Reducing Low Frequency Noise (LFN)

Past and future technologies

This paper examines the escalating issue of low-frequency noise (LFN) pollution, which predominantly originates from man-made sources, contributing significantly to sleep disturbances and other health risks. The focus is on the evolution and efficacy of various noise reduction technologies, particularly those designed for fans. Techniques ranging from passive mufflers and geometric blade modifications to advanced materials are discussed. Additionally, the paper introduces an innovative solution, the Anechoic Broadband Compact (ABC) muffler, specifically designed for the HVAC industry (heating, ventilation and air conditioning), offering significant potential in mitigating LFN across a broad spectrum of frequencies.

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Introduction

Noise Pollution (NP) is a significant global issue. According to a report by the European Heat Pump Association (EHPA) and WHO, the most profound effect of noise pollution is the loss of sleep [1,2]. Noise from highways, airplanes, wind turbines, heavy industries and construction activities significantly disturbs residents near these sources. Low frequency noise (LFN) is variably defined across different sources. RIVM categorizes LFN as sound between 20 Hz and 100/125 Hz [3]. LFN mainly originates from man-made sources like heat pumps, ventilation systems, traffic, and (wind) turbines. As industrialization continues to expand, there has been an increase in both the sources of LFN and the complaints regarding it. Notably, since 2016, RIVM has received more reports of LFN than of regular noise [3]. Many devices emit noise in frequency range of 20-1000 Hz, which significantly impacts both device performance and public acceptance.

For example, heat pumps, with their main noise sources being the fan and compressor, typically produce noise between 70-300 Hz. Similarly, wind turbine noise, typically ranging from 20 to 400 Hz, is particularly bothersome due to its heightened annoyance factor compared to higher-frequency noise [4,5] worries have emerged that the turbine noise would move down in frequency and that the low-frequency noise would cause annoyance for the neighbors. The noise emission from 48 wind turbines with nominal electric power up to 3.6 MW is analyzed and discussed. The relative amount of low-frequency noise is higher for large turbines (2.3-3.6 MW. Such annoyance may lead to complaints, public opposition, and potential legal challenges, hindering the expansion of green technologies like wind power projects and heat pumps. Furthermore, the perception of LFN as more irritating poses health risks to nearby residents, including sleep disturbances, stress, and potential cardiovascular and cognitive effects.

Traditional Low Frequency Noise Reduction techniques

In the state of the art for noise reduction, particularly concerning fans, researchers have explored numerous innovative approaches, utilizing a broad array of design solutions. These include traditional passive mufflers with Helmholtz and quarter-wave resonators attached to the fan housing [6,7], as well as geometric modifications of the blade. Additionally, researchers are incorporating acoustic absorbing materials such as fibrous, porous, reticulated, and micro-perforated materials into the fan housing. Thomas Carolus has detailed almost all the current "Design Features of Noise Reduced Fans" in Chapter 8 of his book on fans, published in 2022 [8]. For example, increasing the spacing between stationary and rotating components weakens the interaction of their potential fields, which can be expected to reduce both tonal and broadband noise [8].

The foundational patent "Low Noise Fan," by Gray [9] in 1980, introduced blade skew into the axial fan industry. Howe [10] J. Fluids Struct. 5, 33–45 (1991 was among the first to recognize the potential of a serrated trailing edge (Fig. 1a), aimed at mitigating trailing edge noise. The most recent research on the trailing edge has focused on the broadband noise reduction by serrated trailing edges [11]. In another study from the same university, Carpio applied porous materials at the trailing edge of the blades (figure 1), purportedly reducing noise by 6 dB [5].

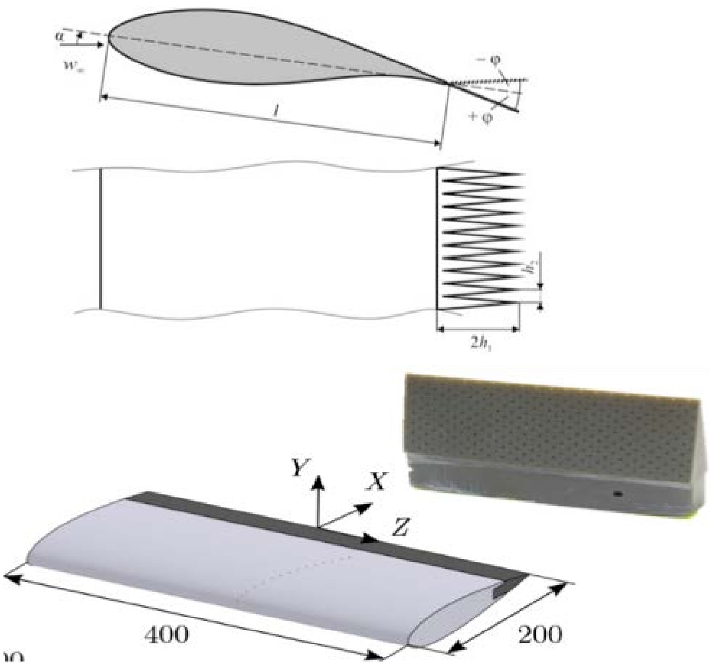

Figure 1. Mitigating trailing edge noise, photos are taken from [5] and [8].

However, much of the work prior to Howe's work involved leading edge serrations [12]. For instance, Polacsek et al [13]. investigated an airfoil segment at rest in a wind tunnel with an upstream turbulence-generating grid.

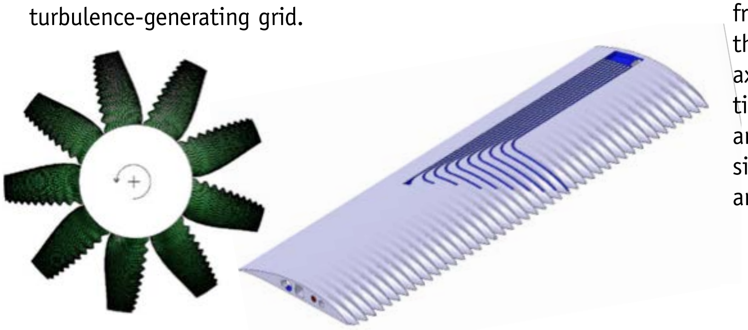

Figure 2. Mitigating leading edge noise, photos are taken from [5] and [13].

Another approach has involved so-called tandem blades (figure 3) [14,15]. Here, a gap within the blade allows a jet from the blade pressure side to the suction side, supplying additional kinetic energy to the boundary layer. However, the effect of this method on overall noise reduction is relatively minor. Bio-inspired structures with various ridged shapes for the fan blade surface (figure 3) have also been developed as potential ways to reduce fan noise, achieving a sound pressure level reduction of almost 4 dB(A) compared to the original design [16].

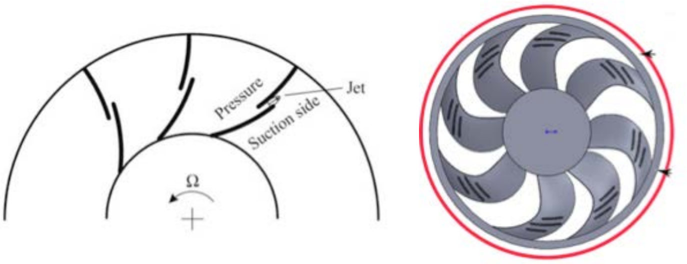

Figure 3. Blades with Tandem or ridged shapes techniques, photos are taken from and [8] and [16].

The use of metamaterials has gained considerable attention; for instance, subwavelength materials designed for integration in ducts have also successfully attenuated low frequencies in airflow channels by leveraging folded side branch tubes (see figure 4) [17]

Figure 4. Applying metamaterial on the fan housing for LFN mitigation [17]

In 1955, to improve axial flow turbine blades, they were unshrouded and feature at least one aperture located near the rotor hub wall or the turbine casing. The purpose of these apertures is to direct a portion of the operating medium from the high-energy side of the blade to its low-energy side, counteracting the edge effects in these zones in an attempt to fill up the spaces brought about by cavitation [19]. One notable patent focusing on noise reduction from the fans and compressors is from Rolls Royce in 2010, which mainly added perforations to the blade. This shroudless blade design for compressors or fans in axial flow gas turbine engines includes a treatment to the blade tips to improve the surge margin of the compressor. The tip clearance gaps provide a gas leakage path between the higher pressure side of the aerofoil and the lower pressure side. This effect is analogous to an electrical "short circuit' [20]. See also figure 5.

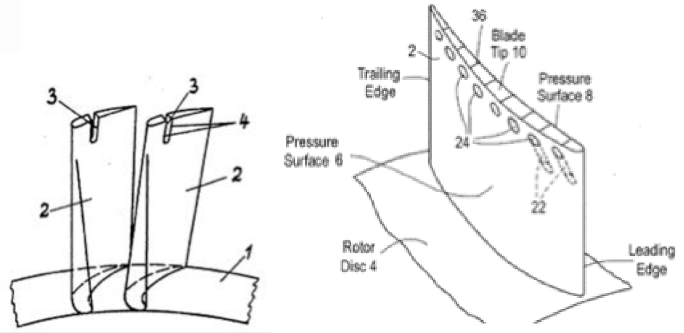

Figure 5. Applying apertures and holes on the blades, photos are taken from [19] and [20].

As shown in figure 6, a similar concept has been developed and applied to the propellers of ships, as demonstrated by the "PressurePores" technology retrofitted on marine propellers to mitigate tip vortex cavitation noise, achieving quieter propellers. This technology strategically introduces pressure-relieving holes to modify the presence of cavitation, significantly reducing the overall cavitation volume and consequently the radiated noise levels while maintaining design efficiency with minimal compromise [21]

Another work shows that the noise radiated by two flat plates in a tandem configuration in a turbulent flow is reduced at low

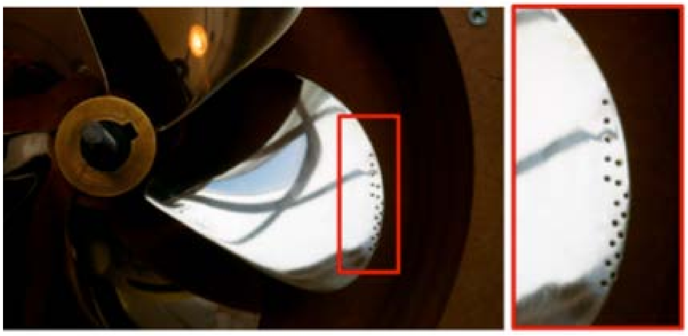

Figure 6. Applying holes on the propeller of the ship [21]

frequencies relative to a baseline aerofoil [22]. Recently, a paper from the same group has been published and highlights a fundamental experimental investigation into reducing noise caused by the interaction of a turbulent stream with an aerofoil by using a Kevlar section downstream of the aerofoil's leading edge, see figure 7. The innovative approach bridges the air gap between two flat-plate aerofoil sections with Kevlar fabric, showing that this technology can suppress additional noise penalties while still providing significant levels of noise reduction in both flat plates and thin aerofoil geometries typical of outlet guide vanes in aero-engine applications [23].

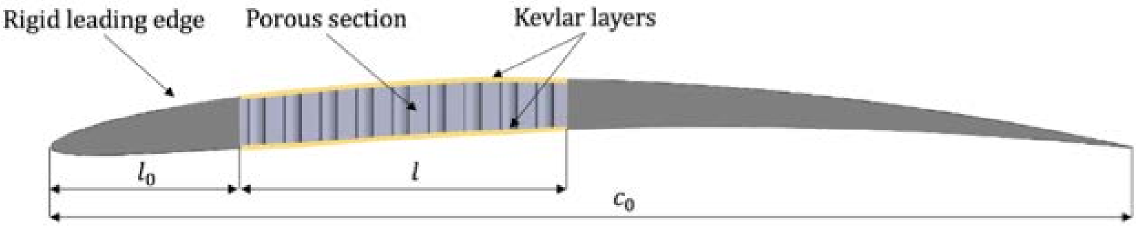

Figure 7.Schematic diagram of an aerofoil with downstream porosity and Kevlar fabric [23].

Although some companies applied these technologies on their products, there is still a LFN issue with HVAC systems like heat pumps. Heat pumps, one of the most promising technologies for high energy efficiency and long-term sustainability [2], face consumer acceptance issues due to the low-frequency noise they generate, often exceeding 50 dB(A) near facades at night. Some companies attempt to mitigate this noise by adding acoustic-absorbing material inside the covers or even adding an extra costly casing to the outside unit, see figure 8.

Figure 8: Some example of extra acoustic casing for the heat pumps.

Modern Low Frequency Noise Reduction techniques

In 2021, the Technical University of Technology (TU/e) developed a generic high-tech technology for stabilizing boilers. The patented technique [24] was integrating an anechoic muffler (silencer) to the air inlet to remove thermo-acoustic combustion instability of the boiler. Later, it was discovered that this high-tech technology could be applied to other applications to absorb noise, particularly LFN which is difficult to be absorbed by current technologies. One of the desired applications of this technique is to remove LFN from fans, which can have a huge impact on the HVAC industry. The core of this muting technology is the patented Anechoic Broadband Compact (ABC) muffler that can perfectly be applied at a wide broadband range of frequencies. The ABC muffler can operate from 20 Hz to 10 kHz; however, it can be tuned to work at a specific region of frequencies with higher absorption performance. The muffler has been designed, built, and verified by analytical solutions and numerical simulations, and it is verified by laboratory tests. The muffler has a thickness ranging from 0.2 to 2 millimeters [25]. Because of the ultra-thin size of the muffler, it can be integrated to any kind of geometry, particularly axial and centrifugal fans of HVAC systems. It can also be used as acoustic absorber inside the cover of the HVAC systems or surrounding any other kind of noise sources inside of the HVAC systems like compressors. The absorption coefficient of the muffler is between 65% to 99.9% which means it can mute the noise at any desired frequency.

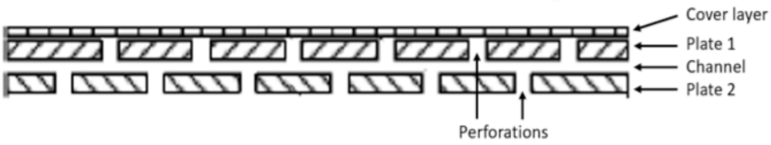

Figure 9: 2D sketch of an ABC muffler technology [25].

The primary mechanism for absorbing acoustic energy in our invention ABC mufflers is thermal and viscous losses in narrow acoustic channels. The ABC muffler has at least two perforated plates (see figure 9). The distance between layers is small enough that thermo-viscous boundary layer effects significantly impact the propagation of sound along the narrow, rigid-walled channel formed between plates giving substantial acoustic attenuation within the audio frequency range. The openings are covered with an acoustic membrane to ensure that the air velocity profile and pressure profile remain unchanged which means no efficiency changing, and to prevent any air leakage in some applications and prevent the dust in others. This attenuation is a function of Stokes's boundary layer and the channel width; the attenuation in air can exceed 16 dB/wavelength [26]

The recent application of this concept to axial fans is illustrated in Figure 10, which depicts a small axial fan (diameter: 25 cm) featuring surface perforations and acoustic tape to create the ABC muffler. Figure 10a compares the thrust measurements of the normal fan and two prototypes. The first prototype shows no reduction in efficiency, while the second prototype experiences less than a 10% efficiency reduction only at high velocities. Initial noise reduction results are promising, with an overall noise reduction of 4.0 dB(A) at 3 volts. The figure highlights that the maximum noise reduction occurs at 400 Hz, achieving a reduction of 15 dB(A) without compromising the fan's efficiency.

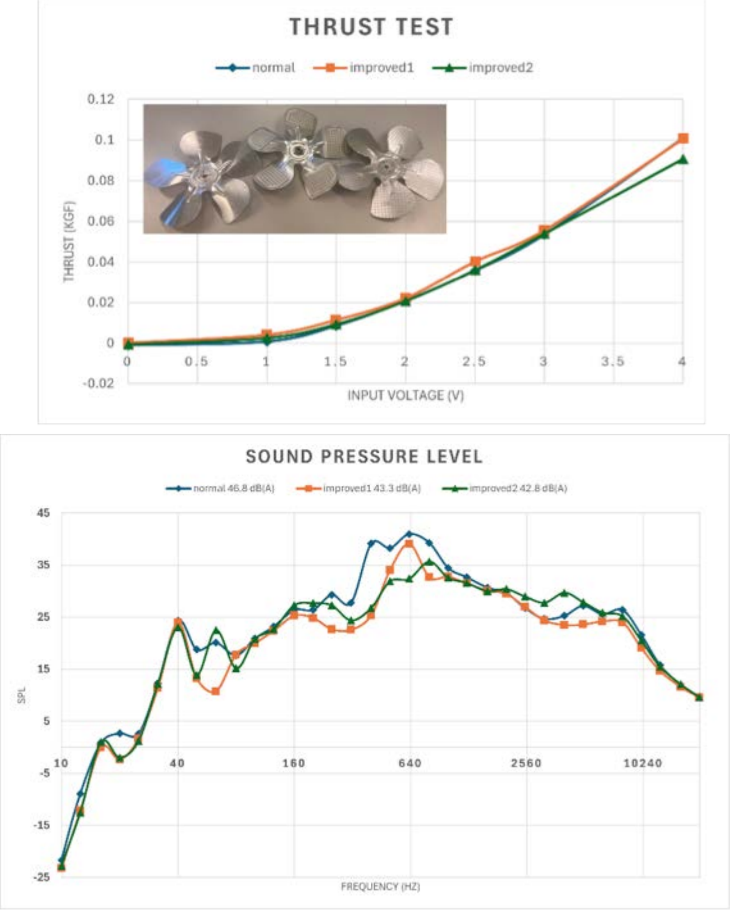

Figure 10: Primary result of applying the ABC muffler to blades of the axial fan [25].

Conclusion

This review paper outlines more than fifteen established solutions for the reduction of LFN in fans, particularly emphasizing the innovative ABC muffler technology as a promising approach. While significant strides have been made in developing effective noise reduction techniques, there is still a need for continued research to further mitigate LFN. Future initiatives should concentrate on refining the design and integration of noise reduction systems to specifically tackle the unique acoustic challenges associated with fan-generated noise. Such advancements are crucial for enhancing environmental quality and improving public health outcomes.

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