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Structural and Vibration Analysis of a Machine Shaft using Finite Element Analysis

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ABSTRACT

The present study is a simulation of a machine shaft. The study will be done on FEM simulation software called Ansys 14.5, where a modal would be developed which will undergo a process of meshing. Meshing will divide the modal in extremely small units without changing the shape of actual geometry which will help the software to study the change at every small unit of the model. Then the of the modal would be defined in terms of inlet and outlet thereafter the boundary condition and design equation would be applied to get the desired result.

Keywords: *Ansys 14.5, FEM simulation software, Stability, Stiffness, Strength, design equation*

INTRODUCTION

Human consumption of the Earth's resources increases the need for a sustainable development as an important ecological, social, and economic theme. Re-engineering of machine tools, in terms of design and failure analysis, is defined as steps performed on an obsolete machine to return it to a new machine with the warranty that matches the customer requirement. To understand the future fatigue behaviour of the used machine components, it is important to investigate the possible causes of machine parts failure through design, surface, and material inspections. Failure analysis is an indispensable tool that is used widely by industry sector to develop or improve the product design. The failures of machine elements are studied extensively by scientists to find methods in order to identify their causes and to prevent them from reoccurring. To determine the failure modes, analytical, experimental, and finite element analysis methods can be used.

A structure as a whole, and each individual member, must be designed with reference to the three 'Ss': strength, stiffness and stability: **Strength** is the ability to carry the applied loads without yielding or breaking. Examples of strength failures are a cable which snaps, a vehicle body which' crumples, and a glass panel being smashed.

Stiffness is the ability to carry the applied loads without too much distortion. A material can only sustain stress at the expense of some strain ($\sigma = E\varepsilon$). Sometimes the strain, even though very small, may be the limiting factor. For example, a machine tool must be stiff enough to produce the required accuracy in machining, and a camera tripod must be stiff enough to prevent camera shake.

Stability is the ability to carry compressive loads without collapsing or buckling out of shape. For example, a metal rod in compression longitudinally will suddenly bow out of shape under a compressive stress which is well below the compressive yield stress.

The importance of the different types of failure, in considering any particular member, depends on how the loads are applied to it.

Tie: A member in tension.
Strut: A member in compression.
Beam: A member with loads that causes bending.
Shaft: A member in torsion.

In fact the members are categorized according to the way in which the forces are applied. These four type of loading define the four structural components: ties, struts, beams and shafts. Real members often carry a combination of loads.

Shaft The term shaft refers to a rotating machine element, circular in cross section which supports elements like rollers, gears, pulleys & it transmits power. The shaft is always stepped with maximum diameter in the middle and minimum at the ends, where Bearings are mounted. The steps provide shoulders for positioning of gears, pulleys & bearings. The fillet radius is provided to prevent stress concentration due to abrupt changes in the cross section. Shafts have various names depending on the application such as Axle, Spindle, Countershaft, Jackshaft, Line Shaft etc. Ordinary transmission shafts are made of medium carbon steels with a carbon content from 0.15- 0.40 percent such as 30C8 or 40C8, for greater strengths high carbon steels are used such 45C8 or 50C8. For applications where corrosion and high wear takes place, shaft material used is alloy steel. Common grades are 16Mn5Cr4, 40Cr4Mo6. Overload failures are caused by forces that exceed the yield strength or the tensile strength of a material. Shaft failures do not happen every day, but when they do, it can be a challenge to determine the cause of failure. Here's a technical explanation of what happens when the shaft bends or breaks.

1. Transverse Vibrations.
2. Torsional Vibrations.
3. Critical Speed Vibrations.
4. Component Failure.

- **Transverse vibrations** are typically the result of an unbalanced drive shaft. A transverse vibration will occur once per every revolution of the drive shaft. This could be because of damage to the shaft, missing balance weights or foreign material stuck to the drive shaft.
- **Torsional vibrations** occur twice per revolution of the drive shaft. They could be due to excessive u-joint angles or a shaft not in phase with its design specifications. A yoke outside of its design phasing by just one spline can cause torsional vibration issues.
- **Critical speed vibrations** occur when a drive shaft operates at an RPM too high in relation to its length, diameter and mass.
- **Component failure** of the drive shaft or the motor and transmission mounts can cause vibration. A failing u-joint is a prime example.

Figure1. Failure of a shaft.

Fatigue Failure

Fatigue is caused by cyclical stresses, and the forces that cause fatigue failures are substantially less than those that would cause plastic deformation. Confusing the situation even further is the fact that corrosion will reduce the fatigue strength of a material. The amount of reduction is dependent on both the severity of the corrosion and the number of stress cycles.

Once they are visible to the naked eye, cracks always grow perpendicular to the plane of maximum stress. Figure 1.2 shows the fracture planes caused by four common fatigue forces. Because the section properties will change as the crack grows, it's crucial for the analyst to look carefully at the point where the failure starts to determine the direction of the forces. For example, while it is common for torsional fatigue forces to initiate a failure, the majority of the crack propagation could be in tension. That's because the shaft has been weakened and the torsional resonant frequency has changed.

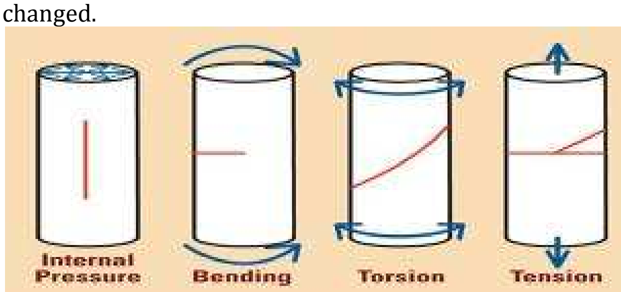

Figure2. shows the fracture planes caused by four common fatigue force

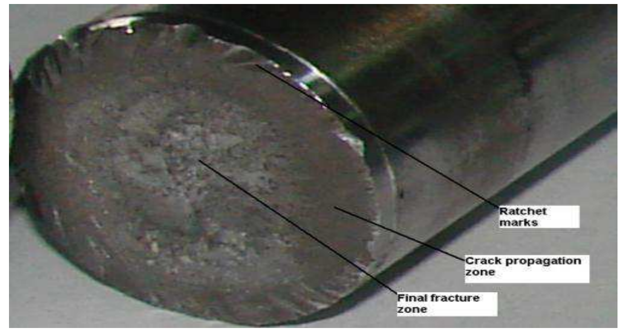

Figure3. Fracture Surface of a shaft under fatigue loading.

One of the more common causes of shaft failure is due to fatigue. Metal fatigue is caused by repeated cycling of the load. It is a progressive localized damage due to fluctuating stresses and strains on the material. Metal fatigues cracks initiate and propagate in regions where the strain is most sever. The concept of fatigue is very simple when a motion is repeated the object that is doing thework becomes weak. Fatigue occurs when a material is subject to alternating stresses, over a long period of time. Examples of where Fatigue may occur are: springs, turbine blades, airplane wings, bridges and bones. There are 3 steps that maybe view a failure of a material due to fatigue on a microscopic level.

1. Crack Initiation: The initial crack occurs in this stage. The crack may be caused by surface scratches caused by handling or toolingof the material, threads (as in a screw or bolt), slipbands or dislocations intersecting the surface as a result of previous cyclic loadingor work hardening.
2. Crack Propagation: The crack continues to grow during this stage as a result of continuously applied stresses.
3. Failure: Failure occurs when the material that has not been affected by the crack cannot withstand the applied stress. This stagehappens very quickly. Location of the 3 steps in a fatigue fracture under axial stress. One can determine that a material failed by fatigue by examining the fracture sight. A fatigue fracture will have two distinctregions; one being smooth or burnished as a result of the rubbing of the bottom and top of the crack (steps 1 & 2).The second is granular, due to the rapid failure of the material.The most effective method of improving fatigue performance is improvements in design.

A. Eliminate or reduce stress raisers by stream lining the part
B. Avoid sharp surface tears resulting from punching, stamping, shearing or other processes
C. Prevent the development of surface discontinuities during processing. Reduce or eliminate tensile residual stresses caused by manufacturing.
D. Improve the details of fabrication and fastening procedures. Metal fatigue is a significant problem because it can occur due to repeated loads below the static yield strength. This can resultin an unexpected and catastrophic failure in use because most engineering materials contain discontinuities. Most metal fatigue cracks initiate from discontinuities in highly stressed regions of the component. The failure may be due the discontinuity, design, improper maintenance or other causes. A failure analysis can determine the cause of the failure. Understanding fatigue strength and endurance limits is important because most shaft failures are related to fatigue

associated with cyclic loading. These limits are expressed by an S–N diagram, as shown in Fig. 1.4. For steel, these plots become horizontal after a certain number of cycles. In this case, a failure will not occur as long as the stressis below 27 klbf/in. No matter how many cycles are applied. However, at 10 cycles, the shaft will fail if the load is increased to 40bf/in. The horizontal line is known as the fatigue or endurance limit. For the types of steels commonly used for motors, good design practice dictates staying well below the limit. Problems arise when the applied load exceeds its limits or there is damage to the shaft that causes a stress raiser.

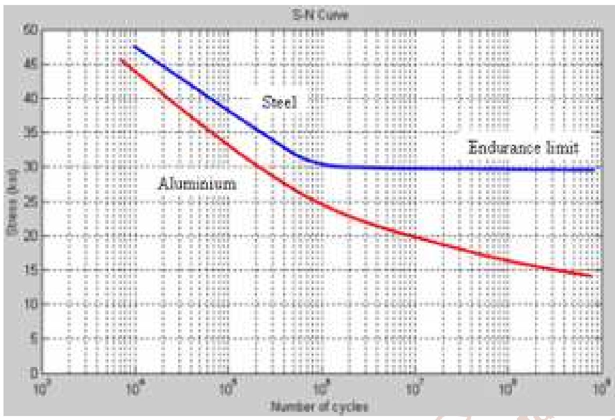

Figure.4 S-N Curve

Modes of Fracture (Monotonic Overload)
1. **Brittle:** Brittle fracture may occur at stresses for below the yield strength. In case of materials subjected to impact and shock loads and usually occur without warning. Brittle fractures are most likely to occur on large-sized components or structures as a result of shock loading.
2. **Ductile:** If a material is subjected to load above the yield point and the process of deformation continues, fracture eventually occur. Ductile fractures require a considerable amount of energy to plastically deform the material in necking region. Ductile fractures are very important in metal working operations, such as deep drawing, forging etc.

Subcritical Crack Growth

A. Failure under static load Parts under static loading may fail due to:

1. **Ductile behaviour:** Failure is due to bulk yielding causing permanent deformations that are objectionable. These failures may cause noise, loss of accuracy, excessive vibrations and eventual fracture. In machinery bulk yielding is the criteria for failure. Tiny areas of yielding are in ductile behaviour in static loading.
2. **Brittle behaviour:** Failure is due to fracture. This occurs when the materials (or conditions) do not allow much yielding such as ceramics, grey cast iron, or heavily cold-worked parts.

B. Dynamic loading:

Under dynamic loading, materials fail by fatigue. Fatigue failure is a familiar phenomenon fatigue life is measured by subjecting the material to cyclic loading. The loading is usually uniaxial tension, but other cycles such as torsion or bending can be used as well.

Fatigue failures are caused by slow crack growth through the material. The failure process involves four stages
1. Crack initiation
2. Micro-crack growth (with crack length less than the materials grain size) (Stage I)
3. Macro crack growth (crack length between 0.1mm and 10mm) (Stage II)
4. Failure by fast fracture.

Cracks initially propagate along the slip bands at around 45 degrees to the principal stress direction this is known as Stage I fatigue crack growth. When the cracks reach a length comparable to the materials grain size, they change direction and propagate perpendicular to the principal stress. This is known as Stage II fatigue crack growth.

Theories of Failure

Unfortunately, there is no universal theory of failure. Instead, over the years several hypotheses have been formulated and tested, leading to today's accepted practices. Being accepted, we will characterize these "practices" as theories as most designers do. Structural metal behaviour is typically classified as being ductile or brittle.
Theories have been developed for the static failure of metals based upon the two classes of material failure:
- ☒ Ductile metals → yield
- ☒ Brittle metals → fracture

The various theories are as follows:
- ➢ maximum principal stress theory also known as **rankine's theory**
- ➢ maximum shear stress theory or **guest and tresca's theory**
- ➢ maximum principal strain theory also known as **st. venant's theory**
- ➢ total strain energy theory or **haigh's theory**
- ➢ maximum distortion energy theory or **vonmises and hencky's theory**

Literature Review

Silva (2003) has investigated the crack produced in the two crankshafts of diesel van which were used for 30,000 km and then grinding is done. After machining both the crankshafts lasted only for 1000 km and resulting into the Journal damage. Due to wrong grinding process small fatigue crack developed along the centre of journal causing journal damage.Xu Xiaolei et. al. (2009), this paper is an analysis of failure of main shaft of locomotive turbo charger. The fracture position is located at a groove between journals with different diameter. The rotating bending fatigue is the dominant failure mechanism of the shafts. Detailed metallurgical analysis indicates that fillet region of the groove had subjected to high temperature. Katari et al. (2011), has considered 3 different crankshafts made up of same material, i.e., forged steel which is used in train. The investigation shows that crankshaft failure is due to fatigue which is supported through examination of mechanical properties of crankshaft material. Gys Van Zyl et. al. (2013), the case study is based on the analysis of Failure of Conveyor Drive Pulley Shafts. This paper investigates the failure root cause by visual examination, optical and scanning electron microscope analysis, chemical analysis of the material and mechanical tests. **Applications of FEA to the mechanical engineering industry:**

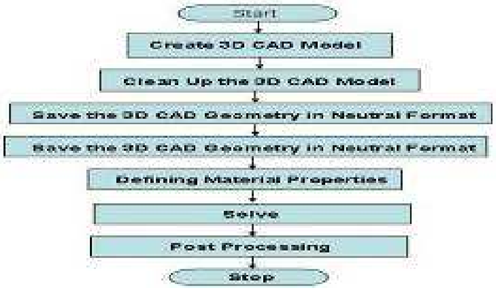

Figure.5. Flowchart of FEM analysis

Geometry Description

The Geometrical model has been generated on Ansys 14.5 The figure shows the geometrical model of machine shaft.

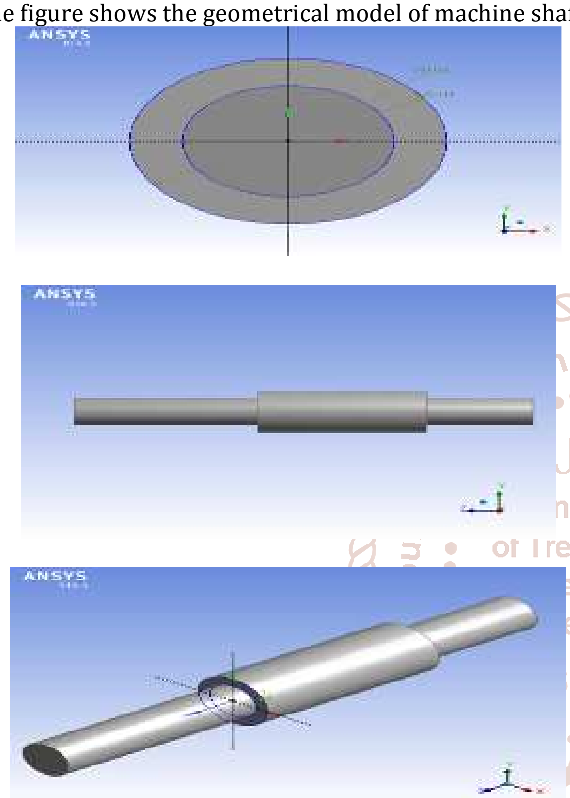

Figure.6. Geometry of shaft in 2D and 3D with dimension in mm.

Meshing

Meshing is a critical operation in FEM in this process the CAD geometry is divided into numbers of small pieces. The small pieces are called mesh. The analysis accuracy and calculation duration depends on the mesh size and orientations. By, default, a coarse mesh is generated by ANSYS software. Mesh contains mixed cells per unit area (ICEM Tetrahedral cells) having triangular faces at the boundaries. Number of nodes-15086 and Number of elements- 8430, Curvature- On and Smooth – Fine meshing.

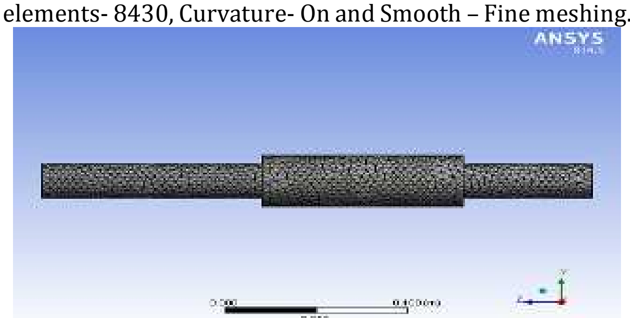

Figure7. Meshing of Machine shaft

Boundary Condition

Table.1 Physical and mechanical properties of shaft

Material	Steel
Mass density	7.85 Kg/cm^3
Mass	2.44247 Kg
Area	37,098.1 mm^2
Volume	311,143 mm^3
Yield Strength	207 MPa
Ultimate Tensile strength	345 MPa
Young's Modulus	210GPa
Poisson's Ratio	0.3
Shear Modulus	80.7692 GPa
Center of Gravity	x= 158.425mm y=- 0.0472625mm z= 0 mm

Table.2 Loads on the shaft

Quantities	Unit	Value
Mass	Mass	2.45 Kg
Length	L	300 mm
Maximum Bending Stress	σ_b	153. 25 MPa
Maximum Shear Stress	τ_s	29.55 MPa
Maximum Tension stress	σ_T	0.00 MPa
Maximum Torsional stress	τ	2.70 MPa
Maximum Reduced stress	σ_{red}	158.93 MPa
Maximum Deflection	f_{max}	178.92 µm
Angle of Twist	φ	0.01

Maximum Torque applied: 72.00 N-m

Phase angle: 0 degree and 1 degree

RESULTS AND DISCUSSIONS

After putting the boundary conditions, the solution is initialized and then iteration is applied so that the values of all parameters can be seen in a curve or line graph. After the

For 30mm diameter machine shaft at phase angle zero degree

Object Name	Static Structural (A5)
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

Alternating Stress MPa	Cycles	Mean Stress Pa
3999	10	0
2827	20	0
1896	50	0
1413	100	0
1069	200	0
441	2000	0
262	10000	0
214	20000	0
138	1.e+005	0
114	2.e+005	0
86.2	1.e+006	0

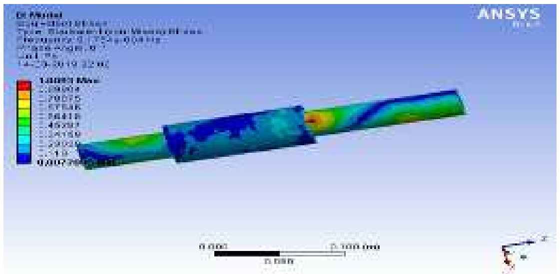

Figure Equivalent Von-mises stress at 0 degree phase angle

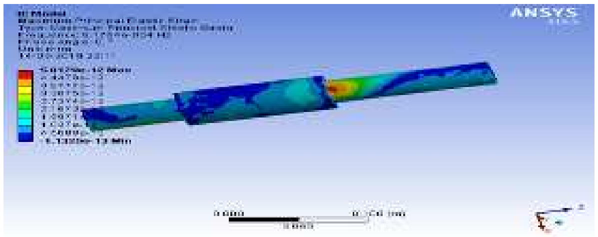

Figure .8. Maximum Principal elastic strain at 0 degree phase angle

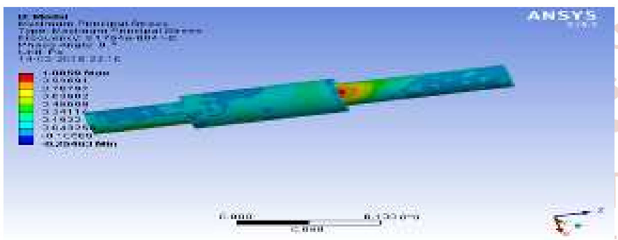

Figure.9.Maximum PrincipalStress at 0 degree phase angle

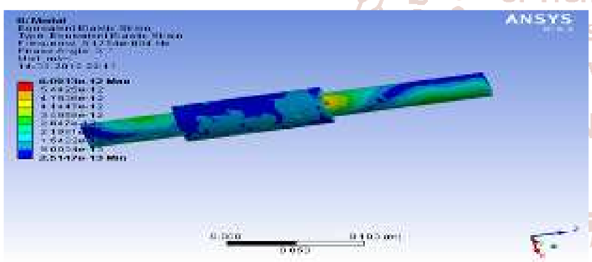

Figure.10 Equivalent elastic strain at 0 degree phase angle

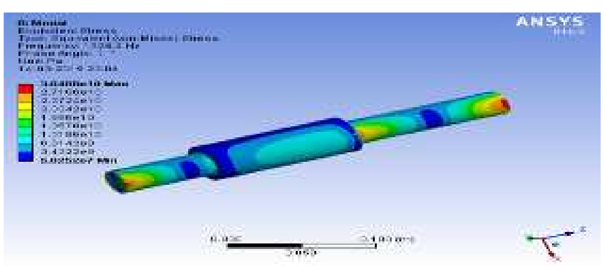

Figure.11. Equivalent Von-mises stress at 1degree phase angle

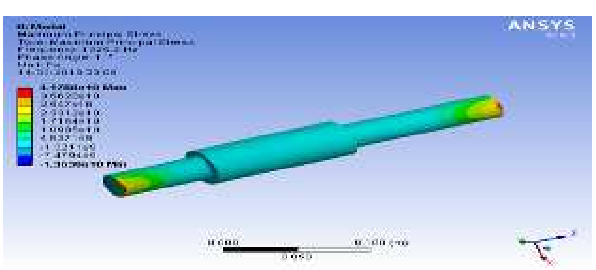

Figure.12. Maximum Principal Stress at 1 degree phase angle

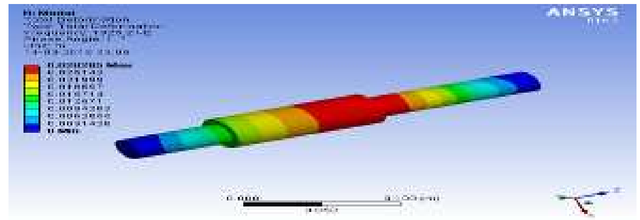

Figure.13. Total Deformation at 1 degree phase angle.

Table.3. Alternating stress & mean stress act on shaft

The following bar chart indicates the frequency at each calculated mode.

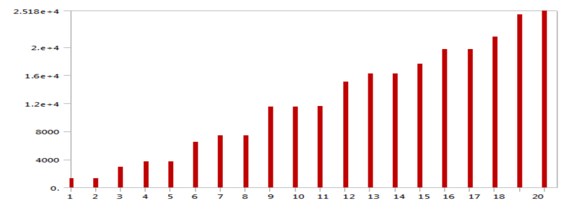

Figure.14. Damped frequencies [in Hz] at every mode

Table4. Tabular form of damped frequency in Hz

Mode	Damped Frequency [Hz]	Stability [Hz]	Logarithmic Decrement
1.	1325.2	0.	0.
2.	1325.3		
3.	2910.7		
4.	3729.3		
5.	3729.9		
6.	6503.5		
7.	7417.4		
8.	7418.4		
9.	11546		
10.	11547		
11.	11600		
12.	15089		
13.	16219		
14.	16221		
15.	17606		
16.	19703		
17.	19706		
18.	21475		
19.	24674		
20.	25180		

Conclusions

From the above results it can be concluded that the FEM analysis of shaft, vibration analysis and fatigue life analysis have been done.This shows the better results as compared to previous work. In this study the maximum principal stress, deformation, maximum von misses stress, fatigue life and corresponding to their stress act on the shaft and vibration analysis have been done. All these things are described in the previous chapter. According to the result stability frequency of design shaft is 0 Hz up to the 25000 Hz Damped frequency. The maximum alternative stress occurs on the shat after applying 10 Lac cycles of shaft is approximate 86 Mpa.

Scope of future work

Different material can also be trying for better performance and surface refinement can be done for better and accurate results. The results provided in this work can be experimentally verified.

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