Acoustic imaging applied to fault detection in rotating machine

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Abstract

Fault detection in rotating machines is generally based on vibration signal analysis. However, the sound radiated by a structure and its vibration are closely linked. We can therefore imagine that acoustic measurements could be useful for diagnostic improvement. In this paper, a fault diagnostic method based on acoustic imaging is proposed. Beamforming is used to describe the acoustic field generated by an operating machine. Usually, the source strength is mapped in order to identify the radiating areas. In this paper, fault detection features are plotted instead. The spectral kurtosis is mapped as a function of space and frequency to separate and localise impulsive sources.

1 Introduction

Acoustic imaging is most likely used as a noise source identification method than a diagnostic tool. Although some studies have already been done [3, 4], fault detection based on acoustic imaging requires more attention. Actually, surveillance and diagnostic of rotating machines usually belongs to vibration analysis domain. One of the reason is that only a few accelerometers are needed to achieve the diagnosis whereas acoustic imaging requires an expensive antenna with a lot of microphones. Another reason is due to the scientific heritage which provides a wide range of signal processing tools for fault detection based on vibration analysis. However, acoustic imaging can be seen as a complement to vibration-based diagnostic. Signal processing methods used in the vibration domain can also be applied to acoustic signals. Moreover, acoustic imaging will provide spatial information of the fault allowing to localise it, which is not always possible in vibration analysis. Another advantage of acoustic measurement is that it does not require a contact with the part to be analysed.

The aim of this paper is to highlight the relevance of acoustic imaging as a fault detection tool. The spatial localisation aspect brought by acoustic imaging can be combined with standard fault diagnostic tools. The spectral kurtosis allows to separate impulsive components buried into a signal. Knowing that different faults in rotating machines produce a series of repetitive short transient forces justifies the use of kurtosis to detect them.

Beamforming [1, 2] is first used to give displays of time varying source distribution on a machine surface. Then the spectral kurtosis [5, 6] can be applied to this generated signals in order to obtain an ”impulsive” source distribution as a function of space and frequency. The efficiency of this approach for separating impulsive noise sources will be demonstrated.

2 Beamforming

Beamforming can be considered as one of the oldest acoustic imaging methods. This source location technique was inspired by telecomunication methods and is often refered to as ”acoustic telescope” [1]. In spite of its age, beamforming is still used in the industrial field [2] because of its many advantages. Indeed, this array-based measurement technique can be used from short to long distances, requires a poor calculation time and is less sensitive to noise compared to other methods. However, beamforming has a low spatial resolution at low frequencies.

The principle of source location lays on the numerical focusing of the microphone array toward a direction (or point). The amplitude of planar (or spherical) waves coming from this direction (or point) is estimated.

Chosing a set of different directions will allow to map the source strength distribution over a surface. This calculation can either be processed in time or frequency domain depending on the results needed. In this paper, only the time approach is considered. The algorithm used is equivalent to a "delay and sum" beamformer. Each signal is delayed relatively to the distance separating the microphone and the source under consideration.

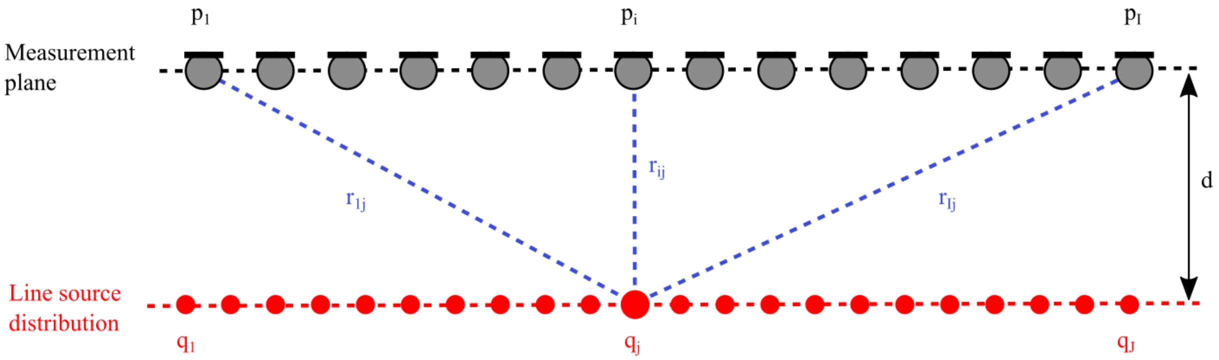

Figure 1: Beamforming setup focusing on q_j

Figure 1 shows a typical 2D setup for beamforming processing. A linear array made out with I microphones is placed in parallel with a radiating line. The distance d between the antenna and the identification line is taken so as to consider spherical waves. Thus, the linearly distributed sources q_1 to q_J are monopole radiators. The pressure measured by microphone i can be written as follow

$$p_i(t) = \sum_{j=1}^{J} \frac{q_j(t-\Delta_{ij})}{r_{ij}} \tag{1}$$

$$\Delta_{ij} = \frac{r_{ij}}{c} \tag{2}$$

r_{ij} being the distance from microphone i to source j, c the spherical waves speed, and Δ_{ij} the delay. Equation (1) can be written for each microphone, leading to a set of equations to be inverted in order to identify q_j. The least squares solution gives

$$q_j(t) = w_j \sum_{i=1}^{I} \frac{p_i(t+\Delta_{ij})}{r_{ij}} \tag{3}$$

$$w_j = \left(\sum_{i=1}^{I} \left(\frac{1}{r_{ij}} \right)^2 \right)^{-\frac{1}{2}} \tag{4}$$

w_j is a weighting factor which takes into account the mean distance between each microphone and the source. Thanks to equation (3) it is possible to identify all the sources by computing an iteration over the whole surface. The results can be mapped as function of time and space.

3 The spectral kurtosis

It has been shown that the spectral kurtosis is a relevant tool for fault detection [5, 6]. Rotating machine components such as bearings or gears generate impulsive vibration when they fail. However, it is not an easy task to enhance these signatures because of the noise generated by the other parts of the machine.

The kurtosis is a statistical feature that measures the impulsiveness of a signal. It only gives a scalar result when applied to a time-varying signal, which isn't sufficient to conclude about a failure on a machine. The spectral kurtosis (SK) is an optimized version of the kurtosis. It makes possible to identify the frequency band in which the kurtosis is important. Therefore, calculations are made in the frequency domain. SK computing can be interpreted as follow : a filter bank decomposition of the signal will feed a spectral kurtosis algorithm. Such a decomposition can be processed by the short-Time Fourier Transform (STFT). Let us consider a signal $Y(n)$, the sampled version of $Y(t)$. A definition of the STFT is given by

$$Y_w(kP,f) = \sum_{n=-\infty}^{+\infty} Y(n)w(n-kP)e^{-j2\pi nf} \tag{5}$$

$w(n)$ is the N_w length analysis window and P a temporal step. Now, the $2n$th order spectral moment of $Y_w(kP,f)$ has to be introduced

$$\hat{S}_{2nY}(f) = \langle |Y_w(kP,f)|^{2n} \rangle_k \tag{6}$$

$\langle \bullet \rangle_k$ being the time-averaged operator over the portion k. A definition of the SK estimated with STFT is given in reference [5]

$$\hat{K}_Y(f) = \frac{\hat{S}_{4Y}(f)}{\hat{S}_{2Y}(f)} - 2, \quad f \neq 0 \tag{7}$$

Notice that the spectral kurtosis results lay on one parameter : the window length N_w introduced in equation (5). It will directly influence the spectral resolution of SK. It has been shown [6] that too small values of N_w lead to a strong bias whereas a too fine spectral resolution will make the SK decrease to zero. Thus, a compromise has to be found.

Equation (7) can be used to design an optimal filter filtering out the mechanical signature of faults when applied to the original signal. Here, a different approach is proposed. The combination between acoustic imaging and SK will allow to visualise a new kind of mapping : the impulsiveness as a function of space and frequency.

4 Combination of beamforming and SK

In the previous sections, we've been through some theoretical knowledge and definitions. In this section we will get to the root of the problem which is to apply acoustic imaging to fault detection. As it has been said previously, we will use the signal generated by the beamformer to feed a SK algorithm.

Equation (3) provides a set of time varying signals $q_j(t)$. Lets apply equation (7) to these signals

$$\hat{K}_{q_j}(f) = \frac{\hat{S}_{4q_j}(f)}{\hat{S}_{2q_j}(f)} - 2 \tag{8}$$

It is noteworthy to say that beamforming results which are function of time and space are turned into functions of frequency and space through equation (8) as it is illustrated in figure 2.

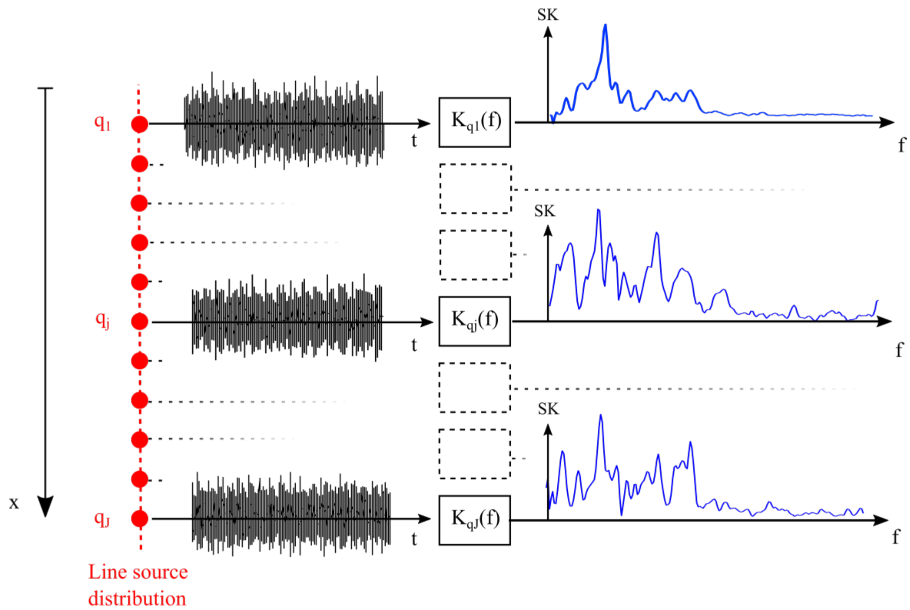

Figure 2: Illustration of the mapping of spectral kurtosis as a function of space and frequency.

In the next section, this approach will be tested on real signals.

5 Application to fault detection

The experimental application concerns a machine which can be considered as a linear distribution of point sources. A linear microphone array is placed in parallel with the radiating line. The antenna is made out with 30 microphones regularly distributed with a 2 cm step. A 15 seconds measurement is processed while the machine is operating.

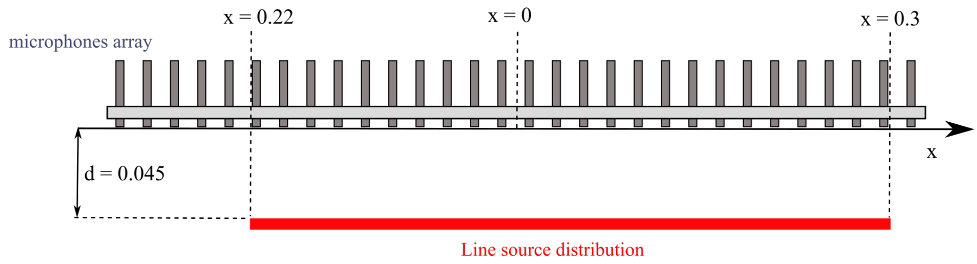

Figure 3: Study setup.

It could be useful to map the source strength as a function of frequency and space in order to visualize radiation features of the mechanism. The output of the beamformer in the frequency domain allows us to obtain such results which are presented in figure 4. At first sight, we can hardly identify sources that can be related to a fault. Moreover, the energy radiated is more important at low frequencies which is the domain where beamforming has a bad spatial resolution. Hence, this visualization is not optimal for fault detection in our case.

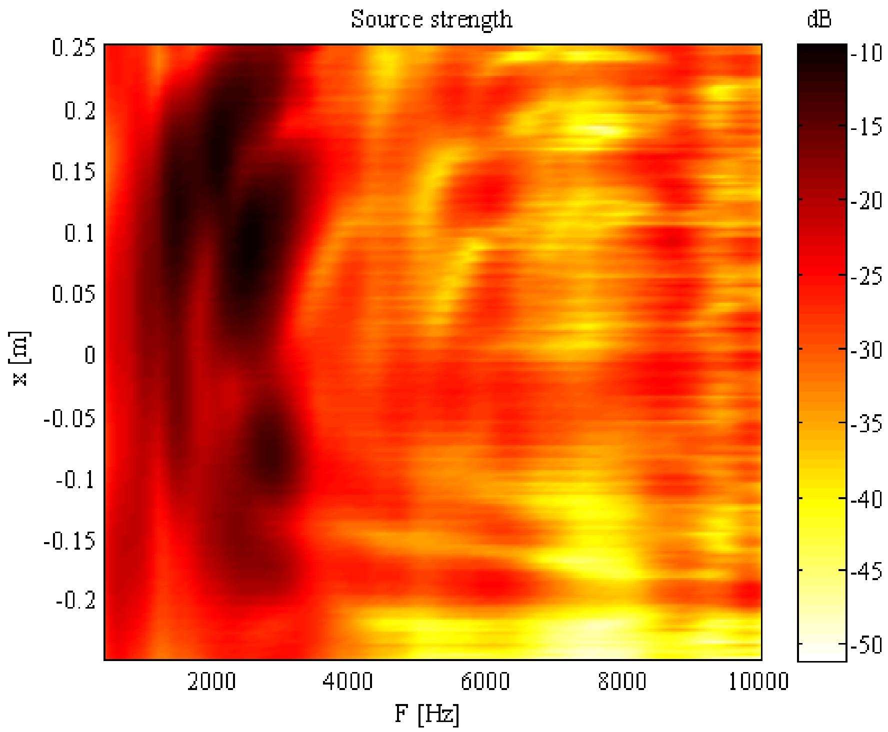

Figure 4: Beamforming output as a function of frequency and space

As previously said, the spectral kurtosis makes possible to find the location of an impulsive excitation. Figure 5 shows the spectral kurtosis layout as a function of frequency and space. This mapping confirms the effectiveness of the method to separate impulsive sources. While figure 4 reveals a wide radiation zone, figure 5 highlights a few well-defined sources. Actually, we can spot two main areas where the kurtosis is high. The first one is located at $x = -0.2$ and the second and main one at $x = -0.158$. Forthcoming analysis should concentrate on this positions in order to identify precisely what kind of failure it is, which is not the point of this paper.

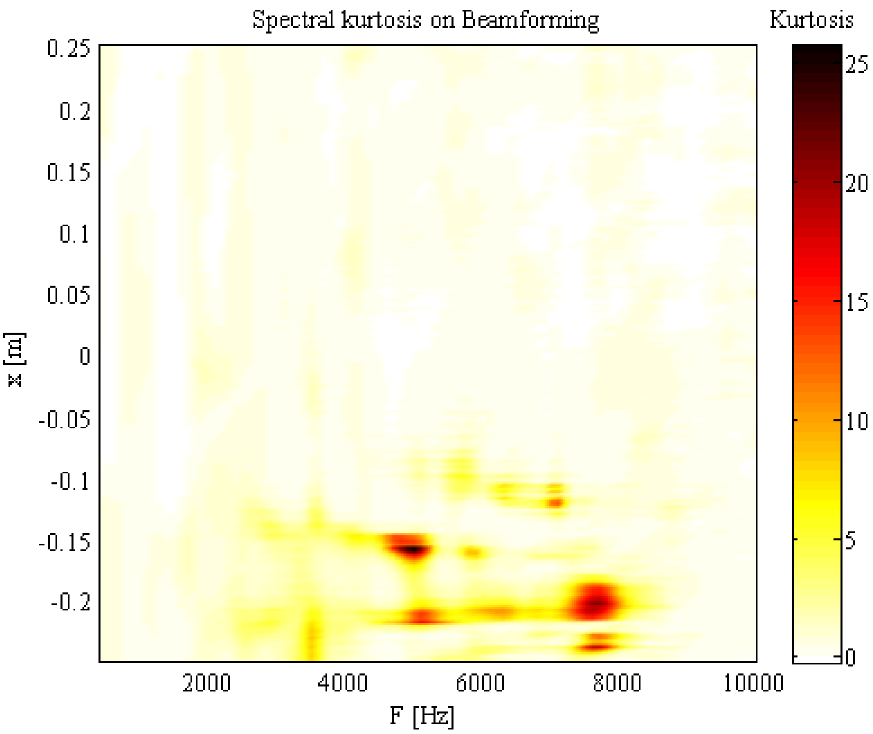

Figure 5: Spectral kurtosis applied to beamforming output

It is possible to extract the time-varying signals at the identified locations. A band-pass filtering selected around the maximum kurtosis is a way to emphasize the impulsive feature of the signals, as shown in figure 6. Classical fault detection analysis can then be applied to these signals.

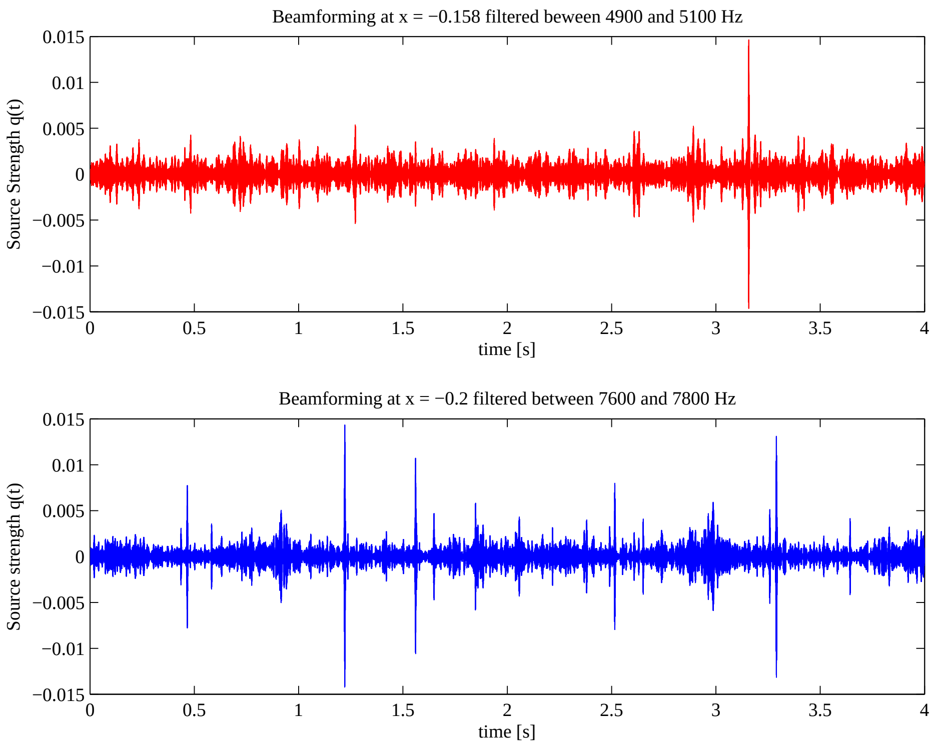

Figure 6: Filtered beamforming signal.

6 Conclusion

In this paper, a new method for fault detection, and more precisely fault location, was proposed. In the first section, the theory of beamforming and spectral kurtosis were introduced. Then, the relevance of combining beamforming and the spectral kurtosis was demonstrated. Since spectral kurtosis is a usefull tool for identifying the frequency bands in which the impulsiveness of the signal is important, adding the spatial dimension to it will make possible to localise impulsive sources. The method proposed was tested on a real case and showed its effectiveness.

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