 SDHM, vol.8, no.4, pp.329-340, 2012

Rolling Contact Fatigue Damage Detected by Correlation between Experimental and Numerical Analyses

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Abstract: A study on vibrations related to rolling contact fatigue test bench and a possible way to correlate this mechanical behavior and damage of the specimens is presented. In particular it has been evaluated the possibility to detect and quantify, thanks to vibration analysis, the damage on two discs subjected to rolling contact fatigue in different working conditions. Paper is divided in two parts. In the first part there is a description of test bench and results of its static and modal analyses. Then, some tests were carried out changing working conditions and specimens' parameters and a procedure that allowed both to monitor the specimen's damage state and to record accelerometric data was implemented. A set of piezoaccelerometers was placed on the machine and a virtual instrument for automatic data handling and analysis was performed. Taking into account the FEM results derived from the first part of work, data were analyzed both using a standard approach and by implementing custom digital weighting filters for a windowed RMS in order to define, real-time during the measurement, a good estimator for the specimen damage state development.

Keywords: rolling contact fatigue, experimental and vibration analysis, damage evaluation

1 Introduction

Rolling contact fatigue is a typical phenomenon that affects mechanical components such as bearings, cams and gears during working conditions and plays a fundamental role in railway field with regard to damage in wheel rail contact[Nélias, Dumont, Champiot, Vincent, Girodin, Fougères and Flamand(1999); Tyfour, Beynon and Kapoor(1996); Bormetti, Donzella and Mazzù(2002)]. As is known in some cases the failure of these components has serious consequences. For this reason,

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since the past it has been tried to reproduce this phenomenon in laboratory through the design of test benches[Cambiaghi, Donzella and Isceri(2003)] able of simulating the real operating load conditions of components subjected to rolling contact fatigue in order to study the damage and make prediction models. Therefore it becomes necessary to have tools to monitor the tests that allow to find variables useful to the prediction of failure [Bendat and Piersol(1993)]. With high precision image acquisition instruments it is possible to capture the rolling surface during the test. At the same time since natural frequencies of vibration of a component depend on stiffness and geometry of the component itself, it is becoming common practice to monitor vibrations in order to detect either a material degradation or a mechanical alteration of geometry, both of which would result in a stiffness change in time. Availability of reliable and fast frequency analysis tools [Norton(1989); Randall and Upton(1985)], combined with widespread usage of accelerometers, with the help of contact surface images, suggested the idea of developing a system able to not only detect, but also monitor and assess the damage level evolution of a couple of discs in rolling contact fatigue tests.

2 Test bench description

Figure 1 shows a mechanical draw of the object of this study. It is a high performance rolling contact fatigue test bench. It is designed and built at the Department of Mechanical and Industrial Engineering of University of Brescia and is dedicated to test and study the interactions between two components subjected to cyclic contact in different working load conditions. It is equipped with two independent mandrels driven by a.c. engines of 33 kW coupled with a two stages planetary gearbox and fixed transmission timing belt pulley. One of the mandrels can translate on linear slides thanks to a servo-hydraulic actuator that allows also a contact load application up to 70kN, corresponding about 3000 MPa (depending on the size (diameter, thickness and radius of curvature) of the specimen).

Specimens, whose position is highlighted in figure 1, are usually disc shaped (but they can also have different geometry by mounting dedicate interface flanges on the bench) and their diameter, thickness and radius of curvature can vary within a range in order to study the eventual scale effect. It is a very flexible and precise system that also permits to set and independently control the rotating speed of the samples (up to 1000 r.p.m.) or engine torque and the contact force. There is also the possibility of performing tests in dry or lubricate (water or oil) conditions. The machine is controlled by software that allows to remotely set and continuously monitor all operating parameters, thereby enabling an even diagnostic of the damage of the specimens. Finally, figure 2 contains the image acquisition system located on the bench, which, by means of high-resolution (1μm) line scan camera, can capture

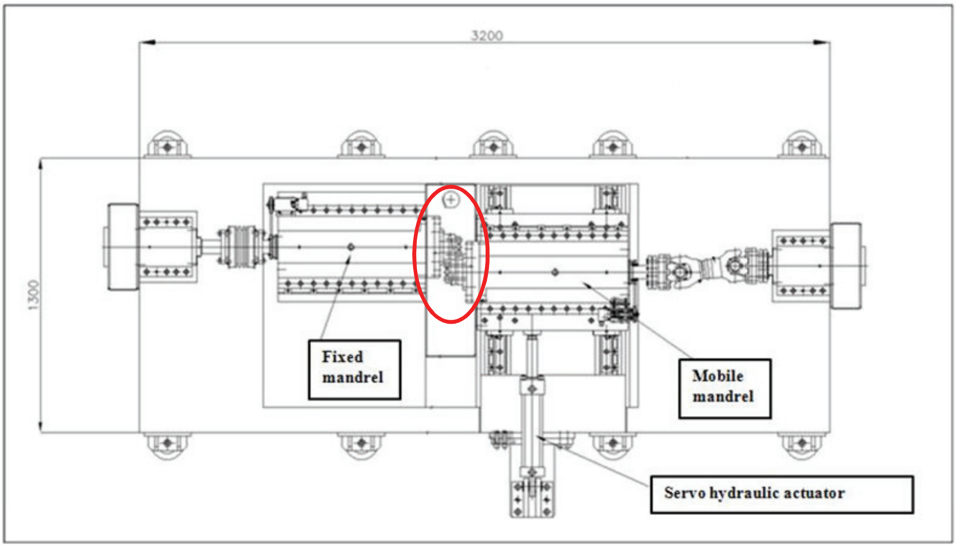

Figure 1: Test bench: Mechanical draw, highlighted specimens.

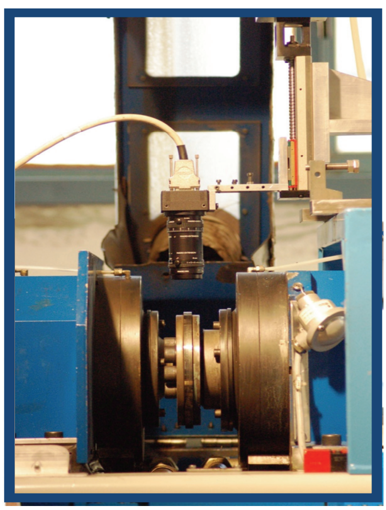

Figure 2: Image acquisition system.

images of the rolling surfaces and track the evolution of the damage of the samples.

The test bench is made of different sections in commercial S355JR UNI 7729 welded. Its dimensions are approximately 3200x1300x1000 mm and its total weight is about 5500 kg. The simplified solid model of the structure is shown in the figure 3.

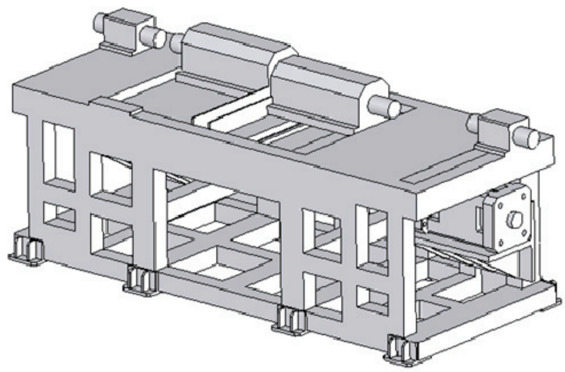

Figure 3: Solid model of test bench.

3 Numerical Analysis

The purpose of this paragraph is to evaluate both static and dynamic behavior of the bench through numerical analysis and, in particular, to determine the stresses and displacements at the maximum applied force and the first natural frequencies of the bench. To identify in which frequency range useful information could be gathered, a preliminary analysis using FEM software has been performed. From such analysis not only natural frequencies of the test bench were found, which were then confirmed by a series of accelerometric measurements, but also mode shapes involved which were used to identify the most suitable number and position of accelerometers to be used for a continuous monitoring. Figures below show the results of the analyses performed at the maximum applied force (see fig. 4) between the specimens and at the first three vibration modes assuming a linear elastic structural behavior for the bench.

The displacement between the specimens, induced by the load, is very low and so the correct distribution of the stress in the components is guaranteed and corresponds to the Hertz theory.

In particular, as shown in figure 5, the first mode shape, which corresponds to a

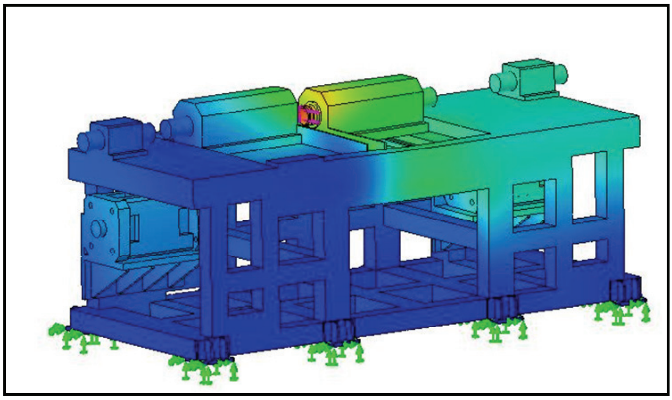

Figure 4: FEM analyses results: deformed shape at maximum applied load F=70kN; max displacement = 0,01 mm

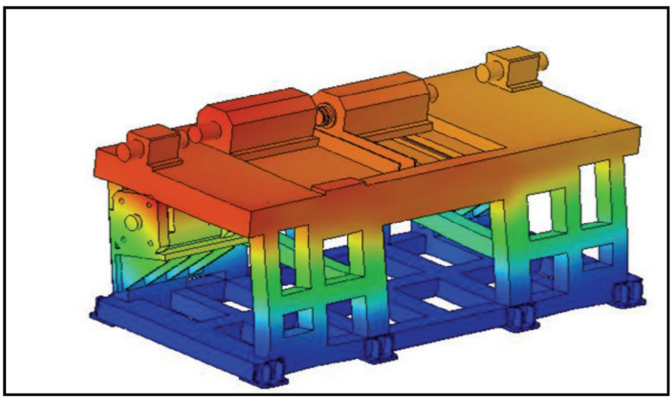

Figure 5: FEM analyses results: deformed shape at first vibration mode (f=53.3 Hz)

frequency of 53.3 Hz is the most important because the others are very peripherals and therefore not useful for the accelerometer investigation.

This is justified because this frequency shows a high coefficient of mass modal participation, respect to the other.

As can be clearly noticed the first mode shape display deformation highly localized near the specimen itself, while the others only involve marginal participation of the specimen in vibration, therefore accelerometer information is sought only closer to the specimen itself, and at frequencies closer to 50Hz.

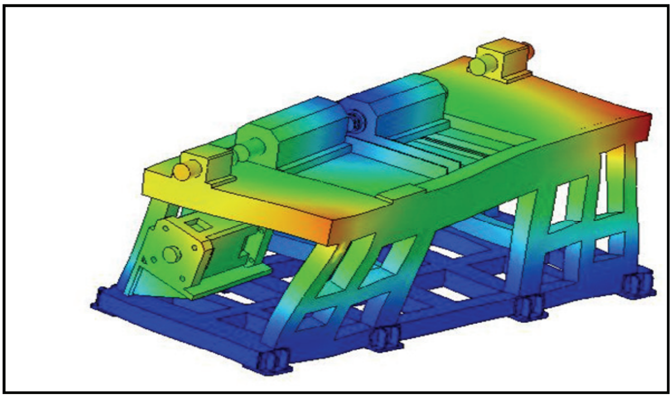

Figure 6: FEM analyses results: deformed shape at second vibration mode (f=79.9 Hz)

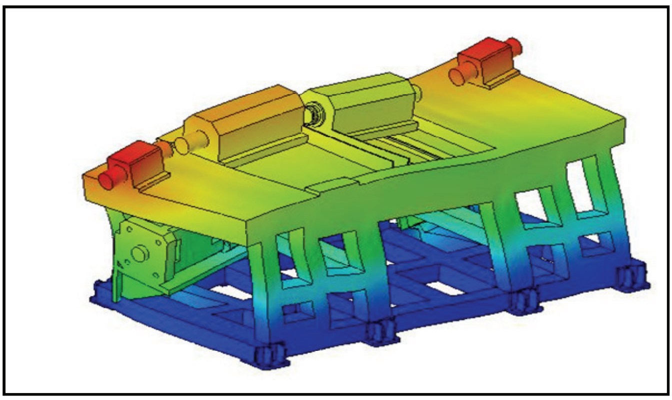

Figure 7: FEM analyses results: Deformed shape at third vibration mode (f=121.1 Hz).

4 Experimental Analysis

In order to highlight and then monitor the damage that occurs in components subjected to rolling contact fatigue some tests in pure rolling and sliding conditions varying specimens dimensions, rolling speed and applied load have been carried out. At first, starting from the data hence gathered, a preliminary set of accelerometric measurement was performed with the aim to validate FEM results and to choose the best sampling frequency, transducer type and full scale: varying both transducers type (uniaxial and triaxial), number and disposition considering the direction of spindle axis and the distance from specimens, a set of RMS evaluation and a set of reciprocal frequency response function[Heylen, Lammens and Sas(1998); Baker(1996)] were computed in order to identify the best configuration and to have the maximum sensitivity of the signal in relation to damage of the specimen. It was found that transducers measuring along the radial direction with respect to the spindle axis showed sensible variation in their reciprocal FRF during the test and only the closest two to specimens were used. For these reasons the measurement chain finally chosen was composed of only two piezoaccelerometers, with a 450 m/s^2 full scale connected to a 16bit NI cDAQ acquisition board with onboard IEPE conditioning and a sampling frequency of 25kHz per channel, one for each mandrel located as shown in figure 8.

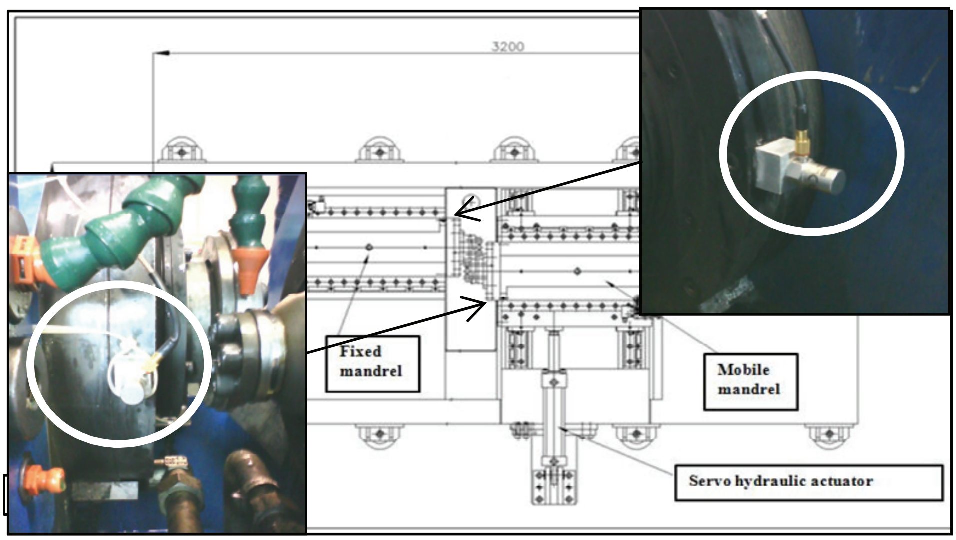

Figure 8: Accelerometers position.

The first approach involved using a sensible change in the frequency response function between reading of the two accelerometers, either using a shape comparison or a synthetic indicator [Mottershead and Friswell(1993); Zang, Friswell and Imregun(2003)]. However, first experimental tests pointed out high variability in the higher frequency range, making a reliable evaluation of damage progression difficult; therefore, a set of time-frequency analysis (using a waterfall representation, as can be seen in figure 9) has been performed, and showed that intensity of vibrations in the range below the first resonant frequency is less influenced by actuators presence and environmental noise and bench resonant mode shapes interference whose frequencies range is indicated as zone 1.

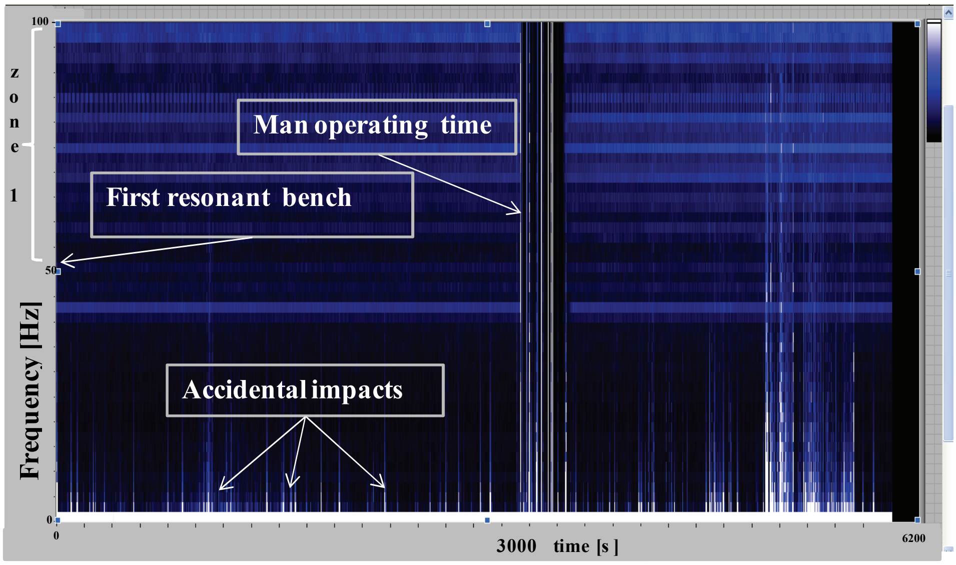

Figure 9: Waterfall diagram.

For these reasons a lowpass filter isolating frequency lower than 43Hz has been inserted before RMS evaluation.

RMS was preferred over indicators commonly found in modal analysis and modal updating [Randall(2003)], because, due to the dependence of the latter on the "undamaged" state measurements, which, in the case presented, was subject to a high variability due to the counteractor state.

A further issue that waterfall analysis pointed out is the high sensitivity to events typical of the low controlled environment such as accidental impacts, temperature and noise sudden variation and variable human presence. In figure 9 it is also visible the man operating time during which, the rolling speed of engine and load application are firstly reduced and then restored soon. Hence the generation of singular impacts concentrated in a short period of time that is not index of damage and should be neglected. To avoid false reading and misinterpretation of the RMS as damage indicator, a running exponential averaging filter, described with the equations 1, has been implemented, to increase sensitivity with respect to permanent variation in the RMS level, while offering a reduced weight to occasional accidental events. Such a choice was made after comparing the results of different filtering and weighting methods for the RMS: at first a direct estimation of the root mean square as a sample reduction (see eq. 1a), then a running averaging with a rectangular window (see eq. 1b), and at last a running averaging with an exponential window (see eq. 1c).

$$a^2\left(j \cdot dt\right) = \frac{\sum\limits_{i=j-dt/2}^{j+dt/2} a_i^2}{dt} \tag{1a}$$

$$a_j^2 = \frac{\sum\limits_{i=j-\delta}^{j+\delta} a_i^2}{2\delta} \tag{1b}$$

$$\hat{a}_j^2 = \frac{\sum\limits_{i=0}^{j} e^{(t_i - t_j)\alpha} a_i^2}{\sum\limits_{i=0}^{j} e^{(t_i - t_j)\alpha}} \tag{1c}$$

The direct evaluation of the RMS is unable to discern between a permanent variation and on occasional event, while the rectangular window depends too heavily on the window size to avoid either false positives or false negatives and maintain the required readiness. The exponential averaging was inspired by commonly used acoustics post processing techniques, and its settling time was set small enough to grant both readiness and capability of avoiding false positives; using α = 0,5 (the constant, shown in equation 3, is reciprocal to settling time coefficient [Bendat and Piersol(1993)]).

The final damage indicator is therefore computed by acquiring acceleration data at a 5kHz sampling frequency from each accelerometer using 0.5s consecutive windows; for each window a weighted RMS is computed thanks to a lowpass filter set to the aforementioned cut-off frequency of 43Hz, and evaluated using a mobile exponential averaging filter.

This indicator has been successfully used to monitor damage progress in a set of specimens under test.

In particular the results are referred to pure rolling water lubricated tests: the specimens, made of high strength steel, were ring shaped with an outer diameter of 175 mm, inner diameter of 148 mm and 10 mm of thickness. They were coupled with a 100Cr6 UNI 3097 counteracting disc having diameter of 60 mm and thickness of 10 mm. The rolling speed of the latter was set on about 500 r.p.m. and the contact pressure varied between 1500 MPa to 2500MPa. Tests have been monitored continuously for all their duration and periodically an acquisition of ten minutes was recorded and elaborated until the appearance of spalling phenomenon. Therefore they lasted several days. All tests showed a common behavior, well described in figures 10 that is composed by both accelerometers acquisition with signal processing and contact surfaces images at increasing number of cycles until the end

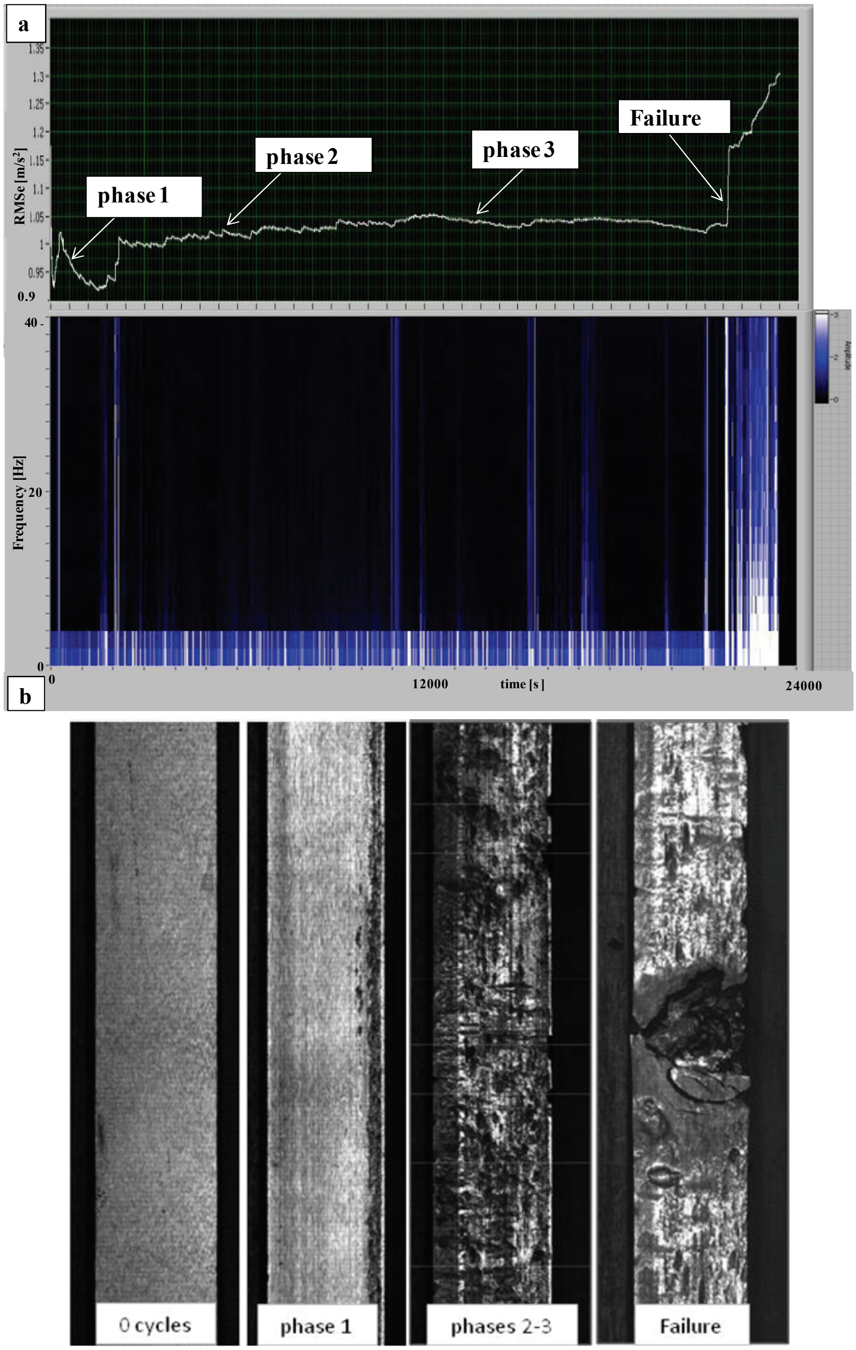

Figure 10: Rolling contact fatigue test acquisition: a) RMSe diagram; b) Waterfall diagram; c) Rolling contact surfaces

of test. Initially (phase 1) there is a decrease in the value of RMSe followed by an offhand way at the beginning and then more gradual increase (phase 2). After that there is a stabilization (phase 3) and this condition persist until a sudden increase of vibrations of about 0.05 $m/s^2$to which correspond the occurrence of the failure of the specimen. By observing figure 10c it can be noticed that during the first life cycles of the new specimen or of the counteracting disc the applied load flats ridges of roughness which can be found on their rolling surface because of mechanical production process with a consequent reduction in vibration. After this phase a nucleation of surface cracks could be found that, under certain conditions, for example the presence of lubrication, can propagate causing micropitting phenomena followed by an increase of surface irregularities and, as consequence, of vibrations. Parallel to this there is also the nucleation of subsurface cracks that grow and suddenly emerge on surface causing spalling phenomenon and a great increase in vibrations and noise [Donzella, Mazzù and Solazzi(2001)].

5 Conclusions

A first study on rolling contact fatigue test bench vibrations and a possible way to detect and quantify damage on the specimens using vibrations analysis was presented. In particular according with the results acquired by both static and modal fem analyses and by experimental test using a specific test bench. A set of piezoaccelerometers were placed on the machine and a virtual instrument for automatic data handling and analysis was developed. Data acquired were analyzed both using a standard approach and by implementing custom digital weighting filters for a windowed RMS and a similar behavior for all specimens tested was found. Finally the supposition explaining its characteristics have been confirmed, at a preliminary level, thanks to surface image analysis performed by a high resolution linear video camera in parallel with vibration recordings. Furthermore, the vibration level computed as explained has been successfully used as a damage level indicator for test bench monitoring purposes. Apart from increasing the statistical base on which the vibration level/damage correlation proposed has been validated, further development of this work which are actually being evaluated are the automatic synchronization of video recording of surfaces with acceleration measurement in order to describe damage progression more in detail, and the introduction of artificially created damages on the specimen to associate known damages pattern with noticeable vibration level behavior.

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