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Research Article

A RELIABILITY APPROACH FROM MECHANICAL ENGINEERING POINT OF VIEW

Beril EKER GÜMÜŞ*

Yıldız Technical University Science and Technology Application and Research Center, Beşiktaş-ISTANBUL; ORCID:0000-0002-4185-4470

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ABSTRACT

No mechanical product will perform reliably unless it is designed specifically for reliability. There are many studies about reliability in mechanical design but most of them focus on the one part of entire reliability problem. The ability to see the bigger picture is essential in the field of mechanical reliability. Reader can gain a holistic viewpoint for the consideration of mechanical reliability by this approach. In this study failure modes, reliability variables, models, measures and methods from mechanical engineering point of view were investigated. From the open literature, published research work was compiled. Search results were classified and evaluated in terms of suitability for mechanical engineering. As an example, the procedure to find the reliability of shaft was investigated in support of our approach. Analysis and documentation of failed mechanical components are essential for preventing designers from repeating the same errors. Therefore, this research is expected to provide an easy way to investigate reliability problems of mechanical components such as shafts.
Keywords: Mechanical reliability, failure modes.

1. INTRODUCTION

As reliability is closely linked to customer satisfaction, designing reliable products is key to future market success of companies. There is a definite need for reliability because of global competition and other factors. From consumer products to larger systems, the significance of reliability is perceived at every stage of daily life. Obviously, the reliability of an elevator cable, a medical instrument or the critical components of an aircraft must be much higher than a tap or a pencil. Reliability becomes more crucial when one’s life depend upon the proper functioning of thousands of parts, each produced by the lowest bidder. The importance of reliability must be understood firstly by the designers and consumers of the products but it is equally important in the mass production of items for the civilian economy. High reliability reduces downtime and maintenance personnel, improves product utilization. It can also prevent accidents and failure, loss of reputation [1-3]. The warranty costs depend on the reliability of the product and the expected warranty cost can be reduced by improving product reliability [4-7].

* Corresponding Author: e-mail: berilekergumus@gmail.com, tel: (212) 383 80 26

Reliability is the probability of a product that will perform its intended function in a given environment for a specified period while in normal use by the customer and without failure.

Achievement of acceptable safety levels at minimum capital cost and with minimized operating and maintenance costs requires a deep understanding of the factors leading to failure of the system elements and an understanding of the behaviour of the system when failures do occur. Over recent decades, reliability engineering research has adressed these problems and much progress has been made since Bazovski identified the reliability engineering approach based on risk assessment in an early text [7]. The history of risk assessment has been considered in some detail by Moss [8] who has also described the background and relevance of hazards and operability studies, failure mode and effect analysis, failure mode and effect criticality analysis and fault tree analysis. These are now extensively applied as a basis for the safety assessment of a wide range of technological systems and are now well documented in texts such as that by Andrews and Moss [9]. In considering the reliability of mechanical components and systems, O'Connor [3] has considered that mechanical components can fail prematurely if they break owing to overload, leading to fracture, or owing to degradation of strength so that working loads cause rupture. The mechanisms which result in such failures have been carefully described by O'Connor and predominance of degradation failures in mechanical equipment is now well known, but O' Connor pointed out that mechanical systems can also fail for other reasons, some of which he has listed, e.g. excessive vibration or noise, due to wear, out of balance of rotating components or resonance.

Nomenclature

E Modulus of Elasticity
S_e' endurance limit for bending
K_f fatigue stress concentration factor
k_a surface condition modification factor (cold rolled)
k_b size modification factor
k_c load modification factor
k_d temperature modification factor
k_e miscellaneous effects modification factor
I Moment of inertia
P_f the probability of failure
S_e endurance limit at the critical location of a machine part in the geometry and condition of use
$\bar{\sigma}_a'$ the von Mises amplitude component
$\bar{\sigma}_m'$ the von Mises steady stress component
$\overline{Sa}$ the amplitude component of strength S_a
ϕ_{30} fatigue ratio

2. METHOD

2.1. Failure Modes

The common sense perception of reliability is the absence of failures. Machine components experience several types of failure. Some of the important failure modes are presented such as wear failures, corrosion failure, fatigue failure and metal degradation in this study. The four major forms of wear are: Adhesive wear, abrasive wear, fretting, fluid erosion and corrosive wear. The major classifications of corrosion are: Galvanic corrosion and pitting corrosion. The major forms of fatigue are: High-cycle fatigue, low-cycle fatigue, crack growth. Material degradation can be divided as thermal degradation and radiation damage [10].

2.2. Variables

The design variables involved must be determined before a reliability model can be developed. Previous literature defining design variables was studied and cited variables were included. From this, the following classifications for design variables were derived: Material strength, applied load, applied stress, geometry and manufacturing tolerances. Static and dynamic loads are presented. Dynamic loads are subdivided to the five categories: Varying load, reversing load, shock load, wind load, earthquake loads [11].

In most cases, the random variables are assumed to follow normal distribution for computational simplicity. Reliability of static and dynamic endurance limits of the materials are essential in reliability based mechanical design, because performance depends on the material itself. Yielding and breaking points are considered as static strength limits. The fatigue limit value (continuous strength value) as dynamic strength limit under variable stresses is the stress value providing with theoretically infinite life. Dynamic strains cause fatigue in the sections of the machinery parts. The time that has passed until fatigue breaks is the lifetime. Fatigue experiments suppose that the best conditions exist for promoting long fatigue lives but this situation can not be guaranteed for design applications. Because of this the part's endurance limit must be modified or reduced from the material's best-case endurance limit.

The resistance of materials to failure in terms of the yield strength or fracture toughness must be evaluated by materials tests. Stiffness, strength, weight and cost usually affect the selection of material. There might be additional requirements such as maximum permissible deflection for beam. Choosing adequate materials is important for mechanical reliability, and it is essential that designers are aware of the convenient properties in the application environments. For example, the ultraviolet content of sunlight causes some plastics to become brittle, and wood decreases in strength with time, especially if exposed to moisture. As a further example, steels become brittle if exposed to neutron radiation over long periods of time, and this affects the retirement life of nuclear reactors [12-14]. Designers should obtain data and application advice from suppliers, handbooks and other databases for the wide and increasing range of materials available.

2.3. Models

Basically, models are grouped under three classifications: Modeling variables, single parts and systems. Both deterministic and probabilistic reliability professionals are interested in models to measure and predict failures, although they may use them in different ways. Probabilistic reliability engineers are more interested in failure accommodation models, while deterministic reliability engineers are more interested in models to prevent failures. There are many statistical probability distribution functions, among which are the normal, lognormal, Weibull, exponential, gamma, binomial, Poisson etc. Of these, the first four are widely used in reliability. If different models fit a given set of data equally well, we can base our choice of model on previous use in the same area, conservative extrapolation, or other considerations. For example, the Weibull model eventually will predict a shorter probable failure time than the lognormal model [14-16]. For detailed information see references [3, 16] and [17-20] Calculating reliability according to situations is given in Table 1.

The load–strength interference model is the most important analytical method in reliability assessment for mechanical components. Stress/Strength design approach is discussed for modeling single parts. An item's stress and strength are random variables. If the probability density functions of stress and strength are known, the reliability of a component may be determined through analytical means [20]. If these probability density functions (pdfs) are completely separated (that is, there is no interference between them), the result in theory is an absolutely reliable component. This is illustrated in Fig. 1. If, however, the probability density function curves for both strength and stress are shown to interfere, in that they intersect one another, as shown in Fig. 2, then in this case the shaded area where the curves intersect is an indication that the component will fail, because the load exceeds the strength. The mean difference μ_D is given by

Table 1. Calculating reliability according to situations [18]

Situation	Distributions	
	Continuous Distributions	Discrete Distributions
The sizes of machine parts, the lives of items subject to wearout failures and strength of materials	Normal Distribution	
There are only two outcomes, such as pass or fail, and probability remains the same for all trials		Binomial Distribution
If events are Poisson-distributed they occur at a constantaverage rate, with only one of two outcomes countable,e.g the number of failures in a given time or defects in a length of wire		Poisson Distribution
When partial failures can exist, i.e. when a given number of partial failure events must occur before an item fails	Gamma Distribution	
For the occurence of load events and describing the strength distribution of materials	Weibull Distribution	
Wear and corrosion studies	Exponential Distribution	
For populations with wearout characteristics	Lognormal Distribution	

$$\mu_D = \mu_S - \mu_\sigma \tag{1}$$

where μ_S and μ_σ are the mean strength and mean stress, respectively. The difference standard deviation $\hat{\sigma}_D$ can be expressed as

$$\hat{\sigma}_D = \sqrt{\hat{\sigma}_S^2 + \hat{\sigma}_\sigma^2} \tag{2}$$

where $\hat{\sigma}_S$ and $\hat{\sigma}_\sigma$ are the standard deviations for the strength and stress, respectively [21].

When the stress and strength are represented by normal distributions, the probability of failure is the probability of having a negative difference between the stress and strength. This probability can be shown to be the negative tail end of a difference distribution, as shown in Fig. 3. The probability of failure $P_F(D)$ is equal to the area of the negative tail and is given as

$$P_F(D) = \int_{-\infty}^{0} f_F(D)\, d\mu_D \tag{3}$$

where $f_F(D)$ is the probability density of the difference. For a normal distribution, the negative tail area can be determined by using

$$z = \frac{\mu_D}{\hat{\sigma}_D} \tag{4}$$

After calculating the value of z, the probability of failure (area) can be obtained from Standard Tables. Once the probability of failure is known the component reliability can be determined using Equation 5.

$$R = 1 - P_F(D) \tag{5}$$

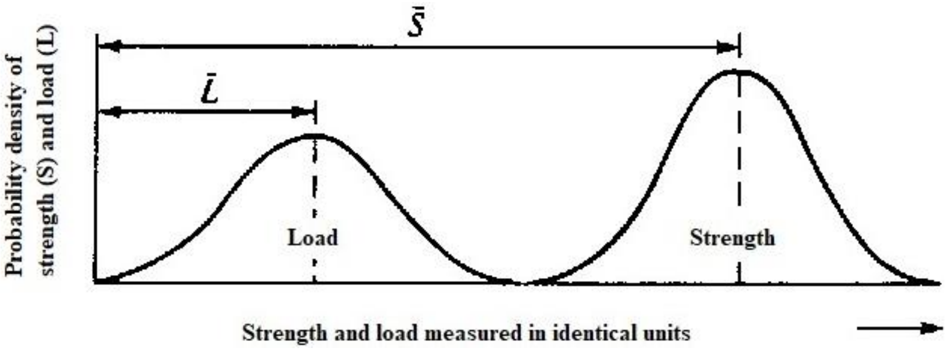

Figure 1. Strength-load interference diagram with complete separation

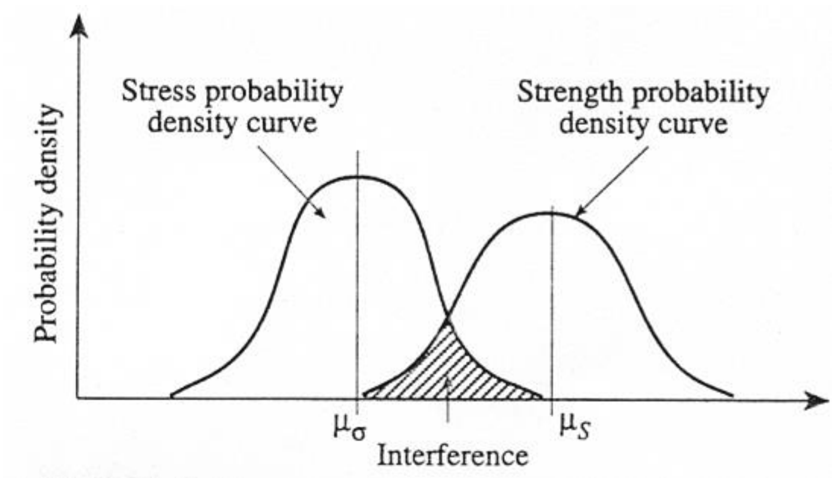

Figure 2. Stress and strength density functions [22].

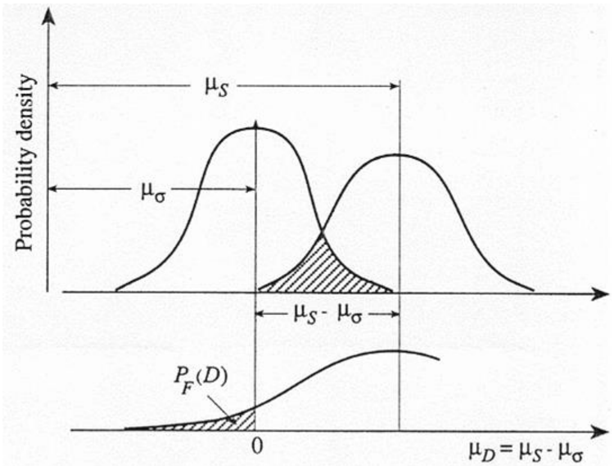

Figure 3. Difference diagram for normal distribution [22].

Determining the reliability of a complex system can be difficult. In principle, proceeding methodically by starting with the simplest units, combining them into subsystems, and then combining the subsystems into the complete system, and determining reliability at each step will lead to the final system reliability. Establishing the criterion of adequate performance of the system is the most important aspect. In a series system, all components are so interrelated that the entire system will fail if any one component fails. A parallel system fails if and only if every one of its components or subsystems fails [23-25]. The parallel reliability concept is important in the design of backup systems. Electrical or hydraulic systems in an aircraft typically are backed up by mechanical systems. Such systems are called redundant systems.

Two techniques concerned with the reliability analysis of mechanical engineering systems are given; fault tree analysis, failure modes and effects analysis (FMEA) approach. Reliability prediction (which includes probabilistic design), techniques such as failure modes and effect analysis (FMEA) and fault tree analysis (FTA) aim to seek out the potential causes and effects of failures in components and systems before they become a reality. FMEA is a powerful reliability assessment technique of designing capable and reliable components and between 70 and 80 per cent of failure modes could be identified at the design stage by its effective use [8,26-35].

2.4. Measures

The measure of the reliability of an individual component is its lifetime- the time elapsing between its start of life and the time at which it fails. According to purpose, the other reliability measures are safety, life cycle cost implication, mean time to failure, mean time between failures and failure rate. Safety factor, safety margin, loading roughness which are currently used extensively by design engineers [35].

The most commonly used forms of life distribution are the probability density function (pdf), the cumulative density function (cdf), the reliability function, and the hazard rate [18].

The Hazard Rate Function is a measure of the probability that a component will fail in the next time interval, given that it has survived up to the beginning of that time interval [19-21].
The Hazard Rate Function

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{6}$$

where f(t) is probability density function, R(t) is reliability.

Fig. 4 shows the bathtub hazard rate curve which is used to describe failure rate for many engineering components. The three phases of Bath-tub Curve are described below

Phase 1 (Burn-in Period, break in region, debugging region)

Phase 1 shows a declining (t) due to the premature failure of components- similar, for example, to genetic deficiencies in some babies, for this reason this phase often called the infant mortality phase.

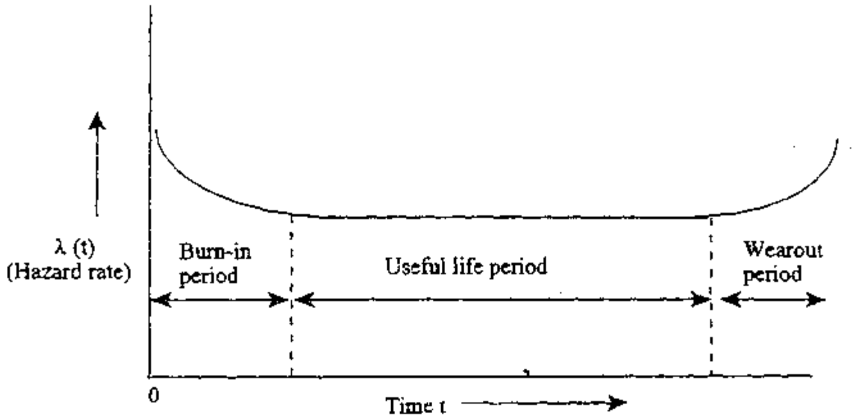

Figure 4. Bathtub hazard rate curve [1]

Phase 2 (Useful Life Period)

Phase 2 shows an approximately constant (t) due to the chance failure of the component because of its unexpected over stressing. An example of this phenomenon would be the accidental dropping and breaking of a plate. Sometimes failures which occur in this phase are called random failures.

Phase 3 (Wear Out period)

Phase 3 shows an increasing (t), meaning that the probability of a component failing between equal and successive time intervals increases. This is similar to the phenomenon of ageing in people after the first 25 to 30 years and gives rise to the title wear-out phase.

While this description is conceptually useful it should not be taken too literally. One reason for this reservation is that all three types of failure regime can occur simultaneously, but with varying degrees of severity, so a graph of $\boldsymbol{\lambda}$(t) is specific to the type of component and the way in which it is stressed [17,40].

2.5. Methods

Testing, Monte Carlo Simulation and optimization are the reliability methods, which are examined in this study. Reliability tests may be grouped under four classifications: Reliability development and demonstration tests, qualification and acceptance tests, operational tests, and accelerated reliability tests. Accelerated reliability tests are also grouped under three classifications: Accelerated life tests, design verification tests, environmental stress screening. Monte Carlo algorithm is widely used in the simulation of stochastic or random systems of any type [34]. The Monte Carlo algorithm provides the reader with a powerful means to predict the reliability of mechanical designs, particularly when the number of design variables is limited. Optimization is the process of obtaining the best result under given circumstances. It plays an important role in system design. In the design of any component, we will be interested either in maximizing reliability subject to a constraint on the cost or in minimizing the cost with a restriction on the reliability of the component [41]. Therefore, the reliability design of products can be divided into two types of the mathematical model of optimum reliability design.

- Reliability as the objective function.
- Reliability as a constraint condition

Any optimization problem has three components: (1) objective function(s), (2) constraints and (3) algorithm to search for the optimum solution [30]. Depending on the design requirements, three formulations of a probabilistic optimal design problem can be envisioned:

P1 : Minimize the cost of the design subject to reliability and structural constraints.

P2 : Maximize the reliability of the design subject to cost and structural constraints.

P3 : Minimize the initial cost plus expected cost of failure, subject to reliability and structural constraints [42].

Since any complex system has to satisfy many design criteria, resulting in multiple objectives and constraints, techniques using the concepts of multi-objective, multi-constraint optimization have also been used [43-45].

3. CASE STUDY

The case study develops reliability analysis for a shaft under a constant torque and a bending force and includes probabilistic concepts to account for the uncertainties in loading, material properties and geometries. This overhung shaft receives torque through a belt drive and transmits it to a gear pair. A pair of ball bearings within closed bearing boxes supports it. Reliability problem of this shaft is examined through the methodology developed in this study. Failure modes of the shaft, variables affecting the reliability, modeling for reliability determination and methods used in the computations were presented in detail. Machined steel shaft used for this case study is shown in Fig 5.

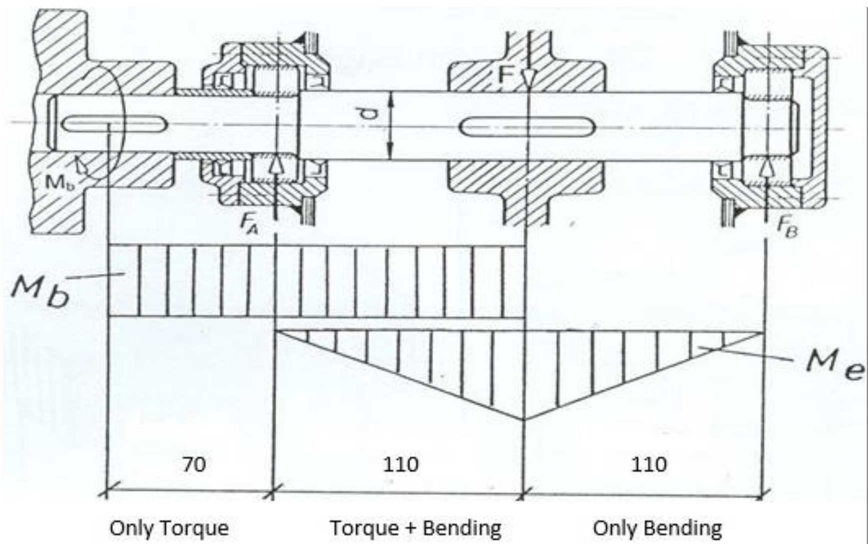

Figure 5. Machined steel shaft [47].

Previous literature defining mechanical reliability was studied. From this, the following classifications and investigation steps were derived as seen from Figure 6 and Figure 7.

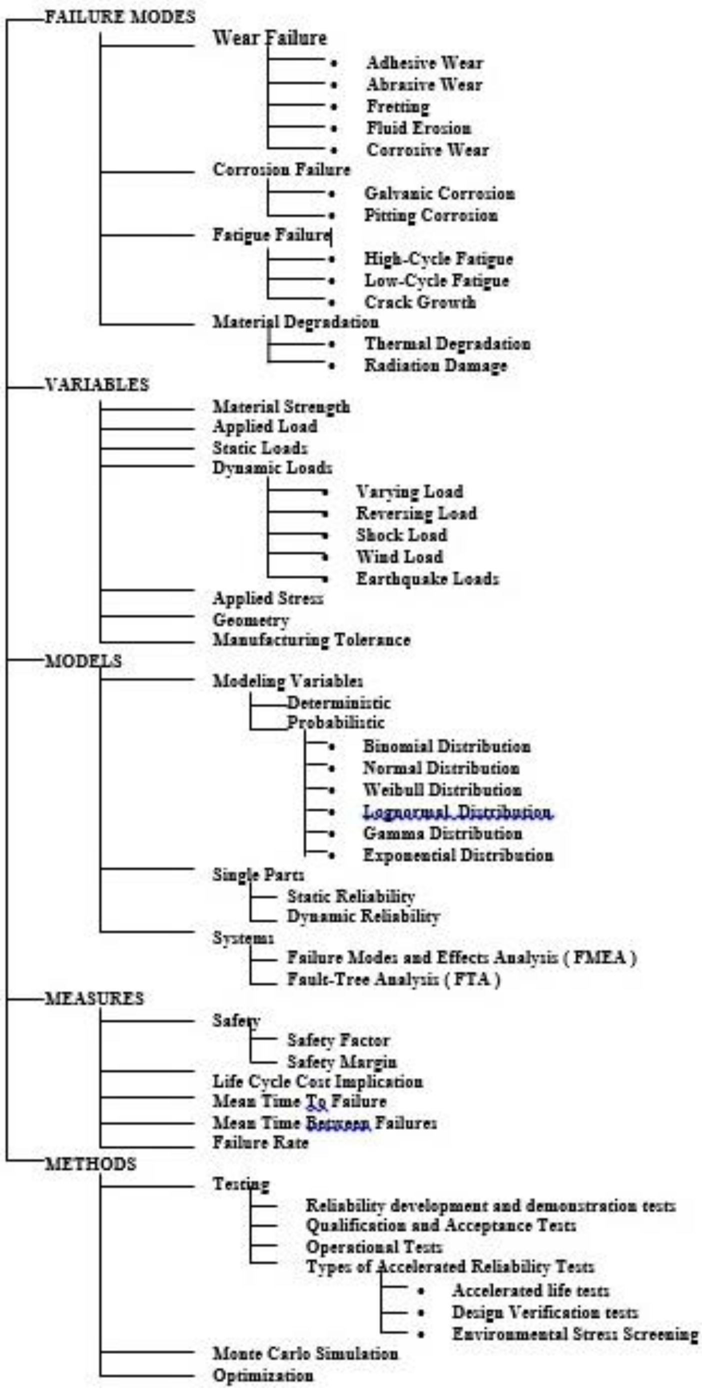

Figure 6. Result of the classification

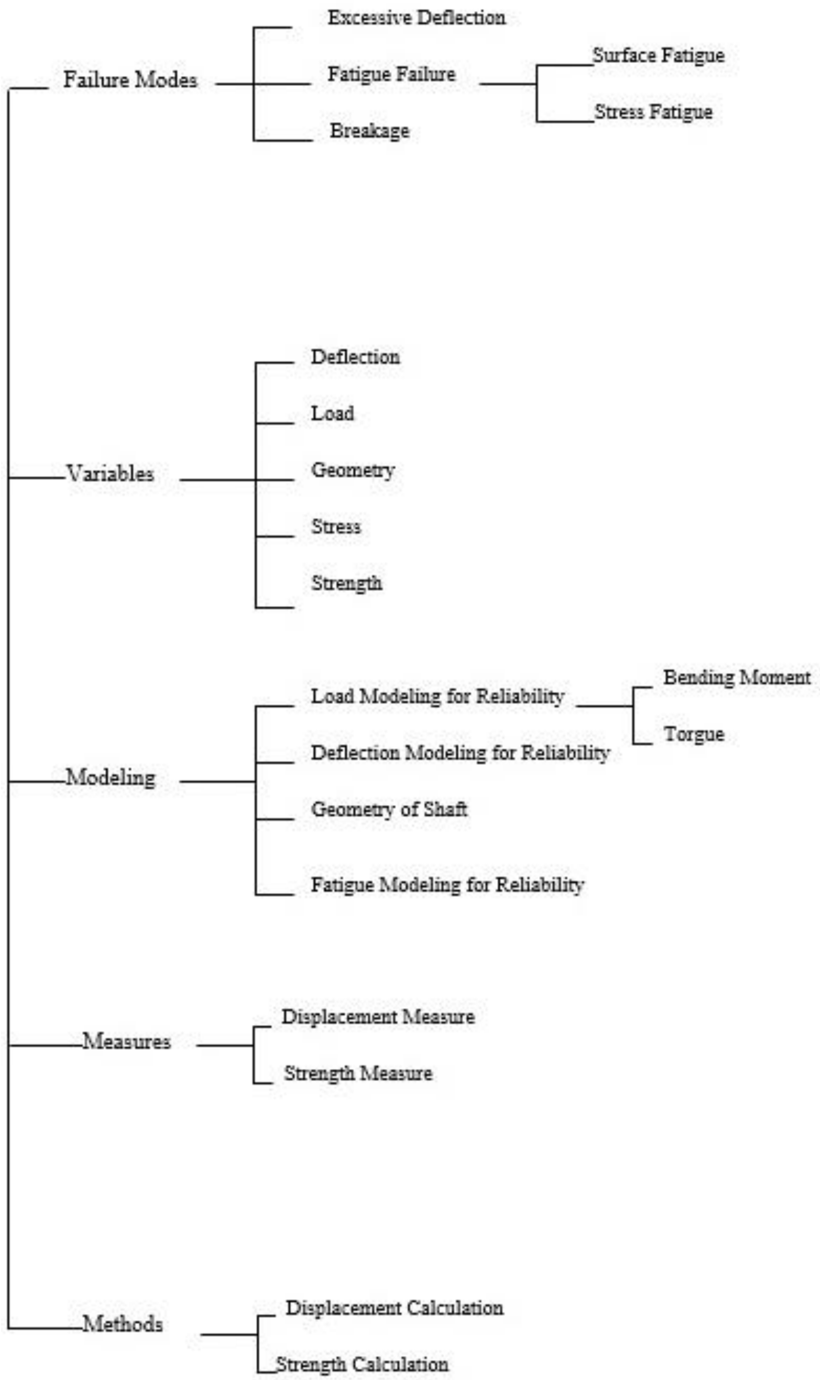

Figure 7. Investigation steps of case study

In this shaft problem, failure modes are assumed to be excessive deflection, fatigue failure, breakage. These are common failures for this type of application. Excessive misalignments in gear meshes, bearings, cams, sprockets, or seals may lead to failure of these elements to function properly. Excessive shaft bending deflection or excessive shaft slope may therefore lead to failure of the shaft in this case. Fatigue is the most critical failure mode of shafts. Often shafts are found to have failed under the action of repeated or fluctuating stresses; even when the magnitude of maximum stresses were below the yield strength. Initially, failures usually begin with a crack at a point stress concentration and end with the propagation of the crack, which cause the final fracture. In this case study, probabilistic fatigue failure will be taken into consideration. When loads are excessive, breakage can occur within a few cycles. In this case maximum loads will be checked not to cause breakage.

Shaft material strength, applied load, developed stress, shaft geometry, and tolerances are determined as variables. Bending deflection is taken as a variable. It is assumed that a torque is received from overhung end and this torque transmitted to a gear. From gear a radial force acting on the shaft, creates bending. Torque and radial load are assumed to be constant. Shaft variables are related to geometry are radia at different sections and the length. Length variables are taken as constant, but radia have tolerances.

Transverse loads from gears, pulleys, and bearings that are mounted upon a rotating shaft result in completely reversed cyclic bending stresses. In this case, transverse load results in completely reversed transverse bending stress. Transmitted shaft torque induces torsional shearing stress. Torsional shearing stress is assumed to be steady.

For shaft material, S_{yt}, S_{ut} and other variables derived from these will be taken as probabilistic variables. Other variables will be assumed as constant. The material of which the shaft is machined is cold-rolled AISI 1035 having ultimate strength of S_{ut} ~ 550 MPa and a yield strength of S_{yt} ~ 460 MPa [39, Table E-20, pp. 1205].

The state of reliability of the shaft will be modeled in details here to have a preparation for further computations in methods section. If probabilistic descriptions are available in the form of statistical data for loading distributions, this data should be utilized to determine the distribution of loads whether they are normal, lognormal etc. Applied load F is assumed to be distributes log normally as F = 9600 ± 250 N. Applied load F is creating a bending moment. Torque is assumed to be constant at T = 530 Nm. Shaft opening L = 220 mm is assumed to be constant. Shaft diameters are given by D = 45 ± 0.25 mm, d = 40 ± 0.25 mm and fillet radia, r = 1.5 mm**.** From above variables and parameters, fatigue stresses will be calculated probabilistically.

For this shaft, two important measures will be taken account.

Displacement measure:

Max deflection δmax should not exceed, δallow = 0.002 L when L is the length of shaft. Since δmax is a probabilistic number Reliability = Probability (δmax ≤ δallow) ≥ 0.99 is required.

Strength Measure:

Von Misses stress calculated for bending and torsion should be within the allowable range for the selected failure criteria (i.e, Soderbeg etc.) Expressed briefly, we require that Reliability, R=P(σ≤S) ≥ 0.99.

Required calculation should be performed to calculate the reliability based on the measures.

Displacement Calculation

$$\delta_{\max} = \frac{FL^3}{48EI} = 1.10^{-6} \le 0.002L = 0.44\ mm \tag{8}$$

In this case, no deflection is deemed to be important.

Strength Calculation

We can proceed as follows [39]:

Identify potential critical locations

Estimate the mean and the coefficient of variation of loads, moment, and torques caused by the loading.

Estimate the mean and coefficient of variation of the salient material properties: Se, Sut or Syt, E.

Estimate the Marin fatigue strength reduction factors.

Use the correlation method with $S_e = k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot \phi_{30}$,Sut, noting that the multiplicative assocation drives S_e toward a lognormal distribution.

$$\sigma_a = \frac{32K_f\, M_a}{\pi\, d^3} \qquad \sigma_m = \frac{16\sqrt{3}K_{fs}\, T_m}{\pi\, d^3}$$

The distribution of σ_a is driven toward lognormal.

Find the amplitude component of strength S_a

Find the amplitude component of stress, σ_a .

Interfere the S_a distribution with the σ_a distribution on a lognormal-lognormal basis using equations and find the reliability estimate from table E-10.

For the endurance limit for bending (S_e') and (k_a) surface condition modification factor (cold rolled) see reference 39, Table 7-14.

Estimations are made by applying Marin factors which quantified the effects of surface condition, size, loading, temperature, and miscellaneous items to the endurance limit. A Marin equation is therefore written

$$S_e = k_a k_b\, k_c\, k_d\, k_e\, S_e' \tag{9}$$

In SI units for steels $S_e = k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot \phi_{30}\ S_{ut}$ (10)

$\phi_{30} \rightarrow$ fatigue ratio$\phi = S_e' / \bar{S}_{ut}$ represents to estimate the endurance limit S_e' from the mean ultimate strength $\bar{S}_{ut}$ (11)

$S_e' = 0{,}506\ \bar{S}_{ut}$ LN (1,0.138) kpsi or MPa $\bar{S}_{ut} \leq 212$ kpsi (1460 MPa) (12)

$S_e' = 0{,}506\ (550)$ LN (1,0.138) = 278,3 LN (1,0.138) (13)

$k_a = a\,\bar{S}_{ut}^{\,b}$ LN (1,C) $\cong$ 0,84 LN (1,0.058) (14)

a = 4,45 b = -0,265 c = 0,058 (Machined or coldrolled)

$\bar{k}_a = 4{,}45\ (550)^{-0{,}265}\ (1) = 0.835$ (15)

$\sigma_{ka} = 4.45\ (550)^{-265}\ (0.058) = 0.048$ (16)

So k_a ~LN (0.835, 0.048)

For size modification factor (k_b) see reference 39, Equation 7-10.

$k_b = (d/7.62)^{-0.107} = 1.24\ d^{-0.107} \quad 2.79 \leq d \leq 51$ mm (17)

$$k_b = \left(\frac{d}{7.62}\right)^{-0.107} = \left(\frac{45}{7.62}\right)^{-0.107} = 0.826$$

k_c = load modification factor

k_d = temperature modification factor
k_e = miscellaneous-effects modification factor
$k_c = k_d = k_e$ = LN (1,0)
S_e = endurance limit at the critical location of a machine part in the geometry and condition of use

When endurance tests of parts are not available, estimations are made by applying Marin factors which quantified the effects of surface condition, size, loading, temperature, and miscellaneous items to the endurance limit. A Marin equation is therefore written

$$S_e = k_a k_b\, k_c\, k_d\, k_e\, S_e' \tag{18}$$

In SI units for steels $S_e = k_a \,.\, k_b \,.\, k_c \,.\, k_d \,.\, k_e \,.\, \phi_{30}\ S_{ut}$ (19)

$\phi_{30} \rightarrow$ fatigue ratio $\phi = S_e' / \bar{S}_{ut}$ represents to estimate the endurance limit Se' from the mean ultimate strength $\bar{S}_{ut}$

Se = 0.84 LN (1,0.058) . 0,826 . 278,3 LN (1,0.138)
Se = 0.84 . 0.826 . 278.3 = 193 MPa
C_{Se} = (0.0582 + 0.1382)1/2 = 0,15
Se = 193 LN (1,0.150) Mpa

Fatigue stress -concentration factor K_f ~1.5 LN (1,0.11), K_{fs} ~ 1.28 LN(1,0.11)

The distribution of σ_a is driven toward lognormal.

$$\sigma'_{xa} = \frac{32 K_f\, M_a}{\pi\, d^3} = \frac{32.1{,}5\, LN(1{,}0.11).528.10^3}{\pi\,.45^3} = 88.53 \text{ MPa} \tag{20}$$

$$C_{\sigma' xa} = (0.11^2 + 0.05^2)^{1/2} = 0.121 \tag{21}$$

$$\tau_{xym} = \frac{16 K_{fs}\, T_m}{\pi\, d^3} = \frac{16.(1{,}28) LN(1{,}0.11) 530.10^3\, LN(1{,}0.05)}{\pi\,.45^3} = 37.91 \text{N/mm}^2 \tag{22}$$

$$C_{\tau\, xym} = (0{,}11^2 + 0.05^2)^{1/2} = 0.121 \tag{23}$$

$$\bar{\sigma}'_a = \left(\bar{\sigma}^2_{xa} + 3\bar{\tau}^2_{xya}\right)^{1/2} = \sqrt{88.53^2 + 3(0)^2} = 88.53 \text{ N/mm}^2 \tag{24}$$

$$\bar{\sigma}'_m = \left(\bar{\sigma}'^2_{xm} + 3\bar{\tau}^2_{xya}\right)^{1/2} = \sqrt{0 + 3(37.91)^2} = 65.66 \text{ N/mm}^2 \tag{25}$$

$$r = \frac{\bar{\sigma}'_a}{\bar{\sigma}'_m} = \frac{88.53}{65.66} = 1.35 \tag{26}$$

$$\bar{S}_a = \frac{r^2 \bar{S}^2_{ut}}{2\bar{S}_e}\left[-1 + \sqrt{1 + \left(\frac{2\bar{S}_e}{r\,\bar{S}_{ut}}\right)^2}\,\right] = 181.47 \tag{27}$$

$$C_{Sa} = \frac{\left(1+C_{sut}\right)^2}{1+C_{se}} \frac{\left\{-1+\sqrt{1+\left[\frac{2\bar{S}_e\left(1+C_{Se}\right)}{r\,.\,\bar{S}_{ut}\left(1+C_{Sut}\right)}\right]^2}\right\}}{\left[-1+\sqrt{1+\left(\frac{2\,\bar{S}_e}{r\,\bar{S}_{ut}}\right)^2}\right]} - 1 = 0.05 \tag{28}$$

The S_a distribution is interfered with the σ_a distribution on a lognormal-lognormal basis using equations and then the reliability is estimated from table E-10.
The corresponding z variable is

$$z = -\frac{\ln 181.47/88.53}{\left(\left(0.134\right)^2 + \left(0.121\right)^2\right)^{1/2}} = -3.95 \tag{29}$$

The reliability estimate from table E-10. in [39]

$P_f = 0.0000481$
$R = 1 - P_f = 0.99995$ is obtained. (30)

As a result, all the measures set up for this case study are satisfied.

4. DISCUSSION OF RESULTS

The reliability discipline has branched into many specialized and application areas such as software reliability, structural reliability, power system reliability, robot reliability and safety, human reliability and mechanical reliability. This study introduces the concept of reliability as applied to mechanical engineering. Based on the failure rates of mechanical components, reliability is discussed from a statistical point of view.

Researchers have been working on various reliability problems for several decades in the field of mechanical reliability. However, their works presented reliability based on narrow perspective. This paper offers a specific approach from an overall perspective. Compared to other approaches, the advantage of this particular one is fulfilment of mechanical reliability perspective. It will help designers to take action based on the information provided from all the reliability spectrum in order to design reliable mechanical elements.

A classification of results obtained is provided in a graphical form to facilitate easy application. Figure 6 summarizes failure modes, reliability variables, models and methods for mechanical reliability. Also, this figure illustrates reliability approach of this study. This approach is used step by step in order to assess shaft reliability. Figure 7 shows investigation steps of case study. Having the entire knowledge about mechanical reliability makes one design better products.

5. CONCLUSIONS

Mechanical Reliability has to deal with a wide spectrum of issues, including failure modes, reliability variables, models and methods. This study is expected to determine the suitability of reliability variables, both product and reliability models, performance measures and methods for mechanical reliability. This object is achieved by developing the streamlined method which provides an effective approach to assessing the reliability of machine products, such as a shaft. The approach studied is very useful in order to minimize the probability of failure and appropriate to identify all possible modes of failure and the mechanism by which these failures occur. Further studies are needed for the development of mechanical reliability.

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