Correlation between the stator current signal and the kinematic model of the rolling bearing for the diagnostics

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SUMMARY. This paper deals with ball-bearing diagnostics in variable-speed applications. In particular it focuses on stator current signal as diagnostics tool. The use of the current signal to detect bearing fault, instead of vibration signal, is been proposed and developed in literature, but most of these papers focus on constant speed applications. In fact is well-known that the presence of a mechanical fault on the bearing (e.g. pitting) causes peaks at given frequencies in the spectrum of both vibration and current signals. These characteristic frequencies depend on the type of fault, the bearing geometry and the rotational frequency of the shaft (in case of the current signal, frequencies depend also on power supply frequency). It follows that in variable speed applications the rotational frequency changes continuously, then it is not possible to apply the literature models since the fault characteristic frequencies change too. In a former paper the authors proposed a method, based on vibration signal, to overcome the aforementioned problems. It is based on the cross-correlation between the acquired vibration signal and a set of artificial ones, each of them simulating the presence of a specific fault on the bearing. Major or minor correlation with a specific-fault simulated signal allows to assess the presence of a damage. In this paper the authors extend their method to the stator current signal. In particular they substitute the on-field vibration signal with the on-field current signal, maintaining the model of the fault simulated signals. The idea is that if a high-dynamic relation exists between the cause (i.d. the mechanical fault) and the effect (i.d. the presence of current ripples), the cross-correlation between the current signal and the simulated vibration signal could reveal it. Indeed this is a preliminary study on the feasibility of that diagnostics tool. It is proposed a fault index to automate the process and three different fault cases are investigated. The study compares the response of the fault indexes when three input signals are used: the stator current, the gradient of the stator current as improved signal-to-noise signal and the vibration signal as reference. Additional pre-processing of data is made by the use of Spectral Kurtosis and of demodulation. The results are taken on a test-bed which reproduces an industrial application.

1 INTRODUCTION

Bearing diagnostics is been investigated deeply through the years and the classic literature methods are mainly focused on constant speed applications [1]. In fact it is well known that if a damage occurs to the bearing it could be revealed by the frequency analysis of the motor vibration signal. The presence of a fault, e.g. on the outer race of the bearing, produces an impact every time a rolling element passes on it and if the shaft is moving with a given rotational frequency fr than the fault makes a train of impulses with a characteristic frequency which is proportional to fr. This proportional coefficient is calculated once the bearing geometry is known. In particular the rolling bearing can be modelled as a conical epicyclic gear where the races and the rolling elements act like gears and the cage like the carrier, then the relative velocities between all bearing components can be calculated and they only depend on bearing geometry [2]. Unfortunately the presence of a wired external accelerometer which measures the vibration signal, is often seen as an additional cost. The need of a nearly sensorless diagnostics leads to investigate the monitoring of stator current as bearing fault detector [3]. Although bearing diagnostics through current monitoring achieved good results, it has been proved that, in a faulted bearing application, the current signal is very weak if compared with vibration signal and then the diagnostics is more difficult [5]. Since the torque acting on the shaft is proportional to stator current signal, the current gradient is used. A new challenge comes from the modern direct-drive motors. These motors are real-time controlled in order to follow complex shaft position profiles with variable speeds, avoiding the presence of a gear reducer between the motor and the user. In this case there is no more a constant rotational frequency f_r and then there are no more fault characteristic frequencies in the signal spectrum. As a consequence, all the constant speed techniques cannot be used in both cases of vibration and current signal analysis. Diagnostics techniques on variable speed applications have been proposed using the vibration signal of the motor [1, 6]. Particularly the authors [7] proposed an algorithm for the bearing diagnostics in servomotors which execute arbitrary motion profile, reversal of rotation included. In this paper the authors extend the results of their previous studies [7, 8] in order to use the stator current as indicator. In particular this paper investigates the correlation between the bearing components impacts and torque ripples in time domain. The algorithm needs as inputs the motor position profile and the stator current signal. The current signal is replaced by the gradient of itself. The method checks the presence of a defect through a cross-correlation function between two signals: the current signal and an artificial one which is the expected vibration signal if a fault occurs in the bearing (e.g. on the outer race, etc) when the shaft rotates with the given position profile. In modern servomotors which work as electric cams, the cyclic position profile is known because it is used in the position control loop. At last the envelope of the cross-correlation signal is done. The kinematic model of a faulted bearing supplies a simulated signal which acts as road map to investigate the current signal content. Major or minor matching between simulated signal and the current content is quantified by the kurtosis of the cross-correlation signal in correspondence of three cycles of the machine. The paper is structured as follows: the fault detection algorithm for variable speed application is recalled, the use of current signal and the purpose of a fault index are provided. A pre-processing of data is made and in the dedicated Section, reference will be given regarding the technique used, that is the Spectral Kurtosis [9, 10, 11, 12]. Experimental results and comments close the paper.

2 FAULT DETECTION IN A VARIABLE SPEED APPLICATION

In this Section we recall the algorithm we developed for the bearing diagnostics based on the vibration signal in variable speed applications. This algorithm will be used on current signal in the following Sections. It needs as inputs two signals: the vibration signal acquired on the motor and the vibration signal expected from a faulted bearing. The cross-correlation between these two signals measures how the signals are similar to each other. In other words the algorithm compares the acquired signal with different-fault cases and looks for the higher correlation. The vibration signal expected from a faulted bearing is computed via software once the geometry of the bearing is known and the position profile of the motor is available. Since the motor changes continuously its speed and acts electric cam (e.g. direct-drive motors) and then it has to be controlled, the real-time position profile of the motor is measured. The sampling frequency of the position profile depends on the manufacturer and in this paper the direct drive motor has a sampling frequency of 8 kHz. The most used kinematic model of the bearing is based on the representation of the bearing as a epicyclic gearing. With reference to the gear terminology: the bearing inner race acts like the sun, the balls as planet gears, the cage as the planet carrier and the outer ring as annulus fixed to the frame. The gear ratio between all the elements of the bearing could be easily calculated. The main drawback of this model is that it does not take into account the slip between the bearing elements. Suppose that a fault is present on the bearing (e.g on the outer ring or on the inner ring), the position profile of the motors allows to calculate the time instants when an impact is expected, and then to generate the expected vibration signal for the given fault. We generate different-fault simulated signal which is used as fault sign in the correlation with the on-field vibration signal. We expect that if we correlate the on-field signal with a simulated one where the same fault is present on both, the output shows a steep peak at every motor cycle, since there is a high correlation when two machine-cycle are phased. On the other side, if the two signals present a different fault the correlation output shows a large-width peak at every motor cycle since there is a low correlation even when the signals are phased. This algorithm works well for vibration signals and is been proved also in addition to pre-processing techniques of the data (Wavelet Transform, Hilbert-Huang Transform) [8].

Summarising the steps of the algorithm for the diagnosis of ball bearing in variable speed applications:

- Take as inputs the geometry of the bearing, the position profile of the motor's shaft and the vibration signal acquired on-field from the testing motor.
- Simulate the expected vibration signal if a given fault is present on the motor.
- Correlate the on-field signal with the expected one.
- Look for the shape of the peaks in correlation output.
- Repeat the correlation with another fault simulated signal.
- Compare the cross-correlation outputs in the different cases.

For more details on the algorithm please refer to the papers [7, 8] of the authors reported in the Reference section.

The main drawback of this diagnostic technique is that a scalar indicator of the degree of correlation has not be found yet. The results are visually appreciable, but is seems to be difficult to determine a robust indicator which stands for every cases. In the following Sections we will suggest a possible fault index and its response will be evaluated in different working conditions.

3 CURRENT SIGNAL AS FAULT SENSOR

A critical comparison between the use of vibration and current signal in bearing diagnostics has been already proposed in literature [5]. Such a comparison lies outside the aim of this paper. We are interested in a comparison between those signals in a specific field which is their use in the algorithm referred in the previous Section. If the current signal is somehow correlated to the presence of a fault on the bearing, we think that the current signal has to be correlated also to the vibration signal since that the last one is a consequence of the fault presence. This is the main idea we develop in this paper. We underline that most of the literature contributions are focused on constant speed applications. In fact, since the presence of the fault causes a modulation of the current signal, in a constant speed application the frequency of the modulating signal is constant too and its presence is revealed by anyone of the different techniques available in literature. In variable speed application instead, the modulating signal is a sum of different frequency components and the presence of a specific fault cannot be done with ordinary techniques. The ways the current signal is affected by a fault are mainly two as stated in literature. The first mode is due to the passage of bearing's ball on a fault that induces a vibration of the shaft and then a fluctuation of the air gap between stator and rotor part of electric motor. The fluctuation of the air gap causes a fluctuation of the in-coming current. This effect is more relevant for large fault when the amplitude of the shaft vibration is higher. The other mode is linked to mechanical imbalance due to the impact between the rolling element and the fault. Although the vibration direction is usually radial with reference to the shaft, the changes in contact conditions causes changes in the resisting moment induced by the contact between the bearing elements. The resulting dynamic imbalance affects the working condition with reference to its characteristic curve. Moreover the control system of the motor measures the imbalance and try to correct it changing the absorbed current as a consequence. These considerations suggest that the signal of current could be correlated to the vibration signal. As an additional diagnostic signal, in the following we will calculate also the gradient of the current signal. In fact, since we are looking for the fluctuations of the current, the gradient of current itself should be highlighted by them. In practice, the controller of the motor does not provide the current signal as it is, but it provides the torque supplied by the motor. There is a linearity relation between the torque and the current in the motor so we will speak of current and torque without distinction except where indicated in the following Sections. Figure 1 shows an example of the three signals that will be considered in this paper as fault sensor.

4 PRE-PROCESSING OF THE DATA

In order to reduce the noise present in the acquired signal - both vibration and current - a pre-processing of the data is been proved to be helpful [8]. In this paper we use the spectral kurtosis (SK) developed by Antoni and Randall, which proved to be a powerful tool to the bearing diagnostic. In particular the SK selects a frequency band window in the signal spectrum, computes the kurtosis - the definition of kurtosis is provided in the next Section - and then shifts the frequency band window along the frequency domain. The same operation is done varying the dimension of the frequency window. The number of the process iterations augmented by one is called SK level. The SK returns a colour map (kurtogram) that highlights the central frequency and the bandwidth that maximize the kurtosis. A higher value of the kurtosis indicates the presence of non-stationary processes such as impacts. Refers to the work of Antoni and Randall [9, 10, 11] for a more detailed informations about the spectral kurtosis and its use as diagnostic tool. Noise reduction for each signal is done by a demodulation at the frequency band suggested by the spectral kurtosis. The SK level used is significant since we showed in a previous paper [12] that with current signals the kurtogram tends to lock onto high frequency component of the spectrum.

5 DATA PROCESSING AND RESULTS

In this Section we present the data processing, the suggested indicator to reveal the presence of a fault and the results obtained in different working conditions.

5.1 *Experimental set-up*

A test-bed is available which is made of a direct-drive motor (Rockwell Automation Kinetix 6000), a mono-axial piezoelectric accelerometer (Entek 81001) and acquisition hardware (National Instruments cDAQ-9172 board with NI-9215 and NI-9233 modules). The vibration signal is acquired by the accelerometer and the NI-9233 module, while the torque signal, which is provided as analog output by the controller of the motor, is acquired by the NI-9215 module. An additional channel on NI-9215 module is used to acquire the velocity profile of the motor which is measured by on-board encoder - as already mentioned the direct drive motor needs to know the angular position of the shaft for control independently from the aim of our experiment. The sampling frequency is

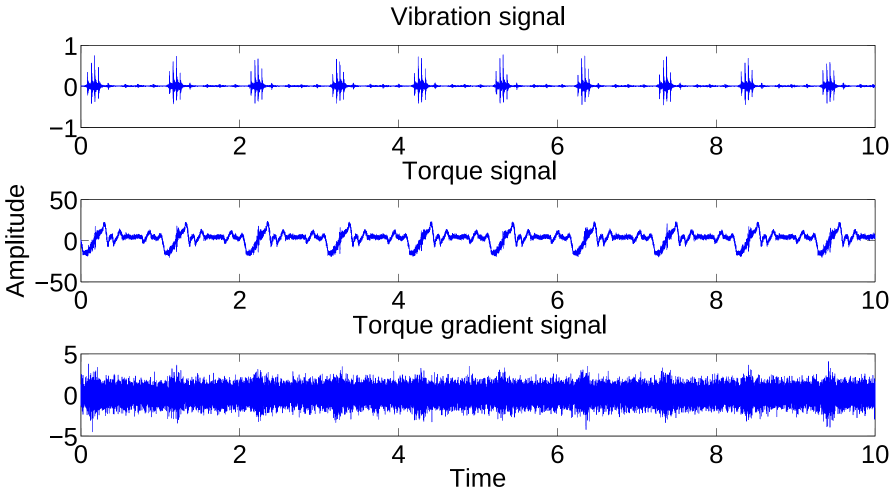

Figure 1: Vibration, torque and torque gradient signals for a direct-drive motor.

$10kHz$, and the acquisition time is 10 seconds. Vibration, torque signal and velocity profile are acquired simultaneously, while the calculation of the gradient of the torque and the data processing are made subsequently by Mathworks'MATLAB software. The position profile executed by the motor is reported in Fig.2 together with its corresponding velocity profile. The position profile is a polynomial curve and it is used as motion profile for direct drive motors in industrial food-packaging process. The motion profile is cyclic and the time of the cycle is about 1.028 seconds. The bearing used in the motor is a SKF-6309. Three different bearing condition have been tested: sound bearing, outer race faulted bearing and inner race faulted bearing. In the faulty cases the damage has been artificially made by a cutting tool (Dremel tool 300-series with 9905 tungsten carbide cutter).

5.2 *Fault indicator*

As already mentioned in the previous Section, in this paper we propose to correlate together an experimentally acquired signal and a fault-simulated one to measure how close are the two signals. On the other side if there is low correlation, there will be a spread of peaks near the main one. The mathematical definition of the cross-correlation function for two discrete functions f and g is given in Eq.1:

$$(f \star g)\,[n] \triangleq \sum_{m=-\infty}^{+\infty} f^*\,[m] g\,[n+m] \tag{1}$$

where f^* is the complex conjugate of f.

For a discrete set of elements there is a specific statistical indicator which measures how outlier-prone the distribution is: the kurtosis. Kurtosis is the fourth standardized statistical moment and its mathematical formulation is reported in Eq.2:

$$k = \frac{E(x-\mu)^4}{\sigma^4} \tag{2}$$

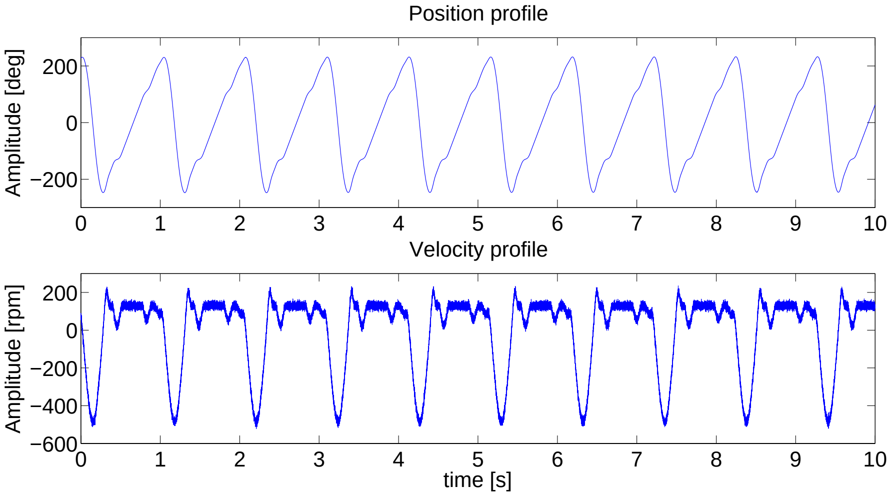

Figure 2: Position and velocity profile for the application analysed in this paper.

where μ is the mean of x, σ is the standard deviation of x, and $E(t)$ represents the expected value of the quantity t. As reported in [13] the kurtosis of a normal distribution is 3. Distributions that are more outlier-prone than the normal distribution have kurtosis greater than 3; distributions that are less outlier-prone have kurtosis less than 3. In this paper is determinant for the faulty detection the relative value of the kurtosis, which means the comparison between the kurtosis in two test cases.

If we compare two cyclic functions with the same cycle-period, it would be logical that a local-maximum correlation occurs with a frequency given by the cycle-frequency. Unfortunately this condition is not certain in this case even when we analyse two signals which refer to the same fault. In fact on one side we have a simulated signal based on slip-free kinematic model, but on the other side the bearing is subject to slip between balls and races, and then the real signal slightly differs from the simulated one. The main consequence of the slip is that the cyclic peaks could decrease quickly in the correlation function, and then the calculation of the fault index will be done only in a short part of the signal, e.g. three machine cycles.

The fault index is computed as follow:

- Consider only half of the cross-correlation function output (positive or negative shift).
- Take a sector (let’s call A) of the cross-correlation function which corresponds to a 1.5-times the cycle period.
- Find the maximum of the sector A.
- In the cross-correlation function, take another sector (B) which corresponds to a one cycle period and centred on the maximum determined in the previous step.
- Compute the kurtosis of this sector B.
- Repeat from the second step moving along the cross-correlation function of a cycle period.
- Stop after three cycles.

- The fault index is the mean value of the three kurtosis.

5.3 *Results*

Due to the limitations of the paper length only few cases are provided, while particular cases of interest could be asked contacting the authors. The algorithm which calculates the cross-correlation is the same used in diagnostics with the vibration signal, and more details are reported in [7]. Tests are performed on vibration signal (VS), torque signal (TS) and the gradient of the torque signal (GS). Figure 3 shows the cross-correlation function between the vibration signal acquired on the motor in all the three fault-cases and the simulated signals. In particular, regarding the picture as a matrix of $3x2$ dimensions, the first column shows the correlation with the outer-race-faulted simulated signal, while the other one shows the correlation with the inner-race-faulted simulated signal. The rows specify the nature of the fault which is really present on the bearing under test. Some of the sub-plot don't report the axis in order to make the picture more legible. In that picture the axis are the same at the beginning or the end of the corresponding row or column. Figures 5-4 shows a similar plot but with reference to torque signal and gradient of torque signal respectively. Consider the second and the third row of Figure 3. The comparison between the two graphs shows that there is a lower spread of peaks in those correlation circled in red colour. The use of vibration as diagnostic tool proves to be effective, while the results are quite difficult to interpret when electric parameter is used. In fact Figs.5 and 4 show little differences between the two correlations, although a through analysis displays a rise of peaks in that correlation between the same faulted signals. In the comparison of the two cross-correlation we consider: the value of the maximum peak and the spread of the curve near the peak. This second characteristic is hardly measurable and then personal opinion could misrepresent the facts.

If we apply the proposed fault index, that is the kurtosis, the results for different level of the Spectral Kurtosis are summarised as follows:

- The kurtosis on VS works correctly in every fault condition and it is appreciable the difference between its value in sound and faulty conditions. Moreover a variation of the number of Spectral Kurtosis (SK) levels doesn't affect the results.
- The kurtosis on TS works correctly for faulty condition of the bearing if the the signal is used as it is, without any pre-processing of the data.
- The kurtosis returns wrong results if TS is demodulated in the frequency-band suggested by the SK, independently of the SK level.
- The kurtosis on GS works correctly for faulty condition of the bearing if the signal is demodulated in the frequency-band suggested by the SK when SK-level is equal to 4.
- The kurtosis returns wrong results on GS if SK-level is different from 4.
- It is not appreciable the difference between the kurtosis value in sound and faulty conditions in TS and GS cases.
- In the analysis of TS and GS signals the band-frequency suggested by the SK is independent from the type of fault.
- In the analysis of VS signal the band-frequency suggested by the SK is dependent from the type of fault.

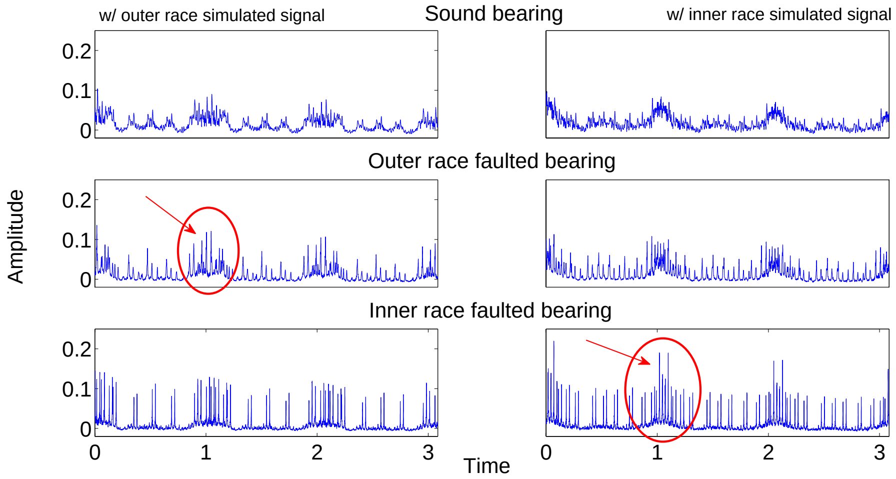

Figure 3: Cross-correlation between fault-simulated signal and real vibration signal in three different fault-cases.

- The most significant content of GS is at the low frequency, then high-pass filtering has to be avoided.

This preliminary study allows some considerations. The kurtosis as fault index seems to works very well on vibration signal and its use could be investigated more through a specific test-plan. On the other side, the use of kurtosis for electric parameters proved to be effective in a limited number of cases. Moreover the comparison between the cross-correlation outputs in some of those negative cases shows that the kurtosis doesn't get the effective correlation that seems to be at a visual inspection. Probably the kurtosis has to be supported with other index in order to be used in diagnostics with current signal. For example, the signal energy seems to be a good discriminant between sound and faulty condition in every case.

Other considerations regard the Spectral Kurtosis as a pre-processing technique. The Spectral Kurtosis was born to characterise vibration signal and indeed it works very well on the vibration signal. Must be pointed that the kurtosis index applied to the pure vibration signal gives a wrong result, while if the signal is filtered in anyone of the bandwidth suggested by the Spectra Kurtosis (i.e. for any level) it works correctly. The bandwidth located by the Spectral Kurtosis in the case that an electric parameter is used is interesting: it is independent from the type of fault, that is is the same for sound and faulty bearing. This result suggests that the Spectral Kurtosis points a non-stationary phenomena which is not correlated to the mechanical fault. Level variations of the Spectral Kurtosis don't move the result. As a consequence the use of Spectral Kurtosis together with an electric signal should be avoided in the proposed algorithm. In the future other type of pre-filtering data will be tested.

In time-domain the relation between the impacts in a faulted bearing and the consequent torque ripples of the motor seems to be weak but real. The results obtained justify future analysis, e.g. on the influence of fault dimension.

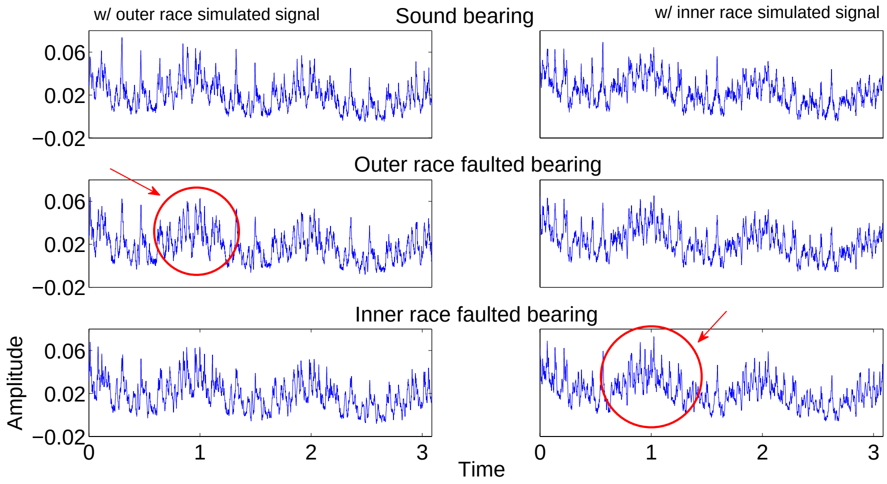

Figure 4: Cross-correlation between fault-simulated signal and real gradient of torque signal in three different fault-cases.

6 CONCLUSIONS

This paper studies the correlation between the stator current signal and the kinematic model of the rolling bearing for diagnostics purpose. The proposed algorithm has been tested on three different conditions: sound bearing, outer race faulted bearing and inner race faulted bearing. Spectral Kurtosis and demodulation have been used to pre-process data, and the kurtosis of the correlation output has been suggested as fault index. This procedure has been run three-times using as input one of the following: the vibration signal, the torque signal and the gradient of the torque signal. The paper reports a qualitative comparison of the results in different conditions.

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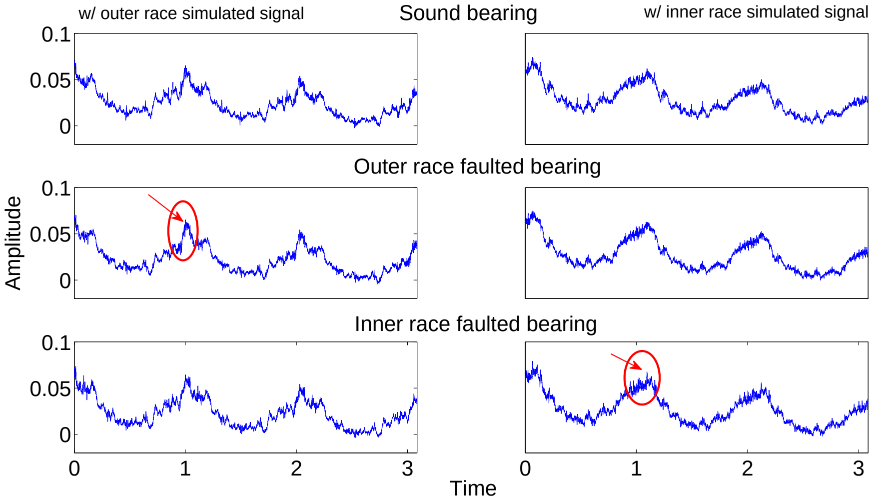

Figure 5: Cross-correlation between fault-simulated signal and real torque signal in three different fault-cases.

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