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Ducted rotor noise analysis

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Abstract. This paper provides a description of the important noise sources for low-Mach number ducted propellers. It presents an analysis of various noise source strengths using generic acoustic models from the literature. The paper shows that for low-Mach number applications, unsteady noise sources are of major importance. The duct expansion ratio is shown to reduce tonal noise from steady loading because as the expansion ratio increases, the rotor thrust is reduced. Haystacking noise, created by multiple cuts of the same eddy by subsequent rotor blades, is analysed using an analytical approach. The time and length scales within the ducted propeller are shown to significantly affect the intensity of the noise created by this interaction. The relationship between rotor thrust, duct geometry, turbulence distortion and noise is found to be an important research gap that needs to be addressed by future research programs.

Keywords: Ducted Propeller, Acoustics, Haystacking.

1 Introduction

Sustainable aviation design principles are incentivising the development of new technology that will reduce both carbon and noise emissions in new aircraft [1]. New propulsion designs, such as boundary layer ingestion (BLI) ducted fans and propellers [3], coupled with electric [8] or sustainable fuel energy sources [1] promise large energy savings; however, they are susceptible to higher levels of noise due to distorted turbulent inflows. Further, proposed urban air mobility (UAM) vehicles are being developed for use in urban environments but concerns over noise are a key challenge to their successful introduction to service [6].

New sustainable propulsion systems will most likely be ducted fans or propellers running with low tip Mach number as they are ideally suited to electric propulsion systems [6]. Ducted propellers have superior aerodynamic performance, but also have noise emission challenges [12]. Unsteady loading noise sources will dominate the noise spectrum of these low-Mach number rotating systems, rather than steady loading and thickness noise sources typical of higher Mach number fans. This means that turbulence interaction noise (from wakes, the atmosphere or boundary layers) and distorted (non-uniform) inflows will create the most important noise sources for future air propulsion systems.

This paper explores, in a general manner, the role of a duct on two propeller noise sources, steady loading and haystacking tones, an unsteady loading source. Steady loading is created by the constant loads (thrust, torque) on the rotor while haystacking is caused by the interaction of a single turbulent eddy or flow structure with multiple blades in the rotor. Rather than explore the acoustic scattering of the duct, this paper looks at the role of duct geometry and thrust level on the noise source itself. It provides a general, engineering-level analysis whose purpose is to spark interest in the subject and provide some guidance for future research needs.

2 Open and Ducted Rotor Flows

Open propellers draw air through a rotor disc and accelerate the flow, resulting in thrust. The propeller wake subsequently contracts to half the rotor diameter far downstream as pressure is equalised. For ducted propellers, the flow expansion downstream of the rotor is controlled by the geometry of the duct, with the expansion ratio ($\sigma_d = A_{exit}/A_{rotor}$) is defined as the ratio of duct exit area to propeller (rotor) area. This changes the flow through the duct so that the duct itself sustains some of the total thrust [9]. This means that for the same thrust ratio, a ducted propeller rotor carries less thrust than an unducted (or open) propeller. Momentum theory [9] can be used to estimate the effects of a duct on thrust levels. Figure 1 shows momentum theory results illustrating these effects for a hovering propeller. Figure 1(a) shows that the ratio of thrust for a ducted propeller system to an open rotor system in hover increases with expansion ratio. Figure 1(b) presents the ratios of duct and rotor thrust to total ducted propeller system thrust. The amount of thrust taken by the rotor decreases with expansion ratio implying that a duct can assist in efficiency and possibly reduce noise levels. Note that this analysis does not consider duct drag, which can be significant at high speeds and long duct lengths.

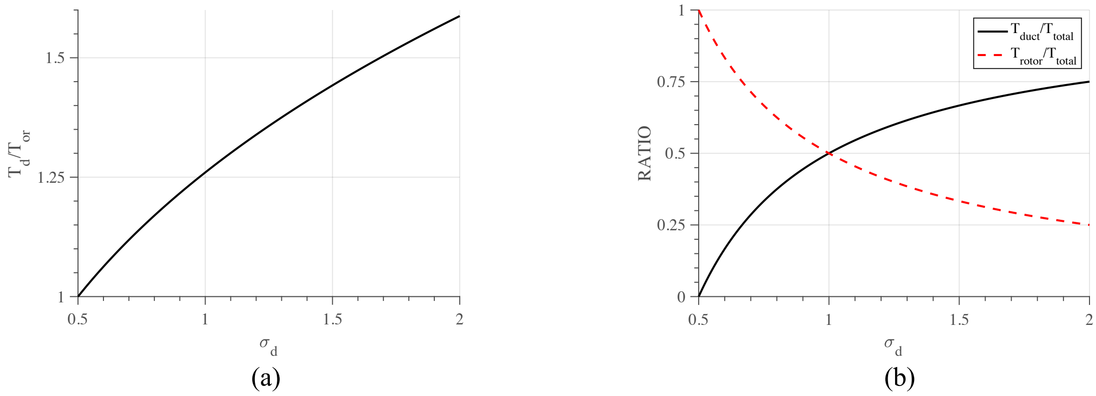


Fig 1. Momentum theory results for open and ducted rotor thrust ratios for hovering propellers. (a) Ratio of ducted rotor to open rotor thrust; (b) Ratios of duct and rotor thrust to total ducted rotor thrust.

3 Ducted Propeller Noise Sources

Figure 2 illustrates the idealised flow and noise sources inside a low-Mach number ducted rotor system. The rotor (green) supports steady and unsteady pressures (loading) that are sources of noise [4]. These noise sources are scattered by the duct or in some cases may excite the duct acoustic modes. This paper is concerned with the sources of noise themselves rather than the acoustic effect of the duct. While the duct is important, we will assume that its effects are similar in all cases investigated below.

The steady pressure on the blade (constant with azimuthal angle) creates tonal noise. Unsteady loading will create both tonal and broadband noise, depending on the excitation provided by the flow. The interaction of the turbulent wake of the rotor will create tonal noise as it interacts with the downstream stator. The ingestion of upstream turbulence into the rotor can create either broadband or tonal noise depending in the state of the turbulence in the flow. The duct and rotor will accelerate the flow through a pressure gradient. This pressure gradient will distort the turbulence so that it becomes anisotropic. If the turbulent eddies are small enough to interact with each rotor independently, then it is likely that broadband noise will be created. If eddies are stretched so that the same eddy interacts with multiple rotor blades, then it is possible that tonal noise, known as haystacking will occur. The effect of a duct on this type of noise is investigated later in the paper.

Unsteady loading noise may also occur from flow distortion. The most important is the interaction of the turbulent boundary layer on the inside surface of the duct with the tip-clearance region (the small space between the blade tip and duct wall). The flow in this region is highly complex and unsteady and has the potential to create intense noise. Another important flow distortion may occur from a large upstream boundary layer in the case of wing or fuselage boundary layer ingestion.

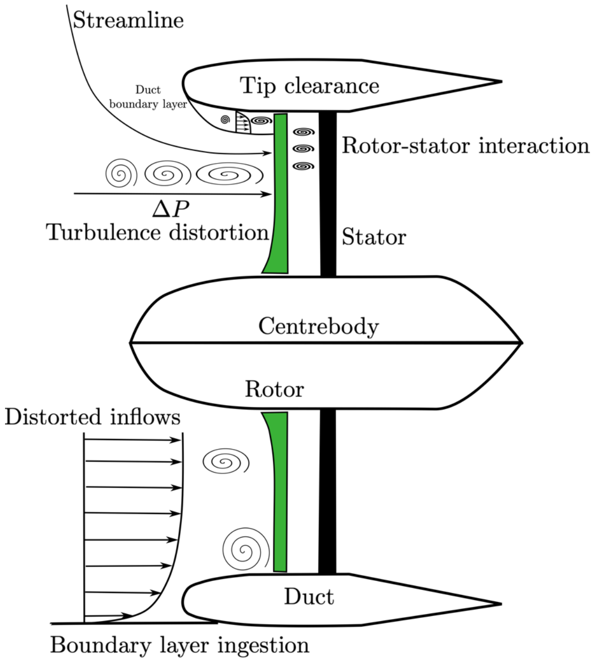


Fig 2. Schematic illustrating a variety of acoustic sources in a ducted rotor.

4 Effect of a Duct on Steady Loading Noise

From Hanson's propeller theory [7], we can write an approximation for the amplitude of the steady loading tonal noise,

$$|p'| \approx \frac{B\Omega(f_L A)_{\text{tip}}}{4\pi r_0 c_0} \tag{1}$$

where p' is the acoustic pressure, B is the number of blades, Ω is the rotational speed of the rotor, f_L is the steady aerodynamic loading force on the blade tip region, A is the area of the tip region (assumed to be approximately the outer 20% of the rotor blade), r_0 is the distance from the blade tip to an observer and c_0 is the speed of sound of the surrounding fluid. Assuming,

$$(f_L A)_{\text{tip}} \approx \frac{T_{\text{rotor}}}{B} \tag{2}$$

We can write,

$$|p'| \approx \frac{\Omega T_{\text{rotor}}}{4\pi r_0 c_0} \tag{3}$$

Now, from momentum theory [9] we know,

$$\frac{T_{\text{rotor}}}{T_{\text{total}}} = \frac{1}{2\sigma_d} \tag{4}$$

Thus, the acoustic pressure in the far-field is inversely proportional to expansion ratio ($p' \approx 1/\sigma_d$). Using this information, a simple equation for noise reduction (NR, dB) can be found,

$$\text{NR} = 6 + 20\log_{10}[\sigma_d] \tag{5}$$

Figure 3 shows the noise reduction determined from Eq. 5. It shows that quite a substantial decrease in tonal amplitude is possible by increasing the expansion ratio. This result, however, is only applicable to the steady loading tones, which normally means a reduction in the fundamental tone and perhaps the first 1-2 harmonics.

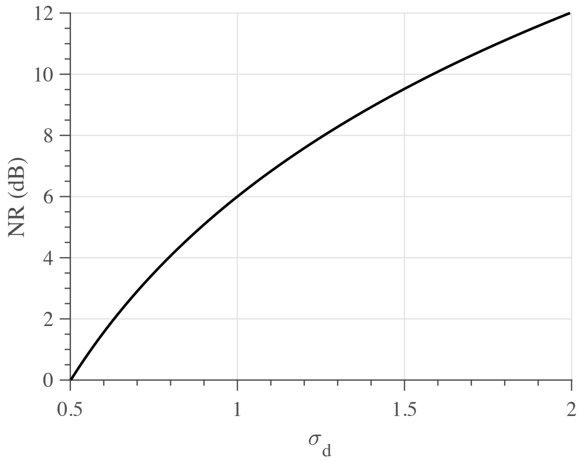


Fig 3. Steady loading noise reduction (NR, dB) for ducted rotors with various expansion ratios.

5 Steady vs Unsteady Loading Noise

Recently, Ref. [10] showed that the ratio of unsteady to steady noise source strength on a rotor is,

$$\frac{S_{L1}}{S_{L2}} = \frac{\dot{p}\, c_0}{a_r p} \tag{6}$$

where S_{L1} is the unsteady loading noise source strength (on the rotor), S_{L2} is the steady loading noise source strength, $\dot{p}$ is the time rate of change in pressure on the blade surface, a_r is the acceleration of the blade towards the observer and p is the mean (steady) pressure on the blade surface.

To understand the relative importance of steady and unsteady sources on a rotor, a straightforward analysis is presented. Figure 3 describes the situation where a propeller tip interacts with an idealized streamwise velocity disturbance, representative of an eddy, gust or wake. The width of the disturbance is W, the distance the blade tip moves in time δt is $\delta x = V_{tip}\delta t$, and the tip velocity is V_{tip}.

Assuming the blade tip profile is aerodynamically thin, and the gust velocity profile is Gaussian, we can write an expression that approximates the maximum time rate of change of surface pressure on blade,

$$|\dot{p}|_{max} \approx \frac{2\pi V_{tip}}{W} q_\infty \tag{7}$$

where q_∞ is the dynamic pressure experienced by the blade tip.

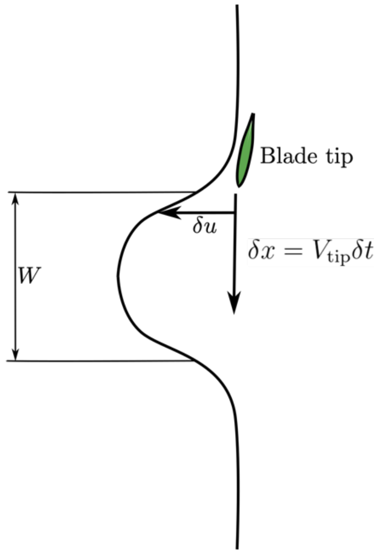


Fig 3. Idealised schematic showing a blade moving through a general velocity disturbance.

Similarly, an expression for the maximum (time-averaged) aerodynamic load on the blade tip can be deduced,

$$|p|_{max} \approx 2\pi\overline{\alpha}q_{\infty} \tag{8}$$

where $\overline{\alpha}$ is the mean angle of attack over one revolution. Finally, the acceleration of the blade tip can be approximated by,

$$a_r \approx \Omega^2 R \tag{9}$$

Where R is the radius of the rotor blade. Using Eqs. (6-9), the ratio of unsteady to steady noise source strength on a rotor is now,

$$\frac{S_{L1}}{S_{L2}} \approx \frac{R}{WM_{tip}\overline{\alpha}} \tag{10}$$

Equation (10) tells us that unsteady loading noise more important as the Mach number of the tip reduces. It also shows that unsteady loading becomes more important as the eddy, gust, or wake size (W) reduces. So, we expect turbulence-rotor interaction to be a major source of noise on low Mach number propellers and rotating systems.

6 Haystacking

Haystacking is an unsteady loading noise source that can occur during turbulence-rotor interaction. It relates to the situation where a single eddy is cut multiple times by rotor blades passing through turbulent flow. This creates noise spectra that can resemble a `haystack', but in some cases can be very tonal. Figure 4 shows the idealised situation where a turbulent eddy is approaching a rotor. It is in an `unwrapped' or linear view where the rotor blades can be thought to extend to infinity either side of the eddy. The blades move with velocity ΩR and are spaced $2\pi R/B$ apart. The eddy moves with velocity U_0 and is distorted by the pressure gradients upstream of the rotor. These pressure gradients are caused by the thrust generated by the rotor and the internal profiles of the duct and hub. The distortion causes the eddies to have anisotropic dimensions, L_x in the streamwise direction and L_t in the orthogonal direction (shown in Figure 4). The condition for haystacking to occur can be defined in terms of length and time scales of the flow. Multiple eddy cuts will occur when the ratio of eddy passage time (τ_x) to blade passage time (τ_b) is greater than 1. Mathematically we can write this ratio as,

$$\frac{\tau_x}{\tau_b} = \frac{L_x \Omega B}{2\pi U_0} \geqslant 1 \quad (11)$$

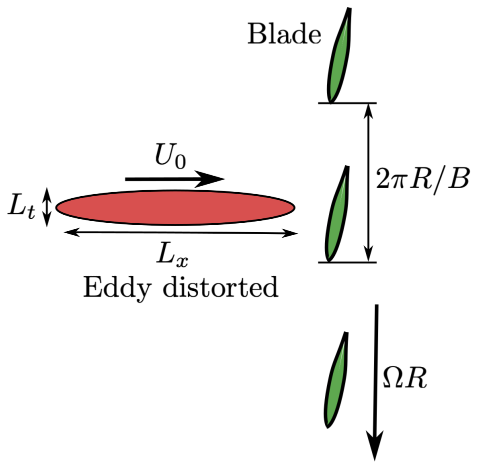


Fig. 4. Unwrapped view of a distorted eddy passing through a rotor.

We can now explore how the time ratio defined in Eq. (11) can affect the acoustic signature of a low Mach number rotor. Glegg and Devenport [5] have a useful generic model of noise created by an eddy cut,

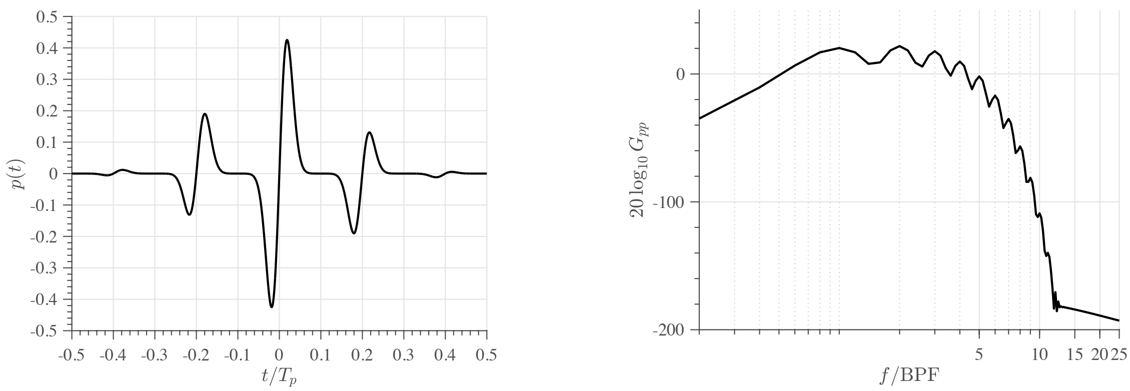
$$p'(t) = \sum_{n=-\infty}^{n=\infty} \frac{V_B}{L_t}\left(t - \frac{nT_p}{2B}\right) e^{-\frac{V_B^2}{L_t^2}\left(t-\frac{nT_p}{2B}\right)^2} e^{-\left(\frac{U_0 t}{L_x}\right)^2} \quad (12)$$

where n is the blade number, $V_B = \Omega R$ is the velocity of the blades and T_p is the period of rotation.

For the case where the timescales are balanced,

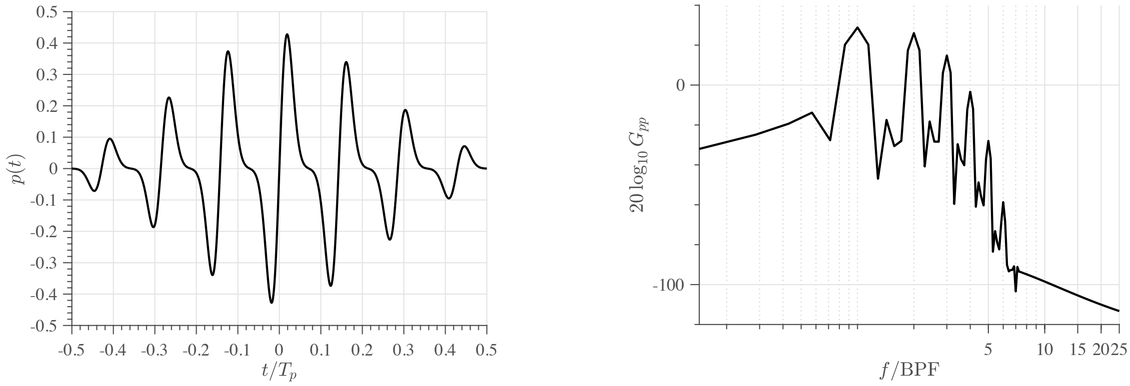
$$\frac{\tau_x}{\tau_b} = \frac{L_x \Omega B}{2\pi U_0} = 1 \quad (13)$$

The resulting acoustic signature is shown in Figure 5. Here, the temporal acoustic signature (Figure 5(a)) shows one major cut and some much lower amplitude cuts at each end of the eddy. The resulting acoustic spectrum (Figure 5(b)) shows a broadband spectrum overlaid with a small hump at the blade-pass-frequency (BPF) and many small harmonics beyond 10 multiples of the BPF. This spectrum somewhat resembles a haystack, giving the phenomenon its name.



(a) (b)

Fig. 5. Acoustic signature for $\frac{\tau_x}{\tau_b} = \frac{L_x \Omega B}{2\pi U_0} = 1$. (a) Temporal acoustic pressure; (b) Acoustic spectrum.



(a) (b)

Fig. 6. Acoustic signature for $\frac{\tau_x}{\tau_b} = \frac{L_x \Omega B}{2\pi U_0} = 2.33$. (a) Temporal acoustic pressure; (b) Acoustic spectrum.

The intensity of the haystacking tones increase when the timescales become unbalanced, so that the eddy passage time is longer than the blade passage time. Figure 6 shows the modelled haystacking acoustic signature and spectrum when,

$$\frac{\tau_x}{\tau_b} = \frac{L_x \Omega B}{2\pi U_0} = 2.33 \tag{14}$$

As shown in figure 6, the tones are more pronounced than figure 5, and this is due to the greater number of coherent sources being excited during one rotor revolution. The results of figures 5 and 6, while idealised, broadly agree with some observations in the literature, such as the rotor-boundary layer interaction results of Alexander *et al*. [2]. Further evidence of haystacking in drone propeller-turbulence interaction can also be seen in Yauwenas *et al*. [11]

The effect of a duct and turbulence distortion on the haystacking tone amplitude can be estimated using the simple model presented above. The maximum pressure amplitude can be estimated from Eq. (12) by solving $\frac{\partial p'}{\partial x} = 0$ for p'_{max}. To simplify the process, we assume this occurs when $n = 0$ (effectively the blade cut closest to the middle of the eddy). This results in the following expression,

$$p'_{max} \propto \frac{1}{\sqrt{1+(L_t/L_x)^2(U_0/V_B)^2}} \tag{15}$$

Equation 15 illustrates that the maximum haystacking tonal amplitude is controlled by the ratio of length and velocity (time) scales in the flow.

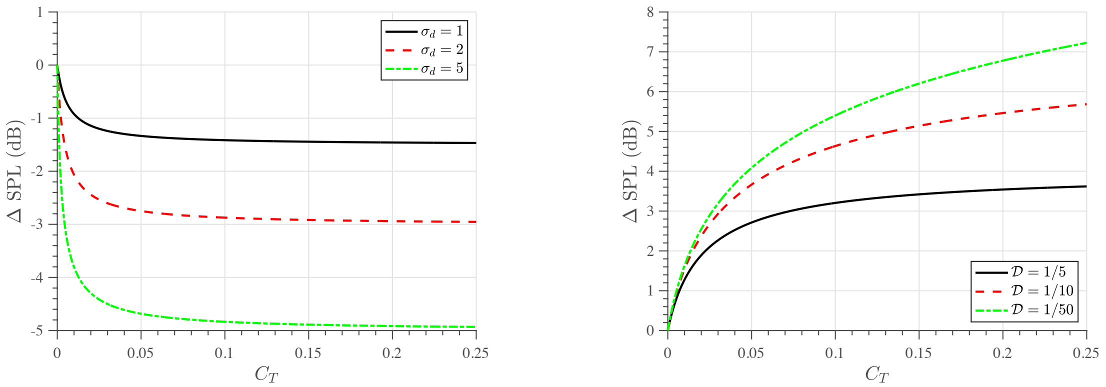
Ducted rotor momentum theory [9] can be used to estimate the axial flow velocity through the duct,

$$U_0 = \sqrt{\sigma_D C_T}\,\Omega R \tag{16}$$

where C_T is the ducted propeller thrust coefficient,

$$C_T = \frac{T_{\text{total}}}{\rho A_R \Omega^2 R^2} \tag{17}$$

and ρ is the fluid density and A_R is the rotor area. Effectively, momentum theory has been used to estimate the mean velocity through the duct and rotor based on thrust level and duct expansion ratio σ_d.



(a) (b)

Fig. 7. Change in sound pressure level (ΔSPL) with thrust level between ducted and open rotors. (a) variation with expansion ratio (σ_d) and fixed eddy dimensions $\left(\frac{L_x}{L_t}\right)_{OR} = \left(\frac{L_x}{L_t}\right)_{DR} = 15$; (b) variation with distortion factor $\mathcal{D}$ for fixed expansion ratio $\sigma_d = 2$.

Knowing that the performance of a ducted propeller is the same as an open (unducted) propeller when $\sigma_d = 1/2$, an expression comparing the haystacking noise level from these propellers can be found,

$$\frac{p'_{max,DR}}{p'_{max,OR}} \approx \frac{\sqrt{1+\left(\frac{L_t}{L_x}\right)^2_{OR}\frac{1}{2}C_T}}{\sqrt{1+\left(\frac{L_t}{L_x}\right)^2_{DR}\sigma_d C_T}} \quad (18)$$

where the subscripts DR and OR refer to ducted rotor and open rotor respectively. Finally, the turbulence distortion of the duct can be characterised by a ratio,

$$\mathcal{D} = \frac{(L_t/L_x)_{DR}}{(L_t/L_x)_{OR}} \quad (19)$$

Equations 18 and 19 can be used to understand the effect on timescales on ducted rotor noise. Figure 7 shows the estimated change in sound pressure level (SPL) between ducted and open rotors assuming that the eddy dimensions at the rotor face for the open rotor is $\frac{L_t}{L_x} = 15$. Figure 7(a) illustrates the effect of duct expansion ratio on SPL for fixed eddy dimensions (no distortion) as thrust is increased. Ducted rotor SPL reduces with thrust level and expansion ratio. In Figure 7(b), the effect of eddy distortion is included. In these cases, SPL increases as the length of the eddy increases. What is interesting about these results is that the expansion ratio and distortion act in an opposing manner. They are also linked to each other, but in what exact way is not known. An important research question that remains to be solved is: what is the relationship between thrust, turbulence distortion, expansion ratio and noise? Add to this the complexity of a non-uniform inflow, the research challenges are very large indeed.

The reader is cautioned that the results presented are estimates based on a simple model and are designed to show the importance of flow length and timescales on noise level. More accurate noise predictions will rely on more sophisticated theoretical and numerical approaches.

7 Conclusions

This paper has considered the flow and noise generated by ducted propeller systems. After describing the important ducted noise sources, the paper uses order-of-magnitude approximations to estimate the effect of duct expansion ratio on the steady loading source strength. The analysis shows that the duct expansion ratio can potentially significantly reduce the tonal noise level due to steady loading. The paper then describes an analysis of the relative importance of steady and unsteady loading noise source strengths. The analysis shows that for low-Mach number flows (such as those that occur in ducted rotors for new sustainable aviation and eVToL aircraft), unsteady loading noise will dominate the noise spectrum.

An analysis of haystacking noise is then considered. Using a generic acoustic model, the intensity of haystacking noise was shown to be controlled by the length and time scales of the flow and rotor blade. This analysis was extended to include ducted propeller momentum theory, and shows the relationship between thrust, expansion ratio and eddy dimensions. The relatively large noise level changes observed shows that it is very important to focus research on understanding the link between thrust, turbulence distortion, expansion ratio and noise in order to produce quiet aircraft propulsion systems in the future.

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