CONTACT STRESS AND BENDING STRESS ANALYSIS OF A PAIR OF MATING SPUR GEARS BY THEORETICAL AND FINITE ELEMENT ANALYSIS APPROACH

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ABSTRACT - The American gear manufacturers organization (agma 2101-d04) is the majority leading empirically-based analytical gear stress analysis method for identifying contact and root bending stress in involute spur gears. Although based on the same fundamental principles, they have evolved to such an extent that, for various reasons, they are not necessarily in agreement. Nowadays the adoption of analytical formula-based approach and commercial finite element analysis based software has become an increasingly popular alternative for gear stress analysis. Hertzian formula and lewis formula are two well-known alternatives for finding out contact stress and bending stress respectively for a pair of gears. In this study, the main purpose is first, to determine contact stress and bending stress on involute spur gear teeth by using a formula-based approach and agma standard and compare the result of these approaches to check the percentage difference between the values. This task of analysis was accomplished at different points of contact in rotating gears. Using specifications of gear, a model is generated and the process of obtaining the model is automated with a computer program developed in this study. Furthermore, the same model is used for finite element analysis for obtaining contact stresses and bending stresses by using ansys software. For a mesh cycle, variations of contact, and bending stresses obtained from the two approaches are determined for different points of contact during rotation. These results are also compared with agma standard results. The study shows that the formula-based results and software-based results are in good agreement with the agma standards. It was also noticed that magnitude of contact stress is higher than bending stress and having no specific relationship with changes in points of contact.

Key words: agma; involute spur gear; finite element analysis; ansys.

1. INTRODUCTION

This paper presents a diagram of the inspiration towards the current work, the difficult assertion, targets, and extents of the current work. A concise diagram is introduced in this paper about the means towards the inception of the current exploration work followed by work targets.

1.1. GEARS

Gear can be defined as a rotating cylindrical wheel, having a tooth cut on it that meshes with another gear for transmitting torque or power from one shaft to another. Both the gears rotate either in opposite directions or in the same direction during motion. The direction of the motion is dependent on the type of gearing arrangement, i.e., external gearing or internal gearing. Gears usually produce a change in torque, creating a mechanical advantage, through their gear ratio. It is one of the most effective methods for transmitting power and rotary motion with or without change of speed or direction as per requirement.

1.1.1 CLASSIFICATION AND ITS APPLICATIONS

Gears are broadly classified according to various criteria, such as, according to the axis of the shaft, the type of gearing, the amount of power to be transmitted, and many more. As per these criteria, numbers of gears are there such as spur, helical, bevel, double helical, hypoid, crown, rack and pinion, worm gears, etc. as per industrial requirements. The detailed classification chart of gears is shown in figure 1.1.

The modern engineering machinery is highly equipped with these gears for ease of their functioning. These are practically used in the entire industrial segments, such as, automobiles, aerospace, manufacturing, power transmission machinery, lifting and hoisting machinery, and many more. The broad application area of the gear drive can be 2 seen from its uses in tiny wristwatches to huge machinery equipment (Narayankar & Mangrulkar, 2017).

Out of this vast category of gears, spur gear can be categorized as the simplest type of gear used for transmitting power because of its simplest design having straight teeth cut on the periphery, and the shafts at which the pair of gear is mounted rotates parallel to the axis of rotation. It is the ubiquitous and worthwhile type of gear, which is widely used in nearly all industrial and non-industrial segments. The numerous preferences of spur gears guarantee their utilization in a wide assortment of fast and high burden applications, in a wide range of gear trains, and over a wide scope of velocity ratios. They are most appropriate to duplicate the force, or force, of an article, or to build/decline the speed of an item. Subsequently, spur gears are utilized in a few mechanical applications, for example, tickers, electric screwdrivers, and so on and numerous family unit apparatuses, for example, clothes washers, blenders, wavering sprinklers, garments dryers, and so on what's more, for high force applications, for example, airplane motors and railroad trains and furthermore reasonable for moderate speed vehicles, for example, bikes.

As per the mating phenomenon in gear drive, the contact between two mating teeth follows the line of action. For external gearing, the driving gear begins at the tooth root and moves towards the top, while the driven gear moving reversely from top to root, as shown in figure 1.2. When contact is placed between the root and the pitch circle of the driving wheel in the first half of the meshing, the friction force moved towards the root of the driving tooth and the rotation counteracts. The schematic diagram of the motion of the spur gear is illustrated in figure 1.2 (Damtie & Tilahun, 2014).

1.1.1 Statistical Data of Gear Drive

Due to the increasing demand for gears in the entire mechanical segment, accurate analysis of the characteristics of gear systems has become the basic need. The demand growth of the gears is mainly because of automation in the industries and gear drive is the heart of the automation system. The ubiquitous and worthwhile type demanding growth can be shown by a report that in 2023, the worldwide industrial gearbox market is predictable 3 to reach 31.9 billion $ in value, which was only 25.91 billion $ in the year 2018. This data is showing increased use of this technology in the industrial segment. Hence, deep research is needed for failure analysis of such a system. (Source: www.statista.com).

The growth in any segment is mainly driven by technological advancements in that sector to improve efficiency and reliability of operation. The key to growing automation in the field of manufacturing and production segment is to reduce faults & delays in the process, which will increase the efficiency of the system. With advancement and automation in technology, the combination of gears is widely used in numerous fields, such as assembly lines, robotics, packaging, controlling the conveyor belts, bottling, and positioning in a production or assembly line, etc.

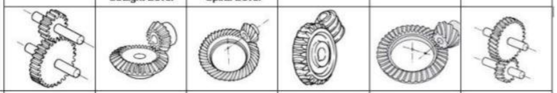
	Spur	Bevel		Worm	Hypoid	Helical
		Straight Bevel	Spiral Bevel			
Type						
Shaft Arrangement	Parallel shaft	Intersecting shaft	Intersecting shaft	Non intersecting, non parallel shaft	Non intersecting, non parallel shaft	Parallel shaft
Meshing	Same pitch & pressure angle	same pitch, pressure angle & face width	same pitch, pressure angle & face width	same thread, pitch & pressure angle	same pitch, pressure angle & face width	Same pitch, pressure angle & helix angle
Gear Ratio	1:1 to 6:1	3:2 to 5:1	3:2 to 4:1	5:1 to 75:1	10:1 to 200:1	3:2 to 10:1
Efficiency	94-98%	93-97%	95-99%	50-90%	80-95%	94-98%
Features	Most common & cost-effective type of gear	Durable & ideal for high load applications	Highly durable & can handle high load than straight bevel	Can be used for special occupations	Durable & ideal for high load applications and transmit high torque	Higher strength and durable than spur gears
Noise and Vibration	Noisy	Less than spur gear	Less than straight Bevel	Quiet and Smooth	Quiet operation than spiral bevel	Less than spur gears
Application	Conveyors, Constant	Printing press, Differential gear	Tractors, final reduction gearing	Anti Reversing, Indexing devices	Large trucks	Automobile transmission

Fig. 1.1: Classification of Gear Drive with their Specifications (Davis Hans S J)

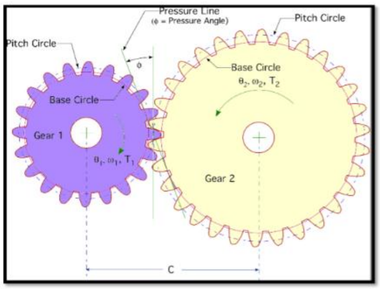


Fig. 1.2: Schematic Diagram of Spur Gear Motion

Moreover, accurate design of gears offers several advantages, such as, improved torque, ease of running, lack of maintenance, compact structure, and design with high load capacity, which further increases its usage in precision industries.

1.1 FAILURE OF GEARS

Failure of the gears can simply be defined as the phenomenon in which a material cannot withstand the working conditions of the machine. This situation causes failure of the system or itself of the gear. There are numerous reasons by which failure of gears can take place. This failure phenomenon is treated as a challenge, especially in complex industrial machinery, when mating gears are in working conditions. Failure of gears can sometimes cause even breakdown of the system. There are several modes or sources of failure of gears.

Lawrence Kren (2007) classified the failure modes into few categories, such as bending failure, pitting failure (micro and macro pitting), scuffing, and wear failure. 5 While failure occurs, it is the prime phase to analyze the mode of failure for determining its causes and further recommending for the solution. In such cases, it depends on inspection personnel that the gear should be replaced or it might work further till it creates some problem.

2. LITERATURE REVIEW

The writing overview is typically completed to evaluate the previous examinations done regarding the matter to control the exploration pursue its targets. It covers past examinations identified with research interest, which includes the targets of the investigations, exploratory subtleties, results, and ends alongside the suggestions for additional work. Subsequently with the assistance of this writing, a 'research gap' can be distinguished among past examinations and the current work which will be refined.

2.1 LITERATURE REVIEW FOR FAILURE ANALYSIS OF GEARS

Current and past examinations are evaluated to break down the hole between the past and current work situation. By top to bottom examination of these investigations, it tends to be handily decided that how the exploration work is pushing forward and still what the lacuna is there that can be a stride ahead towards the future expansion of that specific work. Subsequently, the writing survey gives a way and direction to future work to design targets. There are chiefly two strength standards for the plan of spur, helical, and worm gears, i.e., AGMA (Source: Official site of AGMA) and ISO standards (Source: Official site of ISO), which are generally utilized. However, the measurements taken with these methods are only valid with the assumption of uniformly distributed load on the gears. The results obtained with this assumption are not always true because there is variation in the load per unit length across different contact points (Li, 2008 and Pedrero et al., 2011).

Raptis et al. (2010) stated that for decades, researchers are working to develop some universal theories for surface pitting but still no universal theory has been defined yet. FEA technique is most suitably used for identifying changes in contact stresses at any point on the line of contact (Dassault Systemes, 2009.)

Lewis (1892) firstly documented bending stress analysis of the gear in 1893. In his study, Lewis suggested considering gear analyses as a parabolic beam in bending. Furthermore, the study highlighted actual tooth thickness importance. Although, the study was not able to explain the concept of stress concentration at the root fillet radius.

Furthermore, Timoshenko and Baud (1926) overcame this drawback in 1926 by utilizing photoelastic experiments to gear tooth models considering stress concentration factors into account. The study reported that the critical values of root bending stress are observed to be higher than the Lewis formula values. Consequently, they established a simple stress concentration factor to account for the influence of the root fillet radius.

Afterward, Heywood (1948); Jacobson (1955); Kelley and Pederson (1958), and Allison and Hearn (1980) conducted experimentations in their studies considering photo-elastic theory to identify root fillet stress. Finally, this theory was filtered down by Dolan and Broghamer and known by the American AGMA 2101-D04 standard and is still in use today.

Now a day, the most widely adopted technique for gear stress analysis is finite element analysis (FEA) and widely adopted by most researchers. If boundary conditions are applied appropriately, FEA is the best and accurate gear stress analysis technique than ISO or AGMA.

Numbers of studies were made for internal and external gearing system considering the FEA technique for at least three teeth [Vonn, 1990; Çelik, 1999; Sfakiotakis, 2001; Kawaleck and Wictor, 2004; Kawaleck, 2006; Atanasovska, 2009,] or in some instances partial adjacent teeth (Andrews, 1991).

Chen & Chung (2002) used the FEA approach for evaluation of the contact stress and bending stress of a helical gear set. The proposed helical gear set was comprised of an involute pinion and a double crowned gear. Mathematical models of the complete tooth geometry of the pinion and the gear have been derived based on the theory of gearing. Accordingly, a mesh- generation program was also developed for the FEA approach.

2.2 RESEARCH GAP

The 'Research Gap' distinguished from any past work is a further advance towards as good as ever work. The improved work gives significant accentuation on decreasing every one of those deficiencies which can improve the results of the current work. Subsequently, likewise, for recognizing a specific course for present work targets, a few sorts of writing have been evaluated as examined in the above area.

Through the previous literature, it has been identified that most of the studies considered contact stresses only either in rotating or non-rotating condition of the gear drive. A few studies were there which considered the identification of both contact and bending stresses over the spur gear drive. Least studies were found considering hybrid analytical and FEA approach for both contact and bending stresses.

In this work, an attempt will be made to analyze contact stresses and bending stresses of mating gears using ‘Hertzian theory’ and ‘Lewis equation’ respectively. Furthermore, the finite element analysis (FEA) technique will be used to measure both stresses at the surface of mating gears. ANSYS software will be adopted to accomplish the FE analysis task. With the help of ANSYS, maximum and minimum contact stresses and bending stresses can be determined for two mating gears and local stresses at any required points can be predicted. Finally, the percentage error will be calculated between stresses obtained by both methodologies. Furthermore, the same results will be verified using AGMA standards to check the severity of operation of gear drives.

3. MATERIAL AND METHODS

This section presents a meticulous description of the selection criterion for the specifications and material of the spur gear and methodology adopted for completion of the present work. This section also covers the detailed description of mathematical calculations required for contact and bending stress analysis.

3.1MATERIAL SELECTION AND ITS PROPERTIES

The material chosen for the present study is Stainless Steel 18CrNiMo7-6, which is case hardened steel. The material chosen is the same for both mating gears i.e. for gear and pinion. This is a commonly used material in the industrial segment and widely adopted for the manufacturing of stubs, gears, shafts for the wind industry, crankshafts, reducers, automobile gearboxes, and pieces for industrial and agricultural vehicles, and many more. The wide applications of this kind of steel are mainly because of its good hardenability, high resistance, and toughness. The properties of 18CrNiMo7-6 areas are presented in Table 3.1 and the chemical composition is presented in Table 3.2.

There are a variety of gears available as per their industrial requirements as discussed in previous sections. For the present study, the Spur gear set has been used for study purposes. Some of the specifications of the mating gears are presented in Table 3.3.Furthermore, Solid Works modeling software has been adopted for the design of gear and pinion.

S. No.	Property	Gear 1	Gear 2	Unit
1	Density	7700	7700	Kg/m^3
2	Young's modulus (E)	206000	206000	N/mm^2
3	Poison's Ratio	0.300	0.300	-
4	Tensile strength (σ_b)	1200	1200	N/mm^2
5	Yield strength (σ_s)	850	850	N/mm^2
6	Fatigue Strength	275	275	N/mm^2
7	Elongation	8-25	8-25	%
8	Surface hardness	61	61	HRC
9	Thermal Conductivity	25	25	W/mK
10	Melting Point Temperature	1450-1510	1450-1510	Deg. C

table.3.1 properties of gear material

Constituents	C	Mn	Si	P	S	Cr	Mo	Ni
Min.	0.15	0.50	-	-	-	1.50	0.25	1.40
Max.	0.21	0.90	0.40	0.025	0.035	1.80	0.35	1.70

Table 3.2: Chemical Composition of gear material

Parameters	Gear	Pinion
Reference Diameter (mm)	440	176
Number of Teeth	55	22
Module (mm)	8	8
Pressure Angle (degrees)	20	20
Face Width(mm)	120	120
Base Pitch(mm)	23.617	23.617
Type of Gear	Spur gear	Spur gear
Reference diameter (mm)	440	176
Operating Pitch Diameter (mm)	444.41	177.76
Root diameter (mm)	420	162.4
Base Diameter (mm)	413	165
Addendum (mm)	7.887	11.087
Dedendum (mm)	10.00	6.8
Torque (Nm)	1987	794.8

Table 3.3: Mating Gear Specifications

4. ANALYSIS OF GEARS

The study is mainly focused on analyzing the bending and contact stresses on the spur gears, which are the two major modes of failure of the gears. In this paper, first, the accurate calculation of two-dimensional spur gear contact stresses and gear bending stresses were determined. Contact stress and Bending stress calculations will be made using the Hertzian approach and Lewis formula. Furthermore, their values will be compared with AGMA (American Gear Manufacturers Association) standards for contact stress and bending stress.

4.1 CONTACT STRESS CALCULATIONS

There are various standardized methods to predict contact stress i.e. AGMA, ISO. However, the basis of all the methods is the Hertzian contact theory. When mating takes place between two curved bodies, contact stress appears. These bodies may be cylindrical or spherical. If the bodies are spherical, theoretically the contact area is a point and if the bodies are cylindrical in the shape contact area is a line. In both cases due to negligible contact area, contact stress will be infinite and it will start yielding. Nevertheless, in real life, the deformation will take place in the contact area will resulting in infinite stress and will be known as Hertzian stress. In most cases, cylindrical shaped bodies are taken into consideration. The Hertzian contact stress formula is as follows:

Where,

Ym = material coefficient

Yp= pitch point coefficient

Ft= transmitted tangential load

b= face width (mm)

d1= diameter of a pinion (mm)

u= gear ratio

4.2 Bending Stress Calculation

Firstly, Wilfred Lewis presented the bending tress calculation in 1892, which is still recognized as the basis for gear tooth bending stress analysis. According to Juvinall and Marshek [14], Lewis made the following assumptions for bending stress analysis in gears:

1. Only a single tooth of the gear bears the full load at the tip.

2. There is a negligible value of the radial component of the force.

3. The load is distributed uniformly across the full-face width.

4. Tooth sliding friction forces are negligible.

Where,

Wt = transmitted tangential load (N)

b = face width (mm)

m = module (mm)

Y = Lewis form factor

4.3 AGMA EQUATION FOR CONTACT STRESS

The American Gear Makers Affiliation (AGMA) is an intentional relationship of organizations, experts, and academicians with an immediate interest in the plan, production, and use of gears, and other power transmission parts since 1961. AGMA is the worldwide organization for specialized standards for makers, providers, and clients of mechanical power transmission parts (Source: AGMA Standards, 1961).AGMA standards are International Organization for Standardization (ISO) compliant and help in assuring product excellence and performance measurements (Source: ISO gear standards). AGMA standards, http://www.agma.org/.

Where,

ZE = AGMA elastic coefficient (MPa)

Ft= transmitted tangential load (N)

Ko= overload factor

Ks= size factor

Kv= dynamic factor

KH= load distribution factor

ZR= surface condition factor

r1= radius of pinion (mm)

b= face width (mm)

ZI= geometry factor pitting resistance

4.4 AGMA EQUATION FOR BENDING STRESS

These constants are calculated using their respective formula or standard table or chart is given in the book authored by Budynas and Nisbett, 2011.

Where,

Wt= transmitted tangential load (N)

Ko= overload factor

Ks= size factor

Kv= dynamic factor

KH= load distribution factor

b= face width (mm)

m= module (mm)

YJ= geometry factor for bending stress

4.5 GEAR MODELLING AND SIMULATION

Modeling plays a crucial role in industries as it saves a lot of money before going to the manufacturing process. Simulation can be performed as per calculations to ensure that the model is fulfilling the design requirement. Modeling is a very sensitive operation, as it needs to be approximated to the real-life running condition taking into consideration for reliable results. To design gears for transmission, there are some important measurable parameters such as, transmission error, bending stress, and surface stress, which are needed to calculate. Nowadays, there are several software that can perform this analysis in a short period and provide accurate results.

4.6 FINITE ELEMENT ANALYSIS

The finite element analysis is a numerical method used to solve any differential equation written in matrix form. There are different software tools based on the FE theory, such as ANSYS, COMSOL, and Abaqus. In this work, ANSYS has been used to simulate two spur gear pairs in mesh and it can also be used to calculate the contact pressure, tooth root stresses, and the transmission error. For FE analysis, the gear tooth profile is taken as an involute profile. There are two ways to create parts for modeling and analysis; the first way is to use the part creator in FEM software. However, it is a complex process having limitations of microgeometry modification. The second way that was used here, which is to import the parts from any other software. For that, KISSsoft was used to generate the gear geometry. The finite element analysis (FEA) approach will be used for modeled gears in ANSYS software to analyze contact stress and bending stress at different points of contact respectively. The points of contact chosen for calculation and analysis purpose are 100 , 90 , 80 , 70 , 60 , 50 , 40 , 30 , 00 , -10 , -20 , -30 and -50 .

2. Result and Discussion

After a thorough review of the work done in the field of failure analysis of gear drive, the analysis tables have been developed for both bending and contact stress calculations. The tables were developed after calculating all the required constants for Hertzian, Lewis, and AGMA equations. In this section, a description is presented about the task of stress calculations from the respective formulas and equations and their analysis according to the proposed methodology, this complete task has been divided into three stages:

1) Contact stress analysis

2) Bending stress analysis

3) ANSYS result analysis

S. No.	Point of Contact	Contact Stress (MPa)	Bending Stress (MPa)
1	10^0	77.059	9.1647
2	9^0	89.155	8.2027
3	8^0	67.488	7.4455
4	7^0	59.729	6.7415
5	6^0	32.112	6.1409
6	5^0	19.939	6.6258
7	4^0	26.012	6.7425
8	3^0	30.162	6.8455
9	0^0	25.688	6.9009
10	-1^0	15.984	6.6627
11	-2^0	18.838	6.5536
12	-3^0	21.471	31.553
13	-5^0	21.147	36.088

Contact Stress and Bending Stress Analysis through FEM Approach using ANSYS Software

The obtained percentage difference is shown to be very small showing better approximation with results of ANSYS in comparison to AGMA standard

S. No.	Point of Contact	ANSYS Contact Stress (MPa)	AGMA Contact Stress (MPa)	Difference (%)
1	10^0	77.059	76.125	1.23
2	9^0	89.155	78.075	14.19
3	8^0	67.488	66.75	1.11
4	7^0	59.729	59.29	0.74
5	6^0	32.112	31.11	3.22
6	5^0	19.939	19.86	0.40
7	4^0	26.012	25.75	1.02
8	3^0	30.162	29.83	1.11
9	0^0	25.688	25.64	0.19
10	-1^0	15.984	15.36	4.06
11	-2^0	18.838	18.78	0.31
12	-3^0	21.471	21.8	1.51
13	-5^0	21.147	21.01	0.65

Percentage Difference in Contact Stress Values measured by ANSYS software and AGMA Standard

S. No.	Point of Contact	ANSYS Bending Stress (MPa)	AGMA Bending Stress (MPa)	Difference (%)
1	10^0	9.1647	8.95	2.40
2	9^0	8.2027	8.074	1.59
3	8^0	7.4455	7.21	3.27
4	7^0	6.7415	6.32	6.67
5	6^0	6.1409	5.78	6.24
6	5^0	6.6258	6.33	4.67
7	4^0	6.7425	6.33	6.52
8	3^0	6.8455	6.76	1.26
9	0^0	6.9009	6.77	1.93
10	-1^0	6.6627	6.55	1.72
11	-2^0	6.5536	6.345	3.29
12	-3^0	31.553	28.9	9.18
13	-5^0	36.088	33.78	6.83

Percentage Difference in Bending Stress Values measured by ANSYS software and AGMA Standard

5. CONCLUSIONS

The present study aimed at obtaining values of contact stress and bending stress through a theoretical approach using Hertzian and Lewis contact stress formula and FEA based approach using ANSYS. Furthermore, the same values were also calculated using the AGMA standard equation. AGMA standard values were used to check the rate of error or percentage difference between values as obtained by formula based results and ANSYS results. Finally, the following conclusions may be drawn from the study done for gear failure analysis:

· In the present study, effective methods to estimate the tooth contact stress and bending stress by the two-dimensional and three-dimensional models are proposed.

· Hertzian Formula is proven to be the best choice for identifying contact stress values with given gear parameters and at different points of contact.

· Similarly, Lewis Formula is also proven as the best choice for identifying bending stress values with given gear parameters and at different points of contact.

· AGMA standard is the best way to check stress values at given parameters and widely adopted method to identify the difference between formulas based values and AGMA standard values.

· Varying points of contact chosen for analysis purposes shows a broad aspect of analysis. Thus, the results obtained can be applied practically also if required

· The rate of error or percentage difference identified between the formula-based values of stress and AGMA standard values is almost the same as previous researches in this field and showing a better relationship between values obtained with both methods.

· Furthermore, the FEM technique is also proven as the best approach to identify stress values for any type of gear and at any point of contact with given gear parameters with a high degree of accuracy.

· The rate of error or percentage difference identified between the FEM-based values of stress and AGMA standard values is also very low which showing a better approximation of FEM results.

· Stress investigation utilizing Limited component portrays nearer to sensible outcome. In any case, it takes enormous computational time and relies upon the client's competency who defines in FE programming. In the business where various undertakings are there, it isn't practical to display every calculation for limited component examination. In any case, the primary inspiration driving this investigation is to realize how much the outcomes stray from standard qualities.

6. FUTURE WORK

Through the outcomes and ends got from the current work, various recommendations can be suggested which will be productive for future business related to disappointment examination of the gears.

• The outcomes got from the equation based qualities and AGMA standard qualities show that the rate contrast could be diminished if some more factors or boundaries were viewed as which influence the estimations of contact and bowing anxieties.

· Similarly, the percentage difference with FEM based values and AGMA standard values could also be decreased if some more boundary conditions are modified taking into consideration some more impacting parameters or factors

. · Furthermore, in this study, stress analysis is carried out at specified points of contact, which are in the scope of this study. For proper analysis with decreased percentage difference, the randomized point of contact could be chosen with an increased number to get a robust model with high accuracy.

· An experimental set up can be proposed to justify the simulation results. That will validate the finite element model and ultimately fortify this study.

· The scope for this research was limited to only one pair of the spur gear and the maximum load case for that specific pair. In the future, a study can be done for multiple types of gears with different load cases.

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PHOTOGRAPHY

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