TURBO-COMPRESSOR AND PIPING NOISE ASSESSMENT USING A PARTICLE VELOCITY BASED SOUND EMISSION METHOD

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Currently, there are very few in-situ measurement procedures available to evaluate the noise emissions of large machinery. Pressure based techniques often encounter difficulties adapting to industrial scenarios from controlled laboratory experiments. The presence of high background noise levels generated by surrounding equipment, along with the reverberant characteristics of most industrial sites, prevents the application of standard sound characterization techniques. In contrast, particle velocity measurements performed near a rigid radiating surface are less affected by background noise and can potentially be used to address noise problems even in such conditions. The vector nature of particle velocity, an intrinsic dependency upon surface displacement and sensor directivity are the main advantages over sound pressure based solutions. In this paper, the foundations of the proposed method are presented along with the experimental evaluation of the flow-induced noise of a large turbo-compressor and piping system. The results show the capabilities of this method for identifying and quantifying noise emissions of problematic elements, despite high levels of background noise.

INTRODUCTION

The radiated noise defines the acoustic performance of a machine or device. The standard procedure for benchmark testing usually implies dismounting the machine and installing it in a testing chamber in order to capture the noise emitted by the device solely. This procedure is effective for small devices which can be moved, but applying it to large turbo-machinery is simply unfeasible.

Many noise sources and room reflections contribute to the sound pressure at a particular position. Even close to the radiating surface it is hard to distinguish the direct contribution from other disturbances. However, the normal component of the particle velocity near the vibrating surface is less affected by background noise and reflections for three main reasons[1] :

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- The particle velocity level, due to vibration of the surface itself, is higher than sound pressure because of near field effects.
- The particle velocity level, due to background noise, is usually low because many objects have high surface impedance. The incoming and reflected sound waves are nearly equal of strength but opposite in phase thus they interfere destructively.
- Particle velocity sensors are directional and can be pointed toward the vibrating surface, reducing the noise contributions from other directions.

For a long time, reliable particle velocity sensors were lacking. Invented in 1994, the so called Microflown sensor cover the full audible frequency range, have reduced dimensions, can easily be extended to full 3D probes, and can be used in environments with high levels of background noise or reflections [2–4]. It can also be used for measuring non-contact vibrations [4, 5], however using it for sound power estimation without combining it with sound pressure stands as a novel approach (presented in [1]) and it is hereby further investigated.

This paper evaluate the reliability of measuring the sound power emitted by large machinery using a novel particle velocity based in-situ technique. The sensor is firstly described before outlining the foundations of the sound power estimation method. Sound visualization results produced with the Scan & Paint measurement methodology [6] are then shown and finally, the practical implementation of the technique for evaluating the noise emitted of a larger turbo-compressor is discussed.

1 THE PARTICLE VELOCITY SENSOR

The particle velocity transducer consists of two short, thin and closely spaced platinum wires that are heated to about 300 °C [7]. The resistance of the wires depends on the temperature. An acoustic particle velocity signal in the perpendicular direction changes the temperature distribution instantaneously, because one of the wires is cooled more than the other by the acoustic flow, and this difference in resistance is measured with a bridge circuit that provides a signal proportional to the acoustic particle velocity. This particle velocity sensor is usually mounted along with a pressure microphone on a sound intensity *p-u* probe. A picture of its two heated wires is shown in the following Fig. 1 (right).

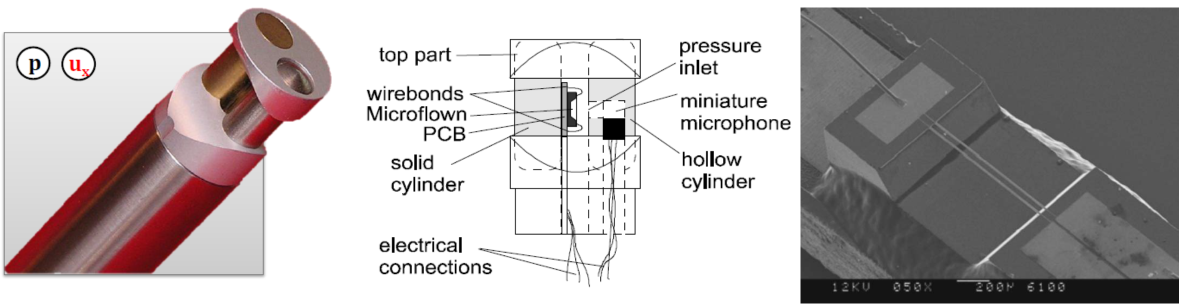

Figure 1: A sound intensity *p-u* probe (left), its structure (center) and the two wires of the Microflown particle velocity sensor (right).

2 SOUND POWER ESTIMATION

Sound power is one of the main characteristics defining the acoustic output of a noise source. This quantity has a fundamental role in many practical applications since it allows for the estimating of the acoustic impact of a machine or device in its operational environment. Furthermore, it is often used for benchmarking products from different suppliers. The particle velocity based intensity estimation principle is firstly detailed, introducing then the limitations linked to the impedance assumption implied in the calculation.

2.1 U-U Measurement Principle

Sound power is generally defined by the integral of the normal intensity over the radiating noise surface [8]

$$\Pi = \int_S I_n \mathrm{d}S, \tag{1}$$

where I_n is the normal component of the active intensity. I_n can be written as

$$I_n = \langle p\, u_n \rangle_t = \frac{1}{2}\mathrm{Re}\{p\, u_n^*\}, \tag{2}$$

where p is sound pressure, u_n is normal particle velocity and $\langle . \rangle_t$ indicates time averaging. The local ratio of the sound pressure to the particle velocity component in the direction of propagation is known as the wave impedance or specific acoustic impedance[9], i.e.

$$u_r = \frac{p}{Z}, \tag{3}$$

where Z is the specific acoustic impedance, and u_r is the radial component of the particle velocity. Assuming that most of the sound emitted by the assessed machine propagates normal to its surface, the sound intensity (Eqn. 2) can be then estimated from particle velocity measurements by using an equivalent impedance model [1]. For simple scenarios, depending on the type of sound wave - plane or spherical - the impedance term can be written as

$$Z = \frac{p}{u_r} \begin{cases} Z_{plane} & = \rho c & \text{Plane wave} \\ Z_{sphere} & = \rho c / \left(1 + \frac{1}{jkr}\right) & \text{Spherical wave} \end{cases} \tag{4}$$

where k denotes the wavenumber, c the speed of sound in air and ρ is the air density.

A different expression of the impedance can be implemented depending on the practical situation. The particle velocity intensities can thus be written as

$$I_{plane} = \frac{1}{2}\mathrm{Re}\{Z_{plane} u_n u_n^*\} = \frac{1}{2} \mid u_n \mid^2 \rho_0 c, \tag{5}$$

$$I_{sphere} = \frac{1}{2}\mathrm{Re}\{Z_{sphere} u_n u_n^*\} = \frac{1}{2} \mid u_n \mid^2 \left(\frac{k^2 r^2}{k^2 r^2 + 1}\right) \rho_0 c. \tag{6}$$

2.2 Practical Implications

According to the expression of Z_{sphere} (Eqn. 4), when $kr \gg 1$, the spherical wave impedance tends to the value of the plane wave impedance $Z_{plane} = \rho c$. However, when this parameter is small - in near field conditions - the spherical impedance value becomes much lower. The two impedance values are plotted according to the parameter kr in the following Fig. 2.

In practice, estimating the intensity from particle velocity measurements is more convenient if the plane wave assumption can be employed. Using the Eq.5, the distance probe-source does not have to be considered. However, if the product $kr \ll 1$, a non-negligible error on the impedance assumption might compromise the reliability of the estimation. The following Fig. 3 solves the error made estimating the intensity of a point source when using the plane wave impedance assumption, according to the distance r and the frequency.

When using the plane wave form of the intensity estimation I_{plane}, this representation can be used as tool to have an idea of reliability of the measurements, according to the probe-source

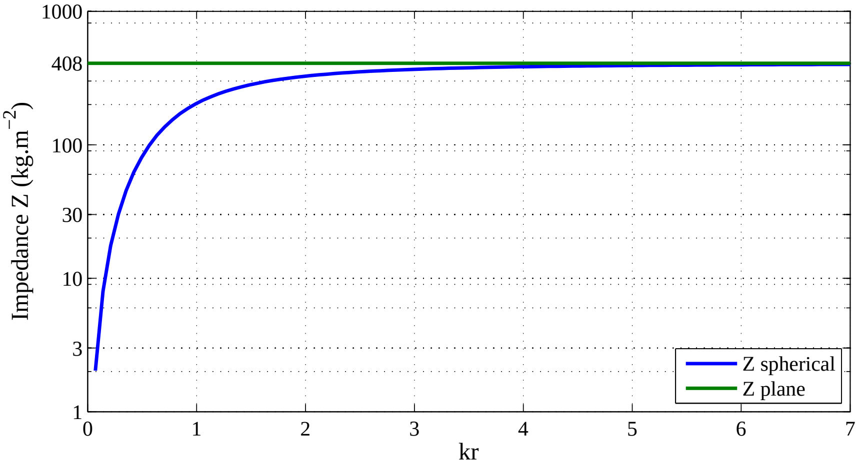

Figure 2: Impedance value with spherical and plane wave assumption according to the adimensional parameter kr

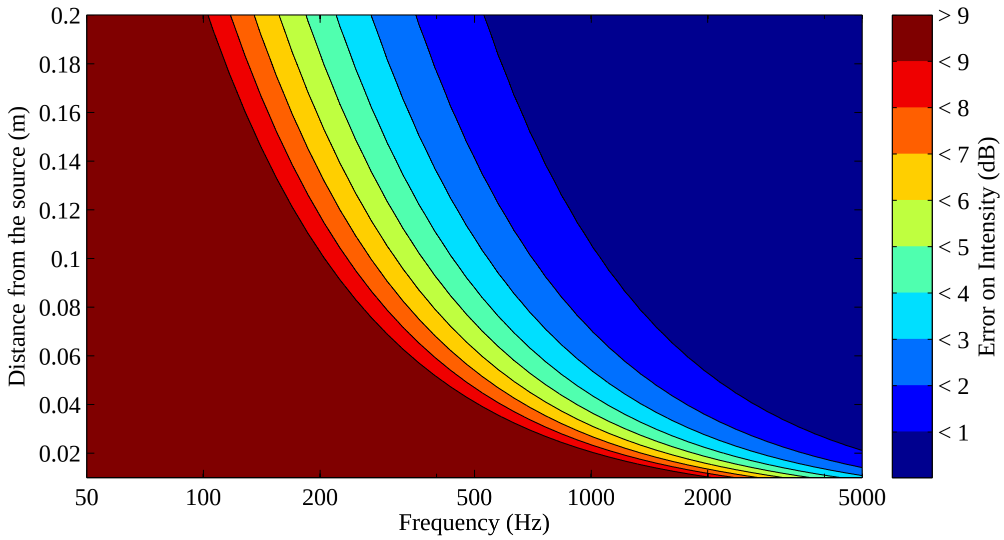

Figure 3: Error on the *u*-*u* based intensity estimation using plane wave impedance for a point source model, depending on the frequency and the distance from the source.

distance r and the frequency range of the study. For instance, at 10 cm from the source, the plane wave assumption induces less than 3 dB error when measuring above 550 Hz. If nevertheless the purpose of the study implies to characterize low frequency signals, it might be necessary to increase the measurement distance, but the method might loose of its interest.

Previous studies [10] have assessed the reliability of measuring the sound level from particle velocity measurements close to rigid boundaries and with high level of background noise. In such conditions, pressure measurements performed near a rigid boundary are always high. Incident and reflected sound pressure waves sum coherently resulting in reinforcements close to the boundaries. This effect can cause ambiguous results since high levels could be interpreted as radiated sound from the machinery instead of reflected sound from an external source.

In contrast, the particle velocity measurements present many advantages for source localization purposes. The figure-of-eight directivity pattern of the probe pointed toward the vibrating surface allows reducing the noise contributions from other directions. The background noise influence is also reduced because of the near field effect. Particle velocity level are actually higher than pressure level, which provides a better signal-noise ratio. However, close to non-vibrating structure, the normal particle is very low since it is proportional to the surface displacement.

3 MEASUREMENT METHODOLOGY: SCAN & PAINT

The measurement procedure to acquire the data is based upon the scanning technique "Scan & Paint" [6]. The acoustic signals of the sound field are acquired by manually moving the sensor across a measurement plane whilst filming the event with a camera. In the post-processing stage, the sensor position is extracted by applying automatic color detection to each frame of the video. The recorded signals are then split into multiple segments using a spatial discretization algorithm, assigning a spatial position depending on the tracking information. Therefore, each fragment of the signal will be linked to a discrete location of the measurement plane. Next, spectral variations across the space are computed by analyzing the signal segments. The results are finally combined with a background picture of the measured environment to obtain a visual representation which allows us to "see" the sound. Figure 4 presents a sketch of the measurement methodology.

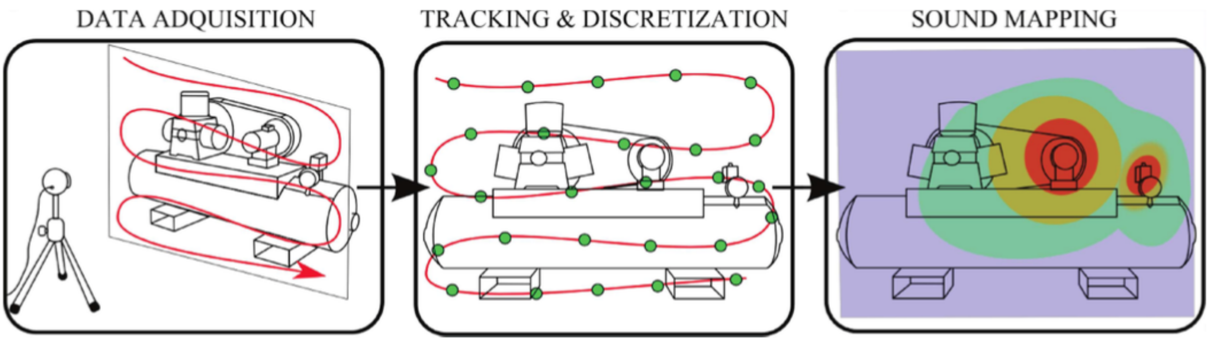

Figure 4: Illustration of the basic steps undertaken with the Scan & Paint measurement method.

The use of a 2D tracking system limits the ability to estimate the distance of source from the sensor. Nonetheless, 3D trackers got available nowadays [11], but they have not been used for these experiments for a matter of process convenience.

4 PRACTICAL IMPLEMENTATION

The proposed method has been tested on a turbo-compressor located in a reverberant industrial room, with high background noise levels. Scanning measurements were performed on the gas turbine package, the compressor and its associated pipework, the turbine building intake filter, the walls and the exhaust stack. The purpose of these experiments was first to locate the sources of noise, to then estimate the sound power of each part of the turbo-compressor. The following Fig. 5 shows an overview of the system.

4.1 Instrumentation and measurement scenario

All measurements were carried out with a Microflown P-U probe which contains a pressure microphone (unused) together with a particle velocity sensor. The probe was connected to a signal conditioner, itself connected to a DAQ (MF Scout 422). The displacement of the probe was filmed by one camera placed at three different spots (Fig. 5). A reference microphone has been placed to check the stationarity of the source.

After having set up the material (about 5 minutes), the scan could be performed by moving the sensor close to the surface of the turbo-compressor. The camera recorded the displacement of the probe, then discritized to 120 points each, for a total of 360 measurement points. Each

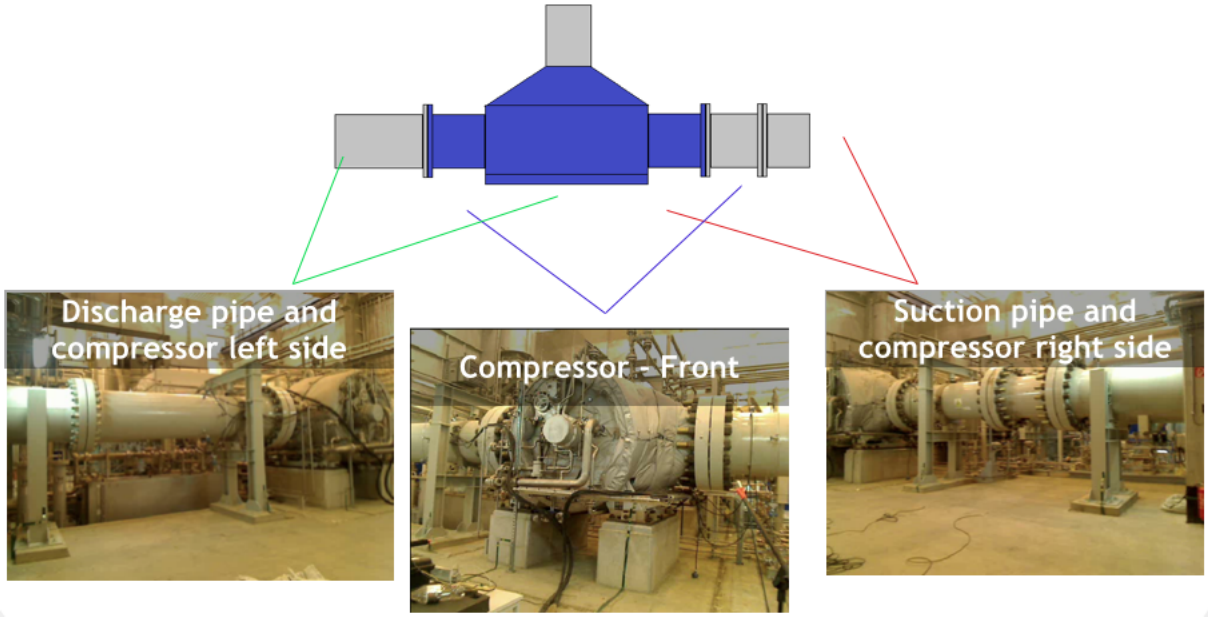

Figure 5: Overview of the turbo-compressor system.

scanning session lasted about 10 minutes, because of the size of the machine. Once the data was acquired, the probe tracking and the sound mapping were post processed. These three steps are illustrated in Fig. 6.

Figure 6: 3 steps of the process : scanning measurements (left), probe tracking (center), sound mapping (right).

4.2 Experimental results

The Scan & Paint system enabled to plot intensity maps (Fig. 7) from the plane wave intensity I_{plane} (Eq.5). The results have been computed into two frequency bands of 40 Hz-200 Hz and 200 Hz-2000 Hz. The absolute dynamic range is omitted due to confidentiality agreements. The following plots have been normalized to maximum measured value.

These pictures show that the left section of the compressor (the discharge pipe) is the dominant source at lower frequencies. However the total energy on this frequency range is negligible compared to the mid and high frequency excitation. The computation of the 200 Hz - 2000 Hz band (on the right) reveals that the noisiest element is the middle section of the suction pipe, on the right of compressor.

In addition, the average sound power spectra of each of the three parts of the machinery are plotted in Fig. 8. It is computed using the average intensity of each scan and their estimated area using Eq.1.

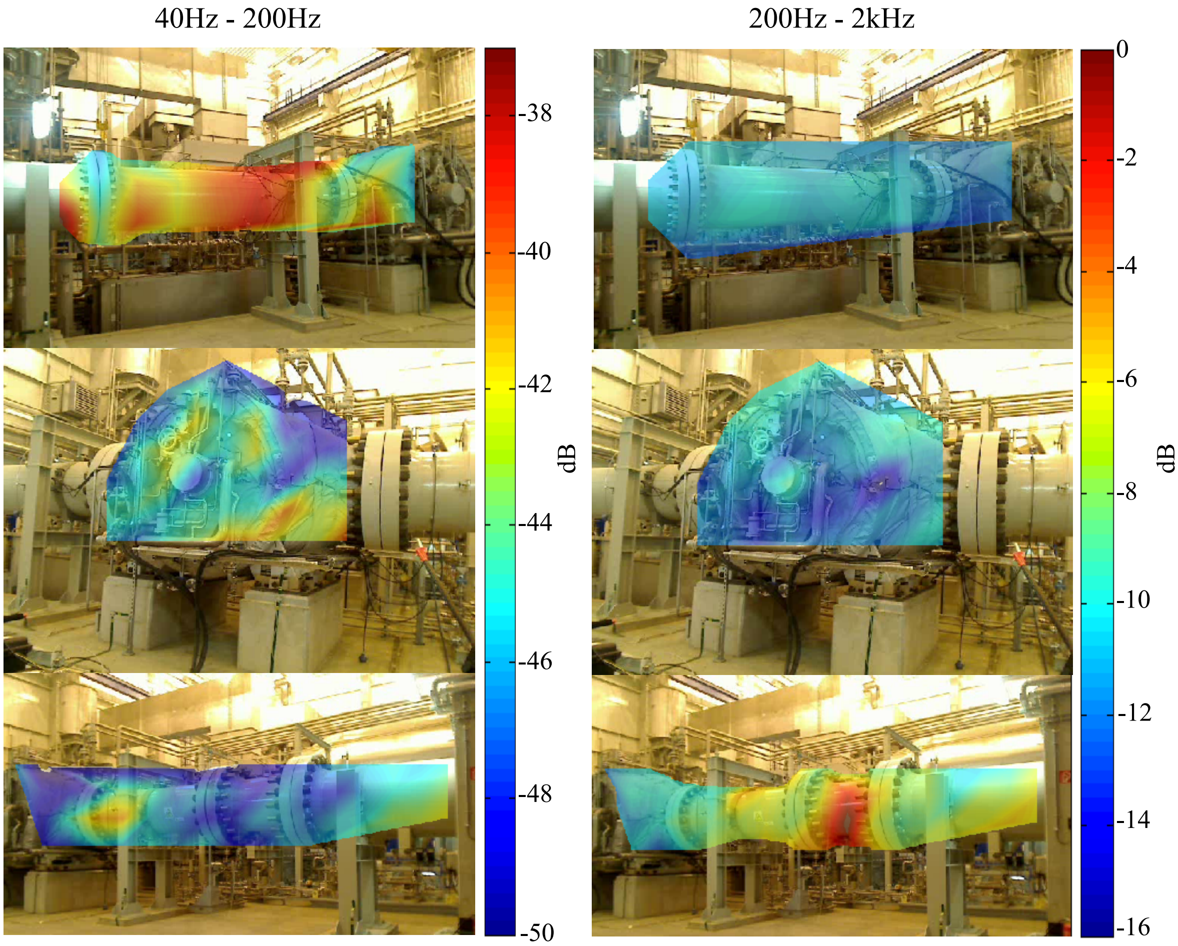

Figure 7: Particle velocity based Scan & Paint sound intensity mapping on the frequency bands 40 Hz-200 Hz (left), and 200Hz-2000 Hz (right).

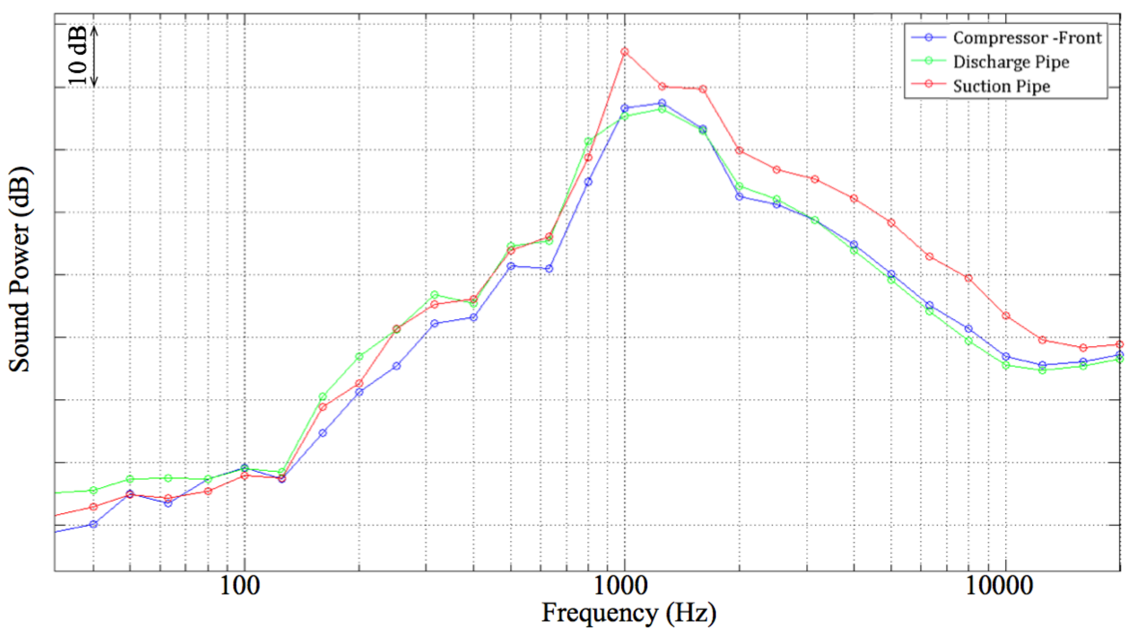

Figure 8: Particle velocity based sound power estimation on the three parts of the turbo-compressor system according to the frequency.

This results confirms the previous observation. The radiated sound power measured on the suction pipe is from 5 dB to 10 dB higher than on the compressor and the discharge pipe up to 1 kHz.

This study was performed in order to solve a noise issue encountered on the operating turbo-compressor. The results revealed the main problematic source : the middle section of the suction pipe. According to the sound power spectra comparison shown in Fig. 8, this part of the installation appeared to be the dominant noise source from 1 kHz to 10 kHz. After dismounting this duct, it was found that the strainer contained inside was badly mounted, causing a strong rattling noise.

CONCLUSION

The experiments have proven the reliability of *u-u* based intensity estimation along with the Scan & Paint method, providing quick and useful results. The particle velocity sensor characteristics allow for the adaptation of acoustic intensity measurements to industrial scenarios despite high levels of background noise or reverberation. For the turbo-compressor case, sound maps provided a clear location of the dominant noise source. Furthermore, the computation of sound power enabled the ranking of different elements. Further investigations should be undertaken to assess the *u-u* intensity method capabilities on non-reflective surface materials. A 3D tracker would make better detection of the probe position possible, providing information about the distance of the probe from the machinery surface during the scan process, and thereby enhancing the accuracy of the results.

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