KU Leuven
Department of Mechanical Engineering
Celestijnenlaan 300 - box 2420
B-3001 Heverlee (Belgium)

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Noise and Vibration Engineering

USD2020

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Uncertainty in Structural Dynamics

7 to 9 September, 2020
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Motor current cyclic-non-stationarity analysis for bearing diagnostic

G. D'Elia [1], M. Cocconcelli [2], M. Strozzi [2], E. Mucchi [1], G. Dalpiaz [1], R. Rubini [2]
[1] University of Ferrara, Department of Engineering
Via G. Saragat 1, 44124 Ferrara, Italy

[2] University of Modena and Reggio Emilia, Department of Sciences and Methods of Engineering
Via G. Amendola 2 - Pad. Morselli, 42122 Reggio Emilia, Italy
e-mail: **marco.cocconcelli@unimore.it**

Abstract
The Motor Current Signature Analysis (MCSA) is a research area focused on the diagnosis of components of electric motors based on post-processing of the current signal mainly. In particular, the bearing diagnostics is based on two different assumptions: the fault on the bearing causes a vibration of the shaft it supports, so there is an air gap variation between stator and rotor causing a modulation in the current signal; the fault on the bearing hinders the rotation of the shaft, so it can be modeled as an additional loading torque that the motor satisfies increasing the current signal. In this paper, a cyclic-non-stationarity analysis of the motor current is used to assess the status of ball-bearings in servomotors, running at variable speed. Both speed of the motor and motor current are provided by the control loop of the servomotor, that is no external sensors are used. The cyclic nature of the application allows an average of the cyclic-cyclic order maps to increase the signal-to-noise ratio. The proposed technique is successfully applied to both healthy and faulty bearings.

1 Introduction

The Motor Current Signature Analysis (MCSA) is a research area focused on the diagnosis of electric motors based on post-processing of the current signal mainly [1, 2, 3]. Among the non invasive monitoring methods, MCSA relies on the monitoring of electrical quantities, that are already acquired in the main drive application, e.g. for over-current protection, or to implement the control of an electric drive. Thus MCSA does not require the installation of additional dedicated transducers. Diagnosis of bearing faults via MCSA is the topic of many research activities [4, 5, 6]. Depending on the specific type of electric motor analyzed, so far is possible to identify broken bars, misalignment of the shaft and bearing defects [7, 8]. In particular, the bearing diagnostics is based on two different assumptions: the fault on the bearing causes a vibration of the shaft it supports, so there is an air gap variation between stator and rotor causing a modulation in the current signal; the fault on the bearing act is an obstacle for the rotation of the shaft, so it can be modeled as an additional loading torque that the motor satisfies increasing the current signal. Due to the mechanical stiffness of the motor, these effects became evident in the current spectrum when the size of the defect (e.g. spalls or brinelling) is relevant, reducing the time-to-failure for motor maintenance. Indeed, this is a con compared to consolidated techniques like vibration analysis, but the most relevant pro is the lack of additional sensors (e.g. accelerometers for vibration analysis) and cables, since the current is already monitored by the control loop embedded in the motor. Clear example comes from brushless servomotors, also known as electric cams. These motors are able to follow complex motion profiles, varying their speed and also the direction of the motion. This is made possible thanks to an embedded encoder that tracks the angular position of the shaft, a current sensor to monitor the current adsorbed and a control loop able to chase the reference motion. Thanks to their flexibility and potential, servomotors are quite common in automation field such as packaging machines, where they realize cyclic motions as a consequence of the hourly production rate of packages. These working conditions make the condition monitoring of critical components like ball-bearing difficult due to cyclic non-stationary nature of the application, due to the continuous varying speed of the motor within each cycle. In the field of vibration-based condition monitoring, cyclostationary analysis is, de facto, the reference technique for stationary signals. Its application has been initially proposed by Capdessus et al. [9, 10] and then deeply developed by Antoni [11, 12] and others [13, 14]. In case of variable speed application is still possible to use cyclostationary tools as long as moving from the time domain to the angular one, i.e. introducing the cyclo-non-stationary tools. The cyclo-non-sationarity was first proposed and formulated by D'Elia et al. [15] who fused together two powerful techniques: the order tracking and cyclostationarity. It was based on a generalisation of both the Spectral Correlation Density (SCD) and the Cyclic Modulation Spectrum (CMS), in order to obtain two-dimensional functions which displays cyclic Order versus Frequency. An extended work on cyclo-non-stationarity processes that embrace a complete analysis framework could be found in [16], while a specific application to the diagnostics of ball-bearing could be found in [17]. Despite the diffusion of these methodologies in vibrational analysis, the authors do not know applications in the field of current analysis. In this paper, a cyclic-non-stationarity analysis of the motor current is used to assess the status of ball-bearings in servomotors. Both speed of the motor and motor current are provided by the control loop of the servomotor. The repeating nature of the application allows an average of the current signal in order to extract the second order cyclo-non-stationary content. The proposed technique is successfully applied to both healthy and faulty bearings. The paper is organized as follows: Section 2 details the mathematical background of the proposed approach. Section 3 presents the experimental setup. Section 4 reports the results of the application of cyclo-non-stationary approach to the MCSA in case of a healthy and faulted bearings, followed by conclusions.

2 Methods

In this work, the cyclo-non-stationary framework is briefly introduced, a complete theoretical background can be found in [16]. A possible definition of cyclo-non-stationary signal was given in [18], as a signal that undergoes period modulations whilst been non-stationary on a long term basis. The second order moment periodicity of cyclo-non-stationary signals can be exploited by jointly analyse the covariance function both in time and angle domains. In particular, considering two time instants $t(\theta)$ and $t(\theta) - \tau$, loked on a given angular position and spaded apart by a time lag τ, the Angle-Time (AT) covariance function can be given by:

$$C(\theta, \tau) = \mathbb{E}\{x(t(\theta))x(t(\theta) - \tau)\} \quad (1)$$

Similarly to the cyclostationary realm, the Order-Frequency Spectral Correlation can be obtained by a double Fourier Transform of the covariance function as:

$$S(\alpha_\theta, f) = \mathcal{F}_{\substack{\theta \to \alpha_\theta \\ \tau \to f}}\{C(\theta, \tau)\} \quad (2)$$

where α_θ stands for cyclic order, while f for frequency. Equation (2) can be estimated via a proper Welch-based method. Additional details on the theoretical background as well as on the estimators can be found in [16], as previously said. In this work, Equations (1) and (2) are computed on the engine torque signal after a complex signal pre-processing method described later in Section 4.

3 Experiment

The experimental activity regards a real case of industrial diagnostics. In particular, the device under test (DUT) is the front ball bearing of a servomotor used in a packaging machine. The servomotor is an MPL-B680B AC brushless motor by Rockwell Automation equipped with a SICK Hiperface ® encoder. The latter is a sin/cos encoder with 1024 periods per revolution and a resolution of 32768 steps per revolution. The velocity signal of the motor and the torque signal are retrieved using the analog outputs available in the motor drive, a Kinetix 6000 series BM-01 by Rockwell Automation. The signals are connected to a

(a) Lateral view of the motor.

(b) Frontal view with bearing.

Figure 1: Rockwell Automation MPL-B680B AC brushless motor and NSK 6309 bearing.

Table 1: Geometric parameters of the tested bearing.

Geometry parameters	NSK 6309
Outer diameter D (mm)	100
Inner diameter d (mm)	45
Width B (mm)	25
Contact angle $(^\circ)$	6
Number of spheres N	8
Outer ring fault coefficient K_{OR}	3.04

National Instruments acquisition board, made by a CDAQ-9172 backplane upon which a NI-9233 module collected an accelerometer output (not used in this paper) and a NI-9215 module is connected to the Kinetix analog output. It is worth noting that the torque signal is an indirect measurement derived from the current provided by the driver. As a consequence, the torque analysis is related to the current analysis and then it is properly included in the MCSA definition. This servomotor actuation provide rapid variations of speed and inversions in the rotation sense of the shaft. The DUT is a NSK 6309 deep groove single-raw ball bearing, whose geometrical characteristics are reported in Table 1. Figure 1 shows the brushless motor and the frontal bearing tested.

The motion profile is cyclic, following a polynomial profile and consists of both a clockwise and counter-clockwise rotation of the shaft. Figure 2 shows the speed profile as returned by the drive controller of the motor, while the units have been normalized to the maximum value to preserve the industrial secrecy of the data collected. The cyclic periodicity is equal to 0.972 seconds (1.029 Hz).

The sampling frequency chosen for all the experiments has been 10 kHz; both the acquisition board and the accelerometer would have allowed an higher bandwidth, but the analog output of the Kinetix, being generated by a DAC that converts digital information processed internally by the drive, has a bandwidth limited to 7.2 kHz.

A bearing was artificially damaged using an electric drill. A dent was made on the outer race surface of the bearing, then it was remounted on the motor and tested. Figure 3 shows few seconds of the torque data acquired for the faulted bearing and an healthy one. For confidentiality reasons, the amplitude values have been normalized with respect to the maximum value among the two signals to preserve the different excursion range.

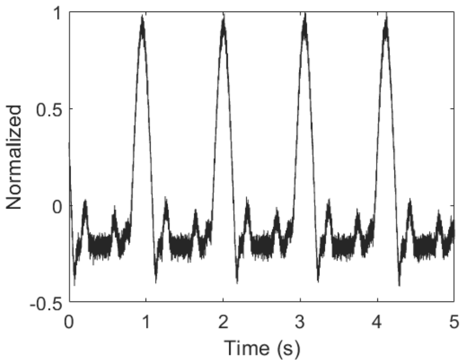

Figure 2: Velocity profile of the motor during the test.

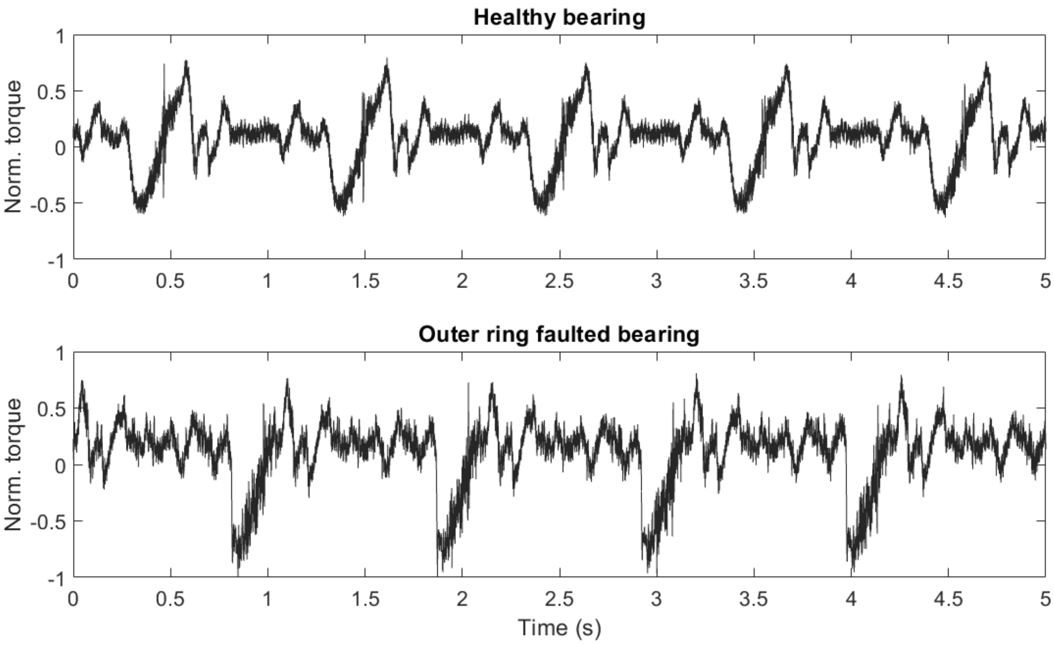

Figure 3: Normalized torque for healthy and artificially faulted bearings

4 Results

Figure 4 (a) shows the normalised torque signal of the artificially damaged bearing. No evidence of the outer race fault can be seen. De facto, fast torque variations around $0.2s$ and $1.2s$ are due to the highest speed variation and therefore are related to the complex machine kinematics, Figure 4 (b) and (c).

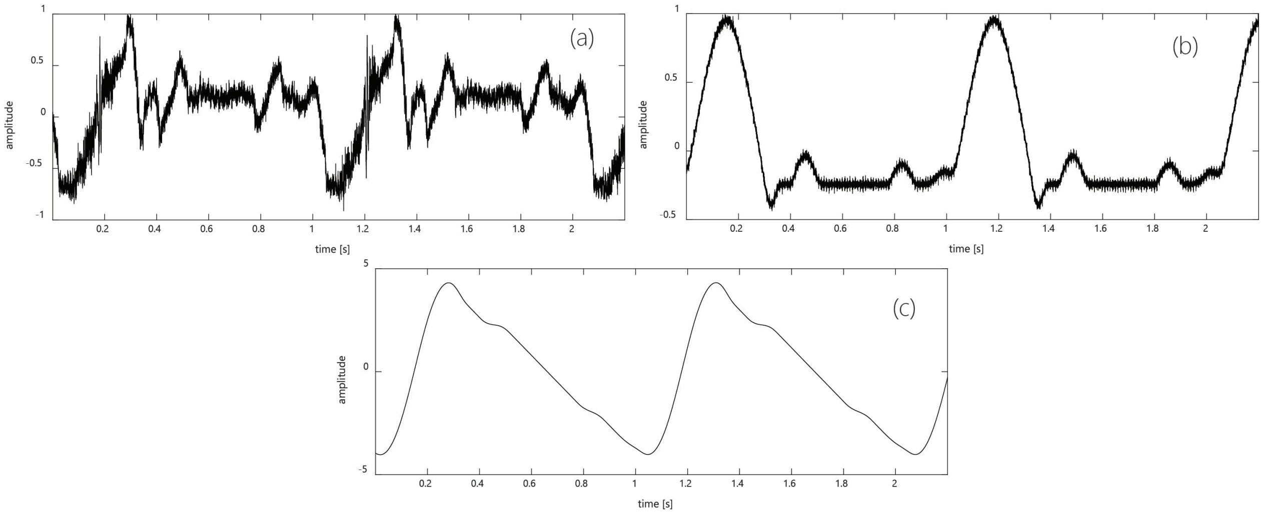

Figure 4: Artificially faulted bearing: (a) Normalised torque, (b) Normalised velocity, (c) Position [rad]

In this complex scenario, fault information cannot be extracted from the torque signal via a "global"investigation, but ad hoc pre-processing analysis must be performed in order to accommodate for the rapid speed variations and inversions of the shaft rotation sense. Figures 5 summarises the aforementioned procedure. Firstly the torque signal is sampled in the angular domain, then only shaft revolutions related to the highest speed profile are taken into account and concatenated together shaping a new angle signal which is synchronously averaged (TSA). This averaged signal is used for the estimation of the cyclostationary residual signal which is the starting point of all the subsequent analysis. As a matter of fact, the pivotal signal feature for the diagnostics of bearing faults, concerns the second order cyclostationary signature, which can be exploited by removing the deterministic part for the engine torque signal.

Figure 6 depicts the result of the applied pre-processing method. It is possible to see a strong torque variation is the TSA signal (Figure 6 (a)), according to the maximum speed variation of the machine. This variation is not only deterministic, but a counterpart is still visible in the residual signal (Figure 6 (b)). Even if the residual signal is in the angle domain, fault information can be highlighted by analysing the hidden periodicity related to the power flows. This cyclostationary investigation can be simply carried out by the evaluation of the Spectrum of the squared signal modulus also called Cyclic Spectrum, (Figure 6 (c)).

It is possible to see from Figure 6 (c) how the cyclostationary signature is related to the first order and all its harmonics. This is an expected result due to the strong power release at each shaft revolution, visible in the residual signal, related to the kinematics of the machine. At this stage, more complex signal processing techniques must be taken into account for highlighting the hidden fault signature inside the engine torque signal.

Figure 7 shows the result of the Order-Frequency Spectral Correlation. It is possible to see how the low frequency range is dominated by power flowing accordingly to the shaft rotation, and no bearing fault signature is visible. However, this power flows are not present in the higher frequency range and moreover, it is possible to see a component around the third cyclic order, which could be related to the bearing outer race fault, see Table 1. This advanced signal processing techniques has highlighted a frequency range in which, via a signal band-pass filtering procedure, it could be possible to extract and subsequently study the bearing fault signature. Therefore, the engine torque signal is band-pass filtered in the $600 \div 800Hz$ frequency range before been analysed via the procedure previously described in Figure 5.

Figure 8 depicts the extraction of the residual cyclostationary counterpart from the filtered engine torque

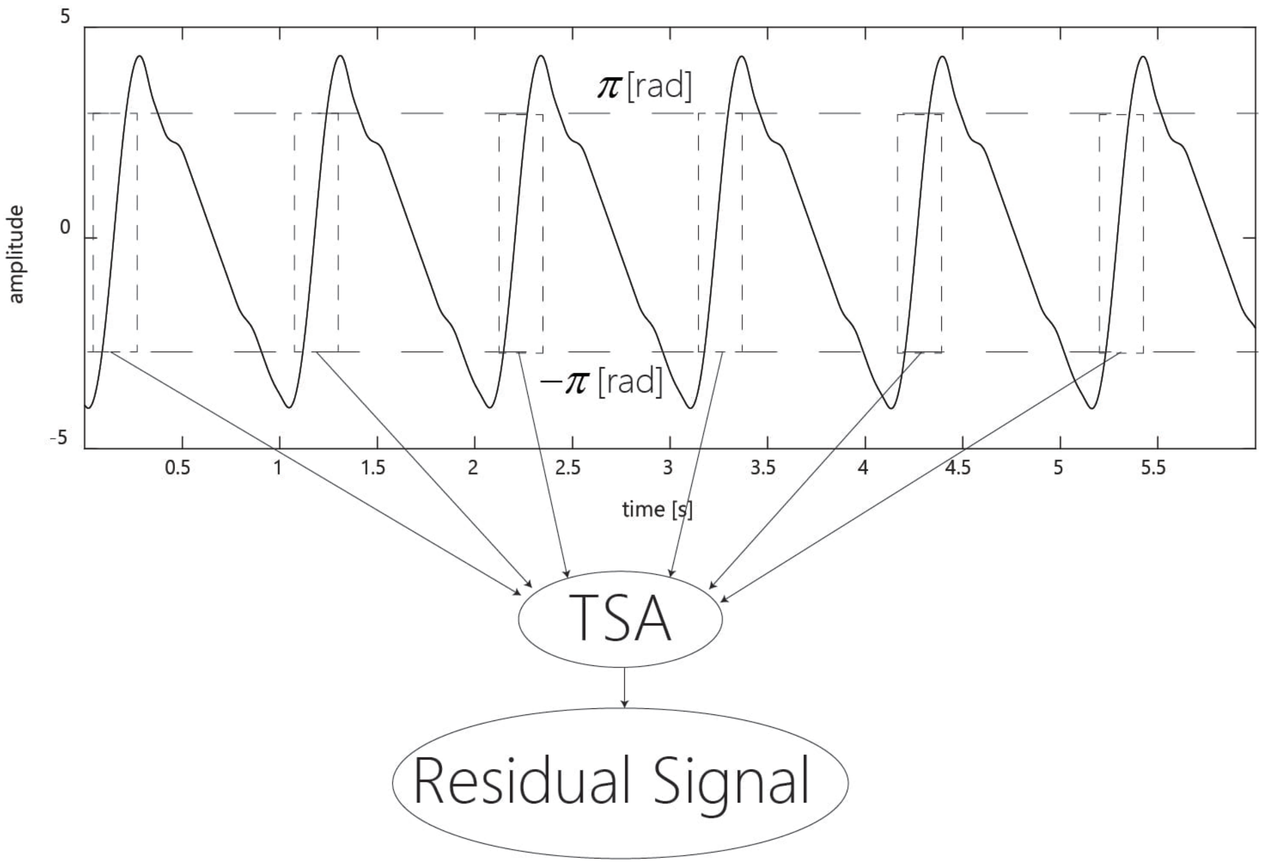

Figure 5: Signal analysis schema

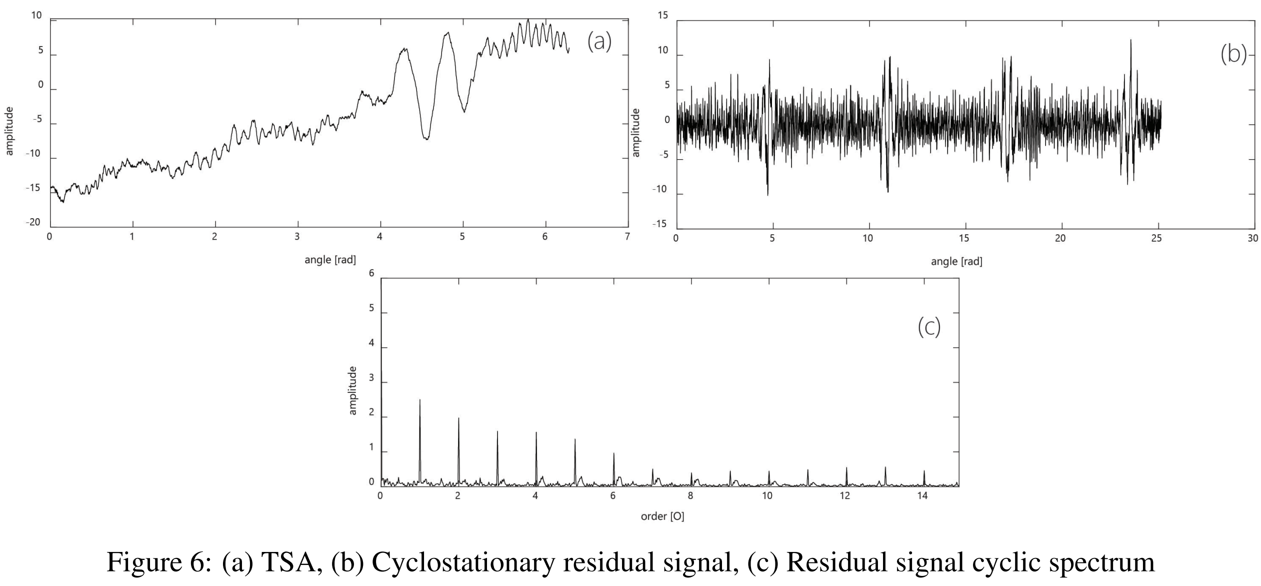

Figure 6: (a) TSA, (b) Cyclostationary residual signal, (c) Residual signal cyclic spectrum

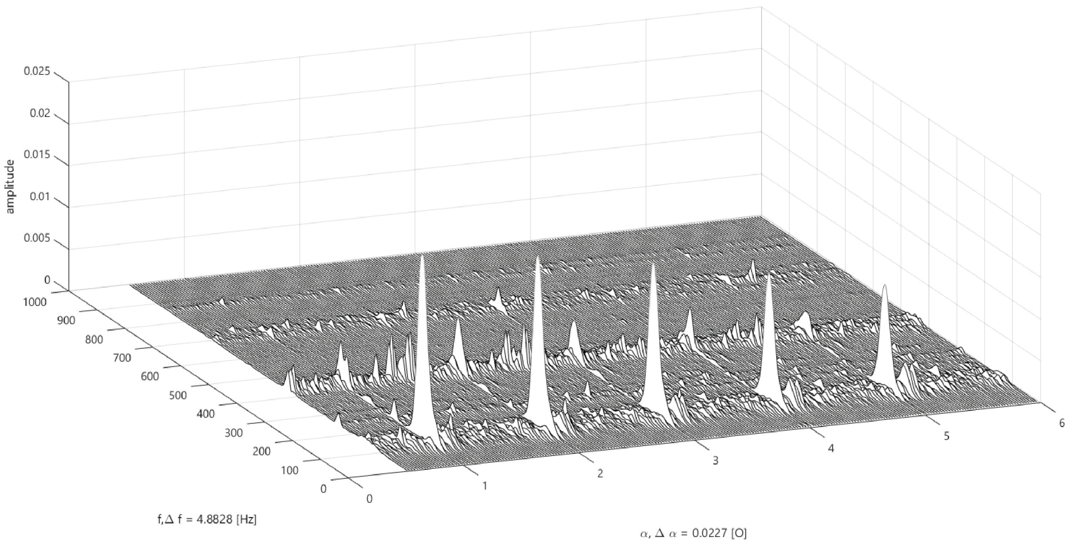

Figure 7: Order-Frequency Spectral Correlation

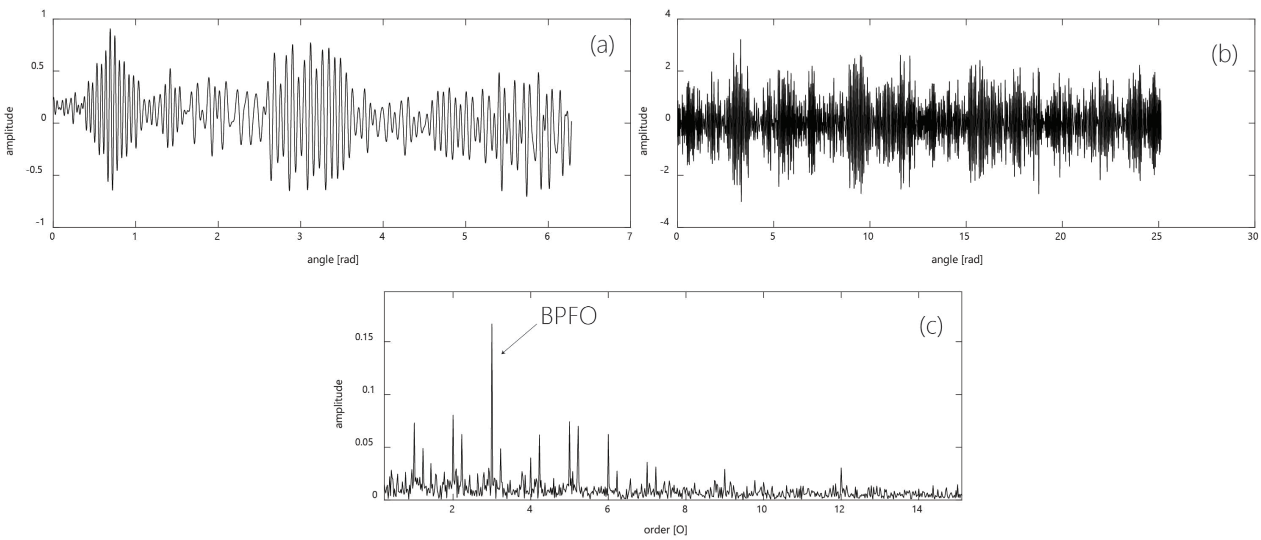

Figure 8: Filtered signal: (a) TSA, (b) Cyclostationary residual signal, (c) Residual signal cyclic spectrum

signal. At this stage, the strong torque variation due to the machine kinematics is not visible in both TSA an residual signals, Figures 8 (a) and (b). As a matter of fact, the Cyclic Spectrum of the residual signal shows a component around the third cyclic order, which could be related to the bearing outer race. A final remark on the bearing fault diagnosis could be given by the study of the angle-time cyclo-non-stationarity signal content.

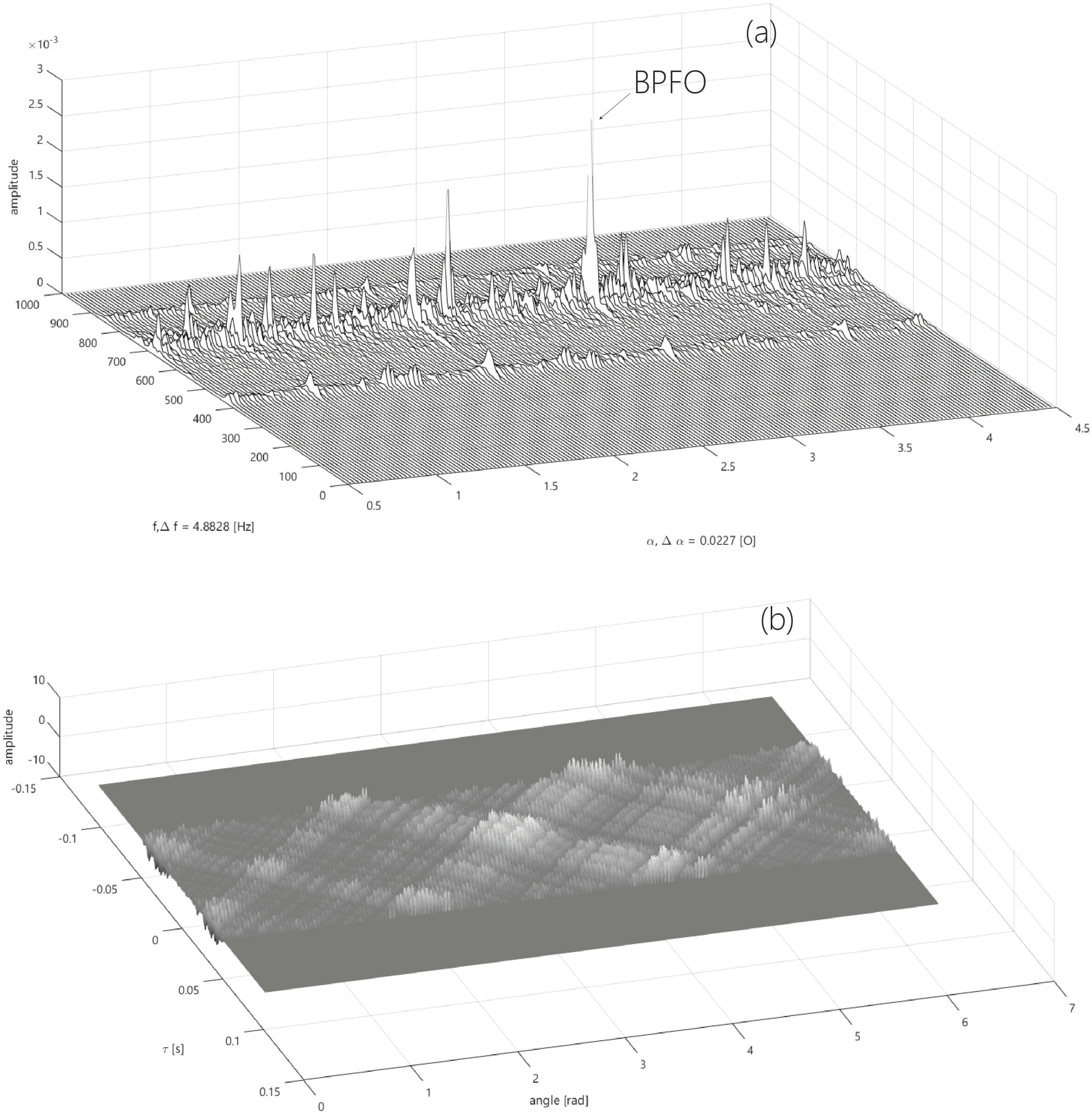

Figure 9: Filtered signal: (a) Order-Frequency Spectral Correlation, (b) Angle-Time Covariance Function

Figure 9 plots the different representations of the cyclo-non-stationarity signal content, i.e. order-frequency and angle-time. This two correlated domains exploit the bearing fault signature in different manners. In more detail, in Figure 9 (a) the fault signature is highlighted by the comparison of the component around the third cyclic order, whilst Figure 9 (b) shows a strong correlation three times per shaft revolution, which is related to the fault periodicity.

In this work, the bearing fault diagnostics is ended by comparing the results presented in Figure 9 with the analysis of a sound bearing, Figure 10. It is possible to see how the components related to the bearing fault are not visible in Figures 10 (a) and (b). Moreover, even if the torque signal was pre-filtered before the

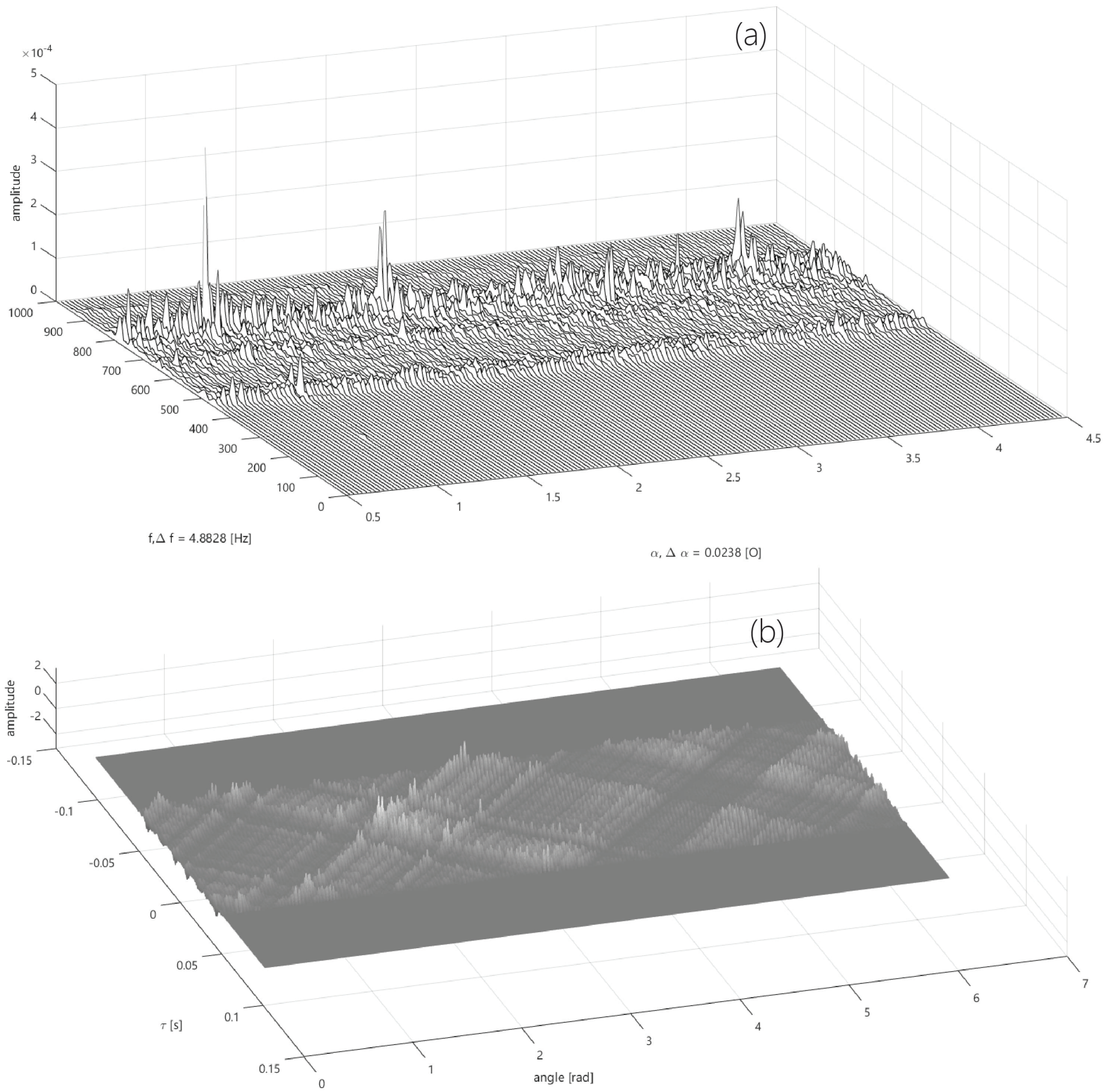

Figure 10: Filtered sound bearing signal: (a) Order-Frequency Spectral Correlation, (b) Angle-Time Covariance Function

analysis, the kinematics of the machine is still visible inside the results. As a matter of fact, the first cyclic order is visible in Figure 10 (a) and a strong correlation is present one per shaft revolution in Figure 10 (b).

5 Conclusions

In this paper the cyclo-non-stationarity paradigm is applied to the torque data of a brushless servomotor to make diagnostics of bearings. The torque data is derived from the current signal fed by drive controller and it does not require external sensors. The same drive returns also the instantaneous speed of the shaft thanks to an encoder embedded in the motor. These auxiliary signals are used in order to firstly, resample the signal in the angular domain for the assessment of deterministic counterpart used for the evaluation of a proper second order cyclo-non-stationary signal. Finally, the instantaneous speed was used in order to resample back in the time domain the residual cyclo-non-stationary signal allowing the angle-time and order-frequency signal analysis. The combination of a complex pre-processing methods with advanced cyclo-non-stationary techniques has led to the exploitation of the outer race bearing fault from the brushless servomotor torque data.

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