

Impact of Ball-Screw Pre-loading on Thermal Behavior Simulation of Vertical Machining Center During End-Milling Operation

[Sunilkumar S Honnunar^{*1a}, V Prabhu Raja², P R Thyla³, P Ganesan⁴]

Abstract— Thermal drift at tool centre point (TCP) is caused mainly due to positional errors in feed drive system of machine tool. The important sources of these errors are frictional heat generated at contact areas such as ball screw-nut, bearing races and balls. In addition to this, heat losses of motor also contribute resulting in thermo-elastic deformation in feed drive system. The objective of the work presented here is to predict and analyse the thermal behavior at key locations of feed drive system by considering pre-load on ball-screw of feed-drive system. The boundary conditions in simulation were applied considering the losses incurred in bearing, nut as well in motor during end milling operation considering with and without pre-loading of ball-screw. The simulation model was developed and validated with the experimental data recorded on feed drive system of a Vertical Machining Center (VMC) considering non-cutting operation prior to this. The developed model may be used for design optimization of feed drive system. The virtual method explored here also avoids lot of physical experimentation that would have been conducted for knowing thermal behaviour of feed drive in machine tool with and without considering pre-loading of ball-screw.

Keywords— Machine Tool; Simulation; Thermal Error; Ball-screw system; Finite Element

I. Introduction

Ball-screws of feed drive system in machine tools have become popular due to their low friction coefficient and high stiffness characteristics [1]. However, their utility has been further explored by increasing the speeds to reduce the non-cutting time. Eventually the increased speeds of feed drives resulted in posing the challenges in power losses due to frictional transmission leading to lower positioning accuracy of the machine tool. If the sources of thermal errors in machine tool causing inaccuracies in the machined components are considered, next to spindle units feed drive system is a major heat source [2]. Accordingly, it is important to understand the thermal behavior of the feed drive system during cutting conditions. The literature review on feed drive system reveals that, researchers have focused on the thermal behavior of the ball screw feed drive system and compensation strategies to overcome the same. Multiple linear regression model was developed [3-5] for forecasting thermal deformation of ball screw feed drive system.

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Modified Lumped Capacity Method (MLCM) based on fundamental energy conservation equation was developed by Kim and Cho [6] to determine the temperature profile of CNC lathe feed drive system. A parametric program using ANSYS package in APDL language was developed by Horejs Otakar [7] to characterize the displacement of bearing housing due to thermo structural properties. The ANSYS simulation was done on simplified feed drive model of vertical machining center and the simulated results were found to be in good agreement with experimental values after modifying the convective boundary conditions [1]. However, the simulation was done for only non-cutting cycle.

Several authors have contributed in predicting temperature as well deformation patterns of ball screw system using FEA packages, not much work has been done on simulation of feed drive system considering cutting action with pre-loading of ball-screw feed-drive system. The main objective of this paper is to analyse and understand thermal behavior at different components of feed drive system considering end milling operation along with pre-loading effect. The classical approaches were used in determining the heat generated in bearing, motor and screw-nut pair. The thermal boundary conditions were obtained using Fourier's law. The temperatures at different locations of feed drive systems were obtained experimentally with PT-100 temperature sensors interfaced with LAB-VIEW software during non-cutting operation.

II. Thermal Error Analysis

There are two basic thermal error modes, namely, thermal expansion and thermal bending of machine element resulting from thermal error factors [8]. Even then, as the machine structure has large assemblies it is still not easy to determine the influential error modes [9]. As the objective of this paper is ball screw analysis alone and hence the following sections deal with the feed drive system only.

III. Experimental set-up

A horizontal X-axis feed drive system of a VMC has been considered for thermal analysis. The main components of feed drive system are ball screw-nut pair, Linear Motion (LM) guide ways, servo motor, and support bearings. The experimental set up and placement of temperature sensors is as shown in Figure 1. Platinum Thermister-100 (PT-100) resistance type thermal sensors were interfaced with LABVIEW for recording the temperatures during non-cutting

operation on VMC. The temperatures were recorded at every 250 seconds of operation starting with non-cutting operation till stopping of the machine and continued further up to 9300 seconds.

For clarification of feed-drive system along with thermal sensor interface, a CAD model is shown separately in Figure 2. Figure 3 above gives the loading cycle considered for non-cutting operation on VMC.

The details of end milling operation considered in this research work as a case study for simulation are as mentioned below [10], material considered for estimating the cutting forces is hard CI (material to be cut), milling cutter diameter 40 mm with 300 helical, four fluted carbide cutter. Rough cutting operation has been considered for force estimation with 3 mm depth of cut, 0.3 mm/tooth feed-rate, and 38 m/min cutting speed. The job length to be cut is 150 mm with 2 mm tool approach.

Further, two dimensional force analysis was considered as axial force in end milling operation does not contribute in power loss of feed drive system. The flute engagement is the main criteria in end milling operation [11]. Accordingly, the cutting forces due to machining operation are transferred to end support bearings through screw-nut pair of feed drive

system. These cutting forces further result in heat generation in motor, support bearings as well at ball screw-nut pair. The cutter movement path and velocity profile are as depicted in Figure 4(a) and Figure 4(b) respectively. In Figure 4(b), “-ve” velocity indicates the velocity of cutter during backward machining cycle. The cutting force analysis has been done considering a radial depth of cut much lesser than the milling cutter radius ($\ll 50\%$). Table 1 gives the details of operation cycle. The empirical relation for the tangential force in end milling operation as per Kovan [9] is given in Eq.1,

$$F_t = Ch^X S_z^Y Zb^P D^q \quad (N) \quad (1)$$

where, C is constant that depend upon tool material, h is depth of cut, S is feed rate per tooth, Z is number of teeth on cutter diameter, b is chip width, D is cutter diameter and X, Y, p and q are constants that depends upon the material to be cut. The radial force component is as given by Eq. 2,

$$F_r = 0.15 F_t \text{ to } 0.25 F_t \quad (N) \quad (2)$$

where, F_t is tangential force and F_r is radial force. The average axial force was calculated considering positive and negative axial forces (forward machining and backward machining cycles) using Eq.3-5.

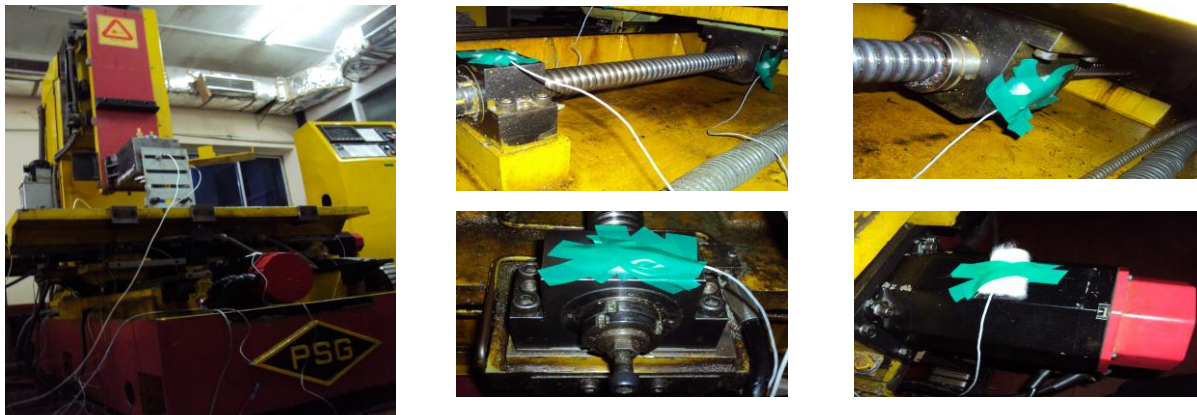


Fig.1 Experimental set up and placement of PT-100 Sensors on key locations of feed drive system

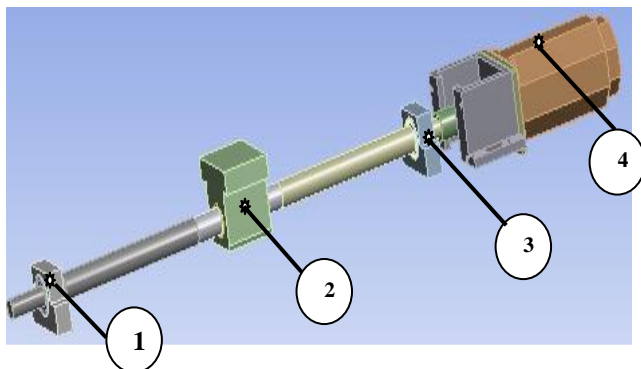


Fig.2 Placement of PT-100 Sensors on Feed Drive System during Experiment

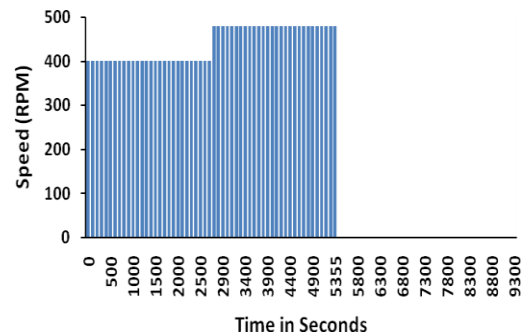


Fig.3 Loading Cycle Selected During Non-Cutting Operation on VMC

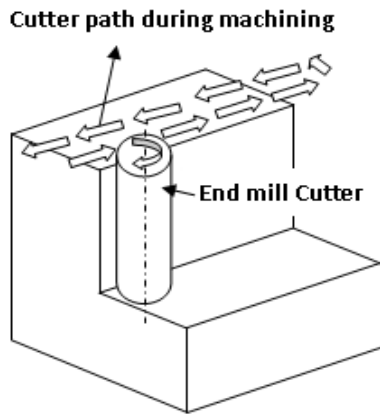


Fig.4 (a) Movement of Cutter During End Milling

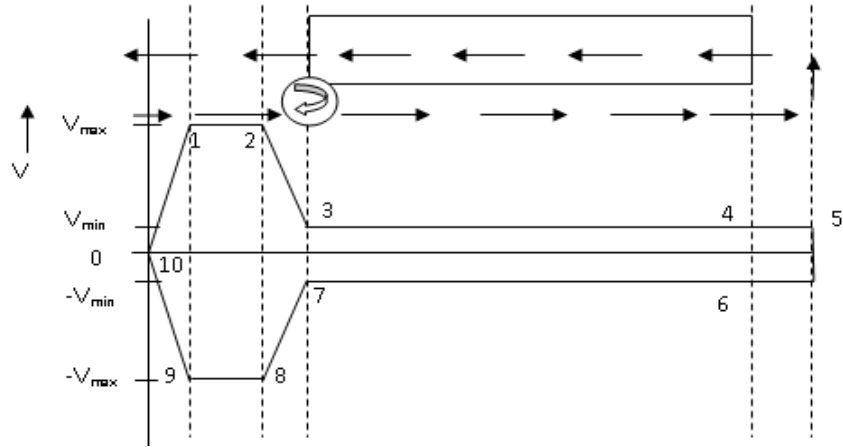


Fig.4 (b) Velocity Profile During End Milling

$$\text{Positive axial forces} = F_{a+} = \sqrt[3]{\sum_i \frac{F_{ai+}^3 l_{i+}}{l_i}} \quad (\text{N}) \quad (3)$$

$$\text{Negative axial forces} = F_{a-} = \sqrt[3]{\sum_i \frac{F_{ai-}^3 l_{i-}}{l_i}} \quad (\text{N}) \quad (4)$$

where, F_i is inertia force, F_f is frictional force at machine slides at tool tip and l_i is length of cut. $F_{a1}, F_{a2}, \dots, F_{a10}$ are axial forces during respective cutting cycle.

$$\text{Mean axial Force} = F_m = \frac{F_{a+} + F_{a-}}{2} \quad (\text{N}) \quad (5)$$

The estimated axial forces considered for evaluating boundary conditions for simulation are as mentioned in Table 2 with and without considering pre-loading of ball screw.

Table 1 Details of Machining Cycle

Sl No	Cycle Step	Details (For forward and backward machining respectively)
1	0-1 & 7-8	Acceleration cycles with variable speed during
2	1-2 & 8-9	Maximum speed cycles
3	2-3 & 9-10	Deceleration cycles with variable speed
4	3-4 & 6-7	Machining cycle with constant speed
5	4-5	Over travel cycle during forward machining.
6	5-6	Depth of cut during backward cycle.

A. Heat generation in bearings

The main source of heat generation in a rolling bearing is the contact between rolling element to race. According to Palmgren [12] the heat generation in bearing is due to two important parameters namely, load independent friction moment and load dependent friction moment.

The empirical relations of the same are as mentioned in Eq.6 (a-b), Eq.7 respectively,

$$M_0 = 10^{-7} f_0 (\gamma * n)^{2/3} d_m^3 \quad (\text{N} - \text{mm}) \quad \text{if,} \quad (6a)$$

$$\gamma * n > 2000$$

$$M_0 = 160 \times 10^{-7} f_0 d_m^3 \quad (\text{N} - \text{mm}) \quad \text{if} \quad (6b)$$

$$\gamma * n < 2000$$

Table 2 Estimated Axial Force Components Accounting End-Milling Operation (With & Without Considering Pre-Loading of Ball-Screw)

Sl. No	Axial Force (N)	Total Axial Force (N) (Without Pre-Load)	Total Axial Force (N) (With Pre-Load)	Machining Contour length (mm)
1	F_{a1}	$F_i + F_f = 576$	1576	$l_1 = 5$
2	F_{a2}	$F_f = 8$	1008	$l_2 = 10$
3	F_{a3}	$-F_i + F_f = -560$	440	$l_3 = 5$
4	F_{a4}	$F_m + F_f = 212$	1212	$l_4 = 150$
5	F_{a5}	$F_f = 8$	1008	$l_5 = 2$
6	F_{a6}	$-F_f = -8$	992	$l_6 = 3.5$
7	F_{a7}	$-F_m - F_f = -212$	788	$l_7 = 15$
8	F_{a8}	$-F_i - F_f = -576$	424	$l_8 = 5$
9	F_{a9}	$-F_f = -8$	992	$l_9 = 10$
10	F_{a10}	$F_i - F_f = 560$	1560	$l_{10} = 5$

$$M_1 = f_1 F_\beta d_m \quad (N - mm) \quad (7)$$

where, M_0 = Moment due to viscous friction (N-mm),
 f_0 = Factor that depends upon type of bearing and lubrication,
 f_1 = Factor that depends upon type of bearing and lubrication,
 γ = Kinematic viscosity of oil (mm²/s), n = Bearing speed in rpm, d_m = Bearing pitch diameter (mm), M_1 = Load dependent frictional moment because of imperfect mechanical bodies under load.

The empirical relation for power loss (heat generation) H_g in ball bearings [11] is given by Eq.8,

$$H_g = 1.047 \times 10^{-4} n M_T \quad (W) \quad (8)$$

The total torque M_T is given in Eq.9,

$$M_T = M_0 + M_1 \quad (N-mm) \quad (9)$$

B. Heat generation in ball screw pair

As the nut traverses over a specific zone with a shaft rotating with a constant speed, the heat generated by the nut is assumed to be distributed on a specific zone [13]. When the nut traverses between a_1 to a_2 , the distributed heat input is given by the empirical relation [14] as in Eq.10,

$$q_{nut} = \frac{n\pi}{30} T_f Z_m \frac{a_2 - a_1}{L} \quad (W) \quad (10)$$

where, T_f = Frictional torque = $PF/2\pi\eta$ (N-m), P = Screw lead (mm), F =frictional force (N), η_{screw} = Feed screw efficiency, Z_m = Motion ratio= Linear movement of nut/ rotary movement of screw= $10/2\pi$, $a_2 - a_1$ =Length of nut travel, L = Total screw length (mm).

C. Heat generation in motor

The main sources of power loss in electric drives are, the heat generation in rotor and stator. With the knowledge of speed and torque, motor heat generation (q) can be calculated by the empirical relation [15] is as given in Eq.11,

$$q = 2\pi f_{motor} T_{motor} \left[\frac{1 - \eta_{motor}}{\eta_{motor}} \right] \quad (W) \quad (11)$$

where, f_{motor} = Motor frequency (Hz), η_{motor} = Motor efficiency. The efficiency of motor [16] was considered as 84% in Eq.11.

D. Heat dissipation from structure

The convective heat transfer is estimated considering the feature size and mean velocity of fluid with respect to surface of features. Due to complexity involved in mathematical modeling of the heat transfer through lubricant, the same is being not considered here; instead it was assumed that heat is transferred by convection from surfaces of bearing races to surroundings. Further, it is assumed that the surfaces of bearing races are being unwrapped and flow of air assumed over flat surfaces [17]. The Reynold's number is given in Eq.12,

$$R_e = \frac{u_{fluid} d}{\gamma_{fluid}} \quad (12)$$

and the Nusselt number is given in Eq.13,

$$N_u = 0.133 R_e^{(2/3)} (P_r)^{(1/3)} \quad (13)$$

the equation is valid for, $Re < 4.3 \times 10^5$, $0.7 < Pr < 670$.

The convective heat transfer coefficient is then calculated using Eq.14,

$$h_{convt} = \frac{N_u}{d} \kappa_{fluid} \quad (W / m^2) \quad (14)$$

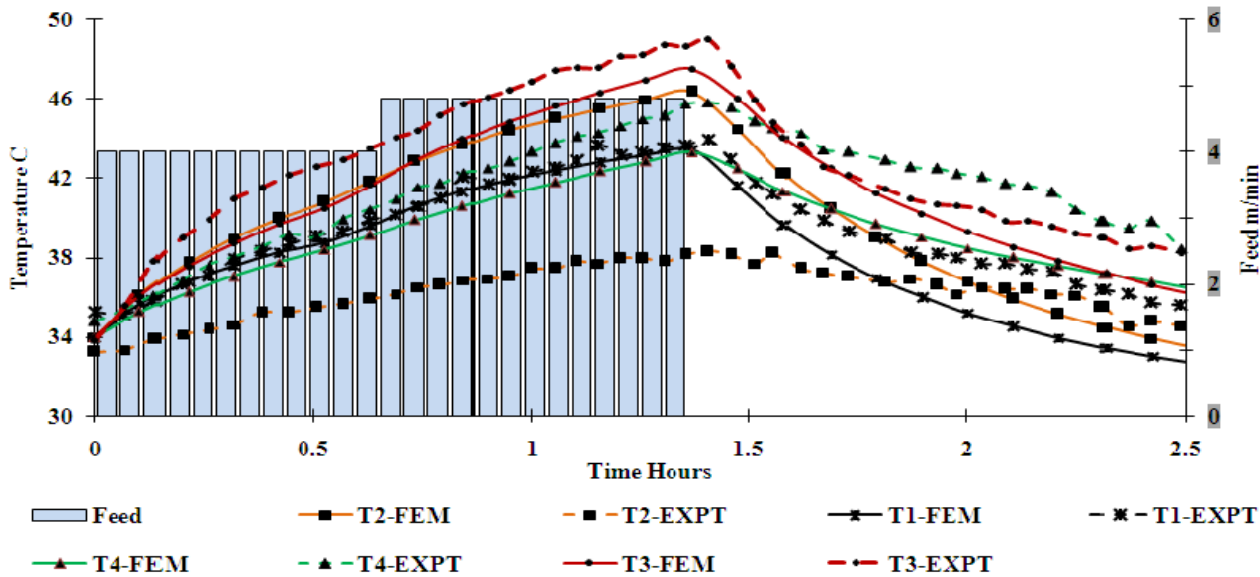


Fig.5 Experimental and simulated temperature distributions at key locations of feed drive system during non-cutting operation

where, K_{fluid} = Thermal conductivity of fluid and d is characteristics dimension (m). The convection coefficients were calculated at key points using equation 12 to 14 and applied as boundary conditions during simulation.

IV. Finite Element Modelling

For estimating the boundary conditions as given in the preceding sections, the feed drive system of machine is operated with the non-cutting cycle as mentioned previously in Table 1. The temperature probes were placed in simulation similar to the locations in experimental set up. Sweep meshing option of ANSYS-11 workbench was used with 20% adaptivity convergence criteria for verifying the solution accuracy. After meshing the feed drive system model there are total of 42595 elements and 99597 nodes. The convective heat transfer coefficient at bearing races, and nut surfaces were modified in order to correlate the simulation temperature obtained with that of experimental readings. Figure 5 depicts the comparison of temperature at key locations of ball-screw feed drive system between simulated and experimental results during non-cutting cycle captured at every 250 seconds till the end of cycle. It can be observed from Figure 6 that, temperature profiles at key points shows an increasing trend as the end milling operation continues till 5355 seconds and there after drops gradually as the cutting operation was put off after 5355 seconds.

A. Effect of Ball-Screw Pre-Loading

Pre-loading of ball screw is done to avoid axial play of feed-drive system. Pre-loading is generally specified by the manufacturer in their catalogue. As the pre-loading of the ball screw is increased, there will be increase in temperature of feed drive system further leading to axial inaccuracies of machined components. Figure 7-8 shows variation in heat generation during free spinning at key locations of ball-screw

feed drive system with and without pre-loading. There is nearly 32% increase in heat generation at bearings compared to with (1000N) pre-loading and without pre-loading considering end-milling cutting forces taken in both cases. Similarly, at ball-screw nut there is 30% increase in heat generation compared to without and with pre-loading force of 1000N.

V. Conclusions

The transient thermal simulation of feed drive was performed without much simplification of FEA model. The details of bearing, motor were modeled similar to physical details. The boundary conditions including heat generation and heat sinks were estimated by classical approach. The results of simulation were compared with that of experiments conducted on VMC with a varying load cycle. When the model is created without much simplification, the simulated temperature results are nearer to experimental readings. However, the convective heat transfer coefficient values were taken approximately 1.2 times that of estimated values. The proposed model has been tested for simulating the temperature behaviour assuming end-milling operation. It was noticed that, the temperature behaviour of feed drive is almost in line with that of non-cutting conditions.

Pre-load plays an important role in heat generation at bearing, nut as well as feed-drive motor. It is noticed that at support bearings and nut there is an increase in heat generation of 32% and 30% respectively when pre-loading effect is taken into account. However it is noticed that, the pre-loading of ball-screw system has more impact on motor heat generation. This is quite obvious that, the friction losses as well as inertia effect will directly impact upon motor.

The developed model may further be made use for design optimization in reducing the temperature effect of feed drive system under different machining conditions as well as pre-

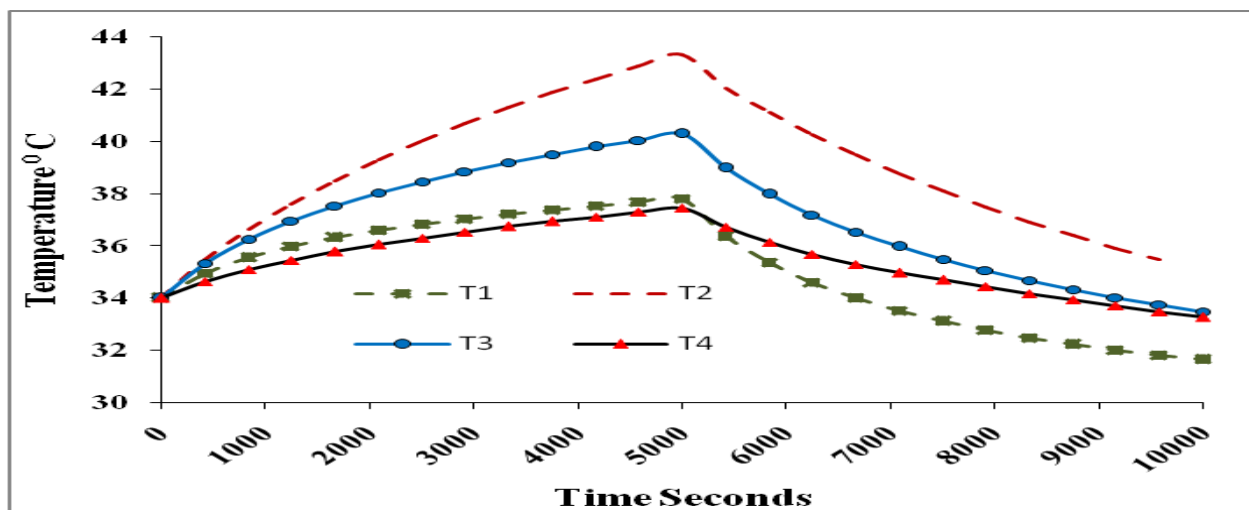


Fig.6 Temperature Distributions at Key Locations of Feed Drive System during Simulated End-Milling Operation

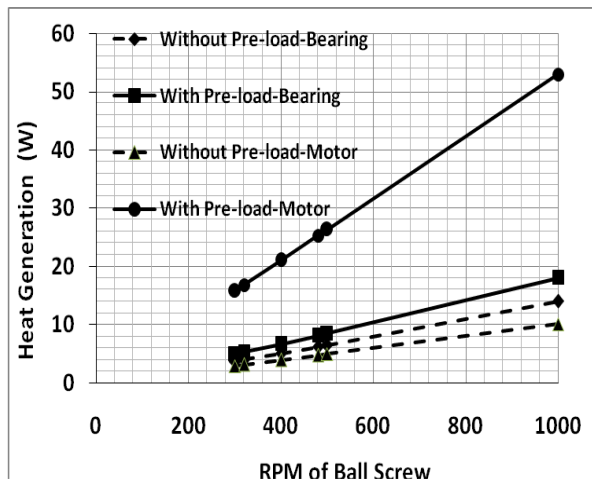


Fig.7 Effect on Heat Generation at Bearing and Motor with and without Ball Screw Pre-loading (with machining force taken into account)

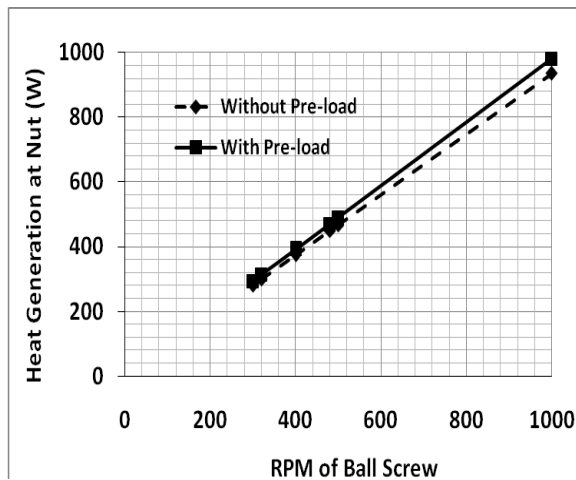


Fig.8 Effect on Heat Generation at Nut with and without Ball Screw Pre-loading (with machining force taken into account)

loading of ball-screw system. However, the complex cutting model may be tried further considering weight of heavy specimen. The cutting cycle considered in this study was for only two passes and also due to smaller specimen size the effect of specimen weight on radial force was assumed to be negligible.

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