Dynamic characteristics analysis of a lead screw by considering the variation in thread parameters

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Abstract. A lead screw is a mechanical transmission device which transforms rotary motion into translational movement. The main elements are screw and nut which establishes connection among them by the means of threads on respective element. It plays a major role in transferring the load between screw and nut during the travel stroke. This paper investigates the behavior of the lead screw, inside the withdrawal part of the circuit breaker of switchgear, by analyzing the mechanical response of the lead screw system. The various thread parameters such as thread pitch, nominal diameter etc. play an important role in force transmission as well as in overall efficiency of the mechanical system. This study is done by creating models of various thread profile such a square thread, acme thread, trapezoidal thread and simulating the results in the finite element analysis software ANSYS Workbench. This paper focuses on the effect of the thread pitch, nominal diameter, helix angle, screw length on the stress state and deformation within the screw. Also, the influence of screw pitch, screw length and screw nominal diameter on the withdrawal part of the circuit breaker’s natural frequency along its whole stroke is carried out using modal analysis.

1. Introduction

Lead screw is a mechanical device used in power transmission defined by threads that transfer force between the nut and the screw. Lead screw drives are the simplest, most efficient, accurate and highly economical devices used for application that require precise motion and transmission of force. The most common thread profiles used in lead screws are square threads, trapezoidal threads, and acme threads. Square threads poses better efficiency but are weaker at the root. They are also costly to manufacture. From manufacturing perceptive, trapezoidal threads can be manufactured easily and thicker at the root of the thread and hence poses higher loading carrying capacity. Withdrawal devices housed within a medium voltage switchgear framework are periodically disconnected for maintenance, testing or replacement. This disconnection of the withdrawal device from the switchgear is known as “racking out”. The connection of the withdrawal device to the switchgear is known as “racking in”. For both of the above mentioned operations lead screw plays an important role. In this application, lead screw transfers the torque from the
motor (rotational motion), coupled to the screw shaft, to the nut, carrying the circuit breaker which moves linearly. The present system employs manual racking of the circuit breaker by the means of a handle. Manual racking is a laborious job and dangerous due to the potential for an arc flash. The operator who does the racking operation must wear protective equipment to prevent sudden arc flash, injuries or death. So an automatic racking mechanism is a better alternative. For this purpose, the design and dynamics of the lead screw, a vital element in the power transmission in the withdrawal part, is studied in the next session for the purpose of automation.

1.1 Background
Enormous research has been done to find the distribution of force in the threads of the lead screws as well the effects of thread parameter on the efficiency of transmission. Varanasi [1] developed a dynamics model of a lead screw system considering the inertia of screw along with the damping and compliance of bearing and nut. Dragoni [2] studied the effect of thread pitch and coefficient of friction on the stress concentration within the screw. Murphy [3] studied the distribution of load on a lead screw undergoing wear subjected to varying operating conditions. Pick and Burns [6] determined load distributions in threaded end closures by finite element method. Miller et al [7] modeled the threaded connection element by axisymmetric rings by springs to evaluate the distribution of load in threaded connections.

2. Design of lead screw
The main element in the withdrawal part is the lead screw which helps in racking in and racking out of the circuit breaker. So, the design of the lead screw is calculated in this section. Even the torque required to drive the mechanism including torque required for overcoming the friction is calculated. The lead screw in the withdrawal part of the withdrawal indoor type circuit breaker is constrained with the help of rotary bearings and rotated by a remote portable driver which houses a motor with a gearbox and coupling. The nut is attached to the carriage whose movement is constrained axially by sliding over fixed supports on either side. The end of the screw nearest to the drive motor is axially constrained to the base by means of a thrust bearing. Analyzing the mechanics including friction and inertia of the load to be positioned is the first step in determining the requirements of a motion control system.

![Figure 1. The schematic sketch of the lead screw system.](image)

![Figure 2. Trapezoidal move profile.](image)

According to the loading condition, bending theory and comparing in ANSI Standard table for threads $A_c = 519 \text{ mm}^2$, $d_c = 25.7062$ (26mm approx.), $d = 30\text{ mm}$, $p=3.5\text{ mm}$
Table 1. Formulas used in the design.

| Formula                                      | Value       |
|----------------------------------------------|-------------|
| Load torque reflected to motor               | $T_r = \frac{F_i}{2\pi Pe} + \frac{\mu F_{pf}}{2\pi P}$ | 3.442588 Nm |
| Load torque due to friction                  | $T_f = \frac{F_f}{2\pi Pe}$                              | 1.996759 Nm |
| Maximum velocity                             |             | 8.2222*10^-3 m/s |
| Torque due to acceleration                   | $T_a = \left( \frac{J}{e} + J_{ix} + J_{cp} + J_{motor} \right) \frac{\omega}{I_a}$ | 0.035506 Nm |
| Peak Torque                                  | $T = T_r + T_f + T_a$                                   | 5.4745 Nm   |
| Rms Torque                                   | $T_{rms} = \sqrt{\frac{T_1^2 + \frac{T_2^2}{t_2} + \frac{T_3^2}{t_3}}{t_1 + t_2 + t_3}}$ | 1.9996 Nm   |

3. Modelling and Simulation

The withdrawal part which houses the lead screw system is modeled in CATIA V5 as shown in the figure 3 and is analyzed in ANSYS Workbench. The boundary conditions are fixed supports, a load of 2800N acting on the nut vertically downwards and a torque 6 Nm applied at the left end of the lead screw, which is shown in the figure 4.

Table 2. Parameters of the constructed lead screw drive for simulation.

| Parameters of the lead screw drive            | Value      | Units |
|-----------------------------------------------|------------|-------|
| Material of the lead screw                    | Structural steel | -     |
| Density $\rho$                                | 7850       | kg/m$^3$ |
| Modulus of elasticity $E$                     | 2x10$^{11}$ | Pa    |
| Poisson’s Ratio $\mu$                         | 0.3        | -     |
| Bulk Modulus                                  | 1666666666666.667 | Pa    |
| Shear Modulus                                 | 76923076923.0769 | Pa    |
| Root Diameter of screw $d_c$                  | 26         | mm    |
| Pitch Diameter of screw $p$                   | 3.5        | mm    |
| Nominal Diameter of screw $d$                 | 30         | mm    |
| Screw length                                  | 370        | mm    |
| Inertia of lead screw $I$                     | 0.0354375  | kg m$^2$ |
| Mass of load $m_l$                            | 280        | kg    |
4. Results and Discussion

4.1 Influence of the screw length on the natural frequency
The effect of thread screw length on the natural frequency of the system is depicted in figure 5. The thread profile is square of pitch 3.5mm and the position of the nut is at the center of the lead screw. The parameters for simulation are from table 2 with a change to the lead screw length (300mm/350mm/400mm/450mm). The natural frequency decreases with screw length. For the lower range of screw length, all the frequency mode values indicate relatively high variation in natural frequency value. While on further increasing the screw length, the variation in the magnitude of the natural frequency decreases in case of Mode 1, Mode 2 and Mode 3.

![Figure 5. Natural frequency variation for different screw length](image)

4.2 Influence of the screw pitch on the natural frequency
The effect of thread pitch on natural frequency is illustrated in figure 6. The position of the nut is at the center of the screw and screw thread profile is square of different thread pitches, such as 2.5 mm, 3.5 mm, 4.5 mm, 5.5 mm and 6.5 mm. The other parameters used for the simulation are shown in table 2.

From figure 6 it is observed that the screw pitch has minimum influence on the value of the natural frequency. Moreover, as the pitch of the lead screw changes, the system frequency is not drastically affected. The various modes of natural frequency show the same trend with the lead screw having different pitch that is the natural frequency of the system shows slight decrease with increase in the screw pitch and after reaching a minimum value it again increases.

![Figure 6. Natural frequency variation for different screw pitch](image)

4.3 Influence of the screw nominal diameter on the natural frequency
Figure 7 shows the effect of the nominal diameter of screw of square thread profile, such as 29.1mm, 29.3mm, 29.5mm, 29.7mm, and 29.9mm, on the value of the natural frequency of the system. The screw is of square thread profile with thread pitch 3.5mm and the nut is located at the center of the screw. Other parameters for simulation are kept same as shown in table 2.
4.4 Influence of the position of worktable on the natural frequency

The natural frequency changes with the variation in worktable location as seen in figure 8. The thread profile considered is square of pitch 3.5mm. Other parameters for simulation are as shown in table 2. The trend seen is that the natural frequency increases as the worktable moves from the front support end to the center and decreases when the worktable moves further towards the rear support end.

![Figure 7. Natural frequency variation for the different screw nominal diameter]({fig7})

![Figure 8. Natural frequency variation for different position of worktable.](fig8)

4.5 Influence of thread pitch variation on stress distribution

The stress distribution is evaluated for the lead screw for different thread profiles with pitch ranging from 2.5mm to 5.5mm. The effect of pitch variation on stress values at different location of the nut along the screw is depicted in figure 9. The stress value decreases as the nut moves from left support end towards the center. Later it increases as it moves towards the right end support. As in case of all the thread profiles, the trend seen is similar. As the location of nut increases, the variation of stress values is significantly less near the center of the screw in all thread profiles. It is seen in three thread profiles that under the same loading condition, trapezoidal thread stress values are higher compared to square and acme profile at almost all location of the nut.

![Figure 9. Stress distribution on the lead screw due to variation in pitch in a) square profile b) acme profile c) trapezoidal profile.](fig9)

![Figure 10. Stress distribution on the lead screw with square profile of various pitch of a) 2.5mm b) 3.5mm c) 4.5mm d) 5.5mm.](fig10)
4.6 Influence of nominal diameter variation on stress distribution
The stress distribution is evaluated for the lead screw for different thread profiles of pitch 3.5mm with
nominal diameter ranging from 29.1mm to 29.7mm. The effect of nominal diameter variation on stress
values at different location of the nut along the screw is illustrated in figure 11. Similar trend as in the case
of variation of thread pitch is seen here also. The magnitude of stress in all the thread profile decreases
towards the center of the shaft and stress values increase as the nut approaches the other end support.

![Figure 11. Stress distribution on the lead screw due to variation in nominal diameter in a) square profile
b) acme profile c) trapezoidal profile.](image)

5. Conclusion
The present analysis is performed to study the effect of the change in thread parameters on the frequency
of the system and stress distribution. From study, it can be concluded that the parameters like screw
length, nominal diameter and worktable position remarkably affect the natural frequency of the system.
The amplitude of natural frequency of the system decreases with the change in screw length along the
stroke length. The change in thread pitch shows less influence on the natural frequency. The natural
frequency changes remarkably with the change in worktable position along the stroke length. The
amplitude of stress by varying the pitch decreased apparently with increase in movement of the nut
towards the center of the screw and further shows an increase as it moves to the rear end.

6. Reference
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