Condition monitoring of gear grinding processes

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Abstract

Grinding is one of the most prominent abrasive processes with geometrically non-defined cutting edges and is widely applied to achieve accuracy and high quality mechanical, electrical and optical parts, generating the final surface quality of machined parts. The grinding process dependents on the tool performance, on the machine stability as well as on the correct clamping/positioning of the workpiece. Monitoring systems of the grinding process could be capable of detecting any unexpected malfunctions in the process with high reliability leading to a minimization of substandard parts and maintaining the desired workpiece quality. Grinding is often used in gear manufacturing process as a last phase being the finishing operation which shapes the micro-geometry of the gear tooth flank and improves its surface quality. This step is decisive as it has a direct impact on the operating quality of gears and in particular on the running noise behavior of the end product. Among other procedures, online vibration monitoring could be used in order to a) evaluate the quality of the workpieces and detect defects that occurred in prior processes and b) detect and identify grinding process malfunctions at an early stage. The process monitoring could be used as a product quality control and could lead to the overall reduction of production losses and to the prevention of sending defective parts to customers. The goal of this paper is to propose a number of features which could be used in order to monitor the grinding process and identify specific type of defects. As significant material removal takes place and due to the kinematics of the gear grinding process (entering/exiting of the worm into the workpiece, and alternating number of contact points), the cutting forces vary leading to non-stationary (load varying) operating conditions. The methodology is evaluated on real signals captured during the emulation of process malfunctions of a gear grinding machine.

1 Introduction

Europe is believed to be at the beginning of a new industrial revolution labelled Industry 4.0, in an effort to reverse the past decline in industrialisation and increase total value added from manufacturing to a targeted 20%. The EU supports industrial change through its industrial policy and through research and infrastructure funding in the frames of H2020. The key to industry 4.0 is information: how to gather, filter, analyse, store and retrieve data and extract useful information from it. The information is then subsequently shared and used to drive, control and monitor processes. This direction is supported by the continuous need for lower production cost, higher quality, more flexibility, better safety and more environmentally friendly, as well as the ever-increasing per currency computing power of microprocessors and the ever-decreasing cost of sensors and measuring platforms. The application of monitoring in manufacturing can contribute to the machine health monitoring, to the tool condition monitoring (e.g. wear, breakage etc), to the workpiece inspection and quality (e.g. geometry) as well as to the process monitoring [1]. As a result, the manufacturing monitoring could from one side reduce the downtime and possible repair costs and from the other side be used as a product quality control, leading to the overall reduction of production losses and to the prevention of sending defective parts to customers. Manufacturing processes and equipment are numerous and vastly different. As a result a plethora of sensors and signal processing tools have been proposed being usual adapted to the specific application. Among others approaches online vibration monitoring could be used in order to monitor manufacturing processes and consequently accurately, on time and online malfunctions and defects can be identified, detected and diagnosed.

Grinding is one of the most prominent abrasive processes with geometrically non-defined cutting edges and is widely applied to achieve high accuracy and high quality mechanical, electrical and optical parts. Monitoring systems for a grinding process should be capable to detect unexpected malfunctions in the process with high reliability so that the production of substandard parts can be minimized. Major anomalies in the grinding process are chatter vibration, grinding burning and surface roughness deterioration.These anomalies should be identified as soon as possible in order to maintain the desired workpiece quality. In this paper, the analysis is concentrated on the gear grinding. The grinding process depends on the tool performance, on the machine stability as well as on the correct clamping/positioning of the workpiece. In gear manufacturing processes, honing and continuous generating grinding present similarities with the conventional gear meshing. As a result, monitoring of malfunctions in these types of processes can be bootstrapped and inspired itself by the existing knowledge acquired by the research in the fields of fault detection and diagnosis of classical gear defects. The diagnosis of gear defects has been extensively studied in literature and a plethora of methodologies have been proposed and successfully applied in many industrial cases [2], [3], [4]. The equivalent of the continuous generating gear grinding process in the conventional meshing is the worm gear. The use of vibrations for the diagnosis of worm gear in the literature is rare [5]. This could be explained by the complexity of this meshing phenomenon which is rather dominated by the frictional forces between the surface in contact than by normal forces which, in conventional meshing, stresses the stiffness of the teeth and generates the presence of the GMFs with the possibility of their modulation in case of default. In [6] a number of time domain indicators are used in order to monitor and further predict the machine tool condition using Support Vector Machines. Moreover a correlation analysis of motor current and chatter vibration in grinding has been presented in [7] using complex continuous wavelet coherence in an effort to achieve accurate and reliable chatter detection using motor current.

The work of this paper focuses on the analysis of the vibration behaviour of the system worn-workpiece during gear grinding. Gear manufacturers have identified that the presence of increased lead form error, increased profile form error, lead slope variation and profile slop variation at the producted gears may lead to limited vibroacoustic quality when the product is used. As a result in order to improve the final quality of the gears it is important to develop advanced signal processing tools capable to monitor the gear grinding process and detect on time and accurately any deviations in order to identify under standared products. In order to emulate the abovementioned four effects on the workpieces (high form error, high lead error, variation in profile slope, variation in lead slope) the following four different malfunctions have been introduced: high feed rate, high infeed, eccentric workpiece mounting, non-flat workpiece mounting, . Furthermore, four specific monitoring features are proposed in order to detect these four types of seeded grindding faults. The rest of the paper is organised as follows. In section 2 a small introduction to the generating gear grinding is presented. Moreover the feature extraction methodology is presented in section 3. The experimental study and the analysis of the results are included in section 4 while some conclusions are summarised in section 5.

2 Continuous generating gear grinding

Continuous generating grinding uses a threaded wheel to hard finish the gear surface. Due to its high process efficiency, generating gear grinding has replaced other grinding processes such as profile grinding in batch production of small- and middle-sized gears. In transverse section, the profile of the grinding worm equates the rack profile while the rolling motion generates the involute profile.

Continuous generating gear grinding is characterized by a high stock removal rate and is thus suited for high productivity batch processing. One of the main challenges is the determination of the abbrasive/grinding forces due to their significant influence on the dynamics of the grinding process. During the grinding there are multiple points of contact between the worm and the gear, however the number of these contacts changes continuously. This involves also continuous change of the excitation forces.Thus, optimizing the cutting forces can lead to an increased quality of ground gears and a minimized wear behavior of the grinding worm. Currently, despite its wide industrial application, the knowledge of the generating grinding process is limited. The process design is based on experience along with time- and cost-intensive trials and research is based mostly on empirical studies.

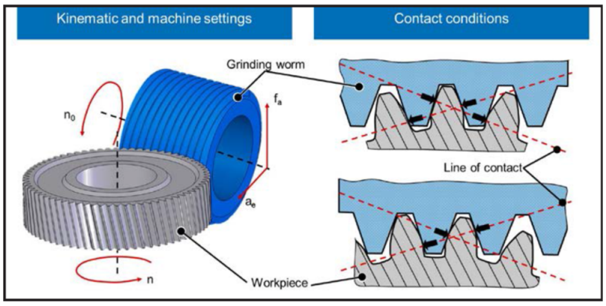

Figure 1: Contact condition in generating gear grinding ([8]).

3 Grinding defects and their expected vibration manifestations

The aim of this study is the proposal and evaluation of monitoring features which are able to detect four possible workpiece defects by using vibration signals. In order to emulate the four possible workpiece defects (high form error, high lead error, variation in profile slope, variation in lead slope), four faults have been seeded in an industrial grinding machine, as presented in Table 1 and further analysed in section 4.

Part defect	Seeding of fault
High form error (ffa)	High feed rate
High lead error (ffb)	High infeed
Variation in profile slope (delta fHa)	Eccentric workpiece
Variation in lead slope (delta fHb)	Non-flat workpiece

Table 1: Part defects and emulated faults

The continuously changing contact mechanics between the grinding worm and the gear is quite complicated leading to complex vibration signatures. In order to develop adequate vibration-based signal processing tools to monitor, identify and detect the abovementioned malfunctions, the expected vibration manifestation should be understood [9].

3.1 High feed rate

Choosing the grinding process parameters is mainly based on the know-how of the process user and one comes to the right settings after a hard and costly iterative process made of several trials [8]. Inadequately chosen parameters may result to low quality and out of specifications machined parts.

The feed motion is defined by the relative translation of the grinding worm in the direction parallel to the workpiece axis. The feed rate [mm/rev] is the distance that the worm travels after one revolution. It indicates the stock removal rate in the lead direction. As physical effects, grinding with high feed rate results in high grinding forces and high contact area with possible variation of the pressure angle [10]. The expected vibration manifestation is the increase of the meshing frequency amplitude due to the increase of grinding forces. The amplitudes of some multiples of GMF are also expected to increase. The location of the harmonics depends on how many times the number of contact points changes in a time interval corresponding to one gear tooth grinding, i.e it depends on the flank sequence. These events can be seen in the time signal when the suspected meshing interval is isolated (Figure 2). In the frequency domain, the excitation of high harmonics of the meshing frequency is obvious. Figure 3 compares typical spectra from normal and high feed rate cases and the frequency band $4-7 \times GMF$ is the most excited in latter case. Moreover, the amplitude of the modulations of the GMF by the worm rotation frequency will be increased because of the grinding forces.

Therefore, the definition of a monitoring feature for high feed will be based on the above described vibration manifestation (Figure 4):

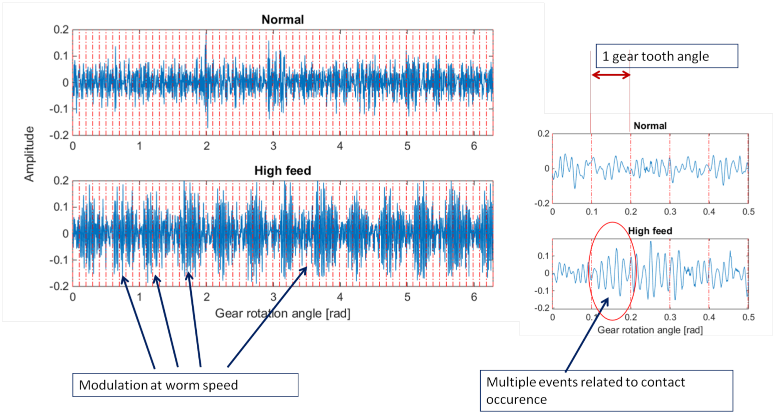

Figure 2: Time domain manifestation of high feed.

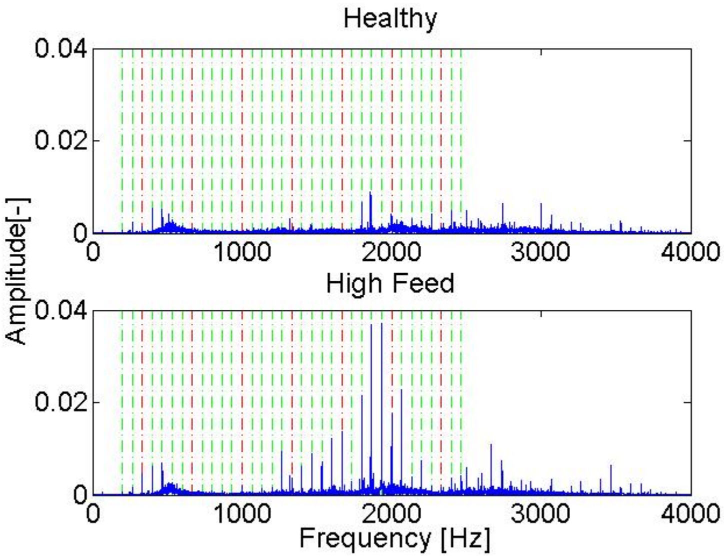

Figure 3: Frequency spectrum of signals captured during a healthy and a high feed grinding operating condition.

$$Feat(High - feed) = \sum_{f_i \in \{(1:6)\times GMF\}} A\left(f_i\right) + \text{Sidebands at worm rotation} \tag{1}$$

where $A(f_i)$ is the amplitude of the peak at frequency f_i.

3.2 Non-flat workpiece

The non-flat workpieces present the characteristic that the reference surface and the gear axis are not perpendicular. A non-flat workpiece defect can occur on the incoming gear from the preceding gear manufacturing process or from an inadequate clamping. During grinding, it leads to a wobbling motion which changes the contact conditions once per gear revolution. This change in contact conditions is combined to feed movement to result in varying feed rate. It is also expected that high harmonics of GMF are excited but sidebands at workpiece rotation frequency. The proposed feature is described as:

$$Feat(Non - flat) = \sum_{f_i \in \{(1:4)\times GMF\}} A\left(f_i\right) + \text{Sidebands at gear rotation} \tag{2}$$

3.3 Eccentric workpiece

This fault occurs when a workpiece is not centered on the spindle rotating axis (Figure 5). As physical effect, an eccentric workpiece grinding process will be characterized by a variation in the infeed penetration once

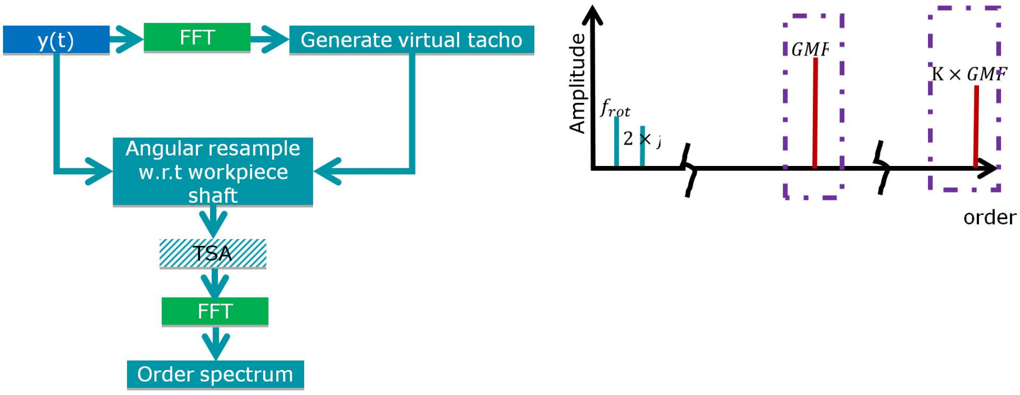

Figure 4: High feed diagnostic feature definition.

per gear revolution. This results in modulation of the GMF. The proposed feature is calculated as following:

$$Feat(Eccentricity) = \sum_{f_i \in \{(1:2) \times GMF\}} A\left(f_i\right) + \text{Sidebands at gear rotation} \tag{3}$$

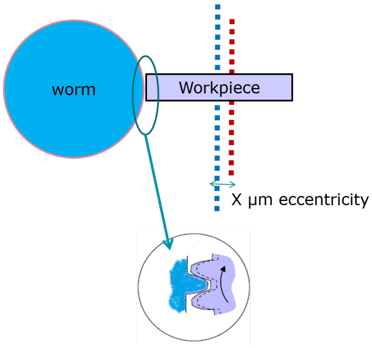

Figure 5: Eccentric workpiece fault

3.4 High infeed

Improper (high) infeed rate affects (increases) the profile form error and lead to inaccurate workpiece sizing, having a serious impact at the amount of stock removal. The profile form error is critical to the running behavior of gears, affecting their vibroacoustic behavior. In case the defective product is finally delivered to the customer, a low vibroacoustic behavior might appear at the application leading to customer complaints concerning the product quality. for this reason it is important to detect this problem as soon as possible and remove the influenced workpieces from the delivery. High infeed is expected to present increased vibration energy at the Y-Z plane. High infeed seems to affect the amplitude of the first gear mesh frequency and the amplitude of sidebands at distance equal to the rotation frequency of the worm (tool). Interestingly the phenomena leads to asymmetric sidebands with the first lower sideband presenting the highest amplitude. This occurs because there is a constantly changing phase relationship between the gearmesh frequency and the worm/gear speeds.

The proposed feature is calculated as following:

$$Feat(High - infeed) = \sum_{f_i \in \{1 \times GMF\}} A\left(f_i\right) + \text{Sidebands at worm rotation} \tag{4}$$

4 Experimental study

In order to validate the developed diagnostic features, a series of experimental tests have been performed on a grinding machine where faults are seeded.

4.1 The test setup and the fault seeding procedure

A number of experimental campaigns with the abovementioned seeded grinding faults have been realised on an industrial grinding machine. Two triaxial accelerometers have been mounted on the machine, the first one on the grinding worm holder and the second one on the base of the workpiece spindle. The accelerometers axes are oriented as following:

1. Grinding worm holder
    - X: Parallel to the worm axis
    - Y: Upward, Direction of Feed
    - Z: Direction of Infeed
2. Base of Workpiece spindle
    - X: Normal to the surface, in the plane perpendicular to the gear axis
    - Y: Parallel to the gear axis
    - Z: In the plane perpendicular to the gear axis

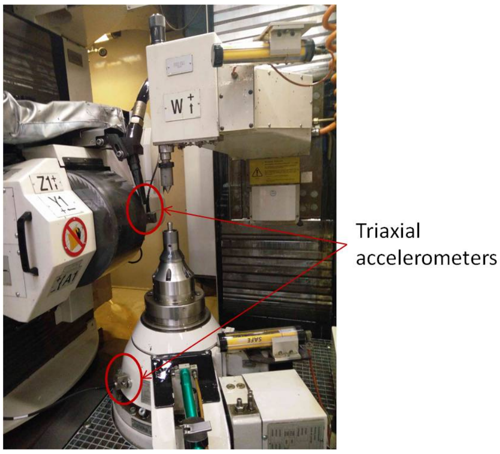

Figure 6: Experimental setup of the grinding machine

In order to emulate the four malfunctions, some changes have been introduced to the parameters of the grinding program. The grinding program is realised in two stroke passes. The high feed malfunction is seeded by doubling the nominal feed rate during the second pass. The eccentric workpiece is emulated by mounting the clamping arbor eccentrically and the non-flat workpiece is obtained by adding a $20\mu m$ washer at the base of the workpiece. Furthermore the high infeed anomaly is introduced by doubling the infeed rate. All the amlfunctions have been introduced only at the second pass. For each type of fault, five measurements are captured sequentially by grinding five gears in the raw (workpieces). Initially five measurements are realised in order to set up the baseline. Moreover the faults are introduced in the following series: High Feed, High Infeed, Excentric Workpiece, Non-flat Workpiece. After the end of the first series of measurements a second one has followed without redressing the grinding worm. The duration of the signal is equal to approximately 40 sec and the sampling frequency was selected equal to 25600 Hz.

4.2 Results and discussion

The time signals have been analysed in the time domain, in the frequency domain as well as in the time-frequency domain using the Short Term Fourier Transform (STFT), in order to understand first the influence of each seeded defect to the vibration behavior of the system. It has been concluded that it is important to analyse independently the stroke passes especially as the malfunctions are introduced only at the second pass. As a result a specific methodology has been developed in order to identify the start and the end time of each stroke pass (Figure 7). For each signal and each pass, one frequency line is selected at the STFT and is normalised

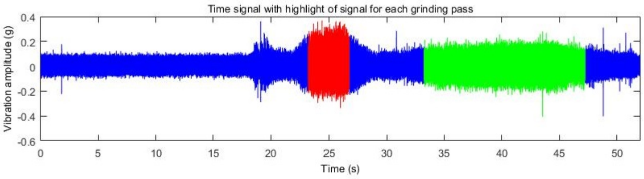

Figure 7: The two stroke passes.

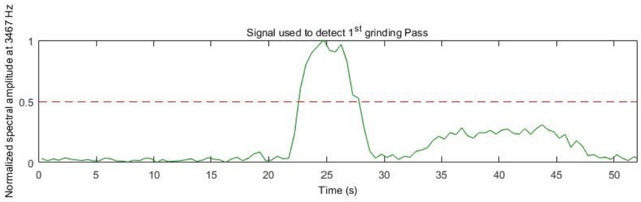

Figure 8: Detection of the start and end time of the first pass.

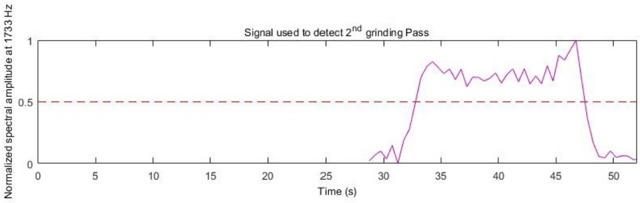

Figure 9: Detection of the start and end time of the second pass.

by its maximum. Furthermore a threshold is set equal to 50 % of the maximum amplitude and the start and end time of each pass are selected respectively, as demonstrated in Figure 8 and Figure 9.

Firstly the eccentric workpiece seeded fault is analysed. The frequency spectra of a normal measurement and of a measurement with an eccentric workpiece are presented in Figure 10, in order to demonstrate the influence of the eccentric fault of the gear mesh frequency. Comparing the two spectrums, it can be clearly noticed that two sidebands at the gear speed around the first GMF are generated. Furthermore the diagnostic eccentric workpiece feature is estimated and its time evolution is presented in Figure 11. It can be concluded that the fault has not been corrected during the first stroke pass as its effect can be seen on the second pass as well. The mean value of the diagnostic feature as well as its variability (minimum and maximum values), calculated for the five healthy cases and the five eccentric cases are presented for comparison at Figure 12.

The diagnostic high feed feature is also calculated for the five measurements and is compared to the values obtained during the healthy operating condition. The time evolution of the high feed feature is presented in Figure 13. The difference between the healthy condition and the high feed fault is visible on the second pass. The diagnostic features are calculated on a signal segment taken in the region of the quasi-stationary behavior during the second stroke pass. The mean value and the variability of the diagnostic feature are shown in Figure 14.

Furthermore the non-flat workpiece diagnostic feature is calculated and its evolution is presented in Figure 15. It can be seen that this fault affects both the grinding passes. The diagnostic feature is calculated on a signal segment taken in the region of the quasi-stationary behavior during the first pass. The mean value and the variability of the diagnostic feature is presented in Figure 16.

Finally the high infeed diagnostic feature is calculated. As the anomaly was introduced during only the second stroke pass, the start and the end time of the second pass have been estimated using the abovementioned methodology and only this part of the signal was further processed. The diagnostic feature is calculated using the signals captured at the z direction by the accelerometer based on the worm tool. Ten signals captured during the normal operating condition(baseline) and another ten captured during the anomalous operation have been processed. The mean value and the variability of the diagnostic features is presented in Figure 17.

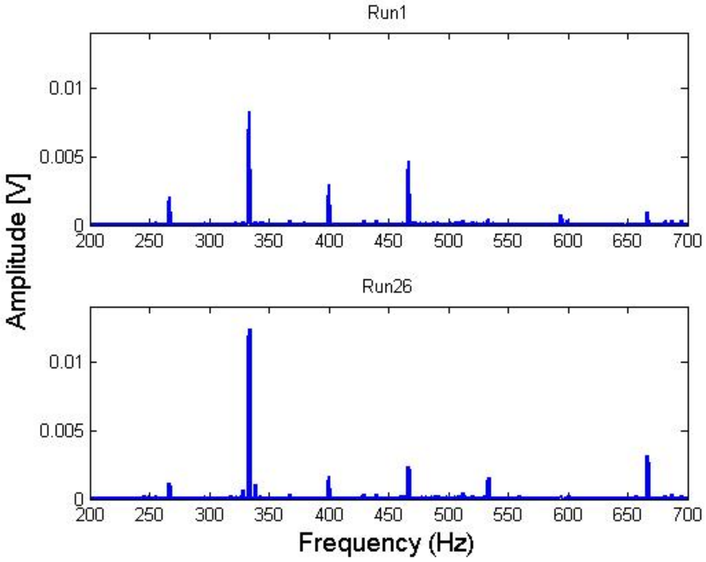

Figure 10: Typical frequency spectra of a healthy and a eccentric workpiece case.

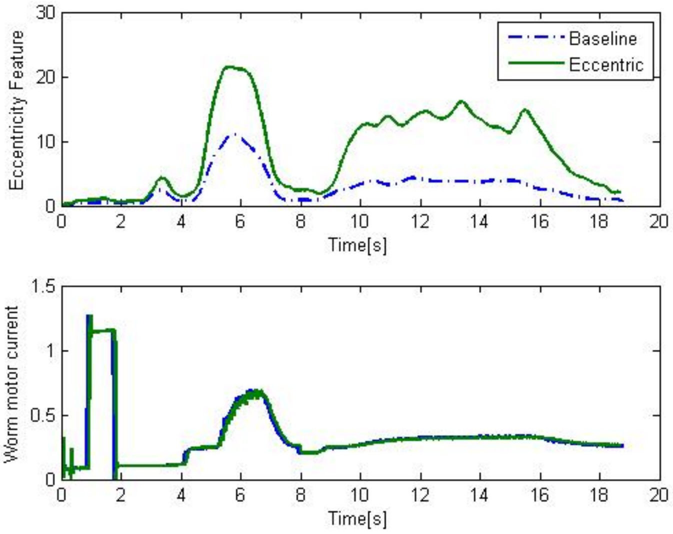

Figure 11: Evolution of the diagnostic eccentricity feature during the grinding process.

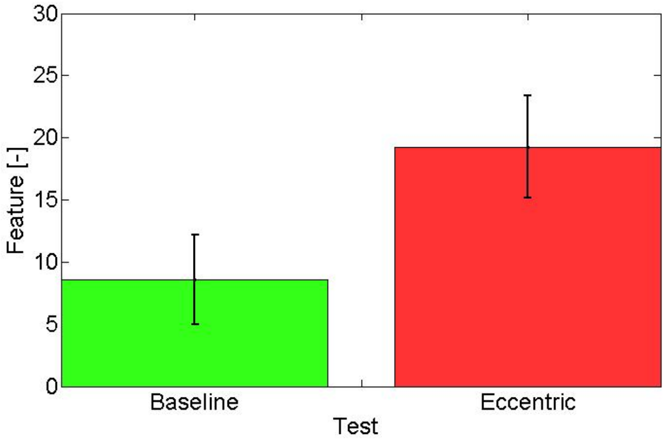

Figure 12: Mean value and variability of the eccentric workpiece diagnostic feature.

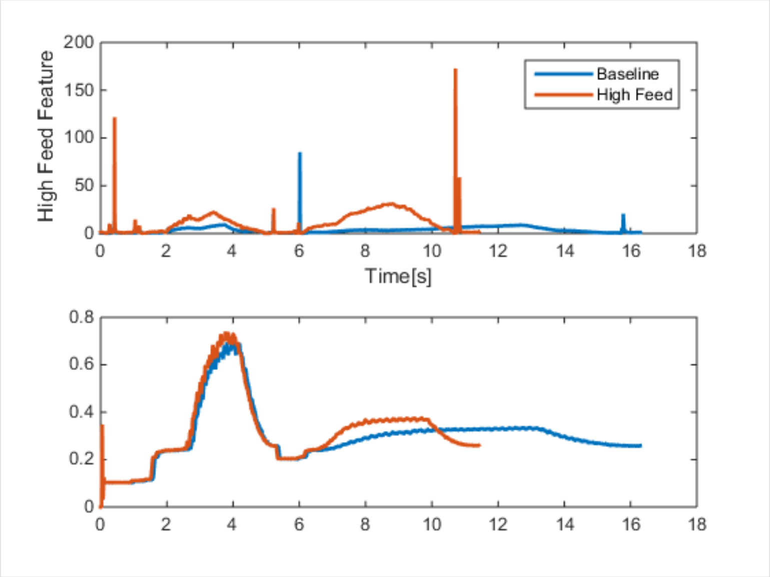

Figure 13: Time evolution of the high feed diagnostic feature during the grinding process.

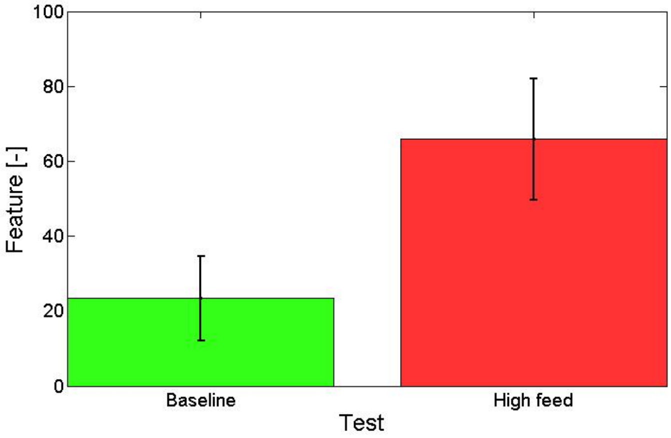

Figure 14: Mean value and variability of the high feed diagnostic feature.

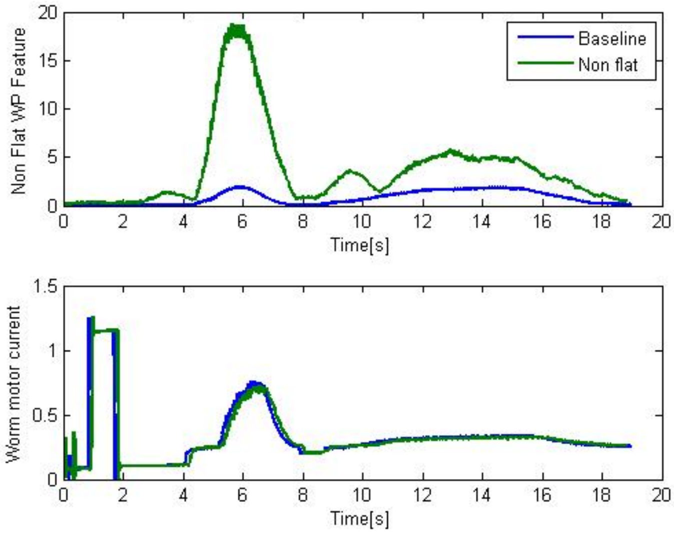

Figure 15: Time evolution of the non-flat workpiece diagnostic feature during the grinding process.

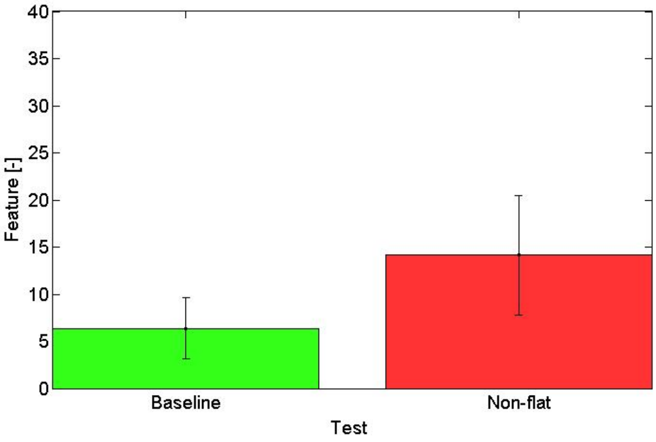

Figure 16: Mean value and variability of the non-flat workpiece diagnostic feature.

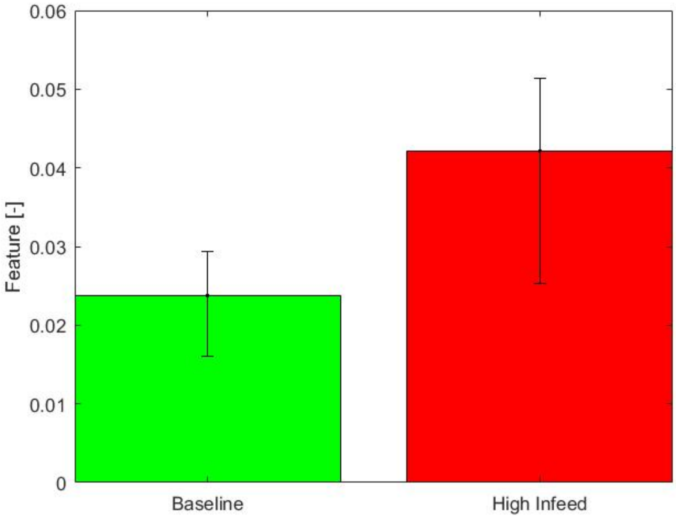

Figure 17: Mean value and variability of the high-infeed diagnostic feature.

5 Conclusions

The online monitoring of manufacturing machinery allows for the early and accurate detection of malfunctions of the process, of the machinery as well as of the product (workpiece) itself. Vibration based monitoring could be used to evaluate the quality of the workpieces as well as to detect and identify grinding process malfunctions at an early stage. In this paper four diagnostic features have been proposed in order to monitor four common gear grinding faults, including high feed, high infeed, non-flat workpiece as well as eccentric workpiece. The features seem to detect accurately the malfunctions, being evaluated on real signals captured on a gear grinding machine. The diagnostic features will be further evaluated using additional signals focusing towards the preparation of a diagnostic platform for monitoring of gear grinding.

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