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Intitulé

Maintenance Based on Simulation of Static Structural Analysis for Bearings Behaviour

Domaine : Sciences et Technologie

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About the Algerian National Laboratory in Maintenance Education

For Algerian economy, Africa's fourth economy, to be able to compete successfully both at national and international levels, production systems and equipment must perform at much better levels. Requirements for increased product quality, reduced throughput time and enhanced operating effectiveness within a rapidly changing customer demand environment continue to demand a high maintenance performance. Unfortunately, few companies in Algeria address the significant synergies of knowledge and skills in maintenance and maintenance operations. Currently, there are no any maintenance programmes at academic level while training in maintenance is isolated being performed solely in few large companies.

Today, the universities are further stressed by huge classes, overstressed infrastructures, inadequate and unskilled supervisors, insufficient and old equipment, and a lack of up-to-date educational and scientific materials. Vocational education suffers from problems with the language of instruction, poor teaching, haphazard job placement (lack of systematization), lack of industrial linkages, and lack of flexibility. These problems produce graduates with inadequate skills in unwanted areas and the inability to adapt. Investing in education and training in maintenance engineering and management at all professional levels, engineers, managers and technical personnel in various industries, will boost the Algerian economic competitiveness and will create thousands of new jobs in universities, training centres, and for engineers, managers and technicians in all economic sectors. Youth, men and women, will find a rewarded carrier path and professional satisfaction in Algerian economic sector.

The Algerian National Laboratory in Maintenance Education, ANL-MEd, has the mission to create the next generation educated workforce in industry. There are two major driving forces for the ANL-MEd project proposal: i) Matching the educational and training programmes at universities to the needs of industry and generally of the Algerian economy, for creation of new jobs. ii) Creation of a strong coalition between university - industry - governmental organizations for long-term collaboration in education, training and research, for revitalization of Algerian economy and in particular of Algerian industry.

ANL-MEd assembles for 36 months a consortium with 14 partners with unique combination of skills and expertise. The consortium, coordinated by USTHB, has a hierarchical structure that ensures an efficient communication and cooperation. Four European universities with solid competence in maintenance engineering and management will contribute to development of teaching material and training students, teacher, trainers and industry staff. The four Algerian universities will collaborate with EU partners and the Algerian industrial partners to develop and implement the specialization and training programmes, and to create the ANL-ORG, the national laboratory which will coordinates all activities related to maintenance education. The key factor for implementation of the project objectives is the active collaboration between academic and industrial partners. Therefore, important resources have been allocated for creating a harmonious working environment – ANL-ORG – with activities for creating synergies between project partners and stakeholders. This will contribute to strengthening the active cooperation between university and industry, as well between Algeria and EU. The project activities are distributed in 7 work packages according to a detailed work plan that adequately structures the efforts into manageable work packages with clear responsibilities and objectives. For improved effectiveness in the project for organization of implementation, the partners are grouped in three clusters: ANL-EDUC – cluster for education, ANL-VET – cluster for vocational education and training and ANL-ORG for organization of the ANL, coordinating the resources for integration, communication and exploitation.

Avec tout respect et amour je dédie ce modeste travail

À mes chers parents,

À mon mes sœurs Yasmine et Meriem,

À mon défunt Professeur Madame Boubsil Wassila puisse dieu l'accueillir dans son paradis et dans son infinie miséricorde,

À tous mes amis en Souvenir des plus beaux instants qu'on a passés ensemble Aussi bien à tous ceux qui m'ont aidé Merci

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I would first like to thank my thesis advisor Professor Viorel PAUNOIU, head of Department of Manufacturing Engineering from Faculty of Engineering, "Dunarea de Jos" University of Galati, ROMANIA. The door to Professor Viorel PAUNOIU office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it as well as to all members of the ERASMUS + ANL MED project for these last 5 months in ROMANIA.

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Finally, I must express my very profound gratitude to my parents and my sisters Yasmine and Meriem BELABEND, and to my partner and colleagues for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis and a special thanks to my college and best friend Youcef. This accomplishment would not have been possible without them. Thank you.

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Abstract

Ball and roller bearings, commonly known as bearings, are commonly used machine elements. The first chapter describes the types of bearing their classification and mode the choice of bearings as well as their maintenance; the second chapter describes the defects present in the bearing. The bearing failure can occur for various reasons, their possible causes as well as the modes of inspection of their defects according to the standards and using the Non-Destructive Control. Accurate determination of the cause of a bearing failure is essential to formulate appropriate recommendations for its elimination. Simple and widely applied.

The third chapter, which is the heart of this dissertation, presents the simulation of ball bearings using 3D simulation software: SOLIDWORKS ANSYS and MESYS calculation software. The analysis of finite elements by contact, stress, deformation, penetration, sliding distance, etc.. ANSYS gives a good impression for the analysis of contacts, which, using ANSYS and MESYS, based on the drawing of the model under SOLIDWORKS. Based on the state of nonlinear contact has been researched and analysed and those following different configuration to see what gives optimal results.

For the maintenance part: given in the last and fourth chapter

Total Productive Maintenance (TPM) is an innovative Japanese concept. Total Productive Maintenance (TPM) concepts have been accepted by many organizations around the world. This part aims at giving the first evaluation for the implementation of a policy of total productive maintenance in the TPM rolling bearing industry

Keywords : Bearing , Inspection , Modelling , Simulation ; ANSYS , SOLIDWORKS , FEM , Bearing Behaviours , Static Load , Hertzian Contact .

Résumé

Les roulements à billes et à rouleaux, généralement appelés roulements, sont des éléments de machine couramment utilisés. Le premier chapitre décrit les types de roulement leurs classification et mode le choix des roulements ainsi que leur maintenance ; le second chapitre décrit les défauts présent dans les roulements, La défaillance du roulement peut survenir pour diverses raisons .Leur causes possible ainsi que les modes d'inspection de leurs défauts suivant les standard et en utilisant les Contrôle Non-Destructive. La détermination précise de la cause d'une défaillance d'un roulement est indispensable pour formuler les recommandations appropriées en vue de son élimination. Simple et largement appliquée.

Le troisième chapitre qui est le cœur de cette dissertation présente la simulation des roulements à bille en utilisant les logiciels de simulation 3D : SOLIDWORKS ANSYS et logiciel de calcul MESYS. L'analyse des éléments finis par le contact, les contraintes, la déformation, la pénétration, la distance de glissement, etc. ANSYS donne une bonne impression pour l'analyse des contacts, qui, utilisant ANSYS, basé sur le dessin du modèle sous SOLIDWORKS. Basé sur l'état de contact non linéaire a été recherché et analysé et ceux suivant différente configuration à fin de voir la quel donne des résultats optimaux.

Pour la partie maintenance : donné dans le dernier et quatrième chapitre

La maintenance productive totale (TPM) est un concept japonais novateur, Les concepts de maintenance productive totale (TPM) ont été acceptés par de nombreuses organisations à travers le monde .Cette partie vise à donner la première évaluation pour l'implémentation d'une politique de Totale maintenance productive dans l'industrie du roulement du TPM dans le roulement

Mots clés : Simulation, Modélisation, Méthode Des Eléments Finis, Roulement à billes, ANSYS, MESYS, Pression de Hertz.

ملــــخص

تستخدم مدحرجات الكريات والأسطوانة ، والمعروفة باسم المحامل ، في عناصر الماكينة. يصف الفصل الأول أنواع تحمل التصنيف ووضع اختيار المحامل وكذلك صيانتها ؛ يصف الفصل الثاني العيوب الموجودة في المحامل ، يمكن أن يحدث عطل محمل لأسباب مختلفة .أسبابها المحتملة وكذلك طرق فحص عيوبها وفقًا للمعايير وباستخدام التحكم غير المدمر. تحديد دقيق لسبب فشل تحمل أمر ضروري لصياغة توصيات مناسبة و بسيطة وتطبيقها على نطاق واسع للقضاء عليه.

يقدم الفصل الثالث الذي يمثل جوهر هذه الرسالة محاكاة الكرات باستخدام برنامج محاكاة ثلاثي الأبعاد: برنامج حساب ANSYS SOLIDWORKS و MESYS. تحليل العناصر المحددة عن طريق الاتصال ، والإجهاد ، والتشوه ، والاختراق ، ومسافة الانزلاق ، إلخ. يعطي ANSYS انطباعًا جيدًا لتحليل جهات الاتصال ، باستخدام ANSYS (طريقة العناصر المحددة) ، استنادًا إلى رسم النموذج تحت SOLIDWORKS. بناءً على حالة الاتصال غير الخطي تم بحثه وتحليله وتلك التي تتبع التكوينات المختلفة لمعرفة النتائج المثلى.

لجزء الصيانة: الواردة في الفصل الأخير والرابع

TPM هو مفهوم ياباني مبتكر ، وقد تم قبول مفاهيم الصيانة الإنتاجية الشاملة (TPM) من قبل العديد من المؤسسات في جميع أنحاء العالم. يهدف هذا الجزء إلى إعطاء التقييم الأول لتنفيذ سياسة الصيانة التكميلية المنتجة في العالم. TPM المتداول صناعة الحاملة

الكلمات المفتاحية: المحاكاة، النمذجة ، طريقة العناصر المحددة ، كروي ، ANSYS، MESYS، ضغط هيرتز.

Nomenclature

A

a :crack semi-width 53

a_{mean} : mean crack semi-width 53

B

b : semi-minor axis of elliptical contact patch 53

B : nominal width of the inner ring · 46

B_s : single width of the inner ring · 46

C

C : nominal width of the outer ring · 46

C_r: Basic dynamic load rating · 30

C_{r0} : basic static load rating, kN · 52

C_s ingle width of the outer ring · 46

D

d : diameter of ball

d : nominal bore diameter or shaft washer nominal bore diameter for thrust bearings · 45

D : Nominal Outside Diameter Or Housing Washer Nominal Diameter · 45

d_{1} : Nominal Diameter At The Theoretical Large End Of The Tapered Bore · 53

D_1: nominal outside diameter of the outer ring rib · 46

d_{2} : nominal bore diameter of the shaft washer for double directions thrust bearings · 45

d_{psmax} : maximum bore diameter, in a single radial plane · 45

d_s : deviation of single bore diameter · 45

Ds : single outside diameter maximum · 46

E

E: Young's modulus 53

F

F: Force · 61

F_a : axial component of the heaviest static load, kN · 52

FEM: Finite Element method · 48

F_r : radial component of the heaviest static load, kN, · 52

L

L_h: Rated service life · 30

.

P

p_{o} : max elliptical contact pressure

P : Dynamic equivalent load rating · 30

P_0 : equivalent bearing static load, KN · 52

P_{r0} : equivalent static load, KN · 52

R

List of Abbreviations:

ASTM :	American Society for testing and materials
CAD :	Computer Aided Design
NDT:	Non Destructive Testing
OEE :	Overall Equipment Efficiency
REB :	Rolling Element Bearing
TPM :	Total Productive Maintenance
URB :	Ultra Reliable Bearings

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Introduction

Rolling bearings allow for the transfer of forces between the moving and fixed parts of the mechanical system, and are designed to minimize friction arising from power and energy transfer. Due to their multiple use, increasing emphasis is placed on their development and improvement, because, in many cases the bearings do not provide the required durability according to the calculation values. There may be more then a reason, for example, overload, load lower than required, inadequate lubrication, ineffective sealing, inadequate over fitting, or impact load on the bearing that leads to permanent deformation in the form of imprints in the bearing ring path . This very latest case of damage is becoming more and more frequent, that's why it is necessary to look after the problem in order to examine the given load conditions, using FEM method and to obtain optimal results for further research, and apply modifications in bearings in order to decrease the impact damage with the intention of eliminating it. Researchers continue with the intensive development and research in field of bearings with purpose to investigate new theory of bearing aspects, solving significant parameters and values of rolling bearings in order to ensure maximum quality and accurate prediction.

And because every employee at levels in the organization is concerned about the maintenance, the quality and efficiency of their equipment, the concepts of Total Productive Maintenance (TPM) have been accepted in many organizations across the world. The main aim of TPM implementation is to reduce the six big losses that are equipment failures or breakdown losses, setup and adjustment losses.

General Presentation of the University "Dunarea de Jos" of Galati

My internship took place in Romania, in a laboratory of the Department of Manufacturing Engineering, Faculty of Engineering, Dunarea de Jos University of Galati. During my internship I visited the society URB Group - Rulmenti S.A. from Barlad.

"Dunarea de Jos" University of Galati functions according to the university charter, whose provisions are in agreement with the national legislation and with the principles of the European Space and Higher Education, being recognised by all members of the university community.


Fig 1 *University "Dunarea de Jos" of Galati*

The history of higher education in Galati covers the following stages:

- 1948: establishment of the Land Improvement Institute;
- 1951: establishment of the Naval-Mechanical Institute;
- 1953: merging the Naval-Mechanical Institute with the Agronomic Institute, and with the Fish Farming and Fishing Institute (transferred from other university centres), and the establishment of the Technical Institute in Galati;
- 1955: merging of the Technical Institute with the Food Industry Institute in Bucharest;
- 1957: transforming the Technical Institute into the Polytechnic Institute;
- 1959: establishment of the Pedagogic Institute and relocation of the Land Improvement Institute to Iaşi;
- 1974: establishment of the University of Galati by merging the Polytechnic Institute with the Pedagogic Institute (State Council Decree of 20 March 1974);
- 1991: the University of Galati becomes "Dunarea de Jos" University of Galati (Government Decision of 4 January 1991).

In the structure of the above mentioned institutes, there were a series of study programmes that were unique in the country: Naval Constructions, Harbours and Ship Exploitation, Food Industry, Fish Farming Technology, Cooling Devices – which meant that an important creation process on elaborating educational curricula and syllabi, lectures, laboratory equipment etc., presently being used in other university centres around the country, was fully the work of the academics in Galati higher education.

The academic community of “Dunarea de Jos” University of Galati is composed of the following:

- 12.500 students
- 1000 teaching staff
- 14 faculties
- 67 Bachelor Study Programmes
- 52 Master study Programmes
- 3 Doctoral Schools
- 13 Doctoral Study Programmes
- 230 doctoral students
- More than 2500 international students

“Dunarea de Jos” University of Galati has concluded more than 100 partnership agreements with universities from 34 countries.

Faculty of Engineering

The Faculty of Engineering is a strong branch of “Dunarea de Jos” University of Galati through its academic offer, the quality of the teaching staff and modern teaching and research spaces.
Studies are focused towards national and international subjects, increase contentment of the students and employees, promoting values during the development process of the human resources, multidisciplinary cooperation in all segments of teaching and scientific research activities.

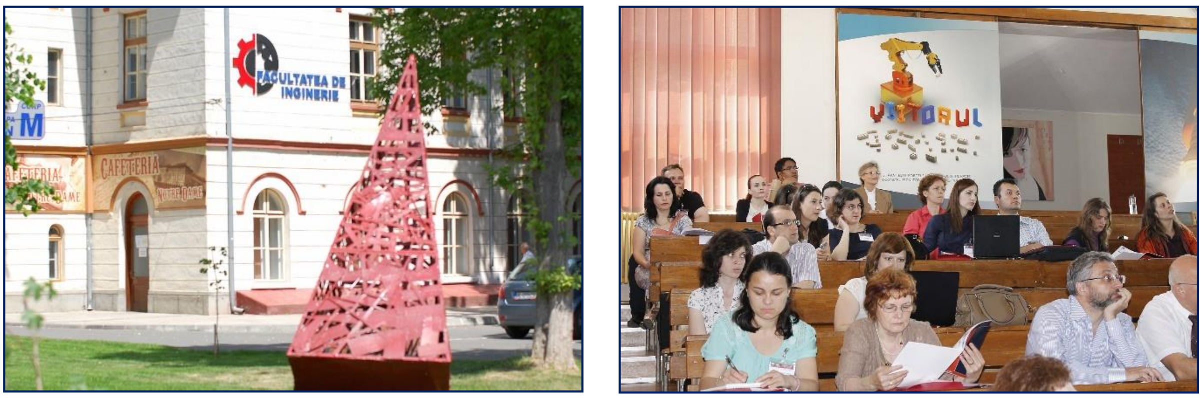


Fig 2 The Faculty of Engineering

Motivation and objectives of the work

The motivation to do this work comes from the large importance of bearings, as they are widely used in rotating machinery to support rotating shafts. The major cause of machinery breakdowns is bearing failure, and that last comes from the repeated high stressing on the contacts between the rolling element and the raceway eventually causes fatigue damage. In addition to this, the main reason for bearing failures is an improper handling-and-mounting procedure, corrosion, wear and manufacturing defects.

However, and based on the motivation above, the main objectives of the dissertation thesis are the following:

- Describes the types of bearing, their classification, the choice of bearings as well as their maintenance;
- Analyse the possible causes of bearing failures, the modes of inspection using destructive and Non-Destructive Control (according to the standards).
- Analyse the rolling ball bearing using the finite element stress or displacement behaviour and the pressure contact of rolling ball bearing.
- Analyse of the pressure contact of rolling ball bearing using the methodology of Hertz theory and equations based on specific ball bearing parameter and with the result of MESYS software.
- Make a comparison between the three results obtained from the analyse of pressure contact:
  - FEM analysis;
  - The methodology of Hertz theory;
  - MESYS software calculus.
- Analysing the ball bearing behaviours with different configuration of bounding condition and meshing in order to see the dependence of the number of elements and nodes;
- Evaluate the bearing industry in order to implement the Total Productive Maintenance like a first initiation step.
- Establish a plan of action for the implementation of the 5S in the bearing industry based on the evaluation and results obtained.

Chapter I

Bearing's state of the art and their maintenance

1.1.Introduction

Ball and roller bearings, generically called rolling bearings, are commonly used machine elements. They are employed to permit rotary motion of, or about, shafts in simple commercial devices such as bicycles, roller skates, and electric motors. They are also used in complex engineering mechanisms such as aircraft gas turbines, rolling mills, dental drills, gyroscopes, and power transmissions. [2]

1.2.History of bearings

For centuries, man had to rely on his own power to push or pull large objects over the earth.

The concept of a bearing – to lessen friction between an object and the surface over which it is moved – is nearly as old as man himself.

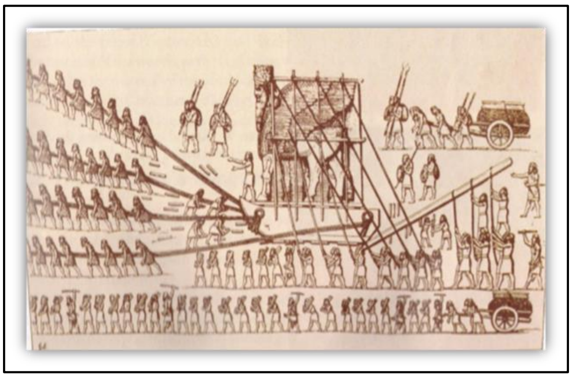


Fig.1.1 History of bearing [3]

The first solution to relieving some of this sliding friction was recorded as early as 3,500 B.C. It was then that Mesopotamians were using one of the first bearings known to man, an invention called the wheel. Where the wheel and axle touched, they put a bearing made of leather or wood and lubricated it with animal fat.

Ancient drawings from 1,100 B.C. show the Assyrians and Babylonians moving huge rocks for their monuments and palaces with rollers, illustrating the basic bearing principle – to lessen friction. But this was sliding – not rolling – friction.

The roller and ball bearings of today may bear little resemblance to their predecessors but the concept has remained the same: to lessen friction. Today, bearings are used in almost every imaginable application, such as roller skates and bicycles, where two surfaces are turning or moving against each other. They are used in thousands of ways, from the minute internal workings of a clock to large turbine engines in a ship [4].

1.3.Definition

Rolling bearing is the key component of rotating machinery, whose running state has an important effect on the healthy condition of rotating machinery equipment [5].

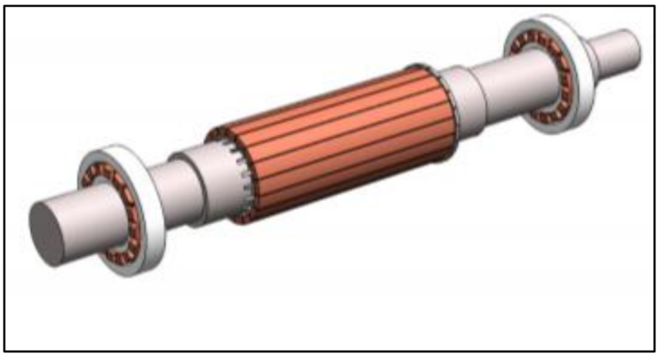


Fig.1.2 Rotating system with bearings [4].

A bearing is a support or guide that locates one machine component with respect to others in such a way that prescribed relative motion can occur while the forces associated with machine operation are transmitted smoothly and efficiently [5].

A wide range of bearings has been developed; some involve rolling motion, sliding motion, and both rolling and sliding motions. Lubrication of a bearing is frequently used to reduce friction and, therefore, the wear and power absorbed by the bearing, as well as to remove heat. This ensures the operation of the bearing assembly at temperatures compatible with the materials and lubricant used [6].

Bearings can be classified in several ways: according to the basic mode of operation (rubbing, hydrodynamic, hydrostatic, or rolling element), according to the direction and nature of the applied load (thrust or journal), or according to geometric form (tapered land, stepped parallel surface, or tilting pad). There is much to be said for classification according to the basic mode of operation, with subdivisions to account for different geometric forms and loading conditions [5].

Rolling element bearings are widely used in rotating machinery to support rotating shafts, and the major cause of machinery breakdowns is bearing failure. Hence, it is necessary to detect bearing faults at an early stage. Rolling element bearings usually consist of an inner race, an outer race, several rollers and a cage. When the surface of one of these components develops a localised fault, the impacts generated excite the resonant frequencies of the bearing and adjacent components, and induce a modulating phenomenon.

1.4.The parts of bearings

The parts of a bearing a bearing’s smooth performance is assured by a combination of basic working part **Fig.1.3** :

• The inner ring, or cone, is mounted onto the shaft.

• The outer ring, or cup, sits in the housing (hub).

• The tapered rollers, or rolling elements, allow relative motion between the cone and cup thus minimizing friction between the two.

• The cage, or separator, spaces and holds the rolling elements in the proper position.

• The races are the surfaces on the cup and cone where the rolling elements make contact [7].

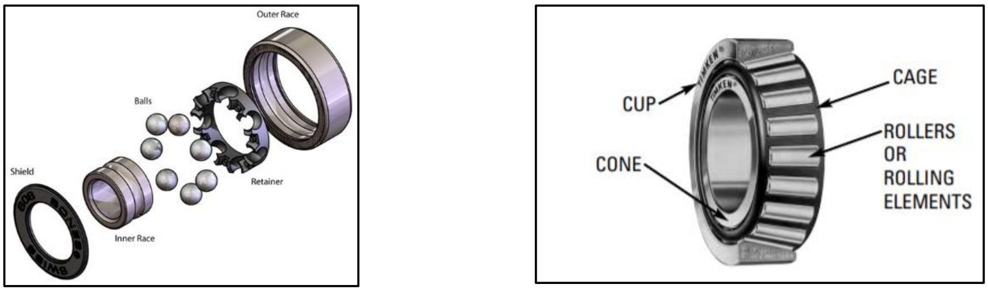


Fig.1.3 The parts of bearings [8]

The outer race, or cup, is the bearing’s exterior ring. Since it protects the bearing’s internal parts, it must be machined smoothly and accurately. The inner race, or cone, is the part of the bearing that sits directly on the shaft.

The rolling elements, shaped as balls or rollers, provide the cushion that eases the moving friction of the shaft within its housing. These elements keep the outer and inner races separated and enable them to move smoothly and freely. The shape of the rolling elements depends on the type of load, operating conditions and particular applications.

The rolling elements distinguish the two basic bearing categories

– Ball bearings and roller bearings.

There is a groove called the ball path on both the inner and outer races of ball bearings in which

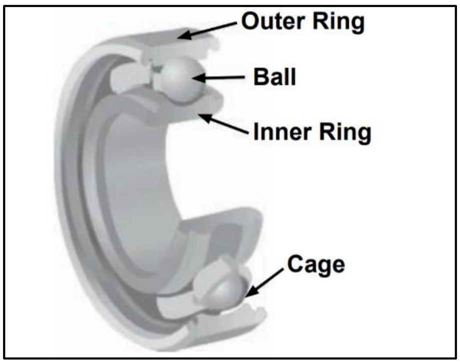


Fig.1.4 the parts of ball bearings [9]

The balls roll. For roller bearings, the rollers roll on the flat surface of each race. This surface is called the roller path.

Finally, the separator is a metal retainer that holds the balls or rollers. Positioned between the inner and outer races, the separator keeps the rolling elements evenly spaced [4].

Rolling bearings fall into two main classifications: ball bearings and roller bearings. Balls geometrically contact the raceway surfaces of the inner and outer rings at "points," while the contact surface of rollers is a "line" contact. Rollers come in four basic geometric styles: cylindrical, needle, tapered and spherical.

Rolling bearings can further be classified according to the direction in which the load is applied: radial, thrust, or a combination of both. While the rolling elements and the bearing rings take any load applied to the bearings (at the contact point between the rolling elements and raceway surfaces), the retainer takes no direct load. It only serves to hold the rolling elements at equal distances from each other, forcing the rolling elements to enter the load zones and prevent them from falling out [9].

1.5.Classification of bearings

Bearings can also be classified according to their geometry related to the relative motion of elements in machinery. Examples are journal, plane-slider, and spherical bearings. A journal bearing, also referred to as a sleeve bearing, is widely used in machinery for rotating shafts. It consists of a bushing (sleeve) supported by a housing, which can be part of the frame of a machine. The shaft (journal) rotates inside the bore of the sleeve. There is a small clearance between the inner diameter of the sleeve and the journal, to allow for free rotation.

In contrast, a plane-slider bearing is used mostly for linear motion, such as the slides in machine tools. A bearing can also be classified as a radial bearing or a thrust bearing, depending on whether the bearing load is in the radial or axial direction, respectively, of the shaft [10].

1.5.1. Ball bearing

The most popular type of ball bearing has a single row of balls.

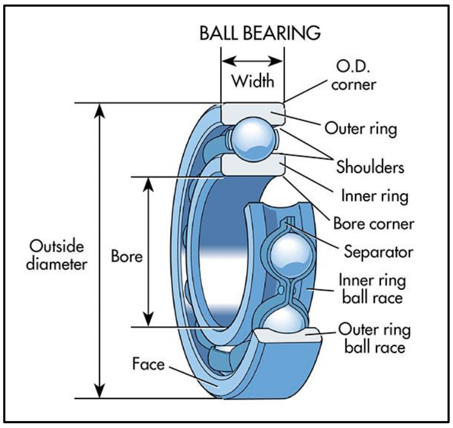


Fig.1.5 Ball bearing [11]

Ball bearing use balls that roll on conformal raceways on the inner and outer rings (races) outer and inner surfaces respectively. By having the raceway closely conform to the ball, rather than rolling on a pure cylinder, orders of magnitude greater load capacities are obtained.
So common has this basic design become, that the term ball bearing has come to mean not just a spherical metal ball used in bearings, but a bearing itself that uses balls. There are many

different types of ball bearings, but in general, when the term ball bearing is used, it is usually referred to a deep-groove radial bearing, which is sometimes called a Conrad bearing after Robert Conrad who invented its means of manufacture. Ball bearings are extremely common because they can handle both radial and thrust loads. In these bearings a ball provides rolling function. They are low friction high speed bearings meant for light to medium loading.
Ball bearings generally are used for lower cost, lower load, or higher precision applications. They are normally being used in light and general machine applications. They are commonly found in fans, roller blades, wheel bearings, and under hood applications on cars etc [12].

In addition to the single row design, there also are double row, angular contact and ball thrust bearings.

1.5.2. Angular-Contact Ball Bearings

Angular-contact ball bearings can be regarded as a variation of deep-groove ball bearings. Unlike deep groove bearings, an angular-contact bearing has at least one race ring that has only one side shoulder. Angular-contact ball bearings are capable of carrying an appreciable thrust load in one direction with or without a radial load. Because an angular-contact bearing must have a thrust load acting on it, no endplay (lateral movement) exists within the bearing. The line that

connects the nominal contact between the inner raceway and a ball and the contact between the outer raceway and the ball lies at an angle with the radial plane of the bearing. This angle is called the contact angle. It ranges from 15 to 40° for commercially available angular-contact ball bearings. Angular-contact ball bearings are commonly used in pairs to accommodate heavier radial loads, two directional thrust loads, or various combinations of radial and thrust loads. Tandem mounting is used for heavy unidirectional thrust loads and duplex mounting of either face-to-face or back-to-back is used for two-directional thrust loads. [15].

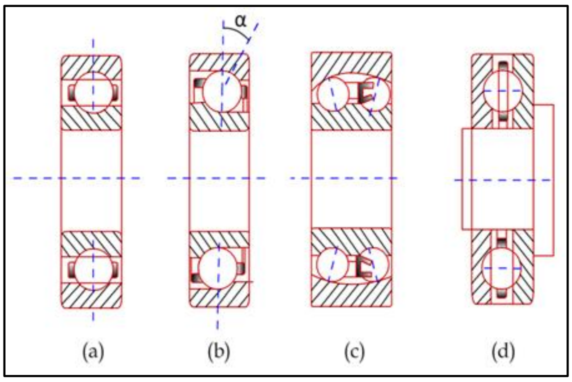


Fig.1.6 Bearing contact angle [14]

1.5.3. Roller bearing

In cylindrical roller bearings, the rollers are axially guided between integral flanges on at least one of the bearing rings. The most popular type is the single-row design, which offers various flange arrangements. **Fig.1.7** shows a typical single-row cylindrical bearing with two flanges on the outer ring. Cylindrical roller bearings have exceptionally high radial load-carrying capacity. They are also capable of carrying a small amount of thrust load when two flanges are positioned on opposing rings at opposite sides. In theory, true rolling motion exists in cylindrical bearings under radial load. Therefore, cylindrical bearings have lower starting torque and lower operating temperature than other roller bearings. This makes them suitable for high-speed applications. To achieve greater load capacity without increasing the tendency of roller skewing

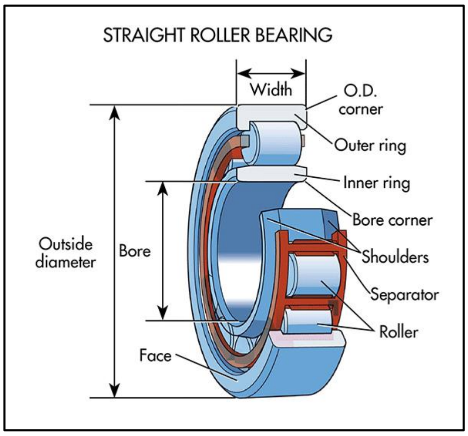


Fig.1.7 Straight roller bearing [11]

on the raceways, cylindrical bearings are frequently constructed in two or more rows rather than with one row of longer rollers [15].

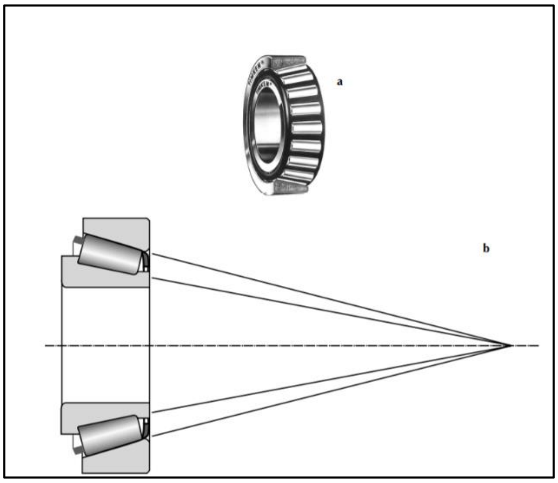


Fig.1.8 Roller bearings [11]

One variation of roller bearings – the tapered roller – is used extensively for fleet, automotive and other vehicular applications. Its construction differs significantly from ball bearings and other types of roller bearings. The rolling elements and both races slant inward, much like a cone. If you extend a line along the surface of the races and rollers, and also draw one through the bearing's axis, those lines would all meet at a common point .Those same lines along the surfaces of ball or cylindrical roller bearings are parallel. The advantage of this design is that the tapered rollers have a positive alignment with the shaft. That is, each roller will align itself perfectly on the tapered faces of the cup (outer race) and cone (inner race).

A bearing is a device used to support and guide a rotating, oscillating, or sliding shaft, pivot or wheel. Whenever a shaft rotates, it needs a bearing for smooth, effective operation. A bearing is designed to:

- **Reduce friction.**
- **Support a load.**
- **Guide moving parts.**

– Wheel, shafts, pivots Reduce friction Whether they are used in fleet, automotive or industrial applications, bearings perform the same function and have the same objective.

– To keep the shaft moving smoothly and consistently while reducing friction.

A bearing's rolling internal mechanism greatly reduces the effort and energy it takes to slide or move an object over the surface. This is why the invention of the bearing is so important.

1.5.4. Support a load:

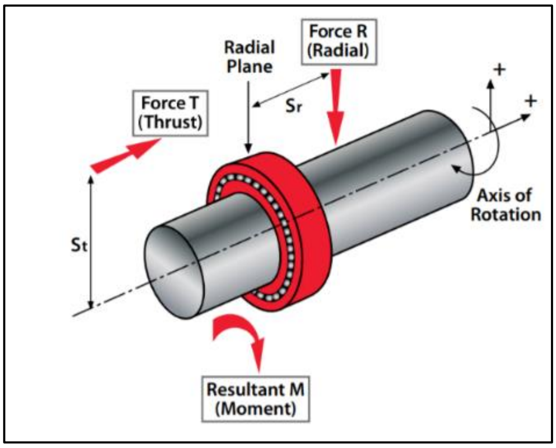


Fig.1.9 Bearings Load *[3]*

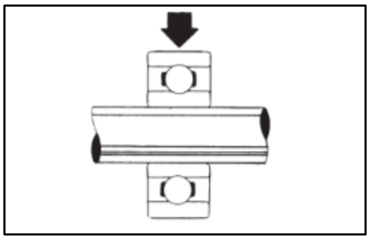


Fig.1.10 Radial load [4]

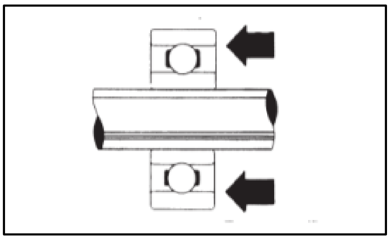


Fig.1.11 Thrust load [4]

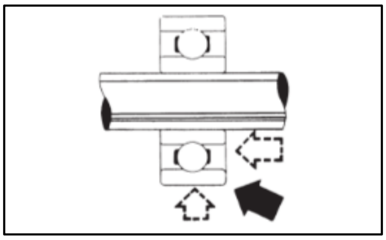


Fig.1.12 Angular load [4]

1.5.5. Radial loads

Bearings designed primarily for transferring radial loads are called radial bearings **Fig.1.10**. They have a nominal contact angle of $\alpha \leq 45$ °. Line contact bearings are more suitable for higher radial loads than single-point contact bearings, and bearings with a full number of rolling bodies have a higher load capacity than corresponding bearings with a cage.

Ball bearings are designed for small and medium large loads. Different type radial bearings can transfer both radial as well as axial loads.

Bearings designed mainly for axial loads (thrust ball bearings) have a contact angle α>45°.

Combined loads are composed of simultaneously acting radial and axial loads.

Axial load capacity of a bearing depends on the angle of contact. The larger the angle, the larger the axial load bearing capacity of the bearing. Larger axial clearance in single row ball bearings increases their load bearing capacity. Single and double row angular contact ball bearings or tapered roller bearings are best for capturing combined loads. **Fig.1.12**

Combined loads can also be borne by double row spherical roller bearings, thrust ball angular-contact bearings, and to a limited extent, also spherical roller thrust bearings. Self-aligning ball bearings [16].

The word “radial” means in the direction of a radius: moving from the circumference inward, or the centre outward.

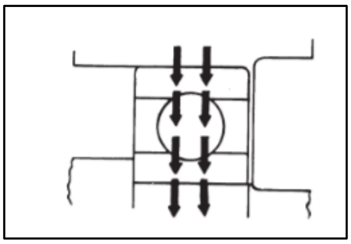


Fig.1.13 Radial load [4]

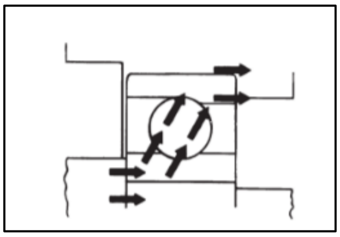


Fig.1.14 Thrust load [4]

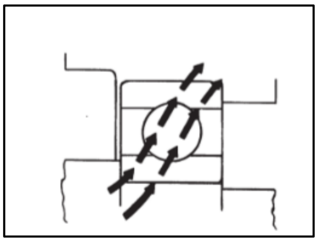


Fig.1.15 Angular load [4]

In this case it moves from the outside in. A radial load pushes down, from the outer race inward to the balls, cage and inner race at the centre of the bearing.

The load is at right angles (90º) to the shaft on which it is being supported.

Thrust” means a pressure or pushing force exerted by one part against a touching part. Pressure is exerted sideways, pushing the shaft either right or left. This shaft movement then pushes the inner race of the bearing in the same sideways direction. The line of pressure, that is, the load, runs parallel to the shaft **Fig.1.11**.

An “angular” load is actually a combination of radial and thrust loads. As the load moves at an angle toward the shaft, it pushes against the corner of the inner race.

Pressure is transmitted diagonally, through the corner of the race, cage and rolling elements, to the opposite corner of the outer race

The third function, to guide moving parts, is a result of the other two functions. By supporting a load while reducing friction, a bearing guides shaft operation. It assists the movement of crucial shafts, wheels and pivots [4] .

Without a bearing, the rotating part could not continue operating on a smooth, constant basis ;

Plain bearings rely on either rubbing contact between the bearing surfaces or pressure to separate the two surfaces. The pressure required can be induced in a lubricant by the movement of one component relative to another or by the external supply of the lubricant under the required pressure. Plain bearings are also available from specialist bearing suppliers. In principle, they can be significantly less expensive than rolling element bearings because they involve fewer moving components.

1.6. Selection of bearing type

REB[1] designs have evolved into numerous bearing types displaying geometrical characteristics that make them more or less appropriate depending on the application.

The selection of an appropriate bearing for a given task, however, is an involved activity, which needs to take into account, among other factors: [6]

- Overall bearing arrangements in the mechanical system and possible combinations
- Magnitudes and directions of the applied loads
- Desired rotational speeds
- Desired lifetime based on static and dynamic load capacities
- Available space and acceptable weight
- Mounting and dismounting constraint
- Stiffness, accuracy, internal clearance and misalignment constraints
- Overall environment, lubrication, temperature and possible contamination
- Costs [17].

Design is a creative process for finding a solution to a particular problem. Can be explained in many ways, can be interpreted in many ways.

For example, it may be desirable to produce:

- The cheapest design
- The easiest to build with available materials
- The most reliable
- The one that takes up the smallest space
- The one that is lightest in weight.
- The best from any of a whole variety of possible standpoints
- The task of the designer is not so clear-cut, because he or she has chosen a reasonable compromise between these various requirements and then one of the possible designs that could meet this compromise [18].

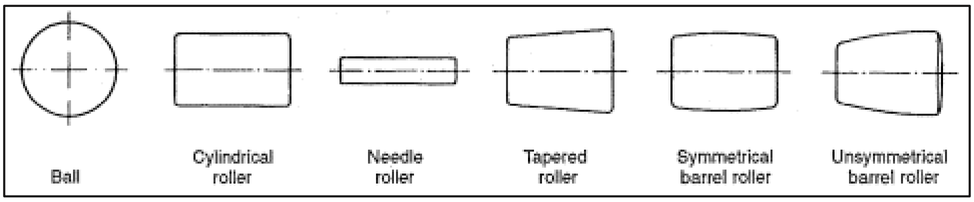


Fig.1.16 Rolling elements for ball and roller bearings [19]

[1] Rolling Element Bearing

1.7.Bearing Load, Fatigue, and Lifespan

Rolling fatigue is a material failure caused by the application of repeated stresses to a small volume of material. It is a unique failure type. It is essentially a process of seeking out the weakest point at which the first failure will occur. We can surmise that on a microscale there will be a wide dispersion in material strength or resistance to fatigue because of inhomogeneity's in the material. Because bearing materials are complex alloys, we would not expect them to be homogeneous or equally resistant to failure at all points. Therefore the fatigue process can be expected to be one in which a group of supposedly identical specimens exhibit wide variations in failure time when stressed in the same way. For this reason it is necessary to treat the fatigue process statistically.

Maintenance of bearings

Since failures in engineering structures can lead to severe economic loss, its health monitoring is very essential particularly in aerospace, civil, marine and other structures to avoid premature failures. Precise incipient structural damage identification and its location is of great interest to many researchers [20].

In rotating machinery, early fault detection of the rolling elements, i.e. bearing and gear faults has been gaining importance in recent years because of its detrimental influence on the reliability of equipment. Different techniques have been developed for monitoring and diagnosis of rolling element bearings [21].

The bearing may also become unserviceable because of seizing, breakage, wear, false brinelling, corrosion, etc. These problems are caused by improper selection or handling of the bearing. The problems are avoidable by correct selection, proper handling and maintenance, and are distinguished from the fatigue life of the bearing. However, breakdowns due to improper application, bearing design, and maintenance are more frequent than flaking due to rolling fatigue in the field [22].

Ball and roller bearings have three components that typically experience damage. They are the rolling element, inner race, and outer race. The signature produced varies according to the damaged component and whether or not the impact location is in a loaded zone of the bearing. A defect present on a rotating component produces periodic pulses that depend on the load characteristic of the system, with the largest pulses originating in the peak of a loaded zone. A defect on a stationary race in a loaded zone is intuitively easiest to detect, with a pulse of constant frequency (assuming constant rotational velocity) and higher magnitude.

Most difficulties posed in bearing initial fault detection stem from the presence of a variety of noises and the wide spectrum of a bearing defect signal. Therefore, the success of bearing fault detection methods usually depends on increasing a bearing defect signal-to-noise ratio. Identification and quantification of key signal features dictating the condition of the element is then the main priority [23].

1.8. Maintenance Objectives

Maintenance is vital for the process industry .this fact was recognised and raised with the development of the Japanese's industry. The strengthening, year by year, of maintenance management in the process industry occurred for different reasons. In the industry, production relies heavily on the plant itself, so that the most of the factors like productivity, quality, safety, pollution, and production costs depend on the condition of the plant. Also most of the industry production is of the continuous, integrated type, so plant and equipment problems generate enormous financial losses.

The primary objectives of maintenance are:

• To extend equipment life.

• To keep the plant and equipment in the optimal condition for production or service and secure maximum return on the investment.

• To constantly maintain the ability to cope with emergencies.

• To assure safety [24].

Traditional maintenance operations by observing the variations and/ or trends of some condition-monitoring indices is usually time consuming and not always reliable when multiple features (techniques) are applied for fault diagnostics, particularly as the data are noise affected [25] [26].

Detection of the fault and its severity are two important steps or features of a condition monitoring system. Lifetime of a machine component is determined by the severity of the fault. It is crucial, especially in critical systems, where continual operation is generally indispensable. The bearing defects can be either distributed or local type or combination of both. The distributed defects can be due to surface roughness, waviness, misaligned races, and off size rolling elements [27].

Localized defects are developed in the raceways, rollers and cage of a bearing. The periodic impacts occur at ball passing frequency (characteristic defect frequencies), which can be estimated from the bearing geometry and the rotational speed. The vibration signal is not sensitive to the incipient defects in the bearings; sometimes the defect frequencies are not observable, because the impulses generated by the defects are masked or distorted by the noise generated by other parts of the equipment. To overcome this problem, many researchers to detect bearing local faults implement advanced signal processing techniques [20].

How well – and how long – a bearing wears also depends on maintenance. This includes:

• Inspection of the bearing, shaft, and housing for damage;

• Double checking the mounting and assembly;

• Re-lubrication at suggested intervals;

• Making adjustments as necessary; and

• Cleaning the bearing [4].

Chapter II

Analyses defect and inspection of bearing

2.1. Introduction

Rolling element bearings are among the most common components to be found in industrial rotation machinery. They are found in industries from agriculture to aerospace, in equipment as diverse as paper mill rollers to The Space shuttle Main Engine Turbo machinery. There has been much written on the subject of bearing vibration monitoring over the last twenty-five years. This chapter attempts to summarise the underlying science of rolling element bearings across these diverse application from the point of view of machine condition monitoring using vibration analysis. The key factors, which are addressed in this chapter, include the underlying science of bearing vibration, bearing life, vibration measurement, signal processing techniques and prognosis of bearing failure [28].

It has been considered that if a rolling bearing in service is properly lubricated, properly aligned, kept free of abrasives, moisture, and corrosive reagents, and properly loaded, then all causes of damage are eliminated save one, material fatigue.

Historically, rolling bearing theory postulated that no rotating bearing can give unlimited service, because of the probability of fatigue of the surfaces in rolling contact. The stresses repeatedly acting on these surfaces can be extremely high as compared to other stresses acting on engineering structures [29].

2.2. Rolling Bearing Damage

Rolling bearing damage is generally detected by unusual operational behaviour of the bearing arrangement. Uneven running and uncommon running noise usually indicate flaked running surfaces due to material fatigue or an alteration of the radial clearance due to wear. High friction i.e. resistance to smooth running, can indicate detrimental preload, poor lubrication or damaged rolling contact surfaces. Higher than normal temperatures are a sign of an increase in friction. Breakdown of the lubrication may be responsible for a sudden rise in operating temperature occurring without a change in the operating conditions.

In the case of machine tools, wear and other bearing damage are evidenced by the deterioration in quality of the work pieces.

These operational characteristics of a damaged bearing can be exploited to monitor the bearing arrangement, perhaps using temperature and vibration measuring instruments. At the first signs of premature bearing damage, the causes and effects should be analysed so that steps to avoid further damage can be taken. To this end, it is often necessary to dismount and examine the bearing.

It is not always easy to diagnose the primary cause; the original failure may often be obscured by consequential damage. In a severely damaged bearing, for example, it may only be possible to ascertain that overheating and seizure took place. The primary cause, e.g. detrimental preload due to faulty installation, starved lubrication or fatigue damage, can no longer be recognized [30].

Fig.2.1 The progression of surface rolling contact fatigue [31]

Fig.2.2 The progression of surface rolling contact fatigue [31]

Fig.2.3 The progression of surface rolling contact fatigue [31]

Fig.2.4 The progression of surface rolling contact fatigue [31]

In general, if rolling bearings are used correctly they will survive to their predicted fatigue life. However, they often fail prematurely due to avoidable mistakes. Failure of the rolling bearing can occur for a variety of reasons. Accurate determination of the cause of a bearing failure is must to make suitable recommendations for eliminating the cause. The major factors that singly or in combination may lead to premature failure during service include incorrect mounting, excessive loading, excessive preloading, inadequate & insufficient lubrication, impact loading, vibrations, contamination, entry of harmful liquids. It is difficult to determine the root cause of some of the premature failures. If all the conditions at the time of failure, and prior to the time of failure are known, including the application, operating conditions and environment, then by studying the nature of failure and its probable causes, the possibility of similar future failures can be reduced. Two or more failure pattern can occur simultaneously and can thus be in competition with one another to reduce the bearing life. Also a pattern of failure that is active for one period in the life of a bearing can lead to or can even be followed by another failure mechanism, which then cause premature failure. Thus in some instances, a single failure pattern will be visible and in other indications of several failure pattern will be evident, making exact determination of root cause difficult. So when more than one bearing failure pattern has been occurred, proper analysis depends on careful examination of failed components [32].

Severe vibrations of bearing can even cause the entire system to function incorrectly, result in downtime of the system and economic loss to the customer. Vibration signature analysis of machine components is a commonly used fault-detection technique employed in rotor-bearing systems. There are two critical states in the condition monitoring of machine components: the first is the detection of the fault and the second is the determination of severity of the fault, that is, the lifetime of the machine component [33].
Even when bearings are being used under ideal conditions, failures of bearings are caused by deterioration of the material due to rolling fatigue. Generally, the service life of bearings is expressed either as a period of time or as the total number of rotations before the occurrence of failures in the inner ring, outer ring or rolling element because of rolling fatigue, due to repeated stress.(section 2.3 page14) Rolling bearings sometimes fracture earlier than expected. The following causes should be considered;

1. Inappropriate use of bearings
2. Faulty installation or improper processing
3. Improper lubricant, lubrication method or sealing device
4. Inappropriate speed and operating temperature
5. Contamination by foreign matter during installation
6. Abnormally heavy load [34].

2.3.How is bearing life defined ?

Generally, a rolling bearing cannot rotate forever. Unless operating conditions are ideal and the fatigue load limit is not reached, eventually material fatigue will occur.
Fatigue is the result of shear stresses cyclically appearing immediately below the load-carrying surface. After a time these stresses cause cracks which gradually, extend up to the surface. The fatigue failure of metals is the well-known type of failure that occurs after the repetition of several cycles - from a few to millions - of stresses applied to the specimen, or to the component. The simplest fatigue failure everyone can obtain can be produced by the repeated bending of, say, a paper clip, made of soft steel: after some reversed cycles (often only five to ten are enough), it will break in two parts (and one must be careful, because they can be very warm) [35].

As the rolling elements pass over the cracks fragments of material break away and this is known as flaking or spelling. The flaking progressively increases in ex- tent and eventually makes the bearing unserviceable.

The life of a rolling bearing is defined as the number of revolutions the bearing can perform before incipient flaking occurs. This does not mean to say that the bearing cannot be used after then. Flaking is a relatively long, drawn-out process and makes its presence known by increasing noise and vibration levels in the bearing. There- fore, as a rule, there is plenty of time to prepare for a change of bearing [30].

Rated service life of rolling bearing

L: Rated service life, 10^6 rotations
L_h: Rated service life, h
C_r: Basic dynamic load rating, N
P: Dynamic equivalent load rating, N
n: Rotational speed, min^{-1}
p: 3 ……Ball bearing,
10/3 …Roller bearing [34].

$$L = \left(\frac{C_r}{P}\right)^p \quad \text{…………………………………………….. (1)}$$

$$L_h = \frac{10^6}{60n}\left(\frac{Cr}{P}\right)^p \quad \text{……………………………………….. (2)}$$

The standard relies on a visible inspection of rolling element contact and other functional surfaces – such as raceways – which will suggest the mechanisms involved in each type of damage or failure. The main causes of bearing damage can be linked to six main damage/failure modes:

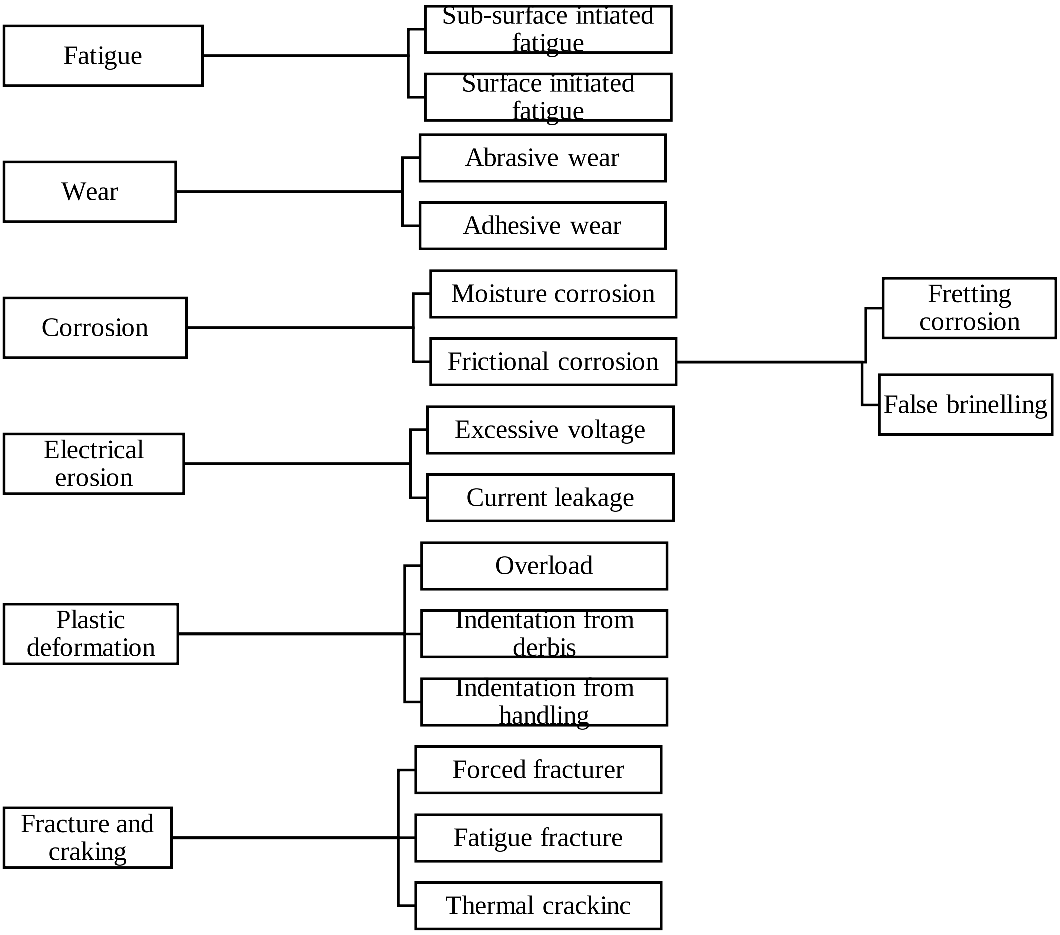


Fig.2.5 ISO 15243 Bearing damage classification [36].

Among these rolling inspection standards, we give more detail in the following section

2.4.1 Definitions

Table 2-1 Bearing damage ISO classification

Fatigue	A change in the material structure caused by the repeated stresses developed in the contacts between the rolling elements and raceways.
Subsurface fatigue	The initiation of micro-cracks at a certain depth under the surface.
Surface initiated fatigue	Flaking that originates at the rolling surfaces as opposed to subsurface.
Wear	The progressive removal of material resulting from the interaction of the asperities of two sliding or rolling contacting surfaces during service.
Abrasive wear	Wear that occurs as a result of inadequate lubrication or contamination ingress.
Adhesive wear (smearing)	A transfer of material from one surface to another.
Corrosion	A chemical reaction on a metal surface.
Moisture corrosion	The formation of corrosion pits as a result of oxidation of the surfaces in the presence of moisture.
Frictional corrosion (fretting corrosion)	The oxidation and wear of surface asperities under oscillating micro-movements.
Frictional corrosion (false brinelling)	A formation of shallow depressions resulting from micro-movements under cyclic vibrations.
Electrical erosion	The removal of material from the contact surfaces caused by the passage of electric current.
Excessive voltage (electrical pitting)	Sparking and localized heating from current passage in the contact area because of ineffective insulation.
Current leakage (electrical fluting)	The generation of shallow craters that develop into flutes that are equally spaced.
Plastic deformation	Permanent deformation that occurs when the yield strength of the material is exceeded.
Overload (true brinelling)	The formation of shallow depressions or flutes in the raceways.
Indents from debris	When particles are over-rolled
Indents from handling	When bearing surfaces are dented or gouged by hard, sharp objects.
Fracture	When the ultimate tensile strength of the material is exceeded and complete separation of a part of the component occurs.
Forced fracture	A fracture resulting from a stress concentration in excess of the material’s tensile strength.

Fatigue fracture	A fracture resulting from frequently exceeding the fatigue strength limit of the material.
Thermal cracking (heat cracking)	Cracks that are generated by high frictional heating and usually occur perpendicular to the direction of the sliding motion. [37]

2.4.2. Wear – Abrasive Contamination

Fine foreign material in the bearing can cause excessive abrasive wear.

Sand, fine metal from grinding or machining, and fine metal or carbides from gears wear or lap the rolling elements and races. In tapered bearings, the roller ends and cone rib wear to a greater degree than the races. This wear causes increased endplay or internal clearance, which can reduce fatigue life and create misalignment in the bearing. Abrasive wear also can affect other parts of the machine in which the bearings are used. The foreign particles may get in through badly worn or defective seals. Improper initial cleaning of housings and parts, ineffective filtration or improper filter maintenance can allow abrasive par ticles to accumulate [38].

Table 2-2 Wear

Condition	Cause	Solution
surface is worn and dimensions are reduced compared with other portions. Surface mostly roughened and scored.	ingress of solid foreign objects. Dirt and other foreign objects in lubricant. Poor lubrication. Skewing of rollers	Selection of optimum lubricant and lubrication system Improvement in sealing efficiency Filtration of lubrication oil Elimination of misalignment

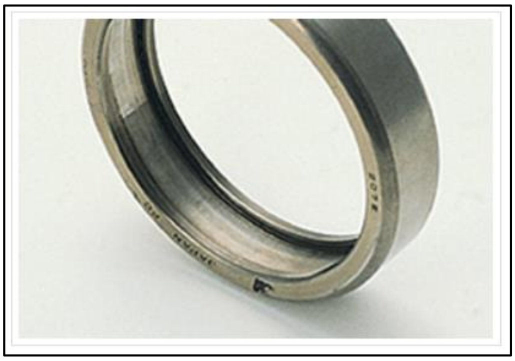


Fig.2.6 Outer ring of cylindrical roller bearing

Stepped wear on raceway surface

The cause is poor lubrication. *[93]*

Fig.2.7 Outer ring of double row angular contact ball bearing (rub unit bearing).

Wear on one side of the raceway.

The cause is poor lubrication *[93]*

Fatigue

General definition

The fatigue failure of metals is the well-known type of failure that occurs after the repetition of several cycles - from a few to millions - of stresses applied to the specimen, or to the component. The simplest fatigue failure everyone can obtain can be produced by the repeated bending of, say, a paper clip, made of soft steel: after some reversed cycles (often only five to ten are enough), it will break in two parts (and one must be careful, because they can be very warm) [35].

The change in the structure, which is caused by the repeated stresses developed in the contacts between the rolling elements and the raceways, is described as fatigue. Fatigue is manifested visibly as a flaking of particles from the surface.

a. Subsurface initiated fatigue

Under the influence of cyclic loads in rolling contacts, described by the Hertzian Theory, structural changes will occur and micro cracks will be initiated at a certain depth under the surface, i.e. subsurface. The initiation of the micro cracks is often caused by inclusions in the bearing steel Fig2.12 Heavy grey stained areas (Scale 1,25:1) .

The micro cracks, which are observed at the edge of the white etched areas (butterflies) **Fig.2.13**, will normally propagate to the rolling contact surface producing flaking, spelling (pitting) **Fig.2.12** and then peeling [39].

The changes might appear at metallurgical investigation .these cracks propagate and when they come to the surface, spalling occurs **Fig.2.8** [40]

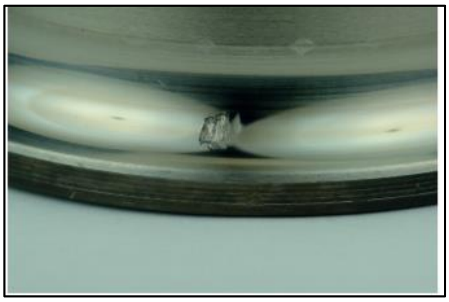


Fig.2.8 Initial subsurface spalling in a deep groove ball bearing

_ Rotating inner ring [40]

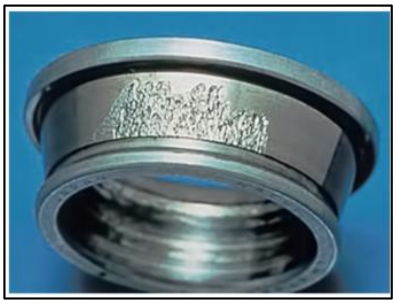


Fig.2.9 Advanced subsurface spalling in a tapered roller bearing

_ Stationary inner ring [40]

b. Surface initiated fatigue

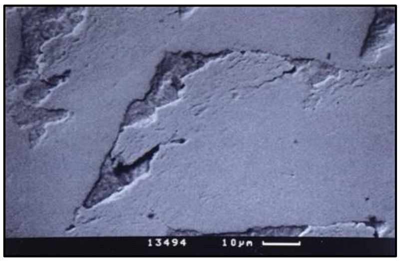


Fig.2.12 Microspalls *[40]*

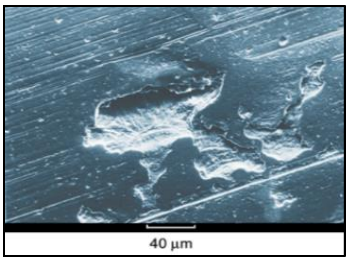


Fig.2.12 Micro cracks forming a “fish-scale” appearance *[40]*

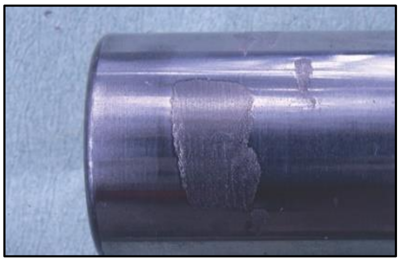


Fig2.12 Heavy grey stained areas (Scale 1,25:1) *[40]*

Fatigue initiated from the surface is, among other things, caused by surface distress.

Surface distress is the damage to the rolling contact metal surface asperities under a reduced lubrication regime and a certain percentage of sliding motion, causing the formation of

- asperity micro cracks, see **Fig.2.**12 Micro cracks forming a “fish-scale” appearance;
- asperity micros palls, see **Fig.2.**12 Microspalls;
- Micros palled areas (grey stained), see **Fig2.12**;

Indentations in the raceways caused either by contaminant particles or by handling can also lead to surface initiated fatigue . Surface initiated fatigue caused by indentation arising from plastic deformation [39].

Fig.2.13 Subsurface micro crack with the “butterfly phenomenon” (white etched area) (Scale 500:1) [40]

2.4.3. Fracture and Cracks

Fig.2.14 Fig.2.15 shows fracture on the large rib of the inner ring of a tapered roller bearing. This occurs when an abnormal axial load or a shock load is applied to a bearing or when an abnormal force is applied to the rib when mounting or dismounting the bearing. Causes of cracks include application of a heavy shock load and excessive interference. Where the bearing is supported only by the two edges of the outer ring, it may break along the axial plane and where there is slippage between the inner outer ring and the shaft or housing, a crack will occur at right angles to the direction of slippage. This phenomenon is seen in cases where the outer ring is loosely fit with the shaft and creeping occurs [41].

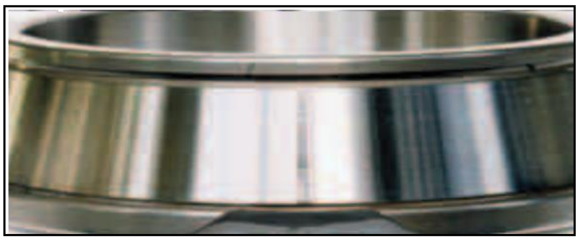


Fig.2.14 Fracture [41]

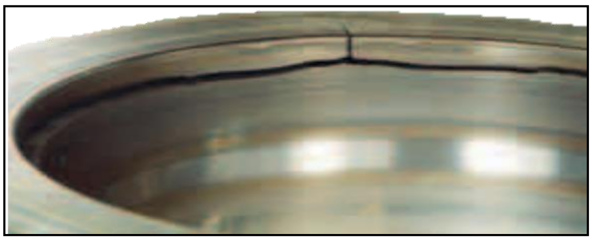


Fig.2.15 Crack [41]

The bearing is generally usable up to the end of the rolling fatigue life if handled properly. If it fails earlier, it may be due to some fault in the selection, handling, lubrication, and/or mounting of the bearing.

It is sometimes difficult to determine the real cause of bearing failure because many interrelated factors are possible. It is, however, possible to prevent the recurrence of similar problems by considering possible causes according to the situation and condition of the machine on which the bearings failed. Also, installation location, operating conditions, and surrounding structure of the bearings should be taken into consideration.

Fig.2.16 Split of raceway surface in the axial direction The cause is excessive interference fit.
Fig.2.17 Originating point is observed at the middle of the left raceway surface

Fig.2.16 Fracture of inner ring *[93]*

Fig.2.17 Inner ring of spherical roller *[93]*

2.5. Inspection of bearings

The repeated high stressing on the contacts between the rolling element and the raceway eventually causes fatigue damage. In addition to this, the main reason for bearing failures is an improper handling-and-mounting procedure, corrosion, wear and manufacturing defects [42].

Non-destructive Testing (NDT) techniques assess the conditions of rolling bearings without affecting their structural functionality, thus have played an important role in bearing health diagnosis. Among the various NDT techniques investigated for bearing applications, vibration and acoustic-based techniques are the most popular, since vibration and acoustic signals measured from bearings contain physical information that directly reflect the defect severity. In this section, a review of such NDT techniques is presented, and related sensors and sensing principles are discussed

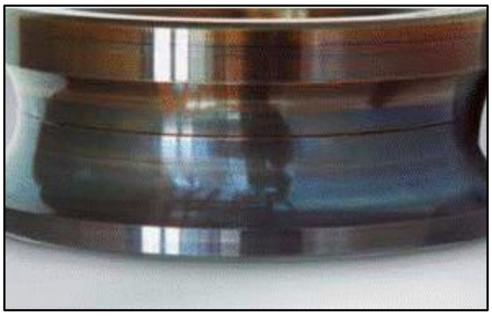


Fig.2.18 Discoloration [43]

Fig.2.19 Rust [43]

1. Destructive testing – This is not possible because the bearing is purchased for an intended use and destructing it, in no way answers the ultimate usage of a perfect bearing.

2. Non Destructive testing – This is a best and well known method for testing of the bearings as the bearings are tested without any damage to them. Moreover a bearing passing through these tests can be utilized as a flaw free bearing.
Non destructive testing has the advantage of detecting the internal flaws and imperfections in the various bearing components that with other means of testing can go undetected. Some of the methods that are used for the non-destructive testing of bearings are

1. Liquid Penetrant Inspection
2. Magnetic Particle Inspection
3. Etch Inspection
4. Eddy Current Inspection

Specific non-destructive controls like the Magnetic Particle Inspection, for detecting superficial micro-cracks, and the Ultrasonic Micro-Crack Detection, for under-surface micro-cracks location, are regularly performed on rings and rollers during the production process. Moreover, a visual check of the parts ready for assembly is constantly carried out to avoid any noticeable anomaly [44].

Bearing may be subjected to the post-process controls, which encompass both non-destructive tests (visual, dimensional, geometrical and surface quality) and destructive tests (chemical composition, macro- and micro-structure and mechanical properties).

2.5.1. Visual inspection

Visual testing is the first NDT method that should be considered before applying more sophisticated and expensive methods. In this method direct visual and optically aided inspection is applied to the surface of object to detect flaws and anomalies. If significant flaws are detected during visual inspection then the part being inspected can be rejected on that basis. There is then hardly any need or justification for applying the other NDT methods [45].

The only manual control is the visual inspection of the final product at the end of the line. This operation includes:

- Checking the presence of all parts;
- A functional test (manual free running control);
- The detection of esthetical or surface defects;
- The readability of markings [46].

- The classification of visual defects on ball bearings

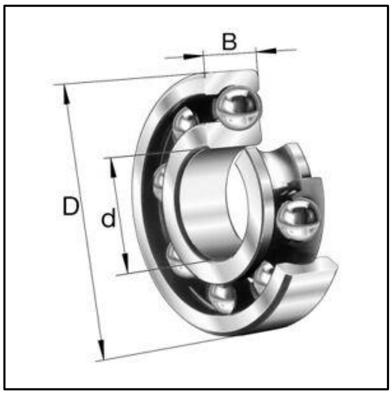


Fig.2.20 bearing part *[4]*

- The ball bearing surfaces to be inspected are:
- The two lateral plane faces of the inner (IPF) and outer (OPF) rings;
- The two flingers (F);
- The inner cylindrical surface (IS);
- The outer spherical surface (OS)

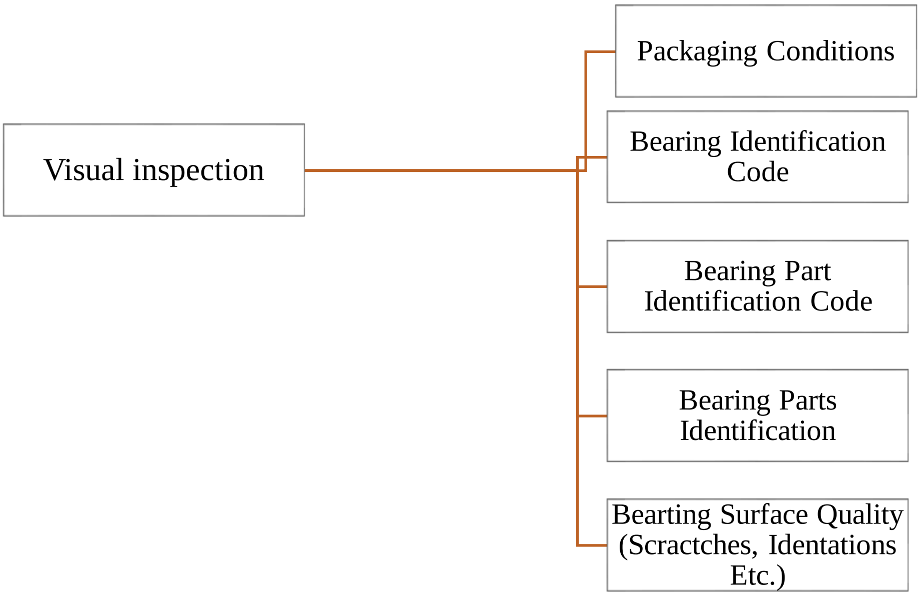


Fig.2.21 Visual inspection *[44]*

Dimensional and geometrical control

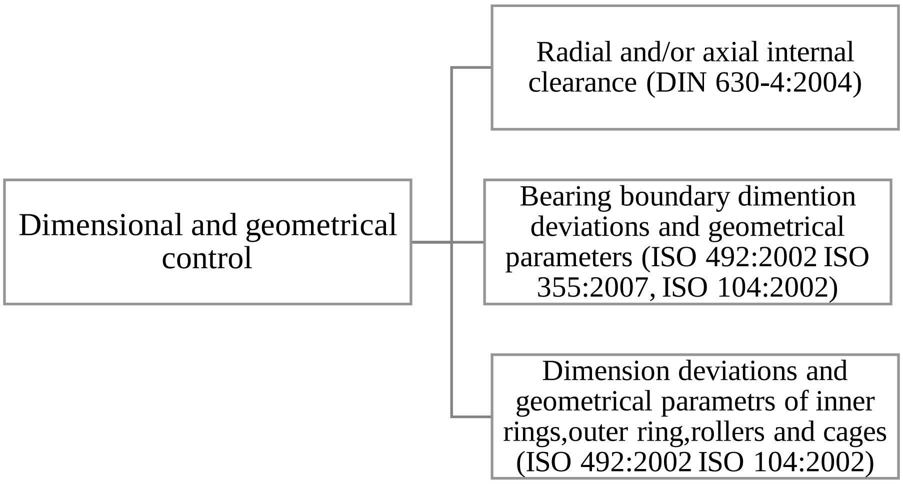


Fig.2.22 Dimensional and geometrical control [44]

2.5.2. Surface quality control

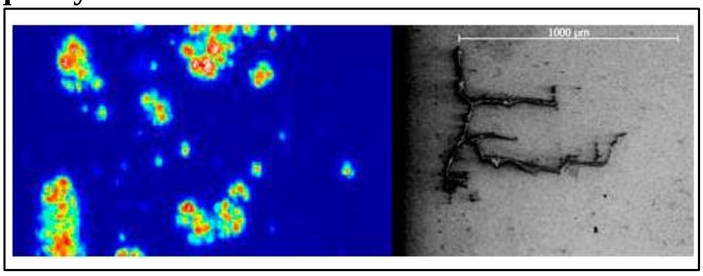


Fig.2.23 Surface control *[90]*

Fig.2.23 : C-scan image (left) of a bearing raceway representing ultrasonic energy reflected from subsurface defects. After sectioning at the subsurface cracks, ultrasound testing can be correlated with results in optical microscopy (right)

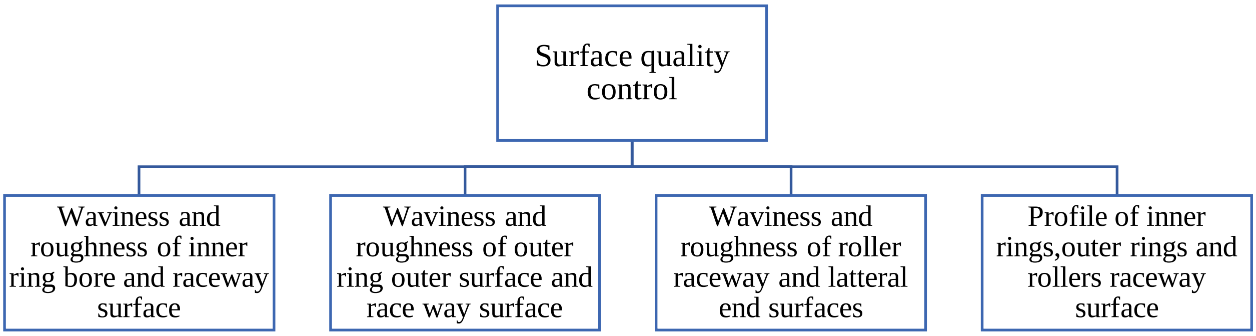


Fig.2.24 Surface quality control [44]

2.5.3. Macro-structure inspection

Liquid penetrant testing (PT)

This is probably the most widely used NDT method which can be employed for the detection of open-to-surface discontinuities in any industrial product which is made from a non-porous material. It is a simple, low-cost technique for detecting surface-breaking flaws. The test object is coated with a visible or fluorescent dye and any surface-breaking imperfection draws in the penetrant by capillary action. After cleaning away excess penetrant from the surface, a developer is used to act like blotting paper to draw the penetrant from the imperfection, thus revealing the defect [45] [47]. The process is illustrated in **2.25**

Fig 2.26 Liquid Penetrant Testing *[98]*

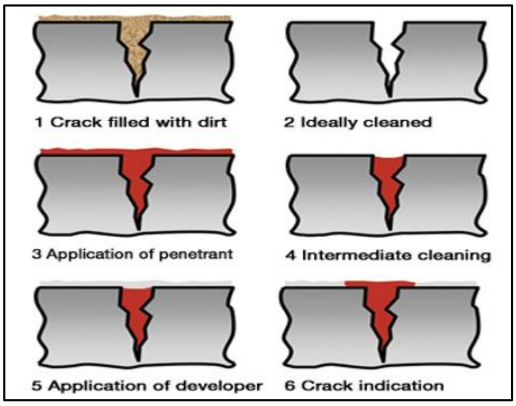


Fig 2.25 Liquid Penetrant testing *[106]*

Magnetic particle testing

Magnetic particle testing is used for the testing of materials which can be easily magnetized. This method is capable of detecting open-to-surface and just below-the-surface flaws. Magnetic particle testing is used for the testing of materials which can be easily magnetized. This method is capable of detecting open to surface and just below the surface flaws. In this method the test specimen is first magnetized either by using a permanent or an electromagnet or by passing electric current through or around the specimen [45] [48]. Figure illustrates the basic principle of this method **Fig.2.28**

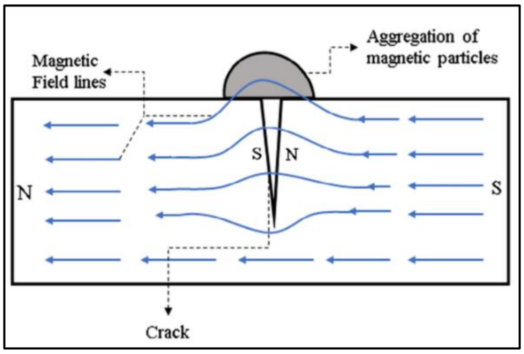


Fig.2.27 Magnetic particle testing *[85]*

Fig.2.28 *[92]*

Eddy current

Eddy current testing is employed for the detection and measurement of defects such as cracks, porosity, blowholes, inclusions, overlaps, shrinkages and soft spots in a wide variety of test specimens in solid cylindrical, hollow cylindrical or other complex shapes. Corrosion and cracking due to stress corrosion can also be detected. Changes in electrical conductivity and permeability can be measured which in turn have a bearing upon the material properties such as hardness, homogeneity, degree of heat treatment, existence of internal stresses, decarburization, diffusion, alloy composition, presence of impurities, etc.

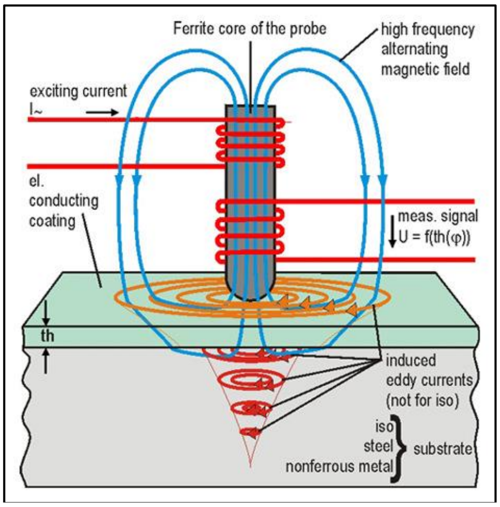


Fig.2.29 Eddy current test method according to the standard ISO 21968 *[99]*.

Thickness measurements can be made on metallic plates, foils, sheets, strips, tubes and cylinders. Eddy current testing technology, which is based on the electromagnetic induction theory, set up the rolling bearing roller in the alternating magnetic field, and then there will be induced current in the roller, that is eddy current. The function of this eddy current magnetic field produced by itself in the roller is to change strength of original magnetic field, then inducing the diversification of coil voltage and impedance [45] [49].

2.5.4. Macro-structure inspection

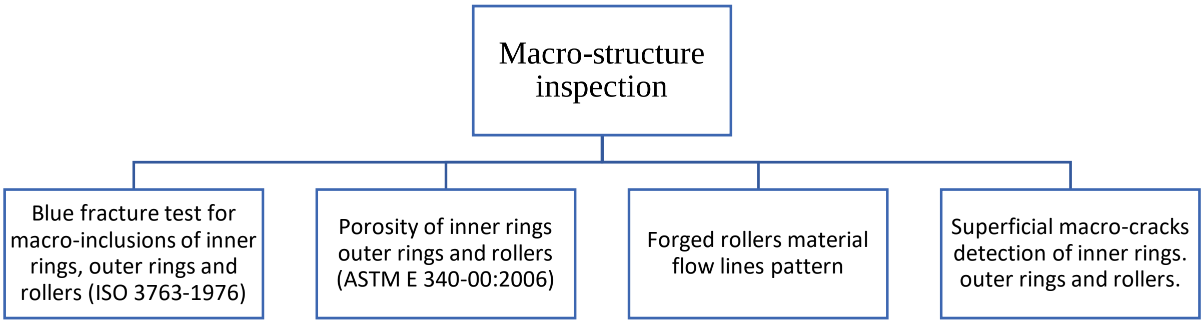


Fig.2.30 Macro-structure inspection [44]

2.5.5. Chemical composition analysis

Fig.2.31 Chemical composition analysis [17]

2.5.6. Mechanical properties determination

Fig.2.32 Mechanical properties determination *[44]*

2.5.7. Micro-structure inspection

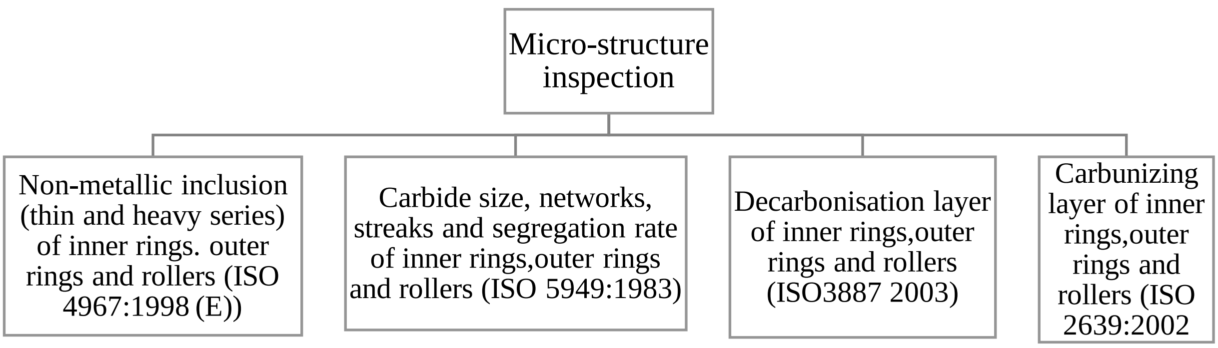


Fig.2.33 Micro-structure inspection [44]

Bearings that have been in service or endurance-tested in a test rig may be examined by various NDT methods. This is to provide more insight into the root cause of bearing failure and bearing degradation mechanisms or, in the case of bearing remanufacturing inspection, to check for subsurface damage and see if the bearing component is fit for further service.

2.6. Conclusion

The bearing is an element with a very important role and dominates the performance of some machines and process equipment. If one of the bearings fails, the damage can be minimal. On the other hand, bearing failure on a transportation device can have severe consequences. Every bearing becomes unserviceable after a certain operating time, even if it is installed correctly and operated properly. To prevent unnecessary bearing failure, a regular inspection must be carried out.

When bearing failure is found, even if it is insignificant, it is important to investigate the phenomenon to determine the causes. At this time, not only the bearing but also the shaft, housing, and lubricant used with the bearing should be comprehensively investigated, together with the bearing. To judge the causes of failure, sufficient knowledge and experience in bearings and lubricants and a good understanding of the characteristics of the equipment are necessary. In addition, consideration of the installation conditions and operational process of the bearing is required.

Chapter III

Modelling and Simulation of Bearings

FEM analysis is very efficient method for achieving stresses at different loading condition according to forces and boundary conditions applied to the component from the static analysis. The use of numerical method such as Finite Element Method now a day commonly used to gives detail information about structure or component.

Bearings are an important mechanical components that help in maintaining the liner and rotational movements of a machine. To ensure a long operational life of bearings it is necessary to predict the load which are supposed to carry. In the case of stationary bearings, low oscillations, working at low speeds, or when taking large short shocks during rotation, loading is considered to be static.

Thus, in-service safety is determined by the magnitude of the deformations at the runway rolling paths. This work aims to simulate and model the behaviour of the ball bearings under a static loading with a comparison of two variants of the application of load, axial and radial. We also considered two types of constraints.

The analysis is performed using the finite element method.

This work aims at analysing the behaviour of the ball bearings under a static load, for this fact the simulation and modelling by finite element in order to study behaviour and make comparisons. This work has two study variants in two different configuration and comparing the result with analytical result

ANSYS is commonly used and enjoyed by an extended use in the structural areas, for analysis. ANSYS it consists of three main phases : Pre-processing, conducting or importing of the solid model system that are to be analysed, solid meshing design in finite elements, implementation of conditions and loads at the limit, Processing, numeric solving of the characteristic equations behaviour of the system and getting the solution. Post-processing, viewing the results in order to analyses system reaction and identification of areas with critical applications.

The purpose of the study was to collect data's using two different software's and after to compare them with mathematical results. Using the ANSYS in this purpose it was able to analyses the design of the structure of the ball bearing in detail [50].

The first case: apply the load on the inner ring and fix the outer ring.

The second case: apply the load on the outer ring and define the inner ring as a fixed support.

Methodology

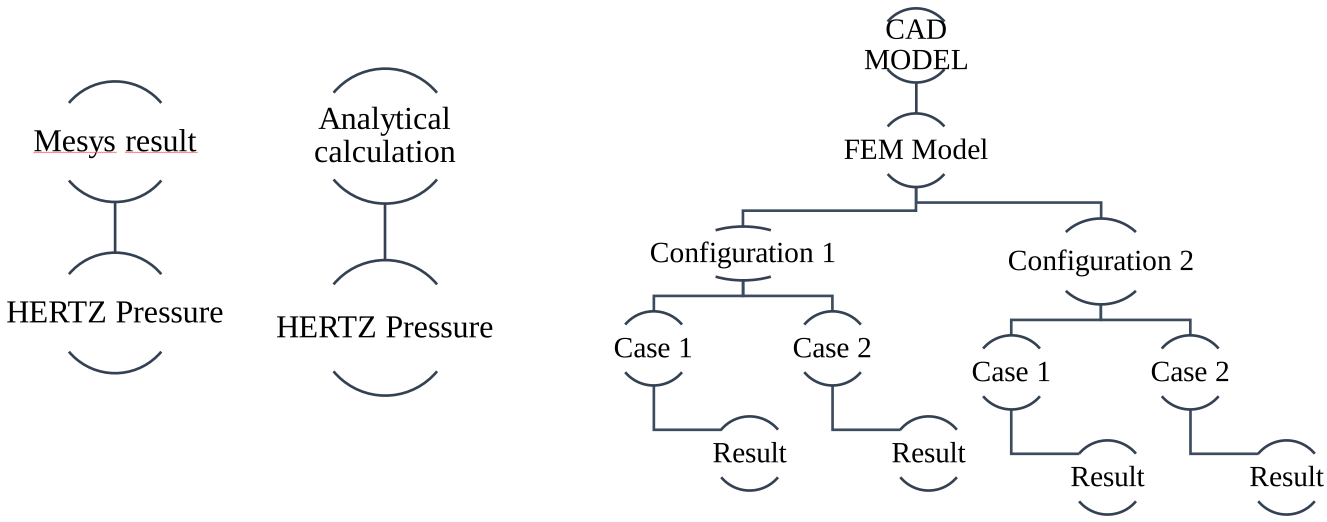


Fig.3.1 Methodology

objects

3.2.1. Geometry

Table 3-1 Geometry

Symbols	
d	nominal bore diameter or shaft washer nominal bore diameter for thrust bearings
d_1	nominal diameter at the theoretical large end of the tapered bore
d_2	nominal bore diameter of the shaft washer for double directions thrust bearings
d_s	deviation of single bore diameter
d_{psmax}	maximum bore diameter, in a single radial plane
A	nominal half-angle of the tapered bore
D	nominal outside diameter or housing washer nominal diameter
D_1	nominal outside diameter of the outer ring rib
D_s	single outside diameter maximum
B	nominal width of the inner ring
B_s	single width of the inner ring
C	nominal width of the outer ring
C_s	ingle width of the outer ring

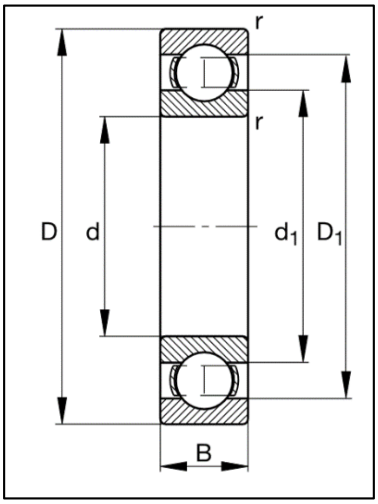


Fig.3.2 Technical drawing of ball bearings [51]

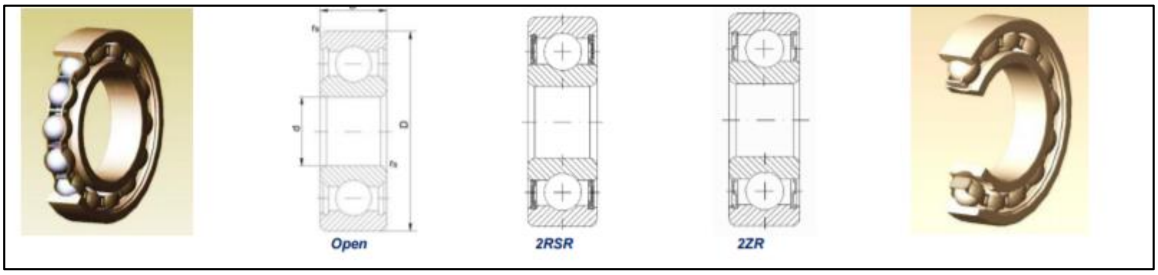


Fig.3.3 Radial ball bearings [51]

Table 3-2 Geometrical properties [51]

Designation 6308 C3L	
Dimensions	
D	40
D	90
B	23
Basic radial KN	
Dynamic	40,8
Static	24
Weight kg	0,641
Risk class	1B

3.2.1. Materials

52100 bearing steel is one kind of special steel with features of high wear resistance and rolling fatigue strength. High-carbon chromium bearing steel, engineering steel and some types of stainless steel and heat resistant steel are used as materials of bearings and for other purposes.

Advantages of Chrome Bearing Steel 52100:

- Superior hardness, 60-67 on Rockwell hardness scale (Rc) at room temperature
- High carbon chrome alloy steel
- Operates continually at temperatures up to 120°C
- Used to produce precision ball bearings and roller bearings
- Cost-effective
- Long working life [51];

ASTM 52100 Bearing Steel

Table 3-3 : Material

Properties	Metric	Imperial
Bulk modulus (typical for steel)	140 GPa	20300 ksi
Shear modulus (typical for steel)	80 GPa	11600 ksi
Elastic modulus	190-210 GPa	27557-30458 ksi
Poisson's ratio	0.27-0.30	0.27-0.30
Hardness, Brinell	–	–
Hardness, Knoop (converted from Rockwell C hardness)	875	875
Hardness, Rockwell C (quenched in oil from 150°C tempered)	62	62
Hardness, Rockwell C (quenched in water from 150°C tempered)	64	64
Hardness, Rockwell C (quenched in oil)	64	64
Hardness, Rockwell C (quenched in water)	66	66
Hardness, Vickers (converted from Rockwell C hardness)	848	848
Machinability (spheroidized annealed and cold drawn. Based on 100 machinability for AISI 1212 steel)	40	40

Analysis was prepared using the finite element method. The applications of the finite element method are only now starting to reach their potential. One of the most exciting prospects is its application in coupled problems such as fluid-structure interaction, thermo mechanical, thermochemical, thermo-chemo-mechanical problems, biomechanics, biomedical engineering, piezoelectric, ferroelectric, and electromagnetics. This method consists of a continuous body mesh and finished in several finite element :(FEM - Finite element method).

The mesh structure is meant in subdivision mathematical model with simple geometric form, which does not overlap, called finite elements. If the answer to each finite element simulations is expressed on a finite number of degrees of freedom that represent the values of unknown function (movement function) in a number of crucial points. Thus the answer to the mathematical model will result as an approximation of the response obtained by assembling discrete model answers all model elements [52].

ANSYS simulation software allows the designer to predict how the product will work under real conditions. Simulation is a powerful modular system.

The rolling bearing analysis software MESYS calculates the life of rolling bearings according ISO/TS 16281 considering the inner geometry of the bearing. Considering the load distribution within the bearing, clearance and tilting angle will affect the resulting bearing life. The inner geometry of the rolling bearing is provided by the user, but it can also be approximated from the load capacities by the software. The calculation returns the pressure distribution between the rolling elements and the reference life according ISO/TS 16281 for a given loading (force and moment or tilting) [53]- [54].

For ANSYS the geometry was prepared before importation. After that the geometry is checked for errors, the elements are meshed the load and constrains are established after the analysis is run. This method consists of a continuous body mesh and finished in several finite elements (FEM - Finite element method). For MESYS it was enough to establish the type of bearing, number of elements and data’s about the dimensions and load conditions [54].

Parts are the basic building blocks in the SOLIDWORKS software. Assemblies contain parts or other assemblies, called subassemblies. A SOLIDWORKS model consists of 3D geometry that defines its edges, faces, and surfaces. SOLIDWORKS models are:

- Defined by 3D design
- Based on components

It has achieved a uniform bearing mesh, with a number of nodes and elements as small as possible, to ease the process of calculating and also to shorten the settlement period.

Creation of the CAD model of each part separatly on SOLIDWORK

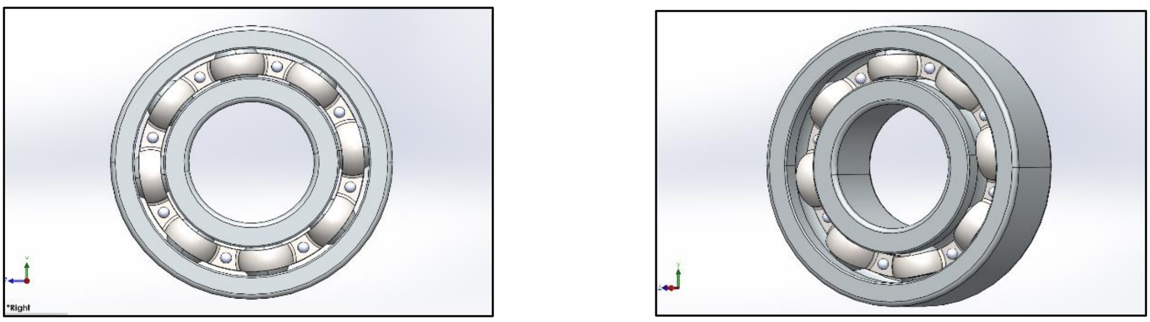


Fig.3.4 CAD Bearing

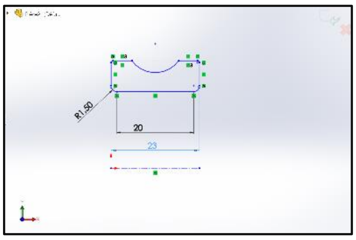


Fig.3.5 Sketch Inner Ring

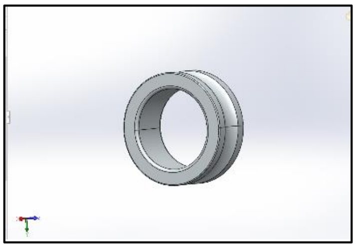


Fig.3.6 Inner ring CAD

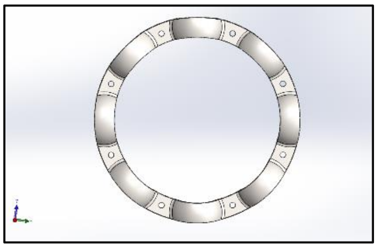


Fig.3.7 Cage CAD

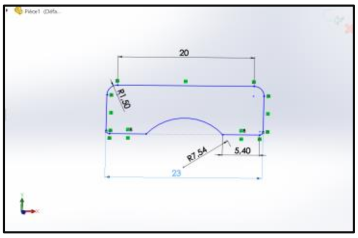


Fig.3.8 Sketch Outer Ring

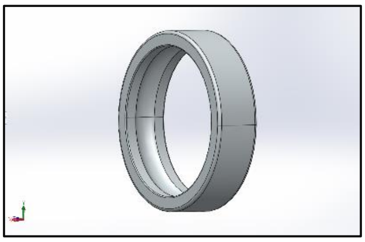


Fig.3.9 Outer ring CAD

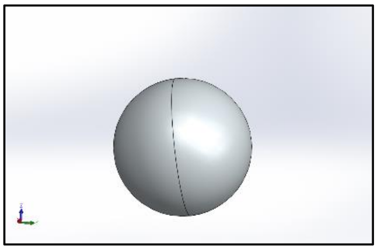


Fig.3.10 Balls CAD

Creation of the bearing assembly

Creation of the constraints between the parts of the bearings:

Coaxial constraint between: the outer ring, the inner ring and the cage;

Creation of a constraint: tangent between the cage and the balls;

Creation of a slide connection by defining the inner ring as a slide and the outer ring as a slide

Use the circular repeat function for the ball, using the inner ring as the object, number of ball: 8, and constant spacing;

Match the frontal planes and facial planes of one of the balls with those of the inner ring so that when the inner ring turns the balls roll.

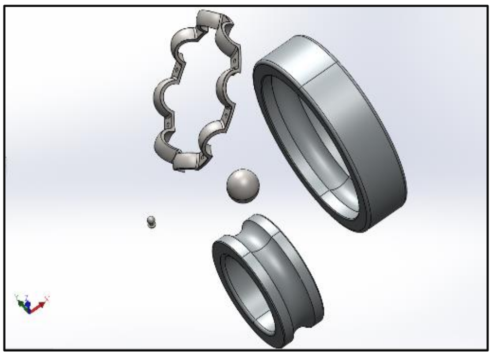


Fig.3.12 Assembly on SolidWorks

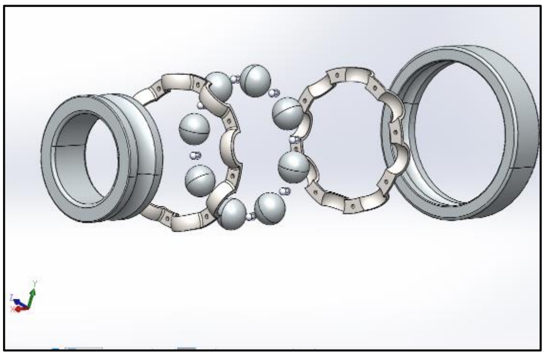


Fig.3.11 Bearing Exploded view 3D

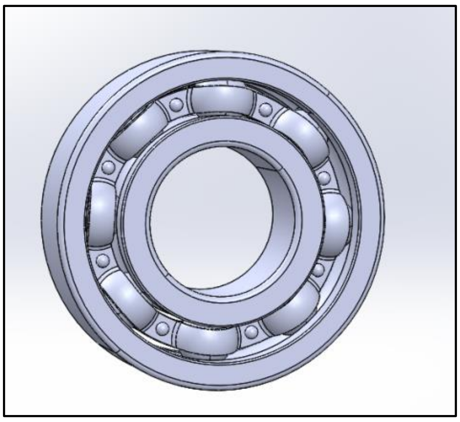


Fig.3.13 Assembled bearing CAD model SolidWorks

CAD (* .SLDASM. format) model are imported into the ANSYS WORKBENCH software.

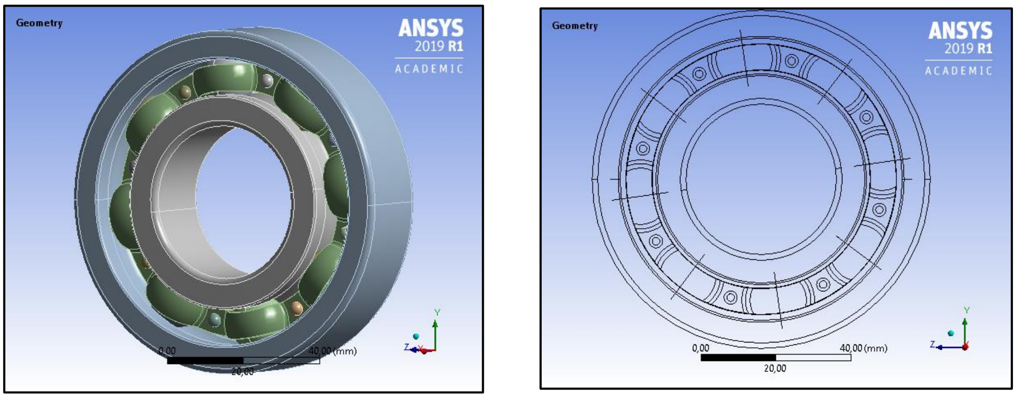


Fig.3.14 Geometry on ANSYS

In the geometry section assign to each piece its material;

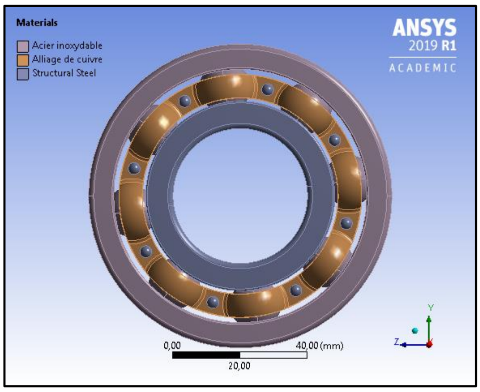


Fig.3.15 Define material to each parts

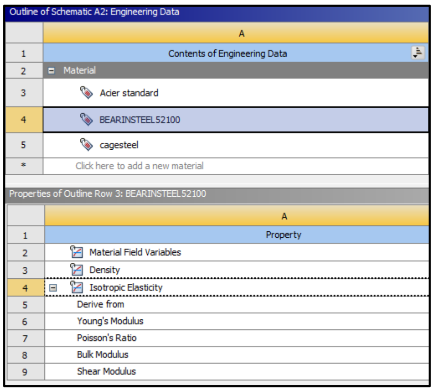


Fig.3.16 Adding materials data on ANSYS Engineering Data

For both rings and balls the material being: ASTM 52100 Bearing Steel; not found in the ANSYS 2019 R1 academic database, in the section engineering data we need to define the name and the properties of the materials including: physical properties, teeth, properties linear elastic ... etc

Define a new coordinate system that originates from the geometric centre of the inner ring (Axis X principal).

A. First configuration

Redefine the connection between the bearing parts as an unseparated part (no separation)

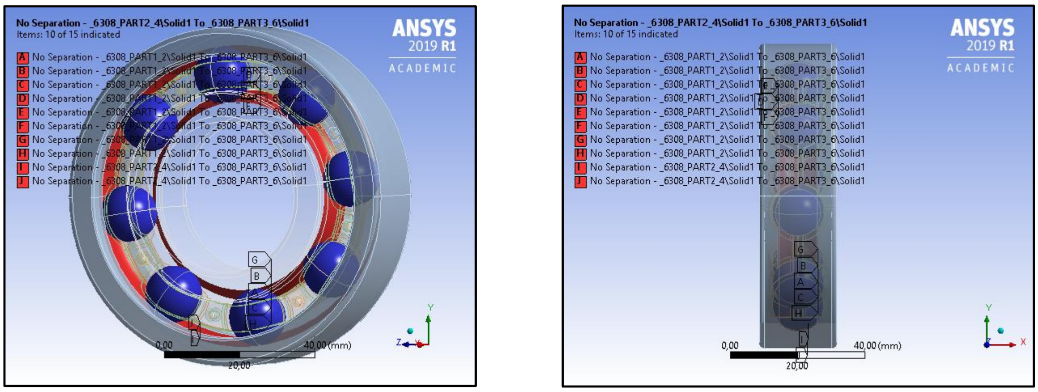


Fig.3.17 Connection balls/cage

Generate meshing: with automatic method

To perform the numerical analysis first it has to discretize the complete body of ball bearing in to number of nodes and elements. In order calculate the dependency of result on nodes and elements, here in this work it perform mesh of ball bearing with different number of 27875 nodes and 12507 elements and calculated the value of the equivalent stress and the deformation [55]. Optimization of the mesh was carried out in order to obtain a continuous mesh and a correlation between the number of finite elements and the number of associated nodes; chose a simple type generally fixed mesh, a mesh type automatic. Also for rings was established a custom mesh [56]

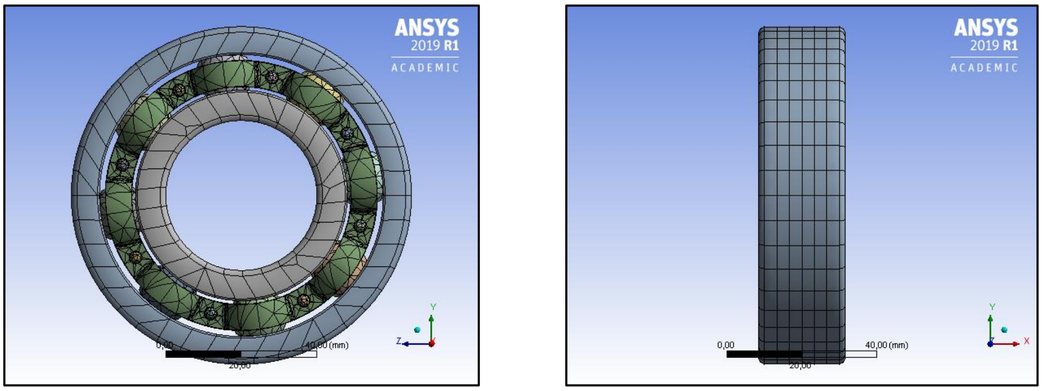


Fig.3.18 shows the meshing of the ball bearing

In general, any body in the space on which external demands act without being disturbed by any support, undergoes a pure movement without being deformed from within. Therefore, when analysing a physical system supporting certain loads and showing an action on it, it is imperative that a fixing system is previously fixed to the system to allow the system to react. For the analysis of the ball bearings presented, the constraints that we applied to the axial and radial load conditions are as follows:

Equivalent static bearing load

Static loads comprising radial and axial components must be converted into an equivalent static bearing load. This is defined as that hypothetical load (radial for a radial bearing and axial for a thrust bearing) which, when applied, would cause the same maximum rolling element load in the bearing as the actual loads to which the bearing is subjected. It is obtained from the general equation [57]

$$P_0 = X_0 F_r + Y_0 F_a \quad (1)$$

For ball bearing in normal operation $S_0=1$ and $S_0=Cr_0/Pr_0$

$$P_{o}= 10KN \quad (2)$$

P_0 - equivalent bearing static load, kN,

F_r - radial component of the heaviest static load, kN,

F_a - axial component of the heaviest static load, kN,

X_0 - radial load factor of the bearing,

Y_0 - axial load factor of the bearing.

The requisite basic static load is calculated using the equation:

$$C_{r0} = s_0 P_{r0} \text{ , kN} \quad (3)$$

Where:

C_{r0} - basic static load rating, kN

s_0 - static safety factor

P_{r0} - equivalent static load, kN.

Table 3-4 Value of static safety factor [51]

Values for static safety factor s_0 — Table 2.12

Type of operation	Requirements regarding quiet running					
	Unimportant		Normal		High	
	Ball bearings	Roller	Ball bearings	Roller	Ball bearings	Roller
Smooth, vibration-free	0,5	1	1	1,5	2	3
Normal	0,5	1	1	1,5	2	3,5
Heavy shock loads	>1,5	>2,5	>1,5	>3	>2	>4

Applying the boundary conditions (fixed / mobile determination, motion determination), in the current case the fixed element is the outer ring and the inner ring is allowed to rotate on axes X

a. **The first case: apply the load on the inner ring and fix the outer ring**,

This load the direction and the components of the force, Here in this case the force is radial so the components will be (0 N; -10 KN; 0N) Loading and boundary conditions basically consist of two steps first is support and second is applying loads;

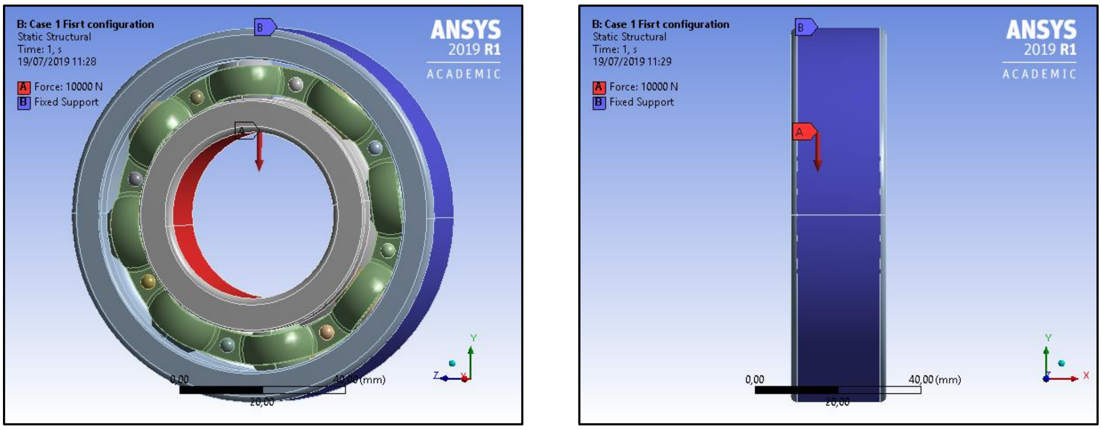


Fig.3.19 Boundary condition first case

b. **The Second case: apply the load on the outer ring; fixed support: inner ring**

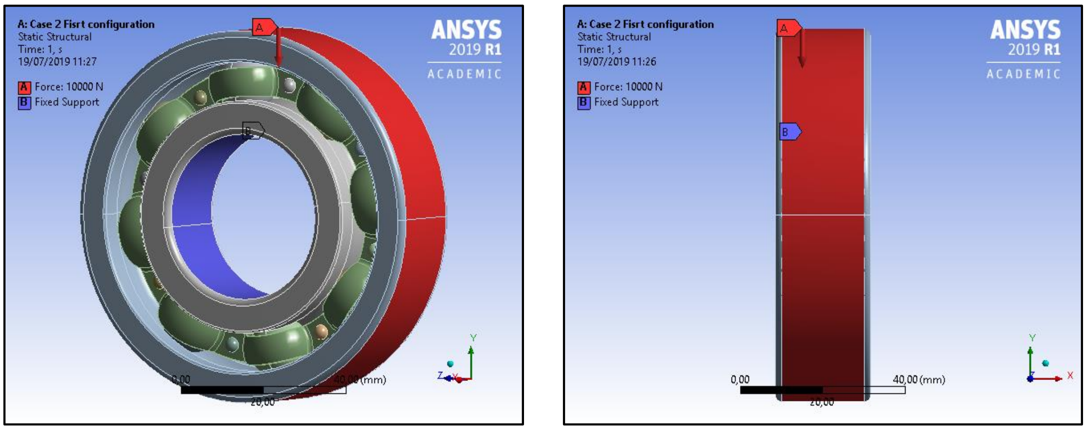


Fig.3.20 Boundary condition second case

c. **Result first configuration: running the solution on ANSYS**

After running the solution of above model we get different values of solutions such as, Equivalent Stress, Total deformation. All the results are described below.

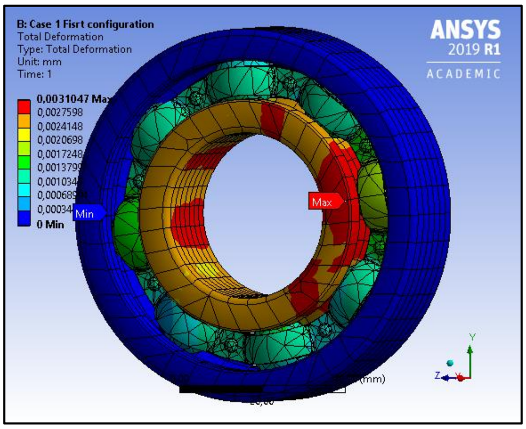


Fig.3.22 Total deformation case 1 *[87]*

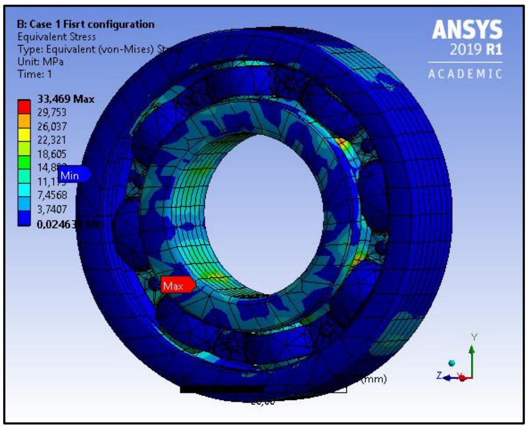


Fig.3.22 Equivalent stress of Von Mises case 1 *[87]*

Result details for the first configuration first case

Table 3-5 Result details for the first configuration first case

Object Name	Total Deformation	Equivalent Stress
Results		
Minimum	0, mm	2,4638e-002 MPa
Maximum	3,1047e-003 mm	33,469 MPa

For the second case

Details of total deformation and the equivalent stress Von-Mises for the first configuration second case

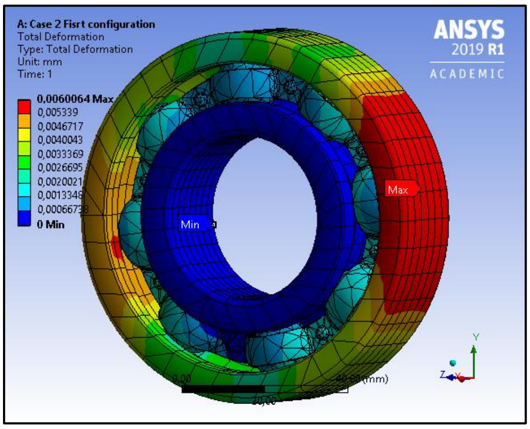


Fig 3.24 Total deformation case 1 [87]

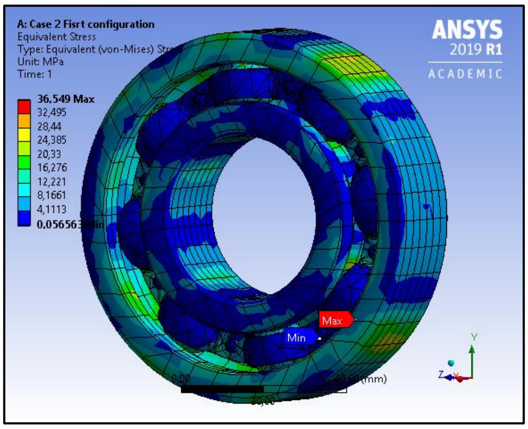


Fig 3.24 Equivalent stress of Von Mises case 2 *[87]*

Table 3-6 Details of the result Von-Mises for the first configuration second case

Object Name	Total Deformation	Equivalent Stress
Minimum	0, mm	5,6563e-002 MPa
Maximum	6,0064e-003 mm	36,549 MPa

In this section, an effort has been made to analyse the rolling ball bearing using the finite element stress or displacement behaviour and the pressure contact of rolling ball bearing. The obtained results were compared with the results obtained through the methodology of Hertz theory and solution of analytical formulas and equations based on specific ball bearing parameter and also with the result of MESYS software.

In order achieve optimal results demonstrate an almost identical similarity of results of numerical and analytical solution and correct setting up computational software ANSYS Workbench and MESYS.

In order calculate the dependency of result on nodes and elements, here in this work it perform mesh of ball bearing with different number of nodes and elements and calculated the value of contact stresses [55].

Optimization of the mesh was carried out in order to obtain a continuous mesh and a correlation between the number of finite elements and the number of associated nodes. chose a simple type generally fixed mesh, a mesh type "Tetrahedrons", the resulting mesh is top quality with a relatively small number of 36269 nodes and 18700 elements in view of the structure and complexity. Also for rings was established a custom mesh [56].

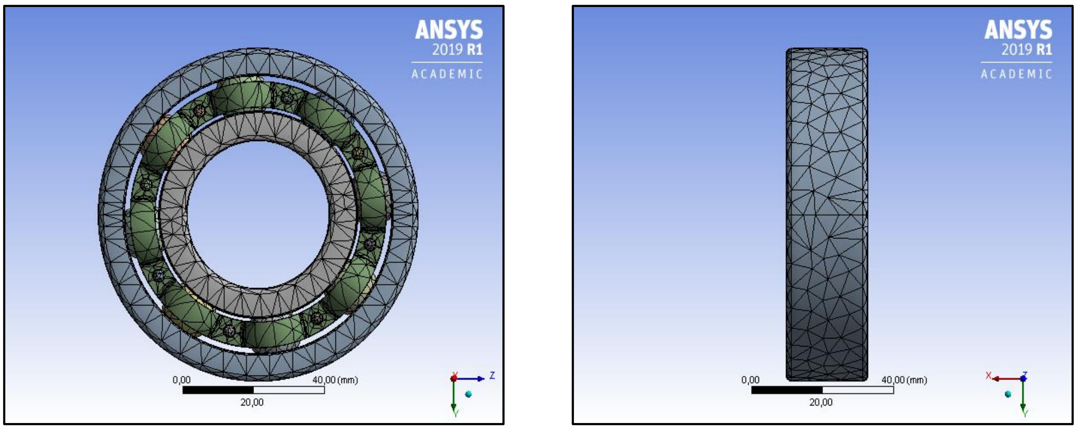


Fig.3.25 Meshing second configuration

The FEM analysis was performed in ANSYS Workbench. The simulation of the investigated bearing was solved as a linear isotropic material model with given material properties of linear structural steel E = 210,000 MPa, ν = 0.29.
The contact pairs have been customized between the individual roller elements and rings as well as the cage through the contact region function. The contact between the elements was given as friction contact f = 0.5.
The boundary conditions of the bearing have been specified for each part as follows:

The outer ring and also inner ring displacement was removed in the x-axis direction and allowed in the direction of the z and y axes in the global Cartesian coordinate system. The coordinate systems are marked in **Fig.3.26**

External load was set with value 10 KN as Bearing Load in the negative y-axis direction with a bearing time of one second for simulation of impact load.

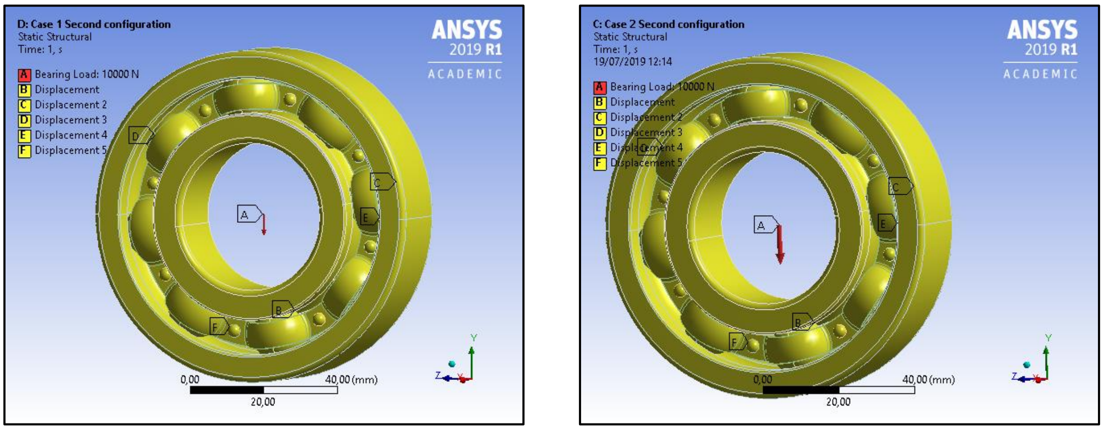


Fig.3.26 First and second case second configuration boundary conditions

The contact pairs have been customized between the individual balls elements and rings (inner and outer) as well as the cage through the contact region function.

The contact between the elements was given as friction contact f = 0.5 as show in Fig.**3.27**

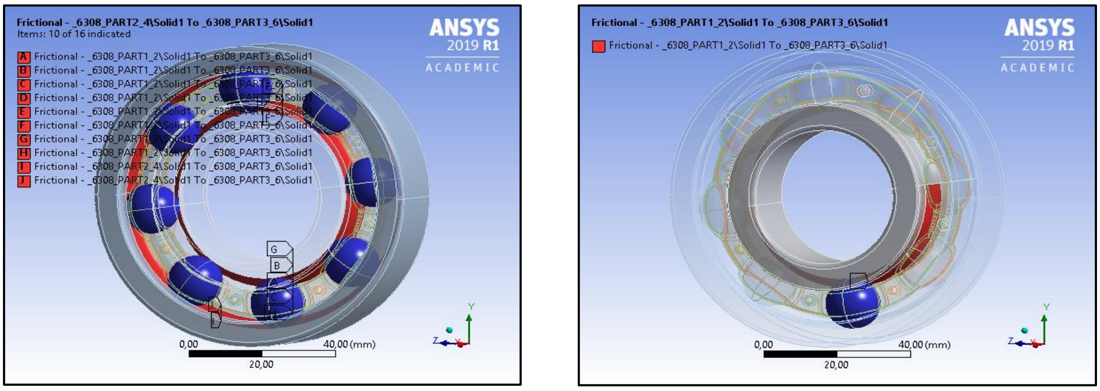


Fig.3.27 Contact Rings/Balls

After running the solution of above model we get different values of solutions such as, Contact pressure, stress, Equivalent Stress, Total deformation. All the results are described below :

First case

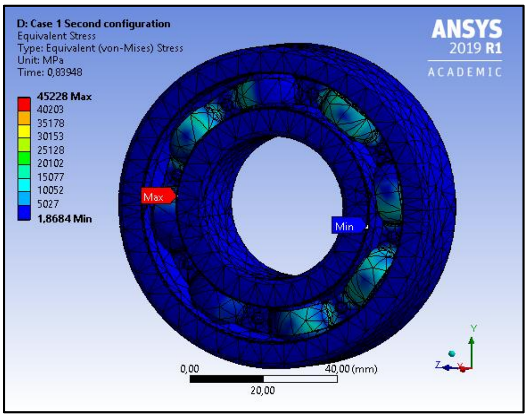


Fig.3.29 Equivalent stress second configuration case 1

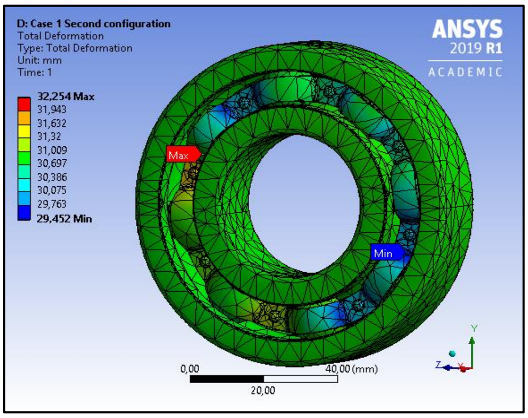
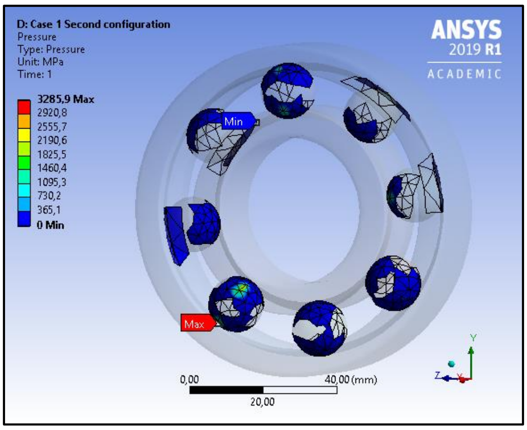


Fig.3.29 Total deformation second configuration case 1

Table 3-7 Detail of the result first case second configuration

Object Name	Total Deformation	Equivalent Stress
Minimum	29,452 mm	1,8957 MPa
Maximum	32,254 mm	45228 MPa

Result of the contact pressure:



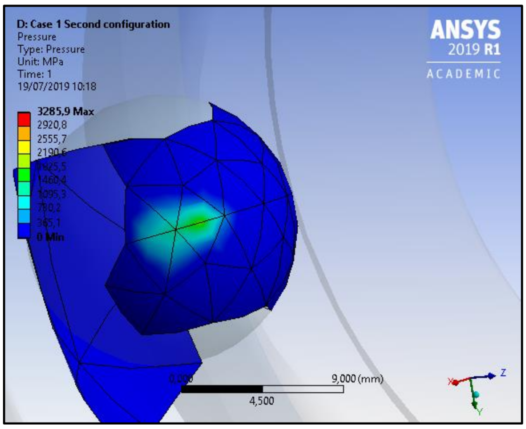


Fig.3.30 Result first case : Pressure contact (Balls/Rings)

Table 3-8 Details of pressure first case

Object Name	Pressure
Minimum	**0, MPa**
Maximum	**3285,9 MPa**

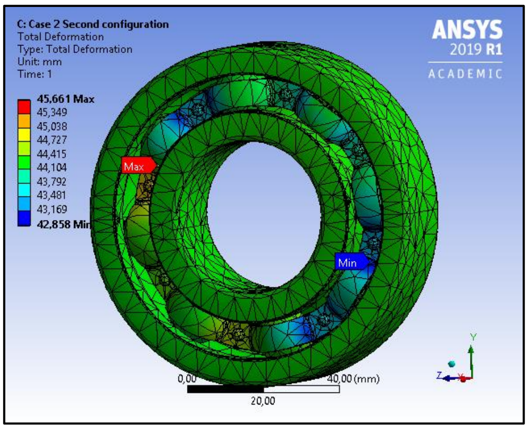


Fig.3.32 Total deformation second configuration case 2

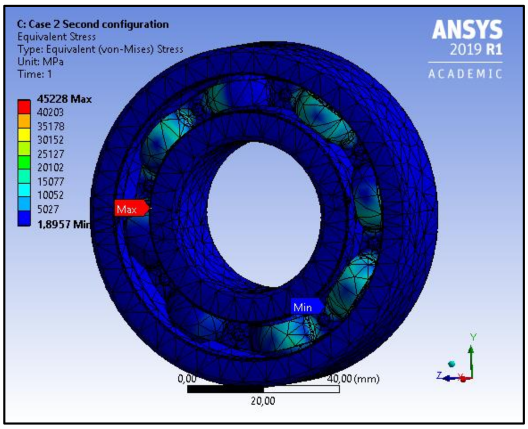
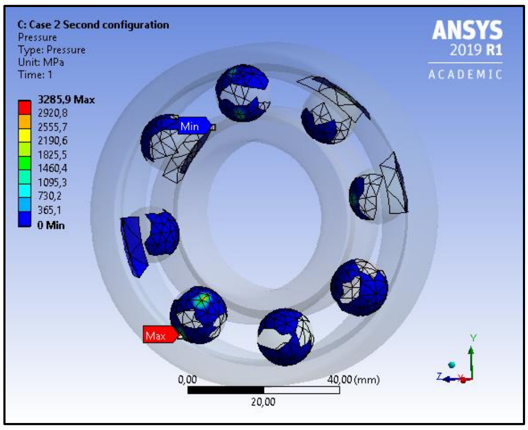


Fig.3.32 Equivalent stress second configuration case 2

Table 3-9 Details of the result of the second configuration second case

Object Name	Total Deformation	Equivalent Stress
Minimum	**42,858 mm**	**1,8957 MPa**
Maximum	**45,661 mm**	**45228 MPa**

Result of the contact pressure:



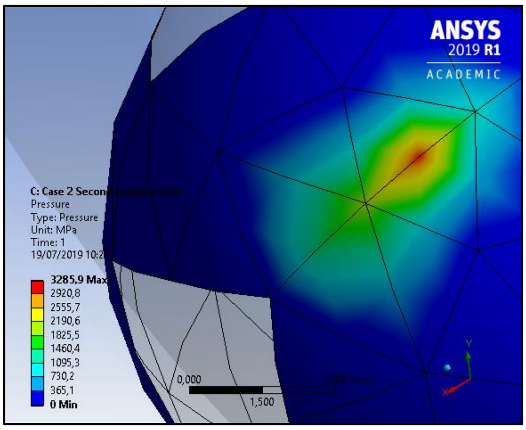


Fig.3.33 Result second case : Pressure contact (Balls/Rings)

Table 3-10 Details of pressures second case

Object Name	Pressure
Minimum	**0, MPa**
Maximum	**3285,9 MPa**

C. Analytical calculation

In the elastic area, it is possible to calculate the contact pressure and the resulting deformation at the contact points of the rolling elements and orbits by means of Hertz theory. Concerning to the contact of the volume elastic bodies.

The general conclusions of this theory are based on three main assumptions.

1. The material of the bodies to be touched must be homogeneous and isotropic.
2. Only normal stress, not shear, can be transmitted in the contact area.
3. The proportional limit of the material must not be exceeded, that is, there can be no plastic deformation [58] [59].

The contact area of the point contact of the load between the two curved bodies in point contact is generally elliptical **(**

Fig.3.*34*). The elliptical contact surface for two components with identical

elastic modulus E and Poisson constant is defined according to Hertz theory with respect to the main axis.

When the rolling ball bearing works, it is usually that more than one rolling ball bears the load. The condition is complex between rollers and rings.

When the load is 0, contact area is a point, i.e., point-contact. When the load increases in running, the bearing inner ring, outer ring and rolling elements bring forth plastic deformation in the contact area, so the point contact becomes face-contact. Furthermore, contact area gradually becomes ellipse, and generates residual stress [60] [61].

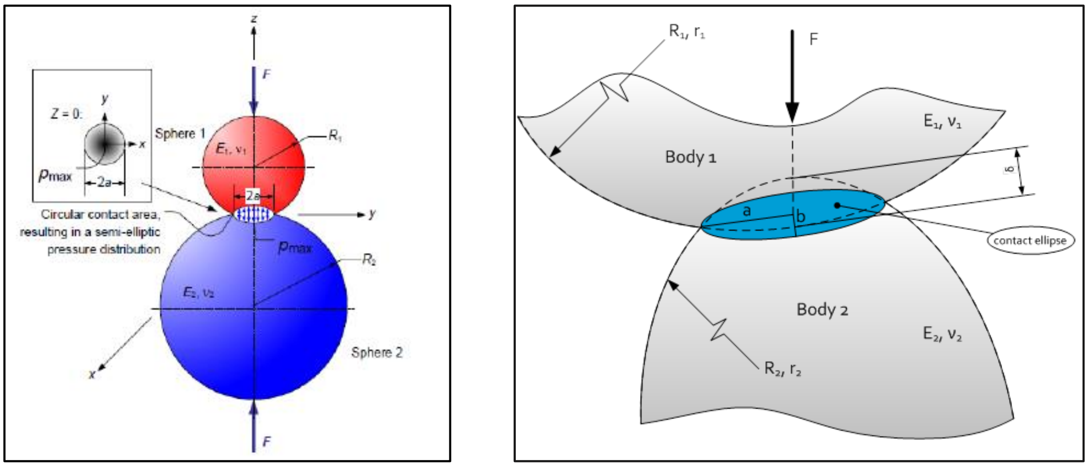


Fig.3.34 Contact between 2 spheres [62] [63]

The contact parameters, such as the place, size, shape of contact area, as well as the contact pressure and friction force distribution, will be variable with the loads changing. These facts are typical boundary conditions for nonlinear problems. When any two curved bodies of different radii of curvature are brought into contact they will initially touch at either a point or

along a line. With the application of the smallest load, elastic deformation enlarges these into contact areas across which the loads are distributed as pressures.
The first analysis of the situation was presented by Heinrich Hertz in 1881 and is based on the following assumptions [64].

$$P = \frac{3F}{2ab\pi} \quad \text{..(4)}$$

The maximum pressure computation was performed by using the following relationships dependent on bearing parameters, external load and mathematical coefficients. External load was defined for value F= 10,000 N according to the empirical formula (Eq. 4), which depends on constructional and physical properties of specific vehicle, wheel drive and rolling ball bearing .

From the

Fig.3.**34** is possible to detect significant parameter a, which is defined as wide of contact area. In case of point contact, the maximum contact pressure is situated in the middle of contact area with appropriate value defined by equation (4 or 13) [65] [61]

$$a = 1{,}145.n_a.(IF.K.\gamma)^{1/3} \quad \text{..(5)}$$

$$b = 1{,}145.n_b.(IF.K.\gamma)^{1/3} \quad \text{..(6)}$$

$$n_c = \frac{1}{E(e)}.(\frac{\pi^2.k.E(e)}{4})^{1/3} \quad \text{..(7)}$$

$$E(e) = \int_0^{\pi/2} \sqrt{1 - e^2.\sin^2(\varphi)d\varphi} \quad \text{..(8)}$$

$$k = \frac{a}{b} \quad \text{..(9)}$$

$$e = \sqrt{1 - (\frac{a}{b})^2} \quad \text{..(10)}$$

$$k = \frac{1}{\frac{2}{R_1} - \frac{1}{R_2} + \frac{1}{R_3}} \quad \text{..(11)}$$

$$\gamma = \frac{(1 - \nu_1{}^2)}{E_1} + \frac{(1 - \nu_2{}^2)}{E_2} \quad \text{..(12)}$$

The maximum pressure [65] [61]

$$P_{Hertz} = 0{,}365.n_c.\left[\frac{IF}{K^2.\gamma^2}\right] \quad \text{..(13)}$$

a :crack semi-width

a_{mean} : mean crack semi-width

b : semi-minor axis of elliptical contact patch

d : diameter of ball

E: Young's modulus

p_o max elliptical contact pressure

R: radius of ball

v : Poisson's ratio

Table 3-11 Input Data (bearing geometry and parameters)

Parameters		Sphere	Circular Race	Unit
Poisson's ratio [v_1,v_2]		**0.29**	**0.29**	---
Elastic modulus [E_1,E_2]		**210000**	**210000**	MPa
Radius of objects	R_1,R_2	**7,54**	**8.01**	mm
	R_1,R_3		**7.665**	
Force [F]		**10**		KN

Table 3-12 The analytical results

RESULTS		
Parameter		Unit
Maximum Hertzian contact pressure [P_{Hertz}]	3110.	MPa
Rigid distance of approach of contacting bodies [d]	0.038	mm
Semi major axis of contact ellipse [a]	0.312	
Semi minor axis of contact ellipse [b]	4.930	

D. MESYS result

At this stage the results obtained with the ANSYS software and the results obtained with the MESYS software were compared to observe the differences and similarities. Input of the bearing geometrical parameters on MESYS and the loading F (0N; 10 KN; 0N)

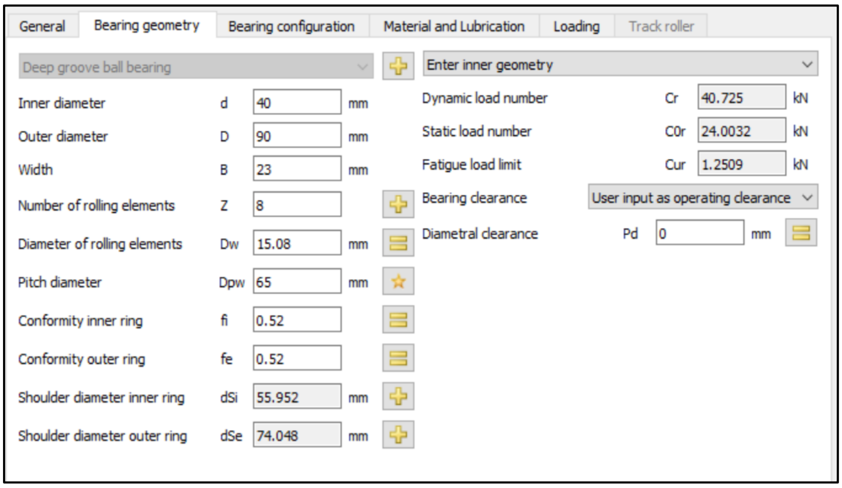


Fig.3.35 Input the bearing properties on MESYS

The geometry is described with number and diameter of balls, pitch diameter, conformity of inner and outer race and the diametral clearance. The number of balls in the bearing is restricted, to be able to assemble the bearing .

The distributions of the loads on MESYS are shown below

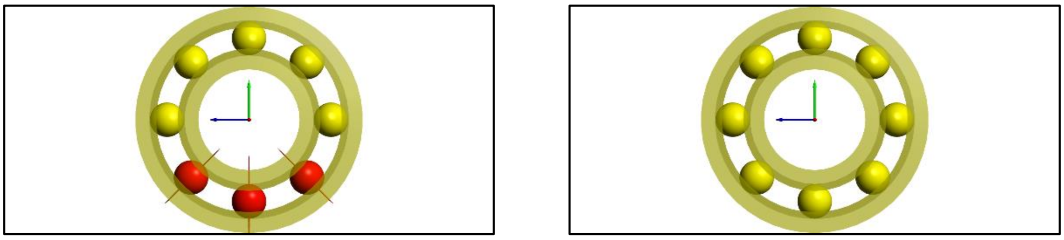


Fig.3.37 Bearing and load distribution on MESYS

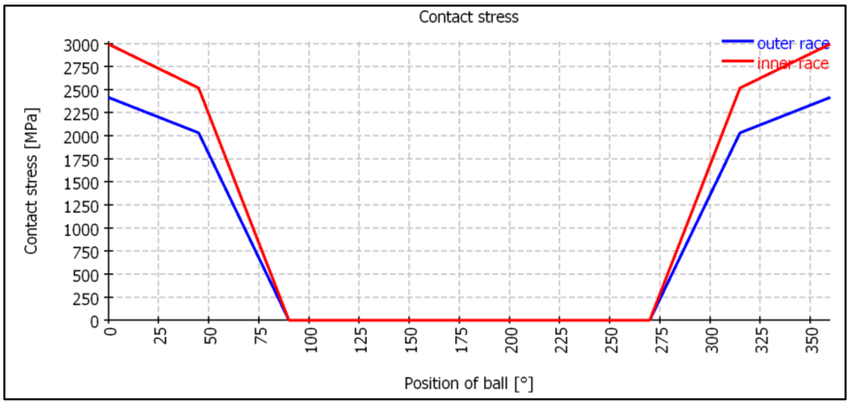


Fig.3.36 Contact stress MESYS position of the balls

The results are shown below : Basic rating life , safety sactor , elispe length ratio inner race, maximal pressure … etc

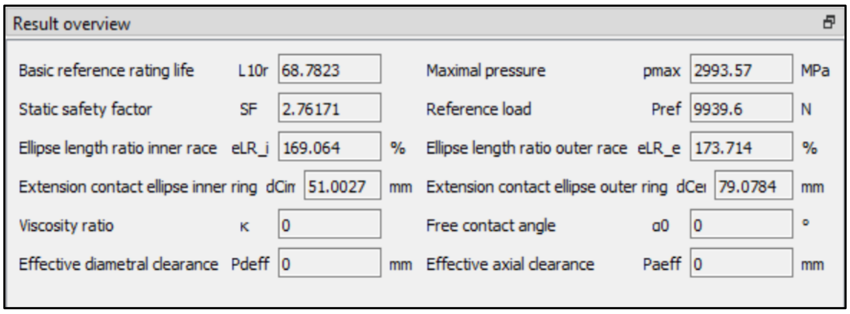


Fig.3.38 MESYS Result

E. Comparsaison with the result on MESYS

Table 3-13 Comparison between the results

	ANALYTICAL RESULT contact pressure	ANSYS RESULT contact pressure	MESYS RESULT contact pressure
Maximum Hertzian contact pressure	**3110**	**3285,9**	**2993,57**
Error analytical result	/	**5,65%**	**1,6%**
Error ANSYS Result	/	/	**5,20 %**

Analyse of the results led to the following conclusions: the observed differences may be due to the fact that MESYS does not take into account the presence of the cage; at the same time, ANSYS does not take into account the roughness of the surfaces,

Using two different methods of analysing the bearing ANSYS and MESYS help us to get more exact data that can be used to improve the geometry and the characteristics of the next generation products.

The difference of the result between the 2 configuration (stress and deformation) in order to calculate the dependence of the result on the nodes and the elements, in this work. carry out a mesh of ball bearing with a different number of nodes and elements and calculate the value of the stresses and displacements, keeping the same geometry , the properties of materials and the intensity of the load.

From the simulation and graphical outputs, the results of the stress-strain analysis using the FEM software can be clearly seen.

The results obtained by mesys and Ansys were then compared to the analytical results obtained using the Hertz theory methodology, which leads to the conclusion that the configuration of the boundary conditions of the simulation given in the ANSYS Workbench calculation software is acceptable. to the fact that the errors are less than 6%.

Chapter IV

First Step for the Implementation of TPM in the Bearing Industry

Total productive maintenance (TPM) is a pioneering Japanese concept, the term total productive maintenance which was accredited to Nippondenso, a company that created parts for Toyota. Seiichi Nakajima is considered as the father of TPM because of his plentiful contributions of TPM [66]. The concepts of Total Productive Maintenance (TPM) have been accepted in many organizations across the world. (TPM) is a scientific company- wide approach in which every employee at levels in the organization is concerned about the maintenance, the quality and efficiency of their equipment [67].

Overall Equipment Efficiency (OEE) is used as the measure of success of TPM implementation. The main aim of TPM implementation is to reduce six big losses that are equipment failures or breakdown losses, setup and adjustment losses, idling and minor stoppage losses, reduce speed losses, defect in process losses and reduce yield losses [68] in all possible area of the industries including top level management to floor workers.

4.2.1. Generalities

Rulmenti S.A., Barlad is a bearing manufacturing company located in Romania. The main shareholder is BERA Holding from Turkey.

The company acts with approximately 1400 employees. Main activities are design, production, sales and service of different types of bearings.

Fig.4.1 URB [51]

4.2.2. History

In 1953, the company started to produce bearings. A continuous improvement process was developed through the actual design, production and control facilities. Numerous changes were implemented in order to raise the life expectancy, loading capacity and operating precision of the bearings.

They include the respect for clients and the satisfaction of their needs among their fundamental principles. Therefore, they tried to respond better to the market requirements by offering, besides the bearings with standardized shapes and sizes, a large range of non-standardized bearings, specific to various utilization.

Tooling department is a competent business partner ready to offer advice, to help and solve problems. They have their own production capacity and can process parts and pieces under customer's orders.

RULMENTI S.A. BARLAD is a worldwide supplier of bearings and services in the rolling bearing business. The Company is among the biggest producers of rolling bearings from Europe and is known in the world market more than 65 years.

Today RULMENTI SA produces and distributes under URB brand a full range of bearings including Radial Ball Bearings, Cylindrical Roller Bearings, Spherical Roller Bearings, Thrust Ball Bearings, Thrust Cylindrical Roller Bearings, Tapered Roller Bearings all well known for their precision and reliability. All bearings are produced in accordance with the standards of International Organization of Standardization (ISO) and DIN standards.

RULMENTI SA is close to the customers through the wide distributor network in more than 40 countries, e.g. Romania, Germany, UK, Italy, Benelux, France, Spain, Ireland, Greece, Poland, Bulgaria, Serbia, Ukraine, Turkey, USA, South Africa, Brazil, Egypt, India, Korea, Taiwan, Thailand, Singapore, Vietnam, U.A.E. and other country [69].

4.3.1. History of total productive maintenance

After Second World War Japanese industries realized that, industries cannot produce good quality products with the help of poor maintenance system of equipment and it cannot stay in this competitive global market. For effective maintenance system, Japanese companies adopted U.S.A. based preventive maintenance policy in 1951 [70] .

Total productive maintenance (TPM) is a Japanese philosophy, which they imported after 1951.M/s Nippon Denso Co. Ltd japan, a supplier of M/s Toyota Motor Company, in the year 1971, firstly introduced TPM concept. "Total productive maintenance is an innovative concept to maintenance that eliminates break downs, optimizes equipment effectiveness and promotes autonomous maintenance technique by operators through day to day activities involving total workforce" [71].

4.3.2. Developmental stages of TPM

Preventive maintenance was introduced in the 1950's, with productive maintenance becoming well established during the 1960's. The development of TPM began in the 1970's. The period prior to 1950 can be referred to as the "breakdown maintenance" period [72].

This is the maintenance activity performed after equipment failure, stoppage or equipment performance gone dangerous and repair it [73]**.** Such a thing could be used when the equipment failure does not significantly affect the operation or production or generate any significant loss other than repair cost.

was introduced in 1951, in which a physical check up of equipment is performed to prevent equipment breakdown and increase equipment service life. In this phase, the maintenance function is established and time-based maintenance activities are generally accepted ;It is a daily maintenance (cleaning, inspection, oiling and re-tightening), design to retain the healthy condition of equipment and prevent failure through the prevention of deterioration, periodic inspection or equipment condition diagnosis, to measure deterioration. It is further divided into periodic maintenance and predictive maintenance. Just like human life is extended by preventive medicine, the equipment service life can be prolonged by doing preventive maintenance [74]**.**

:

Time based maintenance consists of periodically inspecting, servicing and cleaning equipment and replacing parts to prevent sudden failure and process problems.

The service life of important part is predicted based on inspection or diagnosis, in order to use the parts to the limit of their service life in this method. Compared to periodic maintenance, predictive maintenance is condition-based maintenance. It manages trend values, by measuring and analysing data about deterioration and employs a surveillance system, designed to monitor conditions through an on-line system.

It improves equipment and its components so that preventive maintenance can be carried out reliably. Equipment with design weakness must be redesigned to improve reliability or improving maintainability. The purpose of corrective maintenance is to improve equipment reliability, maintainability, safety, design weaknesses and to reduce deterioration and failure.

It indicates the design of a new equipment. Weakness of current machines are sufficiently studied (on site information leading to failure prevention, easier maintenance and prevents of defects, safety and ease of manufacturing) and are incorporated before commissioning a new equipment [75].

Table 4.1 Developmental stages

4.3.3. Definition

A complete definition of TPM includes the following five elements:

1. TPM aims to maximize equipment effectiveness (overall effectiveness).
2. TPM establishes a thorough system of PM for the equipment's entire life span.
3. Various departments (engineering, operations, and maintenance) implement TPM.
4. TPM involves every single employee, from top management to workers on the floor.
5. TPM is based on the promotion of PM through motivation management: autonomous small group activities.

The word "total" in "total productive maintenance" has three meanings that describe the principal features of TPM:

1. Total effectiveness (referred to in point 1 above) indicates TPM's pursuit of economic efficiency or profitability.
2. Total maintenance system (point 2) includes maintenance prevention (MP and maintainability improvement (MI) as well as preventive maintenance.
3. Total participation of all employees (point 3,4 and 5) includes autonomous maintenance by the operators through small group activities [72].

TPM (Total Productive Maintenance) is a holistic approach to equipment maintenance that strives to achieve perfect production:

- No Breakdowns
- No Small Stops or Slow Running
- No Defects

In addition it values a safe working environment:

- No Accidents

TPM emphasizes proactive and preventative maintenance to maximize the operational efficiency of equipment. It blurs the distinction between the roles of production and maintenance by placing a strong emphasis on empowering operators to help maintain their equipment.

The implementation of a TPM program creates a shared responsibility for equipment that encourages greater involvement by plant floor workers. In the right environment this can be very effective in improving productivity (increasing up time, reducing cycle times, and eliminating defects).

Total means improve overall effectiveness of plants, employees and renovate overall plant effectiveness by involving all employees from bottom to top management,

Productive means to produce defect free products with take care of the safety,

Maintenance means to increase the lifecycle of product or production system. Total productive maintenance is interfering between men and machine.

TPM can be considered as a medical science of machines. TPM brings maintenance into key role and focus as a necessary part of the business. The Japan institute of Plant Maintenance (JIPM) introduced the TPM is based on the implementation of series 8 pillars of TPM in a systematic manner to optimize the equipment and plant effectiveness by followed up between men and machine [71].

The Japanese introduced the concept of Total Productive Maintenance (TPM), in 1971 to overcome the maintenance problems. Its main objectives are obtaining ideal performance, enhancing product quality, minimizing losses, and improving effectiveness of equipment. It

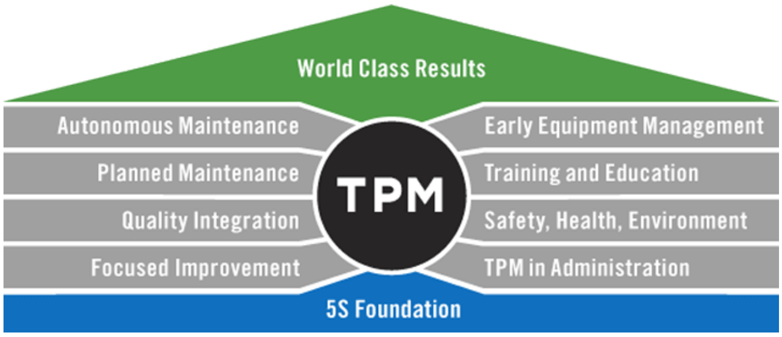


Fig.4.2 The traditional TPM model consists of a 5S and eight supporting activities *[80]* .

consists of eight pillars:

- Autonomous Maintenance,
- Planned Maintenance,
- Quality Maintenance,
- Focused Improvement,
- Early Equipment Management,
- Education and Training, Safety,
- Health and Environment, and
- TPM in Administration [76].

The answer is to view TPM not simply as Total Productive Maintenance in the sense of Overall Equipment Effectiveness (OEE), autonomous maintenance, 5 Ss, clean machines and so on, but rather as the proven roots and origins for applying company-wide TPM **Fig.4.3**. The original fifth pillar of TPM, Early Equipment Management or TPM for Design, links well with the broader view that TPM stands for Total Productive Manufacturing. As such, it is not a Maintenance Department-driven initiative, but actually brings production and maintenance together as equal partners under the umbrella of manufacturing. Similarly, 'TPM in the Office' is better served by broadening the application of these sound and proven principles into 'TPM in Administration', embracing all support functions such as sales, marketing, commercial, planning, finance, personnel, logistics, stores and information technology (IT).

Company-wide TPM recognizes that:

If equipment OEE improves but the overall door-to-door time remains the same, the waste is not removed; if equipment capability improves but quality standards remain the same, a potential area of competitive advantage is lost;

If knowledge gained about the process does not produce higher rates of return on investment, the organization is not making the best use of its capabilities;

If capability is increased but this is not met by generation of new business, an opportunity to reduce unit costs is lost.

Tools of TPM

A variety of tools is often used to help the deployment of activities through TPM programs

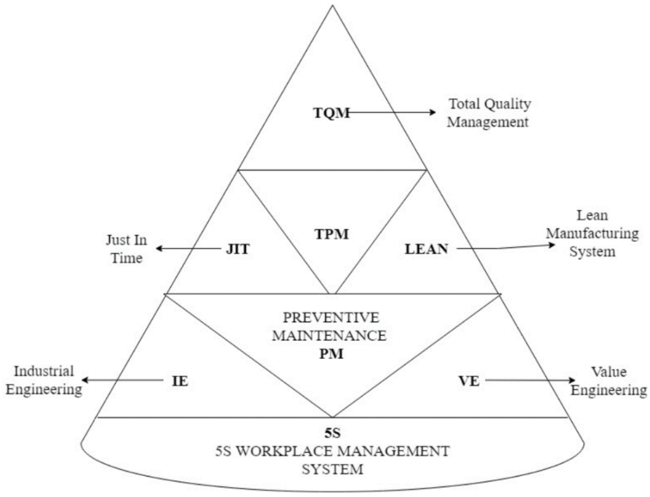


Fig.4.3 Relationship between TPM and lean manufacturing philosophy *[70]*

based on these pillars.

Among the tools used by TPM to analyse and solve equipment and process related problems are Pareto Analysis, Statistical Process Control (SPC – control charts, etc), problem solving techniques like brainstorming, cause and effect diagrams and 5M Approach, visual control like OPLs, Poka-Yoke Systems, Autonomous Maintenance, Continuous Improvement, 5S. Setup Time Reduction, Waste Minimization, Bottleneck Analysis, Recognition and Reward Program and Simulation [77].

The main objectives of TPM implementations is to reduce occurrence of unforeseen machine breakdowns that interrupt production and lead to losses [78].

OEE = Availability (A) × Performance (P) × Rate of Quality (Q)

A. Availability is the proportion of time available for which a machine runs or production purposes. When a process is stopped, it's creating a cost with no associated value . Availability is the ratio of Operating time and Loading time.

Availability (A) = [(Loading time-Downtime) ÷ Loading time] × 100

B. Performance is the results of activities on an organization over given period of time. A Performance score of 100% means when the process is running as fast as possible.

Performance Rate= [(Standard cycle time × Product unit processed) ÷ Operating time] × 100

C. Quality (Q) is percentage of good parts out of total produced parts. A quality score of 100% means there is no defect.

Quality Rate= [(Product unit processed –Defect Units) ÷Product unit processed] ×100 [79] **.**

Table 4.2 TPM TOOLS [79]

Component	**TPM Goal**	**Type of productivity Loss**
Availability	No Stops	Availability takes into account Availability Loss, which includes all events that stop planned production for an appreciable length of time (typically several minutes or longer). Examples include Unplanned Stops (such as breakdowns and other down events) and Planned Stops (such as changeovers).
Performance	No Small Stops or Slow Running	Performance takes into account Performance Loss, which includes all factors that cause production to operate at less than the maximum possible speed when running. Examples include both Slow Cycles, and Small Stops.
Quality	No Defects	Quality takes into account Quality Loss, which factors out manufactured pieces that do not meet quality standards, including pieces that require rework. Examples include Production Rejects and Reduced Yield on startup.
OEE	Perfect Production	OEE takes into account all losses (Availability Loss, Performance Loss, and Quality Loss), resulting in a measure of truly productive manufacturing time [80].

Six Big Losses

One of the major goals of TPM and OEE is to reduce or eliminate what are called the six big losses which they are the most common causes of efficiency loss in manufacturing. The link of the losses and the effectiveness in TPM is defined in terms of both the quality of the product and the equipment availability. Any operation time may face losses and these losses can be visible like scrap, changeovers and breakdowns or invisibles such as the slow running, the frequent adjustment to maintain the production within tolerance, Nakajima summarised the loss in a six big losses [81].

Six big losses [82]

Major loss event	OEE Metric	Loss category	Example of Loss category
Machine Breakdowns	Availability	Down time	Equipment failures, Tooling damage, Unplanned maintenance
Machine adjustments/setups	Availability	Down time	Process warm-up, Machine change over's, material shortage
Machine stops	Performance	Speed	Product misdeeds, component jam, product flow stoppage
Machine reduced speeds	Performance	Speed	Level of machine operator training, Equipment age, Tool wear
Machine bad parts	Quality	Quality	Tolerance adjustments, worm up process, damage
Machine production bad parts	Quality	Quality	Assembled incorrectly, rejects, rework

Table 4.3 SIX BIG LOSSES [14]

The successful implementation of the five CAN DO steps provides a powerful organizational learning tool.

This is because CAN DO influences two important areas of corporate memory: process layout best practice routines It provides a positive development path for manager /shopfloor relationships, helping to highlight the barriers to change and conform to world-class values.

The TPM implementation process is built around the CAN DO steps (as are the seven steps of autonomous maintenance).

During visiting the company,

A questionnaire was distributed to 20 employers of different statue and different post to make a first evaluation

Table 4.4 Questionnaire

	POINT	**0**	**1**	**2**	**3**	**4**
	Questions					
1	Qualified personnel inspect actions plan before being set up.					
2	A flash meeting closes each cleaning activity (point / unfolding, observation ...).					
3	The anomalies are resolved in time , there are no unjustified old actions					
4	The respect monthly meeting are planed					
5	A communication board is installed and updated on the workstation					

	POINT	0	1	2	3	4
6	The anomalies are the subject of a plan of action and are quickly treated?					
7	Do operators conduct daily visual inspections of their equipment?					
8	Is the work area free of any slipping hazards such as oil or coolant on the floor?					
9	The anomalies found during the autonomous inspection are systematically recorded.					
10	The path are clean and clear.					
11	There is an useless object on the work station					
12	There is good collaboration with the maintenance department (resolution of important actions) with your department.					
13	Security conditions are well respected					
	Environmental, health and safety standards (conditions) are applied (respected)					
14	An autonomous maintenance indicator is monitored and updated (number of anomalies noted ...)					
15	Examples of zero defects are visible at the workstation					
		Total : 00 /60				

The result of the questionnaire give us some material to evaluate the factory

The average is : 50,41 witch is very good , but if we look at the details: the average decreases more often on a few points:

5 .The respect monthly meeting are planed 6 .The anomalies are the subject of a plan of action and are quickly treated (insufficient) 8 .Is the work area free of any slipping hazards such as oil or coolant on the floor? 10.The path are clean and clear. 13. Security conditions are well respected

The relation with the 5S :

- Seiri (sort): Cleanliness

The path are clean and clear.
Is the work area free of any slipping hazards such as oil or coolant on the floor?
There is an useless object on the work station

5S is based on a Japanese approach to establishing and maintaining an organized and effective workplace is "a systematic method to organize, order, clean, and standardize a workplace – and keep it that way." [83].

It is a system to reduce waste and optimize productivity and quality through maintaining an orderly workplace and using visual signals to achieve more consistent operational results. It is aimed at to implant the values of organization, neatness, cleaning, standardization and discipline into the workplace in its existing configuration. In the daily work of a company, routines that maintain organization and orderliness are essential to a smooth and efficient flow of activities. Sort, the first S, focuses on eliminating unnecessary items from the workplace that are not needed for current production operations. Set in order focuses on creating efficient and effective storage methods to arrange items, so that they are easy to use, and to. 5S is considered to be the first lean method implemented by firms. The description of the steps of 5S is given below

• Seiri (sort): Remove all items from the workplace that are not needed for current production operations or for records. Unnecessary material at the work place can lead to errors and defects.

• Seiton (set in order): Arrange and label needed items so that they are easy to locate and use.

• Seiso (shine): Clean floors, equipment, and work stations, this step also includes identifying and preventing the sources of contamination or dirt.

• Seiketsu (standardize): Adopt methods and practices to maintain Sort, Set in Order, and Shine on an ongoing and continuously improving manner.

• Shitsuke (sustain): Make 5S standard practice [73].

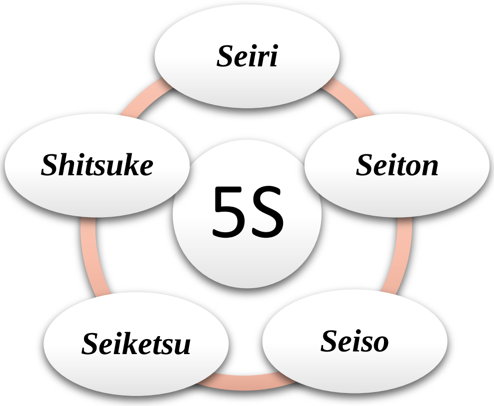


Fig.4.4 THE 5S [authors]

In English-speaking countries an alternative way of expressing the 5 Ss is the more easily remembered CAN DO of

- Cleanliness
- Arrangement
- Neatness
- Discipline
- Order

The philosophy is exactly the same, however:

1. Get rid of everything and anything unnecessary.
2. Put what you do want in its right place so that it is to hand.

3. Keep it clean and tidy at all times, recognizing that cleanliness is neatness (a clear mind/attitude), is spotting deterioration (through inspection), is putting things right before they become catastrophes, is pride in the workplace, giving self-esteem.
4. Pass on that discipline and order to your colleagues so that we all strive for a dust-free and dirt-free plant.

The CAN DO approach, therefore, is to look at the production facility and clean the workshop and its plant and machinery as it has never been cleaned before, whilst at the same time casting a ruthlessly critical eye at everything in the workplace. Nothing must be allowed to remain anywhere on the shopfloor unless it is directly relevant to the current production process. Good housekeeping thereafter becomes everyone's responsibility and a way of life.

The cleaning process involves the operators of machines and plant. As they clean, they will get to know their machines better; they will gradually develop their own ability to see or detect weaknesses and deterioration such as oil leaks, vibration, loose fastenings and unusual noise. As time goes on, they will be able to perform essential, front-line asset care and some minor maintenance tasks within the limits of their own skills. The process will take place in complete co-operation with maintenance people, who will be freed to apply their technical skills where needed. With the attitude to cleanliness and good housekeeping understood, we can move on to explain the main principles on which TPM is founded [84].

Step1 Preparing the site: Take note of the process, use the guide and its annexes to prepare all the necessary equipment. Set up the activity table and prepare the communication / training materials for the staff.

Step 2 The big storage room: Remove from the workstation all that is useless, to repair or to put away somewhere.

Step 3 The upgrade: Processing labels, and set up the cleaning kit. Preparation and realization of the DAY 5S. Treatment of anomaly observations and improvement ideas from the 5S day.

Step 4 Assignment: Define the ideal layout of the workstation and perform temporary floor marking with colored tape. Also identify all locations: tools, consumables, working documents etc ...

Step 5 Maintaining the established standard: Write cleaning ranges, establish a daily, weekly and monthly schedule.

Step 6 Analyse and remove sources of soiling. Facilitate access to clean, drive, adjust: transparency, speed of disassembly.

Step 7 Sustainability: Set up maintenance audits to avoid drifting. Take stock of the site and record the lessons (+/-).

Finalize the action plan. Develop maintenance tools (self-maintenance ranges)

This treats information, collation, equipment, understanding and maintenance as things that are necessary, compared to sources of contamination, human error and hidden losses as unnecessary items. Having decided what is necessary, work processes can then be formalized/refined. One of the outcomes of implementing best practice in this way is that many tasks can be simplified such that the most appropriate person can carry them out.

This releases specialist maintenance or production personnel to concentrate on optimization of plant and equipment, providing the gateway to ‘better than’ new performance. The stepwise implementation philosophy of the TPM principles is set out below. Continuous improvement in OEE The initial process of cleaning and establishing order leads to discovering abnormalities, and progresses through four steps:

1. Discover equipment abnormalities.
2. Treat abnormalities and extend focus to supply chain losses.
3. Set optimal equipment conditions to deliver future customer expectations.
4. Maintain optimal equipment conditions during delegation of routine.

The objective of this process is to move progressively towards a situation where all production plant is always available when needed and operating as closely as possible to 100 per cent effectiveness. Achieving this goal will certainly not come easily and may take years. The basic concept is one of continuous improvement: ’What is good enough today will not be good enough tomorrow’ [84].

Chapter V

General conclusion

The bearings industry began to use remarkable technological advancement to improve products quality. Optimization of standard construction, improving the calculation and testing methods including the Finite Element Method have provided high quality product with low cost.

Since failures in engineering products especially in rotating machinery, early fault detection of the rolling elements as bearings can lead to severe economic loss because of its detrimental influence on the reliability of equipment, its health monitoring is very essential particularly in aerospace, civil, marine and other structures to avoid premature failures. Precise incipient structural damage identification and its location is of great interest to many researchers.

Different techniques have been developed for monitoring and diagnosis of rolling element bearings

Simulation is a powerful modular system that uses numerical software and allow the engineer to predict the behaviour of the structure under its working conditions. By using ANSYS to numerically simulate and analyse on stress and strain during deep groove ball bearing contacts, the finite element solutions were got, which had good consistency with the Hertzian theory solutions. The contact analysis of finite element method can easily and intuitively get the strain values. Which can efficiently understands the parts running information, such as contact penetration, contact-sliding distance, and so on. Those will provide reference and evidence for strength Analysis, life-design and structural optimum about complex bearing.

Concerning the total productive maintenance: The crux of the above literature review is that, in order to improve the 5S Japanese approach, in otherwise the CAN DO approach, a systematic and methodological step is required and that is implementing pillars of TPM. It is thus observed, that TPM forms the basis of OEE (Overall Equipment Efficiency) implement, in all industries and more research work are always useful to optimize the method, to improve productivity. The three parameters of OEE viz Availability, Performance and Quality rate needs to be taken special care off, and their improvement, directly contributed to improve OEE of concern machine, or entire manufacturing unit.

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