TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

TTÜ Department of Electrical Power Engineering and Mechatronics

ULTRASOUND AND VIBRATION: RESEARCH OF COMBINING TWO TECHNOLOGIES TO DETERMINE ROTATING MACHINERY HEALTH

ULTRAHELI JA VIBRATSIOON: METOODIKA KAHE TEHNOLOOGIA KOOSKASUTUSEKS LAAGRITE OLEKU HINDAMISEL PÖÖRLEVA LIIKUMISEGA SEADMETES

MASTER THESIS

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Tallinn, 2019

AUTHOR’S DECLARATION

Hereby, I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

“.......” 2019

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Thesis is in accordance with terms and requirements

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Accepted for defence

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Deparment of Electrical Power Engineering and Mechatronics

THESIS TASK

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Thesis topic:

(in English) *ULTRASOUND AND VIBRATION: RESEARCH OF COMBINING TWO TECHNOLOGIES TO DETERMINE ROTATING MACHINERY HEALTH*

(in Estonian) *Ultraheli ja vibratsioon: METOODIKA kahe tehnoloogia kooskasutuseks laagrite oleku hindamisel pöörleva liikumisega seadmestikus*

Thesis main objectives:

1.Form a methodology for necessary measurements and measurement data analysis

2. Find a relationship function between ultrasound and vibration measurements and describe what other variables may affect the relationship function.

3. Create a logical function that would allow to determine the bearing faults and its failure stage using ultrasound measurements.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Form the measuring methodology	01.04.19
2.	Statistical analysis of measurement points	14.04.19
3.	Regression analysis on the obtained data	01.05.19
4.	Create a function to determine bearing condition using ultrasound measurements	14.05.19

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PREFACE

The author has been working in DeltaE Engineering Bureau applying ultrasound and promoting ultrasound measuring devices for industrial use. A common problem encountered in a weekly basis for potential clients is the lack of a straight forward measuring method and data analysis method. Maintenance personnel in most of the cases are not up to the task of performing complicated data analysis for a bearing ultrasound or vibration measurement or just do not have the time for it.

The idea of developing a method or a mathematical function that would reduce such concerns for maintenance personnel came from the thesis consultant David Faro Ruiz. Additionally, such a relationship function between ultrasound, vibration and rolling bearing condition could also be applied to verify other predictive maintenance technologies' predictions.

The main component of the thesis task completion has been the measurements. The measurement device SDT340 generously provided by the device manufacturer SDT International. Multiple companies were forthcoming to cooperate in order that the necessary number of measurement points would be recorded.

I would like to thank my supervisor, Priit Põdra, for the support during the thesis creation process and for all the knowledge and ideas that I have been able to gain for him.

Keywords: Measurement, Ultrasound, Vibration, Regression analysis, Master Thesis

List of abbreviations and symbols

PdM – Predictive Maintenance

PM – Preventive Maintenance

TWF – time waveform

FFT – Fast Fourier transformation

g – gravitational acceleration g = 9,81 m/s^2

rpm – revolutions per minute (1 *rpm* = 60 *Hz*)

BFF – Bearing Fault Frequency

BPFI – Bearing pass frequency inner race

BPFO – Bearing pass frequency outer race

FTF – Fundamental Train Frequency

BSF – Ball spin frequency

1 INTRODUCTION

Predictive maintenance (PdM) has had a growing interest since the beginning of the century. It is self-evident, the industrial companies try to maximize the availability of their assets, increase safety and reduce production planning problems due to unplanned system failures.

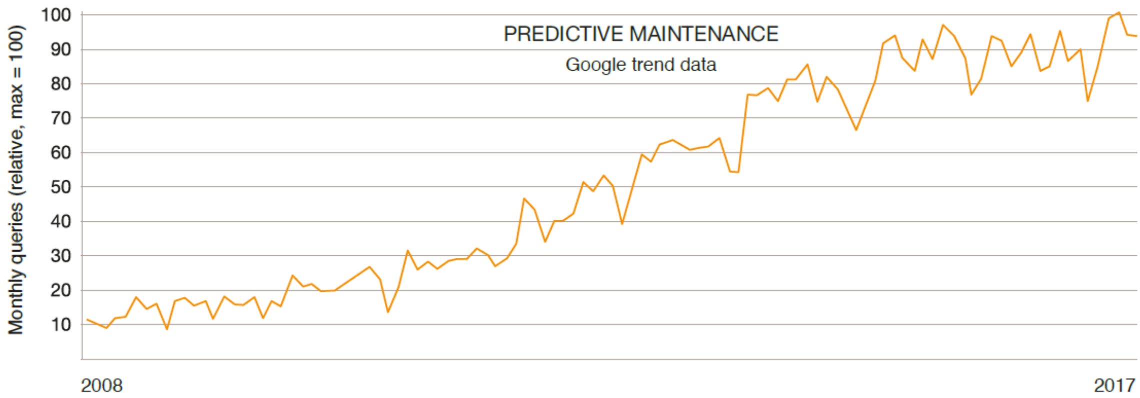

Figure 1.1 Google trend data for queries “Predictive Maintenance” [1]

A survey done by PricewaterhouseCoopers in 2017 stated four levels of maturity for PdM. 67% of the respondent companies in the survey either did not use PdM, were relying on visual, inspector expertise-based checks or were using some measurement instrumentation for periodic inspections [1].

A key point, why these companies have not developed their maintenance systems, have been problems with the data availability and data processing. The main problem here is usually either lack of the necessary technologies, lack of skilled specialists or missing maintenance culture [1]. This proves the necessity of methods to easily obtain data, store it and have the tools that can be implemented to successfully use the data to take decisions.

The thesis has been completed on behalf of an internationally proven PdM focused company SDT International using the aid of Estonian industrial companies to provide the necessary data to solve the problems presented in the thesis.

Ultrasound and vibration measuring are methods for an industrial enterprise when developing their maintenance program. These technologies have been in use since the 1980’s to predict and diagnose developing ang occurring defects in various types of equipment. Both of these technologies are mainly used for rotating equipment inspections, that focus on bearings – a critical component of any industry.

A popular conception is that 90% of bearings do not last until their designed lifetime [2]. Due to this a significant amount of resources and production capacity is lost constantly. To reduce these problems after the design and installation of a machine a multitude of factors need to be introduced.

- Increase the industry’s understanding of costs of failures and their effects in their major scope.
- Introduce more easily applicable measuring techniques to obtain data in correct ways and from correct positions.
- Implement databases that store data in a more easily findable way.
- Have more qualified specialists to analyse, deal with and tackle the increasing amount of statistical data of failures
- Have better, more applicable and accurate methods to analyse the data.

The later from the previous points, is what this thesis is focusing on as industrial assets contain vast amounts of data about their condition already. Although, there are few systems in place that are able to accurately and reliably use the data to provide reliable info in order to make justified decisions.

2 ULTRASOUND AND VIBRATION IN INDUSTRIAL MAINTENANCE

2.1 Predictive Maintenance

Ultrasound and vibration, both, are the key elements of a modern predictive maintenance (PdM) program. The main focus of such a maintenance strategy is to maintain the assets of the company based on their condition. PdM has additional benefits compared to the preventive maintenance strategy (PM), where maintenance is conducted based on time. The common problems of PM are related to the necessity of the maintenance task.

- Time based maintenance tasks could be done too early, which
  - increase the risk of faults from improperly done maintenance tasks;
  - reduce the availability of the asset;
  - increase maintenance costs
- Time based maintenance tasks could be done too late, which
  - reduce availability from unplanned stoppages;
  - increase strain on production, maintenance and personnel planning
  - increase costs due to costly reactive maintenance tasks

On the other hand, PdM has its drawbacks as well. These aspects illustrate, why such a strategy is not solely used in the industry.

- PdM strains maintenance planning with additional analytical tasks.
- PdM can require costly measurement systems.
- PdM implementation can be time consuming.
- PdM requires appropriately qualified analysts.

Additionally, determining the condition of an asset, is complicated and various different technologies and methods are used. Each method and technology have advantages and disadvantages – no single method or technology can be relied on to set up a well operating PdM system.

When focusing on rotating machinery, the main PdM technologies used to determine a developing defect or a deterioration of condition in its infancy are vibration analysis, ultrasound testing and lubricant analysis.

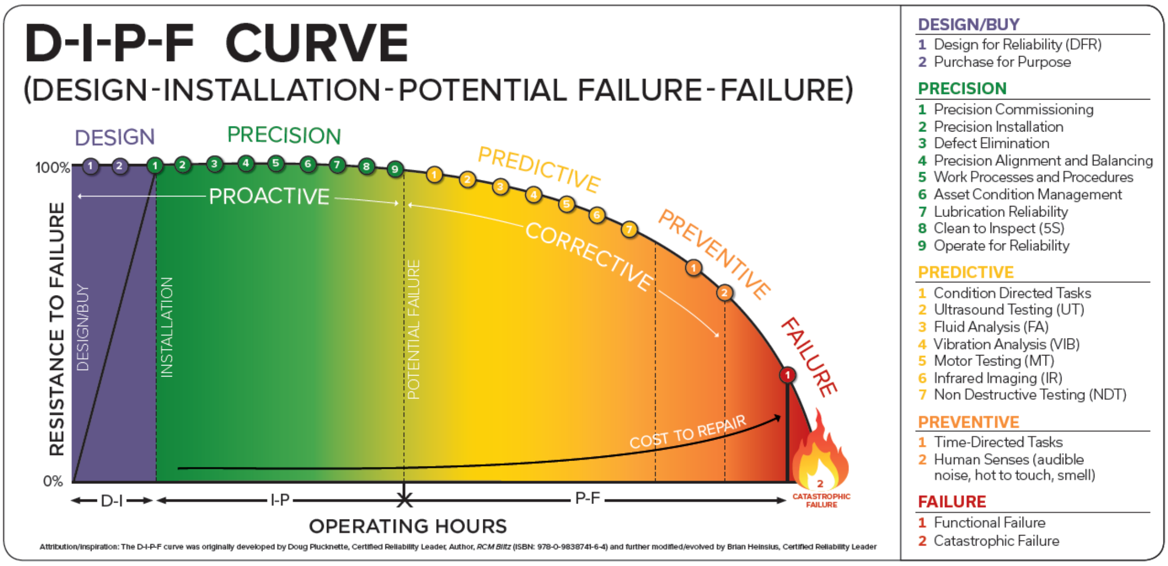

Figure 2.1 Failure occurrence in the D-I-P-F curve [3]

2.2 Ultrasound Testing

2.2.1 Types of Tests

Ultrasound testing in rotation equipment can be implemented in multiple ways depending on the test complexity and required accuracy.

- Listening – an operator uses an ultrasound to audible sound converting device and determines the condition of the asset.
- Statistical analysis – an asset ultrasound RMS and peaks values are measured at a specific frequency (i.e. once a month), statistical data determines the deterioration of the asset condition.
- Time waveform (TWF) and Fourier Fast Transformation spectrum (FFT) analysis are carried out to determine the magnitude and properties of developing failure modes.

The thesis will focus on mainly on the TWF and FFT analysis.

2.2.2 Ultrasound Measurements

Ultrasound measurements for rotating equipment is done using contact probes that incorporate piezoelectric sensors. The sensor creates a voltage signal, when pressure (ultrasound) is exerted on it. The sensor output voltage is registered and converted to a unit of dBµV based on the following equation [4].

$$M_{us} = 20\log\left(\frac{V_1}{V_0}\right) \tag{2.1}$$

Where M_{us} is the measured value in dBµV;

V_1 is the measured voltage from the piezoelectric sensor;

V_0 is the reference value.

Heterodyning is used for the filtering of ultrasound and audible sound frequencies. The filter can, depending on the measurement device be set on values from 20 kHz to 100 kHz.

Lower frequencies have less data of developing failures as more energy is required for ultrasound to be generated in the equipment. This states that developing failures cannot be determined earlier. This is demonstrated in the following equation [5].

$$P = A \cdot 2\pi^2 \rho a^2 f^2 v \tag{2.2}$$

Where *P* is the power of a wave in Watts;

A is the area the wave is crossing;

ρ is the density of the medium;

a is the amplitude of the wave particle oscillation;

f is the frequency of the oscillation;

v is the velocity of the wave.

When the amplitude of the oscillation is smaller, the same power is transmitted if the frequency of the oscillations is increased. This means that smaller defects in bearings that generate less power to form higher amplitude oscillations from friction and impacting can be detected at higher frequencies. This also means that there is additional noise from attuned sources further away from the measured point.

Additionally, the sampling rate of the ultrasound measurement device needs to be understood. Higher sampling rates increase the accuracy of the TWF and FFT. This means that data of peak oscillations in the ultrasound wave are not missed [6]. Depending on the devices, the sampling rates may be from 8 kHz to 256 kHz. Higher sampling rates ensure higher accuracy, however can prove a strain on the device’s data storage limit.

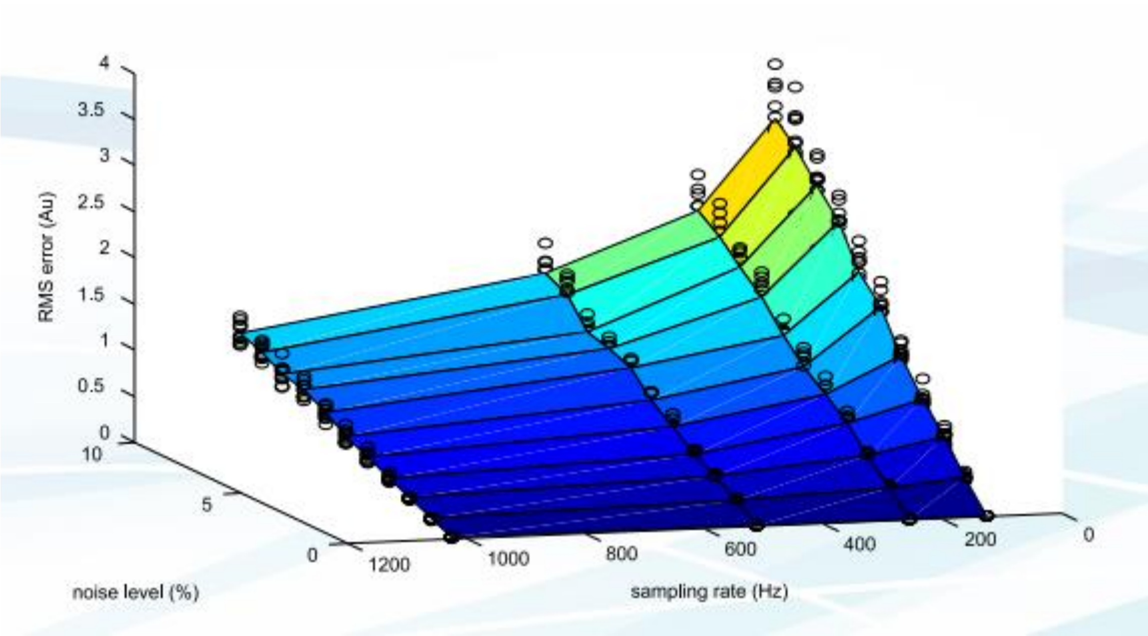

Figure 2.2 Example of sampling rate, noise and RMS error for a signal with noise [6]

When dealing with ultrasonic mechanical waves in bearing diagnostics, it is important to differentiate ultrasound frequencies from the frequencies of events being conveyed by the sound. The idea here is that sound pressure waves change their oscillation amplitude or intensity at times when impacting occurs in a bearing. I.e. when a bearing ball passes over a damaged surface on a bearing ring.

2.3 Vibration Analysis and Failure Stages

2.4 Vibration compared to Ultrasound

Vibration analysis is overall similar to ultrasound. The methodology, how measurements are taken and how data is used is the same. The main differences are in the measured signal properties. Mechanical vibrations have significantly lower frequencies. The frequencies of high vibration peaks, which usually occur at bearing fault frequencies (BFF) are the same as ultrasonic frequencies of the events conveyed by the change of the ultrasound intensity. These frequencies are highly dependent on the rotational speed and less dependent on the bearing dimensions.

The vibration velocity RMS value suitability is vaguely defined in the ISO 10816 for Machine Vibration, presented in the figure below.

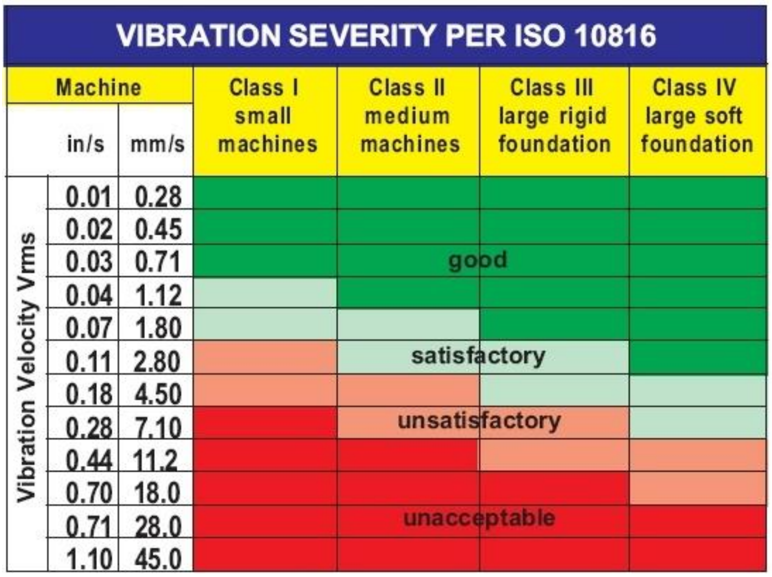

Figure 2.3 ISO 10816 table of vibration severity [7]

When going more in depth with the vibration TWF and FFT or Enveloped FFT analysis different sources presented different guidelines based on how to determine a bearing failure stage.

2.4.1 First failure stage

At the first failure stage, the bearing defect does not have any humanly noticeable temperature rise, audible noise or changes to feelable vibration. The defect remains in a microscopic region. Usually effects occur on frequencies higher than 20 kHz (ultrasound). High accuracy vibration measuring methods such as the envelop spectrum, shock pulse method, can detect defects at these stages. More common vibration velocity methods are unlikely to detect anything noticeable. The accuracy of vibration methods is reduced the lower the rotational speed of the bearing.

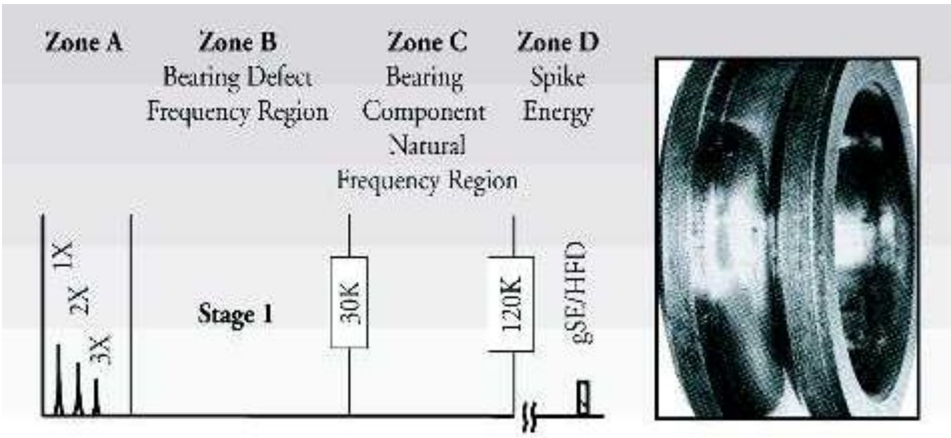

Figure 2.4 Bearing first failure stage [8]

When the microscopic level of damage has already occurred in the bearing, it has been evaluated that approximately 20% of the bearing life is remaining [9]. The average value for single highest bearing fault frequency harmonic amplitude can vary from (0,254…1,524) mm/s depending on the rotational frequency of 0,8 Hz to 67 Hz. The maximum TWF peak-to-peak magnitude for the rotational speeds from 0,8 Hz to 120 Hz can be (0,16…20,00) *g*

2.4.2 Second failure stage

In the second failure stage bearing defects begin to vibrate in the bearing component natural frequencies, which usually are in the range of 500 kHz…2000 kHz. These defects are easily detectable with ultrasound and significantly harder for vibration especially if the rotational speed is low (less than 3 Hz…4 Hz). Sideband frequencies start developing at the end of the second failure stage below and above the natural frequency [9].

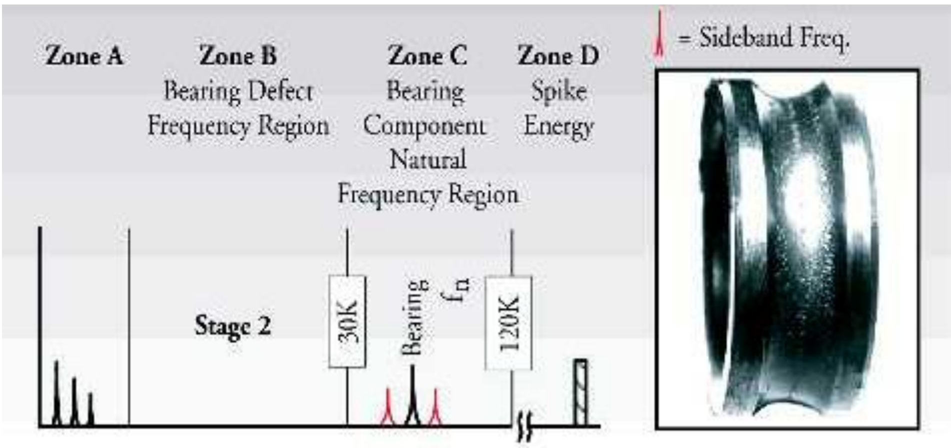

Figure 2.5 Bearing second failure stage [8].

approximately 10% or less of the bearing life is remaining [9]. The average value for single highest bearing fault frequency harmonic amplitude can vary from (0,508…3,048) mm/s depending on the rotational speed of 0,8 Hz to 67 Hz. The maximum TWF peak-to-peak magnitude for the rotational speeds from 0,8 Hz to 120 Hz can be (0,32…40,00) *g*

2.4.3 Bearing third failure stage

The third bearing failure stage may have humanly visible and feelable characteristics. Damage to the raceways, and rollers has grown substantially. On the vibration spectrum, defect frequencies, their harmonics, and sidebands for these frequencies start forming. The analysis of the vibration spectrum can provide certain problems, their causes and methods to repair the bearing.

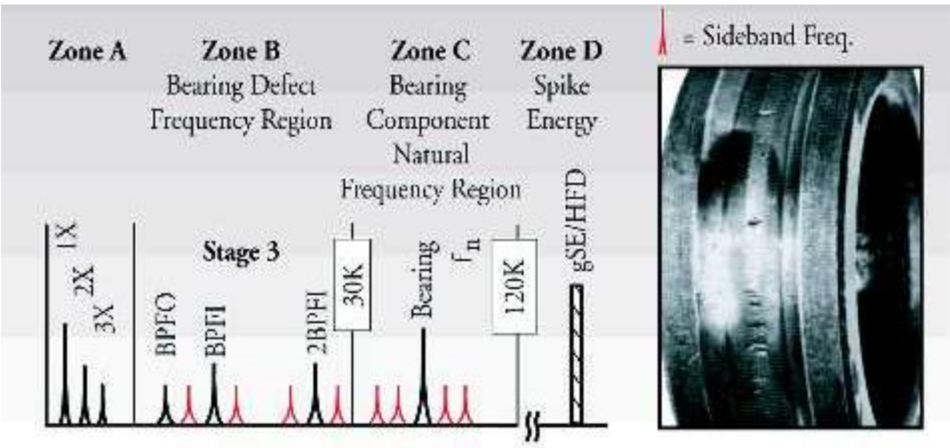

Figure 2.6 Bearing third failure stage [8]

It is considered, that less than 5% of the bearing life remains and it is advisable to replace the bearing as soon as possible [10]. The average value for single highest bearing fault frequency harmonic amplitude can vary from (1,016…6,096) mm/s depending on the rotational speed of 0,8 Hz to 67 Hz. The maximum TWF peak-to-peak magnitude for the rotational speeds from 0,8 Hz to 120 Hz can be (0,64…80,00) *g* [9]

2.4.4 Bearing Fourth Failure Stage

In the fourth bearing failure stage, a significant amount of ware and debris is inside the bearing. This will render ultrasound measurements to be basically unusable to diagnose the bearing from the TWF or FFT. The same can be said about the vibration enveloped FFT, however not totally. Vibration spectral velocity will carry relevant information especially about the bearing looseness. The vibration usually becomes feelable by hand. [9]

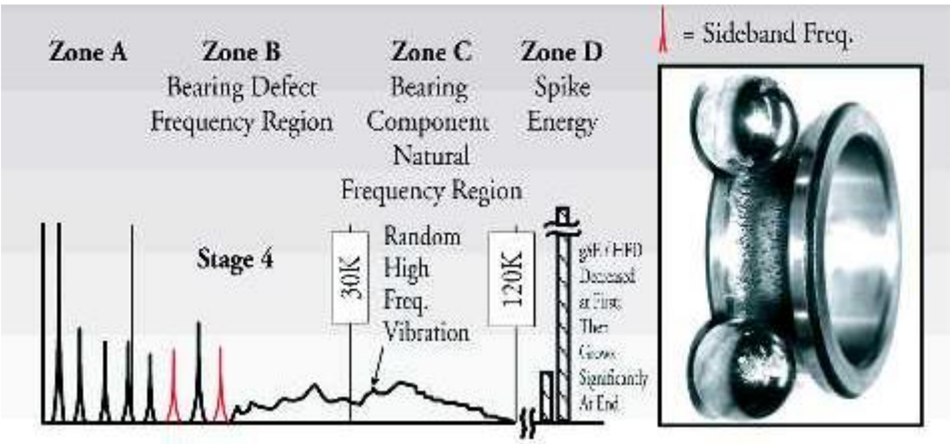

Figure 2.7 Bearing fourth failure stage [8]

In the fourth failure stage, less than 1% of the bearing life remains. The loss of bearing function is imminent and depending on the bearing criticality in the process, a catastrophic failure may occur. The average value for single highest bearing fault frequency harmonic amplitude can vary from (2,032…12,192) mm/s depending on the rotational speed of 0,8 Hz to 67 Hz. The maximum TWF peak-to-peak magnitude for the rotational speeds from 0,8 Hz to 120 Hz can be (1,28…160,00) *g* [9].

3 PROBLEM STATEMENT

As previously stated, failure stages are determined by the occurrences of high-frequency natural bearing resonance indicators and the occurrences and magnitude of vibration in the bearing fundamental frequencies.

The failure stages describe the bearing in the final 20% of its life. During this time, the speed of the failure development starts to increase exponentially, which strains an industrial maintenance team to react on time with appropriate measures.

In order to determine the failure stage of a bearing using vibration measurements, usually either 100 mV/g or 500 mV/*g* accelerometers are used, whereas the 100 mV/*g* accelerometers are more prominent due to lower price. These sensors are precise and suitable to measure and determine the bearing failure stages quite reliably in ideal conditions, however if errors are made during the measurement process and/or rotational speeds of the machine are lower, problems may arise.

For bearings in the first failure stage or in a better stage, the vibration measurements have mainly info at very high frequencies. Usually this info is conveyed in the bearing resonance frequencies. At the same time, ultrasound measurements may have signal peaks at bearing characteristic frequencies. The accuracy of vibration measurements becomes even lower at the first failure stages when the rotational speed is reduced.

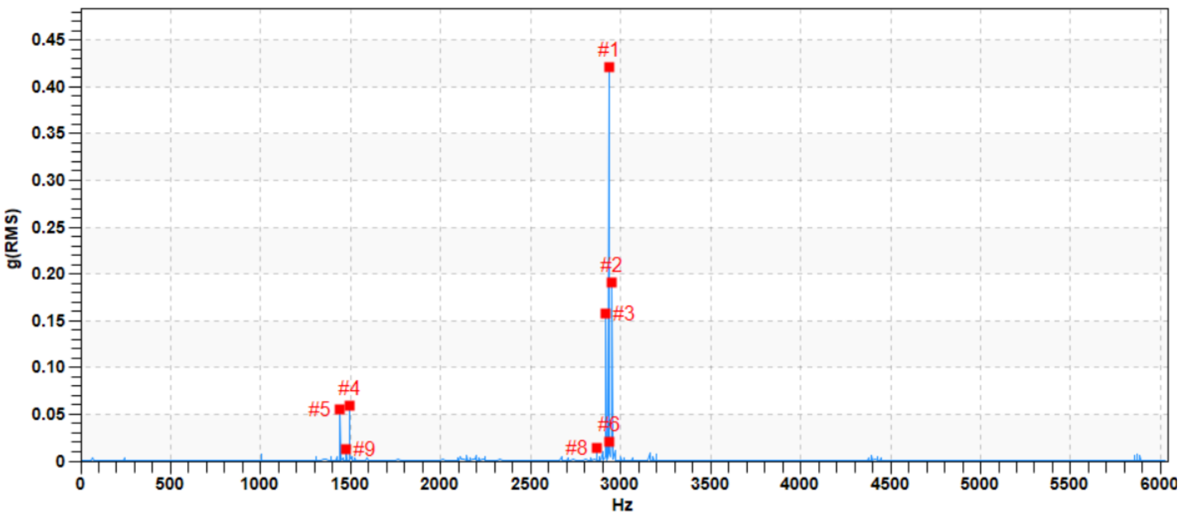

Figure 3.1 Vibration acceleration FFT with significant data only in resonant frequencies

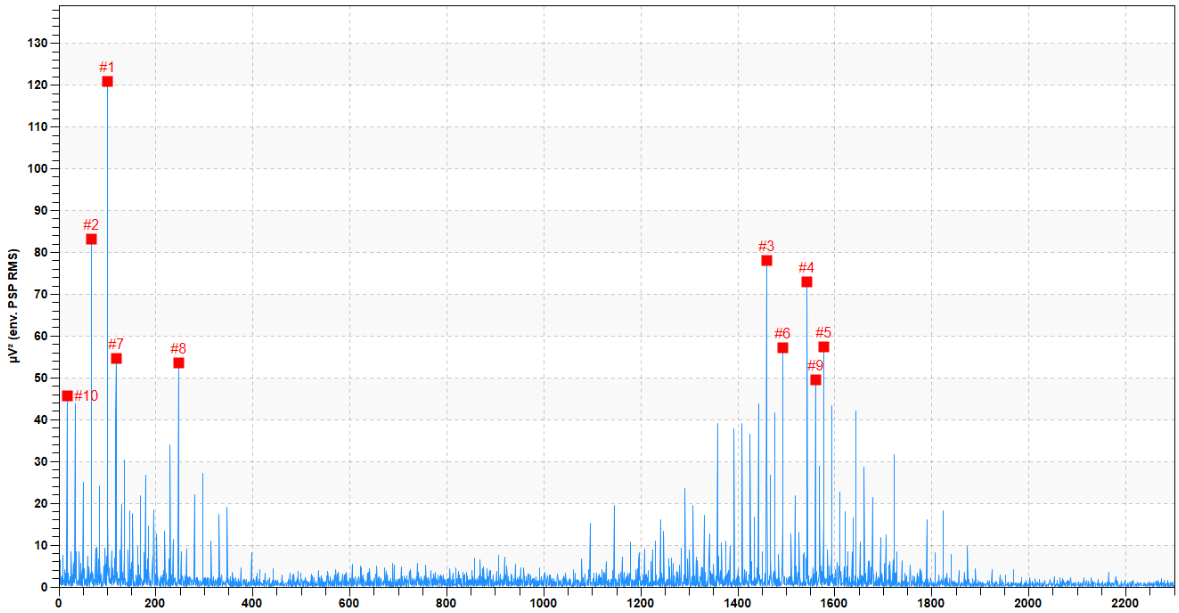

Figure 3.2 Ultrasound FFT for the previous vibration acceleration FFT

For example, if a bearing produces vibration of velocity 2 mm/s at the rotational frequency of 50 Hz, the corresponding acceleration vibration is 0,03 g. A 100 mV/*g* accelerometer would produce a signal of 3 mV. If the same bearing was at the rotational frequency of 1 Hz, the corresponding vibration acceleration would be 0,0006 *g*. This vibration would produce a signal of 60 µV. These signals usually have a presence of a 20 µV noise, which would make the decision process using the vibration acceleration signal very complicated.

Ultrasound can be used more successfully to determine the first two stages of bearing failures as the energy required to generate ultrasound waves according to equation 2.2 is lower. The problem, however, with ultrasound is that it is significantly more complex to use in order to signify the magnitude of the failure. No guidelines are present that clearly state an ultrasound magnitude for a specific failure stage as for vibration in ISO10816 and ISO20816.

Currently, PdM programs that incorporate ultrasound monitoring depend on statistical data to determine the severity of the bearing failure stage. This could mean that depending on the equipment, it's exploitation and workhours at least 3 months to 2 years of prior monthly or weekly measurement data is required. Solutions to reduce this problem is usually to compare similar machines, which can be highly inaccurate due to no knowledge about the workhours, the machines operating at different loads etc.

Another solution is to state the ultrasound magnitude for a good machine after installation. Although this incorporates uncertainties that can be caused by improper installation, faulty parts and machine wear-in process.

Using vibration measurements and in conjunction with the ultrasound measurements can prove to reduce the previously stated problems for both technologies. A good PdM system incorporate multiple methods and technologies to be successful. The aim of this work is to find based on the statistical data a way to link the ultrasound magnitude of characteristic frequencies to vibration magnitude and increase the probability to determine failures and their severity more accurately at an earlier stage, when corrective actions cost less.

The current goal is to find a general guideline similar to what is present for vibration measurements in the ISO10816 and ISO20816 documents. In order to achieve this the following tasks will be done.

- Specify a measurement procedure for both ultrasound and vibration measurements.
- Follow the specified procedure and conduct measurements in order to obtain a significant enough data set for the statistical analysis
- Conduct a regression analysis of vibration and ultrasound measurements' key indicator values for each measurement point.
- Evaluate and find the measurement and regression analysis uncertainties.
- Create a function or a method that could tie ultrasound measurement values to machine condition of vibration values.
- Evaluate the success of the results.

4 METHODOLOGY

4.1 Measurement Equipment

The measurements will be taken using the ultrasound measuring device SDT340. The device uses two inputs for ultrasound and vibration sensors. At the highest sampling rate (256 kHz), up to 10 min of measurement info can be stored. In addition, the device has a laser sensor for measuring rotational speed and the temperature. [11]

Figure 4.1 SDT340 Ultrasound and vibration meter SN:284190002

The ultrasound and vibration sensors will be attached to the bearing block using a magnetic sensor foot. The sensor foot will ensure somewhat similar sensor attachment forces for the measurements to be more repeatable compared to using a handheld sensor.

Figure 4.2 Hansford vibration sensor SN:524892 (left) and SDT FU.SEN.RS2T ultrasound sensor SN: 532180684 (right)

The device and the sensors have been calibrated proved by the SDT International calibration report added to the appendices.

4.2 Measurement process

The overall measurement process of a measurement point is described in the flowchart below. The process encompasses both vibration measurement and ultrasound measurement.

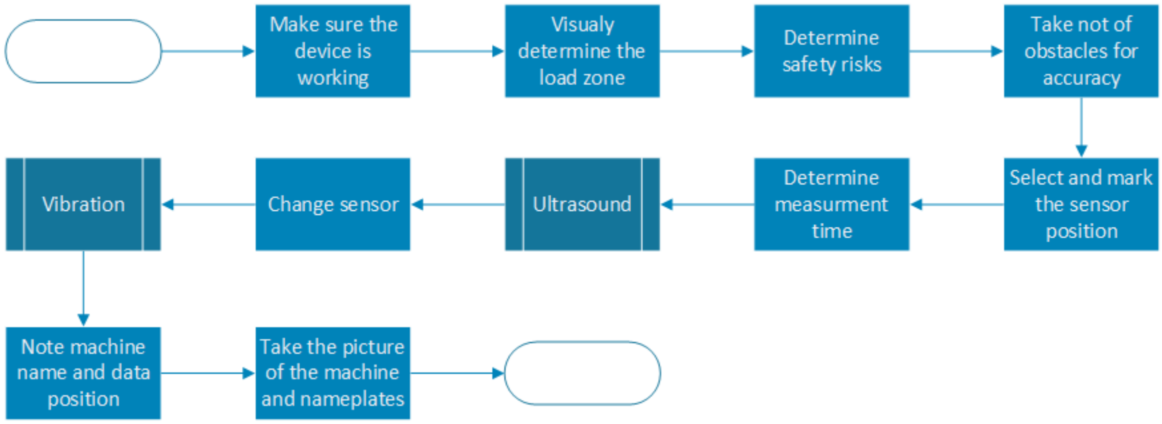

Figure 4.3 Measurement process

The first steps of the measurement process determine if the bearing in a machine is measurable. This mostly means that the device has to be working. This also means that the machine is dangerous – no measurements will be taken if any serious safety risks are present for the sensors, measurement device or the user.

4.2.1 Sensor Placement

The determination of the load zone is necessary to find the sensor position that is probable to have the highest measurement signals for both vibration and ultrasound measurements. If the measurements were taken from a non-load zone position, the bearing failure stage will be determined inaccurately (machine will seem to be in a better condition). Although, both sensors will be positioned in the same position which means that the measurement can still be used for the statistical analysis.

Obstacles that may affect the measurements need to be taken into consideration. The main such obstacle for vibration measurement is external vibration that may be present from other machines nearby, nearby railroad tracks etc. For ultrasound, materials that may absorb and attenuate ultrasound waves significantly need to be avoided. Usually these are various rubber seals or other soft materials in between the ultrasound sensor position and the potential ultrasound source. This could also be thick layers of paint on the machine.

4.2.2 Measurement time

The measurement time is selected based on the rotational speed of the bearing shaft. At least 3…4 rotations worth of signal needs to be measured for the measurement RMS signal values and FFT to be accurate enough. This is manly a concern for machines with slow rotational speeds (0,5 Hz or less). Otherwise 5 s worth of signal will be measured for both ultrasound and vibration. A measurement time of 5 s is applicable to measurement points with shaft frequencies down to 0,8 Hz.

The “Vibration” and “Ultrasound” blocks on Figure 4.3 contain a detailed process of the on-site validation, sensor and device setup. These will be described more thoroughly in the following chapters.

4.3 Ultrasound Measuring Procedure

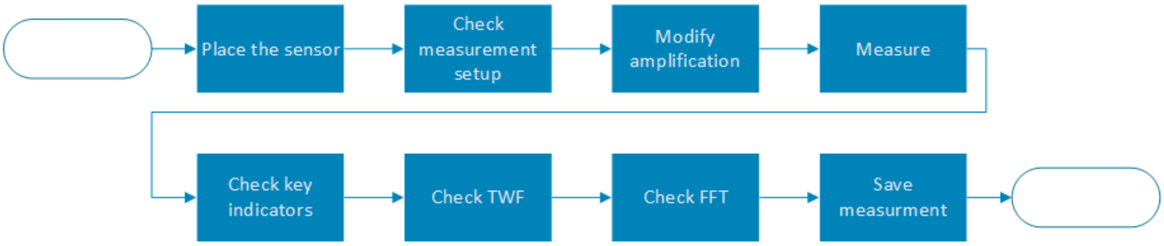

Figure 4.4 Ultrasound measurement process

Firstly, the sensor will be placed in the previously determined and marked location. The measurement setup should be checked to ensure, that the correct sampling rate (256 kHz) has been selected for the measurement. Also, the measurement time will be changed if necessary. [12]

Then the amplification has to be modified the amplification values range from 30…90 for the contact sensor. The device screen shows an upwards or downwards arrow, if the amplification is incorrect. Too high amplification will clip the signal peaks shown in the following figure. This will reduce the peak values and the crest factor. Too low amplification, means that the signal noise and signal levels itself are closer, which increases the error of the signal analyse later. In general, the device manufacturer suggests that the amplification should be selected based on the following equation. [12]

$$A_{\mathrm{mp}} = 90 - RMS \qquad 4.1$$

Where A_{mp} is the amplification factor value;

RMS is the approximate ultrasound root mean square value displayed on the screen of the device.

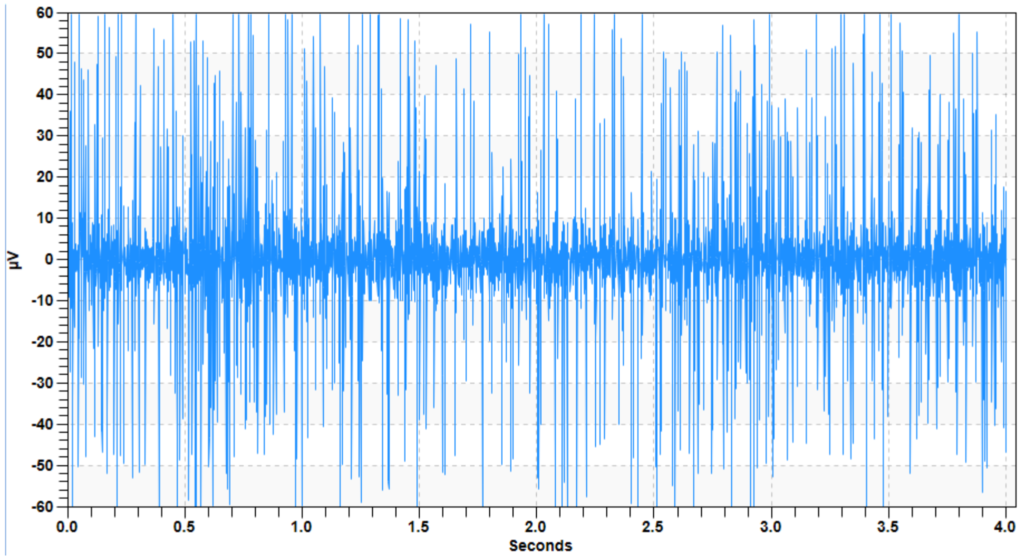

Figure 4.5 Clipped ultrasound signal in TWF

The checks following the measurement are to determine if the measurement is usable. The main key indicator that has to be checked is the Crest factor. If the crest factor is lower than 3, there may be a problem with the sensor, sensor cable or the device itself. A crest factor value cannot be lower than 2,9…3 for naturally occurring ultrasound.

TWF check is required to make sure no clipping is present. Additionally, significant changes in the signal average value in the TWF may state a drastic change in the machine load. The measurement should be retaken to improve the ease of the later analysis of the measurement.

The check of the FFT may give initial quick oversight to the measurement. Any irregularities here should be noticeable already in the TWF check. A very wavy FFT graph is less optimal as it is also more difficult to analyse, however such FFT can be the product of oil swirl or other fluid turbulence.

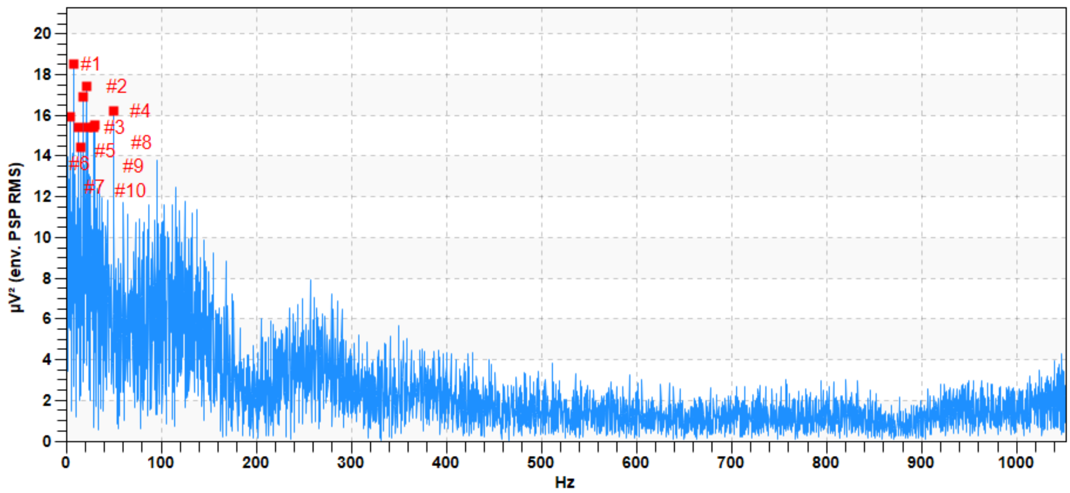

Figure 4.6 Ultrasound signal FFT with probable lubricant turbulence

4.4 Vibration Measuring Procedure

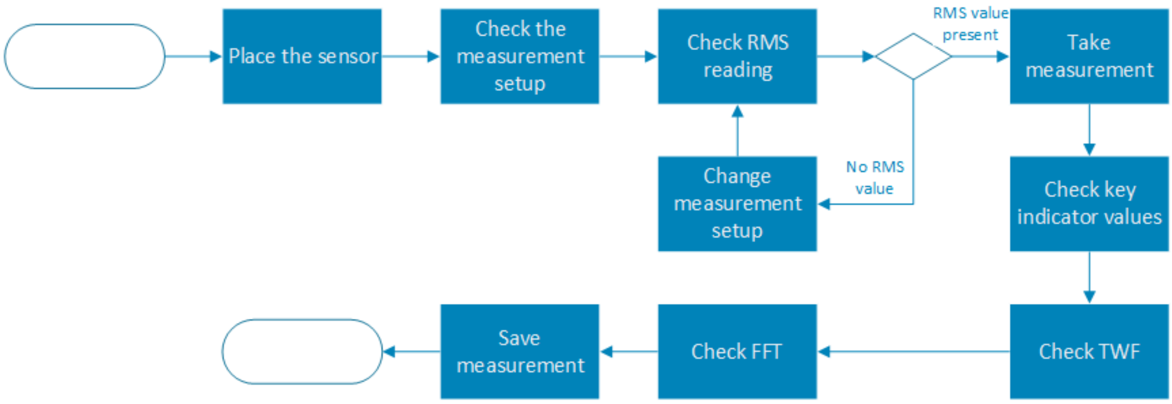

Figure 4.7 Vibration measurement procedure

4.4.1 Measurement Setup Check

As with ultrasound the vibration sensor will be positioned in the same previously marked load zone position. Then the measurement setup has to be selected. This means that the measurement time should be checked as with ultrasound. The highest possible sampling rate is used. Initially the 1 Hz – 1000 Hz filter is applied. This filter may not have a reading when the bearing is in good condition. If so, the 10 Hz – 10000 Hz filter is applied.

4.4.2 TWF and FFT Check

Key indicator and TWF check are done to check for sensor, sensor cable and device error. Measurement accelerations values should be in range of (0...80) *g*. If the values are not in that range, either it is a faulty measurement or the machine may have a sudden critical failure (machine vibration should be visible and staying in close proximity of the machine is dangerous). The sensor, sensor cable or device error can be found also in the FFT if there is a significantly higher peak in the 0 Hz position.

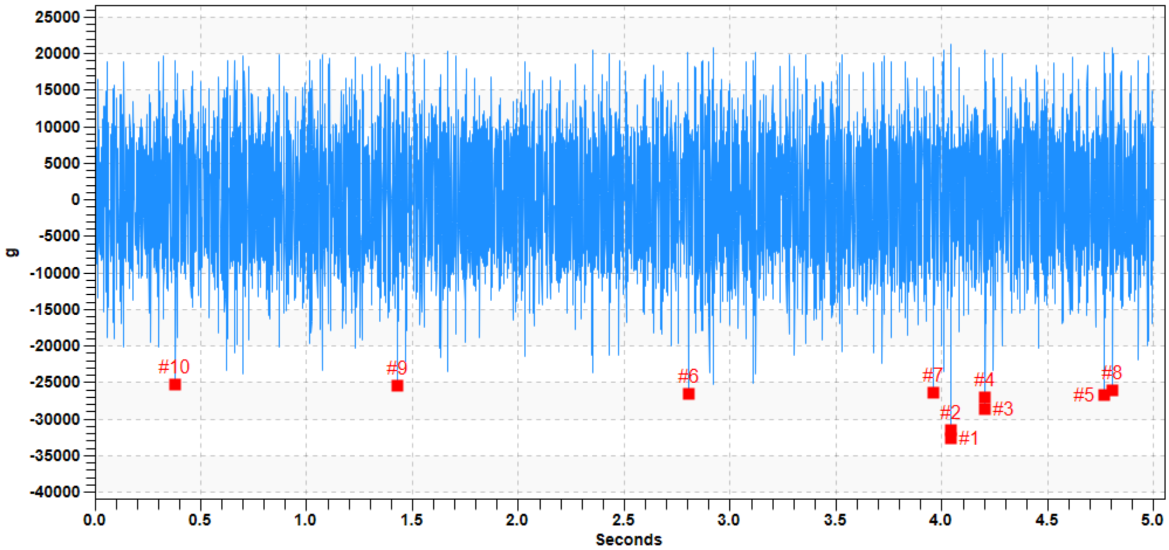

Figure 4.8 TWF of a faulty signal (impossible values for vibration acceleration)

The measurement results will be saved to the same data position as the ultrasound measurement. The device software will distinguish the measurements based on the sensor used.

4.5 Type-B Measurement Uncertainties

4.5.1 Ultrasound

Based on the device calibration data, the measurement uncertainty for the device reading values is ±1 dBµV. This is applicable for all ultrasound amplification levels.

Also, additional uncertainties are present from temperature deviations from the calibration temperature (23,5 °C) and the difference of the magnetic foot attachment force. The sensor information says that the sensor sensitivity starts changing at the upper limit of 60 °C. The rate of sensitivity changes above 60 °C is -0,15 dBµV/°C. [13]

The attachment force of the magnetic foot depends on the bearing block of casing material ferrousity. It is not controllable mostly. Measurement points that have non-ferrous materials will not be measured due to the unknown uncertainty.

4.5.2 Vibration Measurement uncertainty

The used HS-1001005006 vibration sensor has a standard sensitivity of 100 mV/g. The sensitivity changes at very high vibration frequencies (>10000 Hz). The sensor has a transverse sensitivity of less than 5%. Based on the measurement device manufacturer's advice, the suggested measurement uncertainty for vibration acceleration measurements is 0,1 g.

4.6 Individual Measurement point Analysis

4.6.1 Process

In order to begin the analysis process, the measurements have to be imported into the Ultranalysis Suite 4.0 software [14]. Usually, this is done on the same day the measurements have been taken. The software determines the key indicator values for the ultrasound and vibration signals automatically.

- Vibration acceleration RMS values (g)
- Vibration acceleration peak value (g)
- Vibration crest factor
- Ultrasound RMS value (dBμV)
- Ultrasound peak value (dBμV)
- Ultrasound crest factor

The crest factor is an indicator value used in various signal processing applications. The crest factor shows the ratio of the signal peak and RMS values and is also calculated based on the RMS and peak values as follows ultrasound and vibration signals [15]. The difference between the ultrasound and vibration calculation is due to the unit of the ultrasound values (dBμV), whereas vibration values are not logarithmic.

Vibration crest factor is calculated as follows.

$$Cr_{vib} = \frac{Peak_{vib}}{RMS_{vib}} \qquad 4.2$$

Where Cr_{vib} is the vibration crest factor (unitless);

RMS_{vib} is the RMS value of the vibration signal in g;

$Peak_{vib}$ is the peak value of the vibration signal in g.

$$Cr_{Us} = 10^{\frac{Peak_{Us}}{RMS_{Us}}} \qquad 4.3$$

Where Cr_{US} is the ultrasound crest factor (unitless);

RMS_{US} is the RMS value of the ultrasound signal in dBµV;

$Peak_{US}$ is the peak value of the ultrasound signal in dBµV.

Necessary data described in the further chapters will be inserted in to MS Excel for each measurement point. Table 6.1 in the appendices contains all the final information that will be used in MATLAB to do the regression analysis.

The following figure shows the analysis process for each measurement point vibration and ultrasound signals. The process flowchart elements have numbers in top left corners that determine the chapter number, where additional information is described.

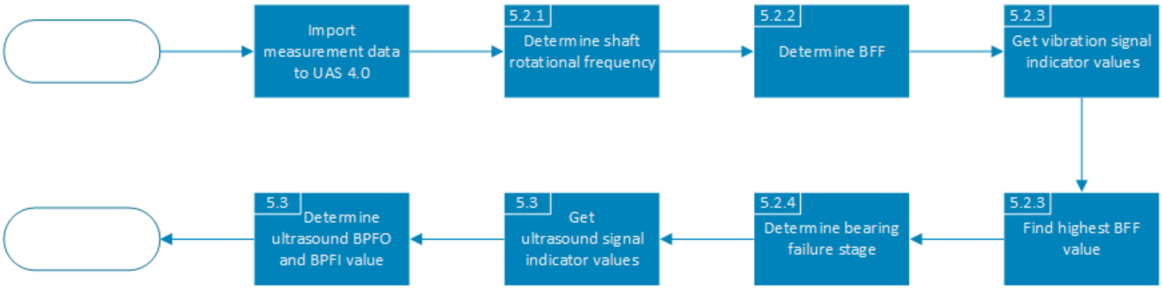

Figure 4.9 Measurement point ultrasound and vibration signal analysis

4.6.2 Measurement Point Vibration Signal Analysis

The bearing shaft rotation frequency needs to be known in order to find the BFF for the analysis. The rotational frequency is obtained through either:

- the used motor nameplate information;
- noting it during the measurement procedure from the motor drive display;
- measuring separately using the device's on-board velocity meter;
- the ultrasound or vibration FFT signal based on the most likely peak.

Additionally, the rotational frequency will be used for the failure stage determination.

Bearing fault frequencies are found using the SKF bearing calculator is used [16]. The calculator calculates the BFF based on the bearing code and the bearing rotational speed as follows [17].

$$BPFI = \frac{N}{2} \cdot f \left(1 + \frac{B}{P}\cos(\theta)\right) \qquad 4.4$$

Where *BPFI* is the ball pass frequency of the inner race in *Hz*;

N is the number of bearing balls;

f is the rotational frequency in *Hz*;

B is the bearing ball diameter in *mm*

P is the bearing pitch diameter;

θ is the bearing contact angle.

$$BPFO = \frac{N}{2} \cdot f \left(1 - \frac{B}{P}\cos(\theta)\right) \tag{4.5}$$

Where *BPFO* is the ball pass frequency of the outer race in *Hz*.

$$FTF = \frac{f}{2}\left(1 - \frac{B}{P}\cos(\theta)\right) \tag{4.6}$$

Where *FTF* is the fundamental train frequency *Hz*;

$$BSF = \frac{P}{2B} \cdot f \left(1 - \left(\frac{B}{P}\cos(\theta)\right)^2\right) \tag{4.7}$$

Where *BSF* is the ball spin frequency in *Hz*;

UAS 4.0 provides the key indicators automatically.

- vibration acceleration RMS value (*g*);
- vibration acceleration peak value (*g*);
- vibration velocity RMS value (mm/s);
- vibration signal crest factor.

The peak-to-peak value for the vibration acceleration will be found on the TWF of the vibration signal. This is done manually using the highest peak location.

Based on the previously calculated BFF, the vibration signal FFT is used to find the highest BFF. For this the peaks of the appropriate BFF values or their harmonics are looked at. A number of problems can occur here as:

- The BFF first harmonic may not have the highest value;
- The further BFF harmonic is used, the higher is the chance of other fault frequencies or shaft frequencies are also present.
- The vibration values for single BFF can be significantly lower than the device uncertainty for vibration measurements.

The failure stage of the bearing is determined based on the previously obtained vibration values. The following Table 4.1 presents the corresponding values for three methods to determine a failure stage. Three methods are used presented here.

- average high frequency vibration RMS value

- vibration acceleration peak-to-peak value;
- Highest vibration velocity of a bearing characteristic frequency or its harmonic.

To determine each value a table of values that also uses the rotational speed as another input. The total bearing failure stage is determined by the average of each failure stage type. Values for rotational speeds between two table entries are linearized.

Table 4.1 Vibration values with rotational frequencies to determine bearing failure stage [9]

Rotational frequency (Hz)	**High frequency band Acceleration RMS [*g*]**				**Vibration acceleration peak-to-peak value [*g*]**				**Highest vibration velocity at a characteristic bearing frequency or its harmonic [mm/s]**			
	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
0,83	0,225	0,450	0,900	1,800	0,254	0,508	1,016	2,032	0,16	0,32	0,64	1,28
1,67	0,335	0,670	1,340	2,700	0,381	0,762	1,524	3,048	0,26	0,52	1,02	2,04
3,33	0,392	0,785	1,569	3,149	0,508	1,016	2,032	4,064	0,50	1,00	2,00	4,00
5,00	0,450	0,900	1,800	3,600	0,572	1,143	2,286	4,572	0,75	1,50	3,00	6,00
7,50	0,500	1,000	2,000	4,000	0,635	1,270	2,540	5,080	0,88	1,75	3,50	7,00
10,00	0,950	1,900	3,800	7,600	0,762	1,524	3,048	6,096	1,00	2,00	4,00	8,00
15,00	1,100	2,200	4,400	8,800	0,826	1,651	3,429	6,858	1,70	3,40	6,90	13,60
20,00	1,300	2,600	5,200	10,400	0,889	1,778	3,556	7,112	2,40	4,80	9,60	19,20
30,00	1,500	3,000	6,000	12,00	1,016	2,032	4,046	8,128	4,10	8,20	16,40	32,80
60,00	1,750	3,500	7,000	14,000	1,270	2,540	5,080	10,160	10,20	20,40	40,80	81,60
66,67	1,889	3,778	7,556	15,112	1,524	3,048	6,096	12,192	11,29	22,58	45,16	90,31
120	3,000	6,000	12,000	24,000					20,00	40,00	80,00	160,00

4.6.3 Measurement Point Ultrasound Signal Analysis

The ultrasound values used in the following regression analysis to find the relationship functions between ultrasound and vibration values.

- Signal RMS
- Ultrasound signal peak value
- Ultrasound signal Crest factor
- Ultrasound signal FFT BPFI value
- Ultrasound signal FFT BPFO value

The ultrasound signal RMS and peak values are automatically calculated by the measurement device software. The crest factor is automatically calculated based on equation 4.3.

Similarly, the vibration signal analysis, the ultrasound values for the BPFI and BPFO are found manually from the ultrasound signal FFT. The previously determined shaft rotational speed and the values given by the SKF bearing frequency calculator are used.

4.7 Regression Analysis

4.7.1 Regression Analysis Method and Values

The goal of the regression analysis is to find a relationship function between the ultrasound and vibration values. The relationship function can then be used to extrapolate for ultrasound values for bearing conditions better than the condition of the first failure stage.

Mainly, the MATLAB function of “fitnlm” will be used to determine, the parameters of the regression model [18].

- Estimation parameters b_i (see equations 4.8, 4.9, 4.10 and 4.11 below)
- Estimation parameter standard error (SE)
- Estimation parameter *p*-value
- Relationship function Root mean square error (RMSE)
- Relationship function R-squared value
- Relationship function *p*-value

The *R*-squared value shows the likelihood of the measurements being close to the relationship function line. The R-squared value is mostly used for the determination which relationship function is more suitable under the same measurement point sample conditions.

The *p*-value is to determine the possibility of the approval of the hypothesis. In the cases of the following regression analysis

Three main types of relationship functions around which the correlation fit will be found, will be used displayed below. The relationship functions have been selected based on the most likely probable fits.

4.7.2 Relationship functions

Estimation parameters will be found in the linear relationship function. The linear relationship function is selected as it can be true that in cases of change in vibration values for change in the bearing condition, the ultrasound values may change in a linear relationship. This could be the case for especially the peak values as these values convey the same information of an event occurring in the bearing (probably at BFF).

$$y = b_1 x + b_2 \tag{4.8}$$

Where *y* is the output of the function selected to be the ultrasound values;

b_1 and b_2 are the estimation parameters of the relationship function

x is the input of the relationship function, selected to be the vibration values.

Two different logarithmic functions with different bases will be used: 10 and *e*. Base 10 is used as the ultrasound values in dBµV have been calculated using the base 10 shown in equation 2.1. Base *e* is used since the deterioration of a bearing condition for ultrasound an overall value is usually an *e* exponent function. [19]

$$y = b_1 \cdot \ln(x) + b_2 \tag{4.9}$$

Where *y* is the output of the function selected to be the ultrasound values;

b_1, b_2 and b_3 are the estimation parameters of the relationship function

x is the input of the relationship function, selected to be the vibration values.

$$y = b_1 \cdot \log(x) + b_2 \tag{4.10}$$

The exponential function is also used as it is probable that ultrasound values relate to bearing health and could also relate to vibration at an exponential function. [19]

$$y = b_1 \cdot e^{x b_2} + b_3 \tag{4.11}$$

Where *y* is the output of the function selected to be the ultrasound values;

b_1, b_2 and b_3 are the estimation parameters of the relationship function

x is the input of the relationship function, selected to be the vibration values.

5 MEASUREMENTS

It was estimated, that 150…200 measurement points would be the minimum necessary amount for a regression analysis. In total, 162 bearings were measured using both ultrasound and vibration sensors using the measurement procedures described in chapters 4.3 and 4.4. The problems that arose during the measurement process and further analysis were caused by a multitude of factors and had the following effects.

A number of bearings for the FFT analysis could not be identified as the machines, motors etc. measured were produced more than 50 years ago. These machines had no usable information present on their nameplates or no readable nameplates present at all. No easily available information was found online.

A large number of machines measured had no vibration values. Machines in probably very good condition did not produce enough vibration for the sensor to sense. Also, machines with shaft rotational frequencies of less than 5 Hz…10 Hz did not produce enough vibration for the used vibration sensor to pick up. In order to solve this problem and analyse vibration values with ultrasound values, a more sensitive (500 mV/g) vibration accelerometer should have been used.

As described in the vibration measurement process, there is a risk, where unrealistic vibration acceleration values (more than 80 g) are obtained. Whereas the ultrasound values for these cases were believable. The measuring device manufacturer has been notified about the problem. It is believed to be a software related problem.

The measurement points with the problems described above have not been used for the further analysis. In total 52 measurement points with realistic and usable measurements for both ultrasound and vibration were used in the following statistical analysis. The bearing code, shaft frequency, bearing characteristic fault frequencies, vibration values with the corresponding determined failure stages and ultrasound values are presented in the Appendices.

5.1 Full Data Analysis

The applicable 55 measurement points that have all of the data present will be firstly analysed for the correlation to the proposed relationship functions in order to find the estimation parameters. Below are show graphs with ultrasound and vibration measurement data, relationship function and relationship function curve confidence bounds. The whole data will be used to narrow down the probable relationship functions tested. Also, additional limitations will be applied to the measurement points if no conclusive results are present. The found statistical parameters for each relationship function and estimated parameters are brought in Table 5.1.

5.1.1 RMS Values

The following figure shows the linear relationship of vibration and ultrasound RMS values for all the measurement points.

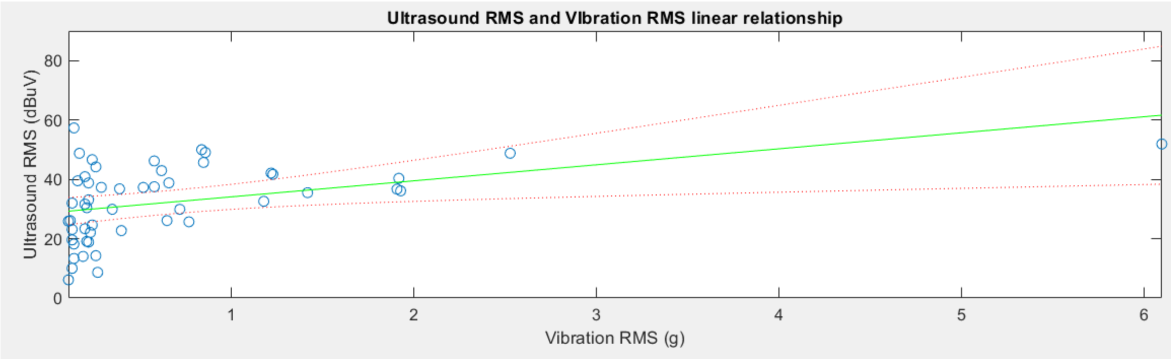

Figure 5.1 Vibration RMS and Ultrasound RMS linear relation

The following figure shows the logarithmic base 10 relationship of vibration and ultrasound RMS values for all the measurement points.

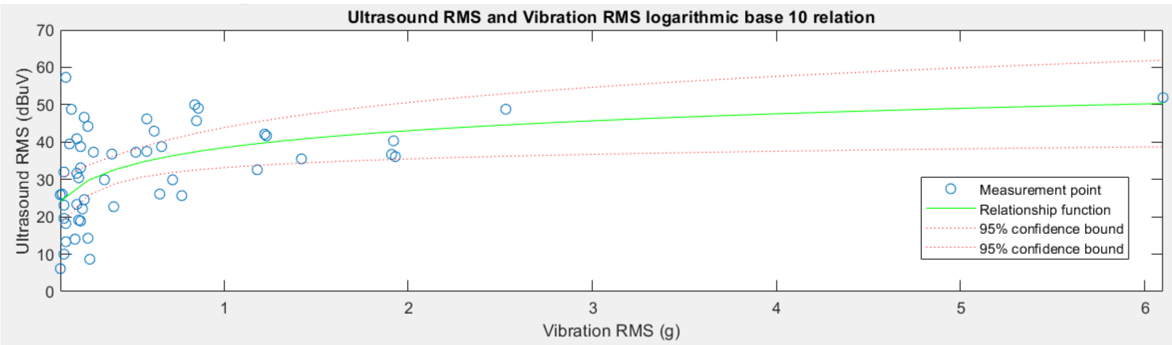

Figure 5.2 Vibration RMS and Ultrasound RMS logarithmic base 10 relation

The following figure shows the logarithmic base *e* relationship of vibration and ultrasound RMS values for all the measurement points.

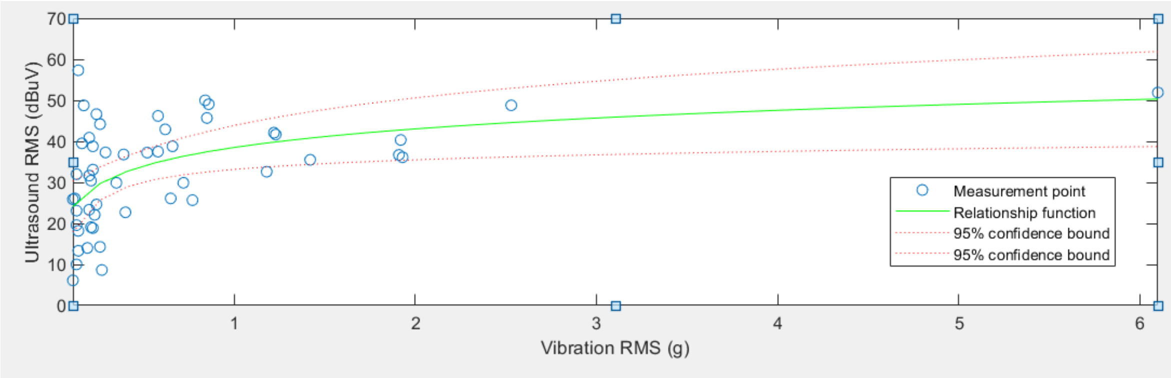

Figure 5.3 Vibration RMS and Ultrasound RMS logarithmic base *e* relation

The following figure shows the exponential relationship of vibration and ultrasound RMS values for all the measurement points.

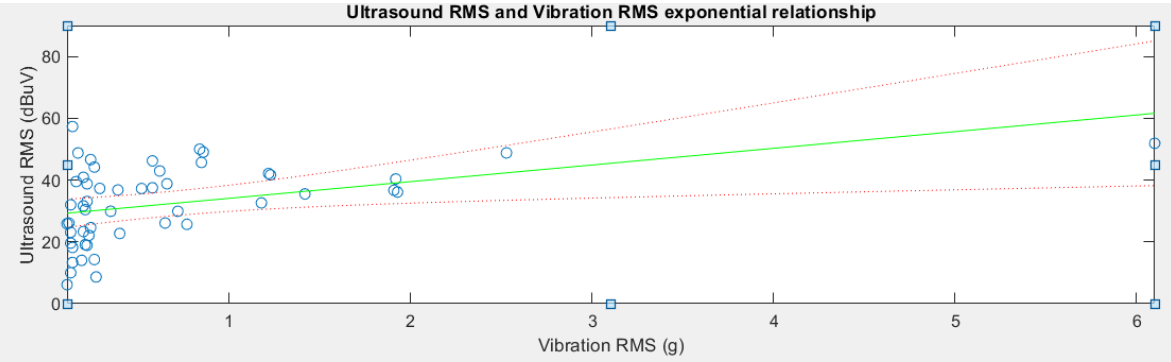

Figure 5.4 Vibration RMS and Ultrasound RMS exponential relation

Statistical parameters for the functions for the selected data do not satisfy the hypothesis of the relation based on the less than 0,05 *p*-value. Also, the *R*-squared values show no correlation of the measurement points to the data. This in addition visible in the previous graphs. A note that the exponential relation estimation parameters here are incorrectly determined, the *b* values for the relationship turn the exponential function basically to a linear function.

5.1.2 Peak Values

The following figure shows the linear relationship of vibration and ultrasound Peak values for all the measurement points.

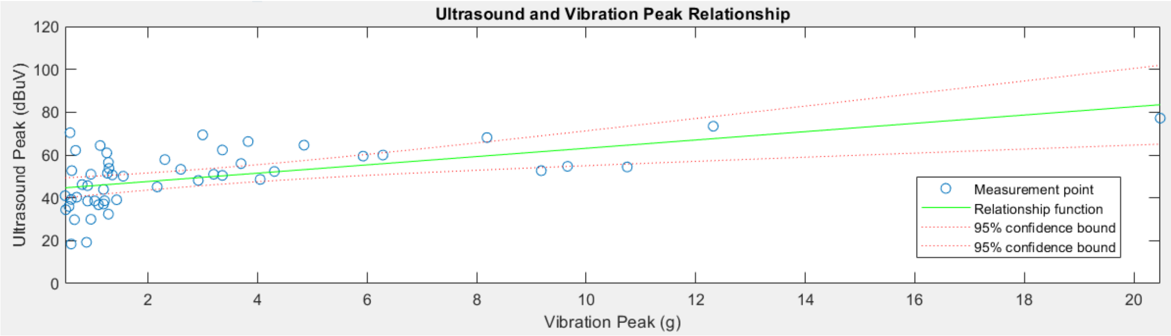

Figure 5.5 Vibration Peak and Ultrasound Peak linear relation

The following figure shows the logarithmic base 10 relationship of vibration and ultrasound Peak values for all the measurement points.

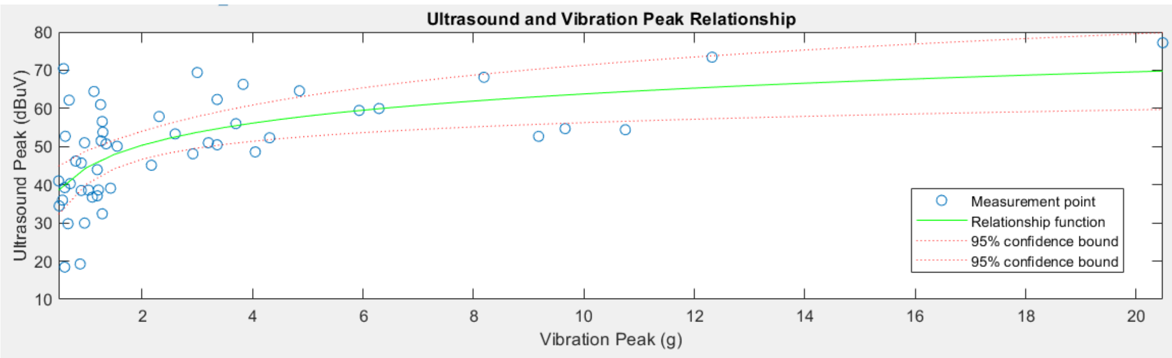

Figure 5.6 Vibration Peak and Ultrasound Peak logarithmic base 10 relation

The following figure shows the logarithmic base *e* relationship of vibration and ultrasound Peak values for all the measurement points.

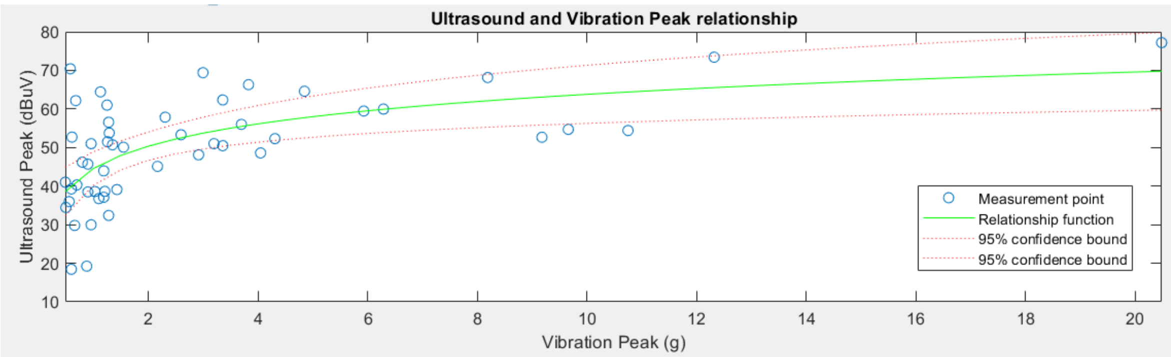

Figure 5.7 Vibration Peak and Ultrasound Peak logarithmic base *e* relation

The following figure shows the exponential relationship of vibration and ultrasound Peak values for all the measurement points.

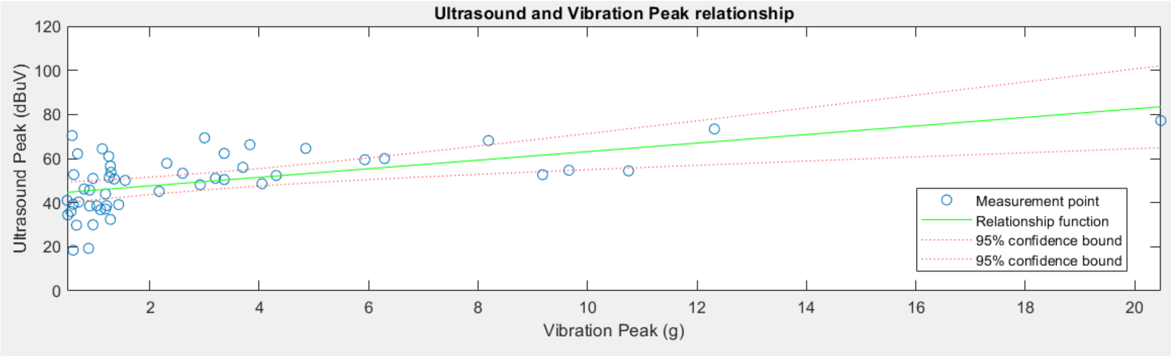

Figure 5.8 Vibration Peak and Ultrasound Peak exponential relation

Statistical parameters for the functions for the selected data do not satisfy the hypothesis of the relation based on the *p*-value. Also, the *R*-squared values show no significant correlation of the measurement points to the data. As in the RMS graphs, the exponential relation here was incorrectly determined, the *b* values for the relationship turn the exponential function basically to a linear function.

5.1.3 Crest Factor

The following figure shows the linear relationship of vibration and ultrasound Crest Factor values for all the measurement points.

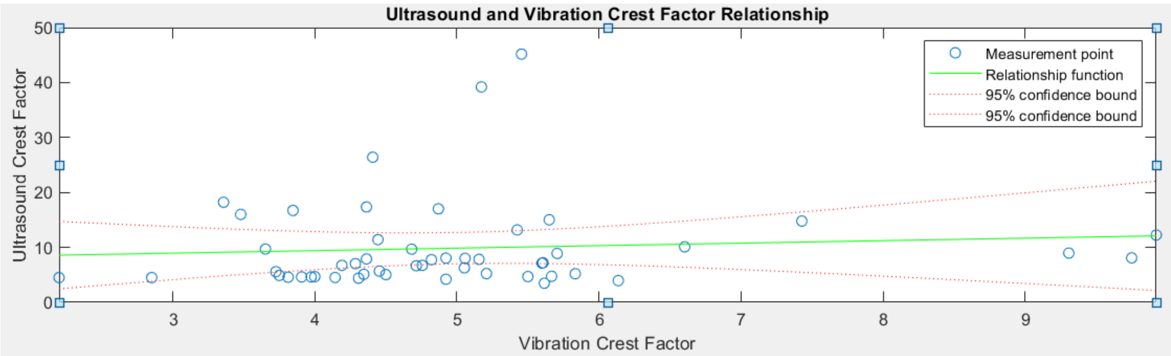

Figure 5.9 Vibration Crest Factor and Ultrasound Crest Factor linear relation

The following figure shows the logarithmic base 10 relationship of vibration and ultrasound Crest Factor values for all the measurement points.

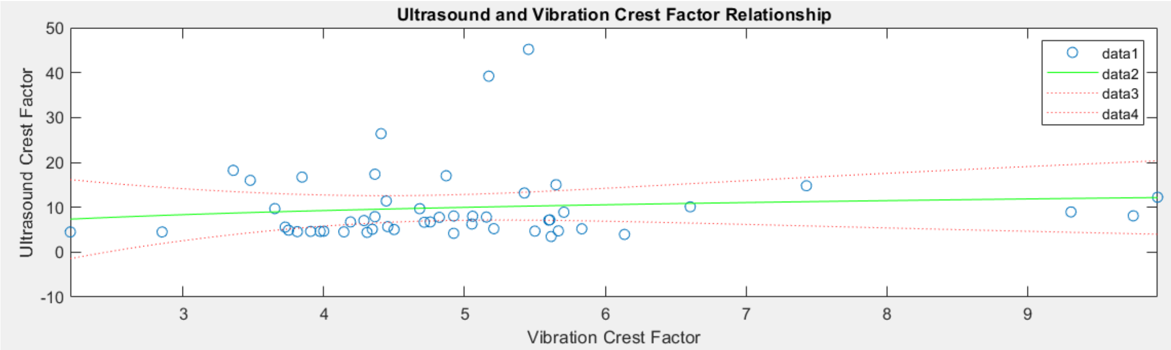

Figure 5.10 Vibration Crest Factor and Ultrasound Crest Factor logarithmic base 10 relation

The following figure shows the logarithmic base *e* relationship of vibration and ultrasound Crest Factor values for all the measurement points.

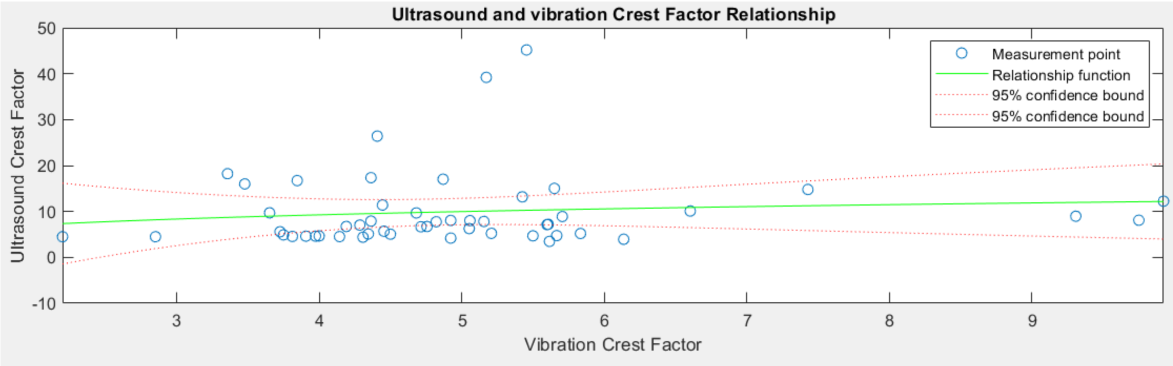

Figure 5.11 Vibration Crest Factor and Ultrasound Crest Factor logarithmic base *e* relation

Statistical parameters for the functions for the selected data do not satisfy the hypothesis of the relation based on the *p*-value. Also, the *R*-squared values show no correlation of the measurement points to the data. This in addition visible in the previous graphs. A not that the exponential relation here was incorrectly determined, the *b* values for the relationship turn the exponential function basically to a linear function.

5.1.4 Whole data analysis conclusions

Firstly, based on the estimated parameters values for the exponential relationship functions, it is clearly visible, that the exponential function does not satisfy the measurement data. Basically, a linear function is created from the exponential function.

Secondly, the difference between the logarithmic base *e* and base 10 functions is marginal. Only the base logarithmic function will be used in further analyses.

From the previous graphs, it is clearly visible, that most of the measurement data used is present near the lower vibration values (0…2) g. A more accurate and suitable relationship function could be found if only measurement points of previously found same failure stage are used.

Additionally, as the vibration values for the failure stages are dependent on the shaft rotational frequency, measurement points are narrowed down to a 5 Hz frequency ranges for further analysis. This means that only (24…29) Hz frequencies will be currently analysed as there is not enough data to for other frequencies.

Table 5.1 Relationship function parameters for all data

Data	Relationship	b_1			b_2			b_3			RMSE	*p*-value	*R*-squared
		Value	SE	*p*-value	Value	SE	*p*-value	Value	SE	*p*-value			
RMS	Linear	5,396	1,667	0,002	28,692	1,909	0,000	-	-	-	11,3	0,002	0,173
	Logarithmic base 10	15,023	3,603	0,000	38,517	2,121	0,000	-	-	-	10,7	0,000	0,258
	Logarithmic base *e*	6,524	1,565	0,000	38,517	2,121	0,000	-	-	-	10,7	0,000	0,258
	Exponential	18940,000	0,954	0,000	0,00000	0,0003	0,002	-18911	0,954	0,000	11,3	0,002	0,173
Peak	Linear	1,940	0,409	0,000	43,740	1,959	0,000	-	-	-	10,9	0,000	0,311
	Logarithmic base 10	19,238	3,540	0,000	44,552	1,724	0,000	-	-	-	10,5	0,000	0,371
	Logarithmic base *e*	8,355	1,537	0,000	44,552	1,724	0,000	-	-	-	10,5	0,000	0,371
	Exponential	8669,000	0,979	0,000	0,000	0,000	0,000	-8619,300	0,9788	0,000	10,9	0,000	0,311
Crest factor	Linear	0,455	0,768	0,557	7,586	4,008	0,064	-	-	-	8,2	0,556	0,007
	Logarithmic base 10	7,364	9,685	0,451	4,831	6,713	0,475	-	-	-	8,1	0,451	0,011
	Logarithmic base *e*	3,198	4,206	0,451	4,831	6,713	0,475	-	-	-	8,1	0,451	0,011

5.2 Selected data analysis

The selected data contains 23 measurement points at shaft frequencies of (24…29) Hz. The highest and the lowest values for both ultrasound and vibration will be removed from the data.

5.2.1 RMS Values

The following graphs describe the logarithmic and linear relationship functions with the confidence lines based on observations at 95%.

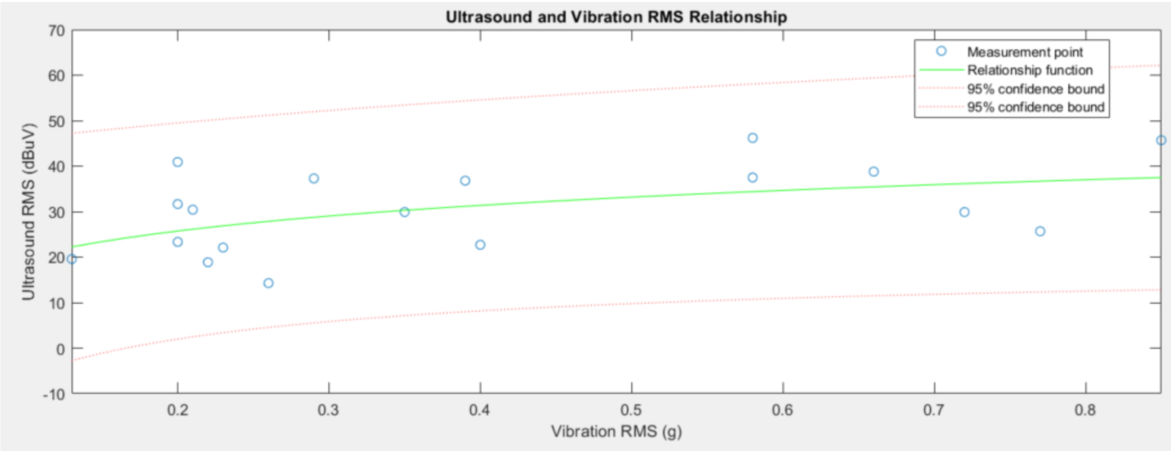

Figure 5.12 Ultrasound and Vibration RMS logarithmic relationship at 24…29 Hz shaft frequency

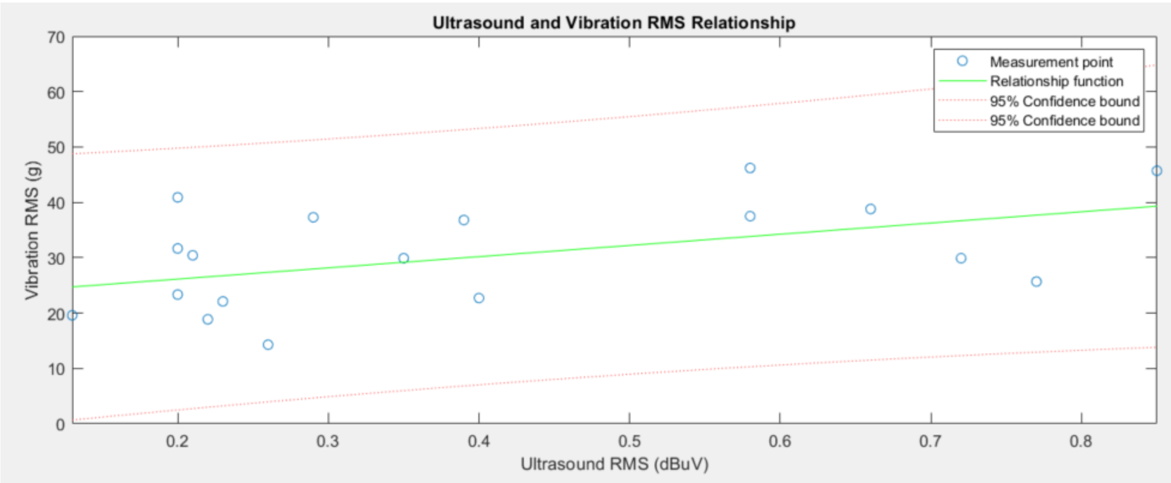

Figure 5.13 Ultrasound and Vibration RMS linear relationship at 24…29 Hz shaft frequency

Both graphs show a significant dispersion throughout the whole vibration range. This is also indicated by the low *R*-squared values. In addition, the low (less than 0,05) *p*- values state that the hypothesis of the relationship is not present.

Table 5.2 Relationship function parameters for selected data RMS values

Relationship	b_1			b_2			RMSE	p-value	R-squared
	Value	SE	p-value	Value	SE	p-value			
Linear	20,262	8,881	0,036	22,083	4,060	0	8,42	0,036	0,189
Logarithmic base e	38,820	4,231	0	8,128	3,562	0,036	8,42	0,036	0,189

5.2.2 Peak Values

The following graphs describe the logarithmic and linear relationship functions with the confidence lines based on observations at 95%.

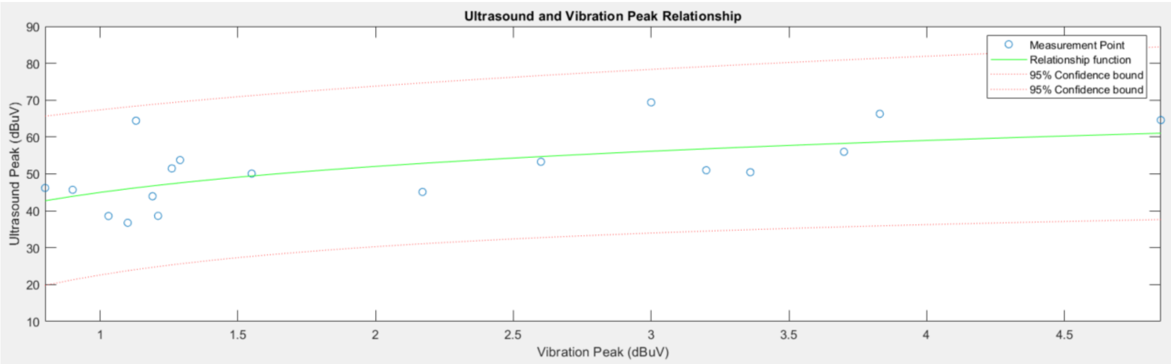

Figure 5.14 Ultrasound and Vibration Peak logarithmic relationship at 24…29 Hz shaft frequency

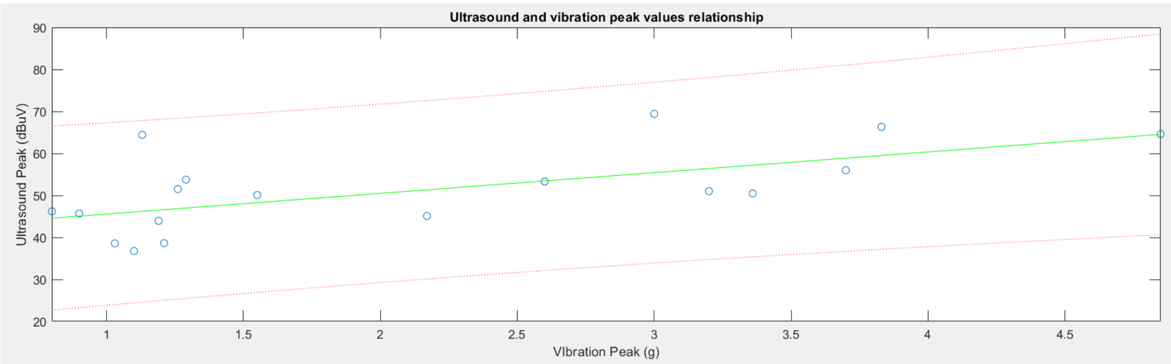

Figure 5.15 Ultrasound and Vibration Peak linear relationship at 24…29 Hz shaft frequency

Both graphs show a significant dispersion throughout the whole vibration range. This is also indicated by the low R-squared values. In addition, the low (less than 0,05) p- values state that the hypothesis of the relationship is not present.

Table 5.3 Relationship function parameters for selected data RMS values

Relationship	b_1			b_2			RMSE	*p*-value	*R*-squared
	Value	SE	*p*-value	Value	SE	*p*-value			
Linear	4,926	1,502	0,004	40,643	3,647	0,000	7,73	0,004	0,388
Logarithmic base *e*	10,158	3,297	0,006	44,998	2,6862	0,000	7,91	0,007	0,358

5.2.3 Crest Factor

The following graphs describe the logarithmic and linear relationship functions with the confidence lines based on observations at 95%.

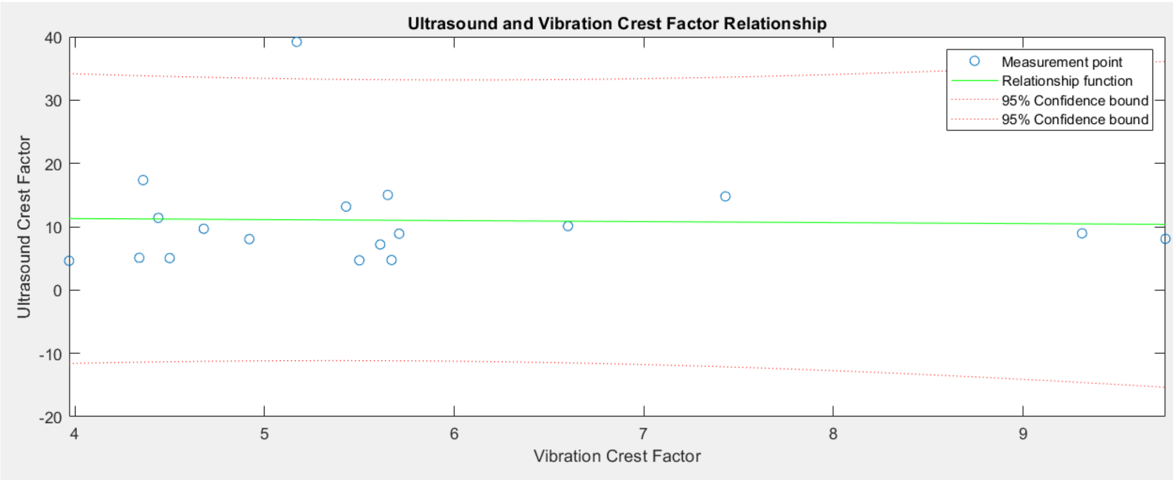

Figure 5.16 Ultrasound and Vibration Crest Factor linear relationship at 24...29 Hz shaft frequency

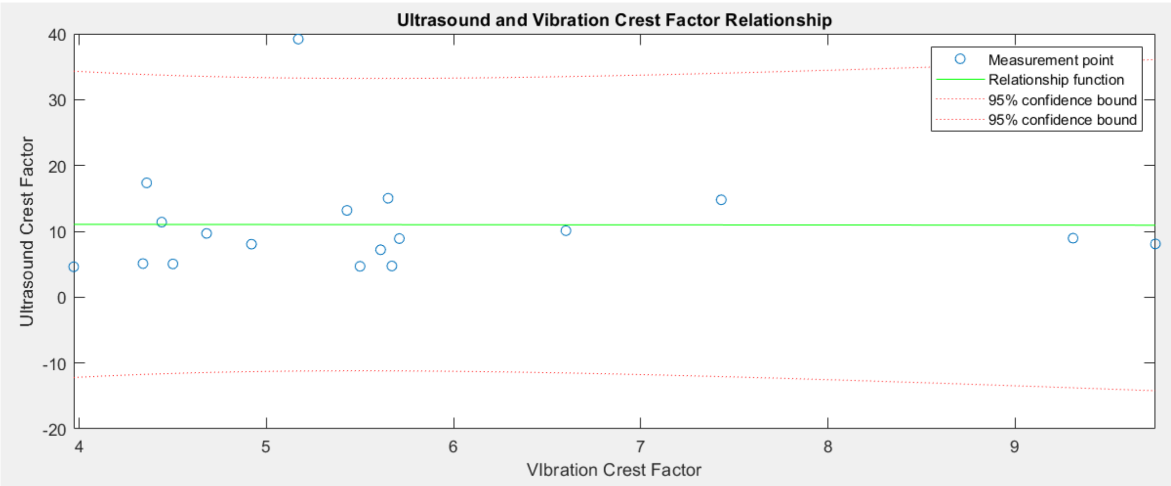

Figure 5.17 Ultrasound and Vibration Crest Factor logarithmic relationship at 24...29 Hz shaft frequency

Table 5.4 Relationship function parameters for selected data Crest Factor values

Relationship	b_1			b_2			RMSE	*p*-value	*R*-squared
	Value	SE	*p*-value	Value	SE	*p*-value			
Linear	-0,159	1,203	0,897	11,921	7,112	0,112	8,07	0,897	0,001
Logarithmic base *e*	-0,142	7,784	0,986	11,259	13,45	0,414	8,08	0,986	0,000

The linear crest factor has otherwise acceptable parameters for the regression analysis. However, the R-square value is so low, that a relationship between the ultrasound and crest factors is probably not present.

The previous Crest factor graphs are manly showing that ultrasound and vibrations crest factors only share a weak relationship. This is also proven by correlating different types of ultrasound values (Peak *vs.* RMS).

5.3 Regression Analysis Conclusions

The done analyses have not provided significant data to surely describe a relationship between ultrasound and vibration values. In all cases the *p*-values were not in range to prove the hypothesis true. To increase the certainty of these decisions, more measurement points with additional information has to be present. In such cases, there would be the better possibility to understand and find additional relationships.

It is very likely as the vibration values for bearing condition are dependent on shaft frequency, that there can be a relation between shaft frequency and ultrasound also. Other likely parameters that may affect ultrasound values are:

- the amount and type of grease in the bearing;
- bearing ball or cylinder dimensions and mass.

The mostly likely fit for the relationship function is a logarithmic function. These types of functions should be considered in future analyses.

6 SUMMARY

Both ultrasound and vibration monitoring methods are used in the industry to gain an insight of the machinery condition and plan the maintenance activities in order to minimise unplanned stoppages. Vibration monitoring has been used in a wider scale than ultrasound for rolling bearing diagnostics. ISO standards are present for vibration and not for ultrasound measurements.

The aim of the work was to determine a relationship between these two predictive maintenance technologies. This is necessary in order to relate ultrasound measurement magnitudes with rolling bearing condition. Having such information present would significantly reduce the time needed to appropriately set the bearing condition alarm levels for ultrasound diagnostics.

To reach the goal, both ultrasound and vibration measurements were conducted in parallel for many rolling bearings. The measurement device SDT340 from SDT International was used with the ultrasound sensor RS2T and vibration sensor HS100. In total 5 different companies were visited, where the measurements were performed. In total 162 measurement points were recorded with ultrasound and vibration parameters measured. It was

Unfortunately, most of the measurement points' data was difficult to evaluate as for the following reasons.

- Vibration signal was not determined as the bearing condition was nearly perfect.
- Vibration signal was not determined as the bearing shaft rotational frequency was too low.
- Vibration measurement signal values (compared to those of ultrasound) were unrealistically high for probable reasons such as software errors etc.

Another drawback was related to the uncertain information about the bearings to be measured. A significant number of measurement points were from machines with no nameplate information or so old, that the information was not available in online sources.

Only 52 (out of 162) measurement points were considered suitable for further analysis, where the RMS, Peak and Crest factor values were viewed using four different relation functions to determine the estimation parameters, standard deviations, R-squared values and *p*-values.

It can be concluded based on the study above, that there is no significant correlation between the ultrasound and vibration Peak, RMS and Crest Factor values. Further steps should focus on the following.

- Enlarge the data analysis scope for all measurement points

- Study of the correlation based on additional parameters such as BFF, bearing dimensions etc.
- Increase the number of input parameters and influencers such as shaft frequencies, rolling bearing type and dimensions, lubricant amount etc.
- Determine the ultrasound values to rolling bearing condition
- Create a practical tool or a mathematical function for setting ultrasound monitoring alarms.

7 KOKKUVÕTE

Ultraheli ja vibratsiooni mõõtmisi kasutatakse tööstuses, et hinnata laagrite seisundit ning selle läbi paremini planeerida korrashoiu tegevusi. Vibratsiooni mõõtmisi on antud ülesande täitmiseks kasutatud enam. Vibratsiooni alased standardid on veerelaagritele olemas, aga ultraheli alased standardid puuduvad.

Töö eesmärgiks oli leida sõltuvus funktsioon ennustava tehnoloogia väärtuste vahel. Antud funktsiooni on vajalik, kuna selle alusel saaks efektiivsemalt seadistada laagritele ultraheli mõõtmistega seonduvaid alarme.

Tulemuseni jõudmiseks teostati ultraheli ja vibratsiooni mõõtmisi paralleelselt veerelaagritele tootmisettevõtetes. Mõõtmisteks kasutati SDT340 mõõteseadet koos ultraheli sensori RS2T ja vibratsiooni sensoriga HS100. Kokku viidi läbi mõõtmisis viies ettevõttes, kus kokku mõõdeti 162 mõõtepunkti.

Suur hulk mõõtepunktidest polnud usaldatavad järgnevatel põhjustel.

- Vibratsiooni signaal puudus, kuna laagri seisukord oli piisavalt hea, et seal ei esinenud sensorile piisavalt vibratsiooni.
- Vibratsiooni signaal puudus kuna laagri võlli pöörlemissagedus oli liiga madal.
- Vibratsiooni signaali väärtused olid ebarealistlikult kõrged võrreldes ultraheli väärtustega, mis tekkis tarkvaralistest probleemidest jms.

Täiendavalt puudus mitmete mõõtepunktide puhul laagri tüübi kohta informatsioon, sest mõõdetud seadmetel puudusid nimeplaadid või seadmete vanuse tõttu polnud vajalik informatsioon leitav.

Ainult 52 mõõtepunkti 162 hinnati sobilikuks edasiseks analüüsiks. Teostati regressiooni analüüs kasutades ultraheli ja vibratsiooni tipu ja ruutkeskmiseid väärtuseid. Regressiooni analüüsid viidi läbi kasutades nelja arvatavat sõltuvusfunktsiooni, millele otsiti mõõteandmete alusel funktsiooni parameetreid. Regressiooni analüüsi tulemusi hinnati kasutades standard viga, p-statistikut ja *R*-ruut väärtuseid.

Töö tulemusel saab väita, et sõltuvusfunktsioon tipu ja keskmiste väärtuste baasil puudub või pole antud teema järgnevad sammud peaksid olema suunatud järgnevatele tegevustele.

- Laiendada andmete analüüsi skoop kõikide mõõtepunktide jaoks.
- Viia läbi regressiooni analüüs kasutades täiendavaid parameetreid nagu laagri tõrkesageduste vibratsiooni ja ultraheli väärtused.

- Suurendada analüüsi sisendparameetrite hulka kasutades näiteks pöörlemissagedusi, veerelaagri tüüpi, veerelaagri dimensioone, määrdeaine kogust jne.
- Hinnata ultraheli väärtuseid, mis vastaksid veerelaagri oleku tasemetele.
- Luua praktiline tööriist või matemaatiline funktsioon ultraheli monitooringute alarmide seadistamiseks.

8 References

[1] M. H. M. Mulders, “Predictive Maintenance 4.0 - Predict the unpredictable,” PwCNetherlands, Mainnovation, 2017.

[2] P. Burge, “Identifying The Causes of Bearing Damage and Failure,” Process Industry Informer, 4 December 2017. [Online]. Available: https://www.processindustryinformer.com/editorial/identifying-causes-bearing-damage-failure/. [Accessed 13 March 2019].

[3] Uptime Elements system, “How Failure Occurs,” Reliabilityweb.com, 2019.

[4] P. J. Hass, “Introduction to Acoustics,” Indiana University, 2017. [Online]. Available: http://www.indiana.edu/~emusic/etext/acoustics/chapter1_amplitude4.shtml. [Accessed 13 March 2019].

[5] J. K. O. M. W. Lane, “Intensity and Energy in Sound Waves,” Project PHYSNET, Michigan, 2000.

[6] M. Scholz, “Every sample counts: the relationship between sampling rate, precision and accuracy when measuring time varying signals.,” Northern Digital Inc., 2015.

[7] International Standard Organisation, *ISO 20816 Mechanical vibration - Measurement and evaluation of machine vibration,* International Standard Organisation, 2016.

[8] J. E. Berry, Tracking of Rolling Element Bearing Failure Stages Using Vibration and High Frequency Enveloping and Demodulation Spectral Techniques", Charlotte, NC: Technical Associates of Charlotte, P.C, 1997.

[9] K. S. Brian P. Graney, “Rolling Element Bearing Analysis,” *Materials Evaluation,* vol. 70, no. 1, pp. 78-85, 2011.

[10] I. Abbas, “Bearing Failure Stages,” 2016.

[11] SDT International, SDT340 Asset Health Evaluation Meter User Manual, Brussels: SDT Inernational, 2018.

[12] SDT Intenrational, SDT340 Manual, Brussels: SDT International, 2018.

[13] SDT International, *Product Change Notification,* Brussels: SDT Inetrnational, 2017.

[14] SDT International, “SDT Software,” SDT International, 2019. [Online]. Available: https://www.sdtultrasound.com/products-solutions/products/software. [Accessed 10 May 2019].

[15] SDT International, “Asset Condition Monitoring,” SDT International, 2019. [Online]. Available: https://sdtultrasound.com/products-solutions/solutions/asset-condition-monitoring. [Accessed 25 April 2019].

[16] SKF Group, “SKF Bearing Frequencies Calculator,” SKF Group, [Online]. Available: http://webtools3.skf.com/engcalc/CalcBearingFrequencies.do. [Accessed 3 April 2019].

[17] J. Mais, “Spectrum analysis,” SKF USA Inc., San DIego, 2002.

[18] The Mathworks Inc., “Matlab fitnlm function,” The Mathworks Inc., [Online]. Available: https://www.mathworks.com/help/stats/fitnlm.html?searchHighlight=fitnlm&s_tid=doc_srchtitle. [Accessed 21 May 2019].

[19] N. L. L. G. N. L. T. Y. J. L. Yagou Lei, “Machinery health prognostics: Asystematic review from data acquisition to RUL prediction,” *Elsevier,* vol. Mechanical Systems and Signal Processing, no. 104, pp. 799-834, 2018.

[20] L. S. Sterling, The Art of Agent-Oriented Modeling, London: The MIT Press, 2009.

APPENDICES

Table 0.1 Measurements

Measure-ment nr.	Bearing code	Shaft frequency (Hz)	BPFI (Hz)	BRFO (Hz)	FTF (Hz)	BSF (Hz)	RMS (*g*)	RMS (*g*) Failure stage	Peak (*g*)	Peak-to Peak (*g*)	Peak-to-peak Failure Stage	RMS (mm/s)	Highest BFF (mm/s)	BFF (mm/s) Failure Stage	Average Failure stage	US RMS (dBµV)	US Peak (dBµV)	US Crest factor	US BPFI (μV^2)	US BPFO (μV^2)
FTU 2	6209	32,20	191,50	130,50	13,10	82,00	0,12	0	0,70	1,11	0	0,16	0,10	0	0,00	26,10	40,30	5,20	20,01	31,40
FTU 4	6232	20,00	136,90	103,70	8,60	69,50	1,42	1	4,05	7,00	2	1,32	0,00	0	1,00	35,50	48,60	4,50	136,66	206,04
FTU 5	6232	20,00	136,90	103,70	8,60	69,50	0,24	0	0,90	1,56	0	0,28	0,00	0	0,00	24,60	38,50	4,90	7,27	18,24
FTU 6	6232	16,80	115,00	86,60	7,20	58,30	0,65	0	1,43	2,78	1	0,39	0,00	0	0,33	26,10	39,10	4,50	6,89	24,13
PK 1	6313	24,70	121,60	75,70	9,50	50,20	0,58	0	3,00	4,00	1	8,62	1,68	1		37,50	69,40	39,20	1958,70	3281,00
PK 2	6313	24,70	121,60	75,70	9,50	50,20	0,72	0	3,20	5,10	1	11,26	2,30	2		29,90	51,00	11,40	49,50	116,20
PK 3	6313	24,70	121,60	75,70	9,50	50,20	0,23	0	0,80	1,50	0	3,37	0,47	0		22,10	46,20	16,00	14,60	65,50
TLNV 21	6314	29,00	142,80	89,20	11,20	59,50	0,26	0	1,28	2,00	0	0,86	0,22	0	0,00	44,20	56,56	4,20	1066,00	997,00
TLNV 38	N/A	24,80					0,26	0	1,28	1,55	1	1,14				14,28	32,39	8,05		
TLNV 39	N/A	24,80					0,22	0	1,03	1,86	1	0,52				18,87	38,59	9,68		
TLNV 40	6305	18,50	81,90	47,60	6,80	32,50	0,22	0	0,96	1,39	0	0,50	0,66	0	0,00	33,10	51,00	7,90	166,20	57,90
TLNV 42	6309	24,67	122,40	74,90	9,40	48,20	1,18	0	4,31	8,28	4	2,45	0,06	0	1,33	32,60	52,30	9,70	77,90	118,30
TLNV 43	6309	24,67	122,40	74,90	9,40	48,20	1,91	1	9,66	16,10	4	2,46	0,39	0	1,67	36,70	54,70	8,00	340,10	338,80
TLNV 44	6309	24,67	122,40	74,90	9,40	48,20	0,66	0	3,70	6,86	3	0,90	0,42	0	1,00	38,80	56,00	7,20	333,40	592,20
TLNV 45	6309	24,67	122,40	74,90	9,40	48,20	0,29	0	1,26	2,33	2	1,50	0,20	0	0,67	37,30	51,50	5,10	255,00	1262,00
TLNV 46	6309	24,67	122,40	74,90	9,40	48,20	0,58	0	3,83	7,43	3	0,88	0,04		1,50	46,20	66,30	10,10	2924,80	2618,00
TLNV 47	6309	24,67	122,40	74,90	9,40	48,20	0,85	0	4,85	9,24	4	0,86	0,12		2,00	45,70	64,60	8,90	1804,80	1818,00
TLNV 48	6309	24,67	122,40	74,90	9,40	48,20	0,20	0	0,90	1,20	1	1,36	0,00		0,50	31,66	45,70	5,05	54,20	40,30
TLNV 49	6309	24,67	122,40	74,90	9,40	48,20	0,39	0	1,55	3,02	2	0,86	0,41		1,00	36,80	50,09	4,62	685,70	198,30
TLNV 50	6310	12,67	62,73	38,60	4,80	25,10	1,93	2	9,18	18,75	4	1,91	0,05	0	2,00	36,12	52,67	6,72	306,20	251,40
TLNV 51	6310	12,67	62,73	38,60	4,80	25,10	6,10	3	20,48	40,35	4	3,99	1,97	1	2,67	51,90	77,20	18,22		42428,00
TLNV 52	6310	12,67	62,73	38,60	4,80	25,10	1,92	2	10,75	19,78	4	2,49	0,80	0	2,00	40,34	54,41	7,13	1161,00	
TLNV 55	6310	12,67	62,73	38,60	4,80	25,10	2,53	2	12,32	23,78	4	2,46	0,21	0	2,00	48,79	73,42	17,02	6163,40	4294,80
TLNV 56	6310	12,67	62,73	38,60	4,80	25,10	1,22	1	6,29	11,42	4	2,68	1,08	0	1,67	42,11	59,97	7,82	881,60	914,90
TLNV 57	6212	11,67	69,23	47,40	4,74	30,10	0,86	0	3,36	6,10	3	3,90	3,70	2	1,67	49,05	62,34	4,62	1585,67	5579,65
TLNV 60	6315	18,00	88,54	55,46	6,93	37,12	0,22	0	1,35	2,65	2	0,33	0,00	0	0,67	38,79	50,71	3,95	0,00	0,00
TLNV 61	3311	18,00	87,14	56,86	7,11	35,43	0,21	0	0,88	1,60	1	0,56	0,00	0	0,33	19,10	19,25	6,73	0,00	0,00
TLNV 62	N311	18,00	140,80	93,20	7,17	42,42	0,19	0	0,96	1,72	2	0,59	0,00	0	0,67	14,02	29,97	6,27	0,00	0,00

Measure-ment nr.	Bearing code	Shaft frequency (Hz)	BPFI (Hz)	BRFO (Hz)	FTF (Hz)	BSF (Hz)	RMS (*g*)	RMS (*g*) Failure stage	Peak (*g*)	Peak-to Peak (*g*)	Peak-to-peak Failure Stage	RMS (mm/s)	Highest BFF (mm/s)	BFF (mm/s) Failure Stage	Average Failure stage	US RMS (dBµV)	US Peak (dBµV)	US Crest factor	US BPFI (µV²)	US BPFO (µV²)
TLNV 63	3309	18,00	86,44	57,56	7,20	37,31	0,14	0	0,60	1,01	1	0,62	0,00	0	0,33	18,19	18,44	7,04	3,91	7,29
TLNV 64	6309	18,00	89,34	54,65	6,83	35,20	0,14	0	0,66	1,22	1	0,40	0,03	0	0,33	13,33	29,80	6,66	1,11	1,79
TLNV 65	6315	36,40	179,04	112,16	14,02	75,06	0,52	0	2,92	5,70	3	1,84	0,02	0	1,00	37,27	48,11	3,48	203,90	200,40
TLNV 66	6315	36,40	179,04	112,16	14,02	75,06	0,62	0	2,31	4,32	3	3,08	0,00	1	1,33	42,93	57,87	5,58	327,60	696,50
TLNV 67	N/A	24,40					0,20	0	1,10	1,59	1	2,23			0,50	23,34	36,76	4,69		
TLNV 68	N/A	24,40					0,11	0	0,60	1,32	1	1,61			0,50	6,13	39,25	45,18		
TLNV 69	6306	47,00	232,48	143,52	17,94	93,77	0,13	0	0,56	0,99	0	0,36	0,01	0	0,00	23,11	35,98	4,40	22,89	8,80
TLNV 70	6306	47,00	232,48	143,52	17,94	93,77	0,11	0	0,49	0,97	0	0,46	0,01	0	0,00	25,89	41,00	5,69	27,80	17,58
TLNV 71	6309	42,20	209,46	128,14	16,02	82,52	1,23	0	5,93	11,25	4	4,02	0,34	0	1,33	41,67	59,47	7,76	918,71	580,13
TLNV 72	6309	24,60	122,10	74,70	9,34	48,11	0,40	0	2,17	3,70	2	3,86	0,18	0	0,67	22,71	45,11	13,18	5,33	11,09
TLNV 73	6309	24,60	122,10	74,70	9,34	48,11	0,21	0	1,19	2,89	2	0,87	0,26	0	0,67	30,43	43,95	4,74	31,81	133,29
TLNV 74	6206	28,80	156,44	102,76	11,42	66,56	0,13	0	1,21	2,40	2	0,24	0,08	0	0,67	19,59	38,64	8,96	13,07	8,79
TLNV 75	3306	28,80	139,51	90,90	11,36	56,48	0,13	0	1,29	2,19	2	0,71	0,23	0	0,67	32,00	53,76	12,24	391,70	234,81
TLNV 80	6206	28,80	156,44	102,76	11,42	66,56	0,84	0	8,19	13,19	4	2,56	0,64	0	1,33	49,99	68,15	8,09	7332,85	11454,25
TLNV 81	3306	28,80	139,51	90,90	11,36	56,48	0,35	0	2,60	3,49	3	1,49	0,30	0	1,00	29,90	53,31	14,79		
TLNV 82	3306	28,80	139,51	90,90	11,36	56,48	0,20	0	1,13	2,16	2	1,03	0,45	0	0,67	40,90	64,43	15,02	1872,00	2817,10
TLNV 83	6206	28,80	156,44	102,76	11,42	66,56	0,14	0	0,58	1,10	1	0,95	0,16	0	0,33	57,32	70,42	4,52	7556,19	35034,13
TLNV 86	6310	24,60	121,83	74,97	9,37	48,73	0,40	0	2,17	3,70	2	3,86	0,18	0	0,33	22,71	45,11	13,18		11,09
TLNV 94	22318	24,80	233,77	163,03	10,19	65,72	0,77	0	3,36	5,86	3	1,19	0,13	0	0,67	25,68	50,47	17,36	44,31	37,40
FMW 3	6206	46,20	228,52	141,08	17,64	92,17	0,13	0	0,50	0,85	0	1,19	0,19	0	0,00	10,01	34,46	16,72	1,03	0,94
FMW 4	6308	46,20	227,68	141,92	17,74	94,20	0,27	0	1,19	1,69	1	2,68	0,05	0	0,33	8,65	37,10	26,41	0,85	0,96
FMW 6	6308	29,80	146,86	91,54	11,44	60,76	0,16	0	0,61	1,09	1	1,18	0,20	0	0,33	39,51	52,70	4,57	201,79	171,76
FMW 7	6308	29,80	146,86	91,54	11,44	60,76	0,24	0	1,25	1,59	1	2,38	0,44	0	0,33	46,63	61,00	5,23	5762,83	9094,63
FMW 8	6308	29,80	146,86	91,54	11,44	60,76	0,17	0	0,68	0,86	0	1,51	0,22	0	0,00	48,77	62,16	4,67	934,60	2518,20