MARMARA UNIVERSITY
FACULTY OF ENGINEERING

FINITE ELEMENT ANALYSIS OF PLANETARY ROLLER SCREW MECHANISM

Osman ÖZMEN

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Department of Mechanical Engineering

Supervisor
Prof. Dr. Aykut KENTLİ

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Finite Element Analysis of Planetary Roller Screw Mechanism

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Osman ÖZMEN

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Signature of Author(s) ....

Department of Mechanical Engineering

Certified By ....

Project Supervisor, Department of Mechanical Engineering

Accepted By.. ....

Head of the Department of Mechanical Engineering

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ABSTRACT

Finite Element Analysis of Planetary Roller Screw Mechanism

Hydraulic Actuators in spite of all its disadvantages have been used for many years. Electromechanical actuators can efficiently replace the hydraulic actuators. Different electromechanical actuators like the ball screws, roller screws can be used in place of hydraulic actuators. Roller screws when compared to ball screws can carry higher loads, have a longer life, and can provide higher speeds and accelerations. Roller screw provides finer leads as compared to ball screws. Roller screw consists of different components like screw, shaft and roller. Initially the literature survey is carried out. Then the CAD modelling of the telescopic roller screw actuator is carried out in Solidworks software. The deformations and stresses induced in the telescopic roller screw actuator is calculated from finite element analysis and the results aren’t compared with the other literature results. Because there is not enough literature in this topic.

SYMBOLS

L_S : Screw Lead

L_R : Roller Lead

L_N : Nut Lead

γ_S : Screw's Helix Angle

γ_R : Roller's Helix Angle

γ_N : Nut's Helix Angle

n_S : Number of Screw's Thread Heads

ABBREVIATIONS

PRSM **:** Planetary Roller Screw Mehacnism

BSM **:** Ball Screw Mechanism

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1. INTRODUCTION

The roller screw mechanism (RSM) is a high efficiency mechanism which transforms the rotation motion into a linear motion or vice versa (see Figure 1), similar in principle to a ball screw mechanism (BSM). There are two primary types of roller screw mechanisms that are planetary roller screw (PRSM) and the recirculating roller screw (RRSM). This research is concerned with the PRSM. As you can see in the figure 1, the main elements of the PRSM are: the screw shaft, the nut, and the rollers. As the screw turns, the rollers roll around within the nut like the activity of a planetary gear system. In the event that the nut is compelled from rotating, rotating the screw will make the nut advance one lead of the screw for each total turn of the screw.

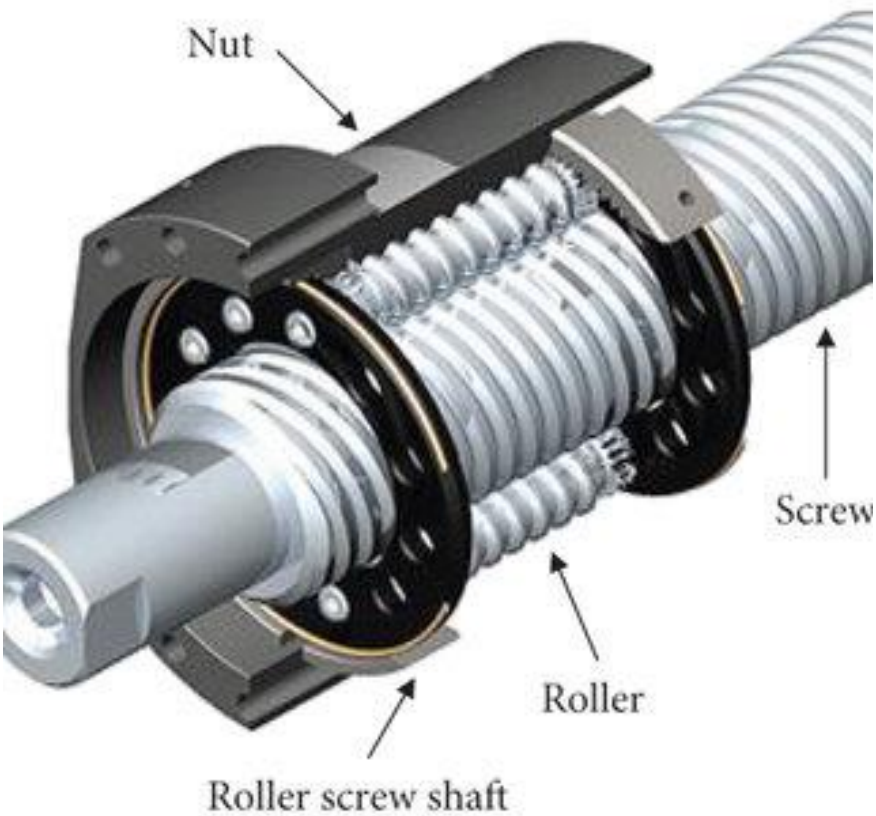

Figure 1.1 Parts of PRSM

As such, the planetary roller screw mechanism finds its applications as an actuator device in various machineries, such as machine tool, medical equipment, port equipment of ship, and flight control equipment of more-electric aircraft.

Generally, planetary roller screw mechanism has many advantages and a few disadvantages when compared to the working boundaries in comparison to ball screw which is more familiar than the planetary roller screw mechanism. Despite these advantages, there has been little fundamental research to support its engineering application.

1.1 Comparison with the Other Mechanisms

There are several main types of linear motion devices, such as ball screws, acme screws, hydraulic cylinders, pneumatic cylinders, and roller screws. The relative characteristics of three linear motion mechanisms are summarized in Table 1.

Table 1.1 Comparison of linear motion mechanisms

	Planetary Roller Screw	Acme Screws	Ball Screws	Hydraulic Cylinders	Pneumatic Cylinders
Load	Very High	High	High	Very High	High
Speed	Very High	Low	Moderate	Moderate	Very High
Acceleration	Very High	Low	Moderate	Very High	Very High
Lifetime	Very Long	Very Low	Moderate	Long	Long
Stiffness	Very High	Very High	Moderate	Very High	Very Low
Shock tolerance	Very High	Very High	Moderate	Very High	High
Efficiency	High	Low	Very High	Moderate	Moderate
Electronic Positioning	Easy	Moderate	Easy	Difficult	Very Difficult
Space Requirements	Low	Moderate	Moderate	High	High
Maintenance	Very Low	High	Moderate	Very High	High

As we can see in the table, PRSM has many advantages and a few disadvantages compared to their other mechanisms. Because of the PRSM is most comparable to the BSM, it is worth comparing these two directly. Compared to BSM's, PRSM's. PRSM has so many advantages that are mainly: higher speed and acceleration, higher load carrying capacity, more accurate positioning, higher impact resistance and stiffness. To the extent that disadvantages, PRSM's usually have lower efficiencies and higher cores than BSM's. The detailed comparison of planetary roller screw mechanism and ball screw is shown in the Figure 2.

	Planetary roller screw	Ball screw
Load capacity	Very large	Large
Life span	Very long	Long
Speed	Very fast	Appropriate level
Acceleration	Very large	Appropriate level
Rigidity	Very high	Appropriate level
Impact resistance	Very high	Appropriate level
Heat resistance	Very resistant	Appropriate level
Space required	Very small	Appropriate level
Friction	Small	Small
Vibration/noise	Very small	Small
Efficiency	75 to 90%	85 to 95%
Ease of maintenance	Very easy	Appropriate level
Environmental load	Very small	Very small
Unit price	Slightly expensive	Appropriate level
Total cost	Appropriate level	Appropriate level
Customizability	Very high	Appropriate level

Figure 1.2 Positioning of PRSM vs Ball Screws [1]

1.2 Aim of Thesis

As mentioned previously, there has been little fundamental research to support the engineering application of roller screws. Indeed, the literature review presented here represents great importance in examining the roller screw mechanism using ANSYS, which was very rare in the literature before. As a result, this research aimed to examine the effect of PRSM on the durability of some features with the help of ANSYS. As such, this work will help to understand these mechanisms that are cheaper to manufacture and have improved efficiency and durability.

1.3 Literature Review

1.3.1 Where PRSM is used?

The PRSM is a well-known device with several significant and crucial applications, including the medical business [2-4], aircraft industry [5, 6], optical equipment [7], high-precision machine tools [8, 9], and rail vehicle suspension [10, 11].

1.3.2 Mechanics

The paper published by Velinsky et al. [12] deals primarily with the kinematics of the PRSM. The kinematic relations for the angular and axial motions of the device, as well as the lines of constant velocity within the contact patch, are derived. Their results show that some slip must always occur on the contact patch and that the lead of the overall mechanism is independent of slip at the screw/roller interface. Some geometric relationships and constraints are given, and an efficiency based on rolling friction is derived. Sokolov et al. [13] derive some of the same kinematic relationships as [12], and also present some additional geometric relationships.

Ryakhovsky et al. [14] discuss more geometric relationships, including the necessary spur/ring gear ratio to ensure the roller does not slip on the inside of the nut; a condition that will cause the rollers to move axially relative to the nut. The paper stresses the importance of minimizing axial migration of the rollers, however, the paper does not develop any kinematics with regard to this slip or the axial migration of the roller.

Blinov et al. [15] recognized that the contact point between two parallel screws of arbitrary helix angle is generally not on the line connecting the axes of the two screws (i.e. the line of centers). A numerical solution to determine the point of initial contact is proposed. Given the equations for the parametric surfaces of the two screws, a grid is constructed over the thread overlap. At each point on the grid, the distance between the two threads is calculated. The contact point is taken as the grid point with the smallest distance between the two surfaces. However, the solution is incomplete, as no equations for the parametric surfaces are given so a solution cannot be obtained.

Sokolov et al. [16] discuss several issues concerning forces in the PRSM: the loads transmitted by the individual threads of the roller are determined, and some contact mechanics are also presented including the maximum contact pressure and the major and minor axes of the contact ellipse. References [17-19] discuss static stiffness of the PRSM, with [17, 18] being theoretical models and [19] being experimental. In [19], it is determined that the stiffness of the PRSM varies depending on the loading of the mechanism, i.e. the combination of tension or compression the screw and nut experience, respectively. Tselishchev et al. [20] propose a numerical method calculating the displacement of the elastic elements in the PRSM. The method is particular to the elastic elements that include the sprung plates and half-rings, both of which allow radial and axial preloads to eliminate backlash.

In the paper by Hojjat et al. [21], a different type of roller screw is investigated where the rollers are not permitted to move about the screw. For arbitrary lead angles of the screw and roller, they examine the phenomenon of slip caused by the forces generated when the screw is rotated. It is shown that for fine leads, there can be no slip at the screw/roller contact as there is no force to generate slip. Otsuka et al. [22] measure the apparent coefficient of friction for the PRSM as 0.015, which is somewhere between that of the lead screw and the ball screw. They explain this as being since the PRSM has additional friction on the carrier plate and spur/ring gears. Qianzhong et al. [23] analyze the friction characteristics of the recirculating RSM and derive relationships between the friction torque and the applied load.

Kozyrev [24] quantitatively compares the performance between roller screw and ball screw mechanisms. Sokolov et al. [25] discuss the roller screw in terms of its wear resistance. Lemor [26] discusses empirical load capacity, heat management, and failure modes of the PRSM. Blinov et al. [27] discuss the modification of the thread profiles of the components of the PRSM, and [28] measure some component dimensions after manufacturing. Falkner et al. [29] look at roller screw lifetime under oscillatory motions with dry and liquid lubrication. Schinstock [30] experimentally investigated dynamic loads within the PRSM. They observed a spotting pattern on the threads which is consistent with the contact mechanics developed herein. Karam et al. [31] develop a model for simulating a roller screw electromechanical actuator using bond graphs. T. A. Jadhav and P. P. Kulkarni et al [32] observe the finite element analysis of telescopic planetary roller screw mechanism.

While the noted literature has looked at numerous detailed issues concerning the planetary roller screw mechanism, many fundamental issues have been ignored which need to be investigated. Only [32] has considered the finite element analysis of PRSM. The intent herein is to extend this work to allow for much additional analysis and subsequent design.

1.4 Mechanical Details

Because the nut is not allowed to rotate, turning the screw causes the rollers to process inside the nut. The planar operation (imagine a cross section orthogonal to the screw axes and parallel to the nut flange) is similar to that of a planetary gear system, with the screw resembling the sun gear and the rollers like planet gears. For each complete revolution of the screw, the nut advances axially one lead of the screw. In ideal conditions, the rollers are axially aligned with the nut. Slip between the roller threads and the nut threads causes the rollers to move relative to the nut, where they might bind and finally destroy the mechanism. Spur gears cut into both ends of each roller mesh with ring gears fitted at both ends of the nut to prevent slide at the nut/roller threaded contact as you can see in figure 1. These spur/ring gear pairs are precisely synchronized to reduce slip at the nut/roller threaded contact.

1.5 Geometric Constrains of PRSM

The screw's lead (L_S) and the nut's lead (L_N) must be equal.

$$L_S = L_N \quad (1)$$

The screw's helix angle (γ_S) and nut's helix angle (γ_N) and roller's helix angle (γ_R) are equal.

$$\gamma_S = \gamma_N = \gamma_R \quad 2$$

The radius of nut (r_N) is equal to sum of twice radius of roller (r_R) and a radius of screw (r_S).

$$r_N = 2r_R + r_S \quad 3$$

The roller radius is related to the screw radius by

$$r_R = \frac{r_S}{n_S - 2} \quad 4$$

where n_S is the number of screw's thread heads.

The nut, roller and screw's helix angles and radius are related by

$$L_N = 2\pi r_N \tan(\gamma_N) \quad 5$$

$$L_R = 2\pi r_R \tan(\gamma_R) \quad 6$$

$$L_S = 2\pi r_S \tan(\gamma_S) \quad 7$$

2. FINITE ELEMENT ANALYSIS

According to the optimum results, the 3D model of the PRSM is constructed with Solidworks and contact analysis is conducted with Ansys. The finite element model of the PRSM is built and shown in Fig.XX.

2.1 3D Model

In this project PRSM is modelled with Solidworks. The structural parameters of the PRSM are taken in Table 2.

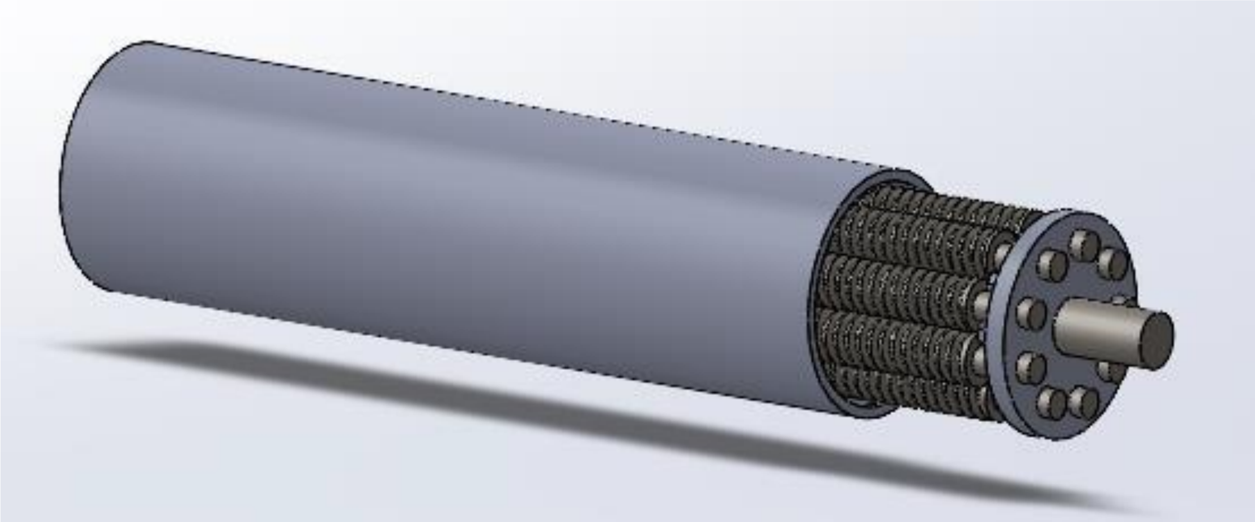

Figure 2.1 Solidworks 3D PRSM Modelling

Table 2.1 Structural parameters of planetary roller screw.

Parameter	Part		
	Screw	Roller	Nut
Nominal diameter	25.00 mm	8.33 mm	41.66 mm
Number of heads	5	Single	5
Thread profile	Triangle	Triangle	Triangle
Thread angle	90°	90°	90°
Lead 1	10.00 mm	2.00 mm	10.00 mm
Lead 2	12.50 mm	2.50 mm	12.50 mm
Lead 3	15.00 mm	3.00 mm	15.00 mm

2.2 Material Characteristics Parameters

The element type and material characteristic parameters used for the calculation are listed in Table 2.

Table 2.2 Element type and material characteristic parameters.

Element Type	Elastic Modulus (GPa)	Poisson Ratio	Density (kg/m^3)
Structural Steel	71	0.33	2770
Aluminum	200	0.3	7850

2.3 ANSYS Finite Element Testing

ANSYS Workbench platform is the backbone for delivering a comprehensive and integrated simulation. It is used to perform various types of structural, thermal, fluid, and electromagnetic analyses. The entire simulation process is tied together by a project schematic, from which you can interact with applications that are native to ANSYS Workbench or launch applications that are data-integrated with ANSYS Workbench.

2.3.1 Statical Structural Test

In this project, the PRSM test was performed as a static structural. In static structural analyses in ANSYS, loads, stresses, strains, and other physical loads like them are assumed to not change extremely with the changing time. So, unlike dynamic analyses, damping and inertia effects are negligible in static structural analyses in ANSYS Mechanical.

Then, you need to have a proper geometry to define it in the ANSYS Workbench environment. We recommend that take your geometries in .step or .igs forms into ANSYS Workbench. You can import your geometry from the geometry section on Static Structural analysis.

After importing geometry inside ANSYS Workbench, double click on ‘Engineering Data’ to define materials for your parts. There are vast materials that are available in ANSYS Workbench, and you can select one of them from the ‘Engineering Data’ section. In this project structural steel and aluminum alloy was selected. The properties of these materials are mentioned in Table 2.2.

After selecting material and importing geometry parts, next part is creating a mesh structure. Proper mesh structures are very important for static structural analyses to obtain correct and near-real results, but in this project Academic ANSYS version was used. This version allows up to a maximum of 35000 elements. After obtaining mesh structure in ANSYS Mechanical, next part is creating required connections between your parts to obtain the required system or mechanisms and define the required boundary conditions such as loads and supports.

2.4 Finite Element Analysis of Screw and Roller

The linear static structural analysis of screw roller is carried out in order to check stresses and deformation induced in screw and roller. The material selected is structural steel or aluminum. The program made the mesh automatically. The mesh model of roller screw arrangement is shown in Fig.3. Due to symmetry of the components and to reduce the computational time only one roller is considered in contact with the screw.

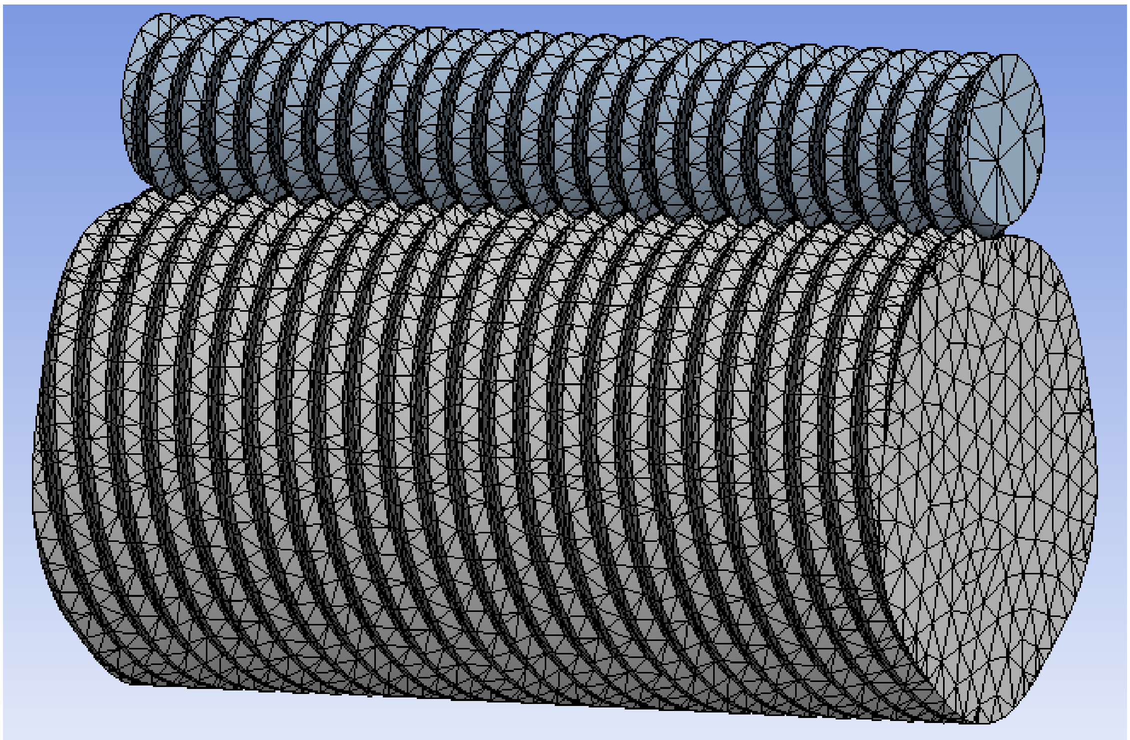

Figure 2.2 Meshing of screw and roller

In this project all the contacts is assumed to no separation since there is little information about the coefficient of friction.

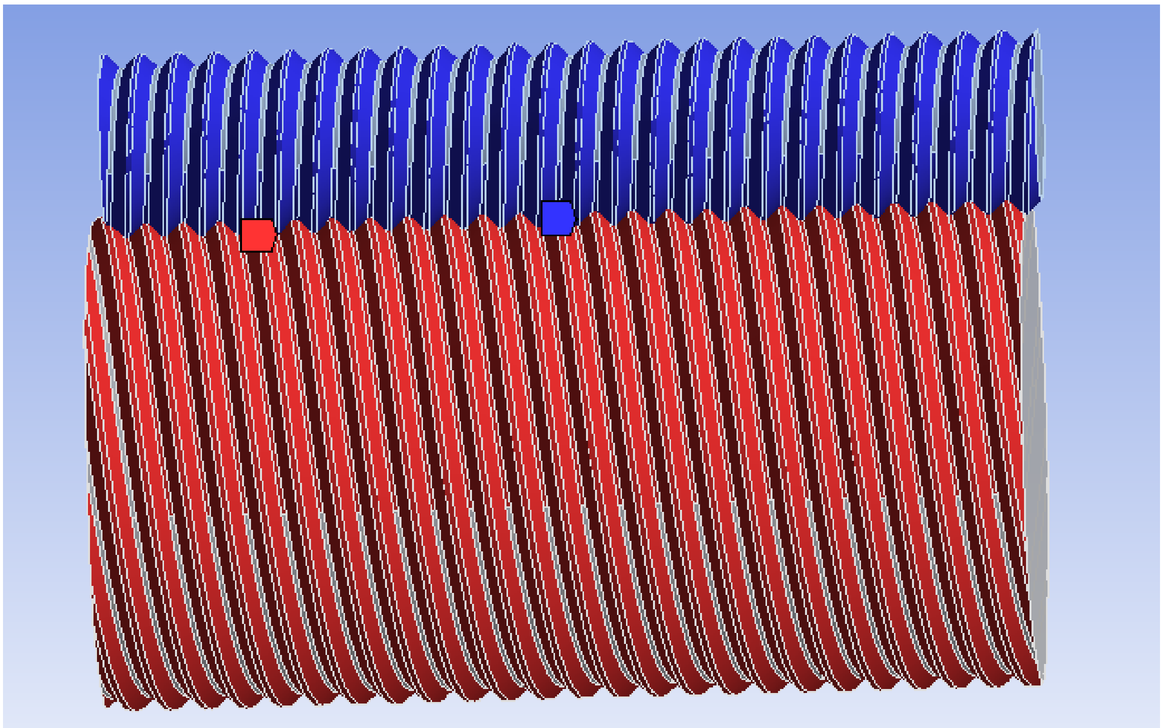

Figure 2.3 Contacts between roller and screw

It is assumed that the total load acting on the roller screw is equally distributed on each roller. For analysis purpose, only the part of the screw which is in contact with the roller is considered. For calculating the deformation one end of the roller is fixed while force is applied at end of the screw.

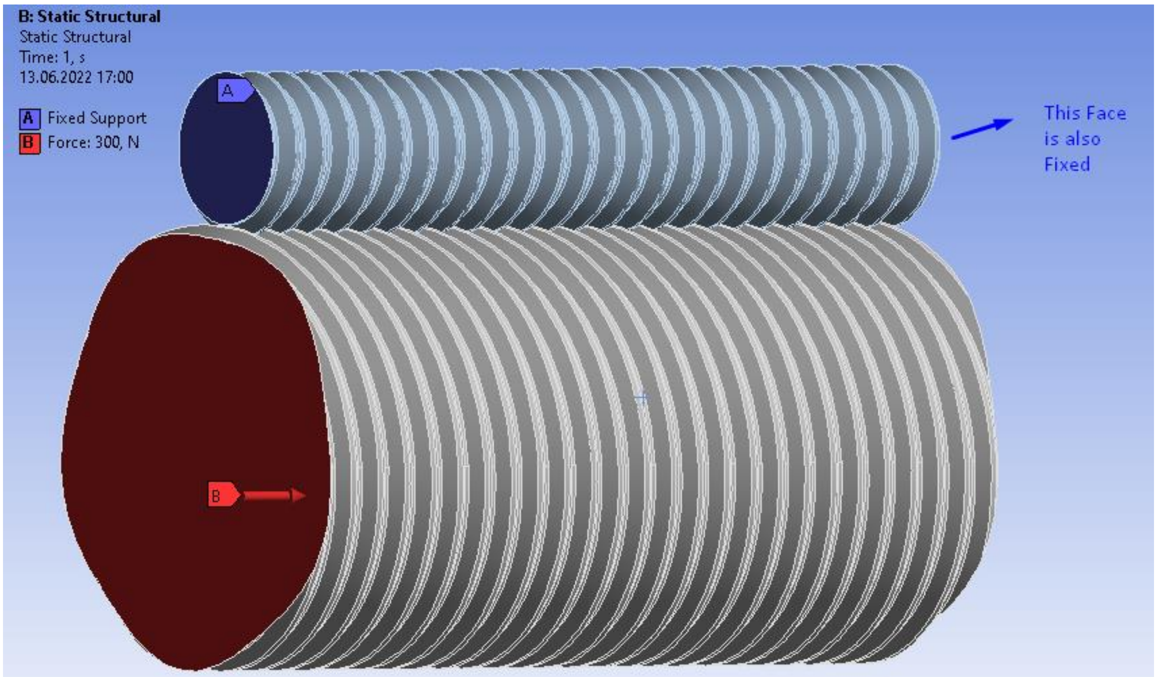

Figure 2.4 Boundary conditions of screw and roller

2.5 Finite Element Analysis of Roller and Nut

After carrying out finite element analysis of screw and roller, finite element analysis of nut and roller is carried out. The material is also selected aluminum alloy and structural steel for nut and roller. Connections between nut and roller is assumed no separation. For reducing the solution time, only one roller is considered in contact with the nut. The meshing of the nut and roller arrangement is carried out in ANSYS Workbench.

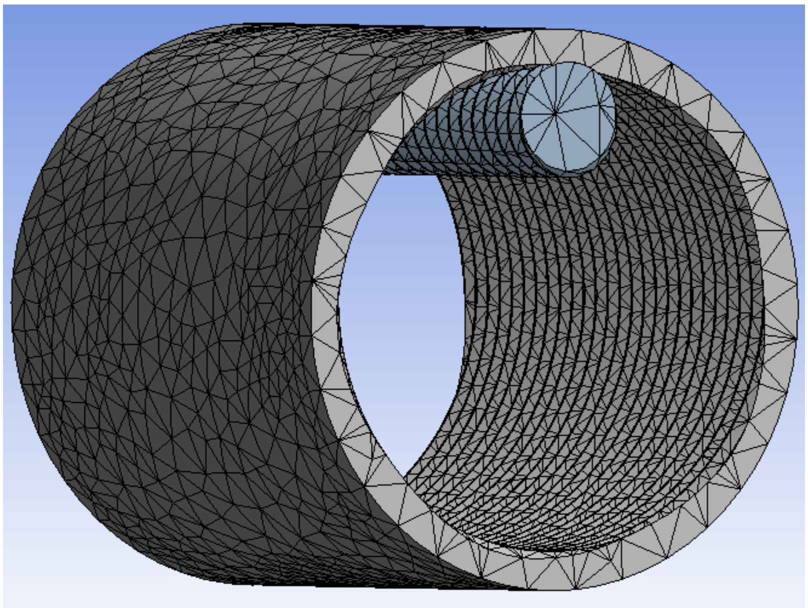

Figure 2.5 Meshing nut and roller

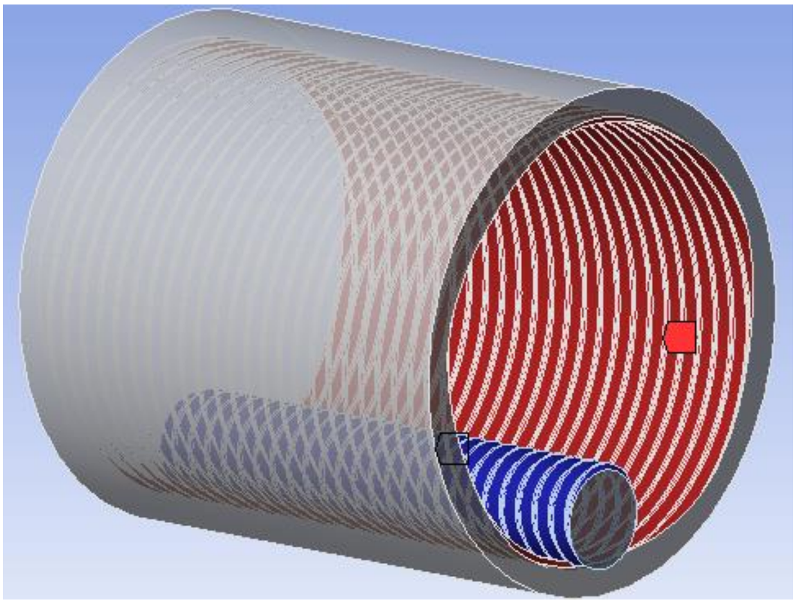

Figure 2.6 Contacts between nut and roller

While applying the load it is considered that the load is equally distributed on all rollers. For calculating the deformation body of the nut without threads is fixed while force is applied on the roller.

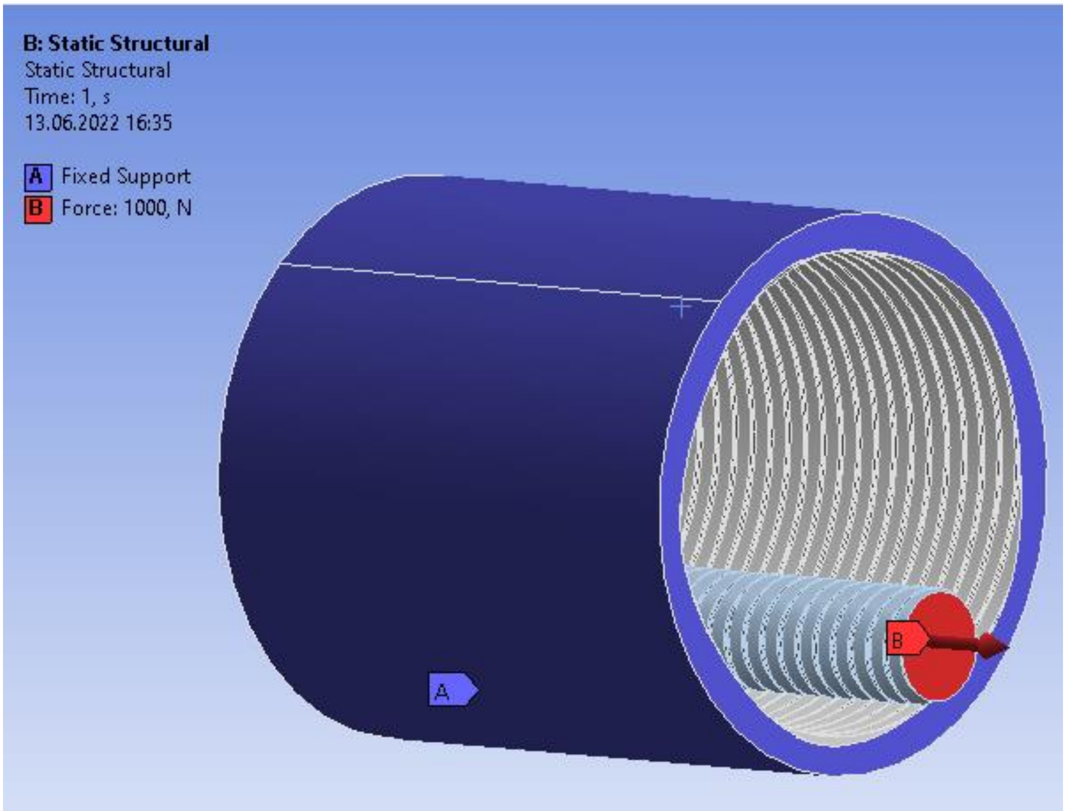

Figure 2.7 Boundary conditions of nut and roller

3. RESULTS & DISCUSSIONS

In this project, the effect of the change of pitch and material on the result was observed.

3.1 Effects of Changing Pitch

3.1.1 Screw and Roller

Table 3.1 The effect of changing pitch on maximum deformation and maximum stress.

Pitch (mm)	Maximum Deformation (mm)	Average Deformation (mm)	Maximum Stress (MPa)	Average Stress (MPa)
2.00	0.19718	0.095886	155.11	0.59826
2.50	0.350164	0.12028	160.96	0.8925
3.00	0.42071	0.20327	175.49	1.0968

As shown in the Table 3.1, Firstly, the pitch is 2.00 mm and the maximum stress is 155.11 MPa and maximum deformation is 0.19718 mm. When the pitch is increased to 2.50 and 3.00 mm and the maximum stress is also increased to 160.96 and 175.49 MPa and maximum deformation is also increased to 0.350164 and 0.12028 mm. Therefore, we can say the pitch increases maximum stress and deformation are also increase.

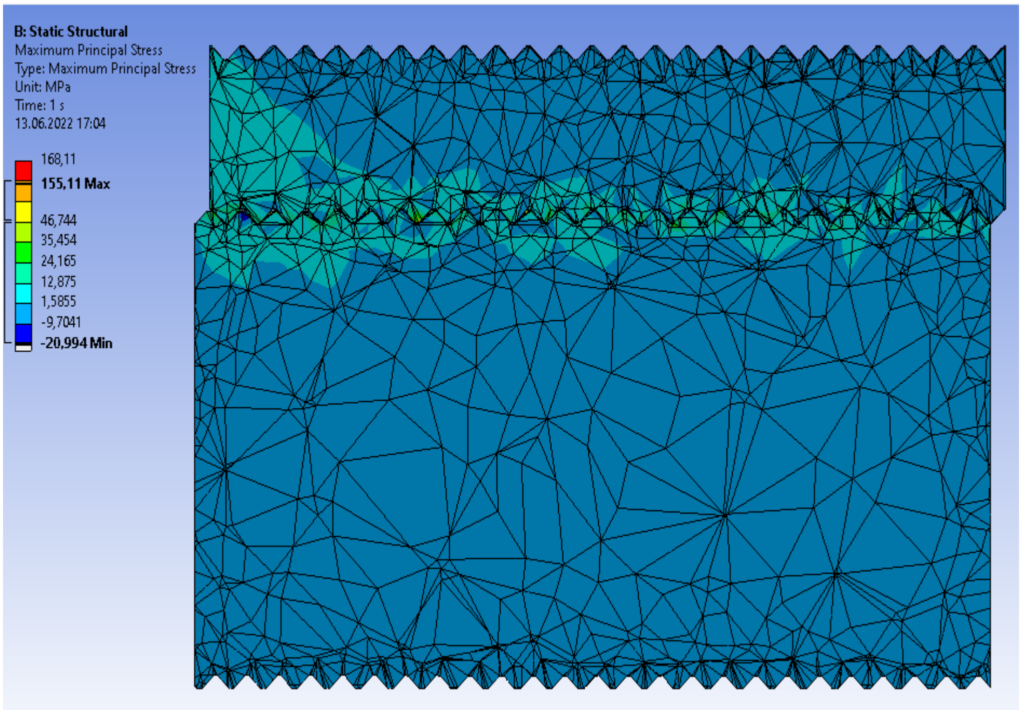

Figure 3.1 Maximum principal stress in screw roller arrangement

It is observed that the maximum stress occurs at the contact between the screw and the roller. It is also observed that the stress is high on the face where the force is applied. Furthermore, Figure 3.1 also shows that the stress on the roller decreases progressively in the opposite direction of the force applied.

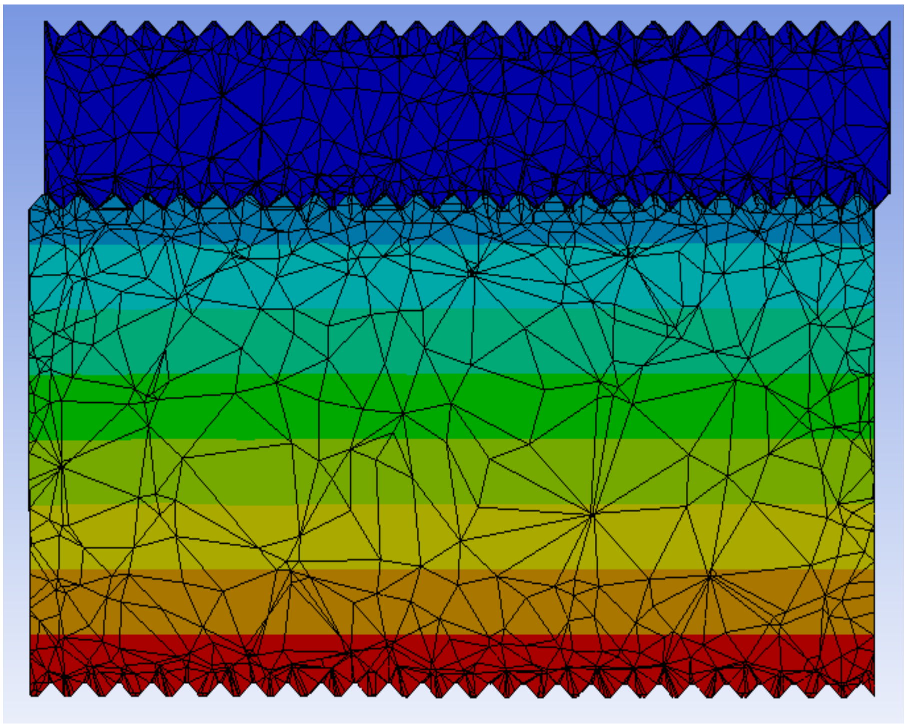

Figure 3.2 Total deformation of roller and screw

In general, the screw seems to increase as the deformation goes from the intersection of the two parts in the opposite direction. Still, since the mechanism is symmetrical, we used one roller, and if we consider it as if there are other rollers, the maximum deformation is in the middle of the screw.

3.1.2 Nut and Roller

Table 3.2 The effect of changing pitch on maximum deformation and maximum stress.

Pitch (mm)	Maximum Deformation (mm)	Average Deformation (mm)	Maximum Stress (MPa)	Average Stress (MPa)
2.00	0.001817	0.001641	57.96	0.29133
2.50	0.007373	0.00112	71.877	0.25197
3.00	0.013512	0.002384	82.988	0.33164

As shown in the Table 3.2, Firstly, the pitch is 2.00 mm and the maximum stress is 57.96 MPa and maximum deformation is 0.001817 mm. When the pitch is increased to 2.50 and 3.00 mm and the maximum stress is also increased to 71.877 and 82.988 MPa and maximum deformation is also increased to 0.007373 and 0.013512 mm. Therefore, we can say the pitch increases maximum stress and deformation are also increase same as screw and roller.

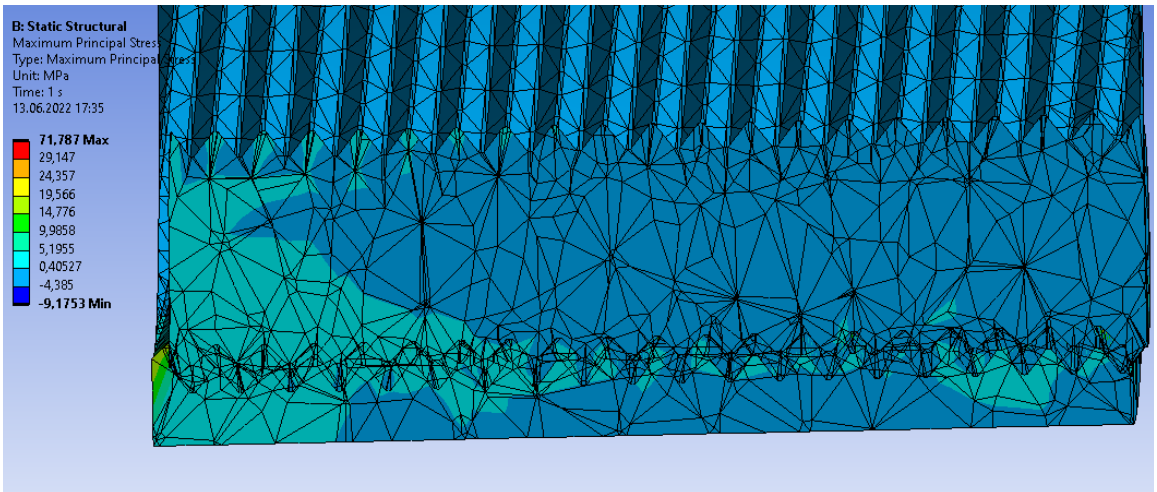

Figure 3.3 Maximum principal stress in nut roller arrangement

It is observed that the maximum stress occurs at the contact between the nut and the roller. It is also observed that the stress is high on the face where the force is applied. Furthermore, Figure 3.3 also shows that the stress on the roller decreases progressively in the opposite direction of the force applied.

3.2 Effects of Changing Material

3.2.1 Roller and Screw

Table 3.3 The effect of changing material on maximum deformation and maximum stress.

Material	Maximum Deformation (mm)	Average Deformation (mm)	Maximum Stress (MPa)	Average Stress (MPa)
Aluminum Alloy	0.54641	0.26572	161.5	0.592
Structural Steel	0.19718	0.095886	155.11	0.59826

3.2.2 Roller and Nut

Table 3.4 The effect of changing material on maximum deformation and maximum stress.

Material	Maximum Deformation (mm)	Average Deformation (mm)	Maximum Stress (MPa)	Average Stress (MPa)
Aluminum Alloy	0.037647	0.006403	85.679	0.32984
Structural Steel	0.013512	0.002384	82.988	0.33164

As seen in table 3.3 and 3.4 maximum stress is not changing when change the material. But when we look at the deformation structural steel is better than aluminum alloy.

4. CONCLUSION

The PRSM is a popular device with many important and critical areas of application, however, there has been little fundamental research to support its engineering application. Prior work has neglected to apply fundamental mechanics to form a foundational understanding of this device. In particular, most literature has failed to recognize that the contact point between the screw and the roller is not along the line of their centers, and no literature has provided a rigorous development of the contact geometries of the load transferring threaded surfaces of the mechanism. As a consequence, detailed analysis of aspects such as contact mechanics, friction, lubrication, and wear are not carried out correctly.

There are other critical issues missing from the literature: a kinematic understanding of the phenomenon of roller migration; a model for the overall stiffness of the mechanism; and equations of motion and detailed efficiency analysis. Thus, the scope of this thesis, mechanical properties, finite element analysis is not proven with the help of literature.

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