Harmonic Product Spectrum revisited and adapted for rotating machine monitoring based on IAS.

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Abstract

A few years ago, Instantaneous Angular Speed (IAS) signal analysis has been proven able to detect natural bearing faults. This major experimental demonstration shows that mechanical faults can be detected through the reading of the torsional shaft movement rather than the transverse vibration of the equipment housing. Amongst the different techniques that can be used to get IAS signal, Elapse Time seems to bring the best results and is under consideration in this paper. However, since the lack of advance processing tool limits the development of this technology, this paper proposes an alternative technique to extract dry impacts components from IAS spectrum and therefore, greatly enhance its capacity to detect bearing fault. The efficiency of the proposed technique is shown on real measurements issued from a wind turbine main bearing fault, and compared to classical IAS analysis tools.

1 Introduction

A few years ago, Instantaneous Angular Speed (IAS) signal analysis has been proven able to detect natural bearing faults [1]. This major experimental demonstration shows that mechanical faults can be detected through the reading of the torsional shaft movement rather than the transverse vibration of the equipment housing. Amongst the different techniques that can be used to get IAS signal, Elapse Time seems to bring the best results and is under consideration in this paper. This acquisition method introduces specific limitations which have recently been detailed [2] and which mainly account for the difficulty to use classical vibration signal processing tools. For instance, within many methods that have been developed to improve bearing fault detection, the most favoured one is probably the envelope spectrum analysis of the vibration signal filtered on a conveniently chosen frequency band. However, the adaptation of this technique to Instantaneous Angular Speed (IAS) signals is not straightforward, since neither the impact nor the structural response reach the quantification threshold obtained with current acquisition systems.

This paper proposes an alternative way to extract dry impacts components from IAS spectrum. Originally proposed in 1968 by M.R Schroeder [3] and soon after democratized by Noll [4], Harmonic Product Spectrum is a method derived from Cepstrum analysis and used to detect fundamental frequency in a noisy signal. In the domain of speech signal processing, this methods eases a precise voice pitch tracking, which fundamental frequency can be mixed with the noise if not pointed out by its higher harmonics. This paper proposes a revision of HPS to IAS analysis (based on elapse time acquisition technique). The efficiency of the technique will be finally shown on real measurements issued from both healthy and defective wind turbine main bearing.

2 Theory

2.1 Description of HPS

Harmonic Product Spectrum is a tool dedicated to reveal the fundamental frequency of a harmonic set mixed with noise. The intuitive reasoning for the method is that the peach peaks in the log spectrum add coherently while the other portions of the log spectrum are uncorrelated and add non coherently. The frequency compression results in a sharper final peak as depicted in Figure 1. This figure, along with section, is largely inspired from the original paper which proposed HPS for the first time [4]. The antilog version of this schematization is the Harmonic Product Spectrum, and is simply defined such as:

$$\pi(\omega) = \prod_{k=1}^{K} X(k\omega) \tag{1}$$

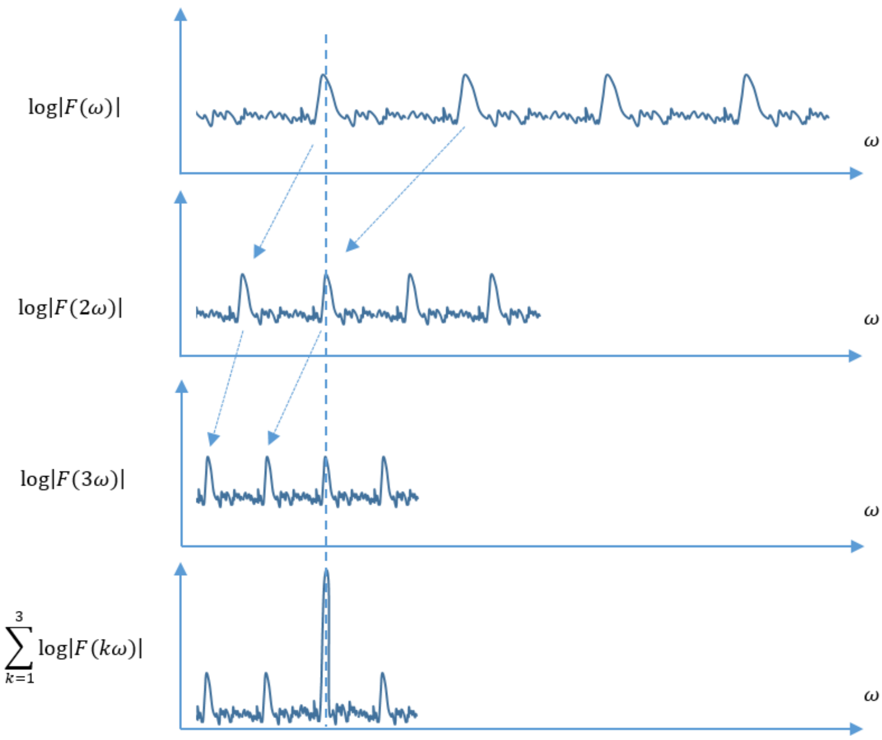

Figure 1: Developpement of the Harmonic Product Spectrum as the antilogarithm of the sum of harmonically compressed log spectra.

With K the number of harmonics taken into account and $X(\omega)$ is the amplitude spectrum of the time signal. Therefore, the HPS is a function of the frequency and its unit is the original spectrum unit power K.

2.2 Application to rotating machinery

The main difference between speech analysis and rotating machinery monitoring is that the user is not only looking to locate the harmonic set frequency, but also to apprehend its amplitude in order to estimate a fault severity. Regarding this peculiarity, the fact that HPS unit is the original spectrum unit power K might pose a problem. A first proposal to tackle this issue is to present the HPS as a probability function, such as:

$$\pi(\omega) = \prod_{k=1}^{K} \frac{X(k\omega)}{\int_0^{f_{max}/k} X(k\omega)\mathrm{d}\omega} \tag{2}$$

This slight modification transform the original HPS in a probability function without unit, that can be interpreted as the chance for a frequency to correspond to the fundamental frequency of the harmonic set. The intended result is that the amplitude of the fundamental frequency observed on the HPS will only increase with an increasing number of harmonic taken into account. Still, several difficulties are to be tackled:

1. In case of bearing monitoring, the healthy mode is not supposed to induce a harmonic set in the signal. This will be discussed in the end of the paper.
2. Rotating machinery signals are never populated with only one harmonic set. the more harmonic sets in the signal, the lower the probability will be. It appears therefore necessary to limit the frequency span of interest to a frequency band $[f_1; f_2]$ where no other harmonic set is expected:

$$\pi(\omega) = \prod_{k=1}^{K} \frac{X(k\omega)}{\int_{f_1}^{f_2} X(k\omega)\mathrm{d}\omega} \tag{3}$$

3 Materiel and Methods

3.1 Instantaneous Angular Speed

Instantaneous Angular Speed (IAS) has recently appeared as an original and promising tool to monitor mechanical parts of rotating machines. Mechanisms running under non stationary conditions, such as wind turbine, are especially suited for this method since the issued signal is intrinsically sampled in the angular domain. Readers interested by the acquisition method can refer to [2]. Measurements have been obtained with the Elapse Time method, on a 8192 ppr [1] magnetic encoder sampled with a 120MHz counter clock. The aim of this paper is not to present IAS monitoring, especially since HPS might bring interesting results on classical vibration measurements too. However, the fact that Elapse Time technique yields an angular sampled signal is important since it helps harmonics components of cyclo-stationary phenomenon to be concentrated in one frequency channel. And since the signal is sampled in the angular domain, cyclic frequency unit will be labelled $(lss)^{-1}$ throughout the paper and refers to the low speed shaft revolution power $^{-1}$ rather than Hertz.

3.2 Wind turbine defect

The wind turbine studied in this paper is a 2MW nominal power machine which hub diameter and weight are respectively is in the order of 80 meters and 20 tonnes. the double spherical roller bearing supporting by itself the whole load is commonly mentioned as the main bearing in the wind industry. Obviously, these 1 meter width bearings are not off-the-shelf products and their failures often lead to time and money consuming operations. A turbine suffering from such a defect was equipped with a low cost magnetic encoder on the low speed shaft. The low speed shaft is linking the blades hub to the gearbox, which is crossed by the shaft to open an access to the slip ring. Figure 2 illustrates the mechanical shaft line and the location both of the encoder and the main bearing.

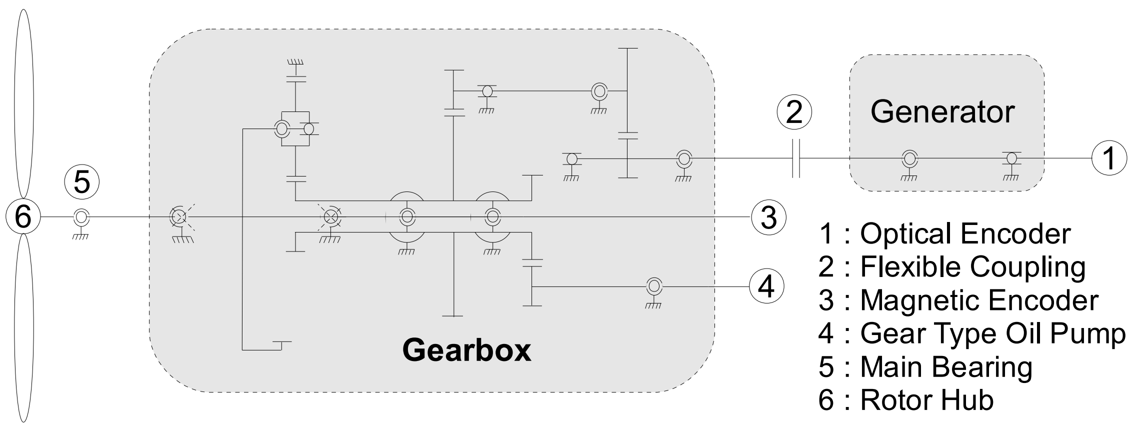

Figure 2: Kinematic Scheme of the wind turbine set-up.

The speed of the low speed shaft does not exceed 20 revolutions per minute, and is of course never steady. This difficulty, inherent to large scale wind turbine, was already discussed in a previous paper and was shown to

[1] pulses per revolution

be partially soved with angular sampling [5]. The main bearing was spalled on its outer ring, in a static position regarding the load, on two different spots. Figure 3 shows the spalls are on the edge of the bottom part, on the generator side, as if they were caused by an excessive axial load and a pinching of the outer ring by the housing. Although the aim of this paper is not to build the root cause analysis of this defect, it is important to note the distinctive characteristic of this twin spall defect. According to the manufacturer, the caracteristic frequency of an outer ring defect for this bearing is: $f_{BPFO} = 13.2(lss)^{-1}$.

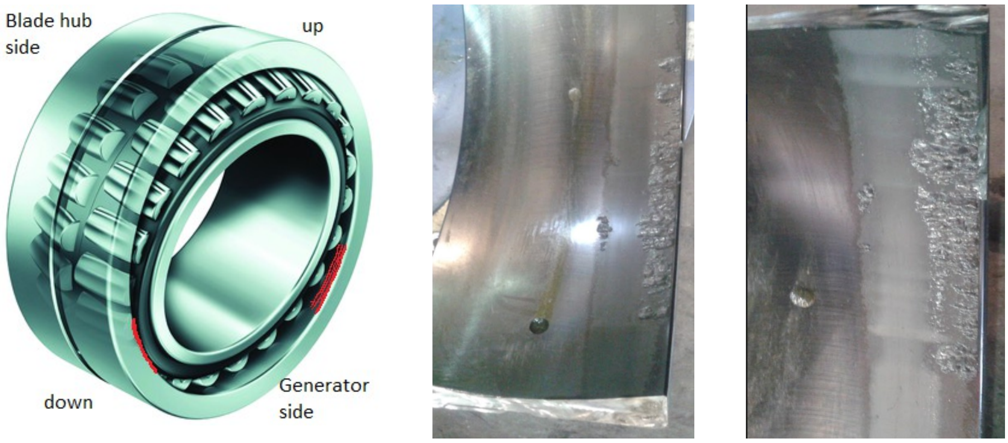

Figure 3: on left: 3D view of the bearing with the spall spots colored in red. on right: photograph of the defective outer ring once dismantled and cut out from the bearing.

The wind turbine operator shared 130 IAS signals. 100 measurements have been taken once the fault was detected by an advanced vibration monitoring system, while the other 30 have been made once the bearing was replaced. the triggering of these measurements was not conditioned on speed nor on power, and are representative of day to day wind turbine monitoring.

4 Results

4.1 State of the art results

Outer ring characteristic frequency should be detectable using either vibration monitoring or IAS monitoring even though there is no defect on it. The reason behind it reflects the cyclically varying number of rolling elements passing through the load zone [7]. This is not often revealed using vibration monitoring since most of these systems are based on time sampled signals, and cannot reach the cyclic spectral resolution needed to overcome surrounding noise. Actually, this appears also difficult to confirm on these IAS signals, probably because the magnetic encoder installed on the low speed shaft suffers a weak signal to noise ratio. On figure 3, the right side plot shows a coarse estimation of the wind turbine speed for the defective signal and even worse for the healthy signal. This noise is mostly due to the geometrical error of the encoder as its spectral energy is condensed in every harmonics of the low speed shaft order [2]. The plot on the left confirms this issue where the only peaks visible either on the healthy or the defect signals are located on integer values of cyclic frequency, scaled in $(lss)^{-1}$. No peaks can be seen on the BPFO cyclic frequency on both signals, allthough these two have both been measured during nominal power production. these conditions are maximizing axial thrust and should therefore optimize the detection of spalls located on the corner of the ring, as observed on Figure 3.

4.2 HPS results

At first, the original definition is applied on the signals presented on Figure 4 for different values of K. The number of harmonics considered in the HPS computation has been shifted from 2 to 20 in order to understand its influence over the results. 5 shows that the greater K is, the lower the corresponding HPS drops. This is due to the average level of the IAS spectrum on the observed interval that is inferior to one. spectra shown on Figure 4 where of order $10^{-4} rpm$, the HPS is therefore of order $10^{-4 \cdot K} rpm^{K}$. More importantly, A peak is visible at cyclic frequency $13.19(lss)^{-1}$ on every HPS computed for this faulty signal. allthough its amplitude

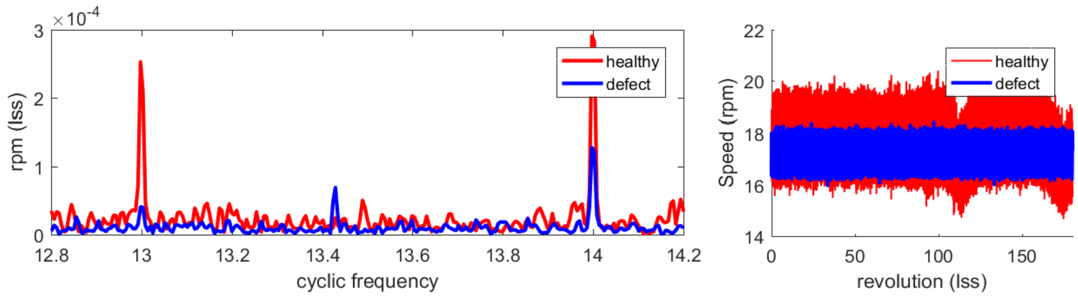

Figure 4: Comparaison of a healthy and a defective IAS measurement. on left: spectral observation focused around BPFO. on right: angle observation of the speed signals.

is still meaningless, this indicates that a combination of harmonics will improve somehow the visibility of the defect.

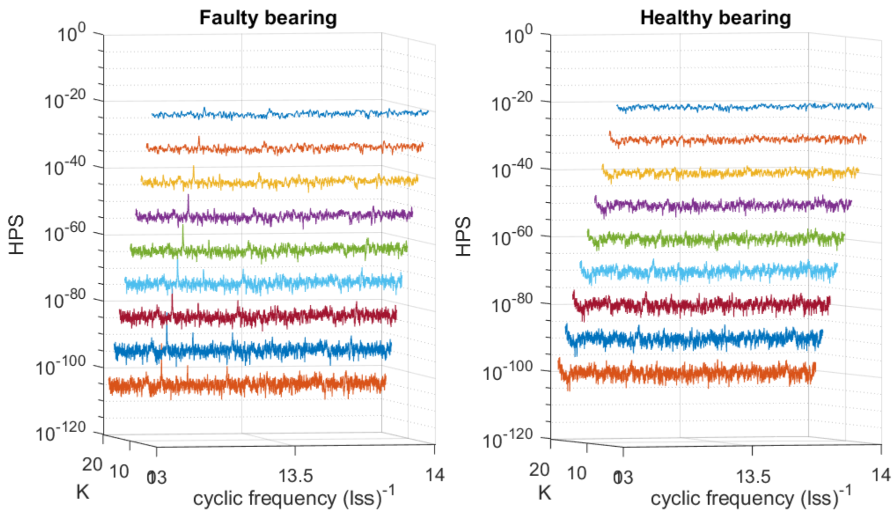

Figure 5: HPS used in its original definition.

Figure 6 shows the impact of weighting the HPS as was proposed in section 2.2. The weighted HPS gives the probability for each channel frequency to host the fundamental frequency of the set of harmonics inhabiting the observed interval. In the present case, the interval is limited to $[13,14](lss)^{-1}$. The amplitude of the HPS is now meaningfull: the max value of the defective signal HPS is converging towards 100% on the BPFO as K is increasing, while no value is higher than 20% on the healthy signal.

4.3 Campaign analysis

The weighted HPS appears to bring satisfying results on signals obtained during full load operating conditions, but the analysis of the whole campaign might turn out more challenging. To keep an eye on the role played by the parameter K (number of harmonics taken into account), the processing of the 130 signals is performed according to the following procedure:

- Multiple HPS are computed from each HPS whith paremeter K varying such as: $K \in \{2i\}_{i=2..10}$.
- Every HPS are weighted by the mass of the interval $[13,14](lss)^{-1}$
- The maximal probability on the same interval along with its corresponding cyclic frequency are hold back.
- These frequencies are split in a histogram containing one hundred uniform bins (bin width: $0.01(lss)^{-1}$).

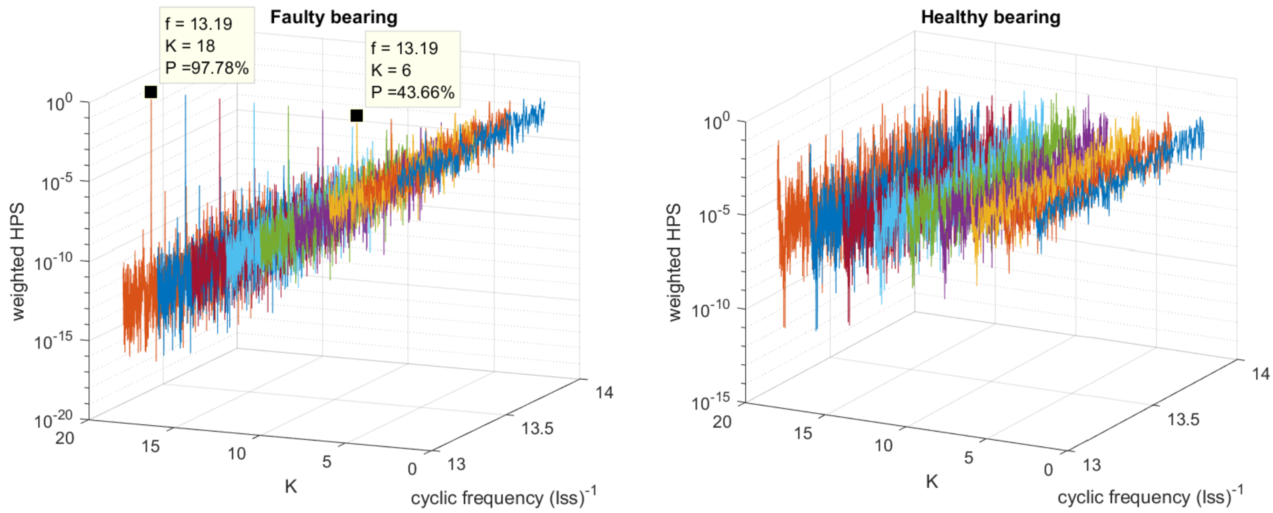

Figure 6: weighted HPS used in its original definition.

This procedure is proposed to describe the maximal values obtained by each HPS on the observed interval as an estimate of a probability density fonction. Figure 7 shows the results in four complementary plots. The top left plot indicates that most of the defective bearing measurements have their maximal value located around BPFI. Bottom left plot does not present HPS results which maximal probability stays below 50%. This appears to exclusively filter out values that are not located around BPFI and therefore indicates that defective bearing measurements either detect a set of harmonics induced by the inner ring problem (value above 50%) or detect nothing (max frequency randomly distributed within the observed interval + corresponding probability under 50%). Right plots show the results obtained with the healthy bearing measurements. First, it appears on top right plot that no cyclic frequency is favoured. Secondly, only few values are present on the bottom right plot, indicating that most of the HPS max values are not likely to be the fundamental frequency of a real harmonic set. Finally, these values are all corresponding to cyclic frequency above $13.30(lss)^{-1}$ and are far from the BPFI given by the manufacturer. This results proves already the capacity of the proposed approach to detect a main bearing bearing fault using Instantaneous Angular Speed with a low quality magnetic encoder.

However, this encouraging result could be considered to have been eased by the selection a relatively broad frequency interval, making possible to discriminate actual harmonic events from implausible values. Would another set of harmonics be present in the vicinity of the bearing BPFI, the frequency interval should then be reduced to contain only the BPFI. This span is lower-bounded by the characteristic frequency degree of precision. Bearing manufacturer give average values, that does not correspond to any combination of thrust/radial load, temperature, preload... the last experiment will show the results obtained focusing on the smallest bandwidth that insure to observe the BPFI. Figure 8 shows the results obtained when the same procedure that has been applyed on Figure 7, except that the HPS are weighted on the interval $[13.15, 13.25](lss)^{-1}$ rather than $[13, 14](lss)^{-1}$. the histogram bins are still $0.01(lss)^{-1}$ width. This last figure confirms the effectiveness of this method, since the faulty bearing measurements can still be easily distinguished from healthy bearing measurements. Moreover, both of Figure 7 and 8 shows that the amount of harmonics considered in the HPS (parameter K) has little influence on the rate of deffective bearing measurement that can detect the bearing frequency.

5 Conclusion

This study shows the adaptation of HPS to IAS signal applied to rotating machine monitoring. This tool adapted from very old processing techniques discovered in the 60's in the domain of speech analysis to precisely track voice pitch, help IAS monitoring to step forward in the Condition-Monitoring-System hall of fame ! The precise detection of an low speed bearing fault is now proven to be possible using only a magnetic encoder. These tools present the ability to concatenate information from several elements of a set of harmonics and therefore yields a more precise estimation of the characteristic frequency. This appears to be valuable in regards

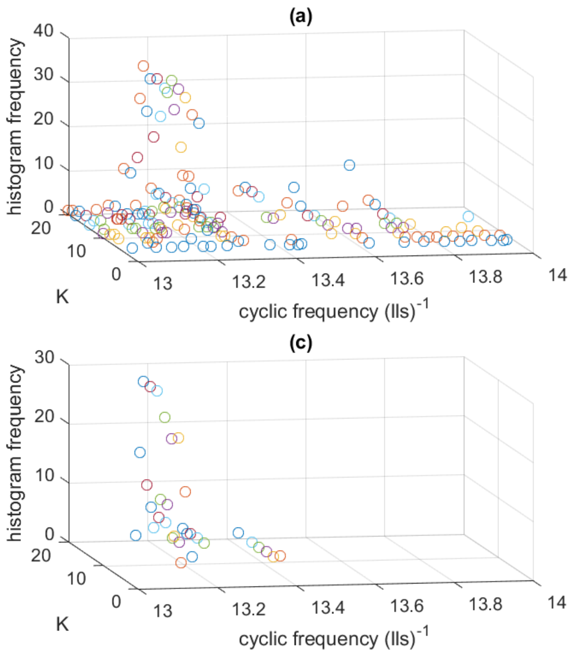

Figure 7: Histogram the most probable cyclic frequency determined by several HPS, respectively obtained for different values of K. (a) and (c): defective bearing measurements. (b) and (d): healthy bearing measurements. (d) and (c): only values above 50% are considered.

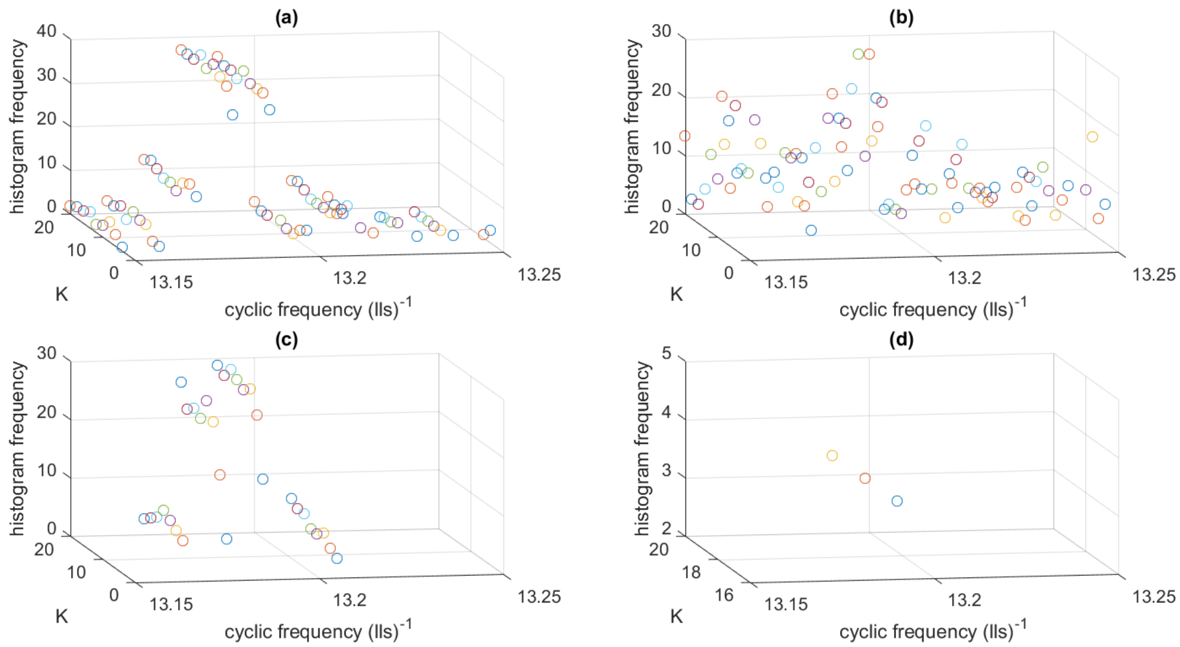

Figure 8: Histogram the most probable cyclic frequency determined by several HPS, respectively obtained for different values of K. (a) and (c): defective bearing measurements. (b) and (d): healthy bearing measurements. (d) and (c): only values above 50% are considered.

with two observations:

1. Vibration signals as well as IAS signals can contain a multitude of cyclic phenomena. Once a bandwidth is determined by the expert as surrounding a characteristic frequency of interest, HPS can be used to clean this interval from non harmonic content.

2. Up to now, experts can hardly predict which harmonic number of a wide set makes the biggest contribution into the fault severity. Not only the diagnostic is simplified since the information is condensed in the characteristic frequency, but it is not needed anymore to follow simultaneously the various harmonics.

In the meantime, it is important to underline the drawbacks which were not overcome yet by the authors (damn them)... they are mainly linked to very strong hypothesis made at the beginning: the observed signal is expected to have one and only one set of harmonics. If this is a real life signal, the chance is very few that only one set of harmonic set inhabits it. The expert must then be aware that the larger the frequency bandwidth, the smaller the harmonic set of interest, until it might not be prominent anymore. The proposal of the author to window the observation is suboptimal, since it increases the number of parameters to tune, although it dit not appear to strongly impact the defect observability.

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