading. The rotor-alone tones have peak levels close to the plane of rotation. Interestingly, these tones also radiate at angles at, and close to, the propeller axis which, as discussed previously, is not expected. The tones with zero azimuthal mode order (the \(\{1,1\}\), \(\{2,2\}\) and \(\{3,3\}\) tones) have a dipole-like radiation pattern. This is expected according to eq. (13) where the polar directivity is dominated by the product of a \(\cos(\theta)\) term, which has a null at 90° and peaks on axis, and the Bessel function term, which has similar behaviour (in this particular case). The \(\{4,3\}\) interaction tone which has a non-zero azimuthal mode order exhibits a null on-axis - as expected because of the
behaviour of the Bessel function, and a more complex directivity pattern in general, presumably due to the behaviour of the Bessel function (with non-zero order) and the non-zero term associated with the tangential loading in the integrand in eq. (13).

Figure 2. Sound pressure level spectrum (dB ref. $20 \times 10^{-6}$ Pa with 1 Hz bandwidth) measured at 0° produced by a contra-rotating propeller configuration with two 15” diameter, 2-blade propellers spaced at 17 mm spacing producing 19 N of thrust.

Figure 3. Polar directivity plot for a 15”-15” configuration with 17 mm spacing between the propellers that generated 1.94 kg of thrust. BPF tones, the first three zero-azimuthal-mode-order interaction tones and the $\{4,3\}$ interaction tone are shown.

Figure 4 plots contours of constant thrust, electrical power supplied to the contra-rotating propeller system and OASPL at a polar angle of 135° (dBA) as a function of propeller rotational speed for a contra-rotating propeller configuration with 15” diameter, 2-blade propellers with 48 mm spacing. Such plots are useful for identifying the optimal operating point for a propeller configuration to minimise noise or power supplied.

Figure 5 plots the sound pressure level against propeller spacing for the zero azimuthal mode order interaction tones, broadband noise and overall noise for a microphone at 0°. Results for a configuration with two 15” diameter, 2-blade propellers and a 15” diameter, 2-blade propeller top and 12” diameter, 2-blade propeller bottom were tested at a thrust of 19.6 N for each propeller spacing. The level of all
interaction tones generally decreases with increasing propeller spacing, with the total reduction in level generally decreasing with increasing tone frequency. The rate of decay of the interaction tones with increasing propeller spacing is not smooth and further investigation is required to explain the reduction in levels observed in these experiments. Interestingly, the broadband noise is relatively independent of propeller spacing. The overall noise level is dominated by the interaction tones and thus generally decays with increasing propeller spacing. At most spacings the interaction tones considered here have lower amplitude for the cropped propeller configuration, which is also true of the overall sound pressure level at spacings less than 50 mm. The cropped configuration produces an overall sound pressure level which is observed to fluctuate significantly at higher spacings. The broadband noise produced by both configurations is relatively similar.

Figure 4. Performance curves for a 15”-15” contra-rotating propeller with 48 mm spacing. Power, OASPL at a polar angle of 135° and thrust are shown for various speed ratios.
Figure 5. Sound pressure level plotted against propeller spacing for the zero azimuthal mode order interaction tones, broadband noise and overall noise for a microphone at 0°. Results are presented for a configuration with two 15” diameter, 2-blade propellers and a configuration with a 15” diameter, 2-blade propeller top and 12” diameter, 2-blade propeller bottom. Both propeller configurations generated a total thrust of 19.6 N for each propeller spacing.
5. Conclusions

This paper has presented selected results and analysis of the noise produced by a small contra-rotating propeller system used on small unmanned aerial vehicles (UAVs). In these experiments a commercially available contra-rotating propeller with 2- and 3-blade propellers was statically tested in a large anechoic chamber. It was observed that the noise spectrum contained a large number of interaction tones which dominated the overall noise level at most observer angles. In order to explain some of the observed phenomena, a simple theoretical model for predicting these tones was presented. Along the propeller axis, tones with zero azimuthal mode order dominated the radiated noise field. It was shown how the number of such tones could be reduced by careful selection of the propeller blade numbers. Interaction tones for which the azimuthal mode number was equal to zero were observed to radiate very efficiently along the propeller axis and these tones were observed to have a dipole like radiation pattern radiating strongly along the propeller axis, in contrast to the rotor-alone tones at the blade-passing frequency which radiate strongly in the plane of the propeller. It was also shown how the amplitude of the interaction tones generally decayed with increasing propeller spacing.

References

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