ASSESSMENT OF THE REASSIGNMENT TECHNIQUE APPLIED TO VIBRATORY DIAGNOSIS ON TURBOMACHINERY

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ABSTRACT

In turbomachinery vibration analysis, time-frequency representations are a common way to represent a signal's frequency evolution as a function of time or rotating speed. Examples of such representations are the Short Time Fourier Transform or the Spectrogram. Nevertheless, the main issue of those representations comes from the underlying method. In fact, vibration engineers need to deal on the one hand with the time-frequency uncertainty principle and on the other hand with a loss of resolution coming from the windowing process of the time decomposition.

Our purpose in this paper is to introduce the reassignment technique applied to vibration signals. The reassignment method aims at reconcentrating diffracted energy due to the windowing process. Instead of being assigned to the window's gravity center, the energy will be reassigned to the signal's gravity center. With this technique, time-frequency representations are completely independent from the window, and physical energetic structures of the vibration signal can be well-localised.

Tested on different kind of measurement signals, the reassignment technique applied to the vibration domain gives very relevant results, in terms of resolving power, joint time-frequency resolution and signal to noise ratios.

INTRODUCTION

The main excitation sources of a turbomachine are the gas engine and power turbine rotating speeds. That's why, to study the vibratory behaviour of engines, it's of great interest to assess the vibration signals' spectrum as a function of those speeds. Many time-frequency representations exist and among them, the spectrogram is one of the most useful and easiest to compute.

Applying time-frequency algorithms on numerical data leads to introduce specific phenomena due to the convolution of the numerical signal's spectrum with the window's spectral representation. Indeed, energy diffraction around the signal's physical components appears, preventing the user from being able to localise precisely the signal's components. Thus, this transform suffers from a compromise between the frequency and the time resolutions, and moreover, the signal can't be resolute on the maximal reachable resolution because of the energy diffraction. Furthermore, the representation is fully dependent on the chosen analysis window.

Other representations ([3], [4]) not based upon windowing, like the Wigner distributions, can give a better resolution of energetic structures, but at the expense of interference terms which prevent the reader from interpreting easily time-frequency diagrams. Moreover, the time execution of those techniques is often appalling compared to the spectrogram one.

That's why the spectrogram is commonly used for studying the evolution of signals' spectrum, at the expense of a compromise between time and frequency resolutions determined by the window chosen to perform the transform.

Therefore, processing means based upon mathematical tools coming from signal's properties have to be developed. They can give a better joint time-frequency resolution ([2]) and thus, more accurate vibratory diagnosis. The reassignment technique [1], yet assessed in other fields of interest, is one of those useful methods the vibration specialist should be supplied with.

Reassignment is based on local instantaneous frequency and group delay. Those quantities are assessed for each (t,ω) while, that is to say for each windowed part of the signal and its associated spectrum. Their computation introduces a field of reassignment vectors whose purpose is to reorganize the energy in the time-frequency domain.

Let introduce x the signal to be analyzed. The computation of the Short Time Fourier Transform of x (STFTx(t,ω)) leads to define the phase φ(t,ω) for each cell of the time-frequency decomposition.
A field of reassignment vectors can then be defined, which leads to a new energy assignment $(\hat{t},\hat{\omega})$ in the time-frequency domain, as follows:

$$\hat{t}_x(t,\omega) = t - \frac{\partial\varphi(t,\omega)}{\partial\omega}\ (Eq.1)$$

$$\hat{\omega}_x(t,\omega) = \omega + \frac{\partial\varphi(t,\omega)}{\partial t}\ (Eq.2)$$

The reassigned spectrogram $\hat{F}_x(t,\omega)$ can now be computed, taking into account the energy reassignment (complete development of the method can be found within reference [1]):

$$\hat{F}_x(t,\omega) = \iint_{R^2} \left|STFT_x(s,\eta)\right|^2 \delta(t-\hat{t}_x(s,\eta), \omega-\hat{\omega}_x(s,\eta)) \frac{dsd\eta}{2\pi}\ (Eq.3)$$

where $\delta(t-t_0,\omega-\omega_0) = \begin{cases} 1\ if\ t=t_0\ and\ \omega=\omega_0 \\ 0\ otherwise \end{cases}$.

In order to illustrate those principles, let introduce a single-tone signal at 260 Hz, with a sampling frequency of 1000 Hz. The time decomposition has been set to 2048 points, which leads to a time resolution of 2.048 msec and a frequency resolution of 0.48 Hz for the spectrogram (Gabor cell). The analysis window chosen for this example is the well-known Hanning window.

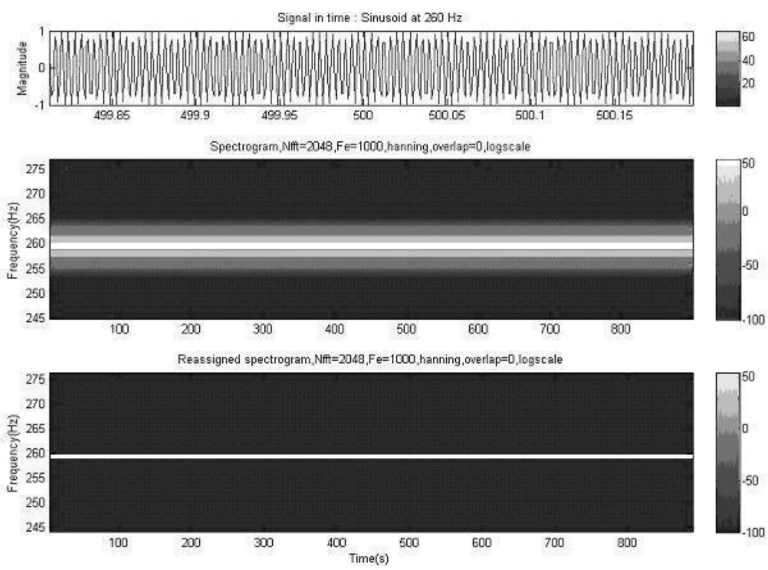

Fig. 1: Reassignment applied to a single-tone signal

This synthetic signal and its spectrogram can be shown on the two first graphs of figure 1. Energy diffraction due to windowing process clearly appears on the spectrogram. After applying the reassignment technique, we can observe that the energy has been reconcentrated on the physical ray of 260 Hz and all the diffraction effects have been cancelled, thus leading to a more precise estimation of the amplitude of the sine (third graph of figure 1).

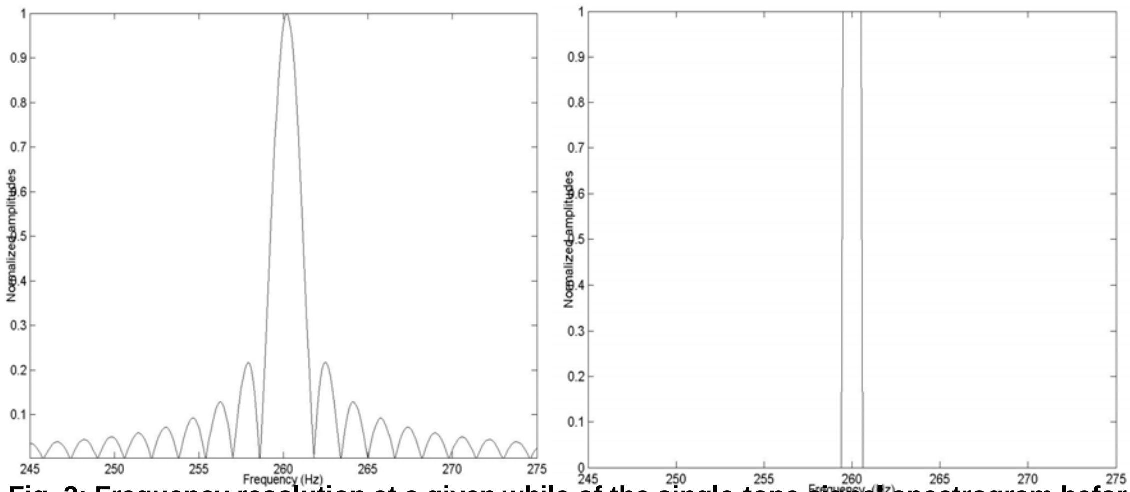

Fig. 2: Frequency resolution at a given while of the single-tone signal spectrogram before applying the reassignment method (left side) and after applying it (right side)

In order to show the gain obtained on the previous example, figure 2 represents the spectra at a given instant for both time-frequency diagrams.
Before reassignment (left side of figure 2), the energy is diffracted symetrically on both sides of the physical ray: The motif of the window's spectrum can indeed easily be recognized through the left representation of figure 2 (convolution of a tone at frequency f_0 with a window's spectrum, resulting in this spectrum translated at f_0). After reassignment, the time-frequency signal is defined on the diagram frequency resolution (i.e. the maximum reachable frequency resolution, that is to say the one given by the number of points the Fourier Transform is computed on). The single-tone signal is thus better represented.

In our case, as vibration signals are mainly composed of many harmonic components, the reassignment technique should offer promising results as shown above.

RESULTS AND DISCUSSION

Measurements in turbomachinery give many kind of spectral information about the structural response of elements but also about their own excitation sources. As the main excitations come from the rotating parts (blade passing frequency or rotor unbalance), much of these signal components are synchronous to the rotating speed. By representing the frequency decomposition as a function of rotating speed (which is fairly equivalent to decomposition in time, each instant being associated with a given speed), we can observe all those responses as a linear function of the rotating speed. Obviously, the reassignment technique can also be applied to this kind of decomposition.

The example we propose for the validation of the method (see figure 3) was obtained from a measurement in the static frame near a rotating assembly. Therefore, the signal is composed of many excitation orders. We can also observe structural responses excited by turbulent flow, which leads to asynchronous responses in the rotating speed-frequency diagram (refer to figure 4).

The spectrogram proposed within left side of figure 3 was computed with a Hanning window. This window offers a well-known compromise between time and frequency resolutions.
First, we can notice that all the spectra components are not defined on the resolution given by the Gabor cell size (i.e. 11.72 Hz in this case) but with a 35.16 Hz frequency resolution, due to the windowing process (the Hanning window resolution).

After reassignment (right side of figure 3), the resolution of the representation has been improved. This technique removing the spectral representation of the window that has been convoluted with all the physical components of the signal, the resolution after reassignment is exactly the one coming from the time-frequency decomposition.

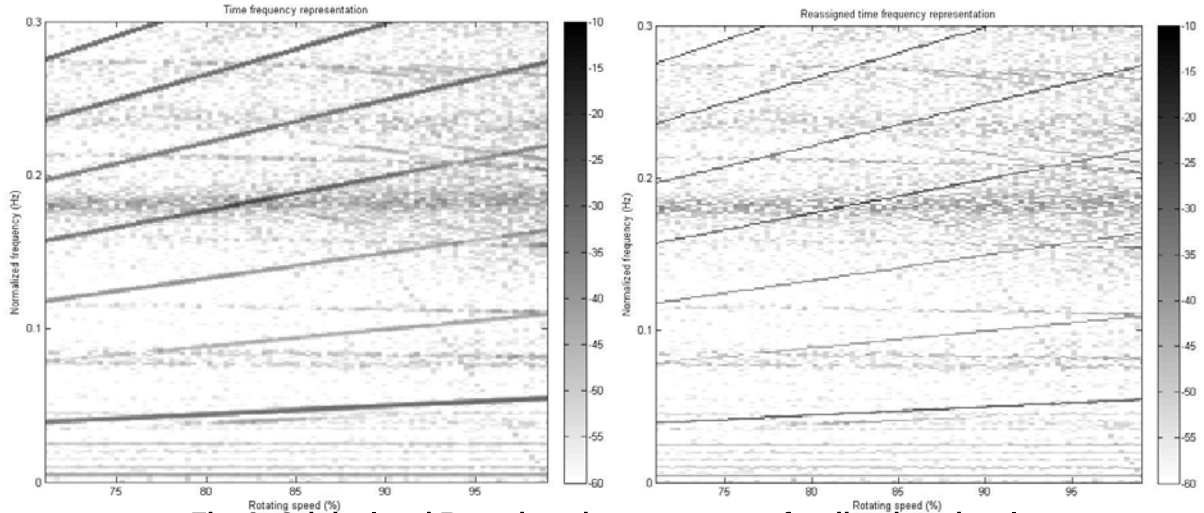

Fig. 3: Original and Reassigned spectrogram of a vibration signal

The effects of the reassignment technique on synchronous components can be directly linked to the previous statement. The resolution of engines orders is improved, as it is also the case for the synchronous response of structural components. The second improvement coming from the technique is the amplitude correction due to energy reassignment. As the windowing process diffracts energy around the physical components of the signal, the amplitude is then corrected without any further information about the window previously used to compute the spectrogram.

Figure 4 shows more precisely the reassignment process. That part of the signal is also made of a synchronous component coming from the blade passing frequency as explained before.

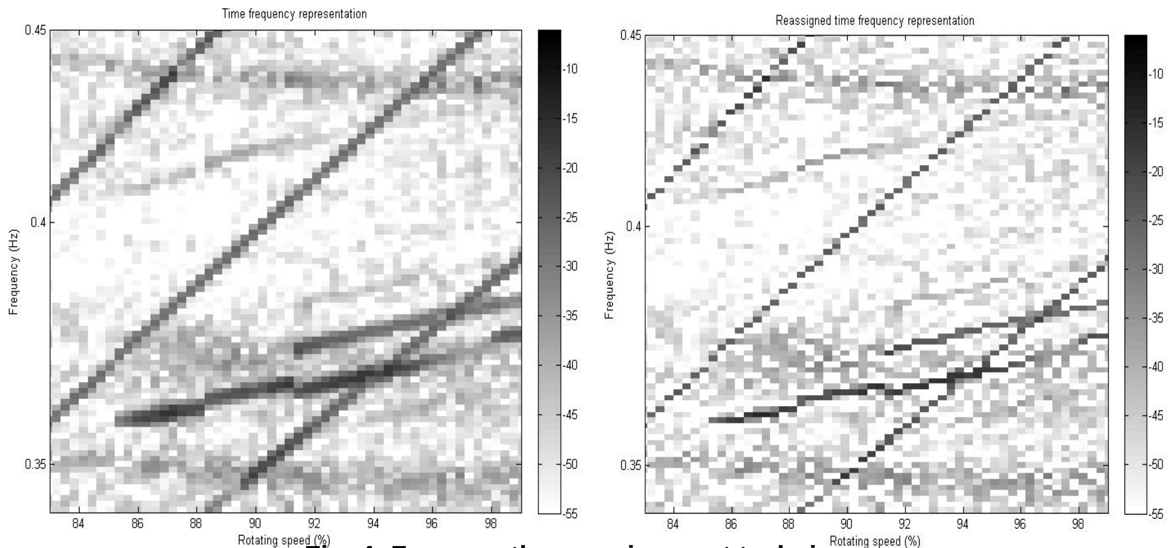

Fig. 4: Zoom on the reassignment technique

What's more interesting here in this zoom is an asynchronous phenomenon due to a cavity resonance where different acoustic modes are shown. We can also identify the modal response of a structure excited by random excitation (turbulent flow).
The reassignment technique is working well on each kind of responses (right side of figure 4).

Furthermore, reassignment of noise is also assessed through representations in figure 4. Even where harmonic components appear within noisy areas, the technique manages to reassign energy on the physical rays.

To conclude, we explained in this paper why the spectrogram was the most interesting representation for vibration signals even if it suffers from an inherent compromise between time and frequency resolutions. Fortunately, the introduction of the reassignment technique (based upon the computation of the local instantaneous frequency and group delay of the windowed signal) allows improving resolutions in the time-frequency diagrams. Assessment of this processing on synthetic signals being quite promising, we tested it on vibration signals: We are provided with very relevant results whatever the kind of component to be characterized. The reassignment technique seems really adapted to signals composed of multiple harmonic rays such as vibration signals. Moreover, amplitude estimation is improved, the signal energy being reassigned on the components signal's gravity centers. This new tool, easy to use and to compute, allows more accurate diagnosis for the vibration specialist.

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