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# Theoretical and Experimental Study of Signal Processing Techniques for Measuring Hermetic Compressor Speed through Pressure and Current Signals

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## ABSTRACT

Measuring means extracting information from acquired signals. Either in the frequency or in the time, mathematical processing tools are applied to get information from measurement signals. It is usual, when processing measurement signals in the frequency domain, the application of Fourier analysis, mainly through Fast Fourier Transform (FFT) algorithms. Nevertheless, there are other digital signal processing tools that can overcome FFT performance in computation time or accuracy, and they can be very useful when extracting information from measurement signals. This paper presents some powerful mathematical tools and it shows how useful they can be, when measuring hermetic compressor speed through externally-measurable quantities.

## 1. INTRODUCTION

In the refrigeration industry, speed measurement is important in many different situations. Performance tests, for example, are intended to evaluate compressor refrigerating capacity, power consumption, and coefficient of performance (COP). Compressor speed measurements are also important in determining the steady-state operation (Walter, 1973). The ISO 917 Standard determines that the speed of a compressor under test should not vary more than 1% during the test (ISO, 1989).

As shown in Demay *et al.* (2011), it is possible to measure hermetic compressor speed through externally-measurable quantities, as current and discharge pressure, with specific mathematical processing tools.

Section 2 describes mathematical tools which may be used in hermetic compressor speed measurement. The third section outlines how it is possible to get knowledge about compressor speed from current and discharge pressure signals. In the fourth section is presented a performance comparison, in order to verify the performance of FFT against other mathematical tools. Finally, the sixth section summarizes the conclusions.

## 2. MATHEMATICAL TOOLS

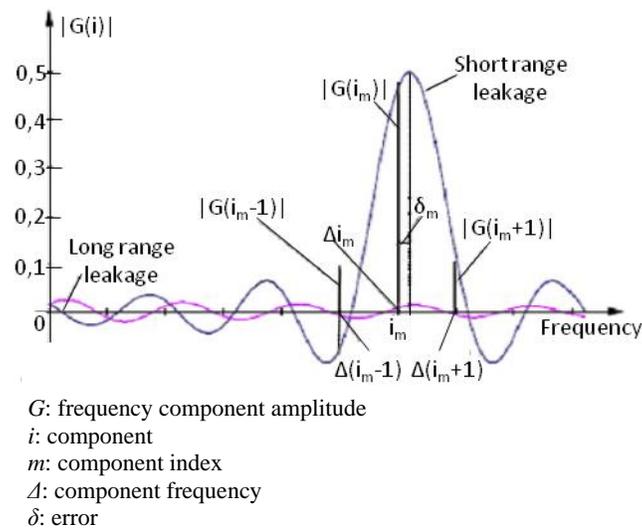
There are several mathematical tools, which may be applied in compressor speed measuring. The most notable are: FFT, zero padding, interpolated FFT, Chirp-Z transform, and Hilbert transform. These tools will be presented in sections from 2.1, 2.2, 2.3, 2.4 and 2.5, respectively.

## 2.1. Fast Fourier transform (FFT)

Fourier transform is a mathematical operation able to change the domain of the signal from time to frequency or vice versa. Each signal is assumed to be a weighted sum of trigonometric functions. An algorithm known as Fast Fourier Transform (FFT) can be used for the calculation of this transform (Proakis and Manolakis, 1996). FFT is the most known algorithm to process signals in the frequency domain. It is reliable, easy to use and understand, and does not demand intense computational resources.

However, FFT accuracy depends on the relation between the sampling rate and measurement time. Besides the measurement uncertainty of the sampled points, FFT has two main uncertainty sources. The first is the  $\delta$  error, caused by the spectral leakage, originated from the acquisition process. It may not be eliminated, only reduced, with window functions.

After windowing and FFT processing, spectral leakage occurs across the entire spectrum. The value of a component comprises itself (short range leakage) and the spectral leakage values originated by other components (long range leakage). This composition may result in a shift error between the evaluated frequency component and its true value, as shown in Figure 1 (Agrez, 2006).



**Figure 1:** Frequency estimation identification error (Agrez, 2006)

The second main uncertainty source is the resolution in the frequency domain, which is directly proportional to the sampling frequency and inversely proportional to the number of samples. In the frequency domain, resolution can be evaluated through Equation (1) (Ramos, 2006).

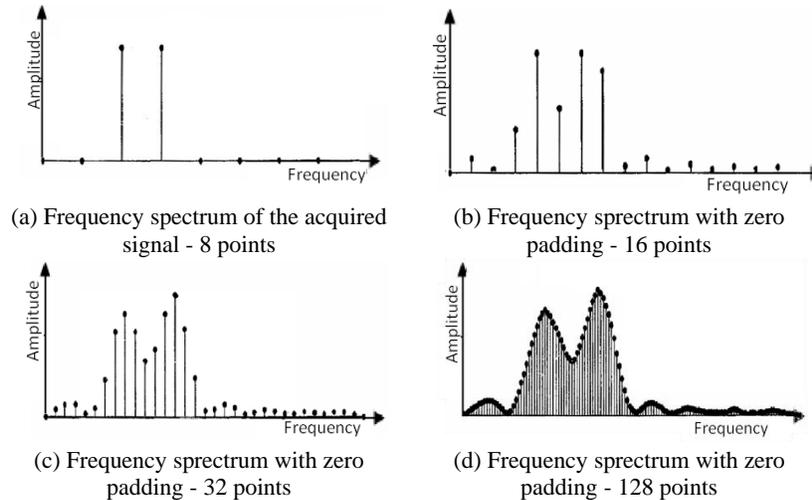
$$\Delta_f = \frac{1}{T_p} = \frac{f_{sr}}{N} \quad (1)$$

$\Delta_f$ : resolution in the frequency domain  
 $T_p$ : observation period  
 $f_{sr}$ : sampling rate  
 $N$ : number of acquired points

The simultaneous action of these uncertainty sources may significantly distort the measurement result. Considering only the resolution error in the frequency, an acquisition of 1000 points at a frequency of 3 kHz would lead to a resolution of 3 Hz, i.e. an error of 1.5 Hz. At an operating frequency of 3600 rpm (60 Hz), this leads to a measurement error of 2.5%. Several techniques have been studied in order to minimize the estimation error caused by windowing, and to improve the resolution of the frequency. In the scope of this work, zero padding, interpolated FFT and Chirp-Z transform will be outlined.

## 2.2. Zero padding

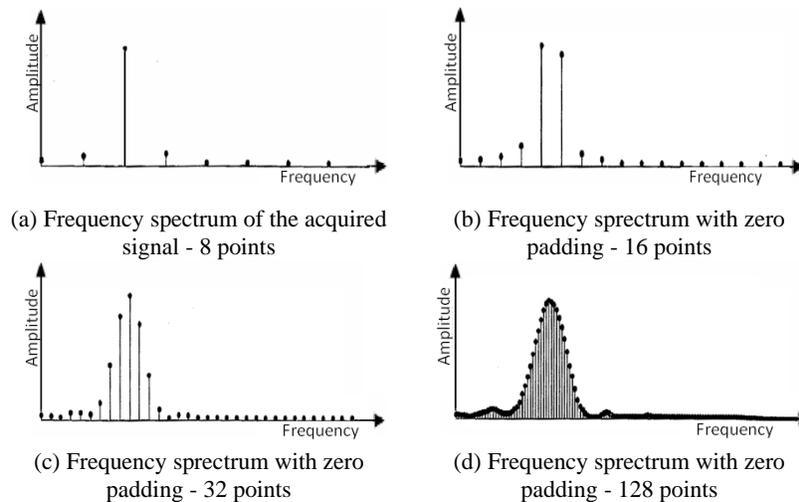
This technique consists of adding some points with zero amplitude to the sampled signal. Its purpose is to improve the resolution in frequency through the expansion of the evaluated points, without changing the signal characteristics – see Equation (1). This technique can be used to improve the identification of components already present in the spectrum, as represented in Figure 2, which represents a signal composed by two frequency components in the frequency domain, determined in 8 points of the spectrum. The results obtained with zero padding technique, for 16, 32, and 128 points of the spectrum are also presented in Figure 2.



**Figure 2:** Zero padding technique applied successfully to improve the identification of a frequency component (Proakis and Manolakis, 1996)

However, zero padding is not valid for components that do not appear in the original spectrum. Its application allows only a more accurate identification of a frequency component within a shorter sampling time interval, in other words, sampling a lower number of points (Proakis and Manolakis, 1996; Hurst and Habetler, 1997).

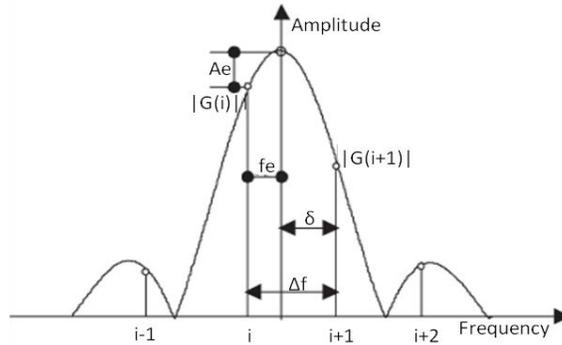
Figure 3 represents the same signal in the frequency domain, but the resolution in frequency was not adequate to identify both components. It can be visualized that zero padding is inefficient in this case, because the components are not present in the spectrum.



**Figure 3:** Zero padding technique is not adequate when all components are not represented in the spectrum (Proakis and Manolakis, 1996)

### 2.3. Interpolated FFT (FFTInt)

Similarly to zero padding, the objective of FFTInt is to use real points on the spectrum to estimate others which lie between these points, but the aim is not to improve the spectrum visualization. The resulting points from FFT can be interpolated in order to estimate the behavior of the spectrum when its obtainment is not possible. The interpolation does not provide further information on the signal, it simply allows an estimation of the intermediate points. Nevertheless, through interpolation it is possible to estimate the  $\delta$  error – see Figure 4, which is attributable to both the noise in the measured signal and the spectral leakage from other components. Equation (2) shows the value of the  $\delta$  error for a two-point interpolation, when a Hanning window is applied.



Ae: amplitude error  
 G: frequency component amplitude  
 i: component index  
 fe: frequency error  
 $\delta$ : difference between component i+1 and the true component  
 $\Delta f$ : resolution in frequency

**Figure 4:** Errors in FFT spectrum and estimation with FFTInt (Shi, 2006)

$$\delta = \frac{2|G(i)| - |G(i+1)|}{|G(i)| + |G(i+1)|} \quad (2)$$

FFTInt is appropriate for improving the identification of strong frequency components. However, there are some limitations to its application related to perturbations around the component of interest and to the frequency changing during sampling (Ramos, 2006).

### 2.4. Chirp-Z transform (CZT)

Z-transform is another tool used to transport a signal from the time to the frequency domain, and vice-versa. However, it is more powerful than the Fourier transform. Fourier transform can be considered as a particular case of the Z-transform when calculated over a circle with unitary radius (Proakis and Manolakis, 1996). The Chirp-Z transform is an algorithm used in the Z-transform evaluation. In contrast to FFT, CZT generates many points in the complex plane for each sampled point. Thus, where FFT would generate only points, curves are generated (Rabiner *et al.*, 1969). CZT evaluates the Z-transform of sampled points, but it is limited to a specific frequency band. The spectral resolution obtained is shown in Equation (3) (Aiello *et al.*, 2005; Rabiner *et al.*, 1969):

$$\Delta f = \frac{f_w}{N} \quad (3)$$

$\Delta f$ : resolution in frequency domain  
 $f_w$ : observed frequency window  
 N: number of acquired points

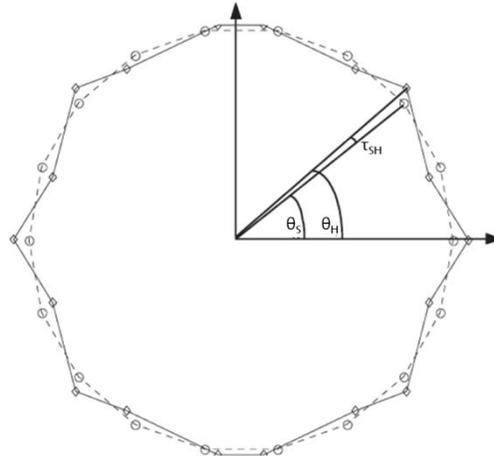
When compared with FFT, CZT has some important advantages, primarily regarding the frequency resolution obtained, due to the narrow observation window. Moreover, it requires a smaller number of points. On the other hand, one drawback is the need for greater processing resources: the number of operations for CZT is  $N^2$ , while is  $N \log_2 N$  for FFT (Aiello *et al.*, 2005; Ramos, 2006).

## 2.5. Hilbert transform

Hilbert transform is a powerful tool for demodulating signals. Hilbert transform shifts each component of a given signal by  $90^\circ$ , without changing its amplitude. Considering a signal  $x(t)=\sin(2\pi ft)$ , with  $x'(t)$  being its Hilbert transform, a signal  $y(t)$  can be defined, according to Equation (4) (Shi *et al.*, 2006).

$$y(t) = x(t) + jx'(t) \quad (4)$$

If  $x(t)$  is purely sinusoidal,  $y(t)$  will be a perfect circle. However, with the presence of harmonics in  $x(t)$ , fluctuations in the module and phase of  $y(t)$  appear, as shown in Figure 5 (Shi *et al.*, 2006). The analysis of these fluctuations provides an easier and more exact measurement, without the influence of the fundamental component, represented by the perfect circle.



$\theta_S$ : reference signal - perfect circle  
 $\theta_H$ : real signal with harmonics  
 $\tau_{SH}$ : fluctuations caused by harmonics

**Figure 5:** Module and phase fluctuations caused by harmonics. Dashed line: purely sinusoidal (reference signal), solid line: real signal with harmonics (Shi *et al.*, 2006).

## 3. MEASURING HERMETIC COMPRESSOR SPEED THROUGH EXTERNALLY-MEASURABLE QUANTITIES

As described Demay *et al.* (2011), in order to measure hermetic compressor speed, the most relevant quantities which are measurable from outside a compressor are the supply current and discharge pressure. They are often measured in procedures performed in the refrigeration industry and their sensors are quite well-known and reliable. Also, their measurement procedure is normally very simple.

### 3.1. Speed measurement through compressor supply current signal

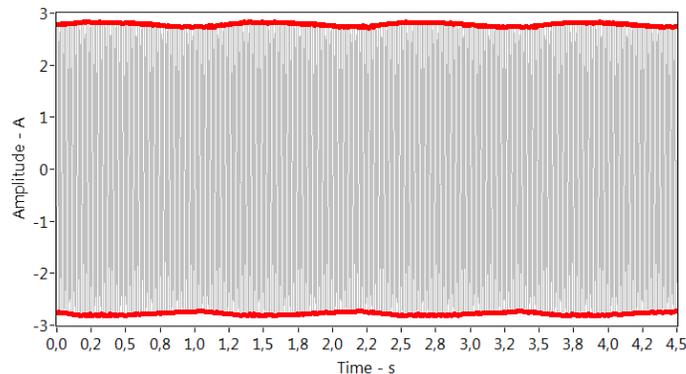
The information of compressor speed may be obtained from current signal through two methods: identifying slip frequency components and identifying harmonics related to the gap between the rotor and stator.

3.1.1. Identifying the slip frequency: The frequency component corresponding to the motor slip may be identified through the supply current signal oscillation, as exemplified in Figure 6. The oscillation present in the supply current signal envelope is generated by the presence of a component, whose frequency is equal to the motor slip. The evaluation of the peaks and the valleys of this signal allows the estimation of the frequency corresponding to the motor slip (Walter, 1973).

3.1.2. Identifying harmonics related to the gap between the rotor and stator: Due to the rotor eccentricity and slots, and the implicit variation in the magnetic gap, some harmonics related to the speed appear in the frequency

spectrum. Its evaluation demands knowledge of some constructive parameters (Hurst and Habetler, 1996; Blasco-Gimenez *et al.*, 1996; Ferrah *et al.*, 1992a; Ferrah *et al.*, 1992b).

Another possibility for estimating speed from the current signal is the analysis of eccentricity harmonics. They are always present due to the imperfect positioning of the stator or rotor, a bent rotor, worn bearings or coupling misalignment (Hurst *et al.*, 1994). In the frequency spectrum, these harmonics lie symmetrically to those of the supply current frequency and can be evaluated as shown in Equation (5) (Hurst and Habetler, 1996; Aiello *et al.*, 2005).



**Figure 6:** Compressor supply current and slip frequency component (in detail)

$$f_h = f_s \left( 1 \pm \left( \frac{1-s}{p} \right) \right) \quad (5)$$

$f_h$ : eccentricity harmonics frequency

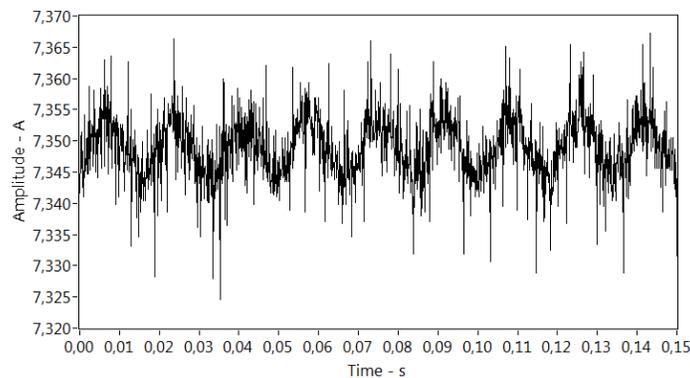
$f_s$ : supply frequency

$s$ : rotor slip

$p$ : number of poles

### 3.2. Speed measurement through discharge pressure signals

The pressure inside the chamber is constantly changing, in a cyclic or pulsed manner, and the same applies to the behavior of the suction and discharge pressure signals (Bloch and Hoefner, 1996). Figure 7 shows an example of the discharge pressure signal.



**Figure 7:** Output of a pressure transmitter applied to compressor discharge pressure measurement

The maximum and minimum pressure points correspond to the upper and lower dead points of the piston movement. In the suction or discharge line, the period between two maximum points is the time interval between two upper

dead points. Therefore, there is a relationship between the pressure signal periodicity and the piston oscillation period; in other words, the compressor speed. Some mathematical tools that allow the identification of components of the supply current and suction/discharge signals that are related to compressor speed frequency are outlined in section 4.

#### 4. EXPERIMENTAL RESULTS

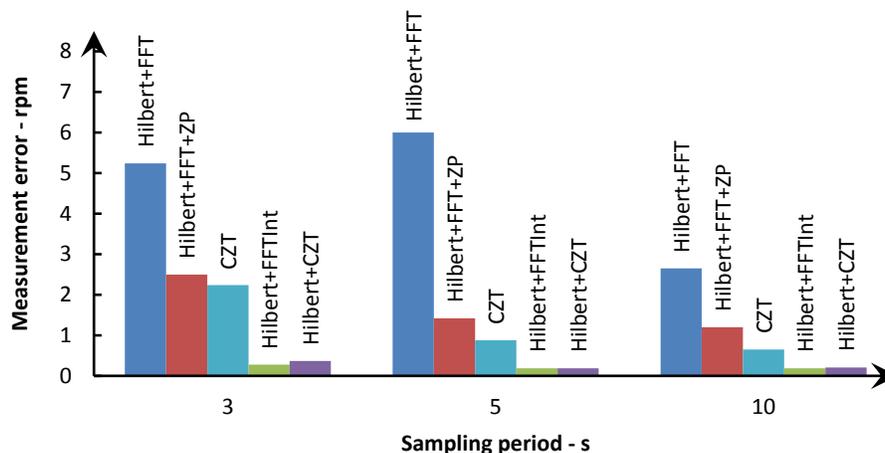
In order to compare the performance of the presented mathematical tools against FFT, it was built a practical experiment. A complete refrigeration system was built, and a magnetic pickup was inserted into a mono-cylinder compressor, as measurement standard.

The compressor was supplied with a voltage of 110 V, 60 Hz. After refrigeration system reached steady-state condition, current and discharge pressure signals were acquired, with a sampling rate of 12 kHz, during 3 s, 5 s and 10 s. Compressor speed was evaluated with each one of the mathematical processing tools presented in section 2 and compared with the speed evaluated with the magnetic pick-up. The mean error, the repetitivity and the maximum error, at the 95% confidence level, were then evaluated.

The transducers used in the tests present high reliability and are commonly used in industry. An Agilent 1146 A current probe was used to measure the current. This transducer operates in a bandwidth ranging from DC to 100 kHz, with an uncertainty lower than  $3\% \pm 50$  mA in the range of 100 mV/A (Agilent Technologies, Inc., 2010). To measure pressure, the analog transducer GE PDCR4070 was used, which presents an uncertainty of 0.04% (General Electric Company, 2008). The output signal of the pressure transducer is filtered by a third order filter with a bandwidth ranging from DC to 150 Hz. An NI USB-9215A DAQ was used for the acquisition of both current and pressure signals. The resolution of the DAQ is 16 bits and the maximum sample rate per channel is 100 kS/s (National Instruments, 2010).

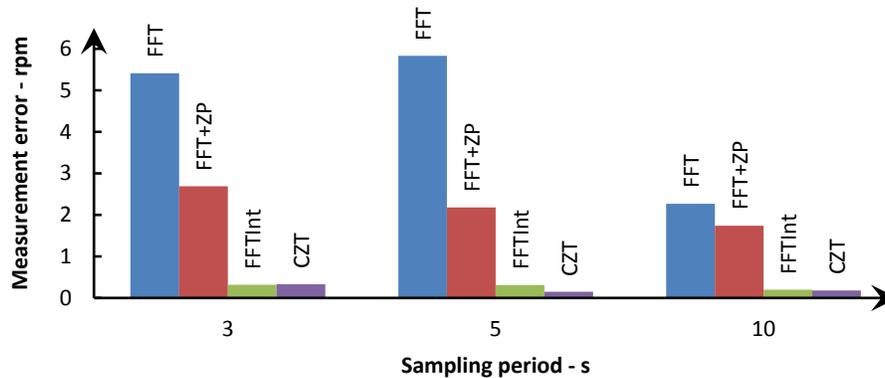
Since the frequency is the variable of interest, the frequency response of the transducers is the most important characteristic to be analyzed. The bandwidths in which the transducers operate are much higher than the frequency of interest, around 60 Hz, and thus it can be concluded that the influence of the uncertainty of the transducers is negligible. In the case of the measurement of the speed from the pressure signal, it is of no interest to measure higher frequency components. In fact, the aim is to isolate the component close to the supply frequency, and therefore the presence of the 150 Hz filter is appropriate and of importance in this measurement.

The first method tested was speed measurement through the identification of eccentricity harmonics frequency on current signal. Five mathematical processing tools were applied: FFT, FFT with zero padding, FFTInt, CZT, and Hilbert Transform, in order to avoid the influence of supply current frequency component in measurement process. Their results were compared with the magnetic pickup. Figure 8 presents the maximum measurement error obtained with each tool.



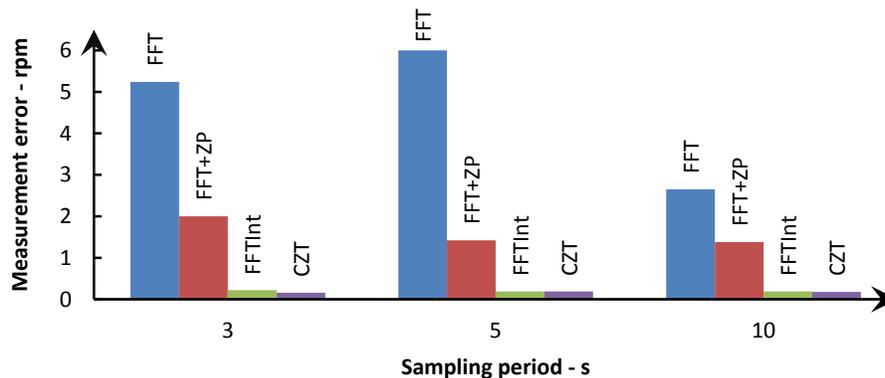
**Figure 8:** Measurement error of mathematical tools: eccentricity harmonics measured through current supply signal

The second method tested was speed measurement through identification of slip frequency on current signal. Four mathematical processing tools were compared: FFT, FFT with zero padding, FFTInt and CZT. As it was not need to avoid the influence of supply current frequency component, Hilbert Transform was not evaluated. Figure 9 presents the maximum measurement error obtained with each tool.



**Figure 9:** Measurement error of mathematical tools: slip frequency measured through current supply signal

Finally was tested the speed measurement through discharge pressure signal. Four mathematical processing tools were compared: FFT, FFT with zero padding, FFTInt and CZT. As it was not need to avoid the influence of supply current frequency component, Hilbert Transform was not evaluated. Figure 10 presents the maximum measurement error obtained with each tool.



**Figure 10:** Measurement error of mathematical tools: pressure discharge signal

The analysis of the figures above presented shows clearly that FFT is not the best alternative for speed measurement. For three different sampling periods, FFT has reached the poorest performance among all the analyzed mathematical processing tools. FFTInt and CZT performance were by far superior to FFT performance, and zero padding was also useful, in order to reach smaller measurement errors.

The main reason to the higher measurement error of FFT is the frequency resolution. According to Equation (1), a FFT with a 10 s sampling period will reach a frequency resolution  $\Delta_f$  of 100 mHz, or 6 rpm. With the application of other mathematical processing tools, it is possible to obtain a better frequency resolution and also to estimate values between points calculated via FFT, to get better measurement results.

## 5. CONCLUSIONS

This work presented some mathematical tools to measure hermetic compressors speed in the frequency domain. Their performance in measuring this quantity through current and discharge pressure signals were analyzed and

compared. The obtained results show that the FFT performance may be by far inferior to other mathematical processing tools, mainly Chirp-Z transform and interpolated FFT: an error reduction around 90% was achieved. It means that it is possible to reach better results, with more accuracy and in a smaller measurement period, with other mathematical tools than FFT, the most common choice for measurement in the frequency domain.

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