# CONDITION MONITORING INDICATORS FOR PITTING DETECTION IN PLANETARY GEAR UNITS

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Abstract

In industrial field, there is an increasing demand for monitoring systems enabling predictive maintenance programs. In this context, the present work concerns the monitoring of distributed wear (pitting) in planetary gearboxes. For this purpose, some metrics of the synchronous average of the vibration signal, based on the statistical moment of the fourth order, are present in literature; in this paper, a new indicator is proposed, namely *NA4mod*. The effectiveness of this metric in identifying the early stage of pitting has been evaluated by conducting an accelerated life test of about 700 hours on a test bench using a back-to-back configuration. The paper introduces the proposed metric, describes the test, presents and dis-cusses the results. Metric *NA4mod* exhibits satisfactory capability to detect pitting with better reliability than other metrics in literature. In addition, the metric is shown to be sensitive to both early stage damage and pitting severity in the final stage. Results are verified by means of wavelet-transform analysis.

Keywords: condition monitoring, planetary gearbox, distributed wear, vibration metrics.

## 1. INTRODUCTION

Every machine with moving components gives rise to vibrations and noise; depending on its operating status, a specific "vibratory signature" characterizes each machine. It is therefore possible to detect the changes on this signature and use them as indicators of the imminent appearance of a fault. Numerous analysis procedures of the vibratory signature have been developed for condition monitoring and diagnostics, especially in the last 30 years [1, 2]. In particular, several applications of signal processing techniques to fault detection in planetary gearboxes can be found in literature; as examples, the applications to gearboxes used in lifting systems [3], wind turbines [4] or helicopter transmissions [5] can be cited.

Signal analysis techniques can be classified according to their domain: techniques based on time, frequency or time-frequency domain. In the context of time-based techniques, an effective investigation tool for many types of defects is the Time Synchronous Average (TSA) of the signal [6, 7]. As a matter of fact, the TSA contains the signal components that are synchronous with the rotation of a reference shaft and its harmonics, while the non-synchronous and random components of the signal are heavily attenuated by the averaging operation. The TSA may be then further manipulated by applying band-pass filter that allows to isolate the mesh frequency or the rotation components. The subsequent computation of the Hilbert transform provide the chance to determine both amplitude and phase of the modulation [8-10], which typically represent an indication of the presence of faults.

Within this context, in order to obtain indexes of the presence of faults and their severity, the raw time signal or the TSA may be characterized by statistical parameters or metrics of various type [11-15]. D'Elia et al. [14] have compared the performances of some condition metrics of the TSA presented in the literature [16], during an accelerated life test on planetary gearboxes, where distributed pitting developed. The obtained results show the limits of the metrics presented in the literature. In particular, metric FM4 [16] is sensitive to very heavy pitting at life end and not to the early pitting development, while metric *NA4* [13, 17], seems to be sensitive to the pitting initial development and not to its growth. Thus, two new metrics of the TSA - more promising for the detection of pitting - are proposed and validated in [14], namely the Residual Variance (RV) and the Cumulative Residual Variance (CRV). Fault detection can be carried out also in the frequency domain, as described by Randall R. in ref. [18]. It is worth noting that the discrete Fourier transform can be applied to periodic stationary signals or single transients. However, localized gear defects typically introduce non-stationary components into the signal [10], which cannot be studied by conventional frequency analysis techniques. In this scenario, the adoption of advanced techniques based on the time-frequency domain such as the Continuous Wavelet Transform (CWT) [10, 19, 20]

and the Wigner-Ville distribution (WVD) [11, 21, 22] becomes mandatory.

The present work concerns the development of a new TSA-based metric, namely *NA4mod*, for pitting detection in planetary gearboxes. Such a metric is based on the fourth-order statistical moment, developed as a modification of metric *NA4* introduced in Refs. [13, 17]. Both metrics are applied on two gearboxes working in back-to-back configuration with electric power recirculation, demonstrating that metric *NA4mod* is effectively capable to follow the evolution of the pitting severity, while the sensitivity of metric *NA4* is limited to initial development of the phenomenon. The robustness of the technique is then verified by applying the Wavelet Transform on the same set of data.

The structure of the paper is as follows. In this section, the state of the art about the monitoring of distributed defects in planetary gearboxes is introduced. Section 2 details the theoretical bases of the methodology and the proposed metric. In Section 3, the experimental apparatus and the accelerated life test are described, while Section 4 reports the results about the metric effectiveness and its comparison with metric *NA4*. Finally, the last Section is devoted to concluding remarks.

## 2. PROPOSED METRIC *NA4mod* AND PROCESSING METHODOLOGY

As mentioned above, the new proposed metric is computed from the TSA of the gear of interest and, in particular, it is based both on the regular signal and the residual one [23], obtained from the TSA. Thus a short background about this processing is first given.

In the case of planetary gearboxes, the evaluation of the TSA evaluation is complicated by the movement of the planets, that causes the continuous variation of the distance between the meshing teeth and the fixed transducer mounted outside the annulus. The variation of such a relative position produces a periodic variation in the transfer function between the two components. For this reason, a specific procedure, able to eliminate the effect of the variation of the transfer functions, is needed in order to extract the TSA of each gear from the overall vibration signal. Based on this purpose, McFadden proposed a technique in the early '90s [7]. In subsequent studies, Forrester and Blunt [24] presented further modifications and improvements thanks to a specific technique that is actually covered by patents. For this reason, in the present study, devoted to industrial applications, the McFadden method has been used.

The procedure for extracting the TSA of planetary gearboxes is here shortly summarized. Firstly, by using a tachometer signal, the acceleration time signal is resampled in the angle domain according to the rotation of the carrier of the planetary stage of interest. Then, starting from the angle-based signal referred to the carrier, the signal of the tooth of the planet that meshes with the tooth of the annulus under the accelerometer is extracted one by one. In order to achieve this goal, a time window of appropriate length is used and the operation is repeated once per turn of the carrier, until the signals relating to all the teeth of the gear of interest, planet or sun, have been extracted. Finally, the operation is repeated, obtaining the signal corresponding to several turns of the gear of interest, and the signals of the different turns are averaged in a synchronous manner. A suitable number of averages should be used to obtain a high signal to noise ratio.

It is worth noting that the periodic nature of the TSA provides more possibilities to manipulation of the signal with respect to the raw vibration signal. As a matter of fact, the Fourier transform of a periodic signal, such as the TSA, consists of leakage-free discrete spectral lines suitable to be further processed by means of an ideal filter. Thus, one or more frequency lines (which here represent orders of rotation of the wheel of interest) can be completely removed from the spectrum, without causing discontinuity when the signal is one more time translated to the angle domain. This allows the application of various signal analysis techniques, specifically designed for the treatment of the TSA, and of a series of related signal metrics to be used for fault detection and diagnosis.

In particular, by filtering the TSA, the following signals can be obtained [23]: *i)* Regular signal: containing only the meshing frequency and its harmonics; *ii)* Residual signal: obtained from the TSA, eliminating the meshing frequency and its harmonics, as well as the rotation frequency and its second harmonic in the low frequency range.

One of the metrics based on the fourth-order statistical moment of the TSA is the *NA4* metric, already introduced in literature [13, 17], which is defined as the ratio between the fourth order statistical moment of the residual signal and the current average of the square of the variance of the residual signal itself (the averaging process is performed on all the records prior to and including the current measurement):

$$NA4 = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(r_{iM} - \overline{r}_M\right)^4}{\frac{1}{M}\sum_{j=1}^{M}\left[\frac{1}{N}\sum_{i=1}^{N}\left(r_{ij} - \overline{r}_j\right)^2\right]^2} \qquad (1)$$

where $r$ is the residual signal, $\overline{r}$ is the mean value of the residual signal, $j$ is the record index, $i$ is the sample index, $M$ is the number of current records and $N$ is the number of sample in the time records.

The new metric proposed in this work, indicated as *NA4mod*, has been developed as a modification of *NA4*, with the purpose to obtain an indication related to the severity of the fault, even when such a fault passes from localized to distributed. Thus, the new metric is characterized by the normalization of the fourth statistical moment of the residual signal

with respect to the current average of the square of the variance of the regular signal (this average is calculated on all the records prior to and including the current measurement):

$$NA4\,\text{mod} = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(r_{iM} - \overline{r}_M\right)^4}{\frac{1}{M}\sum_{j=1}^{M}\left[\frac{1}{N}\sum_{i=1}^{N}\left(sr_{ij} - \overline{sr}_j\right)^2\right]^2} \quad (2)$$

where $sr$ is the regular signal and $\overline{sr}$ is the mean value of the regular signal. Such a normalization to the regular signal is finalized to account for the specific meshing condition.

## 3. EXPERIMENTAL APPARATUS AND ACCELERATED LIFE TEST

In order to assess the capabilities of metric *NA4mod*, a dedicated set of data is firstly achieved. The experiment has been designed to produce a real case of damage, including the complete development of pitting, without compromising the functionality of the gearbox and the test bench.

This end-of-life test has been performed by using two Bonfiglioli gearboxes model 304 L3 220 P CP100, called respectively 'Gearbox A' (GB A) and 'Gearbox B' (GB B), in back-to-back configuration with electric power recirculation (Fig. 1.a). Based on this layout, one of the two gearboxes, GB B, works as a speed multiplier, while the other, GB A, works as a speed reducer. The two identical gear units are connected through the output shaft by means of a double universal joint. The main gearbox data are shown in Tab. 1, while the gearbox scheme is given in Fig. 1.b.

Table 1. Gearbox data

| Data | Stage 1 | Stage 2 | Stage 3 |
|---|---|---|---|
| Sun tooth number | 10 | 10 | 24 |
| Planet tooth number | 25 | 25 | 26 |
| Annulus tooth number | 62 | 62 | 78 |
| Number of planets | 3 | 3 | 4 |
| Stage ratio | 7.2 | 7.2 | 4.25 |
| Total ratio | 220.32 | | |

Each gearbox is driven by a 4 kW asynchronous electric motor (Bonfiglioli BN 112 L4) equipped with a 1024-line Sick incremental encoder, used for feedback control. In order to effectively manage the power, two Bonfiglioli Active-CUBE inverters are used. The first one drives the electric motor related to gearbox GB A, controlling the speed of the test bench through its encoder. The second inverter, on the contrary, controls the motor connected to GB B, which actually works as a current generator. The inverter allows to regulate the current absorption.

Two B&K 4507 piezoelectric accelerometers are positioned onto the casings of the two gearboxes, close the second stage annulus gear. The vibration signals are continuously acquired at a sampling rate of 25600 Hz by using National Instruments NI9234 card. The tachometer signal is

obtained through an inverter function, which duplicates the encoder signal by reducing the number of lines by 1/30, according to the capacity of acquisition card. In order to speed up the end-of-life test, the speed multiplier GB B was filled with the standard lubricant indicated in the data sheet, while a lower viscosity lubricant was used in GB A, object of the damage test. In addition, the load was increased beyond the nominal one, in order to promote wear development. The end-of-life test has been carried out for about 700 hours at the constant speed of 1500 rpm, with a torque equal to 4400 Nm, i.e. 30% higher than the nominal torque reported in the data sheet for this speed.
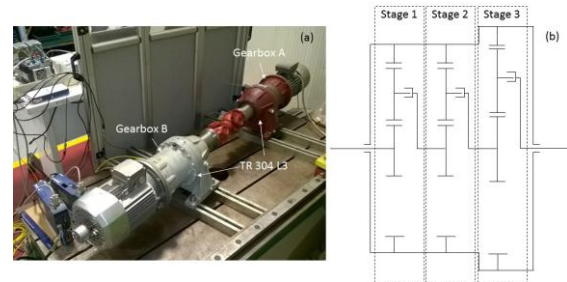


Fig. 1. Test bench setup (a) and internal gearbox scheme (b)

At the end of the test, the gearboxes were inspected. The effects of the accelerated fatigue test may be easily recognized on the sun gear of the second stage of GB A (see Fig. 2.a), that presents distributed pitting and strong upsetting in the contact area, due to the meshing with the planet gears. Damages affecting the head profile and the non-meshing side (crushing) have been also detected. Analysing GB B, only slight pitting was found at the base of the teeth on the sun gear of the second stage (see Fig. 2.b).
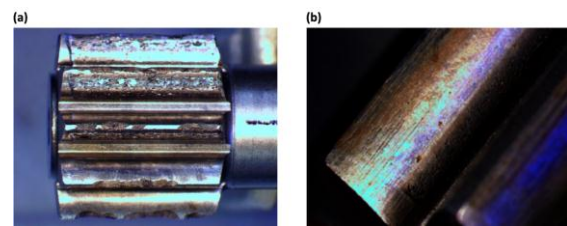


Fig. 2. Detailed view of the wear on the teeth of the sun gear of the second stage of (a) GB A and (b) GB B

## 4. RESULTS AND DISCUSSION

The present Section details results concerning the proposed metric *NA4mod* in comparison with metric *NA4*. The analysis is hereinafter performed on the sun gear of the second stage for both gearboxes, although the metrics have been also computed for the TSA of the planets and the sun of all the stages.

As a first step, the trends of the most common statistical parameters, i.e. RMS values and kurtosis
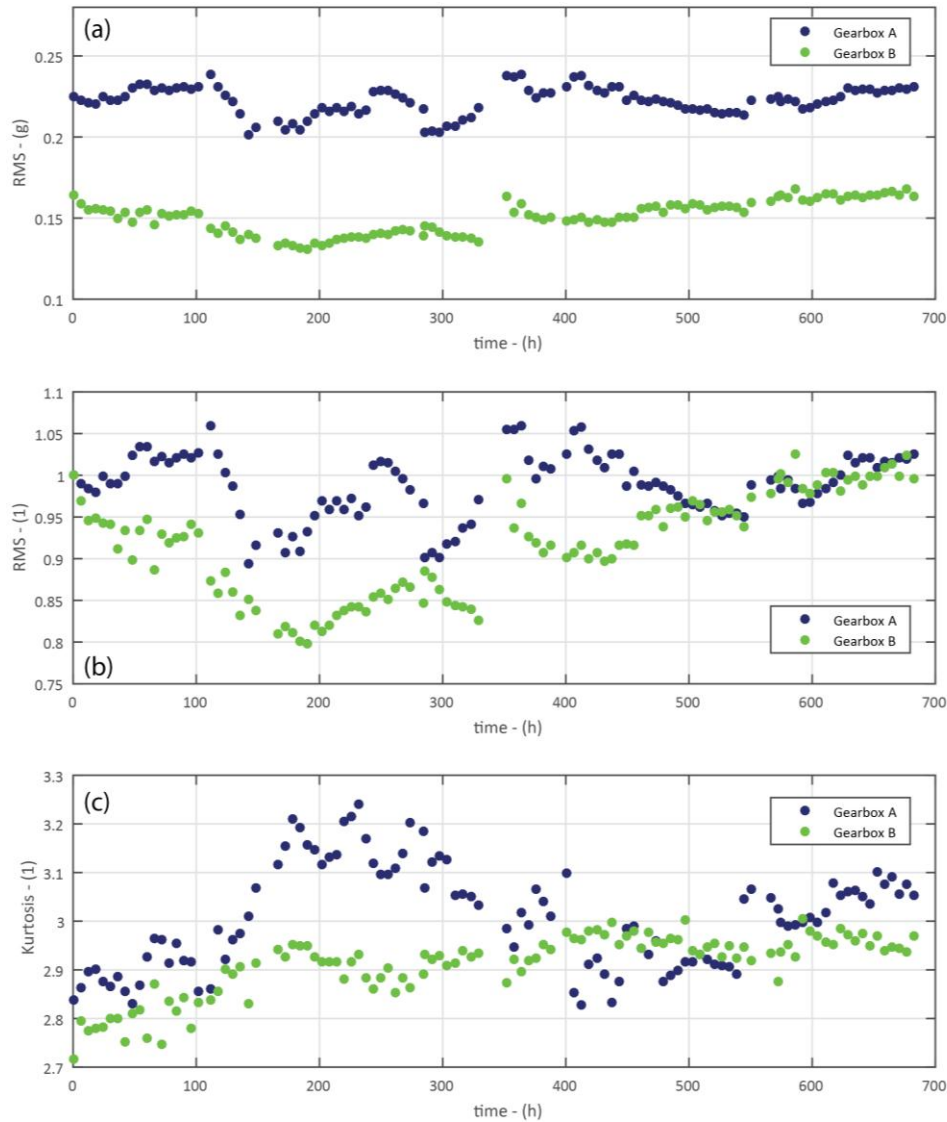
Fig. 3. RMS (a), RMS normalized values with respect to the first record (b) and kurtosis of the raw vibration signal (c) for GB A (blue) and GB B (green)

values, have been considered. They have been evaluated from the raw signals in time domain measured by the accelerometers mounted on the casings, close to the second stage annulus gears. As it is well known, RMS is related to the energetic content of the signal, while kurtosis is sensitive to impulsive contents. Figure 3 shows the result of this analysis. The RMS values concerning GB A are greater than those of GB B (Fig. 3.a) for the whole test; this effect could be related to the different viscosity of the lubricant in the two gearboxes. In order to better compare the RMS trends with reference to variations due to faults, Fig. 3.b depicts RMS values after normalization with the value of the first record of the test: the trends are oscillating until 500 hours, while they are comparable at the end of the test. Thus, from this result, no evidence of faults can be detected.

The results about kurtosis, reported in Fig. 3.c, gradually increases during the test from about 2.7 to 3.0 for gearbox GB B, while kurtosis values referred to GB A slightly increase until 3.25 in the range of 150-300 hours and in the following period they exhibit lower values, between 2.8 and 3.1, which are comparable to those of GB B. This increase in the 150-300 hours range could be related to the initial development of a localized fault, producing impulsive contents in the time signal that are detected by the kurtosis. However, as the fault grows and becomes more distributed, the impulsive content decreases and the kurtosis values fall down. Therefore, this statistic may be able to detect the initial development of localized faults, but it cannot follow the subsequent propagation and the actual severity.

Figure 4 reports the trends of metric *NA4mod* computed for the two gearboxes. As it may be observed, *NA4mod* metric related to gearbox GB A exhibits a sudden increment within the 150-200 hours interval, which is not recognized in the

DIAGNOSTYKA, Vol. 21, No. 1 (2020)
Berlato F, D'elia G, Battarra M, Dalpiaz G.: *Condition monitoring indicators for pitting detection in ...*

7

results related to GB B. This increment is an index of the possible triggering of the pitting in GB A.

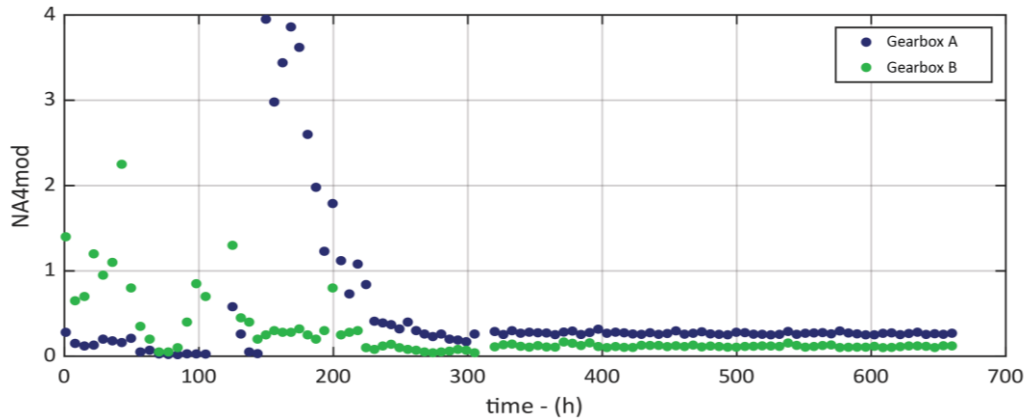hours (index of the possible triggering of the pitting), but the difference between GB A and GB



Fig. 4. *NA4mod* metric calculated on the TSA of the sun gear of the second stage for GB A (blue) and GB B (green)
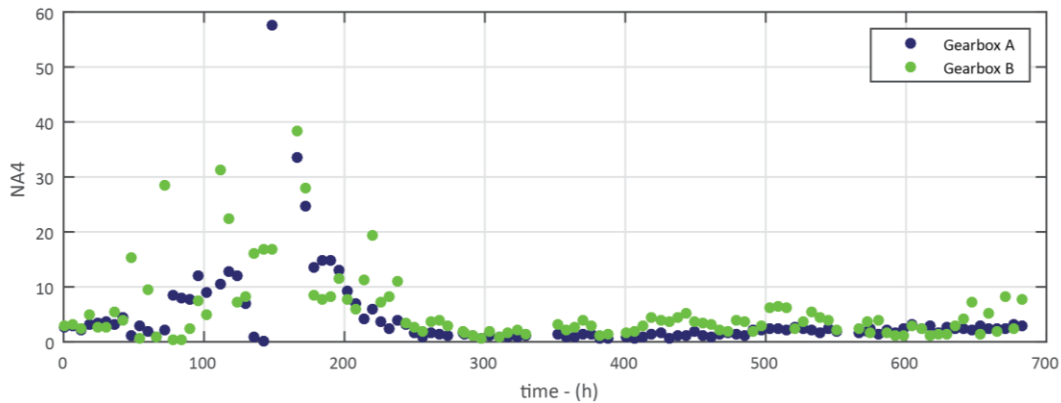


Fig. 5. *NA4* metric calculated on the TSA of the sun gear of the second stage for GB A (blue) and GB B (green)

Furthermore, this parameter proves to be sufficiently robust to monitor the progress of the defect, since its value related to GB A remains always higher than that related to GB B after the defect appearance. This aspect is particularly effective in the last part of the test, which is characterized by heavy, distributed pitting. The slight difference detected between the values of *NA4mod* for the two gearboxes at the end of the test is the result of the condition of wear of the two sun gears, which were very different. For the sake of completeness, it has to be observed that the described trend is reversed at the beginning of the test, throughout the first 80 hours, despite the absence of damages on both gearboxes. This aspect, which represents limitation of the proposed metric, is actually smoothed by the fact that the computed values are still below the increment observed in the 150-200 hours range.

In order to assess the capabilities of metric *NA4mod*, Fig. 5 reports the trends of metric *NA4* for the two gearboxes, concerning the same sun gears of the second stage. As it may be observed, such a metric exhibits an increment between 150 and 200

B is not easily recognizable as for metric *NA4mod*. Moreover, in contrast with respect to *NA4mod*, metric *NA4* cannot distinguish the conditions of GB A and GB B at the end of the test. As a matter of fact, metric *NA4* is not sensitive to the pitting severity in the last part of the test and therefore it is not capable to monitor the progress of the defect.

The described behavior is confirmed by the Wavelet Transform analysis of the TSA signal of the sun gear of the second stage for GB A and GB B reported in Fig. 6 and 7, respectively. Each figure is computed by considering the range between the 40th and 50th order and it depicts three conditions during the test: start of the test, at 150 hours, end of the test. As it may be appreciated, at the test inception (Fig. 6.a) gearbox GB A exhibits higher signal amplitude then GB B even though Fig. 6.b demonstrates that the trigger of localized pitting occurs at around 150 hours in GB A. At the end of the test (Fig. 6.c), GB A signal presents higher distributed amplitude in range 40-50 orders, in agreement with the results achieved with metric *NA4mod*.
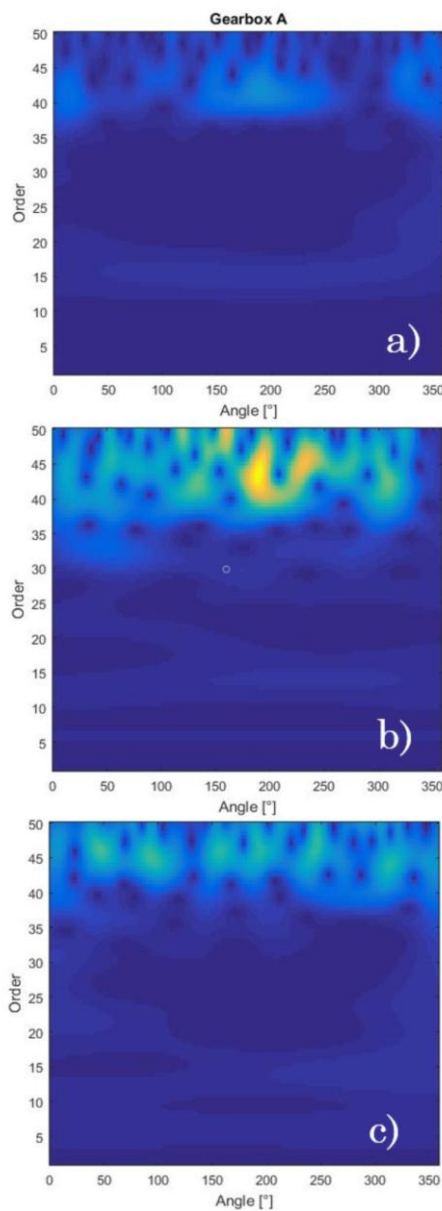
Fig. 6. Wavelet Transform calculated on the TSA of the sun gear of the second stage for GB A in three different conditions: (a) start of the test, (b) at 150 hours, (c) end of the test
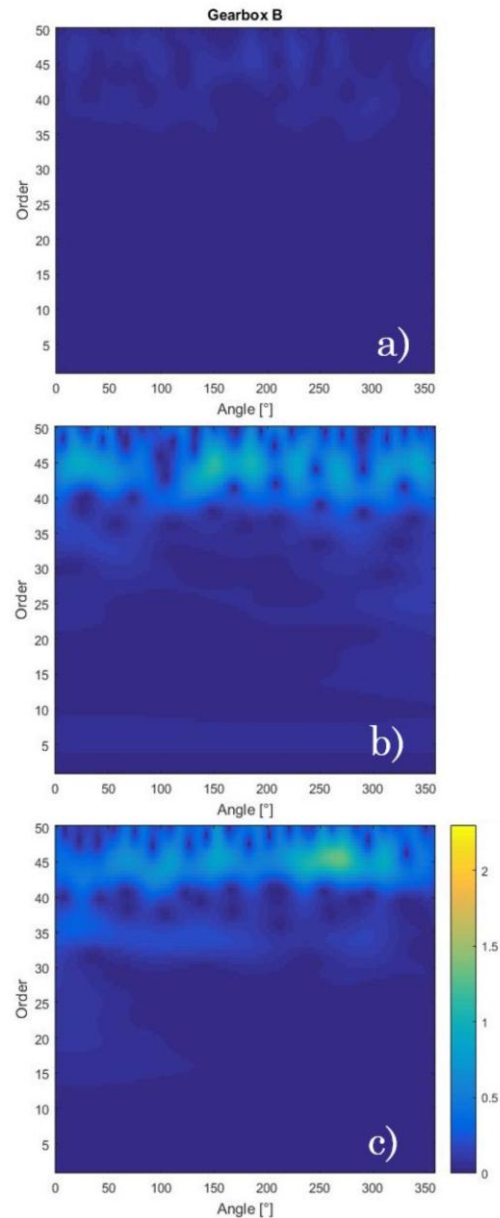
Fig. 7. Wavelet Transform calculated on the TSA of the sun gear of the second stage for GB B in three different conditions: (a) start of the test, (b) at 150 hours, (c) end of the test

## 5. CONCLUDING REMARKS

The present study has described a new metric of the TSA for pitting detection in planetary gearboxes and its effectiveness is evaluated through an accelerated fatigue test, specifically designed to promote the pitting phenomenon on the sun gear. The test follows the entire pitting evolution until the gearbox functionality is effectively compromised. The proposed metric, *NA4mod* - defined as the ratio between the statistical moment of the fourth order of the residual signal and the current mean of the square of the variance of the regular signal - has been developed as a modification of *NA4*, with the aim to obtain an indication related to the severity of

the fault, even when it progressively switches from localized to distributed.

Metric *NA4mod* is shown to provide satisfactory detection capabilities, with greater reliability than other metrics proposed in the literature. As shown by the computed trends, the metric exhibits a sudden increment at the triggering of the pitting and it later follow the pitting severity, even though its sensitivity is slightly downgraded. In order to obtain a comprehensive evaluation of the metric sensitiveness, the results are compared with the RMS and the kurtosis values of the raw signal in time domain and with metric *NA4* of the TSA. In this context, the analysis demonstrates that the RMS does not exhibit fault detection capability in

DIAGNOSTYKA, Vol. 21, No. 1 (2020)
Berlato F, D'elia G, Battarra M, Dalpiaz G.: *Condition monitoring indicators for pitting detection in ...*

9

this application, while Kurtosis detects the initial development of a localized fault but not its propagation and severity. Metric *NA4* is sensitive to the pitting initial development, but, in contrast with respect to *NA4mod*, it is not sensitive to its severity in the final stage. The correctness of the analysis is finally verified by calculating the Wavelet Transform of TSA signals.

Based on this analysis, the proposed metric may represent a useful indicator for pitting monitoring in industrial environment, in which advanced techniques, such as analyses in the Time-Frequency domain and EMD-based algorithms, may not be suitable due to the high computational costs related.

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