New aspects concerning the generation of Acoustic Emissions (AE) in spur gears and the influence of operating conditions

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Abstract

Acoustic Emission analysis has developed in recent years as a tool with interesting possibilities regarding machine condition monitoring. More specifically, in the case of gears, advances have been made in attempts to understand the process of AE generation, the influence of operating conditions, and the prospects offered by the method for fault diagnostics. Several experiments have been developed in order to investigate these topics; however, there is still doubt about the commonly accepted hypothesis for AE generation. In a similar manner, contradictory results can be found when comparing the effects of operating parameters on AE signals. In this study, alternative methods of AE generation in gears are presented and compared to the commonly accepted hypothesis of asperity contact. Emphasis is given to the pressure peak generated during teeth contact. The pressure peak hypothesis is based on the analysis of the elasto-hydrodinamic lubricant (EHL) film that separates the surfaces in contact. The effects of load, speed and lubricant viscossity on film thickness and pressure distribution are discussed, in relation to the source mechanism of AE in gears. This theory is applied to experimental AE measurements taken from a non-faulty, single stage, spur epicyclic gearbox. The results show a strong relation between load and the amplitude of the AE generated by gears; on the other hand, speed appears to be significant only at high values. These results are compared to the behavior expected from EHL theory and the asperity contact hypothesis. It is found that AE generated with a thinner lubricant are greater in magnitude and are greatly influenced by changes in load. The conclusions derived from the test bench analysis are applied to AE measurements taken from the planetary gearbox of a bucket wheel excavator (BWE). The BWE works under variable load conditions, therefore the speed also varies continuously. The behavior observed, regarding the influence of load and speed on AE amplitude, is in agreement with the conclusions derived from the test bench measurements. In conclusion, the analysis presented in this paper sheds light on an overlooked aspect of AE generation: lubricant behavior. At the same time, it offers other possibilities to be discussed regarding AE in spur gears. Insights are also offered on the behavior of AE signals under different load and speed conditions, where the influence of continuously variable operating conditions is also investigated.

1 Introduction

Acoustic emissions (AE) are elastic waves generated within a material, and/or on its surface, by a rapid release of energy produced by a sudden change in strain conditions [1]. The use of AE in structural analysis is well established and documented [1]. Meanwhile, the application of AE analysis in machine condition monitoring has been developing at a steady pace during the last decades. Important advances can be found in the subjects of bearings and reciprocating machines [2]. On the other hand, AE analysis on gearboxes is still at a basic level of development, as numerous questions are yet to be answered on the topics of AE source mechanisms, effects of operation conditions, and failure diagnostics.

AE analysis has demonstrated interesting possibilities on the topic of failure diagnostics, as evidenced by Gao et al. [3] and Loutas et al. [4], who were respectively able to detect and identify the abrasion marks and cracks present in the gear teeth. Toutountzakis and Mba [5] were able to detect symptoms of abrasion on tooth flanks by measuring AE activity on the driven wheel bearing casing. Contradictory to these successful cases, Tan and Mba [6], [7], [8] experienced difficulties when analyzing AE signals measured on gear boxes' bearing cases.

Tan and Mba, and Raja Hamzah and Mba [6], [7], [9] have studied the effects of rolling and sliding conditions between gear teeth, and pointed to asperity contact as the main source of AE generation. Different hypotheses to explain AE generation have not been thoroughly discussed.

Another aspect frequently addressed on gearbox AE analysis, regards the effects of operating conditions. Important contradictions can be found when comparing experimental results, especially on the topic of load influence. Tan and Mba [6], [10] found that changes in load had little or no influence on AE RMS amplitude. On the other hand, Raja Hamzah and Mba [11], [9] showed that load directly influenced AE amplitude. The main parameters studied were load (torque) and rotational speed. However, these parameters are not ideal due to the fact that they cannot be directly correlated to other experimental results, without the geometric specifications of the gears in question.

This article presents an experimental study on AE generated on spur planetary gearboxes (PG). This type of gearbox is considerably more complex than a fixed shaft gearbox. Due to the number of meshing processes occurring simultaneously (two times the number of planet gears), and to the fact that the planet gears do not only rotate around their shafts, but also revolve around the sun gear, the AE activity generated is complexer. Experimental results are presented, corresponding to AE measured on a planetary grearbox under laboratory settings, and on the gearbox of a bucket wheel excavator, which operates under continuously variable conditions. These results are correlated with the study on lubricant behavior.

Molina [12] had previously measured AE on a PG under different load and speed combinations. He observed that load greatly influences AE levels when operating at lower speeds (under 1000 rpm). He also identified speed as the predominant parameter with regards to AE amplitude, noting that under high speed conditions (over 1500 rpm), load shows no clear influence.

Lubricant is necessary for preserving the mechanical integrity of gears [13]. It is of most importance to separate the teeth during the mesh process; this separation is achieved through the lubricant film. Considering that the main AE source mechanism regards the interaction between surface irregularities, authors have included the study of the lubricant film conditions in their research [11], [6], [10], [8]. These attempts are restricted to the correlation between film thickness and AE amplitude, therefore the study in depth of oil behavior, and more importantly, of pressure peaks generated in the lubricant film, has not been applied to AE generated in gears.

2 Hypotheses for AE generation in gearboxes

While a single stage planetary gearbox operates, AE are generated on each of the different meshings occuring at the same time. The PG used for this investigation has 3 planet gears, and each planet meshes simultaneously with the sun and ring gear, therefore there are 6 meshing processes. It would be logical to think that the AE signal generated in a PG would not be comparable to the AE obtained from a fixed shaft gearbox. This would be valid if the different meshings were not in-phase, but this is not the case for the PG studied. Bearing this in mind, we believe that the PG-based AE analysis offered can be correlated with the previously cited investigations.

The time domain signature corresponding to AE measured on the single stage PG studied, shown on Figure 1, can be described as a continuous signal superposed with a series of transient bursts, repeated at the mesh frequency. A very similar phenomenom occurs on a normal single stage gearbox [5]. Researchers' efforts were first oriented towards identifying the mechanical phenomena that generates this particular waveform, since understanding the background of the information being acquired is of vital importance in developing the technique.

Nowadays it is commonly accepted that the AE activity generated during the meshing of gears is due to asperity contact along the contact area. This notion was first discussed in detail by Tan and Mba [6] and they explain the signature waveform as the combined effects of sliding and rolling along the mesh line. Asperity contact is common in gears, due to the fact that teeth surfaces are subjected to manufacturing capabilities, meaning that superficial irregularities can be of around 2 μm [14]. Under these circumstances, the thickness of the lubricant film is important in determining whether these asperities will be in contact. For the case presented by Tan and Mba, the film thickness calculated was of 1 μm, therefore asperity contact was assumed to be present. This hypothesis assigns the continuous waveform to the rolling and sliding section of the contact, and the bursts to the pure rolling instant corresponding to the pitch point. Further studies by the same authors [7], [10], [8] continued to study the generation of AE in gears assuming this source mechanism as valid.

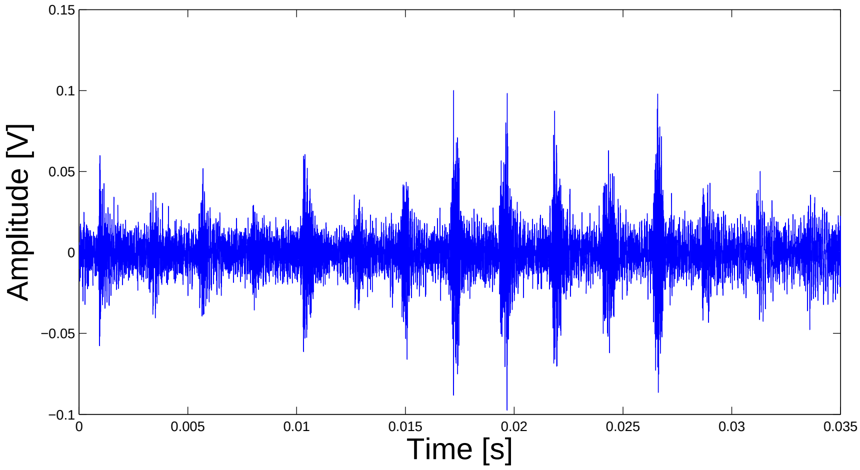


Figure 1: AE time signal measured on a single stage planetary gearbox running at 1800 rpm and 65 Nm.

Although not actually discussed in modern literature, we believe there are aspects yet to be discussed before accepting the asperity contact theory as the valid AE source mechanism. The first of these is the adequate evaluation of other hypotheses, some of which are discussed later in this article. Another aspect that generates doubts is the absence of definitive experimental results that point to this hypothesis with certainty. Also, a clear theoretical model explaining how AE are generated by asperity contact has not been developed.

Two other possible source mechanisms where briefly addressed by Tan and Mba: tooth resonance and secondary pressure peak generated in the lubricant film. The tooth resonance hypothesis was discarded as the tooth resonance frequency was calculated at 75 kHz, and fell out of the AE frequency range (100 to 1200 kHz).

The secondary pressure peak is a rapid increment of lubricant pressure, which occurs after the pitch point and can surpass the maximum Hertzian pressure [13]. The magnitude of the pressure peak, and how far from the pitch point it occurs depends on the speed parameter, according to EHL theory. The secondary pressure peak coincides with an abrupt drop in film thickness, so one or both of these events could be the source mechanisms that generate the transient bursts repeated for every matching pair of teeth. Tan and Mba disregard this hypothesis on the basis that the secondary pressure peak would require isothermal conditions to occur, a case that does not happen in the gear mesh, where rolling and sliding are experienced.

It is the authors' opinion that currently there is not enough evidence to completely discard the secondary pressure peak hypothesis. Moreover, considering the numerous doubts surrounding the asperity contact theory, different source mechanisms should be examined in order to further develop the AE method.

A new hypothesis proposed by the authors is also based in lubricant analysis, more specifically in the phenomenon of mixed lubrication. When surface irregularities surpass a certain height, in relation to the oil film separating the gear tooth surfaces, transient EHL occurs. This event is studied in detail by Evans et al. [15], where the effects of surface roughness on gear teeth are examined. Their results show a clear and important influence of surface asperities on the pressure distribution in the oil film, where extreme pressure perturbations and film breakdown events are observed. These events are proposed as a possible source for the transient AE bursts discussed previously. This hypothesis, however, is limited to the validity of the cited study, and whether the events described can in fact create an AE peak, once per contact.

It is interesting to consider how the proposed source mechanisms would behave towards changes in operating conditions, according to EHL theory. On the case of secondary pressure peak, Dowson and Higginson's [13] model on lubricant film behavior states that load does not affect the thickness of the oil film, but it does influence the pressure distribution. This implies that surface asperities will not be closer to each other if the transmitted load is increased, therefore AE activity should not augment. This contradicts with a series of experimental results [6], [10], [11], published that acknowledge asperity contact as the primary source mechanism for AE activity. On the other hand, increased AE amplitude could be explained by changes in the pressure distribution of the lubricant film.

Another possible source mechanism relates to the effects of changing sliding conditions along the tooth flank. During contact, the teeth involved experience two instances of a combination between sliding and rolling, separated by a brief moment of pure rolling (at the pitch point). This means that the sliding coefficient between the two surfaces goes from being kinetic, then static, then again kinetic. The static slide coefficient is larger than the kinetic. This hypothesis proposes that the changes in sliding conditions are responsable for the transient burst repeated at the mesh frequency. As there is one instant of pure rolling along the contact, that repeats for every pair of teeth in contact, the change in the coefficient could force a variation in the strain distribution that could in turn, generate a transient AE. The effects of the phenomena described have not been studied and should be the topic of further research.

An additional hypothesis to discuss concerns the bending and deformation of gear teeth. In gearboxes, tooth deflections are an inherent behavior of every transmission. Furthermore, this phenomenon is responsible for generating vibrations at the mesh frequency. Therefore, the possibility of a similar occurrence for the case of AE is not farfetched and should be examined.

3 Experimental setup

3.1 Sensors and data acquisition systems

The AE sensor used for acquiring data on all experimental procedures was a Kistler 8152B211 model, with a frequency range between 100 kHz and 900 kHz. The signal from the AE sensor was preamplified at 10 dB. It was acquired with a National Instruments data acquisition system at a rate of 2 MHz.

3.2 Planetary gearbox test bench

A PG test bench was constructed for this investigation, it consisted on a 3 kW asynchronous motor connected to the sun gear of the PG through a flexible coupling. The carrier plate of the PG was connected, also through a flexible coupling, to a Placid Industries magnetic particle break, model PFB-100. The PG has three planet gears equally spaced between them, further specifications can be found on Table 1. The motor speed was adjusted through a frequency converter and the magnetic particle break was controlled by a DC power source. The AE sensor was mounted on a previously milled surface on the PG's outer ring gear. Figure 2 shows a picture of the test bench, Figure 3 shows the AE sensor mounted on the PG.

Aspect	Magnitude
Gear tooth type	Spur
Number of teeth of the sun gear Z_S	18
Number of teeth of the planet gears Z_P	26
Number of teeth of the ring gear Z_R	72
Number of planets N	3
Speed reduction	$1:5$
Planet gears angular placement [Rad]	$0; 2\pi/3; 4\pi/3$

Table 1: Test bench PG general data.

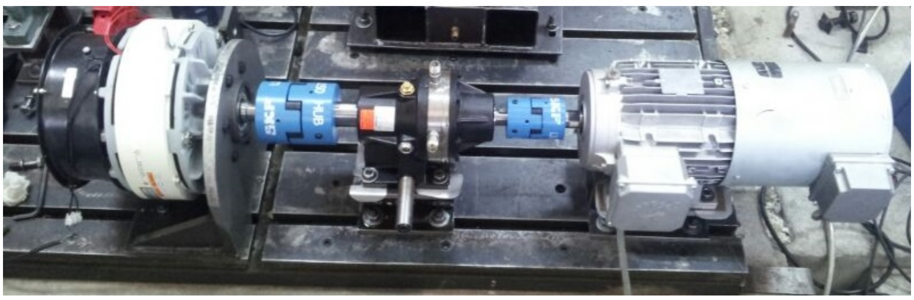


Figure 2: PG test bench.

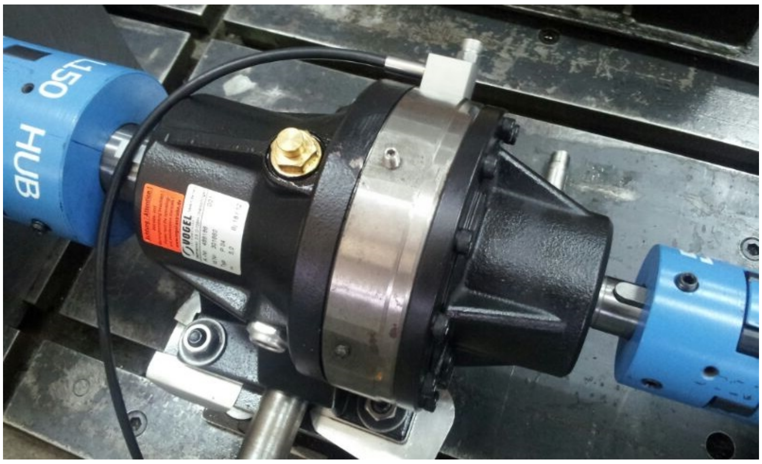


Figure 3: Acoustic sensor mounted on PG.

Several sets of tests were carried out with this test bench, under different lubrication conditions and with different load and speed combinations. The lubricants studied where Lubricant A: SAE 20W50, and a considerably less viscous Lubricant B: SAE 5W20, whose specifications are detailed on Table 2 and 3.

Aspect	Magnitude
Type	Multigrade Oil
Viscosity at 40 °C	123,8 cSt
Viscosity at 100 °C	18,9 cSt
Viscosity index ASTM D2270	143

Table 2: Lubricant A, SAE 20w50 properties.

Aspect	Magnitude
Type	Multigrade Oil
Viscosity at 40 °C	49,8 cSt
Viscosity at 100 °C	8,9 cSt
Viscosity index ASTM D2270	160

Table 3: Lubricant B, 5W20 properties.

3.3 Planetary gearbox of a bucket wheel excavator

Vibrations and AE were measured in the planetary gearboxes of two bucket wheel excavators (BWE) used in open pit lignite mining. Both BWE are identical and their fault condition was unknown. The last reduction stages in the drive system of the BWE are conformed by two PGs in series. Figure 4 shows a general view of the BWE. The sensors were installed on the outer ring of the second PG, as shown by Figure 5.

The gearbox of the BWE's drive system has a reduction ratio of 397.4 : 1. This is achieved by fixed shaft bevel reduction stage, followed by two fixed shaft gear reduction stages, and then by two PG reduction stages. The second PG's carrier plate connects to the bucket wheel. The nominal speed of the motor is of 900 rpm, and the bucket wheel spins at 2.83 rpm. Specific information regarding the PG analyzed is given in Table 4.

As the BWE operates, the bucket wheel digs in the overburden with each bucket as the wheel spins. This results in variable load and speed combinations, as the bucket wheel slows down when the load increases, and vice versa. Accordingly, angular measurements were taken corresponding to the rotational speed of the first PG's sun gear.

Figure 4: Bucket Wheel Excavator

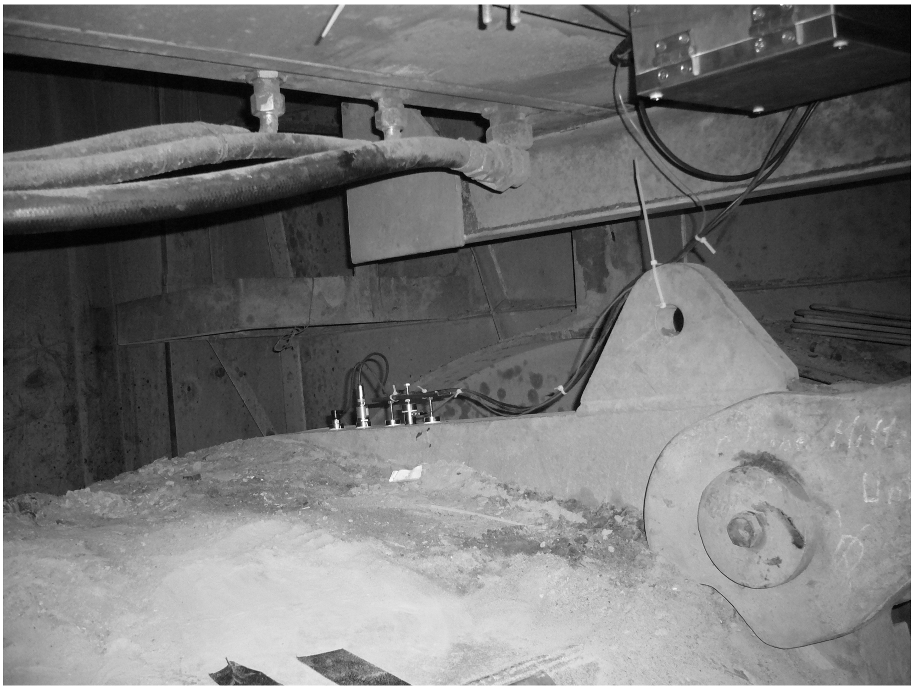


Figure 5: AE and acceleration sensors mounted on BWE.

4 Experimental results and discussion

4.1 Planetary gearbox test bench

All experimental data presented was filtered between 500 and 2000 kHz. The filter was used to enhance the signal-to-noise ratio of the transient bursts.

AE measured on the outer ring of a PG are as shown in Figure 1. Transient bursts are repeated at the mesh frequency. These bursts are modulated according to the relative position of the planet gears and the AE sensor. Figure 6 shows the spectrum of the AE signal from Figure 1. The information offered by this spectrum is limited, due to the fact that the transient bursts previously discussed are not exactly periodic.

In light of these circumstances, it is decided to calculate the envelope spectrum of the AE signal, shown in 7. Clear components of the gear mesh frequency can be identified. Under the operating conditions used for this example, up to the tenth multiple was clearly observed. As the envelope spectrum offers information directly correlated to the meshing processes occurring in the PG, it is decided to use this tool in further experimental

Aspect	1st PG stage	2nd PG stage
Gear tooth type	Spur	Spur
Number of teeth of the sun gear Z_S	21	27
Number of teeth of the planet gears Z_P	64	31
Number of teeth of the ring gear Z_R	150	90
Number of planets N	3	3
Speed reduction	$1:8.143$	$1:4.333$
Planet gears angular placement [Rad]	$0;2\pi/3;4\pi/3$	$0;2\pi/3;4\pi/3$

Table 4: BWE's PG general data.

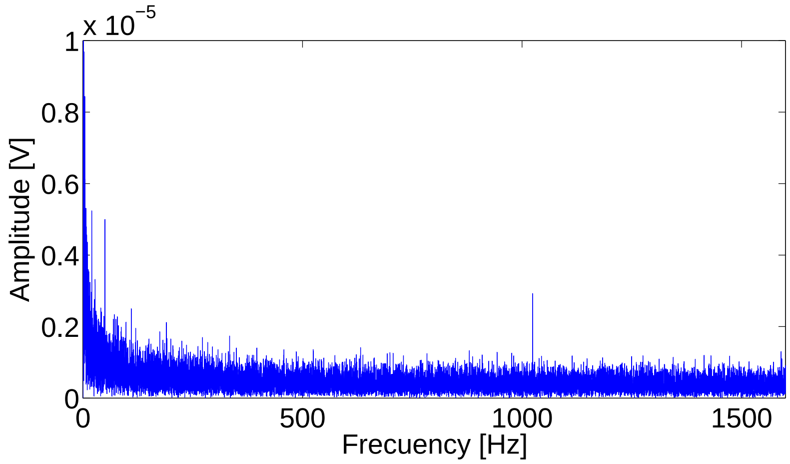


Figure 6: Spectrum of AE measured on PG, running at 1800 rpm and 65 Nm.

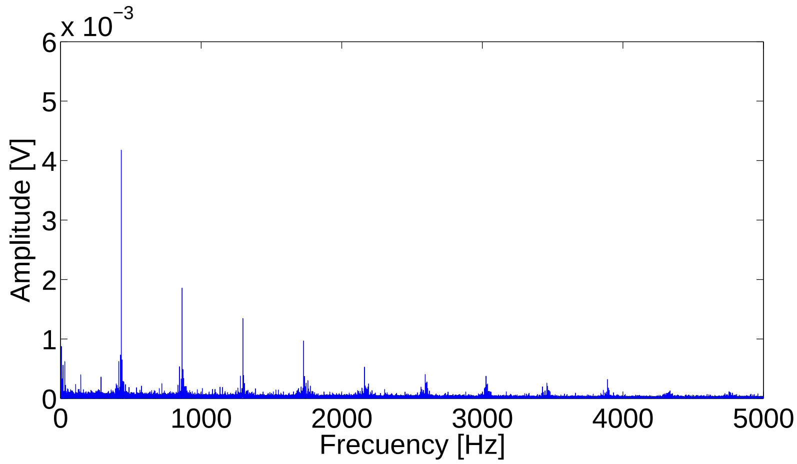


Figure 7: Envelope spectrum of AE measured on PG, running at 1800 rpm and 65 Nm.

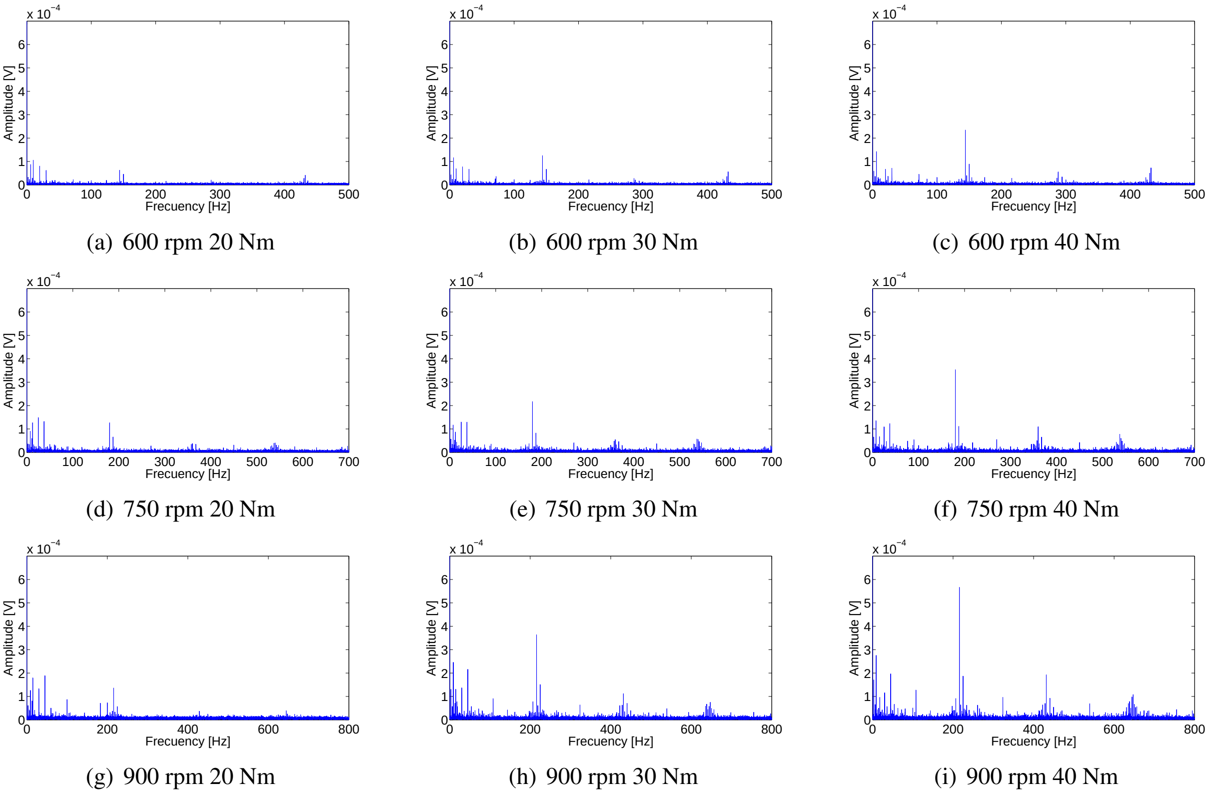
data.

Figures 8 to 12 show the AE envelope spectrum for different speed and load combinations, obtained with both lubricants. The following observations can be made from these figures:

- For lower speeds, AE generated during the tests with Lubricant B are higher in magnitude.
- During the tests with Lubricant B for low speeds, load greatly influences AE amplitude. This is not the case for Lubricant A, where the effects of load are not as clear, even though increments in load still result in higher AE.
- As Figure 10 shows, for Lubricant B, speed does not influence AE amplitude for speeds under 1000 rpm.

This point is further demonstrated by Figure 9, where speed influence on AE magnitude is irregular, including cases where higher speeds result in reduced amplitude. This does not happen with Lubricant A, where speed increments result in higher AE activity.

- For higher speeds, (Figures 11 and 12), load does not show clear influence on AE levels, for both Lubricants. Contrary to the case of lower speeds, it's the velocity parameter which appears to be more important regarding AE amplitude.



(a) 600 rpm 20 Nm (b) 600 rpm 30 Nm (c) 600 rpm 40 Nm

(d) 750 rpm 20 Nm (e) 750 rpm 30 Nm (f) 750 rpm 40 Nm

(g) 900 rpm 20 Nm (h) 900 rpm 30 Nm (i) 900 rpm 40 Nm

Figure 8: AE envelope spectrums obtained with Lubricant A.

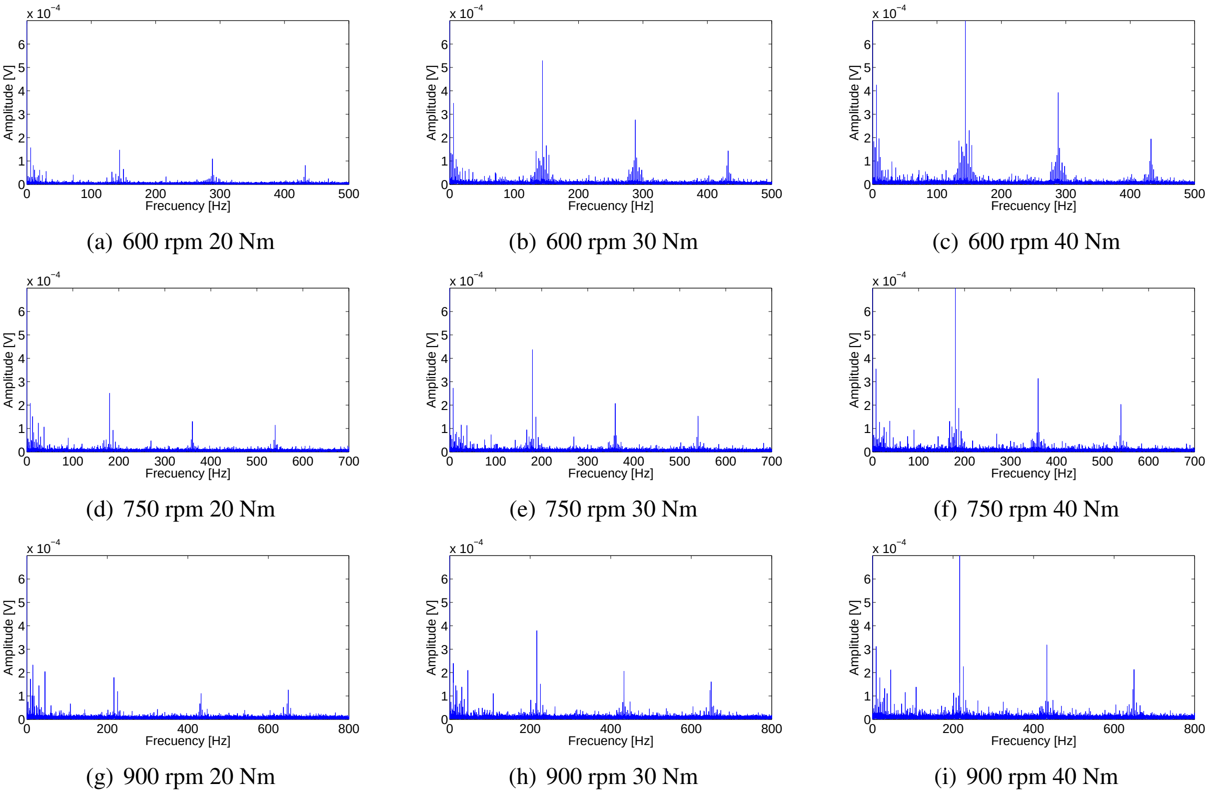
Figures 13 and 14 compare the amplitude of the AE gear mesh components obtained at different combinations of load and speed. These graphs were constructed by adding the RMS of the first three gear mesh components in the envelope spectrums. The sidebands of each component were considered by using a window of $\pm F_M$ Hz around each component, where F_M corresponds to the sun gear's velocity. Through these figures it is easy to appreciate the direct relationships between load–AE and speed–AE. It can also be noted that speed becomes more relevant at higher magnitudes, as exemplified by Figure 13, where speeds 1200 to 1500 rpm which are very close in AE magnitude, in opposition to curves corresponding to 1650 and 1800 rpm, which are higher in amplitude and are separated by a wider margin.

Another observation to be made from Figure 13 is that the influence of load is clear for all speeds, but it becomes more relevant for speeds above 1350 rpm. Figure 14 exhibits a similar behavior, but the difference is made clearer above 1650 rpm.

The presented experimental results neither confirm nor deny any of the previously discussed source mechanism hyphoteses. Asperity contact is verified as a plausible source mechanism for AE activity, as the AE generated during the tests with the least viscous oil (Lubricant B) were higher in amplitude. It is logical to assume that with a thinner oil film, the tooth asperities will be closer to each other, therefore producing higher AE bursts.

On the other hand, the asperity contact theory does not explain why some levels of speed are more important than others for generating AE (Figure 10), neither does it offer any reason as why to load exerts such a clear influence on AE amplitude at lower speeds.

In summary, the results provided fulfill the expected behavior in relationship to the discussed possible AE source mechanisms. Both the asperity contact theory and the pressure peak hypothesis should perform similarly

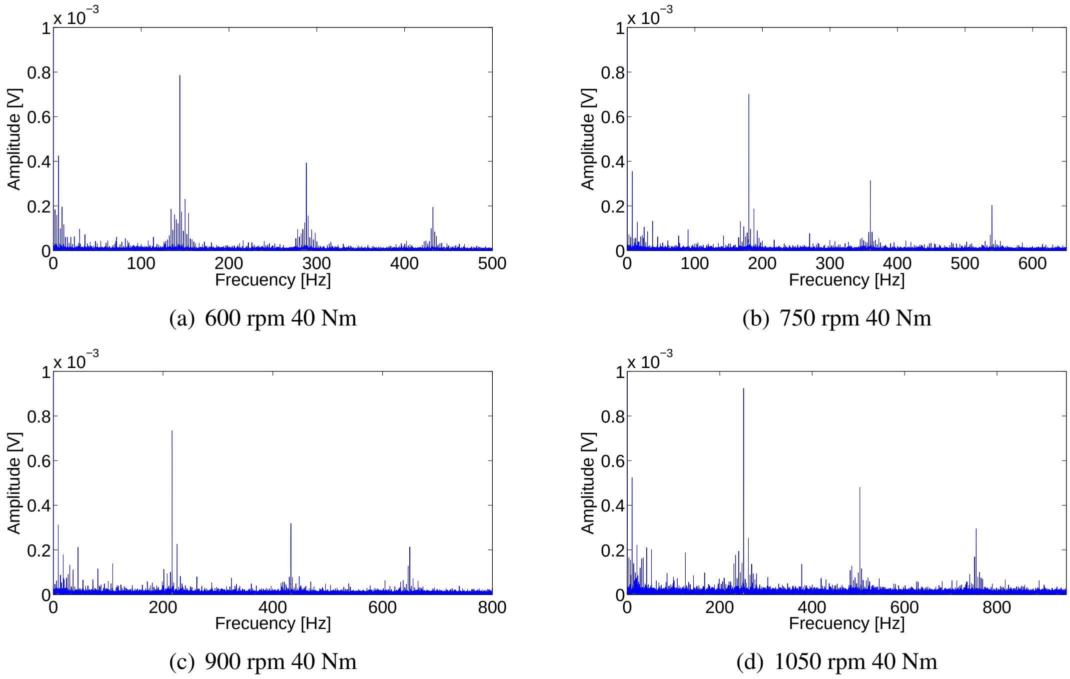


(a) 600 rpm 20 Nm (b) 600 rpm 30 Nm (c) 600 rpm 40 Nm

(d) 750 rpm 20 Nm (e) 750 rpm 30 Nm (f) 750 rpm 40 Nm

(g) 900 rpm 20 Nm (h) 900 rpm 30 Nm (i) 900 rpm 40 Nm

Figure 9: AE envelope spectrums obtained with Lubricant B.



(a) 600 rpm 40 Nm (b) 750 rpm 40 Nm

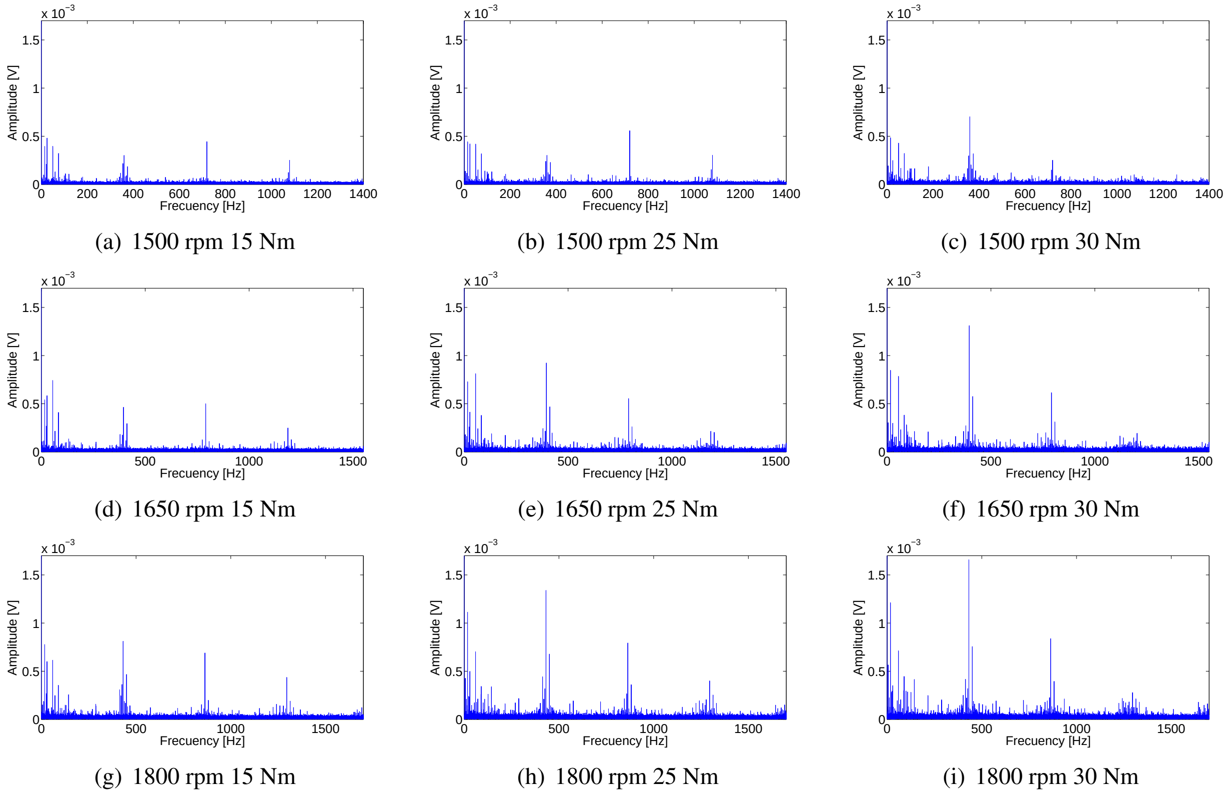
(c) 900 rpm 40 Nm (d) 1050 rpm 40 Nm

Figure 10: 600, 750, 900 and 1050 rpm AE envelope spectrums obtained with Lubricant B.

in relation to changes in operating conditions. The sliding conditions hypothesis should be further developed before seriously assessing how it would behave in relation to changing operating conditions.

4.2 Bucket Wheel excavator

The BWE operates with varying speeds and loads; this, according to vibration analysis experience produces smearing in the magnitude spectrum lines. Therefore the AE signals were sampled in the angular domain.

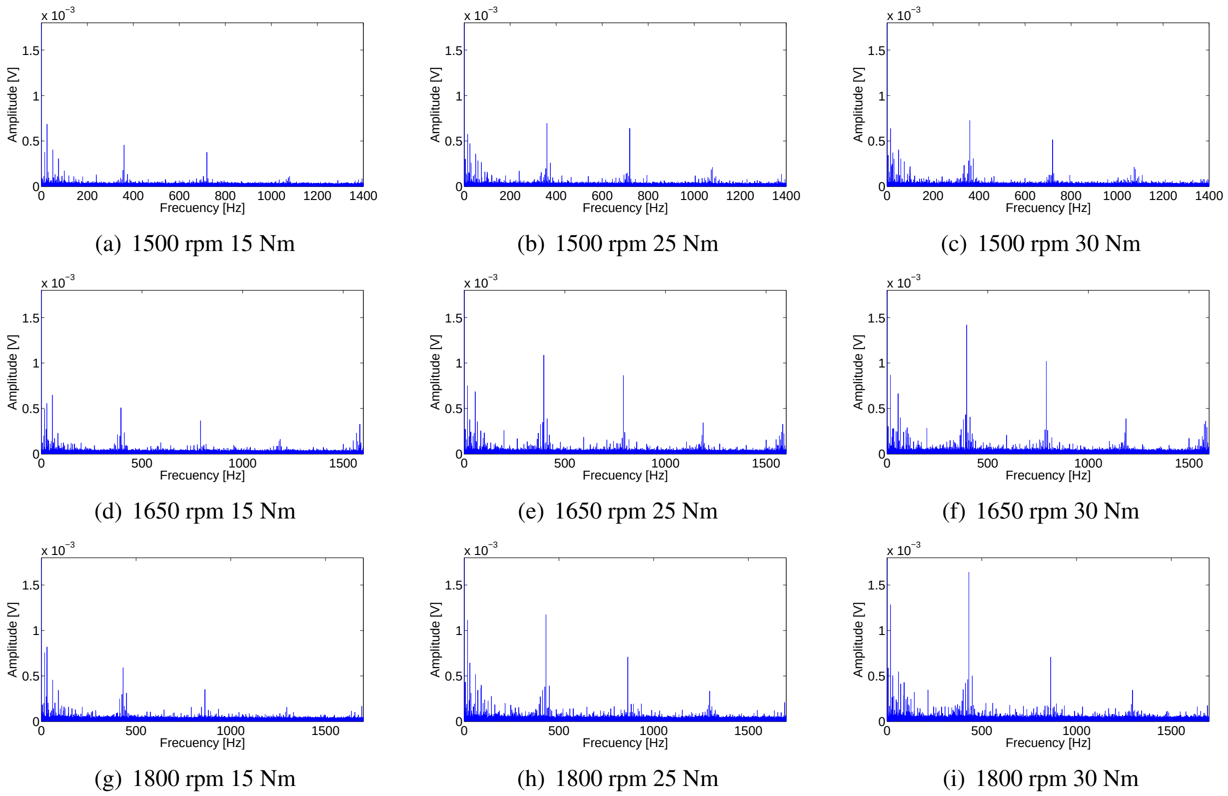


(a) 1500 rpm 15 Nm (b) 1500 rpm 25 Nm (c) 1500 rpm 30 Nm

(d) 1650 rpm 15 Nm (e) 1650 rpm 25 Nm (f) 1650 rpm 30 Nm

(g) 1800 rpm 15 Nm (h) 1800 rpm 25 Nm (i) 1800 rpm 30 Nm

Figure 11: High speed AE envelope spectrums obtained with Lubricant A.



(a) 1500 rpm 15 Nm (b) 1500 rpm 25 Nm (c) 1500 rpm 30 Nm

(d) 1650 rpm 15 Nm (e) 1650 rpm 25 Nm (f) 1650 rpm 30 Nm

(g) 1800 rpm 15 Nm (h) 1800 rpm 25 Nm (i) 1800 rpm 30 Nm

Figure 12: High speed AE envelope spectrums obtained with Lubricant B.

Figure 15 shows a portion of the AE time signal obtained. The signal is composed by a series of bursts, repeated at the first PG's gear mesh frequency. It must be noted that the bursts are not exactly periodic. The AE signal is modulated in amplitude by the load variations experienced by the BWE as it operates. Changes in load induce variations in speed, this means that as the shovel digs in the overburden and load increases, the rotational

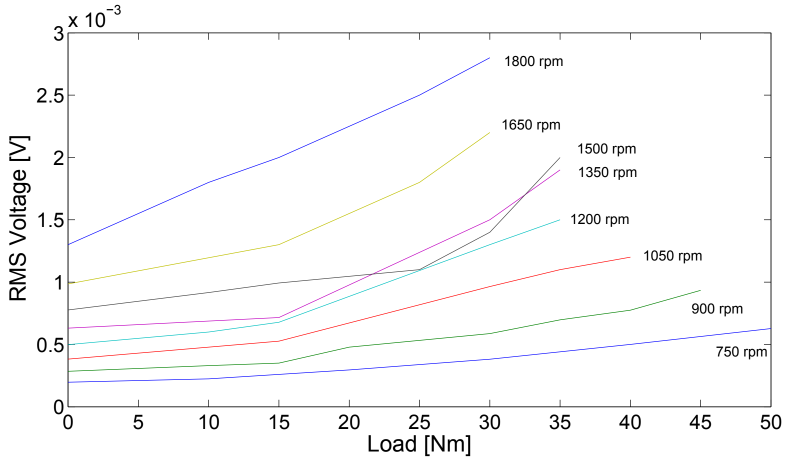


Figure 13: AE amplitude of gear mesh frequency components for Lubricant A.

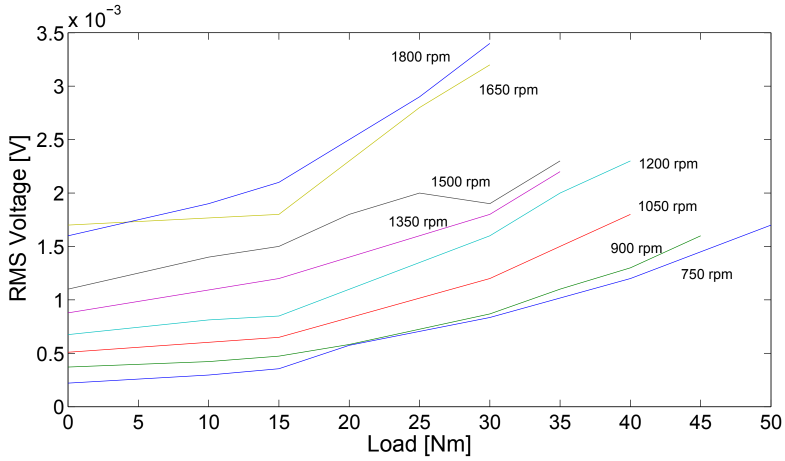


Figure 14: AE amplitude of gear mesh frequency components for Lubricant B.

speed in the PG diminishes. As no signal was available to directly measure the load, Figure 16 was constructed using the speed signal measured, and the AE envelope. The y-axis of the speed signal was inversed to serve as an estimate for load changes. From Figure 16 a strong and clear influence of load/speed can be noted on AE magnitude. As load increases, AE activity is reduced. This is of real interest as in the test bench results it was observed that both speed and load directly influence AE magnitude, therefore it was not clear which parameter would predominate. Considering that the first PG's mean speed was of 100 rpm, it can be concluded that at lower speeds, load strongly influences AE magnitude.

5 Conclusions

This investigation provides insights into the AE method applied to both regular spur teeth gears, and to epyciclic gearboxes.

The use of the envelope spectrum is demonstrated to be an effective tool in processing experimental AE data from gearboxes, as it offers information easily correlated to the meshing process.

The importance of lubricant behavior is demonstrated by contrasting results obtained with oils of different viscosities. AE generated with the thinner oil are higher in magnitude and are greatly influenced by changes in load. This behavior is not maintained for changes in speed.

Both load and speed directly influence the amplitude of AE generated during the gear mesh. Load appears to be the predominant parameter in low speeds (600 to 900 rpm). Increments in rotational speed generate significant jumps in AE amplitude, but only above the apparent threshold of $\sim$1350 rpm. Experimental AE

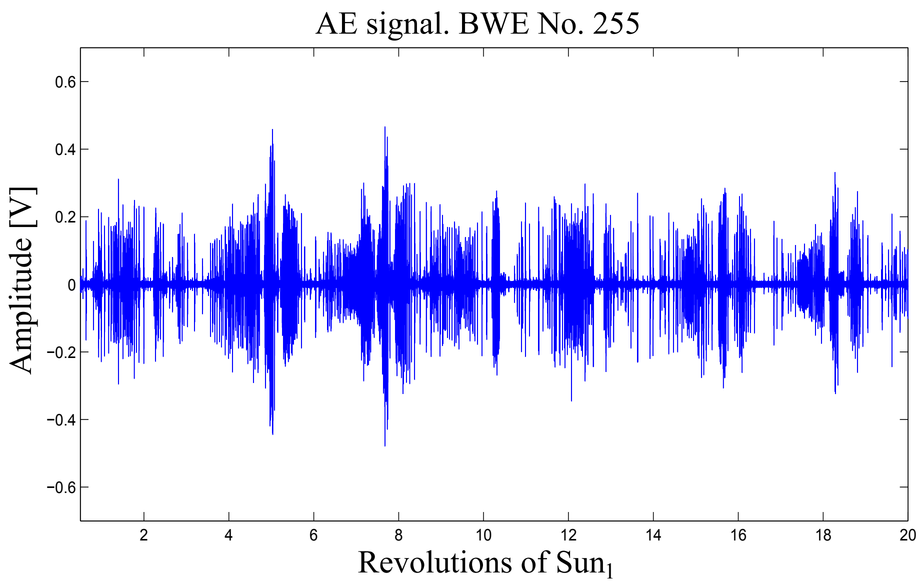


Figure 15: AE angle domain signal measured on BWE.

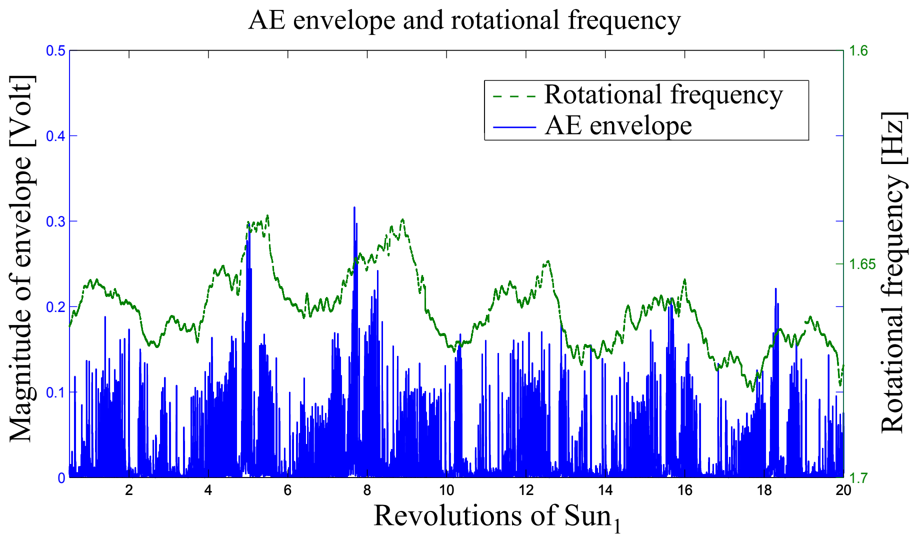


Figure 16: BWE measurement. AE envelope signal and inverted speed.

data from the PG of a BWE confirm the test bench results concerning the influence of operating conditions.

On the topic of AE source mechanisms, this article provides different options to be revised when discussing this topic. We propose that the relationship between asperity contact and lubricant behavior, correlated to AE, be further investigated. We also propose the study of other possible source mechanisms, such as the changing sliding conditions hypothesis.

Acknowledgements

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