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Quality Control of Automotive Gearbox Based On Vibration Signal Analysis

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***Abstract*—**In more complex systems, such as automotive gearbox, a rigorous treatment of the data is necessary because there are several moving parts (gears, bearings, shafts, etc.), and in this way, there are several possible sources of errors and also noise. The basic objective of this work is the detection of damage in automotive gearbox. The detection methods used are the wavelet method, the bispectrum; advanced filtering techniques (selective filtering) of vibrational signals and mathematical morphology. Gearbox vibration tests were performed (gearboxes in good condition and with defects) of a production line of a large vehicle assembler. The vibration signals are obtained using five accelerometers in different positions of the sample. The results obtained using the kurtosis, bispectrum, wavelet and mathematical morphology showed that it is possible to identify the existence of defects in automotive gearboxes.

***Keywords*—**Automotive gearbox, mathematical morphology, wavelet, bispectrum.

I. Introduction

THE study of damages in automotive gearboxes is an area that has attracted much interest [1]. One of the reasons is the challenge to develop a computational tool that facilitates quality control of such components in production lines. Several techniques based on vibration signals have been used to analyze the operating condition of gearboxes.

The main methods based on vibration signals are: *Cepstrum analysis* [2], [3]; *acoustic emission* [4], [5]; *statistical methods* [6]-[10]; *wavelet analysis* [11]-[15]; *morphologic analysis* [16]-[20]. Defects in components of machinery and structures can be detected by monitoring vibration. The bispectrum, a third-order statistic and kurtosis, a fourth-order moment, helps to identify faults in mechanical components. The bispectrum technique relates one set of mixing waves through the spectral coupling. The kurtosis gives an indication of the proportion of samples that deviate from the mean by a small value compared to those, which deviate by a large value [9].

The aim of this work is analyze the operational condition of automotive gearboxes through vibration signals obtained in a controllable test bench and taking account samples without and with damage. Different techniques of signal analysis, bispectrum, wavelet transform and mathematical morphology are used to obtain parameters for comparison of the system behavior. Two type of damage are analyzed: bearing with outer race fault and a gear with intentionally damaged tooth through a hit.

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II. Signal Analysis Techniques

A. Bispectrum Theory

A quadratic non-linearity will relate three wave components in such a way that [9]

$$X_m = \sum_{m=k+l} A_{k,l} X_k X_l + \varepsilon \tag{1}$$

where X_k and X_l denote the complex Fourier spectral components at ω_k and ω_l, with phase θ_k and θ_l, respectively. $A_{k,l}$ denotes the coupling coefficient and is dependent on the properties of the non-linearity system. The term ε denotes any errors associated with this model. In this system, X_k and X_l will interact to create a third component, X_m, where $\omega_m = \omega_k \pm \omega_l$ and $\theta_m = \theta_k \pm \theta_l$.

The bispectrum of a discrete time series *x(n)* is defined as:

$$b_x(k,l) = X_k X_l X_m^* \tag{2}$$

where X_m^* denotes the complex conjugate of X_m. It can be clearly seen how the bispectrum takes into account the mixing between two frequencies. If ω_k, ω_l and ω_{k+l} are independent, each one will have an independent random phase (relative to each other). Therefore, the bispectrum is a statistical is of great importance in the study of those non-linear vibrations where the relationships between three spectral components are in question, such as generation of combinational resonance modes or quadratic mode couplings. The bispectrum, the third-order spectrum, can be viewed as a decomposition of the third statistical moment (skewness) of a signal over frequency as such can detect non-symmetric non-linearities.

The probability distribution of a random variable X is defined as:

$$F(x) = P(X < x) \tag{3}$$

The probability density function (p.d.f.) is the derivative of this

$$f(x) = \frac{dF(x)}{dx} \tag{4}$$

The expectation operation, which gives the expected value of a function g(x) , is defined as

$$E\{g(x)\} = \int_{-\infty}^{\infty} g(x) f(x) dx \quad (5)$$

In most cases, the p.d.f. can be decomposed into its constituent moments or cumulants. If a change in condition causes a change in the p.d.f of the signal then the moments and cumulants may also change. The moments of the signal are defined as:

$$m_n = E\{x^n\} \quad (6)$$

where $E\{\}$ can be estimated.

The most common simple statistical feature used in signal monitoring is the mean square value (second-order moment) of the signal.

$$m_2 = \frac{1}{N} \sum_{i=1}^{N} x(i)^2 \quad (7)$$

A second common statistical feature used is the kurtosis which gives an indication of the proportion of samples which deviate from the mean by a small value compared to those which deviate by a large number. The fourth-order moment can be normalized by the second-order moment squared:

$$\gamma_4 = \frac{m_4}{m_2^2} \quad (8)$$

The zero mean Gaussian distributed variable has a kurtosis of 3.

These statistical tools are useful for detecting an incipient failure, while the bispectrum can be used for uniform state system.

B. Wavelet Theory

The continuous wavelet transform (CWT) is defined as [11]-[15]:

$$C(a,b) = \int_{-\infty}^{+\infty} f(t) \psi_{a,b}(t) dt \quad (9)$$

where

$$\psi_{a,b}(t) = a^{1/2} \psi(\frac{t-b}{a}) \quad (10)$$

is a window function called the mother wavelet, where *a* is a scale and *b* is a translation. The term wavelet means a small wave. The smallness refers to the condition in which this (window) function is in the finite length (compactly supported). The wave refers to the oscillatory condition of this function. The term mother implies that the functions with different support regions that are used in the transformation process are derived from one main function, or the mother wavelet. In other words, the mother wavelet is a prototype for generating the other window functions.

C. Mathematical Morphology

The vibration signal dealt with in this paper is a discrete 1-D signal, the multivalued morphological transformation for this type of signal is addressed in following paragraphs [16]-[20].

If *f(n)* is the original 1-D signal, which is the discrete function over a domain *F=(0; 1; 2; . . . ;N-1)* and g(n) is the SE (flat structuring element), which is the discrete function over a domain *G =(0; 1; 2; . . . ;M -1)*, two basic morphological operators, the erosion and the dilation, can be defined as.

$$(f \ominus g)(n) = \min[f(n+m) - g(m)],\ m \in 0, 1, 2, ..., M-1 \quad (11)$$

$$(f \oplus g)(n) = \max[f(n+m) - g(m)],\ m \in 0, 1, 2, ..., M-1 \quad (12)$$

where $\ominus$ denotes the erosion operator and $\oplus$ denotes the dilation operator.

Based on the dilation and erosion, two other basic morphological operators, the opening and the closing, can be further defined.

$$(f \circ g)(n) = (f \ominus g \oplus g)(n) \quad (13)$$

$$(f \bullet g)(n) = (f \oplus g \ominus g)(n) \quad (14)$$

where ○ stands for the opening operator and • for the closing operator.

These four morphological operators can all be used to extract morphological features of a signal, but different operators fit different morphological features.

Multi-scale MM refers to a morphology analysis with SEs at different scales. The SE scale, especially the length scale, is important for the multi-scale morphology analysis of 1-D signals. The multi-scale morphological operations have also opening and closing operations. The correlation coefficient of two pattern spectra is expressed as

$$\rho = \frac{Cov[P_1, P_2]}{\sqrt{Var[P_1]Var[P_2]}} \quad (15)$$

where P_1 and P_2 represent two different pattern spectra, and ρ is their correlation coefficient which measures the similarity of two signals (with and without damage).

III. Materials and Methods

An important part of the work is the definition and implementation of vibrational procedure of the tested automotive gearboxes in good condition and damaged in specific test cycle. The equipment used for the experiment, as well as details regarding the experimental methodology for measuring data used in the work are presented. Initially, the test bench and its operation scheme will be described. Finally, all the tools used in the process of measuring the vibration signal and the executed procedure will be demonstrated.

A. Test Bench

The bench is composed of two electric motors (Siemens model 1PH7184-2NF00-0AA0 51 kW) with operating speed of 1500 rpm. The front engine is coupled to the input shaft simulating the vehicle's engine action. The rear engine, in turn, is engaged in output gearbox shaft and acts as a brake by applying constant torque of 200 Nm in the opposite direction to rotation of the output shaft. In this way, is simulated small loads in the gearbox, which amplifies the intensity of vibration and noise levels generated by geared pairs and bearings at the system.

Being a test bench that simulates, even partially, the conditions to which the automotive gearbox is subjected, the oil supply is necessary during the testing cycle. Thus, added to the set of engines, the bench also has a hydraulic power unit responsible for the supply, removal and filtering to gearbox oil reuse. Fig. 1 shows a schematic representation of the test bench, main components and operation of sub-groups.

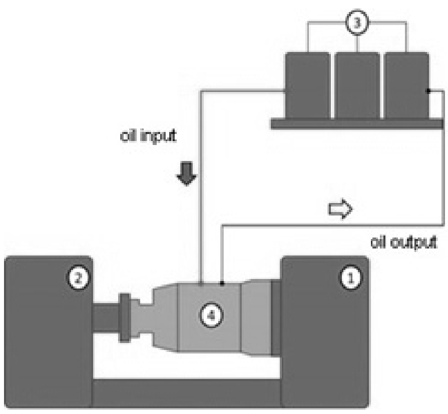


Fig. 1 Schematic test bench

The components of the test bench are: 1- front electric motor; 2 - rear electric motor; 3 - supply and filter oil system; 4 - gearbox.

TABLE I
PARAMETERS AND SEQUENCE OF THE TESTS

Step	Angular velocity (rpm)		Engaged gear	
	Input	Output	Sequence	Code
1	600	0	neutral	NLSLR
2	300	0	neutral	NLSLR
3	500	10	1° reverse	RLSLR
4	1500	30	4° gear	2HSLR
5	1500	270	5° gear	3LSLR
6	1500	556	8° gear	1HSHR
7	300	50	5° gear	3LSLR
8	700	259	8° gear	1HSHR
9	1500	340	6° gear	3HSLR
10	1500	1178	11° gear	3LSHR

The full test cycle consists of ten sequential steps. At each step, a specific gear is engaged and an input angular velocity is applied. After stabilization of the input velocity, the rear motor applies torque to the opposite direction of rotation so that the data acquisition starts. Table I shows the test steps to engaged gears and input angular velocities applied the test bench.

The code of the transmission gears is composed of five letters. The first letter refers to which gear is transmitting torque (N - neutral, R - reverse, 1 - first 2 - second and 3 - third gear). The second and third letters refer to a pair of gears called split (HS - High split and LS - low split). The last two letters refer to the reduction gear unit of the box (called the range). Thus, HR - high range (not acting) and LR – low range (acting).

B. Measurement Parameters

Acceleration signals were acquired in the gearboxes on the test bench. All measurements were carried out in boxes with 16 liters of oil at temperature of 50° C and with a load applied to the output flange. The process of measuring each gearbox occurred in all test steps, following the sequence shown in Table I, after which the input speed was stabilized and the load applied to the output flange.

Ten automotive gearbox approved by subjective method currently used have been tested and three boxes damaged were purposely introduced for control purposes, comparison and initial validation of the method developed. Table II details the information of the damaged boxes and their failure modes.

TABLE II
GEARBOXES TESTED

Gearboxes	Quantity	Comments
Approved	10	subjective method used for analysis.
Damaged	1	gear tooth damaged of gear 3.
Damaged	1	outer race of rear rolling-element bearing damaged
Damaged	1	outer race of front rolling-element bearing damaged

C. Measurement System

Five accelerometers (Measurement Specialties model 4610-050) were used to obtain the experimental data. The acceleration signals were acquired in the time domain to be further processed. The data were acquired with 4000 Hz sampling rate for 10 s in each test step.

The measurement occurred simultaneously at five different points in the bearings of the gearbox. Its distribution was developed considering directions of measurement, x, y and z. Fig. 2 shows the position of the five accelerometers.

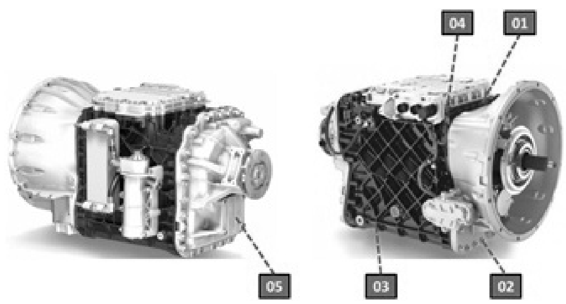


Fig. 2 Accelerometers position

The distributions of the sensors are:

- accelerometer 01 measured the acceleration in the z-axis of the upper front bearing;
- accelerometer 02 measured the acceleration in the z-axis of the lower front bearing;
- accelerometer 03 measured the acceleration in the z-axis of the lower rear bearing;
- accelerometer 04 measured the acceleration in the x-axis in an intermediate position between the front bearings;
- accelerometer 05 measured the acceleration in the y-axis in the lower rear bearing.

Fig. 3 shows schematically a gearbox with the bearings.

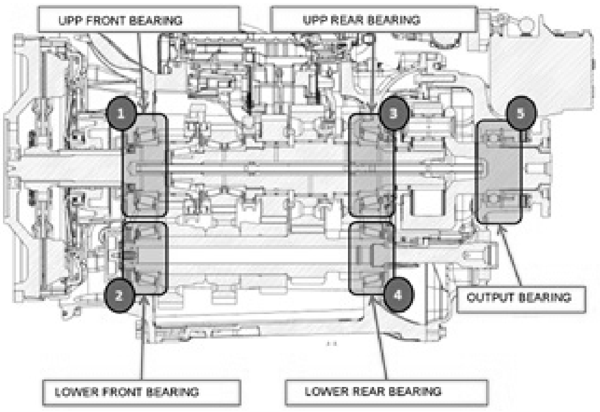
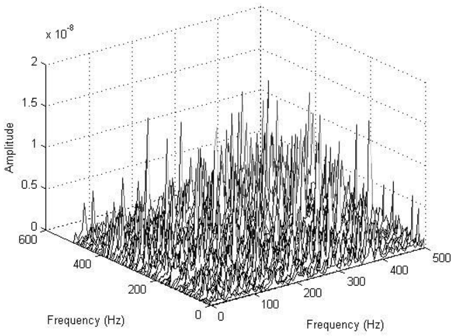
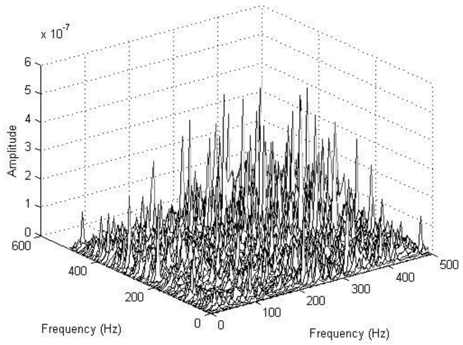


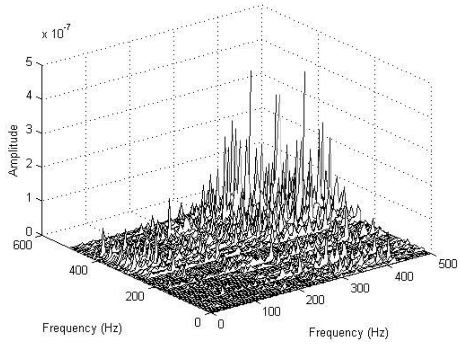
Fig. 3 Bearings in the gearbox



(a)



(b)



(c)

Fig. 4 Bispectrum curves

IV. Results

As a first step it was analyzed the signals in the frequency domain and noticed a great complexity in the signal. Thus, the bispectrum was used to verify changes in the signals. Fig. 4 (a) shows the system signal in good condition, Fig. 4 (b) the system signal with the lower front bearing damaged and Fig. 4 (c) the signal with a tooth damaged in one gear.

It was defined a relative parameter contained the sum of all values of the bispectrum [9] defined by (2):

$$IndB = \sum_{i=1}^{n} b(k,l) \tag{16}$$

$$Brel = \frac{|IndB_b - IndB_a|}{|IndB_a|} \tag{17}$$

where $IndB_b$ is the bispectrum parameter of the system with damage and $IndB_a$ is the bispectrum parameter of the system without damage.

Figs. 5 and 6 show the bispectrum and kurtosis curves. In these figures the solid line represents the system without damage 1; discontinuous line the system with front bearing damaged; ○ system with rear bearing damaged and □ system with tooth gear damaged.

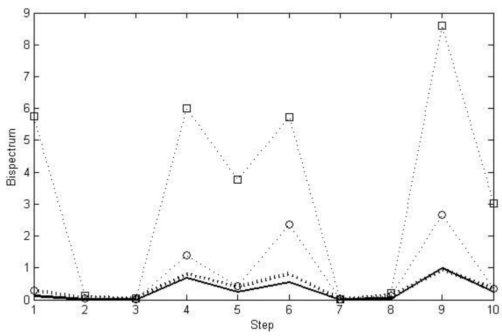


Fig. 5 Bispectrum curves of the system without and with damage

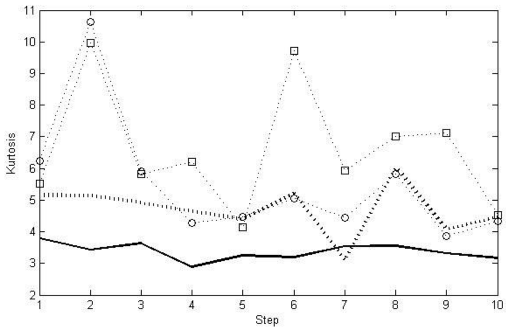


Fig. 6 Kurtosis curves of the system without and with damage

Another parameter based on the energy of the wavelet transform was used. Fig. 7 show the energy index obtained through wavelet transform.

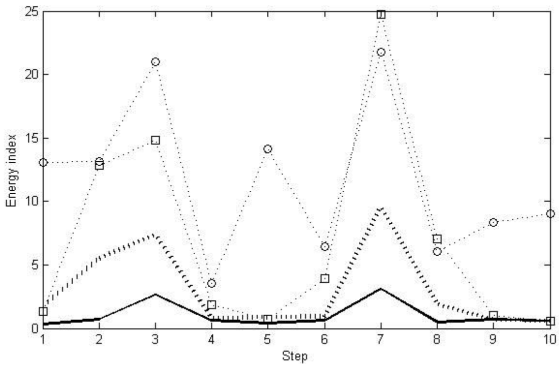


Fig. 7 Energy index curves of the system without and with damage

Figs. 8-11 show the correlation index (15) curves using mathematical morphology. Fig. 8 shows the curves using dilation operator (12); Fig. 9 erosion operator (11); Fig. 10 using closing operator (14) and Fig. 11 using opening operator (13).

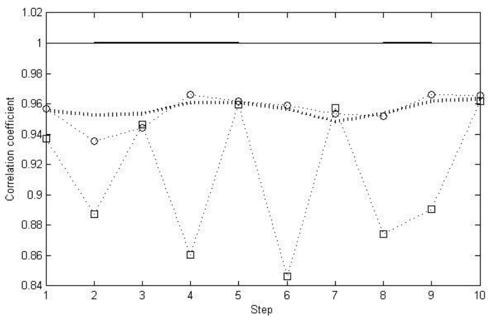


Fig. 8 Correlation index (dilation operator)

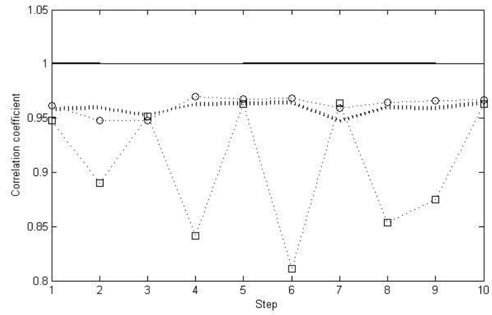


Fig. 9 Correlation index (Erosion operator)

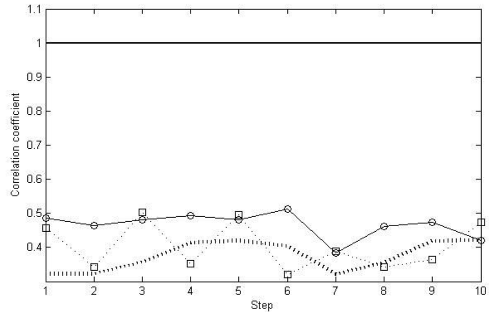


Fig. 10 Correlation index (closing operator)

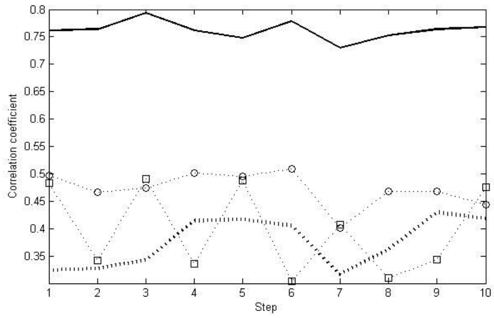


Fig. 11 Correlation index (opening operator)

V. CONCLUSIONS

It was noted that the application of statistical methods for assessing damage in automotive gearbox is a potential tool.

It was observed large variations in values of the bispectrum and the energy index. The three parameters, bispectrum, kurtosis and an energy index using wavelet transform presented good results, that is, higher values of the parameters to the damaged systems.

Results using the mathematical correlation and morphological index showed inverse results showed, that is, smaller values for the damaged systems. Apparently, the results using this parameter present less fluctuation.

All parameters analyzed will serve as a reference for expert system damage detection and analysis will be used as quality control in a production line of automotive gearboxes.

REFERENCES

[1] W. Wang, "An evaluation of some emerging techniques for gear fault detection", *Structural Health Monitoring,* vol. 2, pp. 225-242, 2003.

[2] M. El Morsy and G. Achtenova, "Vehicle Gearbox Fault Diagnosis Based On Cepstrum Analysis", World Academy of Science, Engineering and Technology, *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering* , vol. 8, No. 9, pp. 1533-1539, 2014.

[3] L. Nacib, K. M. Pekpe and S. Sakhara, "Detecting gear tooth cracks using cepstral analysis in gearbox of helicopters", *International Journal of Advances in Engineering & Technology*, vol. 5, pp. 139-145, Jan. 2013.

[4] P. Mazal, L. Nohal, F. Hort and V. Koula, "Possibilities of the damage diagnostics of gearboxes and bearings with acoustic emissions method", *18th World Conference on Nondestructive Testing*, 8 p., 16-20 April 2012, Durban, South Africa

[5] S. M. Metwalley, N. Hammad and S. A. Abouel-seoud. "Vehicle gearbox fault diagnosis using noise measurements. *Journal of Mechanical Engineering Research*, vol. 2(6), pp. 116-125, November 2010.

[6] F. Combet and L. Gelman, "Optimal filtering of gear signals for early damage detection based on the spectral kurtosis", *Mechanical Systems and Signal Processing*, vol. 23 , pp. 652–668, 2009.

[7] N. Sawalhi, R. B. Randall and H. Endo, "The enhancement of fault detection and diagnosis in rolling element bearings using minimum entropy deconvolution combined with spectral kurtosis", *Mechanical Systems and Signal Processing* , vol. 21, pp. 2616–2633, 2007.

[8] L. Gao, Z. Ren, W. Tang, H. Wang and P. Chen, "Intelligent Gearbox Diagnosis Methods Based on SVM, Wavelet Lifting and RBR", *Sensors*, vol. *10*, pp. 4602-4621, 2010.

[9] N. Barbieri and R. Barbieri, "Study of Damage in Beams with Different Boundary Conditions", World Academy of Science, Engineering and Technology, vol. 7, pp. 115-121, 2013.

[10] F. E. H. Montero and O. C. Medina, "The application of bispectrum on diagnosis of rolling element bearings: A theoretical approach", *Mechanical Systems and Signal Processing*, vol. 22, pp. 588–596, 2008.

[11] W. J. Wang and P. D. McFadden, "Application of wavelets to gearbox vibration signals for fault detection", *Journal of Sound and Vibration,* vol. 192 (5), pp. 927-939, 1996.

[12] X. Fan and M. J. Zuo, "Gearbox fault detection using Hilbert and wavelet packet transform", *Mechanical Systems and Signal Processing*, vol. 20, pp966–982, 2006.

[13] S. Hou, Y. Li and Z. Wang, "A resonance demodulation method based on harmonic wavelet transform for rolling bearing fault diagnosis", *Structural Health Monitoring,* vol. 9(4), pp. 297–312, 2010.

[14] S. Hussain and H. A. Gabbar, "Fault diagnosis in gearbox using adaptive wavelet filtering and shock response spectrum features extraction", *Structural Health Monitoring, vol.* 12(2), pp. 169–180, 2013.

[15] N. Vincenzo, Q. Giuseppe and F. Aniello, "The detection of gear noise computed by integrating the Fourier and Wavelet methods", *WSEAS Transactions on Signal Processing*, vol. 4(3), pp. 60-67, March 2008.

[16] L. Zhang, J. Xu, J. Yang, D. Yang and D. Wang, "Multiscale morphology analysis and its application to fault diagnosis", *Mechanical Systems and Signal Processing*, vol. 22, pp. 597–610, 2008.

[17] H. Li and De-yun Xiao, "Fault diagnosis using pattern classification based on one-dimensional adaptive rank-order morphological filter", Journal of Process Control, vol. 22, pp. 436– 449, 2012.

[18] Z. Chen, N. Gao, W. Sun, Q. Chen, F. Yan, X. Zhang, M. Iftikhar, S. Liu and Z. Ren, "A Signal Based Triangular Structuring Element for Mathematical Morphological Analysis and Its Application in Rolling Element Bearing Fault Diagnosis", Shock and Vibration, vol. 2014, p. 1-16.

[19] A. S. Raj and N. Murali, "Early classification of bearing faults using morphological operators and fuzzy inference", *IEEE Transactions on Industrial Electronics*, vol. 60(2), Feb. 2013.

[20] L.J. Han, L.J. Zhang, J.H. Yang, M. Li and J.W. Xu, "Method for EEG feature extraction based on morphological pattern spectrum". *IEEE International Conference on Signal Acquisition and Processing*, pp.68-72, 2009.