COMPARISON OF SOUND QUALITY METRICS FOR AXIAL FLOW FANS WITH STRAIGHT AND FORWARD SWEPT BLADES

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SUMMARY

The design of industrial axial flow fans is driven by regulations regarding the efficiency as well as the noise generated during operation. The purpose of this paper was to compare subjective sound quality metrics (loudness, sharpness, roughness, fluctuation strength and annoyance) of a straight bladed fan and one with forward swept blades. As such, two 630 mm diameter fans with similar blade designs were tested in a ducted facility for a variety of flow rates where their performance as well as sound quality metrics could be determined. It was found that, as expected, the fan with forward swept blades generated lower tonal and broadband noise levels, but that the improvement in sound quality was dependent on the operating point.

INTRODUCTION

Axial flow fans are used in a great number of applications ranging from air conditioning systems to the cooling of process steam at thermal power stations. The design of industrial axial flow fans is driven by the requirement to meet noise restrictions as well as regulations regarding fan efficiency. In general axial flow fan noise is specified as an A-weighted sound pressure level (SPL) value. The A-weighting takes into account the frequencies at which humans are more sensitive to sound and as such is a better metric than the unweighted SPL when the well-being of people in the workplace is to be considered. However, an A-weighted SPL does not account for the subjective preference that a person has regarding the sound generated by a source such as an axial flow fan.

Fastl and Zwicker [1] introduce several subjective metrics for the evaluation of sound quality. These metrics are loudness, sharpness, roughness, and fluctuation strength. When multiple fan designs are to be evaluated, sound quality, in addition to SPL, may be used to determine which design is preferable.

The validity of using sound quality metrics to compare three computer fan designs was investigated by Novak *et al.* [2]. The researchers reported the loudness, sharpness, prominent tone and articulation index as a function of fan rotational speed. Unfortunately, no description of the designs were provided, but it was suggested that sound quality metrics be used for qualitative product analysis.

Sottek and Genuit [3] state that loudness alone is not a sufficient metric when analyzing fan noise as it is often tonal components or modulated sounds that cause customer complaints. As such, the researchers implemented a hearing model that combines modulation analysis, such as roughness, with loudness evaluations. It was found that the hearing model provides a much better prediction of annoyance caused by fan noise than loudness alone.

More recently Minorikawa *et al.* [4] investigated the tonal components of a small cooling fan by using the tone to noise ratio and prominence ratio metrics. A jury test showed that there is a strong correlation between the tone to noise ratio, prominence ratio and the subjective response. This result further reinforces the notion that sound quality metrics, in addition to SPL, need to be considered when analyzing fan noise.

A thorough psychoacoustic evaluation of a large number of axial and centrifugal fans was performed by Schneider and Feldman [5]. It was shown that various inlet configurations, fan speeds and operating points affected the sound quality. Furthermore, through jury testing the researchers found that there is a strong correlation between loudness and the subjective annoyance factor, but also state that the fluctuation strength and tonality can play an important role when the fan is operating near stall.

Finally, Yang and Zhu [6] performed a non-linear regression analysis on the sound quality metrics, objective metrics and the results of a subjective comparison of several stimuli recorded from a cooling fan at a transmission station in China. The regression model for predicting the subjective evaluation of a stimulus that is presented by these researchers is only a function of loudness, sharpness, sound pressure level and A-weighted sound level. This result indicates that for the specific fan being tested tonality, speech intelligibility, articulation index, fluctuation strength and roughness do not affect the subjective evaluation of the sound. It is not expected that this finding will be true for a more general case, but does further justify the need for the evaluation of fan sound quality.

The research highlighted in the preceding paragraphs demonstrate the use and value of sound quality evaluation for fans. However, literature regarding the use of sound quality metrics to guide low noise fan design could not be found. The two main sources of axial flow noise are unsteady blade loading causing discrete or tonal noises and vortex shedding that generates broadband noise [7, 8, 9]. Axial flow fans with swept blades have been shown to generate lower noise levels than equivalent fans with straight blades [10] as they exhibit reduced broadband and tonal components. However, the effect of blade sweep on sound quality metrics has not yet been investigated. As such, the current investigation aims to determine whether or not the subjective sound quality metrics are also improved when comparing an axial flow fan with forward swept blades to one with straight blades.

DESCRIPTION OF EXPERIMENTS

Test fans

Two 630 mm diameter fans were selected for the comparative tests and are shown in Figure 1. These fans were selected due to the fact that they had very similar designs, with the primary distinguishing factor being that one of the blades had straight blades whereas the other had blades that were swept forward. Both fans had a total of 8 blades making use of the same NASA LS (GAW1) profile while the forward swept fan had a maximum sweep angle of 11.51°. For the sake of brevity, from this point onward the straight bladed fan will be referred to as the R-fan and the fan with forward swept blades as the FS-fan.

(a)

(b)

Figure 1 – 630 mm diameter test fans with straight blades, R-fan, (a) and forward swept blades, FS-fan (b).

Test facility

Tests are conducted in a test facility according to ISO 5801 [11], for performance, and ISO 5136 [12], for noise. The test facility, shown in Figure 2, is a Type-D facility with anechoic terminations where the inlet and outlet are both ducted and noise is measured downstream of the fan using a *HEAD acoustics SQuadriga II* mobile recording and playback system. Fan performance is determined by measuring the pressure rise over the fan as well as the flow rate and torque. Finally, the operating point is altered by varying the position of a throttle plate at the facility outlet.

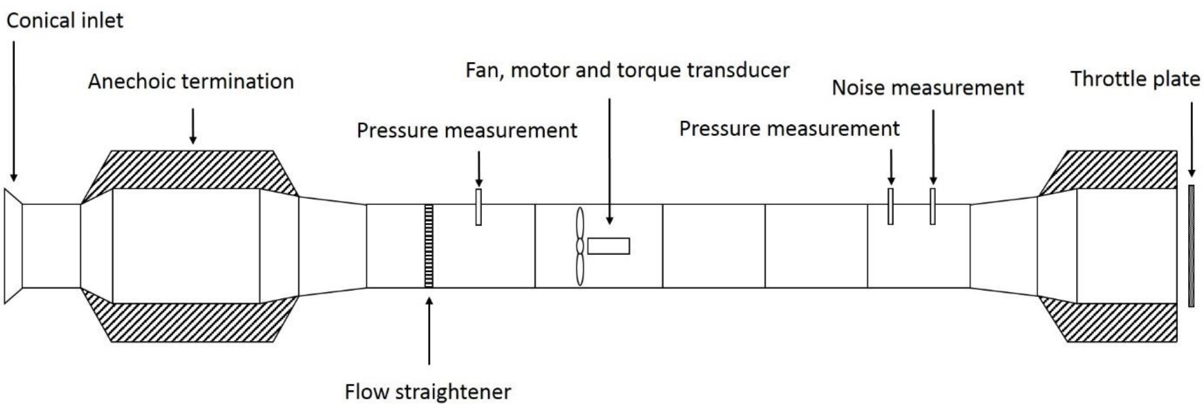


Figure 2 – Type-D ducted test facility [14]

RESULTS

Fan performance

The performance of each of the two fans is indicated by the fan static pressure rise and static efficiency as a function of volumetric flow rate. All tests were conducted at a fixed speed of 1440 rpm while the volumetric flow rate was varied using the throttle plate.

The R-fan reaches a higher static pressure rise when fully throttled, but has a lower efficiency than the FS-fan. The maximum static efficiency of the R-fan is 54 % while the maximum static efficiency of the FS fan is slightly higher at 57 %.

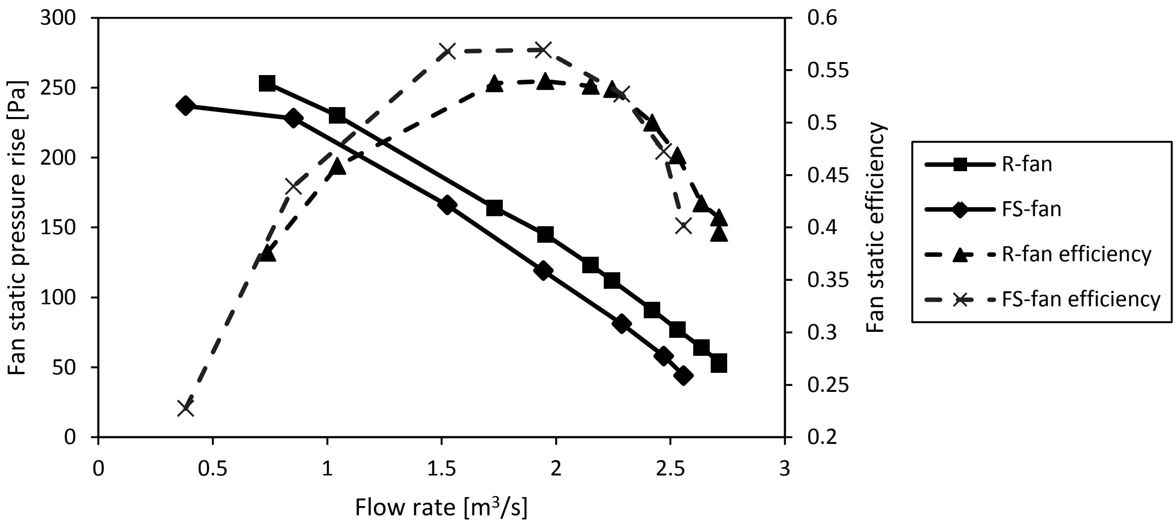


Figure 3 – Comparison of fan performance

Fan noise

The overall noise level for each fan as a function of flow rate is shown in Figure 4. As expected, the noise generated by the R-fan greatly exceeds that of the FS-fan. Additionally, both fans exhibit increased noise levels as the flow rate increases with a point of maximum noise at approximately 2 m^3/s before reducing as the flow rate is further increased. The difference of approximately 10 dB(A) between the two fans means that the R-fan should be perceived as being twice as loud as the FS-fan.

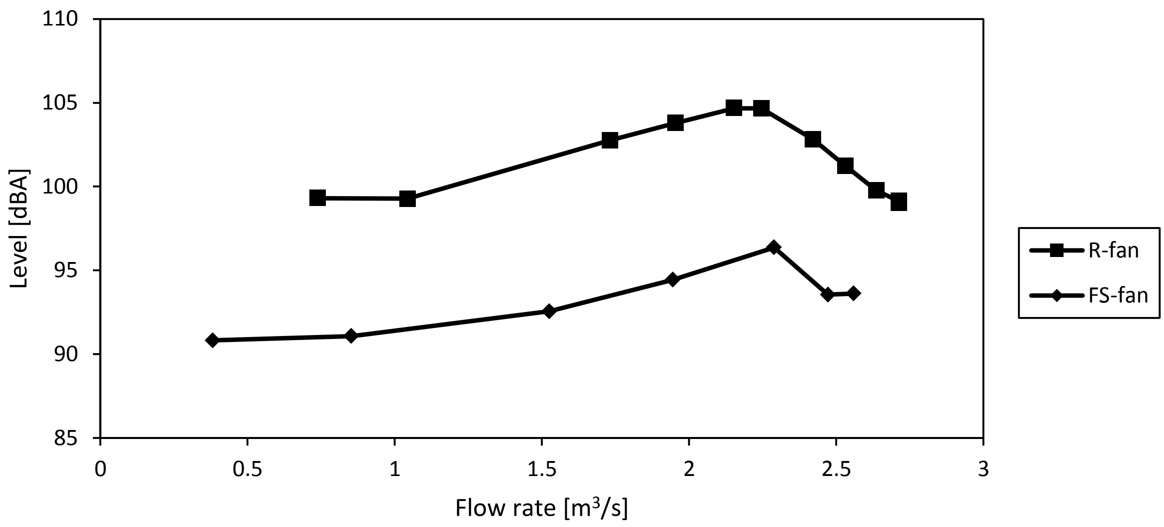
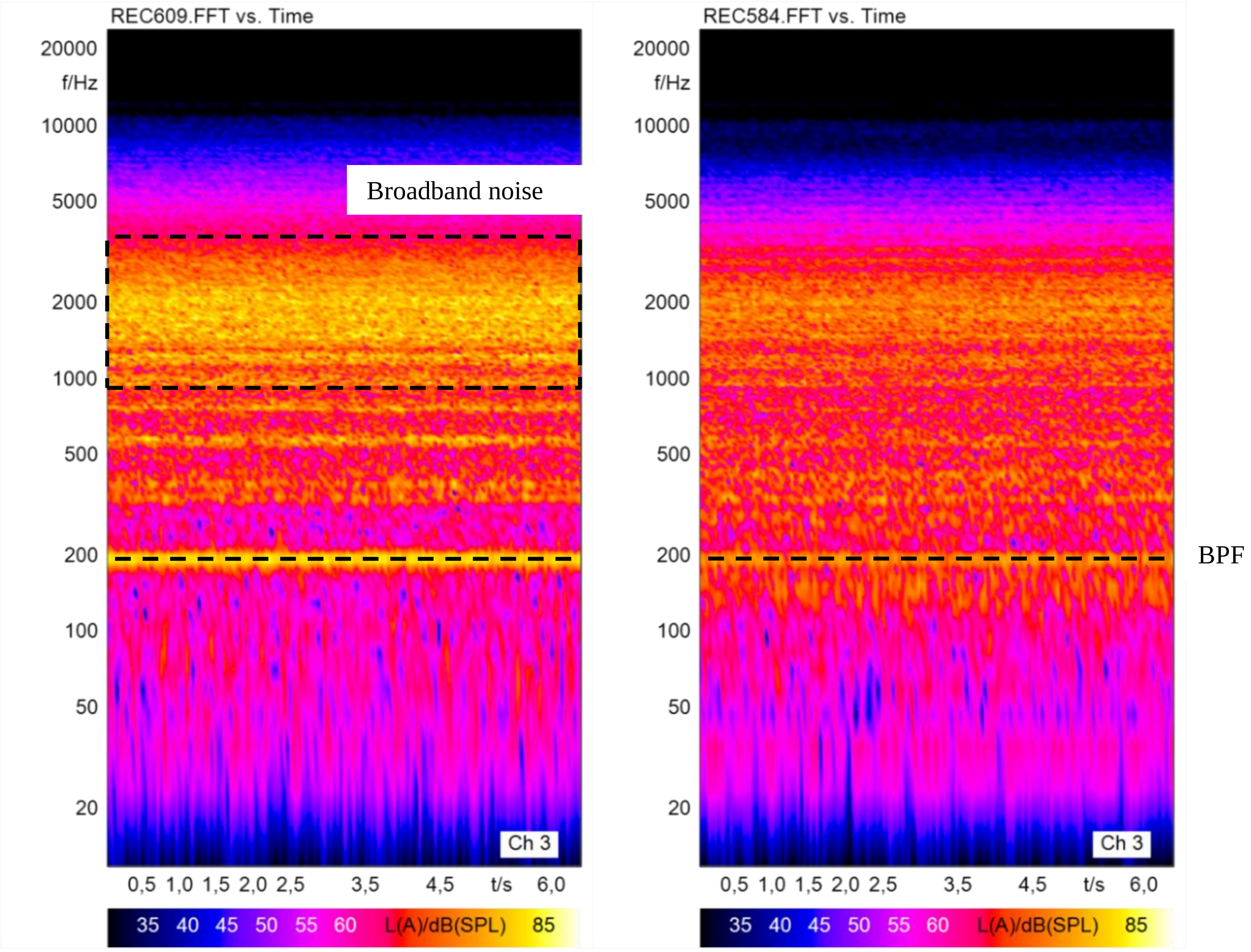


Figure 4 – Comparison of overall fan noise levels as a function of flow rate

The FFT vs. time (spectrogram) plot of each fan when the throttle is fully open is shown in Figure 5. In this figure the noise generated by the R-fan for a period of 6 s is shown on the left and the noise generated by the FS-fan on the right. A spectrogram is presented instead of an average FFT to observe the presence of fluctuating components within the noise. A steady tonal component at the blade pass frequency (BPF) of 192 Hz for both fans with this component of the fan noise being more pronounced for the R-fan. Also evident in the figure is the fact that the noise generated by both fans exhibit some measure of fluctuation over time and that the R-fan exhibits a much higher level of broadband noise in the region of 2 kHz than the FS-fan.



(a) *(b)*

Figure 5 – Spectrograms of the noise generated by the R-fan (a) and the FS-fan (b) at maximum flow rate; Block size of 4096, Hanning window with an overlap of 50 % and maximum time variables of 600.

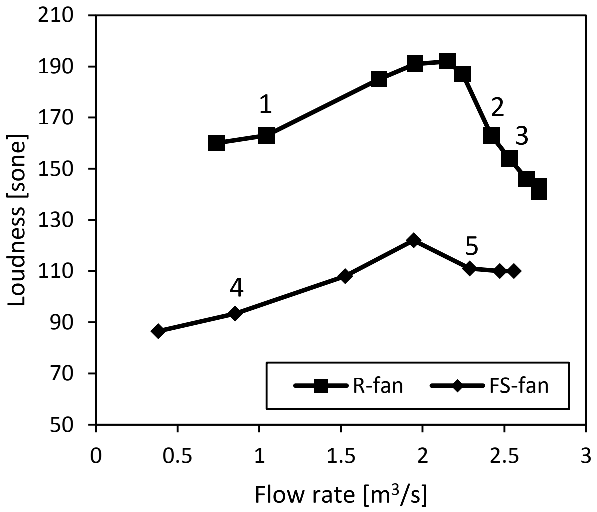
Comparison of sound quality metrics

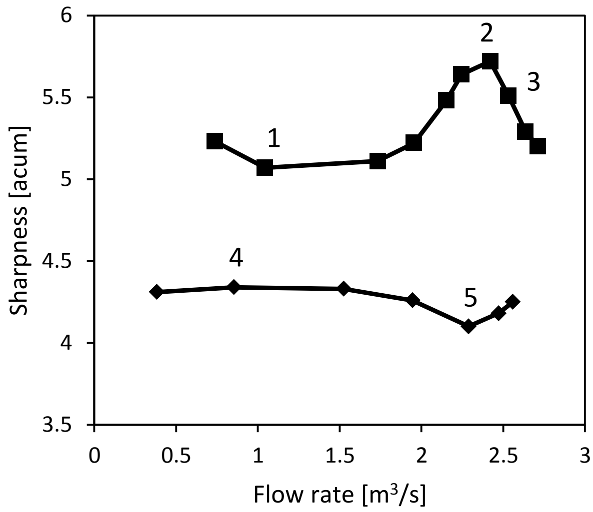
In addition to the performance metrics, SPL and spectral analysis, the aim of the current paper is to investigate whether forward skewed blades have benefits when considering sound quality metrics as well. The sound quality metrics to be compared for the two fans at different operating points are:

1. Loudness – The subjective felt sound intensity (calculated according to DIN 45631 [13]).
2. Sharpness – The relationship between high and low frequency noise components (calculated according to Aures sharpness due to the difference in loudness between the two fans).
3. Roughness – Fluctuations in the signal between the modulation frequencies of 15 Hz and 250 Hz.
4. Fluctuation strength – Low frequency fluctuations in the signal up to a modulation frequency of 20 Hz.

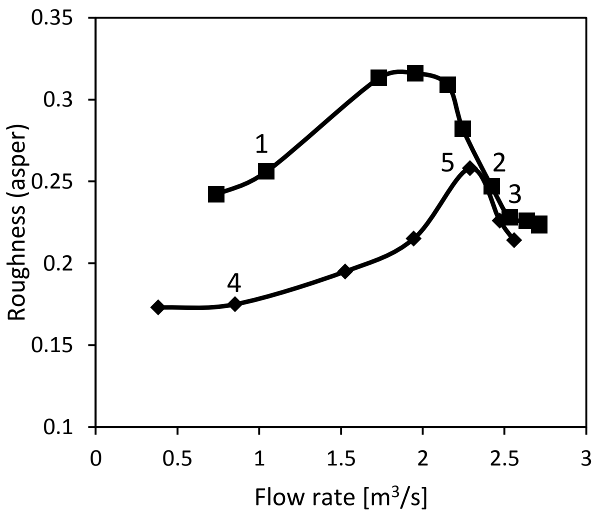
In general, the increase in value of the abovementioned metrics result in a less pleasant sound. The results of the comparisons of these metrics between the R-fan and FS-fan are presented in Figure 6. Due to the much higher noise levels of the R-fan its loudness is also higher than that of the FS-fan regardless of the operating point. Additionally, the sharpness of the noise generated by the R-fan is also higher than the FS-fan. Interestingly, the R-fan exhibits a much greater fluctuation in sharpness than the FS-fan when being throttled. This implies that the noise generated by the R-fan is highly dependent on the operating point with flow rates past the point of maximum efficiency producing much sharper sounding noise while the sharpness of the FS-fan reduces in the same operating region.

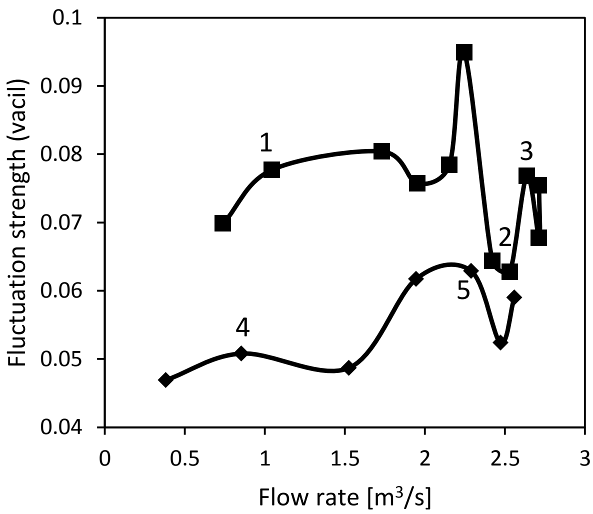
The roughness of the noise generated by both fans exhibit a similar dependence on operating point with the FS-fan and R-fan roughness reaching equal values at high flow rates. A similar trend is observed when comparing the fluctuation strength for the two fans; the difference of the sound quality metric decreases with increasing flow rate.





(a) *(b)*

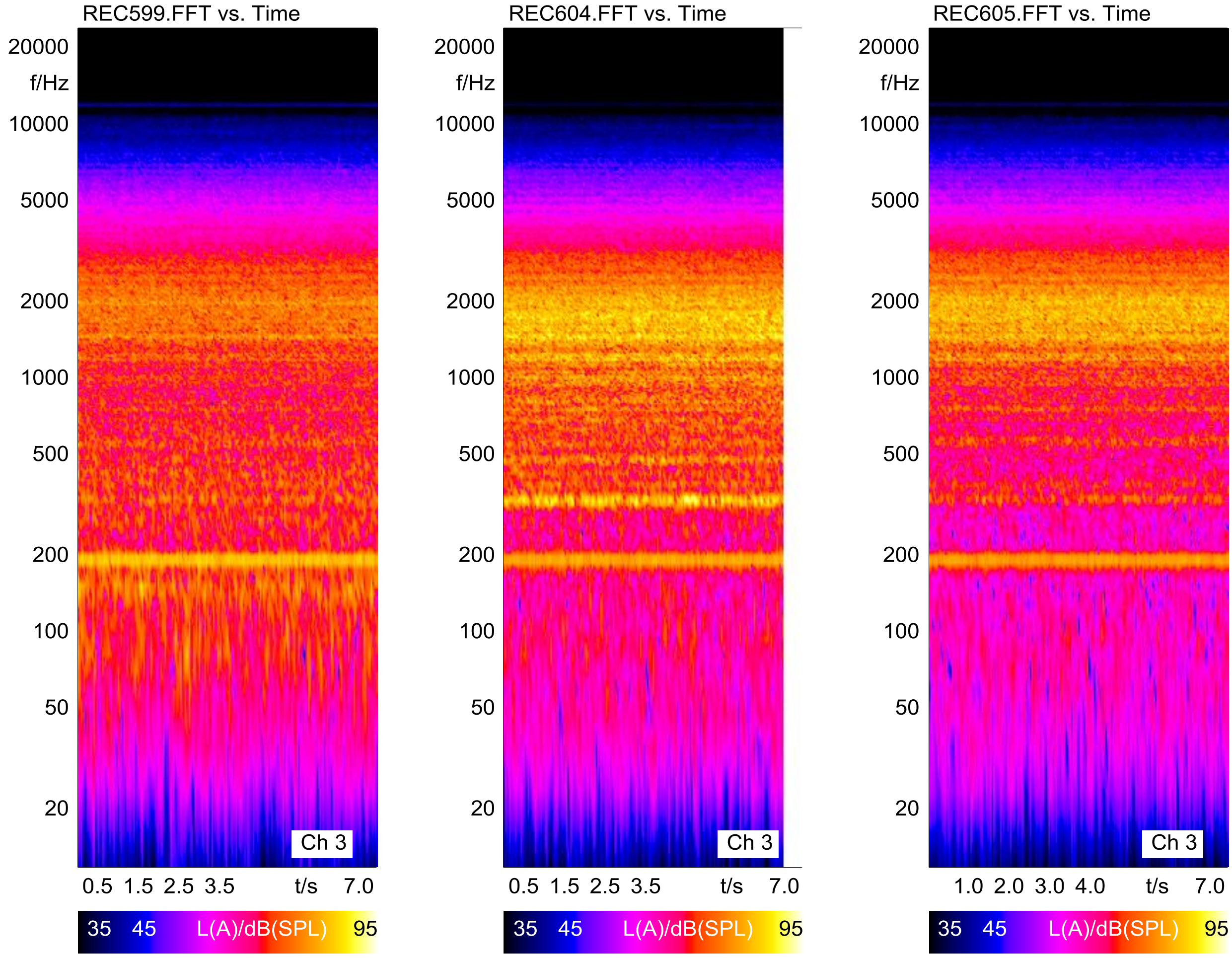




(c) *(d)*

Figure 6 – Psychoacoustic metrics calculated for the straight and forward swept fan: Loudness (a), sharpness (b), roughness (c), and fluctuation strength (d).

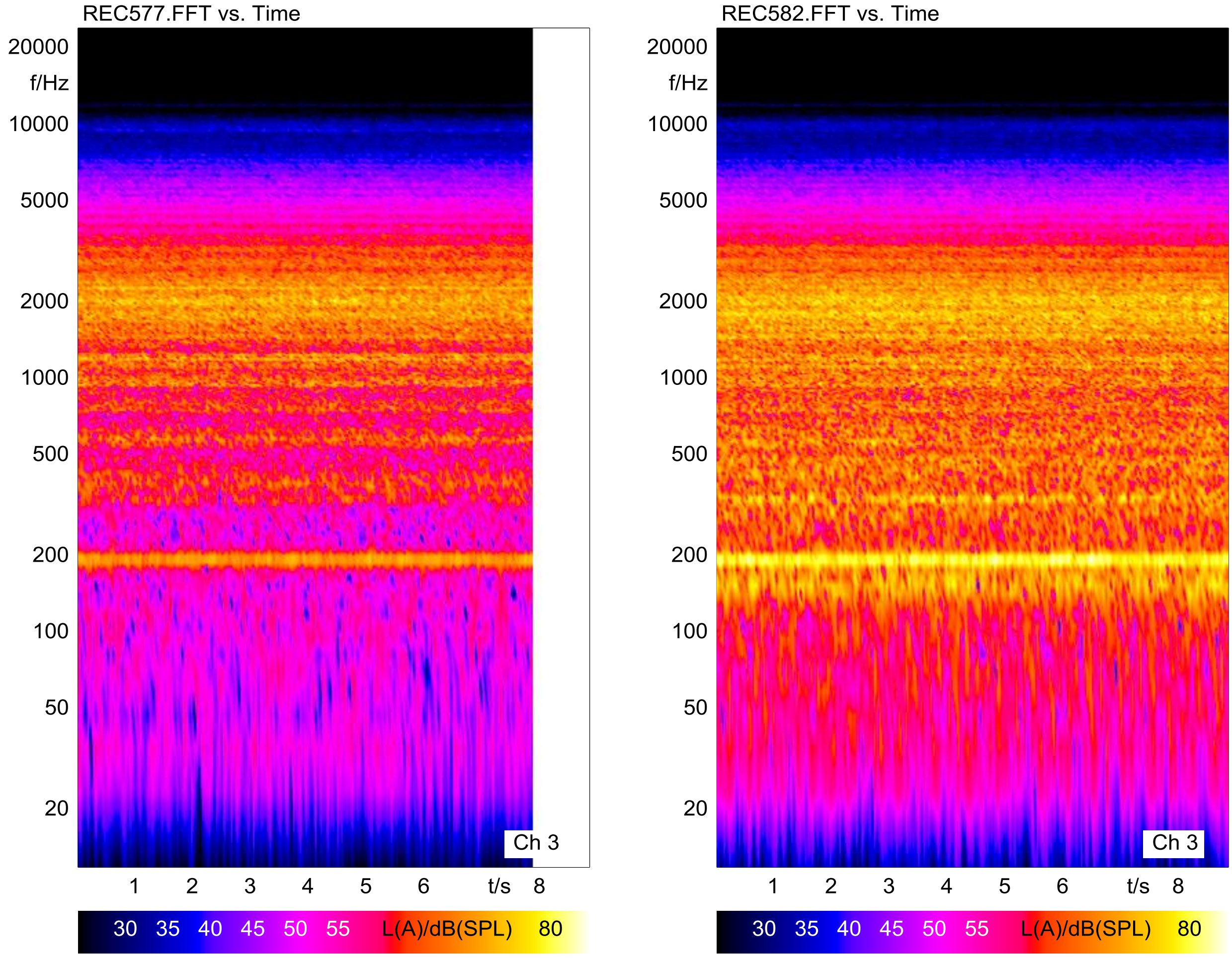
To further investigate the difference in sharpness of the R-fan the spectrograms of the noise generated at points 1, 2 and 3 in Figure 6 has been plotted in Figure 7. At point 1 the most prominent component of the noise is the tonal noise generated at the BPF of 192 Hz. When operating at point 2 there is a larger broadband component with an additional tonal component at twice BPF. This dominant tonal component of noise at twice BPF is only present when operating at point 2 as can be seen when comparing to the noise generated when operating at point 3. At point 3 there is a strong tonal component at BPF with additional broadband noise at of 2 kHz. It is as a result of the increase in broadband noise at 2 kHz that the sharpness increases from point 1 to point 2. The reduction in sharpness from point 2 to point 3 may be attributed to the reduction in magnitude of the tonal component at twice BPF.



(a) *(b)* *(c)*

Figure 7 – Spectrograms of the noise generated by the R-fan at point 1 (a), point 2 (b) and the point 3 (c) as depicted in Figure 6; Block size of 4096, Hanning window with an overlap of 50 % and maximum time variables of 600.

When considering the sharpness of the FS-fan between point 4 and point 5 depicted on Figure 6 (b) one can see that the sharpness reduces while the overall SPL increases. This is explained by Figure 8, which is a spectrogram calculated for the noise generated at each of these operating points. At point 4 the tonal and broadband noises are both at a relatively low level with little discernable difference between the two. At point 5 the level of both the tonal and broadband noises have drastically increased, resulting in the increase of overall SPL. However, the difference between the high and low frequency components is not enough to generate a large difference in sharpness between the two operating points. In fact, the increase of the tonal component relative to the higher frequency broadband noise results in a decreased sharpness for this operating point.



(a) *(b)*

Figure 8 – Spectrograms of the noise generated by the FS-fan at point 4 (left) and point 5 (right) as depicted in Figure 6 (top right); Block size of 4096, Hanning window with an overlap of 50 % and maximum time variables of 600.

Psychoacoustic annoyance, PA, is a metric that can be used to quantify annoyance ratings obtained from psychoacoustic experiments and is calculated using equation 1 [1]. In this equation N is the loudness while w_S^2 describes the effects of sharpness, S, and w_{FR}^2 describes the influence of fluctuation strength, F, and roughness, R, in equation 2 and 3, respectively.

$$PA = N\left(1 + \sqrt{w_S^2 + w_{FR}^2}\right) \tag{1}$$

$$w_s = (S - 1.75) \cdot 0.25 \log(N + 10) \ \text{ for } \ S > 1.75 \tag{2}$$

$$w_{FR} = \frac{2.18}{N^{0.4}}(0.4 \cdot F + 0.6 \cdot R) \tag{3}$$

Figure 9 shows how the annoyance value for the two fans is almost entirely dominated by the difference in loudness with the aforementioned changes in sharpness having little effect across the range of operating points.

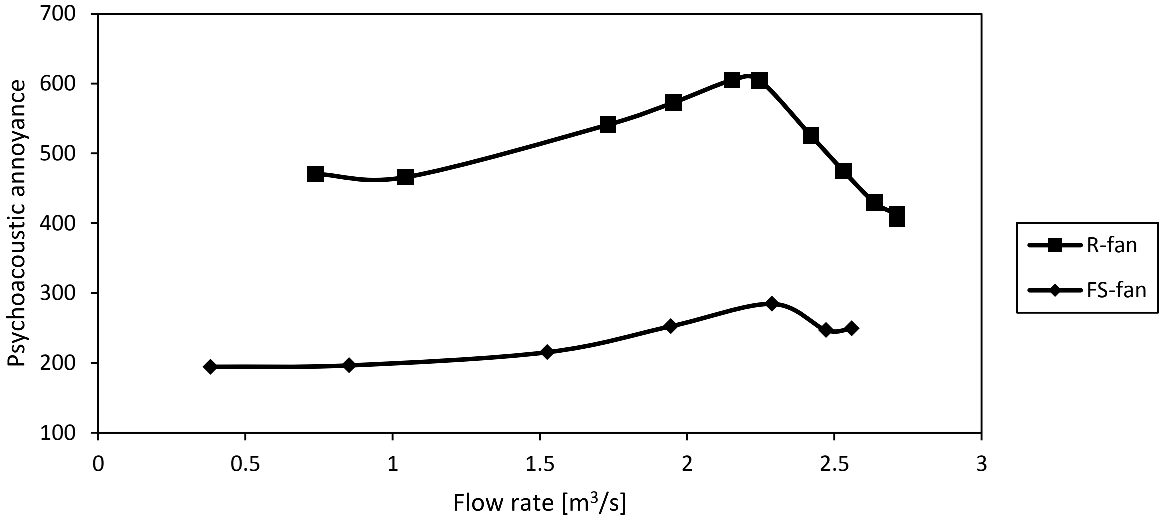


Figure 9 – Comparison of psychoacoustic annoyance

CONCLUSION

When considering the findings presented in this paper the following conclusions can be made regarding the sound quality of a fan with straight blades when compared to that of a fan with forward swept blades:

1. The reduction in noise level generated by a fan with forward swept blades is the dominating factor when comparing such a fan to a similarly designed straight bladed fan due to the large reduction in loudness.
2. Annoyance levels of axial flow fans, regardless of their blade design, is a function of the operating point. However, the annoyance level of a fan with forward swept blades is less sensitive to changes in operating point than a fan with straight blades.
3. As a result of the first finding it is recommended that the improvement of fan sound quality be regarded as a secondary objective to the reduction in the level of fan noise generation. Further research should be conducted to determine the levels at which it is no longer feasible to reduce noise levels, but rather focus on the improvement of sound quality metrics.

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