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Influence of Gear Loads on Spline Couplings

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Involute splines are commonly used in gearboxes to connect gears and shafts, especially when high torque is transmitted through the coupling. The load is shared among multiple teeth around the coupling circumference resulting in higher load capacity than a conventional single key. However, the total load is not equally shared among all spline teeth, mainly because of pitch deviations resulting from the manufacturing process. The load distribution along the spline engagement length is also non-uniform because of tooth misalignments and shaft torsional effects. A typical modeling assumption is that pure torsion load is applied to the spline coupling. In gearbox applications, when splines are used to connect a gear to a shaft, the torque is transmitted from the gear teeth in mesh to the shaft, or vice-versa, through the coupling. The gear loads, such as tangential and radial loads, can affect the load distribution of spline teeth. This paper presents an investigation on the influence of spur gear loads on load distribution of spline teeth. A generalized analytical model was developed to include external gear loads on spline couplings. The method divides the spline teeth into stations in the tooth axial direction, and calculates the load applied to each station based on separation between the mating points. A constant for tooth stiffness was used to calculate tooth deflections. The load distribution problem was solved using a simple approach from industry gear standards. The method was implemented into a spreadsheet for numerical example analyses. The results showed significant effect of side clearance, which is the difference between the space width of internal spline grooves and external spline tooth thickness, on the maximum load applied to the spline teeth. The greater the side clearance, the greater is the maximum load applied to the spline teeth. The proposed method may be helpful to quickly assess load distribution of spline teeth in gear applications, to determine tooth stresses, and to define lead modifications as needed.

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Introduction

Spline couplings are often used in power transfer systems to connect mechanical components such as shafts, flanges, brakes, clutches, pulleys, sprockets, and gears. A spline coupling has multiple teeth equally spaced around its circumference, which results in higher load capacity than a conventional single key. Spline teeth can be straight sided, in which both tooth flanks are parallel to each other with the same tooth thickness along the tooth height. Involute profiles are also used in spline teeth. Involute spline teeth are similar to gear teeth but shorter in height to provide great strength and compact size. Involute splines are typically preferred over parallel-side splines because they best center the two connecting components radially, and also provide lower root stresses with a larger tooth base thickness and smooth transition from tooth side to fillet radius. In a typical involute spline coupling of a shaft-gear connection the shaft has the external teeth machined on it in the same number of internal grooves machined at the gear bore.

Ideally both the external teeth and internal grooves should have the same size to result in no clearance between them. Perfect splines under no clearance condition would evenly share the total load among the spline teeth in the circumferential direction. However, real-life splines are commonly designed to have a certain amount of allowable clearance on tooth sides and diameters to make them easy to assemble, to accommodate manufacturing tolerances, and also to allow lubricant to flow through the splines to help prevent fretting-type wear [1].

Depending on the application, the spline fit is defined on tooth sides, between major diameters, or between minor diameters of the splines. Diameter-fits are used in applications where reduced radial clearance is required. In those cases the spline diameters are hard finished after heat treatment to a tight tolerance [2]. On the other hand, side-fit splines are often soft machined only, with no additional post-heat treatment operation, which provides a cost advantage over diameter-fit splines. The downside is larger variation among parts and larger radial clearance. The side clearance causes non-linearity similar to other components such as gears, bearings, and clutches, which, when combined with manufacturing deviations, such as spacing errors, and heat treatment distortions, result in uneven load sharing among spline teeth, especially in the circumferential direction, with consequent stress increase [3-4].

Analytical and experimental studies done by Tjernberg [3] showed that about half of the spline teeth carry load because of spacing errors, resulting in between 26% to 36% stress increase and over 50% life reduction. Chaplin [1] also recommended assuming that half of the teeth share the full load. When subject to torsional load, splines demonstrate non-uniform load distribution along the engagement length of the tooth, which is in the axial direction, because of shaft torsional effects, as shown in Figure 1 [5-7]. Volfson [6] suggested that about a quarter of the teeth carry the full load. More recently, Chase [8-9] presented a statistical approach to determine the load distribution in a spline coupling, and showed for a 10-tooth spline case study that approximately half of the teeth carried the full load.

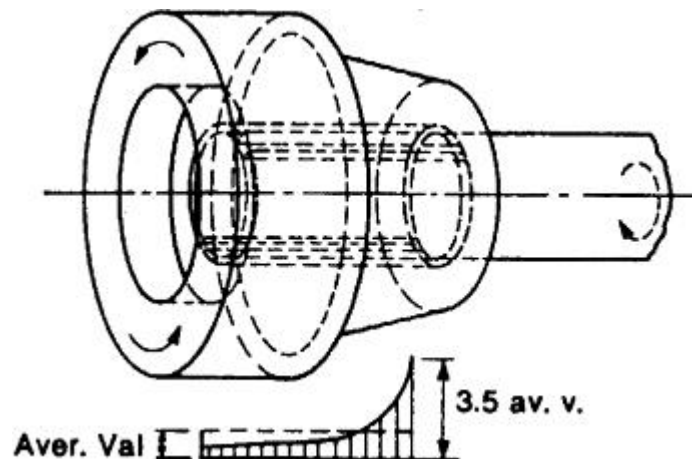


Figure 1. Load distribution in the axial direction for a pure circumferential torsional load case [6]

It becomes clear from previous studies published in the literature that both manufacturing deviations, especially spacing errors, and shaft torsion significantly affect spline load distribution in the circumferential direction and in the axial direction. However, the studies were limited to the pure torsion loading condition only. In the particular case of drive train applications where involute splines are often used to connect gears to shafts, the gear mesh loads cause the splined components to be offset from their common center axis affecting the load distribution of the spline teeth.

The objective of this paper is to investigate the gear load effects on spline load distribution, and propose a generalized and practical technique that can be used in the gear industry to calculate spline load distribution and to determine spline load capacity. A parametric procedure was developed to determine the gaps between internal and external spline teeth accounting for the gear mesh loads, and manufacturing deviations such as spacing errors. The general formulation of the problem of load distribution in gear teeth was applied to splines. The generalized elastic contact problem was solved using a simple procedure given in AGMA 927 [10] and ISO 6336-1 [11]. Elastic deflections of spline teeth were calculated using a constant stiffness value that was obtained through Finite Element Analysis (FEA) of a spline coupling model in [8].

The results showed that gear mesh loads significantly affect the load distribution of spline teeth. The maximum spline tooth load increased as the amount of side clearance between the internal and external splines increased. The procedure only applies to side-fit splines that have sufficient radial clearance between major diameters and minor diameters. Although not as accurate as a FEA, the spreadsheet solution is ideal for the beginning design work because it is fast and does not require FEA capability.

Analytical model

A simple iterative method for the load distribution evaluation of spline teeth was developed from initial gaps among the spline teeth. Manufacturing deviations such as spacing errors and misalignment in the axial direction, intentional design modifications such as lead crown, and the spline centers offset by the gear loads were accounted. When subject to gear loads, the pair of mating spline teeth with the smallest gap comes into contact first and load is transferred through it, resulting in elastic tooth deflections. Those deflections cause the gaps between the other spline teeth to get smaller and eventually other pairs of teeth come into contact and share the load. The final number of teeth in contact and their load sharing depend on the gap distribution, the elastic deflections and the load applied. An iterative procedure based on AGMA 927 [10] and ISO 6336-1 [11] was used to solve the load distribution problem, which was implemented into a spreadsheet. In the first step of the computational process, the spline teeth were divided into n points, or stations, across the engagement length. The gear loads were calculated from the gear tooth geometry and torque transferred through the gear mesh. The initial gaps were calculated from the spline geometry and radial location of one component to the other. The gaps also included manufacturing deviations and tooth misalignment. Then the load was evenly spread at all stations of all teeth to calculate the initial spline tooth elastic deflections such as bending and torsion. The total displacement of each point was obtained by adding the elastic deflections to the initial gaps under no load. From that point onward an iterative procedure was used to identify the non-contacting points and adjust the load values. The equations, assumptions and other details of the method are described in the following sections.

Gaps analysis and tooth engagement

In perfect splines with no manufacturing deviations, no assembly misalignments, and both splined components sharing a common center axis, the side clearance is equal to the difference between the circular space width of the internal spline grooves and the circular tooth thickness of the external spline teeth taken at the same diameter as illustrated in Figure 2. The side clearance is the same for all pairs of mating spline teeth around the coupling, and also across the spline length. When transmitting torque through the coupling the splined driver component turns in a given direction to eventually close the gap on the drive flanks. In the case of perfect splines all mating spline teeth come into contact simultaneously and share the full load evenly in the circumferential direction.

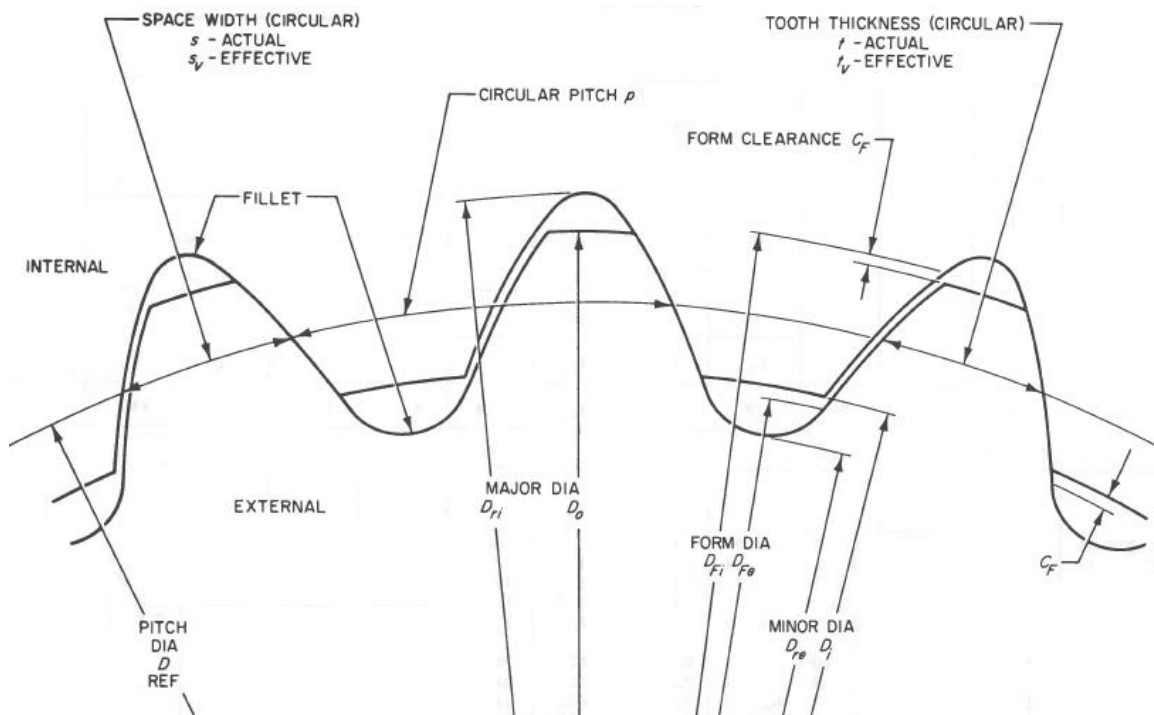


Figure 2. Side clearance of perfect splines [12]

One important manufacturing deviation of spline teeth for load distribution is spacing error [3, 8]. Spacing errors cause the spline teeth to be misplaced in the circumferential direction related to their theoretical location. This means the teeth are not equally spaced around the circumference, which results in different gaps, as illustrated in Figure 3. Spacing errors were entered in this model as a circular value with positive sign to indicate more gap (opposite to what is shown in Figure 3), and negative sign to indicate less gap as shown in Figure 3. The spacing errors of internal and external spline teeth were added together for a given assembly position, which defines the mating pairs of external teeth and internal groove with their respective spacing errors. The worst case for analysis occurs when the external tooth of maximum spacing error is assembled with the internal groove also with maximum spacing error but in the opposite direction.

Misalignments and linear modifications in the tooth axial direction were also entered as a combination of deviations of the internal and external splines. Positive sign is used to indicate that the gap starts as zero at the left hand end of the spline coupling and increases linearly towards the right hand side of the coupling.

Lead crown is a barrel-shape modification across the length of the splines, where its maximum value is found at both ends of the spline teeth. Material is removed from the spline teeth according to a quadratic function from the middle of spline length toward the spline ends. In the model, lead crown was considered for the external splines only. It would be of small practical relevance to consider lead crown for internal splines based on manufacturing difficulty using conventional processes.

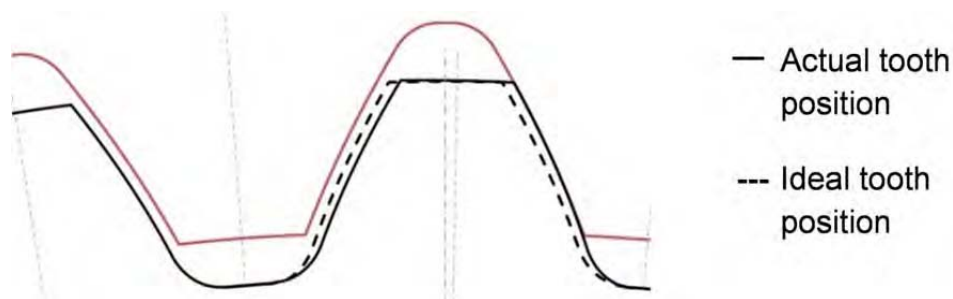


Figure 3. Spacing error of a spline tooth