

DRONE NOISE REDUCTION VIA RADIATION EFFICIENCY CONSIDERATIONS

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ABSTRACT

This paper is the first in a series which investigates counter-rotating drone engine noise reduction from a radiation efficiency perspective. This paper takes two design guidelines suggested in the literature for counter-rotating open rotor airplane engine technology and shows how they can be carried over to counter-rotating drone technology. These earlier design guidelines state that a large number of blades should be used on each rotor, and that the number of blades on each rotor should be the same. This paper then goes on to state the theoretical background behind a third design guideline. The third design guideline suggests using dissimilar rotational speeds on the two rotors in order to separate the tonal components of counter-rotating drone engines into separate frequency bins, while retaining the advantages associated with having the same number of blades on the two rotors.

Keywords: acoustics, counter-rotating drone engine, personal air vehicle, radiation efficiency, turbomachinery.

NOMENCLATURE

| | | |
|----------|---------|-----------------------------------|
| B | [-] | blade number |
| f | [Hz] | frequency |
| m | [-] | azimuthal mode number |
| n | [-] | harmonic index |
| Ω | [rad/s] | amplitude of the rotational speed |

Subscripts and Superscripts

| | |
|-----|---------|
| A | aft |
| F | forward |

1. INTRODUCTION

Drone noise levels are becoming more of a nuisance as their numbers are quickly rising. Not only are more drones appearing in the skies, but efforts are being made to develop large drones capable of carrying out a wide assortment of tasks [1, 2], including the transportation of passengers with the quickly developing technology of personal air vehicle [2]. Therefore, the noise reduction of these aircrafts has become a relevant topic of interest [2, 3]. Though drones are a relatively new field of technology and hence research, there are many noise reduction guidelines available in the turbomachinery literature that can be carried over to help reduce the noise of this technology if one takes into consideration the main similarities and differences between the various configurations. For drones having two fan stages, the layout is often very similar to that of Counter-Rotating Open Rotor (CROR) airplane engines (examples of drones can be seen in Figure 1. and in [1] as compared to those of CROR in Figure 2. and in [4]). The main difference between the two layouts is that while CROR are in general mounted with their axes lying in the horizontal plane and observers who are exposed to the noise of the airplane engine are located in the radial direction, the opposite can be stated regarding many drone designs. The axes of drone engines are most often lying in the vertical plane and observers are located in the axial direction, more specifically in only one of the axial directions, on the ground. This is especially relevant during take-off and landing. This is unfortunately not seen in Fig. 1, which depicts the counter-rotating drone engine as it was tested in a wind tunnel, but the reader can refer to other literature to see typical drone layouts.

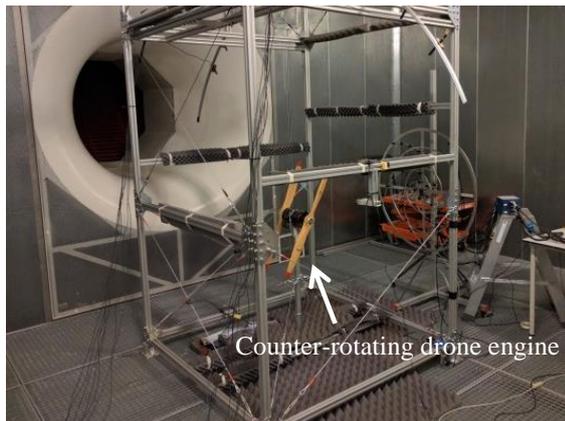


Figure 1. ‘One-Man-Drone’ counter-rotating drone engine in a test section [5].

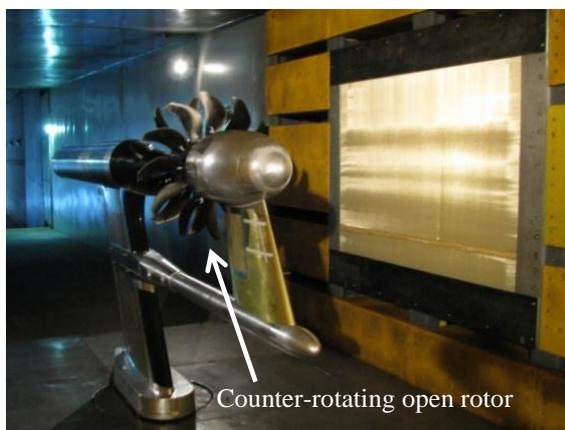


Figure 2. F31/A31 CROR in a test section [6]

This investigation approaches the question of quiet drone design via the effect of radiation efficiency and acoustic modes on the acoustic signature and the acoustic directivity pattern. Similar analytical studies have been carried out in the literature [7, 8, 9, 10], and while the basis of the theory behind these design guidelines has been provided there, when considering the theory as it applies to drones, some important similarities and differences between the various engine configurations need to be taken into consideration. In this paper, the azimuthal mode number and hence the radiation efficiency will be looked at, explaining how acoustic modes influence the acoustic characteristics of drones and how this can be taken advantage of in modern designs. A similar discussion regarding two noise reduction design guidelines for CROR airplane engines has been submitted by the corresponding author along with co-authors and is under consideration for publication [11]. The two design guidelines which were given in [11] for CROR airplane engines suggest that the number of blades on each fan stage be large and that the same number of blades be used on each of the two rotor stages. The current paper looks at applying these same design guidelines to

counter-rotating drone engines, but the novelty of the current paper is that it goes beyond what has already been stated in [11], providing a third design guideline and a means for further reducing the acoustic impact of counter-rotating unducted turbomachinery. As will be discussed below, the third design guideline suggests the use of dissimilar rotational speeds for each stage in order to separate the tonal noise sources into separate frequency bins. The aim of the current publication is to introduce the ongoing research which is based on the theory presented herein. This article is therefore the first in a series regarding the noise reduction of counter-rotating drone engines via radiation efficiency considerations, presenting only the theory. In future articles the arguments will be supported with uninstalled counter-rotating drone engine sideline microphone directivity and phased array microphone measurement data, which has been collected in a laboratory environment as well as basic simulation data.

As stated above, none of the three design guidelines presented herein are entirely new but rather come from the literature and have been carried over and rethought regarding their application to counter-rotating drone engines, with special consideration for how they influence the radiation efficiency. Investigations regarding the variation of RPM values of CROR rotors are available in the literature and have been looked at in order to make a preliminary assessment regarding factors which need to be kept in mind in further investigations aimed at supporting the design guidelines presented herein. Elliott presented investigations of CROR having various RPM settings in [12]. These investigations were limited to two blade pitch angle settings and the forward and aft rotors always had equal RPM values. No dissimilar RPM values were looked at. The results show that simultaneously increasing the RPM values of both of the rotors without changing the blade pitch angles will increase the noise of the CROR for all frequencies. Elliott states that this result would be expected as the blade pitch angle influences the aerodynamic performance and hence the amplitudes of many of the noise sources.

Parry and Vianello [13] looked at many CROR blade number configurations altering the RPM values on the two rotor stages independently. The description of the investigation suggests that a single blade pitch angle was investigated. The investigation concludes that for fixed blade numbers, no trend is seen with the variation of forward rotor RPM, except for an increase of noise when the RPM is excessively high. For the aft rotor, the study concludes that reducing the RPM will reduce the noise. Though many configurations were investigated, equal blade numbers were avoided. The authors of [13] support this decision by stating

that numerous studies and anecdotal evidence suggest that such configurations should be avoided.

The research carried out by Delattre and Falissard [14] looked at the influence of torque ratio on CROR noise. In this case the total thrust was kept constant. The number of blades on the two stages were kept constant and various blade pitch angles were looked at in order to find the appropriate settings for a given torque ratio. The investigation concludes that the torque ratio had a small influence on the aerodynamic performance, but a large impact on interaction noise levels. The dominant noise source mechanisms were linked to the forward rotor blade-tip vortices, the forward rotor blade wake, and the forward and aft rotor potential fields, which strongly influence the interaction noise, and to the rotor self-noise of both stages. It is stated that the self-noise is largely dominant at cruise conditions, while the interaction noise is significant if not dominant at take-off conditions.

While the above publications compared various RPM settings for CROR, the publication of Magliozzi, Hanson, and Amiet [15] suggested the use of dissimilar rotational speeds for separating the tonal components of CROR with equal blade numbers into individual frequency bins, though not approaching the question of counter-rotating unducted turbomachinery noise reduction from a radiation efficiency perspective as done here.

2. CURRENT DESIGN GUIDELINES FOR A LARGE AND EQUAL NUMBER OF BLADES

The turbomachinery community has developed multiple design guidelines for reducing the noise of many turbomachinery applications. Since the goal of a large portion of the research was to reduce community noise associated with the airplane industry, it is not surprising that most of the advancements are associated with ducted turbofan engines. As the state of the art of drone technology, together with that of personal air vehicles quickly advances, the tools and techniques which have made quieter airlines a reality can be utilized in developing the drones of tomorrow. Therefore, taking ideas from currently available technology and fitting them to drone technology is something which can and should be carried out.

The research presented in [11] suggests two design guidelines for reducing the noise of CROR aircraft engines. These two design guidelines come from an analytical investigation of the radiation efficiency of CROR and suggest using a large number of blades on each rotor stage and having the number of blades on each rotor stage be the same. The paper goes on to support the guidelines with numerical as well as measurement results [11]. The comparisons showed that a test case consisting of 12 blades on the forward rotor and 10 blades on the

aft rotor was louder than one having 12 blades on both rotors. The simulation and measurement results therefore demonstrated how the suggested guidelines can be applied to CROR technology in future. This chapter aims to summarize and carry over the findings in [11] given for CROR engines to counter-rotating drone engine technology.

In order to understand the approach presented in [11] and the results which were reached, first some topics investigated in earlier literature need to be looked at. Tyler and Sofrin showed that the Blade Passing Frequency (BPF) and interaction tones of blade row pairs (rotor-stator or rotor-rotor interaction tones) can be characterized by acoustic modes [10]. These modes can be characterized according to the direction in which their wave fronts propagate, with azimuthal and axial modes being relevant in the case of unducted counter-rotating axial flow turbomachinery. The modes can also be characterized based on their level of radiation efficiency. Certain modes radiate very efficiently, while others are evanescent. Evanescent waves can be characterized by a quick decay of pressure amplitude as a function of distance travelled from the source [8, 16, 17], similar to that of cut-off modes discussed in early ducted compressor investigations [10]. In general, independently of whether one examines ducted or unducted turbomachinery, if blade row interactions produce efficiently propagating acoustic modes, it is advantageous to reduce or eliminate them at the source. The literature has shown that axial modes radiate very efficiently, and therefore most investigations dealing with turbomachinery noise have avoided the use of equal blade numbers for rotor-stator and rotor-rotor pairs, as they would result in axial modes [13, 18]. By doing so, the effect of axial modes was minimized, eliminating the need to further deal with their noise.

$$m = |n_F B_F - n_A B_A| \quad (1)$$

Let us investigate the azimuthal mode number equation, as seen in Eq. (1) [16, 17]. The azimuthal mode number, m , is equal to the number of lobes rotating around the axis for the given mode, n is the harmonic index, B is the number of blades on a given rotor, and subscripts F and A refer to the two rotors, forward and aft, respectively. This is a variation of the general formula for the azimuthal mode number equation that is provided in the literature [10]. Here the equation is limited to sum tones ($n \geq 0$), which have been shown to radiate efficiently [7, 8, 16, 17]. The literature also states that if $m > 0$, then the lobes of the azimuthal mode are co-rotating and if $m < 0$ then they are counter-rotating, with the case of $m = 0$ referring to axial plane modes [7, 10], which are the only modes which radiate efficiently in the axial direction [8]. Since counter-rotating turbomachinery is being

investigated here, an absolute value is taken, and the direction of rotation is determined based on whether the multiple $n_F B_F$ is less than or greater than $n_A B_A$ as described in [6].

Carefully choosing the blade numbers of each blade row, the azimuthal mode numbers pertaining to the BPF and blade row interaction frequencies of counter-rotating turbomachinery can be manipulated (see Eq. (1)). The investigations presented in [8, 16, 17] have shown that as the absolute value of the azimuthal mode number of a BPF or interaction tone is increased, its radiation efficiency will decrease. This is generally true for low tip-speed Mach numbers [8]. Therefore, in order to reduce the radiation efficiency, one should design counter-rotating turbomachinery to have large absolute values for the azimuthal mode numbers of all the tones. In this way the amplitude of the noise will drop off quickly as it travels away from the source toward the observer for the BPF and interaction tones.

The first aspect of the design guideline proposed in [11] is therefore that the number of blades on the forward and aft rotors should both be large. Looking at Eq. (1), it can be seen that in choosing a fix value for n_F or n_A and increasing the value of the other harmonic index, the values of the azimuthal mode numbers will change steeply and therefore the radiation efficiencies of the BPF and interaction tones of dissimilar harmonics will be low.

For interaction tones where $n_F = n_A$ there would have to be a large difference between B_F and B_A in order to receive large values for the azimuthal mode numbers. On the other hand, a set of rotors having a large number of blades on both rotors as well as having very different blade numbers (e.g. $B_F=20$ and $B_A=10$) is rather unrealistic. As discussed above, having $m = 0$ results in axial modes. The highest radiation efficiency of such axial modes will be in the axial direction, as these modes are significantly mitigated in the radial direction. As can be seen from Eq. (1), if B_F does not significantly differ from B_A , then the values for the azimuthal mode numbers for the case when $n_F = n_A$ will be relatively low, but can be varied by making slight changes in the number of blades on each rotor. This leads up to the second design guideline proposed in [11], which suggests that the number of blades on each rotor be the same. The interaction tones for $n_F = n_A$ will in this case result in axial modes. Taking into consideration both design guidelines suggested in [11] and discussed above, designing counter-rotating turbomachinery of low blade tip Mach number to have the same large number of blades on each rotor will result in all tones having large azimuthal mode numbers (low radiation efficiencies) or being associated with axial modes (which are significantly mitigated in the radial direction). At first glance, the use of equal

blade numbers might seem counterintuitive, and therefore [11] investigated the above stated design guidelines via measurement and simulation data, the results of which support the proposed guidelines well.

The two design guidelines discussed above and presented in [11] have been shown to reduce the noise of CROR airplane engines. One of the main thoughts in applying the guidelines came from the geometric properties of axial modes, which radiate in the axial direction, away from all bystanders. As compared to ducted turbofan engines, CROR do not have a natural shielding in the radial direction to help reduce the sound levels reaching bystanders and therefore the reduction of radial modes, taking into consideration the potential penalty associated with axial modes, was investigated. The measurement and simulation results showed that even though an increase of noise was expected in the axial direction, this was not the case. The configurations having the same number of blades on both rotors were better in both the radial as well as the axial direction when looking at the overall noise propagating to the far field (see [11]).

In comparing a CROR engine to a counter-rotating drone engine, the most significant difference is that typical drone engines have vertical axes. During take-off and approach most bystanders will therefore be located at some position which is for the most part aligned with the axis. One approach to reducing the noise associated with counter-rotating drone engines could therefore be to tune the azimuthal mode numbers so that $m \neq 0$, in other words, to not have any axial modes. Though this approach could be advantageous in some cases, there are two points of view which need to be kept in mind. First of all, as the results of [11] have shown, there was no axial noise level penalty associated with using the even blade numbers and hence having axial modes. It would therefore be logical to use the same configuration for counter-rotating drone engines. Second of all, the quickly growing personal air vehicle industry will soon need solutions for counter-rotating drone engines that are quiet in both the radial as well as axial direction, making the use of axially quiet but radially loud counter-rotating drone engines insufficient.

3. NEW DESIGN GUIDELINE FOR DISSIMILAR ROTOR RPM VALUES

As discussed in the previous section and in [11], having a large and equal number of blades on the two stages of counter-rotating drone rotors will result in a reduction of noise in the far field. A concern that has been brought up regarding these design guidelines is that setting the blade numbers equal on the two rotors will result in multiple tonal components falling in the same frequency bin. Let us examine this using a basic equation for the

frequency of the various tonal components as given in [17] and presented in Eq. (2).

$$f_{(n_F, n_A)} = n_F B_F \Omega_F + n_A B_A \Omega_A \quad (2)$$

In Eq. (2), Ω refers to the amplitude of the rotor rotational speed. Since this investigation is limited to counter-rotating propellers, the sign of the direction of rotation has been incorporated into the equation ($\Omega \geq 0$). As was done with the equation for azimuthal mode number, Eq. (2) is a simplified equation which is limited to sum tones. The equation also neglects the effects of flight velocity and viewer angle when compared to similar equations presented in other literature [6]. The combination frequencies for the various BPF and interaction tones are given as $f_{(n_F, n_A)}$. This form of the equation is sufficient for us here since we want to investigate the frequencies of the dominant BPF and interaction tones which will appear in the far field sound pressure level spectra of counter-rotating turbomachinery in parametric form.

Table 1. Frequencies of various BPF and interaction tones for the case when $B_F = B_A = B$

| $f_{(n_F, n_A)}$ | $f_{(n_F, n_A)}$ for $\Omega_F = \Omega_A = \Omega$ | $f_{(n_F, n_A)}$ for $\Omega_F = 1.3\Omega_A = 1.3\Omega$ |
|------------------|---|---|
| $f_{(1,0)}$ | $B\Omega$ | $1.3B\Omega$ |
| $f_{(0,1)}$ | $B\Omega$ | $B\Omega$ |
| $f_{(2,0)}$ | $2B\Omega$ | $2.6B\Omega$ |
| $f_{(0,2)}$ | $2B\Omega$ | $2B\Omega$ |
| $f_{(1,1)}$ | $2B\Omega$ | $2.3B\Omega$ |

As stated above, having $B_F = B_A$ along with $\Omega_F = \Omega_A$ results in multiple tonal components falling in the same frequency bin. Table 1 shows a few examples for combination frequencies as a function of BPF and interaction tone in order to help the reader visualize the problem. The frequencies are given in parametric form in order to remain general. As can be seen in the left-hand column of the table, for most typical CROR applications, where the rotational speeds of the two rotors are equal ($\Omega_F = \Omega_A$), setting $B_F = B_A$ results in multiple components falling in the same frequency bin. It is therefore expected that their magnitudes will add together constructively in the far field, resulting in higher noise levels for those particular frequencies and hence a greater annoyance for bystanders. Interestingly, the results of [11] showed that having multiple tonal components fall in the same frequency was all in all a less significant influencing factor than the magnitude of the radiation efficiency, with the case having $B_F = B_A$ being quieter than the case where $B_F \neq B_A$. The results in [11] therefore demonstrated why it is advantageous to keep $B_F = B_A$.

In investigating Eqs. (1) and (2), a solution has been noticed for separating the various components of the noise into individual frequency bins while not sacrificing the advantages associated with having $B_F = B_A$. While in Eq. (1) the number of blades influences the azimuthal mode number, the rotational speed only plays a role in Eq. (2) providing the frequencies at which the various BPF and interaction tones radiate while not influencing their azimuthal mode numbers and hence their radiation efficiencies. Therefore, it is possible to keep the number of blades the same while at the same time separating the noise sources into separate frequency bins by setting dissimilar rotational speeds for the two rotors. The third design guideline for counter-rotating drone engines suggested in this paper is therefore that the rotational speeds of the two rotors should be dissimilar. To help the reader visualize the difference between this case and the one described above, BPF and interaction frequencies are given for the arbitrarily chosen case of $\Omega_F = 1.3\Omega_A$ in the right-hand column of Table 1. (The rotational speed ratio was chosen purely for demonstrational purposes.) It can be seen that as compared to the case of $\Omega_F = \Omega_A$ the various tonal components are sorted into individual frequency bins, while the advantages of having equal blade numbers is retained. In applying this guideline together with the two presented in [11] and summarized above, further noise level reductions should be realizable.

4. FURTHER STEPS

Many other aspects other than blade number and rotational speed also need to be considered when reducing the noise of counter-rotating unducted turbomachinery. These are also discussed in the literature for topics which include rotor diameter [15], blade loading [8, 9, 15], blade stacking [15], blade thickness [15], blade shape [15], and noise source directivity patterns (monopole, dipole, quadrupole) [8]. It is stated in [15] that the best approach would consist of a complete aerodynamic and acoustic methodology so that all the trade-offs between noise and performance could be investigated, while taking into consideration additional factors such as weight, cost, and reliability. Such investigations would be extremely costly and therefore alternatives need to be considered. In addition, since the current investigation approaches the question from a radiation efficiency perspective, it would be best to eliminate most of these factors from the investigations. Though beyond the scope of this the first article in the series, future investigations will look at simplified numerical models for rotating point sources. It is given in [8] that it is possible to lump the forces acting on a blade at one radius without losing any accuracy and therefore rotating point sources will provide a quick and easy means

for the investigation of various variables (blade number, RPM, and noise source directivity pattern) without having any influence on the results from other variables (blade shape, blade loading, blade stacking, and blade thickness). Future investigations will also look at uninstalled counter-rotating drone engine sideline microphone directivity and phased array microphone data, which has been collected in a laboratory environment. Though the current results seem promising, it is interesting to note that a few comments in the literature need to be clarified. In two articles [13, 16], it is stated that rotational speed influences the radiation efficiency of acoustic modes. Though most of the literature seems to agree that this is not so, and the two articles mentioned above might also have meant to say that increasing the rotational speed increases the magnitude of various sources, this needs to be clarified with the help of the simplified numerical models described above.

5. SUMMARY

Drone technology is quickly advancing and with the expected introduction of personal air vehicles and other large size drones on the market in the upcoming years the question of drone noise reduction is an up and coming topic of interest. This paper is the first in a series which approaches the question of drone noise reduction from a radiation efficiency perspective. It was shown how two earlier design guidelines for CROR noise reduction, also coming from radiation efficiency investigations, could be carried over to counter-rotating drone engines. These design guidelines have suggested, and measurement and simulation results have supported, that a large number of blades should be used on each rotor of counter-rotating drone engines and that the number of blades on each rotor should be the same. A third design guideline was introduced in this paper, which suggests that the RPM settings of the two rotors be dissimilar. In this way BPF and interaction tones falling into coinciding frequency bins can be shifted into separate frequency bins while not losing the advantages associated with having the same number of blades on the two rotors. Though the article did not support these results with measurement or simulation data, the future of the theory seems promising, and an outline as to how the theory will be supported with simulation and measurement data has been provided. The use of rotating point sources will provide a means for investigating counter-rotating drone engine design from a radiation efficiency perspective while being able to eliminate other factors which could influence the results.

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