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Investigation of The Effect of Design Variables on Slip Assembly: Spline Module and Slip Length

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Abstract

The driveshaft which transmits the power from the engine to the wheels in the motor vehicles is one of the vital elements in the driveline. Driveshafts have two basic motions depending on the road conditions: angular and axial movements. Angular movement is provided by the universal joints while the axial movement is provided by the slip assembly which involves a group of sliding components. Therefore, the slip assembly is an important part of the drive shaft. Basically, a slip assembly consists of two parts which are connected to each other by means of their spline forms. The parts can move back and forth longitudinally while they transmit the torque thanks to the connection interface of their spline forms. And so, they can slide, and adjust the drive shaft lengths due to the changing position of the axles under road conditions.

During the motor vehicle movement, slip assembly are subjected to torsion like the other components on the driveshaft. In this context, spline size and magnitude of the length compensation are highly important in the design process of a slip assembly. In this study, the effect of the spline size and the slip length were investigated for the yoke shaft design, by using analytical and numerical methods in terms of shear stress. It has been observed that the analytical and the numerical methods give the similar results in shear stress on the pitch diameter of the spline. Thus, the analytical method can be preferred instead of the finite element analysis (FEA), especially considering that the FEA is a time consuming method compared to the analytical method in the design process.

Keywords: Driveshaft, spline, design, analytical method

1. INTRODUCTION

A driveline covers a large number of components which transmit the torque from engine to the driven wheels (Figure 1). Among these components, driveshaft which transmits the torque and the rotational motion is the most vital element because it is an intermediate element providing a connection between driveline components such as transmission and differential. In this sense, it allows relative movement between two adjacent components in driveline [1]. The basic facility of a driveshaft is that it has angular

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and longitudinal plunging movement at the same time. And so, it can compensates the displacement of the axles depending on the road condition and maintains the connection between two other driveline components.

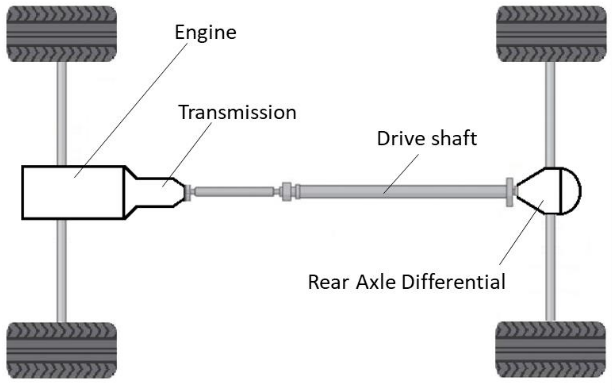


Figure 1 A classical driveline for the motor vehicle [2]

The abilities of angular and longitudinal plunging movements of a driveshaft are respectively provided by joint and slip assembly. A slip assembly totally involves two components which are connected to each other by means of the spline form (Figure 2). Spline form is a kind of profile with equally and circumferentially spaced teeth/grooves. They are used to make a contact between two mating pieces which transmit torque and rotation. The parts relatively exhibit a motion back and forth during transmitting the torque. They can slide and adjust the drive shaft length due to the position of the axle which changes depending on the road conditions.

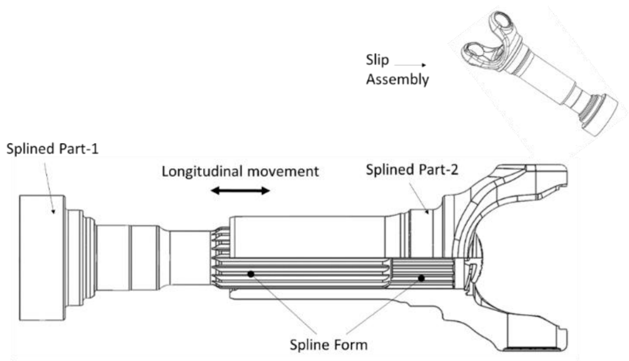


Figure 2 An illustration of slip assembly and yoke shaft

Driveshaft, and so slip assembly operate under torsion and shear stress between driving and driven components in a driveline. For this reason, they should be sufficiently durable against to the stress.

Spline module and slip length are the variables which should be taken into consideration in design process of slip assembly. There are many alternatives of spline modules for the design according to international standard DIN 5480 [3, 4]. The important point is to consider the longitudinal plunging motion of the splined parts composing the slip assembly.

The contact area between the teeth surfaces of mutual splined parts depends on the compensation length in a driveshaft, while the contact area between the teeth surfaces of mutual gears is steady during the operation in a gear system. In brief, the contact area between the teeth of the splined parts in a driveshaft changes, unlike the gears. Here, it should be taken into consideration that the splined parts move longitudinally and the contact area between the teeth of the mutual splines changes during the length compensation of driveshaft. In this study, the effect of the design variables spline module and slip length was investigated. Different spline modules and plunging length were considered and analyzed by using an analytical method.

As a result of the literature research, it has been observed that the studies on the slip assembly are highly limited. When these studies of limited numbers were examined, it was seen that they focused more on the load distributions along the spline teeth. As differing from these studies, Schäfer and Garzke [5] studied on the way to improve the load capacity of splines for various applications. They proposed some modifications on some features such as root geometry, radius and helix angle. It was reported that the stress concentration could be reduced by changing the root geometry and the root radius. And they added that a homogeneous load distribution could be reached by modifying the helix angle for the spline connections whose ratio of length to diameter was equal to 0,6 or greater.

Ding et al. [6] carried out a study on the wear strength of a spline tooth in a spline coupling by implementing a finite element based on simulating the effects of material removal with fretting wear. They predicted that low frequency, torque, and axial loading induced wear reduced the fretting fatigue and, also increased the life while higher frequency, rotating moment, and fluctuating torque increased the fretting fatigue.

Barrot et al. [7] extended a model developed by Tatur [8] so as to consider different loading cases and geometries. The extended model was used to optimize the design. On the other hand, a finite element analysis was performed. The result showed that the extended model gave an excellent design. Thus, they suggested using the extended model.

Hong et al. [9] investigated the load distribution on the spline interfaces by applying a finite element analysis and surface integral contact analysis model. Finally, they proposed a model to determine the effects of the manufacturing tooth indexing error on the spline load distribution.

Pardhi and Khamankar [10] worked on the stress in the spline shaft under different load conditions from transmitted torque. They used finite element method along with experimental technique of photo elasticity. As a result, they observed that both results were highly close to each other, and maximum shear stress concentration was at the rot diameter of the spline teeth.

Barsoum et al. [11] determined the torsion strength of hardened involute splined shafts by regarding the spline geometry and the hardness profile together. They revealed that the transmitted torque causing distortion of induction hardened splined shafts was dependent on the hardness depth, by using the finite element method. Additionally, they reported that an optimum hardness depth improving the torsional strength could be reached by means of hardening the shafts through half radius.

In another study, Suresha and Mruthunjaya [12] studied to investigate the root cause of the yoke shaft failure in steering assembly. They implemented a fatigue analysis by means of finite element method. Finally, they suggested an improvement in the design/production process by evaluating the current model under various crack conditions in terms of life estimation.

In this study, the effect of the spline size and slip length on the yoke shaft design were investigated by using an analytical method. Most important part of the study is to consider the changes in the contact area of the spline couple during the length compensation of the drive shaft. The aim of the study is to determine the optimum values of the spline parameters by using an analytical method and according to international standard DIN5480 [3,4] as well.

2. METHODOLOGY

An optimum spline module has been analytically determined by considering the contact surfaces between the mutual splines. But it should be noticed that the contact surfaces change depending on the longitudinal plunging movement. In the analytical investigation, the combinations of the spline module and the length of engagement were handled in terms of stress at the pitch diameter of the teeth. For this purpose, different models were prepared for each combination of the spline module with the engagement length. The spline profiles of the models were involute spline according to DIN 5480. The splines in DIN 5480 are within a module range 0,5 to 10, having number of teeth ranging 6 to 32, and with a pressure angle of 30° [3, 4].

Basic dimensions for each combination were given in Table 1 below. In the combinations, the reference diameter has been kept stable while the length of engagement changes, and so the effect of the engagement length has been investigated (see combination 1 vs. 2) for a certain number of teeth. On the other hand, reference diameter and engagement length were kept stable while the module changed, and so the effect of the module was investigated (see combination 1, 3, 4 and 5). The investigation was carried out by using analytical method as well as numerical method. The numerical method FEA was applied for combination 1 to compare both methods with each other, and to prove the validation of the methods with respect to other one.

Table 1 The basic dimensions for the combination of spline module and engagement length

Combination	Reference Diameter (mm)	Module	Pitch diameter (mm)	Number of Teeth	Engagement Length
1	38	2	36	18	62
2	38	2	36	18	42
3	38	2,5	35	14	62
4	38	1,5	36	24	62
5	38	1,75	35	20	62

2.1. Analytical Method

Analytical method was applied to calculate the shear stress on the pitch diameter of the spline for each model. The calculation which was carried out for each combination given in Table 1 provided a comparison of the combinations. In this context, the shear stress on the pitch diameter was calculated by the following equation [13].

$$S_s = \frac{4\,T\,K_a\,K_d}{D\,z\,L_e\,s\,K_f} \qquad (1)$$

where T, Ka, Kd, D, z, Le, s, Kf are respectively torque applied in Nmm, spline application factor, load distribution factor, pitch diameter in mm, number of teeth, engagement length of spline in mm, tooth thickness in mm and fatigue life factor. The factors of Ka, Kd and Kf for the calculations were given in the Table 2. It should be noticed that “torque cycle” term in Table 2 involves one start one stop, not the number of revolutions.

Table 2 Factors for calculation of shear stress [13]

Spline Application Factor, Ka	Load distribution factor, Km	Fatigue-Life Factor, Kf
2 for medium shock from engine	1 for flexible spline, according to the face width	0.4 for a fully reversed 100,000 torque cycles

The calculations were implemented by considering the applied torque of 4600 Nm on the splined part, for all combinations in the Table 1. The material of the splined parts, AISI 5140 is quenching and tempering steel, and so shear strength of the material is 809 MPa as hardened steel.

2.2. Numerical Method

Finite element method (FEM) was implemented to validate both methods (numerical and analytical) with another one. For this reason, FEAs were carried out for different engagement lengths (combination-1 and combination-2). In the analysis, it was assumed that splined part runs under a constant torque and it has a uniform geometry. The 3D models of splined part-1 and splined part-2 designed by computer aided design (CAD) software SolidWorks were transferred to computer aided engineering (CAE) software HyperWorks so as to carry out the finite element analysis.

In order to create a mesh structure which was the first step of the finite element analysis, the necessary geometric arrangements were carried out on the three-dimensional (3D) models. Considering the study implemented by Kahyalar and Sen [14], in which a proper element size was determined as a result of the correlation between test and finite element analysis, the mesh structure on which the boundary conditions and external loads were applied, were defined by using R-trias and 3D tetra elements with 1 mm element size respectively.In the next step, FREEZ contact definition was implemented to create a connection between splined part-1 and part-2. After this step, rigid elements were defined on the surface of the splined part-1 which was welded with the tube, while boundary conditions were defined by assigning fixing elements to the midpoints of these rigid elements. Thus, there was no freedom in translation with rotation.

The rigid elements of splined part-2 defined on the inner surface of the ear hole and a torque of

4600 Nm was defined at the midpoint of the rigid elements. Finally, the material definition was made by using the values given in Table 3 (yield strength of AISI 5140 is the final property after quenching and tempering) and the pre-processing step was completed. The 3D model after all these preparations was expressed in Figure 3. The analysis was carried out structurally in a linear static condition.

Table 3 Material properties of the AISI 5140

Part ID	Density	Young's Modulus	Poisson's Ratio	Yield Strength
Splined Part-1	7,85 g/cm^3	210 GPa	0,3	1402 MPa
Splined Part-2	7,85 g/cm^3	210 GPa	0,3	1402 MPa

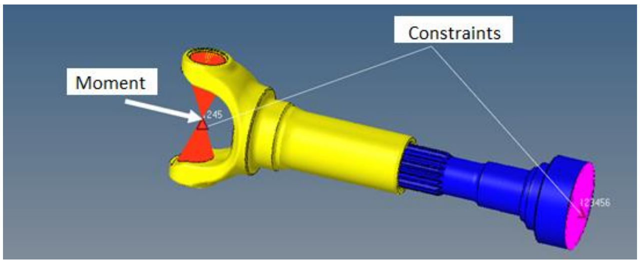


Figure 3 Pre-processing for FEA

3. RESULTS

The shear stress values on the pitch diameter were respectively calculated for all combinations given in Table 1, by using the analytical method. The results for each combination considering the engagement length and spline module were given in Table 4.

Table 4 The max. shear stress values on the pitch diameter of spline teeth for each combination of spline module and engagement length

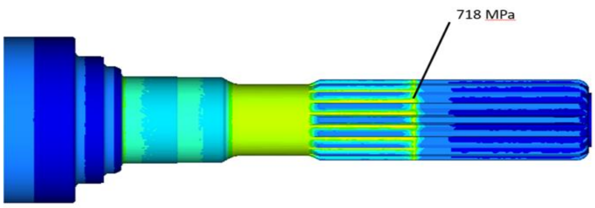
Combination	Module	Engagement Length	Max. Shear Stress	Shear Stress Limit	Safety Factor
1	2	62 mm	729 MPa	809 MPa	1,11
2	2	42 mm	1076 MPa		0,75
3	2,5	62 mm	771 MPa		1,05
4	1,5	62 mm	729 MPa		1,11
5	1,75	62 mm	771 MPa		1,05

When the results for combination 1 and 2 are examined, it is obvious that the shear stress on the pitch diameter of the spline increases along with the decrease in the engagement length.

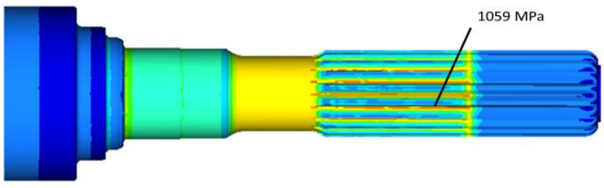
If combination 1 and 4 are examined as a couple, the results show that the splines with the same engagement length as well as pitch diameter show the same shear stress on the pitch diameter of the spline.

In addition to the analytical calculations, FEA were implemented for combination 1 and combination 2. And so, analytical and FEA methods were compared with each other.

In this context, the finite element model with 1398653 elements has been used for combination 1 and 2. The results of FEA for combination 1 and 2 showed that the max. shear stress values on the pitch diameter were respectively 718 MPa and 1059 MPa as seen in Figure 4. Similarly, the results of the analytical calculations for combination 1 and 2 gave respectively a max. shear stress value of 729 MPa and 1076 MPa on the pitch diameter (Table 4).



a) Maximum shear stress for combination 1



b) Maximum shear stress for combination 2

Figure 4 The maximum shear stress on the pitch diameter of the spline as a result of FEA

The percentage errors between the results of FEA and numerical analysis were calculated by means of Equation 2. The results for combination 1 and 2 are respectively %1,53 and %1,60.

$$E_{\%} = \frac{|FEA - NUM|}{NUM} \tag{2}$$

where $E_{\%}$, FEA, NUM are respectively percentage error, FEA result and numerical result.

4. CONCLUSION

In this study, five combinations including spline module and engagement length were considered in order to achieve the aim. In this context, the analytical studies were carried out to reveal the relationship between the shear stress and the design parameters such as spline module and engagement length while the numerical analysis was carried out to compare both methods (analytical and numerical) with each other.

The results from the study are as follows:

- The results from the analytical and the numerical studies, which have been implemented for combination 1 and combination 2 are similar each other with a percentage error of 1,53-1,60 respectively. The results point out that the analytical method can be preferred instead of finite element analysis, especially considering that the finite element analysis is time consuming.
- The spline parameters given in the combinations 1 and 4 gave the best results in terms of the shear strength on the spline teeth when compared to the other combinations in Table 1.
- The shear stress on the pitch diameter for the splines having the same reference diameter, pitch diameter and engagement length (see Table 1 for combination 1 and 4) is the same.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The first and second authors contributed to study equally with 40% while the third author has contribution of 20%.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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