Importance of Broadband Noise for Advanced Turboprops

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An assessment has been made of the likely importance of broadband noise for future propfan operations. In flight, the tone noise is 8 PNdB higher than the broadband, but as the forward and the helical tip Mach numbers are reduced, the tones fall more rapidly than the broadband component until, at approach conditions, the broadband noise is dominant by 8-16 PNdB. A survey of the state-of-the-art of broadband noise prediction suggests that it can be predicted to within 5 dB.

Nomenclature

B	= number of blades
b/b	= broadband
BPF	= blade passing frequency
b/w	= bandwidth
C_p	= power coefficient, $= P/\rho N^3 D^5$
D	= propeller diameter
EPNL	= effective perceived noise level
log	= logarithm to base 10
M	= freestream Mach number
M_{ht}	= helical tip Mach number
N	= rotational speed
N_c	= corrected rotational speed, $= N/\sqrt{T_a/T_0}$
PNL	= perceived noise level
shp	= shaft horsepower
shp/D^2	= power loading
SPL	= sound pressure level
t	= tone
T_a	= ambient temperature
T_0	= standard temperature
θ	= measuring angle, = 0 deg upstream
θ_e	= emission angle, $= \theta_m - \sin^{-1}(M \sin\theta_m)$

Subscripts

1/3	= third-octave
n/b	= narrow-band

Introduction

CURRENTLY, a number of the world's leading aerospace companies are studying the concept of highly loaded, many-bladed propellers for use at transonic tip speeds (see Fig. 1). The design philosophies and the terminology vary,[1] but with fuel savings of up to 35% claimed for a contrarotating propfan over projected turbofan designs, the motivation is clear. One of the problems common to all these proposals, however, is noise.

Considerable effort is being expended on understanding and reducing propfan noise. It seems, however, that all the theoretical work (e.g., Hanson[2-7] and Tam[8]) and many of the experimental studies (e.g., Dittmar et al.[9,10]) are addressing the question of tone noise levels and that very little attention is being paid to broadband noise. This is understandable (see Fig. 2), but the present paper will investigate whether it is justified and whether broadband noise is considered to be amenable to theoretical prediction.

Two of the reasons for the effort on propfan noise are passenger acceptance and airport noise certification. The former is primarily an acoustic near-field problem involving high values of M_{ht} (helical tip Mach number) and including the consideration of sound propagation through the fuselage boundary layer and possible sound insulation. The latter, however, is an acoustic far-field problem relating to comparatively low forward speeds, which can be overcome only by propeller design or changed operating technique. In either case, subjective measures of annoyance are needed.

Broadband Noise Mechanisms

In a recent review of the broadband noise generated by rotors, George and Chou[11] identified five mechanisms: 1) load fluctuations due to inflow turbulence, 2) load fluctuations due to turbulent boundary layers passing the blade trailing edge, 3) load fluctuations due to local stall or tip vortex formation, 4) load fluctuations due to vortex shedding from a laminar boundary layer, and 5) load fluctuations due to vortex shedding from a blunt trailing edge. Using the analyses of George and Kim[12] and Amiet,[13] George and Chou conducted numerical studies on the first three mechanisms (arguing that vortex shedding noise due to laminar boundary layers or trailing-edge bluntness could be avoided) and made comparisons with experimental data from helicopters, wind turbines, and low-speed fans. They concluded that inflow turbulence noise was the dominant broadband component at low frequencies (below 1 kHz). Trailing-edge noise and tip vortex noise were found to be important at high frequencies when inflow turbulence was weak.

Trailing-edge noise was found to be especially important for large rotors (such as wind turbines) and to increase slowly with the angle of attack. Tip vortex noise was found to be more important at high angles of attack for wide-chord, square-tip rotors (such as helicopters') and to increase with the angle of attack faster than trailing-edge noise.

Figure 3 compares the different mechanisms and analyses with experimental data for a helicopter rotor. From this and other comparisons, George and Chou[11] concluded that broadband noise can be predicted to within 5 dB. It should be pointed out, however, that no experimental comparisons have been presented for broadband noise in the plane of the rotor and that some of the analyses studied by George and Chou are not applicable within about 10 or 15 deg of the rotor plane. Similarly, Grosveld,[14] in studying wind turbine broadband noise, limited his semiempirical analysis to on-

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axis predictions. He does, however, predict vortex shedding noise due to trailing-edge bluntness (one of the mechanisms neglected by George and Chou), showing a much peakier one-third octave spectrum than the other mechanisms, with a maximum SPL around 1.5 kHz.

Published Experimental Results and Analysis Procedure

To assess the level of broadband noise from propfan tests, results need to be presented in the form of narrow-band spectra. Such results have been published by Glover et al.[15] and Plunkett et al.[16] for the NASA SR-6, by Brooks and Mackall[17] for the NASA SR-3, by Wilby and Wilby[18] for a four-bladed NASA SR-2, and by Fujii et al.[19] for three different designs developed by the National Aerospace Laboratory (NAL) in Tokyo. All of these data were assumed to have been taken in the far-field (beyond 1.5–2 D, according to Plunkett[16]), except those for the SR-3, which were obtained from in-flight measurements of the NASA Jetstar aircraft at 1.3 D from the propfan axis. Summaries of the model characteristics and test conditions are provided in Tables 1 and 2.

Table 1 Propfan model design characteristics

Model	shp/D^2, kW·m^{-2}	Tip speed, ms^{-1}	Tip speed, deg	D, m	B
SR-6	241	213	40	0.69	10
SR-3	301	244	45[a]	0.61	8
SR-2	301	244	0	0.61	8
NAL	301	250	27[b]	0.4	8

[a]Aerodynamic tip sweep quoted as 34.5 deg by Brooks and Mackall.[17]
[b]Aerodynamic tip sweep.

The SR-6 data were taken at $M=0.49$ in Boeing's transonic wind tunnel[15] and at Mach numbers of up to 0.25 in their large anechoic test chamber.[16] For the former, results are presented both with and without acoustic treatment in the working section, but only the "soft-wall" data have been used here (e.g., Fig. 4) since the "hard-wall" results suffered from spurious reflections. For the low-speed tests, a range of Mach numbers were covered, but only one narrow-band spectrum was presented (Fig. 2).

Fujii et al.[19] have designed a propfan with a similar specification to some of the NASA SR series (see Table 1). They tested it in three configurations: with aft-swept blades, forward-swept blades, and alternately aft- and forward-

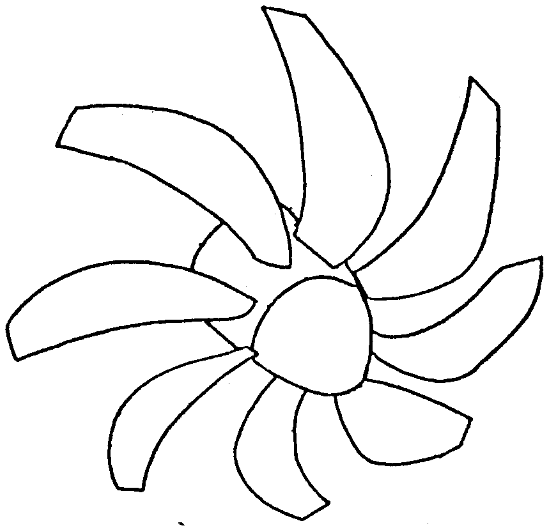

Fig. 1 Typical propfan.

Table 2 Test conditions

Data point[a]	Configuration	M	M_{ht}^{b}	$N^{b,c}$	θ, deg^{b,d}	
G9	SR-6 in BTWT "soft"	0.49	0.946	7950	60	
G10		0.49	0.946	7950	90	
G11		0.49	0.946	7950	110	
P6	SR-6 in *LTC*	0	0.843	7950	90	
B14a	SR-3 in flight (boom)	0.8	1.14?	7600	?	
B14b	SR-3 in flight (fuselage)	0.8	1.14?	7600	?	
W30a	SR-2 + Y-tail	0.13	0.39	4000	70	sideline
W30b	↓	0.18	0.41	4000	70	↓
W31a		0.13	0.39	4000	120	
W31b		0.18	0.41	4000	120	
W32a		0.13	0.76	8200	70	
W32b		0.18	0.77	8200	70	
W33a		0.13	0.76	8200	120	
W33b		0.18	0.77	8200	120	
W34		0.18	0.77	8200	70	flyover
W35a	SR-2 + I-tail	0.13	0.76	8200	70	↓
W35b	SR-2 + I-tail	0.18	0.77	8200	70	
F4	Aft-swept blades	0.09	0.62	10000	?	
F13	Aft-swept blades	0.09	0.5	8000	90	
F14	Alternately swept blades	0.09	0.5	8000	90	
F15	Forward-swept blades	0.09	0.5	8000	90	

[a]The data identification letters G, P, B, W, and F refer to Refs 15–19 respectively. The rest of the identification refers to the figure number within each reference. [b]A question mark indicates data not supplied or values estimated from other information. [c]For data points F4–F15, N_c was quoted. [d]Some data for points G9–G11 come from Ref. 26.

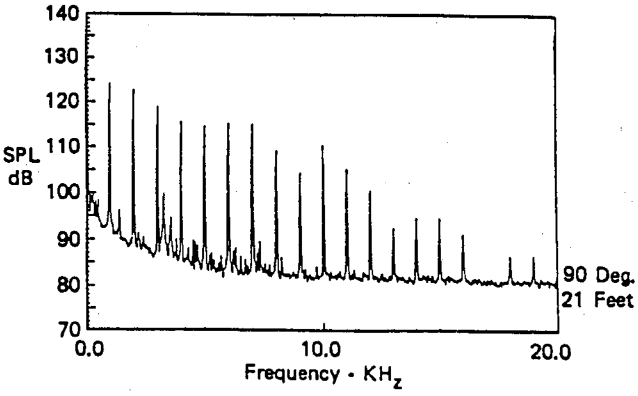

Fig. 2 Narrow-band spectrum for SR-6 propfan in the Boeing large anechoic test cell—$M=0$ (from Ref. 16).

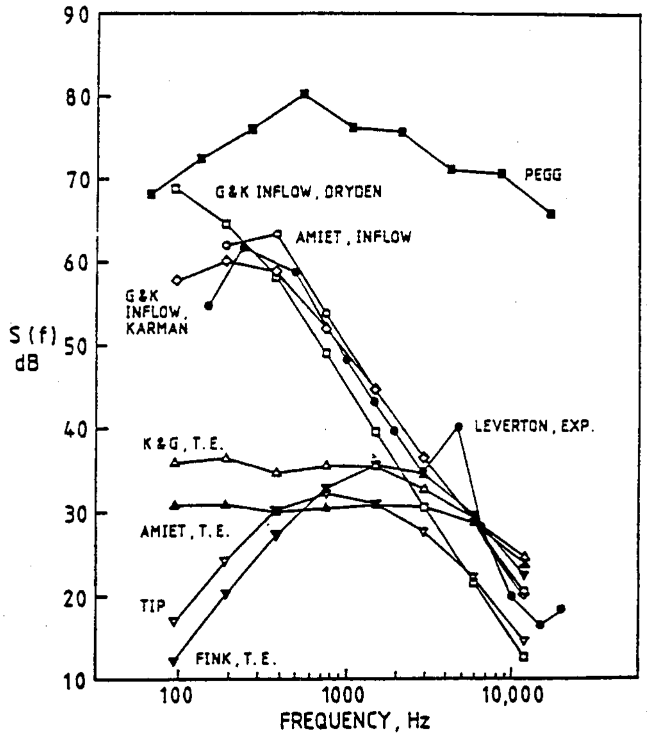

Fig. 3 Comparison of various broadband noise predictions for a full-size helicopter rotor with experiment (from Ref. 11).

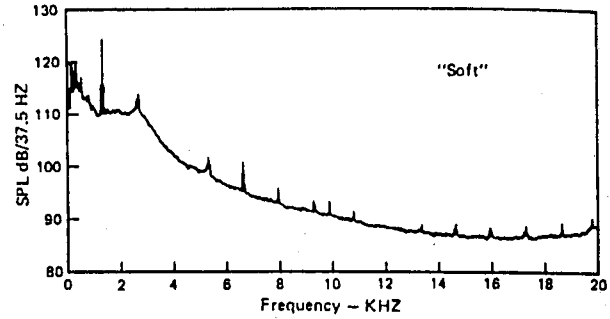

Fig. 4 Narrow-band spectrum for SR-6 propfan in the Boeing transonic wind tunnel with acoustic treatment—aft emission angle, $M=0.49$ (from Ref. 15).

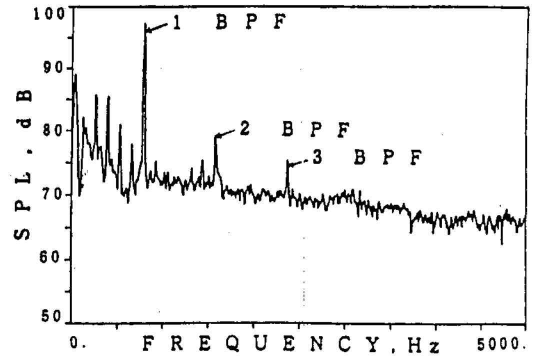

Fig. 5 Narrow-band spectrum for NAL propfan with forward-swept blades—$N_c=8000$ rpm, $M=0.09$, measured on sideline (from Ref. 19).

swept blades. The forward-swept blades were designed with the same aerodynamic parameters as the aft-swept blades. In each case, the propfan was designed for eight blades but tested with six ("to reduce the shp required"[19]) in an open-jet anechoic facility at speeds of 30 ms^{-1}.

Wilby and Wilby[18] tested the SR-2 propeller in a four-bladed pusher configuration with various representative empennages and a fuselage upstream. They present extensive results, including narrow-band spectra for different empennages and measuring positions and two freestream velocities (45.7 and 62.5 ms^{-1}). "Prop-off" noise levels are presented in each case, allowing nonpropeller noise sources to be subtracted from the spectra before analysis.

Both the SR-2 (eight-bladed) and the SR-3 have been tested in flight, but narrow-band spectra were presented by Brooks and Mackall[17] only for the SR-3. One spectrum was taken from a fuselage-mounted microphone (below the propeller) and one from a boom-mounted microphone (above it), allowing the effects of the fuselage boundary layer to be shown.

Each of these spectra was first split into broadband and tone contributions and scaled (on a Strouhal number basis) to an assumed full-size propfan of $D=3$ m (10 ft).† Third-octave plots were then synthesized for each component, the broadband level being obtained by using

$$SPL_{1/3} = SPL_{n/b} + 10\log\left[(b/w)_{1/3}/(b/w)_{n/b}\right]$$

(If the bandwidth of the original narrow-band spectrum was not given, it was assumed to be 20 Hz.) The third-octave tone level was obtained by straightforward logarithmic addition and the overall third-octave spectrum was obtained by a logarithmic addition of the broadband and tone contributions within each third-octave band. Perceived noise levels (PNL) were then determined for the broadband, tone, and overall spectra. A-weighted third-octave spectra were also obtained.

Except for the in-flight data,[17] the third-octave spectra and PNL values were corrected to 40 D (120 m) by allowing for spherical divergence and atmospheric attenuation.[20] This allowed comparisons to be made at typical approach noise measuring distances.

The model propfans being studied here were typically one-fifth scale or less; consequently, the maximum frequencies of the third-octave spectra were correspondingly reduced from those of the original data (see Figs. 2 and 4–6). For the SR-6[15,16] and SR-3[17] results, this gave a maximum frequency of 4 kHz, which was considered acceptable for the PNL analysis. For the SR-2[18] and NAL[19] propfans, however, a lower maximum frequency resulted (1250 and 630 Hz, respectively), so some extrapolation was needed, at least for the broadband level (generally assumed constant) and in some cases for the tones as well.

†Except the SR-6,[15,16] which was assumed to be one-fifth scale.

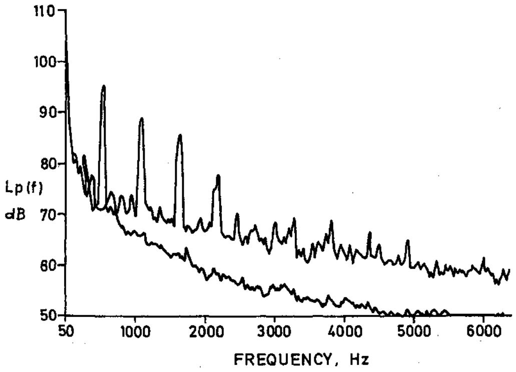

Fig. 6 Narrow-band spectrum for four-bladed SR-2—I-tail upstream, $M=0.13$, $\theta=70$ deg (flyover), lower curve is "prop off" (from Ref. 18).

Results and Discussion

The results of the PNL analyses are presented in Table 3, with typical third-octave spectra shown in Figs. 7-13. The narrow-band spectrum of Fig. 2 becomes the third-octave plot of Fig. 7, which confirms that the tones are indeed as dominant as they appear, 12 PNdB above the broadband component. Also of note in this plot is the fairly flat broadband spectrum. Figures 8 and 9 show the third-octave spectra for the same propfan at high forward speed and high power loading ($C_p=1.101$ compared with 0.094 for the static case). The original measuring distance is not given in Ref. 15, but was apparently 2.2 D.[26]

What can be seen from these data is some measure of directivity, with the broadband noise levels being higher for the forward emission angle than for the rear, but being more important in the rear relative to the tones. The third-octave spectrum for an angle of 90 deg is similar to that of Fig. 9, but with slightly higher levels for the first few tones. However, all the broadband levels deduced from the data gathered in the Boeing transonic wind tunnel must be treated with caution because of the high tunnel noise levels.[15]

To a certain extent, these doubts about the broadband levels on the SR-6 at high Mach numbers are reduced by the (near-field) results for the SR-3 in high-speed flight (Fig. 10)[17]. Here, the tones dominate the broadband noise by 8 PNdB, compared with 10 PNdB for the SR-6 forward emission angle. It can also be seen that the fuselage boundary layer has the same attenuating effect on the tones as on the broadband content (4 PNdB).

Fujii et al.[19] tested their propfan designs at low forward speeds and power coefficients (0.8–0.85) representative of takeoff (0.83 if $C_p=1.7$ is assumed for cruise and takeoff thrust is four times cruise). For most of their tests, however, $M_{ht}=0.5$, which is more appropriate to approach (where $C_p=0.24$) than to takeoff. In all these cases the broadband noise appears to dominate by up to 16 PNdB over the tone PNL.

Figures 11 and 12 compare forward- and alternately swept configurations, confirming Fujii's claim that the latter has a lower tone content, but showing a higher broadband level. Also visible in Fig. 12 is a "kink" in the broadband spectrum at 630 Hz, suggesting that the constant (narrow-band spectrum) level used to extrapolate to 4 kHz is incorrect and that the broadband level is overestimated here. This is not felt to be a large effect since, as seen in Fig. 2 (with no extrapolation), the broadband spectrum is quite flat.

The aft-swept configuration also tested by Fujii et al. shows a similar spectrum to Fig. 12, but only the first two tones are visible. This propfan has also been tested with $M_{ht}=0.62$ and $C_p=0.95$, conditions under which higher order tones appear, bringing the tone level to within 1 PNdB of the broadband (while also raising the broadband level). It

Table 3 Results of acoustic analyses

	PNdB[a]			dBA(max)[a]	
Data point	Broadband	Tone	Overall	Broadband	Tone
G9	117	128	131	96	117
G10	106	109	113	87	98
G11	106	103	110	87	93
P6	108	120	121	82	106
B14a	142	150	152	-	—
B14b	138	146	148	-	—
W30a	88	68	88	66	55
W30b	90	?		69	
W31a	86	70	87	65	55
W31b	87	74	88	67	60
W32a	92	84	93	69	68
W32b	95	85	96	74	72
W33a	91	80	92	69	63
W33b	92	84	94	71	67
W34	95	85	96	72	69
W35a	90	80	91	68	65
W35b	93	85	94	71	73
F4	90	89	95	69	78
F13	86	74	87	66	62
F14	89	73	90	69	60
F15	84	76	85	64	63

[a]Data corrected to 40 D, except B14a and b (1.3 D).

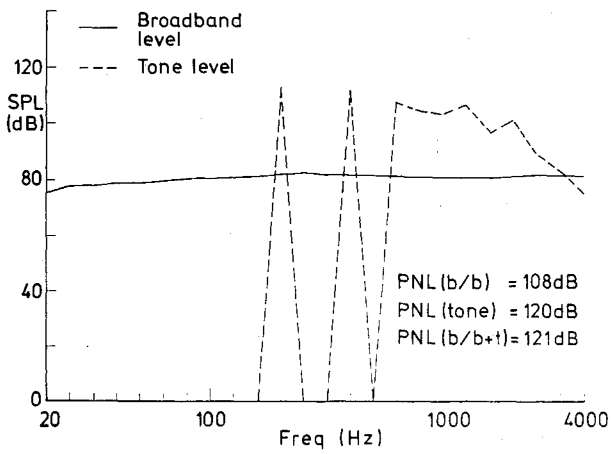

Fig. 7 Broadband vs tone one-third octave spectra for SR-6 propfan ($M=0$ as in Fig. 2).

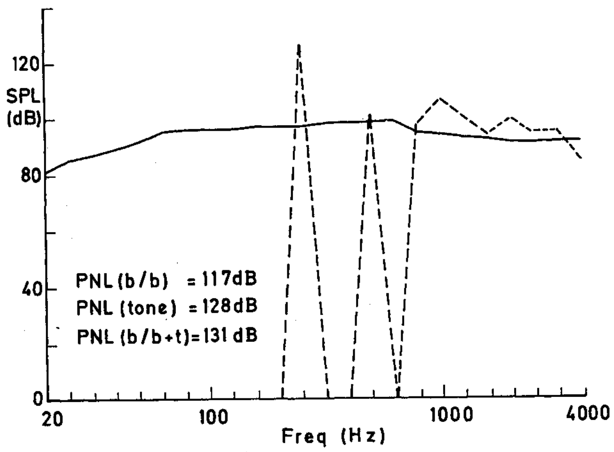

Fig. 8 Broadband vs tone one-third octave spectra for SR-6 propfan, $M=0.49$, forward emission angle (key as in Fig. 7).

is not certain, however, that these results were taken at the same angle. Tunnel background noise is not given by Fujii et al., but the peak jet mixing noise is estimated to be below 50 dB.[21]

A similar effect can be seen in the results from Wilby and Wilby's[18] data, where raising M_{ht} from 0.39 to 0.76 at $M=0.13$ (or 0.41 to 0.77 at $M=0.18$) causes the broadband level to rise 5 PNdB, but causes the tones to rise at 2–4 times this rate. Fujii et al. have a similar ratio of increases, but for a much smaller change in M_{ht}.

The set of data from Wilby and Wilby also allows the effect of forward speed to be assessed for the same M_{ht}. A typical third-octave comparison is shown in Fig. 13. As Table 3 also shows, the PNL of the tones seems to rise at about twice the rate of that for the broadband noise. For all the SR-2 data, however, the broadband noise dominates the tones by 8–20 PNdB.

From the foregoing, it seems that broadband noise can be important on propfans, particularly at low helical tip Mach numbers and low power loadings, as typified by approach conditions. As shown by Lange[22] and in Fig. 14, approach is expected to be the most difficult condition from the point of view of propfan noise certification, even without the broadband contribution.

PNL values cannot be compared directly with noise certification limits, as these usually employ the duration-weighted EPNL. Some airports, however, use the dBA scale, so comparisons can be made with Table 3. Washington National Airport apparently has a nighttime limit of 85 dBA for approach.[23] None of the low-speed, low-M_{ht} results come near this, being typically in the range of 65–75 dBA (except the static SR-6 data[16]). It should be noted, however, that the results here are for single, isolated propfans. Trebble et al.[24] found high-frequency noise levels in the far field approximately 5 dB higher for a full-scale aircraft (with traditional propellers) compared with a quarter-scale model. Also, for a traditional propeller aircraft, Burrin and Salikuddin[25] found

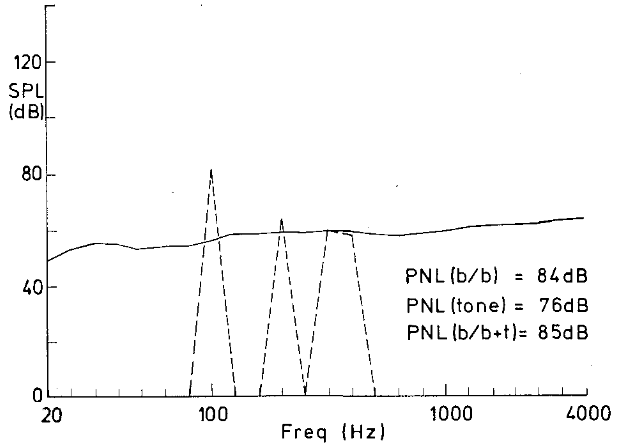

Fig. 11 Broadband vs tone one-third octave spectra for NAL propfan with forward-swept blades as in Fig. 5 (key as in Fig. 7).

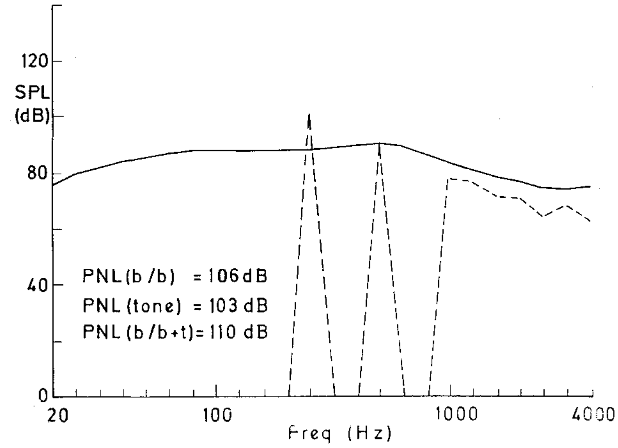

Fig. 9 Broadband vs tone one-third octave spectra for SR-6 propfan, $M=0.49$, aft emission angle as in Fig. 4 (key as in Fig. 7).

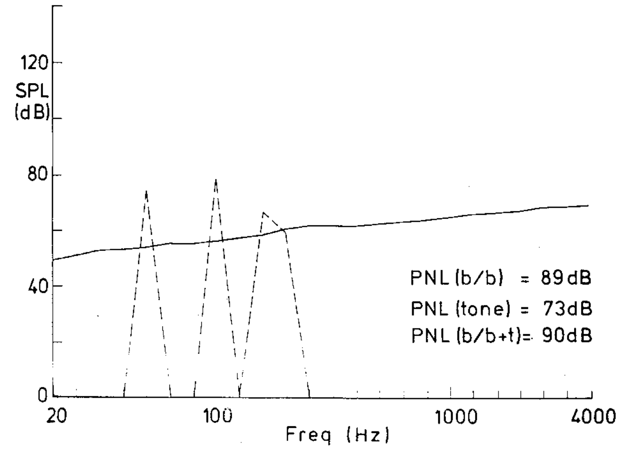

Fig. 12 Broadband vs tone one-third octave spectra for NAL propfan with alternately swept blades—conditions as in Fig. 11 (key as in Fig. 7).

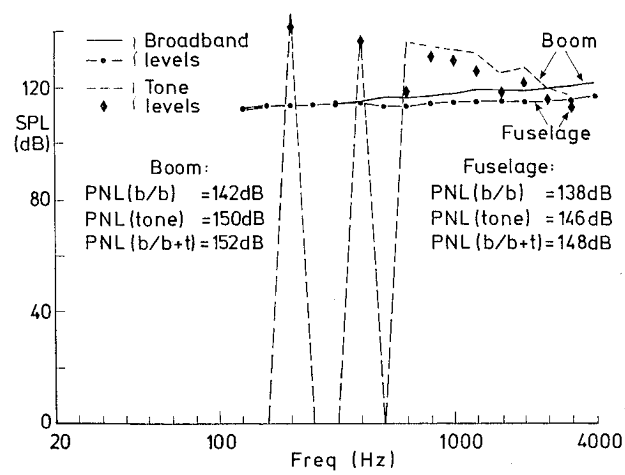

Fig. 10 Broadband vs tone one-third octave spectra for SR-3 propfan in flight, $M=0.8$—showing effect of fuselage boundary layer.

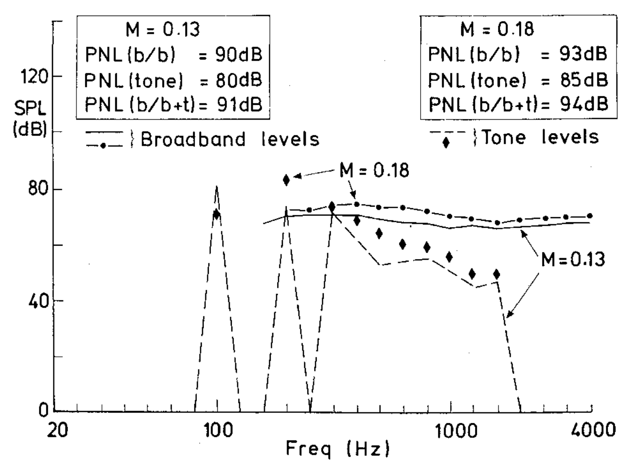

Fig. 13 Broadband vs tone one-third octave spectra for four-bladed SR-2 propfan, showing effect of forward speed.

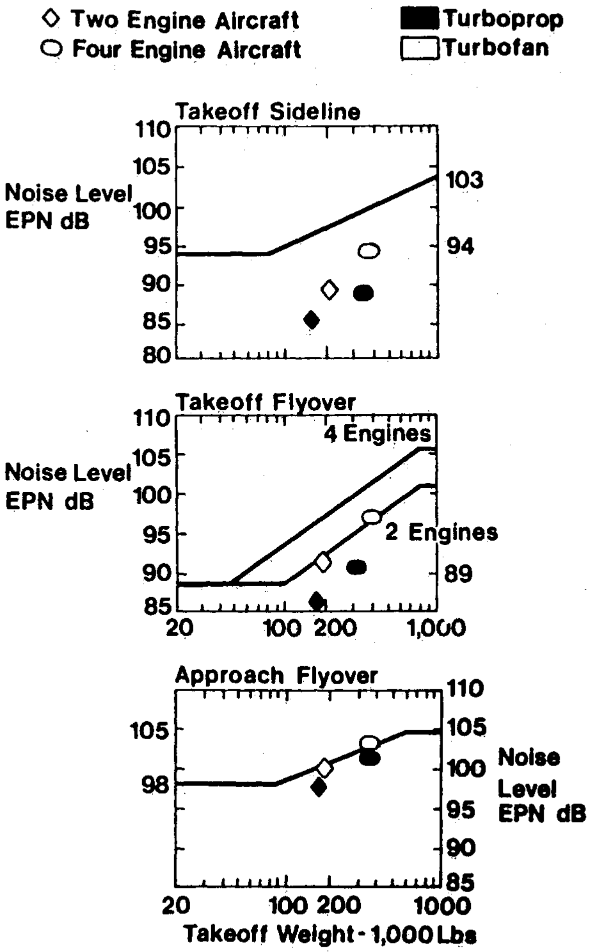

Fig. 14 Propfan-powered aircraft noise prediction compared with FAR 36 stage three noise limits (from Ref. 22).

an excess of broadband noise (approximately 5 dB) for an installed propeller over an isolated model. Furthermore, if inflow turbulence is an important factor (and it is not clear that it is for propfans), then the rear disk of a contrarotation device will generate extra broadband noise and pusher installations may be susceptible to extra broadband noise from wing wake ingestion at approach.

There is no experimental evidence available yet to support this conjecture on propfan installation effects and counterrotation noise. Even the evidence for single-rotation propfans that has been examined here is fragmented as far as broadband noise analysis is concerned. Nevertheless, it does seem that propfan broadband noise should not be ignored.

Conclusions

It is concluded that broadband noise can be predicted, apparently to within 5 dB for helicopters, and that it should be possible to apply these methods to propfans. Some of the predictions, however, are not strictly applicable near the plane of the propeller.

In cruise conditions, the tones dominate the broadband noise of typical propfans by 8 PNdB. As forward speed is decreased, the tone PNL seems to fall at about twice the rate of the broadband content. Also, as the helical tip Mach number is reduced, the tone PNL falls faster than the broadband. Thus, for low-speed, low-power loading conditions, the broadband noise becomes the dominant component by more than 8 PNdB, typical broadband levels being 85–95 PNdB. It is felt that broadband noise could be an important problem for propfans under approach noise certification conditions.

Acknowledgments

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