23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

NON STATIONARY SPECTRAL ANALYSIS OF VIBRATION GENERATED BY ROTARY HERMETIC COMPRESSORS

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Abstract. *The rotary hermetic compressors are target of study and innovation, because of the mass production the research costs are accessible, and consumers who buy such equipment are very aware of the noise they may generate. However, the techniques used for noise and vibration analysis consider the stationary signal, which affect the analysis and the results obtained. Thus, it is proposed to apply the Short Time Fourier Transform or Hilbert Huang Transform techniques, which consider the signal non- stationary. At the end of the non stationary analysis seems to be more attractive. Different frequency characteristics can be seen depending on the time position. The high frequencies are present at specific instants of time, while the average frequency is observed during all cycle operation. The other results are presented and discussed at the end of work.*

Keywords: *Non stationary analysis, Rotary hermetic compressor, Noise and vibration*

1. INTRODUCTION

The rotary hermetic compressors are targets of study and innovation, for the mass production makes them accessible research costs, and consumers who buy such equipment are very aware of noise that they can generate

Of the factors which determine human comfort, noise and vibration are the two factors which most affect human perception and were intensely by Harris (1957), Crocker (1975), Yerges (1978), Beranek (1971), Foreman (1990), Erwins (1984) e Allemang (1984) apud Kim, Cho, and Chou (2000). In addition, Bistafa (2006), list three ways of how noise affects the human: physiological, psychological and mechanical.

From Allemang (1984), there is a high amount of work themed rotary hermetic compressor.

Some Works and results ilustrate that fact. A strong pure tune in 4 kHz is usually observed in rotary compressor (Bagepalli, 1989). According to Kim et al (2004), from the noise viewpoint, the hermetic rotary compressor is one of the most important components in a refrigeration unit, once it has great influence on performance, noise and vibration of the system. Noise and vibration occur due to fluid pulsation during compression and unbalanced dynamics forces. Malcolm, 2007, mentions that the sound generated by rotary compressors depends on the rotational frequency and its multiple, number of rotating elements, flow capacity and other flow related factors. Ling (2008) noted that due to the accumulator's large volume, it effectively contributes to the noise level. Okur and Sinan, 2011, proposed the substitution of the vane with spring by an articulated vane as at higher operation frequencies the articulated vane has isentropic efficiency.

Lee, et al (1994) by the signal processing technique of acceleration and sound pressure observed that gas pressure pulsation and vibration of the housing are sources of noise in the 3 to 4 kHz band. Kim, et al (1998) mentioned that although the technique of signal processing is a powerful tool, it is not quite appropriate to identify sources in complex structures such as rotary compressors, because it shows a strong correlation between various sources. An analysis by sound intensity and vibration of the surface was proposed. It was concluded that the suction accumulator is a source of noise and after some modifications a reduction of 20 dB at 2 kHz was obtained Kim, Cho and Chou (2000) noted that due to the complex nature of the generation and transmission of noise and vibration of rotary compressors it is essential to apply various techniques to identify the various sources and transmission paths. Their paper proposed a technique of analyses by finite elements, experimentation and signal processing. The gas pressure and the housing are the main sources of noise in 5 kHz. In 2008, Huang et al, and later in 2012, Gu, Zhang and Xu, evaluated by spectral analysis the critical moment of noise generation based on the angular position of the compression system for various operating frequencies and found that at discharge valve opening (210° to 360°) larger amplitudes occurred.

In addition research and innovations were proposed. Some patents are:

- Holes in vane and roller in order to diferente impact conditions (Bagepalli, 1984);
- Helmholtz resonators in the discharge valve (Jeung, 1988);

- Redesign of the discharge valve retainer for a smooth and continuous contact (Aldo, 1993);
- Fibers are introduced into vane, weight reduction, higher abrasion resistance and vibration absorption (Chan-Soo, 2002);
- Improved structural suspension, reducing noise and vibration (Lee, 2013).

There is therefore a growing demand for improvements and innovations searches in the context of rotary hermetic compressors. Together, there is the Brazil historical context it is, where Correio Brasiliense publishes the following news: 2014 was the hottest year in modern history, according to an analysis by the Oceanic and Atmospheric Agency (Brasilense, 2015). In parallel with the data published the Associação Brasileira de Refrigeração, Ar Conficionado, Ventilação e Aquecimento (Abrava, 2015), consumption of the air conditioning , either split or window, presents sales growth from 2008 to 2014, with growth forecast to 2015 of 10%. Although it is noted that sales have growth in all sectors: industry, commercial and services. Where the most important factors in buying a residential air conditioning are price and quality.

Therefore, there is a growing air conditioning and compressors in Brazil. In addition, consumers are aware of the noise they cause and can be a deciding factor in purchase.

2. NON STATIONARY SPECTRAL ANALYSIS

According Pinto (2009) spectral analysis aims to identify regularities and has its base in mathematical theory f Fourier anakysis, where it is proposed to decompose periodic functions into sums of sinusoidal functions. The classical spectral representations are defined for stationary and linear data systems, these features being major limitations of such techiniques. For example, Fourier Transform (FT) of a signal in the time domain $s(t)$ into frequency domain $S(f)$ is defined by:

$$S(f) = \mathcal{F}\{s(t)\} = \int_{-\infty}^{\infty} s(t) e^{-i2\pi f t} dt \tag{1}$$

However the signals have time variation, as observed by Huang et al (2008) and then Gu, Zhang and Xu (2012) where the signal of a rotary hermetic compressor presents moments that occur in larger amplitudes (valve opening time). Thus, for time - frequency analysis it is proposed to Short Time Fourier Transform (STFT) and the Hilbert - Huang Transform (HHT).

2.1 Short Time Fourier Transform

Since one of the problems of using FT is temporal location, a natural idea is divide the signal into windows, and calculate FT for each of these windows. More formally you can multiply the signal by a window $w(t)$ centered in instant t_n considered of interest, and calculating the FT of this product. In order to obtain the spectral variation with time, this procedure is repeated for all times t. So define STFT in Eq. (2) and STFT energy in Eq. (3):

$$STFT(t,f) = \int_{-\infty}^{\infty} s(t) w(t-\tau) e^{-i2\pi f t} d\tau \tag{2}$$

$$S(t,f) = \left| \int_{-\infty}^{\infty} s(t) w(t-\tau) e^{-i2\pi f t} d\tau \right|^2 \tag{3}$$

It is noted in Eq. (2) the signal amplitude as a function of time and frequency , so it is considered the non- stationary signal , enabling an analysis of the frequency components into time interval , for example , at the moment of opening valve. However, when a higher temporal resolution is required, the window $w(t)$ should be as small as possible, which brings a reduction in frequency resolution because the signal energy (Eq. (3)) is governed by duality of the time frequency. The lower limit value for the product time frequency of the Heisenberg - Gabor inequality is $1/4\pi$ (Boashash, 2003; Flandrin, 1993 e Gabor, 1946 *apud* Pinto, 2009).

2.2 Hilbert Huang Transform

The actual data that must be processed in the most varied fields of knowledge, are mostly non stationary and nonlinear. In the case of HHT, the problems of non stationary and nonlinear are not exceeded since it uses a decomposition which derive from the signal itself, it is adaptive and afterwards. However, the strength of the mathematical formulation that support the non adaptive methods (FT, STFT, …) contrast with the fragility of the empirical method proposed by HHT.

The HHT is a method of analysis in time frequency that has two stages: first (Empirical Modal Decomposition - EMD) gives a set of base functions adaptively, and second (Hilbert Spectral Analysis) allows obtaining a representation in time frequency domain by calculating the Hilbert transform of each functions obtained in the first part by EMD (Pinto, 2009).

Limitations on the direct use of Hilbert Transform, to obtain components for which the instantaneous frequency is not negative, it is necessary that the elements are symmetrical relative to local average and have the same numbers of zeros and relative extremes. Based on such observations it was proposed a class of function (Intrinsic Mode Functions - IMF) that meets the stated requirements (Huang *et at*, 1998, *apud* Pinto, 2009).

Thus, let $x(t)$ an IMF, the analytic signal $z(t)$ is obtained by Hilbert transform, according to Eq. (4).

$$z(t) = x(t) + iH\big(x(t)\big) = x(t) + iy(t) = a(t)e^{i\theta(t)} \tag{4}$$

Where can set the instantaneous frequency by:

$$w = \frac{d\theta(t)}{dt} \tag{5}$$

After calculating the Hilbert transform and the instantaneous frequency of each IMF, it is possible to represent the original signal through a synthesis process defined by:

$$X(t) = \sum_{j=1}^{n} a_j(t)e^{i(\int w_j(t)dt)} = H(w,t) \tag{5}$$

Equation (5) shows the spectrum Hilbert Huang, where observed to every moment the contribution frequency and also de energy associated with each pair of time frequency.

3. EXPERIMENTAL PROCEDURE

In order to evaluate the analytical techniques in the time frequency, a rotary hermetic compressor is instrumented. The experimental procedure consists in evaluate the vibration and noise of two groups of compressor: Baseline and Modified Muffler.

The Baseline set consists of four compressors collected from the production line. Due to variation in all industrial processes, carefully select only compressors considered good in customer perception. On the other hand the Modified Muffler set consist of four compressors, where eight 2 mm holes are distributed at positions 2 and 4 (4 each), and eight 2, 75 mm holes are distributed in positions 1 and 4. The 1 to 4 positions are shown in Fig. (1) and original muffler for comparison.

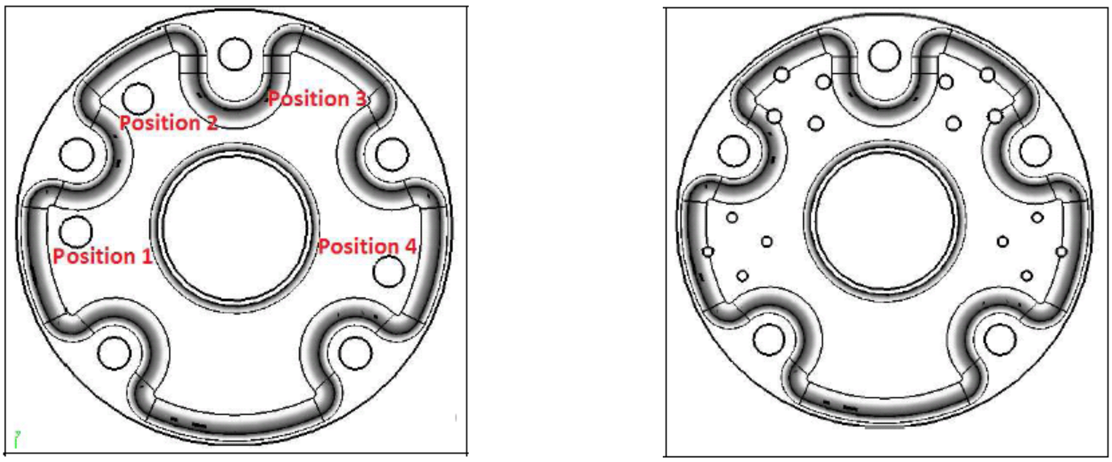

Figure 1 – Original and modified muffler

In the acquisition of vibration signals are proposed 5 points, the first on weld point between kit and housing, next to accumulator, the second on compressor cover, the third on electrical motor, the fourth on 105° in counter clockwise direction from the accumulator and the last on accumulator. In Fig. (2) the positions are illustrated.

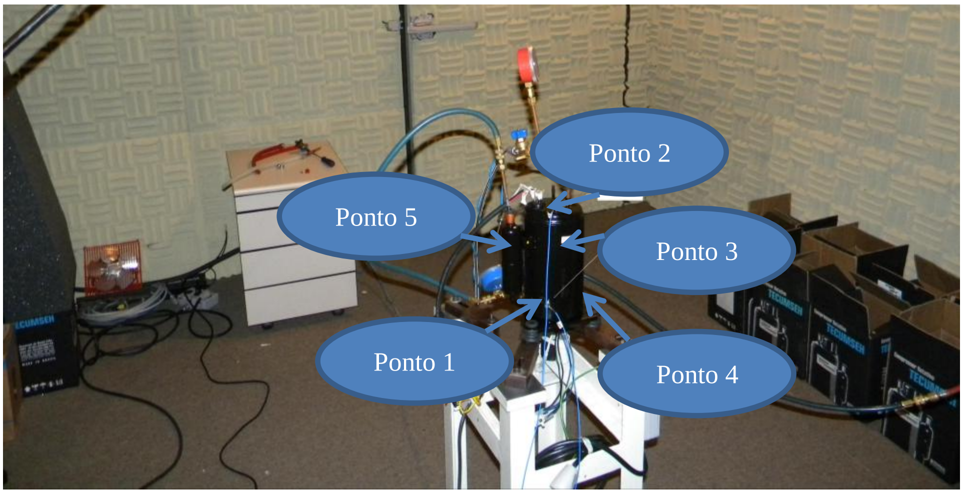

Figure 2 – Measurement positions

The signals with 20000 points are acquired for 10 seconds with an acquisition frequency of 20 kHz. Besides the acceleration transducers, a data acquisition, a signal conditioning and a notebook are required. Figure (3) illustrates the arrangement of the measuring chain and Tab.1 shows equipment name and models.

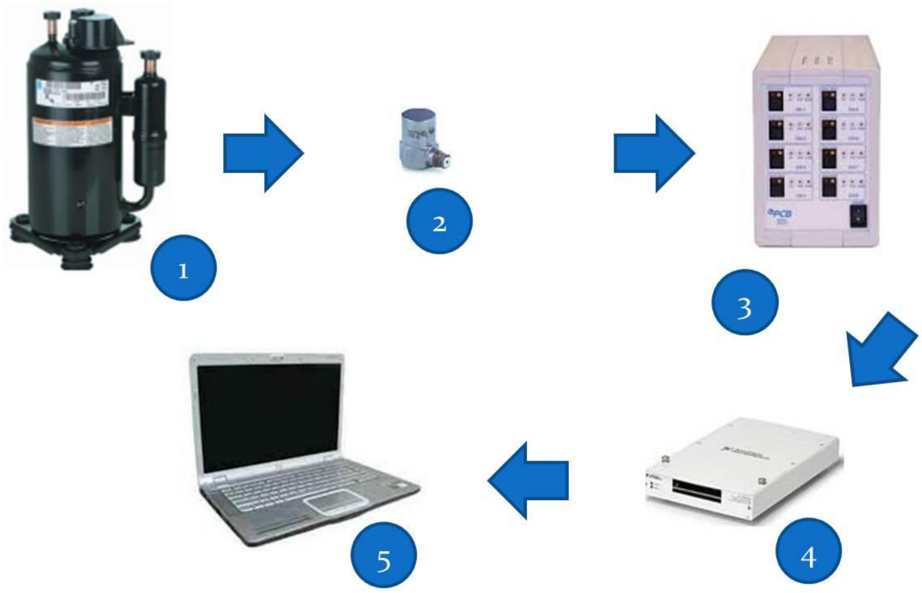

Figura 3 – Measurement chain

Tabela 1 – Equipment identification and trial

Item	Name	Model
1	Rotary hermetic compressor	RG 171AR
2	Accelerometer	PCB 352C33
4	Signal conditioning	PCB 482A20
5	Data acquisition	NI USB 6251
6	Notebook	HP

4. RESULTS

They are shown in Fig. (4) the characteristic signals in time domain to 5 periods, the Baseline compressor in blue and Modified Muffler in red, among the 5 measurement points only point 1 (Weld Point) is showed, because it is the highest amplitude, in addition to being geometrically the transmission path between kit and housing.

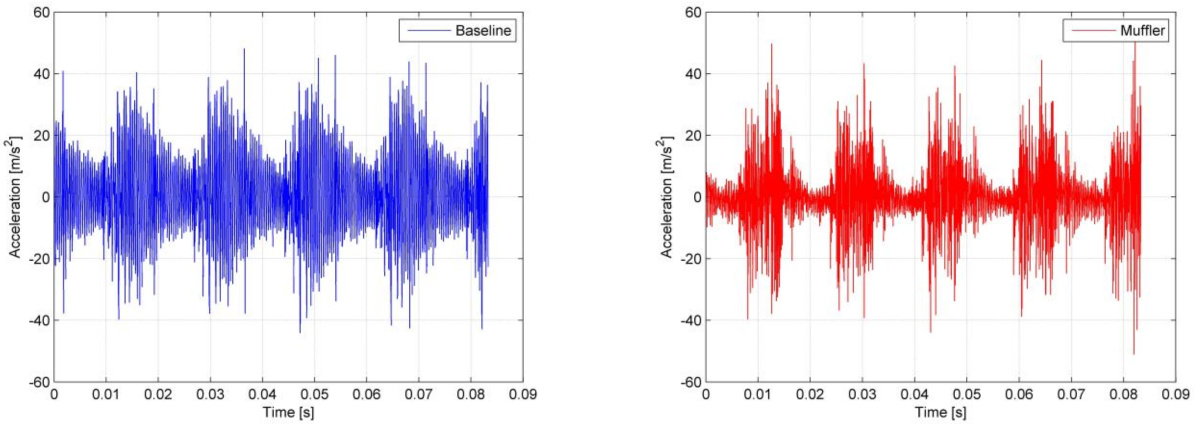

Figura 4 – Time signal

Acceleration in weld point has amplitude in the range of 50 to -50 m/s² for Baseline and Modified Muffler. However, the transition amplitude from one cycle to another in Modified Muffler are smaller than in Baseline. Furthermore, there is a amplitude modulation on both signals.

In sequence in Fig. (5) the frequency spectrum of acceleration by FT with 1024 points.

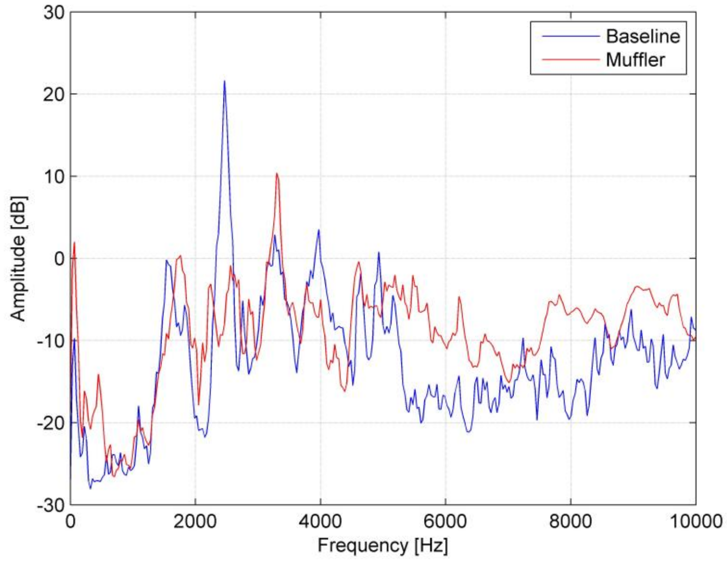

Figura 5 – Frequency spectrum by FT

Frequency spectrum shows differences between the study groups. Basically the muffler with more holes reduces vibration frequencies near 2,5 kHz, on the other hand the frequencies above 5 kHz and below 600 Hz have increased.

However all analysis was carried with stationary signal by FT, which prejudge the conclusions. As Fig. 4 observes instants in which the signal presents different characteristics, for example, peak region in Modified Muffler.

Thus, Fig. (6) shows the time frequency analysis signals by STFT.

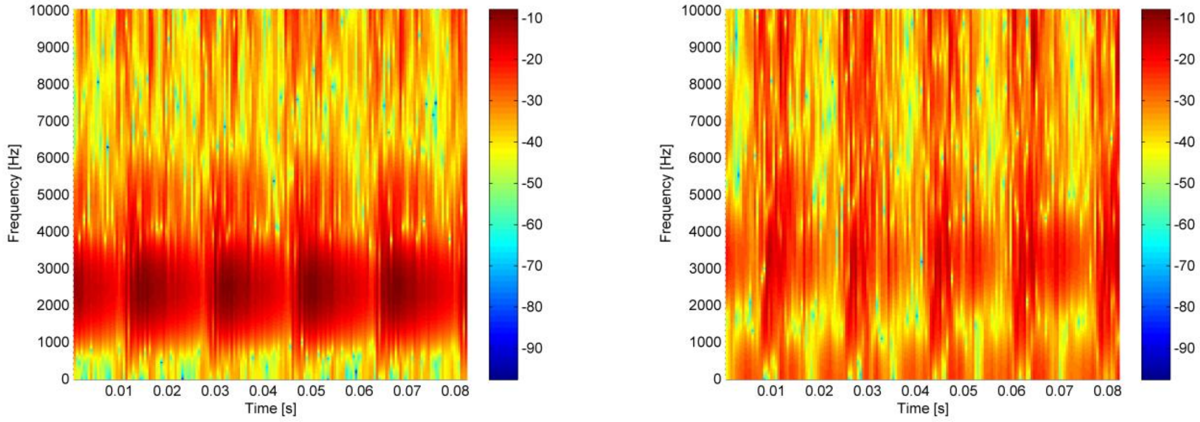

Figura 6 – Time frequency by STFT

High frequency components are present at specific instants at both groups, but Modified Muffler has larger amplitudes and present for a longer interval. However, the pattern of frequency components between 1 and 4 kHz are present during all time. Baseline has critical amplitudes in this interval. Modified Muffler presents a situation more smooth in this frequency band. On the other hand, observe higher amplitudes between 6 and 8 kHz, as well at low frequencies, which appear to be alternating with high frequency components.

Figure (7) presents acceleration HHT Baseline and Modified Muffler for the two more energetic IMF.

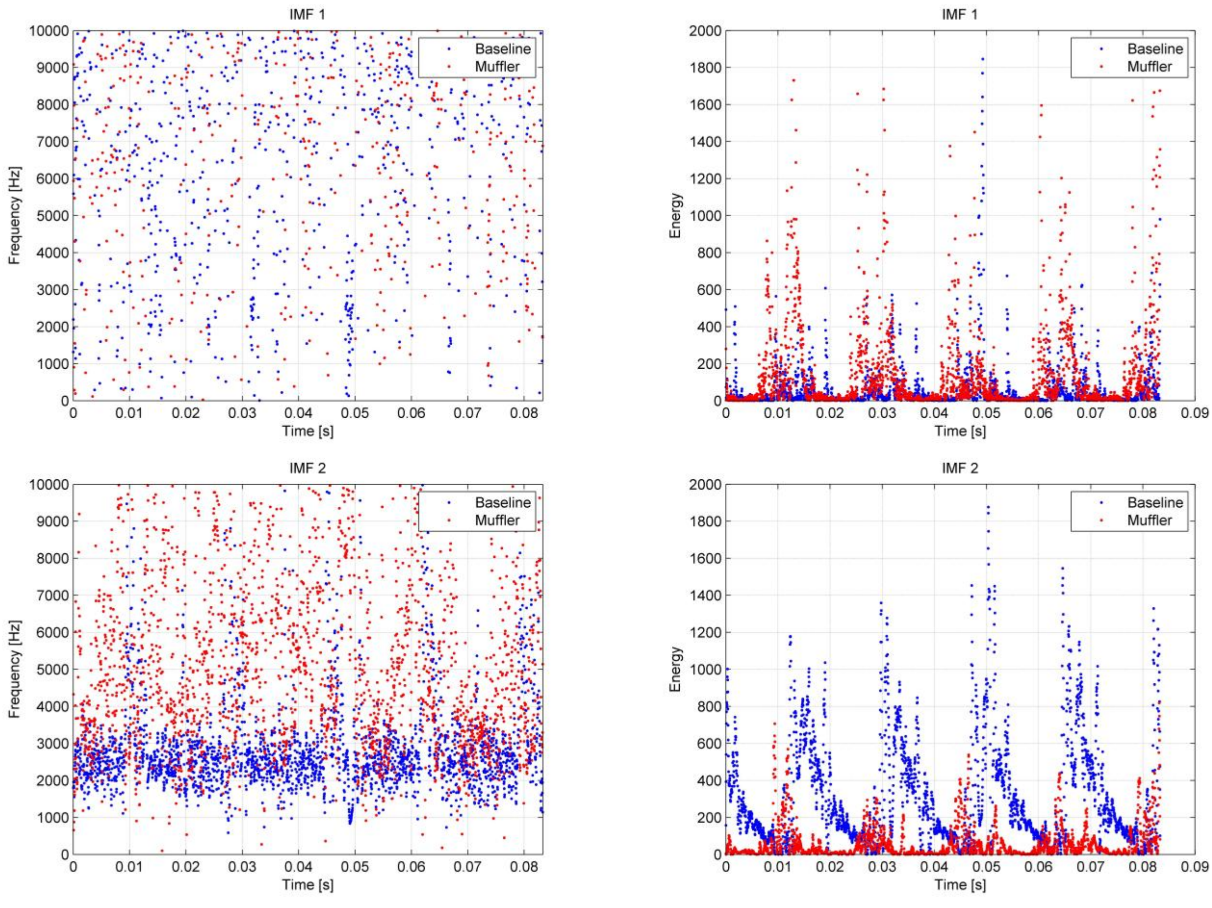

Figure 7 – Time frequency for the two more energetic IMF

For IMF 1 both Baseline and Modified Muffler has moment characteristic energy distribution, with frequency present along all band. The energy of IMF 1 has regions of increased amplitude, representing critical areas of noise generation. Modified Muffler present an average amplitude higher than Baseline.

Baseline IMF 2 has frequency spectrum mainly between 2 to 3 kHz bands, however at certain intervals the frequency band ranges up to 10 kHz, probably represents the instant of an impact. The energy associated with this frequency allows affirming that during an operation cycle there are on average three energy peaks beyond the cycle itself be represented by a high energy region. On Modified Muffler the energy is lower and cycle duration is smaller. Further, Modified Muffler has frequency distributed along entire spectrum.

Then, in order to study others IMFs is presented in Fig. (8) the frequency and energy for IMF 3.

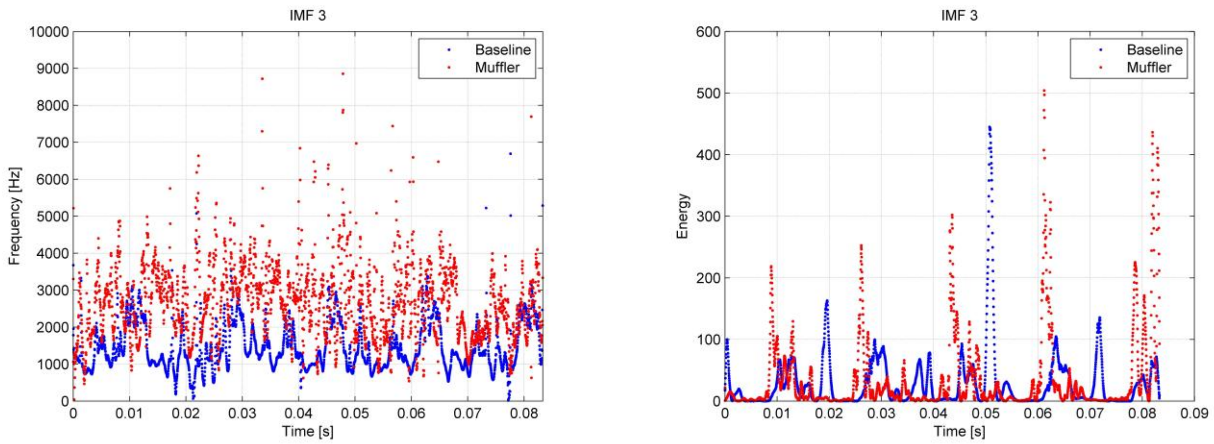

Figure 8 – Time frequency HHT for IMF 3

Modified Muffler IMF 3 has a periodic energy pattern, represented by 2 to 4 kHz frequency band, but Baseline has random pattern into energy distribution, and they are associate to low frequencies components. Moreover, the energy contained on IMF 3 is smaller than that in the first two IMFs, so other IMFs are not discussed, because of lower energy components.

Finally, non stationary analysis tools appear attractive, because they allow analysis of frequency components together with time. Through them, concludes middle frequencies are present throughout the operation cycle, particularly on Baseline. High frequencies appear at specific instants, in addition, the high and middle frequencies have periodicity. Low frequencies have a random feature.

Thus, changes that minimize middle frequencies energy are interesting, Modified Muffler is a design that reduced amplitudes on that band. However, new frequency components appeared on Modified Muffler, therefore further studies on number of holes have to be evaluated. Although time frequency analysis presents richer results, it is necessary to refer the acquisition by the angular position of the eccentric shaft, to associate events with positions of the compression cycle.

5. CONCLUSION

Based on the presented results we can conclude that:

- The welding point due to its higher amplitudes and geometrically be a transmission path between kit and housing is used to compare the compressor groups.
- Baseline and Modified Muffler time signal differ, where more number of holes reduces the various acceleration amplitudes during operation cycle, also both signals have amplitude modulation.
- FT analysis allow to evaluate differences in frequency spectrum, where Modified Muffler have low noise near 2,5 kHz, but higher noise at low and high frequencies.
- STFT analysis enables evaluate frequency components over time. Baseline have 1 to 4 kHz band frequency during entire cycle, while high frequency occur due to impacts presented at certain times. Modified Muffler features smooth frequencies from 1 to 4 kHz and new component of frequency between 6 kHz to 8 kHz.
- HHT analysis shows the IMF 1 is composed of frequencies distributed over all spectrum band, but with energy present in certain moments. IMF 2 the Baseline energy is higher than Modified Muffler energy, furthermore almost all Baseline energy is contained in 2 to 3 kHz range, while Modified Muffler energy is present over all spectrum band. Moreover, it is observed high and middle frequencies have periodicity while low frequencies have random distribution.
- New muffler hole configuration should be evaluated and the acquisition should be referenced with angular shaft angular position.

6. ACKNOWLEDGEMENTS

The authors would like to thank CAPES (Coordenação de Aperfeiçoamento de Pessoal de Ensino Superior), FEMEC (Faculdade de Engenharia Mecânica) of UFU (Universidade Federal de Uberlândia), for their financial support and TECUMSEH for their base data and rotary compressor.

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