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VIBRATION MEASUREMENT OF HIGH-SPEED ELECTRIC MOTOR IN POST-ASSEMBLY TESTING

SUURNOPEUSSÄHKÖMOOTTORIN KOKOONPANON JÄLKEINEN VÄRÄHTELYMITTAUS

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Uusille koneille on tärkeää suorittaa kokoonpanon jälkeinen testaus. Pyörivillä koneilla alentunut suorituskyky voi johtua monista eri syistä, yleisiä vikoja ovat epätasapaino, linjausvirheet, väljyys tai asennuksessa syntyneet muodonmuutokset. Vikoja pystytään analysoimaan sen värähtelykäyttäytymisestä. Selvittääkseen mikä aiheuttaa liian suuren värähtelyn koneessa on ymmärrettävä, kuinka eri vikatyypit käyttäytyvät. On myös ymmärrettävä mitattavan koneen ominaisuuksien vaikutus mittaukseen luotettavan tiedon tuottamiseksi. Tässä työssä luodaan yhteistyössä The Switch:n (osa Yaskawa yhtiötä) kanssa heidän suurnopeussähkömoottorinsa käyttöönottotestaukselle sopiva värähtelymittaus ohjeistus. Tiedot ohjeistuksen luomiseksi hankitaan kirjallisuudesta.

Suurnopeussähkömoottorin tapauksessa mittalaitteisto tulee olla suojattu sähkömagnetismia vastaan ja sen tulee pystyä havaitsemaan tarkasti korkeat taajuudet. Korkeita taajuuksia mitattaessa on tärkeää asentaa kone ja sensorit mahdollisimman jäykästi välttääkseen resonanssit. Värähtely tulee mitata useassa suunnassa korkealla näytteenottotaajuudella. Mitattavan taajuuskaistan ollessa hyvin laaja ei yhdellä mittalaitteistolla pystytä tuottamaan tarkkoja tuloksia joka taajuudella. Eri vikatyypit värähtelevät osittain samalla tavalla, joka tuo lisähaastetta analysointiin. Mittauksessa voidaan tehdä analysointia helpottavia toimenpiteitä kuten ramp-up tai coas down testaukset. Tuloksista huomattiin, ettei nykyinen mittausprosessi täytä kaikilta osin vaatimuksia vikatyyppien tunnistamiseksi. Radiaalisuuntaan on lisättävä toinen sensori, sensorien kiinnitystapa on muutettava kiinteäksi ja aksiaalinen sensori on asennettava myös laakeripesään. Näillä muutoksilla saadaan värähtely mitattua tarkasti vika-analysointia varten.

ABSTRACT

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Vibration measurement of high-speed electric motor in post-assembly testing

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For new machines, it is important to perform post-assembly testing. The performance of a rotating machine is often reduced due to faults such as imbalance, misalignment, looseness, or deformation during installation. Faults can be analysed from the vibration behaviour of a machine and to determine the cause of excessive vibration, it is necessary to understand how different types of faults behave. It is also important to select suitable measurement method for different machine type in order to produce reliable information. In this work, in collaboration with 'The Switch' (part of Yaskawa company), a vibration measurement instruction for post-assembly testing of their high-speed electric motors is created. Information for creating guidelines is obtained from the literature.

The literature reveals that for a high-speed electric motor, the measuring equipment should accurately detect high frequencies while being protected against electromagnetism. To avoid resonances at high speeds, it is also mandatory to install the machine and sensors with high rigidity. The vibration must be measured in several directions at a high sampling frequency. For a wide frequency band, a single measuring device cannot produce accurate results at every frequency. The different types of faults lead to partially similar vibrations, which brings more challenge to the analysis. Additional measurement procedures, such as ramp-up or coast-down testing can facilitate broader analysis of fault types. The results showed that the current measurement process does not fully meet the requirements for identifying multiple fault types. A second sensor must be added in the radial direction, fixed mounting method should be sued for the sensors and the axial sensor must be mounted on the bearing housing. These changes will ensure accurate vibration measurement for multiple fault analysis.

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ABBREVIATIONS

°	degree
1X	rotating speed
2X	two times rotating speed
3X	three times rotating speed
A	amplitude
AC	alternating current
B	breadth
BPFI	ball pass frequency – Inner
BPFO	ball pass frequency – Outer
BSF	ball spin frequency
d	diameter- inner
D	diameter- outer
Dp	pitch diameter
DC	direct current
EMC	electromagnetic compatibility
f_L	power line frequency
f_P	pole pass frequency
f_R	rotating speed
f_S	synchronous speed
f_{SL}	slip frequency
FFT	Fast Fourier transformation
FTF	fundamental train frequency (Cage)
GCL	geometric centerline
IEC	International Electrotechnical Commission
ISO	International Standards Organization
M8	standardized thread size (8mm diameter)
nX	n number of rotating speed
Nb	number of rolling elements
p	pole-pair number
PIA	principle inertia axis

rpm	revolution per minute
RBPF	rotor bar pass frequency
SFS	Suomen Standardisoimisliitto (Finnish Association for Standardization)
SPM	shock pulse measurement
t	time
T	cycle time
UMP	unbalanced magnetic pull

α	contact angle
θ	contact angle in degrees
φ	initial phase of the wave
ω	angular frequency

1 INTRODUCTION

Data collection has been a growing trend for several years. There are no signs of fading for this growth yet. (Collin & Saarelainen 2016, p.21) Individuals collect information about themselves, companies in the consumer market want information about their customers and industry needs information about the operational processes. At the core of data collection is the benefits in relation to the costs involved. Collin and Saarelainen (2016) cite the reason for the increase is in lower costs for both sensors and data storage. Information has also begun to be centralized in massive data centers, making data storage very reliable and inexpensive. In industry, measuring and monitoring the process has been a key part throughout its operation. Measurement and data collection are focused on monitoring critical and operationally important areas and data may not have been stored for analysis at a later stage. However, lower prices of sensors and data storage have made it possible to extend the measurement to coverage the whole process. (Collin & Saarelainen 2016, p.43,61,153)

The general competitive situation and the need to produce sustainable products are forcing companies to invest more in the efficiency of products and processes. In recent years, the industry has invested heavily in the development of data analysis and artificial intelligence applications. The aim is to extend and optimize the use of machines, shorten the time spent on maintenance, improve the co-operation between production and administration, and generate as much added value as possible for the customer. (Collin & Saarelainen 2016, p. 62, 73-75) However, the task is not easy despite the increased information. Efforts have been made to optimize machines and processes without a large amount of data, and in many areas the efficiency of machines is already at a good level. However, even small improvements can achieve great benefits in certain applications. As an example, approximately 97% of the life cycle cost of an electric motor is generated by the electricity consumed during operation (Motiva 2017 p.6). Even a percentage improvement in machine efficiency would bring significant savings to the machine operator and reduce the carbon footprint. In order to achieve the improvement, all activities, from the design of the machine to its recycling, must be optimized.

Vibration measurement is used throughout the life cycle of a machine to monitor its condition, the first measurements take place immediately after assembling the machine

(SFS-ISO 13373-1 2002, p.21). This work was driven by the desire of a high-speed electric motor manufacturer to improve its own data analysis. In order to perform the analyzes, the accuracy of the data must first be verified.

Vibration has long been used to monitor machines and has also been extensively studied. On the basis of the study, standards have been created that define the basic level of implementation of vibration measurement. Vibration analysis has also been studied for several decades. The objectives of the analyzes have changed in recent years. A proactive warning about the machine breakdown is no longer enough. The information obtained from the vibration is to be used for the real-time control of the machine till the development of the next product batch. As a result, new analysis methods are constantly being developed. In order to be able to adjust or repair the machine, the cause of the fault must be known as accurately as possible. Different fault situations have their own vibration behaviour. (Scheffer & Girdhar 2004, pp. 1–10, 29, 89.) In this work, the effect of fault situations on machine vibration is highlighted. The aim of this work is to find out the vibration behaviour in different fault situations and to find a suitable measurement method for them. For this reason, the following questions have been set as research questions for the work:

- How vibration measurements should be performed in order to measure the changes in the system caused by the faults?
- How to create a reliable measurement process?
- How to take into account the effect of a high-speed electric motor in the measurement?

The research method is a literature review. The common fault situations in rotating machines have been selected from the literature. According to the fault types, the characteristics of the machine and the correct performance of the measurement, criteria of measurement process have been set. The case study examines the functionality of The Switch (part of Yaskawa company) high-speed electric motor measurement process. The results show how the measurement process should be implemented for a test case electric machine from the company and how well the case meets the requirements. Finally, is evaluated the results and consider what else might be considered in relation to vibration measurement, which was not addressed in this work. Temperature measurement, new methods under development and the data transfer of the measurement process as individual larger entities have been directly excluded from the work. In this way, the scope of the work can be kept at a reasonable level

2 FACTORS TO CONSIDER IN THE MEASUREMENT SYSTEM

The chapter is divided into six parts. The first part deals with the characteristics of a high-speed electric motor. The second part introduces the vibration. The third section briefly discusses data processing. The fourth part deals with the vibration behavior of different types of faults. The fifth part focuses on the vibration measurement process. The last section compiles the above information to plan the measurement process.

2.1 Basic of high-speed electric motor

Electrical machines are machines which generate either electricity from mechanical energy, called generators, or create a movement from electricity, known as motors. The power range of electric machines is very large, from only a few watts to hundreds of millions of watts. (Sen Gupta & Lynn 1980, p.9)

Electric motors operate under the magnetic flux and electric current or flow of charge. Force is developed because charge is moving in a magnetic field. Force is orthogonal comparing charge and a magnetic field. Voltage is created when the current-containing conductor moves through the magnetic field. Electric motors can be extensively covered in two parts: AC (alternating current) and DC (direct current) motors. The difference between the two is current behavior. In DC motors current is constant and AC motors it is alternating. (Beaty & Kirtley 1998, p.2)

2.1.1 Induction Motors

Induction motors are one type of AC motors. Induction motor is one of the most used electric motors. They are simple, rugged and relatively cheap to produce. In the induction motor as its name implies current is induced into the rotor through a rotating magnetic field of the stator. In the stator, the alternating current generates a magnetic field which rotates around the rotor. A rotating magnetic field induces a current in the conductor (rotor). A current-carrying conductor in a moving magnetic field generates an electromagnetic force which causes the engine to rotate. Due to the above phenomenon, the rotor must rotate slower than the magnetic field (synchronous speed (f_S)). (Sen Gupta & Lynn 1980, p.30-35)

The difference between synchronous speed and rotating speed (f_R) is called *Slip frequency* (f_{SL}) (Beaty & Kirtley 1998, p.348). The slip frequency and slip angular speed plays an important role especially in solid-rotor machines. Slip angular speed significantly affects the magnetic flux penetration into the rotor. (Huppunen 2004, p.22-23)

2.1.2 High-speed electric motors

There is no exact limit to distinguishing a high-speed motor from a normal motor. Often, categorization is based on rotation speed. Machine size also influences categorization. Smaller machines are more easily perceived as normal speed machines at higher speeds. Jokinen (1988) presented a classification based on machine peripheral speed, where a machine with peripheral speed exceeding 150 m / s is referred to as a high-speed machine. On machines with 10,000 rpm (revolution per minute), this means a rotor diameter of 290 millimeters.

When operating at high speeds, it is important to consider the mechanical characteristics of the motor. Centrifugal forces take a significant role. The rotor should be as rigid as possible to facilitate the control of its behavior at high-speed. (Gieras 1995, p.293). However, a rigid structure such as a solid cylinder does not offer the best electrical properties (Pyrhönen 1991, p.8). It is often necessary to strike a balance between electrical and mechanical properties.

As stated earlier, the induction motor electromagnetic force is generated when the stator magnetic field rotates around the rotor, the rotor must be in the magnetic field to produce the force. Therefore, the structure of the rotor must not impede the passage of the magnetic field. The commonly used squirrel-cage structure allows a good penetration of the magnetic field. The structure consists of an aluminum or copper cage filled with steel plates. (Beaty & Kirtley 1998, p.3, 42). Thus, the structure does not prevent the magnetic field from penetrating around the rotor. However, in many high-speed applications, this structure does not work due to insufficient rigidity which requires the use of a solid rotor (Pyrhönen 1991, p.8).

“Solid-rotor induction motors are built with the rotor made of a single piece of ferromagnetic material” (Gieras 1995, p.147). There are a few ways to construct the rotor. Rotor can be solid-steel with smooth or slitted surface. It can be added with nonmagnetic highconductivity external cap or cage winding. (Gieras 1995, p.148-149). A solid rotor with cage winding provides the best combination of structural simplicity, mechanical properties (bending stiffness and strength) and electrical performance (Mcguiness, Gulbache & Kocabas 2015, p.589).

2.2 Basic of vibration

Form vibration can be detected the phenomenon of machine behavior. Scheffer and Girdhar (2004, p.13.) represent vibration as “Vibration is the motion of the machine or its part back and forth from its position of rest”. When a part has been moved out from its position of rest, this is called *displacement.* When a part is moved into this position, it has *velocity* and to get velocity *acceleration* must happen. When, the same amount of displacement continues repeatedly between rest and displacement in relation to time it can be presented as a *harmonic wave*. Velocity and acceleration also get the shape of a wave. All the waves are represented as sine or cosine curves. (Scheffer & Girdhar 2004, p.14-16). If displacement is set at phase angle 0°, velocity is 90° and acceleration is 180° ahead of displacement. This can be seen in Figure *1*. Harmonic waves of vibration. Frequency is 2.5Hz. (Inman 2001, p.8).

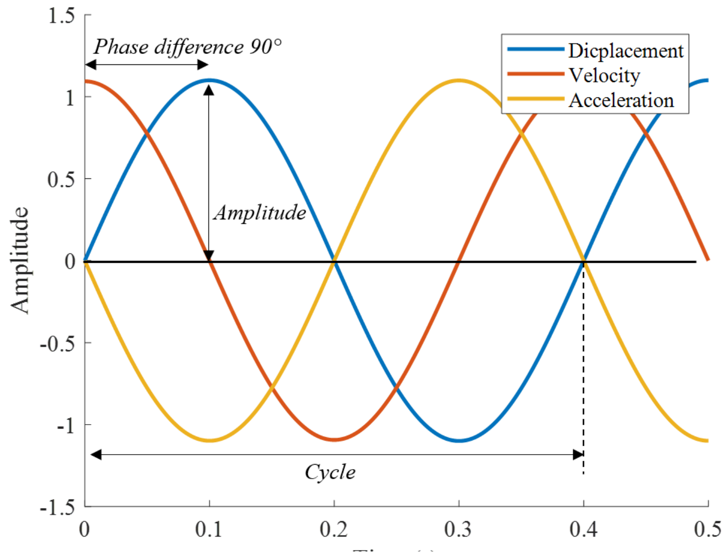


Figure 1. Harmonic waves of vibration. Frequency is 2.5Hz

A few concepts of a wave underlie understanding machine behavior. One *cycle* can be defined to have happened when displacement gone one time to both sides of position of the rest and returned to its starting position (Figure *1*). When cycles occur over time frequency can be determined. A common way to represent frequency is hertz (Hz). Hertz means cycles per second.

When, a rotor is rotating one round per second its rotating frequency is 1Hz. This one round can contain many separate cycles. For example, when the rotor ball bearings hit a groove during a turn, it produces several cycles per revolution. Radian per second (rad/s) is a unit used in calculations. Hertz can be converted to radians per second according to the formula below:

$$Rad/s = 2\pi \times \mathrm{Hz} \tag{1}$$

One of the most important fundamentals of a wave is Amplitude. Amplitude tells how far away displacement goes from the rest position (Figure *1*). Simplified, amplitude can be said to be the maximum and the minimum value of each cycle. The amplitude can be used to determine the effect of vibration. It gives a relative indication of wave energy transfer. (Scheffer & Girdhar 2004, p.16-17) With a mathematical method behavior of a system can be calculated based on this wave energy transfer. (Inman 2001, p.300-320). This is one way to figure out the state of the system from vibration measurement. In this thesis, the methods of solving the state of a system from vibration measurement are not discussed. The target is to identify the influencing factors and figure out how they should be taken into account in the measurements.

Phase and *harmonics* are also important fundamentals to know when is spoken about vibration. A phase describes the space of the vibration. The phase can set at zero when the part is in the rest position. One cycle is 360°. In vibration measurement and analysis is more about *phase difference*. In order to understand the phase difference, it is good to compare two waves with each other. Two waves having the same frequency and amplitude can hold a different position over time. This is called phase difference. In this case, one wave is ahead or behind another wave. If cycle time is represented as a T and the second wave gets its neutral position T/4 later than wave one, then phase angle of these two waves is 90°. Figure *1* clarifies phase difference between two waves.

Harmonics mean wave multiples. When, waves are in neutral positions in the same time over a period of time they are harmonic waves. For example, a 3Hz wave is harmonics of a 1Hz wave. They have the same position in the start and at the time of 1s. A 3Hz wave makes 3 cycles in one second when a 1Hz wave makes only one cycle. This can be seen in Figure 2. (Scheffer & Girdhar 2004, p.17-18)

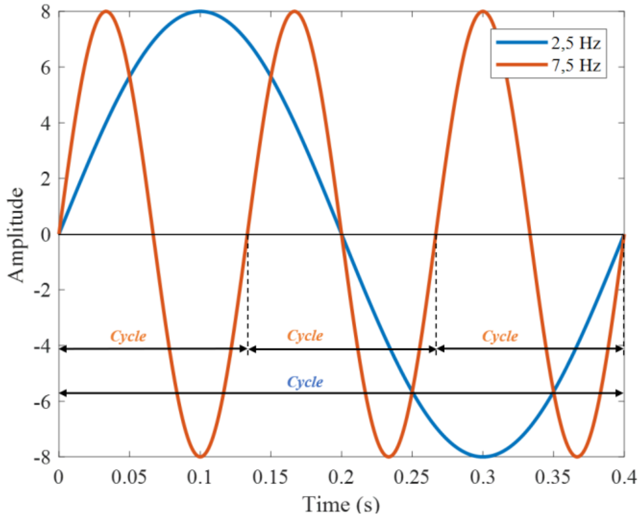


Figure 2. 7,5 Hz wave is harmonic of 2.5 Hz wave.

2.3 Processing the data

Data from the machine is collected in *time-domain* (Asoke & Ahmed 2019, p.33). Sensors measure samples over a period or continuously. A *sampling rate* defines how many samples are collected in one second. The sample rate is an important factor in the measurement. Too low frequency lead to distorted results. Mathematically, the sampling rate should be at least twice the maximum frequency. (Scheffer & Girdhar 2004, p.56). In this case, sampling should take place at the right time. According SFS standard the sampling rate must be at least ten times the maximum frequency under investigation (SFS-ISO 13373-2 2005, p. 4.). The data can consist of many different vibration frequencies. For example, if the highest frequency under investigation is ten times the machine rotating frequency, the sampling rate should be one hundred times the rotating speed. From this time-domain, it may be difficult to analyze the vibration behavior.

A widely used method is to convert a time-domain (Figure 4) into a frequency domain (Figure 5). The idea is to collect all different vibration frequencies (Figure 3) separately in the same plot. From the frequency domain, it is easier to see the different vibration frequencies and their amplitudes. (Asoke & Ahmed 2019, p.63-64.) The commonly used method for conversion is *Fast Fourier Transform* (FFT) (Prabhu 2014, p. 1.).

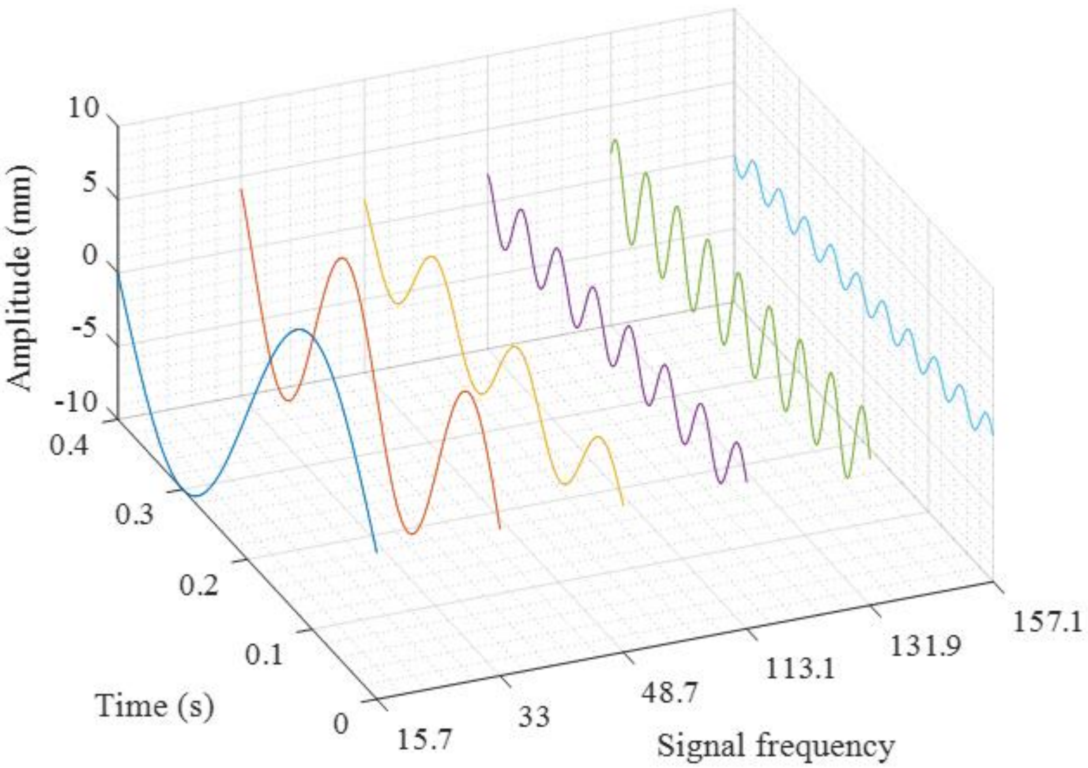


Figure 3. Harmonic waves with different amplitudes and frequencies.

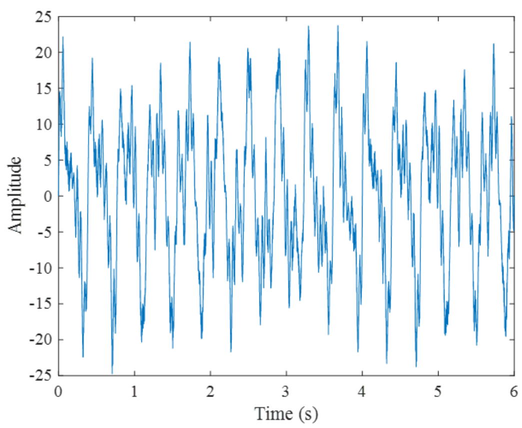


Figure 4 demonstrating of true vibration behavior. A plot contains 6 different waves with varying small random value.

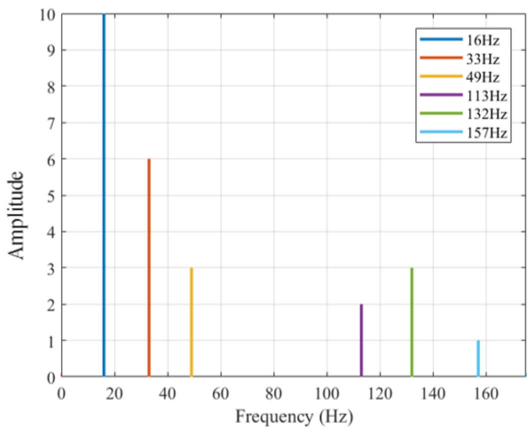


Figure 5 The time domain measurement can also be represented in the frequency domain. Making it easy to read the waves' amplitudes and frequencies.

2.4 Different types of rotor faults

Vibrations beyond acceptable limits are usually indicators for some form of defect in the machine. The common defects that can be detected by vibration analysis are listed below.

- Unbalance
- Bent shaft
- Eccentricity
- Misalignment
- Looseness
- Belt drive problems
- Gear defects
- Bearing defect
- Electrical faults
- Oil/whip whirl
- Cavitation
- Shaft cracks
- Rotor rubs
- Resonance
- Hydraulic and aerodynamic forces

(Scheffer & Girdhar 2004, p.89-90)

The scope of this thesis is limited to only most common defects related to electric motors. These are: Unbalance, misalignment, looseness, bearing defect, resonance and electrical faults (Scheffer & Girdhar 2004, p.90-127). They are introduced in more detail in the following sub-chapters.

2.4.1 Unbalance

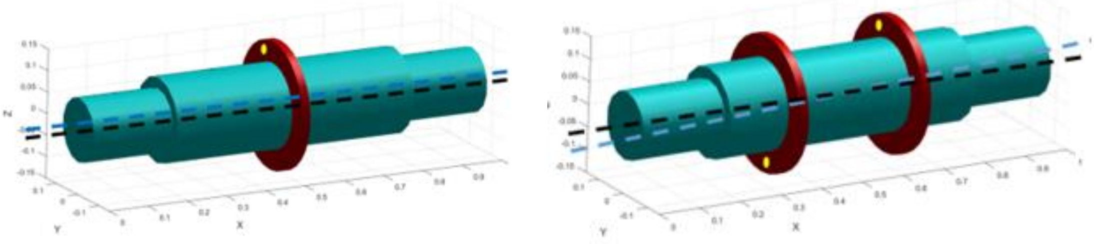
Rotor unbalance is one of the most common defects in rotors (Scheffer & Girdhar 2004, p.90.). An unbalance occurs when the mass of the rotor is asymmetrically distributed around the axis of rotation. This is also called rotating imbalance. (Beaty & Kirtley 1998, s.346.). The International Standards Organization (ISO 21940-2, p.8) defines unbalance as "condition that exists in a rotor when vibration force or motion is imparted to it and its bearings from the centrifugal forces of *mass eccentricities*". Unbalance can occur in three different types of cases, these are:

1. Static unbalance
2. Couple unbalance
3. Dynamic unbalance

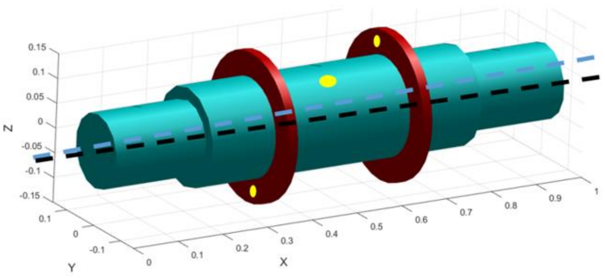
(Scheffer & Girdhar 2004, p.90.)

Static unbalance occurs when the *principle inertia axis* (PIA or *rotating centerline*) are parallel with rotor *geometric centerline* (GCL). Vibration signal has the same phase at both ends of the rotor. Vibration happens in a radial direction. In a coupled unbalance PIA and GCL intersect in the center. In this case, unbalance may cause high radial vibration and as well high axial vibration. Vibrations signals at either end of the rotor have 180° phase difference in vertical and horizontal directions. In a dynamic unbalance, PIA and GCL do not touch or coincide. (Scheffer & Girdhar 2004, p.90.) Vibration can be radial and axial, phase difference is 30-150° between signals at either end of the rotor (Mobius Institute 2020).

In all these cases the phase difference between vertical and horizontal direction is 90°. For all types of unbalance, vibration happens in the same frequency as rotating speed (1X). Amplitude will vary proportionally to the square of the rotational speed and waveform should be very sinusoidal. These three cases can be seen in Figure *6* a, b and c. (Scheffer & Girdhar 2004, p.90-91.)



(a) (b)



(c)

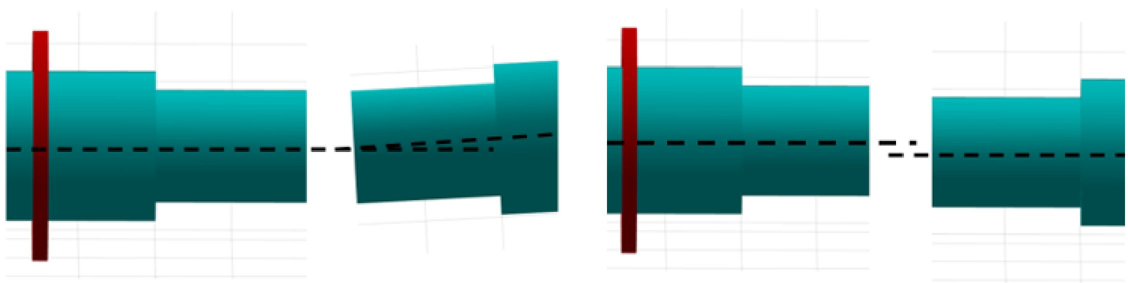
Figure 6. Types of unbalance: (a) Static, (b) coupled and (c) dynamic unbalance. Yellow point(s) indicate location of unbalance. Blue line describes PIA axel and black describes GCL.

2.4.2 Misalignment

Misalignment is also one of the most common vibration causes. Misalignment can occur in the form of:

1. Angular misalignment, when two shafts meets at an angle.
2. Parallel misalignment, when two shaft centerlines are parallel but not in the same positions.

Figure *7* represents both cases, when two shaft ends connect.



a b

Figure 7. Types of misalignment: (a)Angular and (b) parallel misalignment. The black lines indicate how GCL's connected to each other.

Angular misalignment generates axial vibrations that appear in the same frequency as rotating speed. Phase difference of the vibration is 180° across the coupling. It is very rare that pure angular misalignment happens. Thus, the vibration also occurs at the frequency of the rotational speed × 2 (2X) and rotational speed × 3 (3X). These 2X and 3X components come from parallel misalignment. Parallel misalignment happens in radial directions. In this case vibration also has 180° phase difference over the coupling. The amplitude indicates which of two cases is dominant. If parallel is dominate, the 2X component grows bigger. When, misalignment becomes severe it can generate harmonics up to even 8X. (Scheffer & Girdhar 2004, p.94-96.)

Misalignment can occur also between a shaft and a bearing (cocked bearing). This can generate considerable axial vibration frequencies as 1X, 2X and 3X revolutions per minute (rpm). From the same bearing housing, vibration with 180° phase differences from side to side of the shaft can be measured. (Scheffer & Girdhar 2004, p.97.)

2.4.3 Looseness

Looseness occurs when there is a point of discontinuity in a piece or between two pieces where a change in movement can occur. Looseness can be of three different types:

1. Internal assembly looseness
2. Looseness between machine part and base plate
3. Looseness of the structure.

(Scheffer & Girdhar 2004, p.99.)

Internal assembly looseness occurs when there is clearance between two parts. It can be detected, for example, between a roller bearing and a shaft or an impeller on the shaft. Looseness generates a non-linear response, which produce many harmonics (multiple of 1X and sub-harmonics 1/2X or 1/3X). Vibration from looseness are highly directional, meaning they are most prominent in any one direction and are not radially distributed in equal proportions. The phase of vibration can change in the same location. (Scheffer & Girdhar 2004, p.99.)

Looseness between a machine part and a base plate happens typically with a loose pillow-block bolt. It can occur also with cracks in the frame structure or the bearing pedestal. Vibration happens with 2X component and high harmonics (6X). It is due to the movement of the part during rotation. The number of part positions tells the vibration frequency, four positions mean 4X. Figure *8* clarifies this. (Scheffer & Girdhar 2004, p.99.)

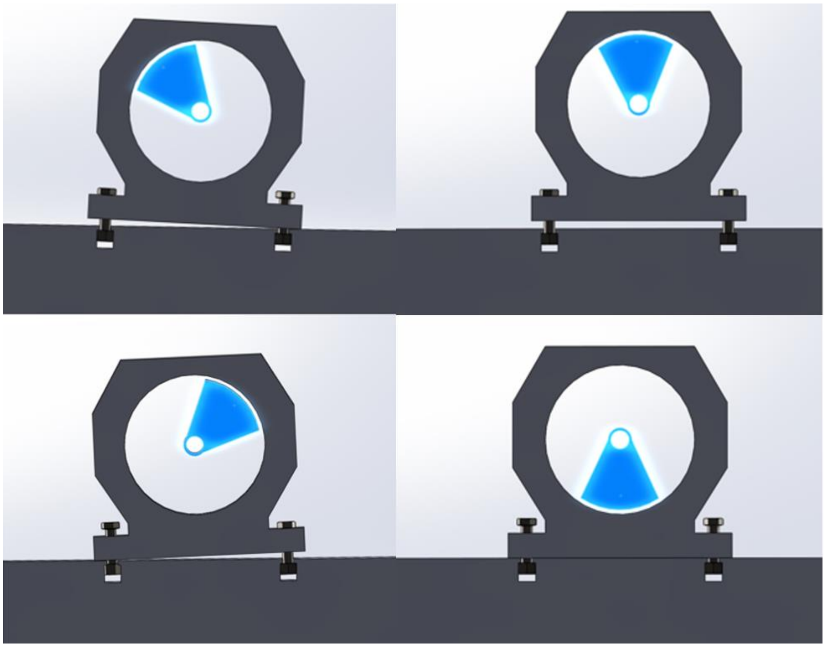


Figure 8. Looseness between a machine part and a base plate. Four different hits during the one round. 2X (up / down) vibration get biggest amplitude.

Looseness of the structure can appear when the machine feet, baseplate or foundation are loose or weak. It can occur when the machine attachment is poor, or when the frame or base have a distortion (called '*soft foot'*). The vibration is radial and occurs once per revolution. (Scheffer & Girdhar 2004, p.100.)

2.4.4 Rolling bearing faults

Rolling bearing consists of inner and outer races, a rolling element and a cage of rolls. The rolling element can be a ball or a roll. Faults can be caused by many things. For example, normal fatigue leads to flaking and inadequate lubricant lead to microscopic cracks. (FAG 1997, p.71.). Faults can be found anywhere in the bearing. Raceways and rolling element faults are relatively easy to detect. All bearing faults cause high-frequency vibration. The severity of the faults determines vibration behavior. (Scheffer & Girdhar 2004, p.112.). Behavior appears as cyclic and non-cyclic (Rao 1996, p. 97-114.). The same fault can occur for the first time as non-cyclic, then as fault severity grows it turns to cyclic behavior. Again, the breakdown due to the fault can occur as non-cyclic. Bearing defect frequencies can be divided into four different classes based on bearing parts as Table *1* shows. (Scheffer & Girdhar 2004, p.113-114.)

Table 1. Bearing frequencies of fault detection. Equation is showed as well.

Name	*Abbreviation*	*Equation*	*Eq. num.*
Ball pass frequency - Inner	*BPFI*	$\frac{Nb}{2}\left(1+\frac{Bd}{Dp}cos\theta\right)\times rpm$	*(2)*
Ball pass frequency - Outer	*BPFO*	$\frac{Nb}{2}\left(1-\frac{Bd}{Dp}cos\theta\right)\times rpm$	*(3)*
Fundamental train frequency (Cage)	*FTF*	$\frac{1}{2}\left(1-\frac{Bd}{Dp}cos\theta\right)\times rpm$	*(4)*
Ball spin frequency	*BSF*	$\frac{Pd}{2Bd}\left(1-\left(\frac{Bd}{Dp}\right)^2(cos\theta)^2\right)\times rpm$	*(5)*

Here Nb is a number of rolling elements, Bd is rolling element diameter (mm), Dp is bearing pitch diameter (mm) and θ is a contact angle in degrees.

Bearing wear deterioration can be divided into four stages. Every stage vibration phenomenon is different. In the first step bearing wear shows up in ultrasonic frequencies, the range is about 20 – 60 kHz. In the second stage minute pits start to develop. Pits act as excitation to the natural frequencies of the bearing component. These frequencies are typically 0,5 – 2 kHz. In stage three it is for the first time possible to detect bearing frequencies (Table 1) from FFT. It is also possible to detect the sidebands and harmonics of bearing defect frequencies. In the last stage rough tracks occur in the bearing raceway. This creates high amplitude vibration, which can be seen in the running speed, its harmonics and bearing defect frequencies. The natural frequency of bearing occurs randomly creating a “hump” in the FFT. All four cases are presented below in Figure *9*. The frequency band is divided into four categories in all of four stages. (Scheffer & Girdhar 2004, p.112-115.)

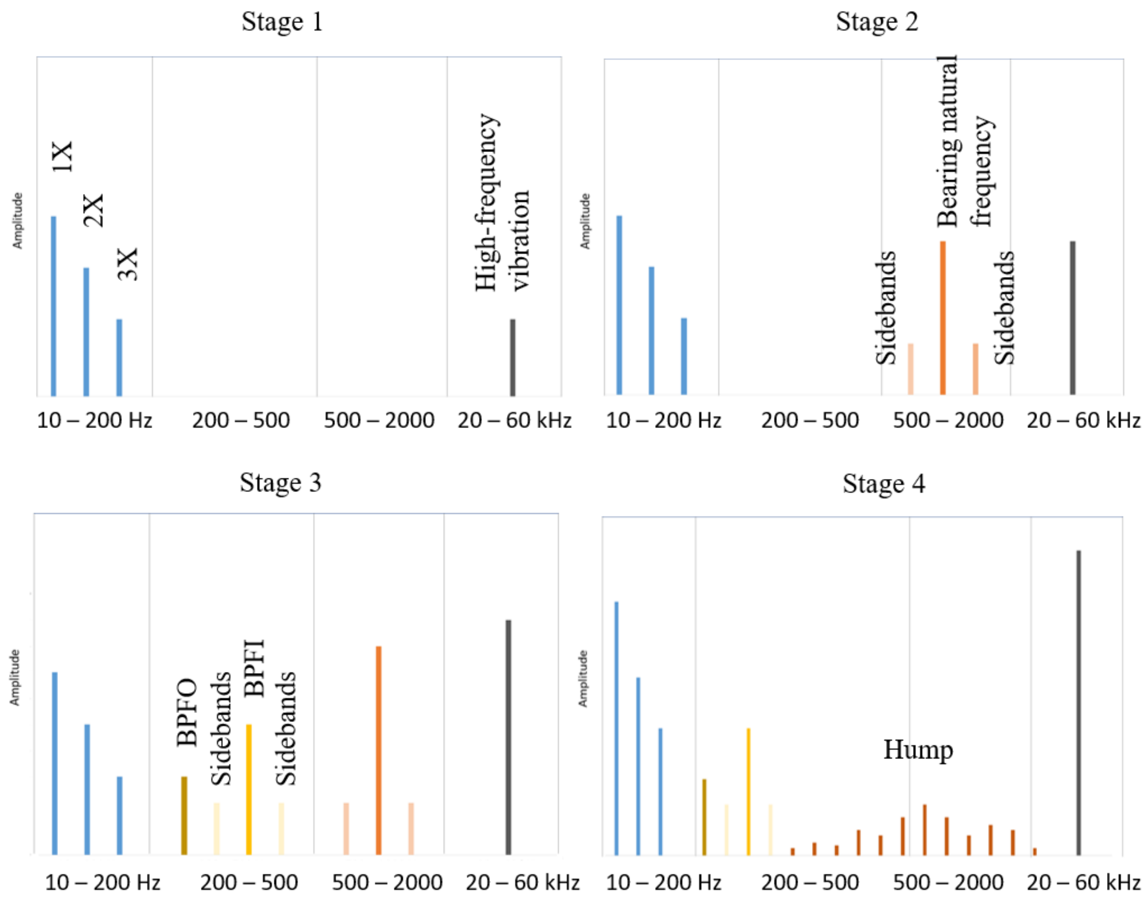


Figure 9. Bearing defects frequency bands categorized by severity of wear.

2.4.5 Electrical faults

Electric motors produce electromagnetic forces during operation. In an optimal motor these forces are balanced but practical situations include deviation. Scheffer & Girdhar (2004) stated that electrical problems appear often in rotating frequency and a radial direction, similar to unbalance. It can be difficult to separate the effects of electrical fault properties from mechanical ones. One way to recognize these from each other is to observe the operation of the machines when the power is turned off quickly. (Scheffer & Girdhar 2004, p.123-124.)

Guo, Chu and Chen (2002) have studied the effectiveness of *unbalanced magnetic pull* (UMP). Their study showed that UMP affects the amplitude of vibration and the natural frequency of the system. UMP is caused by an eccentric rotor or stator where the electromagnetic forces are not in balance. In general, vibration behavior is non-linear.

However, Guo *et al*. noticed that when eccentricity was small, the vibration was almost linear. *Pole-pair number* (p) has a big impact on the response. *Power line frequency* (f_L) effects as well but its behavior changes between cases. In Table 2 are presented some factors of system behavior under different circumstances. (Guo, Chu and Chen 2002)

Table 2 . Vibration behavior under UMP. Power line frequency is 50 Hz.

Rotating frequency (Hz)	*Pole-pair number*	*Eccentricity*	*Response (Hz)*	*Amplitude ratio (1X)* $\frac{\text{UMP}}{\text{without UMP}}$
5	*1*	*Low*	*5, 95*	*1,46*
15	*1*	*Low*	*15, 85*	*2,5*
15	*4*	*Low*	*15*	*3,3*
5	*1*	*Large*	*5, 95, 100*	-
20	*1*	*Large*	*20, 40, 80, 100*	-
20	*4*	*Large*	*20, 40*	-

As shown in Table 2, first line, when the eccentricity is low and there is only one pole-pair vibration occurs at rotational frequency. The vibration also occurs at a frequency of 95 Hz. This frequency is generated by subtracting the rotational frequency (5 Hz) from the double power line frequency (2 x 50 Hz). The same phenomenon occurs on the second line at a frequency of 15 Hz. When eccentricity is large, double power line frequency applies into the system as well (line four and five, 100 Hz). Guo et al. (2002) state that when the pole-pair is bigger than 3, only the rotating frequency response occurs (lines three and six). 2X vibration can appear into the system as well when eccentricity is large (lines five and six, 40 Hz). The last column refers to how much larger the vibration is when the UMP is affected compared the situation without UMP effect. (Guo, Chu and Chen 2002). Beaty and Kirtley (1998) present UMP with sound spectrum from an inexpensive universal motor. From this spectrum, the same phenomenon can be detected. They represent it as “Magnetic runout”. (Beaty & Kirtley 1998, p.347). Sathyan et al. (2019) have studied the behavior of a high-speed induction motor. They found that the UMP can create multiple harmonics for the power line frequency. (Sathyan et al. 2019).

Electrical problems can also occur from rotor bars, a stator's and connector's defects. Rotor bars can be broken, cracked, or left loose. A broken bar problem vibrates at the frequency 1X with *pole pass frequency* (f_P) sidebands. F_P is slip frequency multiplied number of poles. A loose bar can create *rotor bar pass frequency* (RBPF) which occurs at the frequency of rotating speed multiplied by the number of rotor bars. (Scheffer & Girdhar 2004, p.126-127.)

Stator defects can occur because of the looseness or weakness of stator coils. This generates a vibration in the frequency of two times power line frequency with big amplitude. This phenomenon is known as *loose iron.* A loose connector can also generate the same $2Xf_L$ with big amplitude. Difference is that with a loose connector, $2Xf_L$ gets the sidebands of $1/3Xf_L$. (Scheffer & Girdhar 2004, p.126-127.).

2.4.1 Resonance

The resonance differs significantly from the above-mentioned faults and cannot be directly considered as a fault. However, it is a phenomenon that must be considered in every machine. Resonance can arise in a few different ways. Generally, it is known that every part and system have their own natural frequency, a frequency at which a part will vibrate after the excitation signal is removed. Mobius Institute (2020) state that resonance occurs when an external (sound wave, impulse, movement etc.) or internal (faults in machine) source of excitation causes a vibration at a frequency that matches the natural frequency of the machine. Natural frequency can be determined by characteristic of the part such as mass, stiffness and damping. Out of these three factors, damping is the only one that limits amplitude growth, for example by damping out vibrations due to an impulse excitation (Scheffer & Girdhar 2004, p.101). When damping is low and the excitation acts for longer period of time, the vibration can become huge. (Mobius Institute 2020).

According to Inman (2001), a system having multiple degree of freedoms (dofs) has as many natural frequencies as the number of dofs. From very simple models, tens of natural frequencies can be calculated. (Inman 2001, p.303-304). However, in practical applications, only a few lowest frequencies must be considered, as higher natural frequencies are so high that no machines operate on such frequencies.

The phase of vibration is changed when a machine goes over natural frequency. At point of resonance (called *critical speed*) phase difference is 90° from the low frequencies phase. Higher than critical speed (called as *over critical*) phase difference sets up to 180°. (Scheffer & Girdhar 2004, p.103-106.)

Resonance can occur also when two or more excitations vibrates at the same frequency. For example, electric fault and mechanical fault can appear at the same frequency. Also, in higher frequencies can occur resonance between harmonics and e.g. bearing frequencies.

2.5 Data collection

The purpose of this section is to present the tools and method of measurement process. The section is divided into five parts. The measurement sensors are discussed first and then their position and location. The next section contains information about how sensors should be attached and the fourth section deals with the directions in which vibration can be measured. Finally, it is discussed how the machine should be mounted for optimum measurement.

2.5.1 Sensors specification

Sensors are available to measure all three magnitudes of vibration (acceleration, velocity, position). These three different transducers convert mechanical energy into a different type of energy, usually electric current or voltage. (Scheffer & Girdhar 2004, p.29). Sensors are manufactured for a variety of applications. In this study, only the general principles of the different types of sensors and their advantages and disadvantages are discussed. For each measurement case, the most appropriate sensor must be selected.

Displacement probes

When measuring displacement, one of the most important things to consider is the sensor measurement technique. For example, when measuring the movement of the shaft it is easy to attach the sensor to the bearing housing, it should be noted that the bearing housing also moves during the measurement. In this case, the measured value is called relative displacement. (Scheffer & Girdhar 2004, p.35-36.).

The most commonly used displacement sensors are eddy current sensors and capacitive displacement sensors. The operation of the eddy current sensor is based on the change of the magnetic field during operation. As a result, the surface to be measured must be of ferromagnetic material. Any external interference in the magnetic field must also be considered. (Mikkonen et al. 2009, s. 235)

The eddy current transducer can measure movement only in that plane where it is installed. For that reason, one must know the direction where the largest vibrations are expected. When results are needed to be as accurate as possible, it is recommended to use two sensors at the same measurement location (e.g. bearing housing). In that case, the angle between two sensors should be 90°. (Scheffer & Girdhar 2004, p.35-36.)

Velocity pickup

A velocity pickup transducer is often used in a vibration monitoring. They are relatively cheap and easy to install. An operation of the velocity sensor is based of coil wire moving through a magnetic field. The movement generates the induced voltage to the end wires of the coil. Thus, velocity pickup is self-generating sensor and no external devices required. (Nohynek & Lumme 2004, s. 47-48.)

Because of operation behavior, there are also some disadvantages. The sensor measures only that plane where it is installed. And because it is affected by gravity, vertical and horizontal sensors must be different types. The sensors are relatively large, and the frequency response is narrow. It is also sensitive to magnetic fields. (Scheffer & Girdhar 2004, p.29-32)

Acceleration pickup

In rotating machinery applications an acceleration transducer is the most common sensor. They have many advantages comparing velocity and displacement sensors. Acceleration pickups are rugged, compact, lightweight with a wide frequency response range. They do not need calibration. This is due to the way the sensor works. There are no parts subjected to fatigue. Acceleration pickup is an inertial measurement device. It converts mechanical motion into a voltage signal. In piezoelectric sensor, mechanical vibration generates a varying force on the piezoelectric crystal. This generates a charge that is directly proportional to the varying force. The charge amplifier converts the charge output to a voltage output. (Scheffer & Girdhar 2004, p.32-34)

The disadvantages of using the sensor are its sensitivity to impact loads, which creates a requirement for careful installation. The sensor also has a high settling time. The sensor is often used to measure high frequencies, so it is also important to be careful not to generate too much external noise. In order to facilitate this, attention must be paid to wiring. (Nohynek & Lumme 2004, s. 47-48.)

2.5.2 Measurement locations

The characteristics of the machine determine where the vibration should be measured. In rotating machines, the points of interest are the bearing housings and the connection points to the environment. For measurement purposes, it is important to place the sensor in a location where vibration is transmitted as efficiently as possible. For example, a machine with sleeve bearings cannot be measured from the bearing housing using absolute acceleration because the bearing itself greatly dampens vibration. In this case, the measurement shall be made using the relative value of the shaft and the housing and the absolute value of the bearing housing. In the case of roller bearings, measurement from the bearing housing is generally considered sufficient. The roller bearing effectively transmits forces to its environment. (Bartheld & Peregrin 1995, p.619-624). However, the structure surrounding the bearing should be considered. Figure *10* shows how to minimize vibration distortion by correctly positioning the sensor. (PSK 5702 2007, p.2)

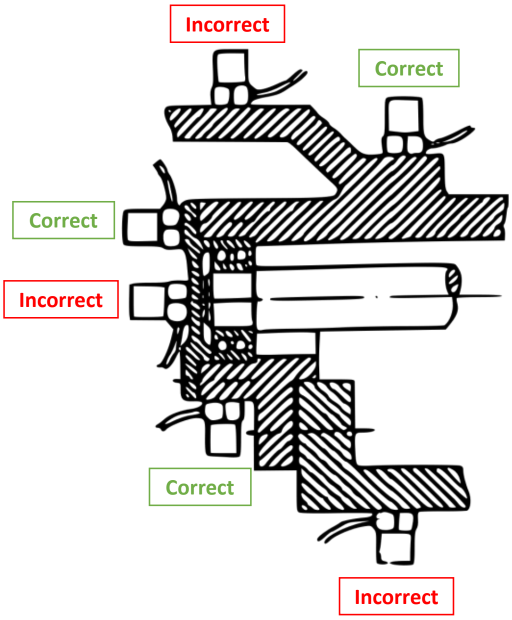


Figure 10. Correct way to install sensor at measurement locations in roller bearing case (PSK 5702 mod., 2007, p.2)

2.5.3 Mounting methods

When it comes to measuring with an accelerometer, there are four main mounting methods.

1. Stud/bolt mounting
2. Adhesive/ glue mounting
3. Magnetic mounting
4. Handheld probes

In all cases, mounting place should be clean and paint-free. It has to be also spot-faced to ensure a smooth surface. The spot-faced area should be little bit larger than the sensor diameter. Appendix 1 shows the Standard organization PSK's instructions for stud mounting the sensor. All the above four methods are functional when selected in the right operating environment. The biggest difference between these is the effect of the mounting method on the frequency band being measured. Stud mounted sensor can detect the highest frequencies. (Scheffer & Girdhar 2004, p.31-35). Figure *11* shows the effect between different methods.

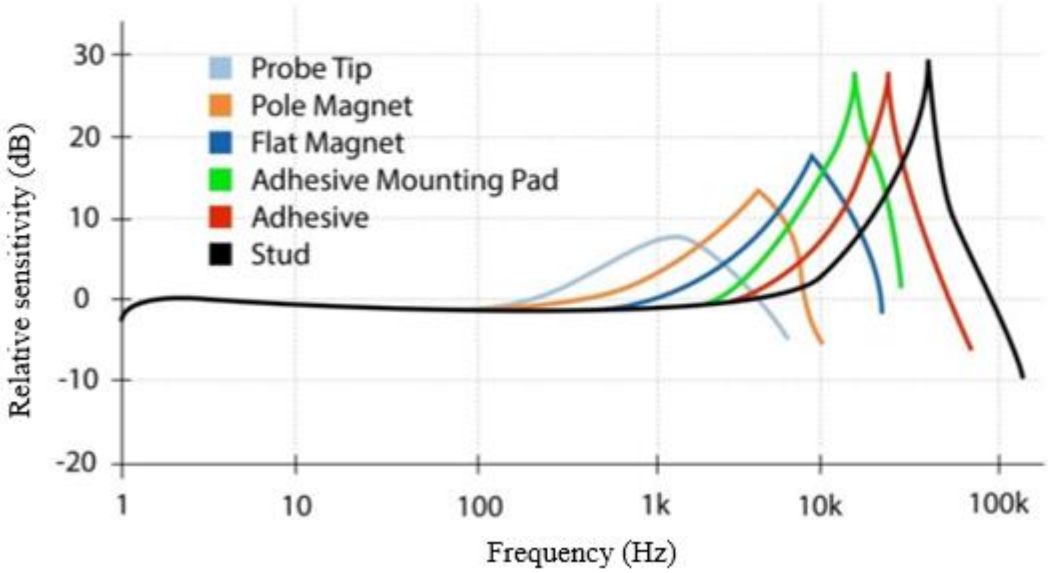


Figure 11. Relatively sensitivity of different mounting methods in relation to the frequency to be measured (Hanly 2016, s. 21).

Mounting method effects also sensors resonance frequency. ISO 13373-1 standard shows in Table *3* the effect of mounting on sensor performance by comparing different mounting methods to a 30 kHz sensor.

Table 3. The sensor usable frequency band relative to the mounting method with the 30 kHz sensor.

Mounting method	Frequency range (kHz)	Proportion of total (%)
Stud	28-30 kHz	99 %
Magnet	7 kHz	25 %
Handheld	2 kHz	7 %

2.5.4 Measurement directions

The best practice is to measure vibration in three mutually orthogonal directions. One axis (z) always corresponding to the axis of rotation. Then the other two direction are horizontal and vertical. In order to determine the radial maximum amplitude of vibration, measurements should be made in both directions as close to the axis centerline as possible. By summing the amplitudes from both directions over one revolution, the axis trajectory relatively to the center point is obtained. From the largest distance inside the trajectory the maximum amplitude of vibration can be calculated. (Bartheld & Peregrin 1995, p.621-623)

2.5.5 Machine mounting

There are two different methods of attaching the machine for measurements. The machine can be installed using elastic or rigid mounting. It is recommended that new machines be elastically attached. The procedure ensure that vibration levels are not depending type of mounting or possible errors in foundation. Large machines may require rigid attachment. In this case, two things have to be taken care of. The surface of foundation must be flat so that no tension is created on the frame. The base on which the motor is mounted must also be of a high weight so that the natural frequency of the test installation is not coincident with the predominant motor frequencies. This can be verified by measuring the vibration of the bearing housing and the motor feet, which should be less than 25% of the vibration of the bearing housing. The advantage of rigid attachment is also the ability to compare results with a field mounted machine. (Bartheld 1995, p.624-625)

2.6 Vibration measurement design

This section compiles information from a literature review in a format from that criteria's can be set for performing the measurement process. Table 4 summarizes the vibration behavior of different fault types.

Table 4. Vibration behavior of different fault types.

Fault subcategories	Frequency range (nX)	Harmonics	Direction	Relative phase difference over fault	Nature of vibration
Unbalance					
Static	1X	In severe cases	Radial	0°	Sinusoidal
Couple	1X	In severe cases	Radial, axial	180°	Sinusoidal
Dynamic	1X	In severe cases	Radial, axial	30° - 150°	Sinusoidal
Misalignment					
Angular	1X	2X, 3X, In severe cases up to 8X	Axial	180°	
Parallel	2X	1X, 3X, In severe cases up to 8X	Radial	180°	
Looseness					
Internal, bearing/impeller - shaft	2X	Multiple of 1X and sub-harmonics	Radial	Varies	Non-linear
Between machine part and base plate	2X, 3X, 4X (depends type)	Multiple of 1X and 0,5X	Radial		
Structural looseness	1X	-	Radial	180°	
Resonance					
	1X	-	Radial	180°, under- to overcritical	
Rolling bearing faults					
Stage 1, no visible wear	20 - 60 kHz		Radial		non-cyclic or cyclic
Stage 2, minute pits	0,5 - 2 kHz, 20 - 60 kHz		Radial		non-cyclic or cyclic
Stage 3, pits	0,2 - 2 kHz, 20 - 60 kHz		Radial		non-cyclic or cyclic
Stage 4, rough tracks	1X, 0,2 - 2 kHz, 20 - 60 kHz	Multiple of 1X	Radial		non-cyclic or cyclic
Electric faults					
UMP, low eccentricity	1X, f_{UL}, *		Radial		Almost Linear,
UMP, high eccentricity	1X, f_{UL}, f_L, *	Multiple of f_L	Radial		Non-linear, **
Broken rotor bars	1X, f_P sidebands	Multiple of 1X	Radial		
Loose rotor bars	1X, RBPF with f_L sidebands	2X	Radial		
Stator defects	$2Xf_L$		Radial		
Connector defects	$2Xf_L$ with $1/3Xf_L$ sidebands		Radial		

*If pole-pair number > 3, f_{UL} and f_L disappear. ** UMP reduce natural frequency

The following categories (Table 5) are set according to the frequency to select the sensor type and mounting method. In the case of the mounting method, the higher frequency method is also suitable for lower frequencies. The sensor type and mounting method in the table have been taken from appendix 2 and Figure *11* trying to keep relative sensitivity as low as possible (below 10%).

Table 5. Frequency between 1 - 20 000 Hz, amplitude 0,01 – 80 mm/s

Frequency range (Hz)	Sensor type	Mounting method
< 300	Velocity / Acceleration	Probe Tip
< 600	Velocity / Acceleration	Pole Magnet
< 1200	Velocity / Acceleration	Flat magnet
< 2000	Velocity / Acceleration	Adhesive mounting
< 5000	Acceleration	Adhesive mounting
< 10000	Acceleration	Stud
>10000	High speed accelerometer	Stud, *

* relative sensitivity > 3dB

(SFS-ISO 13373-1 2002, p.17; Hanly 2016, s. 21; SKF 2018,)

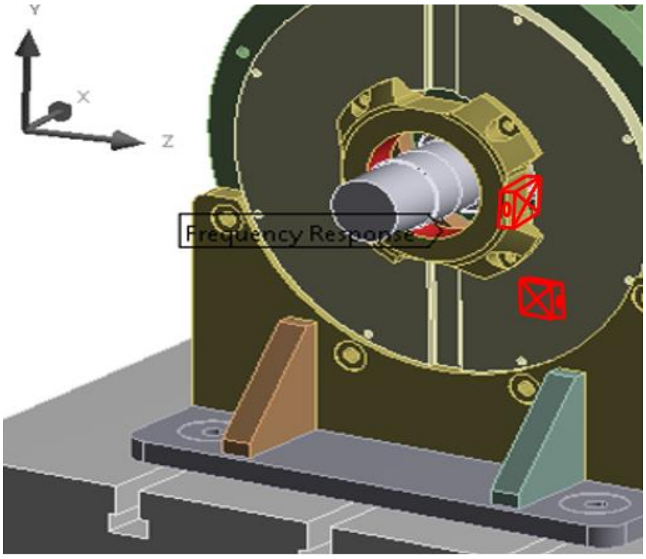
The effectiveness of the sampling rate to the amplitude of the vibration is tested with a harmonic wave by changing the sampling rate and the phase of the wave. To detect the lowest sampling rate in order to correctly detect the vibration frequency and the amplitude of wave. The MATLAB program is used in the calculation. The position of the wave can be calculated with respect to time from the following formula:

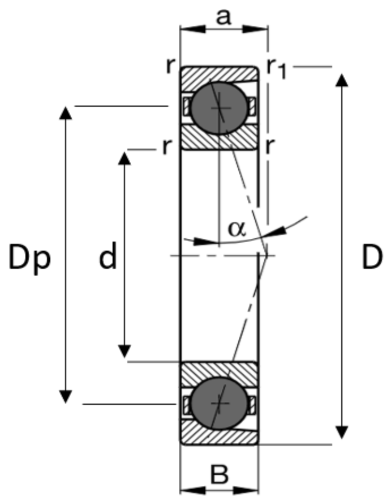
$$x(t) = A\sin(\omega t \pm \varphi) \tag{6}$$

Where A is amplitude ω angular frequency t is time and φ is initial phase. (Inman 2008 p. 8) By changing the time, the magnitude of the different amplitude with respect to time can be calculated.

3 HIGH-SPEED MACHINE CASE

The case study in this research is a high-speed electric motors' post-assembly test system of The Switch. The company conducts post-assembly testing of production machines. The purpose of testing is to ensure the correct operation of the machine. The machines are tested using the IEC 60034 standard. For mounting the sensors, the SPM (shock pulse measurement) nipples are screwed into the M8 threaded holes at both ends of the machine. However, magnetically mounted sensors are currently used in the tests. The motor is mounted on a massive solid steel plate with rigid mounting. The bed has two machines at the same time. Vibration measurements are performed when the machines are not connected to each other (unloaded). The Table 6 show information about the motor, bearing and measurement process. Figure *12* show locations of the sensors (red boxes) (a) and section view of the bearings (b).





(b)

8(a)

Figure 12 (a) Electric motor model on a test bench with magnet mounted acceleration sensor locations (The Switch). Figure 12 (b) present bearing specification, dimensions are listed in Table 6. (Schaeffler 2020)

Table 6. Technical data of the high-speed electric motor and the measurement process

Motor specification		Measurement specification		Bearing specification	
Motor Type	Induction motor	Sensor type	SKF CMSS 2200	Diameter in (d)	95
Rotor Type	Squirrel cage solid	- frequency range (Hz)	0,7 - 10 000	Diameter Out (D)	145
Pole-Pair Number	1	- Error margin ±10 %	1,0 - 5 000	Breadth (B)	24
Power (kW)	580	- Error margin ±3 dB	0,7 - 10 000	Pitch diameter (Dp)	120
Speed (rpm)	9510	- Natural frequency (Hz)	22 000	Contact angle (α)	15°
Bearings	Spindle bearings	- Locations	Horizontal, axial, both ends	Ball number	20
Lubrication	Dry sump	Mounting method	Magnet	Ball diameter (mm)	15,86
Max Vibration (mm/s)	1,5	Phase measurement	No	Ball material	Ceramics
System Natural frequency, 1	125	Sampling rate (Hz)	25 600	Limited speed (rpm)	20 000
System Natural frequency, 2	208	Test speed (rpm)	Nominal speed		
System Natural frequency, 3	213	Motor mounting	Rigid, heavy steel plate		

The desired fault types for analysis were obtained from the company. Company wanted to analyse the machine for possible; component installation errors, bearing installation errors, bearing manufacturing errors, and possible electrical problems. Based on this, the fault types are set to: unbalance, misalignment e.g. cocked bearing, looseness at three different category, bearing faults and electrical faults. Natural frequencies off the system (bench with two motors not connected to each other) are also added to the list.

4 RESULT & DISCUSSION

This chapter contains information on how the case study meets the requirements based on the findings in the literature. The chapter also includes discussion on the changes that should be made to acquire the possibility of detecting and analysing wider spectrum of faults.

4.1 Requirements of the measurement process for identifying different fault types

Based on the literature review, criteria were created to examine the suitability of the measurement process for different types of faults. Table *4* detailed the effect of fault types. By combining the information from case study (rotating speed, line frequency, slip frequency, system natural frequencies and bearing information) with the data in Table *4*, frequency ranges can be calculated where faults should appear in the case study (appendix 3). Bearing fault frequencies were calculated from equations 2 – 5, and the results are shown in Table *7*.

Table 7. Bearing fault frequencies calculated from equations 2 -5.

Speed (Hz)	Speed (rpm)	Angle (°)	Ball number	Ball diameter (mm)	Pitch diameter (mm)
158.5	9510	15	20	15.86	120
Fault type		Frequency (Hz)		Rpm (Hz x 60)	nX (freq. / speed)
Ball pass frequency Inner		1787		107241	11,3
Ball pass frequency Outer		1383		82959	8,7
Fundamental train frequency		69		4148	0,4
Ball spin frequency		590		35391	3,7

Collectively, Figure *13* illustrates the frequencies of the fault types selected in the case study. It shows possibility of resonance between different fault types or natural frequency. The types of faults that occur with the 1X excitation are not specified in the figure. The horizontal axis represents the frequency. The vertical axis is unimportant as it describes arbitrary amplitude, but the main focus of this figure is location of possible fault types, which shows how the proximity of different frequencies and which of them might overlap with each other to create resonance.

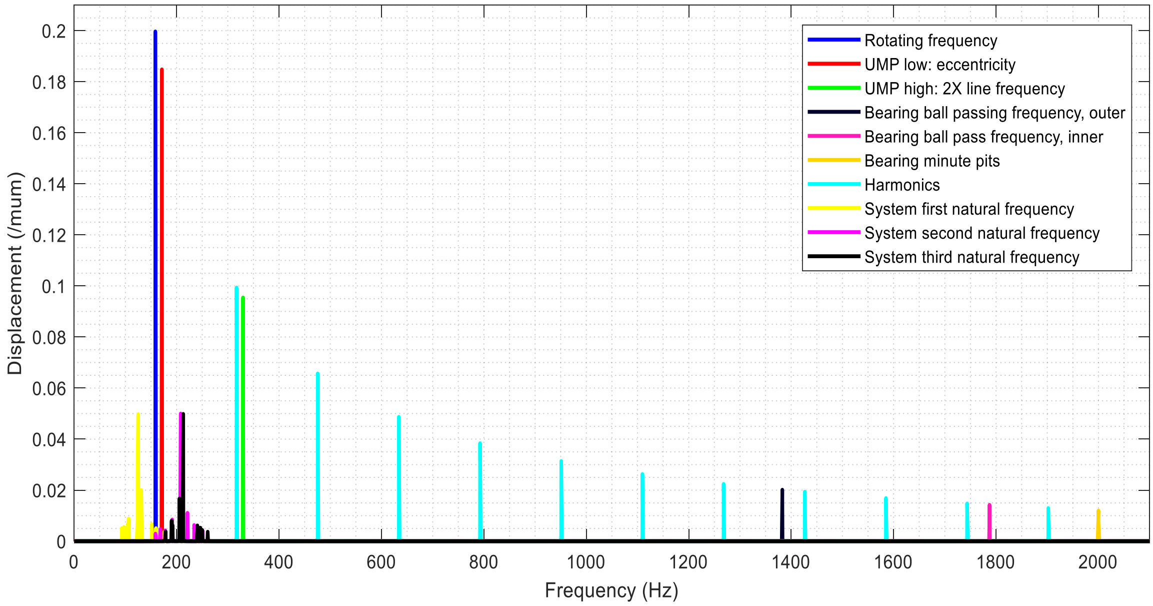


Figure 13. Frequencies of different fault types and their possible mutual resonances. The amplitude is imaginary.

Combining the data from the literature review with the exact fault frequencies, suitable measurement requirements for different types of faults have been created. This information is compared to a case measurement environment that provides information on whether the measurement process is sufficient to interpret the fault. The results contain fault types which are set in the case study section.

Table 8. Requirements of the measurement process to identify different types of faults.

Fault subcategories	Sensor type	Mounting method	Mesurement directions	Phase measurement	Ramp-up testing	Case fulfill demands
Unbalance						
Static	V / A	Probe Tip	Radial	No	No	YES
Couple	V / A	Probe Tip	Radial, axial	Yes, *	No	NO
Dynamic	V / A	Probe Tip	Radial, axial	Yes, *	No	NO
Misalignment						
Angular, e.g. cocked bearing	V / A	Adhesive	Axial	Yes, *	No	NO
Looseness						
Internal, bearing/impeller - shaft	V / A	Flat magnet	Radial	Yes, *	No	NO
Between machine part and base plate	V / A	Flat magnet	Radial	No	Possible	YES
Structural looseness	V / A	Probe Tip	Radial	**	Possible	NO
Resonance						
Machine natural frequency, mode 1 - 3	V / A	Probe Tip	Radial	No	Possible	YES
Rolling bearing faults						
Stage 1, no visible wear	HA	Stud	Radial	No	No	NO
Stage 2, minute pits	A	Adhesive	Radial	No	No	NO
Stage 3, pits	V / A	Adhesive	Radial	No	No	NO
Stage 4, rough tracks	V / A	Adhesive	Radial	No	No	NO
Electric faults						
UMP, low eccentricity	V / A	Probe Tip	Radial	No	Yes	YES
UMP, high eccentricity	V / A	Flat magnet	Radial	Yes, *	Yes	NO
Stator defects	V / A	Probe Tip	Radial	No	Yes	YES
Connector defects	V / A	Probe Tip	Radial	No	Yes	YES

*Synchronized two-plane/place measurement **Synchronized two-place measurement, Possible, comes from differences between performed analysis.

The first factor is sensor type. V means velocity pickup; A means acceleration pickup and HA means High speed accelerometer. Mounting method describes how the sensor should be mounted. Measurement directions indicate the need for radial or axial directions of measurement. The need for phase measurement comes from the change in vibration phase at two different locations on the machine. Ramp-up means when the motor is accelerated across a range of frequencies with a pre-set increment in rotation frequency. In some cases, it is mandatory to perform it to distinguish faults from each other's. In other cases, there may be a need to perform ramp-up testing to ensure the nature of the fault. The last column shows whether the case study process fulfill the criteria, a black frame in the NO rows indicates where the lack of process lies.

4.2 Factors affecting reliability of measurement

The first thing to consider measurement reliability of the case study is machine mounting. If mounting is poor, the rest of the process will be compromised. The two options were elastic or rigid mounting, and due to its large size and high operational speed, a rigid mounting is used for this motor. With rigid mounting, there were two key points to consider; The base plate should have a heavy weight and surface of plate should be flat. The company has just invested in a new test bench with a thick steel plate. They performed FE calculations to determine the natural frequencies of the system (Table *6*). The frequencies were in accordance with the guideline values (± 20 % from natural frequency).

The next factor that affects reliability is the location of the sensor. In the measurements, the sensors are mounted in the radial direction horizontally in the bearing housing, the axial sensor is mounted on the end plate of the machine. The measurement is taken from both ends of the machine. PSK 5702 (2007) showed the correct sensor locations in Figure *10*. The sensor is not in the position shown in the figure, so it can be assumed that it is not an ideal for vibration measurement.

The third factor is the accuracy of the measurement process. The required accuracy may vary depending on the analyzes performed and for that reason, an absolute accuracy limit cannot be determined. The characteristics of the measuring instruments must be considered, and the manufacturers' instructions must be followed. The case study sensor is intended for many different uses. Error margin between 1 to 5000 Hz is 10 % and above 5000 Hz it is 50 %. Measurement is taken in radial direction only from one plane, which influences the accuracy of the amplitude. The literature provided information on the necessary sampling rate so that the signal did not change significantly when it is measured. It is suggested that the sampling rate should be 10 times the highest frequency to be measured (SFS-ISO 13373-2 2005, p. 4.). To understand the significance of the sampling rate, an experimental calculation was performed with MATLAB software. The position of a harmonic wave in relation to time was calculated from equation 6. Displacement position were picked up from the wave according to different sampling rates. Reference wave was calculated with 100 points per cycle (sampling rate 100). The values used in the calculation and the results in numerical form are given in Appendix 4. Appendix 5 show behaviour in the waveform. Figure *14* shows how the accuracy of measurement of displacement of same magnitude and 3 different phases changes with 14 different sampling rates.

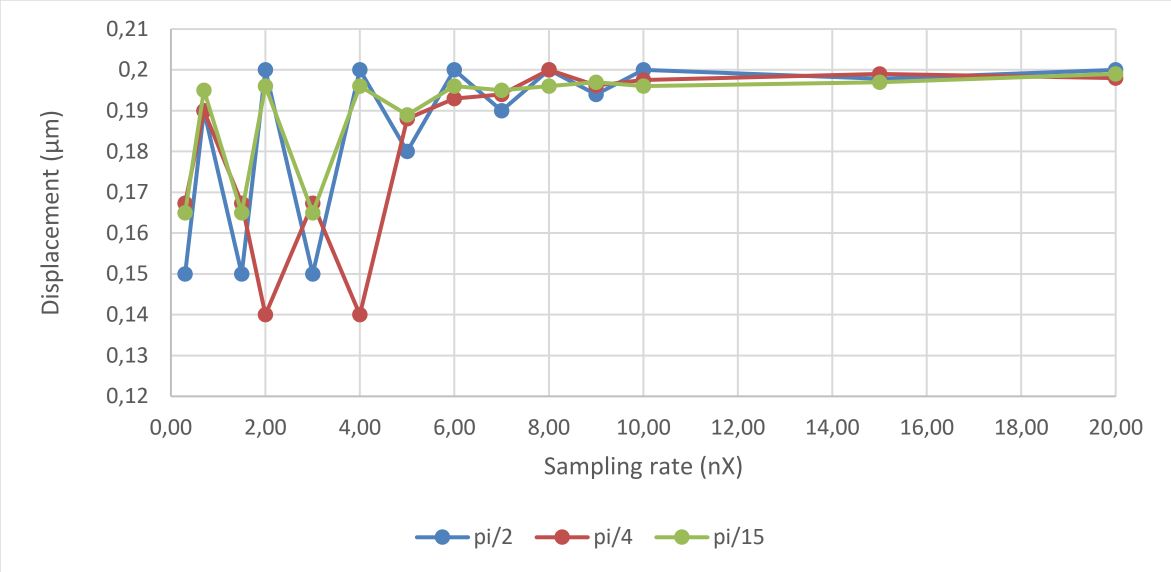


Figure 14. The effect of the sampling rate to the amplitude of the harmonic wave with different initial phases of the wave. Y- axis shows maximum amplitude of the sample within specific sampling rate.

The current sampling frequency used for this machine is 25600 Hz. The only frequency from which cannot measure 10-fold sample is not visible wear on the bearings. Appendix 6 show the same fault frequencies as in Figure *13* at 10 times the sampling frequency.

4.3 Effect of high-speed electric motor characteristics to the measurement process

When it comes to measuring electric motors, electrical properties affect the measurement. The operating principle of many sensors is susceptible to electromagnetism. In case study environment, the electromagnetism is high due to the high power of the motor. The case study sensor has electromagnetic compatibility (EMC) feature. Electromagnetic properties not only affect the measurement process but also the vibration of the machine. Electric motors contain electromagnetic forces that generate vibrations like mechanical faults. These sources of vibration can be tricky to directly distinguish from each other. One alternative to solve this problem is to perform the measurement by turning the power off / on while the machine is running (Scheffer & Girdhar 2004, p.123). In the case study environment, it is possible to perform such testing, but it is not currently operational.

The speed of the machine also brings its own characteristics to its use and to the measurement process. The operating speed of the machine is higher than system (motor + testbench) first natural frequency (the support between the motor and the base plate is the most flexible point in the system). The behavior of the system begins to change from rigid to flexible as the speed of the machine approaches the first critical. In the case study, it means a change in the relative vibration behavior of the machine and the steel plate. The machine itself is designed to be subcritical (the first natural frequency of the machine is higher than the machine speed). Testing must take this into account by avoiding unnecessary use at the natural frequency. Higher speed means also higher vibration frequencies. The vibration occurring at rotational speed are not much higher than with normal 50 Hz machines, but with the harmonic frequencies difference goes high. Table 9 show this difference.

Table 9. Compare the frequency range of a standard 50 Hz motor and a case study motor.

Frequency (nX)	Standard motor (Hz)	Case study motor (Hz)	Frequency difference (Hz)
1X	50	158,5	108,5
3X	150	475,5	325,5
8X	400	1268	868

4.4 Discussion of the measurement process

At the outset, it is good to note that vibration analysis can be performed in many ways. In this work, vibration analyzes were based on frequency band analyzes (frequency and phase of vibration). Criteria for vibration behavior is compiled at the end of the literature review into the Table *4*. Similar information can be found in the PSK 5707 standard 7 (PSK 5707 2011, p. 8–22, 28– 32). The frequency and direction of vibration are specified in the standard. The frequencies are consistent in each case. There is a deviation in the directions of the vibration with the types of electrical faults. The standard states that the vibration occurs axially in addition to the radial direction. Guo, Chu and Chen (2002) reported that the vibration occurs in the radial direction. They also reported that it behaved similarly to the unbalance. Coupled and dynamic unbalance vibrates at radial and axial direction. It is therefore likely that the vibration will occur in both directions but will be stronger in the radial direction. Mobius institute list different vibration analysis definitions in their website. This information is also in line with Table *4*. The table can be considered as a reliable basis for defining the criteria of the measurement system.

In the selection of the sensor type, the measurement based on displacement data was directly excluded based on the literature review. The selection of the sensor was simplified according to the frequency band alone. This is the first step but by no means the last. The selection of the sensor must take into account the specific features of each case. As in the case study, the sensor must be of EMC type.

Lot of information was found on the methods of attaching the sensor. The information in the literature review (Hanly 2016) corresponds to the instructions given by the sensor manufacturer SKF (Vibration sensor catalog 2018, p. 85). Consistent information was found also on the surface preparation and the locations of sensor. Regarding the mounting of the sensor, it can be assumed that the instructions are correct. In connection with the mounting of the sensor, the greatest risks could be related to the performance of the operation itself. It should be ensured that the sensors are attached properly as per the instructions Particularly in the case study, attention should be paid to this issue because the fixed mounting method made for the measurement is not used. In the measurement process, magnet-mounted sensors are used. In terms of sampling range, the data in the literature review and the experimental data corresponded. With 10 times the highest frequency, accuracy of measured wave is high in every case. As the sampling rate decreases, the accuracy of the vibration amplitude decreases. The frequency of vibration can be measured with 2 times the highest frequency. The sampling rate of the case study is sufficient for almost all frequencies. The first fault frequency appearing in the bearing is the only one that cannot be detected. It is very much higher than the other frequencies. Its detection with the same measurement system can be excluded out.

Any errors that may occur in the work may manifest themselves as a misunderstanding of the sources. Efforts have been made to prevent this by looking at different sources. For the Case study, the greatest chances of error occurrence was in the calculations of frequencies. On the other hand, possible individual errors are not serious, because the measurement process is always chosen according to the most demanding case.

4.4.1 Key findings

The study was built from a perspective where the aim was to create measurement system which can offer reliable information to fault analysis. The research questions were formed based on the objective. After going through the literature review and case study, it seems that the research questions were partly successful. From the specific features of the faults, it is easy to see the importance of the success of the measurement process. In order to perform data analysis, it is important the measured data corresponds to reality as accurate as possible. In order to get an accurate result, it is necessary to know what is wanted to measure and what are the special features of the machine. Based on that the right tools and methods can be selected.

In the case study, the measurement process is created to examine the operational condition of the machine. The functional determination of operational condition comes from the IEC 60034-14 standard. A limit value for vibration has been set for new machines. (The Switch 2020). The current measurement process is able to indicate the smooth behavior of the machine or a clear fault. In order to investigate the causes of the fault, there are shortcomings in the measurement process in certain respects as mentioned in *Table 8*.

The most significant areas for development are issues related to accuracy and phase of vibration. To analyze many types of faults, it is necessary to know the phase of the vibration. The phase of the radial vibration can be analyzed from the data when the data is collected at two different points in a perpendicular plane. This measurement can also be used to calculate the maximum amplitude of the vibration (Bartheld & Peregrin 1995, p.621-623). The position of the axial sensor should also be changed to increase accuracy. The vibration is not optimally transmitted to the current position.

Other things worth noting are:

- The baseplate vibration measurement
- Ramp-up / coast down
- Changing the mounting method to the stud mounting
- Changing the sensor to be more suitable for the frequency band of the fault types (lower the error margin).

4.4.1 Use of results in other cases and further research

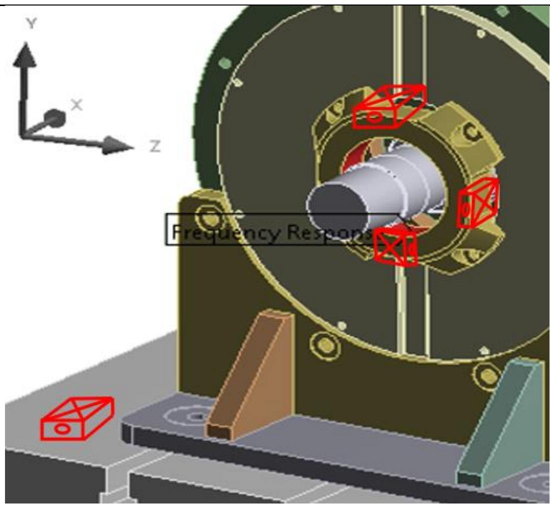
The results are most applicable to very similar types of machines as examined in the case study. At a more general level, the results can be exploited by considering the specific features of the machines.

In the next step, after identifying the fault type, one step further would be to identify the fault parameters in terms of magnitude and location. The measurement process now developed can provide information for studying different fault types. Actual analyses of faults can provide more feedback on whether the measurement methods provided in this work are sufficient. The fault analysis method contributes to determining the measurement requirements. Some changes to measurement may need to be made depending on the type of fault is wanted to diagnose and how it is done. Efforts must also be made to study new measurement methods. In the specific case study considered in this research, particularly in order to know if there are manufacturing defects in the bearings, measurements at very high frequencies should be facilitated. Traditional methods may not provide accurate enough information from very high frequencies.

4.4.2 Recommended changes to the measurement process for the case study

Table 10 present recommended changes in the studied test case to enable the fault analysis of different types considered in this study. The recommended changes are made with the idea of analyzing all the *Table 8* faults.

Table 10. Measurement specification to analyzing wide range of faults.

Sensor	SKF CMSS 793	
Sensor locations	Both ends, Optional: Baseplate measurement	
Directions	In three directions. Three- axial sensor or separate sensors	
Mounting method	Stud	
Testing speed	Nominal speed + Ramp-up, coast down	
Sampling rate	20 kHz * 120 kHz **	*No visible wear in bearings is not included ** No visible wear in bearings is included

5 CONCLUSION

The purpose of the work was to study the implementation of vibration measurement of a high-speed electric motor in a situation where it is desired to find out the causes of possible faults. Excitation frequency of the fault, direction and phase of the vibration, harmonic frequencies and whether there are any other special features. When performing tests and analyzes, it is also necessary to know the interactions between the fault types. Two different types of faults can occur at the same frequency (or very close of each other's), making it challenging to separate them. With an electrical machine, mechanical faults often also interfere with electrical behaviour. For example, the UMP may be due to an eccentric rotor. This results in vibrations equal to the rotational speed due to both the mechanical eccentric and the effect of the UMP. The UMP also affects the critical speed of the machine, making it similar to the reduced stiffness of the machine.

In addition, the effect of a high-speed electric motor on testing had to be determined. Due to the high speed and strong electromagnetism, the measurement must take into account the monitoring of the critical speeds of the system, the measuring equipment must be able to measure very high frequencies and it must not be exposed to electromagnetic phenomena. The machine and sensors should be mounted as rigidly as possible. The sensors must be of high quality and selected to suit the frequency band being monitored. Not all possible excitations of fault types can be measured accurately by the same method.

In the case-study, it was found that the standard measurement arrangement is not able to provide sufficiently accurate data to perform a comprehensive fault analysis. The company must add another sensor to the measurement in the radial direction and make the mounting of the sensors stud. The sampling frequency should be ten times higher than rotating speed or at least increased to twice the maximum desired excitation frequency. Making the changes the current system can be modified to cover almost the entire frequency band. Only wear on the very early stages or manufacturing defects on the surface of the bearings are outside the measuring range. For this purpose, a measurement system based on sound waves can be obtained if it is deemed necessary.

REFERENCES

Asoke, K. N., Ahmed, H., 2019. Condition monitoring with vibration signals: Compressive sampling and learning algorithms for rotating machines. USA. IEEE press. John Wiley & Sons Ltd.

Beaty, H., Kirtley, J., 1998. Electric Motor Handbook. New York. McGraw Hill.

Collin, J. & Saarelainen, A. 2016. Teollinen internet. Helsinki: Talentum.

FAG Bearings corporation, Rolling bearing damage, FAG South East Asia PTE Ltd., 1997, Publ. No. WL 82 102/2 Esi, 71

Gidhar, P., Scheffer, C., 2004. Practical Machine Vibration Analysis & Predictive Maintenance. First Edition. Burlington.

Gieras, J., 1995. Solid-Rotor Induction Motors. p. 147-156; Gieras, J. Solid-Rotor Induction Motor design. p. 293-298 In Engelmann, R., Middendorf, W. Handbook of Electric Motors, Marcel Dekker Inc., New York,

Guo, D., Chu, F., Chen, D., 2002. The unbalanced magnetic pull and its effects on vibration in a three-phase generator with eccentric rotor. Journal of Sound and Vibration. p. 298-309 [Referred to 16.12.2019]. Available: https://www.sciencedirect.com/science/article/pii/S0022460X0194088X/pdf?md5=937dfc0798bae9b4f8e4d0ad15e005a6&pid=1-s2.0-S0022460X0194088X-main.pdf

Hanly, Steve., 2016. Shock & Vibration Testing Overview eBook. [Referred to 15.12.2019]. Available: https://www.researchgate.net/publication/318827258_Shock_Vibration_Testing_Overview_eBook

Inman, D. J. 2008. Engineering vibration. 3rd ed. Upper Saddle River (NJ): Pearson Prentice Hall.

ISO 13373-1. 2002. Condition monitoring and diagnostics of machines. Vibration condition monitoring. Part 1: general procedures. International Organization for Standardization. Switzerland.

Mikkonen, H., Miettinen, J., Leinonen, P., Jantunen, E., Kokko, V., Riutta, E., Sulo, P., Komonen, K., Lumme, Veli E., Kautto, J., Heinonen, K., Lakka, S., Mäkeläinen, R., 2009. Kuntoon perustuva kunnossapito. 1. painos. Helsinki. KP-Media Oy.

Mobius Institute. 2020. [Mobius Institute www-page]. Unbalance. [Referred to 28.1.2020]. Available: https://www.mobiusinstitute.com/site2/item.asp?LinkID=8002&iVibe=1&sTitle=Unbalance

Motiva. 2020. [Motiva www-page]. [Referred to 20.3.2020]. Available: https://www.motiva.fi/files/5342/Energiatehokkaat_sahkomoottorit.pdf

Nohynek, P., Lumme, V., E., 2004. Kunnonvalvonnan värähtelymittaukset. 2. täydennetty painos. Rajamäki. KP-Media Oy.

Prabhu, K. M. M. 2014. Window Functions and Their Application in Signal Processing. Boca Raton, Florida. CRC press, Taylor & Francis Group.

PSK 5702. 2007. Kunnonvalvonnan värähtelymittaus. Mittauspisteen valinta ja tunnistaminen. 3. painos. [Referred to 19.2.2020]. Available: https://psk-standardisointi.fi/standardit/#ryhma57

PSK 5703. 2018. Kunnonvalvonnan värähtelymittaus. Anturin, liittimen ja kaapelin valinta sekä asennus. 5. painos. [Referred to 6.1.2020]. Available: https://psk-standardisointi.fi/standardit/#ryhma57

PSK 5707. 2011. Vibration Measurement in Condition Monitoring. Diagnosis. 5th edition. PSK Standards Association. [Referred to 18.1.2020]. Available:

https://psk-standardisointi.fi/standardit/#ryhma57

Pyrhönen, J., The high-speed induction motor: calculating the effects of solid-rotor material on machine characteristics. Acta Polytechnica Scandinavica, Electrical Engineering Series No 68, Helsinki 1991, Published by the Finnish Academy of Technology.

Rao, B.K.N. Handbook of condition monitoring, 1st edition, Oxford, Elsevier Advanced Technology, 1996. ISBN 1-85617-234-1.

Sathyan S., Belahcen A., Lehikoinen A., Aydin U., Boxberg F., 2019. Investigation of the causes behind the vibrations of a high-speed solid-rotor induction motor. Journal of Sound and Vibration. Volume 463. [Referred to 7.4.2020]. Available PDF-file: https://www.sciencedirect.com/science/article/pii/S0022460X19305383?via%3Dihub

Schaeffler. 2020. [Schaeffler www-page]. [Referred to 5.6.2020]. Available: https://medias.schaeffler.com/medias/en!hp.ec.br.pr/HCB70..-C*HCB7019-C-T-P4S

SFS-ISO 13373-1 2002. Condition monitoring and diagnostics of machines. Vibration condition monitoring. Part 1: general procedures. International Organization for Standardization. Switzerland.

SFS-ISO 13373-2. 2005. Condition monitoring and diagnostics of machines. Vibration condition monitoring. Part 2: processing, analysis and presentation of vibration data. International Organization for Standardization. Switzerland.

SFS-ISO 21940-2. 2017. Mechanical vibration. Rotor balancing. Part 2: Vocabulary. International Organization for Standardization. Switzerland.

Sen Gupta, D.P., Lynn, J. W., 1980. Electrical machine dynamics. London. MacMillan Press.

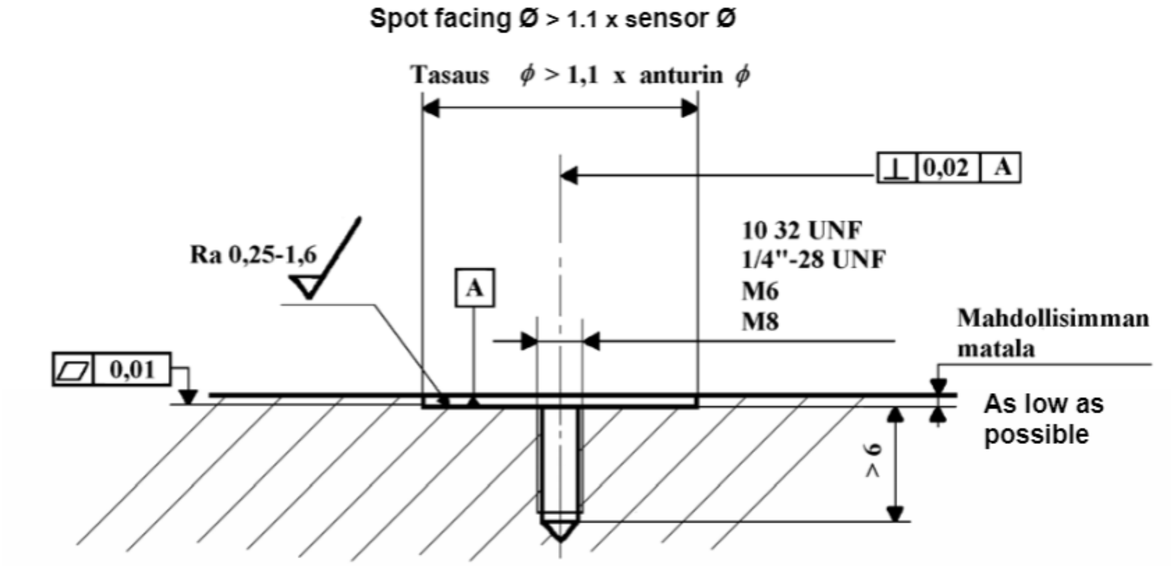
SKF, 2018. [Referred to 12.4.2020]. Vibration sensor catalogue. Available PDF-file: https://www.skf.com/binary/31-267858/0901d196804926fe-11604_16-EN-Vibration-Sensor-Catalogue---OK.pdf

The Switch A Yaskawa company. 2020. Markus Silventoinen & Erkki Ukkola

ATTACHMENTS

Appendix I

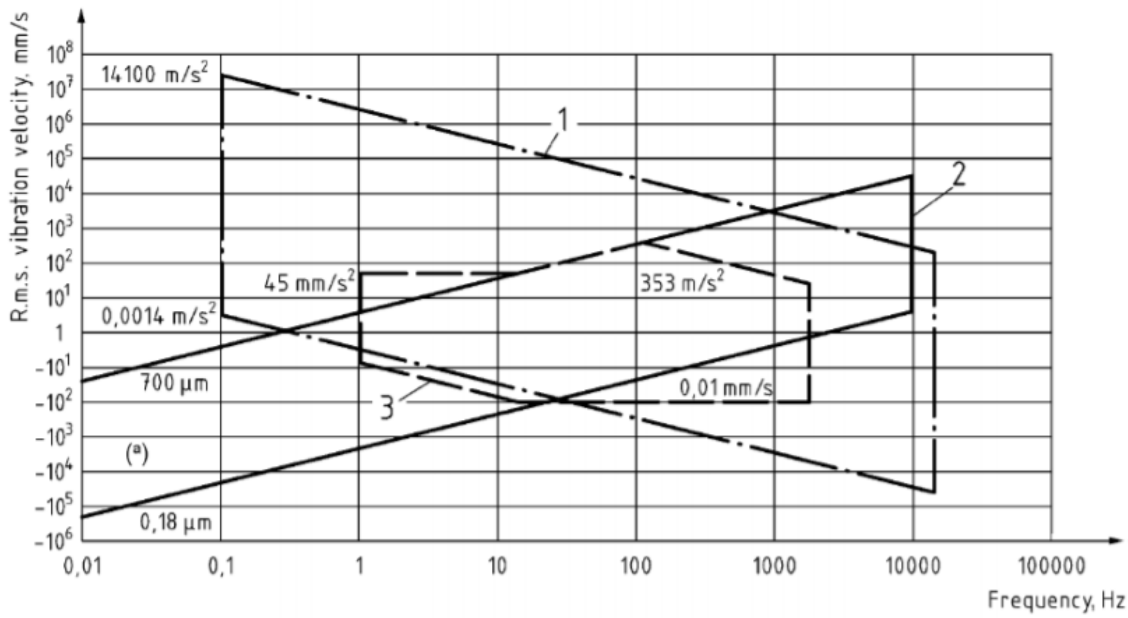
Sensor mounting surface instructions



PSK 5703 2018

Appendix II

Sensor measuring range. 1 Acceleration, 2 displacement, 3 velocity



SFS-ISO 13373-1 2002, p. 17

Appendix III

Case study's fault frequencies with different fault types. The harmonic frequency is the highest frequency at which vibration still occurs

Fault subcategories	Frequency Mechanical	Frequency Electrical	Harmonics
Unbalance			
Static	158,5	0	0
Couple	158,5	0	0
Dynamic	158,5	0	0
Misalignment			
Angular	158,5	0	1268
Looseness			
Internal, bearing/impeller - shaft	317,0	0	793
Between machine part and base plate	475,5	0	793
Structural looseness	158,5	0	0
Resonance			
Natural frequency, mode 1	125,0	0	0
Natural frequency, mode 2	208,0	0	0
Natural frequency, mode 3	213,0	0	0
Rolling bearing faults			
Stage 1, no visible wear	60000,0	0	0
Stage 2, minute pits	2000,0	0	0
Stage 3, pits	1787,3	0	0
Stage 4, rough tracks	1382,7	0	793
Electric faults			
UMP, low	158,5	171	0
UMP high, 2X line frequency	158,5	330	989
Stator defects	158,5	330	0
Connector defects	158,5	330	0

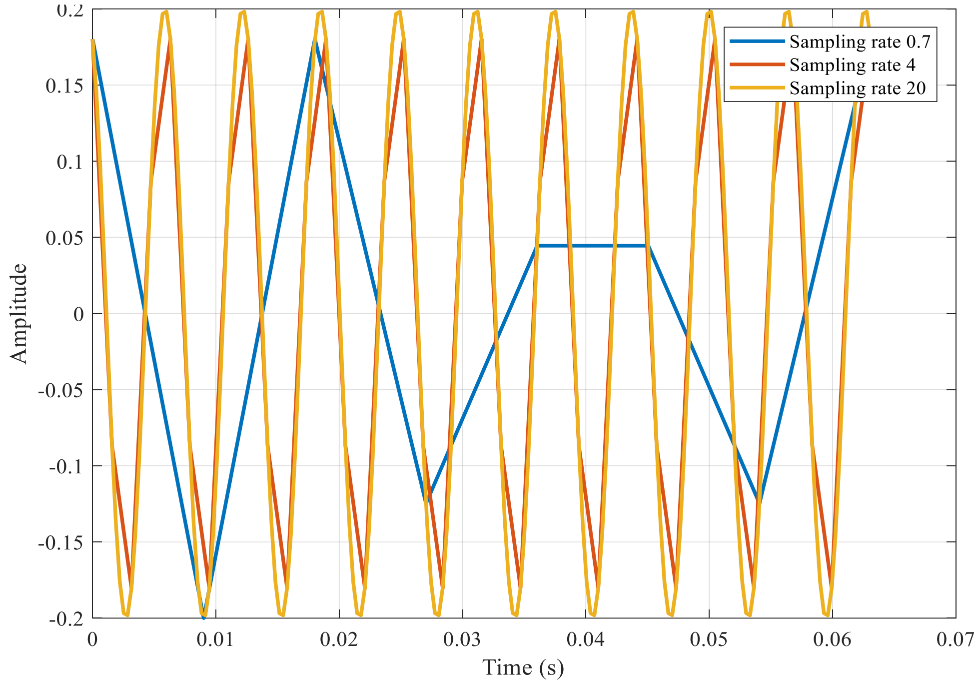
Appendix IV

Values used in the sampling rate calculation

Speed (Hz)			Cycle time (s)		Displacement (um)	
158,5			0,00631		0.2	
Calculated based on Samplin rate						
Sampling rate (speed xn)	Phase difference (degree)	Amplitudi (um)	Phase difference (degree)	Amplitudi (um)	Phase difference (degree)	Amplitudi (um)
0,30	pi/2	0,15	pi/4	0,1673	pi/15	0,165
0,70	pi/2	0,19	pi/4	0,19	pi/15	0,195
1,50	pi/2	0,15	pi/4	0,1673	pi/15	0,165
2,00	pi/2	0,2	pi/4	0,14	pi/15	0,196
3,00	pi/2	0,15	pi/4	0,1673	pi/15	0,165
4,00	pi/2	0,2	pi/4	0,14	pi/15	0,196
5,00	pi/2	0,18	pi/4	0,188	pi/15	0,189
6,00	pi/2	0,2	pi/4	0,193	pi/15	0,196
7,00	pi/2	0,19	pi/4	0,194	pi/15	0,195
8,00	pi/2	0,2	pi/4	0,2	pi/15	0,196
9,00	pi/2	0,194	pi/4	0,1962	pi/15	0,197
10,00	pi/2	0,2	pi/4	0,1975	pi/15	0,196
15,00	pi/2	0,1978	pi/4	0,199	pi/15	0,197
20,00	pi/2	0,2	pi/4	0,198	pi/15	0,199
Calculated based on initial phase						
Phase difference (degree)	Sampling rate (speed xn)	Amplitudi (um)	Sampling rate (speed xn)	Amplitudi (um)	Sampling rate (speed xn)	Amplitudi (um)
pi	4,00	0,2	8,00	0,2	20,00	0,2
pi/16	4,00	0,196	8,00	0,196	20,00	0,199
pi/12	4,00	0,193	8,00	0,193	20,00	0,2
pi/8	4,00	0,185	8,00	0,185	20,00	0,199
pi/4	4,00	0,14	8,00	0,2	20,00	0,198
pi/2	4,00	0,2	8,00	0,2	20,00	0,2

Appendix V

Wave shape at different sampling rate



Appendix VI

Case study's fault frequencies x10, compared to the used sampling rate (red line)