www.atmia.put.poznan.pl

AMTM vol. 36 (2016) 1-6

Archives of Mechanical Technology and Materials

`

Sensorless compensation system for thermal deformations of ball screws in machine tools drives

Michał Kowal[a]

[a]*Poznan University of Technology, Piotrowo 3 Street, 60-965 Poznan, Poland*

e-mail address: michal.kowal@put.poznan.pl

A B S T R A C T

The article presents constructional, technological and operational issues associated with the compensation of thermal deformations of ball screw drives. Further, it demonstrates the analysis of a new sensorless compensation method relying on coordinated computation of data fed directly from the drive and the control system in combination with the information pertaining to the operational history of the servo drive, retrieved with the use of an artificial neural networks (ANN)-based learning system. Preliminary ANN-based models, developed to simulate energy dissipation resulting from the friction in the screw-cap assembly and convection of heat are expounded upon, as are the processes of data selection and ANN learning. In conclusion, the article presents the results of simulation studies and preliminary experimental evidence confirming the applicability of the proposed method, efficiently compensating for the thermal elongation of the ball screw in machine tool drives.

Key words: ball screws, thermal compensation, machine tools

1. INTRODUCTION

Achieving increased accuracy and productivity, while reducing the costs of production, of computer numerically controlled (CNC) machine tools requires application of new and better solutions in the areas of structural design, drive and control. Recent progress in structural design and transmission technology of ball screw drives has afforded considerable improvements in their functionality. Operating at increasingly higher velocities and of superior rigidity, the ball screw drives are now becoming an effective alternative to the direct drives [1, 2], particularly in machine tools characterized by short-length work paths. What is more, their utilization enables application of more reliable and less expensive indirect measuring systems (semi closed – loop control). Failure frequency of a direct measuring system (closed – loop control) is related to its close proximity to the machining area where it is exposed to the cutting fluid. However, abandoning the direct measuring system results in an increase in the total accuracy error, mainly stemming from the kinematic chain errors of the applied ball screw drive and the error associated with thermal expansion of its ball screw [3, 4, 5, 6, 7]. Total error occurs as a result of the active participation of the ball screw in the measurement of position of axis. Caused by thermal expansion, the pitch of the screw changes, which leads to an increase in the amount of kinematic errors of position of controlled axis [4]. Figure 1 shows the heating process of the ball screw during machine operation. It should be noted, as far as the thermal expansion coefficient of steel is concerned, that the increase of 5°C will cause an elongation of a meter-long rod by about 60 µm. Such an error is unacceptable for modern CNC machines and requires minimization.

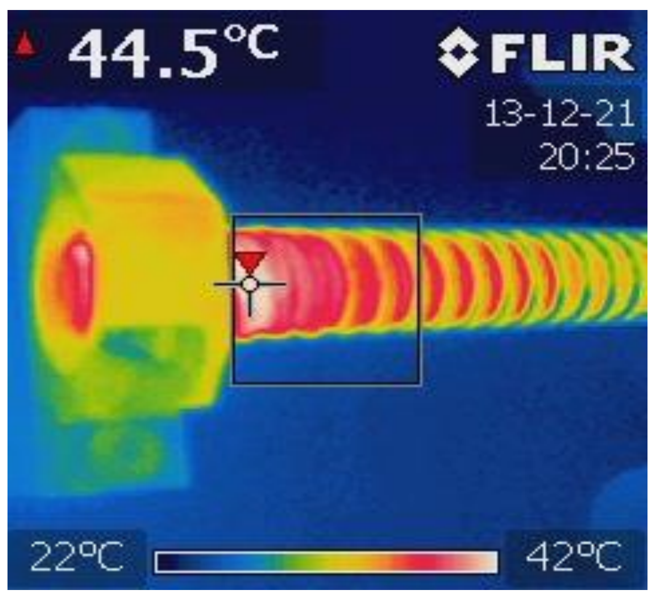

Fig. 1. Temperature distribution during the axis operating movement with traverse velocity of 20 m/min

There are many known methods to minimize the adverse effects of this phenomenon. Literature presents solutions through construction, operation, thermal stabilization and thermal compensation [6, 7, 8, 9]. The most commonly used are a direct measuring system, cooling of ball screw drive or pre-warming of the machine. Most of these methods allow for a significant improvement in positioning accuracy for medium and large machines. However, in the case of small and cheap machine tools, application of a direct measuring system – considering its very high costs is pointless. Furthermore, small heat capacity of the screws in this type of machine tools makes operational methods insufficiently effective [6]. High rate of change of the positioning error causes the implementation of effective methods of compensation for the ball screw drive's elongation to be absolutely mandatory. The real challenge is maintaining sufficient accuracy of the positioning of the axis perpendicular to the spindle axis of small lathes, where a positioning error generates an error twice the size on the work piece. Furthermore, the limited machining space locates the tool change in the axes' most extreme positions, thereby contributing to further increase of the amount of energy dissipated in the ball screw area, as a result of additional movements of the machine. Due to a great practical importance, this issue has been an interest of many research centers around the world and is a part of a new branch of the production of machine tools, the so-called economic machine tools. An efficient, universal, simple and inexpensive method for compensation of elongation of a ball screw drive is still sought-after [3, 4, 5, 6, 7, 10].

2. PROPOSED COMPENSATION METHOD

Analysis of the friction-caused energy dissipation in the screw-nut and the bearing units resulted in the formulation of a simplified assumption stating that the amount of the dissipated energy depends on the structure of the servo drive as well as the conditions of its work, i.e. the angular velocity and torque transmitted by the ball screw. The validity of this assumption was confirmed [11, 12, 13], resulting in the definition of relevant equations (1) and (2):

$$\dot{G}_{nut} = 0{,}12\pi f_0 \nu_0 n M, \tag{1}$$

where:

$\dot{G}_{nut}$ - amount of energy dissipated in the screw-nut unit [W],
f_0 - coefficient describing the type of nut and the method of lubrication,
ν_0 - viscosity of the lubricant [m²/s],
n – rotation speed of the screw speed [rpm],
M - total frictional moment in the screw-nut unit[Nm],

$$\dot{G}_{bearing} = 1{,}047x10^{-4} nM, \tag{2}$$

where:
$\dot{G}_{bearing}$ - amount of energy dissipated in the bearing unit [W],
n - rotation speed of the screw speed [rpm],
M – total rolling friction torque of the bearing [Nm].

The essence of the hereby proposed method of compensation of thermal deformations in the ball screw drive is the application of data concerning the real-time values of rotational speed and torque, as recorded by the control and drive units of the machine tools. This information, due to the sufficient measurement frequency, constitutes the foundation for the design of a thermal compensation model based on artificial neural networks (ANN) taught individually. It further allows determining the influence of the structural drive properties on the amount of dissipated energy. The author intends to prove the hypothesis that the analysis of the instantaneous torque and motor speed values affords the determination, with some approximation, of the amount of energy dissipated in the screw-nut unit and causing its elongation. Combined with the measurement of temperature, the proposed method facilitates effective description of the convection of heat within the system. The main advantage of the postulated approach is the absence of temperature and elongation measuring sensors from the surface of the tested object.

A ball screw drive can be treated as a semi closed loop system. The energy balance in such a system is graphically depicted in Figure 2 and mathematically described by the following equation (3):

$$\frac{dx}{dt} = p(t) - q(t), \tag{3}$$

where:
p(t) - amount of energy flowing into the system per unit of time,
q(t) - amount of energy flowing out from the system per unit of time.

The transmitted energy can be described as: 1) Q_t - energy supplied to the system as a result of friction in the screw-cap unit, 2) Q_u - energy discharged from the system by convection and 3) Q_p - energy supplied to the system and discharged from it by conduction from and to the neighboring units. The amount of energy supplied to the environment through radiation is negligible due to the very low associated temperature variation; the Stefan-Boltzmann law describes it as follows (4):

$$\dot{e} = \varepsilon\sigma T^4. \tag{4}$$

where:
$\dot{e}$– amount of energy radiated,
ε – emissivity,
σ – Stefan–Boltzmann constant,
T – absolute temperature.

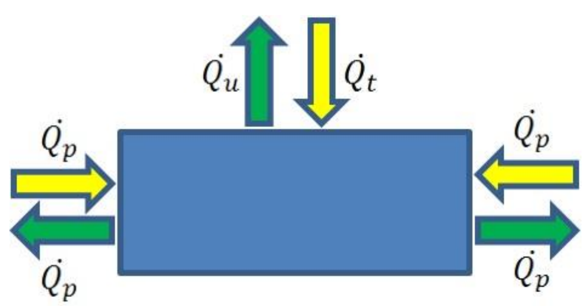

Fig. 2. Energy supplied to and discharged from the system (ball screw)

Due to the nature of their work, the effective compensation for thermal deformations of the ball screw drives in numerically controlled machine tools requires that the screw be divided into elementary segments (Figure 3). The compensation values are then determined on an individual basis, for each segment.

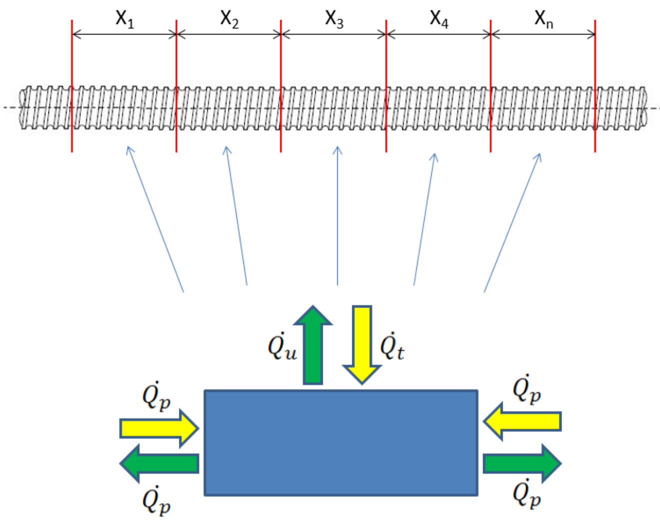

Fig. 3. Division of the drive screw into elementary segments

Each section model should satisfy the assumptions of the energy balance equation (3) of the ball screw drive.

The postulated compensation method facilitates continuous analysis of the velocity and torque transmitted by the ball screw drive. As established in an earlier individual tuning cycle performed for the ball screw, the proposed algorithm determines the change in length of the elementary section in a unit of time. Each elementary section is represented as a partial image of a pitch error array, available in most modern control systems. The elemental change in length is modified by the value of pitch error compensation, which affords effective compensation of thermal deformations without interference in the internal interpolator structure that, in turn, limits the contour errors of the workpiece. It is important that the new value of the pitch error compensation be not assigned in course of the cutting process, as step changes in compensation will introduce a contour error visible on the machined surface. Tool exchange processes provide viable opportunities to assign the new compensation values. These are quite frequent, especially in small-sized machines characterized by highly dynamic changes in the positioning error stemming from the thermal expansion of the ball screw drive.

3. PRELIMINARY TESTS

Preliminary studies aimed at the confirmation of the hypothesis that the compensation of thermal elongation of the ball screw drive based on the information recorded by the servo drive control system was possible. A test rig, consisting of a servo drive characterized by a travel length of 640 mm, was assembled. The applied control system was provided by Beckhoff Automation GmbH & Co. Elongation measurements of the ball screw drive were performed using the Renishaw XL-80 laser interferometer. Figure 4 shows the utilized test stand.

To determine the heating effect of friction on the ball screw drive as well as the impact of heat convection, the drive was uniformly heated along its entire length. Considering the entire ball screw drive as an elementary unit allowed simplification of the initial research model. This, in turn, justified the exclusion of conduction within the screw from further considerations.

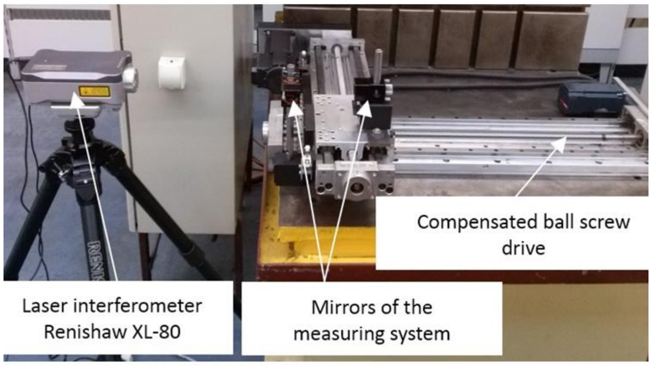

Fig. 4. The assembled test rig

3. 1. Energy transmitted to the elementary section as a result of friction

Relying on the previously adopted simplified assumption, it was established that the dissipated energy within the elementary section was a function of torque transmitted by the screw and its rotational speed (5):

$$\Delta Q_f = f_n(M, v), \tag{5}$$

where:
M - torque transmitted by the screw,
v – speed of the support carriage.

Based on the aforementioned assumptions, a compensation model was developed using a unidirectional artificial neural network characterized by two inputs (M, v), ten neurons in the input layer with the tansig activation function (hyperbolic tangent) and one neuron in the output layer with the purline (linear) activation function. The key step in the set-up of an ANN-based model is learning the designed structure [14]. In case of a model describing the amount of energy delivered to the ball screw drive, it becomes necessary to determine the range of the training data in which the value of convection is negligible. To reach this goal, the measurements were performed in a wide range of axis velocity values. Assuming that the convection value depends on the difference in temperature between the transmission media [15], the main focus was put on the initial stage of ball screw heating process.

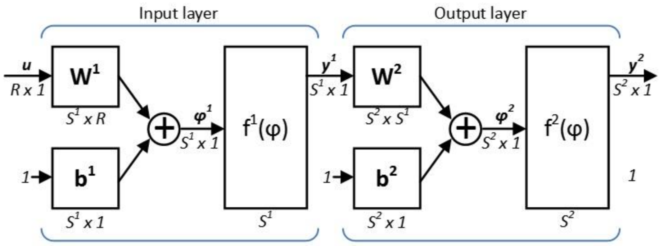

Fig. 5. Structure of applied artificial neural network

The first three measurement points, corresponding to the first three cycles of measurement, were approximated onto a linear function. Subsequently, the function describing the thermal extension was subtracted from the obtained line. Results of the performed operations are presented in Figure 6.

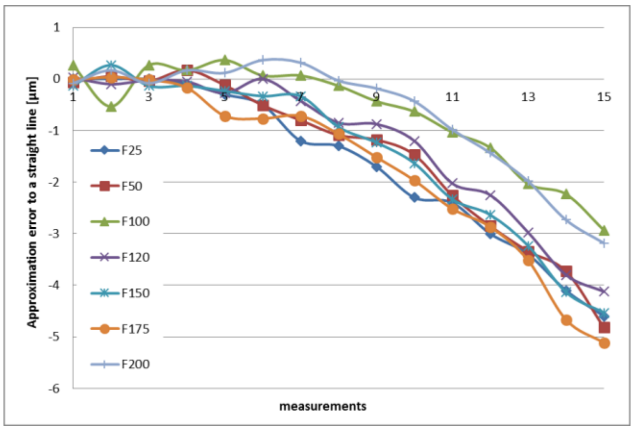

Fig. 6. Approximation error to the straight line observed in initial phase of heating ballscrew

The simulation clearly revealed that in the first phase of heating of the ball screw drive, where the error of approximation fluctuated around zero the convection was negligible. This is due to the fact that the energy supplied by the friction phenomenon $\dot{Q}_t$ is significantly greater than the amount of energy returned to the environment through convection $\dot{Q}_t$ in initial warming-up phase.

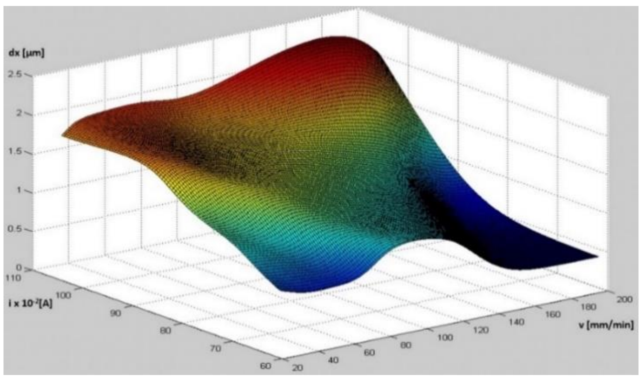

Fig. 7. Response of ANN describing the process of heating of a ball screw

This finding supported the implementation of the learning process of the artificial neural network, carried out with a specially selected set of training data. Results of the simulation of the artificial neural network response are shown in Figure 7.

3. 2. Energy returned to the environment through convection

It was assumed that the amount of energy transferred to the environment was a function of time, angular velocity of the ball screw and ambient temperature.

$$\Delta Q_u = f_n(t, \omega, T), \tag{6}$$

where:
t - time,
ω - angular velocity,
T – temperature of the environment.

Due to the preliminary nature of the study, the experiments were carried out at a constant temperature. It was, therefore, excluded from further considerations regarding the model discussed below. Determining the temperature of a rotating screw with sufficient precision is difficult [16]; therefore, the increase in temperature, accompanying the process of elongation of the ball screw, was measured indirectly. The experimental studies showed that, due to the rotating velocity of the screw, the observed energy discharge had the character of forced convection. The adopted measurement method, however, significantly impeded the determination of the influence of the rotating speed on the value of convection. Thus, it became necessary to quantify the convection as a function of speed experimentally and to introduce a correction coefficient, kω (10).

$$\Delta Q_u = f_n(t), \tag{7}$$

$$\Delta Q_t = \Delta Q_{ut}, \tag{8}$$

$$\Delta Q_{ut} = \Delta Q_u \cdot k_\omega \tag{9}$$

The correction coefficient, k_ω was determined as a ratio of the amount of energy supplied to the ball screw drive as a result of friction (modelled previously) (5) and the value of natural convection described by function (7). According to the energetic balance (3) assumptions, equation (8) was defined. Determining the amount of energy supplied to the elementary segment as well as the value of natural convection enabled the formulation of an equation describing the aforementioned phenomenon of forced convection (9). Based on the enumerated considerations, the correction factor, k_ω was described as (10). Operating within the area of temperature stabilization of the ball screw drive, allows determination of the correction factor, k_ω with sufficient accuracy.

$$k_\omega = \frac{\Delta Q_t}{\Delta Q_u}. \qquad (10)$$

To establish the value of natural convection (7), a unidirectional artificial neural network, characterized by one entrance (t), twenty-five neurons in the input layer with a tansing activation function and one neuron in the output layer with a purline activation function, was used. Generalized structure of the ANN is presented in Figure 5 . Subsequently, relying on the experimental data, the learning data set was defined and the ANN learning process was performed. The simulation response results are shown in Figure 8.

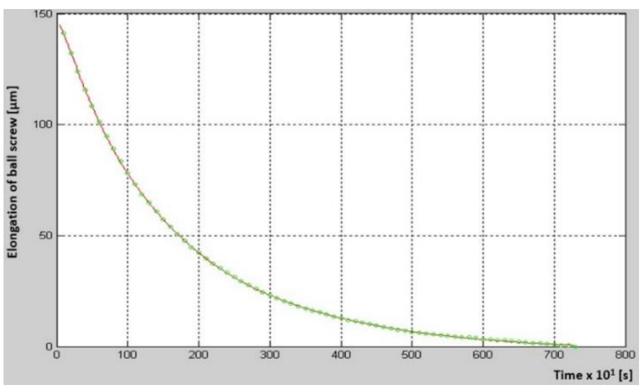

Fig. 8. Response of the ANN describing the cooling process of ball screw drive

4. MODEL VALIDATION

In order to validate the model, an experiment was conducted, aiming at the cyclical movement of the support carriage, according to a testing program. Movement of the carriage was kept at a variable speed.

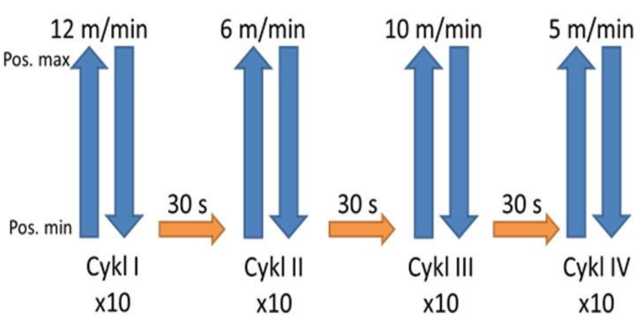

Fig. 9. Course of the test program

Due to the fact that, in the initial model, a uniform heating of the ball screw was adapted, the movement of the carriage was performed along the entire range of the servo drive. The exact course of the test program is shown in Figure 8. The measurement of elongation of the ball screw was performed after every cycle.

Based on the developed models, the compensation value for each of the measurement points was determined. Results of the experiment are shown in Figure 10.

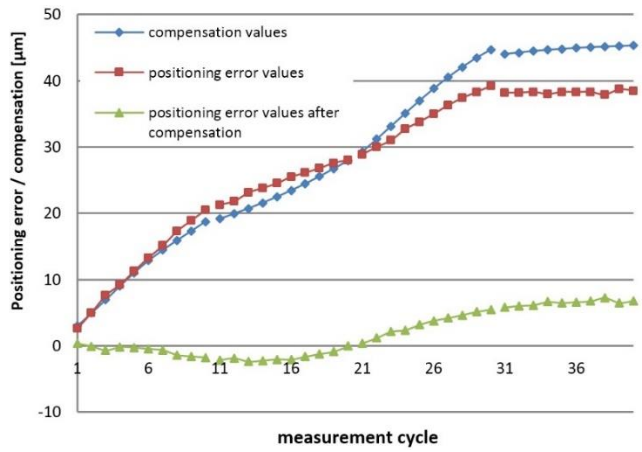

Fig. 10. Validation results

The performed test showed that the positioning error and compensation functions were largely convergent, proving the operation accuracy of the proposed model. The maximum positioning error, after compensation, was reduced by 75% and fluctuated in the range of -2.4 to 7.2 µm. A 50% decrease in the change dynamics of the positioning error was further observed.

5. SUMMARY AND CONCLUSION

Accurate ball screw drives are widely used in modern numerically controlled machine tools. Continuous demand for increased productivity, being met, for example, through escalation of controlled axes velocity, strongly correlates with the upsurge in the amount of energy dissipated in the screw-nut unit [1]. This, in turn, has a direct impact on the increase in the positioning error values of servo drives equipped with indirect measurement systems [6,]. Due to the great practical importance of the issue in question, establishing an effective, reliable and affordable method of compensation for thermal deformations of the ball screw drives remains a major challenge, particularly for small-sized machine tools, in case of which the existing procedures are ineffective or economically unfeasible.

The preliminary tests proved the feasibility of the proposed method of compensation for thermal deformations of the ball screw, relying on the use of artificial neural networks taught with a set of data concerning the operation of the servo drive as recorded by the control system. A 75% decrease in the value of the positioning error as well as a 50% reduction in its change dynamics were achieved. The obtained results imply high potential of the proposed sensorless compensation method , and encourage its further development . In addition, taking note of the shifts in heat conduction within the ball screw, included in the proposed compensation model, will further improve its effectiveness. It is noteworthy that the introduced technique does not require any additional equipment and is, therefore, highly cost-effective. The absence of any additional components, including mobile ones renders the postulated method infallible, in contrast with the currently utilized compensation procedures. The method can be successfully applied in machine tools, regardless of their size. Moreover, the use of the commonly available function of compensation for the pitch error in modern CNC control systems does not require any changes in their internal structure, allowing for simple integration of the method with machine tool control systems.

REFERENCES

[1] **A.S. Yang, S.Z. Cai, S.H. Hsieh, T.C. Kuo, C.C. Wang, W.T. Wu, W.H. Hsieh, Y.C. Hwang,** Thermal deformation estimation for a hollow ball screw feed drive system, Proceedings of the World Congress on Engineering, Vol. III (2013), London, U.K.

[2] **W. Ptaszyński, R. Staniek,** Badanie silnika liniowego w suporcie poprzecznym zataczarki, Archiwum Technologii Maszyn i Automatyzacji, 28 (2) (2008) 117–127 (in Polish).

[3] **W.S. Yun, S.K. Kim, D.W. Cho**, Thermal error analysis for a CNC lathe feed–drive system, Int. J. Mach. Tool Manu., 39 (1999) 1087–1101.

[4] **J. Bryan**, International status of thermal error research, Ann. CIRP 39 (2) (1990) 645–656.

[5] **R. Ramesh, M.A. Mannan**, A.N. Po, Thermal error measurement and modeling in machine tools. Part I. Influence of varying operation conditions, Int. J. Mach. Tool Manu., 43 (2003) 391–404.

[6] **M. Kowal, R. Staniek,** Compensation system for thermal deformation of ball screws, Proceedings of the 12th Biennial Conference on Engineering Systems Design and Analysis, ESDA 20469 (2014) Copenhagen, Denmark.

[7] **J. Olszewski, W. Ptaszyński, R. Staniek,** Investigation of thermal deformations and their compensation in CTX 210 V3 lathe slide, Proceedings of the 9th Biennial ASME Conference on Engineering Systems Design and Analysis, **ESDA 59354** CD, ISBN 0-7918-3827-7 (2008) Haifa, Israel.

[8] **R. Staniek,** Compensation methods of thermal deformations in NC machine tool bodies, Proc.eedings of the 5th International Carpathian Control Conference ICCC, Vol. 2, (2004) 189–195, Zakopane, Poland.

[9] **M. Pajor, J. Zapłata,** Compensation of thermal deformations of the feed screw in a CNC machine tool, Advances in Manufacturing Science and Technology, Vol. 35, No. (4), (2011) 9–17.

[10] **C.-F. Chang, C.-C. Wang, C.-S. Lin, C.-Y, Chao, and T.-R. Chen**., A theory of ball-screw thermal compensation, Proceedings of the International Multi-Conference of Engineers and Computer Scientists 2009, Vol. II IMC (2009).

[11] Solution for heating of ball screw and environmental engineering, World Manufacturing Engineering and Market , 3 (2004) 65–67.

[12] **A. Verl, S. Frey,** Correlation between feed velocity and preloading in ball screw drives, Ann. CIRP 59(2) (2010) 429–432.

[13] **T. A. Harris**, Rolling Bearing Analysis, Wiley & Sons, New York, (1991), 540–560.

[14] **L. Rutkowski,** Metody i Techniki Sztucznej Inteligencji, WTN, Warszawa (2006) (in Polish).

[15] **J. Szargut,** Termodynamika, PWM Warszawa (1998) (in Polish).

[16] **J. Mayr, J. Jedrzejewski,** E. Uhlmann, M.A. Donmez, W. Knapp, F. Heartig, K. Wendt, T. Moriwaki, P. Shore, R. Schmitt, C. Brecher, T. Weurz, K. Wegener, Thermal issues in machine tools, Ann CIRP - Manufacturing Technology , 61 (2012) 771–791.