Aerodynamic noise from cooling and HVAC systems

Features important to land vehicles in urban traffic conditions

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Abstract—The present paper deals with the aerodynamic noise generated by cooling and HVAC systems employed in land vehicles. After a brief description of the physical origin of aerodynamic noise, the features important to system engineers dealing with fans installation and operation are considered. First, the main scaling laws useful to estimate the sound level spectrum are reported. Then, the main characteristics of the sound pressure level spectrum are related to the typical aerodynamic generating mechanisms and to the quality of the perceived sound, and some guidelines for noise reduction are listed. Finally, a method for the employ of results obtainable from laboratory tests is proposed which aims to identify the origin of annoying fluctuations in the received noise.

Keywords—*fan noise prediction, HVAC and cooling system noise*

I. INTRODUCTION

Noise emissions from land vehicles strongly depend on the operating conditions: generally, at high speed, rolling noise is the prevailing mechanism, at high loadings, internal combustion engines are the main cause of noise but, in urban environment, stop-and-go is a very common condition. In the latter case, the aerodynamic noise generated by fans employed by cooling and HVAC (Heating, Ventilation, Air Conditioning) systems is the prevailing one. Thus, aerodynamic noise is directly connected to acoustic pollution as well as to comfort of passengers and, for this reason, it is surely an aspect to be taken into account when dealing with high traffic density conditions and high events rate.

Two different aspects make the problem crucial:

- regulations and market requirements act in the direction of decreasing noise emissions, thus suggesting that in the next future noisy vehicles may be subjected to traffic restrictions in some specific environment, but
- performance and vehicles room optimization act in the opposite direction: higher thermal loading and less room for fans result in more performing, higher rotational speed fans, more critical in terms of noise emissions.

Furthermore, the electric motors driving such fans may easily consume kilowatts of power, also resulting in important energy related issues. From this point of view, it should also be noticed that standard solutions for noise abatement, such as silencers and shielding cannot be employed since they would result in too high pressure losses given the large volume flow rates. Up to a certain extent, limitation of the noise emissions may be achieved by means of correct installation criteria, but the best action is a careful aerodynamic design of the fan blades, to be done during the design stage. Unfortunately this is a difficult task, since noise reduction often results in a decrease of both fan performance and efficiency.

Since the radiated noise depends on fan design, installation and operation, it is clear that a wide number of different subjects, from aerodynamicists to final users are potentially interested in the noise prediction and reduction. The present paper is aimed at providing non-experienced system engineers and users with the relevant information on the topic.

II. SOME THEORETICAL BACKGROUND

A. Physical Origin of the Aerodynamic Noise

Aerodynamic noise may be defined as noise due to fluid flow in presence of disturbances (typically instantaneous velocity fluctuations) in the air flow and in absence of vibrations of solid parts. It may be generated either by turbulence within the fluid flow or by pressure fluctuations on the boundary surfaces. The problem is under study since many decades and the theoretical explanation for the aerodynamic noise generation is clear [1, 2]: the radiated sound is controlled by an inhomogeneous wave equation, a linear PDE (Partial Differential Equations) whose source terms are aerodynamic in nature. At least in principle, due to linearity, many methods of solution for the wave equation exist. In fact, the difficulty lies in the source term which is usually hard to be computed, since Aerodynamics is controlled by strongly non-linear PDE with very complex boundary geometry.

Pressure fluctuations on the blades surface (both stationary and rotating ones) constitute the generating mechanism relevant

to cooling and HVAC systems, which are characterized by low flow velocity comparing with the speed of sound (low Mach number). The causes of such fluctuations are mainly due to:

- 1) installation: presence of bodies or ducts causing non-axisymmetries or turbulence in the incoming flow (e.g. upstream heat exchangers, duct bends, sharp edges, screens);

Fig. 1. OASPL scaled with D .

- 2) characteristics of the fan itself: turbulence in the blade trailing edge region, interaction between neighboring rotor and stator bladings, leakage at the blade tip which causes flow re-ingestion.

As said, the difficulty in aerodynamic noise prediction lies in the difficulty in predicting the flow fluctuations. In fact, from the physical point of view, Aerodynamics and Acoustics may be considered simplifications of a unique problem of Fluid Mechanics and methods aimed at a full solution are currently under study [3]. The drawback of such methods are the large CPU requirements and computing time, which presently make such an approach unpractical for many technical applications. Therefore, traditional approaches are still currently used, both in the design and in the installation phases. Such approaches employ a mix of simplified theoretical models and empirical information. Experiments in anechoic chambers on fans models or prototypes are of great importance too.

B. Applications of the Similarity Theory

Let us consider a fan with an external diameter D , rotating at a speed Ω [rad/s] and operating on a volume flow rate Q [m³/s] of air at a temperature T_0 [K] and density ρ_0 [kg/m³]. As a result, the air pressure increases of Δp [Pa] with an efficiency η and, at a distance r , an OASPL [dB] (OverAll Sound Pressure Level) is received which is given by

$$\text{OASPL}(r) = 10 \log_{10}(p_{\text{rms}}/p_{\text{ref}})^2 \quad (1)$$

where p_{rms} is the rms value of the received acoustic pressure and $p_{\text{ref}} = 20 \mu\text{Pa}$. The similarity theory allows to transfer the results of experiments or predictions related to a fan of given

geometry to another fan with a similar geometry, but different in size and/or rotational speed and/or air density. Similarity allows to establish a correspondence between points of two characteristic curves related to same quantities, e.g. Δp , η , $\text{OASPL} = f(Q, \Omega, \rho_0, T_0, D)$. Let us introduce the non-dimensional flow and head coefficients $\Phi = Q/(\Omega D^3)$ and $\Psi = \Delta p/(\rho_0 \Omega^2 D^2)$ and consider a second fan, geometrically similar and characterized by D' , Ω' , Q' , T'_0 , ρ'_0 , $\Delta p'$, η' and $\text{OASPL}'(r')$ received at a distance r' . If the second fan operates at similar conditions, i.e. if $\Phi' = \Phi$, then $\Psi' = \Psi$, $\eta' = \eta$, $Q' = Q \times (\Omega' D'^3)/(\Omega D^3)$ and $\Delta p' = \Delta p \times (\rho'_0 \Omega'^2 D'^2)/(\rho_0 \Omega^2 D^2)$. Most of all

$$\begin{aligned} \text{OASPL}' &= \text{OASPL} + 10 \log_{10}[(\rho'^2_0 \Omega'^4 D'^6)/(\rho^2_0 \Omega^4 D^6)] \\ &+ 10 \log_{10}[(Ma'^\alpha/Ma^\alpha) - 10 \log_{10}(r'^2/r^2)] \end{aligned} \quad (2)$$

with $\alpha \cong 1$ if noise is due random phenomena and $\alpha \cong 2$ if noise is due to deterministic phenomena. $Ma = \Omega D/2a_0$ is the Mach number based on the blade tip velocity $\Omega D/2$ and a_0 is the speed of sound at the temperature T_0 ($a_0 \propto T_0^{0.5}$), about 340 m/s at ambient conditions. (In fact, this is a simplified scaling, because a deeper analysis would bring to slightly different values for the exponents to be employed for Ω and for D .) An alternative expression may be obtained expressing the ratio $[(\rho'^2_0 \Omega'^4 D'^6)/(\rho^2_0 \Omega^4 D^6)]$ as a function of Q , Δp , Q' , and $\Delta p'$ and considering that $\Phi' = \Phi$, and $\Psi' = \Psi$:

$$\begin{aligned} \text{OASPL}' &= \text{OASPL} + 10 \log_{10}[(\rho_0'^{0.5} \Delta p'^{1.5} Q'^6)/(\rho_0^{0.5} \Delta p^{1.5} Q^6)] \\ &+ 10 \log_{10}(\Delta p'/\Delta p \times \rho'/\rho_0)^{0.5\alpha} - 10 \log_{10}(r'^2/r^2) \end{aligned} \quad (3)$$

Application of similarity to noise generated by low-speed fans is reviewed in [4] while applications to performance is a classic subject, see for instance [5] pp. 1-12. Strictly speaking, Eqs. (2) and (3) apply to (geometrically) similar fans only. In practice, they may be employed for rough estimations of the noise generated by non-similar fans if their specific speeds n_s at the design operating point are sufficiently close ($n_s = \Omega_{\text{des}} Q_{\text{des}}^{0.5}/(\Delta p_{\text{des}}/\rho_0)^{0.75} = \Phi_{\text{des}}^{0.5}/\Psi_{\text{des}}^{0.75}$). Instances of OASPL scaling, taken from [6], and related to three geometrically similar fans, of different D and rotating at different Ω , are shown in Fig. 1. These plots show that the expected dependence is respected with a good approximation.

Another important quantity is the SPL spectrum, i.e. the level computed by means of Eq. (1), in which p_{rms} is to be substituted by $(p_{\text{rms}})_k$, the rms value related to a frequency band Δf_k about a central frequency f_k :

$$\text{SPL}_k = 10 \log_{10}[(p_{\text{rms}})_k/p_{\text{ref}}]^2 \quad (4)$$

Typically, two different kinds of bands are employed: constant-width bands (useful for detecting peaks related to tonal components) and one-third octave bands (useful for synthetically representing smoother spectra). In the former case, $\Delta f = 25$ Hz or less, while in the latter case $\Delta f_k = 0,232 f_k$ with $f_k = 2^{(k-1)/3} f_1$ and $f_1 = 16$ Hz. Scaling of constant-width spectra is straightforward: considering two geometrically similar fans operating at the same Φ (and thus at the same Ψ), it may be shown that the scaled-SPL, defined as

$$\begin{aligned} (\text{SPL}_{\text{scaled}})_k &= 10 \log_{10}[(p_{\text{rms}})_k r^2 / (\rho_0^2 \Omega^3 D^6 Ma^\alpha)] = \\ &= \text{SPL}_k - 10 \log_{10}[(\rho_0^2 \Omega^3 D^6 Ma^\alpha / r^2) / p_{\text{ref}}] \end{aligned} \quad (5)$$

is independent of D , Ω , T_0 , ρ_0 when plotted versus the Strouhal number (non-dimensional frequency)

$$St_k = 2\pi f_k / \Omega \quad (6)$$

This holds for the continuous part of the SPL spectrum, while the tonal noise peaks scale with Ω^4 and, possibly, with a different value of the exponent α .

Fig. 2. Comparison of the scaled SPL spectra related to the three rotors. (a): Ω scaling, (b): Ω and D scaling.

The SPL spectra reported in Fig. 2, taken from [6], are relative to three similar fans and are scaled according to Eqs. (5-6); these plots provide an evaluation of the extent up to which the scaling law is respected. SPL spectra related to a single fan

rotating at different Ω , Fig. 2a, respect the expected dependence very well, while the dependence on D , Fig. 2b, is clear but some differences are present at the intermediate frequencies. Finally, to show how the operating point influences the SPL spectrum, spectra related to a single fan operating at 4 different Φ values (0.17, 0.21, 0.24, 0.27) are reported in Fig. 3. The plots show that, as the flow rate decreases and the pressure rise increases, the SPL spectra increase in the low to middle frequency range (below 3 kHz), while the high frequency part and the tonal noise peaks remain almost unchanged.

III. IMPORTANT PRACTICAL ASPECTS

A. Generating mechanisms and shape of the SPL spectrum

The active noise generating mechanisms have a clear correspondence in the constant-bandwidth SPL spectrum [6, 7]:

- Self-generated turbulence on the blade surface results in a smooth spectrum (“broadband”) at middle to high frequency range; this is the trailing-edge noise and constitutes a lower limit to noise radiated by a given blade [9].
- Small-scale inlet turbulence, typically due to upstream screens or grids, results in a smooth spectrum at low to middle frequency range [10].
- Large-scale turbulence at the rotor inlet, typically due to localized, slow velocity fluctuations, results in tonal noise peaks at BPF (blade passing frequency) and harmonics, usually in the low frequency range. Boundary layers developing on the upstream duct walls, as well as wakes due to far away upstream bodies, may be the cause for such a kind of noise [9, 10].
- Steady circumferential distortions of flow velocity, due to large bodies (obstructions, struts or stator blades for a rotor, and rotor blades for a stator) adjacent to a blading in relative motion, cause sharp tonal noise peaks at BPF and harmonics, usually in the low to medium frequency range. This kind of mechanism is often called aerodynamic rotor-stator interaction [11, 12] and is correlated with the rotor angular position. For this reason it may be considered deterministic.
- Flow leaking through the blade tip is usually re-ingested by the rotor and results in bumps or in noise peaks about BPF and harmonics, similarly to the ones due to large-scale inlet turbulence [14].
- Flow separations on the blade surface or at the rotor endwalls (hub and shroud) usually result in important contributions in the low-frequency range [14, 15].

Roughly speaking, in most of cases, the major contribution to the OASPL is due to the first and second mechanisms while the fourth one is often the major cause of annoyance but only sometimes is the strongest one. The last mechanism is typical of

low flow rates, off-design operating conditions. From the analysis of the SPL spectrum, it is often possible to identify the kind of noise source. Anyway, identification of the source location and related cause is a further problem which requires much deeper insight, and is the first step towards reduction of the radiated noise. The above listed features are highlighted in the spectra of Fig. 3.

Fig. 3. Effect of the flow rate on SPL spectrum.

B. Installation and operation of a fan versus noise emission

The radiated noise depends on the fan aerodynamic design (mainly the blade geometry and, if a stator is present, also on the axial distance from the rotor) and production precision too. Then, an accurate aerodynamic study has to be carried out during the design phase, which usually results in non-radially stacked blades profiles [9]. Particular solutions such as uneven circumferential blades spacing [17] and rotating shroud [18] are typically used to modify and/or decrease the radiated SPL spectrum. Blade numbers and rotor-stator axial gap are also important [11, 18]. Peculiar blade geometries such as serrated blade trailing edges may also be encountered. As with all problems regarding noise, even small details not affecting performance may render a fan quite noisy. Anyway, these aspects are of concern of the designer and are out of scope to the present work, where existing fans are concerned. In such a case, the problem becomes avoiding installation and operation errors which may let the fan radiate stronger noise.

As far as operation is concerned, the only indication is avoiding the fan working far from the design point, especially lower Q (i.e. higher Δp) than design one. A wrong installation may be the cause of strong annoyance and SPL increase. Basically, in order to avoid excess noise radiation, the incoming flow must be uniform, smooth and steady. To this aim, first, the upstream duct should be short, axisymmetric, and without grids, screens, bends, sudden section variations and sharp edges. If obstacles cannot be avoided, as a general rule, it may be stated that they should be as far as possible from the fan; alternatively, as far as pressure losses are not excessive, flow straighteners may be a solution. It is interesting to notice that an upstream heat exchanger, though generating small-scale turbulence at the fan inlet, may act as a flow straightener, thus destroying possible incoming large-scale turbulent disturbances and reducing the

tonal noise components. Hence, as far as noise issues are concerned, a fan downstream of a heat exchanger may constitute a better solution than an upstream one. No obstacles should be present close to the upstream duct mouth since they could break the flow axisymmetry as well as creating large-scale disturbances. Such aspects are treated in [6, 7, 19].

However, the above listed guidelines are related to the aerodynamic effects of the fan installation, but acoustic effects, such as diffraction and shielding may take place as well, which have important influence on the received noise. These effects are part of the propagation effects, which include all possible interactions between acoustic waves and solid bodies within the acoustic field (ranging from rotor blades, heat exchangers, ducts, engine, and other parts inside the underhood compartment). These aspects will be deepened in chapter IV.

C. Shape of the SPL spectrum and annoyance issues

When dealing with low-speed fans, the OASPL received by listeners hardly exceeds 80 dB and is thus of no harm. Rather, it is usually cause of annoyance, thus affecting quality of life. Annoyance is not directly related to the OASPL, but depends on sound quality, i.e. on not easily quantifiable factors, related to the characteristics of the human auditory system. These factors may be related to the shape of the SPL spectrum and are often included by the user in the fan specifications together with performance and efficiency.

First, the SPL measured by instruments must be corrected to account for the dependence of human hearing on frequency: sensitivity is maximum about 1 to 6 kHz and decreases at the lower and higher frequencies. To this purpose, the so-called A-weighting is commonly employed and constitutes a frequency dependent correction curve to be added to the measured SPL. As a result a perceived relative *loudness* is obtained. Anyway, spectrum properties other than *loudness* are important to annoyance: the sources which mostly contribute to *loudness* are small-scale inlet turbulence and self-generated turbulence, but, even in cases it is less strong, tonal noise may be cause of stronger annoyance. Indeed, the features relevant to sound quality are: (1) the presence of pure tones, i.e. of peaks in the SPL spectrum, and their importance comparing with the broadband part in the neighboring frequencies, i.e. within a one-third octave band; (2) the frequency distance of pure tones; and (3) the relative importance of high frequency noise comparing with the low frequency one. Beyond *loudness*, these aspects are evaluated by means of quantities called *psychoacoustic metrics*, computed by specific algorithms starting from constant-bandwidth SPL spectra. For reasons of space only the main quantities are listed here and the reader is addressed to the specific literature for more detailed information [21]: (1) *tonality*, *prominence ratio*, and *tone-to-noise ratio*; (2) *roughness* and *fluctuation strength*; (3) *sharpness*.

IV. IDENTIFICATION AND EVALUATION OF THE ACTIVE NOISE GENERATING MECHANISMS

A. Aeroacoustic tests

Presently, numerical predictions are not reliable enough to completely substitute experimental investigations and, anyway, their employ requires a detailed knowledge of the system geometry and flow field, which may be available to aerodynamicists but is usually beyond the possibilities of system engineers, who may have a general knowledge of Acoustics. Hence, aeroacoustic tests are commonly performed in anechoic chambers and special devices are employed to create an aerodynamic resistance equivalent to the pressure drop caused by the heat exchanger. Typical solutions are a test plenum transparent to acoustic waves [22] and an anechoically terminated duct test stand [23]. No matter the used device, it should be taken into account that the whole assembly may influence acoustic wave propagation, resulting in an a priori unknown kind of acoustic transfer function (the “propagation function”) between the fan and the microphone. Taking this into account and depending on the noise components to be investigated, two different kinds of tests may be performed:

- To investigate the broadband noise, tests at several Ω values are the best solution. Such tests yield standard SPL spectra, similar to the ones reported in Figs. 2-3. Indeed, the typical frequency scale of the generated noise depends on Ω , while the typical frequency scale of the propagation function depends on a_0 . Then, varying Ω at constant a_0 allows to separate the two different effects. This is typically performed by means of the spectral decomposition technique [23, 24].
- To investigate the tonal noise, tests performed during constant angular acceleration speed-ramps are better suited, since they allow to study with a high resolution the trend of tonal noise peaks as Ω varies. Such tests yield plots of SPL_n , the SPL at the n -th BPF harmonic. Indeed, the tonal noise peaks may be viewed as pure tones of regularly growing intensity and frequency, which sweep the system propagation function. The relation between constant- Ω spectra and SPL_n is shown in Fig. 4, taken from [26]. This aspect is of specific interest since, due to the features of modern brushless electric motors, as the cooling system is switched on by the engine temperature controller, tones of irregularly growing strength can be heard, which may be cause of annoyance.

B. Identification of tonal noise generating mechanisms and of superposed propagation effects

As seen in chapter III, tonal noise, though less strong than the broadband one, is often the most important cause of annoyance. Opposite to the latter, tonal noise may be due either to random mechanisms (large-scale inlet turbulent structures) or to

deterministic ones (aerodynamic rotor-stator interaction), both resulting in similar SPL spectral properties, i.e. peaks at the BPF harmonics. Though difficult, it is useful to distinguish between different kinds of tonal noise: for example, noise control may be more easily performed if noise is correlated to the rotor angular position. A possible method to distinguish between the two mechanisms, [19], is based on the analysis of the phase angle of the acoustic pressure Fourier transform, relative to an one-per-revolution reference signal, and measured during speed ramps. Such a method is based on the fact that SPL spectra computed during speed ramps may be considered as related to independent realization of the same phenomenon. Thus, if noise is generated by a random process (turbulence), then the trend of the phase angle with Ω must be random. On the contrary, if noise is due to rotor-stator interaction then it is characterized by a deterministic trend, linear in the simplest case where propagation effects are negligible, and more complicated otherwise. Similar trends, related to the 2nd BPF harmonic of a 9 blades rotor ($n = 18$) are shown in Fig. 5, taken from [25]. Two cases are shown: a case where inlet turbulence is the dominating mechanism, NS-NB, and a case where the dominating mechanism is rotor-stator interaction, S-NB. Fluctuations in SPL_n during speed ramps, i.e. irregular growth instead of the continuous increase with Ω predicted by Eq. (5), are often cause of annoyance and, in order to eliminate them, it is important to understand their origin, i.e.

Fig. 4. Correspondence between constant- Ω spectra and SPL_0 .

whether they depend on the fan (fluctuations of the generating mechanism and, up to a lower extent, varying propagation effects due to the fan acoustic properties) or on variations of the propagation function part dependent on the installation environment.

Propagation effects due to fan parts are usually of lesser importance and are unavoidable unless the design is modified. Thus, they are mainly relevant to the fan designer. On the contrary, the system engineer who chooses and installs the fan is usually interested in the acoustic effects of installation. To this purpose, one may scale SPL_n with $10\log_{10}\Omega^{4+\alpha}$ and then plot the curves related to different harmonics, i.e. to different n values,

versus $f_n = n\Omega/2\pi$, the frequency of the tone at the n -th BPF harmonic at a given Ω . If shifting the obtained scaled SPL_{*n*} curves along the y-axis allows them to collapse on a single curve, then the observed fluctuations are independent of Ω , i.e. they do not depend on the generating mechanism and may be modified acting on the propagation environment.

Fig. 5. Comparison of the phase angle at the 2nd BPF.

Fig. 6. OASPL and SPL at 1st, 2nd, and 3rd BPF.

An example of such a procedure is reported in [27]: in Fig. 6 the trends of SPL_{*n*}, $n = 9, 18, 27$ (1st, 2nd and 3rd BPF harmonics) are plotted versus Ω , and in Fig. 7 these trends are scaled with $10\log_{10}\Omega^{4+\alpha}$ and then plotted versus f_n . These plots show that the curves collapse fairly on a single curve, thus confirming the

Fig. 7. Scaled SPL (D_n) at 1st, 2nd, and 3rd BPF.

assumption that the fluctuations are independent of Ω and then

are due to propagation effects. Furthermore, if noise is due to rotor-stator interaction the trend of the phase angle with Ω provides information on the importance of propagation effects: a local linear trend (i.e. saw-tooth like) indicates that propagation effects are negligible in that frequency range and viceversa. As an instance, in Fig. 8, the trends of the scaled SPL₁₈ (2nd BPF harmonic) and the corresponding phase angle, taken from [26], are plotted together, showing that a rather constant scaled SPL_{*n*} corresponds to a linear trend of the phase angle. The opposite happens in case propagation effects are important, Fig. 9.

Fig. 8. Scaled SPL (D_{18}) and phase angle at 2nd BPF.

Fig. 9. Scaled SPL (D_{18}) and phase angle at 2nd BPF.

V. CONCLUSIONS

The present paper provides fan users and system engineers with the relevant information concerning prediction and evaluation of laboratory tests of the acoustic emissions from low-speed fans employed in cooling and HVAC systems. First, the main features of the aerodynamic noise are described together with basic criteria for noise prediction; then, some guidelines for noise reduction from existing fans are provided. Second, the main noise generating mechanisms are described in connection with their spectral properties and resulting annoyance for the human auditory system. Finally, the typical laboratory tests are described together with some techniques for experimental data analysis,

useful for identifying noise properties due to installation effects, on which system engineers may act.

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