Reliability Analysis of Self-Aware Components on Network

Submitted in partial fulfillment of the requirements

of the degree of

Bachelor of Technology and Master of Technology

by

Madhusudan Kumar

(13D100014)

Supervisors :

Prof. Makarand S. Kulkarni,

Prof. Tanmay K. Bhandakkar

Department of Mechanical Engineering

INDIAN INSTITUTE OF TECHNOLOGY BOMBAY

(2018)

This thesis/dissertation/report entitled “Reliability Analysis of Self-Aware Components on Network” by Madhusudan Kumar 13D100014 is approved for the degree of Bachelor and Master in Technology, Mechanical Engineering

Examiners

Supervisor

CoSupervisor

Chairman

Date: 21/JAN/2019
Place: IIT-BOMBAY, POWAI.

DECLARATION

I declare that this written submission represents my ideas in my own words and wherever others' ideas or words have been included, I have adequately cited and referenced the original sources.I also declare that I have adhered to all principles of academic honesty and integrity and have not misinterpreted or fabricated or falsified any idea/data/fact/source in my submission. I under-stand that any violation of the above will cause for disciplinary action as per rules of regulations of the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

Madhusudan Kumar
13D100014
13/11/2018

ABSTRACT

Today Large amount of mechanical systems are used form day to day life to Space station and lots of research is going on in the field of lean production which is also called Industry 4.0, which is cost efficient model for industry. In Industry 4.0 major emphasis is given to inter-operateability of devices and effective communication among them without human intervention. One way to achieve this goal is through created semantic web with the help of ontology.The thesis focus on one more core issues common to mechanical system, which is having insufficient failure data for machine parts.This limits our prediction of failure and maintenance at the right time, which causes loss in terms of time and money. This thesis aims at providing solution to above problems using physics based reliability models, ontology tool, and Machine learning methods. The problem has been approached with minimization of cost, processing time and data. The fixed parameters of the component will be in the form of ontology, which is concise and organized way of storing data. The algorithm doing the analysis is designed in python. The algorithm will create more failure data by merging the failure data of the similar components.Finally algorithm provides user with shape and size parameter which can be used to find the reliability of the device at any time.

TABLE OF CONTENTS

List of Figures

Chapter 1

Introduction

Today industries are interested in reducing human involvement in the process of production and maintenance of industry, which is called lean production. The proposed solution is to make machine and its parts self-aware which will allow them to communicate with each other through common framework.Lots of research is going on in building this framework.Many methods have been proposed like *INDUSTRY 4.0, Smart Machines, Internet Of Things, Digital Twins* and *Semantic Web*, which is discussed in chapter 2 of this thesis. They address the various problems which are there in industry for smart communication between two machines/machine's parts.The first challenge that exist for achieving this goal is lack of standardization of data among the different sectors of same industry or among different industries.The common framework (like *INDUSTRY 4.0, Smart Machines, Internet Of Things, Digital Twins* and *Semantic Web*) addresses this issue by creating virtual framework with standard guidelines for standardization of data and this data is available to everyone. Semantic web does this with the help of ontology which represents data in structure way [1, 9, 15, 26].The second issue in achieving the above goal is all the data should be human and machine readable.This is also achieved by above mentioned frameworks.The semantic web can easily achieve this through ontology, which has been demonstrated in this thesis.The another major problem in industry is the problem of not having sufficient failure data for all machine parts.This limits the possibility of having proper knowledge of failure of the parts. This impacts the operation time of the machine because of unexpected failure occurring in the machine.This may also delay the maintenance of the machine because of the unpreparedness of the workers for the failure.The main objective of this thesis is to demonstrate that it is possible to design self-aware machine parts and hence making the whole machine self- aware by following hierarchical structure. Design a framework which connects this self-aware machine parts to other self-aware machine parts.The program can easily extract all information from each self-aware machine parts and use it for computation. This thesis demonstrates the same while providing the solution of the insufficient data problem.The Reliability approach can be helpful in creating the solution of insufficient data problem. The focus of this thesis is to solve the problem of insufficient failure data for components in the industry using virtual representation of the components on the network and designing a algorithm which accesses the available data and uses it to solve the problem at hand.The objectives of the thesis were, firstly, to represent physical components on the network with the help of parameters. Secondly define the structure of this components on the network.Thirdly use physics based reliability model to compute reliability of each components for each mode of failure and compare it to compute similarity of the two components.Finally merge the failure data of the individual components to compute the shape and size parameter. The thesis is divided into 4 chapters after this chapter. Chapter 2 discuss the recent development in the field of manufacturing.Frameworks developed for representing the physical machines virtually and framework of automated factory is also discussed. Chapter 3 sheds light on theoretical stress models for shaft and gear, which is used along with reliability model to develop algorithm used for computing reliability of modes of failure.The failure modes considered for this thesis were failure due to bending, failure due to shear, life failure.How reliability is computed from given stress is also discussed. Chapter 4 presents the methodology which was used for this thesis in details.The methodology is simple create the ontology of all the machine and its parts on the network. Create the file for their loading condition. The program presented in the appendix reads this file and does reliability calculation for each mode of failure and then compares it with others to decide whether to merge the data on not.Chapter 5 presents the brief summary of the thesis and future scope of the work.

Chapter 2

Review Of Literature

The following sections discuss about the various technologies and methodologies being researched in the field of manufacturing. The main focus of all this technology is to solve the problems recognized in the industry. The first problem being "How can two components communicate with each other without human intervention", which has been explained in IoT section.The second problem is "How can a physical object can be monitored in realtime for making efficient decisions",which is discussed in section Digital Twin. The third problem is "How can we automate the whole enterprise itself", which is discussed in section INDUSTRY 4.0.Final problem is "How can we make data transfer efficient between two entities", which has been presented in semantic web.The sections discuss in brief few challenges in their respective fields and what are the solutions which has been proposed till now.

2.1 Internet Of Things

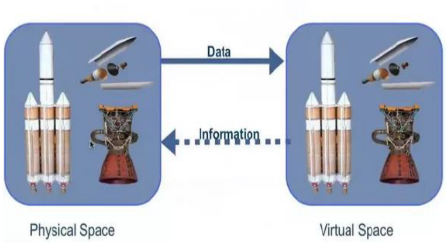
Last few years, the Internet of Things(IoT) has seen lot of development and has drawn significant research attention. IoT is considered as a part of the internet of the future and will comprise billions of intelligent communicating things.Pretz has suggested that the Internet of things (IoT) is a things connected network, where things are wirelessly connected via smart sensors [22].IoT is able to communicate with each other without human intervention.IoT applications in the field of health care, transportation,agriculture and automotive industries [7, 8, 16, 24, 22, 37, 38]. Kevin Ashton is considered as the first person to propose the idea of

IoT in 1999 and he referred the IoT as uniquely identifiable interoperarable connected objects with radio-frequency identification (RFID) technology.IoT was generally defined as ”dyanmic global network infrastructure with self-configurating capabilities based on standards and interoperable communication protocols; physical and virtual ’things’ in an IoT have identities and attributes and are capable of using intelligent interfaces and being integrated as an information network”[10]. The words ”Internet” and ”Things” mean an inter-connected world-wide network based on sensory, communication,networking and information processing technologies, which may become new version of information and communications technology (ICT), allowing them to communicate with other devices and services to achieve useful goals[17, 37]. The fundamental of IoT implies that physical things can be accessed and identified uniquely in the virtual representations.[17]

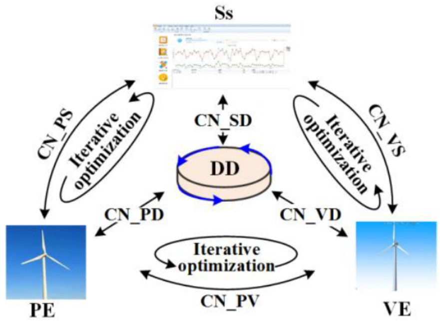
2.2 Digital Twin

Many areas in different industries have started applying Digital Twins.DTs allows manufacturers to take rational decision, create informed plans and to make accurate prediction [30].Tao et al have suggested 13 potential DT applications in the areas such as product design,production,planning, assembly, man-machine interaction in workshops etc [31].DTs is regarded as an important driver of the paradigm of smart manufacturing because it provides cyber-physical manufacturing system with information about a real-world situation and operating status.This type of information enhance a manufacturing system’s ability to do better analytical assessment, predictive diagnosis, and performance optimization [30].

The idea of DT was proposed by Grieves in his course on ”Product Lifecycle Management (PLM) in 2003 [30].NASA revised the concept of DTs in 2010, which defines DT as a multi-physics, multi-scale, probabilistic, ultra-fidelity simulation that reflects, in a timely manner, the state of a corresponding twin based on historical data, real time sensor data and physical model [6].Gabor et al defines DT as special simulation, built based on expert knowledge and real data collected from the existing system, to do more accurate simulation in different scales of time



(a) Three parts of the DT [30]



(b) Five parts of the DT[32]

Figure 2.1: Digital Twin Framework

and space [4].Maurer says DT is a digital representation that can depict the production process and product performance [29]. Recently DT special notions such as the Airframe Digital Twin (ADT) and Experimental Digital Twin(EDT) have been presented [25, 36].In literature two models of DT has been presented.First model of DT has basic framework, in which the virtual space is mapped to the physical space through the connection part that exchanges data and information (Figure 2.1(a)) [**M.2014DigitalReplication**].Recently Tao and Zhang proposed that a complete DT has five parts: physical part, virtual part, connection, data, and service. The framework is shown in Figure 2.1(b), where PE represents physical entity, VE represents the virtual entity, Ss represents the services for both PE and VE, DD stands for the DT data and CN menas the connection of different parts.Virtual part is derived from physical part. The virtual part supports simulation, decision- making and control the physical part. Data lies in the center of the DTs because it is a precondition for creating new knowledge.DTs provide services to improve convenience, reliability and productivity of an engineered system. Finally the connections are the means to communicate between the physical part, virtual part, data and service [32].

2.3 Industry 4.0

Today competition in industry demands more reliability and quality products for customers and less cost of production and faster rate of production.Lean Production principle has been widely accepted in industry after their first appearance in 1990. The Lean production strictly integrates humans in the production process, a continuous improvement and focus on value adding activities by avoiding of waste.The new paradigm called Industry 4.0 has become popular in industry for lean production solutions as well as production's applicability to different production types. Industry 4.0 is a network approach where components and machines are becoming smart and a part of a standardized network based on the well proven internet standards.All entities of the whole production-market network will have relevant data [12]. All the communication technologies, communication entities will be able to communicate with each other and utilize data from the production owner during the all life cycle of systems without respect to broader among enterprises and countries.All entities will have its use, while producers will be able to work out systems with features of very modern components which will be even in the design and testing phase.According to [11], Industry 4.0 is used for three, mutually interconnected factors:

1) Digitization and integration of any simple technical-economical relation to complex technical-economical complex networks

2) Digitization of products and services offer

3) New market model

Two popular models of Industry 4.0 has been presented in the literature. Firstly RAMI 4.0 (REFERENCE ARCHITECTURE MODEL INDUSTRY 4.0)designed by BITCOM, VDMA and ZWEI is presented.

RAMI 4.0

In figure 2.2,the function of layer in vertical axis represent the look from different aspects (a look from the market aspect, a look from a perspective of functions, information, communication, a look from an integration ability of the components).The left hand horizontal axis displays the product life cycle with the value stream which it contains (constant data acquisition throughout the life cycle).The right horizontal axis describes function position of the components in the Industry 4.0 (specifies the functionality of the components).The above model layers is describe in details in [11].

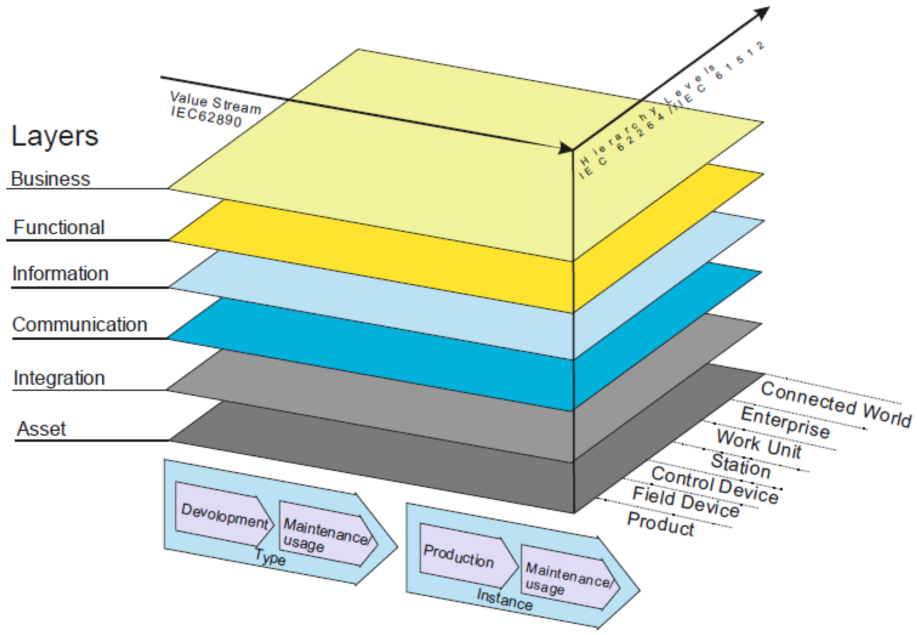
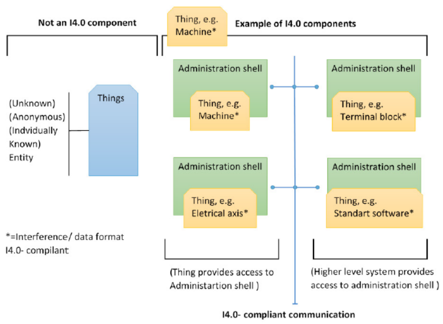
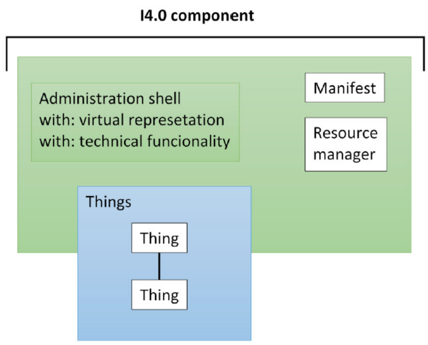


Figure 2.2: RAMI 4.0 model [11]



(a) Industry 4.0 component model [11]



(b) I4.0 component [11]

Figure 2.3: Industry 4.0

INDUSTRY 4.0 COMPONENT MODEL

Secondly, INDUSTRY 4.0 COMPONENT MODEL developed by BITCOM,VDMA and ZWEI.The purpose of this model is to help producers and system integrator to create software and hardware components for Industry 4.0.It provides better description of cyber-physical features and enables description of communication among virtual and cyber-physical objects and processes.The physical realization of above model is that any component of the Industry 4.0 system takes an electronic container of secured data during the all life cycle.This data are available to all entities of the technical-production chain. This model provides standardized, secure and safety real time communication of all components of production.The model is described in details in [11].

2.4 Semantic Web in Manufacturing

Nowadays, most of the manufacturing companies focus on the core competencies and outsource the rest.The *automotive industry* is one example among them.The automotive sector focuses on its core competencies and outsources the rest of it.This new policy is achieved by sharing designs, developments and platforms to reduce the cost associated in non-core activities[5, 9]. This advancement in manufacturing industry is creating more complex manufacturing information and increasing amount of knowledge making it difficult to share and exchange knowledge between the wide variety of users among companies.Many manufacturing projects operate within inter-Enterprise environment face the problem of common information model as different project teams use different information model.The information and knowledge resources distributed among this companies sometimes in incompatible formats, e.g. electronic document, databases, hard copy etc [9, 18].The next challenge is the the engineers from different teams use different vocabulary for same for particular issues which leads to lot of confusion.Today's web arranges the information syntactically, assuming them to be semantically homogeneous, but this cause problems and misunderstanding.This means most of the information is not machine readable so human intervention is required, even the human intervention cannot solve this problem sometimes. Whenever communication happens between two parties that share and exchange information two problems can occur, firstly, that same term can be applied to different concepts (semantic problem) and secondly, that different terms may be used to denote the same entity (syntax problem) [19].Usual approach among organization was to create standardization.However Stouffs and Krishnamurti suggest that the standardization will create more problems rather than solutions. As creating standardization will limit the creativity in ideas and conceptualizations [28]. It is true that standardization will improve the effectiveness of communication and data exchange but it will come with a cost of not supporting flexibility and extensibility from outside their design domain.The researchers are focusing creating a semantic web to solve this problem where information are machine readable and human readable as well [2].However the semantic description itself will not solve the problem of integration and combination of information from divers sources.The solution is to build an ontology of the terms relevant to the field under consideration.The data structuring syntax for presentation and conceptualization inevitably arises when considering ontology based model applications.The MSE ontology model can be used for syntactical level standardization to integrate heterogenic information sources.The ontology has been discussed in details in next section [18, 9].

2.5 Ontology

Ontology is a way of expressing meaningful information in precise structure. It is a way to model data using Classes and Properties. Classes represents objects and Properties represents relationship. Example, Class can be Person and Property can be Name. Hence Person With name is a meaningful information, which can be expressed by ontology.

2.5.1 Expressing Meaningful Information

The purpose of expressing meaningful information is to make it computer readable. This is done by representing information in simple triples. A triple has a subject, a predicate and a object.

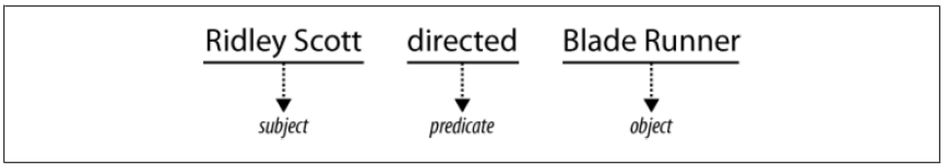


Figure 2.4: Triple representation ([26])

The subject represents a ”thing” for which we have a conceptual class. Components, Shaft, Machine and person are examples of things. Predicate are the relationship of the subject. Shaft's type, Shaft relation with other components, person's name, addhar no of a person are examples of predicates. Objects can be of two types either entities which can be subject of other triplet or literal values like string and numbers. NormalShaft hasDiameter 70. Here subject is NormalShaft, Object is literal value float which has value 70 and predicate is hasDiameter. It means Normal Shaft has diameter 70. NormalShaft hasname NormalShaft is also a meaningful information, where NormalShaft is subject, hasname is predicate and NormalShaft is the object which is an entity.

2.5.2 Classes and Properties in Owl Ontology

The above explained method can represent any data in the form of triples and makes it difficult to infer from the data. Hence we need better way to represent data so that it could be infer much more easily and at the same time it is computer readable. Ontology is one of the ways by which this can be done. Ontology consist of classes and properties. A class is a way of defining a group of entity which provide an abstraction mechanism for grouping resources with similar characteristics. Place, People, Vehicles, Animal are some example of classes in ontology. Properties on the other hand is the relation between two object or between object and literal. Owl has mainly two types of properties. Object properties which relates/links instances to instances which may not be of same class. Datatype properties which relates instances to data values.NormalShaft a Shaft, NormalShaft hasDiameter 70, NormalShaft isPartof Motor1 and Motor1 a Motor. First statement says that NormalShaft is a individual of class Shaft and second statement links the individual NormalShaft with float value 70 with the help of data property called hasDiameter. where as in third statement it is linked to another individual of different class called Motor with the help of object properties called isPartof.

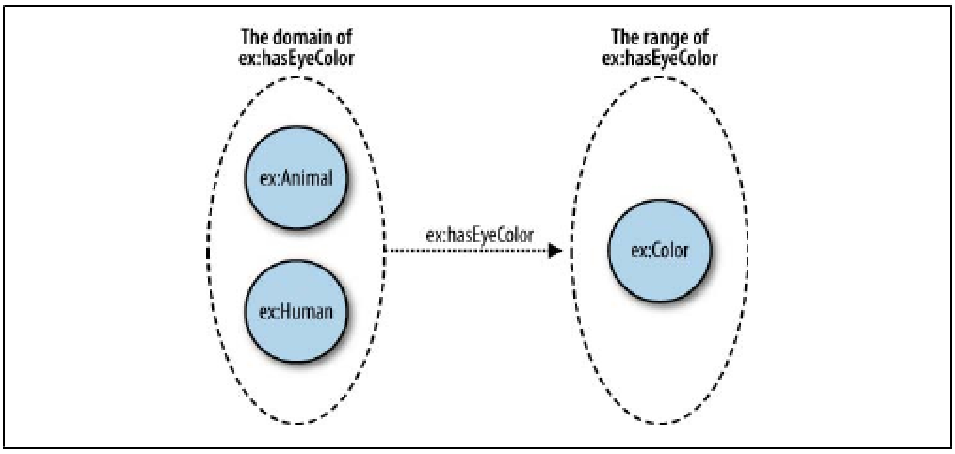


Figure 2.5: The domain and range of a property expressing eye color([26])

All properties have domain and range. The collection of types that use the property is called the domain of the property and likewise a property definition may also indicate which types of values this property can take on, representing the range of the property. The figure 2.2 clearly explains the concept of domain and range. In the figure the ex:Animal is animal class and ex:Human is Human class. This two class can have property ex:hasEyeColor. ex:color is the example of data values. Here domain is ex:Animal and ex:Human and range is ex:Color.

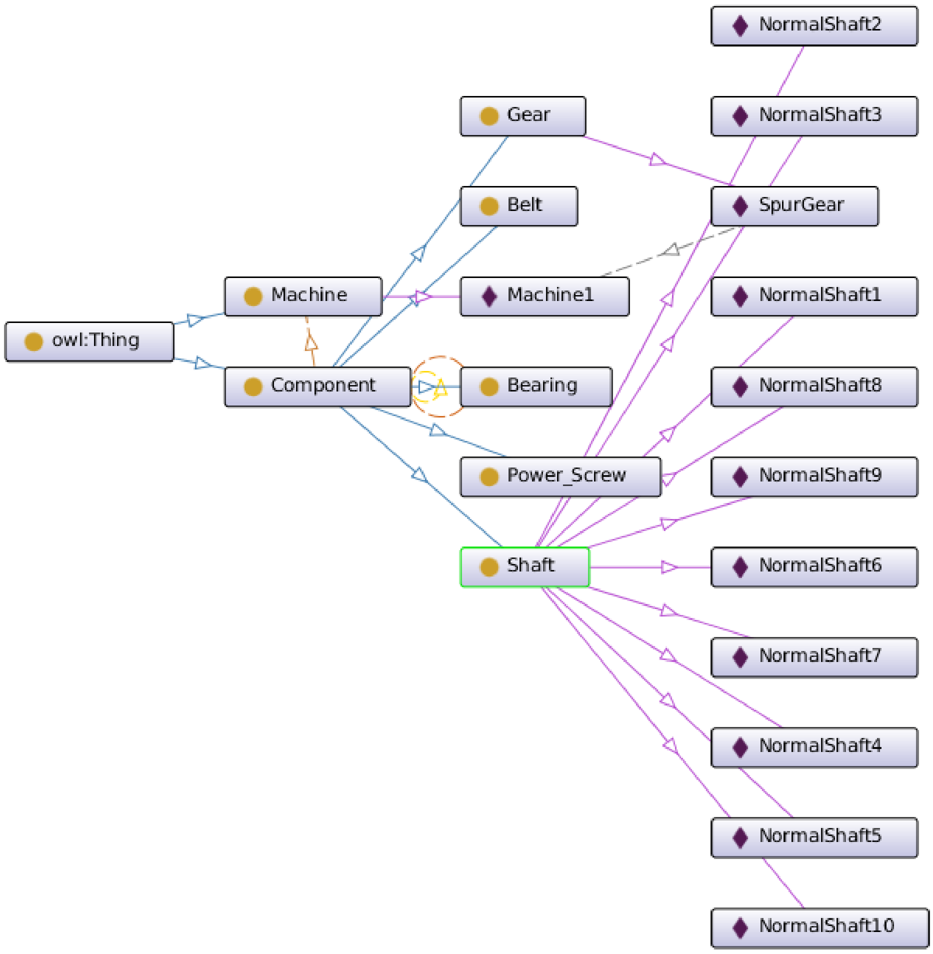


Figure 2.6: Simple Ontology of Machine made using Protege)

Figure 2.3 is a simple ontology which was created using protege software[**Protege**]. Here Owl:Thing is the main class which contains all classes. The classes Machine and Component are the subclasses owl:Thing. A class subsumed by another is called a subclass. What it essentially means all the individuals of subclass are always the member of the class. For example, NormalShaft1 is individual of class Shaft as well as class owl:Thing. Gear, Belt, Bearing and Shaft are the subclass of Component. Machine has one instance/individual called Machine1 and Gear has a instance called SpurGear. Shaft has instances named NormalShaft1 to NormalShaft10 which can be seen from figure. The dotted arrow between SpurGear and Machine Represents the object property called isPartOf which is not visible in the Figure 2.3. Which is evident from figure 2.4. In same figure there are other object properties isParallelwith and isSerieswith. All there of the object properties are subproperty of owl:topObjectProperty.

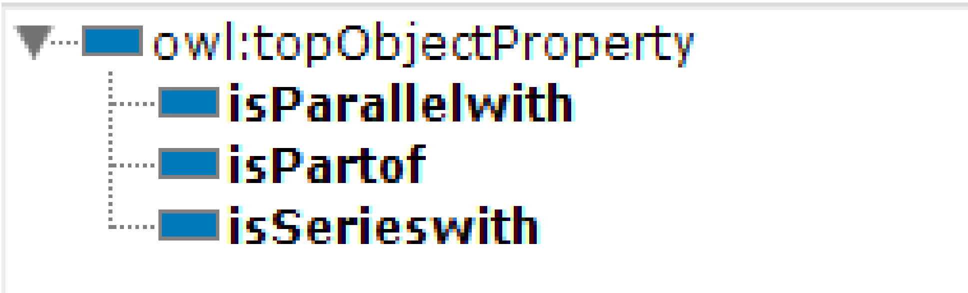


Figure 2.7: Object Properties of Ontology in figure 2.3)

Figure 2.5 contains the partial datatype properties of ontology shown in figure 2.3. It represents the various properties of bearing. All the Data properties are subproperty of owl:topDataProperty. Subproperty means all instances contained in the property extension of subproperty are also members of the property extension of the property.This DataProperty can take values based on their type.Example is NormalShaft hasDiameter 70.

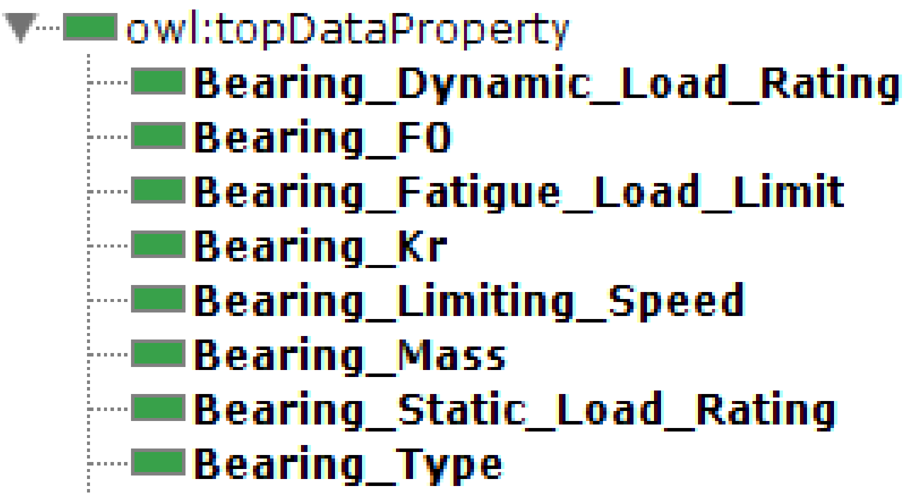


Figure 2.8: Data Properties of Ontology in figure 2.3)

Chapter 3

Physics Based Reliability Models

3.1 Stress Analysis of Shaft

3.1.1 Normal Stress for circular Shaft under Pure Bending

The shaft is considered as a simply supported beam. Its fixed at both the ends and force is acting perpendicular to the neutral axis at the center of the beam. Which results in shear and moment in the shaft. The force applied by one part of the shaft to the other part to keep the shaft in force equilibrium is called shear force. A bending moment is the reaction induced in shaft when a external force is applied to the element causing the element to bend. Figure 2.6 shows the variation of shear force and bending moment and it is called shear force and bending moment diagram. From the bending moment diagram we can easily see maximum moment is $Pl/4$ from [23, 21]

$$M_{max} = Pl/4 \tag{3.1}$$

Figure 2.7 shows a portion of beam having positive bending moment M shown by the curved arrows and straight arrows indicating moment vector. The x axis is coincident with neutral axis of the section and xz plane contains neutral axes of all cross section is called the neutral plane. Elements of the beam coincident with this plane has zero stress. The neutral axis is generally coincident with centroidal axis of the cross section.

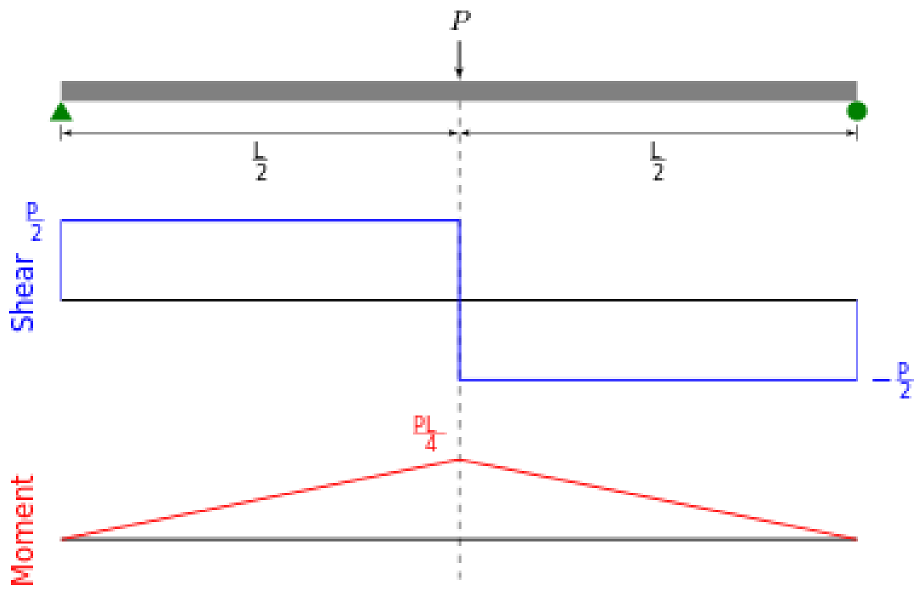


Figure 3.1: The Shear force and Bending Moment at every point on shaft (source: [27])

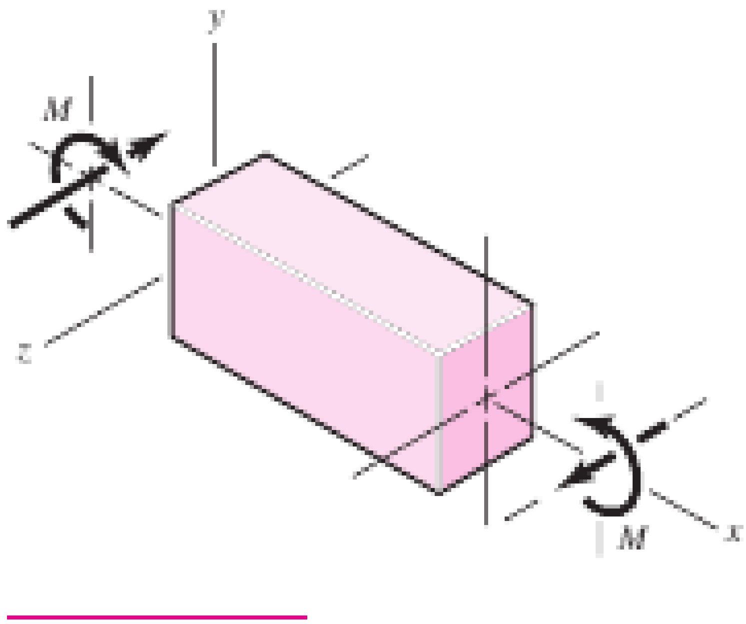


Figure 3.2: Beam in positive bending (source:[23])

Bending stress varies linearly with the distance from the neutral axis y and is given by (from [23])

$$\sigma_x = -My/I \tag{3.2}$$

where I is the second area moment about the z axis. I is given by (from [23])

$$I = \int y^2 dA \tag{3.3}$$

The figure 2.8 shows the stress distribution along the cross section of the shaft. The maxi-

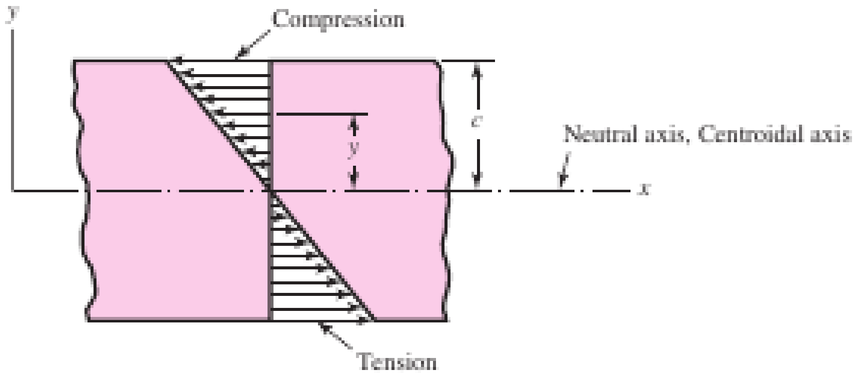


Figure 3.3: Bending Stress according to equation 2.2 (source: [23])

mum bending stress will occur where the the y has the greatest magnitude. let the maximum magnitude of bending stress be σ_{max} and maximum magnitude of y be denoted by c. (from [23])

$$\sigma_{max} = Mc/I \tag{3.4}$$

For Simply supported circular shaft the c is $D/2$, I is $\pi D^4/64$ and $M_{max} = Pl/4$ which gives us σ_{max} as $16Fl/\pi D^3$. Because the shaft is in rotation σ_{max} will switch between tension to compression at the same location.(source: [23])

$$\sigma_{max} = 8Fl/\pi D^3 \tag{3.5}$$

3.1.2 Shaft Under Torsion

Any Moment vector which is collinear with the axis of a mechanical element is called a *torque vector*, because the moment causes the element to be twisted about that axis. A shaft subjected to such moment is also said to be in *torsion*

As visible from figure 2.9 the torque T applied is represented by arrow along the surface to indicate the direction and torque-vector arrows along the axes of twist of the bar. Torque vectors are the hollow arrows shown on the x axis in figure 2.9. The *angle of twist*, for a circular bar is given by (from [23])

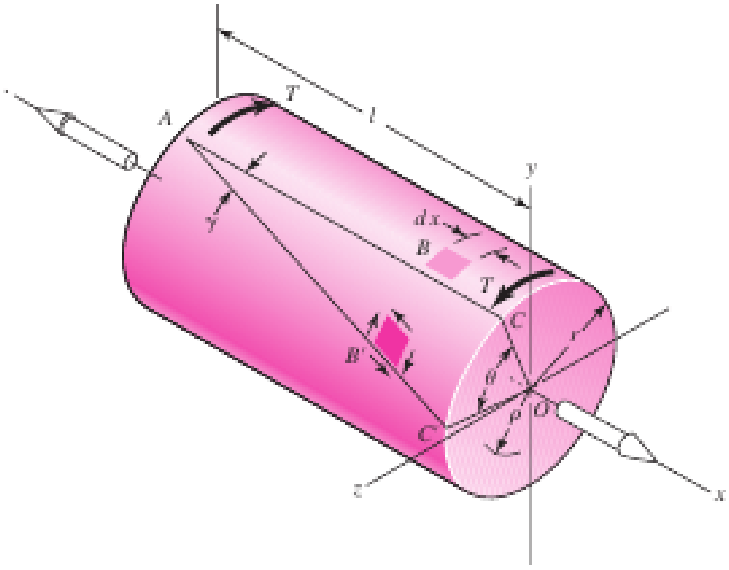


Figure 3.4: Detailed Representation of Shaft in Torsion (Source: [23])

$$\theta = Tl/GJ \tag{3.6}$$

Where T represents torque, l represents length, G represents modulus of rigidity and J represents the polar moment of area.

Shear Stress are there across the cross section. For circular shaft in torsion these stress are proportional to the radius and are given by (from [23])

$$\tau = T\rho/J \tag{3.7}$$

Taking ρ as the radius of the outer surface, we have τ_{max} given by (from [23])

$$\tau_{max} = Tr/J \tag{3.8}$$

For circular Shaft $J = \pi D^4/32$ and $r = D/2$, putting this value in equation 2.7 we get $\tau_{max} = 16T/\pi D^3$ (from [23])

$$\tau_{max} = 16T/\pi D^3 \tag{3.9}$$

3.1.3 Life Calculation of Shaft

When a mechanical shaft is under the action of repeated or fluctuating stresses, even though the stress way below the ultimate strength of the material and many times even below the yield strength still the shaft fails. The shaft did went through large number of cycles of repeated load.This type of failure is called *fatigue failure*. Figure 2.10 shows the image of a shaft failed from repeated cyclic loading.

Figure 3.5: Fatigue failed shaft

Endurance Limit

Endurance Limit is the maximum cyclic stress which can be applied to shaft to have infinite number of cycles (the shaft never fails from fatigue failure). For steels the approximate estimate of endurance limit is S'_e is $0.5S_{ut}$ for $S_{ut} \leqslant 1400MPa$ and $700MPa$ for $S_{ut} > 1400MPa$ The analytical way of calculating the finite cycle of repeated load the shaft can go through before it fails is given by Shigley, Mischke, and Brown. (from [23])

$$S_f = aN^b \tag{3.10}$$

where S_f is cyclic stress, N is cycles to failure and the constants a and b are defined by the points 10^3, $(S_f)_{10^3}$ and 10^6, S_e. Approximately $(S_f)_{10^3} = fS_{ut}$. Here f is the fraction of S_{ut} represented by $(S_f)_{10^3}$. (from [23])

$$a = (fS_{ut})^2/S_e \tag{3.11}$$

$$b = -log(fS_{ut}/S_e)/3 \tag{3.12}$$

The value of f can be obtained from graph. However for this analysis $fS_{ut} = C$ was considered and value of C was computed by taking mean value of product of f and S_{ut} obtained from graph.The graph does follow profile similar to hyperbola but not exactly. $f = 0.9$ for $S_{ut} \leq 70Mpa$ otherwise f is obtained from above mention method.

Assuming the Applied stress to be completely reversible σ_{rev} can be obtained from loading condition of the shaft and stetting $S_f = \sigma_{rev}$ in equation 2.10 the number of cycles to failure can be obtained by equation (from [23])

$$N = (\sigma_{rev}/a)^{1/b} \tag{3.13}$$

Here σ_{rev} is the von mises stress obtained by (from [23])

$$\sigma_{rev} = \sqrt[2]{{\sigma_{max}}^2 + 3\tau_{max}^2} \tag{3.14}$$

Substituting the values of σ_{max}, τ_{max} in above equation gives us

$$\sigma_{rev} = \sqrt[2]{(8Fl/\pi D^3)^2 + 3(16T/\pi D^3)^2} \tag{3.15}$$

3.1.4 Endurance Limit Modifiers

The actual endurance limit is smaller than the endurance limit given for the material or $0.5S_{ut}$. Actual endurance limit can be obtained from the given endurance limit and endurance limit modifying factors. Following equation can be used to calculate the actual endurance limit (S_e) from given endurance limit (S_e') (from [23])

$$S_e = k_a k_b k_c k_d k_e S_e' \tag{3.16}$$

where k_a = surface condition modification factor

k_b = size modification factor

k_c = load modification factor

k_d = temperature modification factor

k_e = reliability factor

S_e' = rotary-beam test specimen endurance limit

S_e = endurance limit at the critical location of a machine part in th geometry and condition of use

Surface Factor k_a

The surface finish of rotating shaft is dependent on the ultimate tensile strength and the process through which it was manufactured. (from [23])

$$k_a = aS_{ut}^b \tag{3.17}$$

where S_{ut} is ultimate tensile strength and a and b are obtained from table given below

Size Factor k_b

The Diameter of the shaft play a role in deciding the endurance limit if the shaft is in bending or torsion. For axial loading there is no size effect which means k_b is 1 For shaft in bending and torsion the k_b is given by $1.24d^{-0.107}$ if diameter is between 2.79 to 51 mm and k_b is given by

Surface Finish	Factor a S_{ut}, kpsi	Factor a S_{ut}, MPa	Exponent b
Ground	1.34	1.58	−0.085
Machined or cold-drawn	2.70	4.51	−0.265
Hot-rolled	14.4	57.7	−0.718
As-forged	39.9	272.	−0.995

Figure 3.6: Parameter for Surface Modification Factor (Source: [23])

$1.51d^{-0.157}$ when its more than 51 mm but not more than 254 mm. (source: [23])

Loading Factor k_c

When fatigue test are carried out with rotating bending, axial and torsional loading, the endurance limit differ with S_{ut}. Average values of the load factor k_c is 1 for bending, 0.85 for axial and 0.59 for torsional loading. (from [23])

Temperature Factor k_d

Shaft operating at higher temperature than room temperature may fail because of yielding as yield strength decreases with increasing temperature. While shaft operating at lower temperature than the room temperature may fail because of brittle fracture. Fourth polynomial was fit to the experimental data which measured variation of $kd = \frac{S_T}{S_{RT}}$ with temperature. The polynomial obtained is given below (from [23])

$$k_d = 0.975 + 0.432(10^{-3})T_F - 0.115(10^{-5})T_F^2 + 0.104(10^{-8})T_F^3 - 0.595(10^{-12})T_F^4 \quad (3.18)$$

where $70 \leq T_F \leq 1000F$

Reliability Factor k_e

The endurance limit obtained in experiments is not a fixed value rather its a distribution which mean value considered as endurance limit. The endurance limit has a standard deviation of 8 percent. Therefore the k_e is given by (from [23])

$$k_e = 1 - 0.08 z_a \tag{3.19}$$

where z_a can be obtained from standard normal distribution table

3.1.5 Maximum Shear Stress theory

The maximum shear stress theory of failure states: The maximum shear stress at the point of failure at the time of yielding equals or exceeds the maximum shear stress when yielding occurs in the tension test specimen. (from [23])

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2} = \frac{S_y}{2} \tag{3.20}$$

Principle stress are given by equation (from [23])

$$\sigma_1, \sigma_2 = (\frac{\sigma_x + \sigma_y}{2}) \pm \frac{1}{2}\sqrt[2]{\frac{\sigma_x - \sigma_y}{2}^2 + 4\tau_{xy}^2} \tag{3.21}$$

Shaft with circular cross section we have maximum bending moment σ_b from equation 2.5 and from equation 2.9 we have maximum shear stress τ_{max} . Substituting $\sigma_x = \sigma_b$ and $\sigma_y = 0$ and$\tau_{xy} = \tau_{max}$ (from [23])

$$\sigma_1, \sigma_2 = (\frac{\sigma_b}{2}) \pm \frac{1}{2}\sqrt[2]{\frac{\sigma_b}{2}^2 + 4\tau_{max}^2} \tag{3.22}$$

Substituting the values of σ_b and τ_{max} in above equation and simplifying gives us

$$\sigma_1, \sigma_2 = \frac{16}{\pi D^3}[\frac{Pl}{2} \pm \sqrt[2]{(\frac{Pl}{2})^2 + T^2}] \tag{3.23}$$

Maximum bending allowable in shaft (from equation 2.5 and equation 2.20)

$$8Pl/\pi D^3 \leq \frac{S_y}{2} \tag{3.24}$$

Maximum shear allowable in shaft

$$16T/\pi D^3 \leq \frac{S_y}{2} \tag{3.25}$$

Maximum stress allowable in shaft

$$\frac{\sigma_1 - \sigma_2}{2} = \frac{16}{\pi D^3} \sqrt[2]{(\frac{Pl}{2})^2 + T^2} \leq \frac{S_y}{2} \tag{3.26}$$

3.2 Stress Analysis of Gear

3.2.1 Introduction

Gears are mechanical part of a rotating machine.It has teeth which mashes with teeth of other gear to transfer power(torque).The advantage of having geared machine is that it can change direction, speed and magnitude of power source. It also ensures that there is no slipping when gears are used in transmission. There are many types of gear available in the market like spur gear,helical gear,bevel gear and many more.However the discussion in this thesis has been limited to only spur gear.

3.2.2 Nomenclature of parameters of Gear

The spur gear has standard terminology given in figure 2.12.There are generally two gears in a mesh. The larger one among the two is called the *Gear* and the smaller one is *Pinion*.

The *Pitch* is the imaginary circle that passes through the points where gear and pinion touch.

The *Pitch Diameter d* is the diameter of the pitch circle and *Pitch Radius r* is its radius.

The *Circular Pitch p* is the distance between the two corresponding points on the adjacent tooth.Circular pitch is sum of *tooth thickness* and *Width of space*

The *Module m* is the ratio of the pitch diameter to the number of teeth.

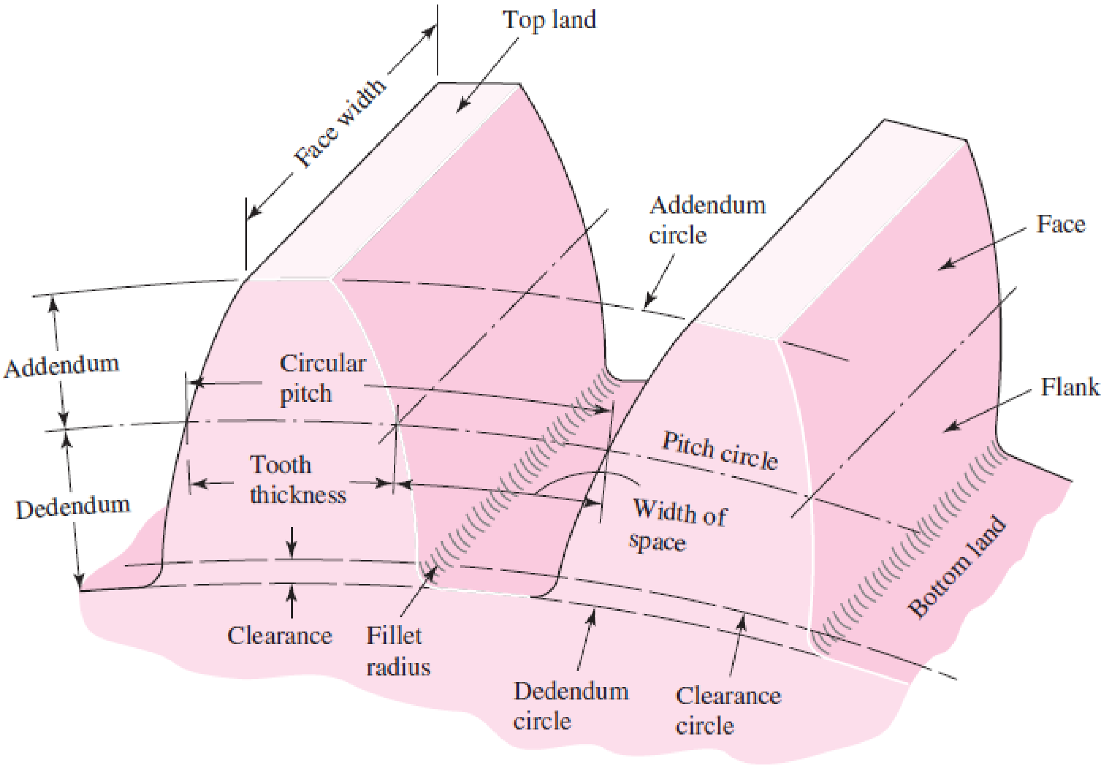


Figure 3.7: Nomenclature of spur gear teeth (Source: [23])

The *Diametral Pitch P* is the ratio of the number of teeth on the gear to the pitch diameter. It is the reciprocal of the module.

The *addendum a* is the radial distance between the top land(top of the tooth) and the pitch circle. It's value can be obtained by (from [23])

$$a = r + 1.0m \tag{3.27}$$

The *dedendum b* is the radial distance between bottom land to pitch circle.

Number of teeth N is the number of teeth on the gear.

The *Pressure Angle* ϕ is the angle between the center line connecting the two gears and the common tangent to the two base circle.

The in-volute curve is the curve traced by a point on a straight line which rolls without slipping on the circle.The circle is called the *Base circle*.The radius of this circle is denoted by r_b (from [23])

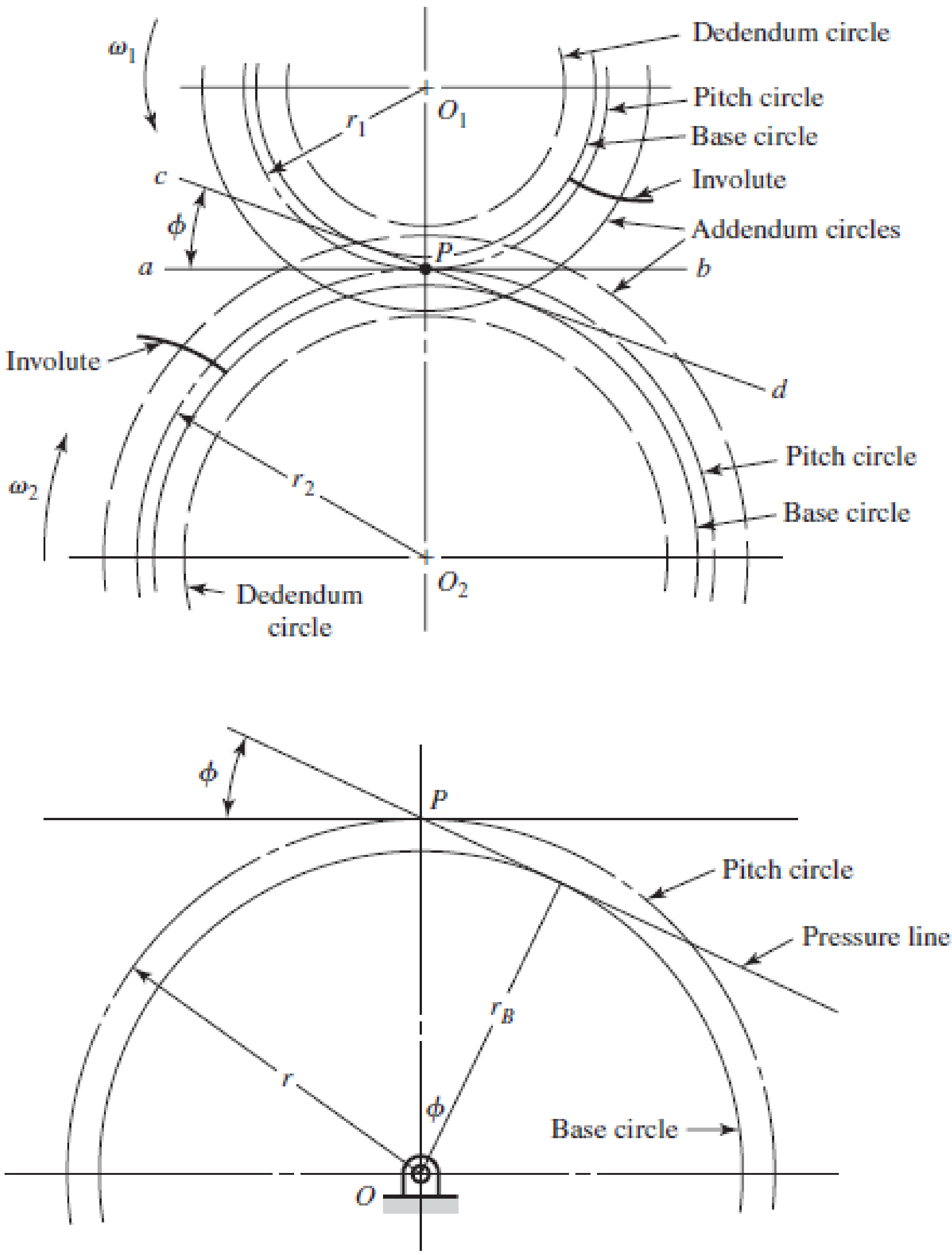


Figure 3.8: Nomenclature of spur gear teeth (Source: [23])

$$P = \frac{N}{d} \tag{3.28}$$

$$M = \frac{d}{N} \tag{3.29}$$

$$p = \frac{\pi d}{N} = \pi m \tag{3.30}$$

$$pP = \pi \tag{3.31}$$

$$r_b = rcos\phi \tag{3.32}$$

Above equation were obtained (from [23])

3.2.3 Hardness of a material

The hardness is the property of material which enables it to resist plastic deformation, usually by penetration or by indentation.There are many hardness test to measure hardness of material. However we will only discuss the Brinell hardness. Brinell hardness is determined by forcing a hear steel or crabide sphere of a diameter D under load F into the surface of a material and measuring the diameter of the indentation left after the test. The Brinell Hardness is obtained by diving load used(Kg), by the actual surface are of the indentation. Generally the hardness is measured in range. like BHN = 220-250. We will be using BH as the symbol for brinell hardness.There is also another test called rockwell test. Disscussing about this test is out of the scope of the thesis. However the Rockwell hardness can be converted into BH using tables from internet.

3.2.4 bending Stress in Gear

Lewis bending Equation

Wilfred Lewis has given a method by which the bending stress in gear teeth is estimated.The derivation of the same is presented below. The gear tooth is assumed to be cantilever beam of cross-section dimensions F and t, having length l and load W^t, uniformly distributed across the face width. The section modulus I/c is $Ft^2/6$ and bending stress is given by (from [23])

$$\sigma = \frac{M}{I/c} = \frac{6W^2l}{Ft^2} \tag{3.33}$$

From Figure 2.14(b), we assume that maximum stress in a gear tooth occurs at point a. Using similar triangles we get

$$\frac{t/2}{x} = \frac{l}{t/2} \qquad or \qquad x = \frac{t^2}{4l} \tag{3.34}$$

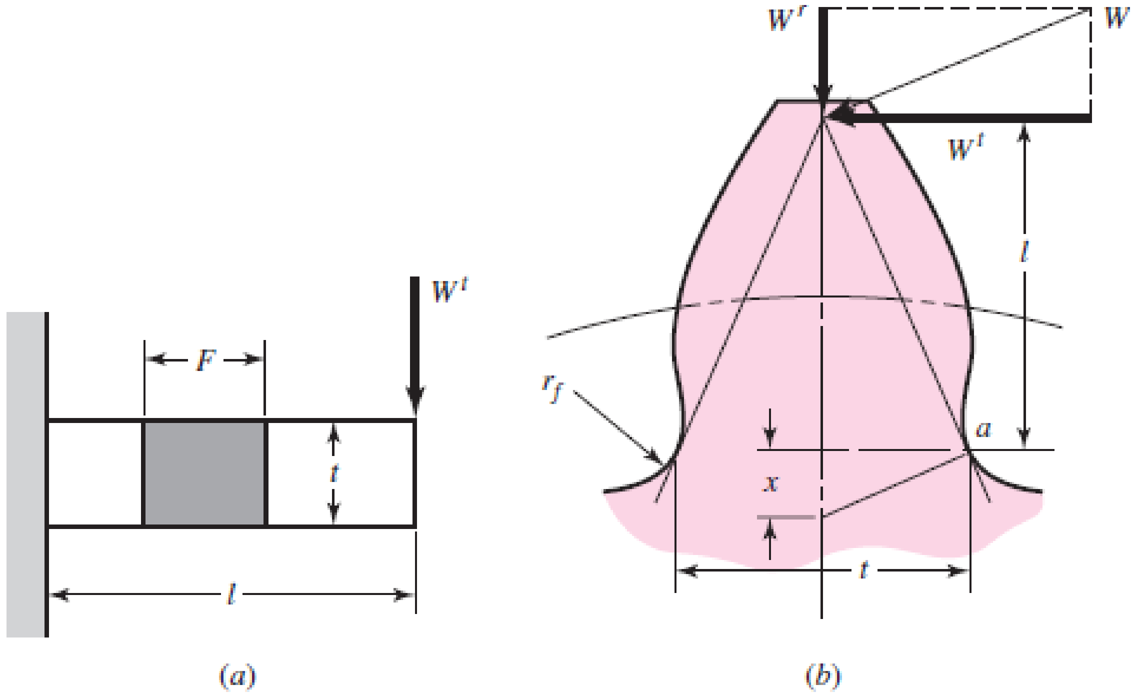


Figure 3.9: Diagram of gear's tooth (Source: [23])

rearranging term in equation 2.32 we get

$$\sigma = \frac{6W^t l}{Ft^2} = \frac{W^t}{F}\frac{1}{t^2/6l} = \frac{W^t}{F}\frac{1}{t^2/4l}\frac{1}{\frac{4}{6}} \tag{3.35}$$

if we substitute the value of x from equation 2.33 in equation 2.34 and multiplying and dividing by the circular pitch p we have

$$\sigma = \frac{W^t p}{F(\frac{2}{3})xp} \tag{3.36}$$

Putting $y = 2x/3p$, we have

$$\sigma = \frac{W^t}{Fpy} \tag{3.37}$$

The above equation can be use for finding bending stress (from [23]). However, below modification to above equation is used by engineers.Substitute $P = \pi/p$ and $Y = \pi y$ in the equation 2.36 results in

$$\sigma = \frac{W^t P}{FY} \tag{3.38}$$

where

$$Y = \frac{2xP}{3} \tag{3.39}$$

AGMA Bending stress equation

The equation 2.38 is modified by AGMA to give us the new equation (from [23])

$$\sigma = W^t K_o K_v K_s \frac{P_d}{F} \frac{K_m K_B}{J} \tag{3.40}$$

where

W^t is the tangential transmitted load

K_o is the overload factor

K_v is the dynamic factor

K_s is the size factor

P_d is the transverse diametral pitch

F is the face width of the narrow member

K_m is the load-distribution factor

K_B is the rim-thickness factor

J is the geometry factor for bending strength

Overload Factor K_o

The overload factor K_o represents to what extent can the gear be overloaded.It can be obtained from below equation.

$$K_o = \frac{Actual\ tangential\ force}{Nominal\ tangential\ force, F_t} \tag{3.41}$$

However, if the tangential force is unknown then below table can be used to determine the value of K_o

Impact from Prime Mover	Impact from Load Side of Machine		
	Uniform Load	Medium Impact Load	Heavy Impact Load
Uniform Load (Motor, Turbine, Hydraulic Motor)	1.0	1.25	1.75
Light Impact Load (Multicylinder Engine)	1.25	1.5	2.0
Medium Impact Load (Single Cylinder Engine)	1.5	1.75	2.25

Figure 3.10: Table for K_o (Source: [23])

Dynamic Factor K_v

Dynamic factor is used to account for inaccuracies in the manufacture and meshing of gear teeth in action.*Transmission error* is defined as the deviation from uniform angular velocity of the gear pair. AGMA uses a set of *Quality numbers* to account for dynamic factors. These number are defined to account for specified accuracy for various size manufactured gear. Quality number 3 to 7 will include mostly commercial-quality gears and 8 to 12 are of precision quality.The AGMA *Transmission accuracy-level number* Q_v is similar to quality number and is used to compute the dynamic factor given below. (from [23])

$$K_v = \left(\frac{A + \sqrt[2]{V}}{A}\right)^B \tag{3.42}$$

where

$$A = 50 + 56(1 - B) \tag{3.43}$$

$$B = 0.25(12 - Q_v)^{2/3} \tag{3.44}$$

The value of K_v can also be obtained from graph if the pitch-line velocity and quality number is known.However for this thesis the above mention equation was used.

Size Factor K_s

There are non-uniformity of material properties due to size, which depends on many factors like tooth size, diameter part, face width and many more.The derivation of the Size factor is out of the scope of this work. However, below equation can be used to find K_s,which was obtained (from [23])

$$K_s = 1.192(\frac{F\sqrt{Y}}{P})^{0.0535} \tag{3.45}$$

But caution must be taken when the K_s calculated from above equation is less then one. Instead of using this value we use $K_s = 1$ when calculated value of K_s is less than 1 . (from [23])

Load-Distribution Factor K_m

The distribution of load is non uniform across the line of contact.Load-Distribution factor modifies the stress equation to take this into account. Load distribution factor K_m is given by (from [23])

$$K_m = C_{mf} = 1 + C_{mc}(C_{pf}C_{pm} + C_{ma}C_e) \tag{3.46}$$

The values of C_{pm} and C_e was assumed to be 1. The values of A,B and C were 0.127, 0.0158 and $-0.930(10^{-4})$ respectively. (from [23])

Rim-Thickness Factor K_B

When the rim thickness is is not sufficient to provide full support to the tooth root, the bending fatigue failure may happen in the rim itself rather than in the tooth.The *rim-thickness factor* K_B accounts for this case and modifies the stress for thin-rimmed gear.K_B is given by (from [23])

$$K_R = \begin{cases} 1.6ln\frac{2.242}{m_B} & m_B < 1.2 \\ 1 & m_B \geq 1.2 \end{cases} \tag{3.47}$$

Where $m_B = \frac{t_R}{h_t}$, also called as *Backup ratio*. t_R is the rim thickness below the tooth and h_t is the tooth height. The below graph can be used to obtain the value of K_B

where

$$C_{mc} = \begin{cases} 1 & \text{for uncrowned teeth} \\ 0.8 & \text{for crowned teeth} \end{cases} \qquad \text{(14–31)}$$

$$C_{pf} = \begin{cases} \dfrac{F}{10d} - 0.025 & F \le 1 \text{ in} \\ \dfrac{F}{10d} - 0.0375 + 0.0125F & 1 < F \le 17 \text{ in} \\ \dfrac{F}{10d} - 0.1109 + 0.0207F - 0.000\,228F^2 & 17 < F \le 40 \text{ in} \end{cases} \qquad \text{(14–32)}$$

Note that for values of $F/(10d) < 0.05$, $F/(10d) = 0.05$ is used.

$$C_{pm} = \begin{cases} 1 & \text{for straddle-mounted pinion with } S_1/S < 0.175 \\ 1.1 & \text{for straddle-mounted pinion with } S_1/S \ge 0.175 \end{cases} \qquad \text{(14–33)}$$

$$C_{ma} = A + BF + CF^2 \qquad \text{(see Table 14–9 for values of } A, B, \text{ and } C\text{)} \qquad \text{(14–34)}$$

$$C_e = \begin{cases} 0.8 & \text{for gearing adjusted at assembly, or compatibility is improved by lapping, or both} \\ 1 & \text{for all other conditions} \end{cases} \qquad \text{(14–35)}$$

Figure 3.11: Equation for various parameters of K_m (Source: [23])

Bending-Strength Geometry Factor J

The AGMA modifies the Lewis form factor (Y) into J which includes *fatigue stress-concentration factor* K_f and a tooth *load-sharing ratio* m_N. The J is given by (from [23])

$$J = \frac{Y}{K_f m_N} \qquad (3.48)$$

The value of Y is computed within AGMA 908-B89 and is often based on the highest point of single-tooth contact. The value of m_N = 1.0 for spur gear. However for the above thesis we have used the curve given below (Figure 2.18) to determine the value of J. (from [23])

AGMA Bending Strength Equation

The *gear bending strength* is designated as S_t and can be obtained from following graph below.Since gear strength are different from other strengths such as S_{ut}, S_e or S_y used in stress

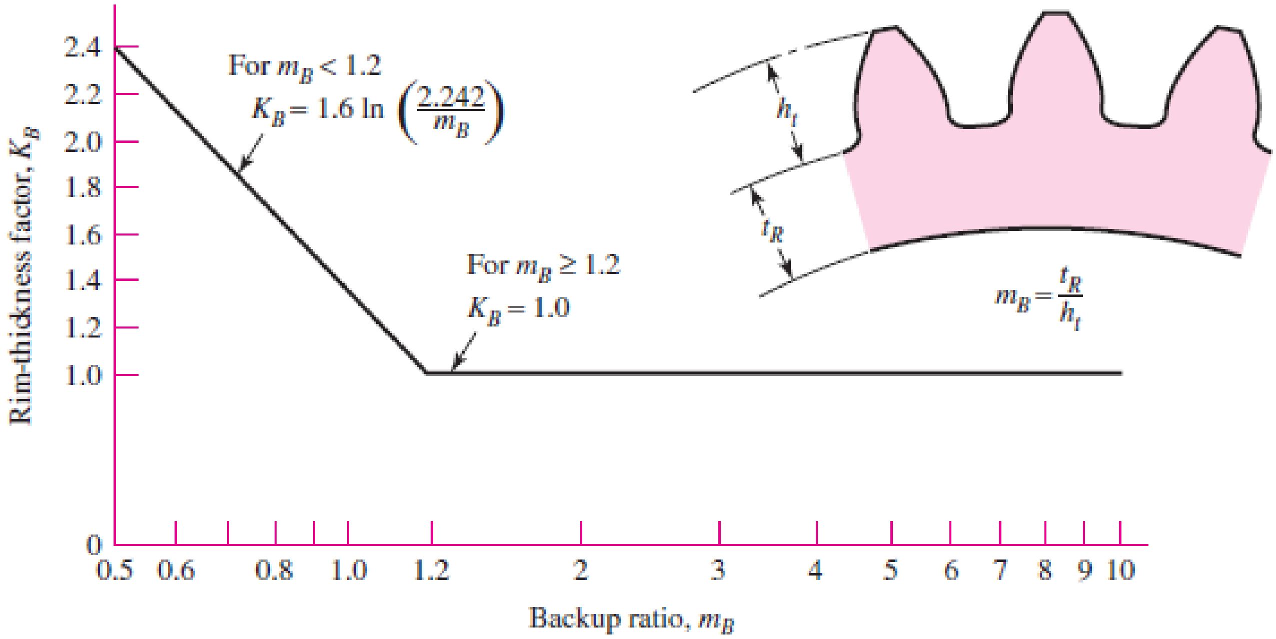


Figure 3.12: Graph between Backup ratio and K_B (Source: [23])

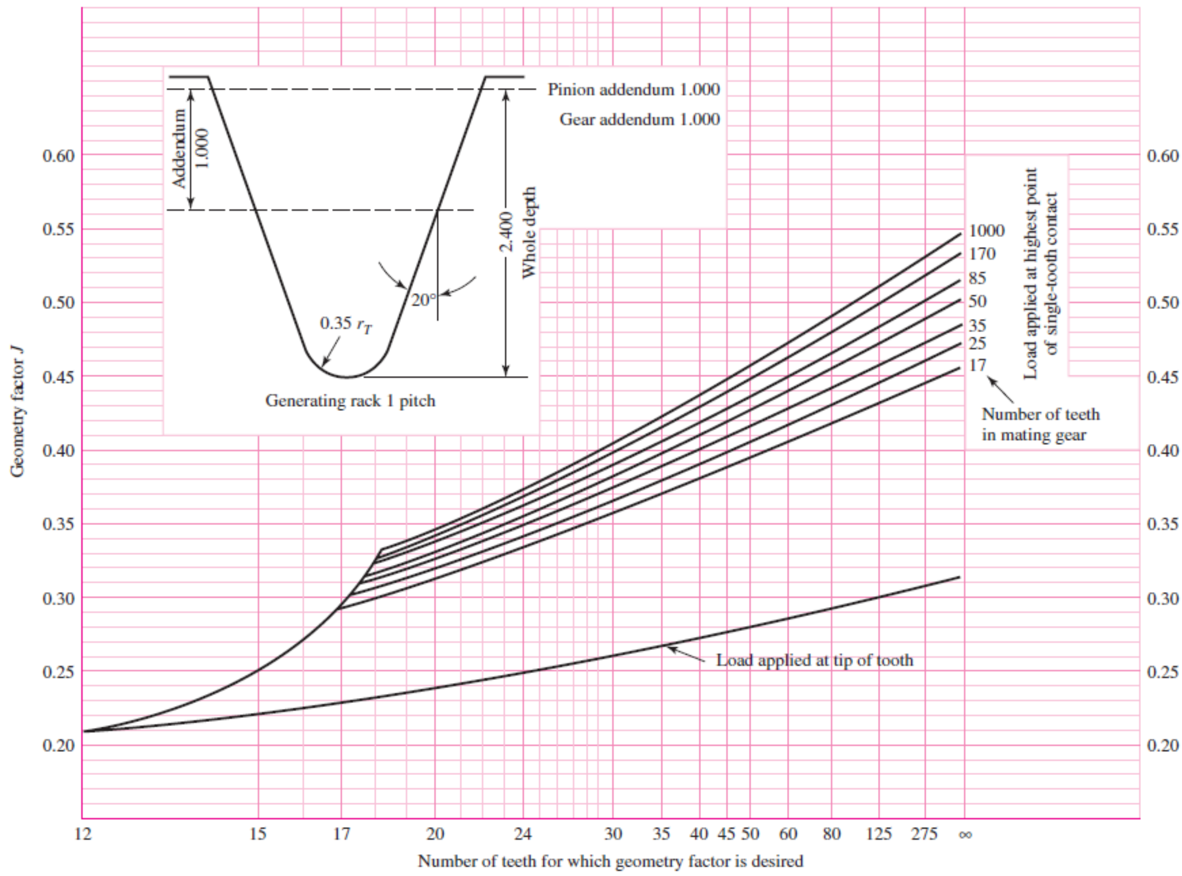


Figure 3.13: Spur Gear geometry factor J (Source: [23])

analysis of shaft, it's use should be limited to gear only.

There are many such graphs for various materials by AGMA.The equation of S_t can be obtained from the above curve if the hardness and heat-treatment is known.There are various factors that modify S_t is given my the below equation. (from [23])

$$\sigma_{all} = \frac{S_t}{S_F} \frac{Y_N}{K_T K_R} \tag{3.49}$$

where S_t is the allowable bending stress

Y_N is the stress cycle factor for bending stress

K_T are the temperature factors

K_R are the reliability factor

S_F is the AGMA factor of safety, a stress ratio.

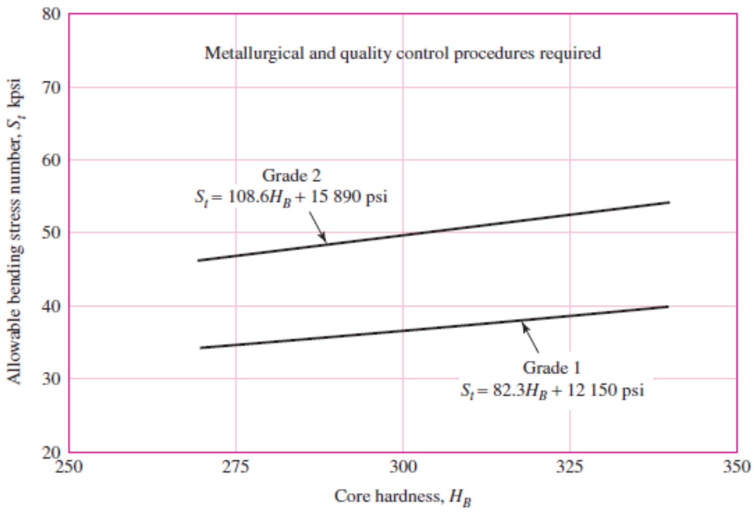


Figure 3.14: Allowable Bending stress for nitrided through-hardened steel(AISI 4140,4340) (Source: [23])

Stress-Cycle Factor Y_N

The values given for S_t are only for 10^7 cycles. The Stress-Cycle Factor Y_N modifies the allowable bending stress for cycles other than 10^7.The value of Y_N depends on the material,

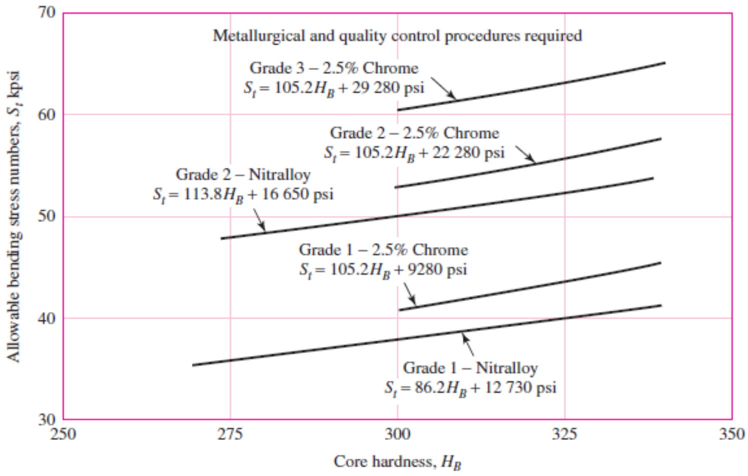


Figure 3.15: Allowable Bending stress for nitriding steel gear S_t (Source: [23])

number of cycles, heat treatment and can be obtained from next given figure.

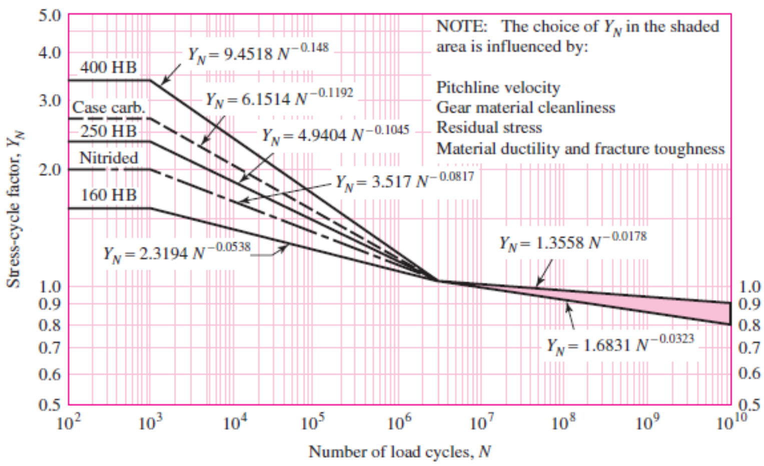


Figure 3.16: Repeatedly applied bending strength stress-cycle factor Y_N (Source: [23])

Temperature Factor K_T

The temperature factor accounts for change in allowable bending stress due to working temperature.For temperature up to 250^oF use $K_T = 1.0$. Higher temperature will have factor greater than unity. (from [23])

Reliability Factor K_R

The material properties like allowable bending stress and allowable contact stress doesn't have any constant value rather they are obtained from statistical distribution of material obtained from failure tests like fatigue failure.Therefore, obtained values are always with a reliability(usually 99 percent).We require a factor for taking into this consideration, which is K_R. The relationship between K_R and reliability is highly non-linear. Hence the relation is obtained by a least-square regression between log reliability and K_R. The same is presented below (from [23])

$$K_R = \begin{cases} 0.658 - 0.0759 ln(1-R) & 0.5 < R < 0.99 \\ 0.50 - 0.109 ln(1-R) & 0.99 \leq R \leq 0.9999 \end{cases} \tag{3.50}$$

Safety Factor S_F

The safety factor S_F is used as guarding against fatigue failure. The definition of S_F is (from [23])

$$S_F = \frac{S_t Y_N/(K_T K_R)}{\sigma} = \frac{fully\ corrected\ bending\ strength}{bending\ stress} \tag{3.51}$$

The safety factor was not computed in this thesis as we are directly interested in computing the probability of survival due to bending stress.

Gear bending failure condition based on AGMA

The AGMA uses Safety Factor S_F to check the threat of failure due to bending, which should be greater than unity. However for our discussion we have modified that into simpler form given below for reliability calculation (from [23])

$$\sigma \leq \sigma_{all} \implies W^t K_o K_v K_s \frac{P_d}{F} \frac{K_m K_B}{J} \leq \frac{S_t Y_N}{K_T K_R} \tag{3.52}$$

3.2.5 Contact Stress in Gear

When any two body with curved surfaces are pressed together, the contact is usually area contact. The two cylinders of length l and diameter d_1 and d_2 the area of of contact between them is the narrow rectangle of width 2b and length l and the pressure distribution is elliptical.The rectangle width 2b is given by (from [3, 23, 33])

$$2b = 2\sqrt{\frac{2F}{\pi l}\frac{(1-\mu_1^2)/E_1 + (1-\mu_2^2)/E_2}{\Sigma_\rho}} \tag{3.53}$$

where F is the load pressing the cylinders together

μ_1,μ_2,E_1 and E_2 are the elastic constants of the materials

Σ_ρ is curvature sum , for cylinder Σ_ρ is $1/d_1 + 1/d_2$

The maximum pressure is (from [3, 23, 33])

$$P_{max} = \frac{2F}{\pi bl} \tag{3.54}$$

Here P_{max} is the largest surface pressure on the surface

We can modify the above equation for the gear by replacing the l (length of cylinder) with F (face width of gear),F (load) with W^t normal load to the gear surface and P_max with σ_C the *Surface compressive stress (Hertzian stress)* and can obtain the below equation. (from [3, 23, 33])

$$\sigma_C^2 = \frac{W^t}{\pi F}\frac{\Sigma_\rho}{(1-\mu_1^2)/E_1 + (1-\mu_2^2)/E_2} \tag{3.55}$$

Let us define a new constant called C_p which can be used to simplify the above equation.The *Elastic coefficient* C_p is the dependent on the material properties (elastic properties) of the mating gears and is given by (from [3, 23, 33])

$$C_p = (\frac{1}{(1-\mu_1^2)/E_1 + (1-\mu_2^2)/E_2})^{1/2} \tag{3.56}$$

C_p can also be obtained by table given below.

The simplified σ_C is given by (from [3, 23, 33])

$$\sigma_C = -C_p(\frac{W^t\Sigma_\rho}{F})^{1/2} \tag{3.57}$$

Table 14–8

Elastic Coefficient C_p (Z_E), $\sqrt{\text{psi}}$ $(\sqrt{\text{MPa}})$ *Source: AGMA 218.01*

		Gear Material and Modulus of Elasticity E_G, lbf/in² (MPa)*					
Pinion Material	**Pinion Modulus of Elasticity E_p psi (MPa)***	**Steel 30×10^6 (2×10^5)**	**Malleable Iron 25×10^6 (1.7×10^5)**	**Nodular Iron 24×10^6 (1.7×10^5)**	**Cast Iron 22×10^6 (1.5×10^5)**	**Aluminum Bronze 17.5×10^6 (1.2×10^5)**	**Tin Bronze 16×10^6 (1.1×10^5)**
Steel	30×10^6 (2×10^5)	2300 (191)	2180 (181)	2160 (179)	2100 (174)	1950 (162)	1900 (158)
Malleable iron	25×10^6 (1.7×10^5)	2180 (181)	2090 (174)	2070 (172)	2020 (168)	1900 (158)	1850 (154)
Nodular iron	24×10^6 (1.7×10^5)	2160 (179)	2070 (172)	2050 (170)	2000 (166)	1880 (156)	1830 (152)
Cast iron	22×10^6 (1.5×10^5)	2100 (174)	2020 (168)	2000 (166)	1960 (163)	1850 (154)	1800 (149)
Aluminum bronze	17.5×10^6 (1.2×10^5)	1950 (162)	1900 (158)	1880 (156)	1850 (154)	1750 (145)	1700 (141)
Tin bronze	16×10^6 (1.1×10^5)	1900 (158)	1850 (154)	1830 (152)	1800 (149)	1700 (141)	1650 (137)

Figure 3.17: Elastic Coefficient C_P Value Table for Different material (Source: [23])

AGMA Contact stress equation

The Hertz equation for σ_C is modified by AGMA to the below equation (from [3, 23, 33])

$$\sigma_C = C_P(W^t K_o K_v K_s K_m \Sigma_\rho \frac{C_f}{F})^{1/2} \tag{3.58}$$

where

C_p is the elastic coefficient

W^t is the tangential transmitted load

K_o is the overload factor

K_v is the dynamic factor

K_s is the size factor

Σ_ρ is the curvature sum

F is the face width of the narrow member

K_m is the load-distribution factor

C_f is the rim-thickness factor

Surface Condition Factor C_f

The surface condition factor C_f is used only in pitting resistance equation. It modifies the equation to account for surface finish, residual stress and plastic effects. Since AGMA has not defined standard surface condition for gear teeth, we take it as unity. However when a detrimental surface finish is know than $C_f > 1$ is taken. (from [23])

AGMA Contact Strength Equation

The *gear contact strength* is designated as S_c and can be obtained from following graph below for hardened steel and from table for other steel.The hardness and heat treatment of the material should be known to get the value of S_c

There are various factors which modify the S_c to get it's corrected value.Here is the equation to correct it's value (from [23])

$$\sigma_{C,all} = \frac{S_C Z_N C_H}{S_H K_T K_R} \tag{3.59}$$

where

S_C is the allowable contact stress

Z_N is the stress cycle factor

C_H hardness-ratio factor

S_H is the contact stress safety factor

K_T is the temperature factor

K_R is the reliability factor

Stress-Cycle factor Z_N

The values given for S_C are only for 10^7 cycles. The Stress-Cycle Factor Z_N modifies the allowable contact stress for cycles other than 10^7.The value of Z_N depends on the material, number of cycles, heat treatment and can be obtained from next given figure.

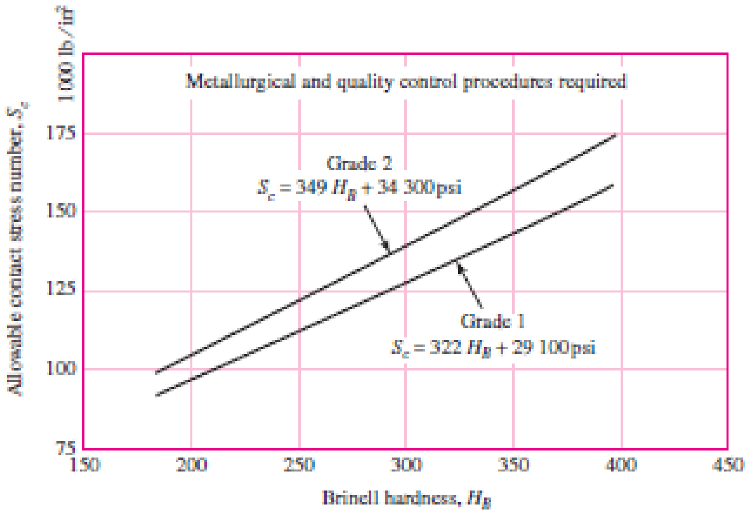


Figure 3.18: [Repeatedly Applied Contact Strength S_c at 10^7 cycles and 0.99 Reliability for steel (Source: [23])

Material Designation	Heat Treatment	Minimum Surface Hardness[1]	Allowable Contact Stress Number,[2] S_c, psi Grade 1	Grade 2	Grade 3
Steel[3]	Through hardened[4]	See Fig. 14–5	See Fig. 14–5	See Fig. 14–5	—
	Flame[5] or induction hardened[5]	50 HRC	170 000	190 000	—
		54 HRC	175 000	195 000	—
	Carburized and hardened[5]	See Table 9*	180 000	225 000	275 000
	Nitrided[5] (through hardened steels)	83.5 HR15N	150 000	163 000	175 000
		84.5 HR15N	155 000	168 000	180 000
2.5% chrome (no aluminum)	Nitrided[5]	87.5 HR15N	155 000	172 000	189 000
Nitralloy 135M	Nitrided[5]	90.0 HR15N	170 000	183 000	195 000
Nitralloy N	Nitrided[5]	90.0 HR15N	172 000	188 000	205 000
2.5% chrome (no aluminum)	Nitrided[5]	90.0 HR15N	176 000	196 000	216 000

Figure 3.19: Repeatedly Applied Contact Strength S_c at 10^7 cycles and 0.99 Reliability (Source: [23])

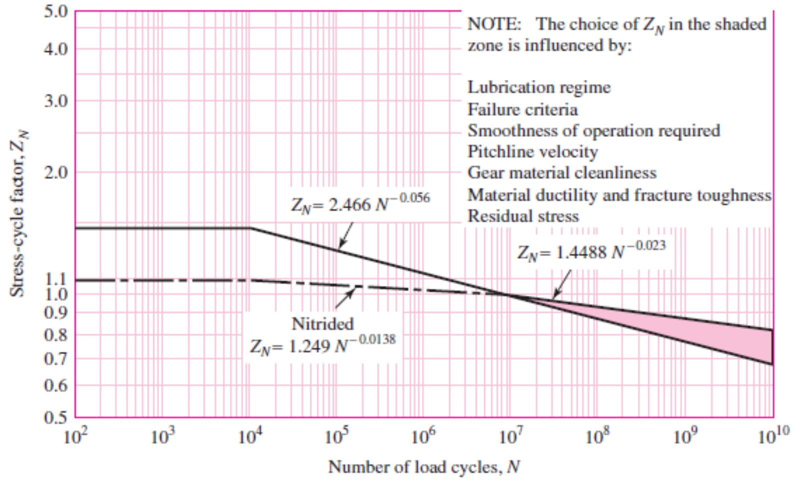


Figure 3.20: Pitting resistance stress-cycle factor Z_N (Source: [23])

Harness-Ratio Factor C_H

The purpose of the hardness-ratio factor is to adjust the surface strength, so that there is uniform surface strength.C_H is used only for gear. The value of C_H is obtained from equation given by (from [23])

$$C_H = 1.0 + A^{'}(m_G - 1.0) \tag{3.60}$$

where

$$A^{'} = 8.98(\frac{H_{BP}}{H_{BG}})(10^{-3}) - 8.29(10^{-3}) \qquad 1.2 \leq \frac{H_{BP}}{H_{BG}} \leq 1.7 \tag{3.61}$$

$$\begin{aligned} A^{'} &= 0 \qquad \frac{H_{BP}}{H_{BG}} < 1.2 \\ A^{'} &= 0 \qquad \frac{H_{BP}}{H_{BG}} > 1.7 \end{aligned}$$

where m_G is the speed ratio of the gear and pinion.

Safety Factor S_H

The safety factor S_H is used as guarding against fatigue failure. The definition of S_H is (from [23])

$$S_H = \frac{S_C Z_N C_H/(K_T K_R)}{\sigma_C} = \frac{fully\ corrected\ contact\ strength}{contact\ stress} \tag{3.62}$$

The safety factor was not computed in this thesis as we are directly interested in computing the probability of survival due to contact stress.

Gear contact stress failure condition based on AGMA

The AGMA uses Safety Factor S_H^2 to check the treat of failure due to contact stress, which should be greater than unity. However for our discussion we have modified the equation into simpler form given below (from [3, 23, 33])

$$\sigma_C \leq \sigma_{C,all} \implies \sigma_C = C_P(W^t K_o K_v K_s K_m \Sigma_\rho \frac{C_f}{F})^{1/2} \leq \frac{S_C Z_N C_H}{S_H K_T K_R} \tag{3.63}$$

3.2.6 Life calculation of Gear

Tooth Life

We will use fatigue-life model proposed by lundberg for determining the fatigue life of gear. The model is commonly accepted theory for predicting the fatigue life of rolling-element bearings. The probability of survival as a function of stress cycle is given by below equation (from [3])

$$log\frac{1}{S} \propto \frac{\tau^c \eta^e V}{Z^h} \tag{3.64}$$

where

S is the probability of survival

τ is the maximum critical stress η is the life required for given reliability V is the stressed volume Z is the depth of the critical shearing stress c,e,h are the constants The equation 2.64 can be modified into (from [3, 20])

$$\eta \propto \frac{Z^{h/e}}{\tau^{c/e} V 1/e} \tag{3.65}$$

for above equation it is clear that greater the stress, shorter the life. The depth below the surface Z where the critical stress occurs is also a factor. Since its takes time for the micro crack to come show up at the surface from the beginning point. Therefor, the life varies by inverse power of depth to the critical stress zone.The stressed volume is also important factor. The pitting initiation are generally develop near small stress rising imperfection in the material. Larger the stress volume greater the likelihood of the fatigue failure. The stress volume is proportional to in volute length,depth of the critical shearing stress and face width. This is represented in equation given below. (from [3])

$$V \propto fZl \tag{3.66}$$

We have earlier used hertz equation to find (from [3, 33]) P_{max} as $\frac{W^t}{\pi F} \frac{\Sigma_\rho}{(1-\mu_1^2)/E_1 + (1-\mu_2^2)/E_2}$. Where Σ_ρ is curvature sum given by

$$\Sigma_\rho = \frac{1}{\rho_1} + \frac{1}{\rho_2} \tag{3.67}$$

where ρ is the radius of curvature.

The failure of the bearing happens dude to maximum reversing orthogonal shear stress occurring at depth Z below the surface with amplitude (from [3, 33]) $\pm\tau$ where $Z = b/2$ and $\tau = P_{max}/4$. where $b = \sqrt{\frac{2W^t}{\pi f}\frac{(1-\mu_1^2)/E_1+(1-\mu_2^2)/E_2}{\Sigma_\rho}}$. Now substituting values of Z,V and τ in equation 2.65, we get (from [3, 33])

$$\eta \propto P_{max}^{-(c-h+1)/2e} f^{(c-h-1)/2e} \Sigma_\rho^{-(c+h-1)/2e} l^{-1/e} \tag{3.68}$$

According to [3, 20, 34], we get $e = 2.5$, $c = 23.2525$ and $h = 2.7525$. Putting values in equation 2.68, we have

$$\eta \propto P_{max}^{-4.3} f^{3.9} \Sigma_\rho^{-5} l^{-0.4} \tag{3.69}$$

Removing proportionality and putting constant K as proportionality constant equation modifies to,

$$\eta = K P_{max}^{-4.3} f^{3.9} \Sigma_\rho^{-5} l^{-0.4} \tag{3.70}$$

where $K = 3.72X10^{18}$ was calculated from data given in [34] and η is the tooth life in millions of cycle.

Gear life

The survival probability of single tooth under constant service condition is given by

$$log\frac{1}{S} \propto \eta^e \tag{3.71}$$

for 90- percent survival rate $S = 0.90$ and the corresponding life is $\eta = T_{10}$, a constant for proportionality is C is assumed. (from [3])

$$log\frac{1}{0.9} = CT_{10}^e \tag{3.72}$$

we get the value of $C = \frac{log\frac{1}{0.9}}{T_{10}^e}$. Now we can write the equation for general survival rate as (from [3])

$$log\frac{1}{S} = (\frac{\eta}{T_{10}})^e log\frac{1}{0.9} \tag{3.73}$$

Now, from basic probability theory the probability of survival for N teeth is the product of individual probability of survival. The probability of survival for gear with N teeth is $S_i = S^N$. Which gives us (from [3])

$$log\frac{1}{S_i} = N(\frac{L_i}{T_{10}})^e log\frac{1}{0.9} \tag{3.74}$$

Let the probability of survival for gear be 0.9 and corresponding life of the gear be called as G_{10}. Putting values in above equation results in (from [3])

$$(\frac{1}{G_{10}})^e = N(\frac{1}{T_{10}})^e \tag{3.75}$$

The above equation gives us the relation between the 10-percent life for the gear and the 10-percent life of a single tooth.

Calculation of in-volute length and curvature sum for gear

let N_1, N_2 be the Number of teeth, r_1, r_2 be the pitch radius, r_{a1}, r_{a2} be the addendum radius, r_{b1}, r_{b2} be the base radius of the gear 1 and 2 respectively.

Then *length of contact path,* Z is given by (from [3])

$$Z\sqrt{r_{a1}^2 - r_{b1}^2} + \sqrt{r_{a2}^2 - r_{b2}^2} - (r_1 + r_2)sin\phi \tag{3.76}$$

The below equations were taken from [3]

base pitch p_b is $2\pi r_{b1}/N_1$

Roll angle increment β_{L1} is $(Z - p_b)/r_{b1}$

Roll angle increment β_{H1} is $(2p_b - Z)/r_{b1}$

Pre contact roll angle δ_1 is given by

$$\delta_1 = \frac{(r_1 + r_2)sin\phi - \sqrt{r_{a2}^2 - r_{b2}^2}}{r_{b1}} \tag{3.77}$$

Length of involute during single tooth contact δ_1 is given by

$$l_1 = r_{b1}\beta_{H1}(\delta_1 + \beta_{L1} + \frac{1}{2}\beta_{H1}) \tag{3.78}$$

Radius of curvature ρ_1 is $r_{b1}(\delta_1 + \beta_{L1})$

Radius of curvature ρ_2 is $(r_1 + r_2)sin\phi - \rho_1$

finally curvature sum Σ_ρ is $\frac{1}{\rho_1} + \frac{1}{\rho_2}$. This curvature sum was used for σ_C

3.3 Reliability Analysis

The methodology taken in this part is standard way of finding the probability of failure for two distribution which are subtracted from one another. This methodology is presented below has been given in [23]. Consider that Force, Torque and Yield Strength follow normal distribution $P = N(P_{mean}, \sigma_P)$, $T = N(T_{mean}, \sigma_T)$, $S = N(S_{mean}, \sigma_S)$ $S_t = N(S_{t_{mean}}, \sigma_{S_t})$, $S_C = N(S_{C_{mean}}, \sigma_{S_t})$ and $W^t = N(W^t_{mean}, \sigma_{W^t})$ respectively.

Putting F and S in equation 2.24 and rearranging terms we have

$$S/2 - 8Pl/\pi D^3 \geq 0 \tag{3.79}$$

if $M = N(M_{mean}, \sigma_M)$ is multiplied by constant a then new normal probability distribution is given by $M = N(aM_{mean}, \sqrt[2]{a^2\sigma_M^2})$. Applying the above method to get normal distribution of σ_b from normal distribution of P. Similarly we can obtain the normal distribution of $S/2$,τ_{max} from S and T respectively. Replacing the distribution of S, P with its modified distribution gives us the below equation.

$$N(\frac{S_{mean}}{2}, \frac{\sigma_S}{2}) - N(\frac{8lP_{mean}}{\pi D^3}, \frac{8l\sigma_P}{\pi D^3}) \geq 0 \tag{3.80}$$

Similarly we can find the equation for S and τ_{max} from equation 2.25

$$N(\frac{S_{mean}}{2}, \frac{\sigma_S}{2}) - N(\frac{16T_{mean}}{\pi D^3}, \frac{16\sigma_T}{\pi D^3}) \geq 0 \tag{3.81}$$

Let us define some constants to make later equations shorter

$$\begin{aligned}
B &= K_o K_v K_s \frac{P_d}{F} \frac{K_m K_B}{J} \\
B_S &= \frac{Y_N}{K_T K_R} \\
c &= C_P^2 K_o K_v K_s K_m \Sigma_\rho \frac{C_f}{F} \\
c_S &= \frac{Z_N C_H}{S_H K_T K_R}
\end{aligned}$$

Similarly we can find the equation of S_t and W^t in terms of above defined variables, from equation 2.5

$$N(B_S S_{t_{mean}}, B_S \sigma_{S_t}) - N(B W^t_{mean}, B\sigma_{W^t}) \geq 0 \tag{3.82}$$

Similarly we can find the equation of S_C and W^t in terms of above defined variables, from equation 2.63

$$N(CS_{c_{mean}}, c\sigma_{S_t}) - N(\sqrt{c}\sqrt{W^t_{mean}}, \sqrt{c}\sigma_{\sqrt{W^t}}) \geq 0 \tag{3.83}$$

The *margin of safety* for any value of stress σ and strength S is defined as $m = S - \sigma$ The overlap of the distribution shown in figure 2.13a, the stress exceeds the strength, the margin of safety is negative and these parts are expected to fail. These shaded area is called the interference of σ and S.

Figure 2.13b shows distribution of m which is dependent on the distribution of stress and strength. The reliability that a part will perform without failure , R, is the area of the margin of safety distribution for m ¿ 0. The interference is the area 1 - R where parts are expected to fail.

Let $S = N(\mu_s, \sigma_s)$ and $\sigma = N(\mu_\sigma, \sigma_\sigma$. The stress margin is $m = S - \sigma$ which will be

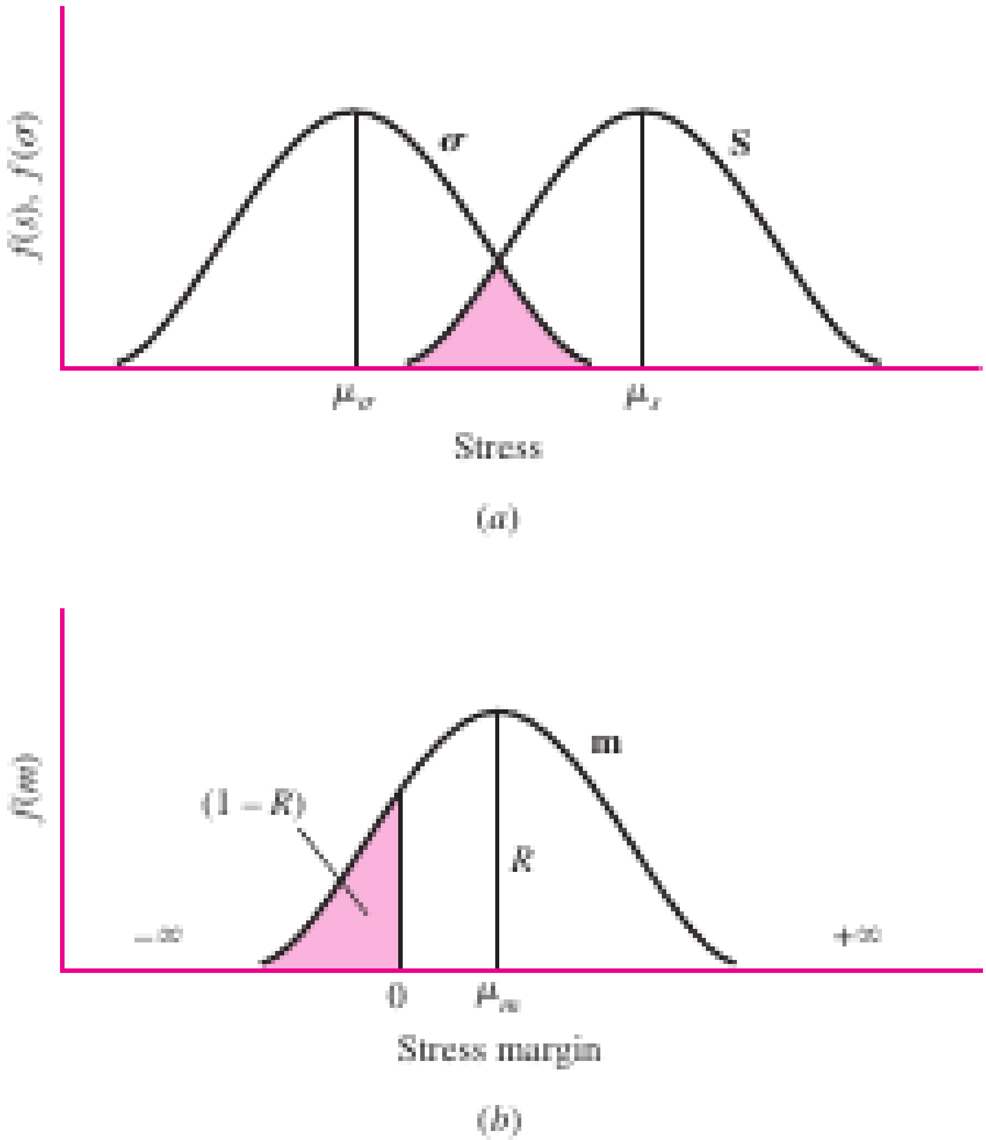


Figure 3.21: Probability density function interference

normal $m = N(\mu_m, \sigma_m)$. Reliability is the probability p such that m >0.

$$R = p(S > \sigma) = p(S - \sigma > 0) = p(m > 0) \tag{3.84}$$

To find the chance of m >0 we form the z variable of m and substitute m = 0. Since $m = S - \sigma$ we get $\mu_m = \mu_S - \mu_\sigma$ and $\sigma_m = \sqrt[2]{\sigma_S^2 + \sigma_\sigma^2}$

$$z = \frac{m - \mu_m}{\sigma_m} = \frac{0 - \mu_m}{\sigma_m} = -\frac{-\mu_m}{\sigma_m} = \frac{mu_S - \mu_\sigma}{\sqrt[2]{\sigma_S^2 + \sigma_\sigma^2}} \tag{3.85}$$

The reliability associated with given z is given by

$$R = \int_x^\infty \frac{1}{\sqrt[2]{2}\pi} \exp(-\frac{u^2}{2})du = 1 - F = 1 - \Phi(z) \tag{3.86}$$

Combing equation 2.80 and 2.85 we get value of z as (To find reliability for bending stress of Shaft)

$$z = -\frac{\frac{S_{mean}}{2} - \frac{8lP_{mean}}{\pi D^3}}{\sqrt[2]{(\frac{\sigma_S}{2})^2 + (\frac{8l\sigma_P}{\pi D^3})^2}} \tag{3.87}$$

Combing equation equation 2.81 and 2.85 we have (To find reliability for Shear stress of Shaft)

$$z = -\frac{\frac{S_{mean}}{2} - \frac{16T_{mean}}{\pi D^3}}{\sqrt[2]{(\frac{\sigma_S}{2})^2 + (\frac{16\sigma_T}{\pi D^3})^2}} \tag{3.88}$$

Combing equation 2.82 and 2.85 we get value of z as (To find reliability for bending stress of Gear)

$$z = -\frac{B_S S_{t_{mean}} - BW^t_{mean}}{\sqrt{(B_S \sigma_{S_t})^2 + (B\sigma_{W^t})^2}} \tag{3.89}$$

Combing equation 2.83 and 2.85 we get value of z as (To find reliability for contact stress of Gear)

$$z = -\frac{CS_{c_{mean}} - \sqrt{c}\sqrt{W^t_{mean}}}{(c\sigma_{S_t})^2 + (\sqrt{c}\sigma_{\sqrt{W^t}})^2} \tag{3.90}$$

3.4 Parameter Estimation for Reliability

The term parameter estimation refers to the process of using failure data available to estimate the parameter of the selected distribution, which is Weibull distribution in this thesis.There are many methods for this estimation, however we will be using least square method.

3.4.1 Linearising the relationship between time and reliability

Reliability using Weibull distribution is given by $e^{-(\frac{t}{\eta})^2}$ (from [**ReliabilityEngineers**])

$$R(t) = e^{-(\frac{t}{\eta})^\beta} \tag{3.91}$$

$$ln(R(t)) = -(\frac{t}{\eta})^\beta \tag{3.92}$$

$$ln(-ln(R(t))) = \beta ln(t) - \beta ln(\eta) \tag{3.93}$$

The above equation 2.93 can be represented in the for of (from [**ReliabilityEngineers**])

$$Y = mX + C \tag{3.94}$$

Where Y is $ln(-ln(R(t)))$

X is $ln(t)$

m is β

C is $-\beta ln(\eta)$

3.4.2 Estimating the value β and η

Best Fit line

The below method used for computing $\eta \; and \; \beta$ were taken from [**ReliabilityEngineers**]. Linear regression is the best fit line to a set of points to estimate the parameters.Assume that a set of data pairs $(t_1, R(t_1))$,$(t_2, R(t_2))$, ...,$(t_N, R(t_N))$ were obtained and plotted, and that the x-values were known exactly. Then the least square method minimizes the vertical distance between the data points and the straight line is fitted to the data, the best fitting line to the data is given by (from [**ReliabilityEngineers**])

$$y = \hat{a} + \hat{b}x \tag{3.95}$$

Such that: (from [**ReliabilityEngineers**])

$$\sum_{i=1}^{N}(\hat{a} + \hat{b}x_i - y_i)^2 = min \sum_{i=1}^{N}(\hat{a} + \hat{b}x_i - y_i)^2 \tag{3.96}$$

where $\hat{a}, \hat{b}$ are the estimated value obtained when the square error is minimum and $\hat{a}, \hat{b}$ are called the least square estimate of a and b. N is the number of sample points in data set. The equations are minimized by estimates $\hat{a}$ and $\hat{b}$ such that: (from [**ReliabilityEngineers**])

$$\hat{a} = \frac{\sum_{i=1}^{N} y_i}{N} - \hat{b}\frac{\sum_{i=1}^{N} x_i}{N} = \bar{y} - \hat{b}\bar{x} \tag{3.97}$$

$$\hat{b} = \frac{\sum_{i=1}^{N} x_i y_i - \frac{\sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N}}{\sum_{i=1}^{N} x_i^2 - \frac{(\sum_{i=1}^{N} x_i)^2}{N}} \tag{3.98}$$

Correlation Coefficient

The correlation Coefficient ρ is a measure of how well the linear regression fits the data.The population correlation coefficient is given by (from [**ReliabilityEngineers**])

$$\rho = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{3.99}$$

where σ_{xy} is the co-variance of x and y, σ_x is the standard deviation of x and σ_y is the standard deviation of y. The value of ρ is computed by below equation (from [**ReliabilityEngineers**])

$$\hat{\rho} = \frac{\sum_{i=1}^{N} x_i y_i - \frac{\sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N}}{(\sqrt{(\sum_{i=1}^{N} x_i^2 - \frac{(\sum_{i=1}^{N} x_i)^2}{N})(\sum_{i=1}^{N} y_i^2 - \frac{(\sum_{i=1}^{N} y_i)^2}{N}})} \tag{3.100}$$

The range of $\hat{\rho}$ is $-1 \leq \hat{\rho} \leq 1$ The values closer to ± 1 implies better linear fit and closer to zero implies data is randomly scattered.

Chapter 4

Similarity Based Approach for Reliability Analysis

4.1 The Solution

The main problem to addressed in this thesis is to address the insufficiency of failure data available for particular mechanical part which leads to untimely failure. This problem can be solved by using combining failure data from multiple parts, But the question arises on what basis should be decide which parts data should be merged?. Can we come up with a algorithm which can takes this decision for us when implemented and can further predict the remaining life of the component.The reliability based approach can be a solution for above problem. In this approach we can compute the reliability of each mode of failure for component which has insufficient failure data and for other components of same type and material.Then computed reliability can be compared and can be used to decide whether the data should be merged or not. Later use the merged failure data of the component to do parameter estimation for weibull distribution parameters.However to achieve this the components should be able to communicate with other components.The data required for the computation for reliability should also be standardized.This thesis demonstrates the solution for all above problem.The Components were represented virtually with the help of ontology and excel file which contains data in standard format and the format is same for same type of component.The Program was designed in python to allow the components to communicate with each other.The program gets the required data form all components and does all computation before deciding whether to merge the failure data of the component or not.

4.2 Similarity of two Components

The similarity of two components depends on many variable like loading condition,material properties and dimensions.Also the computing similarity between two components which are different type or made up of different material has no meaning.For reliability point of view we need to see which of above factors involved will play role in their reliability. The reliability is basically means what is the probability that system will continue working in the same condition. The reliability is dependent on the mode of failures happening in the component.If we want to study the reliability then we should focus on how system can fail. There are many ways in which the component can fail, Examples are failure due to bending, failure due to torsion and due to fatigue. There maybe more modes of failure. The reliability of the mechanical component for all forms of failure must be looked individually and compared with other components if we want to find similarity between two components. The reliability of individual component for individual mode of failure should be the features based on which we should establish similarity. In this thesis we have computed reliability for two modes of failure i.e. Reliability for failure due to bending stress, failure due to torsion for shear and what is the theoretical life of the shaft. The individual reliability of the components were compared and theoretical life was also compared. 10 percent rule is a good approximation for considering similarity of two components. The 10 percent rule gives us average error of 0.025 while 20 percent rule gives us an average error of 0.05. The average was calculated assuming maximum error for reliability from 0.01 to 0.99 evenly spaced with 0.01 as the difference.The similarity of the components is decided by whether reliability of the component lies between the 10 percent of the other component and vice versa. For example reliability of component one is given by R_1 and that of component two is R_2 then whether $R_1 \in R_2 \pm \frac{R_2}{20}$ or $R_2 \in R_1 \pm \frac{R_1}{20}$

4.3 General Procedure for Creating algorithm for virtual representation of Machines and Analysis

The virtual representation of machine requires two things, firstly hierarchy to define machine in terms of its components and secondly a way to represent data required to uniquely and completely define the components.The first objective can be easily achieved with the help of ontology as discussed in literature review.The section 4.5 provides the visual representation of machines. There are two types of parameters for every mechanical component, namely fixed and variable. The properties based on material, dimensions of the component, type of component and manufacturing process it has went through are the fixed type parameters and will ever.While load, RPM, torque and working condition may change and hence are variable parameters.Next challenge is that for different type of component have different set of calculations to be done for their failure analysis.Based on the modes of failure which can occur in the component, do the failure analysis(find out critical conditions to avoid failure) from reliability perspective.One reliability for all modes of failure is computed, we need a algorithm which computes similarity between components based on Type, material and reliability.Computing similarity for type and material is easy, however for reliability its a challenge.Many supervised, unsupervised learning methods are there which can be used here. We have used 10 percent rule because of simplicity and lack of actual data for training this algorithms.Once the similarity is computed the data can be merged and parameter estimation can be done to find the approx time to failure of the new machine. 1.Identify the fixed and variable parameters required for calculation of reliability of different modes of failure.

2.Create OWL-Ontology for Fixed parameters.

3.Create excel file for loading condition.

4.Program the all computation required to find out the reliability of all modes of failure

5.compare the component based on it's Type and material

6.Select a algorithm to compute similarity of two components of same type and material.We have used 10 percent rule.

7.If they are similar then merge the data of the similar components.

8.Use the merged data to estimate the value of β, η using linear regression.

9.Predict the value of time-to=failure based on reliability condition provided by user.

4.4 Fixed parameters of Shaft and Gear

These fixed parameters which are necessary for the calculation of reliability of different modes of failure are

Gear

1.Brinell hardness of the material used

2.Bending strength geometry factor of the gear

3.Diametral Pitch of the gear

4.Elastic Coefficient for two mating gears

5.Face Width of the tooth

6.Heat treatment of the material

7.Lewis for factor of the gear

8.Material used to make gear

9.Number of teeth on the gear

10.Pressure angle of gear

11.Reliability of S_C, S_t

12.Rim thickness of the gear

13.Standard deviation to mean ratio for S_t

14.Standard deviation to mean ratio for S_C

15.Teeth type of the gear

16.Tooth height

17.Type of gear

Shaft

1.Endurance limit of material used for shaft

2.Reliability of endurance limit

3.Length of the Shaft

4.Manufacturing Process of the material

5.Material of the shaft

6.Diameter of the shaft

7.Standard deviation to mean ratio for yield strength

8.Type of the shaft

9.Ultimate Tensile strength of the material used

10.Yield strength of the material used

4.5 Creating Ontology for fixed parameters

Ontology is a good way to represent structure of machine in terms of its components. Owl Ontology was created using Protege software [35]. The ontology contains classes of components and machines. Shaft and Gear are the subclass of components. Object property of has_component was created to address the relationship between machine and components. All machine has components which are instances of either shaft or gear class.Inverse object property component_of was created to address the inverse relationship of has_component. if Machine 1 has_component NormalShaft then NormalShaft is component_of Machine 1 is also true.There 28 instances of shaft, gear and machine in which 2 gears and 2 shaft didn't had failure data available. The aim was to compute similarity of this gear and shaft with other gears and shaft and merge failure data for them. The ontology of Shaft and Gear is presented below. Figure 3.1

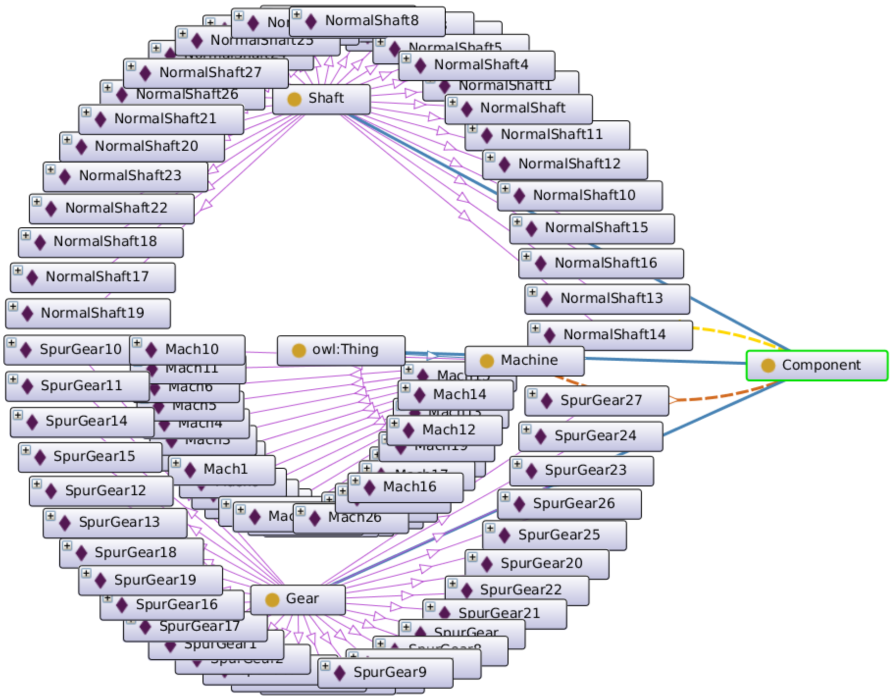


Figure 4.1: Owl Ontology

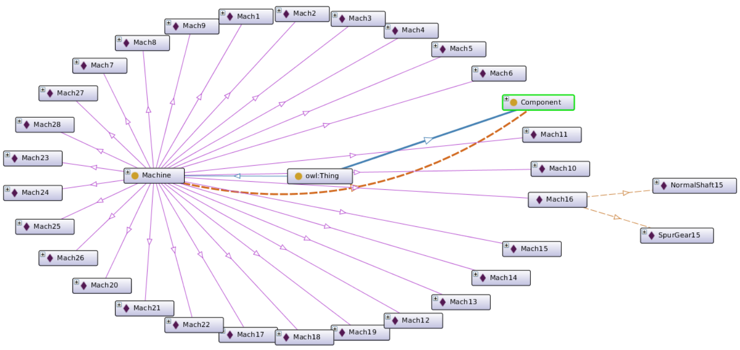
shows the classes owl:Thing, Component, Shaft, Gear and machine along with their relationship with one another. It also shows the 28 instances of class Shaft, Gear and Machine.

Figure 3.2 shows more clear view of the instances of machine, gear and shaft.

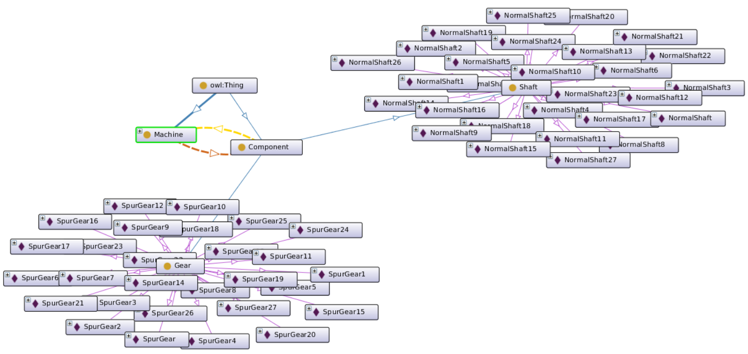
Figure 3.3(a) gives us the object properties defined in ontology for this thesis. Figure 3.3(b) and (c) gives us the data properties which are fixed parameters for shaft and gear respectively. Figure 3.4(a) is representing the values of the data properties (fixed parameters) for a particular gear, similarly Figure 3.4(b) is representing the values of the data properties (fixed parameters) of shaft

4.6 Loading condition (variable parameters)

The loading condition determine few parameters(variable) responsible for computation of reliability for failure modes.The values of the variable parameters are stored in two excel sheets.Few of this values were randomly generated and few of them were obtained after back calculations, specially to prove the algorithm works perfectly. The fix parameters for gear and shaft are given below.

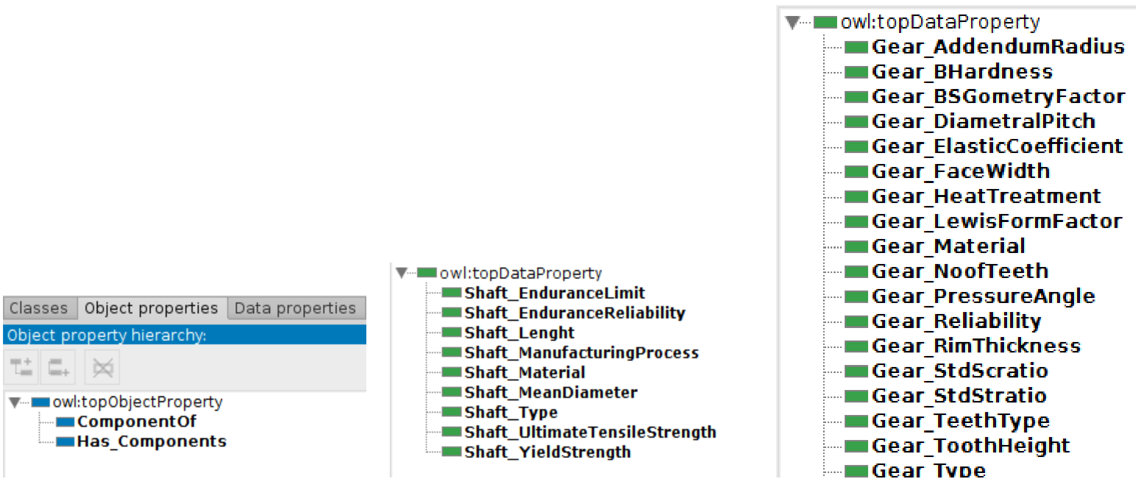


(a) Instances of Machine class in ontology



(b) Instances of Shaft and Gear class in ontology

Figure 4.2: All instances in ontology file

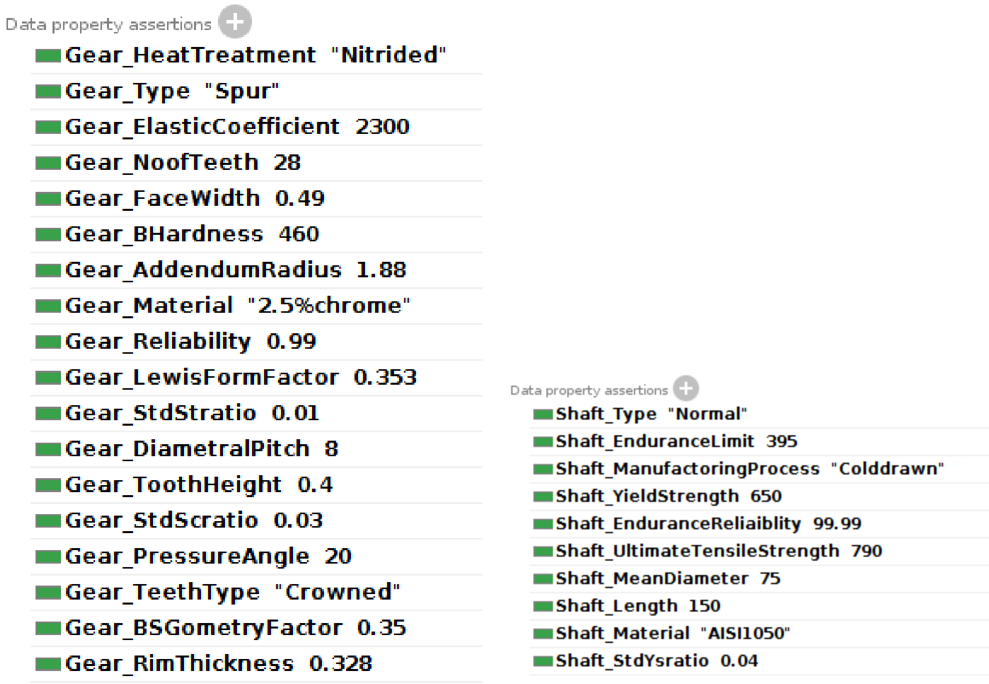


(a) Object properties in ontology

(b) Data properties of Shaft in ontology

(c) Data properties of Gear in ontology

Figure 4.3: All properties in ontology file



(a) Value of data properties of Gear instance

(b) Value of data properties of Shaft instance

Figure 4.4: Values of data properties for an instance

Gear

1.Load

2.Impact due to driver

3.Impact due to machine

4.Quality number of the meshing

5.RPM of the gear

6.Standard deviation to mean ratio of load

Shaft

1.Effective load that will act at the centre of the shaft

2.Torque applied

3.RPM of the shaft

4.Working temperature

5.Standard deviation to mean ratio of load

6.Standard deviation to mean ratio of torque

4.7 Computation of reliability for failure modes

The ontology file and excel file is loaded which has all the information about fixed parameters and variable parameters of the components.The owlready2 [13, 14] python based library is used to parse the ontology in to objects for further calculation and pandas a python based library is used to read and store data from excel.

Shaft

The algorithm computes the z value for bending and shear stress failure using equation 3.87 and 3.88 respectively for shaft from its fixed and variable parameters data obtained from ontology and excel file. For z value the reliability is computed using equation 3.86. The life of the shaft is computed using equation 3.13. The other required calculations for z and life is computed automatically done when we compute the z and life of the shaft.

Gear

The algorithm computes the z value for bending and shear stress failure using equation 3.89 and 3.90 respectively for gear from its fixed and variable parameters data obtained from ontology and excel file. For z value the reliability is computed using equation 3.86. The life of the gear (G_{10} is computed using equation 3.75. The other required calculations for z and life is computed automatically done when we compute the z and life of the shaft.

4.8 Remaining process

The algorithm designed first checks for type of the component i.e. Whether it is shaft or gear in the whole network. After that the materials of the two component is compared for same type of component, if they have same material then computation of reliability takes place for that component. Coding is done in such way that the code for gear and shaft can be easily separated. After the computation is complete 10-percent rule is applied to check the similarity of the two component, if it is similar than the failure data of that component is loaded and merged with the failure data of the component for which we need failure data. After the process is done for all components on the network, then algorithm automatically fits the linear model and find out the value of η and β.Once this two parameters are know we can find reliability and time-to-failure for given reliability.The complete code is presented in appendix

4.9 Algorithm Flow Chart and Demonstration

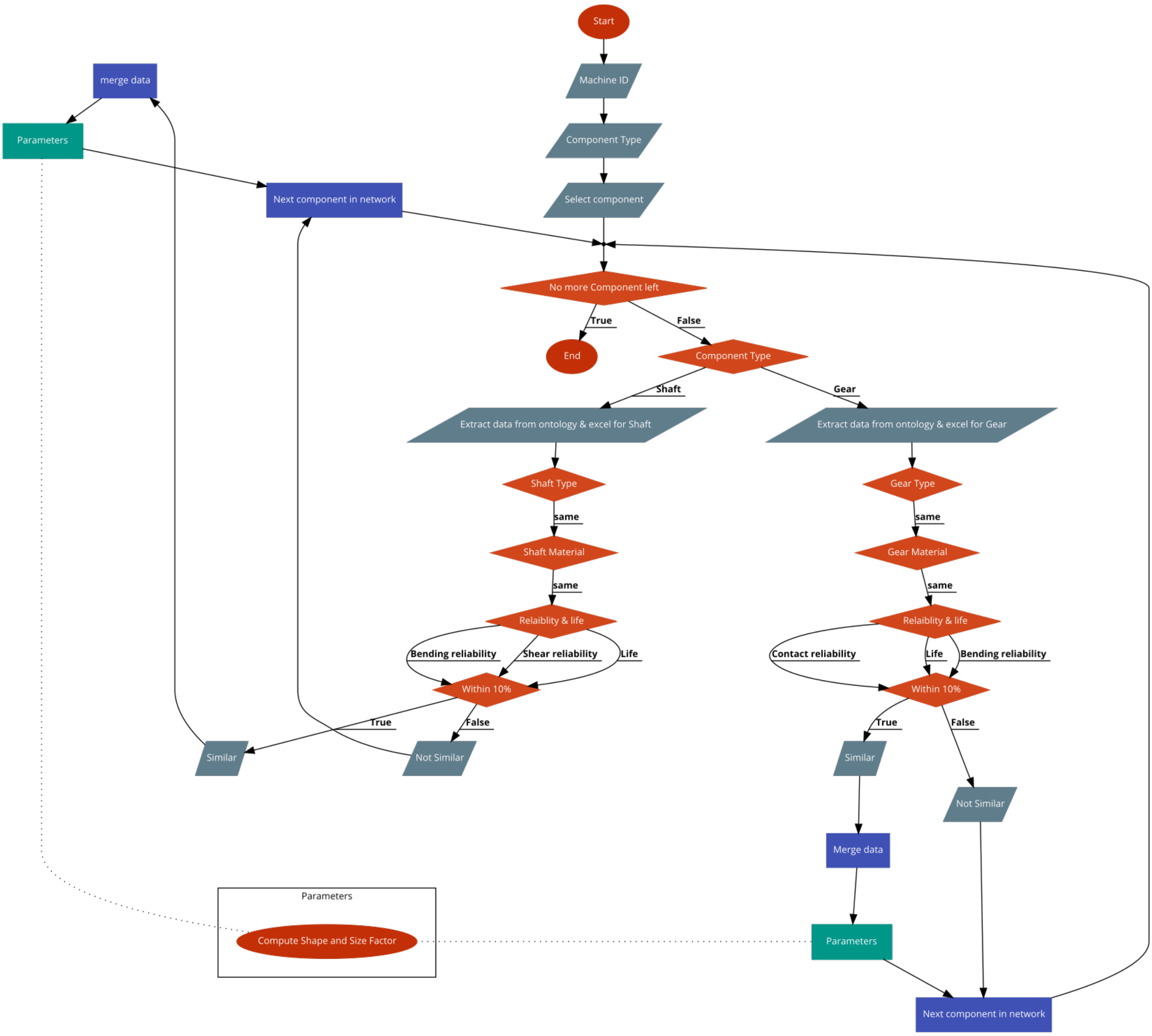


Figure 4.5: Flowchart of algorithm

The program can be executed using shell command python DDP_Project_F_V.py. The program informs the user about how machine IDs are represented in the system. Then it asks user to enter the machine ID of the machine for which they want to do analysis. Once entered, the program next asks user whether they want to do analysis for the gear or the shaft of that machine. After that the program goes into the network searches for the similar components based on the algorithm explained in above sections and prints their machine IDs. The user is asked to enter the reliability at which they want to change the components. The program returns the working hours after which the parts should be changed.The program also provides the shape and size parameter of the weibull distribution.

```
max@maxcom:~$ python DDP_Project_F_V.py
Available Machines ID is given by MachID where ID can take value from 1 to 28. E
g Mach3
Please enter the name of the machine from above
Mach3
Please enter the type of Component (Shaft\Gear)
Shaft
Similar Shaft are present on given Machine.
Mach1
Mach2
Mach9
Please enter the reliability of the compoent for which you want to compute worki
ng Hours
0.2
Linear regression model for reliability and time to failure has yielded with Sha
pe Parameter Neta =  8351764.597347653 and Scale Parameter Beta =  2.46665723957
07376
The selected compoent will have 0.2 reliability at 168816 working Hours
max@maxcom:~$
```

Figure 4.6: Code Demo

Chapter 5

Summary and Future Work

5.1 Summery

The problem of not having enough failure data causes lots of discomfort and wastage in terms of money and operation time. A solution for this problem is proposed. The reliability of different modes of failure is computed and compared with other component of same type and material. If the reliability of each mode of failure of one component lies between 5 percent of reliability of second component for same mode of failure then they are considered similar. Once they are similar their available failure data is merged and we have more failure data for each component. Now we use parameter estimation on this failure data and get the values of η and β which can be used to find the reliability of the component at any time. Also if the reliability is known then time to failure can be predicted.The implementation of the above algorithm for shaft and gear was presented in this thesis. The thesis also solves the famous problem of virtual representation of machine on the network such that its parts maintain its individuality.The semantic web with the help of ontology was used to achieve this. The examples of how to make ontology was also presented. How to completely represent a mechanical component virtually was discussed briefly. The above implementation of the algorithm was done in python with the help of owl-ready to read ontology.The protege was used for creating ontology and excel was used to store loading condition of the machine parts.The program developed was user friendly.

5.2 Future Work

The theoretical analysis as done for shaft and gear can also be done for other mechanical components.A better algorithm than 10 percent rule can be developed for better accuracy in similarity.The program developed can also be extended for doing any other calculation related to failure data.The method presented in this thesis can be used to create data and use to train neural network which will take input as fixed and variable parameter of the component to predict the values of η and β.Above method can be used to do analysis of all components of a machine and get their approx failure time and by using structure of machine, we can find its time to failure.Ontology can easily be used to store the structure of any machine without destroying the entity of component, which means machine and components will preserve their individuality but still be related to one another. example is Mech1 has_component NormalShaft1; here, the Mech1 and Normal shaft are represented as independent entity but still hold relation to one another.

Appendix

```
 #Code of the program developed for this thesis

#Modules Used in this program

import rdflib
from owlready2 import*
import numpy as np
import pandas as pd

import scipy
import scipy.stats
import math
from sklearn import linear_model



# In[3]: Reading owl file



onto = get_ontology("file:///home/max/DDP_project(1).owl")
onto.load()



# In[4]: reading loading files



data_Shaft = pd.read_excel("Loading.xlsx")
data_Gear = pd.read_excel("Loading_Gear.xlsx")

# In[6]: compute reliablity

def reliability(TTFA,Beta,TTFT):
    rel = math.exp(-(TTFA/TTFT)**Beta)
    return rel
#calculate moment
def Shaft_Moment(Force,Diameter,Length):#calculate moment
    mom = Force*Length/2
    return mom


```

```
# In[7]: does the linear regression
def linearreg(df,YA,Tn):
    X = np.array([])
    Y = np.array([])
    for i in range(len(df)):
        X = np.append(X,math.log(df[i]))
        Y = np.append(Y,math.log(-math.log(YA[i])))
    X = X.reshape(-1,1)
    lm = linear_model.LinearRegression()
    model = lm.fit(X,Y)
    a = float(lm.coef_)
    b = float(lm.intercept_)
    neta = math.exp(-b/a)
    print("Linear regression model for reliability and time to failure has
   yielded with Shape Parameter Neta = ",neta,"and Scale Parameter Beta = "
   ,a)
    t = math.exp(((math.log(-math.log(Tn))) + a*math.log(neta))/a )
    t = int(t/60)
    return t

#computes von mises stress
def Shaft_SigmaRev(Force, Torque, Diameter, Length):
    Dia = 3.14*Diameter*Diameter*Diameter
    mom = Shaft_Moment(Force, Diameter, Length)
    Ma = mom*32/Dia
    ta = Torque*16/Dia
    sigmarev = math.sqrt(Ma*Ma + 3*ta*ta)
    return sigmarev


# In[8]:compute f
def Shaft_f(UltimateTensileStrength):
    f = 0.0
    const = (80*0.876 + 100*0.842 + 120*0.82 + 0.805*140 + 0.792*160 +
   0.781*180 + 0.775*200)/7
    if(UltimateTensileStrength <= 70):
        f = 0.9
    else:
        f = const/UltimateTensileStrength
    return f

```

```python

# In[9]:

compute moment reliability
def Shaft_Relmoment(Force, YeildStrength, Diameter, Length, StdYsratio, StdFratio):
    mom = Shaft_Moment(Force,Diameter,Length)
    Dia = 3.14*Diameter*Diameter*Diameter
    mom = mom*32/Dia
    Ys = YeildStrength/2
    Mean = Ys - mom
    stdYs = StdYsratio*Ys
    stdF = StdFratio*mom
    Std = math.sqrt(stdYs*stdYs + stdF*stdF)
    norm = scipy.stats.norm(Mean,Std)
    rel = 1 - norm.cdf(-Mean/Std)
    return rel




# In[10]:compute torsion reliability


def Shaft_Reltorsion(Torque, YeildStrength, Diameter, Length, StdYsratio, StdTratio):
    Dia = 3.14*Diameter*Diameter*Diameter
    Tor = Torque*16/Dia
    Ys = YeildStrength/2
    Mean = Ys - Tor
    stdYs = StdYsratio*Ys
    stdT = StdTratio*Tor
    Std = math.sqrt(stdYs*stdYs + stdT*stdT)
    norm = scipy.stats.norm(Mean,Std)
    rel = 1 - norm.cdf(-Mean/Std)
    return rel


# In[11]:

def Shaft_Ka(UltimateTensileStrengthMPA, ManufactoringProcess):
```

```python
    a = 0
    b = 0
    if(ManufactoringProcess == "Ground"):
        a = 1.58
        b = -0.085

    elif(ManufactoringProcess == "Colddrawn" or ManufactoringProcess == "Machined"):
        a = 4.51
        b = -0.265
    elif(ManufactoringProcess == "Hotrolled"):
        a = 57.7
        b = -0.718
    else:
        a = 272
        b = -0.995
    ka = a*UltimateTensileStrengthMPA**b

    return ka


# In[12]:


def Shaft_Kb(Diameter):
    kb = 0
    if(Diameter <= 51):
        kb = 1.24*(Diameter)**(-0.107)
    else:
        kb = 1.51*(Diameter)**(-0.157)
    return kb


# In[13]:


def Shaft_Kd(Temp):
    kd = 0.975 + 0.432*Temp*(10**(-3)) - 0.115*(10**(-5))*Temp**2 + 0.104*(10**(-8))*Temp**3 - 0.595*(10**(-12))*Temp**4
    return kd

```

```python
# In[14]:


def Shaft_Ke(Za):
    if(Za == 99):
        a = 2.326
    elif(Za == 99.9):
        a = 3.091
    elif(Za == 99.99):
        a = 3.719
    elif(Za == 99.999):
        a = 4.265
    else:
        a = 0

    Ke = 1 - 0.08*a
    return Ke


# In[15]: compute modified endurance strength


def Shaft_ModEnd(EnduranceLimit, UltimateTensileStrength,
    ManufactoringProcess,Diameter,Temp, Za):
    ka = Shaft_Ka(UltimateTensileStrength,ManufactoringProcess)
    kb = Shaft_Kb(Diameter)
    kc = 0.85
    kd = Shaft_Kd(Temp)
    ke = Shaft_Ke(Za)
    ModifiedEnduranceLimit = ka*kb*kc*kd*ke*EnduranceLimit
    return ModifiedEnduranceLimit


# In[16]:life of the shaft


def Shaft_RelLife(RPM,Force,Torque,Length,EnduranceLimit,
    UltimateTensileStrength, ManufactoringProcess,Diameter,Temp, Za):
    modend = Shaft_ModEnd(EnduranceLimit, UltimateTensileStrength,
    ManufactoringProcess,Diameter,Temp, Za)
```

```python
    fc = Shaft_f(UltimateTensileStrength)
    a = fc*UltimateTensileStrength*fc*UltimateTensileStrength/modend
    b = math.log10(modend/fc/UltimateTensileStrength)/3
    sigrev = Shaft_SigmaRev(Force, Torque, Diameter, Length)
    cycle = (sigrev/a)**(1/b)
    durn = cycle/RPM
    return durn
# in[16]
# In[6]:pitch diameter


def Gear_PitchDia(DiametralPitch,NoofTeeth):
    pitchdia = float(NoofTeeth)/DiametralPitch
    return pitchdia


# In[7]:allowable bending stress
def Gear_ST(Material,Heattreatment,Bhardness):
    St = 0.0
    if(Material == "AISI4140" and Heattreatment == "Nitrided"):
        St = 82.3*Bhardness + 12150
    elif(Material == "AISI4340" and Heattreatment == "Nitrided"):
        St = 108.6*Bhardness + 15890
    elif(Material == "2.5%chrome" and Heattreatment == "Nitrided"):
        St = 105.2*Bhardness + 9280
    else:
        St = 102*Bhardness + 16400
    return St


# In[8]:allowable contact stress

def Gear_Sc(Material, Heattreatment, Bhardness):
    Sc = 0.0
    if(Material == "AISI4140" and Heattreatment == "Nitrided"):
        Sc = 150000
    elif(Material == "AISI4340" and Heattreatment == "Nitrided"):
        St = 163000
    elif(Material == "2.5%chrome" and Heattreatment == "Nitrided"):
        Sc = 155000
    else:
```

```
            Sc = 349*Bhardness + 34300
    return Sc


# In[9]: compute gear velocity
def Gear_velocity(Revolution,DiametralPitchp,NoofTeethp):
    Dp = Gear_PitchDia(DiametralPitchp,NoofTeethp)
    Vel = 3.14*Dp*Revolution/12
    return Vel


# In[10]:dynamic factor
def Gear_Kv(Qualitynumber,Revolution,DiametralPitchp,NoofTeethp):
    Vel = Gear_velocity(Revolution,DiametralPitchp,NoofTeethp)
    B = 0.25*(12-Qualitynumber)**(2/3)
    A = 5.0+ 56*(1-B)
    Kv = ((A + (Vel)**(0.5))/A)**B
    return Kv


# In[11]:size factor
def Gear_Ks(FaceWidth,LewisFormFactor,DiametralPitchg):
    F = FaceWidth
    Y = LewisFormFactor
    Ks = 1.192*(F*(Y)**(0.5)/DiametralPitchg)
    if(Ks>1):
        return Ks
    else:
        return 1


# In[12]: load distribution factor

def Gear_Km(TeethType,FaceWidth,DiametralPitchg,NoofTeethg):
    Dg = Gear_PitchDia(DiametralPitchg,NoofTeethg)
    Cmc = 0.0
    Cpf = 0.0
    Cpm = 1.0
    Ce = 1.0
    Cma = 0.0
    #for commercial enclosed unit
```

```
    A = 0.127
    B = 0.0158
    C = -0.930/10000
    Cma = A + B*FaceWidth + C*FaceWidth**2
    if(TeethType == "Uncrowned"):
        Cmc = 1
    else:
        Cmc = 0.8
    if(FaceWidth <= 1):
        Cpf = FaceWidth/(10*Dg) - 0.025
    elif(FaceWidth <= 17 and FaceWidth >= 1):
        Cpf = FaceWidth/(10*Dg) - 0.0375 + 0.0125*FaceWidth
    else:
        Cpf = FaceWidth/(10*Dg) + 0.1109 + 0.0207*FaceWidth - 0.000228*
    FaceWidth**2
    Km = 1 + Cmc*(Cpf*Cpm + Cma*Ce)
    return Km


# In[13]:rim thickness factor

def Gear_Kb(ToothHight,RimThickness):
    Mb = RimThickness/ToothHight
    if(Mb < 1.2):
        Kb = 1.6*math.log(2.242/Mb)
    else:
        Kb = 1
    return Kb


# In[14]:reliability factor
def Gear_Kr(Reliability):
    if(Reliability >= 0.5 and Reliability < 0.99):
        Kr = 0.658 - 0.0759*math.log(1 - Reliability)
    else:
        Kr = 0.5 - 0.109*math.log(1 - Reliability)
    return Kr


# In[15]:compute curvature sum
def Gear_Rhosum(PressureAngle, NoofTeethg, NoofTeethp,FaceWidth,
```

```python
    AddendumRadiusg,AddendumRadiusp,DiametralPitchg,DiametralPitchp):
    Dp = Gear_PitchDia(DiametralPitchp,NoofTeethp)
    Dg = Gear_PitchDia(DiametralPitchg,NoofTeethg)
    Rp = Dp/2
    Rg = Dg/2
    Bcrg = Rg*math.cos(PressureAngle)
    Bcrp = Rp*math.cos(PressureAngle)
    Z = math.sqrt(AddendumRadiusg**2 - Bcrg**2) + math.sqrt(AddendumRadiusp**2 - Bcrp**2) - (Rp + Rg)*math.sin(PressureAngle)
    Pb = 2*3.14*Bcrg/NoofTeethg
    BetaL = (Z - Pb)/Bcrg
    BetaH = (2*Pb - Z)/Bcrg
    Delta = ((Rp + Rg)*math.sin(PressureAngle) - math.sqrt(AddendumRadiusp**2 - Bcrp**2))/Bcrg
    Rocg = Bcrg*(Delta + BetaL)
    Rocp = (Rg + Rp)*math.sin(PressureAngle) - Rocg
    RocSum = (1/Rocg) + (1/Rocp)
    return RocSum


# In[16]:hardness ratio factor
def Gear_Ch(BHardnessg,BHardnessp,DiametralPitchg,DiametralPitchp):
    Mg = DiametralPitchg/DiametralPitchp
    Hbpg = BHardnessg/BHardnessp
    if(Hbpg < 1.2):
        A = 0.0
    elif(Hbpg > 1.7):
        A = 0.00698
    else:
        A = Hbpg*8.98*10**(-3) - 8.29*10**(-3)
    Ch = 1.0 + A*(Mg - 1.0)
    return Ch


# In[17]:compute life of gear
def Gear_life(Load, PressureAngle, NoofTeethg, NoofTeethp,FaceWidth,
    AddendumRadiusg,AddendumRadiusp,DiametralPitchg,DiametralPitchp):
    Dp = Gear_PitchDia(DiametralPitchp,NoofTeethp)
    Dg = Gear_PitchDia(DiametralPitchg,NoofTeethg)
    Rp = Dp/2
    Rg = Dg/2
```

```
    Bcrg = Rg*math.cos(PressureAngle)
    Bcrp = Rp*math.cos(PressureAngle)
    Z = math.sqrt(AddendumRadiusg**2 - Bcrg**2) + math.sqrt(AddendumRadiusp**2 - Bcrp**2) - (Rp + Rg)*math.sin(PressureAngle)
    Pb = 2*3.14*Bcrg/NoofTeethg
    BetaL = (Z - Pb)/Bcrg
    BetaH = (2*Pb - Z)/Bcrg
    Delta = ((Rp + Rg)*math.sin(PressureAngle) - math.sqrt(AddendumRadiusp**2 - Bcrp**2))/Bcrg
    InvL = Bcrg*BetaH*(Delta + BetaL + BetaH/2)
    Rocg = Bcrg*(Delta + BetaL)
    Rocp = (Rg + Rp)*math.sin(PressureAngle) - Rocg
    RocSum = (1/Rocg) + (1/Rocp)
    T10 = 3.72*10**18*Load**(-4.3)*FaceWidth**3.9*RocSum**(-5)*InvL**(-0.4)
    G10 = (NoofTeethg*(1/T10)**2.5)**(-1/2.5)*10**6
    return G10


# In[18]:compute stress cycle factor
def Gear_Yn(Load, PressureAngle, NoofTeethg, NoofTeethp,FaceWidth, AddendumRadiusg,AddendumRadiusp,DiametralPitchg,DiametralPitchp, Heattreatment,Bhardness):
    N = Gear_life(Load, PressureAngle, NoofTeethg, NoofTeethp,FaceWidth, AddendumRadiusg,AddendumRadiusp,DiametralPitchg,DiametralPitchp)
    if(Bhardness == 160 and N < 10**6):
        Yn = 2.3194*N**(-0.0583)
    elif(Bhardness == 250 and N < 10**6):
        Yn = 4.9404*N*(-0.1045)
    elif(Bhardness == 400 and N < 10**6):
        Yn = 9.4518*N**(-0.148)
    elif(Heattreatment == "Nitrided" and N < 10**6):
        Yn = 3.517*N**(-0.0817)
    else:
        Yn = 1.3558*N**(-0.0178)
    return Yn


# In[19]:stress cycle factor
def Gear_Zn(Load, PressureAngle, NoofTeethg, NoofTeethp,FaceWidth, AddendumRadiusg,AddendumRadiusp,DiametralPitchg,DiametralPitchp, Heattreatment):
```

```
    N = Gear_life(Load, PressureAngle, NoofTeethg, NoofTeethp,FaceWidth,
    AddendumRadiusg,AddendumRadiusp,DiametralPitchg,DiametralPitchp)
    if(Heattreatment == "Nitrided" and N < 10**6):
        Zn = 1.249*N**(-0.0138)
    elif(N < 10**6):
        Zn = 2.466*N**(-0.056)
    else:
        Zn = 1.4488*N**(-0.023)
    return Zn


# In[20]:overload factor
def Gear_Ko(imptdriver,imptmachine):
    Ko = 0.0
    if(imptdriver == "Uniform" and imptmachine == "Uniform"):
        Ko = 1
    elif(imptdriver == "Uniform" and imptmachine == "Moderate"):
        Ko = 1.25
    elif(imptdriver == "Uniform" and imptmachine == "Heavy"):
        Ko = 1.75
    elif(imptdriver == "Light" and imptmachine == "Uniform"):
        Ko = 1.25
    elif(imptdriver == "Light" and imptmachine == "Moderate"):
        Ko = 1.50
    elif(imptdriver == "Light" and imptmachine == "Heavy"):
        Ko = 2.0
    elif(imptdriver == "Medium" and imptmachine == "Uniform"):
        Ko = 1.50
    elif(imptdriver == "Medium" and imptmachine == "Moderate"):
        Ko = 1.75
    elif(imptdriver == "Medium" and imptmachine == "Heavy"):
        Ko = 2.25
    else:
        print("Overload factor Not available")
    return Ko


# In[21]:Reliability bending
def Gear_RelB(TeethType,NoofTeethg,Load,StdStratio,StdLratio,BSGFactor,
    Qualitynumber,Bhardness,Reliability,Revolution,LewisFormFactor,
    RimThickness,ToothHight,imptdriver,imptmachine,PressureAngle,NoofTeethp,
```

```
    FaceWidth , AddendumRadiusg , AddendumRadiusp , DiametralPitchg ,
    DiametralPitchp , Heattreatment , Material ) :
    ko = Gear_Ko ( imptdriver , imptmachine )
    kv = Gear_Kv ( Qualitynumber , Revolution , DiametralPitchp , NoofTeethp )
    ks = Gear_Ks ( FaceWidth , LewisFormFactor , DiametralPitchg )
    km = Gear_Km ( TeethType , FaceWidth , DiametralPitchg , NoofTeethg )
    kb = Gear_Kb ( ToothHight , RimThickness )
    yn = Gear_Yn ( Load ,  PressureAngle ,  NoofTeethg ,  NoofTeethp , FaceWidth ,
    AddendumRadiusg , AddendumRadiusp , DiametralPitchg , DiametralPitchp ,
    Heattreatment , Bhardness )
    kt = 1
    kr = Gear_Kr ( Reliability )
    St = Gear_ST ( Material , Heattreatment , Bhardness )
    Sigmab = Load*ko*kv*ks*km*kb*DiametralPitchp /( FaceWidth*BSGFactor )
    Sta =  St*yn /( kt*kr )
    Mean = Sta - Sigmab
    stdSta = StdStratio*Sta
    stdL = StdLratio*Sigmab
    Std = math . sqrt ( stdSta*stdSta + stdL*stdL )
    norm = scipy . stats . norm ( Mean , Std )
    rel = 1 - norm . cdf(-Mean / Std )
    return rel


# In [22]: reliability contact
def Gear_RelC ( NoofTeethg , TeethType , Material , Load , ElasticCoefficient ,
    StdScratio , StdLratio , BSGFactor , Qualitynumber , Bhardness , Reliability ,
    Revolution , LewisFormFactor , RimThickness , ToothHight , imptdriver ,
    imptmachine , PressureAngle , NoofTeethp , FaceWidth , AddendumRadiusg ,
    AddendumRadiusp , DiametralPitchg , DiametralPitchp , Heattreatment ) :
    Bhardnessg = Bhardness
    Bhardnessp = Bhardness
    ko = Gear_Ko ( imptdriver , imptmachine )
    kv = Gear_Kv ( Qualitynumber , Revolution , DiametralPitchp , NoofTeethp )
    ks = Gear_Ks ( FaceWidth , LewisFormFactor , DiametralPitchg )
    km = Gear_Km ( TeethType , FaceWidth , DiametralPitchg , NoofTeethg )
    zn = Gear_Zn ( Load ,  PressureAngle ,  NoofTeethg ,  NoofTeethp , FaceWidth ,
    AddendumRadiusg , AddendumRadiusp , DiametralPitchg , DiametralPitchp ,
    Heattreatment )
    cf = 1
    kt = 1
```

```
    kr = Gear_Kr(Reliability)
    ch = Gear_Ch(Bhardnessg,Bhardnessp,DiametralPitchg,DiametralPitchp)
    rhosum = Gear_Rhosum(PressureAngle, NoofTeethg, NoofTeethp,FaceWidth,AddendumRadiusg,AddendumRadiusp,DiametralPitchg,DiametralPitchp)
    Sc = Gear_Sc(Material, Heattreatment, Bhardness)
    Sigmac = ElasticCoefficient*(math.sqrt(abs(Load*ko*kv*ks*km*cf*rhosum/(FaceWidth))))
    Sca = zn*ch*Sc/(kt*kr)
    Mean = Sca - Sigmac
    StdSca = StdScratio*Sca
    StdL = StdLratio*Sigmac
    Std = math.sqrt(StdSca*StdSca + StdL*StdL)
    norm = scipy.stats.norm(Mean,Std)
    rel = 1 - norm.cdf(-Mean/Std)
    return rel



# In[17]:Value assigment shaft
def Shaft_RelVector(data, obj):
    i = -1;
    for a in range(0,29):
        if(data.iloc[a]['Name'] == obj.name):
            i = a
    RPM = data.at[i,'RPM_Of_Shaft']
    Force = data.at[i,'Effective_Force']
    Torque = data.at[i,'Effective Torque']
    Length = np.array(obj.Shaft_Length)
    EnduranceLimit = np.array(obj.Shaft_EnduranceLimit)
    UltimateTensileStrength = np.array(obj.Shaft_UltimateTensileStrength)
    ManufactoringProcess = obj.Shaft_ManufactoringProcess
    Diameter = np.array(obj.Shaft_MeanDiameter)
    Temp = data.at[i,'Working_Temperature']
    Za = np.array(obj.Shaft_EnduranceReliaiblity)
    durn = Shaft_RelLife(RPM,Force,Torque,Length,EnduranceLimit,UltimateTensileStrength, ManufactoringProcess,Diameter,Temp, Za)
    YeildStrength = np.array(obj.Shaft_YieldStrength)
    StdYsratio = np.array(obj.Shaft_StdYsratio)
    StdTratio = data.at[i,'StdTratio']
    StdFratio = data.at[i,'StdFratio']
    relF = Shaft_Relmoment(Force, YeildStrength, Diameter, Length,
```

```
    StdYsratio , StdFratio)
    relT = Shaft_Reltorsion(Torque, YeildStrength, Diameter, Length,
    StdYsratio , StdTratio)
    res=np.array([relF[0], relT[0], durn[0]])
    return res

# in[17]:value assignment gear
def Gear_RelVector(data_Gear, obj):
    i = -1;
    for a in range(0,28):
        if(data_Gear.iloc[a]['Name'] == obj.name):
            i = a
    Load = data_Gear.at[i,'Load']
    ElasticCoefficient = np.array(obj.Gear_ElasticCoefficient)
    StdScratio = np.array(obj.Gear_StdScratio)
    StdStratio = np.array(obj.Gear_StdStratio)
    StdLratio = data_Gear.at[i,'StdLratio']
    BSGFactor = np.array(obj.Gear_BSGometryFactor)
    Qualitynumber = data_Gear.at[i,'Qualitynumber']
    Bhardness = np.array(obj.Gear_BHardness)
    Reliability = np.array(obj.Gear_Reliability)
    Revolution = data_Gear.at[i,'Revolution']
    LewisFormFactor = np.array(obj.Gear_LewisFormFactor)
    RimThickness = np.array(obj.Gear_RimThickness)
    ToothHight = np.array(obj.Gear_ToothHeight)
    imptdriver = data_Gear.at[i,'ImpactDriver']
    imptmachine = data_Gear.at[i,'ImpactMachine']
    PressureAngle = 3.14*np.array(obj.Gear_PressureAngle)/180
    NoofTeethp = np.array(obj.Gear_NoofTeeth)
    NoofTeethg = np.array(obj.Gear_NoofTeeth)
    FaceWidth = np.array(obj.Gear_FaceWidth)
    AddendumRadiusg = np.array(obj.Gear_AddendumRadius)
    AddendumRadiusp = np.array(obj.Gear_AddendumRadius)
    DiametralPitchg = np.array(obj.Gear_DiametralPitch)
    DiametralPitchp = np.array(obj.Gear_DiametralPitch)
    Heattreatment = obj.Gear_HeatTreatment
    Material = obj.Gear_Material
    TeethType = obj.Gear_TeethType
    Relc = Gear_RelC(NoofTeethg,TeethType,Material,Load,ElasticCoefficient,
    StdScratio,StdLratio,BSGFactor,Qualitynumber,Bhardness,Reliability,
    Revolution,LewisFormFactor,RimThickness,ToothHight,imptdriver,
```

```
imptmachine, PressureAngle, NoofTeethp, FaceWidth, AddendumRadiusg, AddendumRadiusp, DiametralPitchg, DiametralPitchp, Heattreatment)
    Relb = Gear_RelB(TeethType, NoofTeethg, Load, StdStratio, StdLratio, BSGFactor, Qualitynumber, Bhardness, Reliability, Revolution, LewisFormFactor, RimThickness, ToothHight, imptdriver, imptmachine, PressureAngle, NoofTeethp, FaceWidth, AddendumRadiusg, AddendumRadiusp, DiametralPitchg, DiametralPitchp, Heattreatment, Material)
    life = Gear_life(Load, PressureAngle, NoofTeethg, NoofTeethp, FaceWidth, AddendumRadiusg, AddendumRadiusp, DiametralPitchg, DiametralPitchp)
    res=np.array([Relc[0], Relb[0], life[0]])
    return res


# In[34]: similarity calculator gear
def Gear_similar(data_Gear, onto, obj):
    rel = Gear_RelVector(data_Gear, obj)
    array =[]
    for obj1 in onto.Gear.instances():
        if(obj != obj1):
            if(obj1.Gear_Type == obj.Gear_Type and obj1.Gear_Material == obj.Gear_Material ):
                a = Gear_RelVector(data_Gear,obj1)
                if((a[0] > (rel[0]- 0.05*rel[0]) and a[0] < (rel[0] + 0.05*rel[0]) and a[1] > (rel[1]- 0.05*rel[1]) and a[1] < (rel[1] + 0.05*rel[1]) and (rel[2] - 0.05*rel[2]) < a[2] and a[2] < (rel[2] + 0.05*rel[2])) or ((rel[0] > (a[0]- 0.05*a[0]) and rel[0] < (a[0] + 0.05*a[0]) and rel[1] > (a[1]- 0.05*a[1]) and rel[1] < (a[1] + 0.05*a[1]) and (a[2] - 0.05*a[2]) < rel[2] and rel[2] < (a[2] + 0.05*a[2])) )):

                    list.append(array,obj1)
    return array



# In[18]: similarity calculator shaft
def Shaft_similar(data_Shaft, onto, obj):
    rel = Shaft_RelVector(data_Shaft, obj)
    array =[]
    for obj1 in onto.Shaft.instances():
        if(obj != obj1):
            if(obj1.Shaft_Type == obj.Shaft_Type and obj1.Shaft_Material ==
```

```
    obj.Shaft_Material ):
                a = Shaft_RelVector(data_Shaft,obj1)
                if(a[0] > rel[0]- 0.05*rel[0] and a[0] < rel[0] + 0.05*rel[0] and a[1] > rel[1]- 0.05*rel[1] and a[0] < rel[1] + 0.05*rel[1] and a[2] > rel[2]- 0.05*rel[2] and a[2] < rel[2] + 0.05*rel[2]    ):
                    list.append(array,obj1)
    return array


# In[20]: main function to take input from user and call appropriate functions
print("Available Machines ID is given by MachID where ID can take value from 1 to 28. Eg Mach3 ")
print("Please enter the name of the machine from above")
Machine_ID = input()
print("Please enter the type of Component (Shaft\ Gear)")
Type = input()
TTFS = "TTFShaft.xlsx"
TTFG = "TTFGear.xlsx"
df = pd.DataFrame()
A = np.array([])
Y =np.array([])
Mach = []
for obj in onto.Machine.instances():
    if(obj.name == Machine_ID):
        Mach = obj.Has_Components
if(Mach == []):
    print("No Machine found with that name")
    sys.exit(1)
for obj1 in Mach :
    if(Type == "Shaft"):
        for obj2 in onto.Shaft.instances():
            if(obj1 == obj2):
                df = pd.read_excel(TTFS,obj2.name)
                sim = Shaft_similar(data_Shaft,onto,obj2)
                if(sim == []):
                    print("No similar Shaft present on other machine in Network")
                    sys.exit(1)
                else:
                    print("Similar Shaft are present on given Machine.")
```

```
                for shaft in sim:
                    obje = shaft.ComponentOf
                    print(obje[0].name)
                    df1 = pd.read_excel(TTFS,shaft.name)
                    df = df.append(df1,ignore_index = True)

    elif(Type == "Gear"):
        for obj2 in onto.Gear.instances():
            if(obj1 == obj2):
                df = pd.read_excel(TTFG,obj2.name)
                Sim = Gear_similar(data_Gear,onto,obj2)
                if(Sim == []):
                    print("No similar Gear present on other machine in Network ")
                    sys.exit(1)
                else:
                    print("Similar Gear are present on given Machine.")
                for gear in Sim:
                    objec = gear.ComponentOf
                    print(objec[0].name)
                    df1 = pd.read_excel(TTFG,gear.name)
                    df = df.append(df1,ignore_index = True)
    else:
        print("Given type is not added in the system. We are working on it")
count = len(df)
A = np.array(df['TimeToFailureA'])
for i in range(count):
    Y=np.append(Y,reliability(df.at[i,'TimeToFailureA'],df.at[i,'Beta'],df.at[i,'TimeToFailureT']))
print("Please enter the reliability of the compoent for which you want to compute working Hours")
Tn = float(input())
a = linearreg(A,Y,Tn)
print("The selected component will have",Tn,"reliability at",a,"working Hours")
```

Code for Computing Mean Error

```
import numpy as np
import pandas as pd
#Make array of reliability seperated by 0.1
rel = np.linspace(0,1,100)
#Computes the 10% error
rel10 = rel*0.05
#Compute its mean
rel10avg = rel10.mean()
#Print the mean error
print(rel10avg)
#Compute the 20% error
rel20 = rel*0.1
#Compute its mean
rel20avg = rel20.mean()
#Print the mean error
print(rel20avg)
```

Bibliography

[1] Dean Allemang and James Hendler. *Semantic Web for the Working Ontologist*. 2011. ISBN: 9780123859655. DOI: `10.1016/C2010-0-68657-3`.

[2] Mark Burstein et al. "A semantic web services architecture". In: *IEEE Internet Computing* (2005). ISSN: 10897801. DOI: `10.1109/MIC.2005.96`.

[3] John J Coy', Dennis P Townsend, and Erwin V Zaretskyt. *An Update on the Life Analysis of Spur Gears*. Tech. rep.

[4] Thomas Gabor et al. "A simulation-based architecture for smart cyber-physical systems". In: *Proceedings - 2016 IEEE International Conference on Autonomic Computing, ICAC 2016*. 2016. ISBN: 9781509016532. DOI: `10.1109/ICAC.2016.29`.

[5] J. V. Gialelis et al. "Manufacturing collaborative process integration utilizing state of the art technologies". In: *IEEE International Symposium on Industrial Electronics*. 2005. ISBN: 0780387384. DOI: `10.1109/ISIE.2005.1529142`.

[6] Edward Glaessgen and David Stargel. "The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles". In: *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference
20th AIAA/ASME/AHS Adaptive Structures Conference
14th AIAA* April (2012). ISSN: 02734508. DOI: `10.2514/6.2012-1818`. URL: `http://arc.aiaa.org/doi/abs/10.2514/6.2012-1818`.

[7] Wu He, Gongjun Yan, and Li Da Xu. "Developing vehicular data cloud services in the IoT environment". In: *IEEE Transactions on Industrial Informatics* (2014). ISSN: 15513203. DOI: `10.1109/TII.2014.2299233`.

[8] S. M.Riazul Islam et al. "The internet of things for health care: A comprehensive survey". In: *IEEE Access* (2015). ISSN: 21693536. DOI: `10.1109/ACCESS.2015.2437951`.

[9] N. Khilwani, J. A. Harding, and A. K. Choudhary. “Semantic web in manufacturing”. In: *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* (2009). ISSN: 09544054. DOI: 10.1243/09544054JEM1399.

[10] Dimitris Kiritsis. “Closed-loop PLM for intelligent products in the era of the Internet of things”. In: *CAD Computer Aided Design* (2011). ISSN: 00104485. DOI: 10.1016/j.cad.2010.03.002.

[11] K. KNOLLE. “PERVICHNOE UTOLSHCHENIE ’ENDOKARDA V RANNEM DETSKOM VOZRASTE.” In: *Arkhiv patologii* (1963). ISSN: 24058963. DOI: 10.1016/j.ifacol.2016.12.002.

[12] Dennis Kolberg and Detlef Zühlke. “Lean Automation enabled by Industry 4.0 Technologies”. In: *IFAC-PapersOnLine* 48.3 (2015), pp. 1870–1875. ISSN: 24058963. DOI: 10.1016/j.ifacol.2015.06.359.

[13] Jean Baptiste Lamy. “Owlready: Ontology-oriented programming in Python with automatic classification and high level constructs for biomedical ontologies”. In: *Artificial Intelligence in Medicine* (2017). ISSN: 18732860. DOI: 10.1016/j.artmed.2017.07.002.

[14] Jean-Baptiste Lamy. *Owlready2 Documentation Release 0.10*. Tech. rep. 2018.

[15] J. L.M. Lastra and M. Delamer. “Semantic web services in factory automation: Fundamental insights and research roadmap”. In: *IEEE Transactions on Industrial Informatics* (2006). ISSN: 15513203. DOI: 10.1109/TII.2005.862144.

[16] In Lee and Kyoochun Lee. “The Internet of Things (IoT): Applications, investments, and challenges for enterprises”. In: *Business Horizons* (2015). ISSN: 00076813. DOI: 10.1016/j.bushor.2015.03.008.

[17] Shancang Li et al. “The internet of things: a survey”. In: (). DOI: 10.1007/s10796-014-9492-7. URL: http://www.rfid-in-action.eu/cerp/.

[18] H. K. Lin and J. A. Harding. “A manufacturing system engineering ontology model on the semantic web for inter-enterprise collaboration”. In: *Computers in Industry* (2007). ISSN: 01663615. DOI: 10.1016/j.compind.2006.09.015.

[19] H. K. Lin, J. A. Harding, and M. Shahbaz. “Manufacturing system engineering ontology for semantic interoperability across extended project teams”. In: *International Journal of Production Research* (2004). ISSN: 00207543. DOI: 10.1080/0020754041233128l999.

[20] G. Lundberg and A. Palmgren. “Dynamic Capacity of Rolling Bearings”. In: *Acta Polytech., Mech. Eng. Ser* 1.3 (1947).

[21] Robert L Norton and R. L.Norton. *Machine Design: An Integrated Approach,* 2006. ISBN: 0131481908. DOI: 10.1115/1.2472416.

[22] Kathy Pretz. *The Next Evolution of the Internet*. URL: http://theinstitute.ieee.org/technology-topics/smart-technology/the-next-evolution-of-the-internet.

[23] J. K. Nisbett R. G. Budynas. *Shigley’s Mechanical Engineering Design, Ninth Edition*. 2011. ISBN: 0-390-76487-6. DOI: 10.1007/s13398-014-0173-7.2. arXiv: 9809069v1 [gr-qc].

[24] Minwoo Ryu et al. “Design and implementation of a connected farm for smart farming system”. In: *2015 IEEE SENSORS - Proceedings*. 2015. ISBN: 9781479982028. DOI: 10.1109/ICSENS.2015.7370624.

[25] Michael Schluse and Juergen Rossmann. “From simulation to experimentable digital twins: Simulation-based development and operation of complex technical systems”. In: *ISSE 2016 - 2016 International Symposium on Systems Engineering - Proceedings Papers*. 2016. ISBN: 9781509007936. DOI: 10.1109/SysEng.2016.7753162.

[26] Toby Segaran, Colin Evans, and Jamie Taylor. *Programming the Semantic Web*. 2009. ISBN: 9788578110796. DOI: 10.1017/CBO9781107415324.004.

[27] XFEM Skier. *File:Shear Moment Diagram.svg - Wikimedia Commons*. URL: https://commons.wikimedia.org/wiki/File:Shear_Moment_Diagram.svg.

[28] R. Stouffs and R. Krishnamurti. “Standardization: a critical review”. In: *Proceedings of the International Conference on IT in Construction in Africa, CSIR, Building and Construction Technology, Mpumalanga, South Africa,* 2001, pp. 42–1.

[29] Maurer T. *What is a Digital Twin*. 2017. URL: https://community.plm.automation.siemens.com/t5/Digital-Twin-%0AKnowledge-Base/What-is-a-digital-twin/ta-p/432960..

[30] Fei Tao et al. “Digital Twin State of the art”. In: (). DOI: DOI10.1109/TII.2018.2873186,IEEE.

[31] F Tao et al. “Digital twin and its potential application exploration”. In: *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS* (2018). ISSN: 10065911. DOI: 10.13196/j.cims.2018.01.001.

[32] F Tao et al. “Digital twin workshop: a new paradigm for future workshop”. In: *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS* (2017). ISSN: 10065911. DOI: `10.13196/j.cims.2017.01.001`.

[33] Howard R. Thomas and Victor A. Hoersch. “Stresses due to the pressure of one elastic solid upon another with special reference to railroad rails”. In: *University of Illinois Engineering Experiment Station* (1930).

[34] D. P. Townsend, J. J. Coy, and E. V. Zaretsky. “Experimental and Analytical Load-Life Relation for AISI 9310 Steel Spur Gears”. In: *Mech. Des.* 100 (1978), pp. 54–60.

[35] Samson Tu and Tania Tudorache. *protégé*. URL: `https://protege.stanford.edu/`.

[36] Eric Tuegel. “The Airframe Digital Twin: Some Challenges to Realization”. In: *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference
20th AIAA/ASME/AHS Adaptive Structures Conference
14th AIAA*. 2012. ISBN: 978-1-60086-937-2. DOI: `10.2514/6.2012-1812`.

[37] Andrew Whitmore, Anurag Agarwal, and Li Da Xu. “The Internet of Things—A survey of topics and trends”. In: *Information Systems Frontiers* (2015). ISSN: 15729419. DOI: `10.1007/s10796-014-9489-2`.

[38] Li Da Xu, Wu He, and Shancang Li. *Internet of things in industries: A survey*. 2014. DOI: `10.1109/TII.2014.2300753`.

ACKNOWLEDGEMENT

I want to express my sincere gratitude to my project guides Prof. Makarand S. Kulkarni and Prof. Tanmay K. Bhandakkar for his valuable guidance, constant support and encouragement throughout the duration of the project. Without his support and understanding I would have never gone this far.

Madhusudan Kumar

November, 2018