ANALYSIS OF VIBRATION SIGNALS AND SURFACE CHARACTERISTICS OF CYLINDRICAL ROLLER BEARING

by

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DECLARATION

I hereby declare that the work reported in this thesis is the result of my own investigation and that no part of the thesis has been plagiarized from external sources. Materials taken from other sources are duly acknowledgement by giving explicit references.

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"In the name of ALLAH, The Most Beneficent and The Most Merciful"

All praises to Allah S.W.T, the most merciful and gracious, and my peace and blessings of Allah be upon his messenger, Muhammad S.A.W. First of all, I would like to express my gratitude to his greatness, with whose indulgence has given me the strength and convenience to complete this report successfully.

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LIST OF SYMBOLS

Symbols	Descriptions	Units
R_a	Average roughness	µm
R_{sk}	Skewness (asymmetry) of the assessed profile	-
R_q	Root mean square (RMS) deviation of the assessed roughness profile	-
R_t	Total height of the profile	µm
R_{sm}	Mean width of the profile elements within a sampling length	µm
R_v	Maximum depth of the profile below the mean line within the assessment length	µm
R_{q1} & R_{q2}	Surface roughness value of the two bodies in contact	-
S_{sk}	Skewness of height distribution (dimensionless)	-
S_{ku}	Kurtosis of height distribution (dimensionless)	-
λ	Film thickness	-
h_{min}	The minimum film thickness	-
U	Speed parameter	-
G	Material parameter	-
W	Load parameter	-
λ	Specific film thickness	-
d_r	Roller diameter	mm
D_i	Inner bore diameter	mm
D_o	Outer ring outside diameter	mm
d_m	Pitch diameter	mm
B	Bearing width	mm
N_b	Quantity of rolling elements	-
B_d	Ball diameter	mm

P_d	Pitch diameter	mm
θ	Contact angle	-
S	Rotational speed	rev/s
β	Contact Angle	-
f_r	Relative speed between inner and outer races	rev/s
R_{vk}	Maximum valley height of roughness profile	μm
S_q	Root-mean-square deviation of the surface	-
V_o	Oil retention volume	μm
W_a	Waviness	μm

LIST OF NOTATIONS

Symbols	Descriptions
RMS	Root Mean Square
FFT	Fast Fourier Transform
BPF	Ball Passing frequency
RSM	Response Surface Method
AE	Acoustic Emission
EHD	Elastohydrodynamics
ADF	Amplitude Distribution Function
AC	Alternating current
B&K	Brüel & Kjaer
BPFO	Ball passing frequency of the outer race
BPFI	Ball passing frequency inner race
ODF	Outer race defect
IDF	Inner race defect
FIR	Finite impulse response

ANALISIS ISYARAT GETARAN DAN CIRI-CIRI PERMUKAAN BAGI GALAS GULING SILINDER

ABSTRAK

Kajian ini dijalankan untuk mengesahkan kaitan antara paras getaran dan kekasaran permukaan galas yang dijalankan pada keadaan minyak yang nipis, pelinciran gris dan kering. Ujikaji dijalankan dengan beban 633 N dan kelajuan 1500 putaran seminit. Getaran mekanikal dan keadaan permukaan diukur setiap 30 minit. Keputusan menunjukkan paras getaran oleh galas dengan minyak yang nipis meningkat dengan kekasaran permukaan dan gagal selepas 90 minit. Untuk galas yang menggunakan pelincir gris paras pecutan bertambah dengan kekasaran permukaan dan kegagalan berlaku selepas 6480 minit. Galas dalam keadaan kering gagal selepas 20 minit. Pengukuran parameter permukaan melibatkan R_a (purata profil permukaan), pencong (skewness), kurtosis dan ukuran kebulatan untuk mengesan perubahan permukaan galas dan kaitannya dengan kesan getaran keatas galas.

Perkaitan pekali Pearson antara setiap parameter permukaan dan paras getaran di kira dan di dapati bahawa ukuran kebulatan mempunyai pekali perkaitan Pearson yang tertinggi iaitu 0.8. Daripada analisa ini didapati bahawa kekasaran permukaan boleh dikaitkan dengan paras getaran.

ANALYSIS OF VIBRATION SIGNALS AND SURFACE CHARACTERISTICS OF CYLINDRICAL ROLLER BEARING

ABSTRACT

This work aims to establish the relation between the vibration level and the surface roughness of the bearing running under lightly oiled, greased and dry conditions. Tests were performed at a fixed load of 633 N and speed of 1500 rpm. The mechanical vibration and the surface condition were measured at thirty minutes interval. The result showed that the vibration level of the lightly oiled bearing increases with the surface roughness, and failure was detected after 90 minutes. For the grease lubricated condition, the acceleration level increases with the surface roughness and failure of the bearing occurred after 6480 minutes of running. For the dry un-lubricated bearing, failure occurred after 20 minutes.

Measurement of the surface characteristic parameters include Ra (average roughness of profile), skewness, kurtosis and waviness were made to monitor these surface parameters variation and their relationship with the vibration of the bearing. The Pearson Correlation coefficient of each surface roughness parameters with the rms vibration level is calculated. The surface waviness shows the highest Pearson Correlation coefficient of 0.8. This analysis showed that the surface roughness can be correlated with the vibration level of the bearing.

CHAPTER ONE
INTRODUCTION

1.1 General overview

Rolling element bearings support and locate rotating shafts in machines. The term “rolling element” bearing includes ball bearings and roller bearings. Rolling element bearings operate with a rolling action, whereas plain bearings operate with a sliding action. Rolling element bearings can fail due to manufacturing errors, improper assembly, loading, operation or lubrication. However, even if a bearing is perfectly made and assembled, it will eventually fail due to the fatigue of the bearing material (Konstantin-Hansen, 2003).

The vibration signals can be used for time prediction to both failure and maintenance interval. Spectral analysis of the vibration acceleration may detect the rolling element bearing looseness and defects in both ball bearings and cylindrical roller bearings (Orhan, 2006).Most failure modes for rolling element bearings involve the growth of cracks on the bearing raceway or on the rotating element. The level of the vibration produced by a new bearing is low and resembles random noise. As fault begins to develop, the vibration produced by the bearing changes. Every time a rolling element encounters a discontinuity in its path, a pulse of vibration results. The resulting pulses of vibration repeat periodically at a rate determined by the location of the discontinuity and by the bearing geometry (Orhan, 2006).

The surface characteristics of the bearing condition and the vibration level measurement of rotating bearing are the main parameters used in this study. The surface roughness is evaluated periodically with different lubrication, lightly oiled, greased and dry conditions. The changes of surface roughness are monitored simultaneously with the vibration level to determine their correlation.

1.2 Cylindrical Roller Bearing

Cylindrical roller bearing can transmit high radial, but slight axial forces. The inner and outer rings can be dismantled and installed separately with small angular adjustability. The cylindrical-spherical profile at the edge radius prevents the occurrence of edge stresses and produces a modified line contact with comparatively reduced stress distribution in particular the logarithmic profile, prevents discontinuity in the stress profile curve. In this study, the analysis is more made on the cylindrical roller bearing due to its proven high radial load carrying capacity. The cylindrical roller bearing distributes the load over a larger area and can handle much greater loads compared to ball bearing (Dubbel, 1997). The inner raceway is fitted on the rotating shaft and the outer raceway mounted on machined stationary housing. Cylindrical roller bearing has lower friction torque and lower friction power loss compared to other type of bearings. The main advantage of the type used here over other conventional bearings is that the inner ring can be dismantled from the roller and cage assembly. The disadvantages of the cylindrical roller bearing are louder noise when vibrating and sensitive to the metal scraps which may result in early damage. Bearing lubrication is considered important since it forms a layer of film to separate the sliding and rolling surfaces. The bearing must sustain the load of the machineries and the shaft speed and insufficient lubrication can affect the surface characteristics and vibration level resulting in of loud noise. The best bearing operation can be obtained by sufficient lubrication. The failure of long term bearing operation is normally caused by the fatigue of the surfaces which are subjected to continuous rolling contact. There is a need to investigate the relationship between vibration signals, surface characteristics of the cylindrical bearings and conditioned of lubrications.

1.3 Problem statement

Bearing lifetime depends on the setting of operating parameters and the effects of lubrication which is the lubrication film thickness. Insufficient or improper lubrication will shorten the bearing lifetime and affect the surface characteristics. There is a need to establish the relationship between the bearing characteristics such as surface roughness and the vibration level which is widely used in condition monitoring, as the surface of the bearing is worn out, there will be changes in the surface characteristics and this study will look into the changes of the surface parameters with the vibration level.

1.4 Objectives

In this study, the research objectives are:

1) To quantify the vibration level and the surface parameters for the cylindrical roller bearing until failure for two lubrication conditions and compare the effect of lubrication.

2) To monitor the vibration level affected by the surface parameters during operation and the type of lubrication.

3) To determine the strength of the Pearson correlation between vibration level and the parameters of the surface characteristics of the cylindrical roller bearing.

1.5 Research scope

The study focussed on the cylindrical roller bearing with three lubrication conditions which are grease lubricated, lightly oiled lubricated and un-lubricated bearing. The surface characteristics analysis was limited to the inner race of roller bearing because this surface is the one mostly involved with high rolling contact stress. The surface characteristics trend was monitored for the new bearing until its failure. The vibration level and surface parameters were monitored from the beginning of the experiment until the bearings failed. The vibration data is monitored using envelope analysis and Fast-Fourier Transform (FFT) analysis.

CHAPTER TWO
LITERATURE REVIEW

2.1 Condition Monitoring of Machinery

Condition monitoring of machinery concerns with the measurement of various parameters pertinent to the mechanical state of the machinery (which include vibration, bearing temperature, oil pressure, oil debris and performance). Tandon et. al, (2007) pointed out that condition monitoring offers a way to determine the root of the problem.

Harris (1996) elaborates that condition monitoring the basis for on-condition maintenance. In many engineering plants, on-condition maintenance is an important work section as it provides run-to-breakdown maintenance and preventive maintenance (in which mechanical parts are replaced every now and then at fixed time intervals). Vibration measurements and parameter can serve as predictors to the condition monitoring as well as faults before the parts are replaced and the advantages are listed below:

- It avoids any unanticipated catastrophic breakdowns with costly or hazardous consequences.
- Lowers the number of overhauls on machines to a minimum, therefore costs of maintenance can be reduced.
- Removes unimportant interventions carrying the risk of introducing faults on well-operating machines.

- Allows the spare part to be ordered on schedule and on plan, whereby this enables the elimination of expensive inventories.
- Lessens the intervention time, and consequently mitigating production loss. Because the fault that is to be repaired is known ahead of time, overhauls can be scheduled in the most convenient time for relevant parties.

2.2 Vibration Level Monitoring

Vibration data from the monitoring system can be presented in the root means square value (RMS)used to average the vibration signal for statistical and for magnitude of varying quantities to differentiate positive and negative values.

Karacey and Akturk (2009) have developed a method for vibration measurements and signal analysis for condition monitoring of ball bearings based on the vibration signature and examined the defects using time domain analysis of vibration signature such as peak-to-peak amplitude, root mean square, crest factor and kurtosis signals. From the finding the vibration signal shows the development of the defects in the ball bearing found. The first defect was detected at the inner race defect with the slight defect of the ball. The outer race suffered from defects happened at the end of experiments as shown in the microscopic photos of damaged bearing. Vibration data measurement can be used to predict the bearings condition against time. The data showed the bearing condition from starting and gradually deteriorating until it failed. In industrial applications, minimum downtime is one of the most required specifications in maintenance stages and the inability to supervise the machine components' condition can incur maintenance costs that are uncalled for. Therefore, it is important to understand the defect development phases and the prediction of the lifetime of ball bearing. The researcher using statistical measurement to measure the peak-to-peak amplitude, root mean square (RMS), crest factor and kurtosis value were all observed closely for predicting the bearings' wellbeing. It was conclusive that the statistical measures indicate ample degradation in ball bearings.

2.3 Bearing Vibration Analysis

Orhan e.t. al (2006) unravel the issue of the vibration for monitoring the rotating machineries and also analyse the anomalies of the machinery internal structure. The vibration analysis uses the data in the time domain and changes it into the frequency domain using the FFT. The vibration signals can be used for time prediction of failure and maintenance cost. The bearing defect is confirmed to be flawed upon high frequency amplitude levels and decrease caused by a process called 'self-peening'. In their study a spectral analysis of the vibration acceleration was used for detecting ball bearing looseness and defects in both ball bearings and cylindrical roller bearings. The authors observed that when a rolling surface defect comes to a developed stage, amplitudes of high frequency components end to disappear due to the self-hammering of sharp surface flaws originally reasoned by the defects.

Kiral and Karagülle (2006) adopted a method based on the finite element vibration analysis for defect detection in rolling element bearings. The finding is that local defect generates successive impulses at each contact of defect and the rolling element. The housing structure is propelled to vibrate in natural modes.

The studies by Williams et. al (2001) involve running the new bearing until it reaches failure; which are inconsistent with a lot of studies that examine crack propagation due to 'seeded' damage. The damage is caused by surface-scratching and debris is introduced into the lubricant. The vibration analysis makes use of sometime-domain parameters of the vibration data namely skewness, kurtosis, RMS and crest factor to study the execution of both life and testing capabilities. The introduction of a defect onto any contacting surface would generate impulses, thus changing the distribution of the vibration signal and increasing the kurtosis value. From the result, the inner race damage increase to maximum level, decreased and rose again. The initial propagation of the surface defect due to initial damage and the subsequent drop are attributed by phenomenon known as 'healing'. After continuously rolling of bearing the sharp edges of a crack or decreasing in vibration signal are due to smoothing and increase of signal caused by additional flaking.The author developed a new system that was capable of providing 'real' crack information and proof that envelope spectrum was able to detect the defect compared to acoustic emission method.

Harsha (2006) states that bearing that performs high-speed running will create vibrations and noises whereby the gravest conditions occur when the ball passage frequency (BPF) and its harmonic concur with the natural frequency of the rotor bearing.

Harsha et al. (2004) also develop an analytical model in the pursuit of forecasting the nonlinear dynamic response in a rotor bearing system due to surface waviness. The conclusion of this work suggests that the outer race waviness cause severe vibration to occur when the number of ball and waves are equal.

The response surface method (RSM) looks into the effects of design and operating parameters view closely the vibration signature of a rotor-bearing system, as has been established by Kankar et al (2009). The parameters were considered as the defects as internal radial clearance and surface waviness of the bearing components. A review by Tandon and Choudhury, (1999) of vibration and acoustic measurement methods for the uncovering of defects in rolling element bearings is also included in this paper. The discovery of both localized and distributed categories of defect are discussed. Vibration measurement in both time and frequency domains alongside the signal processing techniques such as the high-frequency resonance approach together with acoustic measurement techniques like the sound pressure, sound intensity and acoustic emission have been reviewed. Some of the vibration and wear debris analysis techniques such as vibration, shock pulse, spike energy, spectrographic oil analysis, ferrography and chip detection have also been delved into. Rolling bearing fault detection, it is suggested that out of the time domain statistical parameters, the kurtosis value stands out as the most effective for recognising defect (kurtosis of AE vibration). At the wake of the bearing failure, high frequency techniques such as the vibration acceleration of envelope analysis and the acoustic emission are commonly used.

Rolling element bearings are important in induction motors and monitoring their condition is even more necessary to keep failures at bay. The bearing failure adds the rotational friction of the motor. Even under normal operating conditions of balanced load and good alignment, the onset of fatigue failure is marked by small fissures. Continuing stress causes the material fragments to break loose producing localized fatigue phenomenon known as flaking or spalling. The results showed that the overall amplitudes of vibration of three healthy bearings are also very near to each other and their average overall level is also established. The overall velocity values also follow suit, with the good bearing with increase in load. The overall velocity value has increased even for a small defect of 250 μm. The overall velocity increases to 66% in case of a maximum defect. The vibration correlates with the waviness in rolling bearings of 1500 μm for healthy bearing at 15 kg load. The spectrum of the vibration velocity signal in the low-frequency range was obtained to observe the changes of the defect characteristic of the bearing outer race. (Tandon et., al., 2007)

Experimental study by Mayoof (2009) on rolling element bearings vibration signal observed using the SKF Microlog data analyzer CMXA 50 over a six month period with the analysis started five months after the new installation centrifugal pump. The first reading of the vibration highlight two major peaks on the velocity spectrum at the pump drive end bearing which pointed to the abnormality in the pump and the problem with the pump performance related to the beating phenomenon and the bearing defect frequencies. These appeared in the frequency spectrum with the bearing defect frequencies showing the high spikes. From the work of Mayoof (2009) it can be said that the bearing defect develops over a long period the maintenance is crucial. Monitoring of vibration data for bearing during operation will predict the bearing life before periodical maintenance. The predictions will save operating cost and machine shut down due to equipment failure.

Another alternative method to vibration analysis is acoustic emission (AE). Acoustic Emissions (AE) are sound waves generated during certain occurrences including materials under failure-inducing stress. Classical theoretical studies have led to the conclusion that these elastic waves (sounds) are the result of energy released during deformation and fracture Guo et al., (2005) identify that the acoustic emission technique is useful to monitor the machine's surface finish. From the AE count rate, the crack propagation in the machine surface and form vibration are explored. The AE technique usually draws comparison of results in peak amplitude, with RMS and AE count to illustrate the defect within, or in the surface of material namely crack initiation and propagation. Al-Ghand and Mba (2006) raise a point that the AE technique provides an indication of the defect size, thus permitting them to observe the degradation rate on the bearing. Miettinen (2000) mentioned a small size contaminant particles can generate Acoustic Emission (AE) pulse compared to larger size particles. Cleaning the bearing from contaminants and re-greasing can reduced the AE vibration level of the bearing.

2.3.1 Envelope Analysis

Envelope analysis generally refers to the sequence of operations where by a signal is band pass filtered and enveloped or rectified. Envelope signal processing is a two stage process. The first process involves band-pass filtering of the time domain signal using a band pass filter that centres on the region of high frequency energy. The filtering process results in a series of spiky bursts of energy, which are the impacts from the rolling elements hitting the defect as the bearing rotates. The second stage of the process is to pass this filtered time signal through an envelope in order to extract the repetition rate of the spiky bursts of energy. The FFT spectrum of the enveloped signal displays the bearing characteristics frequency and its harmonics as mentioned by Howieson (2003).

Konstantin-Hansen (2003) have further highlighted envelope analysis as a tool for diagnostics rolling element bearing local faults caused by the increasing trend of amplitude modulating effect on the bearing characteristic frequencies with the presence of faults. The faulty bearing surfaces will produce pulse and a range of force impact during the rolling contact, which is detectable in the envelope spectrum.

Sheen (2007) suggested the use of vibration signal with amplitude modulation to monitor a taper roller bearing (SKF 32208). The bearing was machined to manufacture the defects on the surface at three places- the roller, outer and inner races. The envelope spectrum detection method and amplitude of logarithmic spectrum have demonstrated a defect at these three locations. The experimental result also successfully detects the bearing defects at the seeded location and this is in line with the numerical data.

2.4 Wear in Tribological Studies

Wear takes place when the lubricating film thickness is insufficient for total separation of two sliding or rolling partners. Tribological systems that have worked without lubrication, such as dry bearings, are prone to gradual wear as shown in Figure 2.1. In this figure, the wear process can be divided into three phases of running-in, permanent condition and finally failure. Figure 2.2 shows a more detailed wear magnitude over time which is divided into three phases namely running-in, steady-state condition and fatigue failure phase. In the running-in phase the wear rate is initially high due to the removal of high asperities on the contact surface and this will affect the surface roughness. This is followed by the condition where the wear rate is declines gradually over time during permanent phase before it will finally fail.

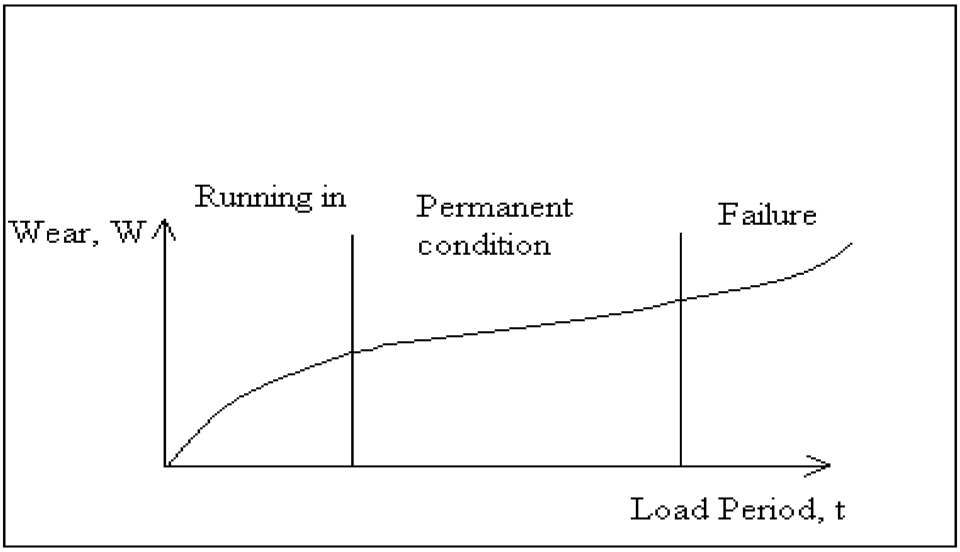


Figure 2.1: Wear magnitude is examined over the load period Dubbel (1994)

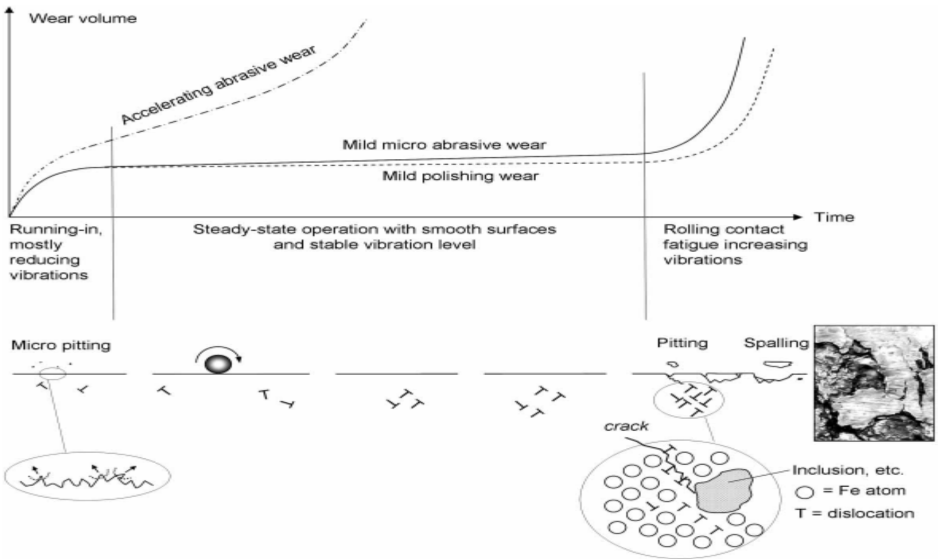


Figure 2.2: Rolling bearing wear during running-in stage, (Halme and Andersson, 2009)

Halme and Andersson, (2009) have described that under running-in conditions as shown in figure 2.2, "roll-polishing" takes place largely due to plastic deformation of surface asperities. The roll polishing effect slowly disappears as the surface roughness decreases and a transitional stage from mixed lubrication into EHD lubrication conditions happens for a period of time during the in running-in stage. Micro-abrasive and sliding fatigue wear in the micro-slip regions of rolling contacts are held accountable for certain surface alterations, for rolling contact wear, and for wear particle formation in the running-in of the rolling bearings. The plastic deformation due to abrasion and the micro cracking caused by fatigue are weak vibration sources. Abrasive wear and surface indentations are explained by particles in the oil in the running-in stage of the bearing. Abrasive wear caused by contaminant particles during the running-in stage of a bearing usually makes rough the rolling surfaces and produces more wear particles, crushing of particles, abrasion by particles, and "contact dynamics due to surface roughening" are all contributors as vibration sources in a rolling contact. Under running-in at stress levels leading to local rolling contact fatigue in asperity interaction zones, surface roughening by micro-pitting can occur eventually. The micropits' small depth give slight volume loss, but with a lot of very small wear debris. Micro-pitting increases the vibration level of the bearing, via contact dynamics, inevitably due to the roughening and the increasing contents of wear particles available in the contacts. The vibration during running-in phase is mostly low and micro-pitting will form during this stage. During 'steady state or permanent condition' the vibration level are considered stable and during 'rolling contact fatigue until failure' the vibration increased to the maximum. From the analysis by Dubbel (1994) and Halme and Andersson, (2009) the running-in is critical part of bearing operation for prediction of failure.

Kuhnell (2004) mentioned rolling element bearings failure due to the surface fatigue phenomenon. After running for a period of time the embryonic particles are liberated from the surface of the load zone and caused progressive of spalling process. There are three types of surface contact damage such as surface distress, fatigue pitting and fatigue spalling. Surface distress appeared as smooth surface in the form of plastic deformation in the asperity dimension typically less than 10 μm for thin surface layer. Pitting appeared as shallow craters in contact surfaces which is approximately 10 μm. Spalling will shown the deeper cavities on the surfaces with a depth of between 20 μm and 100 μm.

2.5 Surface Roughness

Surface roughness denotes an indication of wear and mechanism of wear when the bearing is running. Wear is related to the state of lubrication and also the period of time.

Xiao et al., (2004) stated that the surface roughness will affect the lubrication during normal condition and sliding motion in roller contact. The increase of relative speed does not affect the surface roughness throughout the tests.

Su et al. (1992) discovered that the vibration energy of bearing has a lot to do with surface irregularities. Due to the short interval of excitation, the vibrations induced by defects or manufacturing errors may contain significant wide band energy around the structural resonant frequencies. The magnitude of the contact energy is mainly influenced by the loadings associated with the misalignment or dynamic unbalance of the shaft, the axial loading, the radial loading, the preload and the manufacturing imperfections. The energy of the pulse is increased when the preload is large or the running speed is high. The early phase of fault detection of rolling bearings of a rotating machine is substantial with respect to system maintenance and process automation. The common failure modes of rolling bearings are scratched crack, improper lubrication and the inclusion of foreign material. The defective surface when in contact with its matching surface, produce a short pulse that may excite the bearing assembly's resonances. When the bearing is rotating at a constant speed the contact pulse will occurred periodically with a frequency which is a function of the bearing geometry, the rotational speed and the crack location.

Björklund (2001) studies the influence of surface roughness on contact behaviour. The surface roughness has a marked effect on how loads are transmitted at the contact interface between solid bodies and decreases the real contact area in a significant manner, as compared to the smooth case and calculate the influence of three-dimensional surface roughness in contacts. The results showed that the real contact area is sensitive to the amplitude of the roughness but less sensitive to waviness. Surface roughness causes high local pressures and decreases significantly the real contact area compared to the corresponding smooth cases. Apart from causing high contact stresses the surface roughness is crucial to the wear, friction and lubrication properties of the contact.

Olofsson and Björklund (1998) uses 3D surface parameter to analyse wear mechanism and correlated this with the roughness parameters (skewness, S_{sk} and kurtosis, $S_{ku)}$. Due to the bearing curved contact surface in a spherical roller trust bearing, the roller will undergo sliding in contact. In order to study how the wear depends on the number of revolutions, ten specimens were tested and 3-D surface roughness measurements were made. The results from these measurements showed that there are different wear mechanisms involved. Running-in are subjected to mild wear on the specimen surfaces caused by two-body abrasion and for long-term operation wear are clearly shown on surfaces resulted in failure. The skewness, S_{sk} and kurtosis, S_{ku} are changing during running-in period. The asperity peaks are worn and the skewness, S_{sk} becomes negative but when the surface becomes smoother the

S_{sk} increases to positive. When the asperities are worn away, the valley are affected and the skewness of the amplitude distribution shown larger values.

Wieczorowski et al (2010) established correlation between surface roughness parameters and friction under dry and lubricated sliding. Five samples of different processes were examined - electrochemical polishing, plateau honing, super finish, grinding and high speed milling. The samples were calculated and later on, evaluated using parameters R_a for arithmetic mean deviation of the assessed roughness profile, R_q root mean square (RMS) deviation of the assessed roughness profile, R_z maximum height of the roughness profile within a sampling length, R_t total height of the profile on the evaluation length, R_{sk} skewness (asymmetry) of the assessed profile and R_{sm} mean width of profile elements within a sampling length. Despite the measurement repeatability conditions in all measurement laboratories, the analysis revealed the high variability of the parameters that could be caused by mechanical factors such as slide way errors and geometry of stylus.

The samples of hardened 100Cr6 (AISI 52100) ball bearing steel when tested under dry and lubricated condition produces test result which shows that surfaces with higher S_{ku} and negative S_{sk} values are able to mitigate friction. The coefficient of friction is lower when roughness (R_a, R_q) is low. Surface roughness parameters S_{ku} and S_{sk} were found to show good correlation with the tribological properties of contact surfaces and could be used for planning surfaces and surface topographies with desired tribological behaviour in boundary lubrication regime. At boundary lubricated contact friction tends to get lower when the most dominant parameter is skewness, S_{sk}. With more negative skewness, lower friction is expected. (Sedlaĉek al.2012)

Experiments and analyses of the waviness and roughness effects in lubricated wear related to running-in condition showed the ability of a lubricated slider to form oil film due to the surface waviness. The characteristics of contact can be ascertained by the surface roughness. Running-in affected the surface roughness during contact but barely changes the surface wavelength. If the net load-carrying capacity of the fluid film pressures built up by the local wedges of surface waviness is greater than the applied load, an oil film will be created and the two lubricated surfaces segregated. If the net load-carrying capacity of the fluid film is lower than the applied load, there will be contact of surface asperities.(Wu and Zheng, 1991)

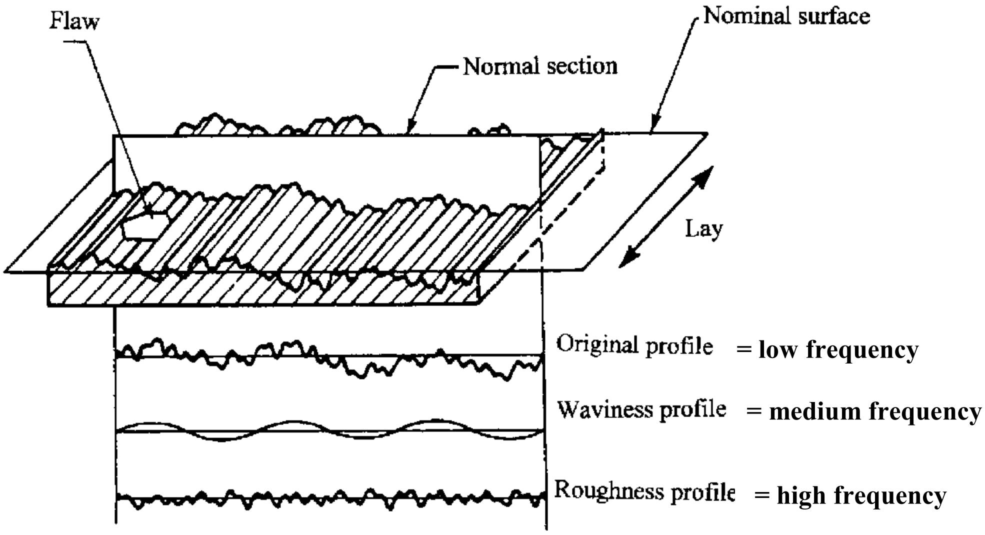
Suh (2003) investigated catastrophic failure of scuffing and produced wear associated with friction, noise, vibration and interface temperature in the sliding contact zone. The surface topography and roughness are significant factors that influence the wear and damage to surfaces.

2.6 Surface Measurements

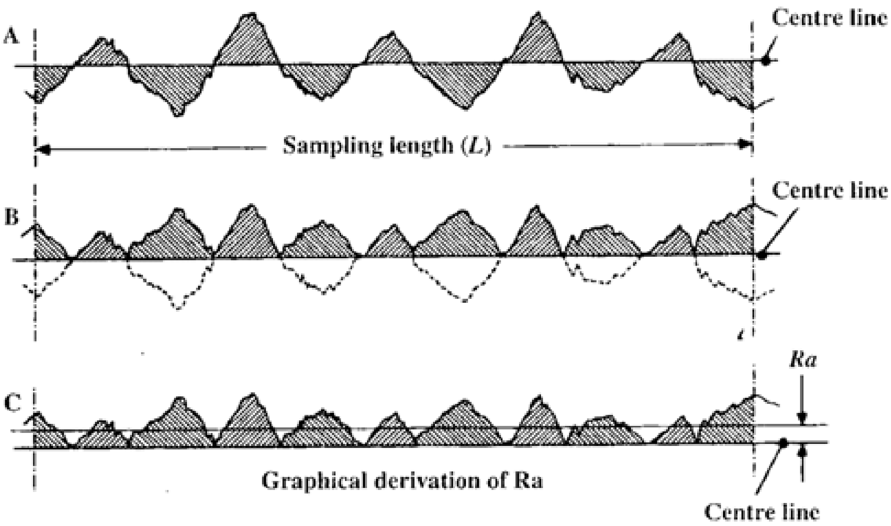
The focus-variation technique from (Infinite Focus Manual, 2007) Alicona (2007) is used for the optical 3D metrology of surface roughness. The system simultaneously captures the whole surface topographic information together with its true colour information. The quality measure is established for each measurement point. Each position in depth is differently imaged based on the specimen's 3D structure. For each position on the object, the degree of sharpness is calculated. The variation of sharpness is utilized for extracting depth information and ISO 25178 is used to classify the surface texture methods.

2.6.1 Surface Characterization

Based on the EN ISO 4287 and ASME B46.1 standards, the engineering surface profiles including primary, roughness and waviness are characterized based on spatial frequency measurement. By using the filters, these types of profile can be identified. Raja et al. (2002) mentioned in typical engineering surface consists of a range of spatial frequencies and the roughness is referred to high frequency or short wavelength. Meanwhile for medium frequency wavelength are identified as waviness and low frequency as form as shown in figure 2.3 (a). The roughness differs from form and waviness as shown in figure 2.3 (a).



(a)



(b)

Figure 2.3: (a): Waviness and roughness in engineering surface profile (ASME B46.1). (b): The Ra parameter processing (Smith, 2001)

2.6.2 Average Roughness

Figure 2.3 (b) shows the method to determine and obtain the average roughness ($R_{a)}$ value. The R_a is the area between the accumulated roughness profile and its mean line, or the integral of the roughness profile height absolute value over the evaluation length (Infinite Focus Manual, 2007).Average roughness, R_a is the arithmetical mean value of the absolute values for the profile or the area between the roughness profile and its mean line or the integral of the absolute value of the roughness profile height over the evaluation length and deviations established in the reference section.

Figure 2.4 highlights the skewness parameters over its evaluation length in a graphical manner. Negative skewness is a surface that indicates porous with deep valleys in a smoother plateau. Positive skewness such as curved surfaces has high spikes that protrude above a flatter average. Surfaces have a skew near zero have an average valley and spikes are random.

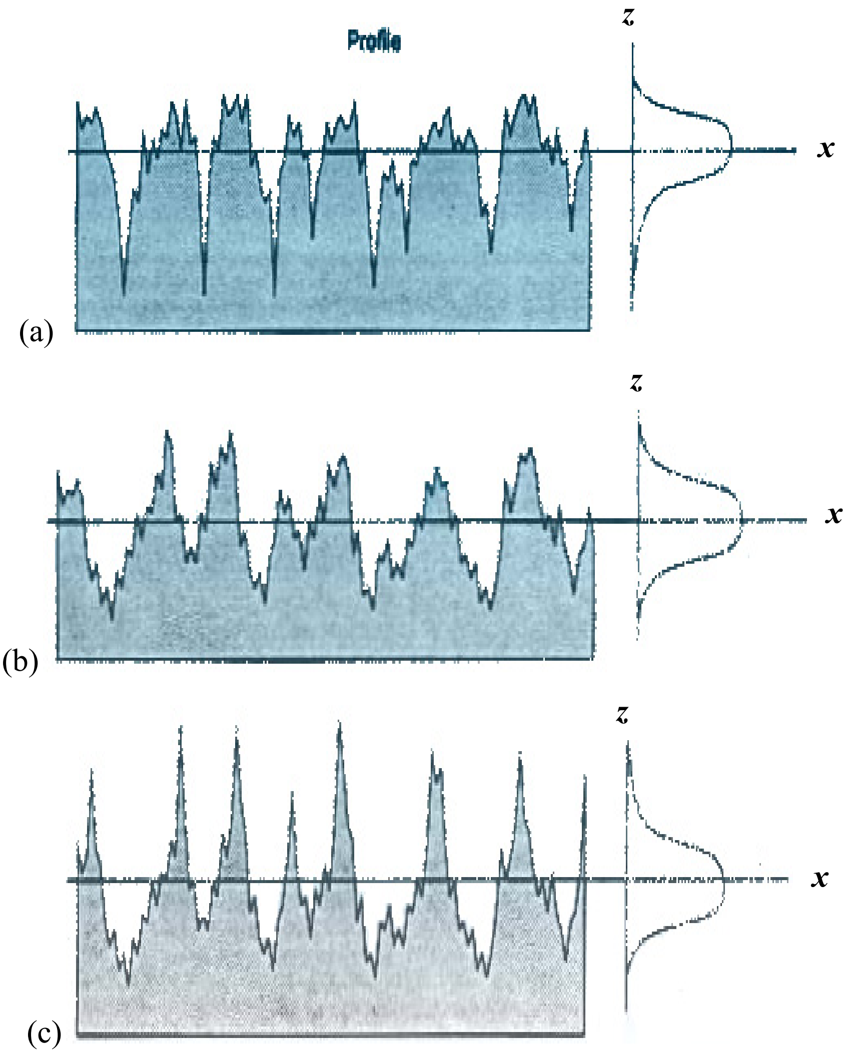


Figure 2.4: (a) 5 $R_{sk}< 0$ (negative), (b) $R_{sk} = 0$ and (c) $R_{sk}> 0$ (positive) (Infinite Focus Manual, 2007)

The Amplitude Distribution Function (ADF) as shown in figure 2.5 is a probability suggesting that a surface profile has a given certain height, Z at a position X. The ADF has a characteristic bell shape like normal probability distributions.

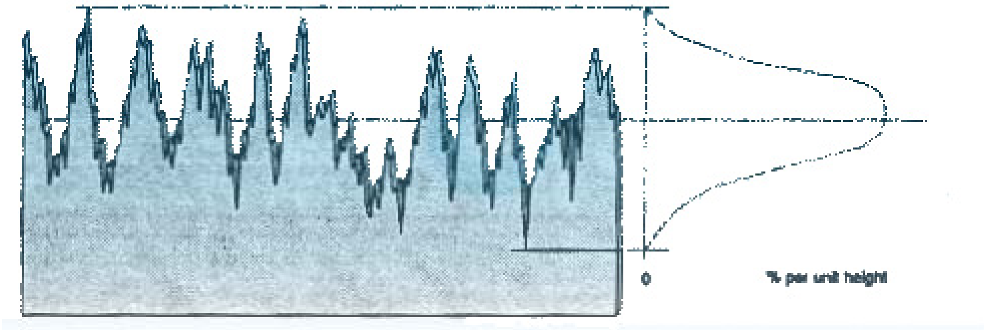


Figure 2.5: Amplitude Distribution Function (ADF) (Infinite Focus Manual, 2007)

Root-Mean-Square roughness of profile (R_q) is a statistical parameter that measures the width of the ADF. The higher value of R_q, the surface becomes rougher. It represents the standard deviation of the profile heights and is used in the computations of both the skew and kurtosis.

Figure 2.4 (a), (b) and (c) shown the skewness of roughness profile (R_{sk}) is another parameter describing the shape of the ADF. Surfaces with positive skewness and pitting will show the $R_{sk>}0$, such as turned surfaces have fairly high spikes that protrude above a falter average surfaces with negative skewness, like porous surfaces that have fairly deep valleys in a softer plateau. R_{sk} illustrates the load carrying capacity, porosity and characteristics of novel, fresher machining processes. Negative skew is a criterion for good bearing surfaces.

Kurtosis of roughness profile (R_{ku}) is linked with the ADF uniformity or equal to the spikeness of the surface profile. Kurtosis describes the machined surfaces and it is also seldom used for optical surfaces. It is sometimes specified for of its ability to control the stress fracture.

Gadelmawla et al. (2002) describe that the profiles with peaks removed or deep scratch have negative skewness, and the profiles with valleys filled in high peaks have positive skewness. R_{ku} Kurtosis coefficient is the fourth central moment of the profile amplitude probability density function measured over the assessment length and it describes the sharpness of the probability density of the profile. If R_{ku}<3 the distribution curve is said to be platykurtoic and has relatively few high peaks and low valleys. R_{ku}> 3 and the distribution curve is said to be leptokurtoic which is has relatively many high peaks and low valleys. The software used was Surf Vision.

$R_a$is defined as the average absolute deviation of the roughness irregularities from the mean line over one sampling length. This parameter is easily definable, provides easy method of measurement and gives a good overall description of height variations. Notwithstanding, it does not give any information about the wavelength and it is also insensitive to small changes in the profile.

R_q is RMS roughness, and it represents the standard deviation of the surface height distribution. Therefore, it is an important parameter for detailing the surface roughness by statistical methods. This parameter is more susceptible to compare the mean line of the arithmetic average roughness R_a.

R_z is defined by the ISO system as the difference in height between the average of the five height peaks and the five lowest valleys along the profile's