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Short Communication

A new statistical model for acoustic emission signals generated from sliding contact in machine elements

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ABSTRACT

This paper proposes a new statistical model to characterise acoustic emission (AE) signals generated from surfaces in sliding contact. Such signals have traditionally been assessed using simple metrics such as RMS or kurtosis, but these metrics assume the signal is both (approximately) Gaussian and stationary, neither of which hold in many practical cases. Sliding contact generally involves the breaking or plastic deformation of surface asperities, producing an impulsive, highly non-Gaussian AE signal. If the sliding contact occurs in a rotating or reciprocating machine, such as from gears, the generated signals are usually not stationary, but rather cyclostationary, with periodic fluctuations in signal power tied to the rotation of the machine.

The proposed signal model abandons these assumptions of mild Gaussianity and/or stationarity, and it is used to derive novel indices as alternatives to the traditional RMS and kurtosis. These indices are applied to a comprehensive AE data set obtained from a pin-on-disc tribometer running over a range of sliding speeds and with specimens of different levels of surface roughness. The correlation of the indices with surface roughness is then illustrated and benchmarked against the traditional indicators. The results show that the proposed AE signal model delivers indices with a stronger correlation with surface roughness, suggesting a better representation of the tribological features associated with sliding contact.

1. Introduction

Having the capability to determine the tribological conditions (e.g., surface roughness, lubrication states, wear rates, etc.) present during sliding contact in a machine or other system using simple measurements such as vibration or acoustic emissions (AE) could deliver important benefits in a number of fields, in particular machine condition monitoring, yet it remains a challenging task. One example is found in gears, in which abrasive wear generated from sliding contact is one of the most common failure modes. Another is contact fatigue pitting, which in gears often occurs along the pitchline, where sliding velocity falls to zero and the lubricating oil film is at its thinnest, sometimes breaking down completely. These phenomena have different underlying causes and progress in very different ways, and so to be able to give a reliable prognosis of remaining useful life (RUL) requires the ability to distinguish between them.

In traditional vibration-based machine diagnostics, wear is often only detectable at an advanced stage, for example when the profile of a gear's teeth has deviated substantially from an involute, typically indicated by a rise in the amplitude of the gearmesh harmonics. Attempts have been made to estimate gear surface roughness (and changes therein) from vibration measurements [1,2], but no conclusive correlation between vibration indicators and roughness has been found. For such a task, acoustic emissions might be more suitable [3]. Tan et al. define AE as “elastic waves generated by the interaction of two media in relative motion” [4], and Hase et al. state that “AE signals are produced when elastic stress waves are generated as a result of deformation and fracture of a material” [5], and so it seems likely that acoustic emission measurements would give a better indication than vibration of the tribological conditions associated with sliding contact.

Some research has been done to investigate, both theoretically [6] and experimentally [7–9], the relationship between surface roughness and AE signals generated in sliding contact. However, while the RMS value of AE signals has been found to be sensitive to variations in surface roughness, the findings seem inconsistent across studies. In Ref. [8], AE RMS obtained from a grinding wheel-on-workpiece friction test showed a *positive linear* relationship with surface roughness. Similarly, in Ref. [7], a mathematical function was simulated to describe an observed linear relationship between AE amplitude and surface roughness from a plate-on-table dry sliding test. However, in Ref. [9] it was found

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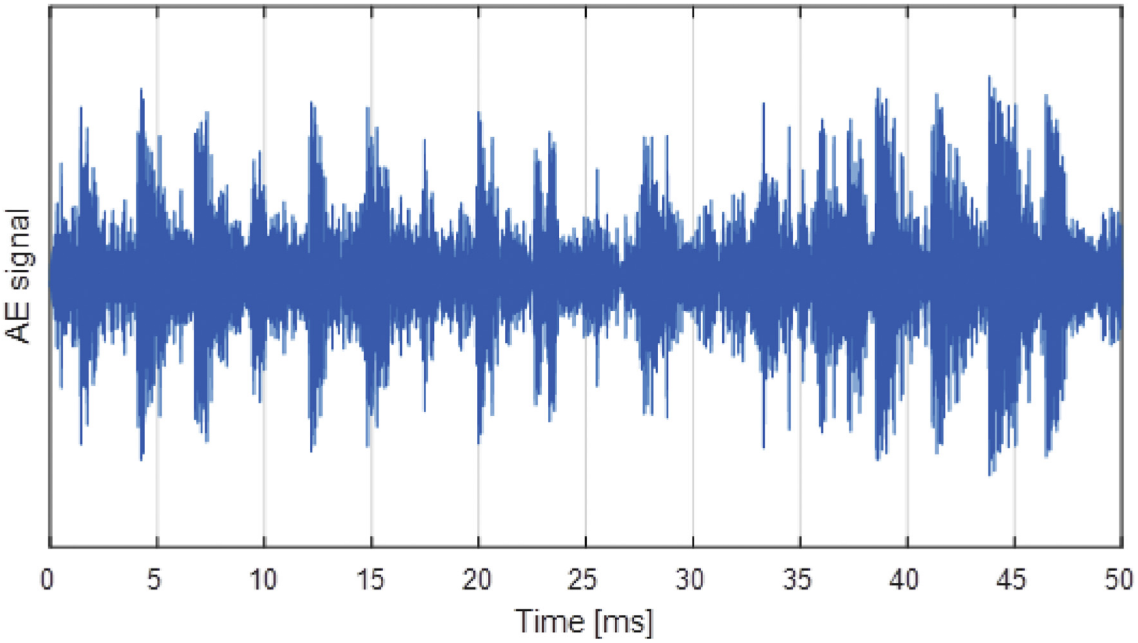

Fig. 1. AE signal generated in the meshing of a spur gear pair. The 19-tooth pinion shaft is rotating at 20 Hz, resulting in an approximate fundamental cyclic (gearmesh) period of ~2.6 ms, which characterises the energy fluctuation in the signal.

in a steel slipper-on-soleplate sliding test that surface roughness and AE RMS had a more *complex, non-monotonic* relationship. AE RMS first showed a positive trend with increasing surface roughness, then there was a significant drop in the RMS when roughness increased further. This suggests further work is required to understand the complex relationship between AE and surface roughness.

The above considerations explain the motivation for the present study, which uses AE data gathered from pin-on-disc tribometer tests designed initially to investigate the specific relationship between surface roughness and AE measurements in sliding contact. The aim of the paper is to show that when analysing such signals, consideration must be given to their non-Gaussian and non-stationary (i.e., cyclostationary) nature in order to obtain indices that best reflect the tribological conditions.

The remainder of the paper is organised as follows: Section 2 gives some relevant background on vibration and AE approaches for machine monitoring and in particular the use of kurtosis; Section 3 proposes a model for AE signals based on non-Gaussianity and cyclostationarity; Section 4 details the tribometer tests undertaken; the results are presented in Section 5; and in Section 6 conclusions are drawn.

2. Use of kurtosis in vibration- and AE-based monitoring approaches

Vibration-based machine condition monitoring (MCM) is now a very well-established field, and a multitude of signal processing techniques have been developed for such purposes [10]. Many of the methods and indicators developed for vibration signals have since been applied directly to acoustic emission signals, with one such metric being the kurtosis, defined as the normalised fourth moment of a signal. This basic statistical tool examines the Gaussianity of signals and is often able to indicate the development of faults, especially for rotating machines [11,12]. For many machines in good condition, measured signals can be expected to be approximately Gaussian, giving a kurtosis of 3, with lower values indicating strong periodic components and higher values indicating impulsive features, or more precisely a leptokurtic (non-Gaussian) distribution.

This impulsivity suggests the occurrence of impacts, often a sign of a localised machine fault in components like gears or bearings, and so kurtosis and kurtosis-based methods (such as the ‘spectral kurtosis’) have been widely used over the last few decades to detect and diagnose machine faults [11–14]. However, sample kurtosis for the detection of impulsiveness is only strictly applicable for stationary signals [15]. In mechanical related applications, signals from defective rotating machines combine impulsiveness with a repetitive energy release, which makes the signal cyclostationary rather than stationary [16,17]. This is taken up again in the following section.

Given its ability to detect faults, vibration kurtosis has been used to detect tribological changes (e.g., in surface roughness) in some research, but no remarkable conclusions have been found. Amarnath et al. calculated the kurtosis of vibration signals to identify incipient faults associated with gear wear in extensive experiments, but with increasing operating time, uneven trends were found in the kurtosis values [18,19]. Similar results were found in Ref. [20] from experiments based on polished and textured sliding contact; the kurtosis of the vibration signals did not show any clear connection with roughness differences under constant sliding velocity. The same conclusion was drawn in Ref. [1], which found only a weak correlation between the vibration kurtosis and the average roughness of gear tooth surfaces.

Kurtosis has also been successfully applied to acoustic emissions – which are generally more impulsive (non-Gaussian) than vibration signals – to diagnose bearing faults [21]. However, research on the use of AE kurtosis to assess tribological conditions is very limited. Hamel et al. used kurtosis to measure the peakedness of AE signals obtained from a pair of helical gears under different lubrication regimes [22,23], but the results only showed that the oil film thickness can influence the impulsiveness (Gaussianity) of AE signals, and no clear relationship was proposed. In the following section a signal model encompassing non-Gaussianity and cyclostationarity is proposed which the authors believe will allow for improved relationships to be established between tribological features and AE signals.

3. A non-Gaussian cyclostationary model for AE signals

AE signals used for the analysis of tribological features of machine components (e.g., gears, bearings) in operation are random by nature. Due to their characteristic cyclic kinematics, AE signals measured in rotating and alternating machines are rarely stationary, i.e. their