Analysis of Tonal Noise Generating Mechanisms in Low-Speed Axial-Flow Fans Postprint

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Abstract

The present paper reports a comparison of experimental SPL spectral data related to the tonal noise generated by axial-flow fans. A nine blade rotor has been operated at free discharge conditions and in four geometrical configurations in which different kinds of tonal noise generating mechanisms are present: large-scale inlet turbulent structures, tip-gap flow, turbulent wakes, and rotor-stator interaction. The measurements have been taken in a hemi-anechoic chamber at constant rotational speed and, in order to vary the acoustic source strength, during low angular acceleration, linear speed ramps. In order to avoid erroneous quantitative evaluations if the acoustic propagation effects are not considered, the acoustic response functions of the different test configurations have been computed by means of the spectral decomposition method. Then, the properties of the tonal noise generating mechanisms have been studied. To this aim, the constant-Strouhal number SPL, obtained by means of measurements taken during the speed ramps, have been compared with the propagation function. Finally, the analysis of the phase of the acoustic pressure has allowed to distinguish between random and deterministic tonal noise generating mechanisms and to collect information about the presence of important propagation effects.

Full Text

Preamble

This paper presents a comparative analysis of experimental sound pressure level (SPL) spectral data related to tonal noise generated by axial-flow fans. A nine-blade rotor was operated at free-discharge conditions in four geometric configurations, each emphasizing different tonal noise generation mechanisms: large-scale inlet turbulent structures, tip-gap flow, turbulent wakes, and rotor-stator interaction. Measurements were conducted in a hemi-anechoic chamber at constant rotational speed and during low angular acceleration linear speed ramps

to vary the acoustic source strength. To avoid erroneous quantitative evaluations that neglect acoustic propagation effects, the acoustic response functions for each test configuration were computed using the spectral decomposition method. The properties of the tonal noise generation mechanisms were then investigated by comparing constant-Strouhal number SPL data obtained from speed ramp measurements with the propagation function. Finally, analysis of the acoustic pressure phase enabled discrimination between random and deterministic tonal noise generation mechanisms and provided information about significant propagation effects.

Keywords: Axial-flow fans, Tonal noise, Acoustic response

Introduction

Low-speed axial-flow fans are employed in numerous applications, from HVAC systems to automotive cooling units, and must satisfy increasingly stringent requirements for compactness and performance. In most cases, the complete assembly geometry is quite complex. Compared to an ideal ducted fan, the presence of non-aerodynamically shaped inlet ducts, structural struts, and downstream stators creates a more complex flowfield. Such conditions can result in the simultaneous presence of different noise generation mechanisms. While broadband noise generated at leading and trailing edges typically contributes most to the overall SPL spectrum, low-frequency tonal components are often the primary source of annoyance.

Tonal noise usually arises from non-uniform inflow conditions and may be attributed to large-scale inlet turbulent structures [?, ?, ?], rotor-stator aerodynamic interaction [?, ?, ?], or tip-leakage flow [?, ?, ?]. Reducing radiated tonal noise first requires identifying the actual source mechanisms, which can be difficult since SPL spectrum analysis often cannot discriminate between contributions from different source types. This necessitates identifying suitable properties that are easily obtainable from standard tests.

Furthermore, in many applications fans operate at variable speed, causing tonal peaks to excite the assembly’ s acoustic response function at different frequencies, which superimposes with the rotational speed dependence of the generation mechanism. The resulting irregular behavior of tonal components can complicate analysis and create additional annoyance. To address these challenges, a methodology for discriminating propagation effect contributions in received noise is employed. In this work, typical instances of such noise components are analyzed and compared using methods developed by the authors [?, ?, ?].

Experimental Facility and Tested Fan

All experimental data were acquired during measurement campaigns in the DIME hemi-anechoic chamber, with the fan mounted on a rectangular wooden panel (670 mm × 720 mm, 25 mm thick). The rotor axis was positioned horizontally at heights between 1 m and 1.6 m from the floor, depending on the case. The microphone was positioned on-axis between 1 m and 1.18 m upstream, according to the specific configuration.

The test fan, shown in Fig. 1 [Figure 1: see original paper], features $z_R = 9$ evenly spaced blades made of polyamide with fiberglass reinforcement. The rotor includes a cylindrical rotating shroud with external diameter $D_{tip} = 460$ mm, a hub diameter $D_{hub} = 181$ mm, and a blade chord c varying between 65 mm at the hub and 72 mm at the tip. Rotational speed was measured using the electric motor' s internal encoder, generating a one-per-revolution TTL signal (hereinafter referred to as the tacho signal).

The design performance specifications are a flow rate $Q = 1.174$ m³/s and a static pressure rise $\Delta p = p_{out} - p_0 = 388$ Pa at $\Omega = 3000$ r/min, with air at ambient conditions (20 °C, 101300 Pa). This yields a flow coefficient $\phi_{des} = Q/(u_{tip}\pi D_{tip}^2/4) = 0.097$ and a pressure coefficient $\psi_{des} = \Delta p/(0.5\rho_0 u_{tip}^2) = 0.121$, where u_{tip} is the blade tip speed. In the present investigation, the fan was operated at free-discharge conditions, for which $\phi_{fd} = 0.164$ and $\psi_{fd} = 0$.

The rotor is driven by a PC-controlled brushless servomotor (Danaher AKM42E-ANCNR-00, rated power 1.14 kW at 640 V) supported by a steel structure that enables precise positioning via a 3-axis system. The structure is fixed to the rectangular wooden panel. This motor is quieter and more stable than brushless motors used in production units, and its noise does not interfere with the aerodynamic noise (see Cattanei et al. [?] for details). The only noticeable effect is a sharp peak at $f \cong 16$ kHz, which does not significantly influence the noise under investigation.

The wooden panel has a central circular hole and is supported by a metal frame, thus establishing free-discharge conditions. The standard tip-clearance geometry consists of 5 mm axial and radial gaps, achieved by inserting appropriate aluminum rings in the hole. Different rings allow modification of the tip gap. It is important to note that in the adopted measurement configuration, which is common for axial fan testing, acoustic interference from waves reflected by the chamber floor may compromise the free-field condition hypothesis. This effect depends on the distance between the acoustic source and microphone relative to the distance from the floor, as well as source characteristics (number, location, directivity, etc.). Specifically, noise from a coherent, compact source (e.g., a localized wake impinging on the rotor) is strongly affected by this phenomenon [?]. Noise from large-scale inlet turbulent structures, tip-gap flow, and rotor-stator interaction is only slightly affected. The random nature of broadband noise prevents acoustic interference, so the power spectral densities of direct and reflected noise simply sum. For the adopted geometry, this results in an average increase of 0.8 dB in the measured SPL spectrum.

Test Configurations

Four different geometric test configurations were employed, all operated at free-discharge conditions. Each configuration was designed to enhance a single tonal noise generation mechanism to highlight its effect on the overall spectrum.

Large-Scale Turbulence (LST) Configuration: The fan was simply mounted on the rectangular wooden panel with no upstream turbulence control screen, as shown in Fig. 3a [Figure 3: see original paper]. In this configuration, the primary tonal noise generation mechanism is related to ingested large-scale turbulent structures. As will be shown, the tip-clearance flow is weak and does not generate a prominent tonal component.

Rotor-Stator Interaction (RSI) Configuration: Similar to the LST case but equipped with a downstream stator (Fig. 3b). The stator is evenly spaced with $z_S = 18$ constant-thickness, cambered vanes of 30 mm chord (Fig. 2 [Figure 2: see original paper]). The axial gap between the rotor blade trailing edge and stator vane leading edge at the rotor tip is 11 mm. In this configuration, the main active tonal noise generation mechanism is rotor-stator interaction, while tip-clearance flow and inlet turbulent structure effects are minor, as will be demonstrated. The choice $z_S = 2z_R$ is not realistic since z_R and z_S are typically not integer multiples, but it enhances SPL at low BPF harmonics.

Tip-Gap Flow (TGF) Configuration: This configuration (Fig. 3c) consists of a 66 mm long cylindrical duct with a bell-mouth inlet. An upstream screen in the form of a fabric hood was adopted to reduce inlet turbulence (turbulence control screen, TCS). The bell-mouth inlet is expected to play an important role in reducing incoming flow distortions [?]. Consequently, the main active source of tonal noise is related to tip-gap flow. Although the fan operates at free-discharge conditions, the cylindrical duct restrains the tip-gap flow, enhancing the related noise.

Turbulent Wake (TW) Configuration: In this case (Fig. 3d), the panel shape was modified and an extension (outer diameter $D_{ext} = 1400$ mm) was added. To control inlet turbulence, a hemispherical TCS was employed, as in the TGF case. To generate a sharp wake, a cylindrical bar of diameter $D_{bar} = 12.5$ mm was inserted upstream of the rotor in the upper part of the panel. The bar extends over the entire blade span and is located 9.5 mm upstream of the rotor blade leading edge. In this configuration, the primary tonal noise generation mechanism is due to bar wake impingement on the rotor blade.

Measurement Procedure and Data Processing Method

Acoustic pressure data were acquired and processed using a Brüel & Kjær 3560 spectrum analyzer and a pre-polarized ½” free-field microphone. Measurements were taken during linear speed ramps (from 500 r/min to 3000 r/min in 1080 s) and at constant Ω. The small angular acceleration, combined with the order analysis algorithm [?], ensured precise spectral results and allowed computation of SPL at harmonics of the rotational frequency, $SPL_n(\Omega)$ (rotational speed-based Strouhal numbers $St = 60f/\Omega$, varying from 0 to 80, with resolution $\Delta St = 0.2$). Additionally, SPL spectra at constant Ω (range 0–20 kHz, 1600 lines with resolution $\Delta f = 12.5$ Hz) were computed. For both measurement types, 100 data records with 50% overlap were collected. For constant-Ω spectra, a von Hann window was employed to limit spectral leakage.

The SPL spectrum may be defined according to:

$$SPL(f,\Omega) = 10\log_{10}\left(\frac{S_{pp}(f,\Omega)}{p_{ref}^2}\right)$$

where $S_{pp}(f,\Omega)$ is the one-sided power spectral density of the measured acoustic pressure for a constant-Ω acquisition. Ω is considered a parameter, $f_k = k\Delta f$, and $p_{ref} = 20$ µPa is the reference pressure.

Similarly, SPL_n may be computed as:

$$SPL_n(\Omega) = 10\log_{10}\left(\frac{S_{pp}(f_n,\Omega)\Delta f}{p_{ref}^2}\right)$$

where $n = St/\Delta St$, $f_n = n\Delta St\Omega/60$ is the central frequency, and $\Delta f = \Delta St\Omega/60$ represents the resulting bandwidth. Δf must be small enough to prevent broadband noise contributions from affecting the tonal component. Adopting $\Delta St = \text{const}$ results in Δf being proportional to Ω. Parametric tests have shown that the chosen settings yield sufficient spectral data precision, with random fluctuations typically affecting spectral quantity plots being sufficiently limited.

Important information can be obtained from scaling constant-Ω SPL spectra based on similarity theory [**?**, **?**]: in the absence of propagation effects from reflections, scattering, and diffraction by fan components, SPL spectra for different Ω values are expected to collapse onto a single curve when scaled SPL:

$$SPL_{scaled}(f,\Omega) = SPL(f,\Omega) - 10\log_{10}\left(\frac{\Omega^\beta}{K}\right)$$

is plotted versus scaled frequency (i.e., versus Strouhal number). In Eq. (3), K is an arbitrary constant and exponent β assumes values around 1 for trailing edge noise and 3 for tonal noise.

When measured during a speed ramp, $SPL_n(\Omega)$ may experience large variations (on the order of 40 dB), preventing proper study of SPL_n fluctuations. Therefore, SPL_n may be scaled similarly to $SPL(f,\Omega)$, allowing extraction of the fluctuating part. However, the linear dependence of Δf on Ω in Eq. (2) requires scaling with a factor of $10\log_{10}\Omega^{4+\alpha}$. If the scaled mechanisms are the same, $\alpha = \beta$ results. Accordingly, the scaled SPL during speed ramps is considered:

$$D_n(\Omega) = SPL_n(\Omega) - 10\log_{10}\left(\frac{\Omega^{4+\alpha}}{C_n}\right)$$

where C_n is an arbitrary constant.

The phase angle $\phi_n(\Omega)$ of the Fourier transform of the acoustic pressure (referenced to the tacho signal) at the BPF and harmonics was calculated. $\phi_n(\Omega)$ exhibits a random trend if the noise generation mechanism is not correlated with rotor position; otherwise, it shows a linear trend in the absence of propagation effects (free-field condition) [**?**].

Description of the Constant-Ω SPL Spectra

Constant-Ω SPL spectra are the most common representation of acoustic pressure data. Their analysis (Fig. 4 [Figure 4: see original paper], $\Omega = 3000$ r/min) provides intuitive preliminary understanding of main phenomena, though detectable information is limited. The features described below summarize the analysis reported in [**?**, **?**, **?**].

In the LST configuration, for $f < 3$ kHz, the main features are tonal noise peaks that clearly emerge from the spectrum up to the 6th BPF harmonic (2.7 kHz). These peaks result from large-scale turbulent structures that are stretched by flow acceleration upstream of the fan and repeatedly chopped by rotor blades [**?**]. A local, slight SPL increase occurs at frequencies slightly lower than the 1st and 2nd BPF harmonics (dotted vertical lines), caused by weak recirculating flow passing through the gap between the rotor shroud and external aluminum ring.

In the RSI configuration, SPL spectra appear very similar to LST, except for the number and height of detectable peaks. Peaks at even BPF harmonics are higher than those at odd harmonics, consistent with the fact that rotor-stator interaction may excite only BPF harmonics whose order is a common multiple of z_S and z_R due to destructive acoustic interference [**?**]. In the present case, $z_S = 2z_R = 18$, so only even BPF harmonics should be present. Peaks at odd BPF harmonics are related to large-scale turbulent structures, which persist since no TCS is used in the LST configuration.

For these two configurations, the difference in SPL at the first BPF is nearly 4 dB. Actually, no difference should be expected, and the likely reason is acoustic effects that will be explored further. At high frequency, broadband noise appears scarcely influenced by stator presence, as spectra are nearly coincident for $f > 3$ kHz.

In the TW configuration, spectra are modified with sharper peaks. This is somewhat surprising since the only geometric difference is the mounting panel size. The broadband portion of the spectrum across the entire frequency range is slightly lower than in LST and RSI configurations, consistent with the presence of TCS which reduces both large- and small-scale inlet turbulence, thereby decreasing leading edge noise from the latter. A bump of about 7 dB appears in the range 500 Hz $< f <$ 700 Hz, likely due to von Kármán vortex shedding from the bar. Compared to previous configurations, the overall spectral behavior in TW is less regular.

In the TGF configuration, the cylindrical duct modifies both incoming flow and tip-gap flow patterns. The strong modification in the blade tip region results in a substantial increase of the entire SPL spectrum below 4 kHz. Compared to the other three cases, a growth of nearly 10 dB occurs. Peaks at BPF harmonics are largely reduced due to TCS presence, while new local maxima appear at frequencies slightly lower than BPF harmonics: characteristic values are approximately $St = 7.2, 15, 23.2, 32.4$, and 41.2 (between 0.82 and 0.89 times BPF). These new peaks result from recirculating flow from the tip-gap and associated flow structures impinging on the rotor at frequencies lower than BPF and harmonics due to positive pre-rotation [**?**, **?**, **?**]. For $f > 4$ kHz, peaks disappear and the typical asymptotic trend is recovered. The increase in the broadband portion is likely due to small-scale turbulence in the recirculating flow increasing leading-edge noise. In the high-frequency portion, broadband noise differs only slightly from LST and RSI configurations, and asymptotic trends are only marginally different.

While information inferred from SPL spectrum analysis is important and may allow evaluation of fan acoustical behavior, in many applications fans operate at variable speed. Transferring results obtained at one Ω to other rotational regimes is not straightforward. Furthermore, differences between test environment geometry or actual operating conditions may result in spectral differences.

Scaling of the Constant-Ω SPL Spectra

To evaluate scaling possibilities, SPL from measurements at $\Omega = 2400, 2700$, and 3000 r/min were scaled according to Eq. (3) (Fig. 5 [Figure 5: see original paper]), using $\beta = 1$. To allow comparison of scaled spectra, SPL_{scaled} was plotted versus St.

In both LST and RSI cases, with the exception of some peaks and limited portions, the three curves for different Ω collapse within a band of about 3 dB width. In the TGF case, dispersion is slightly larger, but many portions show poorer collapse.

In the TW configuration, broadband portions are spread across a broader range (up to 6 dB), and peaks show very significant dispersion, reaching up to 15 dB at the first BPF harmonic.

This discussion demonstrates that the scaling procedure, though simple and useful, can easily become misleading. Reasons may be twofold: first, using a single scaling exponent for the entire spectrum may be incorrect since different noise generation mechanisms may scale differently; second, strong propagation effects may substantially modify received noise, impairing velocity scaling capability.

Description of the SPL During Speed Ramps

Better insight can be gained using D_n from Eq. (4) evaluated at relevant St values. D_n can be represented in contour plots as a function of St and Ω (Fig. 6 [Figure 6: see original paper]). A noise generation mechanism is generally characterized by a fixed St, while propagation effects occur at fixed frequency. In such plots, an $f = \text{const}$ line is a hyperbola of equation $St = 60f/\Omega$, but becomes a straight line $\log(St) = \log(60f) - \log\Omega = \text{const} - \log\Omega$ in bi-logarithmic plots. Thus, propagation phenomena appear as inclined strips, while noise generation mechanisms appear as vertical ones.

In the LST configuration, a D_n valley at $f = 180$ Hz indicates probable propagation effects, possibly due to the test environment. Similarly, in the RSI case, a valley appears at $f = 270$ Hz. In the TW configuration, an analogous feature occurs at $f = 400$ Hz. Unlike previous cases, this valley is very deep: a strong reduction (more than 10 dB) at the first BPF harmonic occurs in the range $2400 < \Omega < 2700$ r/min. In the TGF configuration, a valley at $f = 500$ Hz and a crest at 900 Hz are present. The first reduces D_n by nearly 5 dB, while the second increases it by approximately 7 dB.

Analysis of D_n distributions for all configurations suggests interesting considerations about the scaling process. Fixing Ω means cutting the contour plots along a horizontal line. If propagation effects are present, the $\Omega = \text{const}$ line will intersect inclined strips, and in crossing regions both measured and scaled SPL will be affected by uncertainties that may impair correct evaluation of noise generation mechanism dependence on Ω. Examples can be found in Fig. 5 for RSI and TGF cases. Particularly in RSI, for $\Omega = 2400$ r/min at $St = 180$, a small bump appears in the SPL_{scaled} spectrum. As rotational speed increases, the bump moves to lower St values ($St = 150$ for $\Omega = 2700$ r/min and $St = 120$ for $\Omega = 3000$ r/min). In the TGF case, similar behavior occurs in the range $60 < St < 90$.

Such contour plots provide an immediate and reliable method for qualitative analysis. However, for quantitative analysis, representing D_n as curves may be more appropriate.

For example, Fig. 7 [Figure 7: see original paper] shows curves representing scaled SPL at the first six BPF harmonics for LST, RSI, and TW configurations. In the TGF case, curves correspond to the five previously identified tonal peaks at approximately $St = 7.2, 15, 23.2, 32.4$, and 41.2 (indicated as DI-DV respectively). The D_n curves are represented as functions of $f = St\Omega/60$. For each configuration, the propagation function $G(f)$ is also reported. The D_n curves are typically affected by random errors of several dB, introducing undesired point-to-point fluctuations that obscure trends. Hence, a 5-point running average was employed for smoothing. It is also worth noting that in the adopted spectral decomposition method [**?**], most employed spectral data relate to broadband noise. Consequently, the evaluated propagation function primarily depends on the broadband portion of the SPL spectrum and typically shows a smooth trend when plotted versus f.

Generally speaking, $G(f)$ is related to the Green' s function evaluated at the source location [**?**]. Thus, G may depend on source position on the blade, and different noise generation mechanisms may be associated with different $G(f)$. Particularly, for noise sources distributed across the entire blade surface, some spatial averaging of the Green' s function may be expected. As a result, tonal noise may be affected by a propagation function different from that related to broadband noise.

Considering that during a speed ramp a tonal component sweeps the acoustic transfer function of the system [**?**, **?**], D_n may be regarded as a portion of the propagation function associated with a constant-St generation mechanism. Since D_n curves are defined up to a constant and exponent (see Eq. 4), a trial-and-error procedure is needed to attempt collapsing the D_n curves onto each other and onto $G(f)$. If a unique propagation function exists, a unique trend can be found between the D_n curves and $G(f)$.

In the LST configuration, D_n curves can be clearly superposed on $G(f)$. This behavior indicates that for this configuration, the active tonal noise generation mechanism and broadband noise are influenced by the same propagation function. Indeed, large-scale turbulent structures impinge on all blades at random positions, so the resulting tonal noise generation mechanism likely exhibits spatial distribution behavior sufficiently similar to broadband noise generated continuously along the entire blade span by all blades.

In the RSI configuration, D_n curves related to odd BPF harmonics (D9, D27, D45) can be properly superposed on the broadband $G(f)$, while the D18 trend features a deep minimum at $f = 550$ Hz (nearly 10 dB lower than $G(f)$). A possible explanation is that in this configuration, odd BPF harmonic tonal noise is generated by the same mechanism as in LST (large-scale turbulent structures). In contrast, rotor-stator interaction noise is probably generated by sources well-localized on both rotor blades and stator vanes, resulting in a different propagation function from the broadband mechanism.

In the TW configuration, both $G(f)$ and D_n curves exhibit wavy behavior. A dip at 400 Hz is clearly visible, and in the range 600 Hz $< f <$ 2000 Hz, a regularly oscillating trend appears with separation between maxima/minima of nearly 200 Hz and peak-to-valley variation exceeding 5 dB. This behavior is very interesting and likely due to combined acoustic effects [**?**]: the dip is ascribed to the large circular wooden panel, while the oscillating trend results from floor presence. Thus, this geometric configuration produces strong propagation effects that can substantially impair correct evaluation of source strength, requiring careful test environment design to avoid such effects.

In the TGF case, D_n curves can be fairly superposed on $G(f)$, as in the LST case, indicating that the tip-gap flow generation mechanism behaves quite similarly to large-scale turbulent structure ingestion, at least in terms of source spatial distribution.

For completeness, comparison between different propagation functions is shown in Fig. 8 [Figure 8: see original paper]. Comparing LST and RSI curve values at $f = 450$ Hz reveals that the former is nearly 5 dB larger than the latter, explaining the difference seen in the SPL spectrum (Fig. 4) for the first BPF harmonic peak. Another interesting aspect is the oscillations of approximately 5 dB amplitude in the TGF curve at $f > 600$ Hz. This is a propagation effect probably due to the cylindrical duct, and such oscillations may explain the incomplete collapse of SPL related to tip-gap peaks.

Plots of $\phi_{18}(\Omega)$ during a speed ramp are shown in Fig. 9 [Figure 9: see original paper], considering only LST and RSI configurations for brevity. To clarify ϕ_{18} characteristics, the D18 curve for the RSI case has been added. According to the random nature of LST noise, ϕ_{18} exhibits a random trend. In contrast, for the RSI case, the D18 generation mechanism should have deterministic nature, being related to the mutual circumferential position of rotor and stator, thus expecting a linear ϕ_{18} trend. In fact, its behavior differs from expectation: two linear portions appear with a sudden decrease of about 150° between 450 and 550 Hz (i.e., between 1500 and 2000 r/min). Two reference lines with a -1.06°/Hz slope have been added, representing the typical phase trend for free-field propagation in this configuration [?]. Two bumps appear at 200 and 300 Hz, nearly coincident with oscillations in the D18 trend. In the range $450\ \text{Hz} < f < 550\ \text{Hz}$, a strong phase shift is identified. In the same frequency range, D18 exhibits the large dip already identified in Fig. 7, which has been related to propagation effects. Thus, analysis of ϕ_n plots provides complementary information about both the prevailing generation mechanism and acoustic effects due to the test environment and fan assembly.

Conclusions

Experimental spectral data concerning tonal noise generated by an axial-flow fan rotor operating in different configurations have been compared to provide methods for discriminating between different tonal noise generation mechanisms. A set of easily obtainable acoustic quantities—namely constant-Strouhal number SPL and phase—have been presented, which also allow identification of propagation effects due to the test environment. The fan was operated at free-discharge conditions in four geometric configurations designed to activate four different tonal noise generation mechanisms: large-scale turbulent structures, tip-gap flow, turbulent wakes, and rotor-stator interaction. These configurations also introduce different acoustic propagation effects that influence SPL spectra differently. Measurements were conducted in a hemi-anechoic chamber during low-acceleration rotational speed ramps and at constant rotational speed.

Analysis of conventional SPL spectra collected at constant rotational speed allows identification of basic features of different generation mechanisms. Unfortunately, in many applications fans operate at variable speed, and caution must be exercised when extending results obtained at one rotational speed to other regimes. Furthermore, acoustic properties of the operating environment may differ from testing conditions.

Analysis of constant-speed scaled SPL indicates that scaling procedures may lead to erroneous conclusions, especially for quantitative analysis, since propagation effects cannot be eliminated. Conversely, acquiring acoustic pressure during speed ramps allows computation of SPL at fixed Strouhal number, which is usually related to a single noise generation mechanism. Once scaled, this provides quantitative information about tonal noise generation mechanisms and reveals how propagation effects can impair correct evaluation of noise source dependence on rotational speed. Finally, the phase angle of the acoustic pressure FFT provides further information about both the random or deterministic nature of the prevailing generation mechanism and the presence of propagation effects.

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Note: Figure translations are in progress. See original paper for figures.