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THE EFFECT OF TOTAL LENGTH OF WIRE ROPES ON THE TORSIONAL PROPERTIES OF LOW-STIFFNESS-RESILIENT-SHAFT

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ABSTRACT

The effect of total length and presence of bearings towards torsional stiffness of Low Stiffness Resilience Shaft (LSRS) in Semi Active Steering (SAS) is discussed in this paper. LSRS, an integral component of the SAS is a flexible shaft that can replace the conventional rigid shaft of the steering system and allows active control to be performed. Static structural torsional test simulations using ANSYS^{TM} were performed on arrangements of 4 wire rope strands with different lengths in order to select the best one for the optimum performance of the LSRS. With the total length of the wire ropes equal to their lay lengths being the defining factor, three different LSRS namely LSRS A, LSRS B and LSRS C were modelled and then analyzed. LSRS A was found out to be the stiffest with an average torsional stiffness of 12.30 N.m/rad and LSRS C the most torsionally flexible, having the least average stiffness of 4.93 N.m/rad. Furthermore, LSRS I, II and III were modelled based on the number of bearings along the total length of the LSRS. The total length was kept constant at 300mm. LSRS I with 2 bearings in between was found out to be the stiffest compared to LSRS II with 1 and LSRS III with no bearings in between. It can be concluded that the increase in the length of the wire rope shows a decrease in the torsional stiffness of the LSRS and the presence of bearings along the length of the LSRS increases its torsional stiffness.

Keywords: steering, flexible shaft, wire rope, finite element simulation, torsional stiffness.

INTRODUCTION

There have been astonishing technological headways in the automotive field since the creation of the first automobile around 100 years ago. Based on the necessity of either the drivers or the passengers, the design of various systems has evolved over the period of time such as increasing the ride comfort or revolutionizing the suspension system of the vehicle. Over the years, the capability of vehicle to achieve high speed has increased which made the safety of the driver and the passengers an important issue. To deal with this concern, actions were taken such as novel and enhanced chassis designs, anti-lock braking systems and electronic stability control systems. Steering systems have also evolved a long way from mechanical steering system to Steer-By-Wire system in light of these concerns [1].

Steering while parking of vehicle at low speed had been very difficult for drivers till 50 years after the invention of automobile. Seeking higher vehicle velocities and more power led the engines to become heavier and the rack loads to increase. Due to this reason, drivers required a lot of strength to turn the steering wheel. Similarly, the increase in vehicle speed meant drivers would require improved handling stability at greater speeds [2]. Automotive engineers have developed various types of steering systems to counter these difficulties. One such design concepts is the Semi-Active-Steering (SAS) system technology [3] which counters all of these difficulties, and delivers benefits such as Active control, ease of packaging and enhanced safety to the drivers.

The configuration of the SAS is alike to that of an electric power assisted steering (EPAS) system but a Low-stiffness-resilient-shaft (LSRS) replaces the rigid shaft and introduces active control to the automobile [3]. In a Steer-by-wire (SBW), the rigid shaft is engaged with the help of a clutch mechanism at the failure of the electric system but in the SAS system the LSRS is a fundamental part and is coupled to the system at all times. The LSRS should have certain torsional and axial properties. Firstly, when the SBW system is still being operated, the LSRS should be torsionally flexible enough so that it doesn't interfere with the system. But if the SBW system fails the LSRS should also be torsionally rigid enough to provide the automobile manoeuvring capabilities so that it is steered to safety. The LSRS should also have axial flexibility which allows it to buckle in case of an accident or a front end crash so that the driver remains safe. In addition, LSRS can also improve the ride comfort level of a vehicle. The SAS which has LSRS as part of the component also improves the ride comfort of a vehicle by reducing the amount of vibration at the steering wheel [4]. Wire ropes arranged together with bearings at different intervals for support can be used to construct the LSRS needed for a SAS system.

Wire rope is a very resourceful, flexible, high-strength member that is used in many mechanical systems to provide excellent tensile strength while it remains flexible. Physically disconnected or non-co-linear power transmission application components also make use of wire ropes. Physical properties such as the flexibility of the rope, the rupture strength and the service life are affected by the variations in the make of the wire ropes [5]. An important parameter that effects the physical properties of the wire rope is the lay length. The lay length is the distance measured parallel to the centre line of a wire rope in which a strand makes one complete spiral or turn around the rope. Figure-1 shows a standard wire rope which has six external strands that are laid in the right-hand side direction around a centre core either a strand or

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a single wire depending on the construction of the wire rope. Wire and strand directions are important characteristics of the rope that are often referred to as the "rope lay" [6].

Wire ropes are being successfully used in many applications because they can handle high axial loads and provide high flexibility and strength-to-weight ratios. Due to these reasons, much time and effort have been dedicated over the past few decades in order to come up with theoretical models for the structural analysis elucidating their mechanical behaviors. But it has been very difficult to conduct this analysis because of the structural intricacies and the nonlinear nature of the problem [7].

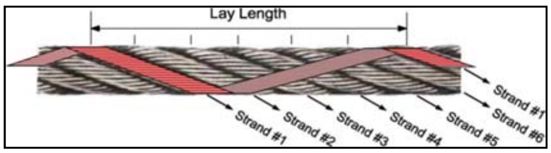

Figure-1. Lay length of a wire rope composed of 6 strands [6].

Furthermore, the analytical studies conducted earlier on the torsional or tensile stresses usually neglect the frictional and contact effects. On the other hands, the application of solid modelling and FEA using computer software allow frictional contacts and other complex working conditions to be considered [8]. Wire rope properties have been analysed using finite element methods since the 1970s but it was limited at that time due to computational problems. With the advancements in computer technology and the creation of finite element software, it has become much more practical and easier to analyse wire ropes not only from a scientific but also from a practical point of views [9].

SYSTEM CONCEPT DESIGN

The main parts of the system include the LSRS, Power motor, Reaction Motor, sensors and controllers. Figure-2 shows the schematic diagram of the SAS system. The existence of LSRS in this system makes it different from any other steering systems. Because of the structure and physical properties of the LSRS, it has several advantages over the rigid steering shaft.

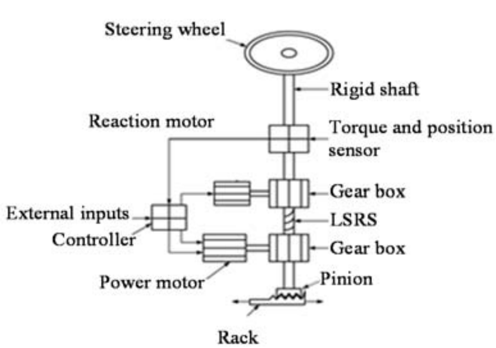

Figure-2. Schematic diagram of the SAS [3].

Its axial flexibility provides safety to the driver in case of an accident as it can buckle upon impact. LSRS can be placed on either side of vehicle dashboard offering a packaging advantage as well. Similarly, because of its torsional flexibility it can allow active steering to be performed on the vehicle while being attached to the system. The LSRS can be made out of a cable which is flexible and resilient to the torque acting along its length. The rigidity and the stiffness of the cable is the main concern because at the failure of the SBW system, it should be torsionally rigid enough to manoeuvre the vehicle to safety.

Basic configuration of the LSRS

The LSRS is supposed to have a certain torsional stiffness and axial flexibility. But with the increase in length of the LSRS it becomes difficult to transmit torque along its axis as the wire ropes in the LSRS will start twisting around each other. Due to this reason bearing at fixed intervals are important parts of the setup as it will prevent the wire ropes from following this behaviour. The proposed LSRS design constituting bearings and wire ropes is shown below in Figure-3(a).

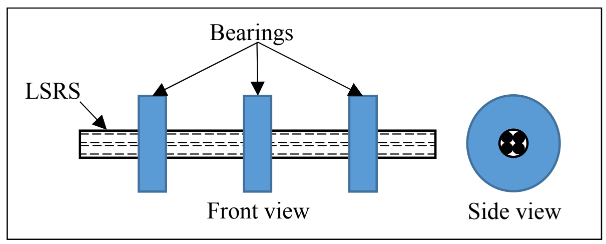

Figure-3(a). Basic layout of the LSRS.

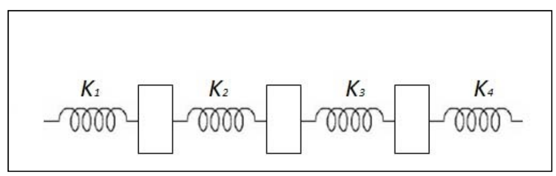

Figure-3(b). Schematic representation of LSRS.

The two major properties defining the LSRS that affects the SAS are torsional stiffness and axial flexibility which are dependent on the distance between the bearings and the arrangement of wire ropes for the construction of the LSRS.

The torsional rigidity of LSRS should be compromised for its applications. It should be torsionally flexible enough not to affect the SBW system much but it should be rigid enough to steer the vehicle to safety upon SBW system failure. The torsional stiffness is characterized by the spring constant or the torsion coefficient. Figure-3(a) shows the basic layout of the LSRS while Figure-3(b) denotes the wire rope sections as their spring constant. The formula for the equivalent spring constant is a function of the number of wire rope sections and can be derived from Figure-3(b).

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$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} + \cdots \quad (1)$$

K_{eq} is the equivalent spring constant or torsional stiffness coefficient measured in Nm/rad. Hence the equivalent Torque on the LSRS can be calculated using the following equation:

$$\tau = -K_{eq}\Theta \quad (2)$$

Where τ, is the torque exerted on the LSRS and θ is the angular deflection made by the LSRS in radians. The negative sign indicates that the direction of torque is opposite to the direction of twist.

Configuration of wire ropes in the LSRS

The wire ropes are arranged in a certain way along with the help of bearings to construct the LSRS. This configuration or arrangement of wire ropes is also very important as it will affect the properties of the LSRS. The individual wires in a wire rope are organized in a circular pattern but are wound in a certain direction, either clockwise or anti clockwise. Due to the lay direction of the wire rope, it exhibits varying torsional properties in both directions and because of this reason the wire ropes need to be arranged in such a way that LSRS exhibits similar torsional properties.

Using earlier simulations performed in ANSYS Workbench 15.0, an arrangement of wire ropes for the LSRS was selected which has similar torsional stiffness in the clockwise and anti-clockwise direction. Figure-4 shows the arrangement in which a 4 strand wire rope has been chosen. In this variation, two alternate wire rope strands are right-hand lay and the other two are left-hand lay of exactly same lay lengths so that the overall arrangement has similar stiffness, K_{eq} in both directions [10].

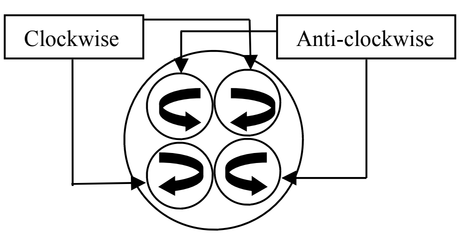

Figure-4. Arrangement of wire ropes best suited for the LSRS.

MODELLING OF THE WIRE ROPE STRANDS AND LSRS

This section discusses the modelling of the 1x7 (1 by 7) wire rope strand and the LSRS. Since there are many parameters which can be varied in the construction of a rope strand, it is important to have a general and accurate model which can predict the effects of possible variations of these parameters on the performance of the strand [11]. To notice the effect of increase in length of the wire ropes on the torsional stiffness of the LSRS, solid models of the right and left lay wire ropes with three different lengths based on the difference of lay length were developed using the SolidWorks^{TM} software. These solid models were then assembled and 3 different LSRS models were generated and later used to perform the simulations in ANSYS^{TM} so that the behaviour of the LSRS at the application of torque could be studied.

In order to correlate between the simulation and the experimental results, the wire rope strands were generated to have the same dimensions as the ones that will be used for the experiment. The selected wire ropes were of type 1x7 strand made out of Galvanized steel with a nominal diameter of 3.56 mm. Table-1 shows the geometrical parameters of the simple strand.

Table-1. Geometric parameters of the 1x7 strand wire rope.

Geometrical parameters	Value
Strand Diameter (d)	3.56mm
Center wire diameter (2R1)	1.20mm
Outer wire diameter (2R2)	1.18mm
Lay length (p1)	35mm
Lay length (p2)	50 mm
Lay length (p3)	65mm

Three different LSRS settings namely LSRS A, LSRS B and LSRS C were modeled based on their lay lengths. LSRS A has 4 wire rope strands, 2 in left lay and 2 in right lay direction with the total length of p1. Similarly, LSRS B and C have wire rope strands with total lengths of p2 and p3 respectively.

The comparison among the simple strand right lay models of the above mentioned geometrical parameters with different lay lengths of p1, p2 and p3 is shown in Figure-5(a). Meanwhile, Figure-5(b) shows the solid model of the LSRS A with an addition of torque handles in order to make it easier to apply boundary conditions to the wire rope model.

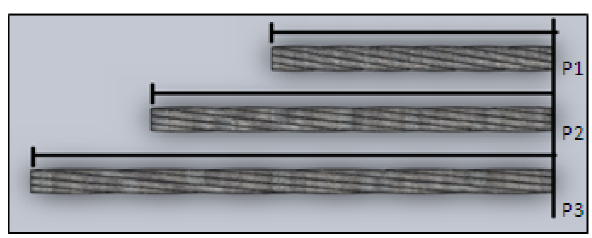

Figure-5(a). Comparison of the simple strand right lay models of lay lengths p1, p2 and p3.

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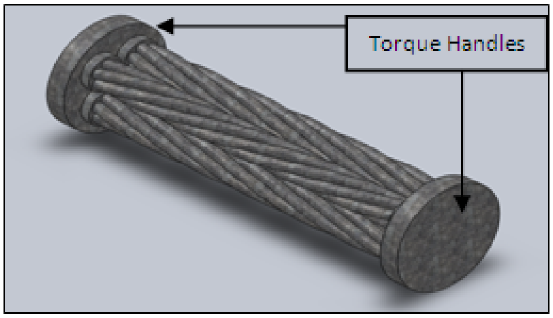

Figure-5(b). Solid model of the LSRS A with torque handles.

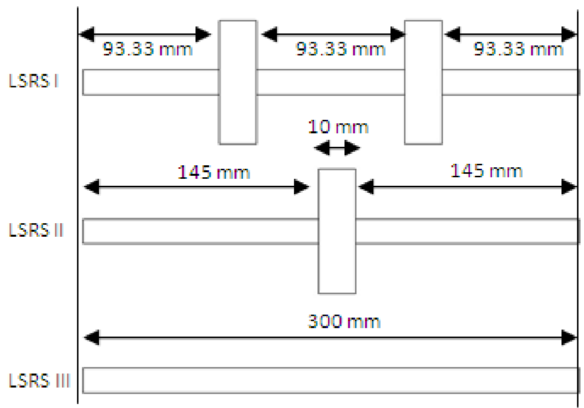

Figure-5(c). Arrangement of bearings for LSRS I, II and III.

As discussed earlier that with the increase in length of the LSRS, bearings will have to be introduced in the LSRS setup so that the wire ropes don't start twisting around each other and torque can be transmitted with ease along the axis. Therefore, three solid models of LSRS namely LSRS I, LSRS II and LSRS III were modelled to notice the affect of bearings on the torsional stiffness of the LSRS. The pitch and total length was kept constant at 50 mm and 300 mm respectively. LSRS I had 2 bearings spaced apart at an interval of 93.33 mm and LSRS II had 1 bearing with two sections of 145 mm each. The width of the bearing was selected to be 10 mm, which is the exact same length of the bearings that will be used in the experiments later. Figure-5(c) shows the arrangement of bearings for the three different LSRS'.

SIMULATION AND RESULTS

In order to find the angle of twist or deformation made by the LSRS at the application of a certain torque in both directions, static structural torsion test was performed. For the analysis, the torque was applied on the LSRS A, B and C in clockwise and anticlockwise directions in order to determine the difference in behaviour of the wire rope in both directions. The frictional contact coefficient between individual wires was set to be 0.115 [12]. The meshing of the models for the analysis was done using the ANSYS workbench Mechanical mesher. Sweep method of meshing and Face Sizing was applied to every individual wire in the LSRS, in order to obtain a uniform mesh. The complexity of the mesh and the element size was chosen as a consequence of compromise between the needs of limiting the computational heaviness and of avoiding any perturbation due to boundary effects. The material assigned to the model was Galvanized steel as the purchased wires for construction of the wire rope strands and the LSRS for the experiment was made of the same material. For the boundary conditions, one end of the wire rope was fixed and not allowed to move in the x, y or z directions and on the other, a moment of 1 to 5 N.m magnitude was applied. The results were then analyzed and compared.

Effect of total length on the torsional stiffness of the LSRS

It is noted that due to the arrangement of wire rope strands in the LSRS, there is almost negligible difference in the angular deflection when the moment is applied in the clockwise direction and anti-clockwise direction. However, had the moment been applied to a single wire rope strand in a clockwise or anti-clockwise direction, there would have been a considerable percentage difference in the angular deflections in both directions because of the one dimensional lay of the strand. Figures-6(a), 6(b) and 6(c) show the angular behaviour of all the three LSRSs at the application of different Twisting moment values ranging from 1 to 5 N.m.

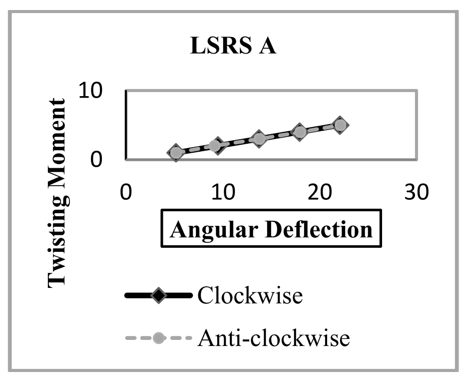

Figure-6(a). Twisting moment vs angular deflection for LSRS A.

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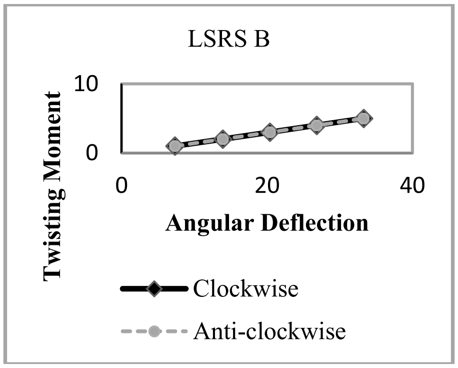

Figure-6(b). Twisting Moment Vs Angular deflection for LSRS B.

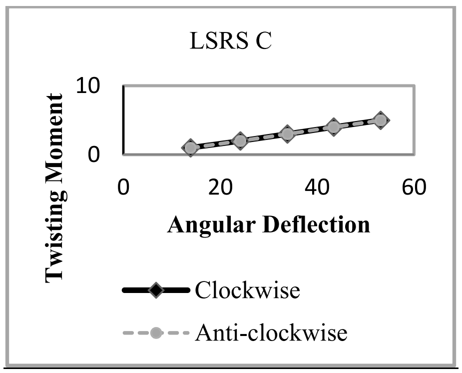

Figure-6(c). Twisting Moment vs Angular deflection for LSRS C.

It is evident from these graphs that all the three LSRS with different total lengths have almost the same linear behaviour in response to the applied twisting moment. Furthermore, the graph also suggests that the angular deflection values obtained through the simulations for the clockwise and anti-clockwise twisting moment are almost equal. This indicates that a vehicle equipped with LSRS is going to have a similar response in the clockwise and the anti-clockwise direction.

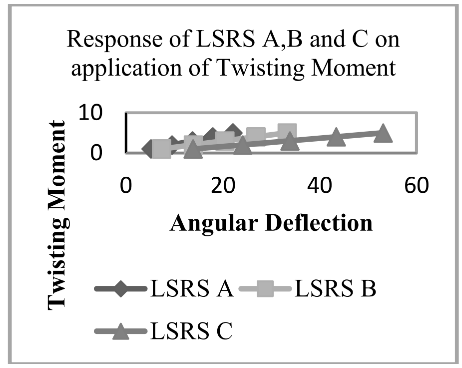

Figure-7. Comparison of response of all three LSRS to applied twisting moment.

Figure-7 elucidates the clear difference in behaviour of various LSRS designs. All three LSRSs behave linearly at the application of moment but LSRS A with the total length of 35 mm has the maximum torsional stiffness. Meanwhile LSRS C with the total length p2 of 65 mm has the least torsional stiffness as evident from the graph. At the application of 1 N.m, LSRS A shows an angular deflection of 5.152 degrees, while LSRS B shows 7.324 degrees and LSRS C shows an angular deflection of 13.847 degrees.

The average torsional stiffness of the LSRS A, B and C is found out to be 12.30, 8.33 and 4.93 N.m/rad respectively. These results suggest that with the increase in the total length of the wire rope, the torsional stiffness of the LSRS decreases greatly and the angular deflection observed for a certain amount of moment would increase.

Effect of bearings on the torsional stiffness of the LSRS

It is observed that the introduction of bearings in the LSRS design increases the torsional stiffness of the setup. A turning moment of 1 N.m was applied to one end of the LSRS while the other end was fixed and wasn't allowed to translate or rotate in any direction. Upon the application of torque, the results noted are mentioned in Table-2 below.

Table-2. Effect of bearings on the torsional behaviour of the LSRS.

	Total bearings	**Total length** (mm)	**Angular deflection** (degrees)	**Torsional stiffness** (N.m/rad)
LSRS I	2	300	39.29	1.46
LSRS II	1	300	39.92	1.44
LSRS III	0	300	40.96	1.40

LSRS I with two bearings spaced apart at an equal length of 93.33 mm has an increased torsional stiffness compared to that of LSRS II with one bearing or LSRS with no bearing at all. The introduction of bearings of 10 mm thickness means that the section of wire rope passing through the bearings becomes stiff which reduces the effective length of the LSRS. That means for LSRS I with two bearings, the effective total length becomes 280 mm and for LSRS II the effective length is 290 mm since it has one bearing, hence the increase in stiffness.

CONCLUSIONS

The effect of the length of wire rope strands and the effect of usage of bearings in the LSRS on its torsional properties using static structural simulations is discussed in this paper. The use of wire ropes for the LSRS of the

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SAS system serves the purpose of allowing active steering to be performed on the system because of its torsional flexibility, as well as making it safe in terms of a head on collision or beneficial in terms of packaging due to the property of it being axially flexible.

The simulations performed on the three different types of LSRS A, B and C were differentiated based on the difference in total length of the wire rope strands. The results indicated that the increase in length of the wire rope strand decreases the torsional stiffness of the LSRS. LSRS A using a wire rope strand of 35 mm total length was found to have the highest torsional stiffness of 12.30 N.m/rad. On the other hands, LSRS C using a wire rope strand of 65 mm length had an average torsional stiffness of 4.93 N.m/rad.

Furthermore, it was observed that the presence of bearings in the LSRS increase its torsional stiffness. LSRS I with 2 bearings was found out to be the stiffest with an angular deflection of 39.29^{o} and a torsional stiffness of 1.46 Nm/rad. Meanwhile LSRS III with a stiffness of 1.40 Nm/rad was found out to be the most torsionally flexible. The presence of bearings makes the LSRS torsionally stiffer because the wire rope section in contact with the bearings becomes stiff and decreases the effective total length.

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