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Problems with using Fast Fourier Transform for rotating equipment: Is it time for an update?

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PAPER TEXT

Condition-Based Maintenance (CBM) is widely used to manage the condition of rotating machinery. They require a number of CBM tools to detect acoustic and vibration signals. One such method is the Fast Fourier Transform (FFT). FFT converts a vibration signal from time domain to its equivalent frequency domain representation. Unfortunately, there are dramatic assumptions made related to the proper use of FFT. The paper will provide evidence that this approach may not be the perfect tool for fault detection and diagnosis. The paper celebrates with the limitations of FFT and does not muffle the culpabilities of our developed diagnosis culture. The aim is to challenge researchers to come up with something more developed to eventually take use of the processing power we have today.

Keywords:Condition Based Maintenance (CBM), Condition monitoring, Signal analysis, Fast Fourier Transform (FFT)

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1. Introduction

A growing number of companies have recognized that Condition Based Maintenance (CBM) concepts such as oil analyses, ultrasound and vibration technologies are necessary if they are to maintain high and planned levels of operation. The aim is to collect and analyses key monitoring data to identify potential problems, reduce reaction time and eventually increase the reliability of a plant's equipment. CBM technologies are utilised to predict failure patterns of an asset and allow maintenance to be scheduled based upon condition and not time i.e. perform maintenance based upon need. CBM is seen as a set of maintenance actions based on real-time or near-real time assessment of equipment condition which is obtained from embedded sensors and/or external tests & measurements [1]. Within the CBM society and its applications, the FFT is widely used, often without a full understanding of its assumptions. FFT is a computerised mathematical algorithm used for transforming vibration signals from time domain into frequency domain. Its origin is in the Fourier Transform developed by Joseph Fourier shown in Figure 1.

Figure 1. Jean Baptiste Joseph Fourier (1768-1830), painting from Wikipedia

FFT can be helpful in diagnosing faults associated with unbalance, misalignment, eccentric components and damaged bearings, gears and motor electric faults.

Cooley and Tukey [4] are generally referred to as the inventors of the Fast Fourier Transform, or the FFT algorithm. The FFT algorithm represents an efficient way to calculate the Discrete Fourier Transform, DFT, from sampled sequences of data with length N = N1N2. (1). FFT uses a sampled signal and finds a one second periodic signal composed of sinusoids that fit the samples. The FFT algorithm implicitly extends the time record of the sampled signal to make it "periodic". If the sampled signal doesn't contain an integer multiple of cycles of the underlying periodic signal(s), additional frequency components are introduced in the FFT result. To reduce the effects of spectral leakage ("noise" in the frequency domain) it is necessary to apply a "window" to the sampled data before taking the FFT. A "window" is a scaling factor applied to each data point that has the result of minimizing the effects of discontinuities in the periodic extension of the sampled waveform. (2) In vibration analysis, components can start add like a multiplication of components. Modulation is such a system. Two vibration components are being "combined" like the following equation:

$$y(t) = x_1 \sin(\omega_1 t) \cdot x_2 \sin(\omega_2 t)$$

In normal system theory, we assume that signals are additive. However, by using "log" as our operator, we can change the multiplication into and addition. Cepstrum transform a signal from the "multiplication domain" into the "additive domain" and the signal components can then be handled as additive. For additive signals we have a "known mathematics." This is the main foundation of the "Cepstrum Transform Theory". Figure 2 below depicts the main idea behind the transforms [4].

Fast Fourier Transform is often labeled as a mystical black box, yet it is the first tool that is used for signal processing of CBM signals. To effectively use FFT, we need to understand its properties, assumptions and limitations.

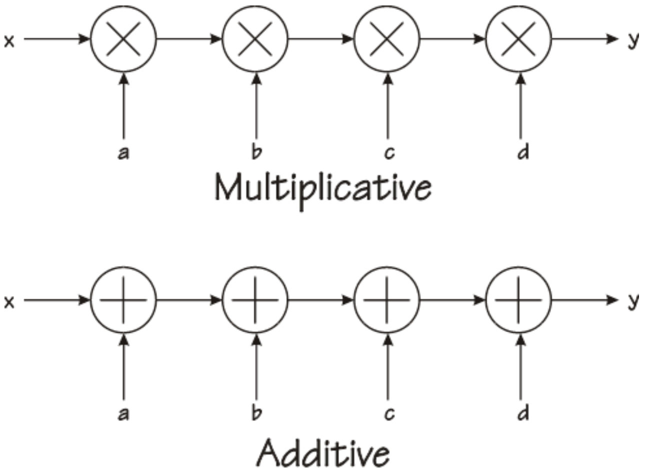

Figure 2. Additive versus multiplicative processes.

2. What is funny about FFT?

As mentioned earlier FFT has a number of restrictions that influence its behavior in signal analysis. In fact we may claim that it is strange that FFT is used in the first place in condition monitoring as it's suited well to monitoring only to a very limit number of fault types – periodic and stationary signals.

Clearly FFT is a good tool to diagnose imbalance assuming the machine is running at constant speed or the speed is not changing rapidly. According to a large number of handbooks which examine condition monitoring of rotating machinery fault types such as bent shaft, misalignment, looseness and cracks, they all discuss an indication as to the multiples of running speed in the spectrum i.e. there are harmonic components in the spectrum. However, the funny thing is that this is not true at all i.e. there is no vibration at the harmonics of the running speed when these faults are present (the reader is encouraged to do an exercise and to imagine how the above named faults could create harmonics of the running speed). Instead the indication of harmonics is a result of how FFT treats the change of vibration signal from sinusoidal to something twisted or flattened.

2.1. Basic cases of distorted vibration signals

Assuming the reader found it difficult to imagine how the listed fault types could be the cause of vibration at the harmonics of the running speed it should be the opposite i.e. very easy to imagine how bent shaft, misalignment etc. can influence the vibration so that it is not sinusoidal anymore and becomes distorted and flattened. Here, it should be remembered that in Fourier Transform everything is assumed to be sinusoidal i.e. is made to look as if it is composed from continuous sinusoidal components and thus the introduction of harmonic vibration components is logical even though they are not present in the original signal. It is confusing to the author of this paper how this “make believe” world exits in the literature i.e. the authors talk about harmonics of the running speed.

In order to illustrate the characteristic frequencies of machine faults and how peak amplitudes appear at certain orders of the rotating speed three principal cases are described:

Case: distortion of the signal symmetry (positive and negative side): In Figure 3 the distortion in the negative side of the signal generates an amplitude peak at the second harmonic 2x of the rotation speed (in fact at all even harmonics) as shown in Figure 4. Non-symmetric clipping (or duty cycle) generate even harmonics!

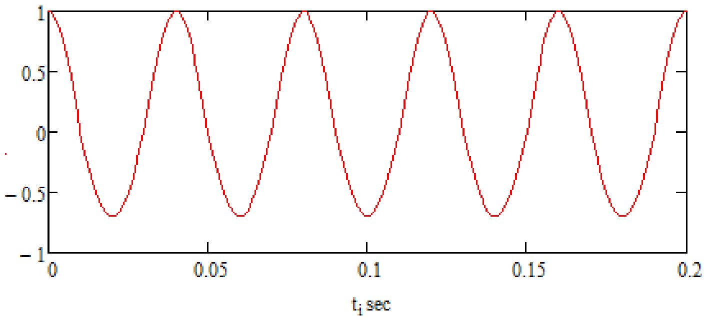

Figure 3. Time signal of case one fault.

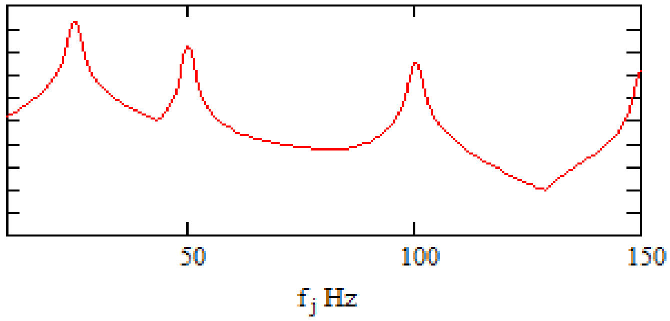

Figure 4. Frequency spectrum of case one fault.

Case 2: Both-sided distortion (from sinusoidal) of the signal (signal is symmetric): This type of distortion is shown in Figure 5. Symmetric clipping generate odd harmonics! In the spectrum, an amplitude peak is observed at the third harmonic 3x of the rotational speed (in fact at all even harmonics) as shown in Figure 6. Consequently we can claim that the both-sided distortion of the time signal with some degree of flatness generates peaks at the odd harmonics of the rotational speed in the spectrum.

Case 3 one-sided distortions of the signal peaks combined with unsymmetrical of the signal. The time signal is shown in Figure 7 and the corresponding spectrum in Figure 8. As is logical to expect this third case is a combination of the first and second case and as a logical result of that both even and odd amplitude peaks can be seen in the spectrum.

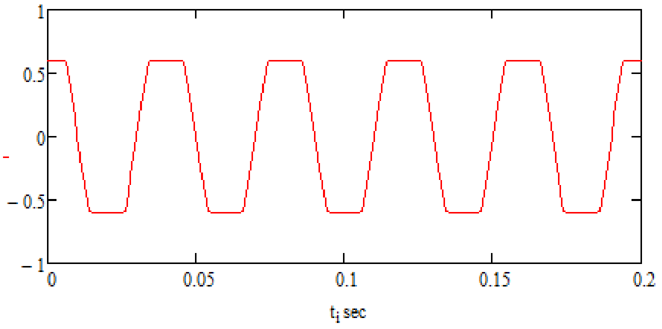

Figure 5. Time signal of case one fault.

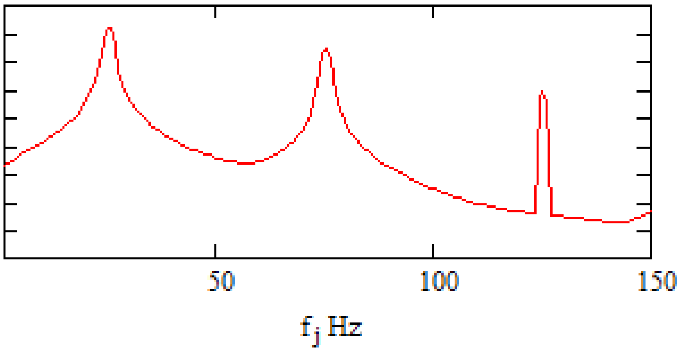

Figure 6. Frequency spectrum of case three fault.

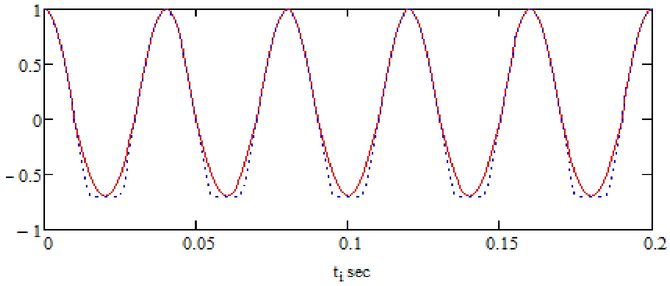

Figure 7. Time signal of case one fault.

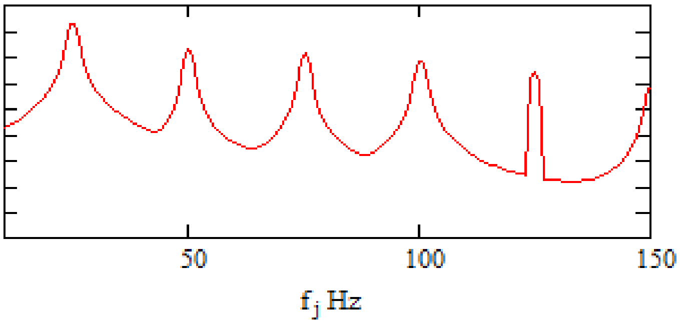

Figure 8. Frequency spectrum of case two fault.

The main conclusions from these three cases are as follows:

1. The distortion of signal symmetry is related to the even harmonic components in the FFT spectrum.
2. The distortion of signal shape from sinusoidal is related to the odd harmonic components in the FFT spectrum.

In the light of the above explanation it is easy to understand that the diagnosis of bent shaft and different types of misalignment is not accurate and therefore not reliable. In addition it is important to remember that the level of vibration at the running speed influences the level of the imagined harmonics that are seen. The fact is that although the diagnosis based on make-believe harmonics is not optimal it has been and is widely used. However, it can logically be claimed that a signal analysis method that would indicate the changes caused by the above named faults as one indicator would be an improvement. However, it is not the purpose of this paper to go further in the development of new methods but just to indicate the drawbacks or limitations of current practices.

3. Illustration of the fault cases

The rotational speed dependent vibrations in machines are caused by several types of machine faults. The most common faults in rotating machines are imbalance, bent shaft, looseness, misalignment, and fatigue crack. The basic idea of several diagnostic approaches are based on the assumption that these faults are distorting the system response. Taylor (1994) has illustrated this phenomenon for a high number of faults. The basic assumption is that when a fault distorts the vibration response of a system the FFT based spectrum will contain harmonics of the shaft speed . The characteristic frequencies of these machine faults are well documented in the condition monitoring literature, as summarized in Table 1.

Table 1. The characteristic frequencies of several machine faults

Fault type	Characteristic frequencies
Imbalance	1xrpm
Bent shaft	1xrpm, 2xrpm
Misalignment	1xrpm, 2xrpm, 3xrpm
Fatigue defect	1xrpm, 2xrpm
Gear fault	Sidebands

In order to gain an understanding of how these characteristic frequencies are related to specific faults, the following section try to describe it in a simple manner.

3.1. Bent shaft

As shown in Table 1 the bent shaft fault is diagnosed when high amplitudes are detece3td in the spectrum at the running speed and at two times the running speed frequency. In order to generate such signal, there is a need for a distortion event that occurs two times each revolution. It is hard to find a physical explanation for that kind of phenomenon. However, based on the discussed distortion cases, the bent shaft can be explained by the first distortion case, as shown in Figure 9 & 10.

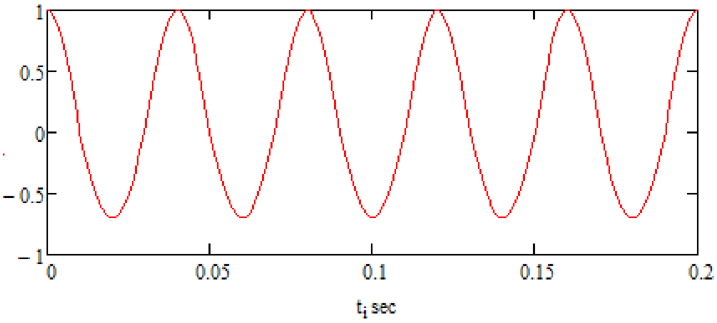

Figure 9. Time signal of bent shaft fault.

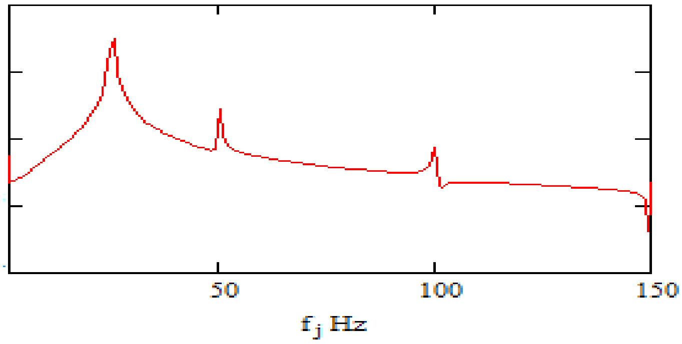

Figure 10. Frequency spectrum of bent shaft fault.

The physical explanation is that the bent shaft fault distorts the signal symmetry rather than the shape of the signal peaks. That means the bent shaft is pushing on one side of the bearing more than on the other side which sounds rather understandable.

3.2. Misalignment

3.2.1. Angular misalignment

It is well know that high amplitudes in the spectrum at 1x, 2x, and 3x time the running speed indicate angular misalignment. It is expected that the amplitude peak at 3x is larger than the amplitude peak at 2x.

In order to generate such a spectrum, there is a need for a distortion event that occurs three times each revolution. It is hard to imagine a physical explanation for such an excitation. However, based on the discussed distortion case, the bent shaft can be explained by a combination of the first and second distortion cases. Thus, it is a case of unsymmetrical two-side peak distortion of the time signal as shown in Figure 11. The FFT spectrum in Figure 12 shows the distortion with weak 2x and strong 3x harmonics.

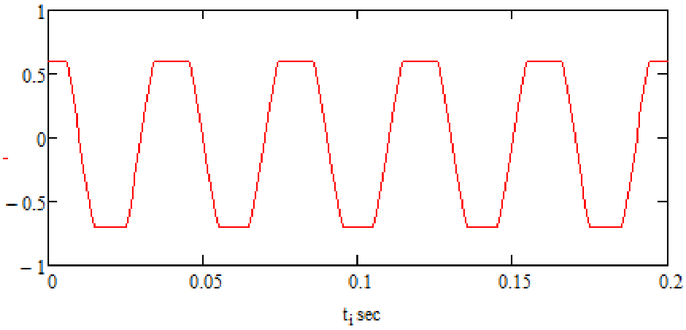

Figure 11. Time signal of angular misalignment fault.

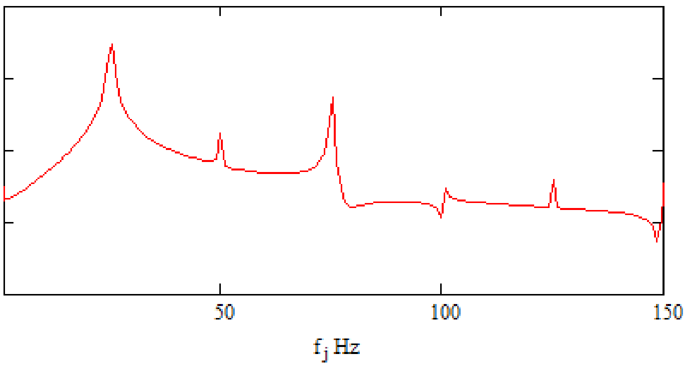

Figure 12. Frequency spectrum of angular misalignment fault.

Physically this means that the angular misalignment fault (as shown in Figure 11and 12) distorts the signal peaks rather than the signal symmetry. That can be explained with the assumption that the misaligned shaft is pushing on all sides of the bearing as shown in Figure13. At certain points due to the phase shift, a pushing action on one part of the coupling is suddenly occurring and that distorts the force on the other part of the coupling. Therefore, the distortion is seen as a flat distortion. However, these distortions are not perfectly equal and therefore they introduce small distortion for the signal symmetry.

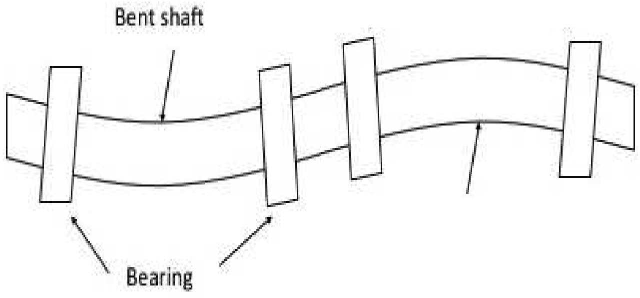

Figure 13. A shaft with angular misalignment.

The response is distorted from both sides due to the misalignment fault Figure 14, and consequently the 3x harmonic component can be seen in the FFT spectrum. However, the distortion is almost equal on both sides (in the time signal) over the contact cycle and therefore the 2x harmonic component is weak.

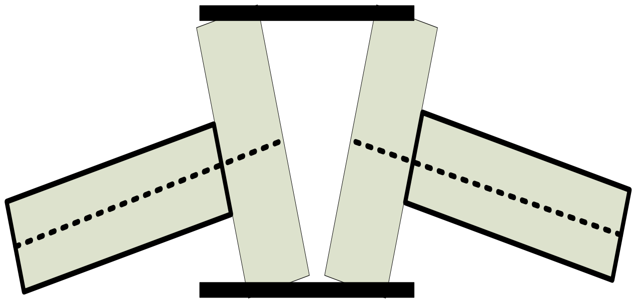

Figure 14. The contact phenomenon of angular misalignment.

3.2.2. Parallel misalignment

It is well know that high amplitudes in the FFT spectrum at 1x, 2x, and 3x running speed and the 2x is larger than 3 x harmonic components indicates parallel misalignment In order to generate such a signal, there is a need for a distortion event that occurs three times during each revolution. It is difficult to explain such an event. The parallel misalignment fault is similar to the angular misalignment fault. However, the distortion due to the bushing action is not equal on both sides of each part, as shown in Figure 15. Therefore, it generates an unsymmetrical time signal.

The parallel misalignment fault can be explained as a combination of the first and third distortion cases, as shown in Figure 16. However, the severity of distortion is higher at one side than on the other i.e. the asymmetry of the time signal is higher than in the case of angular misalignment. The spectrum of parallel misalignment fault is shown Figure 17.

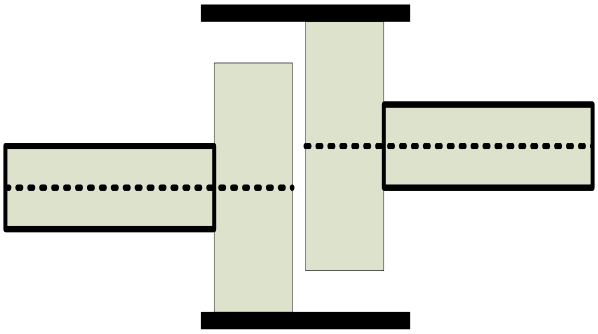

Figure 15. The contact phenomenon of parallel misalignment.

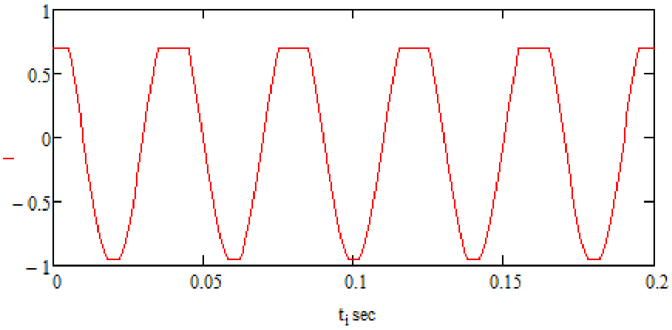

Figure 16. Time signal of parallel misalignment fault.

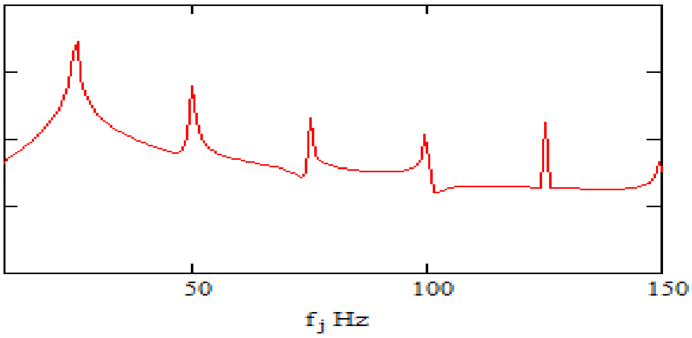

Figure 17. Frequency spectrum of parallel misalignment fault.

3.3. Fatigue fault

The key element in recognizing fatigue failure is that it is typical that cracks influence the vibration of the components in such a way that the signals become distorted i.e. non-linear. This is due to the fact that during vibration the crack is typically open part of the time and then closed part of the time and consequently vibration is not sinusoidal, but flattened when the crack is closed. The time signal of fatigue defect is illustrated in Figure 18. Consequently the asymmetry introduces even harmonics into the spectrum as can be seen in Figure 19.

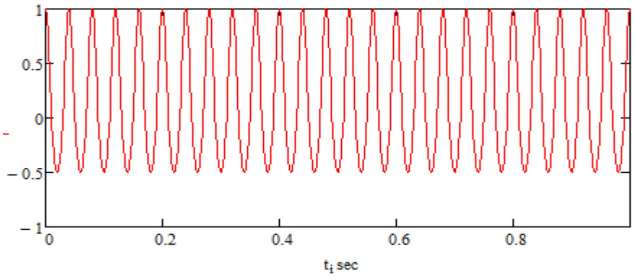

Figure 18. Time signal of fatigue defect.

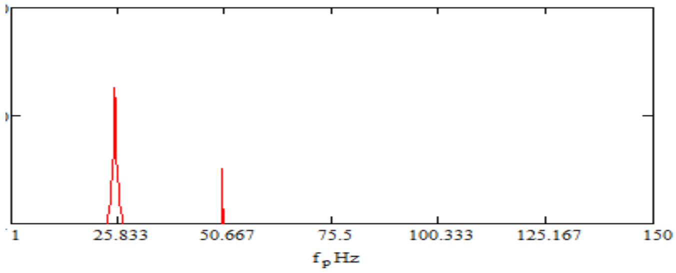

Figure 19. Frequency spectrum of fatigue defect.

3.4. Gear fault

An unusual use of FFT is in the case of gear faults when researchers and engineers discuss sidebands. Again this is something that does not exist in reality but is the results of Fourier Transform. Figure 20 shows the simulated time signal of a gear where one tooth is missing. The corresponding spectrum is shown in Figure 21. Naturally a much more meaningful analysis can be done in time frequency domain.

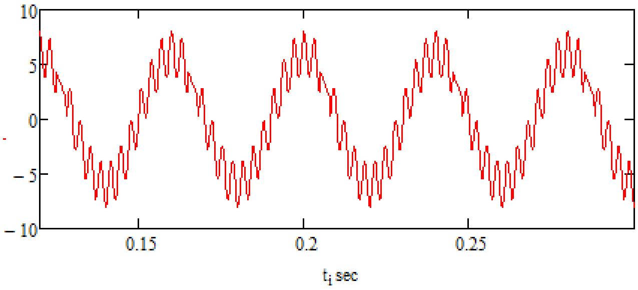

Figure 20. Time signal of gear fault.

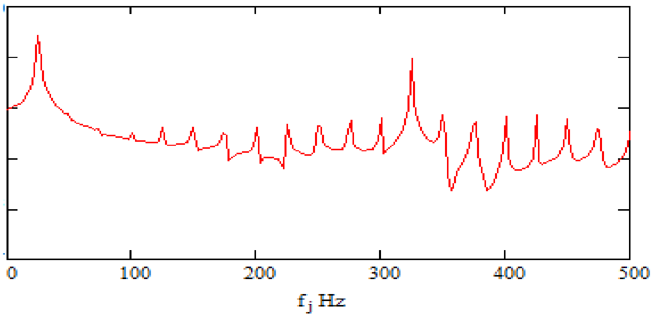

Figure 21. Frequency spectrum of gear fault.

4. FFT the debate

FFT is clearly not the solution to every problem, if used incorrectly, which it often is. Maybe it is time to update the process. In recent years there has been resurgence in the use of time waveform analysis techniques. With the help of this paper, condition monitoring personnel should realize some of the limitations of the FFT process. Since many find FFT analysis process difficult and confusing the technique is rarely used to its full potential. The key to the successful utilization of FFT is knowing when and how to use it. When the FFT process is applied to a signal that contains impacts the true amplitude of the vibration is often greatly diminished, yet still practitioners use this system. According to [3] the human ear is able to characterize and classify non-stationary signals. Whilst the FFT approach will have problems, even if some short-time FFT methods can help to some extent FFT will have difficulties and e.g. the frequency resolution may suffer. Theoretically, the signal must be stationary and if not, the FFT as such is an invalid tool. Yet, again, practitioners still use FFT to ‘identify’ problems, even when they are transient in its nature. Maybe there is a need for an update as to the need and use of FFT.

5. Conclusion

The FFT assumption is based on stationary signals and the fact that a waveform can be constructed using a combination of sinusoids (sine and cosine with different phase and amplitude= Fourier Transforms). When a waveform deviates from the perfect sinusoidal shape, harmonics will arise. This waveform change is easier to investigate in frequency domain that in time domain. We can relate the different harmonics to different deformations of the time signal like symmetric and non-symmetric distortion. This information can be useful when troubleshooting machinery. When signals are not stationary or cannot be divided into sines and cosines, the FFT will generate amplitude scaling errors. Also, when we have signals that are combinations of “harmonics”, noise and transients, a more advanced methodology must be used than just look the FFT result on the screen and reading the markers. What we see might not be what “reality” is about. Hence, a better awareness of these challenges and how to remedy them in the CBM society is of interest. Naturally we can expect that this development will take some time but we could aim for the celebration in 2018 when it comes a quarter of a millennium since Joseph Fourier’s birth. It should be noted that this work has not been aimed to criticize the work of Fourier on the contrary his work and legacy is exceptional. FFT is still the most widely used tool in condition monitoring of rotating machinery even though the technique is often misused or at least misunderstood.

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