Evolution of gear condition indicators for diagnostics of planetary gearboxes

Gianluca D'Elia[1], Marco Cocconcelli[2], Riccardo Rubini[2], Giorgio Dalpiaz[1]

[1]University of Ferrara
Via Saragat 1, 44122 Ferrara, Italy
{gianluca.delia, giorgio.dalpiaz}@unife.it
[2]University of Modena and Reggio Emilia
Via Amendola 2 - Pad. Morselli, 42122 Reggio Emilia, Italy
{marco.cocconcelli, riccardo.rubini}@unimore.it

Abstract

In the last decades diagnostics of planetary gearboxes became a necessity in different fields, such as Industry and Army, and a plethora of gear condition indicators (CI) were proposed. Among the others: FM4, NA4, ER and SI. All of these CIs have proved to be effective in specific conditions, but it is a matter of fact that several indicators may lead to different decisions, while the literature only reports case studies with positive responses for each CI. In this paper a critical comparison among different CIs is carried out during a complete life of a gearbox. In particular a test bench runs a three-stage gearbox for a non-stop target period of 700 hours. At the end of the test the presence of faults are evident from the analysis of the vibrations. Moreover two original CI, namely RV and CRV, have been introduced and tested. The evolution of CIs response is monitored during the test, showing different behavior in both parameter sensitivity and response dynamics. The data analysis allows a choice of the most promising indicators.

1 Introduction

It is a matter of fact that gearboxes are widely used in Industry, aiming power distribution among drivelines and speed reduction of rotating shafts. Since they drive the power inside machines, they are critical components in terms of loss of productivity in case of unexpected failures. Moreover they are subject to possible breakage in the two main constituent elements: gears and bearings. As rotating machines they suffer fatigue cycles in working conditions, often aggravated by non-stationary loads. Among the others, planetary gearboxes are probably the most challenging, due to the motion of some gear axes (planet gears) around a fixed one (sun gear). As a consequence of the importance of gearboxes in mechanical design, more efforts have been spent in developing diagnostics tools to prevent and monitor the health status of the gearbox in working conditions. Actually several papers are available in literature, suggesting very powerful techniques but often requiring complex calculation and advanced skills in signal processing. On the contrary most of Industries ask for quick indicators of the health status that simply measure how much the signal deviates from the ideal model. As reported by Mosher et alt. [1] regarding an interesting benchmark of gear metrics, "Stewart [2] introduced several metrics, including FM0 and FM4. FM0 increases if a periodic signal contains a local increase in amplitude. FM4 increases if a signal contains a local increase in amplitude or local phase change in a periodic signal. Zakrajsek [3] introduced NA4 to detect onset of damage like FM4 and continue to react as the damage increases. Martin [4] introduced M6A and M8A for detection of faults in surfaces. These have also been applied to damage detection in gears by Zakrajsek [3]. Zakrajsek [5] introduced NB4, which identifies localized phase changes in a periodic signal. Decker [6] introduced NA4* to improve trending. Dempsey [7] introduced NA4 reset to decrease the sensitivity of NA4 to torque changes".

These metrics soon became a well-used parameters and others have been added so far, overwhelming the threshold of 30 different metrics. Some of them could be computed directly on raw vibration data, while others require the Time Synchronous Average (TSA) as a pre-processing [8]. TSA [9] extracts stationary contents from the signal that could be subtracted to the raw data in order to divide the contribution of gears from other components (such as bearings) and highlight impacts [10]. The pletora of these metrics suggested critical comparisons and benchmarks among them. Mosher et al. [1] compare six metrics (FM0, FM4, N6A, N8A, NA4, NB4) computed on an helicopter's gearbox, highlighting the relationship among metrics' values with torque and rotor speed. Decker and Lewicki [11] compare thirteen metrics (RMS, CF, Energy ratio, M6A, M6A*, Energy operator, Kurtosis, FM4, FM4*, NA4, NA4*, NB4, NB4*) for a gearbox mounted on a test rig, at different working conditions. Lebold et al. [12] do not compare data outputs but give an exhaustive review of different metrics, classifying them into five main classes.

This paper aims to continue the benchmarking among standard gear metrics, contributing to a conscious choice of the optimal set of metrics based on experimental results. In particular four metrics are used (FM4, NA4, SI, ER) to cover 700 hours of continuous run for a three-stage epicyclic gearbox. The evolution in time-domain of these parameters could help skilled users to choose the optimal parameter depending on the ”age” of the gearbox under test. Moreover two new metrics are proposed (RV, CRV) that proved to have a clear and useful trends during the life cycle of the component. The paper is structured as follow: the mathematical definition of each parameter is given in Section 2, while Section 3 describes the experimental setup and shows the main results. Conclusions close the paper.

2 Metrics

Six different metrics has been used in the processing of the data, namely FM4, NA4, SI, ER, RV and CRV. The last two metrics are introduced for the first time in this paper. In particular all the metrics require the computation of the Time Synchronous Average (TSA) of the vibration data, in order to increase the signal-to-ratio and removing noise.

2.1 FM4

FM4 metric was introduced by Stewart [2]. FM4 detects changes in the vibration signal resulting from damage on a limited number of gear teeth. FM4 is defined as the ratio between the 4th moment about the mean and the square of variance of the difference signal. The difference signal usually refers to the TSA signal after that some regular components are filtered out. The regular components include the first and the second shaft frequencies, gear mesh frequency and its harmonics along with the first order sidebands.

$$FM4 = \frac{\frac{1}{N}\sum_{n=1}^{N}(d_n - \overline{d})^4}{[\frac{1}{N}\sum_{n=1}^{N}(d_n - \overline{d})^2]^2} \tag{1}$$

where d is the difference signal, $\overline{d}$ is the mean value of difference signal, and N is the total number of data points in the time record. De facto the FM4 (like NA4) is a normalized Kurtosis, as a consequence it should be sensible to impacts components inside the signal allowing an early detection of tooth's damage.

2.2 NA4

NA4 metric was introduced by Zakrajsek et al. [3]. NA4 is determined by dividing the fourth statistical moment of the residual signal by the current run time averaged variance of the residual signal, raised to the second power.

$$NA4 = \frac{\frac{1}{N}\sum_{n=1}^{N}(r_n - \overline{r})^4}{[\frac{1}{M}\sum_{m=1}^{M}\frac{1}{N}\sum_{n=1}^{N}(r_{n,m} - \overline{r_m})^2]^2} \tag{2}$$

where r is the residual signal, $\overline{r}$ the mean value of the residual signal, N is the total number of data points in time record, and M is the current time record number in the run ensemble. The NA4 is similar to FM4, since it focuses on the computation of Kurtosis value, but there are two main differences. NA4 works on the the residual signal, which is the TSA signal after the fundamental shaft and mesh frequencies and harmonics have been removed. Compared to the residual signal the difference signal used for FM4 requires to remove also the 1st order sidebands. Finally the NA4 requires the computation of the variance, at the denominator, for all residual signal up to the current time.

2.3 SI

The Sideband Index (SI) is a measure of local gear faults and is defined as the average of the order sidebands of the fundamental gear meshing frequency f_{gm}[14].

$$SI = \frac{f_{gm}^{LSB} + f_{gm}^{USB}}{2} \tag{3}$$

where LSB and USB are the lower and upper sidebands of the gear mesh frequency f_{gm} respectively.

2.4 ER

Energy Ratio (ER) is usually adopted to detect uniform wear [13]. The difference signal d is the resultant signal after the regular meshing components r (mesh and harmonic frequencies) are removed. It compares the energy contained in the difference signal to the energy contained in the regular components signal. The theory is that as wear progresses, the energy is moved from the regular signal to the difference signal.

$$ER = \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N}(d_n)^2}}{\sqrt{\frac{1}{N}\sum_{n=1}^{N}(r_n)^2}} \tag{4}$$

where the numerator is the Root Mean Square (RMS) of the difference signal d_n computed over the total number of data points N. The denominator is the RMS value of the residual signal r_n.

2.5 RV

The Residual Variance (RV) is the first of the two new metric proposed. In particular the RV is computed on the TSA signal, after the gear mesh frequency and harmonics, the first and second harmonics of the shaft frequency have been removed, i.e. on the residual signal as in the computation of NA4.

$$RV = \frac{1}{N}\sum_{n=1}^{N}(r_n - \overline{r})^2 \tag{5}$$

where r is the residual signal, $\overline{r}$ the mean value of the residual signal, N is the total number of data points in time record.

2.6 CRV

The Cumulative Residual Variance (CRV) is defined as the cumulant of the RV to the current time. CRV is the second original metric proposed in this paper.

$$CRV = \sum_{m=1}^{M}\frac{1}{N}\sum_{n=1}^{N}(r_{n,m} - \overline{r_m})^2 \tag{6}$$

Compared to the RV metric, the cumulant is less sensitive to rapid fluctuations of the values. This characteristic is sensible for further application of machine learning to automatize the diagnostics of machines.

3 Experimental setup and results

A lifetime test is carried out on two TR 304 L3 gearboxes in a back to back configuration named respectively Gearbox A and B, Figure 1 (a). The schema and the gearbox data are reported in Figure 1 (b) and Table 1. Low and high quality lubricant oils were used in the two gearboxes, i.e. Gearbox A contains a low quality lubricant oil, whilst Gearbox B is lubricated with an high quality oil. Due to the different lubricants, distributed pitting should develop in the second stage sun gear of Gearbox A. At the end of the test (about 700 hours) the gearboxes were inspected in order to check the gear status, and distributed pitting was found on the second stage sun gear of Gearbox A, while no evidence of gear faults was found on Gearbox B.

Two piezoelectric accelerometers were mounted on the ring gears of the two gearboxes. Vibration signals were continuously acquired with a sample frequency of 25600Hz. Gearbox A was driven at a constant speed of 1500rpm with an applied torque of 4400Nm, which is 30% greater than the nominal gearbox torque. This high torque level was necessary in order to recreate an accelerated lifetime test. The time synchronous averages of all the gears were computed and the statistical parameters were evaluated. In the following only the first and second stage sun gear results are presented. Moreover, a subset of 107 acquisitions is taken into account by displaying the results for every six hours of test.

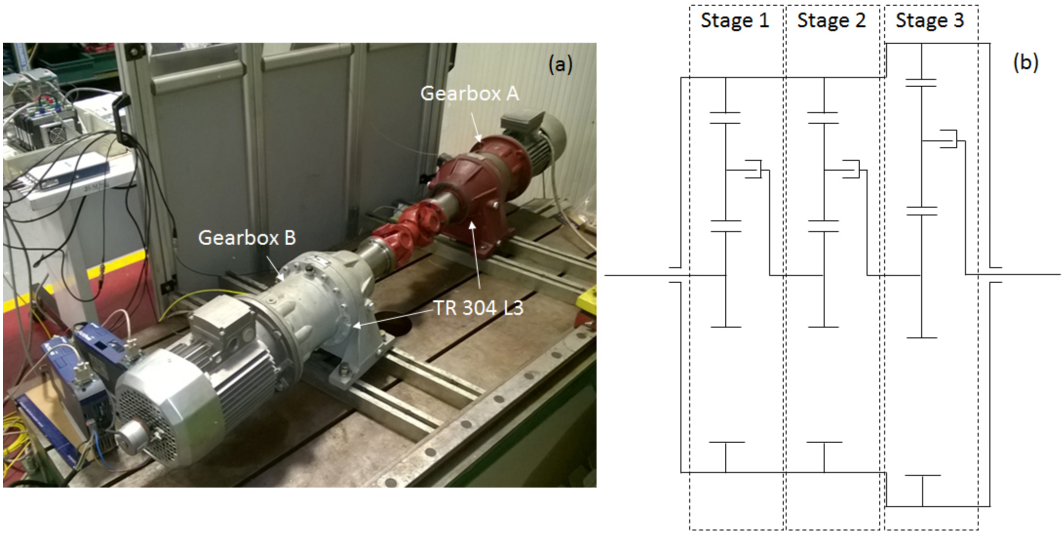

Figure 1: (a) Test rig, (b) Gearbox schema

Data	Stage 1	Stage 2	Stage 3
Sun gear teeth	10	10	24
Planet gear teeth	25	25	26
Ring gear teeth	62	62	78
# of Planets	3	3	4

Table 1: TR 304 L3 gearbox data

Figure 2 depicts the first and the last acquisition for both gearboxes, no abrupt amplitude variation can be detected in both cases. In particular, the last acquisitions (Figure 2 (a) and (b)) do not shows any particular increases in the main vibration energy, therefore no particular evidence of the faulted gear can be visible in the time signals.

In order to obtain possible information about the faulted gear, the main statistical parameters RMS and Kurtosis are evaluated on the time signals. It is well known that RMS is related to the mean signal energy, whilst Kurtosis is sensible to impulsive content. Figure 3 shows the result of this analysis. The RMS values of Gearbox A time signals are greater than those of Gearbox B (Figure 3 (a)), this effect could be related to the different gearbox oils. Because the main time signal energies are different and the evolution of the gear fault is related to an increase of the signal energy, the first sample of the RMS values of Gearbox A and B are normalized to 1. The result of this normalization is depicted in Figure 3 (b). It is possible to see that there is an increase of the main signal energy trend of Gearbox A with respect to B in the time range 100-400[h], whilst the trends are comparable at the end of the test. From this result no evidence of a gear fault can be detected in Gearbox A. The last static evaluated on the time signals is plotted in Figure 3 (c). The results show an increase of the Kurtosis values of Gearbox A with respect to B in the time range 150-350[h], whilst they are comparable at the end of the test. The increase of the Kurtosis values could be related to the beginning of the fault. Actually, the pitting formation is related to an increase of the impulsive content in the time signal. This behavior is detected by the Kurtosis, however as the fault grows the impulsive signal content decreases and the Kurtosis value falls down. Therefore, this statistic can well detect the fault initiation but not its propagation.

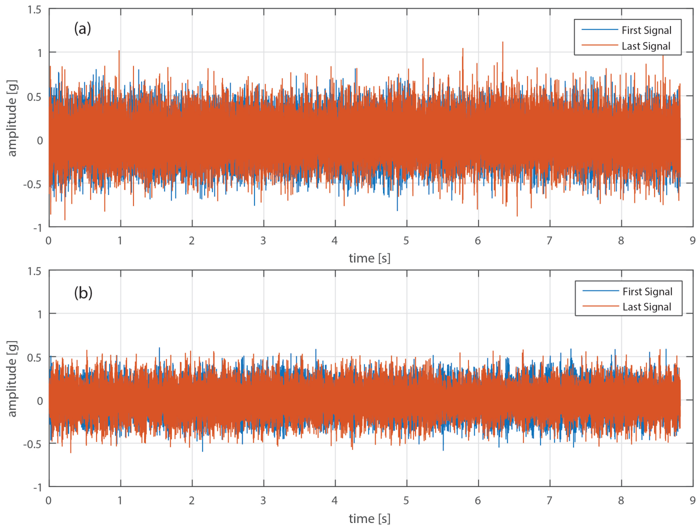

Figure 2: Time signals of first and last acquisitions: (a) Gearbox A, (b) Gearbox B

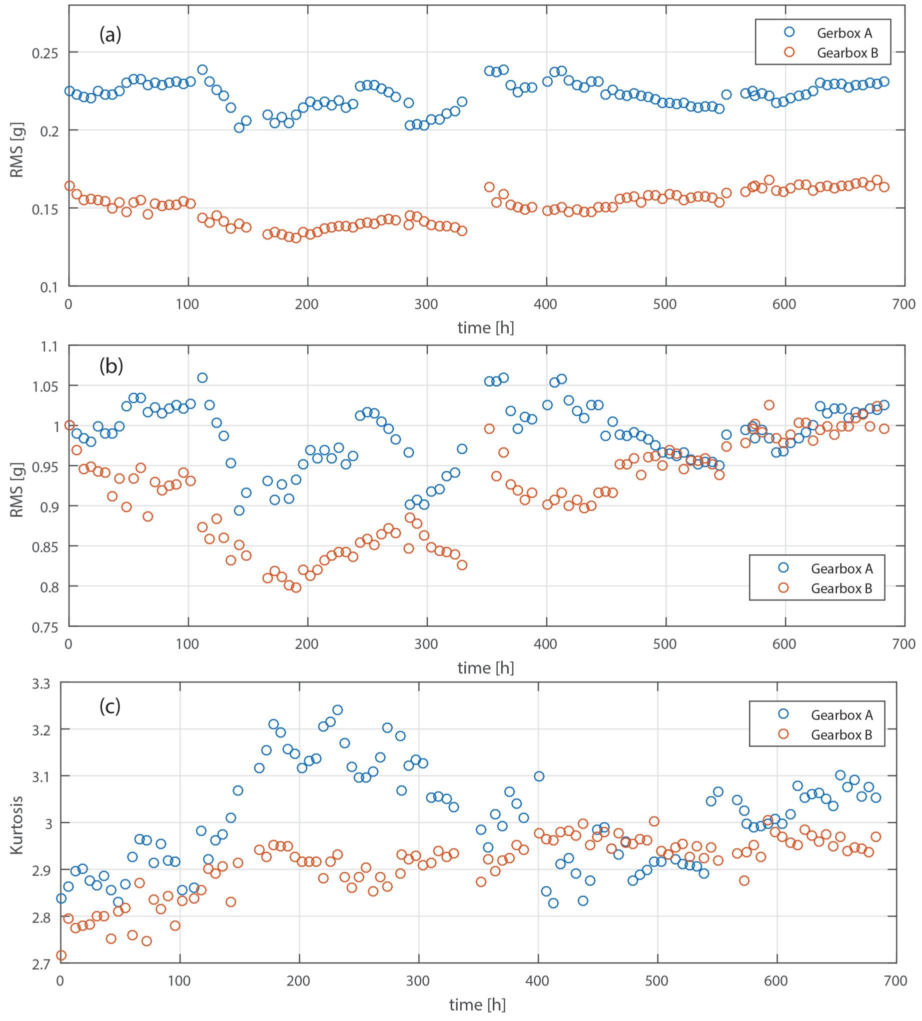

Figure 3: Time signal statistics: (a) RMS, (b) RMS - first sample normalized to 1, (c) Kurtosis

In order to better highlight the fault evolution the previously described statistics are evaluated on all the gears of both gearboxes. In particular, the TSA signals of planet and sun gears are evaluated and the statistical parameters are computed on the extracted signals. The results of this analysis are depicted in Figures 4 and 5 which are related to the first and second stage sun gears respectively. Figure 4 depicts the evolution of the statistical parameters evaluated on the first stage sun gear. In particular, no specific trend can be detected in the statistical parameters, only SI and ER show different values between the two gearboxes, Figures 4 (c) and (d). This behavior could not be related to the presence of a fault in the first stage sun gear of Gearbox A, because the values of these statistical parameters at the beginning and at the end of the test are comparable. Therefore, no evidence of a possible fault can be detect in the first stage sun gear of Gearbox A by the analysis of the statistical parameters.

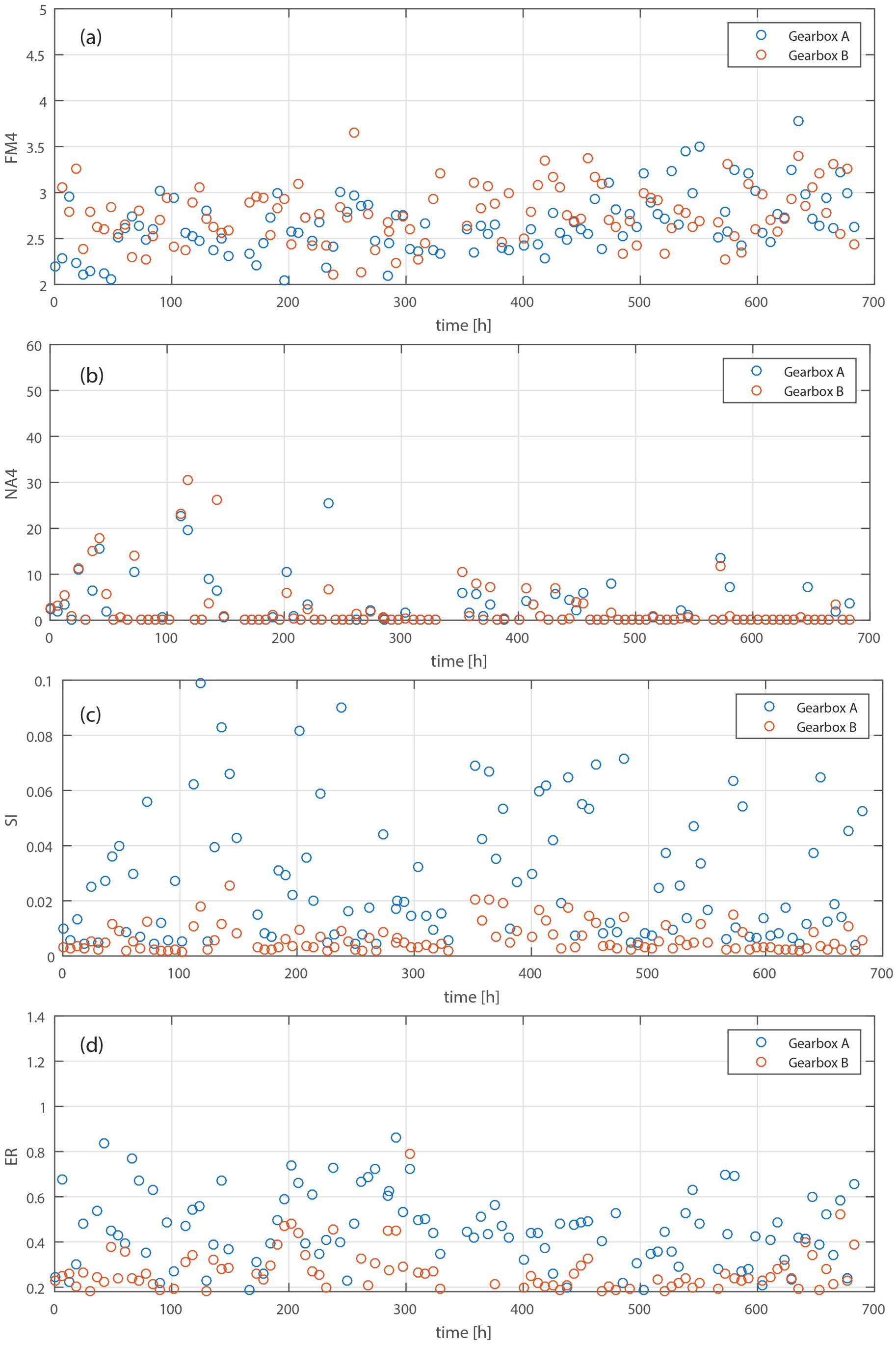

Figure 4: Stage 1 sun gear statistics: (a) FM4, (b) NA4, (c) SI, (d) ER

Figure 5 shows the results of the evaluation of the proposed statistics on the second stage sun gear signals of both Gearbox A and B. The FM4 statistic (Figure 5 (a)) shows an increase of its value at the end of the test for Gearbox A with respect B, however this increase does not completely justify the presence of a distributed fault inside the gear. Interesting diagnostic informations can be obtained by the analysis of NA4 and SI statistics. It is possible to see, especially from Figure 5 (c), an increase of the amplitude value of the statistical parameters of Gearbox A with respect to B around 200[h], which could be related to the beginning of the fault. This behavior is well correlated with the Kurtosis trend, which shows an increase of the Gearbox A values around 200[h]. It seems that these statistics could well detect the beginning of the fault but not its growth.

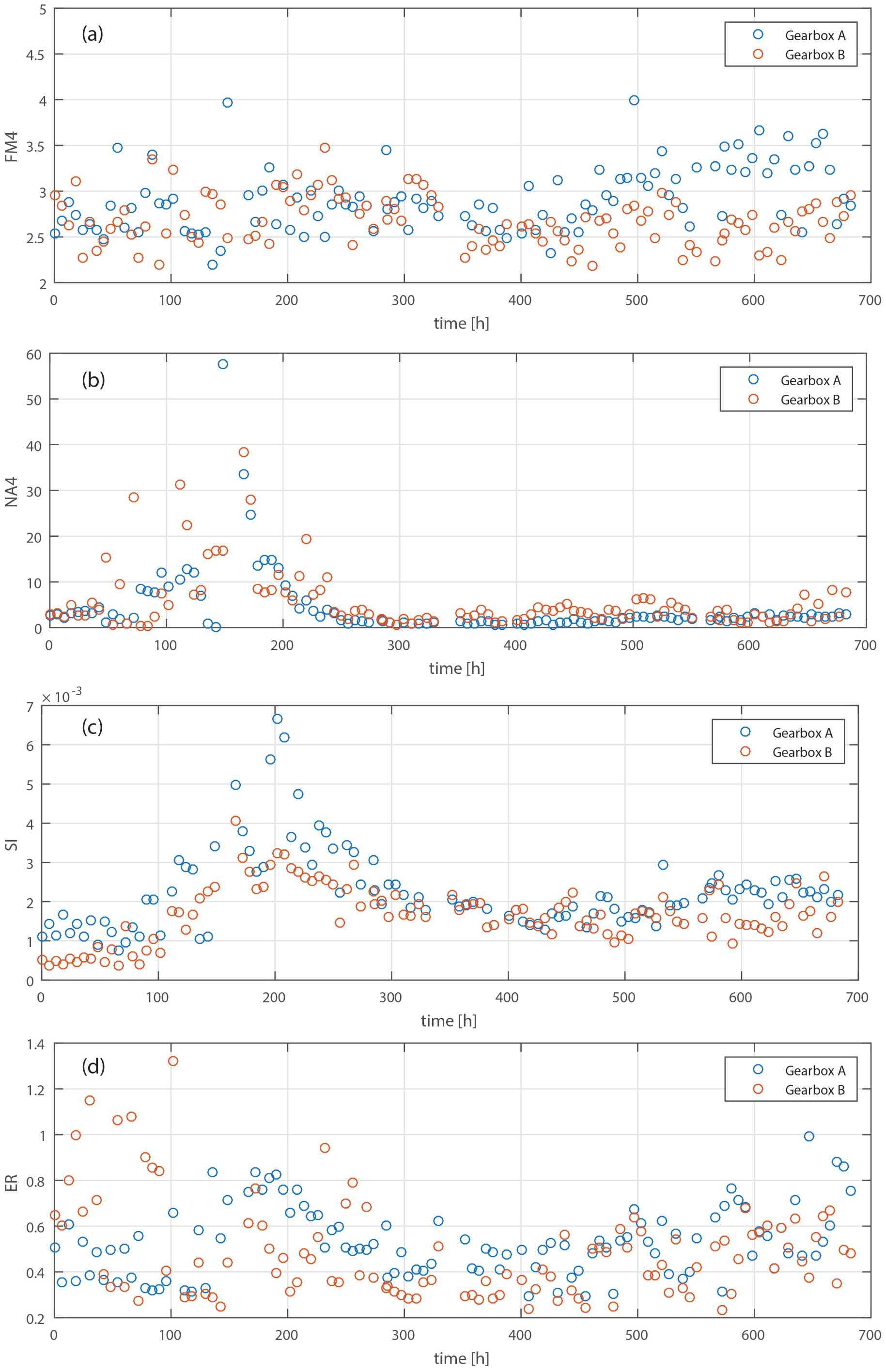

Figure 5: Stage 2 sun gear statistics: (a) FM4, (b) NA4, (c) SI, (d) ER

In order to better highlight both the beginning and the growth of the fault the variance of the second stage sun gear residual signal is studied. Figure 6 show the results of this analysis. In particular, Figure 6 shows an increase of the variance of the second stage sun gear residual signal for Gearbox A around 200[h]. It is possible

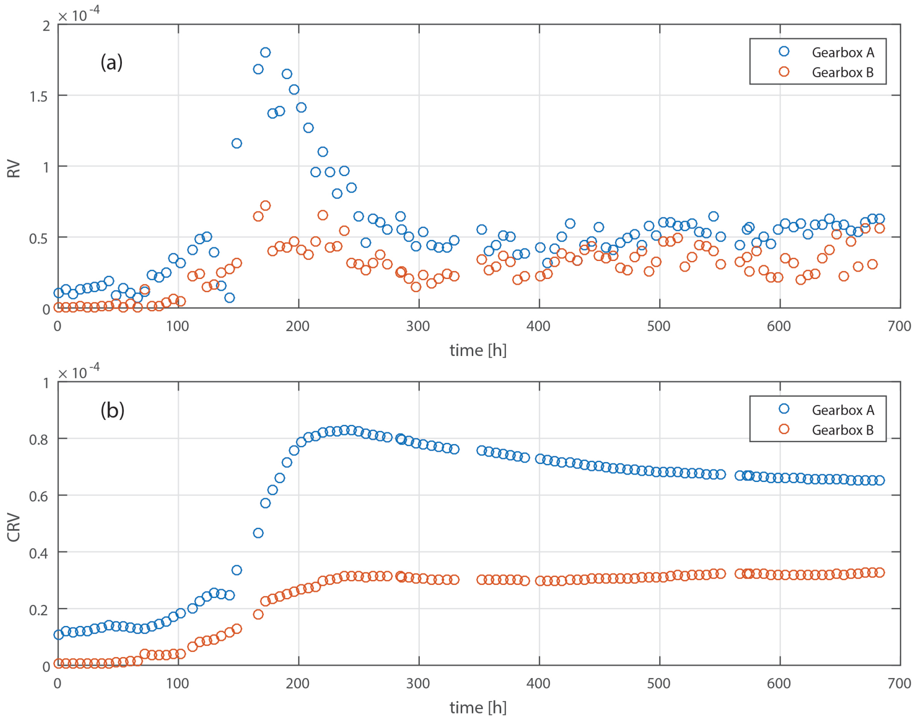

Figure 6: Stage 2 sun gear statistics: (a) RV, (b) CRV

to see, by comparing RV parameter with SI or NA4, that the residual variance can better highlight the beginning of the fault, and in particular the RV values of Gearbox A at the end of the test are still greater than the values of Gearbox B. The RV parameters show better performance with respect the usual statistical parameters, however the drop of the parameter values at the end of the test could cause problems in using this statistic for SVM or others diagnostic systems. In order to avoid the parameter drop, the cumulative residual signal variance (CRV) is evaluated. Figure 6 (b) plots the CRV parameters for the second stage sun gear signals, on which both the beginning and the growth of the fault can be highlighted. Actually, the cumulative value guarantee the increasing trend of the statistical parameters, which it could avoid problems in using this statistic for SVM based diagnostics algorithm.

4 Conclusions

This paper focuses on a benchmarking of different metrics used for the condition monitoring of gearboxes. In particular a complete lifecycle of two three-stage gearboxes in a back to back configuration is monitored. One gearbox is filled with low quality lubricant to accelerate an early damage of the gears' teeth. The test last about 700 hours and a distributed pitting fault was found on the second stage sun gear of the gearbox with the poor quality oil. The data acquisition was performed continuously with a sample rate of 25600 Hz. This huge amount of data has been analyzed with four classic metrics (FM4, NA4, SI, ER) that shows specific pros and cons. In order to overwhelm the cons two original metrics (RV and CRV) has been proposed and compared.

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