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AIRCRAFT TURBOFAN BROADBAND NOISE PREDICTION

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1. INTRODUCTION

Aircraft noise is mainly due to the turbofans. Jet noise has become rather low in high bypass ratio engines, and fan tones have been greatly reduced thanks to several advances during the past decades. Thus, emphasis must be put on the fan broadband spectrum. Many works have been devoted to broadband radiation from a fixed airfoil or from rotating blades, either due to the incoming turbulence or to self noise, but broadband noise from high speed rotors is poorly documented [1, 2, 3]. Indeed, a purely theoretical computation is rather difficult because the sound sources are far more intricate than for tones, and are badly known. The scope of this paper is to check to which extend first principles can be useful for predicting turbofan broadband noise.

2. THEORETICAL BACKGROUND

Ffowcs Williams and Hawkings published in 1969 the basic equations predicting sound radiation from a rotating point source [4]. The most useful equation for the present purpose is that giving the broadband sound pressure spectrum P due to a force $\vec{F}$ (or dipole) rotating on a circle of radius R at the angular velocity $2\pi N$. At an observer position in the far field defined by its distance d to the circle center and by the angle θ to the rotation axis

$$P(d,\theta,f)=\frac{f^2}{4c^2d^2}\sum_{n=-\infty}^{+\infty}G_r(\varphi,f-nN)J_n^2\left(\frac{2\pi f}{c}R\sin\theta\right) \qquad (1)$$

where c is the sound velocity, J_n is the Bessel function of first kind, and φ is the angular location of the source at the temporal origin. An acoustic frequency f is generated by the source frequencies f_s such that $f_s=f-nN$, where n is an integer ($n \geq 0$ or < 0). Let us call G the spectrum of $|\vec{F}|$: (1) if $\vec{F}$ is axial (thrust), $G_r = G\cos^2\theta$, spectrum of the force component in the observer direction; (2) if $\vec{F}$ is tangential (drag), $G_r = \left[n/(2\pi fR/c)\right]^2 G$ (result not given in [4]). It is assumed that the force is purely axial in all the results presented in the paper.

Eq. (1) does not seem to have been directly used in the past although its computation is rather easy. The main question arising before implementing Eq. (1) is to know the source spectrum $G(f_s)$. Several acoustic tests of turbofans in static benches [5] allowed us to estimate that the blade pressure spectra are rather flat. Let us put

- for $f_s \le 1/(10\,C)$ and $f_s \ge 10\,C$: $G(f_s) = \left[\frac{1}{2}\rho_0 S U_{rot}^2 \frac{A f_s}{f_s^2 + C f_s + 1}\right]^2$ (2)
- for $1/(10\,C) < f_s < 10\,C$: $G(f_s) = \text{Constant} = G(0.1/C) = G(10\,C)$

where f_s is in Hertz, ρ_0 is the air density, $S = \pi R^2$, $U_{rot} = 2\pi RN$. Eqs. (2) show that $G(f_s)$ is symmetric around $f_s = 1$ if the horizontal scale is logarithmic. $G(f_s) \approx 1/f_s^2$ at high frequency (slope of -6 dB/octave), and thus the overall blade pressure remains finite. Also, $G(f_s)$ vanishes at low frequency in order to eliminate the steady and very low frequency loads, generating the tones.

The constant A in Eqs. (2) is adjusted to give realistic sound levels (but it is not attempted here to get the actual absolute levels): $A = 10^{-3}$ in the following. C is a constant which would be of the order of 100 for upstream radiation, and 10 for downstream radiation. This means that sources radiating upstream and downstream are not the same. Upstream radiation is probably generated by the rotor itself, and downstream radiation can be due to the interaction of the blade wakes with the outlet guide vanes.

3. RESULTS

The first result to be shown is the overall sound power level (OAPWL). It is computed in the frequency range covering the third-octave bands from 50 Hz to 10 kHz. It is plotted in Fig. 1 versus the logarithm of the rotation Mach number, $M_{rot} = 2\pi RN/c$. Here, $R = 0.863$ m, which is a realistic radius for modern turbofans. The three curves correspond to a constant C in Eqs. (2) equal to 1, 10 or 100. They are very close together at subsonic speeds ($\log(M_{rot}) < 0$), but are quite different at supersonic speeds. This is due to an increase of the contribution of the low-frequency blade pressure fluctuations, which are emphazised when C is small. That effect also explains why the shape of the curve $C = 100$ is smoother. The straight line at the bottom is the variation of OAPWL in $50\log(M_{rot})$, which is the law generally admitted for broadband self noise [1, 6]. It is found for small values of C that there is a strong increase at transonic speeds which is not found in the tests.

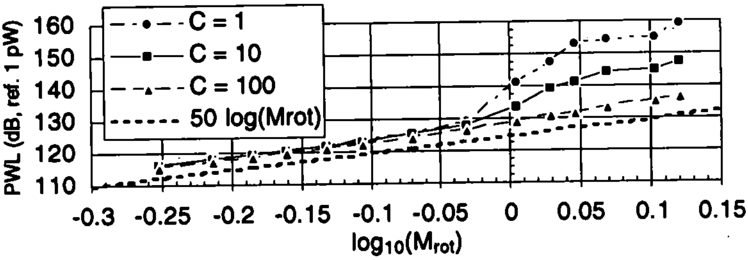
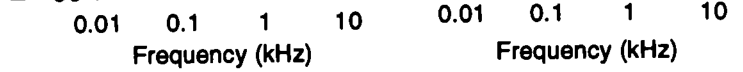


Figure 1 - Theoretical OAPWL radiated by a rotating force: R = 0.863 m

Next step consists in looking at the sound power spectra. Third-octave power levels (PWL) are plotted in Figs. 2a and 2b for C = 100 and 10, respectively. They are computed for three rotational Mach numbers. The dots show the average of turbofan spectra measured at several rotation speeds, radiated respectively by the inlet and by the exhaust. Once again, absolute levels are of no significance, but it must be outlined that the shapes of experimental spectra are quite independent of the velocity in the range covered by the computations. Theoretical curves are in good agreement with test data up to transonic Mach numbers, both upstream and downstream, which justify the choice of the two values of constant C. On the contrary, computed sound power levels increase more sharply than experimental levels at high frequency for supersonic tip speeds.



a) Constant C = 100, and comparison with upstream measurements   *b) Constant C = 10, and comparison with downstream measurements*

Figure 2 - Third-octave sound power spectra: R = 0.863 m

A deeper insight into the phenomena appearing in supersonic is given by the radiated directivity in third-octave bands. An example is displayed in Fig. 3 for C = 100. The constant sound pressure level (SPL) lines are plotted every 3 dB. The directivity looks like $\cos^2\theta$ at subsonic speeds. The increase at supersonic speeds is mainly due to a hump around 50 degrees, which is not found in tests. Finally, Figs. 2 and 3 show that the increase of OAPWL around M_{rot} = 1 in Fig. 1 is due to the high frequency radiation around 50 degrees. The physical explanation of this discrepancy with tests is still under study.

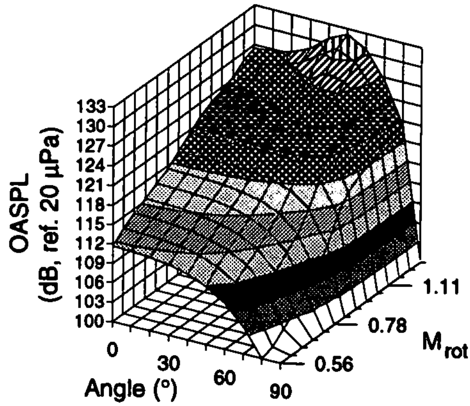


Figure 3 - Theoretical directivity of overall sound pressure levels (computed at d = 1 m): R = 0.863 m, C = 100

It must be outlined that actual directivities do not exactly follow a law in $\cos^2\theta$. They are rather close to the semi-empirical curves given in [7]. Indeed, only thrust has been considered in the present paper. For the drag, G_r is given below Eq. (1), and the combination of both components would more or less flatten the directivities as observed.

4. CONCLUSION

This work is a first step towards theoretical prediction of compressor broadband noise, based on first principles. The assumption on blade pressure spectra seems to be valid for subsonic rotors. It leads to realistic acoustic spectra, and to sound power varying as the velocity to the power five. This is consistent with test data and with more complete calculations on the scattering of blade boundary layer at the trailing edge. More thoroughly studies are required for supersonic rotors.

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References

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