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Approximate Method for the Prediction of Propeller Noise Near-Field Effects

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An approximate frequency-domain method is described for predicting the near-field noise levels generated by a high-speed propeller; a near-field to far-field transfer function is defined, and estimated by way of a point force approximation and asymptotic techniques. The transfer function can then be quickly and easily applied to correct existing far-field prediction schemes for near-field effects, representing a considerable simplification over existing frequency-domain methods, as well as providing explicit scaling laws and design information. The method is valid across the whole range of propeller operating conditions (for both single-rotation and contra-rotation systems), and its accuracy is demonstrated at each stage by comparison with experimental data.

Nomenclature

a	=	propeller radius
B	=	blade number
c	=	chord length
c_L	=	lift coefficient
c_0	=	ambient sound speed
d	=	following Eq. (2)
dL	=	local lift force
M_r	=	relative Mach number
M_t	=	tip rotational Mach number
M_x	=	forward (flight) Mach number
m	=	harmonic number
P_m	=	acoustic pressure, mth harmonic
P_m^{ff}	=	acoustic pressure in the far field, mth harmonic
R_0	=	observer-hub separation normalized by a
r_0	=	observer-hub separation
W	=	effective source strength
z	=	normalized radial station
z_M	=	Mach radius
z_0	=	normalized hub radius
α	=	inclination of blade cross section to flight direction
β	=	$\sqrt{1 - M_x^2}$
η	=	following Eq. (7)
θ_0	=	observer angle
ρ_0	=	ambient density
σ	=	following Eq. (1)
τ	=	transfer function
ϕ	=	azimuthal angle
Ω	=	shaft frequency
$'$	=	effective contra-rotating propeller (CRP) parameter
1, 2	=	CRP front, rear row

Introduction

THE question of predicting the noise generated by high-speed propellers is of considerable significance in the future development of Propfan-powered engines for passenger aircraft. There are essentially two aspects to the problem: 1) the community (far-field) levels which are of particular significance since the Propfan will be required to meet mandatory certification requirements; 2) the near-field levels, which must be minimized for passenger comfort, as well as having implications for the structural integrity of the airframe. Theoretical prediction schemes are required in both cases, and the usual approach involves the numerical evaluation of certain radiation integrals; indeed, propeller noise methods already exist which are valid in both the far field and the near field (e.g., Farassat,[1] Amiet,[2] and Korkan[3] in the time domain, and Hanson[4,5] in the frequency domain). The frequency domain methods are handicapped both by requiring significant CPU time and storage and by being too complicated to be incorporated into preliminary design codes; however, when the observer-propeller separation is far greater than the blade span, simplified far-field expressions can be derived (e.g., Hanson[6]) and evaluated using only modest computer resources. Even greater simplification has been made by Parry and Crighton[7–9] and Crighton and Parry,[10,11] who used asymptotic techniques (based on the blade number being large) to reduce Hanson's far-field integral[6] to a closed algebraic formula, yielding considerable insight into the underlying noise generation process. It is emphasized, however, that these far-field schemes grossly underpredict near-field sound levels (by as much as 20 dB at takeoff), and simple frequency-domain methods of predicting such "near-field effects" are essential.

1) In this article we describe an approach to the prediction of near-field effects in the frequency domain which can be incorporated into existing far-field schemes. The result is an approximate method for calculating propeller noise at any observer location, which will prove considerably more practicable than those general methods requiring numerical evaluation of the near-field radiation integral. Development of our near-field method relies on the work of Parry and Crighton,[7,9] Crighton and Parry,[11] and Peake and Crighton,[12] whose analysis confirmed that for a single-rotation propeller (SRP) the noise generation process (for observers in the far field and in the near field) is dominated by contributions from sources in the neighborhood of a single point on the blade radius; under subsonic operating conditions, by sources in the vicinity of the tip; under supersonic conditions for an unswept blade, by sources in the vicinity of the "Mach radius"[11] (in the case of a swept supersonic blade this effective source radius is modified, as described by Amiet[2]). This has led us

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to extend Wright's results[13,14] on the near field of a point force; an approximate near-field to far-field transfer function is found using the point-force model, which is then used to correct predictions made from far-field schemes (or data) for near-field effects. The legitimacy of this approach is guaranteed by the point-source dominance of propeller noise, and even greater simplification is possible by use of Peake and Crighton's asymptotic analysis, from which algebraic expressions for the transfer function are derived.

2) The near field produced by a CRP is also considered; the rotor-alone tones behave exactly as for an SRP, whereas, since interaction noise is well cut on, near-field effects for the interaction tones are expected to be small.

3) Finally, we demonstrate how the transfer function can be used to derive community noise levels from wind-tunnel test data. At each stage the accuracy of our method is demonstrated by comparison with exact (but more time-consuming) numerical evaluations and with published data, for both the SRP and the CRP, and across the whole range of propeller operating conditions.

Full Integral Expression for Steady Loading Noise

We begin by considering the integral expression for the steady loading noise of an SRP derived by Garrick and Watkins[15] (and in an alternative form by Hanson[5]). For an observer with polar reception coordinates (r_0,θ_0) (see Fig. 1), the mth harmonic of the steady loading noise generated by an unswept, B-bladed propeller (here considering just the lift component of the force) is given by

$$P_m = \frac{i\Omega m B^2 c_0 \rho_0}{16\pi^2} \int_{z0}^{1} \int_0^{2\pi} M_r^2 c c_L \exp[imB(\Omega t + \phi - M_t \sigma)] \times \frac{1}{S}\left(\frac{M_x \sin\alpha}{\beta^2} + \frac{R_0 \cos\theta_0 \sin\alpha}{S\beta^2} - \frac{R_0 \sin\theta_0 \cos\alpha \sin\phi}{S}\right) \mathrm{d}\phi \, \mathrm{d}z \tag{1}$$

where

$$\sigma = \left[\frac{(M_x R_0 \cos\theta_0 + S)}{\beta^2}\right]$$

$$S = \sqrt{R_0^2 \cos^2\theta_0 + \beta^2(R_0^2 \sin^2\theta_0 + z^2 - 2zR_0 \sin\theta_0 \cos\phi)}$$

The integration in Eq. (1) is along the propeller span (radial station z) and over the azimuthal angle ϕ in the propeller plane, so that all sources are included. No restriction is made on the magnitude of the nondimensional observer distance R_0, except that a term of $O(S)^{-3}$ has been neglected, equivalent here to supposing the observer to be at least several acoustic wavelengths from any blade element (i.e., an observer in the acoustic far field). An expression for the thickness noise, exactly analogous to Eq. (1), has been given by Hanson.[5]

The corresponding far-field result can be obtained from Eq. (1) by neglecting terms of $O(R_0)^{-2}$, allowing the ϕ integral to be performed analytically in terms of a Bessel function, and yielding (see Garrick and Watkins[15] and Hanson[6])

$$P_m^{\mathrm{ff}} = \frac{i\Omega m B^2 c_0 \rho_0}{8\pi} \int_{z0}^{1} \exp[imB(\Omega t - M_x M_t R_0 \cos\theta_0/\beta^2 - M_t R_0 \,\mathrm{d}/\beta^2)] \frac{M_r^2 c c_L}{R_0} \left\{\frac{M_x \sin\alpha}{\beta^2} + \frac{\cos\theta_0 \sin\alpha}{\beta^2} - \frac{\mathrm{d}\cos\alpha}{M_t z}\right\} J_{mB}\left(\frac{mBM_t z \sin\theta_0}{\mathrm{d}}\right) \mathrm{d}z \tag{2}$$

with

$$\mathrm{d} = \sqrt{1 - M_x^2 \sin^2\theta_0}$$

It should be emphasized that the full integral expression [Eq. (1)] is valid in both the (geometric) near field and far field, but the far-field approximation (Eq. 2) can, strictly speaking, only be applied in the limit $R_0 \to \infty$; absolute level predictions from the full integral and far-field formulations are compared in Fig. 2, with $M_t = 0.5$, $M_x = 0.2$, $mB = 4$, $\theta_0 = \pi/2$, and a typical blade lift distribution. In the case considered, the far-field expression is accurate for observer-hub separations in excess of about two propeller diameters ($20 \log R_0 > 12$), but as the observer approaches closer to the rotor, the pressure level rises sharply and is increasingly underpredicted by the far-field integral. This increase in the rotor-alone noise has been explained by Wright[13,14]: the sound measured by an observer at large distance from the blades suffers phase interference effects due to differences in the observer-source path lengths as the propeller rotates; in the near field these path length differences depart from their far-field values, thus disrupting the cancellation effects.

We shall proceed to develop an approximate method for handling near-field effects by defining τ between far-field and

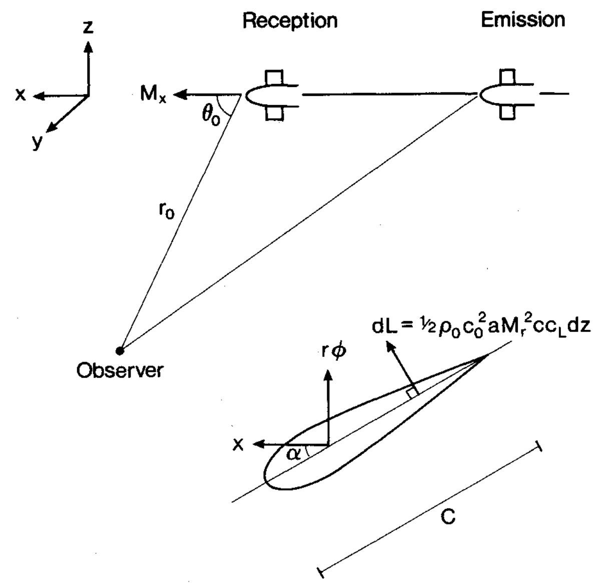

Fig. 1 Coordinate system.

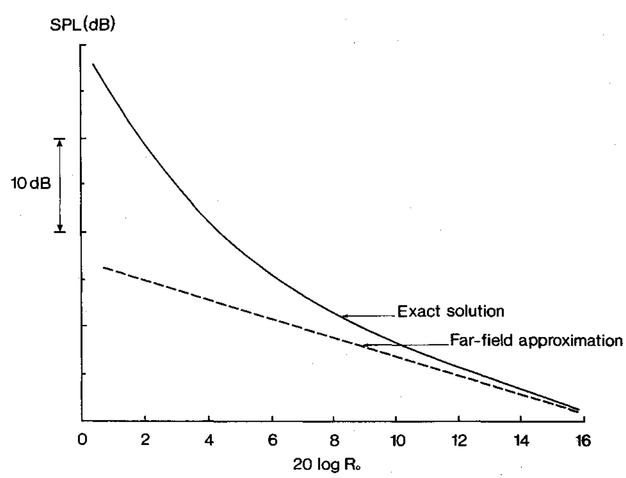

Fig. 2 Comparison of the full integral solution with the far-field approximation.

near-field predictions, given by

$$\tau = \left| \frac{P_m}{P_m^{\mathrm{ff}}} \right| \tag{3}$$

τ is a function of both observer position and operating conditions, and for an observer in the far field $\tau = 1$. An exact formula for τ can be obtained from Eqs. (1) and (2), but evaluation of such an expression would entail considerable computer time (essentially because of the rapidly oscillating integrand in the double integral), as well as requiring a detailed knowledge of the blade loading distribution. Our objective is therefore to derive an approximate transfer function, retaining the full parametric dependence of the exact solution, but one which can be applied to far-field data quickly and simply, to produce accurate near-field predictions. We will demonstrate that such a transfer function can indeed be derived which is independent of almost all blade loading information and which can be used in more complex situations, e.g., for swept or chordwise noncompact blades.

Point Force Expression for the Transfer Function

Parry and Crighton[9] and Crighton and Parry[11] have confirmed that for a propeller with a large number of blades, far-field noise is dominated by contributions from the neighborhood of a single radial station; under subsonic operating conditions by contributions from the neighborhood of tip, and for an unswept blade under supersonic conditions from the neighborhood of the Mach radius. This allows us to use a point force approximation in calculating the far-field noise P_m^{ff}, and furthermore, since near-field effects arise principally from azimuthal and not radial interference, leads us to make the assumption that the full integral expression for P_m [Eq. (1)] can be approximated in the same manner, to give

$$\tau = (1/2\pi) \left| \int_0^{2\pi} \exp[imB(\phi - M_t S/\beta^2)] \frac{1}{S} \left(\frac{M_x \sin\alpha}{\beta^2} + \frac{R_0 \cos\theta_0 \sin\alpha}{S\beta^2} - \frac{R_0 \sin\theta_0 \cos\alpha \sin\phi}{S} \right) \mathrm{d}\phi \right|$$
$$\div \left| \frac{1}{R_0} \left(\frac{M_x \sin\alpha}{\beta^2} + \frac{\sin\alpha \cos\theta_0}{\beta^2} - \frac{d \cos\alpha}{M_t z} \right) \times J_{mB}(mBM_t z \sin\theta_0/d) \right| \tag{4}$$

Equation (4) is significantly easier to compute than the exact expression for τ and has the further advantage of being independent of the detailed load distribution; all that is required is the value of α at the effective source radius ($\pi/2 - \alpha$ is the inclination of the lift force to the flight direction). Direct calculation has demonstrated that under subsonic conditions Eq. (4) is virtually independent of α.

Asymptotic Expression for the Transfer Function

The development of the point force approximation to the transfer function is essentially an extension of Wright's work[13,14] to include the effects of forward motion, with the appropriate choice of effective source radius. This involves the assumption that the point force model is also valid in the near field; in order to justify this and produce an even simpler transfer function, it is necessary to return to the full integral expression in Eq. (1), and apply the generalization of Parry and Crightons's asymptotic analysis[7,9] to the near field.

The asymptotic evaluation of Eq. (1) has been completed by Peake and Crighton.[12] For unswept propellers with supersonic relative tip Mach numbers (i.e., $\sqrt{M_x^2 + M_t^2} > 1$, which implies that $\beta/M_t < 1$), they have demonstrated that, in the formal limit $B \rightarrow \infty$, the near-field noise is dominated by contributions from a source in the vicinity of the Mach radius (denoted z_M) and derived algebraic expressions for the near-field noise (the point on the blade at the Mach radius has an exactly sonic velocity component in the observer direction, at emission). Therefore, we can write down an asymptotic approximation to τ. For steady loading noise, and here for observer angles close to $\pi/2$, the transfer function becomes

$$\tau = [R_0^2/(R_0^2 - z_M^2)] + O(\cos^2\theta_0) \tag{5}$$

where the Mach radius is $z_M = \beta/M_t$ and it has been assumed that the direction of action of the point force at radial station z is $\alpha_t = \tan^{-1} zM_t/(M_x)$. Under supersonic operating conditions the Mach radius lies inboard of the tip so that (as shown in Fig. 3) the transfer function essentially represents a distance correction factor, being the square of the ratio of R_0 and the length of the tangent between the source radius $z = z_M$ and the observer. For thickness noise, the transfer function becomes

$$\tau = [R_0/(R_0^2 - z_M^2)^{1/2}] + O(\cos^2\theta_0) \tag{6}$$

which is exactly the intuitive distance correction suggested by Chidley.[16] For observer distances of practical interest, the near-field effects of a supersonic propeller will therefore be small and become negligible as the relative Mach number increases and the effective source radius retreats further inboard of the tips. The validity of the point force and asymptotic approximations of τ is demonstrated in Fig. 4 by comparison with the exact value of τ [determined by way of a full numerical evaluation of Eqs. (1) and (2)], with $M_t = 0.7$, $M_x = 0.85$, $mB = 4$ amd $\theta_0 = \pi/2$. Good agreement between the point force and full numerical transfer functions is achieved for observer positions not too close to the tips, whereas the

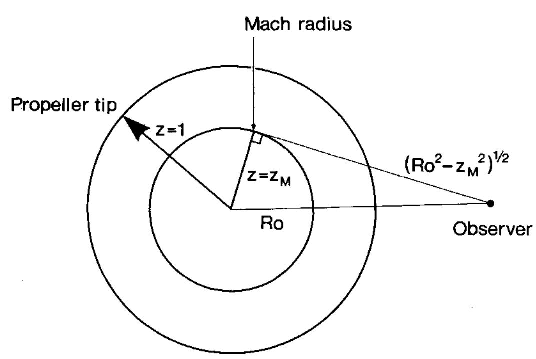

Fig. 3 Near-field correction for a supersonic propeller.

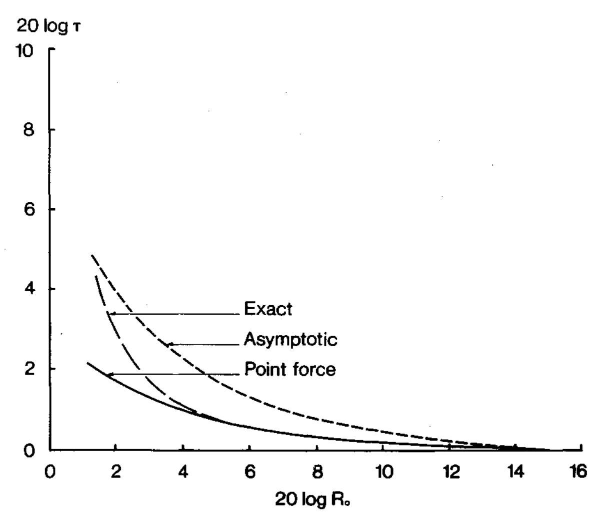

Fig. 4 Comparison of the full integral, point force, and asymptotic transfer functions for a supersonic propeller.

discrepancy between the asymptotic and exact results is not great (even for this relatively small value of $mB = 4$) and could be improved by including higher-order terms in the asymptotic expansion (see Crighton and Parry[10]).

For a subsonic propeller, with $\beta/M_t > 1$, Peake and Crighton's analysis[12] confirmed that the near-field noise is tip-dominated and, for observer angles close to $\theta_0 = \pi/2$, it follows that the transfer function for the mth harmonic of steady loading noise is

$$\tau = \frac{R_0}{(R_0^2 - 1)^{1/4}(R_0^2 - z_M^2)^{1/4}} + O(\cos^2\theta_0)$$

$$\text{for} \quad R_0 \geq z_M[1 + (mB)^{-2/3}/2] \tag{7a}$$

$$\tau = \frac{R_0 \exp[mB(\eta - \tanh\eta)]}{(\sqrt{z_M^2 - 1} - \sqrt{z_M^2 - R_0^2})^{1/2}(z_M^2 - R_0^2)^{1/4}} + O(\cos^2\theta_0)$$

$$\text{for } R_0 \leq z_M[1 - (mB)^{-2/3}/2] \tag{7b}$$

where $\operatorname{sech}\eta = R_0/z_M$. Just as for the point-force approximation, this asymptotic transfer function is independent of the detailed blade loading, and furthermore, both radial and azimuthal integrations have been removed, so that computing time is minimal. Transition across the narrow region around the Mach radius can be completed in terms of Airy functions (see Peake and Crighton[12]), but here simple smoothing is applied. In Fig. 5 the point force and asymptotic transfer functions are compared with a full numerical integration of Eq. (1) under takeoff conditions ($M_t = 0.5$, $M_x = 0.2$, with $mB = 4$ and $\theta_0 = \pi/2$); the small discrepancy between exact and asymptotic transfer functions decreases with increasing mB, and becomes negligible for $mB \geq 20$. Figure 5 also illustrates the magnitude of near-field effects for a subsonic propeller (in the far field $20\log\tau = 0$); for $R_0 \geq z_M[1 + (mB)^{-2/3}/2]$ near-field effects are small and just as in the supersonic case, τ is essentially a distance correction factor involving the distances between the observer and both the blade tip and the Mach radius. However, for $R_0 < z_M[1 - (mB)^{-2/3}/2]$ this is no longer the case, due to the presence of the exponential factor in Eq. (7b), whose argument increases monotonically with increasing M_x, M_t, R_0, and mB. This exponential represents the onset of the near field proper [in contrast to the weak algebraic dependence in Eq. (7a)], and we can therefore say that the boundary between the near field and the far field occurs at $R_0 = z_M$. This is exactly the conclusion reached by Wright,[14] whose intuitive arguments predicted that the radius for the onset of the breakdown in cancellation effects (which predominate in the far field) would be proportional to the source radius and inversely proportional to the mode speed. Since the argument of the exponential increases with increasing m, near-field effects will increase exponentially with harmonic number so that harmonic decay in the near field will be significantly less marked than in the far field. The exponential factor in τ within the Mach radius is associated with the poor radiation efficiency of subsonic rotor-alone tones, and is analogous to the decay suffered by cutoff duct modes.

For plotting field shapes, Peake and Crighton's results[12] can be used over a limited angular range (which can be extended by inclusion of additional terms in the asymptotic expansion), but it actually proves easier to apply the point-force transfer function. In what follows we use the asymptotic formula for τ to predict radial traverse data and the point force approximation [Eq. (4)] for field shapes. The (absolute level) field shape at takeoff ($R_0 \sin\theta_0 = 1.3$ and other conditions as in Figs. 2 and 5), is shown in Fig. 6.

So far, we have only considered near-field effects for chordwise-compact sources on a straight-bladed rotor. However,

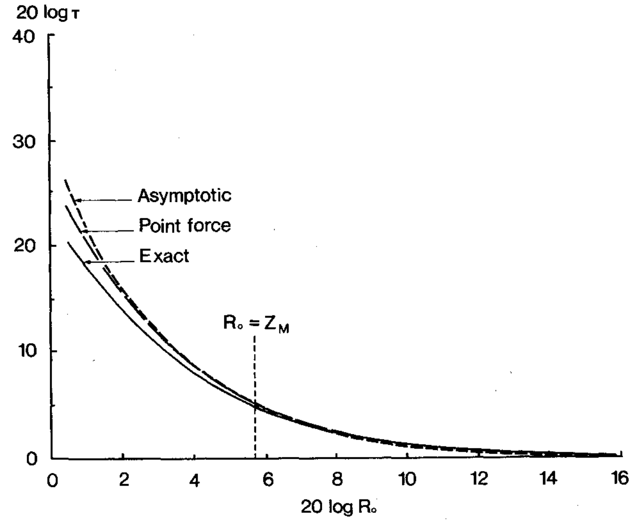

Fig. 5 Comparison of the full integral, point force, and asymptotic transfer functions for a subsonic propeller at takeoff.

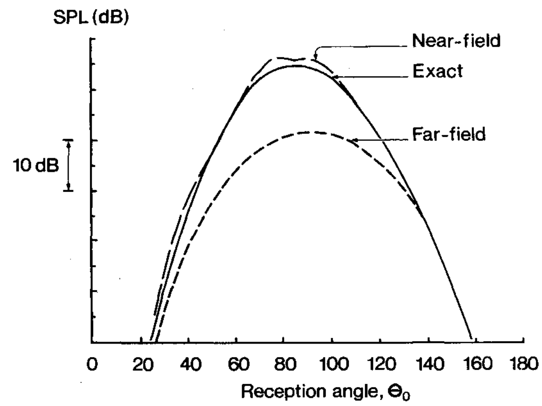

Fig. 6 Absolute level field-shape plots using the full integral and point force forms of the transfer function for a subsonic propeller at takeoff: $R_0 \sin\theta = 1.3$.

when the observer-source distance is of the same order of magnitude as the chord, consideration needs to be given to the axial location of the effective source. We will make the assumption that the near field can be modeled by a point source located at the blade leading edge—with radial station $z = 1$ for a subsonic propeller and $z = z_M$ for a supersonic propeller—but no further correction to τ to account for sweep or chordwise noncompactness will be made. Effectively, we are assuming that the interference effects due to sweep (or chordwise noncompactness) are equivalent in the near and far fields, and therefore only appear in the transfer function through the effective source position. The assumption that the source is located at the blade leading edge will require the introduction of a small angular shift in the tunnel coordinate system.

Finally, we note that while we have primarily considered the steady loading component of the noise here, thickness noise can be treated in exactly the same way; under subsonic conditions the transfer functions for steady loading and thickness noise are identical at $\theta_0 = \pi/2$, but differ away from the propeller plane, reflecting the differing directivities.

Transfer Function for a CRP

Far-field radiation integrals for the interaction noise generated by a $B_1 \times B_2$ bladed CRP have been given by Parry and Crighton[8] and Hanson[17]; e.g., the n_2th harmonic of the interaction between n_1th component of the front row wake (or potential field) and the rear row can be written in the form

$$P_{n_1,n_2} = \int_{z_0}^{1} W(z)\exp[i(n_1B_1\Omega_1 + n_2B_2\Omega_2)t] \times J_{(n_1B_1-n_2B_2)}\left[\frac{(n_1B_1M_{t_1} + n_2B_2M_{t_2})z \sin\theta_0}{\sqrt{1 - M_x^2 \sin^2\theta_0}}\right] dz \tag{8}$$

which is an integration of the effective source strength $W(z)$ along the radial span of the rear row. By comparison with Eq. (2) it is clear that this is equivalent to the rotor-alone tone of an SRP, but with effective harmonic number, mode speed, and tip rotational Mach number given by

$$m' = n_1B_1 - n_2B_2$$
$$m'\Omega' = n_1B_1\Omega_1 + n_2B_2\Omega_2$$
$$M_t' = [(n_1B_1M_{t_1} + n_2B_2M_{t_2})/(n_1B_1 - n_2B_2)]$$

We consider here only the summed, or cut-on, tones (with n_1, $n_2 > 0$), and in the first instance those for which $n_1B_1 \neq n_2B_2$. In this case, Parry and Crighton[8] have demonstrated that, exactly as for the SRP, the integral in Eq. (8) is dominated by contributions from the Mach radius

$$z_M = \frac{\sqrt{1 - M_x^2 \sin^2\theta_0}}{M_t' \sin\theta_0}$$

provided that z_M lies within the range of integration, it then follows that

$$P_{n_1,n_2} \sim W(z_M)\exp(i\Omega t)(z_M/|m'|)$$

indicating that estimation of the interaction noise can be made from a knowledge of W at just one radial station. However, unlike the SRP (for which the Mach radius is less than unity only under supersonic operating conditions), for the CRP z_M will almost always lie inboard of the tip, even for subsonic rotation, so that the cut-on interaction tones are precisely equivalent to the rotor-alone tones of a supersonic SRP with suitable choice of the effective parameters m', Ω', and M_t' and source strength W. We can therefore conclude that, just as for supersonic rotor-alone noise, near-field effects are not significant for these interaction modes.

The special case $n_1B_1 = n_2B_2$ has also been considered; asymptotic analysis shows that contributions now come from the hub and from the tip, but both terms are similar to supersonic SRP tones and are therefore not expected to exhibit any significant near-field behavior.

Comparison with Measured Data

We demonstrate the effectiveness of our near-field correction procedure by considering two sets of published data. First, we examine results taken from an unswept, four-bladed SRP in the lined test section of the ARA Transonic Wind Tunnel at Bedford, UK, over a range of forward Mach numbers between 0.14 and 0.8 (for further details see Wood and Newman[18]). In Fig. 7 the trend in radial traverse data (with $\theta_0 = \pi/2$) is compared with the prediction from our asymptotic transfer function under takeoff ($M_t = 1.05$, $M_x = 0.14$) and cruise ($M_t = 1.05$, $M_x = 0.8$) operating conditions. The quantity SPL $-20 \log R_0$ is used on the vertical axis so that the departure of the plot from a horizontal line is a measure of near-field effects, and in addition the absolute level of the predicted traverse has been adjusted to fit the data (i.e., a one-parameter fit has been performed). An absolute level prediction could of course be made by using our transfer function to correct a far-field prediction (as will be done in

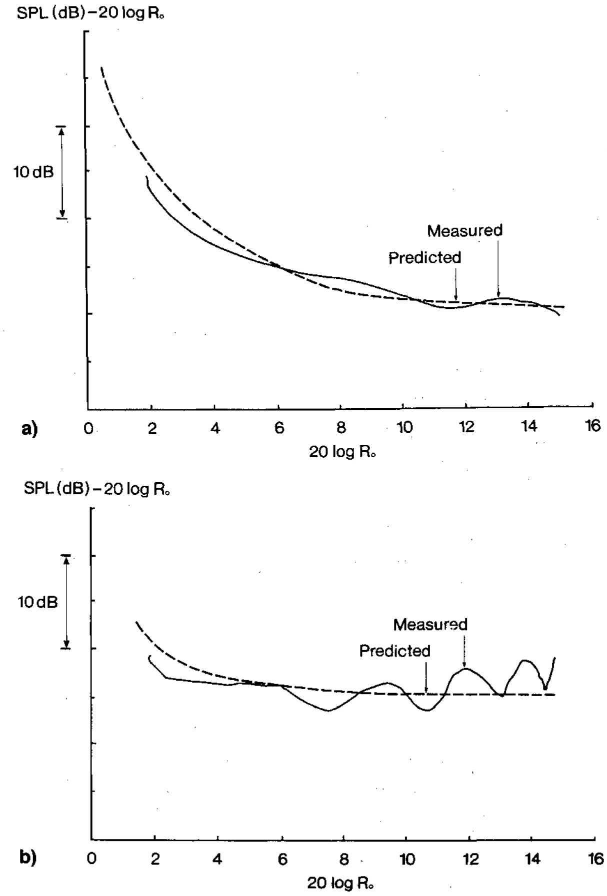

Fig. 7 Measured and predicted trends in radial traverse data (absolute level adjusted) for unswept propellers: a) takeoff, b) transonic.

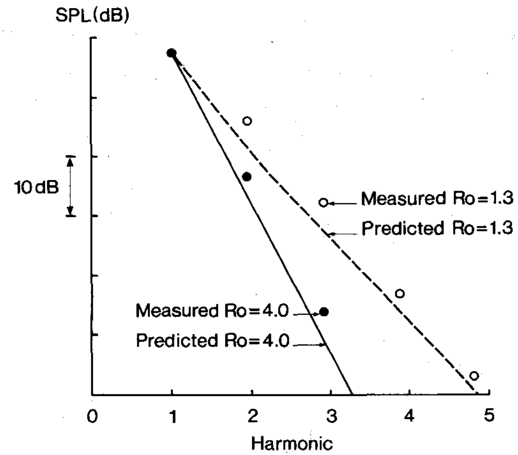

Fig. 8 Measured and predicted harmonic decay at takeoff (normalized by the 1 × BPF level).

Fig. 12), but the latter can only be performed once details of the blade lift distribution are known. In Figs. 7–11 we first aim to establish that our transfer function accurately predicts the trend in near-field effects; once this has been done we see that the accuracy of any absolute level prediction made using our method will only depend on the accuracy of the far-field scheme and the aerodynamic performance code, which are not our concern here. Predictions of the harmonic decay at takeoff are plotted in Fig. 8, which again closely match observed trends. As expected from the discussion in a previous section, near-field effects are important under takeoff conditions, but not for supersonic relative tip Mach numbers. In addition, significantly less marked harmonic decay occurs in the near field than in the far field; at takeoff, near-field

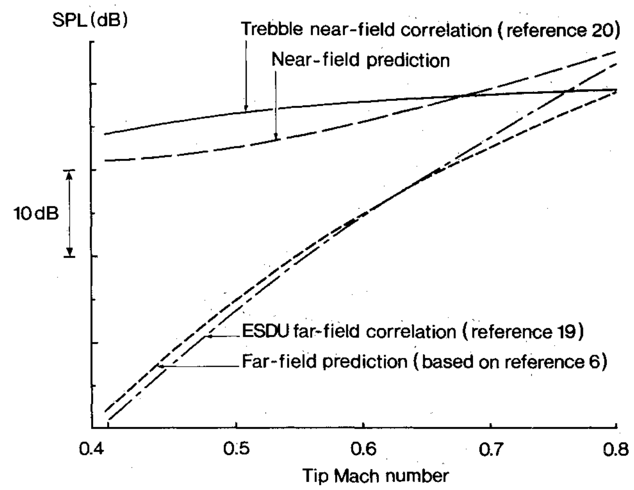

Fig. 9 Comparison of ESDU and Trebble correlations with theoretical predictions.

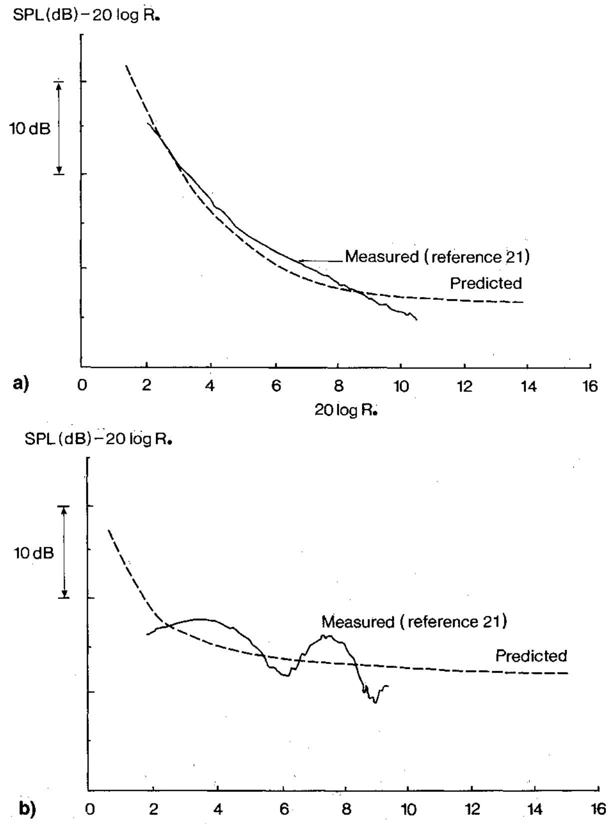

Fig. 10 Measured and predicted trends in radial traverse data (absolute level adjusted) for swept blades (1 × BPF): a) takeoff, b) cruise.

effects at $R_0 = 1.3$ (20 log $R_0 = 2.3$) are worth 12 dB at 1 × BPF (Fig. 7a), rising to about 18 dB at 3 × BPF (Fig. 8) (BPF is blade passing frequency).

In Fig. 9 a further application of the asymptotic transfer function demonstrates the substantial difference between the dependence of the sound level on tip Mach number in the near field as opposed to the far field; here $M_x = 0.08$, $mB = 8$, $\theta_0 = \pi/2$, power $= 5 \times 10^6$ W, efficiency = 75% and the load is assumed to peak at $z = 0.65$. Good agreement is shown between a theoretical far-field scheme (e.g., Hanson[6]) and the ESDU[19] far-field tip speed correlation on the one hand, and between near-field absolute level predictions (obtained by application of our near-field transfer function to the far-field scheme) and Trebble's near-field correlation,[20] on the other.

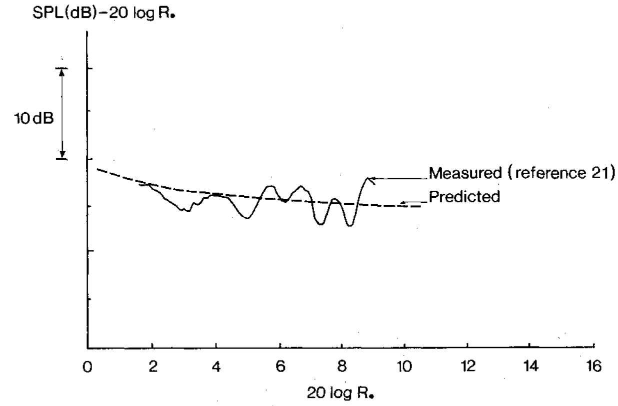

Fig. 11 Measured and predicted trends in radial traverse data (absolute level adjusted) for swept blades at takeoff; (1, 2) interaction tone.

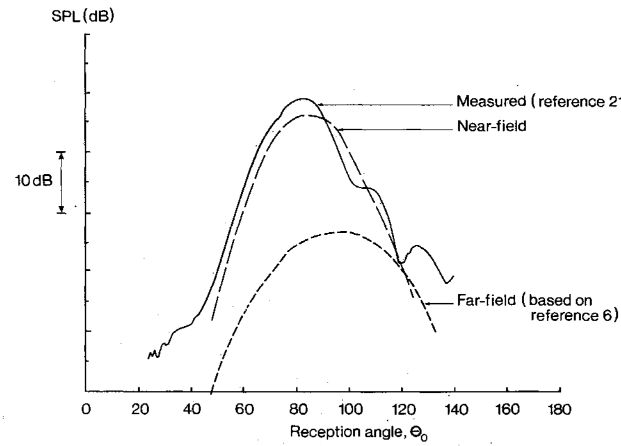

Fig. 12 Absolute level prediction of the field shapes for the 1 × BPF rotor-alone tones at takeoff, at a constant sideline distance of 19 in.

Second, we use data taken from the Rig 140 propeller test program (see Kirker[21]), which involved the noise and performance testing of a $\frac{1}{5}$ scale, 7 × 7 contra-rotating Propfan. We concentrate on the noise from a swept blade configuration (tip radius 15 in.), gathered by axial traverse microphones at constant sideline distances of 19 and 30 in., and by a single radial traverse microphone in the midplane between the pitch-change axes; this includes both the rotor-alone tones (which were separated by running the rows at a slight speed differential) and the interaction noise. We have already confirmed the effectiveness of our approximate transfer function in predicting near-field effects of a straight-bladed propeller; in Fig. 10 it is seen to be equally effective for the rotor-alone noise generated by swept blades. Good agreement is achieved between measured and predicted trends in the sound level with observer distance under the design takeoff condition ($M_t = 0.517$, $M_x = 0.2$), with near-field effects accounting for about 20 dB at $R_0 = 1.3$ (20 log $R_0 = 2.3$). At cruise ($M_t = 0.57$, $M_x = 0.7$) the trend has also been well-predicted (at least within the scatter produced by tunnel reflections), and near-field effects are confirmed to be much less significant than at takeoff.

The radial traverse measurement for the (1, 2) interaction tone is shown in Fig. 11; the overall trend in sound level with observer position is well-predicted, and confirms the low level of near-field effects for interaction noise.

We have therefore established in Figs. 7–11 that our transfer function accurately predicts near-field effects observed in real data; in order to demonstrate how our approach would be used as part of a complete noise prediction scheme, the Rolls-Royce theoretical noise prediction program[7] was used to provide far-field sound levels from the manufacturer's aero-

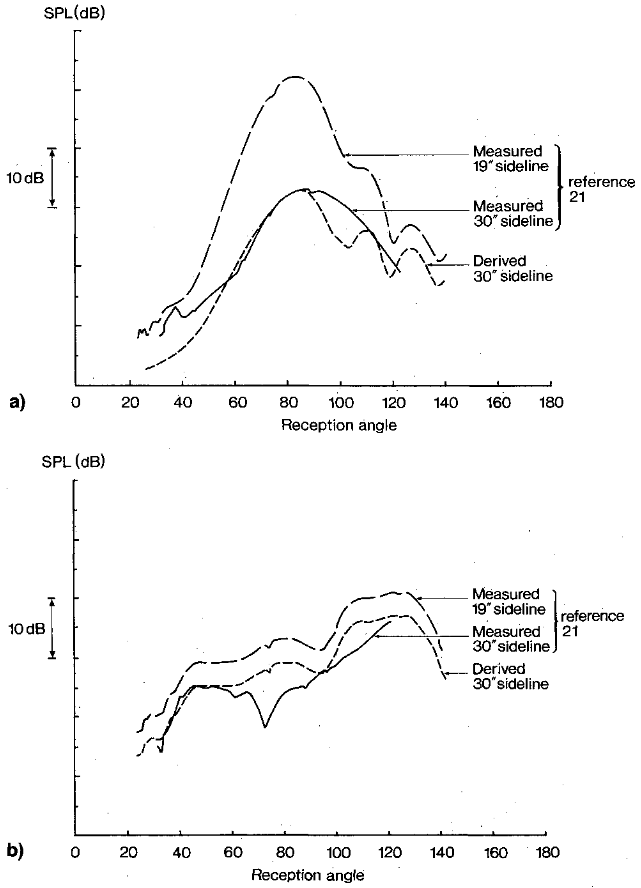

Fig. 13 Derivation of far-field levels from near-field data at takeoff: a) rotor-alone (1 × BPF) tone, b) (1, 2) interaction tone.

dynamic performance data, and including the effects of sweep and chordwise noncompactness; these estimates have then been corrected for near-field effects by use of our point-force transfer function and an angular shift (equal to about 10 deg for the 19 in. linear traverse) applied to the tunnel coordinate system to account for the sweep. Figure 12 compares the (absolute level) measured and predicted field shapes (19-in. sideline distance) for the 1 × BPF rotor-alone tone at takeoff. The prediction of these data made using only the far-field scheme is also shown, again demonstrating the inadequacy of far-field methods for predicting near-field effects.

One final application of the near-field transfer function is to provide estimates of far-field noise from near-field measurements. The usual procedure in obtaining near-field propeller noise data is to test a model propeller in a transonic acoustic wind tunnel, such as the facilities at ARA Bedford or Boeing (see Glover[22]). However, due to size restrictions and problems with tunnel-wall reflections, it is not practical to obtain far-field measurements, and a second test in a low-speed facility is normally required. An alternative approach, which can at least be used to provide early estimates of community noise, is to extend the transonic tunnel testing to include lower speeds, and then apply the transfer function to this near-field data to derive far-field levels. Under takeoff conditions the level of thickness noise is sufficiently low, and the difference between the thickness and steady loading transfer functions sufficiently small, to allow just our steady loading transfer function to be used for the rotor-alone tones, whereas for the interaction tones (with negligible near-field effects) a simple $1/R_0$ distance scaling factor is used. The accuracy of this procedure is demonstrated in Fig. 13; given the Rig 140 data from the microphone on the 19-in. sideline, estimates of the levels at the 30-in. sideline distance are made, which agree closely with the values actually measured for both the 1 × BPF rotor-alone tone and the (1, 2) interaction tone.

Concluding Remarks

In this article we have described how the near-field transfer function can be approximated both by using a point force model and asymptotically. Our method represents a quick and accurate way of predicting propeller noise and is valid for any observer position across the whole range of operating conditions and for swept and noncompact blades. It is envisaged that it will be of greatest practical importance as a means of correcting far-field methods for near-field effects as part of a preliminary design code, and for making community noise estimates from wind-tunnel test data. In addition, the asymptotic formula provide considerable insight into the problem, including the explicit scalings associated with all the main design parameters.

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