Frequency Dependent Velocity Scaling and Small Axial Flow Fans

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Abstract: The strength of an aeroacoustic source scales with velocity in a manner that depends upon the nature of the source. A diagnostic procedure based on this characteristic has been used as a tool in the study of broadband noise generated by small axial flow fans.

INTRODUCTION

Various authors have shown that properties of aeroacoustic sources can be inferred through the application of dimensional analysis.[1] A typical form for a sound power (W) expression obtained in this way is:

\[ W = p^2 U^n \]  

(1)

where \( U \) is a characteristic velocity (e.g., tip speed, mean flow rate, etc.) and \( p \) is sound pressure. The exponent \( n \) varies depending upon the dominant aeroacoustic process(es), and the expected range of exponent values is 4 \( \text{ns} \leq 8 \). Insight into the noise generation mechanisms of rotating turbomachines can be obtained by experimentally determining the value of \( n \) as a function of operating point and frequency. That is, the dominant noise generating mechanisms change depending upon whether a device is heavily loaded or lightly loaded. Similarly, at a fixed operating point, different aeroacoustic sources are likely to dominate particular frequency bands within the radiated spectrum.

ANALYSIS METHODOLOGY

After transforming into the frequency domain, Equation 1 can be put into the general form:

\[ L_{wp}(f, \phi) = n(f, \phi)L_u \]  

(2)

where \( L_{wp} \) is sound pressure level, \( f \) is frequency, \( \phi \) is the non-dimensional flow rate, \( n \) is the characteristic velocity exponent, and velocity level \( L_u = 10\log(V/V_0) \). \( V \) is the magnitude of the characteristic velocity and \( V_0 \) is a reference velocity.) In Equation 2, the function \( n(f, \phi) \) represents the slope of a linear dependence between \( L_{wp} \) and \( L_u \). Therefore, at a constant operating point, the variation of \( n \) with frequency can be determined by examining the variation of sound pressure level with velocity level. A data collection and analysis procedure for accomplishing this is described in Ref. 2. The data analysis procedure relies on the assumption that the velocity dependence of the aeroacoustic sources can be determined without scaling frequency. Frequency “smearing” effects are confined to bands whose width is determined by the speed range used in testing.[2]

AXIAL FAN EXPERIMENTS

The frequency dependent velocity scaling analysis was applied in the investigation of the broadband noise generated by small axial cooling fans. The intent of the experiments was to determine if the method could be used to: (1) differentiate between frequency bands where different aeroacoustic processes dominate, and (2) narrow the list of likely processes within those bands. The test fan used had a 5-bladed impeller with a diameter of 172 mm.

In order to provide flow conditions similar to those seen in an actual installation, the fan was mounted on an ANSI S12.11 test plenum.[3] Within the design operating range of this type of axial fan, it is reasonable to assume that the primary aeroacoustic processes will not change if the non-dimensional operating point is held fixed. In Ref. 4, it was shown that when an air-moving device is mounted on the ANSI plenum, the fan flow rate and non-dimensional operating point can be accurately determined using the plenum pressure. After measuring the in-plenum fan performance curves (shown in Figure 1), the following set of non-dimensional operating points was selected for testing: \( \phi=0.25, 0.29, 0.32, 0.35 \). These points span the useful design range between the test fan’s best efficiency point and free delivery.

Figure 2 contains the resulting \( n(f) \) plots for the full set of four non-dimensional operating points. The data indicates a strong exponent transition near 2 kHz, particularly for high \( \phi \) values. Below that frequency, the highest
exponent values are associated with the $\phi = 0.25$ curve and the values decrease as $\phi$ decreases. To a large extent, this relationship between the data sets is inverted above 2 kHz.

Additional fluid dynamic and flow visualization studies have been conducted using the same model fan.[5] Those studies demonstrated that a likely source of broadband noise was flow unsteadiness caused by tip gap flows, and the studies identified the secondary flows responsible for the noise generation. That work also showed that those secondary flow sources became dominant contributors at the 2 kHz transition frequency noted above, and provided strong indications that trailing edge scattering and radiation from free (or boundary layer) turbulence were the mechanisms for the high frequency noise. Depending upon the relative strength of these sources, the expected velocity exponent would be between 5 and 8, respectively.

Another interesting feature in Figure 2 is that above 2 kHz the exponent values tend to be highest for the $\phi = 0.32$ and 0.35 tests. Given the exponent values noted above for trailing edge radiation and radiation from turbulence, the data indicates that a trailing edge mechanism is weaker in this frequency regime than in the lower $\phi$ tests. Laboratory observations of the liftoff location of tip vortices and the subsequent interaction of unsteadiness with following blades seemed to explain the relative weakness of the trailing edge source at high $\phi$ values.

In the region from 0.5-2 kHz, the interpretation of the results was less clear. Figure 2 shows the measured exponent to be between 4.5 and 6.5. Blake's review of acoustic data from a wide variety of axial fans provides support for a value near 5.[1] So, both the data reported here and Blake's analysis suggest that non-compact radiation maybe a contributor in this low frequency (i.e, long wavelength) range. The physical mechanism underlying this behavior has yet to be determined, but the answer is likely to be linked to impeller/blade loading.

CONCLUSION

The identification and description of dominant aeroacoustic processes are normally obtained through a combination of fluid dynamic and acoustic measurements. In general, the creation of an effective and efficient experimental turbomachinery noise program is often hampered by a lack of a priori information. Fluid dynamic measurements, in particular, are often difficult to set-up and time consuming to conduct. The method described in this paper provides a means for obtaining preliminary indications of dominant sources and the frequency ranges over which they operate. In principle, the technique can be applied to any low-speed aeroacoustic problem where a characteristic velocity can be measured and systematically varied.

REFERENCES