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# A Review on Bending Strength of Asymmetric Gear

Pradeep Kumar V G[1], Dr. G. Mallesh[2]
[1]*Assistant Professor, Jss Science and Technology University, Mysuru*
[2]*Professor, Jss Science and Technology University, Mysuru*

***Abstract: Gear is a mechanical rotating toothed part which meshes with other similar toothed parts to transmit torque and power. Gear tends to play a very vital role in all industries. This article reviews the methodology used to investigate bending strength of asymmetric spur gear; Finite Element Method (FEM), Numerical Calculation and Investigational Techniques were usually carried out in order to understand the bending strength of spur gear. Works and experiment from the literature were studied, and their findings were extracted to understand the methods used. Next stage is to simulate the gear using Finite Element Method (FEM) in order to get the analysis of gear strength. The most important stage is to put the gears to physical experiment or testing facilities to determine and validate all data from the numerical calculation and FEM method. Therefore, this review article highlights importance of asymmetric gear in chronological order so that reader may obtain an overview of contribution of various researchers in development of gears having least bending stress.***
***Keywords: Symmetric gear, Asymmetric gear, Bending stress and FEM.***

## I. INTRODUCTION

A Gear is a machine element used to transmit motion and power between rotating shafts by means of progressive engagement of projections called teeth. In any pair of gears, the smaller one is called pinion and the larger one is called gear immaterial of which is driving the other [1]. The gear tooth profile is mainly based on two engineering curves i.e., involute curve and cycloidal curve. An involute of a circle is essentially a plane curve generated by a point on a tangent that rolls on the circle without slipping [2]. When a circle rolls on a straight line, a point on the circumference of the circle traces a path. This path is called cycloid curve. In an analysis of more than 1,500 gear failure studies, failure of gear due Tooth-Bending fatigue was the most common failure mode, Tooth-bending fatigue results from cracking due to a bending stress [3], hence it is necessary to conduct bending stress analysis. The tooth form has left–right symmetry in the involute cylindrical gear, and the same performance can be obtained at forward and backward rotation in symmetric gear. The asymmetry means that pressure angles are different for the drive and coast sides. In many gear drives, the tooth load on one flank is significantly higher and is applied for longer periods of time than for the opposite one. Present day gears are subjected to different types of failures like fracture under bending stress, surface failure under internal stress etc. Hence in this paper a review on bending stress in symmetric and asymmetric gear is carried out.

## II. LITERATURE REVIEW

Andrews J.D. [4] carried out finite element analysis for predicting the fillet stress distribution experienced by loaded spur gears. The location of the finite element model boundary and the element mesh density were investigated. Fillet stresses predicted by the finite element model were compared with the results of photoelastic experiments. The plot of the variation of the stress across the root section of spur gear teeth shows that the behaviour of the tooth under load is not comparable with that of a cantilever beam. Maximum compressive fillet stresses decrease as the point of load application descends from the highest point of tooth contact to the lowest contact. As the point of load application descends the gear flank, the positions of maximum stress in both tensile and compressive fillets move round the fillet. Alexander Kapelevich et al. [5] presented a method of design of gears with asymmetric teeth that enables to increase load capacity, reduce weight, size and vibration level. Bending stress balance allows equalizing the tooth strength and durability for the pinion and the gear Optimization of the fillet profile allows reducing the maximum bending stress in the gear tooth root area by 10–30%. It works equally well for both symmetric and asymmetric gear tooth profiles. A Kawalec [6] investigated tooth root stresses of internal spur gears. Methods of calculation of the tooth-root stress of internal gears according to the ISO 6336-3:1996 and DIN 3990- 3:1987 standards. Concluded that the influences of the number of teeth of the machined gear and its tooth addendum coefficient on the maximum tooth-root stress are negligible. Results of computations made for the numerous models of internal gears show that the maximum tooth-root stresses obtained, significantly differ from results of the finite element computations of the relevant models.

F. Karpat et al. [7] studied the reliability of the asymmetric gear tooth using probabilistic computer program, in conjunction with finite element program.

Weibull failure theory was used to find the probability of failure of asymmetric gear tooth. Operating range and mean nominal strength of four different types of gear pairs was conducted. The result showed that symmetric gear produces the height operating range and it has the lowest mean nominal strength. Whereas asymmetric gear with pressure angle of 36° was found to be the most suitable for the design. V. Spitas et al. [8] analysed the effect of circular-fillet and trochoidal-fillet in gear tooth design using BEM. The results were calculated using an automated BEM process and presented in generalised diagrams, called 'stress maps'. These maps indicate that the proposed circular-fillet design always exhibits improved strength over its trochoidal-fillet counterpart and the improvement can be as high as 31%. Th. Costopoulos et al. [9] investigated gear fillet stresses by using one-sided involute asymmetric teeth. The design incorporates two main features, which are the substitution of the standard trochoidal fillet with a circular fillet for the reduction of the stress concentration at the driving side and the use of a fully rack or hob-generated, addendum geometry for the coast side. The FEA results obtained over a wide range of tooth numbers indicate a systematic decrease of the maximum pinion fillet bending stresses up to 28% in comparison to standard designs, which directly translates in an increase of the load carrying capacity. Edoardo Conrado et al. [10] studied the effect of true bending stress in spur gears. It analyses the stress field at the tooth root using a 3D, parametric, finite element solid model. Commonly used gear geometries having full body and thin-rimmed body connected to the hub are also analyzed. Results revealed that for face width ratio close to practical gear design, most of the bending stress occurs in the center cross-section and the magnitude is higher than in the plane strain condition. For thin rim gears the backup ratio values larger than 0.75 there is a very small influence on the tooth root stress.

Fatih Karpat et al. [11] carried out the comparative analysis on symmetric spur gear teeth with asymmetric teeth under dynamic loading condition. Results revealed that the dynamic factors for spur gears with asymmetric teeth increase with increasing pressure angles on the drive side. The static transmission error plots indicate that the single tooth contact zone increases with increasing pressure angle. It is determined that the asymmetric teeth with long addendum proposed in this study have a higher performance than the conventional symmetric teeth.Daniela Ristic et al. [12] analysed the stress concentration of a gear tooth root with two fillet radius. Special attention was dedicated to stress concentrations in a gear tooth root with two instead of only one fillet radius. The results were analyzed using finite element method (FEM) and the real working conditions simulation. Results revealed that gears with two fillet radii act as a "disencumber notch" for stress and that the tooth root stress concentration will be lower. This investigation confirmed that it is possible to obtain critical section stress reduction with a correct gear tooth root selection. P.A. Vaghela [13] investigated the effect of bending stress in asymmetric gears. The pressure angle on the drive side was varied from 200 to 350 with the increment of 20. Gear model was developed using Pro-E software and analysis was carried out using ANSYS. Results indicated that bending stress at the critical section increases with increases load for a specific thickness. Asymmetric gear resulted in improvement of load carrying capacity and reduction in weight without compromising bending stress. Tufan Gürkan Yılmaz et al. [14] studied the effect of using internal spur gear with asymmetric trochoid on bending stress using FEA. The coordinates of points of one tooth of internal spur gear were obtained via MATLAB program. These points were imported to CATIA and design process was realized for 2D FEA in ANSYS. According to results, asymmetric trochoid internal spur gear has more bending strength when comparing symmetric trochoid. Using asymmetric trochoid on the drive side of internal spur gear decreases 12% of bending stress.

Jayant Koshta et al. [15] Carried out a comparative study on symmetric and asymmetric gear tooth profile. The bending stress analyses was performed with the help of FEM software. The strain results obtained by FEM analyses and calculable by the developed program are compared. It's been proved that uneven teeth have higher performance than each bilaterally symmetrical tooth it's been confirmed that, because the pressure angle on the drive face will increase, the bending stress decreases and also the bending load capability will increase. Tufan Gürkan Yılmaz et al. [16] analyzed the influence of root geometry on bending stress for involute spur gears. The mathematical equations of involute, trochoid and elliptical curves were programmed in MATLAB, then point cloud of gear tooth were exported to CATIA for generating FEA model, finally the finite element analyses were conducted in ANSYS program for determined gear parameters. According to results, the elliptical curve with higher upper radius value could be used to decrease bending stress. The upper radius value is one of the most crucial parameter in view of bending stress. TJ Lisle et al. [17] carried out a comparative study on nominal stress calculated in accordance with ISO 6336:2006, ISO 6336:1996, VDI 2737:2005 and the AGMA method. The results was compared with numerical finite element analysis (ANSYS) and experimental strain gauge techniques. Results revealed that there is significant variation in the location and magnitude of maximum root bending stress at each of the respective standards (ISO, VDI and internal AGMA) whilst the results established from the strain gauge experiments established that FEA was the most accurate method, with an approximate error of only 0.7%. D. V. Muni [18] investigated the optimization of asymmetric spur gear drives for maximum bending strength using direct gear design method. FEM analysis has been carried out to determine maximum fillet stress in pinion and gear at each set.

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The set of profiles that develops an equal and possible lowest minimum of the maximum fillet stress at its respective fillet is considered as the optimum one for a maximum load carrying capacity. If speed ratio is not specified, the lowest speed ratio is advisable to reduce the maximum fillet stress. Robert F. Handschuh et, al., [19] examined high-pressure angle gearing for possible use in space mechanism applications. Tests were conducted in the NASA GRC Spur Gear Test Facility for 3.18 module (8-diametral pitch), 28 tooth, 20-degree pressure angle gear, 2.12 module (12-diametral pitch), 42 tooth, 25-degree pressure and 1.59 module (16-diametral pitch), 56 tooth, 35-degree pressure angle gears were tested. ISO 6336 analysis was conducted on these three gear designs for tooth bending and contact stress. The results between the three designs were fairly comparable with the 3.18 module gears having the lowest bending stress and the 1.59 module gears having the lowest contact stress. Further it was tested for lubricant test in two different modes, In the high-speed test mode, the gears were lubricated with a synthetic turbine engine lubricant and in the low-speed, grease was applied on to the gears. Fatih Karpat et, al., [20] carried out the experiment to determine the single tooth stiffness of involute spur gear. A special test rig for this purpose was designed, and an experimental technique was proposed to investigate the effects of drive side pressure angle on the stiffness. The validation process of this study was performed using the finite element method. The experiments were repeated in ANSYS Workbench, and the elastic deformations were calculated. Results showed that, the single tooth stiffness increase nearly 38% with the increase in drive side pressure angle from $20^0$ to $35^0$. When both finite element analysis results and experimental measurement results are examined, it was seen that asymmetric tooth was stiffer than symmetric tooth. P. Marimuthu et al. [21] Studied the effect of high contact ratio asymmetric spur gear based on tooth load sharing using Ansys parametric design language code. The load sharing based bending stresses were determined for different drive side contact ratios, along with that the location of critical loading point. It was observed that the Load Sharing Ratio (LSR) varies significantly at the critical loading point. The bending stress is lower when contact ratio is lesser ($\varepsilon d = 2.1$); beyond this contact ratio, the LSR based bending stress increases. Furthermore, the contact ratio is increased due to decrease in pressure angle on drive side and this increase in contact ratio results to increase in the triple teeth contact zone.

Prabhu sekar et al. [22] investigated the fillet stresses on normal contact ratio spur gears to improve the load carrying capacity through nonstandard gears. The influence of gear parameters such as gear ratio, pressure angle, addendum factor, pinion teeth number, and addendum modifications on the maximum fillet stress on the nonstandard pinion and gears of different tooth thickness had been analyzed through finite element method. Results revealed that the non-standard gear cutter coefficient increases with increase in gear ratio, pressure angles and addendum factors but decreases with increase in pinion teeth numbers. R. Prabhu Sekar et, al. [23] Estimated the tooth form factor for normal contact ratio asymmetric spur gear tooth. The standard ISO B methodology has been adapted suitably for estimating the tooth form factor and the stress correction factor in asymmetric spur gear tooth. The studies showed that the highest maximum fillet stress developed in the asymmetric gear is lower than that of the symmetric gear. The highest maximum fillet stress is lower, when the high pressure angle side is used as the drive side. The fillet stress factor considerably decreases with an increase in drive side pressure angle ($\alpha od$). However, it increases with an increase in coast side pressure angle. P. Marimuthu et al. [24] analyzed the bending strength of the non-standard high contact ratio spur gears based on fillet stress of the pinion and gear. The study was focused to optimize the fillet stress with respect to the rack cutter tooth thickness factor of the pinion and gear through finite element analysis. Based on the results following observations were drawn, the rack cutter tooth thickness factor of gear decreases due to increase in gear ratio. Optimum fillet stress decreases significantly due to increase in teeth number of pinion and gear. Increase in pressure angle leads to significant reduction of optimum fillet stress. Optimum fillet stress increases significantly and there is a marginal rise of rack cutter tooth thickness factor of gear due to increase in the addendum height. P. Marimuthu et al. [25] investigated the load carrying capacity of asymmetric high contact ratio spur gear based on load sharing using direct gear design approach. A finite element model for multi-pair contact is adopted to determine the non-dimensional fillet and contact stresses which quantify the load carrying capacity of the gear pairs. The results of direct designed symmetric and asymmetric high contact ratio spur gears were compared with the conventional symmetric high contact ratio spur gears. Following observations were drawn. The non-dimensional fillet and contact stresses in the direct designed asymmetric HCR spur gear is observed to be always lesser than that of the conventional and direct designed symmetric HCR spur gears. The optimum gear pair is obtained from the area of existence diagram, based on the balanced non-dimensional fillet stress of the pinion and gear. The minimum backup ratio required, avoiding failure of the rim and tooth in asymmetric HCR spur gear is 1.63, based on the non-dimensional fillet stress.

P. Marimuthu et al. [26] studied the effect of asymmetric normal contact ratio spur gear drive to enhance the load carrying capacity. A unique Ansys parametric design language code was developed to find the load sharing ratio, maximum fillet and contact stresses. The fillet stress was calculated in terms of non-dimensional stress.

It was concluded from the parametric study that asymmetric gear drive that for a given drive side contact ratio, as an increase in load side pressure angle, coefficient of asymmetry, gear ratio, teeth number and top land thickness coefficient which has resulted in reduction of stresses. It is also preferred to have higher pressure angle at the load side of asymmetric teeth. However, smaller contact ratio gear drives are preferred than the higher one, to enhance the load carrying capacity. Siang-Yu Ye et al. [27] analyzed the computerized method for loaded tooth contact analysis of high-contact-ratio spur gears with or without flank modification. An efficient computerized tool for loaded tooth contact analysis (LTCA) was proposed, that can be used to design high contact ratio (HCR) gears, while taking into consideration the conditions of tip corner contact and shaft misalignment. The results of the analysis showed that the LTCA model is reliable, complete and time-saving for the calculation in comparison to the other mentioned LTCA approaches and the FEM. The HCR spur gears have better contact characteristics than normal-contact-ratio gears. Their contact behaviors are affected strongly by the number of contacting tooth pairs. Increasing the amount of relief can smooth the variation in shared loads and contact stresses during gear meshing, but the loaded contact ratio will be reduced. Benny Thomas et al. [28] predicted gear tooth bending stress in normal contact ratio asymmetric spur gears based on Search Method analytical approach. This study recommends a new coordinate system and method for analytical prediction of gear tooth bending stress in normal contact ratio asymmetric spur gears. With reference to FEM results, maximum gear tooth bending stress predicted by Search methods is more accurate than the results obtained from ISO method adapted for asymmetric spur gears. Effect of bending moment due to the eccentricity of radial component of gear tooth load on gear tooth bending stress reduces with increase in number of gear tooth and asymmetry factor. Search method is much faster than the FEM approach which demands considerable time and proficiency to select the element size and to accurately perform the analysis.

## III.CONCLUSIONS

Based on the finding of various researchers for analyzing the bending stress generated in spur gear, it can be concluded that three methods namely, analytical methods, experimental methods and numerical methods using FEM are equally important. Various parameters such as tooth contact ratio, addendum modification, gear rim thickness, etc. affect nature of stress generated in gear body and gear teeth. While analyzing stress on one gear teeth, adjacent tooth also must be considered because its presence affects the nature and quantity of stress. Stress on gear tooth can be calculated by FEM. First is directly applying concentrated load on single gear tooth. Only bending stress can be calculated by this method. Adopting the larger pressure angle on the drive side bending stress decreases on the gear teeth. Thus, load carrying capacity increases. Hence while designing asymmetric gears it is advisable to consider most of the parameters, so that strength and performance of the gear would be enhanced.

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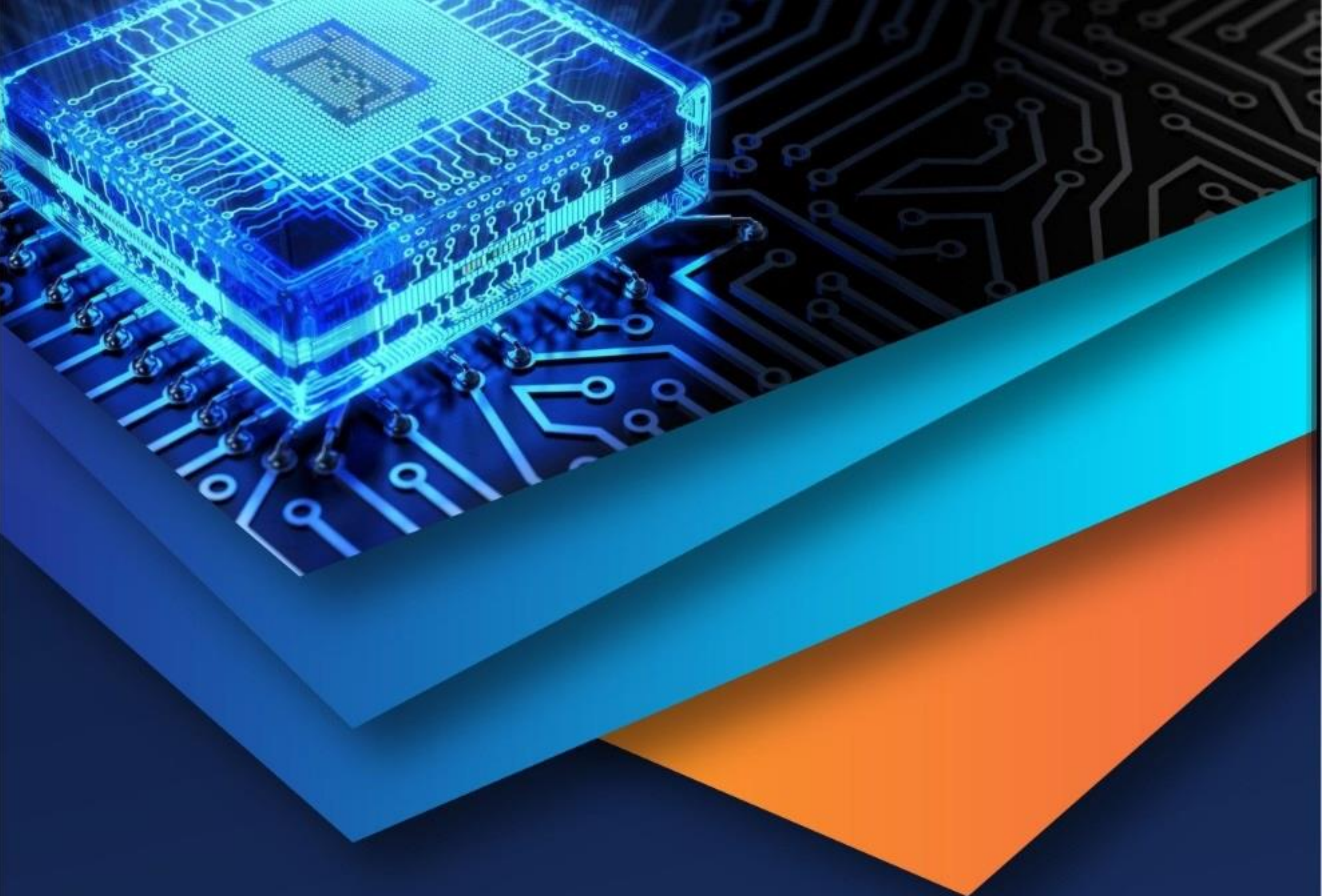

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