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Design Calculation of Precision Ball Screw for Portable CNC Machine

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Abstract

The demand for higher productivity and tight part tolerances requires machine tools to have faster and more accurate feed drive systems. As tried and tested technology, ball screw drive systems are still used in a majority of machine tools due to their low cost and high degree of stiffness. A high-speed ball screw drive system generates more heat and results in greater positioning error, adversely affecting the accuracy of machined parts. In this paper calculation has been done for selecting the Ball screw and there characteristics has been reviewed.

Keywords: Ball screw, Selection procedure, Design calculation, application etc.

I. INTRODUCTION

Ball screws, also called a ball bearing screws, recirculating balls screws, etc., consist of a screw spindle and a nut integrated with balls and the balls return mechanism, return tubes or return caps. Ball screws are the most common type of screws used in industrial machinery and precision machines. The primary function of a ball screw is to convert rotary motion to linear motion or torque to thrust, and vice versa, with the features of high accuracy, reversibility and efficiency.

Heat treatment is also used to ensure the hardness of our balls crews. These result in maximum load capacity and service life. Precision balls screws provide the most smooth and accurate movement, together with low drive torque, high stiffness and quiet motion with predictable lengthened service life

II. CHARACTERISTIC FOR SELECTION

A. *High efficiency and reversibility*

Ball screws can reach an efficiency as high as 90% because of the rolling contact between the screw and the nut. Therefore, the torque requirement is approximately one third of that of conventional screws Ball screws have super surface finish in the ball tracks which reduce the contact friction between the balls and the ball tracks. Through even contact and the rolling motion of the balls in the ball tracks, a low friction force is achieved and the efficiency of the ball screw is increased. High efficiency renders low drive torque during ball screw motion. Hence, less drive motor power is needed in operation resulting in lower operation cost.

B. *Backlash elimination and high stiffness*

Computer Numerically Controlled (CNC) machine tools require ball screws with zero axial backlash and minimal elastic deformation (high stiffness). Backlash is eliminated by special designed Gothic arch form ball track and preload. In order to achieve high overall stiffness and repeatable positioning in CNC machines, preloading of the ball screws is commonly used. However, excessive preload increases friction torque in operation. This induced friction torque will generate heat and reduce the life expectancy.

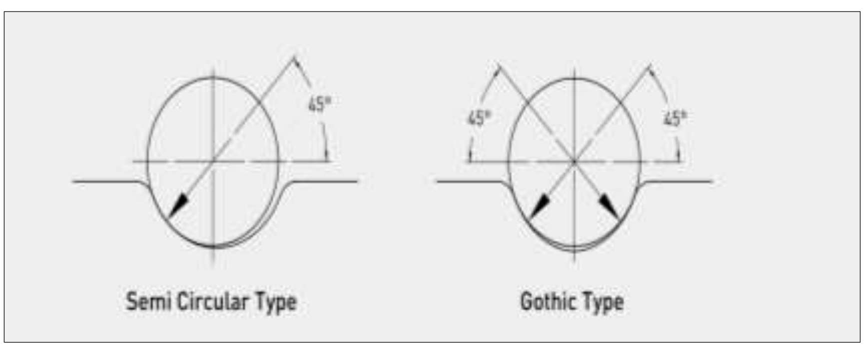


Fig. 1: Typical Contact type of ball screws

C. High Lead Accuracy

For applications where high accuracy is required, manufactures modem facilities permit the achievement of ISO, JIS and DIN standards.

D. Predictable life expectancy

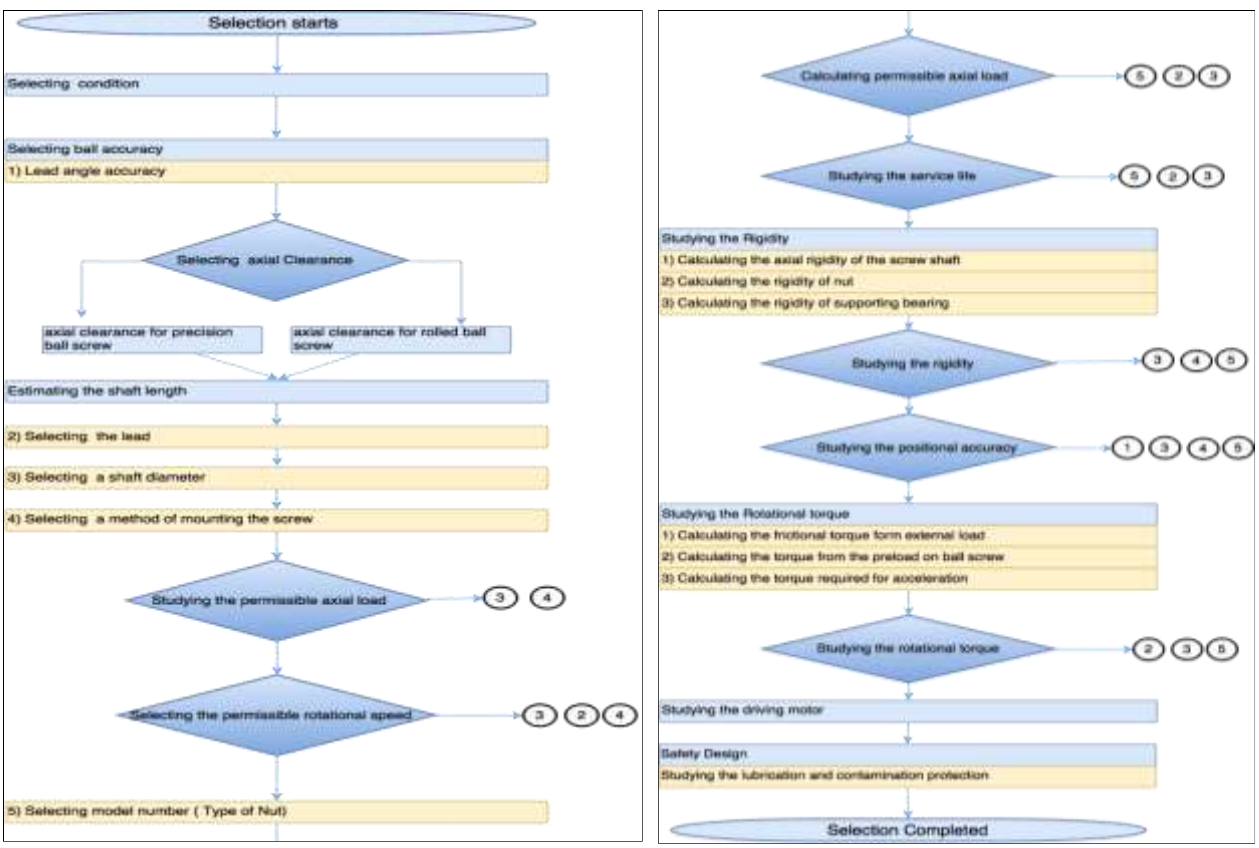
Unlike the useful life of conventional screws which is governed by the wear on the contact surfaces, ballscrews can usually be used till the metal fatigue. By careful attention to design, quality of materials, heat treatment and manufacture, ballscrews have proved to be reliable and trouble free during the period of expected service life. The life achieved by any ballscrew depends upon several factors including design, quality, maintenance, and the major factor, dynamic axial load (C).
Low staring torque and smooth running -Due to metal to metal contact, conventional contact thread lead screws require high starting force to overcome the starting friction. However, due to rolling ball contact, ballscrews need only a small starting force to overcome their starting friction.
Quietness- High quality machine tools require low noise during fast feeding and heavy load conditions.

III. Application

- CNC machinery: CNC machine canter, CNC lathe, CNC milling machine, CNC EDM, CNC grinder, special purpose machine, etc.
- Precision machine tools: Milling machine, grinder, EDM, tool grinder, gear manufacturing machine, drilling machine, planer, etc.
- Industrial machinery: Printing machine, paper-processing machine, automatic machine, textile machine, drawing machine, etc.
- Electronic machinery: Robot measuring instrument, X-Y table, medical equipment, factory automation equipment, etc.
- Transport machinery: Material handling equipment, elevated actuator, etc.
- Aerospace industry: Aircraft flaps, thrust open-close reverser, airport loading equipment etc.
- Miscellaneous: Antenna leg actuator, valve operator, etc.

IV. Design calculation for selection

A. Flow Chart for selecting the Ball screw



B. *Input parameters for selection*

Input	For Horizontal	unit
Table Mass (M1)	6	kg
Work Mass (M2)	10	kg
Stroke Length (Ls)In Mm	350	mm
Maximum Speed (V)Max	0.15	m/s
Acceleration Time (T1)	0.1	sec
Deceleration Time (T3)	0.1	sec
Nu Of Reciprocation Per Unit	2	per min
Backlash	0.01	mm
Position Accuracy ±	0.3	mm/1000mm
Position Repeatability ±	0.005	mm
Minimum Feed Amount (S)	0.02	mm/pulse
Desired Service Life Time	30000	hr
Driving Motor	servo/stepper	
Inertial Moment Of Motor Jm	0.001	kg.m2
Reduction Ratio (A)	1	
Friction Coefficient Of Guide Surface (μ)	0.003	rolling
Guide Surface Resistance (F)	5	n

1) *Selecting the condition:*

Selecting condition means selecting proper input parameters to get desired output. Condition Parameters are as stated in table.

2) *Selecting lead angle and axial clearance:*

- Selecting ball screw accuracy: To achieve position accuracy ± 0.09 /300 by looking manufactures catalogue, C5 class Ground Ball screw meets desired and having ±0.05/300 mm accuracy.
- Selecting the axial clearance: To satisfy backlash 0.01 it is necessary to select ball screw with an axial clearance of 0.01mmor less. 16 mm dia. Shaft is selected as per catalogue

3) *Selecting the shaft diameter:*

AS per standard catalogue of PMI and THK to satisfy the axial clearance the dia. Of shaft must be 16mm of less. Therefore for 16 mm dia. Shaft the nut length will be 42mm and as per CAD model shaft end length required is 108 therefore

Shaft length = Ls+ Nut length +shaft end length

= 350+42+108 = 500 mm

Rotational speed generally required for shaft is consider as 3000

Then, Lead $= \frac{\text{V max} * 1000*60}{\text{Rotational speed}}$

$= \frac{0.15*1000*60}{3000}$

= 3 mm

Therefore the lead to be select 3 mm or higher

4) *Selecting mounting method:*

Since the assumed type has a long stroke length of 350 mm and operates at high speed of 0.15 m/s, select either the fixed-supported or fixed-fixed configuration for the screw shaft support.

However, the fixed-fixed configuration requires a complicated structure, needs high accuracy in the installation.

Accordingly, the fixed-supported configuration is selected as the screw shaft support method.

5) *Studying the Permissible axial Load:*

The calculation table for permissible axial load is as follows

Studying permissible Axial load		
Calculating maximum axial load		
Acceleration α= Vmax /t1	1.5	m/s2
During forward acceleration Fa1= Fa1=μ (m1+m2)g +f+(m1+m2)α	29.47	N
During forward uniform motion Fa2=μ (m1+m2)g +f	5.47	N
During forward deceleration		
Fa3=μ (m1+m2)g +f-(m1+m2)α	-18.53	N
During Backward acceleration		
Fa4= -μ (m1+m2)g -f-(m1+m2)α	-29.47	N
During uniform backward motion		
Fa5=-μ (m1+m2)g –f	-5.47	N
During Backward deceleration		
Fa6= -μ (m1+m2)g -f+(m1+m2)α	18.53	N
Thus Max axial load applied on ball screw is		

Fmax	*29.47*	*N*
Buckling load on screw shaft		
For Fixed -Free	*η 1 =*	*0.25*
	η 2 =	*1.3*
For Fixed- supported	*η 1 =*	*2*
	η 2 =	*10*
for Fixed-fixed	*η 1 =*	*4*
	η 2 =	*20*
Buckling is to be consider in between nut and bearing therefore total length is	*460*	*Fixed support config.*
Screw shaft thread minor dia. d1=	*12.7*	
Buckling load on screw shaft p1=	*12294.17018*	*N*
Compressive & Tensile load of the screw shaft		
P2=	*116 xd1^2*	
P2=	*18709.64*	*N*
Thus, the buckling load and the permissible compressive and the tensile load of the screw shaft are at least equal to the maximum axial load. Therefore, a Ball Screw that meets these requirements can be used without a problem.		

6) Studying the rotational speed:

For selecting shaft dia. And lead we must consider the permissible rotational speed and dangerous speed of the selected shaft is it fails select next lead for same shaft dia.

The calculation for permissible speed and dangerous speed is as follows

Studying permissible Rotational speed		
Max Rotational Speed		
Screw shaft dia.	*16*	*16*
Lead	*3*	*5*
N max.=	*Vmax x60 x10^3 /lead*	
N max. in min -1	*3000*	*1800*
Permissible Rotational speed Determine by the dangerous Speed of the Screw		
For Fixed -Free	*λ1=*	*1.875*
	λ2=	*3.4*
For Supported - supported	*λ1=*	*3.142*
	λ2=	*9.7*
for Fixed-Supported	*λ1=*	*3.921*
	λ2=	*15.1*
For Fixed-Fixed	*λ1=*	*4.73*
	λ2=	*21.9*
Shaft dia 16, lead 5 mm	*d1=*	*12.7*
N1= λ2 x (d1/lb^2)x 10^7	*9062.854442*	*min-1*
Thus with ball screw having 16 mm dia. and lead 5 mm , Permissible Rotational Speed is less than that of Dangerous speed, Therefore shaft of dia. 16 mm and lead of 5 mm selected As per catalogue FSIC model selected		

7) Selecting the type of nut:

The nut must have high accuracy, flange at one end lead of 5 mm, optimum number of circuits to circulate the balls, and 3 number of rows, Therefore as per PMI catalogue "5T3" is selected.

8) Calculating the permissible axial load:

Studying the permissible axial load for model R16- 5T3-FSIC, the calculation is as Follows

Studying permissible Axial load of selected Screw		
Basic Static load rating(C0a) in KN =(Seeing catalogue)		*12.16*
axial load =C0a/Fs (safety factor)		*4.864*
	In Newton	*4864*
Calculating Travel Distance in mm		
Travel dist.mm During Acceleration L(1,4) $= Vmax * \left(\frac{t1}{2}\right) * 10^3$		*7.5*
Travel dist. during uniform motion		
L(2,5)in mm=ls-(Vmax X t1 +Vmax Xt3)/2 X10^3		*335*
Travel During Deceleration		
L(2,6) in mm= Vmax Xt3/2 X10^3		*7.5*
Then the Load and Travel Table is Below		
Motion	*Applied load Fan(N)*	*Travel Dis. Ln(mm)*
During Forward acceleration.	*29.47*	*7.5*
During Forward uniform motion	*5.47*	*335*

During for. Deceleration.	*-18.53*	*7.5*
During back. Acceleration.	*-29.47*	*7.5*
During uniform back. Motion	*-5.47*	*335*
During back. Deceleration.	*18.53*	*7.5*
Average axial load		
In Positive Direction in N		
Fm1= Cube root of ((fa1^3 x l1 +Fa2^3 xl2 +Fa6^3 x l6)/(l1+l2+l3+l4l+l5+l+6) Consider Fa3,4,5=0 N	*7*	
In Negative Direction in N		
Fm2= Cube root of ((fa3^3 x l1 +Fa4^3 xl2 +Fa5^3 x l6)/(l1+l2+l3+l4l+l5+l+6) Consider Fa1,2,6=0 N	*-7*	
	7	

9) *Studying the service life*

The Ball Screw in motion under an external load receives the continuous stress on its raceways and balls. When the stress reaches the limit, the raceways break from the fatigue and their surfaces partially disintegrate in scale-like pieces. This phenomenon is called flaking. The service life of the Ball Screw is the total number of revolutions until the first flaking occurs on any of the raceways or the balls as a result of the rolling fatigue of the material.

The service life of the Ball Screw is calculated from the following equation below using the basic dynamic load rating (Ca) and the applied axial load.

$$\mathrm{L} = \left(\frac{\mathrm{Ca}}{\mathrm{Fw} * \mathrm{Fa}}\right)^3 \mathrm{X} 10^6$$

L = Nominal life

Fw = Load factor

Ca = basic dynamic load rating

Fa = applied axial load

$$\mathrm{L} = \left(\frac{7502}{1.5 * 7}\right)^3 \mathrm{X} 10^6 = 2.97\ \mathrm{X} 10^{14} \text{ rev.}$$

Average revolution per min:

$$\mathrm{N_m} = \frac{2\mathrm{nl_s}}{\mathrm{Lead}} = \frac{2\ \mathrm{x}350\mathrm{x}2}{5} = 280\ \mathrm{min}^{-1}$$

Service life:

$$\mathrm{L_h} = \frac{\mathrm{L}}{5\ \mathrm{xN_m}} = 17697453871\ \mathrm{hrs}$$

Service life in travel distance:

$$\mathrm{L_s} = \mathrm{L\ X\ lead\ X}\ 10^{-6} = 1486586125\ \mathrm{Km}$$

V. CONCLUSION

The paper discusses about the Ballscrew, a high accuracy and precision motion is obtained. It has various advantages like High efficiency and reversibility, Backlash elimination and High Stiffness, High lead accuracy, Predictable Life Expectancy, Low starting torque and smooth running, Quietness, etc. The methods of Preloading of Reciprocating Ballscrew that consists of Double nut preloading, Single nut preloading. Ballscrews are used on various machine tools such as CNC Machining Centre, CNC Lathe, Industrial robots, Semiconductor machines, other machines like Measuring machine, Transporting machine, welding machine, etc., Selection criteria of Ballscrew, Basic Calculations of Ballscrew like Analysis of rigidity, Calculating permissible axial load, studying the critical speed, Service life, calculating led, selecting shaft diameter its length has been calculated for portable CNC machine

After looking in to manufacturer catalog R16-5T3-FSIC-350-500-0.018 has been selected. Which elaborate as R16 means Shaft having diameter 16 mm. 5T3 means lead of 5 mm one circuit and 3 rows of balls. FSIC means Flange type Single nut Internal Circulation precision ground thread having accuracy 0.018mm.350 is thread length in mm and 500 is total length of shaft in mm.

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