An experimental investigation of the load distribution of splined joints under gear loading conditions

Michael BENATAR*, David TALBOT* and Ahmet KAHRAMAN*

*Department of Mechanical and Aerospace Engineering, The Ohio State University
201 W. 19th Avenue, Columbus, OH 43210, United States of America
E-mail: kahraman.1@osu.edu

Received: 5 April 2017; Accepted: 22 October 2017

Abstract
Splined joints are commonly used to transmit rotary motion from a shaft to machine elements such as gears. While computationally efficient spline load distribution models have recently been proposed, there is no validated load distribution model of a splined joint due to lack of high-fidelity experimental data. Accordingly, this study aims to establish an extensive experimental database on load distributions of splined joints subject to both spur and helical gear loading conditions. A quasi-static, spline-specific test setup is developed and instrumented. A test matrix covering various loading conditions is executed in order to form a spline load distribution database. The experimental data illustrates the cyclic nature of loads and resultant stresses on spline teeth caused by rotation of the spline teeth in relation to the gear mesh that loads the splined joint. A nonlinear relationship between torque applied and resultant stress is revealed, as well as the relationship between the location of maximum stress along the face width and the amount of lead crown modification applied. Lastly, simulation results from the model of Hong et al. (2014b) are compared to the experimental data under spur and helical gear loading conditions to assess the premise of such models.

Keywords: Splined joint, Involute splines, Gear-shaft interface, Load distribution, Root stress

1. Introduction
Splined joints transmit rotary motion from a shaft to another shaft or machine element such as a gear. A splined joint consists of two components, an internal spline and an external spline. Both components have the same number of teeth that are conformal so that they are able to fit tightly together. This forms a joint that is coaxial as both the shaft and its splined mate rotate about the same axis at the same angular velocity. Since all teeth of a splined joint are theoretically in contact, loads (torque, radial force, and moments) applied to the spline are potentially distributed among all of its teeth, making it a preferred choice when compared to other methods of joining. Load carrying capacity and the corresponding load distribution of splined joints must be known to meet the required level of strength for proper operation of a drivetrain.

Literature contains several theoretical studies on load distribution of splined joints. One group of studies used finite element (FE) or boundary element (BE) methods. Among them, studies by Tjernberg (2001), Barrot et al. (2005), Barsoum et al. (2014), and Cura and Mura (2014) used conventional FE packages to study load distribution of torsionally loaded splines while Adey et al. (2000) employed a BE package for the same purpose. These computational models were limited to purely torsional loading conditions (as in a splined joint connecting two shafts) without any tooth-to-tooth spacing (index) errors. A recent study by Hong et al. (2014a) used an FE-based gear contact solver, CALYX, to predict contact stresses and tooth-to-tooth load distributions of clearance-fit splined joints. This model was more advanced than the above computational models as it predicted contact stresses for diverse loading conditions caused by gear mesh loading. Another group of theoretical studies employed semi-analytical models. For instance, Barrot et al. (2006) calculated both pressure distribution and tooth stiffness to show the mutual influence between the two under purely torsional loading. Wink and Nakandakar (2014) also proposed an analytical model that allowed radial loads produced by spur gear loading on the load distribution of spline teeth. Building on the results of their earlier FE study, Hong et al.
(2014b, 2015a, 2015b) published a family of semi-analytical models which both reduced the computational time immensely and surpassed the capabilities of the previous models which were mostly limited to purely torsional loading. These models captured the impact of loading type (purely torsional, spur, or helical gear loading) on the resultant load distribution of the joint for clearance-fit (Hong et al., 2014a) as well as major and minor diameter-fit splines (Hong et al., 2015a). The models also displayed the influence of index errors on the resultant load distributions of a splined joint (Hong et al., 2015b).

On the experimental side, there is limited measured data on load distribution of splined joints which leaves the models above essentially without validation. Most of the published experiments on splined joints focus on surface wear and fatigue. Weatherford et al. (1966) experimentally compared spline wear under various lubrication conditions. Ku and Valtierra (1975) studied the effects of angular misalignment on splined joints to conclude that better spline alignment allows for greater flexibility of lubrication, maintenance, and spline design. Brown (1979) studied wear rate of aircraft spline couplings as a function of misalignments and lubrication conditions. Wavish et al. (2009) used a test setup to mimic combined torque, axial, and bending load fretting conditions of spline teeth in a laboratory environment. Cura and Mura (2013) examined the effect of angular misalignments between a hub and shaft while also comparing measured spline tooth stiffness data to theoretical results. Cuffaro et al. (2012) applied pressure sensitive films to spline teeth to measure contact pressure distributions. Phardi and Khamankar (2014) used the technique of photoelasticity to compare stresses on splines under various loading conditions to results of a commercial FE model. These experimental studies were limited in scope and were tailored to address durability concerns. As such, they offered little towards validation of spline load distribution models.

Strain measurements in the root fillet of gears along the face width direction have been used commonly in gears to study load distributions (Hotait and Kahraman, 2013) as a function of misalignments (Hotait and Kahraman, 2008) and index errors (Handschu et al., 2014, Talbot et al., 2016). This study proposes an experimental setup that allows accurate spline tooth root strain measurements with the goal of establishing an experimental database on load distributions of splined joints subject to static spur and helical gear loading conditions. Specifically, spline root stress measurements will be performed as a function of circumferential and face width positions of the spline teeth. Simulations of the tested clearance-fit splined joint will be performed using the model of Hong et al. (2014b) to provide a direct comparison to the experimental results to aid in describing the experiments and, in the process, to assess the fidelity of the model.

2. Experimental Setup

A dedicated test setup that allows a splined joint to be tested under various gear loading conditions has been designed and fabricated. The test setup consists of a test shaft and a reaction shaft. Figure 1(a) and (b) show the assembly cross-sectional side-views of the test and reaction shafts with key components labeled, and Fig. 1(c) shows the experimental test setup while loaded.

The test shaft is supported by two massive brass bushings. In between the bushings, the external spline piece is keyed and severely shrunk-fit on the test shaft in order to provide a nearly rigid connection between the external spline and the test shaft. The internally splined gear is placed on the external spline and held axially by a washer and lock nuts on either side of the splined joint. At one end of the test shaft the loading flange is mounted in a slightly cantilevered manner so that a torque may be applied using a moment arm and calibrated weights. The reaction shaft is supported by two oversized spherical roller bearings, which are placed in rigid bearing caps. The reaction gear, which meshes with the internally splined gear mounted on the test shaft, is slide-fit on the reaction shaft and held axially by a lock nut. In addition, two shear pins are positioned through both the flange of the shaft and the gear blank so that the gear does not rotate independent of the shaft. At the end of the reaction shaft, a 72-tooth external spline mates with an internally splined flange which is fastened to the bearing pedestal through a set of bolts to provide a “fixed” boundary condition. This fixed boundary condition balances the torque applied to the test shaft through the loaded gear mesh. The 72-tooth splined joint at the end of the reaction shaft allows the splined joint to be held at 72 equally-spaced rotational positions such that a single instrumented spline tooth may be located at many circumferential positions in order to capture the load distribution variation with shaft rotation.

The external spline test specimen used in this study was designed in such a manner as to allow instrumentation and testing under static conditions. Table 1(a) lists the basic parameters of the splined joint considered in this study. In addition
to the parameters listed in the table, it is also specified that the external spline teeth have only a lead crown modification of \(10 \pm 3 \, \mu m\) and no profile modification. Table 1(b) lists the design parameters of the unity-ratio spur and helical gears used in this study to load the splined joint. These gear geometries were used in numerous gear dynamic studies (Hotait and Kahraman, 2008, Handschuh et al., 2014, Talbot et al., 2016). For both the spur and helical gear loading cases, data was taken at 20° increments for a full 360° rotation of the spline, relative to the location where the load is applied. At each rotational increment, experiments were repeated under four different torque levels of 150, 300, 450, and 600 Nm.

The root stress instrumentation consisted of five strain gauges placed along the face width of the external spline as shown schematically in Fig. 2. The strain gauges were placed below the start of active profile (SAP) at a radius of 32.22 mm so that they did not interfere with the contact interfaces of the internal and external splines. Furthermore, the gauges were aligned along the profile direction so that strain measurements may be used to calculate bending stress of

![Fig. 1](image-url)

**Fig. 1**  (a) Cross-sectional side-view of test shaft assembly, (b) cross-sectional side-view of reaction shaft assembly, and (c) experimental test setup with loaded torque arm.
Table 1 Parameters of (a) the splined joint and (b) the unity gear pair used to load the splined joint.
(All units are in mm unless otherwise specified.)

(a)

| Parameter                        | External | Internal       |
|----------------------------------|----------|----------------|
| Number of Teeth                  | 18       |                |
| Module                           | 4.00     |                |
| Pressure Angle [Degrees]         | 20       |                |
| Base Diameter (ref)              | 67.658   |                |
| Pitch Diameter (ref)             | 72.00    |                |
| Major Diameter                   | 77.87/78.00 | 81.80 (max)   |
| Form Diameter                    | 67.20    | 78.80          |
| Minor Diameter                   | 60.00    | 68.00/68.13    |
| Max./Min. Circular Tooth Thickness| 5.50/5.45 | 5.55/5.50      |
| Fillet Radius                    | 1.80 (min) | 0.7 (min)      |

(b)

| Parameter                        | Spur     | Helical        |
|----------------------------------|----------|----------------|
| Number of Teeth                  | 50       |                |
| Module                           | 3.000    | 2.898          |
| Normal Pressure Angle [Degrees]  | 20.00    | 19.37          |
| Helix Angle [Degrees]            | 0.0      | 15.0           |
| Base Diameter (ref)              | 140.95   |                |
| Pitch Diameter (ref)             | 150.00   |                |
| Major Diameter                   | 156.00   |                |
| Minor Diameter                   | 140.62/140.74 |        |
| Normal Circular Tooth Thickness  | 4.64     | 4.46           |
| TIF [Degrees]                    |          | 12.15          |

the spline teeth. The gauges were ordered 1 to 5 along the face width, with gauge 1 being the one closest to the loading flange and gauge 5 being the one farthest from the loading flange. Figure 2(a) shows the strain gauge locations of the external spline tooth and Fig. 2(b) shows the strain gauged external spline. Although six different spline teeth were instrumented in pairs of two consecutive teeth being gauged at 120° increments, only the data from one of the three instrumented tooth pairs is presented in this paper as the other two instrumented pairs provided redundancy in case of failure of any of the gauges within the tested tooth pair. Each strain gauge was wired using a three-wire, quarter-bridge circuit. The lead wires from the strain gauges were connected to solder tabs on the side of the external spline and are protected by epoxy. A data acquisition system along with LabView was used to collect data from the root strain gauges. Within LabView, the strain gauge resistance, gauge factor, lead resistance, excitation voltage, and other parameters were set for the strain gauges. Furthermore, the strain gauges were recalibrated before a torque was applied. Data was collected for a specific time interval (the same for every test) at a sampling rate of 100 Hz.
Fig. 2  (a) Strain gauge locations on an external spline tooth (all units in mm), and (b) strain gauged external spline.

3. Experimental Results

3.1 Spur Gear Loading

Spur gear loading of a splined joint produces both a torque and a radial force. The radial force from the spur gear loading causes a circumferential variation in the overall load distribution (Hong et al., 2014b). As such, the root stress experienced by a single spline tooth is expected to vary significantly based on the relative angular position of that spline tooth with respect to the angular position of the gear mesh interface. For this reason, data was collected for a full rotation of 360° at increments of 20°.

Figure 3(a) illustrates the variation of stress for a single tooth of the splined joint over a complete revolution for spur gear loading at an applied torque of 600 Nm and Fig. 3(b) shows that a spline tooth is at 0° when it is at the location of the gear mesh interface. The stress values shown in this figure were measured by gauge 3 that is located at the center of the face width of the spline tooth. Once balanced by the spur gear mesh, the applied torque of 600 Nm produces an additional radial force of approximately 8.5 kN along the direction of the plane of action of the spur gear pair. The maximum stress in Fig. 3 occurs at an angular position of 30° near the angular position of the gear mesh interface, reaching a value of about 77 MPa. As the tooth of the splined joint moves away from the location of the gear mesh, the measured strain and corresponding stress on this tooth decreases, reaching its minimum within the range of 150° and 210°. In Fig. 3, the stress ratio at gauge 3 is $R = \sigma_{\text{min}} / \sigma_{\text{max}} = 4.4/77.4 = 0.056$ with $\bar{\sigma} = \frac{1}{2} (\sigma_{\text{min}} + \sigma_{\text{max}}) = 40.9$ MPa, indicating that the spline tooth experiences fully released cyclic loading for each revolution of the shaft. In contrast, a purely torsional load would not result in any such cyclic variation of stress.

Figure 4 shows the values of root stresses calculated from all five gauges on the spline tooth as a function of rotational position under spur gear loading conditions. Data at each of the four torque values is presented individually. Main observations from this figure are listed as follows:

- The cyclic variation of root stress for one shaft revolution is evident for all face width (gauge) locations and applied load values. The maximum stress amplitudes occur at 30° for the most loaded gauges 1 through 3 for three of the four loading cases. The maximum amplitude occurs at 50° for an applied load of 150 Nm. The stress ratio ($R$) values for gauges 1 through 5 are -0.004, -0.044, -0.052, 0.019, and -0.048 at an applied torque of 150 Nm, respectively. For an applied torque of 600 Nm, the stress ratios for gauges 1 through 5 are 0.034, 0.032, 0.057, 0.117, and 0.120, respectively.
- The effect of applied torque is seen to be proportional to the calculated root stress regardless of the face width (gauge) location or rotational position. With an applied torque of 150 Nm in Fig. 4(a), the maximum magnitude of stress seen by gauge 1 is 25 MPa, whereas in Fig. 4(d), with an applied torque of 600 Nm, the maximum stress is 87 MPa. This indicates that the torque-stress relationship is nonlinear. This nonlinear relationship is expected because an increase in applied torque brings more surface area into contact and causes the joint stiffness to increase (Hong et al., 2016).
- In the case of an unmodified involute spline under spur gear loading, one would expect that gauge 1 (located at the edge of the face width on the side where the load was applied) would experience the highest magnitude of stress. This is clearly not the case here. The reason is that the teeth of the external spline have a lead crown modification of...
10±3 μm. The lead crown would ideally move the stress distribution closer to the center of the face width of the spline tooth. However, the application of torque on one side would still cause larger loads at that side. The combined influence of these two effects result in the location of the second gauge seeing the highest magnitudes of stress which were 31, 58, 77, and 93 MPa at applied loads of 150, 300, 450, and 600 Nm, respectively.

![Graph](image1.png)

**Fig. 3** (a) Variation of stress for a single spline tooth under spur gear loading conditions at 600 Nm and (b) definition of rotational position for a spline tooth with the location of the gear mesh specified.

![Graph](image2.png)

**Fig. 4** Root stress of a spline tooth under spur gear loading conditions at (a) 150 Nm, (b) 300 Nm, (c) 450 Nm, and (d) 600 Nm.
3.2 Helical Gear Loading

Helical gear loading of a splined joint produces a radial force, a torque, and an overturning moment. Similar to spur gear loading, the radial force causes a circumferential variation in the overall load distribution. Unlike spur gear loading, however, an overturning moment results in variations both along the face width direction and the circumferential direction (Hong et al., 2014b). As such, the root stress experienced by a single spline tooth over one rotation under helical gear loading is expected to vary drastically along both the circumferential and face width directions.

Figure 5 shows measured variation of stress for an edge gauge (gauge 1) of a single tooth of the splined joint over a complete revolution under helical gear loading at 600 Nm. For helical gear loading, unlike spur gear loading, the maximum stress does not occur at the location of the gear mesh interface. Also, in general, the maximum magnitude of stress is greater for helical gear loading than for spur gear loading. However, the overall trends for the two loading types are somewhat similar. Maximum stress in Fig. 5 is observed at an angle of 70° with a magnitude of just over 153 MPa, and a much lower stress level is seen 180° away from this peak position. The difference between the spur and helical gear loading conditions is that, for the helical gear loading, there is a much longer period where the magnitude of the stress dwells near the minimum value. For spur gear loading, shown in Fig. 3, only a 60° segment of the rotation contained almost unloaded conditions (less than 10 MPa). However, for the helical gear loading, shown in Fig. 5, the low stress level is evident for almost half of a revolution.

For helical gear loading, the dwell near the minimum point is caused by the overturning moment; it moves the point of maximum stress from one side of the face width of the spline tooth to the other side as the splined joint rotates. Since the point of maximum stress moves to the opposite side of the face width position from the gauge which was used to calculate the stress in Fig. 5, it appears as if there is very little stress for a larger portion of one complete revolution for the helical gear loading case than for the spur gear loading case. The same fully released cyclic loading condition observed in Fig. 3 is also evident in Fig. 5 for helical gear loading. At the location of gauge 1, the stress ratio is \( R = 0.03 \) with \( \bar{\sigma} = 79 \) MPa.

Figure 6 shows measured values of root stresses at all five gauge locations on the spline tooth as a function of rotational position under helical gear loading. Data at each of the four torque values is presented individually. Several observations, similar to those made for spur gear loading from Fig. 4, may be made from this figure:
• The cyclic variation of root stress for one shaft revolution is evident for all face width (gauge) locations and applied load values. Unlike for spur gear loading, however, maximum stress amplitudes for each gauge are not all reached at the same angular location relative to the gear mesh position. The overturning moment causes gauges 4 and 5, along the edge of the face width away from the loading of the splined joint, to reach a peak at an angular position between 310° and 330°. Gauges 1 and 2, along the edge of the face width closer to the loading of the splined joint, reach a peak at an angular position of 70°. Additionally, gauge 3 in the middle of the face width experiences much lower maximum stresses at both of these angular positions. The stress ratio (R) for gauges 1 through 5 are 0.003, -0.001, -0.003, 0.048, and -0.056 at of 150 Nm, respectively. At 600 Nm, the stress ratio for gauges 1 through 5 are 0.03, 0.033, 0.020, 0.022, and -0.045, respectively.

• The effect of applied torque is seen to be proportional to the calculated root stress regardless of the face width (gauge) location or rotational position. The same nonlinear relationship that applies to spur gear loading also applies to helical gear loading due to the fact that an increase in applied torque brings more surface area into contact. With an applied torque of 150 Nm in Fig. 6(a), the maximum magnitude of stress at gauge 1 is 58 MPa, whereas it is 153 MPa in Fig. 6(d) at 600 Nm.

• Unlike spur gear loading, the impact of lead crown for helical gear loading does not have a significant effect on which gauge location has the highest stress values. This is likely due to the fact that the overturning moment overshadows the effect of the lead crown as it causes the location of the maximum stress to shift from one side of the face width of the spline tooth to the other side. However, the side from which the torque is applied is significant. In Fig. 6, gauge 1 (mounted on the edge of the splined joint closest to the side where torque is applied) saw the highest magnitudes of stress of 58, 101, 128, and 153 MPa at 150, 300, 450, and 600 Nm, respectively.

4. Comparison to Simulations

As the last objective, the experimental data presented in the previous section is compared to simulations performed using the model of Hong et al. (2014b). It is noted that this semi-analytical model predicts the load distribution and the corresponding contact stresses. In order to provide a direct comparison between this model and the experiments, the
model was expanded by adding FE root stress prediction capability (Talbot, 2007). The root stress prediction from the resultant load distributions was validated through comparisons to single-tooth point-load experiments. In order to obtain the point load measurements, both the reaction shaft and the internally splined gear from the test shaft were removed from the test setup shown in Fig. 1. A vertical reaction block was placed directly under an external spline tooth at a height that allows contact with the tooth on a horizontal plane. Furthermore, a narrow (1 mm wide) and thin (1 mm thick) shim was placed between the reaction block and the spline tooth so that the spline tooth may be loaded at various face width positions.

Since each gauge measures strain representative of the area it occupies (approximately 1 mm by 1 mm), it was assumed that the exact center of the gauge is at the nominal location specified in Fig. 2(a). The predicted stresses within the 1 mm² area occupied by the actual gauge (centered by the nominal position) were surveyed to define maximum and minimum values of the predicted root stress. Figure 7 shows the single-tooth measurements for five different axial point-loading locations that are aligned with the gauge locations. It is seen that the measurements fall within the band of predictions, indicating that the FE-based root stress predictions are indeed accurate.

As demonstrated by Hong el al. (2015b), index errors of a splined joint have a significant impact on how much load is carried by each tooth, even when the index errors are quite modest. For this reason, while an attempt was made in the experiments to minimize index errors, actual tooth index errors of the test articles must be included in simulations of the experiments. Measurements of index errors were performed for the external spline and the two internal splines of the spur and helical gears using a gear-specific coordinate measurement machine (CMM). Figure 8 shows these measurements. Multiple measurements were performed in order to investigate the repeatability of the index error measurements and to identify the influence of mounting error. For the external spline, the measurements proved very repeatable (less than or equal to 0.1 μm variation) given that the external spline piece can be mounted on the CMM accurately through its qualified bore. Meanwhile, the repeatability for the internal splines of the spur and helical gears showed about a 1.4 μm variance as their mounting on the CMM was less precise. The simulations were performed within these ranges of measured index errors to define a range for each prediction. A lead crown of 7 μm was used in the simulation to represent the actual measured value from the same CMM.

![Graph](image-url)  
Fig. 7 Comparison of single-tooth point load measurements when the point load is at the face width location of (a) gauge 1 through (e) gauge 5 to the predictions of the FE splined joint root stress model. Applied torque is 16.2 Nm.
Fig. 8 Index errors of (a) external spline, (b) internally splined spur gear, and (c) internally splined helical gear.

Figures 9 and 10 compare predictions to measurements under spur and helical gear loading at 600 Nm. It is evident in both figures that the general trends presented in the experimental results are captured well by the model. The circumferential and axial variations of root stresses are predicted accurately. In Fig. 9 for spur gear loading, there is limited discrepancy between measured and predicted stress levels, the largest difference is about 40 MPa for gauge 1. However, most of the measurements fall within the range of predictions. Likewise for helical gear loading, in Fig. 10, while the largest discrepancy is about 45 MPa for gauge 2, the majority of the experimental and predicted stress values agree very well. This suggests that the model of Hong et al. (2014b) effectively captures the nature and magnitude of stress for the load distribution of clearance-fit splined joints under spur and helical gear loading conditions.

5 Conclusions

In this study, an experimental database of load distributions of splined joints subject to both spur and helical gear loading has been established. Specifically, spline root stresses have been measured as a function of circumferential and face width positions of the spline teeth. In addition, simulation results from the clearance-fit spline model of Hong et al. (2014b) have been compared to the measurements. The results of this study lead to the following conclusions:

- For both spur and helical gear loading conditions, the higher the load applied to the splined joint, the higher the stress on the spline teeth. However, the stiffening of the splined joint causes a nonlinear relationship between the applied torque and the resultant stress.
- For both spur and helical gear loading, higher magnitudes of stress are experienced at locations near the edge of the face width of the splined joint closer to the side where the load was applied.
- For spur gear loading, the lead crown moves the location of maximum stress away from the edge where the load is applied. This effect is rather limited for helical gear loading due to the overturning moment acting on the spline.
- The semi-analytical spline load distribution model of Hong et al. (2014b) agrees well with measurements as it accurately captures the variation of root stresses along the circumferential and axial directions.
Fig. 9  Comparison of measurements to predictions under spur gear loading at 600 Nm.

Fig. 10  Comparison of measurements to predictions under helical gear loading at 600 Nm.
References

Adley, R.A., Baynham, J., Taylor, J.W., Development of Analysis Tools for Spline Couplings, Journal of Aerospace Engineering, Vol.214, No.6, (2000), pp.347-357.

Barrot, A., Paredes, M., Sartor, M., An Assistance Tool for Spline Coupling Design, Advances in Integrated Design and Manufacturing in Mechanical Engineering, (2005), pp.329-342, Springer.

Barrot, A., Paredes, M., Sartor, M., Determining Both Radial Pressure Distribution and Torsional Stiffness of Involute Spline Couplings, Journal of Mechanical Engineering Science, Vol.220, No.12, (2006), pp.1727-1738.

Barsoum, L., Khan, F., Barsoum, Z., Analysis of Torsional Strength of Hardened Splined Shafts, Materials and Design, Vol.54, (2014), pp.130-136.

Brown, H.W., A Reliable Spline Coupling, Journal of Engineering for Industry, Vol.101, No.4, (1979), pp.421-426.

Cuffaro, V., Cura, F., Mura, A., Analysis of the Pressure Distribution in Spline Couplings, Journal of Mechanical Engineering Science, Vol.226, No.12, (2012), pp.2852-2859.

Cura, F., Mura, A., Experimental Procedure for the Evaluation of Tooth Stiffness in Spline Coupling Including Angular Misalignment, Mechanical Systems and Signal Processing, Vol.40, No.2, (2013), pp.545-555.

Cura, F., Mura, A., Analysis of a Load Application Point in Spline Coupling Teeth, Journal of Zhejiang University Science A, Vo.15, No.4, (2014), pp.302-308.

Handschuh, M.J., Kahraman A., Milliren, M.R., Impact of Tooth Spacing Errors on the Root Stresses of Spur Gear Pairs, Journal of Mechanical Design, Vol.136, No.6, (2014), p.061010.

Hong, J., Talbot, D., Kahraman, A., Load Distribution Analysis of Clearance-fit Spline Joints Using Finite Elements, Mechanism and Machine Theory, Vol.74, (2014a), pp.42-57.

Hong, J., Talbot, D., Kahraman, A., A Semi-Analytical Load Distribution Model for Side-fit Involute Splines, Mechanisms and Machine Theory, Vol. 76, (2014b), pp.39-55.

Hong, J., Talbot, D., Kahraman, A., A Generalized Semi-Analytical Load Distribution Model for Clearance-fit, Major-fit, Minor-Fit, and Mismatched Splines, Journal of Mechanical Engineering Science, Vol.230, No.7-8, (2015a), pp.1126-1138.

Hong, J., Talbot, D., Kahraman, A., Effects of Tooth Indexing Errors on Load Distribution and Tooth Load Sharing of Splines under Combined Loading Conditions, Journal of Mechanical Design, Vol.137, No.3, (2015b), p.032601.

Hong, J., Talbot, D., Kahraman, A., A Stiffness Formulation for Spline Joints, Journal of Mechanical Design, Vol.138, No.4, (2016), p.043301.

Hotait, M., Kahraman, A., Experiments on Root Stresses of Helical Gears with Lead Crown and Misalignments, Journal of Mechanical Design, Vol.130, No.7, (2008), p.074502.

Hotait, M., Kahraman A., Experiments on the Relationship between the Dynamic Transmission Error and the Dynamic Stress Factor of Spur Gear Pairs, Mechanisms and Machine Theory, Vol.70, (2013), pp.116-128.

Ku, P.M., Valtierra, M.L., Spline Wear-Effects of Design and Lubrication, Journal of Engineering for Industry, Vol.97, No.4, (1975), pp.1257-1263.

Pardhi D.G., Khamankar S.D., Stress Analysis of Spline Shaft Using Finite Element Method and Its Experimental Verification by Photo Elasticity, Int. J. Mech. Eng. & Rob. Res, Vol.3, No.4, (2014), pp.451-458.

Talbot, D., Sun, A., Kahraman, A., Impact of Tooth Indexing Errors on Dynamic Factors of Spur Gears: Experiments and Model Simulations, Journal of Mechanical Design, Vol. 138, No.9, (2016), p.093302.

Talbot, D., Finite Element Analysis of Geared Shaft Assemblies and Thin-Rimmed Gears, MS Thesis, The Ohio State University, Columbus, OH, (2007), pp.69-88.

Tjernberg, A., Load Distribution and Pitch Errors in A Spline Coupling, Materials and Design, Vol. 22, No.4, (2001), pp.259-266.

Wavish, P.M., Houghton, D., Ding, J., Leen, S.B., Williams, E.J., McColl, I.R., A Multiaxial Fretting Fatigue Test for Spline Coupling Contact, Fatigue & Fracture Eng. Materials & Structures, Vol.32, No.4, (2009), pp.325-345.

Weatherford, W.D., Valtierra, M.L., Ku, P.M., Experimental Study of Spline Wear and Lubrication Effects, Transactions of the ASLE, Vol. 9, No. 2, (1966), pp.171-178.

Wink, C.H., Nakandakar, M., Influence of Gear Loads on Spline Couplings, Power Transmission Engineering, (2014), pp.42-49.