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IDENTIFICATION AND DIAGNOSIS OF DAMAGE IN AUTOMOTIVE GEARBOX

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Abstract. *In more complex systems, as in automotive gearbox systems, a close data processing is required because there are many moving parts (gears, bearings, axes, etc.), and thus, there are many possible sources of damage and noise generation. In this work was used a specialist procedure for detection and identification of damages in automotive gearboxes. The detection methods used are wavelet transform and mathematical morphology, associating concepts of energy and entropy. The gearboxes were produced on a production line for heavy vehicles. Ten gearboxes were approved by a subjective method (human hearing) serving as reference and three boxes with different induced damages (two with damage to the bearing running track and another with gear tooth damage) were used in the analyzes. The experimental data were obtained using accelerometers placed at different positions in the samples. The experimental data were treated and analyzed in the Matlab environment. The results obtained, using the different detection methods, enabled the identification of the presence of the damage and the damaged component.*

Keywords: *Automotive gearbox, wavelet, mathematical morphology, energy, entropy.*

1. INTRODUCTION

Automotive gearboxes are sets of difficult to inspect since they contain many moving parts. The quality control methods of these systems, which are used in industry, are, to a certain point, subjective and inefficient, as well as demanding high investment (numerous metrological measurements) and being time consuming. In this scenario one of the possible alternatives is the use of the analysis of damages through vibratory signals. For the analysis of the conditions of operation of gearboxes, through vibratory signals, numerous tools have been used, like Cepstrum analysis (Morsy and Achtenova, 2014); Acoustic emission (Mazal, *et al.*, 2012); Statistical methods (Combet and Gelman, 2009); Wavelet transform (Wang and Mcfadden, 1996); and morphologic analysis (Chen, *et al.*, 2015).

The tools of analysis of defects using the vibratory signals, have already been demonstrated efficient for systems with a lower degree of complexity (Barbieri and Barbieri, 2013). Therefore, the use of these signals is justified for the analysis of more complex systems aiming at the optimization of the quality control in the production lines, both in the reduction of costs and in the significant reduction of the time of control. The objective of this work is the preparation of a specialized system, capable of identification and characterization of damages, for analysis of vibratory signals in automotive gearboxes. The tools used for such analysis are: mathematical morphology and wavelet transform, associating concepts of energy and entropy.

2. SIGNAL ANALYSIS

The signals obtained for the gearbox tests were acquired in the time domain. A mathematical manipulation of these signals, using different detection methods, was required in order to evaluate the characteristics of the samples. The signals were treated using mathematical morphology and wavelet transform, associating concepts of energy and entropy.

2.1 Wavelet Transform

The Wavelet transform allows the decomposition of the signal as a function of time (via translation) and in scale (via dilation or contraction), instead of time and frequency analysis as in the case of the Fourier Transform. The continuous wavelet transform is then defined by (Jedlinski and Jonak, 2015):

$$C(a,b) = \int_{-\infty}^{+\infty} f(t) \cdot \Psi_{a,b}(t) \cdot dt \quad (1)$$

where,

$$\Psi_{a,b}(t) = a^{1/2} \Psi\left(\frac{t-b}{a}\right) \quad (2)$$

is a window function called the mother wavelet, where a is a scale and b is a translation.

The indication of the location of the structural damage can be obtained by the energy index, E_{f_j} , of the wavelet packet. The energy rate of the wavelet packet for the analyzed signals is defined as:

$$\Delta(E_{f_j}) = \sum_{i=1}^{2^j} \frac{|(E_{f_j}^i)_b - (E_{f_j}^i)_a|}{(E_{f_j}^i)_a} \quad (3)$$

where the index is a corresponds to the signal without damage and b correspond to the signal with some damage.

2.2 Mathematical Morphology

The signal processing through mathematical morphology basically modifies the signal format through its interaction with another element of a simpler and more known nature called the structuring element (Nikolau and Antoniadis, 2002). The mathematical operations of the morphological mathematical method are erosion, dilation, opening and closing (Zhang, *et al.*, 2008).

If $f(n)$ is the original one-dimensional signal, and its discrete function in the domain $F = (0; 1; 2; \dots; N-1)$ and $g(m)$ is the structuring element whose function is discrete in domain $G = (0; 1; 2; \dots; M-1)$, morphological erosion (\ominus) and dilation (\oplus) operators, can be defined as:

$$(f \ominus g) = \min[f(n+m) - g(m)], m \in 0, 1, 2, 3, \dots, M-1 \quad (4)$$

$$(f \oplus g) = \max[f(n+m) - g(m)], m \in 0, 1, 2, 3, \dots, M-1 \quad (5)$$

Based on these two operations, the other two fundamental operations of the mathematical morphology, opening (\circ) and closing (\bullet), can then be defined as:

$$(f \circ g)(n) = (f \ominus g \oplus g)(n) \quad (6)$$

$$(f \bullet g)(n) = (f \oplus g \ominus g)(n) \quad (7)$$

The four morphological mathematical operators can be used to extract the characteristics of a signal. Each operator is related to a basic characteristic under its effect on the treated signal. The morphological analysis using structuring elements in different scales is called Multiscalar Mathematical Morphology. The scale of the structuring element, especially the length scale, is very important for the multiscale morphological analysis of one-dimensional signals. In the present work was used the double dot structuring element in different scales.

2.3 Entropy

The spectral entropy describes the complexity of a system. It is obtained using the following step by step:

- Calculate the spectrum of the data signal;
- Calculate the Power Spectra Density (PSD) of the signal via squaring its amplitude and normalizing by the number of samples;
- Normalize the calculated PSD (in this way the power spectra density can be analyzed as Probability Density Function) and its entropy can finally be calculated.

3. EXPERIMENTAL PROCEDURE

In this section, the experimental procedure is described. Details like the damage characteristics, the test bench and the cycle of the test, and finally the process of acquiring the vibrations signals, are explained.

The experiments were performed at ten gearboxes approved by the subjective method (human hearing) and three gearboxes with damage induced for purpose (according to the highest percentile of detection of these kind of damage in quality center). Damage at the outer ring of the roller bearing (39,5%) and damage at gear teeth (49,8%) represent approximately 90% of faults detected in gearboxes models.

The first type of damage, damage at the outer ring of the roller bearing, was manually introduced in two samples of gearboxes (D1 and D2). The second type of damage, damage at gear teeth, was applied in the third damaged sample (D3) at its highlighted gear.

Figures 1, 2 and 3, show the damaged gearboxes D1, D2 and D3, respectively. Table 1 presents the damages main dimensions.

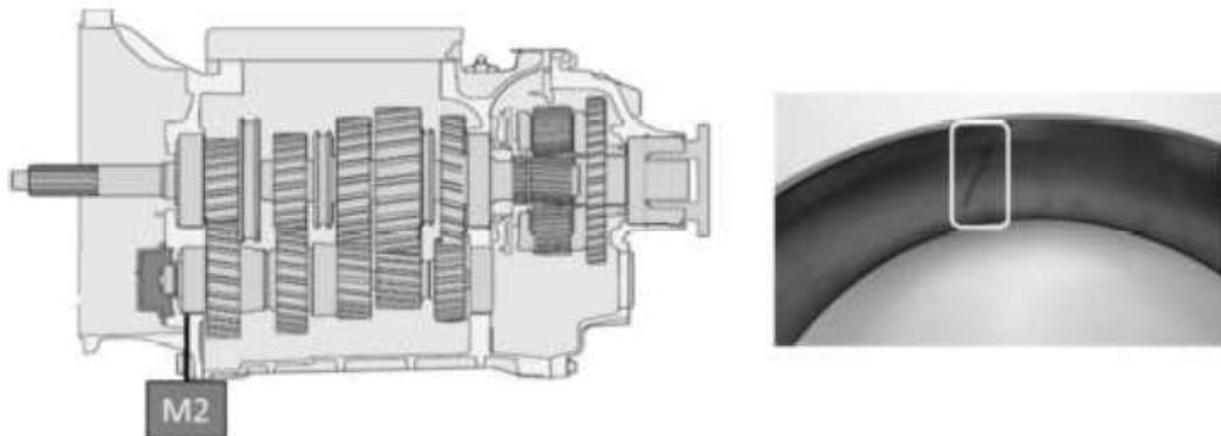


Figure 1. Damaged Gearbox D1

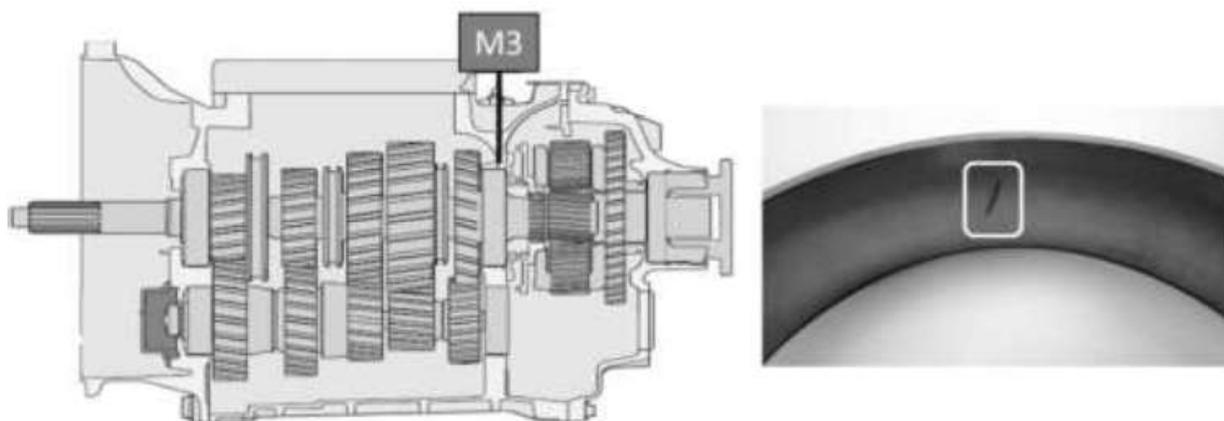


Figure 2. Damaged Gearbox D2

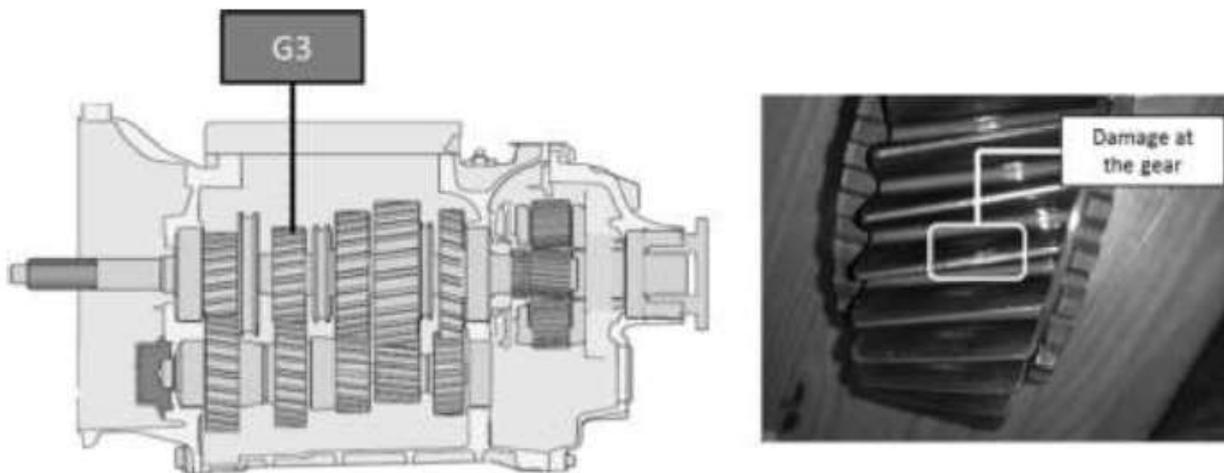


Figure 3. Damaged Gearbox D3

Table 1. Damages Characteristics

Damage Mode	Width (mm)	Length (mm)	Depth (mm)
Damage at Gearbox D1	3.2	48.6	0.1
Damage at Gearbox D2	3.3	23.3	0.1
Damage at Gearbox D3	8.4	4.8	0.5

Acceleration signals were acquired for all the thirteen gearboxes on the test bench. The process of measuring each gearbox occurred in all test steps, following the sequence shown in table 2, after reaching the stabilization of input speed and load applied to the output flange.

Table 2. Parameters of the Test Steps

STEP	ANGULAR VELOCITY (rpm)		ENGAGED GEAR	
	INPUT	OUTPUT	SEQUENCY	CODE
1	600	0	Neutral	NLSLR
2	300	0	Neutral	NLSLR
3	500	10	1st reverse	RLSLR
4	1500	30	4th gear	2HSLR
5	1500	270	5th gear	3LSLR
6	1500	556	8th gear	1HSHR
7	300	50	5th gear	3LSLR
8	700	259	8th gear	1HSHR
9	1500	340	6th gear	3HSLR
10	1500	1178	11st gear	3LSHR

For the acquisition of the accelerations signals five accelerometers (Measurement Specialties model 4610-050) were places in the gearboxes in a specified position. The signals were first obtained in time domain and further processed. The acquisition rate was of 4000 Hz during 10 seconds in each test step. Figure 4 shows the localization of each accelerometer in the sample and the measurement occurred simultaneously for the five point.

- Accelerometer 1 measured the acceleration in the z-axis of the upper front bearing;
- Accelerometer 2 measured the acceleration in the z-axis of the lower front bearing;
- Accelerometer 3 measured the acceleration in the z-axis of the lower rear bearing;
- Accelerometer 4 measured the acceleration in the x-axis in an intermediate position between the front bearings;
- Accelerometer 5 measured the acceleration in the y-axis of the lower rear bearing;

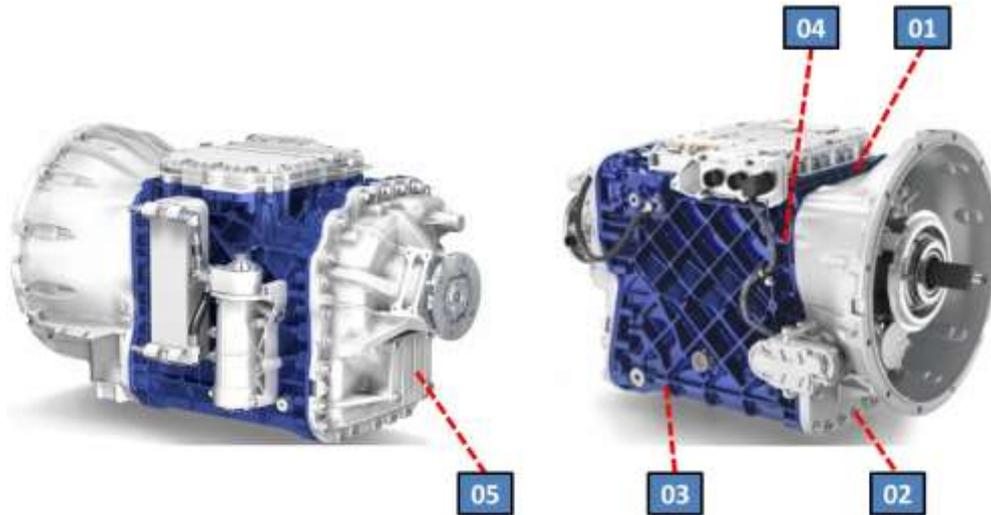


Figure 4. Localization of the accelerometers in the sample

4. RESULTS AND DISCUSSION

The initial step for the comparison between the signs of the gearboxes damaged and approved by the subjective method was the definition of a reference signal. The method used to define the standard signal was from a mathematical manipulation of the results. Each signal of the 10 samples without damage was divided into 4 plots of equal size (each with 8192 points). A comparative coefficient, ρ , was established between the plots of the signal for the same sample and for the other samples, using convolution and variational principles according to equation (8), defined as correlation index, where P_1 and P_2 are the signal pattern spectra.

Signals that had a coefficient greater than 0.95 and less than 1.05 (since that coefficient was obtained from the comparison between the signals) were used to determine the mean signal (reference signal). Finally, the reference signal was obtained by an arithmetic average operation between the portions of the established signals.

$$\rho = \frac{\text{cov}[P_1, P_2]}{\sqrt{\text{var}[P_1] \text{var}[P_2]}} \quad (8)$$

The analyzes of the vibratory signals were made using wavelet transform and mathematical morphology, associated to energy and entropy indices.

By comparing the global analysis using wavelet transform and further calculating the energy and entropy of the signals, it is noticed that the energy of the signal without damage is inferior to the energy of the other systems. The same behavior is observed when the entropy of the signals is verified. Figure (5) and Figure (6) show the energy and entropy of the signals obtained for the accelerometer placed in the upper front bearing.

Using the wavelet, energy and entropy parameters, care must be taken to identify the damage in the samples. Although for all the analyzed situations the damaged rear bearing signal presented a huge difference in relation to the standard signal (evidencing the presence of damage in the sample), for the other types of damage the differences were smaller and with the non constant behavior sometimes the energy and entropy were smaller and in others larger) making it difficult to identify the damage in the sample.

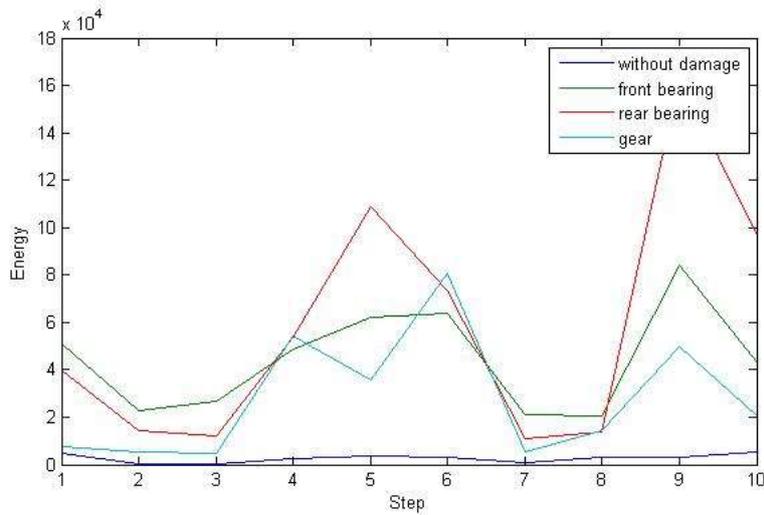


Figure 5. Energy (accelerometer located on upper front bearing)

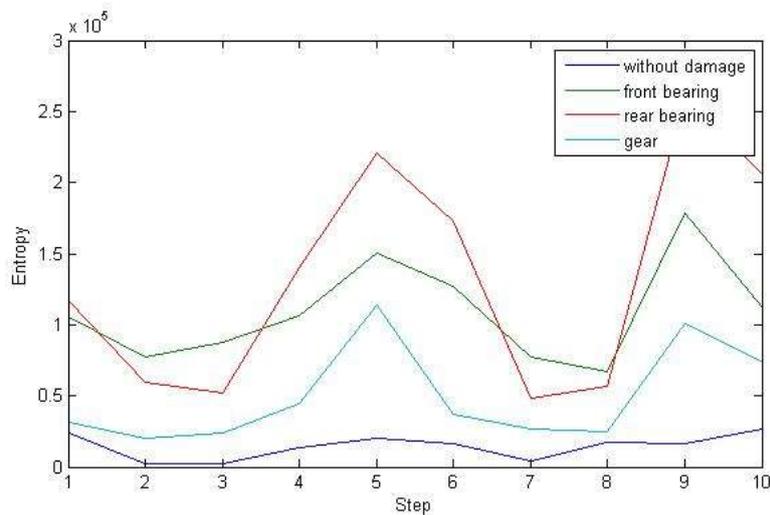
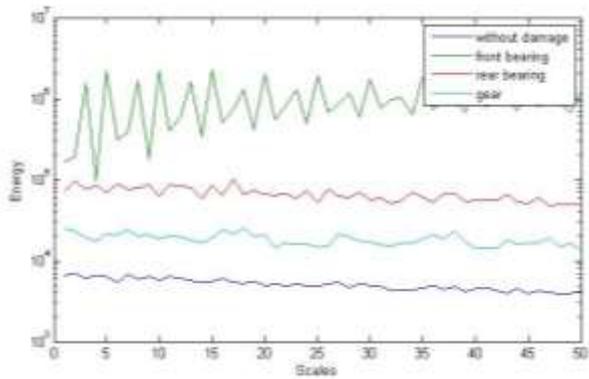


Figure 6. Entropy (accelerometer located on upper front bearing)

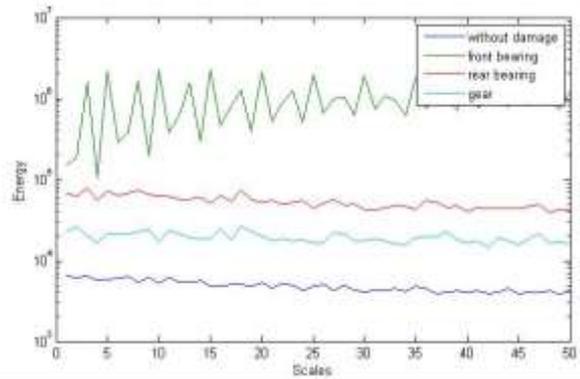
In another form of analysis was used the theory of mathematical morphology allied to energy and entropy indices. Figures 7 (a) to 7 (d) and 8 (a) to 8 (d) show the curves obtained using joint mathematical morphology and energy and entropy parameters. Figure 7 (a) and 7 (a) show the signals for the open operation, Fig. 7 (b) and 8 (b) for closing operation, Fig. 7 (c) and 8 (c) for erosion operation and Fig. 7 (d) and 8 (d) for dilation operation. A great similarity is observed between all the curves of Fig. 7 (a) to 7 (d) of energy. As expected, the undamaged system has lower energy values. In this case the system with damaged front bearing presents higher energy indexes.

When the analysis is made based on the entropy index, Fig. 8 (a) to 8 (d), it is noted that the highest values were found for the curves of the system with damaged rear bearing. The lower values were obtained for the system with damaged front bearing and in this case, this system was a behavior that was different from the others, highly oscillatory. However, the results obtained for the other three types of analyzed systems showed little oscillatory behavior for the 50 scales.

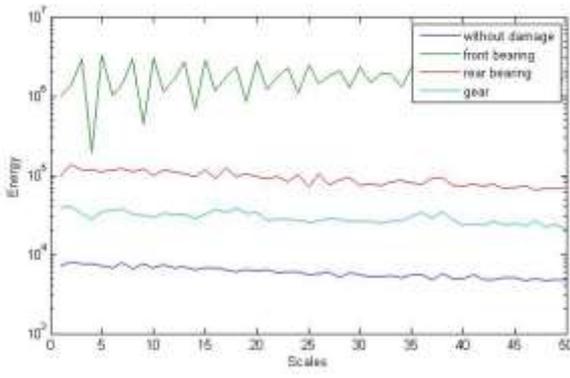
In this type of analysis, mainly for the energy parameter, the obtained results evidences the presence or not of damages in the sample, since the magnitude of the energy for the sample without damage is much lower than the energy for the other signals.



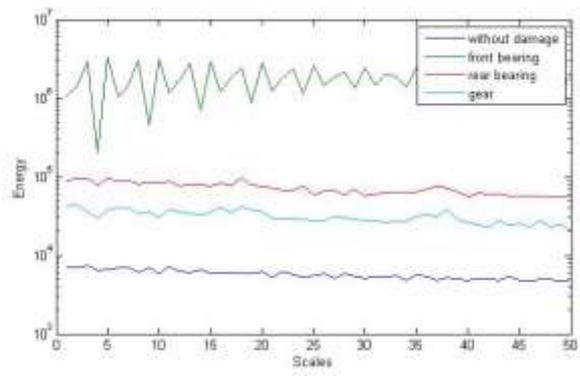
(a)



(b)

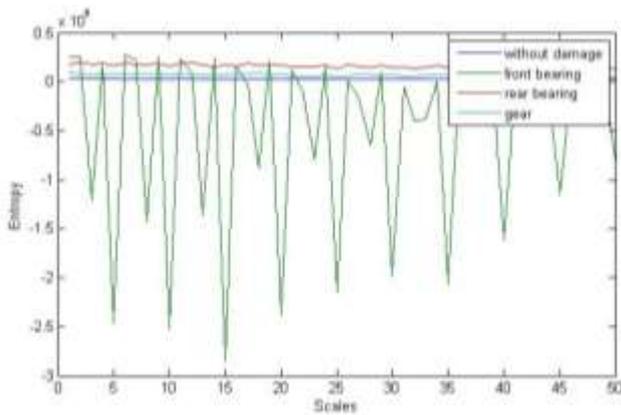


(c)

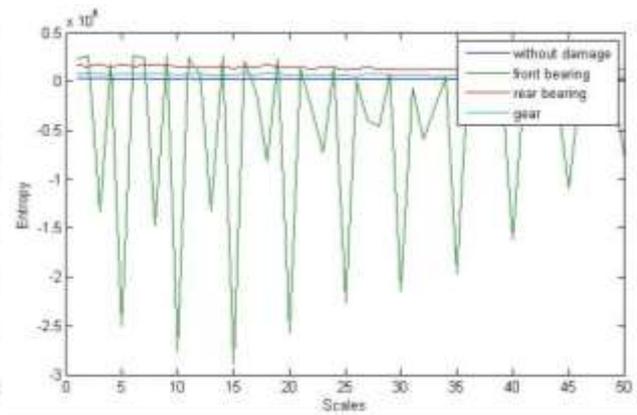


(d)

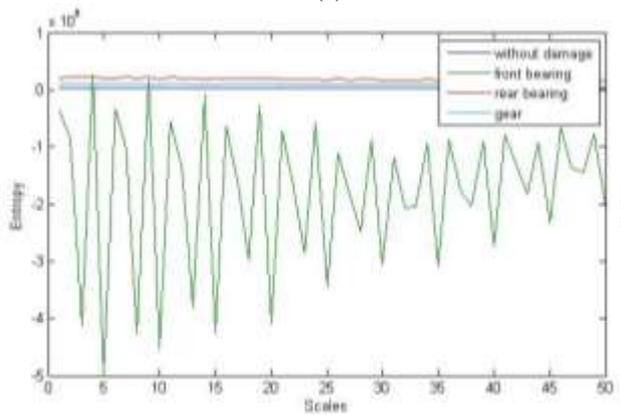
Figure 7. Energy ((a) opening, (b) closing, (c) erosion and (d) dilatation).



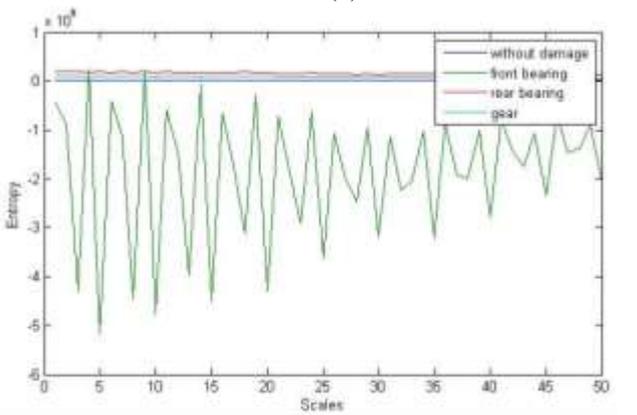
(a)



(b)



(c)



(d)

Figure 8. Entropy ((a) opening, (b) closing, (c) erosion and (d) dilatation).

In an attempt to establish a system for identifying the damaged component, a 4-order Butterworth digital filter with frequency band was used. The bands used for the filtration are related to the characteristic frequencies of bearings faults BPFO and BPFI, and gear mesh frequency (GMF). The frequency bands for the BPFO and BPFI frequencies were in the range of 0.9 BPFI or BPFO to 1.1 BPFO or BPFI. For the gear mesh frequencies the band was (GMF – Frot) to (GMF + Frot) where Frot is the rotation frequency of the gear axis.

At this stage, it was tried to find the characteristic frequencies of the defects of the bearings through an expert system based on the signals generated using mathematical morphology and power spectra. The system is based on a scheme to search for maximum values (peaks) close to the defect frequencies using the previously filtered signals in the range of interest, ie 0.9 BPFO to 1.1 BPFO. From the peak values (signal obtained for the upper front bearing accelerometer), Table 3 was constructed. It is noted that there was a small error (less than 1%) between the theoretical and experimental values for only one step of the tests. In this case step 8 to the BPFO frequency for the front upper bearing defect. However there were no defects in this bearing. For the characteristic frequencies for the lower front bearing it was noticed that in some points the errors were smaller than 2%.

The same procedure was used to identify the damaged gear. Table 4 was constructed considering the numerical values and the experimental values (signal obtained for the upper front bearing accelerometer). In this case an optimum identification of the frequencies was verified. Only in two test steps were the errors greater than 1% and less than 2%. In other cases the errors were insignificant.

In an attempt to obtain better results to identify the problems in the bearings, the signals of the sensor placed in the lower front bearing, that is, closer to the source of the damage were used. A better approximation was found for the theoretical and experimental values to identify the damage in the lower front bearing.

Table 3. Values of the numerical and experimental BPFO

BPFO (Num) [rpm]	BPFO (exp) [rpm]	Error (%)	BPFO (Num) [rpm]	BPFO (exp) [rpm]	Error (%)
Upper Front Bearing			Lower Front Bearing		
83.50	85.45	2.3353	58.30	56.64	-2.8473
41.70	39.06	-6.3309	29.10	30.27	4.0206
69.50	67.87	-2.3453	48.60	47.85	-1.5432
208.60	199.70	-4.2665	185.70	174.80	-5.8697
208.60	202.60	-2.8763	145.70	152.80	4.8730
208.60	197.30	-5.4171	185.70	182.1	-1.9769
41.70	42.97	3.0456	29.10	30.76	5.7045
97.40	97.17	-0.2361	86.60	84.96	-1.8938
208.60	201.80	-3.2598	185.70	182,10	-1.9386
208.60	199.70	-4.2665	145.70	151.90	4.2553

Table 4. Values of the numerical and experimental gear mesh frequencies

GMF (Num) [rpm]	GMF (exp) [rpm]	Error (%)
274.77	274.90	0.0473
137.38	140.10	1.9799
228.97	231.90	1.2796
875.00	874.50	-0.0571
686.91	686.50	-0.0597
875.00	874.50	-0.0571
137.38	137.70	0.2329
408.33	408.20	-0.0318
875.00	874.50	-0.0571
686.91	686.50	-0.0597

5. CONCLUSIONS

The subjective method of inspection of automotive gearboxes (human hearing) carried out today in the big companies is low cost, time of preparation of the test and of low precision. It was verified in the work that the ten boxes that were approved by this method presented very different behaviors when examined with the methods using vibratory signals. In this way, it is not possible to ensure their conformity through the vibration signals.

With the alternative inspection method, proposed by this work, the tests are more time consuming (preparation, obtaining and treatment of signals), more expensive, but, provably, more accurate. The signs of the damaged samples

presented considerably different characteristics than the characteristics of the signals for the systems in good condition. Energy and entropy using different mathematical tools (wavelet, morphological mathematics and Fourier transform) were always superior for damaged systems. With a more detailed analysis, it is observed that the damaged components excite frequencies characteristic of the damages, which can be obtained numerically and identified experimentally. It can also be said that the percentage error of the values of these frequencies, in numerical / experimental relation, became less and less when the results obtained in the accelerometers closest to the damage are analyzed.

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7. RESPONSIBILITY NOTICE

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