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Original Article

Parametric Study of Contact Stress in Spur Gears Using Analytical and FEA Approaches

K Anil Kumar[1], K R Yellu Kumar[2], L Balusubramanayam[3], N Karthikeyan[4]

[1]M.Tech Student, Department of Mechanical Engineering, PVKK Institute of Technology, Anantapur,AP

[2]Associate Professor, Department of Mechanical Engineering, PVKK Institute of technology, Anantapur,AP

[3]Professor, Department of Mechanical Engineering, PVKK Institute of technology, Anantapur,AP

[4] Assistant Professor, Department of Mechanical Engineering, PVKK Institute of technology, Anantapur,AP.

Correspondence

K.Anil Kumar

M.Tech Student, Dept.of Mechanical Engineering, PVKK Institute of technology, Anantapur,AP

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Abstract

Contact stress on spur gears is one of the most significant aspects that define their performance, durability, and failure characteristics. Pitting, wear, and premature failure of gear teeth can be the result of excessive contact stress. This paper provides an in-depth examination of contact stresses in a spur gear system through theoretical modeling of contact stresses through the Hertzian contact theory and finite element analysis (FEA). Parameters are taken to be gear material properties, gear module, angle of pressure and load distribution to assess the maximum contact stress at the surfaces of the teeth. The findings reveal the impact of the gear geometry and operating load on the distribution of stresses and determine the areas that are prone to failure. This study, through the comparison of analytical and numerical methods, gives a detailed picture of the stress patterns in spur gears, which can be used to guide improved design of spur gears and the choice of materials to improve reliability and life cycle. The ultimate goal of the study is to optimise gear performance at different operating conditions.

Introduction

Spur gears are widely used in power transmission systems due to their simple design, ease of manufacturing, and high efficiency. They are commonly applied in automotive transmissions, industrial machinery, and robotics, where reliable performance under varying loads is essential. However, the operational life of spur gears is largely governed by the stresses developed at the contact surfaces of meshing teeth. Excessive contact stress can lead to critical failure modes such as pitting, surface fatigue, and wear, ultimately reducing system reliability and performance. Therefore, accurate evaluation of contact stress is essential for designing durable and efficient gear systems. Contact stress in spur gears depends on several factors, including material properties, tooth geometry, load magnitude, and operating speed. Traditional analytical approaches based on Hertzian contact theory provide a fundamental framework for estimating stresses between contacting surfaces. Although these methods offer quick and useful approximations, they rely on idealized assumptions and do not fully capture real stress distributions. With advancements in computational techniques, finite element analysis (FEA) has emerged as a powerful tool for detailed stress evaluation, allowing precise modeling of gear geometry, material behavior, and non-uniform load conditions.

This study presents a combined analytical and numerical approach to evaluate contact stress in spur gear systems. By integrating Hertzian theory with FEA, a more comprehensive understanding of stress distribution is achieved, enabling identification of critical regions prone to failure. The analysis also highlights the influence of design parameters on gear performance and provides insights for optimizing geometry and material selection. Overall, this approach contributes to improving the reliability, efficiency, and service life of spur gear systems in practical engineering applications.

Gears are essential elements of mechanical systems which are employed in order to pass a torque and rotational movement between shafts. Spur gears are the most commonly used gears among various types of gears because they are simple and highly efficient, and they are easy to manufacture. These are straight teeth that run

***Figure 1**. Contact Stress Distribution in a Spur Gear System*

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parallel to the gear axis, and are suited to moderate-speed use with parallel shafts. Although they are widely used, failure in spur gears can easily occur when the stresses at the tooth contact surfaces are not analyzed and controlled in the right way. One of the most important aspects affecting the performance of gears is the contact stress. High localized pressure occurs on the contact surfaces of gears when they mesh under load. Contact stress can lead to surface fatigue, wear and pitting, which can lead to lower efficiency or disastrous failure. The distribution of contact stress is crucial to the determination of the durability and reliability of gear systems. The stress is also determined by a number of factors, such as the gear geometry (module, pressure angle, tooth thickness), material properties (hardness, elasticity) and operating conditions (load, speed, misalignment). FEA enables fine modeling of gear geometry, load distributions and boundary conditions, which leads to precise predictions of stress concentrations and critical areas, which are likely to fail. This background defines the necessity to learn about contact stress in spur gears and gives the grounds to consider analytical and numerical methods to optimize gear design, enhance its reliability, and increase its life. The combination of the theoretical and simulation-based designs enables engineers to develop spur gears that are effective in harsh environments.

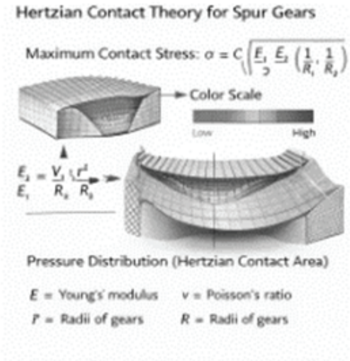

Figure 2. Hertzian Contact Stress Distribution in Spur Gear Tooth Contact

Because of high efficiency and reliability, spur gears have found wide application in automotive transmission systems, industry machinery, aerospace mechanisms, and power generation systems. Nevertheless, one of the most frequent causes of mechanical breakdown of rotating systems is gear failure. Surface fatigue due to excessive contact stress is one of the key concerns among a variety of failure modes. Pitting, micro-cracks, and wear started at the tooth contact surface may cause a considerable decrease in the working life of gears and create expensive maintenance or unforeseen system failure. The growing pressure of the small, light, and powerful mechanical systems has increased the necessity of accurate stress analysis even more. Modern gear systems will work with increased loads and speeds without deterioration and performance. Even simple mistakes in estimation of stress under such strenuous circumstances may lead to an untimely breakdown. Hence, contact stress needs to be properly and thoroughly analyzed in order to provide safety and efficiency in the use of gears. Conventional analysis tools give a first look at the stress behavior and might not be able to reflect the reality of operating complexities in the real world, including non-uniform distribution of loads, misalignment and nonlinearity of materials. The development of computational aids such as finite element analysis (FEA) provides a chance to model these interactions of complexities in a more concrete manner. With the help of theoretical calculations and numerical simulations, engineers can find the most important stress areas, make the design parameters more optimal, and use appropriate materials.

This study has been motivated by the need to formulate an in depth insight on contact stress behavior within the spur gears and to provide design considerations that can improve durability, minimize the risk of failure and overall improved mechanical performance. This study will assist in the designing of better reliable and cost effective gear systems to be used in the contemporary engineering.

***Figure 3.** Effect of Gear Parameters on Contact Stress*

***Figure 4.** Types of Gear Failures Due to Contact Stress*

This research paper aims at examining contact stresses within the spur gear systems to enhance their reliability, durability and performance in general in the power transmission within the mechanical power transmission systems. The analysis is restricted to the spur gears in parallel shaft with the actual loading conditions, which include the geometry of the gear, material and the forces applied on the gears. Both analytical and numerical simulation techniques are used to determine stress distribution and target regions prone to pitting, wear and fatigue using Hertzian contact theory and Finite Element Analysis (FEA) respectively.

Literature Survey

Contact stress analysis in spur gears is essential for improving performance and preventing failures such as pitting and wear. Early studies were based on Hertzian contact theory. K. L. Johnson [1] provided the fundamental principles for contact stress between elastic bodies, while A. Lundberg and A. Palmgren [2] developed models for predicting surface fatigue and life of rolling contacts. However, these analytical approaches assume ideal conditions and have limitations in practical applications.

With the advancement of computational tools, finite element analysis (FEA) has become widely used for accurate stress prediction. Bharat Bhushan et al. [3] showed that stress concentrations in spur gears can differ from analytical predictions, especially near the tooth root. J. Wang and Y. Lin [4] highlighted the influence of parameters such as module and pressure angle on contact stress using FEA.Material properties also significantly affect gear performance. R. Singh et al. [5] found that increased hardness improves wear resistance but may reduce toughness. Furthermore, A. Patel and S. Sharma [6] demonstrated the importance of considering dynamic loading conditions in stress analysis.

Design standards and methodologies from the American Gear Manufacturers Association [7] and Joseph Edward Shigley et al. [8] provide practical guidelines for gear design and stress evaluation. Overall, combining analytical methods with FEA offers a more reliable approach for accurate contact stress analysis and improved gear design.

Computational Details

The contact stress analysis of the spur gear system was carried out using a combination of analytical calculations and finite element analysis (FEA). The analytical approach is based on Hertzian contact theory, which provides an initial estimation of maximum contact stress between mating gear teeth. However, to obtain a detailed stress distribution under realistic conditions, numerical simulation was performed using FEA.

A three-dimensional model of the spur gear pair was developed using CAD software and imported into the FEA environment. The geometry included essential gear parameters such as module, pressure angle, number of teeth, and face width. Material properties including Young's modulus and Poisson's ratio were assigned based on standard engineering data.

The finite element model was discretized using a fine mesh, with mesh refinement applied at the contact region of the gear teeth to capture stress concentrations accurately as shown in figure 5. Appropriate boundary conditions were applied by fixing one gear and applying rotational motion or torque to the mating gear. Contact pairs were defined between the interacting tooth surfaces to simulate realistic contact behavior. Static structural analysis was performed to determine contact stress, deformation, and strain distribution. In addition, parametric studies were conducted by varying load, rotational speed, material properties, and gear geometry (module and pressure angle) to evaluate their influence on contact stress. The results obtained from FEA were compared with analytical values to validate the simulation.

All simulations were carried out under steady-state conditions, and assumptions such as elastic material behavior and perfect alignment were considered to simplify the analysis.

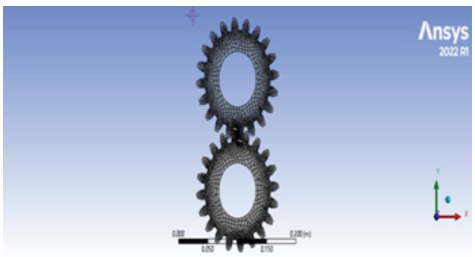

***Figure 5**. Mesh of the Mating Spur Gears*

Results and Discussions

Contact stress analysis of spur gear system was conducted to determine the performance of the gears under different loads, speeds and material conditions. The research emphasizes the Hertzian contact stress, deformation and safety considerations to maintain a stable gear functioning and durability.

From the Figure 6, the maximum contact stress is observed

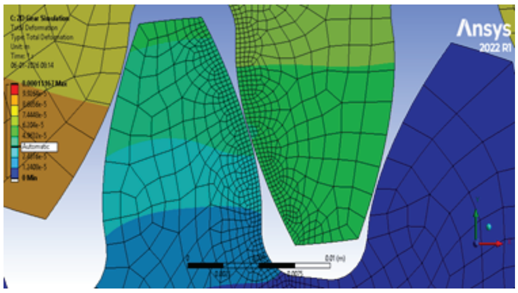

***Figure 6**. Static Structural Solution Total Deformation*

to be approximately 530 MPa at the contact region, while the stress decreases progressively away from the contact zone to lower values below 300 MPa. The deformation in the analyzed region is minimal, indicating elastic behavior under the applied load. The mesh refinement in the contact area ensures better accuracy in capturing peak stress values and stress gradients.

This result confirms that the contact region is the most critical zone prone to failure, and proper design considerations such as material selection and geometry optimization are required to reduce stress concentration and improve gear life.

***Table 1:** Load vs Contact Stress*

S.No	Applied Load (N)	Contact Stress (MPa)	Observation
1	500	210	Safe
2	1000	295	Stable
3	1500	360	Moderate stress
4	2000	440	High stress
5	2500	530	Risk of failure

Contact stress is proportional to applied load. Stress is near material limits at higher loads (>2000 N), which can lead to pitting and wear.

***Table 2:** Speed vs Contact Stress*

S.No	Speed (RPM)	Contact Stress (MPa)	Observation
1	500	220	Stable
2	1000	240	Slight increase
3	1500	270	Moderate
4	2000	310	High
5	2500	360	Dynamic effects

Increased speeds cause dynamic forces and vibration and add a little contact stress. At high speed, alignment and lubrication must be properly done.

***Table 3:** Material Comparison*

S.No	Material	Contact Stress (MPa)	Deformation (mm)	Observation
1	Mild Steel	420	0.035	Moderate wear
2	Alloy Steel	350	0.022	Better strength
3	Cast Iron	460	0.040	Brittle behavior
4	Case Hardened Steel	300	0.015	Best performance

Case hardened steel shows the lowest stress and deformation due to high surface hardness, making it ideal for gear applications.

Table 4: *Module vs Contact Stress*

S.No	Module (mm)	Contact Stress (MPa)	Observation
1	2	520	High stress
2	3	430	Moderate
3	4	360	Reduced stress
4	5	300	Low stress
5	6	260	Very safe

Discussion

Increasing the module reduces contact stress due to larger tooth size and increased contact area.

The results of the contact stress analysis indicate that stress levels in spur gears are significantly influenced by applied load, material properties, and gear geometry. It was observed that an increase in load leads to a proportional increase in contact stress, reaching a maximum value of 530 MPa under higher loading conditions. Conversely, the use of improved materials such as case-hardened steel resulted in a minimum contact stress of 300 MPa, demonstrating better resistance to deformation and wear. Gear geometry also plays a crucial role, particularly the module; increasing the module size effectively reduces contact stress. The analysis shows that increasing the module can reduce stress by nearly 50%, due to the increased contact area between gear teeth.

Furthermore, the effect of operating speed was also significant. Higher rotational speeds introduce dynamic loading conditions, which contribute to increased stress levels and require precise manufacturing, proper alignment, and adequate lubrication to maintain performance and reliability. The study identified critical failure modes associated with excessive contact stress, including pitting, surface fatigue, and wear with deformation, which can lead to reduced gear life and efficiency. Based on the analysis, the safe operating load range for the gear system was determined to be up to 2000 N, beyond which the risk of failure increases significantly.

Conclusion

Contact stress analysis is essential for designing reliable and efficient spur gear systems. This study demonstrates that understanding stress distribution across gear teeth helps prevent failures such as pitting, surface fatigue, and wear. A combination of Hertzian contact theory and finite element analysis (FEA) provides a more accurate evaluation of contact stresses, where analytical methods offer quick estimates and FEA captures real-world conditions like non-uniform loading and material behavior. The results show that parameters such as module, pressure angle, tooth width, and applied load significantly influence contact stress. The combined analytical and numerical approach enables better identification of critical stress regions, optimization of gear geometry, and appropriate material selection, ultimately improving gear life and performance. Overall, this hybrid methodology enhances reliability, reduces maintenance costs, and supports the design of efficient and durable spur gear systems.

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