



Vysoké učení technické v Brně
Fakulta strojního inženýrství
Ústav konstruování

Brno University of Technology
Faculty of Mechanical Engineering
Institute of Machine and Industrial Design

VÝZKUM A VÝVOJ PROSTŘEDKŮ PRO POKROČILOU AKTIVNÍ DIAGNOSTIKU TOROIDNÍCH LOŽISEK

RESEARCH AND DEVELOPMENT OF DEVICES FOR ADVANCED
ACTIVE DIAGNOSTICS OF TOROIDAL BEARINGS

Ing. Housam Mohammad

Pojednání ke státní doktorské zkoušce
Dissertation project for the doctoral state exam

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1 INTRODUCTION

In this work we study the phenomenon of Rolling Contact Fatigue (RCF) on Toroidal Bearings (TB) using the parameters extracted from Acoustic Emission (AE) testing. The aim is to develop techniques and devices for testing toroidal bearings using AE systems to find the characteristics of RCF in these special bearings which will enable the early prediction of this phenomenon in an early stage to try to avoid the drastic consequences of its occurrence, which starts with small spalling in the bearing raceways known as *pitting*, and ends with total break of the bearing, this in turn is considered to be the major reason for the downtime in machinery. We considered the Toroidal bearings in this study, because of their promising future, since they are a newly-designed and produced bearings, and more importantly because of their special design where the raceways of the inner and outer rings are parts of torus, which enables them to tolerate axial and angular misalignment at the same time, combining the features of cylindrical and spherical bearings together. This special ability of toroidal bearing to accommodate angular and axial misalignments will be studied and tested to see how it affects their characteristics, performance, and life expectancy. We will consider these features and study them in details using the AE technique because it was proven through many studies recently of its ability to predict RCF in bearings, and because of the continuously improved sensitivity of this technique.

The rollers are self-guiding. They will always automatically adopt the position at which the load is distributed over the length of the roller, Figure 1 and 3.

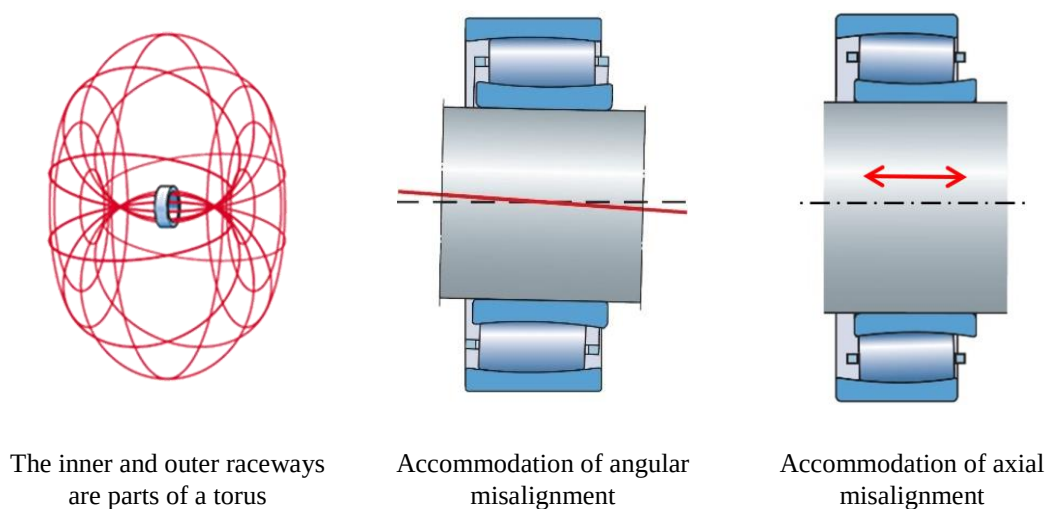


Figure 1. Basic characteristics of the toroidal bearing [7]

The stress distribution at the contact points between the rollers and raceways is determined by the contact profile of the rollers. As a result, the roller profile is matched to the raceway profiles. In addition, the rollers exhibit high dimensional and geometrical accuracy. Consequently, the rollers in an individual rolling element set are practically identical in terms of their size and shape. This gives a favorable and even load distribution across all rollers and over the entire length of the roller, thus preventing edge stresses and stress peaks at the ends of the roller, figure 2 [8]

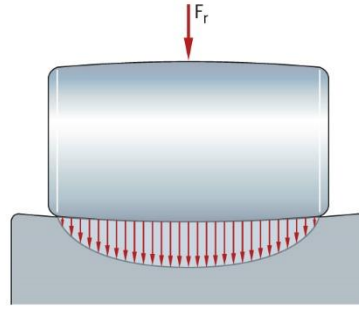


Figure 2. Uniform load distribution due to optimized roller profile [8].

The Acoustic Emission method (AE) is a Non-destructive Testing (NDT) method that depends on capturing and processing acoustic waves, which are caused by local changes in the material. Acoustic waves propagate from the place of origin of the defect to the surface of the material, so we can locate the defects and also monitor the course of their origin [1].

Contact fatigue is a very unfavorable phenomenon and it is better to minimize it as much as possible. Rolling Contact Fatigue (RCF) occurs in surface layers by repeated contact of two non-conformal surfaces [6]. Contact bodies are contacted by mutual contact at a point, on a straight line or along a curve. Because the surfaces of the bodies meet in a small area, very high local contact pressures occur. In pure rolling, the main stresses are compressive. Shear stresses reach their maximum at a certain depth below the surface. In these places, cracks arise and grow, which penetrate the surface and lead to peeling or crumbling of small volumes of material. This creates small cavities, which are collectively referred to as pitting. The main parameters influencing the contact fatigue strength include Hertz stress, number of cycles, surface quality and hardness, temperature, and presence of lubricants [3].

2 DEFINITION OF THE SOLVED PROBLEM AND THE PRELIMINARY OBJECTIVE OF THE DISSERTATION

Toroidal roller bearings are single row bearings with long, crowned rollers. The concave raceways in the inner ring and outer ring are concentric relative to the centre of the bearing. The raceway profiles are matched to each other and ensure optimum distribution of stresses in the bearing as well as low operating friction [8]. The rollers are self-guiding. They will always automatically adopt the position at which the load is distributed over the length of the roller, as shown in Figure 2.

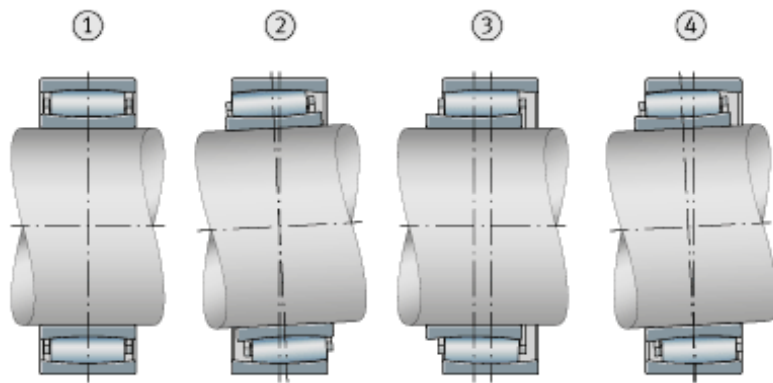


Figure 3. Toroidal roller bearing (angular and axial displacement) [8]

- ① initial position ② inner ring with tilting ③ inner ring with axial displacement
④ inner ring with displacement and tilting

Where a shaft is liable to temperature-induced elongation and misalignment defects, the non-locating bearing is a particularly important concept. In this case, toroidal roller bearings have proved ideal as non-locating bearings, as shown in Figure 4.

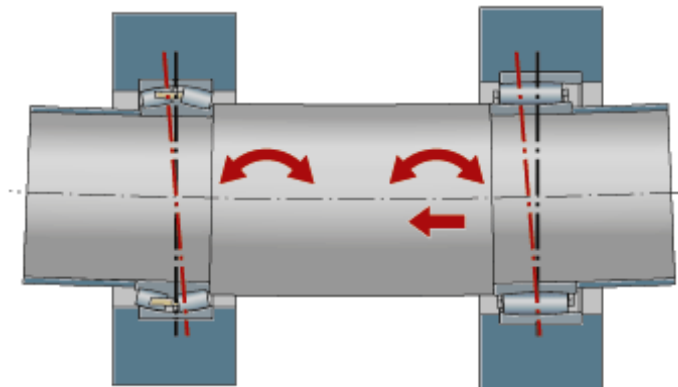


Figure 4. Non-locating concept [8]

The most common use of this concept is in the main shaft of wind turbines. As shown in Figures 5 and 6. In comparison with normal non-locating bearing arrangements, toroidal bearings offer significant advantages: Substantial changes in shaft length are compensated without constraint between the raceways and the rolling elements within the bearing.

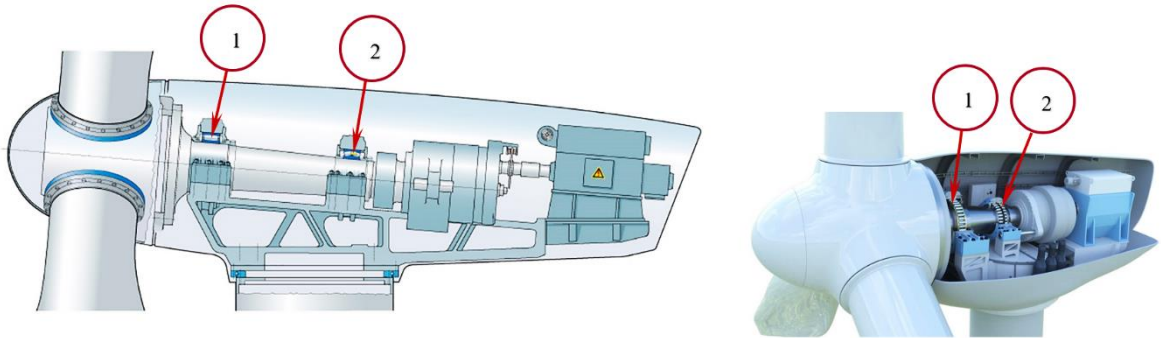


Figure 5. A Common use of toroidal bearings is on the main shaft of wind turbines [7].

Where ① Toroidal bearing, ② Spherical bearing.



Figure 6. The arrangement of toroidal and spherical bearings on the main shaft.[7]

The acoustic emission AE method is used to precisely capture the beginning of pitting. It is one of the methods of non-destructive material testing based on the principle of elastic stress wave propagation in the material [4]. Combining the AE monitoring and the AE source locator can be used to detect the incipient damage and to forecast the position of the damage in rollers, and this technique allows the monitoring of the deterioration rate of the rolling elements [12].

The basic parameters of the acoustic emission signal evaluation include Root Mean Square RMS (RMS value), counts, energy and frequency characteristics of the signal [5]. The most commonly used time-domain acoustic emission signal parameter is RMS. A very often used parameter of the time domain

signal is the counts parameter, which is defined as the number of overshoots over the set threshold level per unit of time [6].

Another commonly used parameter of AE for the condition monitoring of health of bearings is the energy, which will be used very often in every planned test with the work on this dissertation. According to the definition of signal energy, the area enclosed by the squared amplitude of acoustic emission signal can be used as a measure, and the energy of acoustic emission signal can be calculated by root mean square voltage (V_{rms}) or mean square voltage (V_{ms}):

$$V_{ms} = \frac{1}{T} \int_0^{\Delta T} V^2(t) dt, \quad (1)$$

$$V_{rms} = \sqrt{V_{ms}} \quad (2)$$

Where ΔT is average time, $V(t)$ is time-varying signal voltage [38].

A wide range of studies has been conducted to study the rolling contact fatigue in ball bearings and other types of bearings including self-aligning spherical bearings, while in the case of toroidal roller bearings there was almost none. Toroidal bearings share some similarities with self-aligning spherical roller bearings, except the fact that they can also accommodate axial displacement as well as angular misalignment. In this work it is planned to use the AE testing method to experimentally study the behavior of toroidal bearing and the beginning of pitting under various loading and rotational regimes.

The main goal of the dissertation is to create a methodology for testing this type of special bearings and any type of self-aligning bearing that allows angular misalignment. Which will include, and will not be confined to, the design of a testing stand, on the basis of which it would be possible to test toroidal bearings using acoustic emission as a non-destructive testing technique. This is not going to be an easy task since very high accuracy is just one of the essential factors of the test (the allowed angular misalignment of the tested toroidal bearings will be around $0,5^\circ$). The aim of the work will be specified on the basis of research activities at the Institute of Design ÚK (in the Faculty of Mechanical Engineering at Brno University of Technology) and will take into account the needs of cooperation with the industrial partner ZKL Brno, a.s., and ZKL - Výzkum a vývoj, a.s. with which there is cooperation on a project regarding the development of a new type of toroidal bearings for wind turbine industry.

3 SUMMARY OF THE CURRENT STATE OF KNOWLEDGE

3.1 Design and properties of toroidal bearings

Permissible tilting (angular misalignment)

Toroidal roller bearings can be tilted by an angle of up to 0,5° (TORB of Schaeffler) between the centre axes of the inner ring and outer ring without impairment of the function and rating life. In this way, the toroidal roller bearing can compensate a slight geometrical deviation of the housing bore or a shaft that is not precisely aligned without difficulty. Depending on the series and size, tilting of more than 0,5° is also possible but may be associated with a reduction in the rating life.

Axial displacement (axial misalignment)

Toroidal roller bearings can accommodate axial offset and thus compensate thermal expansion or deviations from the required bearing position. The maximum displacement distances S_1 and S_2 , which are specific to the product type, apply only where a sufficiently large operating clearance is present and to untilted bearing rings. Axial displacement and tilting changes the position of the rolling element in the bearing, which affects the operating clearance. During the design process, it must always be checked whether the operating clearance required will be present if there is:

- axial misalignment (displacement)
- angular misalignment (tilting)
- axial misalignment and tilting.

In the case of full complement bearings, the displacement distance S_2 is restricted on one side by the retaining ring. This ensures that the crowned roller does not come into contact with the retaining ring. In order to ensure that the axial displacement distance is available, it is necessary that the free space on both sides of the bearing is observed.

In order to ensure the function of the toroidal roller bearings, two different situations must be checked. On the one hand, it must be checked whether the axial displacement distance in combination with the tilting is still within the permitted displacement distance s_1 or s_2 respectively. Since axial displacement and tilting affect the bearing clearance, it must also be checked whether sufficient operating clearance will be present in the application.

The resulting bearing clearance can be determined using the following equation (1):

$$S_{res} = S_{ini} - K_{\delta} \cdot (\delta_{ax} + K_{\varphi} \cdot \varphi)^2 \quad (3)$$

Where:

S_{res} μm Resulting bearing clearance after tilting and axial displacement

S_{ini} μm Radial internal clearance after mounting

k_{δ} operating clearance factor, (from dimension table)

δ_{ax} mm Axial displacement from central position

k_{φ} Tilting factor, (from dimension table)

φ ° Tilting between inner ring and outer ring (angular misalignment $\pm$ shaft deflection).

Geometrical restriction of the axial displacement facility:

Tilting causes axial displacement of the rollers from the central position. This means that the axial displacement facility of the bearing rings relative to each other is reduced by S_{φ} .

This reduction in the axial displacement facility due to tilting can be calculated as follows [8]:

$$S_{\varphi} = K_{\varphi} \cdot \varphi \quad (4)$$

S_{φ} mm Reduction in axial displacement facility as a result of tilting

K_{φ} Tilting factor, (from dimension tables)

φ ° Tilting between inner ring and outer ring (angular misalignment $\pm$ shaft deflection).

When tilting occurs at the same time, the maximum possible axial displacement facility is calculated as follows:

$$S_{red} = S_1 - S_{\varphi} \quad (5)$$

In the case of full complement bearings, there is an additional effect as follows:

$$S_{red} = S_2 - S_{\varphi} \quad (6)$$

Where:

S_{red} mm Maximum axial displacement facility under tilting

S_1 mm Maximum axial displacement facility from dimension table, in the case of full complement bearings this is in the opposing direction to the retaining ring

S_{φ} mm Reduction in axial displacement facility as a result of tilting

S_2 mm Maximum axial displacement facility from dimension table, in the case of full complement bearings this is in the direction of the retaining ring.

3.2 Restriction due to reduction in radial bearing clearance

The bearing clearance is reduced in the following cases:

- axial displacement
- tilting of the bearing from the central position
- axial displacement and tilting of the bearing from the central position.

Depending on the necessary operating clearance, it must be checked whether the required axial displacement is possible under the tilting present.

The reduction in operating clearance is calculated as follows [8]:

$$\Delta S = K_{\delta} \cdot (\delta_{ax} + K_{\varphi} \cdot \varphi)^2 \quad (7)$$

Where:

ΔS μm Reduction in radial bearing clearance

K_{δ} Operating clearance factor, see dimension table

δ_{ax} mm Axial displacement

K_{φ} Tilting factor, (from dimension tables)

φ ° Tilting between inner ring and outer ring (misalignment $\pm$ shaft deflection).

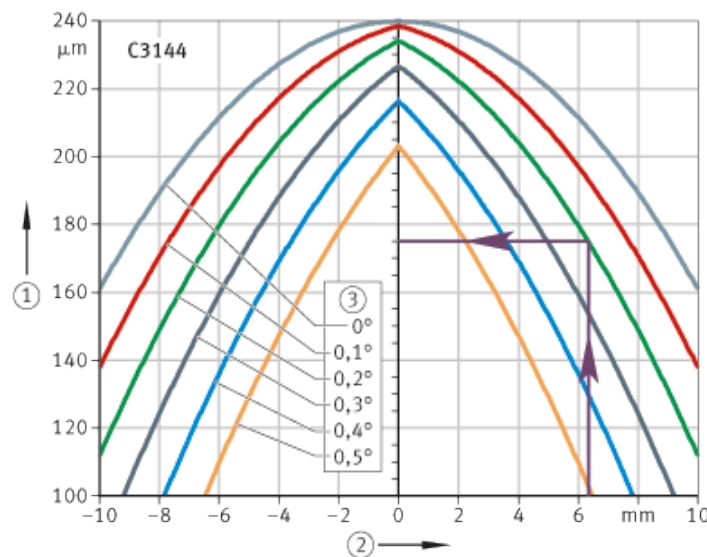


Figure 7. The actual internal clearance as a function of axial displacement [8].

Figure 6 shows a the resulting operating clearance of the Toroidal bearing (TORB C3144) as a function of angular and axial misalignments. Where: ① Operating internal clearance in μm , ② Axial misalignment in mm, ③ Angular misalignment (tilting) in $^{\circ}$. [8]

3.3 Acoustic Emission

Acoustic emission (AE) is the phenomenon of transient elastic wave generation in materials under stress. When the material is subjected to stress at a certain level, a rapid release of strain energy takes place in the form of elastic waves which can be detected by transducers placed on it. Plastic deformation and growth of cracks are among the main sources of acoustic emission in metals. The signal is generated and measured in the frequency range which is greater than 100 kHz. AE monitoring has an added advantage that it can even detect the growth of subsurface cracks whereas vibration monitoring can normally detect a defect when it appears on the surface [9]. Acoustic emission (AE) was originally developed for non-destructive testing of static structures, however, over the years its application has been extended to health monitoring of rotating machines and bearings. It offers the advantage of earlier defect detection in comparison to vibration analysis [10].

Acoustic Emission (AE) is generated by the energy released when microstructural changes occur in a material. The energy is provided by an elastic stress field in the material. The stress field can be generated by stressing the material, for instance using mechanical, thermal, pressure and chemical stressing [29].

As the stress waves propagate from the AE source they are influenced by a variety of factors. These factors include propagation velocities, attenuation, reflection, refraction, discontinuities and the geometry of the material. Furthermore, the propagation velocity of an elastic stress wave depends on the wave type, material properties and frequency. When the stress waves reach the surface they cause it to vibrate and the vibration can be measured. The minute surface displacements are measured using sensitive transducers which respond to surface displacements to the order of several picometers.

Several types of transducers can be used for this: piezoelectric, capacitance, electromagnetic and optical. The last two are non-contact, but electromagnetic transducers are considerably less sensitive than piezoelectric transducers. Optical sensors, e.g. laser, are free of resonance and can be absolutely calibrated by measuring the correct amplitude of the AE [28].

Piezoelectric transducers are the most popular and are either of a broadband or a resonance type. The transducers are made by using a special ceramic, usually Porous Lead Zirconate Titanate (PZT). Figure 7 shows a schematic view of a piezoelectric transducer and how an AE is converted into an electric representation. The transducers are pressed up against the surface of the material and the vibration is transferred to the PZT inside the transducer through the wear plate. When the PZT element vibrates it generates an electric signal. The transducer's signal is, therefore, a 1D voltage-time representation of the 3D displacement-time wave that it senses [29].

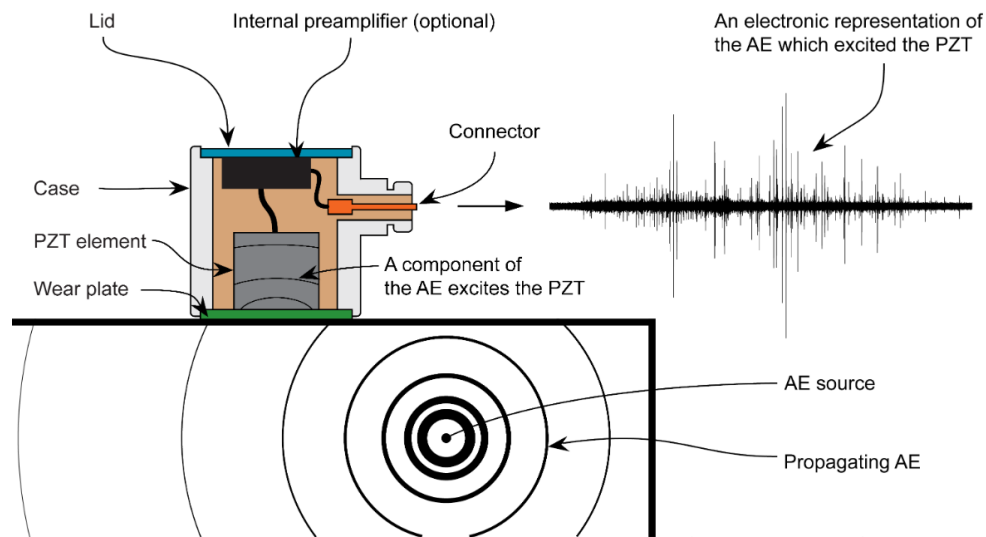


Figure 8. An illustration of a typical resonant piezoelectric AE transducer and how an AE is converted into an electric representation [29]

The application of AE to monitoring damage formation and failures in rolling contact fatigue is comparatively recent for diagnosis in the rolling contact state. The primary advantage of AE comes from its high sensitivity. Since AE is produced at a microscopic level, it is more sensitive as compared to the well-established vibration monitoring technique in order to detect loss of mechanical integrity or defect. However, to date, most researchers have performed the trial experiments with “artificial” or “seeded” damage in rolling elements. This damage or defect has been introduced by scratching the surface, introducing debris into the lubricant of the machine with an electrical discharge, spark erosion method, etc. the AE technique was viable for monitoring rolling elements deterioration, and the AE parameters increased proportionally with the damage size and load. Moreover, the AE technique is able to detect the smaller damages in comparison with vibration measurement. [12]

It was further recommended that the AE could detect crack initiation and growth, while the vibration accelerometer could only detect the crack growth at a later stage of the crack growth process. In addition, AE results were correlated to various damage conditions and gear tooth surface damage such as pitting; however, defect determination was analyzed by conventional vibration metrics. [12]

3.3.1 Main basic features of AE Signal

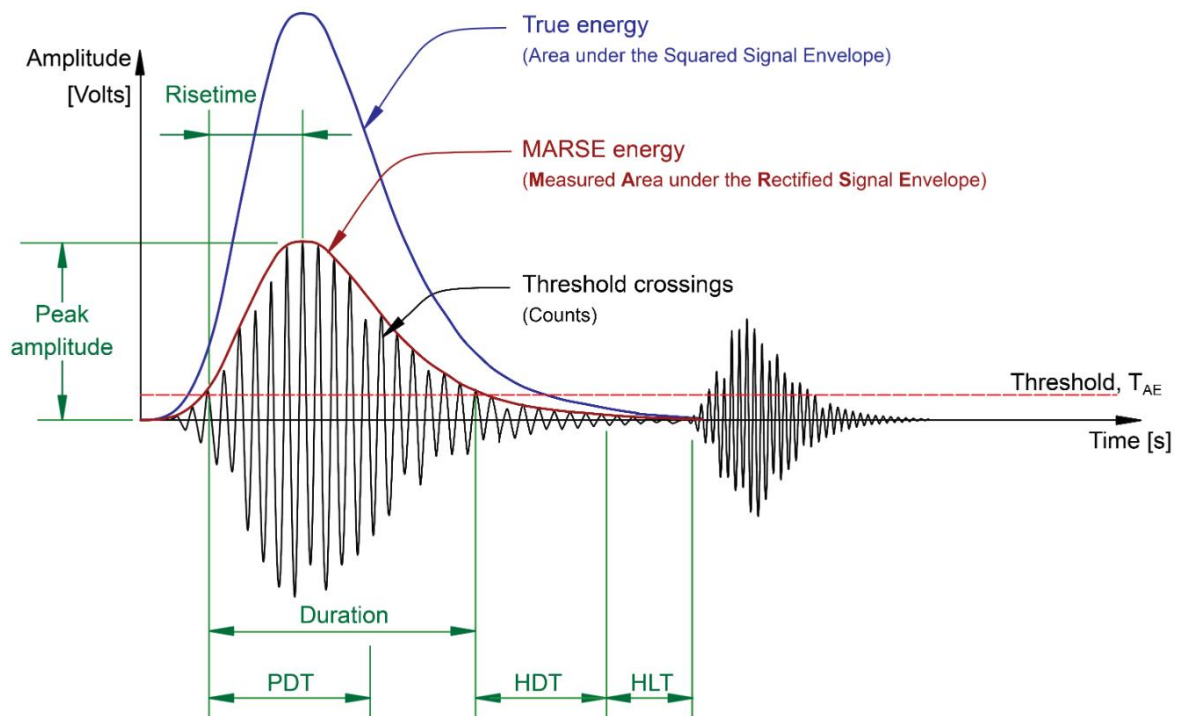


Figure 9. Features of an AE Burst [29]

3.3.1.1 Amplitude

The amplitude is the greatest measured voltage of the signal, corresponding to the greatest surface displacement, and is closely related to the magnitude of the source event.

3.3.1.2 Ring Down Counts

Ring down counts (sometimes simply referred to simply as counts) are a count of the number of the times during a single event the signal exceeds the threshold. The number of counts depends upon the transducer frequency, the damping characteristics of the transducer, the damping characteristics of the structure and the pre-defined threshold [26].

3.3.1.3 MARSE

The Measured Area of the Rectified Signal Envelope (MARSE) is a regularly used parameter in acoustic emission testing. The MARSE represents the energy content of a signal although different system suppliers use variations in the method of calculation.

3.3.1.4 Duration

Duration is measured as the period between the first and last threshold crossings. In a similar manner to counts, the duration can be used to differentiate between sources of acoustic emissions and therefore act as a filter.

3.3.1.5 Rise Time

The rise time is a measure of the time difference between the first threshold crossing and the peak amplitude. It can be used to classify the type of fracture or, as with counts and the duration, eliminate noise signals.

3.3.2 Brief Definition of Acoustic Emission signal features:

Feature	Definition	Unit
Amplitude	$\text{dB}_{AE} = 20\log(U_{\max}/1\mu\text{V}) - \text{dB}_{\text{preamplifier}}$	[dB]
Counts	N_{AE}	[#]
Duration	t_{AE}	[μs]
Rise time	$t_0 - t_{\text{peak}}$	[μs]
Counts to peak	N_{peak}	[#]
Root mean square (RMS)	$\text{RMS} = \sqrt{\frac{1}{T_{\text{RMS}}} \int_{t_0}^{t_0+T} U^2(t)dt}$ with a characteristic time T_{RMS} for averaging ranging from 10 to 1000 ms	[mV]
Average signal level (ASL)	$\text{ASL} = \sqrt{\frac{1}{T_{\text{ASL}}} \int_{t_0}^{t_0+T} (20\log(U(t)/1\mu\text{V}) - \text{dB}_{\text{preamplifier}})dt}$ with a characteristic time T_{ASL} for ranging from 10 to 1000 ms	[dB]
Average frequency	$\langle f \rangle = N_{AE}/t_{AE}$	[Hz]
Reverberation frequency	$f_{\text{rev}} = \frac{N_{AE} - N_{\text{peak}}}{t_{AE} - t_{\text{peak}}}$	[Hz]
Initiation frequency	$f_{\text{init}} = \frac{N_{\text{peak}}}{t_{\text{peak}}}$	[Hz]
Rise angle	$\phi_{\text{rise}} = \tan\left(\frac{U_{\max}}{t_{\text{peak}}}\right)$	[rad]
Decay angle	$\phi_{\text{decay}} = \tan\left(\frac{U_{\max}}{t_{AE} - t_{\text{peak}}}\right)$	[rad]
Absolute energy	$W_{AE} = \int_0^{t_{AE}} \frac{(U(t))^2}{10\text{k}\Omega} dt$ with 10kΩ input impedance of the recording equipment	[aJ]
Peak frequency	f_{peak}	[Hz]
Frequency centroid	$f_{\text{centroid}} = \frac{\int f \cdot \tilde{U}(f)df}{\int \tilde{U}(f)df}$	[Hz]
Weighted peak frequency	$\langle f_{\text{peak}} \rangle = \sqrt{f_{\text{peak}} \cdot f_{\text{centroid}}}$	[Hz]
Partial power	$\int_{f_1}^{f_2} \tilde{U}^2(f)df / \int_{f_{\text{start}}}^{f_{\text{end}}} \tilde{U}^2(f)df$ Frequency range of interest $[f_1;f_2]$ Frequency range of investigation $[f_{\text{start}};f_{\text{end}}]$	[%]

Where:

Feature	Definition	Unit
t_0	Time of first threshold crossing (arrival time)	[s]
N_{AE}	Number of threshold crossings	[#]
t_{AE}	Time between first and last threshold crossing of signal	[μ s]
U_{max}	Maximum signal voltage	[mV]
t_{peak}	Time of maximum signal voltage	[μ s]
f_{peak}	Frequency of maximum signal contribution	[Hz]
N_{peak}	Number of threshold crossings between t_0 and t_{peak}	[#]

3.3.3 AE Modes

Acoustic emission signals can be characterized as continuous, burst or a combination of both sometimes referred to as mixed emission. This distinction was first made by Kaiser in his seminal work on acoustic emissions.

3.3.3.1 Continuous Emission

Continuous emissions are typically low energy emissions which occur when friction mechanisms or dislocation movements occur on or within a structure and do not display any visually obvious features in the time domain. The amplitude of the emission increases with applied load. Noise can also be a component attributing to a signal exhibiting continuous emission. The monitoring of continuous emission is suited to the detection and analysis of signals produced by plastic deformation in ductile materials, stress corrosion cracking and creep. It has been suggested that this type of emission is best measured with RMS or energy rate measuring circuitry; parameters which are calculated over the entire signal for a predefined period [26].

3.3.3.2 Burst Emission

Burst emission signals have definite start and end points with distinct peaks of significantly larger amplitude than the background noise. Such bursts tend to be no longer than a few hundredths of a second long. Deformation mechanisms which tend to exhibit burst type emissions include the fracture of non-metallic inclusions, breakage of corrosive products or crack propagation in brittle materials. Impact, which is particularly relevant when monitoring bearing damage, can also be a source of burst emissions. Situations may occur where burst and continuous emissions are present creating a mixed emission.

3.3.4 AE Source Location Techniques

3.3.4.1 Multi-Channel Source Location Techniques:

Locating the source of significant acoustic emissions is the main goal of an inspection. Although the magnitude of the damage may be unknown after AE analysis, follow up testing at source locations should provide the answers. Most AE systems are capable of using multiple sensors/channels during testing, allowing them to record a hit from a single AE event. The AE systems can be used to determine the location of an event source. As hits are recorded by each sensor/channel, the source can be located by knowing the velocity of the wave in the material and the difference in hit arrival times among the sensors, as measured by hardware circuitry or computer software. By properly spacing the sensors in this manner, it is possible to inspect an entire structure with relatively few sensors.

Source location techniques assume that AE waves travel at a constant velocity in a material. However, various effects may alter the expected velocity of the AE waves (e.g. reflections and multiple wave modes) and can affect the accuracy of this technique. Therefore, the geometric effects of the structure being tested and the operating frequency of the AE system must be considered when determining whether a particular source location technique is feasible for a given test structure.

3.3.4.2 Linear Location Technique

Several source location techniques have been developed based on this method. One of the commonly used computed-source location techniques is the linear location principle shown to the right. Linear location is often used to evaluate struts on truss bridges. When the source is located at the midpoint, the time of arrival difference for the wave at the two sensors is zero. If the source is closer to one of the sensors, a difference in arrival times is measured. To calculate the distance of the source location from the midpoint, the arrival time is multiplied by the wave velocity. Whether the location lies to the right or left of the midpoint is determined by which sensor first records the hit. This is a linear relationship and applies to any event source between the sensors.

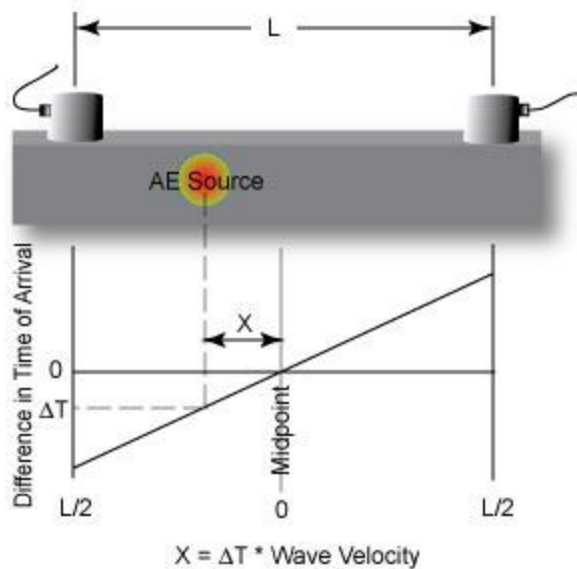


Figure 10. linear location using AE [37].

Because the above scenario implicitly assumes that the source is on a line passing through the two sensors, it is only valid for a linear problem. When using AE to identify a source location in a planar material, three or more sensors are used, and the optimal position of the source is between the sensors. Two categories of source location analysis are used for this situation: zonal location and point location.

3.3.4.3 Zonal Location Technique

As the name implies, zonal location aims to trace the waves to a specific zone or region around a sensor. This method is used in anisotropic materials or in other structures where sensors are spaced relatively far apart or when high material attenuation affects the quality of signals at multiple sensors. Zones can be lengths, areas or volumes depending on the dimensions of the array. A planar sensor array with detection by one sensor is shown in Figure 10.

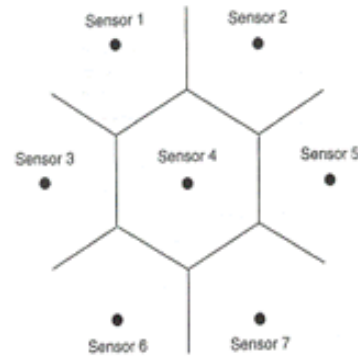


Figure 11. Zonal location using AE [37]

3.3.4.4 Point Location

In order for point location to be justified, signals must be detected in a minimum number of sensors: two for linear, three for planar, four for volumetric. Accurate arrival times must also be available. Arrival times are often found by using peak amplitude or the first threshold crossing. The velocity of wave propagation and exact position of the sensors are necessary criteria as well. Equations can then be derived using sensor array geometry or more complex algebra to locate more specific points of interest.

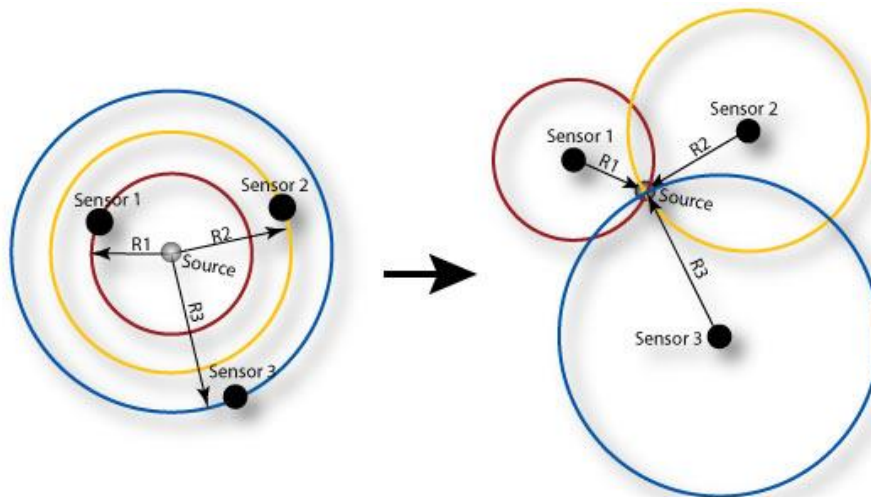


Figure 12. Two geometrical methods to locate the source point in a plane using 3 sensors [37].

3.4 Key publications

3.4.1 A Fundamental Study On the Impact of Surface Integrity by Hard Turning On Rolling Contact Fatigue [11]

The goal: to answer the long-standing question of how residual stress and the white layer affect Rolling Contact Fatigue (RCF).

The hypothesis: The white layer induced by hard turning is very detrimental to RCF.

Acquired knowledge:

- The early fatigue damage and fatigue failure can be accurately captured by the AE amplitude.
- Compressive surface residual stress with a negative slope of residual stress profile in the near-surface can significantly increase RCF life. However, the depth and magnitude of the maximum compressive residual stress in the subsurface seems to be non-critical.

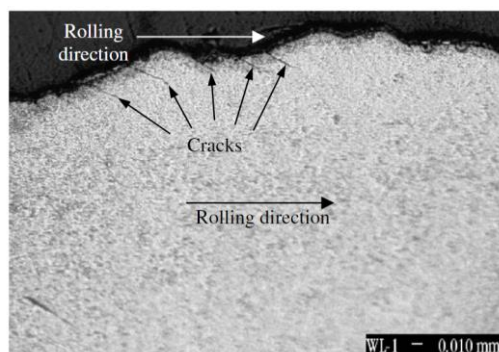


Figure 13. Sub-surface fatigue crack orientation at initiation stage for white layer surface.

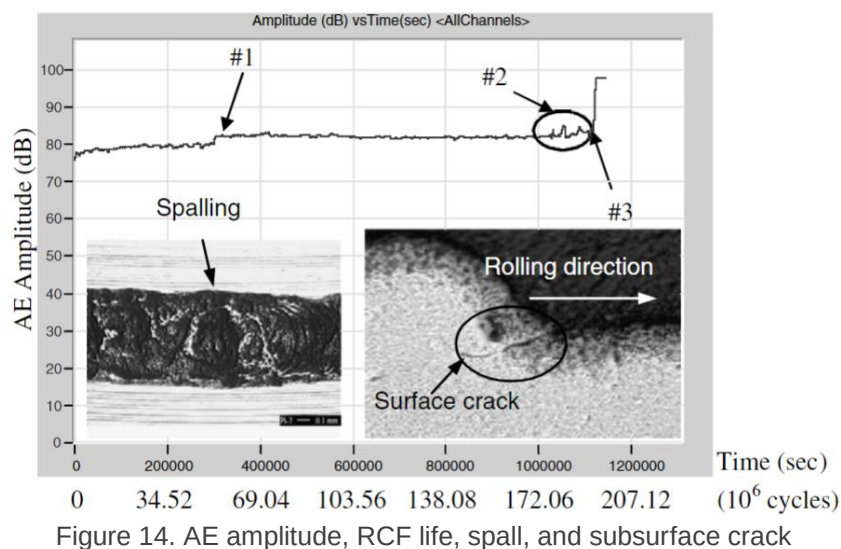


Figure 14. AE amplitude, RCF life, spall, and subsurface crack

Usefulness for the subject:

- The test results have shown that the AE amplitude is most consistent and sensitive to fatigue damage than other AE parameters.
- Surface integrity affects RCF through the mechanism of near surface damage rather than subsurface damage.

3.4.2 A Study on Incipient Damage Monitoring in Rolling Contact Fatigue Process Using Acoustic Emission [12]

The goal: The objective was to elucidate the potentiality of the AE technique as a useful diagnostic tool for the condition monitoring of gears in detecting and locating early damage of rollers during contacts. The study involved the monitoring of sound rolling elements (new undamaged rolling elements with no simulated or seeded damage) running in contacts through its incipient damage evolution by collecting the AE signals from their health condition monitoring.

The hypothesis: Combining the AE monitoring and the AE source locator can be used to detect the incipient damage and to forecast the position of the damage in rollers, and this technique could allow the monitoring of the deterioration rate of the rolling elements.

Acquired knowledge:

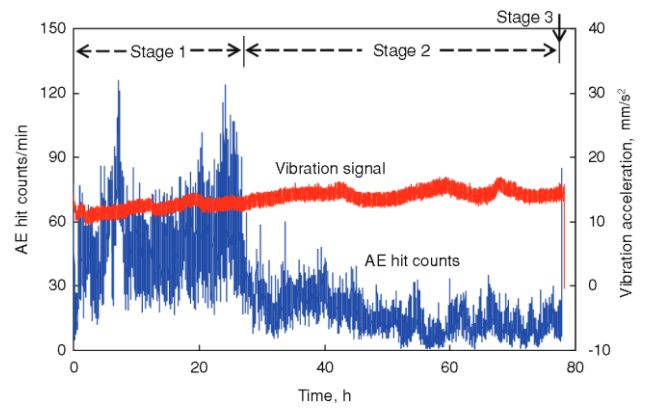
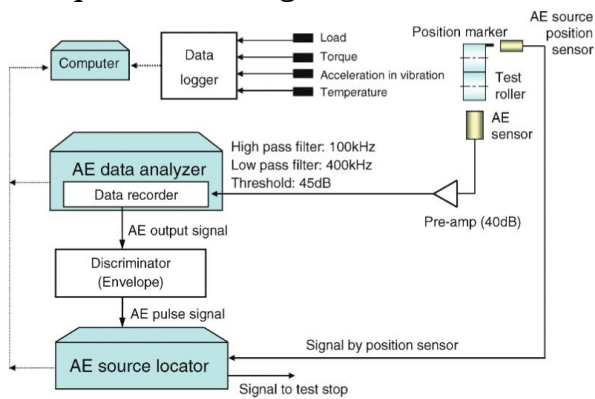


Figure 15. Schematic diagram of data acquisition

Figure 16. AE hit counts rate and its corresponding vibration signals during a test.

The typical AE features, amplitude and energy, were employed to identify and classify AE signatures. Figure 15 displays AE hit counts rate (number of AE hit counts per 1 min) and its corresponding acceleration in vibration with time during in RCF test. Initially, the AE hit counts rate increased gradually because of interaction of the initial surface roughness and plastic deformation of two rollers. This state is termed as “running-in state” This region prevailed up to 27 h ($N=1.3 \times 10^6$ cycles), and then decreased and continued until the incipient damage occurs. The subsequent drop in the AE signal level might be attributed to the phenomenon known as “healing”. The term is applied to the smoothing of the sharp edges of the initial surface roughness due to plastic deformation and/or wear by continued rolling contact.

Usefulness for the subject: The AE hit counts rate is a very important parameter to reflect the incipient damage. the combination of the AE source locator and the AE data analyzer could be used as a useful tool for determining the incipient damage with its position of occurrence.

3.4.3 Correlation Between Features of Acoustic Emission Signals and Mechanical Wear Mechanisms [13]

The goal: To permit the recognition of wear mechanisms by means of acoustic emission (AE) monitoring technique.

The hypothesis: The difference between AE signals detected during adhesive wear in the high-frequency region and the AE signals detected during abrasive wear in low-frequency region permits the recognition of wear mechanisms.

Acquired knowledge:

Acoustic emission (AE) signals are produced when elastic stress waves are generated as a result of deformation and fracture of a material. AE signals are generated when friction and wear processes occur at a frictional interface.

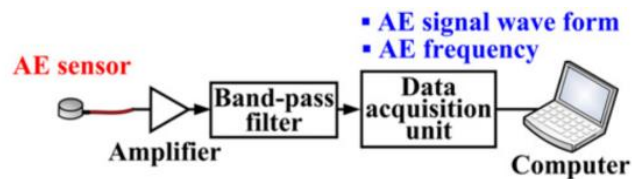


Figure 17. Block diagram of the instrumentation used for the acquisition of the AE signal.

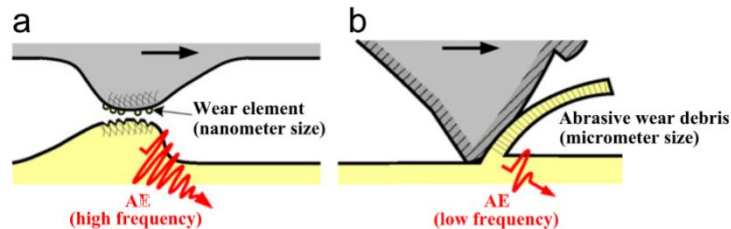


Figure 18. Schematic of sources of AE in (a) adhesive wear and (b) abrasive wear.

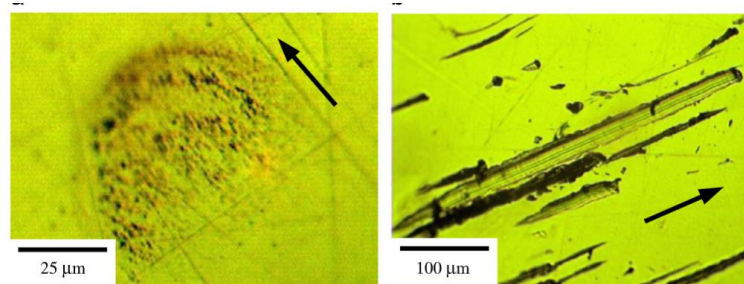


Figure 19. Micrographs of wear tracks for pin specimens: (a) adhesive wear (Fe/Fe, dry); and (b) abrasive wear. The arrow in each micrograph indicates the direction of sliding.

The Figure below (Figure 19) shows a correlation map for the AE frequency spectrum ($\Rightarrow$: frequency band, $\uparrow$: frequency peak) for several phenomena associated with deformation and fracture. The vertical axis represents the amplitude of the AE signal and the horizontal axis represents its frequency. In figure 19, the magnitude of the AE signal on the vertical axis is sequenced roughly because this shows marked changes depending on the type of AE sensor, AE filters, the experimental system (the distance and propagation paths of the waves from the respective AE sources to the sensors), and experimental conditions. The AE frequency spectra obtained in our experiments are shown by thick lines.

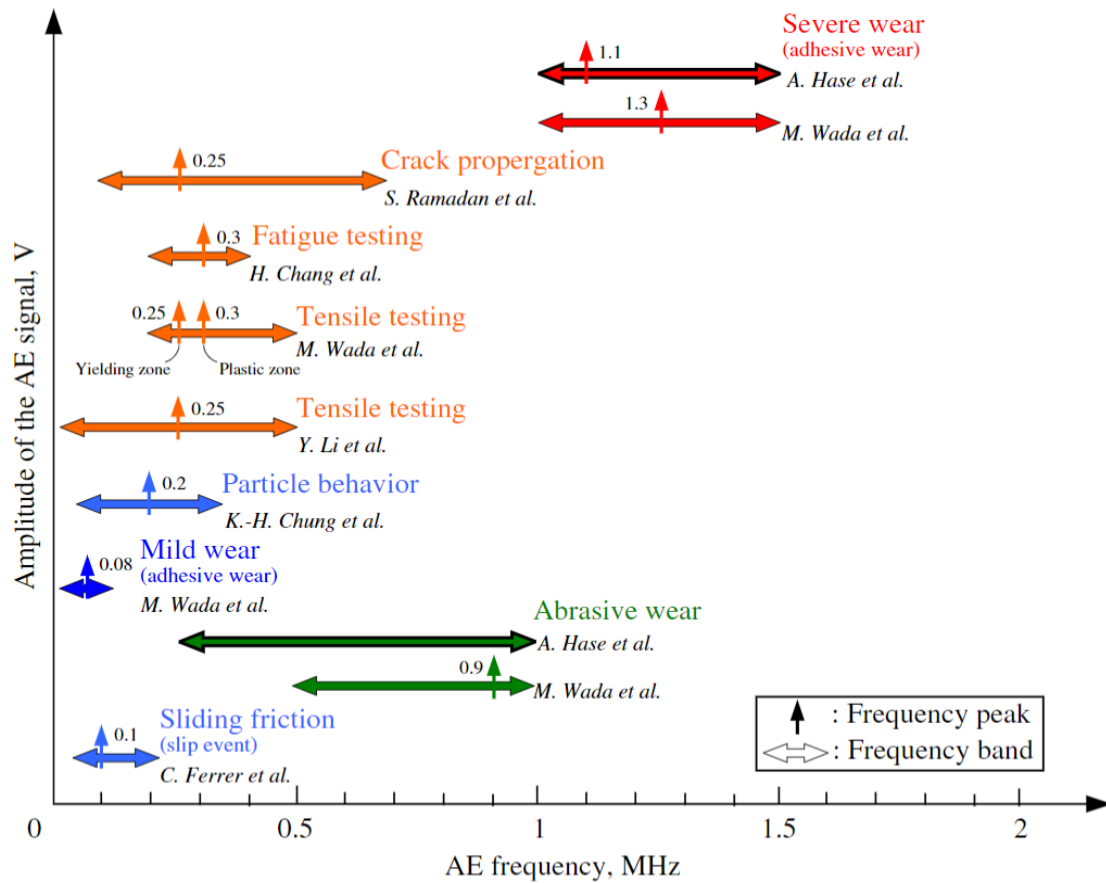


Figure 20. Correlation map of AE frequency spectra for phenomena involving deformation and fracture

(⇔ frequency band, ↑ frequency beak)

The AE signals detected during adhesive wear showed a large peak in the high-frequency region, whereas AE signals detected during abrasive wear showed a few peaks in the low-frequency region.

In adhesive wear, burst-type AE signals are produced as a result of the generation of wear elements and transfer particles. The amount of transfer influences the amplitude of the detected AE signals. The frequency peak of the AE signals occurs at around 1.1 MHz.

In abrasive wear, burst-type AE signals are generated by cutting and plowing of material. The removal capability of the abrasive grains influences the amplitude of the detected AE signals. The frequency peaks are distributed in the region from 0.25 to 1 MHz.

The mechanisms of wear can be recognized from the features of the AE frequency spectrum. Also, the AE signals that correspond to particular wear mechanisms can be discriminated.

Usefulness for the work:

The correlation map that is presented in this study makes clear that the distribution of the AE frequency changes depending on the mode of deformation and fracture. Each wear mechanism produces its own type of AE frequency spectrum, which is not dependent on the nature of the materials involved.

This paper also states clearly that the mechanisms of wear can be recognized from the features of the AE frequency spectrum.

3.4.4 A Novel Approach for Incipient Defect Detection in Rolling Bearings Using Acoustic Emission Technique [15]

The goal: the paper proposes an AE signal envelope analysis method for bearing incipient defect detection.

The hypothesis: The method (envelope analysis) is able to identify localized defects in an incipient stage, in which the signal-to-noise ratio (SNR) is extremely low.

Acquired knowledge:

The proposed method combines Wavelet packet for AE signal de-noising, the Hilbert Transform (HT) for envelope extraction, and autocorrelation function, to find patterns in the AE signal.

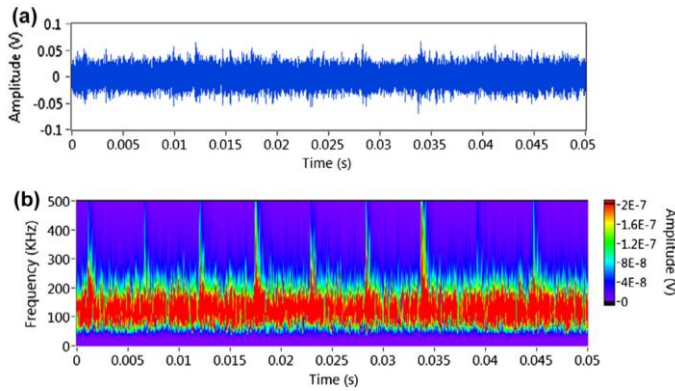


Figure 21. AE signal from defected bearing in (a) time domain and (b) scalogram.

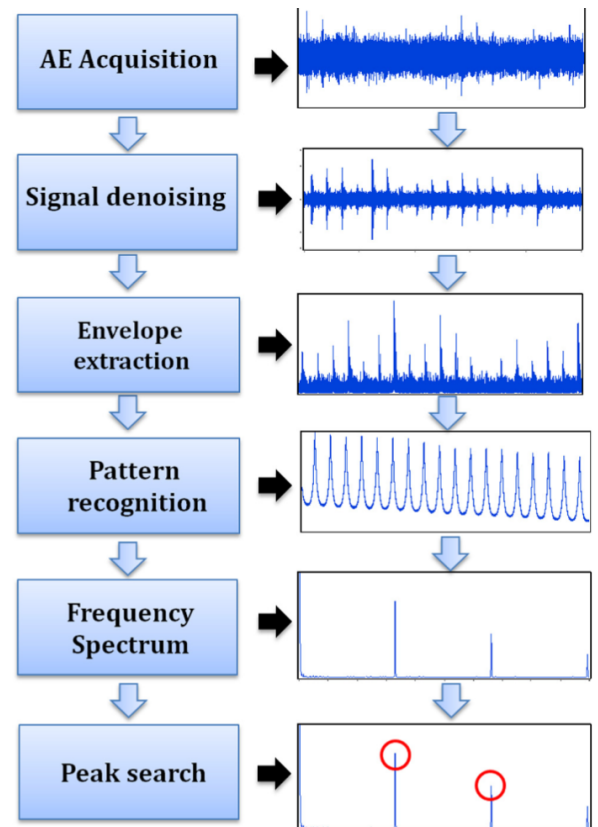


Figure 22. Flow chart of the proposed method.

Usefulness for the subject:

the proposed method is able to detect the defect with 9 dB lower SNR than the traditional method. This scenario, in which the SNR is low, is typically present in defects at an early stage, which would be very beneficial for later studies.

Another interesting finding of this paper is the fact that the high frequency spectrum of AE provides most of the information regarding the seeded defect.

3.4.5 Low Speed Bearing Fault Diagnosis Using Acoustic Emission Sensors [16]

The goal: presenting a new methodology for low speed bearing fault diagnosis.

The hypothesis: The used resampling approach is able to segment the AE signal according to shaft crossing times to compute a single spectral average, which is used to extract features and evaluate condition indicators for bearing fault diagnosis.

Acquired knowledge: This acoustic emission (AE) based technique starts with sampling the AE signals at a rate comparable to vibration centered methodologies. Then, the sampled AE signal is time synchronously resampled to account for possible fluctuations in shaft speed and bearing slippage. This approach can segment the AE signal according to shaft crossing times to compute a single spectral average, which is used to extract features and evaluate condition indicators for bearing fault diagnosis. The approach computes only one average for all bearing fault types. They began with a heterodyne technique that allows AE signals to be sampled at a rate comparable to vibration based approaches.

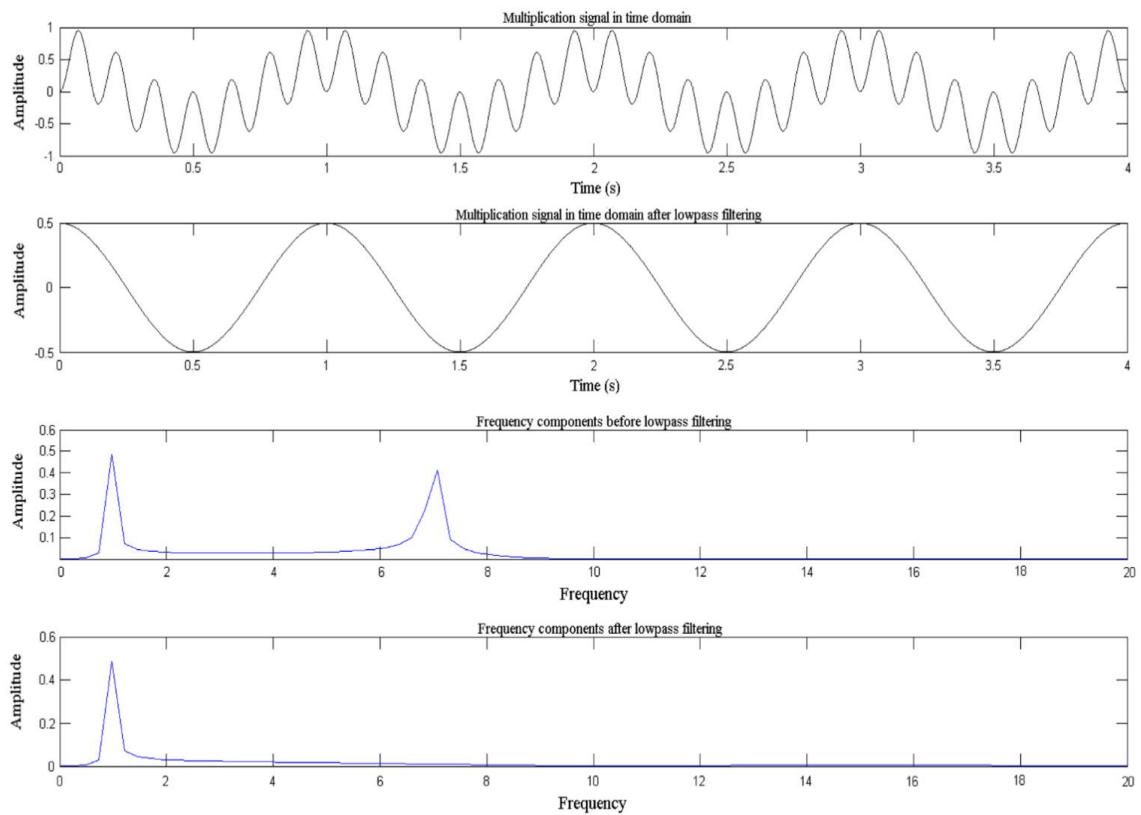


Figure 23. Extracting the heterodyned signal by frequency domain filtering

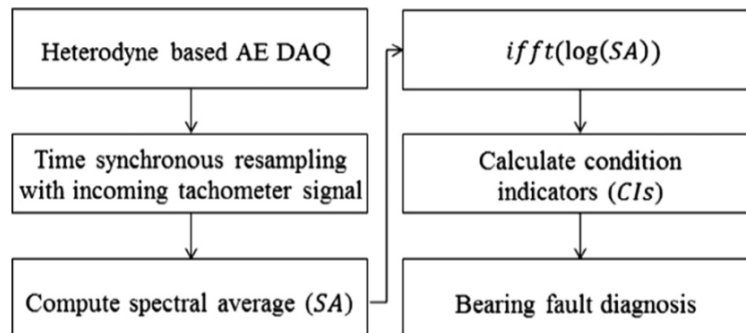


Figure 24. Overview of the methodology.

For the condition indicator Shannon's entropy, the separation of the bearing faults increases with decreasing shaft speeds. This indicates the potential of the methodology to diagnose bearing faults at shaft speeds lower than what was presented in the paper.

Usefulness for the work: The test rig that is used in this work is very similar in principle to what would be a useful test rig for our work. The results in this paper indicate that the low sampled AE signals in combination with the presented approach can be utilized to diagnose the types of bearing faults at low shaft speeds as low as 10 Hz, and we suppose that we could benefit from this results.

3.4.6 Determination of Rolling Element Bearing Condition Via Acoustic Emission [17]

The goal: investigation of the effects of increased speed and load on the generation of AE within cylindrical roller bearings.

The hypothesis: The increase in speed has a higher effect on RMS of the signal than the increase in loading. The root mean square signal level increased significantly with increasing speed whereas increasing load had a far weaker effect.

Acquired knowledge: This work showed that the excitation of the bearings resonant frequencies was responsible for an increase of energy in the frequency range of 20–60 kHz.

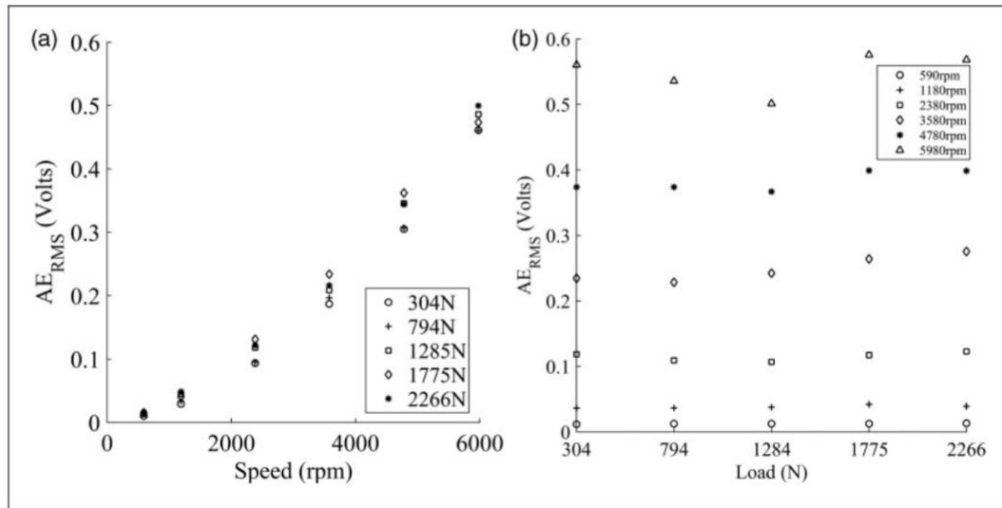


Figure 25. (a) AE_{RMS} vs. Speed and (b) AE_{RMS} vs. Load

Initial analysis determined a strong correlation between speed and AE_{RMS} and a far less significant effect due to increasing load. By studying the frequency response with respect to time, it was shown that the lower frequency range, 20–60 kHz, was highly sensitive to speed and is associated with the bearing's natural resonant frequencies. Whereas load has little effect on the frequencies lower than 60 kHz, the energy released at 330 kHz (the sensor's resonant frequency) increases as load is increased, this is due to increased stresses within the contact zone and hence a greater release of strain energy and increased likelihood of plastic deformation occurring.

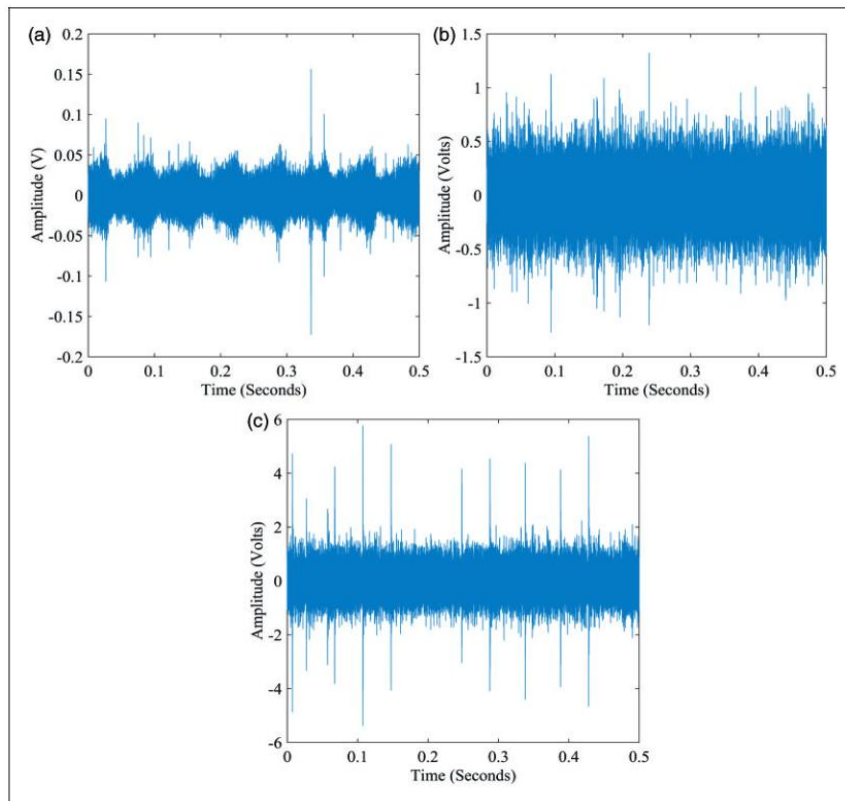


Figure 26. Raw AE waveforms at (a) 590 r/min, (b) 2980 r/min and (c) 5980 r/min

An accelerated life test demonstrated that during a period of continuous wear, the bearings resonant frequencies increased in amplitude even though the bearing was operating at a constant speed and load. Higher frequency components, 115, 125 and 330 kHz all remain at a constant amplitude throughout the constant wear phase. As the bearing tends towards final failure, the frequencies that were previously dominant become less so, and a broader range of frequencies become excited. It is considered that this is due to the over-rolling of multiple debris particles, causing higher frequency signals to become merged together.

Usefulness for the subject: The results presented in this article demonstrate the sensitivity of the AE technique to both bearing operating conditions, and to bearing failure, therefore they demonstrate its great potential for use in bearing monitoring systems.

3.4.7 Modelling of Acoustic Emission Generated in Rolling Element Bearing [18]

The goal: developing a mathematical model to understand the influences of operating parameters on energy of AE generated in rolling element bearing.

The hypothesis: A mathematical model that represents the actual physical mechanism in the bearing can be developed and can explain the experimental results.

Acquired knowledge: The authors developed a theoretical model on the bases of asperities interaction between surfaces of inner race, outer race and rolling element of bearing using Hertzian contact approach, statistical concepts, contact load distribution during the load zone and lubrication effects.

Their model has been validated with experiments.

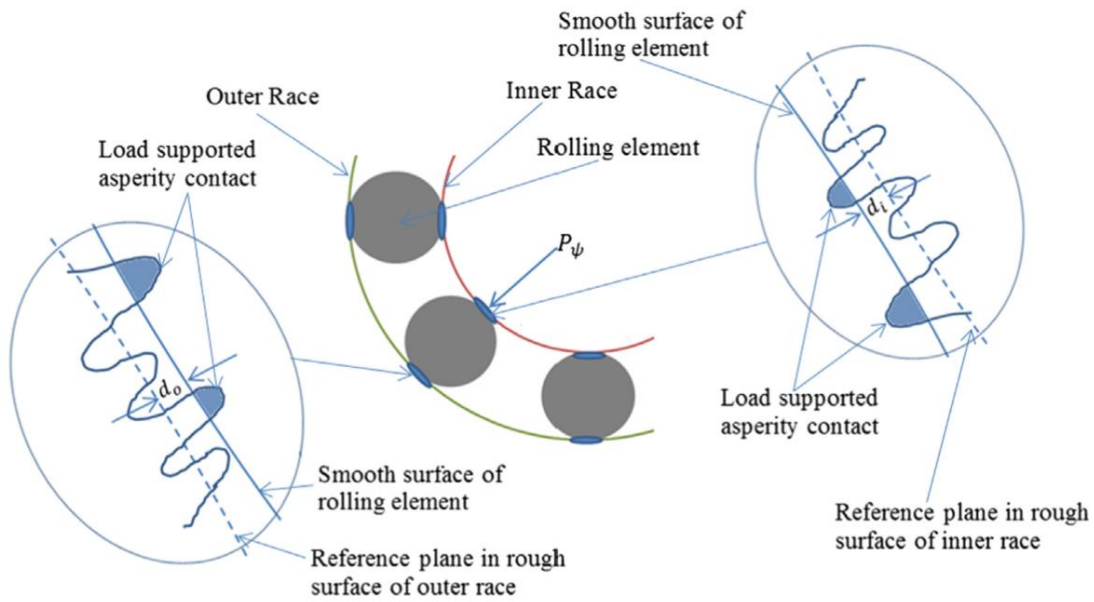


Figure 27. Deformation of asperities during contact between smooth surface and rough surface in rolling element-races contacts.

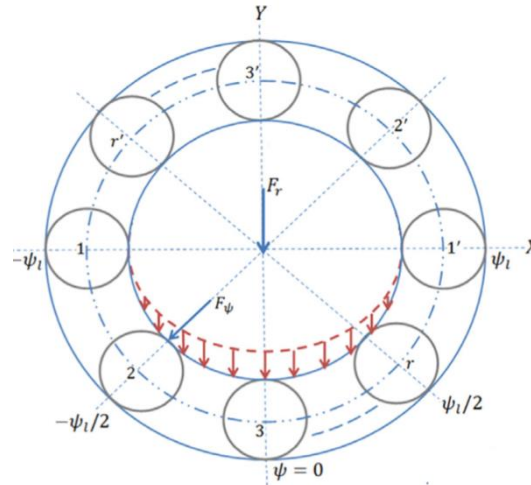


Figure 28. Radial load distribution for $\epsilon = 0.5$, $\Delta_r = 0$

The results of the developed model demonstrate that the level of AE is influenced by the load, rotational speed, defect size, number of asperity contacts, bearing element surface topographic characteristics and specifications/profile of bearing.

The model has been developed by considering the effect of contact load distribution during the load zone, lubrication effect, and influence of presence of defect during the load zone which play the vibrant role in generating of the AE during the bearing operation.

Usefulness for the subject: The developed model correlates AE to bearing operating parameters, and it shows the potential of this model to understand the AE generated during the bearing operation which is an important factor in the condition monitoring of rolling element bearings. The developed model was validated on the bases of experimental studies conducted by other researchers in other papers. And we can use this model to validate any experimental data in the future.

3.4.8 The Detection of Plastic Deformation in Rolling Element Bearings by AE [19]

The goal: the detection of plastic deformation by acoustic emission in rolling element bearing at increased rotational speeds.

The hypothesis: The transient force signals dominate the acoustic emission signal of a rolling element bearing at increased rotational speeds, while at low rotational speed plastic deformation is detected by acoustic emission.

Acquired knowledge:

- The work showed a dominance of transient force signals at high rotational speeds.
- At low rotational speed plastic deformation is detected by acoustic emission.
- detectability of plastic deformation in rolling element bearings caused by particle contamination depends on the ratio between signals caused by plastic deformation and transient force signals.
- The contribution of transient force signals decreases with the decrease of rotational speed. Eventually the contribution of transient force signals is so weak that plastic deformation can be detected with decreased rotational speed.

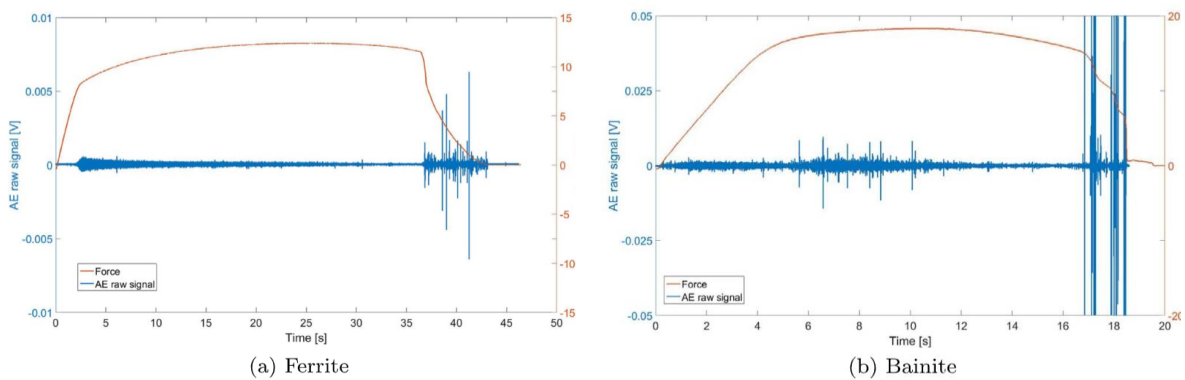


Figure 29. Acoustic emission measurements of a tensile test (a and b are in different scales)

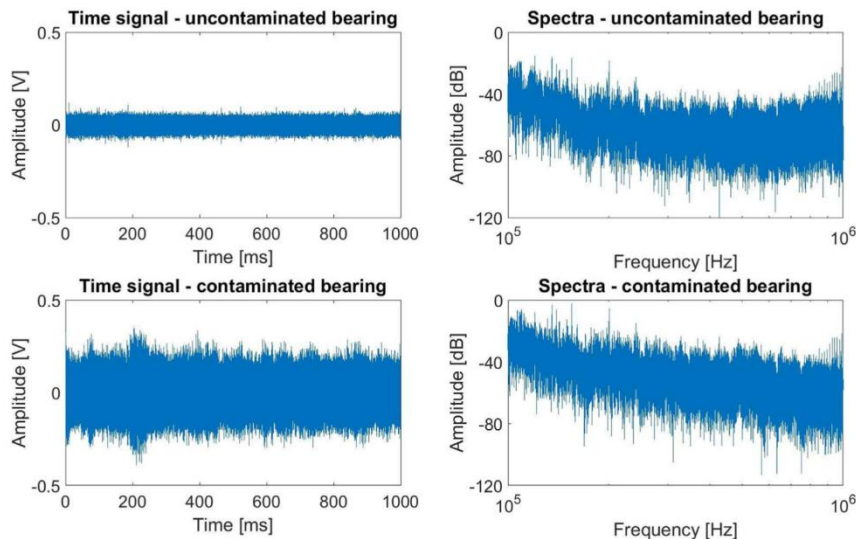


Figure 30. Time signal and spectra of acoustic emission measurements of a contaminated and an uncontaminated bearing at 100 rpm and 10 kN load.

Usefulness for the work: The results of this paper indicate that the full scale bearing tests could be understood better by using component tests, studying isolated phenomena, such as plastic deformation or transient forces. This note should be considered in any future work.

3.4.9 Detection of Sub-Surface Damage in Wind Turbine Bearings Using Acoustic Emissions and Probabilistic Modelling [20]

The goal: presenting a methodology for detecting sub-surface damage using Acoustic Emission (AE) measurements.

The hypothesis:

Damage in bearing parts can be detected before it reaches the surfaces of those parts. In other words, sub-surface damage can be detected using AE.

Acquired knowledge:

The authors of the article have used the probabilistic modelling, more specifically Gaussian mixture models as a principled statistical procedure for damage detection. Damage in bearings starts under the surface, as a result of Hertzian contact mechanics. Sub-surface damage is harder to detect and has received much less attention. AE data were collected from many sensors and processed separately in order to evaluate the detectability of the different levels of defects at each location.

Detection of damage was carried out by first extracting three different damage-sensitive features from the raw AE data, and then fitting a probabilistic model to perform novelty detection. The features chosen in this investigation were hit summary statistics, Auto Regressive (AR) coefficients of the individual AE hit time histories, and the envelope spectra of the raw AE signals. These features all capture a different type of information contained in the AE data. The hit-based summary statistics contain information about the average energy, duration and the distance each individual stress wave has travelled. While the hit AR coefficients on the other hand provide a greater level of detail as to the spectral characteristics of the waveforms. Finally, the envelope spectra capture the amplitude modulation of the signal, so any periodic bursts of energy, which is a characteristic manifestation of damage in dynamic response data, should be evident in this feature.

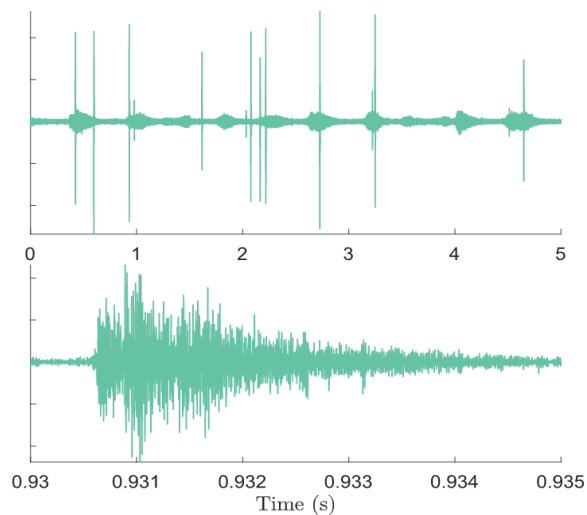


Figure 31. Example of a) an AE signal measured from an undamaged bearing in operation and b) a zoom-in to one of the “hits” characteristic of AE measurements.

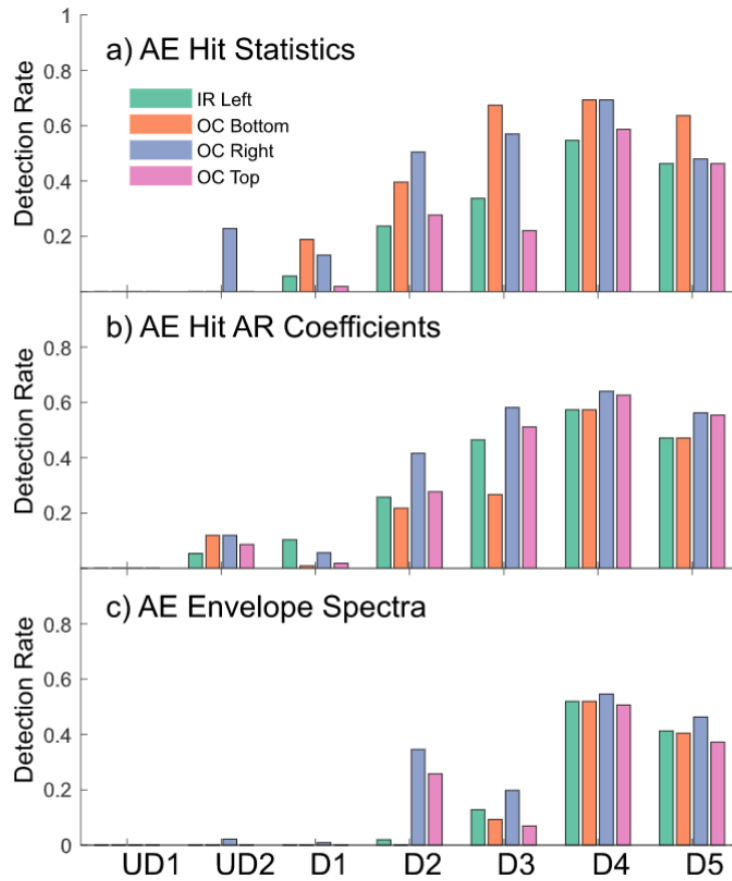


Figure 32. Detection rate for the four different AE sensor locations and the three damage-sensitive feature considered.

it is clear that the larger surface-level defects are evident through a clear change in the probability distribution of the features. This is easy to spot qualitatively. On the other hand, the change in all damage-sensitive features arising from sub-surface damage is not necessarily clear from visual examination. Further-more, in the presence of high levels of noise common in rotating machinery, it is difficult to establish whether a specific burst of AE energy has been generated by a damage process or belongs to the background noise. This motivates the need for a principled statistical approach to the detection problem. The problem is therefore treated as one of inference under a probabilistic model.

The early-stage surface defects were also investigated in this work. A total of five levels of damage were used, two sub-surface and three early-stage surface defects.

Usefulness for the subject: The work provides a complete analysis for the prediction of sub-surface damage detection. And the methods developed here have proved to be robust against challenges like the changes in applied load and temperature. And we know that one of the key aspects of AE activity within a bearing environment is that it is highly dependent on applied load and temperature, as this affects the lubrication properties.

It also showed that it is possible to identify sub-surface damage from a practical measurement location (in their case, at the casing of a planetary gearbox bearing). This is very important statement for any future study concerned with the location of AE sensors when detecting damage in bearings.

3.4.10 Propagation of surface initiated rolling contact fatigue cracks in bearing steel [21]

The goal: studying the growth of RCF cracks before they develop into surface pits, in an attempt to better understand crack propagation mechanisms.

The hypothesis: The crack initiation occurs in early in total life. There are two distinct stages of crack growth in rolling contact fatigue. And contact pressure and crack size are the main parameters controlling the crack propagation rate.

Acquired knowledge: This work provided evidence that there are two distinct stages of crack growth in rolling contact fatigue: stage 1, within which cracks grow at a slow and relatively steady rate, consumed most of the total life; and stage 2, reached at a critical crack length, within which the propagation rate rapidly increases.

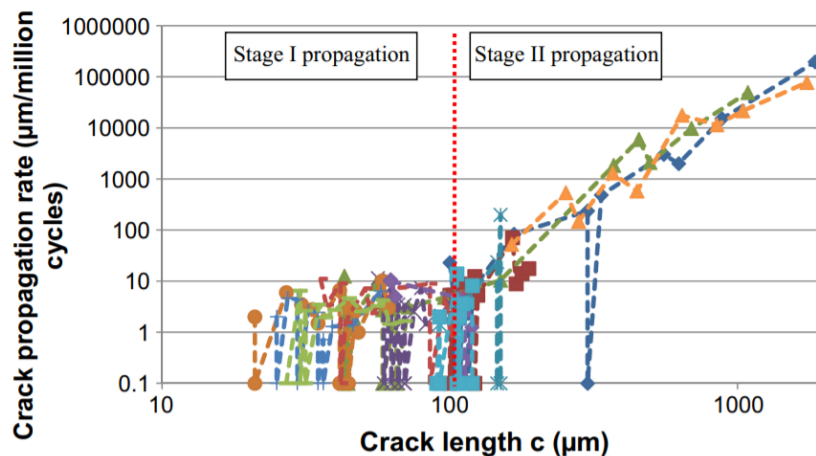


Figure 33. Crack propagation rate across the surface (dc/dN) as a function of instantaneous surface crack length.

Stage I of crack propagation was associated with cracks up to about 100 μm in length, cracks show discontinuous growth with long periods of crack arrest. The average rate of crack growth was relatively low.

In stage II propagation, reached once cracks exceeded the length of about 100 μm , propagation rate increases exponentially with crack length so that cracks extend much faster and eventually lead to pitting. Growth of the stage II rolling contact fatigue cracks can be described by a Paris-type power law, where the rate of crack growth across the surface is proportional to the contact pressure raised to a power of approximately 7.5.

Observations about crack behavior from the experiments:

- Cracks display a v-shaped propagation pattern when viewed at the surface.
- Crack growth occurs in the direction opposite to the direction of the applied friction force.
- In parallel section view cracks have an initial angle of inclination to the surface of 20–30°.
- Secondary cracks form and grow to break the surface, eventually causing a pit to form.

The data in stage II crack growth fall on a straight line when plotted using logarithmic scales. This suggests that the crack growth response to the applied stress intensity in stage 2 can be described by a Paris-type power law. The equation of the trend line fitted to the stage II crack growth data is:

$$\frac{d c}{d N} = 5 \times 10^{-12} \text{ m } \left(\frac{p_0 c^{1/2}}{\text{MPa m}^{1/2}} \right)^{7.5} \quad (8)$$

Usefulness for the work: The observations from the experiments in this study show that the failure mode observed in the present study is representative of the generally accepted mechanisms of surface initiated RCF cracks. And it provided new quantitative data on crack propagation rates within a wide range of crack lengths and at different contact pressures.

4 ANALYSIS OF THE STATE OF KNOWLEDGE

4.1 Citation Map

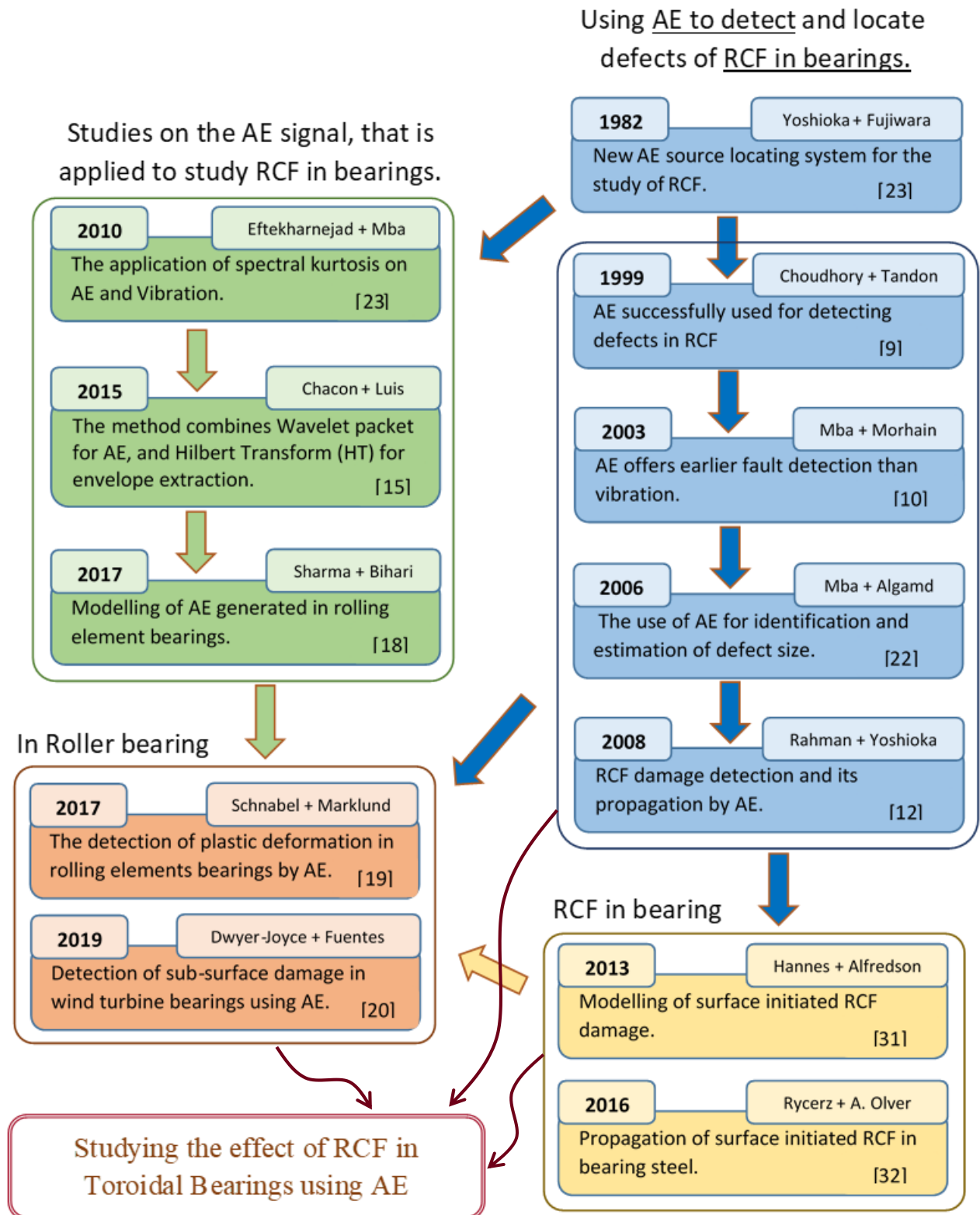


Figure 34. Citation map

4.2 Studying RCF in bearing by AE

In 1982, T. Yoshioka, and T. Fujiwara published a very important and highly-cited article “A new AE source locating system for the study of RCF” [23] and in 1987, in another article “Measurement of propagation initiation and propagation time of RCF cracks by observation of AE and vibration” [24] they reported that AE parameters can identify bearing defects before they appeared in the vibration acceleration range.

Tandon and Chaudhary (1999) [9] reviewed the AE techniques such as sound pressure, sound intensity. They concluded that Acoustic Emission measurements had also been used successfully for detecting defects in rolling element bearings and AE was better than vibration measurements. AE could detect a defect even before it appears on the surface.

A. Morhain and D. Mba (2003) [10] undertook a comparative study on the use of AE and vibration, analysis was conducted and they concluded that AE offers earlier fault detection and improved identification capabilities than vibration analysis. Then A. Algamdi and D. Mba (2004) discussed The use of Acoustic Emission for bearing defect identification and estimation of defect size. And in 2006 they published a comparative experimental study on the use of AE and vibration analysis for bearing defect and estimation of defect size [21].

Y.B. Guo with colleagues in 2005 [11] and 2006 [22] studied the AE monitoring for RCF of super finished ground surfaces, and undertook an experimental investigation of white layer on RCF using AE technique.

Z. Rahman and T. Yoshioka with others in 2008 [12] studied the incipient damage detection and its propagation monitoring of RCF by AE. And in 2009 T. Yoshioka [30] published a study of monitoring ball bearing operation under grease lubrication using a new compound diagnostic system detecting vibration and AE.

4.3 Studies concerning the AE signal characteristics

In 2009 D. Mba with colleagues continued studies and published observations of changes in AE waveform for varying seeded defect sizes in a rolling element bearing, and in 2010 published The application of spectral kurtosis on AE and vibrations from a defective bearing. In 2013, D. Hannes and B. Alfredsson published a key article titled: “Modelling of surface initiated rolling contact fatigue damage”.

Then in 2014 A novel approach for incipient defect detection in rolling bearings using AE technique was proposed by V. Kappatos and colleagues.

Low speed bearing fault diagnosis using acoustic emission sensors was introduced in 2015 by B. Hecke and colleagues.

In 2017 an article titled: Modelling of AE generated in rolling element bearing, by R. Sharma and A. Parey gave a whole new perspective about the subject.

In 2018 a study was published about the detection of plastic deformation in rolling element bearings by AE by S. Schnabel.

And in 2019, a very informative and detailed study about the detection of sub-surface damage in wind turbine bearings using AE and probabilistic modelling was published by R. Fuentes and colleagues.

4.4 Review

An overview look to the current state of knowledge shows that during the 1980s and 1990s, most of the studies concerned with rolling contact fatigue RCF in bearing were concentrating on testing and studying this phenomenon using the new technology back then which was the Acoustic Emission AE. Therefore, during that period, most of the studies were discoveries of this new AE technique in the field of RCF in bearings, and included comparisons between AE and the traditional method of studying RCF which was the Vibration Acceleration.

After 2000, it was more common to use AE technique, especially in studying RCF, and the comparison between AE and the Vibration acceleration continued. By the end of the first decade, it was obvious from most of the studies the conclusion that the AE is far more sensitive and more effective. And it became very popular to study the characteristics of RCF using AE.

During the last decade, 2010-2019, due to the increasing advancements on the AE testing systems with regard to the sensitivity and to the signal processing techniques, there has been more concentration on studying the signal analyses and the signal processing features to extract more useful information of these increasing amounts of data provided by AE testing systems.

There has been an increasing interest in recent years in studying roller bearings (Toroidal bearings are roller bearings) to improve their properties, characteristics, and life expectancy because of the increased demand for such bearings in different fields.

4.5 Blank spot in the Current State of Knowledge

The subject of testing toroidal bearings with regard to their ability to adapt to different working positions (angular and axial misalignments) was not studied before.

Even other types of bearings, which allow only angular misalignment (like spherical bearings), or only axial misalignment (like cylindrical bearings), were not studied with regard to their different working positions.

4.6 JUSTIFICATION OF NECESSITY of this work

- Toroidal Bearings are newly produced type of bearings.
 - First invented and produced by SKF in 1995 as the CARB Toroidal bearings.
 - After 2005, other companies started production, mainly Schaeffler as TORB bearings.
 - In the Czech Republic, by ZKL, just 2 years ago. And there is a pressing need to further study its characteristics and to improve its quality, competitiveness, and applicability.
- There is No research in the current scientific literature on toroidal bearings.
- Toroidal bearings are relatively expensive. They should always be tested by Non-Destructive Testing method. And Acoustic Emission is a well-developed NDT technique and it has been proven through many studies in recent years to be effective for predicting RCF in early stages.
- AE testing systems are still in constant development with regard to the sensitivity, the parameters, and the signal processing techniques, so it is still promising and has a lot of potentials.
- Testing and understanding toroidal bearings and its wide range of applications gives better understanding of other types of bearings, which still can be improved.
- The simulation model that will be developed along this work will allow to simulate the influence of various types of bearings that permit angular or axial misalignment.

5 OBJECTIVES OF THE DISSERTATION AND A PROPOSAL TO SOLVE IT

5.1 Objectives

- ❑ The main objective is to study the detection of Rolling Contact Fatigue (RCF) damage in Toroidal Bearings using Acoustic Emission technique, and to provide a deeper explanation of the origin the RCF damage in these bearings. Using AE technique as the main tool to detect the RCF damage in bearings has been proven by many studies ([9,10], [12], [23], and [24]) that AE is a viable technique for monitoring the deterioration of rolling elements, and those studies concluded that AE parameters changed proportionally with the damage size.
- ❑ Special attention will be paid to studying the ability to accommodate angular and axial misalignment in toroidal bearings, theoretically and experimentally.
- ❑ Studying the application of Toroidal Bearings in wind turbines, because recently they are considered an essential component of the new design of the main shaft of the wind turbine.
- ❑ Designing and constructing a special test rig for bearings that allows angular and axial misalignments. This test rig would be able to test all types of self-aligning bearings (Self-aligning ball bearings, spherical bearings, toroidal bearings...).
- ❑ Along with the experiments a theoretical study will be carried out to support the experimental results, and to explain any contradictions. The theoretical study depends on modelling the toroidal bearing using a finite element analysis software. This model will be developed with collaboration with the R&D of the producer of the tested toroidal bearings.

5.2 Benefits

- With the increased demand for using Toroidal Bearings, especially in the wind energy industry, it is highly important to study their characteristics and properties, and to test their limits, using an advanced and well-established NDT method which is the Acoustic Emission. Besides, the solution of the work will bring new knowledge in the field of RCF in bearings, and this knowledge can be interpreted into improved practices in this field.
- Designing and assembling a special test rig which allows angular and axial misalignment of the driving shaft with the tested bearing. This test rig could be then used to test any type of self-aligning bearing (spherical, toroidal, double row ball bearing...etc.) and to even test cylindrical bearings for axial misalignment.

- The theoretical study that will accompany and support the experimental work, will improve and deepen our understanding of RCF in bearings in general, and that should help us expand our studies in this field.

5.3 CHARACTERISTICS OF THE EXPECTED RESULTS

The outcome is a research and development work that fall in the category between a applied research 40% and an applied industrial research 60%.

An essential part of the outcome will be a comprehensive theoretical study of the signal analysis methods for complex signals.

Designing and executing a special test rig that is capable of testing Spherical, Cylindrical, and Toroidal roller bearings using AE.

Assumed outcomes along the dissertation:

- Publishing at least three articles in journals that are included in the Web of Science.
- Publications in conference proceedings or other similar activities.
- Recognition of novelty for a new testing device.

The first article that was accepted to be published in an impact journal was titled:

Active Monitoring of RCF in Toroidal Bearings Using Acoustic Emission

Abstract. This paper demonstrates the results of testing toroidal bearings using the parameters extracted from Acoustic Emission testing. The aim is to find the characteristics of the Rolling Contact Fatigue (RCF) in these special bearings during testing. Toroidal bearings are characterized by their special design, which combines the self-aligning capability with the axial displacement ability, which contributed to the significant increase in their applications, especially in the wind turbine industry. The main concentration of this paper has been on the period of test before the appearance of pitting. It is thought that by analyzing and studying the Acoustic Emission (AE) signal in the period before pitting starts to take place, it is possible to specify the pattern of the signal which will distinguish the initiation of pitting. And it will enable us later to better understand the behavior of the specimen during the last stages of the test. The experiments took place in a specially-designed stand for this type of bearing to obtain the best results from AE sensors. This study is an initial step towards other more advanced steps to better understand the crack initiation and pitting mechanisms in the specially important toroidal bearings.

The main results:

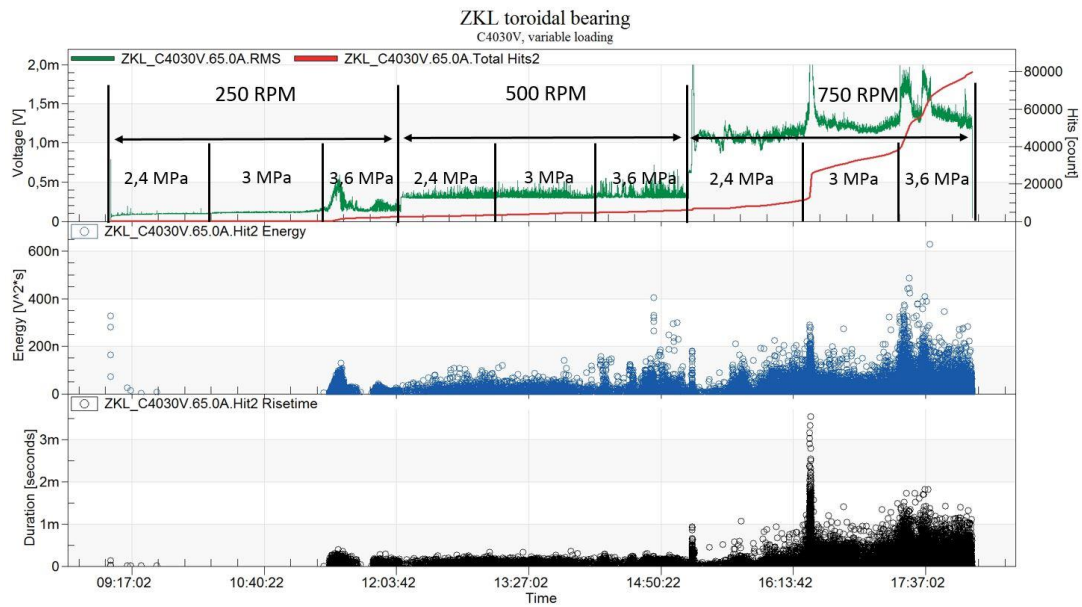


Figure 35. The relationship between AE parameters, the rotation speed, and loading of the toroidal bearing.

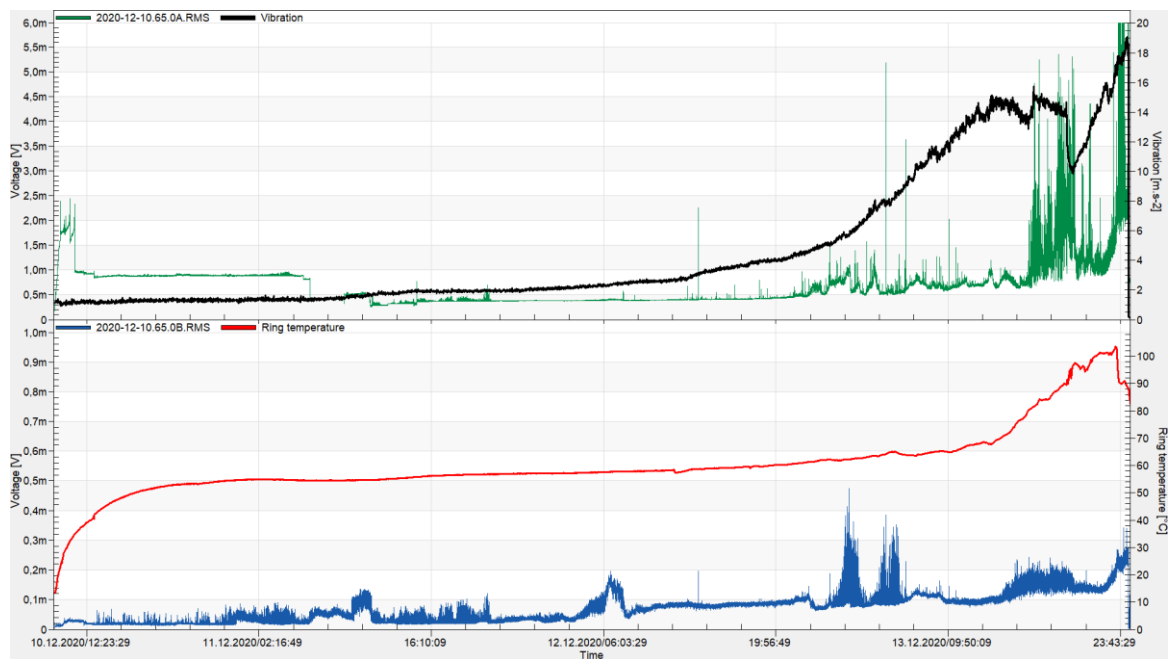


Figure 36. RMS of the AE signal from the two AE sensors, the upper from the bearing outer ring, and the lower from the housing, with the values of vibration (RMS) on the upper graph, and temperature of the outer ring on the lower.

The AE signal parameters were more sensitive to the increase in rotation speed than the changes of loading, therefore, the selection of the rotational speed in rpm will be considered more important in any following test.

The temperature of the bearing rings is not a reliable parameter for fast and accurate detection of the beginning of the RCF effects in the bearing, but it is still can be used as an indicative parameter.

It was accepted for publication in the journal of “Lecture Notes of Mechanical Engineering (LNME)” **IF=0,56**.

The results in the article were achieved from the first part of series of experiments that are supposed to take place in the laboratories of the Czech manufacturer (ZKL) of the toroidal bearings that were used in the tests.

According to the results that we will have, accompanied with deeper theoretical analysis, we expect to have another article ready to be published in an impact journal, as an extension to the current results.

List of the potential target journals for the following publications:

- Journal of Applied Mechanics (IF: 2.77)
- Journal of Vibration and Acoustics (IF: 2,34)
- Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology (IF: 1.137)
- INSIGHT, The Journal of British Institute of Non-Destructive Testing (IF: 0.79)
- Lecture Notes in Mechanical Engineering (IF: 0,56)

6 CURRENT STATE OF THE DISSERTATION SOLUTION

The dissertation is in the phase of completing experimental measurements aimed at investigating the influence of angular and axial misalignment on the lifetime service of toroidal roller bearings, and to use the results for improving the design of these bearings, as well as contributing to the study of other types of bearings that allow angular misalignment (such as spherical bearings and double row self-aligning bearings). The following section presents a brief overview of the solution method in a schematic way, then it shows the principle of a special testing stand that is planned to be constructed, then it outlines the results from the measurements which were performed in a special laboratory for testing toroidal bearings in the factory of production, and how the preliminary results were prepared for publication along-side the preparation of a simulation model that represent the tested model.

However, in order to answer the main question of how the misalignment of toroidal bearings will affect their service life expectancy, it will be necessary to perform different experimental measurements in more than one laboratory. These tests will be done on real toroidal bearings as specimens, as well as on specially designed specimens for testing, and it will include healthy and artificially defected (seeded) specimens of both types. By principle, a comparison between the results of each test will be carried out, but the basics of the comparison criteria will be defined later according to the results. Then a process of validation and verification with the simulated model will take place to check its validity and applicability, hence its real usefulness for satisfying the predetermined goals.

6.1 Schematic overview

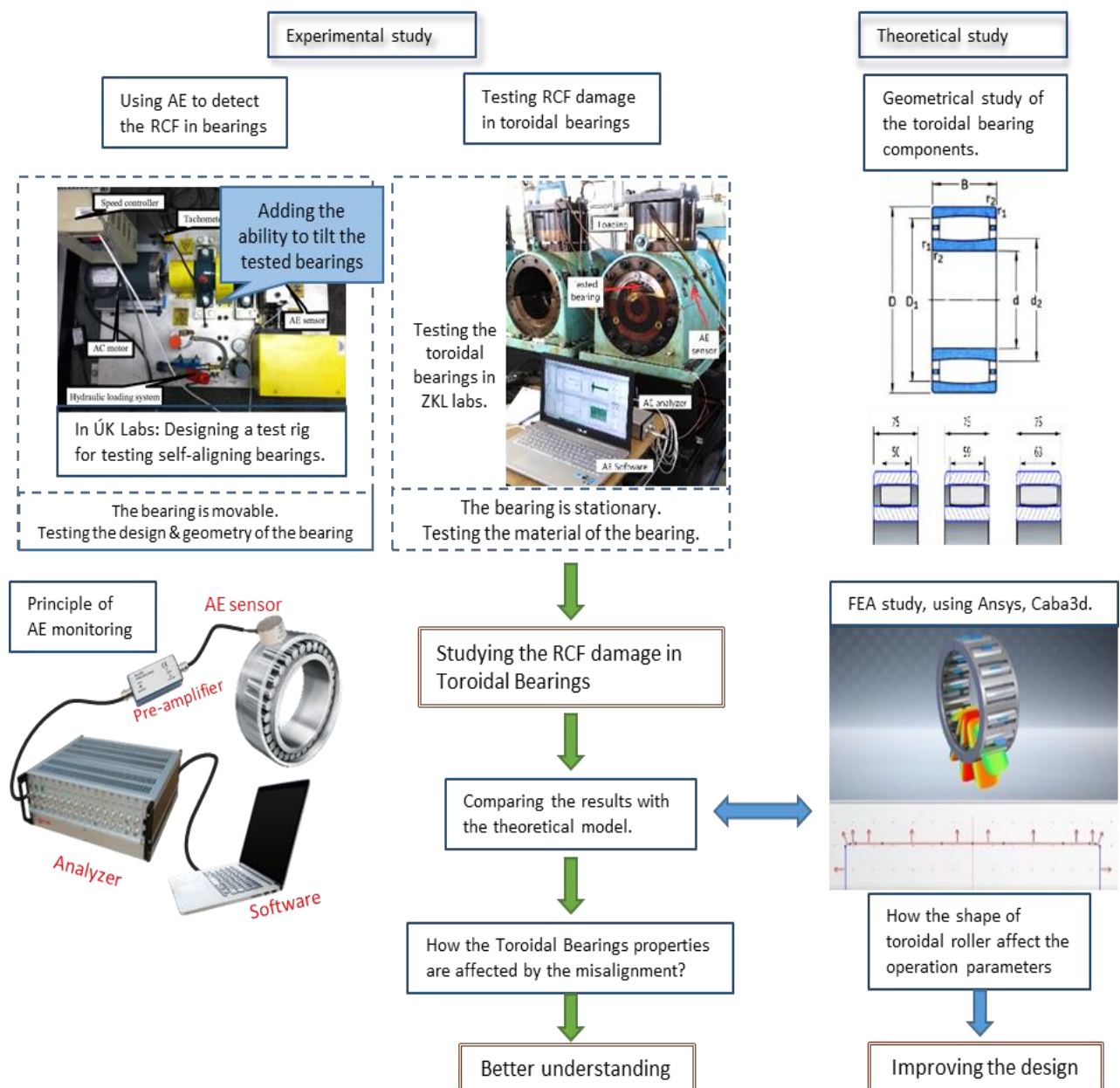


Figure 37. Schematic overview of the solution method of the dissertation

On the other hand, to answer the question of how the shape of the toroidal rolling element affect the operation parameters of the toroidal bearing, it is necessary to theoretically study the geometry of the toroidal bearing (roller and raceways), and the available options for changing the shape of the roller. A geometrical study of the roller will not be enough, because it will only answer the question of how does the shape of the roller affect the internal clearance of the bearing, and that in turn affects the operation parameters of the bearing. So to go with the theoretical study even deeper, a finite element analysis should be carried out with the help of a software (AnSys) as the main tool to provide precise analysis of the geometry and forces that are affecting the bearing elements, which is mostly a static analysis, or even a simple dynamic analysis could be carried out. But in order to achieve a full dynamic analysis of the processes that take place inside the bearing, that would be possible with the help of a more sophisticated software and a more specialized one (Caba3d) which is specialized in bearing analysis, and it allows even higher-performance dynamic simulation. In addition, we can benefit from the simulation model that is currently being developed by the research and development department of the producer of the tested toroidal bearing.

6.2 Laboratory Experiments:

The laboratory experiments that are concerned with testing toroidal bearings (or even other types of bearing that allow angular or axial misalignments, such as self-aligning bearings) will take place on a test rig, that will be designed and developed in the Institute of Machine and Industrial Design. This test rig will be able to perform the tests on an angularly and axially misaligned bearing, while loaded with different loads at the same time, further details in section 6.3. After constructing the test rig, a process for the verification of its measurement should be carried out and then considering the novelty for a new testing device.

6.3 Design of the test rig

The design of this test rig was inspired by the idea of testing the effect of angular misalignment on the types of bearings that allow angular misalignment, such as toroidal, double-row spherical, double row self-aligning ball bearings.

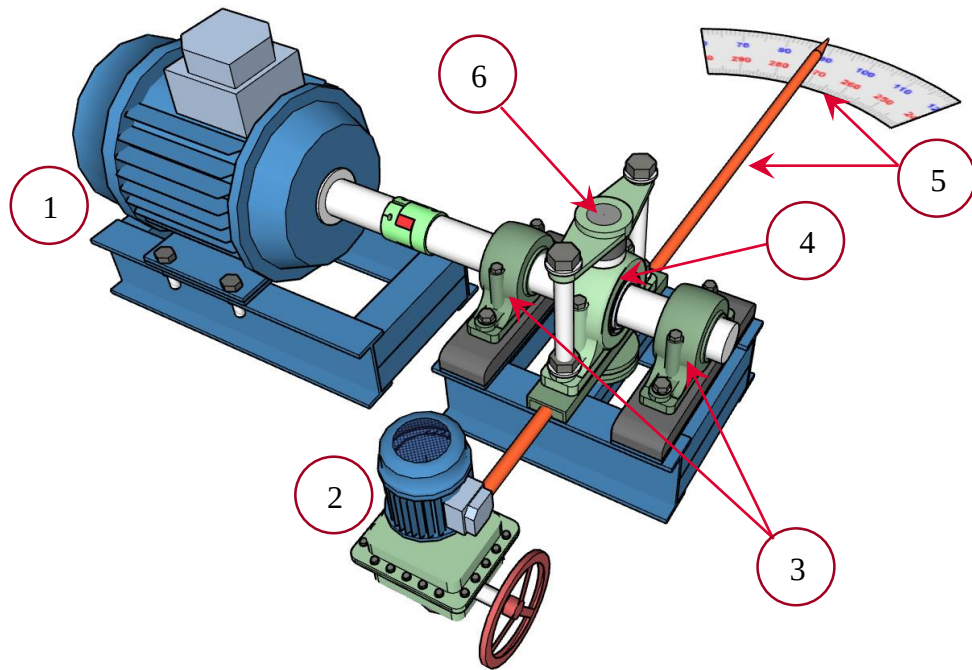


Figure 38: Preliminary sketch of the test rig for testing the angular misalignment effect on bearings

1. The main motor,
2. The secondary motor with oscillation mechanism
3. Two support bearings.
4. The housing of the tested bearing
5. Pointer with part of a protractor for measuring angles
6. Hydraulic loading on the tested bearing.

As shown in figure 38, the test rig consists of the main motor that provides the rotation for the main shaft, and it is fixed on separate base. There is a secondary motor that provides the oscillation movement through a special mechanism, which also has a manual control.

The tested bearing with its housing are on a plate that has the ability to rotate slightly around the vertical axis that goes through the center of the tested bearing.

The test rig is designed to simulate the real life operation of the types of bearings that allow angular misalignment, where there is always a change in the angular alignment between the axis of the outer ring of the bearing and the axis of the shaft (which is the same as the axis of the inner ring of the bearing). This type of misalignment is usually caused by high level of vibration of the load on long shafts. There is another type of angular misalignment which is caused by installation. This type could also be simulated on this proposed test rig using the manual part of the oscillation mechanism, by rotating the base of the housing of tested bearing by a specific degree and fixing it at this degree during the test.

Acoustic Emission will be used as the nondestructive testing method for monitoring the condition of the tested bearing. The principle of the test rig allows to make the comparison between the parameters of acoustic emission that are extracted from a tilted bearing with the same parameters from an untilted one (in its initial position) undergoing the same testing conditions (loading, rotational speed, temperature, lubrication, ...etc.). This comparison would make it possible to answer the question of whether the ability to tolerate misalignment in toroidal bearings has an effect on their characteristics, especially the RCF damage detection. While deeper analysis and comparison of the right parameters of AE signals that were generated from those tests would give a quantifiable measurement of that effect.

As part of the dissertation as well, experiments will take place in laboratories of the producer of tested toroidal bearings (ZKL) in cooperation with their branch in Brno. Those experiments will focus mainly on studying the RCF characteristics in toroidal bearings using AE technique. Since those experiments will be carried out on testing stations that do not allow angular or axial misalignment of the tested bearing, the main objective of the test will be confined to studying the material properties of the tested bearing or their coatings, and comparing between the results of testing healthy and artificially defected (seeded) bearings.

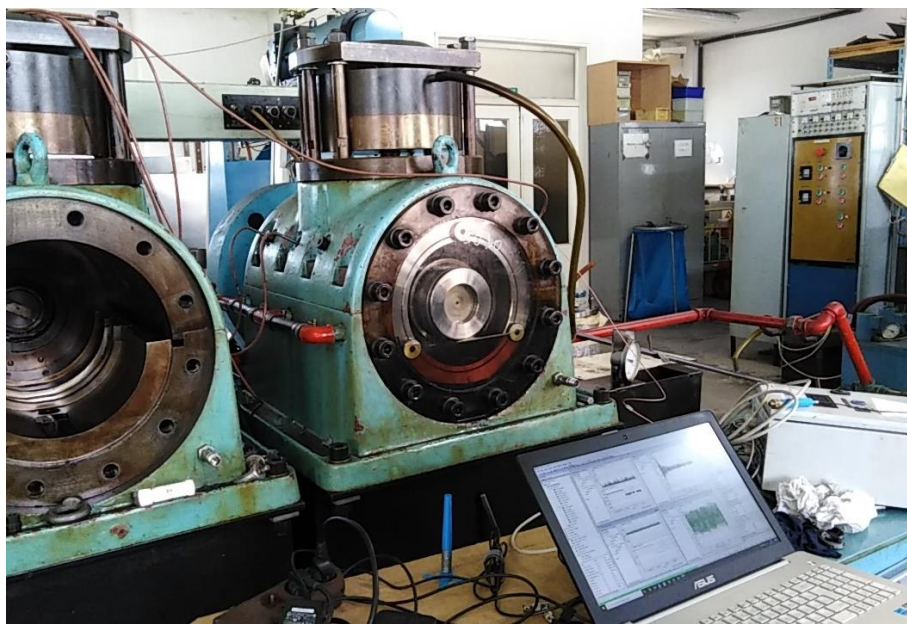


Figure 39. The setup for testing toroidal bearings in the laboratories of ZKL

6.4 Simulation models

Within the same project, which includes this dissertation, a simulation model for the tilting (angular and axial misalignments) effect in toroidal bearings will be developed. The model will depend on the geometrical study of the toroidal rolling element of the bearing. The simulation model will be achieved with the help of a Computer-Aided Design software (SketchUp + Inventor) and a Finite Element Analysis software (AnSys). This simulation model will concentrate only on the geometrical properties of the toroidal bearing components, and their effect on the angular and axial misalignment limitations of the bearing. This work will depend on expanding the efforts that were started in an earlier study by Zhenhuan et al. [35] that was concerned with a similar problem but with cylindrical bearings.

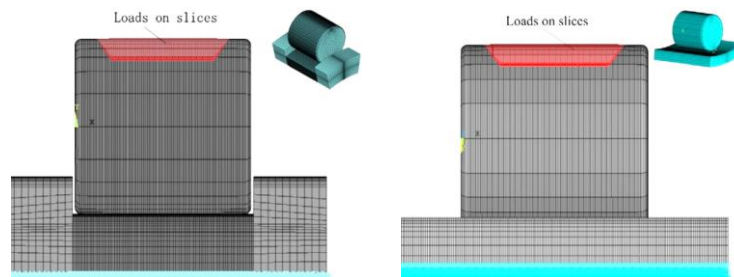


Figure 40. FEA modeling of contact between cylindrical rollers and raceways using AnSys [35]

While a more professional work on the analysis of the toroidal bearing operation parameters and design properties will be achieved with the help of the R&D department in the production company. A special and more specific software will be used (Caba3d). It is specially developed to examine the dynamic internal operation of bearings, while considering the complex boundary conditions and deformations of the surrounding structure that vary over time. This software allows a precise analysis of the dynamic processes that take place inside a rolling bearing. This means that the movement patterns of the bearing components, the forces acting between them, even the frictional power that is generated can be determined.

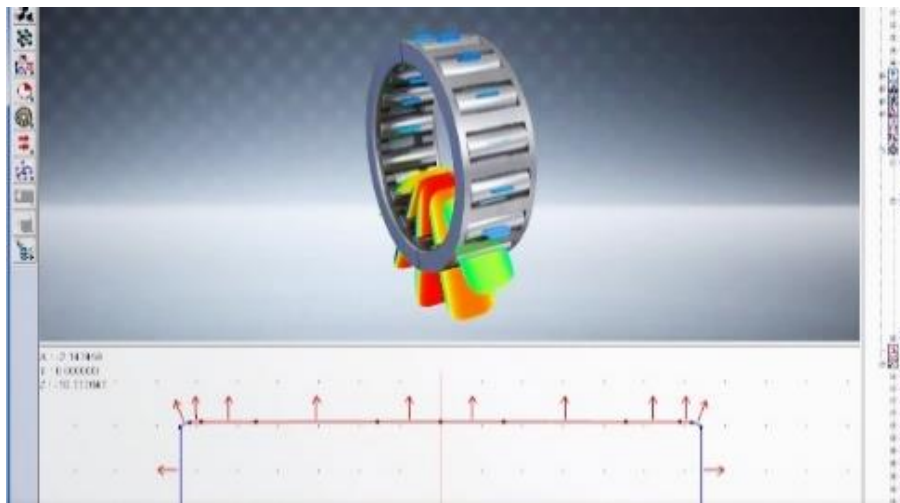


Figure 41. A screenshot of the software Caba3d, a dynamic simulation program for bearings

6.5 TIMETABLE AND SOLUTION STAGES

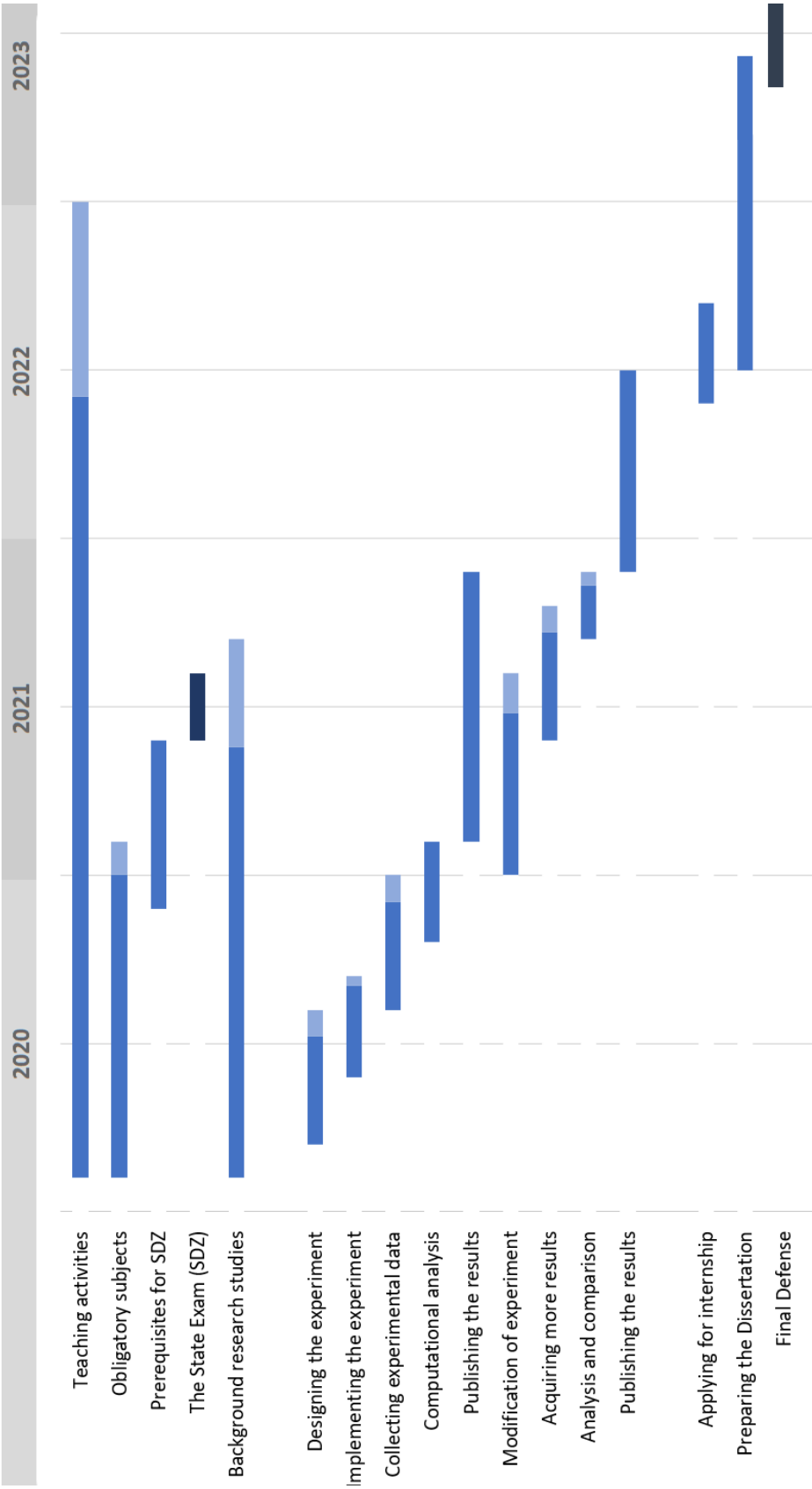


Figure 42. Timetable of the solution stages.

7 CONCLUSION

In this treatise (dissertation project) that is prepared for the state doctoral exam, the topic of using acoustic emission (AE) as a non-destructive testing technique to test toroidal bearings and to study the characteristics of rolling contact fatigue (RCF) in this newly-designed type of bearings was discussed, and a proposal for a methodology was planned. The treatise contains a summary of the main characteristics of toroidal roller bearings and the acoustic emission as non-destructive testing technique, as well as a current state of knowledge about using this technique in similar measurements, where the most important studies from the areas related to using AE for predicting RCF in bearings were studied and analyzed.

The dissertation continues with the analysis and evaluation of the findings from the research, on the basis of which the aim of the work and scientific questions were formulated. The solution procedure and methods are chosen with regard to the suitability of the interpretation of the results in relation to the toroidal bearing and their applications.

In the current state of the dissertation, the current state of individual stages was described, while some partial goals have already been met, progress in solving other tasks and goals is expected.

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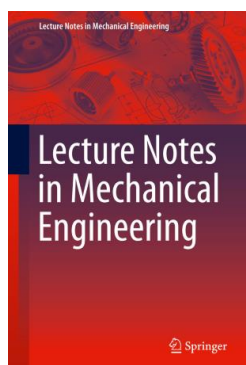
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