ACOUSTIC PERFORMANCES OF IRREGULAR BLADE SPACING FANS TESTED ON AN EXCAVATOR

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SUMMARY

On mobile machinery, fans are often the dominant source of external noise, especially with the reduction in noise generated by internal combustion engines. Initial tests have shown that irregular fans have little impact on the overall A-weighted level but do reduce the level of blade passing frequency components. In order to practically assess the potential of irregular fans, tests were carried out on an excavator with a strong contribution of fan noise. Two irregular fans with different angular distributions have been tested and results are compared with standard fan noise. This paper presents the different steps of this experiment, from design of the Irregular Blade Spacing Fans to the analysis of the noise measurements.

INTRODUCTION

On mobile machinery, fans are often the dominant source of external noise, especially with the reduction in noise generated by internal combustion engines. The gradual arrival of electrified machines will not necessarily solve the problem, as the need for cooling the combustion engine will be transferred to the batteries or accessories, and fan noise is likely to emerge even more with a quieter engine.

Initial tests have shown that irregular fans have little impact on the overall A-weighted level but do reduce the level of *blade passing frequency* (BPF) components. Manufacturers in the sector have expressed a desire to know the acoustic performance of fans with uneven blade spacing blades on a machine, among other noise sources.

For the purposes of the demonstration, 4 excavators were assessed and the one radiating most noise on blade passing frequencies was selected. Two *irregular blade spacing fans* (IBSF) with different angular distributions were tested and compared with standard fan noise. This paper presents:

- An attempt to evaluate the noise radiated by irregular fans using a simple simulation method.
- The techniques used to build irregular fans.
- Comparative tests between regular and uneven blade spacing fans. Different evaluation criteria are used: Overall A-weighted levels, Spectral analyses and psychoacoustic criteria.

FAN NOISE IN CONSTRUCTION MACHINERY

Relative importance of fan A-weighted pressure level in construction machinery

Exterior noise. In order to get a picture of the impact of fans on the noise radiated by building machines, measurements have been performed on different excavators. The increase of acoustic power due to the fan is assessed using ISO 3744 standard (fan is simply switched on and off while the engine is maintained steady). Figure 1 shows that fan noise increases the acoustic power by 1 to 5 dB(A). The contribution of the fan depends on the machine, on the engine speed and on the fan rotation speed (some machines have temperature regulated fans). It should be noted that measurements on *Excavator C* underestimate the fan contribution because engine noise increased when stopping the fan. At the end, as a noise source, the fan ranks from important to dominant component of the overall A-weighted acoustic power.

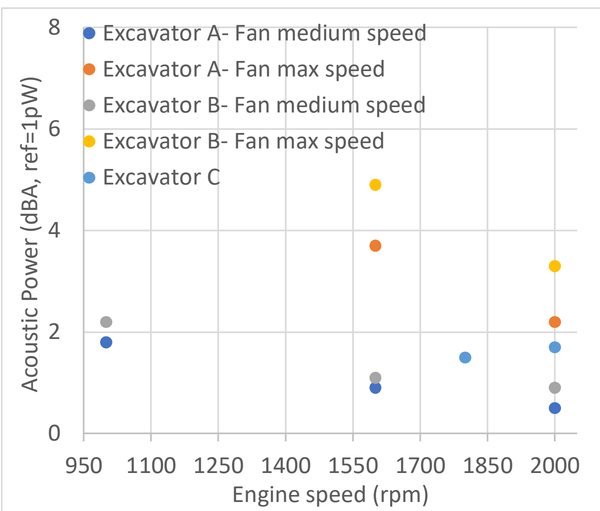


Figure 1. Increase of acoustic power due to fan contribution (dB(A)). Measurements performed on different excavators (standard ISO 3744).

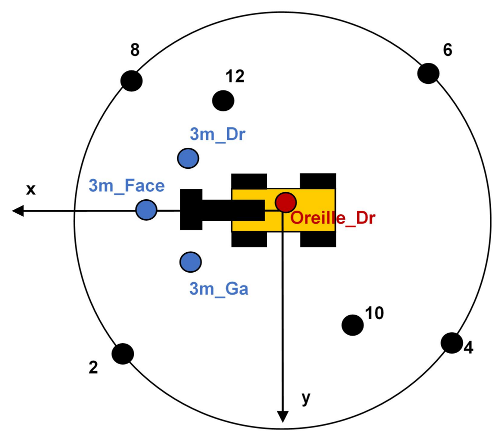


Figure 2. Position of microphones. 6 mics for ISO 3744 type measurement.3 mics at 3 m in front of the excavator. 1 mic at right driver's ear

Interior noise. Fan contribution on global A-weighted level inside the cabin is neglectable for all tested machines.

Tonal shape of fan noise - Choice of a construction machine suitable for testing irregular blade spacing fans

Since IBSFs have no impact on global A-weighted levels, but decrease blade passing frequencies, it appeared essential to perform tests on a machine for which the tonal characteristic of fan noise clearly appears. In order to identify a suitable machine, measurements were performed on 4 excavators. The relative dominance of fan components (BPF) was assessed by computing the ratio of the squared pressure of BPFs to the integrated squared pressure over three 1/3 octave bands (the one containing the BPF and the 2 surrounding 1/3 octave bands). Equation 1 shows how the indicator is computed.

$$\frac{\int P_{FPP}^2}{\int_{N-1}^{N+1} 1/3\_Octave_N} \tag{1}$$

On exterior noise, this indicator showed values lying between 7 and 66 %. The highest values being for BPF-1. The selected machine, a 4-strock engine excavator equipped with an 8-blades fan, showed values lying in between 40 and 66 % for BPF-1. Figure 3 and Figure 4 illustrate the dominance of BPF-1 and BPF-2 and the tonal profile of fan noise on the selected machine.

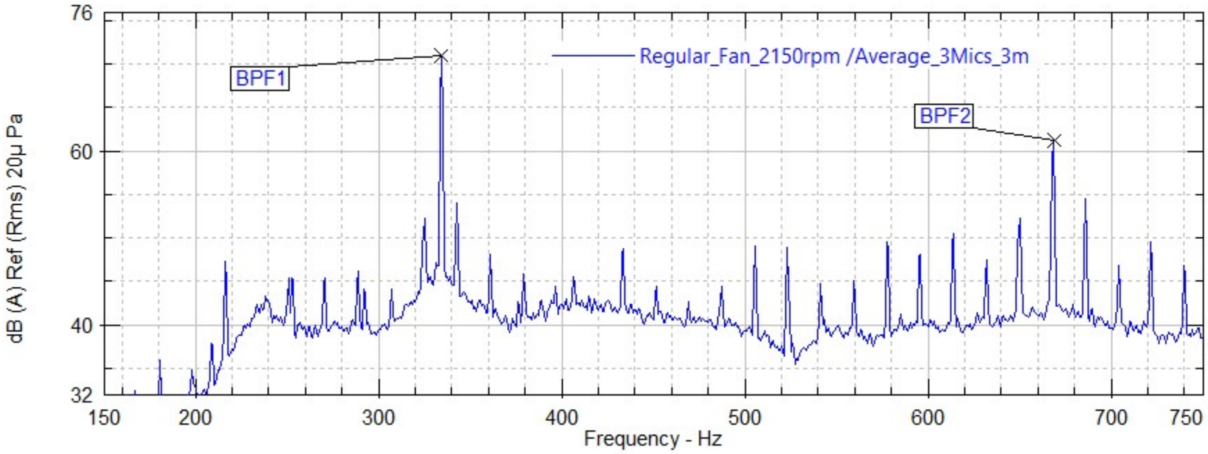


Figure 3. Averaged acoustic pressure (dBA) on 3 microphones placed at 3m in front of the machine (-45°, 0° and 45° incidence relative to longitudinal machine axis). Selected excavator. Engine at 2150 tr/min. Serial Fan. FFP = BPF.

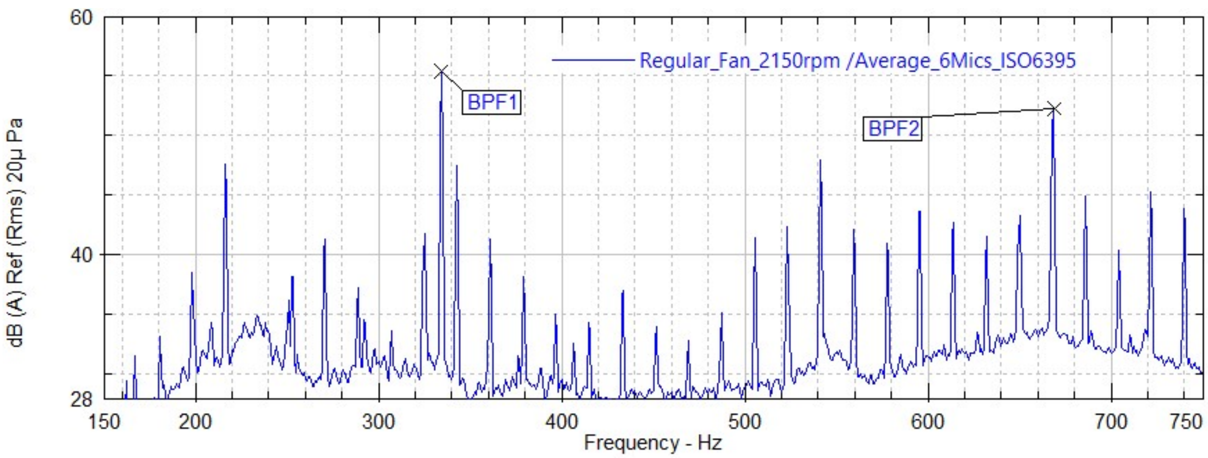


Figure 4. Averaged acoustic pressure (dBA) on 6 microphones (dBA, standard Iso 3744). Selected excavator. Engine at 2150 tr/min. Serial Fan. FFP = BPF.

Concerning interior noise, BPF-1 and BPF-2 are generally clearly identified but are not dominant compared to engine components. However, their presence might cause a beat frequency when BPF 1 or 2 are very close to an engine frequency component. This phenomenon was observed in one of the machines, causing a drop in acoustic comfort.

DESIGN OF IRREGULAR BLADE SPACING FANS

Attempt to evaluate the relative performances of IBSF using a simple computation model

The calculation principle is simple: each blade passage is simulated by a Dirac-type pressure peak. The spectral distribution and the relative amplitude of the different components are calculated.

The accuracy of the approach is probably questionable. Since literature does not provide information on this subject even using powerful simulation tools, the "Dirac" method was an attempt to assess the relative importance of the different peaks.

Finally, comparisons between measurements and calculations have shown that the numerical approach is not sufficiently reliable to allow optimization of the angular distribution of IBSF.

Angular distribution of blades

Table 1 shows the angular distribution of the 2 IBSF tested on the selected excavator. The distribution of the regular fan is 360/8 = 45°.

IBSF Number	Relative Angle (°)						
IBSF 1	59	53	33	34	39	43	49
IBSF 2	53	43	47	38	33	35	49

Table 1: Angle distribution of irregular fans

Construction of irregular fan prototypes

In order to be compared objectively, the 2 selected distributions will be analysed with a regular distribution manufactured with the same elements (blades, hub, etc.), so 3 fans are manufactured.

The main parts are:

- A hub (Spacer) which allows the fan to be adapted to its drive motor.
- 2 flanges connected to the hub that hold the blades in place.
- The blades, whose geometry extracted from the drawings is strictly identical to those existing on the standard fan (only the blade foot is changed to fit the flanges).

Once assembled, the 3 fans are balanced (static balancing) by adding weights to the fixing screws of each blade. Therefore, these screws can be of different lengths.

It was chosen to manufacture the blades by 3D printer in PA12. This is, a priori, the material that is closest to the original material of the blades, although being a little more flexible (the lengths of the blades being relatively small, the dynamic deformation should not be an issue).

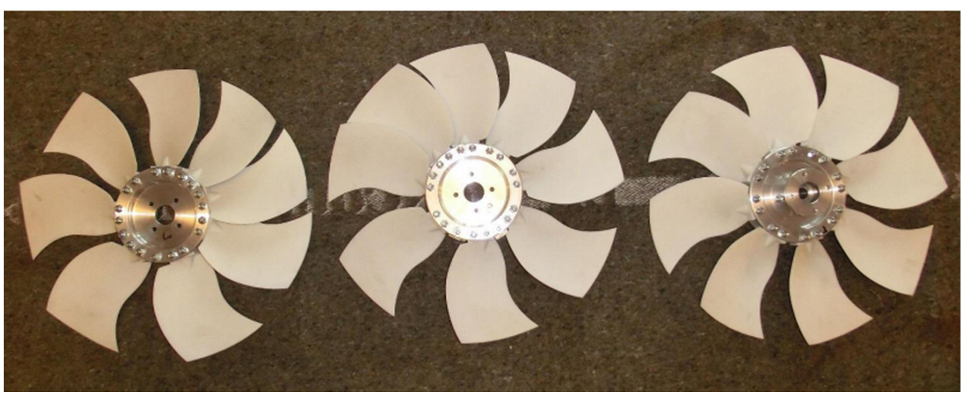


Figure 5. From left to right: IBSF 2, IBSF 1 and regular fan

ASSESSMENT OF IRREGULAR FANS IMPACT ON EXTERIOR NOISE

Impact of irregular fans on overall A-weighted sound pressure

Publications [1] [2] [3] as well as tests carried out at Cetim [4] [5] confirmed that IBSF have no influence on global A-weighted sound pressure or power. Measurement performed on the selected excavator confirmed that statement. Figure 6 shows that IBSF do not affect much the 1/3 octave spectrum profile of the acoustic pressure radiated by the machine. Variations on the overall level do not exceed 0.3 dB(A) between irregular and regular fans.

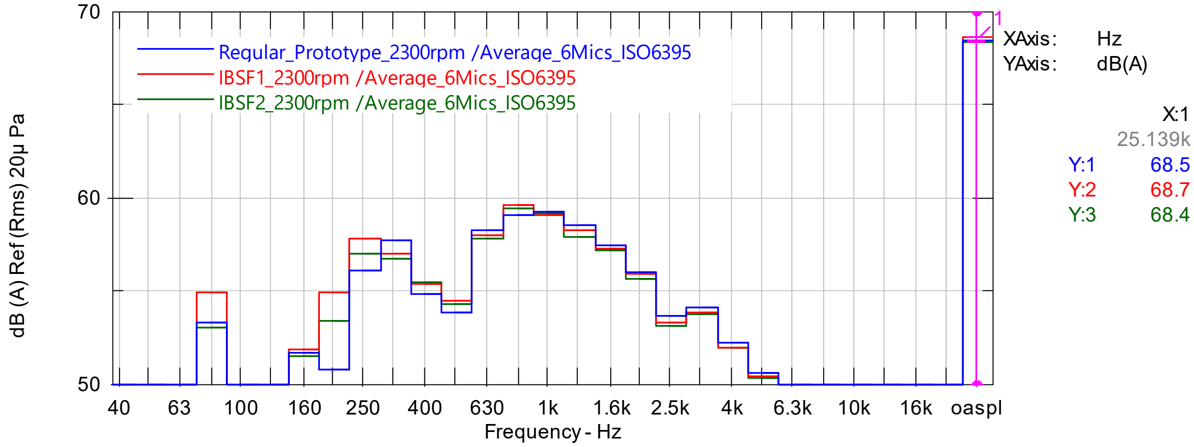


Figure 6. Averaged acoustic pressure (dB(A) – ISO 3744). Engine at 2300 rpm. Regular fan, IBSF 1 and IBSF 2.

Impact of irregular fans on discrete frequencies

The interest of ISF lies in its capacity to eliminate the blade passing frequencies [1] [2] [3], but generally it goes with a redistribution of the acoustic energy in other orders of the fan rotation frequency (often orders adjacent to the BPF). Measurements carried out on the selected excavator confirm that observation. Figure 7 shows that the 8th order of the fan rotational frequency (BPF1) is eliminated, but to the cost of a great increase of x7 and x9 orders.

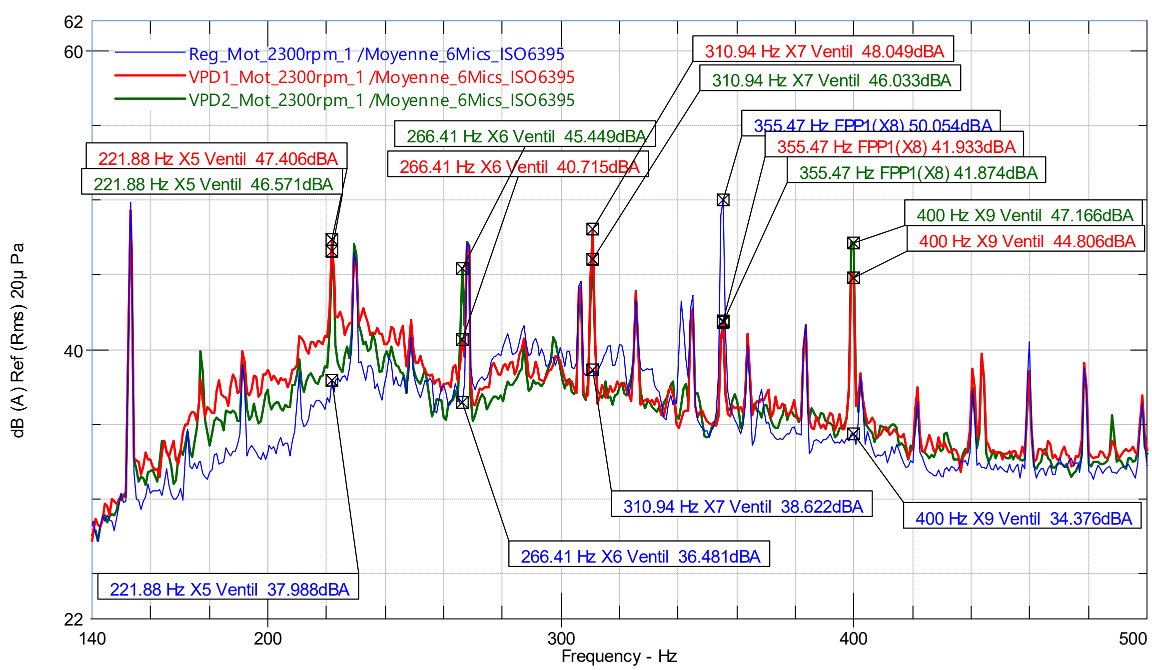
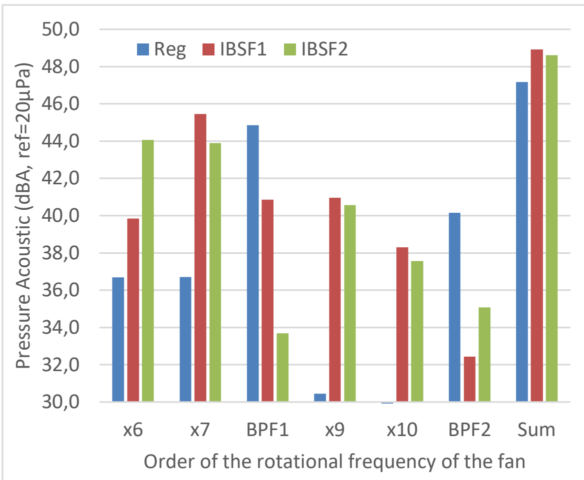
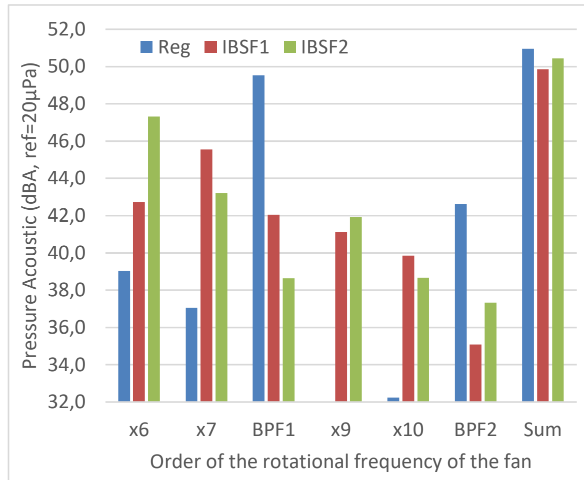


Figure 7. Averaged acoustic pressure (dBA – ISO3744). Engine at 2300 rpm.
Comparison between regular fan, IBSF 1 and IBSF 2.
Blue = Regular Fan, Red = IBSF1 & Green = IBSF2.

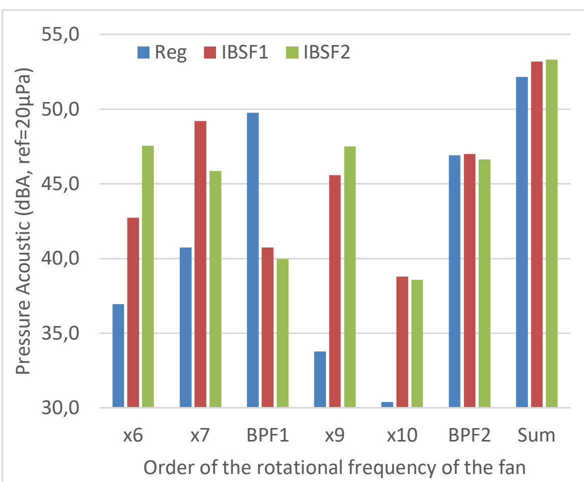
Figure 8 shows a synthesis of results for isolated frequencies. It appears that the level of the x6 and x7 orders sometimes reaches the level of the BPF1 on the regular prototype, which is contrary to the desired result. The sum of the contributions of the different orders results in an approximately similar ranking of regular and irregular fans.



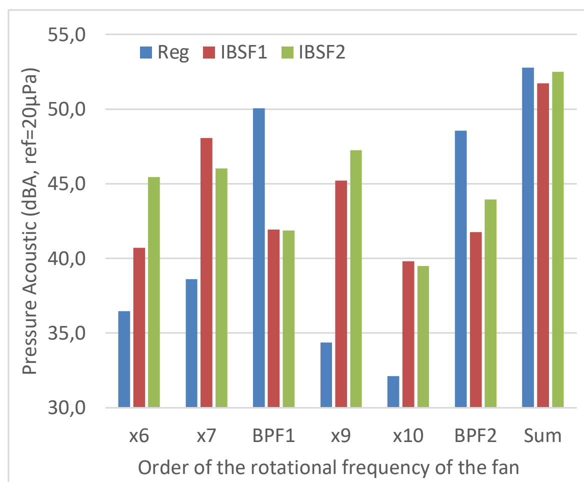
1800 tr/min



2000 tr/min



2150 tr/min



2300 tr/min

Figure 8. Pressure level of orders fan rotational frequency (dB(A)). Comparison between regular and irregular fans.

ASSESSMENT OF IRREGULAR FANS IMPACT ON CABINE NOISE

In terms of overall A-weighted level, the fan noise in the cabs is negligible. The BPFs are not dominant compared to the other engine and hydraulic components. On the other hand, the fan enriches the spectral composition and when the BPF is close to a motor component, this can create a modulation effect (or beat) which impacts acoustic comfort [6]. This is an argument for distributing the energy over several orders instead of concentrating it in BPF1 and BPF2.

IMPACT OF IRREGULAR FANS ON SOUND QUALITY

The psychoacoustic criteria chosen to assess the impact of the fans are *Specific loudness*, *Roughness* and *Tone to Noise ratio*. It appears that:

- *Specific loudness* and *Roughness* applied to the different signals measured outside or inside the cab do not show any trends or differences between regular and irregular fans.
- *Tone to Noise ratio* applied on exterior noise reveals a strong TNR up to 8-11 dB associated with BPF 1 of the regular fan. When applied to irregular fans, TNR algorithm do not always identify a tonality (probably because of high peak density). And when a strong tonality is identified, it is associated with the x4 or x6 engine orders. This shows that IBSF achieves to eliminate the tonal signature of fan noise. When standing in front of the excavator, one may notice that the noise of the regular fan is more tonal than the one of irregular fans.
- Inside the cab, the fan is generally not dominant and most identified tonalities are associated with engine noise. Only the regular fan manages to generate 2 strong tonalities (at 2 different engine speeds). It shows again that IBSF achieves to eliminate the tonal signature of fan noise.

IMPACT OF FLEXIBLE BLADE EXTENSIONS

The standard (regular) fan equipping the selected excavator was equipped with flexible strips attached to the extremities of the blades (the regular prototype was not). The fan manufacturer presents this equipment, which is called BLEX, as a turbulence-reducing device. It appears indeed that the regular prototype without these strips generates more broadband noise than the original or series fan (see Figure 9).

On the regular prototype, however, the amplitude of BPF1 and BPF2 are much lower than on the original fan (up to -6 dB(A) difference, see Figure 9). It would mean that these strips tend to reduce the broadband noise but increase BPFs.

It would be interesting to see if by combining BLEX type devices (to reduce broadband turbulence noise) and a slight dissymmetry of the angular distribution (to reduce BPFs), it would be possible to win on both parts of the acoustic spectrum.

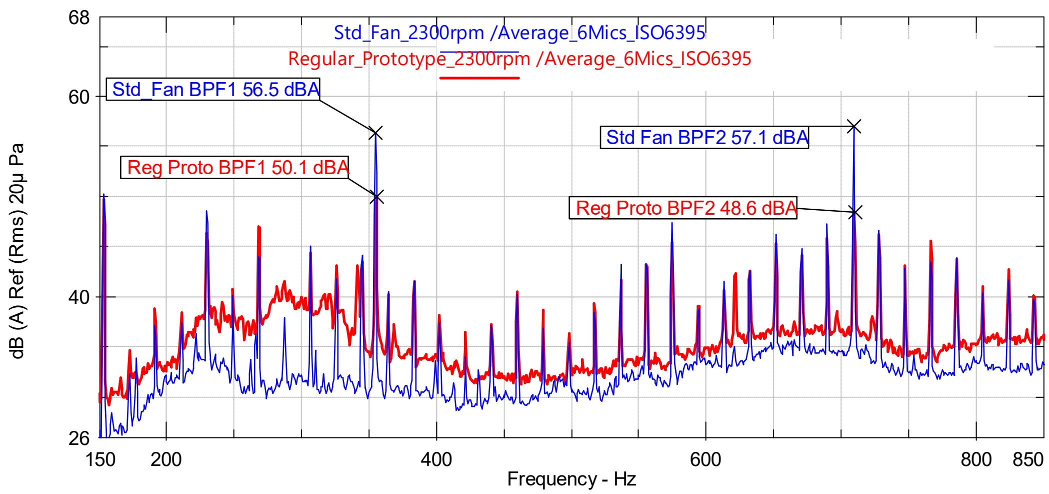


Figure 9. Average sound pressure over the hemisphere (dB(A)). Engine at 2300 rpm. Original and Proto Regular Fan

CONCLUSIONS & FUTUR DEVELOPMENTS

Irregular blade spacing fans were tested on an excavator. This study confirmed that IBSFs do not provide any reduction of the overall A-weighted sound pressure level, but this was not the desired objective. Concerning peak noise, BPF 1 and 2 are effectively eliminated by irregular fans, but to the cost of the increase of adjacent orders. These adjacent orders sometimes almost reach the level of the BPF, which goes against the desired result. Finally, it appears that the acoustic energy cumulated in the dominant orders of the fan is equivalent for regular or irregular fans (Figure 8). The above observations bring to the fore that the challenge of irregular fans is to be able to control how the energy is redistributed over the different orders.

This brings the question of how to optimise the angular distribution of irregular fans? The simplistic "Dirac" computation method appeared unreliable. Therefore, more complex and mature computation technics should be tested (an AAC, aero-acoustics computational study with Ffowcs Williams-Hawkins model is to be tested). In parallel, experimental measurements should be carried out. The parameters to be tested should be:

- Different angular distributions. It would be particularly interesting to test smaller asymmetries than the one tested in the present study. Authors have the intuition that it should end up to more even distribution of the energy on the different orders.
- The influence of obstacles in the flow (heat exchanger & engine), with a varying distance between the fan and the obstacle. The most important thing will be to see if the performances of the IBSF and especially their relative classification vary according to the presence and the position of an obstacle. If this is the case, the application of irregular fans will be very compromised, because the machine manufacturer will not be able to condition the internal architecture of the engine cavity to the issue of fan noise.

Another interesting observation is that standard fan equipped with strips is generating less broadband noise than the regular prototype fan that was not fitted with that device. As well, it appeared that the presence of these strips increases BPF 1 and 2 by 4 to 6 dB(A). If these 2 observations are confirmed, it would perhaps be interesting to see if a fan combining a BLEX type device (intended to reduce broadband turbulence noise) and a slight asymmetry of the angular distribution (to reduce the BPFs) would allow a reduction of both the broadband noise and the tonal characteristic of fan noise.

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