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Enhancing Sound Source Localization with Noise Separation Methods

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Noise source diagnosis is main importance in many fields such as the transport industry, industrial machinery, and household appliances... The spatial localization of these sources is a first step before one can take counter measures. But solutions are usually curative ones to cover external sources. It would be more efficient to identify and to treat the associated original phenomenon. Sound source localization methods usually identify the area that emits the most sound, but they do not give information about the underlying components that contribute to a source. Noise separation methods split raw microphone data into their contributing signals. Examples are separating pure tones from large bands, correlation techniques and cyclo-stationary analysis. Combining both localization and separation methods results in a powerful technique that enables spatial localization of sources depending on their different contributing phenomena. Three examples are presented. First of all, a vacuum cleaner, where the diagnostic tries to separate engine noise from aerodynamic turbulence of the nozzle. The second example aims to separate and localize combustion noise from other mechanical noise sources on an engine. The last example is on fan noise and shows how to identify noise sources due to cyclic events of blade passing.

1 Introduction

Acoustic imaging is a technique to localize noise sources on the object surface. This diagnostic is limited to the identification of the most emissive external components without information on their origin. In most cases, the external components are excited by other phenomena: mechanical sources, aeraulic turbulences … In order to reduce them, it is an advantage to link an emissive acoustic source to its coherent physical origin.

Some noise source separation methods exist and have proved their efficiency in separating a signal into several components which group coherent parts of the signal. The article presents some of them in the first chapter. The more difficult they are to implement, the more information they give.

If these methods are applied to each of the signals obtained with a microphone array keeping their true phase, then it is possible to process each of the components by localization. The combined process is named “referenced acoustic imaging” and is detailed in chapter 2. It links acoustic sources emitted by the noisy product to the physical mechanisms.

Three industrial application cases are presented in the last chapter. The different noise source separation methods presented in the first chapter are applied to better interpret the acoustic imaging of 3 industrial products. The first one works on a vacuum cleaner with simultaneous aeraulic and mechanical sources and tries to separate their contributions in the noise. The second one explains how to apply these methods to a combustion engine with mechanical cyclic sources. The last example separates fan aeraulic cyclic sources from aeraulic sources around the fan blade.

2 Noise source separation methods

The chapter lists some of the noise source separation methods and tries to give their advantages with their fields of application and their drawbacks with their limits of use. They are grouped into two categories: the coherence- based methods better adapted to random signals such as aeraulic noise sources and the cyclo-stationnary methods developed for rotating machines.

2.1 Coherence methods

This paragraph presents the reference filtering methods based on the coherence function defined by:

$$\gamma_{xy}^2 = \frac{\left|S_{xy}\right|^2}{S_{xx}S_{yy}} \leq 1 . \tag{1}$$

This coherence function can be applied to any measurement with reference, acquiring the purest signal of each of the mechanisms synchronously.

The easiest implementation is to use a single reference like an accelerometer on the mechanical sources, or a microphone close to aeraulic turbulences. It filters out a signal x(t) in a coherent part and a non-coherent part with r(t), as follows :

$$X(f) = \gamma_{xr}^2 .X(f) + (1-\gamma_{xr}^2).X(f) . \tag{2}$$

The coherent output spectrum is well-known and has been widely used in the automotive and aircraft industries for ‘measurement noise’ rejection (flow noise rejection [1], direct and reverberant field separation in highly reverberant aircraft cabins [2]]). It is possible to separate them within the signal because their coherence is equal to zero.

The main limitation of the coherent output spectrum method concerns the case where the reference signal is polluted by other uncorrelated sources, leading to under-estimation.

A Three-Microphone Method can be used in order to overcome the limitations of the coherent output spectrum method, for example when measuring turbofan engine noises [1,3].

For multi-reference purposes, the Conditioned Spectral Analysis (CSA) is based on the cross-spectral matrix. It consists in a distortion/conditioning of the matrix so that the auto-spectrum and cross-spectrum terms are modified with respect to each reference-modifying matrix term so that it only contains its part that is uncorrelated with the reference. CSA has to be applied successively with several conditioning channels.

It has been applied to combustion noise and mechanical noise separation in a diesel engine ([4]) and for the extraction of the steady-source noise of an aircraft propeller [5]. Nevertheless, as reference channels are often not made of a unique source, the conditioning operation leads to the attenuation of all sources that are acquired by this reference sensor. The second limitation of CSA concerns the order in which the conditioning channels are taken for successive conditioning.

The Principle Component Analysis (or Virtual Source Analysis (VSA)) is an alternative to CSA. It is also based on the cross-spectrum matrix. It consists in numerically separating the different signals in uncorrelated virtual source contributions. The contributions of virtual sources are provided by the Eigen-value decomposition of the cross-spectral matrix for each spectral line. The difficulty of this method lies in the association of the virtual source and one (or more) real source(s). In that aim, it is possible to estimate the coherence between the complete set of sensors and the virtual source to be identified.

This list points out that coherence-based methods are numerous but their implementation is not easy due to the use of reference sensors. They are only efficient with pure references. The Principal Analysis Component avoids this additive instrumentation but the concept of virtual sources is difficult to link to physical sources.

2.2 Wiener filtering and cyclo-stationary method

This paragraph presents the cyclic Wiener filtering method which is used in the automotive industry and described in [6,7]. It is originally dedicated to combustion noise filtering on an internal combustion engine.

This filtering method differs from coherence-based filtering techniques in so far as a synchronous temporal windowing is needed, the latter depending on the periodicity of the studied machinery. The measured signal y(t) is the sum of x(t), the desired signal and b(t), an unknown additive noise:

$$y(t) = x(t) + b(t) \tag{3}$$

r(t) is a reference signal that is fully coherent with x(t) and uncorrelated with b(t). The aim is to find the best linear filter h(t) satisfying:

$$\hat{x}(t) = h(t) * r(t) \tag{4}$$

Or in the frequency domain

$$\hat{X}(f) = H(f).R(f) \tag{5}$$

With

$$H(f) = \frac{S_{yr}(f)}{S_{rr}(f)} \tag{6}$$

where S_{yr} is the cross-spectrum between y and r, S_{rr} is the autospectrum for the reference r.

The x(t) contribution to a measured channel y(t) can then be computed by applying the transfer function h to the reference r(t).

The Wiener filter has been extended **[1]** to cyclo-stationnary signals that are characteristic of rotating machines, through angular windowing synchronized with the rotation. These angular averaging operations ensure that the desired transfer function H(f) converges and must be carried out with synchronized temporal windows that repeatg themselves with a period that equals a rotation cycle.

The cyclo-stationnary method has been successfully applied to automobile applications for combustion noise extraction. Cyclic Wiener filtering is usually done in the time domain and thus gives the ability to listen to the filtered signal for a subjective evaluation. It has to be noted that the cyclic Wiener filter is sensible to synchronization errors. The latter leads to low-pass filter behaviour with a cutting frequency generally taken at approximately $F_{sync}/16$ ([8]).

3 Referenced acoustic imaging

3.1 Noise source localization preceding by noise source separation

The difference between noise source localization and noise source separation is that the first identifies sources in space and the second identifies sources in raw signals. They can be combined to better understand the noise source generation process.

The preceding chapter has presented a few noise source separation methods. All of them could be applied before the noise source localization algorithm due to method properties (linearity). The noise source separation applied to microphone array gives several components. Each of them constitutes the input data for the noise source localization algorithm instead of raw microphone signals. The retro-projected component gives a partial noise source imaging and their addition gives the complete noise emission map.

In acoustic imaging, the interest of principal component analysis is limited to pre-processing for noise source localization methods based on phase reference (eg Equivalent Source Method [8]). The virtual sources are difficult to interpret physically and they are moreover differently ordered with frequency lines; the first one is always the most energetic. This combination does not improve the comprehension of noise source generation. In any case, it could improve the signal to noise ratio because noise is usually grouped in low level components.

The coherent output spectrum has been widely used in the past when data acquisition systems limited the number of channels and the microphone array was moved to obtain complete measurement grids. With the progress in hardware, this technique is now re-used to obtain real-time referenced acoustic imaging. The interest is to quickly interpret sound source localization results.

Other multi-referenced methods could also be combined to acoustic imaging, but they are still difficult enough to implement in the first noise source separation post-processing to discourage their use.

In recent years, the improvements concern cyclo-stationary analysis. The Wiener filtering combined with cyclic synchronization adds a full comprehension of quasi-simultaneous noise source process generations with successive mechanical or aeraulic excitation. The example detailed in the next chapter points out this interest.

3.2 Experimental set-up

To better illustrate the coupling of noise source separation and localization methods, a simple experiment tried to separate 2 uncorrelated sources based on coherent output spectrum pre-processing. The acoustic maps are carried out by focalization. Figure 1 shows three acoustic imaging results with the same acquired data and beam-forming algorithm but different pre-processing. With a principal component analysis in pre-processing, the tow sources are clearly separated on the same map, then carrying out referencing with a microphone close to one of the sources; it decreases the main lobe level around the second one.

This experiment has combined noise source separation and localization in a simple case, but the next examples point out the power of this double processing to better interpret noise sources.

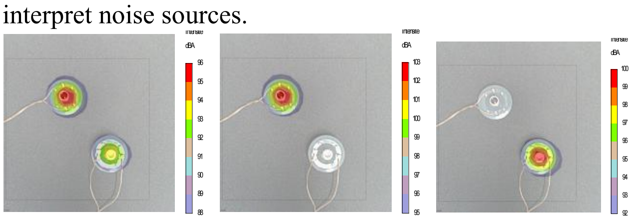

Figure 1: noise source localization results proceeding with principal component analysis (left), upper-left source reference (middle) and lower right reference (right).

4 Application case

4.1 Separating motor and aero-acoustic sources in a vacuum cleaner

This example is interesting because the product itself simultaneously emits sources with mechanical and aeraulic origins.

To reference acoustic sources with the motor, an accelerometer has been patched on it. For turbulences, it is difficult to position references because their origins could be numerous (any cavity, flow deviation). Moreover, the instrumentation should not modify the flow propagation. For this reason, the real-time coherent output spectrum processing combined with noise source localization is an added value. This functionality is available in HDCam acoustic camera, the system used to realize this experiment. A microphone was successively positioned on suspected sources and the real-time referenced acoustic imaging extracted in Figures 3-4-5 authorizes a fast diagnostic. The frequency range of interest is between 1800 and 3200 Hz where the motor emits a pure tone with a global RMS level equal to aeraulic sources as shown on Figure 2.

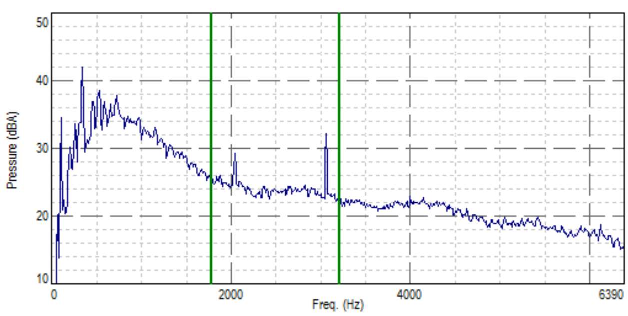

Figure 2: average spectrum on array for a vacuum cleaner on carpet with the frequency range of analysis

The localization maps compare results with three methods.

The principal component analysis on Figure 3 gives the main source areas: on the brush, along the upper handle, on the top of trolley,

The coherence analysis with the accelerometer on the motor (Figure 4) reinforces sources on the trolley, which indicates their mechanical origins. The other sources have not been completely erased, which means that part of the mechanical sources are also propagated inside the handle and exit via the brush.

The coherence analysis on Figure 5 with the microphone inside the brush naturally shows the source on the brush but this noise also propagates and exits along the handle. This source also reflects on the trolley.

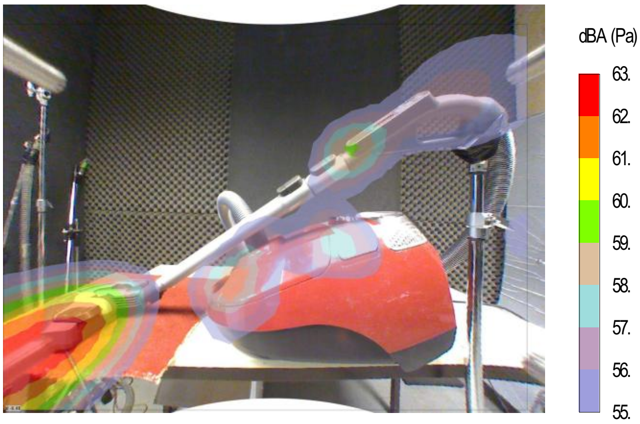

Figure 3: noise source localization with a principal component analysis

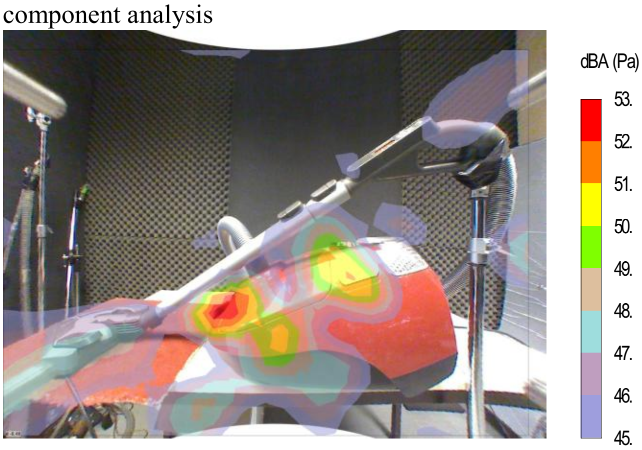

Figure 4: noise source localization with coherence analysis from accelerometer on motor

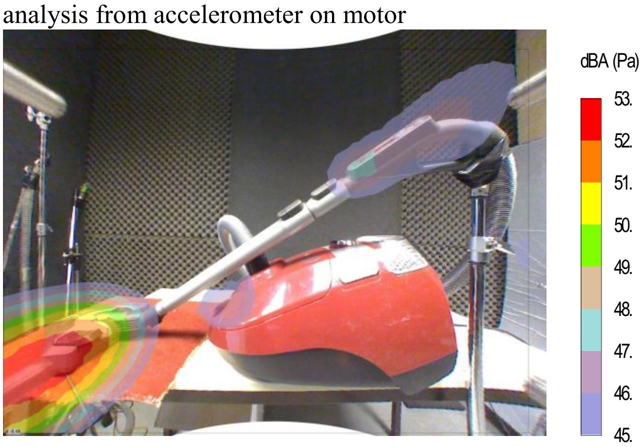

Figure 5: noise source localization with coherence analysis from microphone inside the brush

This simple experiment has pointed out the interest of coupling noise source separation and localization methods to interpret noise source propagation.

4.2 Application case on an engine

References [6,7] show that the cyclic Wiener filter can be used to quantify the part of the acoustic energy due to combustion from the total energy in so far as the combustion noise is separated from the mechanical noises.

The cyclic Wiener filter can be used successively with each of the 4 cylinder pressures as a reference in order to study the contributions of each cylinder separately; they can be individually mapped using acoustical imaging algorithms in conjunction with engine test bench measurements.

Finally, knowing the cylinder pressure and the combustion noise (independently from the mechanical noises) gives access to the estimation of the structural loss of the engine. Examples presented in [6] show that this filtering is convenient for comparing the effect of structural modifications.

In this article, to illustrate the interest of this filtering method to separate combustion noise, raw and filtered data are respectively presented in Figures 6 and 7.

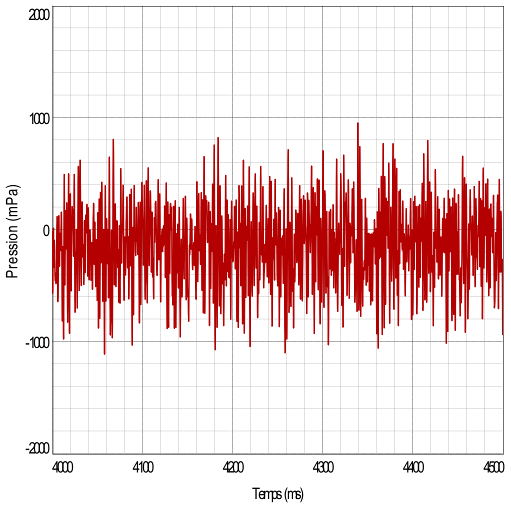

Figure 6: raw data from a microphone of the array positioned in front of an engine

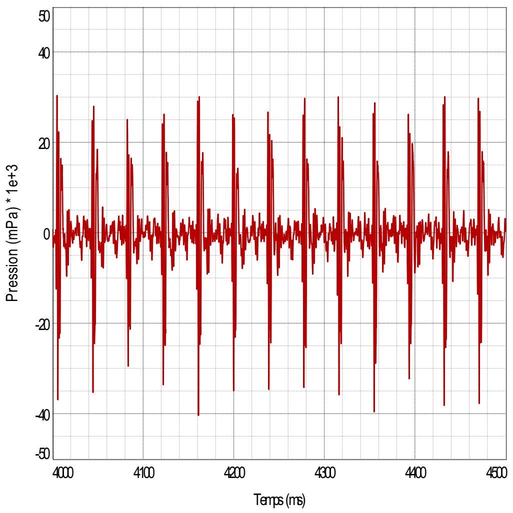

Figure 7: filtered data with cyclo-staionary Wiener filter from a microphone of the array positioned in front of an engine

The cyclic impulsive combustion noise is clearly separate and it is easy to imagine the improvement in noise source localization applying this filtered data.

4.3 Aero-acoustic source separation with a fan in its environment

For confidential reasons, this last example is illustrated in this article by a theoretical case but it has been applied on a real product in the context of AROMAT project supported by ANR for the analysis of electric engine cooling systems.

A fan with 10 blades is powered by a small electric engine. To create an extra source which should be identified in the surrounding independent environment, a small plate was positioned behind the blades, in a perpendicular plane. At high speeds, it is excited by each blade passing the surface. An accelerometer was patched on this plate to obtain a coherent reference.

In this example, to separate sources, cyclo-stationary Wiener filtering was applied with a cycle equivalent to the blade passing frequency. The noise source localization algorithm was then applied. The aim of this study was not to obtain the source contribution of a fixed source but that due to blade passing. An analysis of a rotating reference like ROSI method could also separate fixed and moving sources, but without separating those due to blade passing [10].

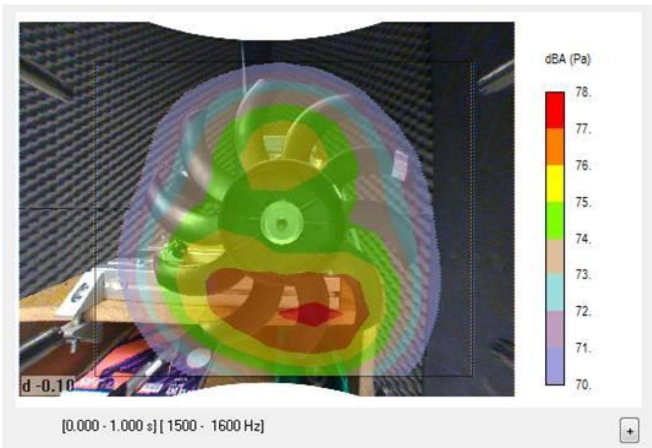

Figure 8: noise source localization with a principal component analysis in 1500-1600 Hz range with the fan.

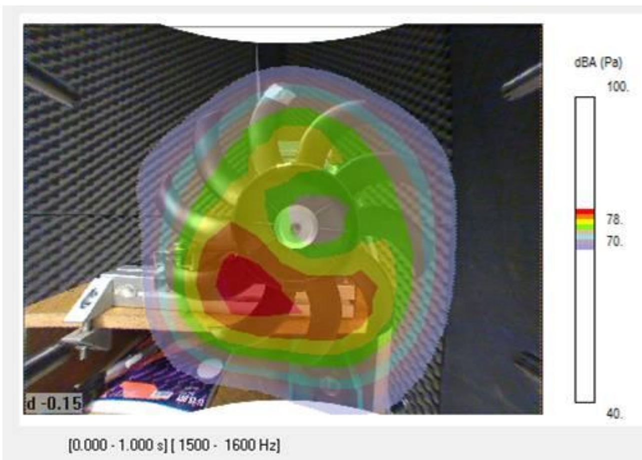

Figure 9: noise source localization with a principal component analysis in 1500-1600 Hz range with the fan and the plate.

After a principal component analysis whose results are shown in Figures 8 and 9 comparing results with and without the plate, the source area was extended to the blade surface because main sources are located around them and are rotating. The maps are similar, but the comparison of average spectrum on the array identified an extra source.

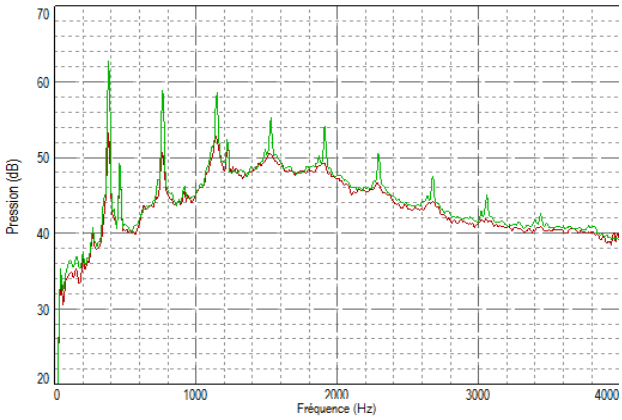

Figure 10: comparison of noise emission between the configuration of the fan (red curve) and the fan and the plate (green curve).

A coherence analysis carried out from simple output spectrum indicates that the source on the plate remains with another source (Figure 11). They are only 4 dB lower with this first filter, indicating that they are of main importance. With cyclo-stationary Wiener filtering, the second source disappears, leaving an accurate localization of the sole source, generated by the regular blade passing the small plate. Another interesting result is the residue of the filtering on Figure 13 because the localization map is the same as the fan in absence of the plate (Figure 8). This proves that this method can also efficiently erase a source.

This experience has demonstrated the added-value of cyclo-stationary Wiener filtering in noise source emission diagnostic for cyclic events due to rotating objects.

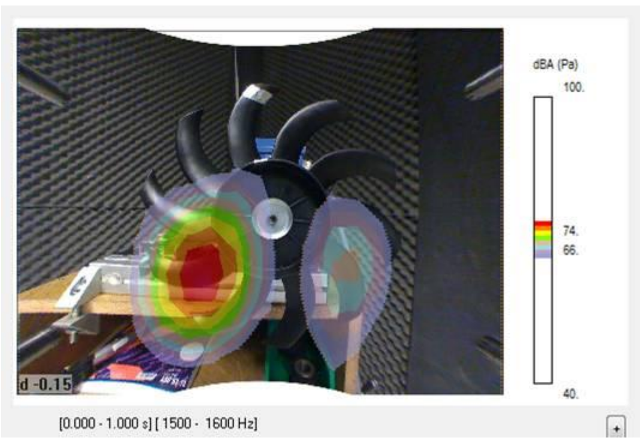

Figure 11: noise source localization with coherence analysis from accelerometer in 1500-1600 Hz range on a fan and a plate exited by blade passing.

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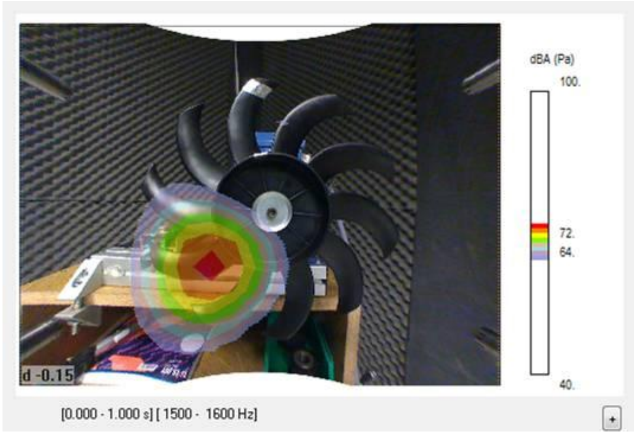

Figure 12: noise source localization with cyclo-stationary Wiener filtering in 1500-1600 Hz range from a fan and a plate exited by blade passing.

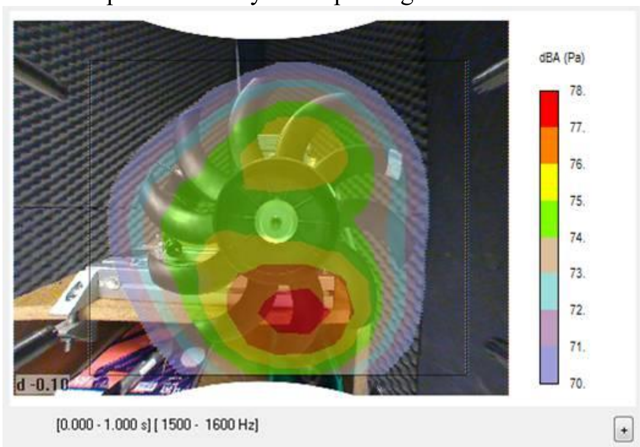

Figure 13: noise source localization the residue of cyclo-stationary Wiener filtering in 1500-1600 Hz range from a fan and a plate exited by blade passing.

5 Conclusion

The examples stated in this article have demonstrated the interest of combining noise source separation and localization methods to better interpret external noise emissions and to associate them with the internal original mechanism in order to treat them. Their implementation is not an easy task in most cases. The noise source separation step needs a dedicated instrumentation attached to the original mechanism to obtain the purest signal. The noise source localization algorithm is applied to each component, increasing computation cost.

However, this technique has many fields of application because of its added-value. It is now industrialized in noise source localization tools like HDCam or 3DCam acoustic cameras to facilitate their use.

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