Investigation of Fan Noise Sources by Blade Pressure Measurements

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Abstract

DISCRETE frequency noise generated by subsonic fans is studied through an experimental program which characterizes each step of the generation process. The aerodynamic profile of the flow impinging on the rotor, fluctuating blade pressure, space structure of in-duct propagating waves, and radiated sound field are successively investigated. Relationships between the various results are highlighted. Moreover, starting from in-flow distortion data as an input to theoretical calculations, blade pressure spectrum, modal intensity distribution, and radiated acoustic power are derived and experimentally compared. Tests reported hereafter were conducted on a scaled 0.47 m, high-pressure ratio, subsonic fan. Three out of the 48 blades of the rotor are equipped with original thin-film pressure transducers, which prove their ability to measure pressure in a severe environment. Comparison of experiment with theory shows reasonable agreement at moderate rotation speeds and emphasizes the importance of nonstationary flow distortions in the noise generation process.

Contents

Experimental Results

The blade passing frequency of the noise produced in static conditions by a modern single-stage fan running at subsonic tip speed is usually thought to be dominated by interaction processes between in-flow distortions and the rotor. Permanent distortions, as well as inlet turbulence, can generate discrete frequency noise when convected eddies are extremely lengthened in the upstream contraction.[1-3] Azimuthal profiles of the dynamic pressure measured in the inlet show a strongly disturbed area around the left part of the duct (front view). Fluctuations of the axial velocity are mainly at very low frequency (less than a few Hertz), and thus, can substantially contribute to tone noise.

The effect of such velocity defects on unsteady blade pressure provides information regarding the strength of this noise source. Blade-pressure measurements are provided by special thin-film transducers[4] that can be attached to the rotating airfoil surface without perturbing the flow. Pressure fluctuations are obtained by capacitance variations. Overall thickness—dielectric and metallized layers—is less than 50 μm and each assembly on one blade contains two or four sensitive areas on both the suction and pressure sides.

Each sample in Fig. 1 shows the space-time history of the blade-pressure signal over 128 successive revolutions[2] for the same operating condition but at two different time intervals. Long, fixed disturbances are present in the first sample, whereas the relatively orderly structure is lost in the right bottom part of the second one. Main disturbances, which last more than 128 revolutions, correspond to frequencies less than 0.8 Hz or to typical length scales greater than 70 m.

Figure 2 gives the comparison between two different analyses of the same recording of blade-pressure fluctuations measured with a thin-film transducer located on the suction

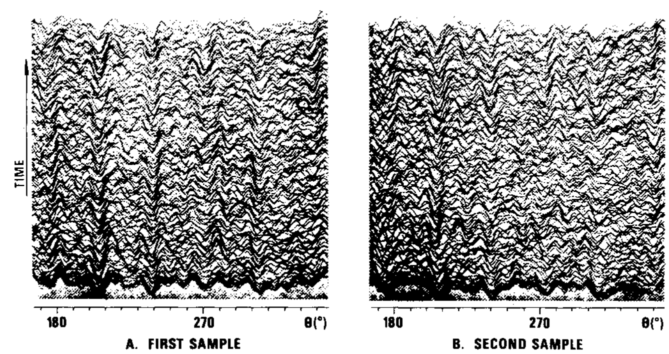

Fig. 1 Space-time history of blade-pressure fluctuations ($N = 0.5$ $Nn = 6300$ rpm; Θ: azimuthal angle).

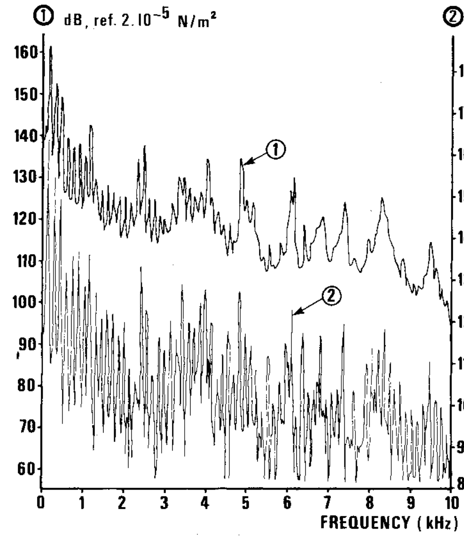

Fig. 2 Average spectrum ① and coherent spectrum ② of blade-pressure fluctuations ($N = 0.7$ $Nn = 8820$ rpm, bandwidth $\Delta f = 20$ Hz).

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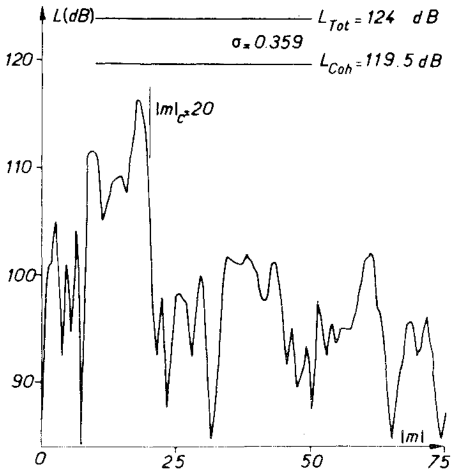

Fig. 3 Azimuthal wave number spectrum (dB, Ref. 2 10^{-5} N/m^2) of the in-duct propagating acoustic field at the blade-passing frequency (N=0.5 Nn=6100 rpm, f=BN=5040 Hz, B: blade number, bandwidth Δf=100 Hz). Measured at the wall, 2 diam upstream of the rotor.

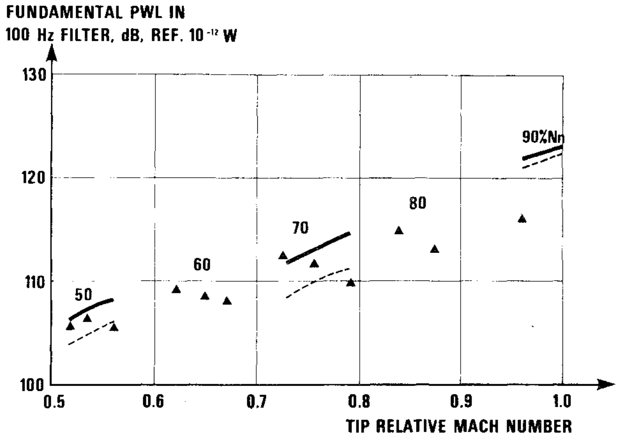

Fig. 4 Comparison of the fundamental radiated acoustic power predicted from distortion data with measurements (dipole noise prediction:——incompressible flow, ----compressible; measurement: ▲).

side near the leading edge and at 80% span. The upper curve is the classical average spectrum, i.e., the mean value of 100 elementary spectra computed from 100 successive samples; the lower one, called a coherent spectrum, is the spectrum of the signal corresponding to the mean value of 100 data acquisitions triggered by a pulse emitted once per revolution. In the latter case the broadband component, random in nature, is almost completely eliminated by the averaging process. Strong loading harmonics of the shaft rotational frequency are found in both curves, but only the second one clearly separates the high-order lines from continuous spectrum. Apart from the first three harmonics, all the line levels are greatly reduced in the coherent spectrum. The level differences between the two spectra mean that a great part of the tone energy is not coherently organized. Such a comparison is of practical importance, since only sufficiently high-order loading harmonics can generate acoustic propagating modes (in the limit of sonic relative tip speed in blade-fixed coordinates).

In fact, it is shown in Fig. 3 that only $\sigma = 36\%$ of the total acoustic intensity L_{tot} of the blade-passing frequency tone is coherent at half the nominal speed. The azimuthal wave number spectrum indicates that the spatially coherent intensity L_{coh} is mainly distributed at the outer wall in a lot of spinning modes, which are clearly merging from noise, in the range $|m| = 8$-20. It can also be noticed that the level drop-off at $|m| = 20$ is explained by the cut-off properties of the duct, since, in this case, the highest propagating mode, according to the dispersion relationship, is precisely $|m|_c = 20$. All wave number spectra were obtained by a cross correlation between the signals of two flush-mounted microphones—one fixed and the other slowly moving in the azimuthal direction, two diameters upstream of the rotor in the inlet duct.[5]

Comparison of Theory and Experiment

A theoretical model, inferred from Goldstein et al.[6] and the work of Mani,[7] is developed to predict the radiated acoustic power. More precisely, some modifications were included in the aforementioned models, in an attempt to improve the acoustic level computation. Particularly, due to the high Mach numbers encountered in aeronautical fans, we must take care of compressibility effects. To this end, in the dipole noise calculation, the unsteady airfoil response function expressed by Sear's function in both models[6,7] is replaced by an approximate solution function derived by Adamczyk.[8] Quadrupole noise can also be computed but can hardly match the experimental results, since the quadrupole model used assumes that the solidity is high, which is inappropriate to the low-solidity fan used in the experiment.

The input of the calculation is the axial velocity profile impinging on the rotor and can be given either by an analytical shape or by experimental values obtained from a Prandtl probe azimuthal survey (Fig. 4). The following results are derived: blade pressure spectrum, upstream or downstream in-duct azimuthal wave number spectrum at any blade-passing frequency harmonic and radiated acoustic power, with the assumption that there is no reflection at the end of the duct.

Figure 4 shows a theory to experiment comparison for the forward radiated acoustic power at the blade-passing frequency and at different rotation speeds and flow coefficients; the experimental values are obtained from integration of the directivity pattern measured in the upstream anechoïc chamber. In this figure, only dipole noise is taken into account, but the effect of the compressibility is investigated. Agreement between predicted and measured forward noise is good at moderate rotation speeds (up to 70% nominal speed), but there is overestimation at high speed, partly due to high-frequency attenuation of fan tones when using a very long inlet duct,[9] but differences hold on even if corrected. However, the general trends observed are sufficient to support the idea that slowly varying flow nonuniformities (used as input data in the calculations) are the main source of rotor noise alone, at least for the type of fan and environment used in this experiment.

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