ACOUSTIC PERCEPTION OF IRREGULARLY SPACED BLADE FAN

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SUMMARY

For acousticians, noise reduction is not the unique issue considering fan noise. In application where human beings are involved (work, domestic, medical) annoyance has to be considered when evaluating the impact of a fan. Blade passing frequency is well known to be a characteristic of fan noise. It is often considered as unpleasant because of its tonal characteristics. But what happen if blades are irregularly spaced? Measurement has been performed on a test bench to compare noise levels and psychoacoustics criteria of fan with regularly or irregularly spaced blades. The paper presents the results obtained for these measurements.

INTRODUCTION

This paper presents the results of the experimental characterization of fans with irregularly spaced blades. To this end, the acoustic performance will be evaluated in a conventional manner but also using relevant psychoacoustic criteria. The airflow performances of the propellers tested were also checked to ensure that it is comparable with the reference fan.

The state-of-the-art in this area has been used to select the angles between the irregularly spaced blades of the propeller. These have been made specifically for this project.

STATE OF THE ART

Acoustics and perceptual aspects

Papers [1], [2] and [3] agree that using propellers with irregularly spaced blades does not change the overall acoustic level or only decreases it slightly. The peak of the first blade passing harmonic (blade passing frequency - BPF) is, however, reduced: [4] and [2]. The other harmonics - linked to the frequency of rotation - are increased. The sound power level of the BPF is spread across several weaker spectral lines ([2] and [3]).

Reducing a peak at a given frequency allows for a reduction in the siren noise [3], the tonal noise (emergence of almost pure sound) can even be sufficiently reduced to the same level as the unavoidable background noise. Reducing this spectral noise affects the directivity: the source of the annoying noise is not as easy to locate ([5]) but it does improve the in-cabin sound quality ([4]).

Papers [2] and [3] highlight the fact that the overall acoustic level does not change, and therefore the benefits are limited to human perception and annoyance is reduced. Dyson ([1]) conducted a more "perception"-centred study on the subject, but on smaller office fans. The tonal noise was clearly identified as being undesirable in the automotive and aeronautical industries. The psychoacoustic criteria (loudness and tonality) have been determined to be representative of the subjective preference of the operators. The A-weighted decibel level is, however, not sufficiently representative. The results of a subjective listening panel points to very clear “educational” behaviour: despite a higher sound power level, the conventional fan is preferred to the fan with irregularly spaced blades.

Aeraulic performance

The presence of a stator is responsible for the presence of spectral lines noise linked to the harmonics of the blade passing frequency. Turbulence and the non-homogeneity of the flow also increase noise, as specified in [4] and [5]. Paper [4] also points out that the turbulence that increases the BPF has no further impact on a weak BPF in the case of propellers with irregularly spaced blades.

Papers [1] [2] [3] [5] argue that spacing the blades at irregular intervals does not modify the aeraulic performance or the cooling capacity.

Balancing

A propeller, like any other rotating machine, must be balanced in order to prevent the phenomenon of imbalancing and, consequently, significant vibrations, which can be destructive for the machine. The blades must therefore be irregularly spaced in a methodical manner in order to prevent unbalancing the propeller.

The proposed and implemented solution is to maintain the center of gravity of the propeller on its rotational axis. To this end, several approaches are used:

- Use of 2 blades to center the center of gravity. For example, for a 7-blade fan, only 5 blades are irregularly spaced at a given angle. The other 2 blades are positioned in such a way that the center of gravity is aligned with the rotational axis. [4]
- Rotation of pairs of diametrically opposed, geometrically identical blades. It should be noted that the optimal angle for the asymmetrical spacing depends on the Mach number at the end of the blade. [5]
- Sinusoidal angular displacement up to 8° in respect of the symmetrical position of each blade. [1]

TEST BENCH

The tests were conducted on a test bench (Figure 1) with external dimensions of 1.08 x 1.14 x 2.5 m and equipped with an electrical 15 kW motor with a variable rotational speed of 500 to 2300 rm. It can accept propeller blades of 400 to 700 mm.

Figure 1 : Fan test bench

Prototype propellers

Fan manufacturers do not supply propellers with irregularly spaced blades. Prototype propellers were therefore manufactured. A prototype conventional propeller with regularly spaced blades was also manufactured in order to not be affected by geometrical differences that are not directly linked to the angular positioning of the blades.

The propellers and their characteristics are presented in Figure 2. The blades used are conventional blades that are mounted on prototype hubs. The angles between the blades were taken from papers [2] and [6].

Propeller	Conventional	Irregular spacing
Nr of blades	7	
Diameter (mm)	610	
Angle between blades (°)		76.6
		40.9
		45.7
	51.43	50.2
		70.9
		36.6
		39.2

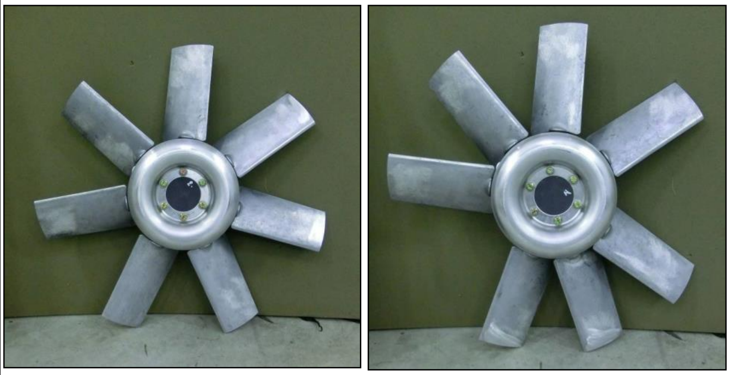
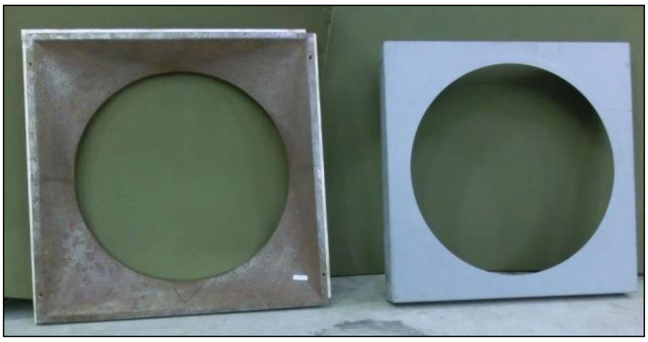


Figure 2: Characteristics of the propellers. Centre: conventional propeller – Right: propeller with irregularly spaced blades

Experimental Plan

In order to compare the propeller with irregularly spaced blades with the conventional propeller, sound measurements were taken at 4 stable speeds (800, 1300, 1800, 2300 rpm). To assess the installation effects, a diaphragm and a shell were used. 5 microphones were used to measure sound pressure (Figure 3).



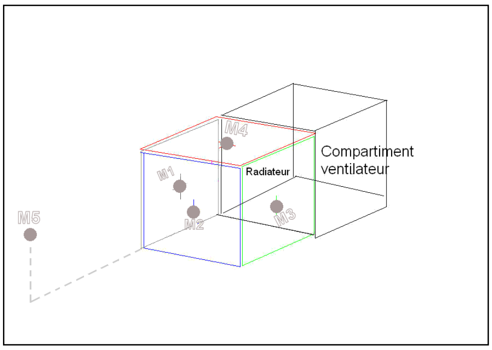


Figure 2 : Left: shell, middle: diaphragm, right: position of the 5 microphones

PSYCHOACOUSTIC CRITERIA

Three psychoacoustic criteria were chosen:

- **Tonality** allows for the re-transcription of the emergence of pure sounds within a wider-band noise. The criterion used is calculated in accordance with standard DIN 45681 [7]. In simpler terms, it quantifies the emergence of a tonal sound in the background noise. This criterion was chosen to quantify the emergence of the BPF.
- **Roughness** is the criterion used to describe the perception of a rough sound. This happens when two pure sounds with close frequencies are played at the same time. It corresponds to a rapid amplitude modulation. There are several roughness calculation models. The model used here is the Sottek auditory model. One Asper corresponds to a pure sound at 1 kHz of 60 dB 100% modulated at 70 Hz.
- **Loudness** describes the perception of sound intensity as a function of frequency. It is expressed in Sone. To be more precise, it is expressed as a function of the Bark. The Bark are frequency bands to which the width of the inner filters of the human ear are receptive. It was decided to use Hertz for the scales in order for them to be more understandable. A Sone corresponds to a sound with a 1000 Hz frequency and a sound pressure of 40 dB. Whenever the perceived intensity seems to be twice as strong, the Sones are multiplied by two.

RESULTS

Aeraulic tests

Aeraulic tests were conducted to check the performance of the fans in this field. The propeller with irregularly spaced blades and the conventional propeller were compared at the same rotational speeds as in the acoustic tests (800 à 2300 rpm) using the shell for different operating points.

These tests were used to compare the aeraulic and acoustic performance of two propeller fans with identical blades spaced regularly and irregularly around its circumference. The aeraulic performance measured at several rotational speeds is very similar on both propellers. However, we noted a slightly higher maximum (or total) static efficiency in the propeller with unevenly spaced blades due to a slight fall in the power absorbed in the flow range around the optimal efficiency point.

Sound pressure levels

We present (Figure 4) the sound pressure levels for microphone #5, which corresponds to the far field, as a function of the rotational speed. The hierarchy of the results is the same as on the other microphones.

If a comparison is made of the propeller with the irregularly spaced blades and the conventional propeller on the same mounting, i.e., a shell or diaphragm, the propeller with the irregularly spaced blades displays a lower acoustic level. If a comparison is made of the two mountings, the mounting with the diaphragm produces a lower acoustic level than with the shell.

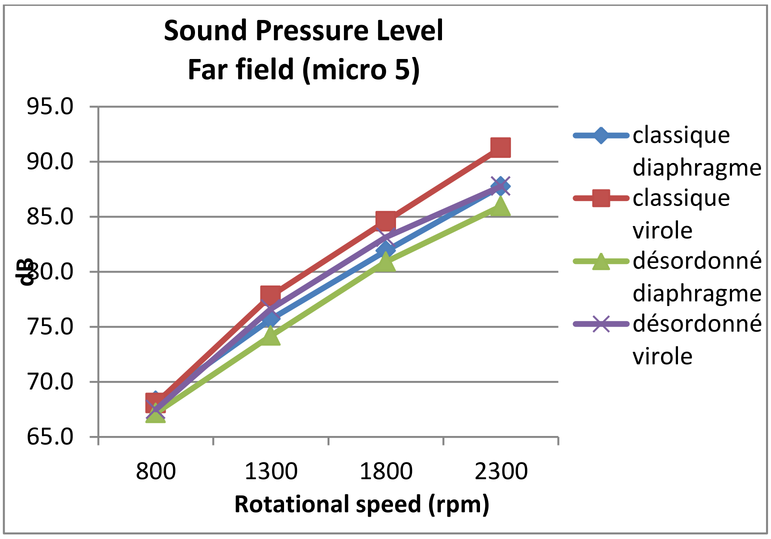


Figure 4: Graph of the sound pressure levels as a function of speed

Spectral analysis

The results are presented for the frequency range 0-1000 Hz, and we are interested more specifically in the blade passing frequency. To highlight the phenomena, we present in this paper the different results at 2300 rpm. The conclusions are transposable to all rotational speeds.

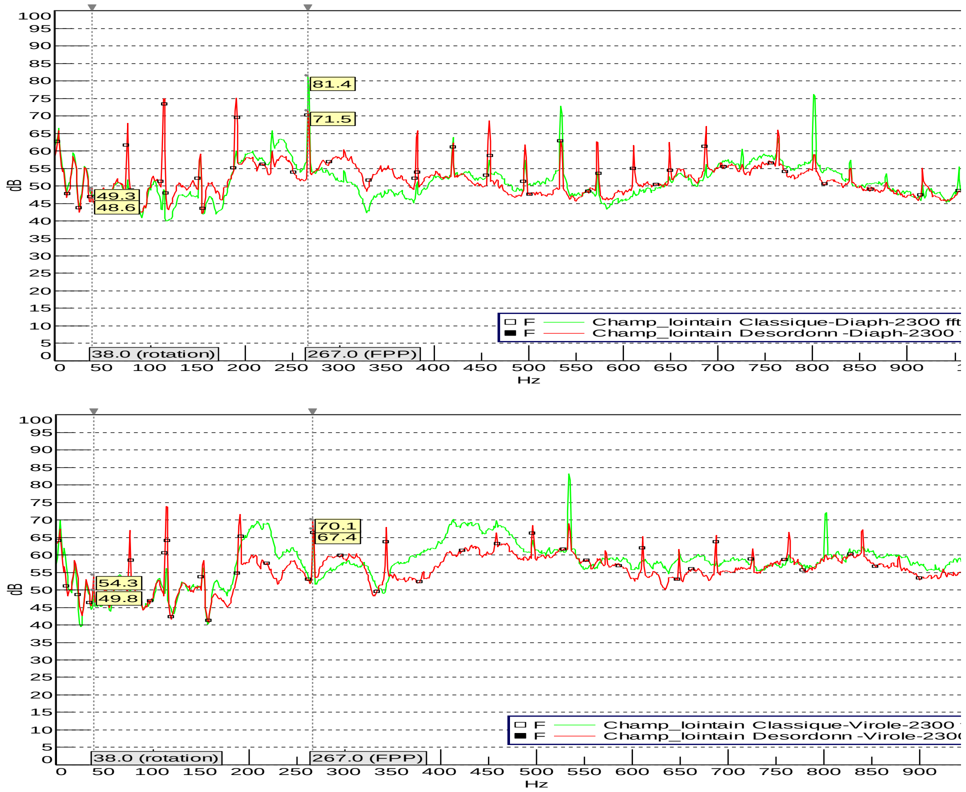


Figure 5: Comparison of conventional propeller and propeller with irregularly spaced blades - Diaphragm (top) and Shell (bottom) 2300 rpm

The first observation, which is perhaps an obvious one, is that when a narrow band comparison is made of the two propeller types, the harmonic content is modified as expected. The harmonics of the blade passing frequency are indeed reduced whereas those of the rotational frequency are amplified on the spectrum of the propeller with the irregularly spaced blades. The wide-band noise, however, is hardly modified or not modified at all.

Loudness

For the propeller with irregularly spaced blades, the perception of noise level is lower on the higher frequencies than on the BPF. The emergence levels of the BPF and its harmonics are indeed lower. However, the low frequency content is higher. The perception of the sound intensity of the fan with irregularly spaced blades is fairly homogeneous across the spectrum, i.e., there is no significant fluctuation in the level from one band (= bark: auditory filter of the human ear) to another. Amplifying the low frequencies can also have an influence on the perception of the power of the machine, which may match with a request from industry.

Figure 6 : Loudness - comparison of conventional propeller and propeller with irregularly spaced blades - Diaphragm (top) and Shell (bottom) 2300 rpm

Tonality

The tonality suitably indicates the BPF for the conventional propeller and the diaphragm mounting. The harmonics frequencies 2 and 3 of the BPF are clearly perceived. For the shell mounting, the tonality is not indicated, except for the highest speed of 2300 rpm.

For each case, when a tonality peak on the BPF is visible for the conventional propeller, the tone is neglectible for the propeller with the irregularly spaced blades. For the propeller with irregularly spaced blades, the tonality highlights a few harmonics of the rotational frequency of the motor, which are located before the BPF. The harmonics that stand out are primarily the third and fifth harmonics. The emergence of these harmonics contributes to increasing the level at low frequency. Conversely, as they have a frequency of less than 200 Hz, they are not perceived to be as annoying as for higher frequencies.

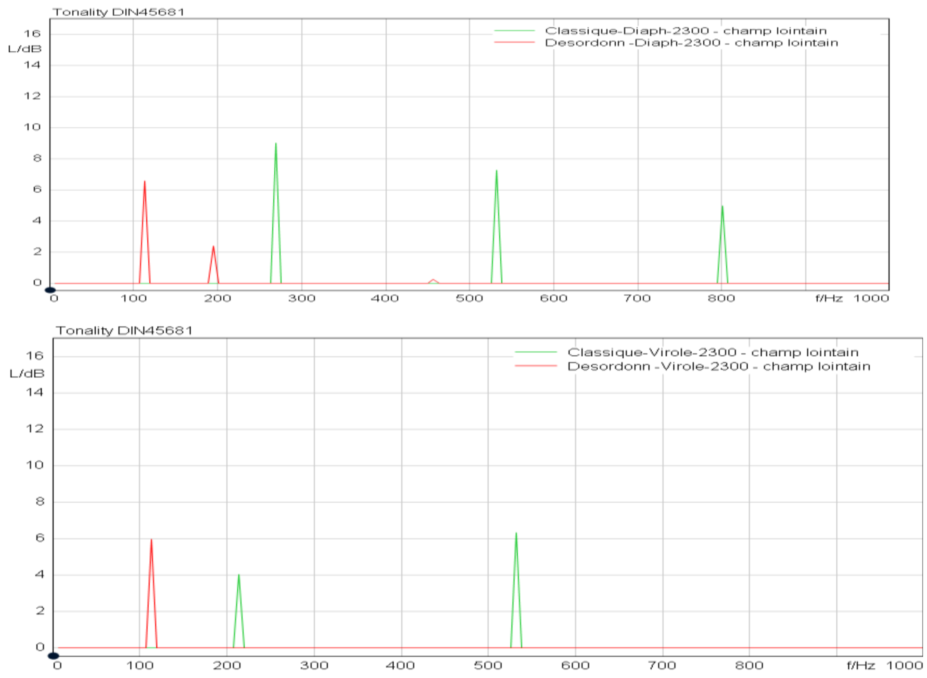


Figure 7 : Tonality - comparison of conventional propeller and propeller with irregularly spaced blades - Diaphragm (top) and Shell (bottom) 2300 rpm

Roughness

The roughness is indicated primarily for information purposes. It was calculated to check that the propeller with irregularly spaced blades did not increase the perception of roughness. For both types of propellers, the roughness is low at below 50m Asper and then the results and the trends are not significant. This order of magnitude means that the roughness is negligible for both types of propellers in this case.

When listening to the propeller with irregularly spaced blades, it produced a faint flapping sound at low frequencies. The criterion of roughness does not function at low frequencies and, by definition, it cannot describe the flapping, which is a slower modulation. The criterion that describes the amplitude modulation is called the fluctuation strength. This criterion did not highlight any fluctuation because it was below 5m Vacil, the unit of fluctuation strength.

Other approaches, which entail observing the level, the loudness or simply the signal over time by searching for waves, have not succeeded in highlighting this perception.

Figure 8 : Roughness - comparison of conventional propeller and propeller with irregularly spaced blades - Diaphragm (top) and Shell (bottom) 2300 rpm

CONCLUSION AND PERSPECTIVES

After testing, it was shown that the propellers with irregularly spaced blades have an acoustic performance that is different from that of conventional propellers, but without modifying the aeraulic performance, and even have a slightly better efficiency level.

The blade passing frequency (BPF) and its harmonics are indeed lower. The energy is distributed across the harmonics of the rotational frequency of the propeller. These increases are seen more at low frequencies, before the BPF and the increase in the loudness clearly shows this.

This increase in the level at low frequencies, while lowering the level on the BPF band, leads to a “flatter” specific loudness graph without an emerging frequency band. The strengthening of the low frequencies can contribute to the sound quality of the motor by strengthening the perception of the power of the machine while reducing the annoyances linked to the tonal emergence levels at higher frequencies.

The tonality criterion shows the reduction in the tonal emergence of the blade passing frequency.

When listening to the propellers during testing, a flapping phenomenon could not be detected and quantified using criteria such as roughness or fluctuation strength.

It is important to note that the tests were conducted on a set of irregularly spaced blades at angles chosen from literature on the subject. Consequently, the propeller with the irregularly spaced blades can potentially be optimised for use in cooling systems, particularly in terms of the angles between the blades and its overall geometry.

The next steps should be to test the fans in their working environment (machine). It would then be interesting to link the acoustic behaviour with geometric and design parameters and to optimise the angles between the blades to adjust them to the cooling systems of the machines. Ultimately, we can control the sound quality of the machines by reducing the tonal emergence of the fans by adjusting behaviour at low frequencies.

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