Design &Analysis, Different Size Ratios of Spline Shafts Under Static and Dynamic Load Conditions Using Finite Element Analysis

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Abstract- *Mostly failure of rotating machinery occurs due to improper power transmission between the machine elements. Splined connections are widely used in power transmission mechanism. Spline shafts transmit torque from one rotating member to another. This project report presents the study of failure of spline shaft under various stress conditions. The different step size ratio (d/D) is taken as the parameter for finite element analysis. Combined effect of static torsion and static bending are applied to each model. The maximum von Misses stress is calculated for the spline shaft with straight sided teeth. The results obtained were compared between the various step size ratios.*

In order to reduce the failure of the spline shaft in such cases, it must to study all the stresses accompanying throughout the shaft. For this study, both stepped splined shafts, and partially splined shafts with various step ratios are taken into consideration. The combined effect of static torsion and static bending loads over the spline shafts are considered for analysis.

I. INTRODUCTION

Spline shafts are the better effective mode of power transmission between to rotating shafts. It employs the use of equally spaced teeth in the radial direction of a cylindrical coordinate system. The teeth on the male spline interlock with the female spline along the longitudinal axis of the cylindrical shaped coupling system. With a substantially larger contact area between teeth when compared to a traditional gear system, spline couplings are used in high torque applications. The load can be distributed in the longitudinal direction of the pressure faces of the teeth.

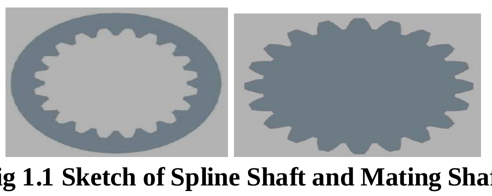


Fig 1.1 Sketch of Spline Shaft and Mating Shaft

Splines have an advantage over shaft key and slot systems. Shafts with external keys are subject to very high stress concentrations at the key root, thus decreasing the fatigue life of the shaft. Shafts with slots cut into them to accept keys are also substantially weakened. Splines allow bending and torsion loads to be distributed over several teeth; each of which acts like a key that is attached to the shaft. This arrangement affords splined connections much greater strength than keyed connections.

Because of their robustness in handling torque, spline couplings are very common to automobiles, ships, and gas turbo fan and turbo jet engines in the aerospace industry. A spline coupling is used to transfer torque from the gear book to the sun gear in automobiles. The challenge in spline design, particularly in automobile applications is the effect that the load distribution across the pressure faces of the teeth. Although the pressure faces of the spline teeth provide a large contact area to distribute the torque load; the challenge lies in distributing that load evenly.

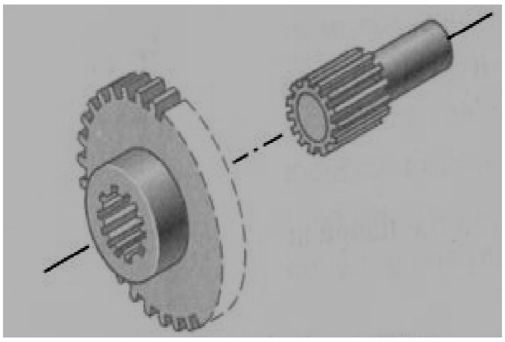


Fig 1.2 Schematic diagram of Spline shaft coupling system

The manufacturing process of a spline has to be done with proper tolerances implemented in it. These tolerances are given in the root fillet radii, the flatness of the pressure faces, and the circular run out of the pitch diameter of the spline coupling. The slight variance of the geometry due to tolerances causes the spline to mate unevenly during torque transfer. The result is that each set of spline teeth sits differently and proper contact is not achieved. These lacks in symmetry causes each tooth to engage slightly with difference in load while each teeth engagement. The tolerances and uneven contact allows the coupling system to vibrate during torque transfer. The vibratory stresses cause the spline teeth wear prematurely from fretting at the pressure faces which leads to failure of the whole spline coupling system. The fretting wear ultimately decreases the life of the part.

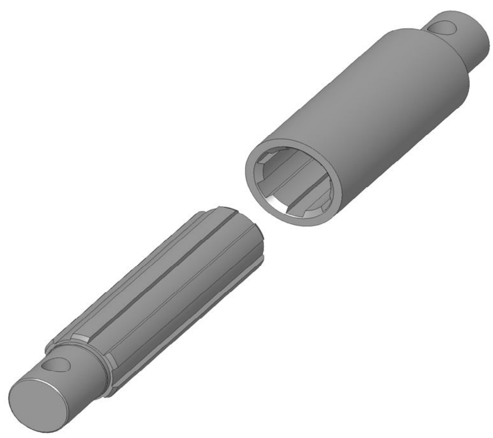
Because of deflection in the coupling system during torque loading, only certain parts of the pressure face of the teeth mesh. As a result there is an uneven load distribution along the face of the teeth. This load distribution is most clearly seen at the root fillet radius along the axial edge of the pressure face of the spline teeth. This is the area where stresses are the highest due to 3D stress concentration factors. Understanding the load distribution in this area during torque transfer gives a designer the ability to more accurately estimate the life of the spline coupling system. The load ratio is directly correlated with the life of the coupling; the higher the pressure ratio the less life can be obtained with all else being equal. In the analysis to follow a spline coupling is modelled using ANSYS software to determine the axial load distribution when a specified torque load is applied to the system. This load distribution is analysed by finite element method and the distribution in the spline coupling system is studied by using the proper boundary conditions. The peak stress on the pressure face is determined and by the average stress across the contact area of the spline teeth. This analysis offers designer a proper stress profile they can expect during operation of the coupling system.

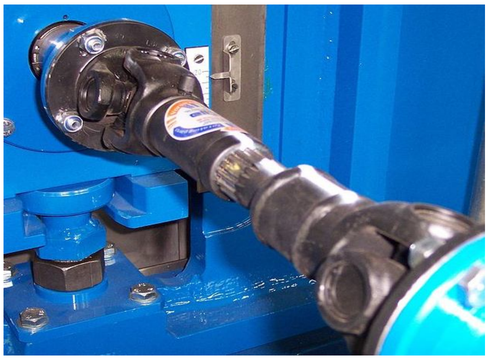
II. LITERATURE REVIEW

Robert A Adey et.al. (2005) describes the development of analysis techniques that can accurately predict surface stress levels for torsional and bending loading which provide an understanding of the elastic and load transfer mechanisms in spline couplings. He also developed methods for generating spline geometry for detailed analysis and determining the required tooth shape. This method enables the designers to carry out much more detailed analyses of their designs and permit optimizations to improve load capacity of the splines. The technology developed is capable of accurately predicting the behaviour of spline joints. The software can simulate the contact stresses, slip and stick conditions and other data necessary to predict durability. The model can predict the impact of manufacturing tolerances on the design and enable the user to investigate design options to achieve anoptimum design. A spline model generator has been developedto simplify the generation of the computer model.

Kin Yeung (2004) improved the performance of an output shaft by adding a taper in the axial direction to its external spline. The taper added to the output shaft depends on the design torque and the stress criterion. The maximum principal stress in the shaft is reduced by as much as 15% if the spline is tapered 0.54˚. He came to a conclusion that this type of reduction in stress would typically result in improvement in fatigue life.

Design of Spline Shaft





Spline Geometry

The general equations used to define the basic proportions of spline teeth are:

- Spline shaft have some advantage over key and slot system.
- Key is subjected to very high stress which leads to damage of the shaft.
- The load in spline shafts are equally distributed over all the teeth's, which also acts like key.
- This, equal distribution of load over the shaft affords shaft with spline much greater strength than key and slot connections.
- A spline shaft consists of two parts; one external spline and another internal spline.
- Grooves are machine over and into the diameter of shaft to make external and internal spline.
- The internal and external spline makes the outer and the inner part of connection respectively.
- The grooves on the internal and external spline shafts should be similar in nature.
- External splines are manufactured by hobbing, whereas the internal spline is manufactured by slotting.

$$P = \frac{N}{D}$$

where P is the diametral pitch, N is the number of teeth, and D is the pitch diameter.

$$p = \frac{\pi D}{N}$$

Finite Element Analysis

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Finite element analysis of a component especially for an 3D component is somewhat tedious one. More steps are involved in the analysis of the component. The design geometry of the part should be correct and the properties assumed should be correct. Much more accurate results can be obtained by proper selection of element type and element size for meshing. The results obtained by finite element method should be interpreted properly to obtain the accurate final results.

The design of the spline shaft is done by using Pro Engineering Version 2.0 software. The spline sleeve and the shaft are separately designed in design software. The individual parts are assembled with proper assembly commands.

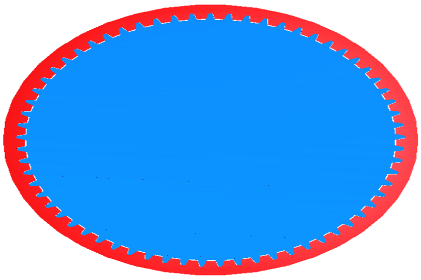


Fig 4.1 Front view of the spline coupling assembly

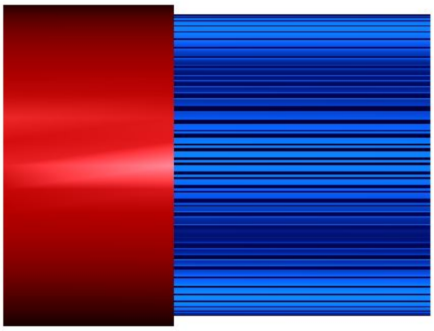


Fig 4.2 Side view of the spline coupling assembly

Since the 3D geometry is of symmetrical in shape one a cut portion of the geometry is taken into account for analysis of the spline shaft coupling. This reduces the post processing time of the analysis of the component and also gives an approximate solution by structural analysis.

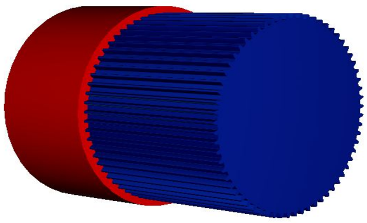


Fig 4.3 3D view of the spline coupling assembly

Fig 4.4 Tooth engagement of spline shaft coupling

Material Properties

Inconel alloys

- Inconel 600: Solid solution strengthened
- Inconel 625: Acid resistant, good weld ability
- Inconel 690: Low cobalt content for nuclear applications, and low resistivity
- Inconel 718: Gamma double prime strengthened with good weld ability
- Inconel 751: Increased aluminum content for improved rupture strength in the 1600°F range
- Inconel 792: Increased aluminum content for improved high temperature corrosion properties, used especially in gas turbines

Specification	Shaft	Unit
Material	INCO718	-
Density	8.19	g/cm^3
Weight	0.7	Kg
Modulus of Elasticity	208	MPa
Shear Modulus	77.2	MPa
Polar Moment of Inertia	0.037	in^4
Yield strength	1172	MPa
Tensile strength	1407	MPa

Meshed section of the spline coupling

After meshing the boundary conditions are applied. First, torsional load is applied to the left and right faces of the sectioned geometry. Second, a surface to surface contact is created between the areas representing the pressure faces of the two pairs of spline teeth. The contact pair consists of Conta174 and Targe170 surface elements to simulate the mating condition of the teeth. In the third boundary condition considered, the ends of the shaft and the sleeve are constrained axially. In the fourth condition, the portion of the sleeve is constrained so it cannot rotate about the axial centerline of the model. Finally, a uniform force is applied to each node at the ends of the shaft to simulate the applied torque received from the sleeve.

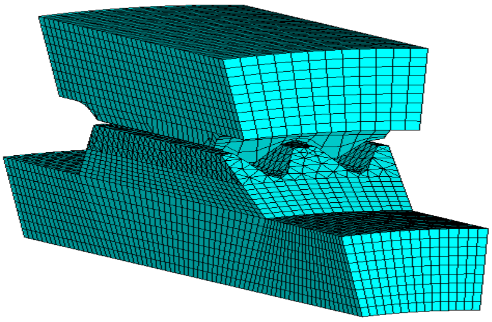
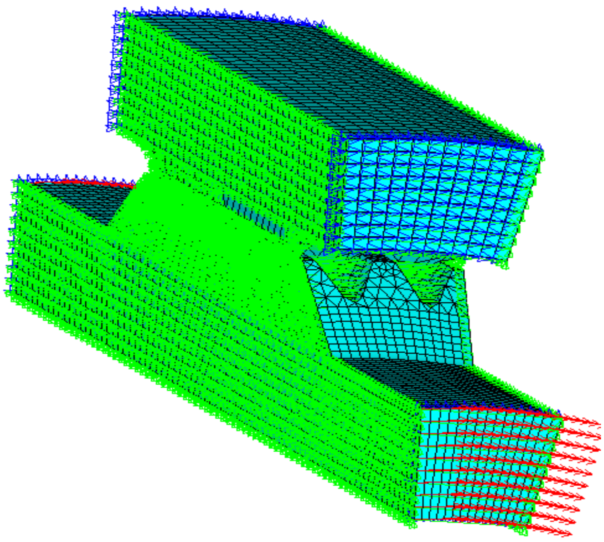


FIG: Meshed section of the spline coupling

Boundary conditions:



To compute the axial load distribution on the spline teeth of the shaft, all geometric parameters of the coupling system are defined. The torque calculated is applied over the geometry. The applied torque over the material is calculated as 28.64 Nm. The contact length of the teeth is 50 mm. The pitch radius of the spline is given by 32 mm. The number of teeth on the spline is 65. The total tooth height of the spline is 18 mm.

III. RESULTS

The maximum deflection on the shaft is seen at the extreme axial ends of the section. The minimum deflection of the shaft is seen at the middle of the shaft where the spline teeth are located. This result makes sense because the outer ends of the shaft should be more flexible than the middle section.

The sleeve has the opposite response due to the fact the section is much thicker than the sleeve spline teeth. Therefore, maximum defection is seen in the spline teeth and the minimum is seen at the outer edges of the full hoop section. For each component the difference between the maximum and minimum deflections are determined.

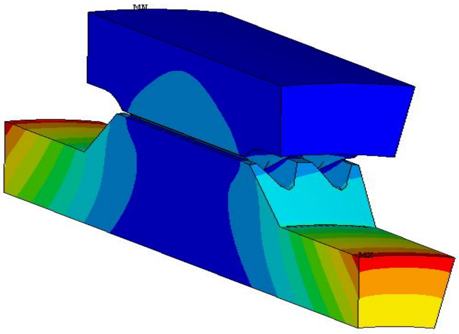


Fig Deflection in the spline coupling

The axial load distribution at the root fillet radius of the spline teeth of the shaft is extracted from the finite element model. Figure which shows the path used to extract the load seen at the root fillet radius of both teeth. The path distance is equaled to the contact length of the spline teeth. The extracted load distribution along the contact length of the spline teeth is summarized. The finite element solution of load distribution along the plotted path in figure is not uniform.

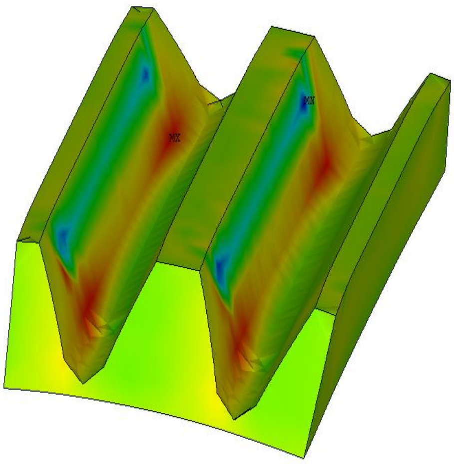


Fig Finite element model axial load distribution in the shaft spline teeth

When observing the entire pressure face of the spline teeth, the red color shows that the highest stress is found in the root fillet radius along the contact length. It also shows that the load in the fillet is not distributed evenly. This result is consistent with the plot of the analytical solution.

The finite element and analytical models produce the same shape of axial load distribution due to torque transfer. The load peaks at both ends of the contact length of the spline teeth in both cases. This response is undesirable because it causes more fretting between the pressure faces and as a result reduces the life and effectiveness in transferring torque.

IV. CONCLUSION

The finite element model incorporates the spline coupling material properties, geometry, and boundary conditions into a 3D analysis. Symmetry and accuracy of the boundary conditions in the finite element model are justified by the fact that both the left and right tooth exhibit the same response to the applied torque load. The 3D finite element solution shows that the 25% of the torque is dissipated during transfer. A portion of that coupled force goes into bending the spline teeth and twisting the overall spline geometry. The 3D finite element model is more accurate, and the stress developed on the right tooth has much more stress when compared to that of the left tooth. This increases the wear rate of the coupling compared to that of spline shaft which leads to failure when sudden torsional load is applied.

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