The Thermal Behaviour of Machine Tools: The Controlled Heat Stabilization Approach

Ing. Jan Hornych, Ing. Otakar Horejš

Abstrakt CZ

Vzhledem ke stále rostoucím požadavkům na výrobní přesnost obráběcích strojů je nutno při konstruování nových typů a vylepšování stávajících disponovat širokým souborem znalostí. Významnou částí této báze jsou informace o termoelastických jevech v rámech obráběcích strojů. Minimalizace teplotních driftů se nejčastěji provádí pomocí softwarových kompenzačních algoritmů v kombinaci s aplikací chladicích okruhů. Bohužel, problémem je současná úroveň a způsob užití chladicích agregátů a okruhů chladicí kapaliny. Běžně používané chladicí systémy plní spíše úlohu ochrany daných částí stroje před přímým poškozením vysokou teplotou. Bohužel, úkol uměle vytvořit a udržet tepelnou rovnováhu je nad jejich současné možnosti, jejichž vylepšení je v příspěvku naznačeno. Blíže popsaným případem je sestava kuličkového šroubu. Kuličkové šrouby jsou velmi rozšířené pro svou vysokou životnost, efektivitu a přesnost přenosu rotačního pohybu na pohyb translační. Bohužel, teplo vznikající při vysokých otáčkách, kromě dilatace samotného šroubu, působí negativně také na konstrukci stroje. Ohřátí a následná teplotní dilatace šroubu je hlavním problémem při použití rotačního inkrementálního čidla, ovšem lineární odměřovací systém je tepelným tokem od sestavy šroubu také negativně ovlivněn. Použití protékaného kuličkového šroubu a běžného chladicího zařízení představuje částečné řešení. Právě výzkum efektivity použití protékaného šroubu je předmětem této práce.

Abstract

The permanently growing demands on the manufacturing accuracy of machine tools means that a broad knowledge base is necessary for the designing of new constructions as well as for improving the operational parameters of an existing machine tools. The very important part of this knowledge consists of information about thermo-elastic effects and drifts in machine tools structures. Minimisation of thermal drifts is frequently solved by an SW compensation algorithm together with circulation cooling. Nevertheless the global thermal stabilization of machine tools is not reflected in cooling system control. Chilled components of machine tools are protected against failure caused by excessive warming, but their thermal stabilization is not ensured by ordinary cooling systems whose improvement is discussed in the paper. The example discussed is a ball screw drive system. It is widely used for rapid translation of precise motion because of its high efficiency and long lifetime. However, a high-speed ball screw drive system naturally produces heat through friction at contact areas, which thereby causes thermal expansion and negatively influences into the machine tool structure. This expansion, in combination with the action of the rotary encoder for the position measurement and fixed bearing at one end, is the primary problem. Unfortunately, the heat flux adversely affects the linear encoder accuracy too. A cooled ball screw could be a treatment for ordinary cooling systems but with some difficulties. Experiments with a standard ball screw and also with a chilled ball screw feed drive were carried out to qualify the efficiency of internal cooling system.

1 Introduction

A ball screw drive system is widely used for rapid translating precise motion because of its high efficiency and long lifetime. However, a high-speed ball screw drive system naturally produces heat through friction at contact areas. It results in thermal deformation of the ball screw. This deformation is a major problem especially when a rotary encoder is used in combination with fixed bearing at one end. Other difficulties becomes in the case of using a fixed bearings at both ends or fixed and preloaded bearings for high stiffness [1]. Generally thermal errors consist of 40-70 per cent of the work piece error in precision machining [2] Utilization of a linear encoder represents only part improvement of this situation. Unfortunately, the heat flux from the ball screw layout adversely affects the linear encoder accuracy too, together with influence at an machine tool frame. Generally, it degrades the accuracy of whole machine tools. To developed high-precision machine tools, the thermal errors of ball screws should be reduced and well predicted. In order to be able to realize an effective solution of the ball screw thermal influence, heat production must be known with respect to its position, since the local temperature depends on the traversing program [3]. To got this information, an experiments on a special test bed and also a direct measurement of machine tool thermal drift was performed. During this measurements an ordinary ball screw and a chilled alternate was investigate.

2 Experiments at the test bed

2.1 Experimental set-up of the test bed

The first series of tests was performed in special test bed as shown in Fig. 2.2.

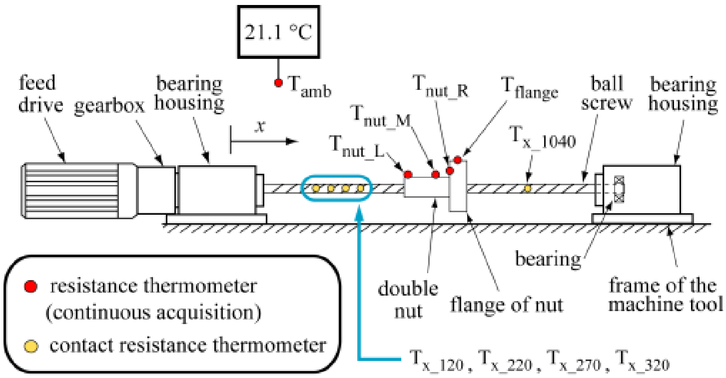

Figure 2.1: Scheme of test bed measurement with sensor locations

The configuration of the ball screw drive system of a horizontal axis X was rotating screw shaft driven by feed drive and double nut connected with test bed by flange. The ball screws were bearing in fixed-floating configuration. The rotational speed was possible to change in range of (0 – 800) rpm. The nuts were moved reciprocally with a different strokes L. The movement was always stopped after 70 cycles due to indirect measurements of the screw temperature by infrared camera. The test bed was equipped with a mechanism generating loading force. The maximum potential loading force FL is 5000 N. A diameter of screw shaft was d = 0.05 m, a lead was h = 0.02 m/rpm and a length of screw was Ls = 1.33 m.

Figure 2.2: Chilled and ordinary ball screws mounted at the test bed

Temperatures at ten points were measured as shown in Fig 2.1. Five resistance thermometers were used for continuous acquisition during moving conditions. Three resistance thermometers were located on the nut surface (Tnut_L, Tnut_M and Tnut_R). The heat transfer to the flange was observed by resistance thermometer placed at the flange (Tflange). Location of sensors placed at nut and flange is shown in right photograph in Fig. 2. The last resistance thermometer was used to measure the ambient temperature (Tamb). Moreover, temperatures of the ball screw at five points (Tx_120, Tx_220, Tx_270, Tx_320 and Tx_1040) were measured by contact resistance thermometers (see Fig. 1) during short breaks. This data especially serve for calibration of thermographic measurements and comparison between experiment and numerical model. The numerical model is made only for an ordinary ball screw for the time being. [4]

2.2 The results of the test bed measurements

It is selected just three measured cases from a set of performed experiments, which is presented in the following text. Their experimental variables were the revolution n=800 rpm, the loading force FL=3000 N and the nut stroke L=0.6 m (the nut traversed approximately around the middle of the ball screw).

Examples of measured temperatures obtained by resistance thermometers constantly placed on non-rotating parts for the ordinary screw ball case is depicted in Figure 2.3. Figure 2.4 shows the temperatures for the same experiment conditions with chilled alternate. During the test with chilled ball screw was used an ordinary heat exchanger (see Fig. 3.1). The various modes of a coolant flow was performed to find an optimal regime.

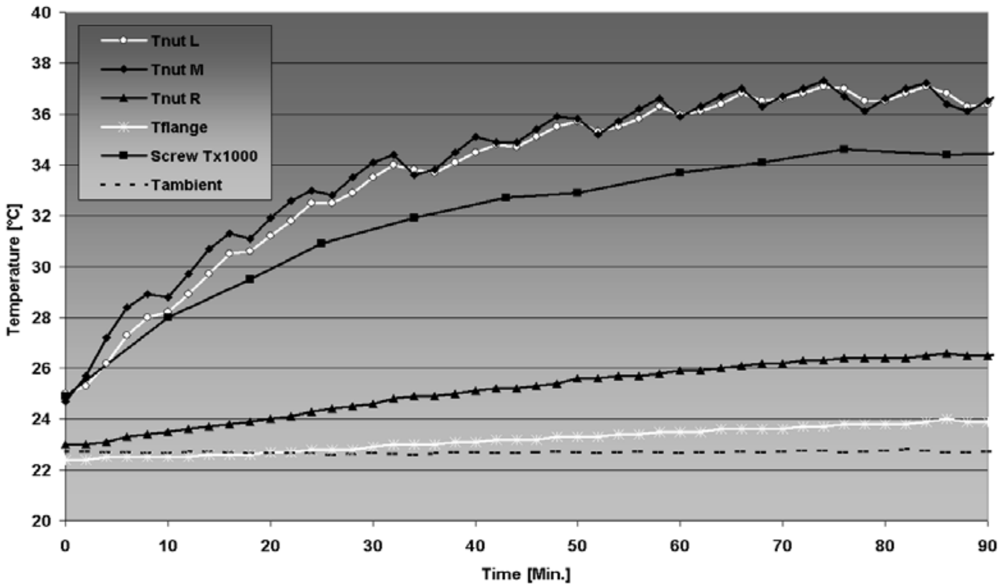

Figure 2.3: Measured data for revolution 800 rpm, loading force 3000 N and with the nut stroke 0.6 at the ordinary ball screw

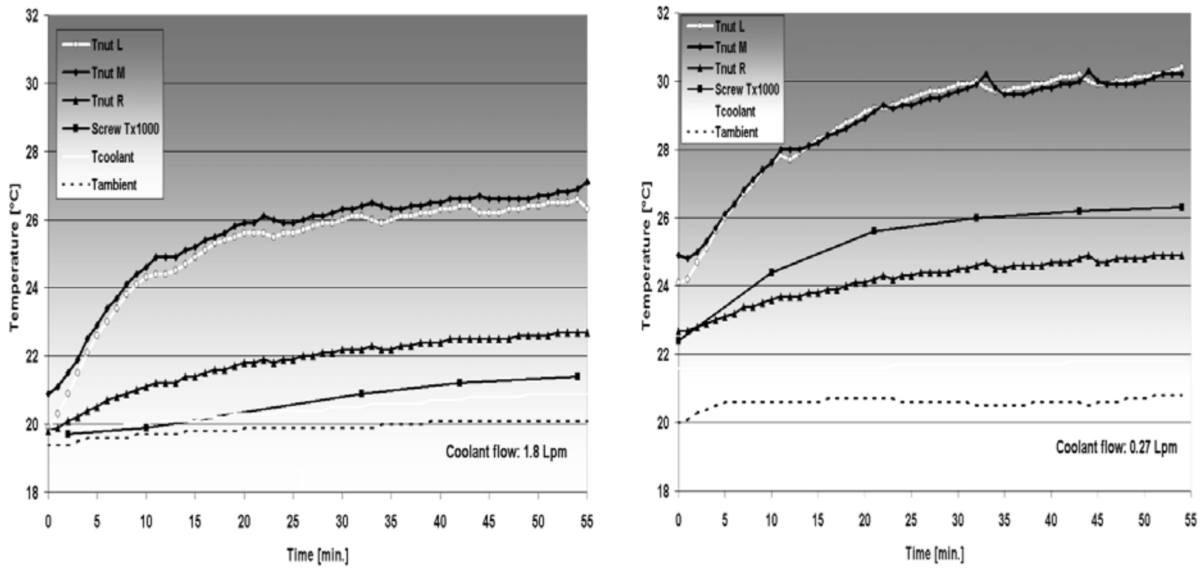

Figure 2.4: Chilled alternate; flow 1.8 Lpm on the left, 0.27 Lpm on the right

3 Experiments at a vertical machining centre

3.1 Experimental set-up of the machine tool

The chilled ball screw which was tested at the test bed was mounted at the vertical machining center to drive a quill, in Z axis direction of course. The rate of the quill movement was 8 metre per minute. The lift was 595 milimetre and the coolant flow was 1.4 litres per minute.

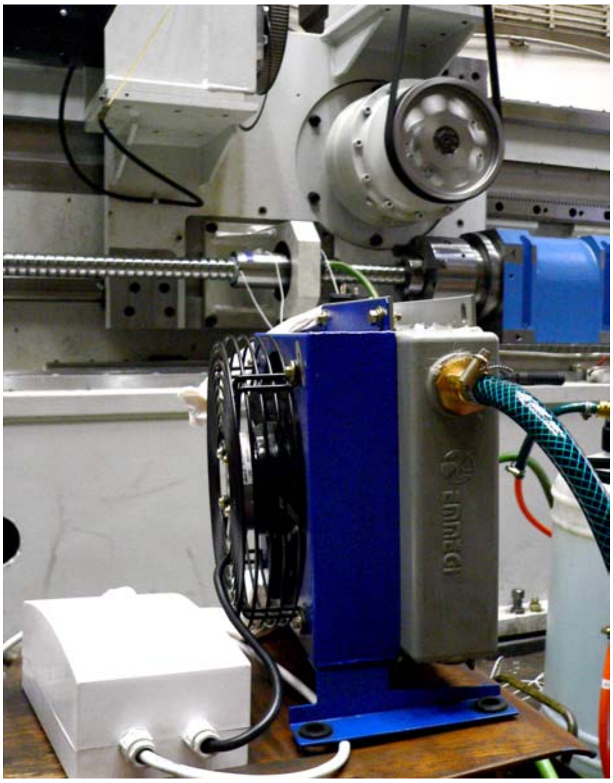

Figure 3.1: Used heat exchanger

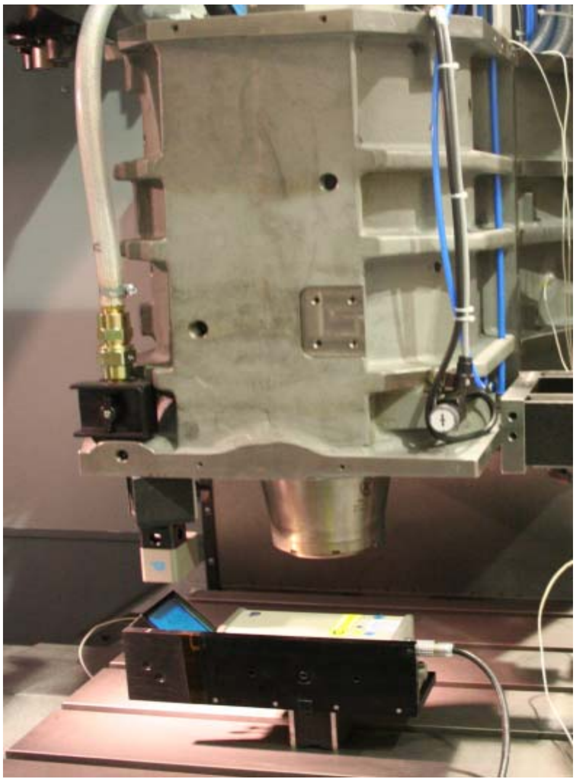

Figure 3.2: Z axis positioning measurement

During this conditions the influence of cooling was tested. For cooling was used same heat exchanger as was used during measurement at the test bed. Only two modes of running were tested; cooling-on and cooling off.

3.2 The results of the machine measurements

The thermal deviations were measured in three points longways a lift: Z1, Z2, Z3. Z1 was a start point in a bottom center and its position was measured relatively compared with a table. On the graf (see Fig. 3.6) is depicted position deviation of Z1 from requiered position. Positions of Z2 and Z3 were measured relatively compared with Z1 (Figures 3.7 and 3.8). Temperature sensors were placed on the upper bearing of the screw ball, on the backside of the frame (see Fig. 3.4), on the front side of the frame; behid the workplace (see Fig. 3.3) and also on the quill and table. The course of the first three is shown on the figure 3.5.

Figure 3.3: Sensor behind the workplace

Figure 3.4: Backside sensor

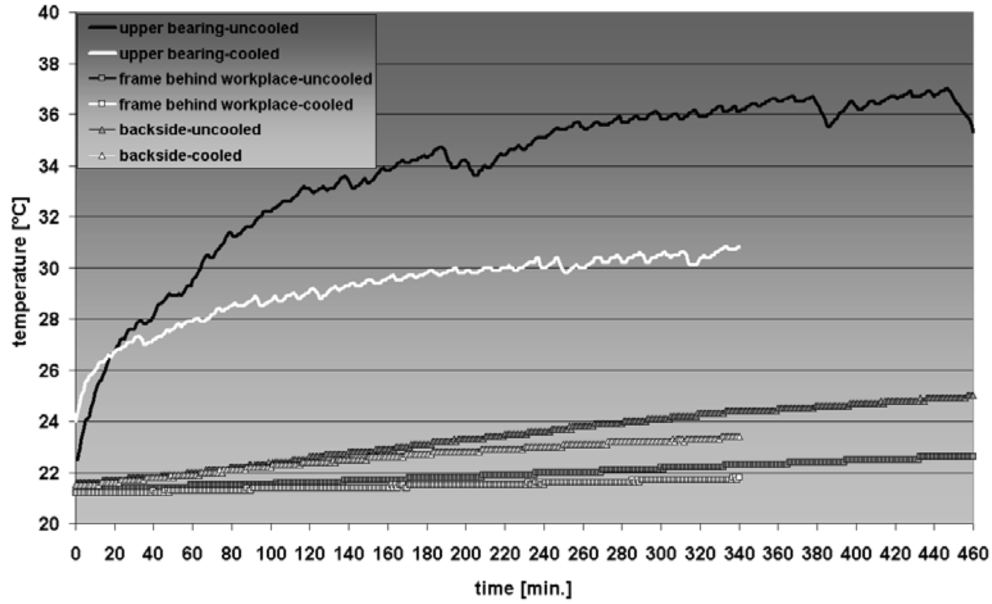

Figure 3.5: The temperatures development

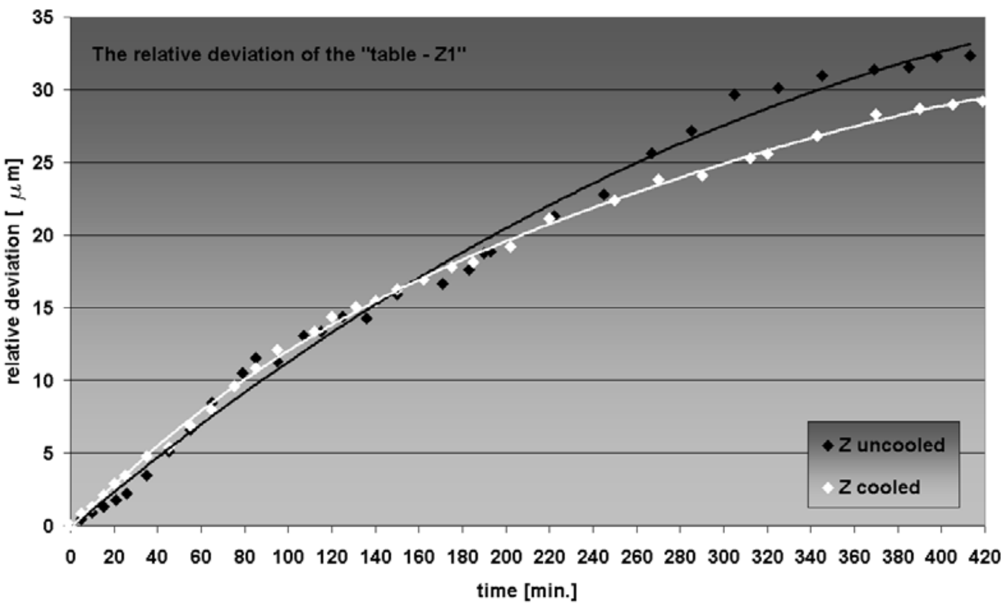

Figure 3.6: The Z1 point deviation compared with the table

On the shown deviations of the Z axis positioning is perceptible position dependance of cooling influence. An improvement in Z3 point is circa 25%. The improvement in Z2 point (the middle of the lift) is circa 15%, but only 8% in Z1 point. Another information is the moment of cooled curves deflection. The Z3 curve deflected in 60th minute. The Z2 curve deflected in 80th minute and the Z3 curve deflected in 160th minute.

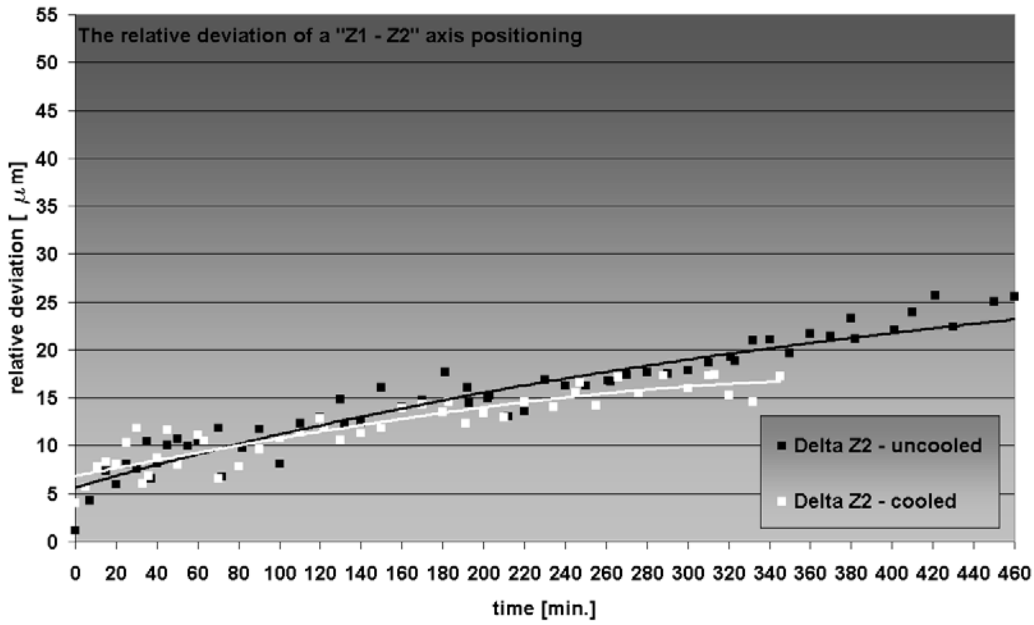

Figure 3.7: The Z2 point deviation compared with the Z1 point

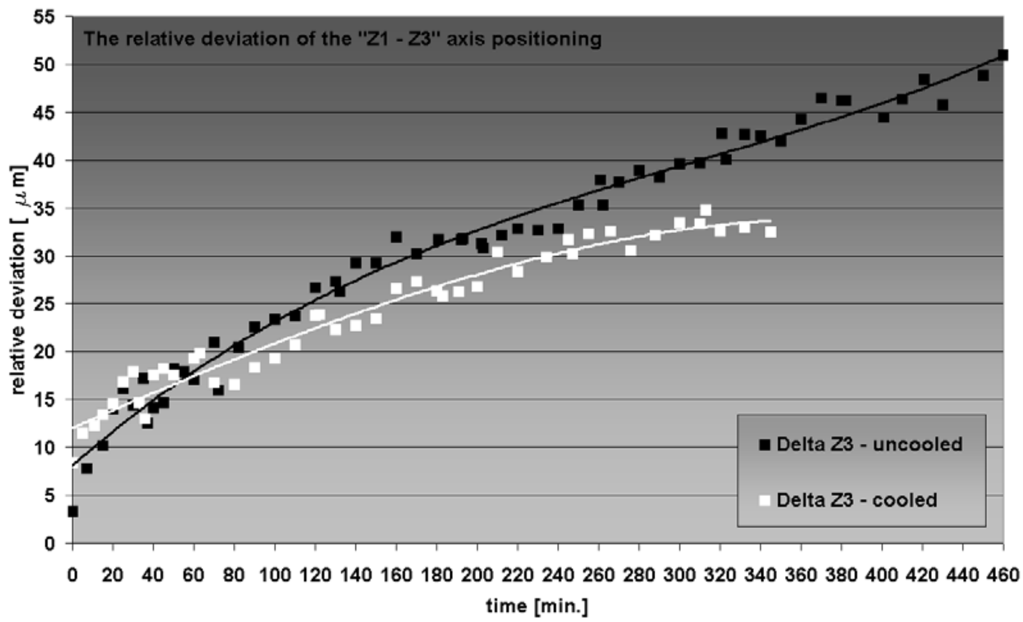

Figure 3.8: The Z3 point deviation compared with the Z1 point

4 Conclusion

The position dependance of the Z axis deviations is probably caused by the thermal affection of the linear encoder. The thermal drift of the frame is the part of resultant thermal deviations, which is same in all points of the lift. The measured deviation curves turns out that the upper part of the linear encoder is affected more than lower part. There is reason to believe it is caused by heat flux from the engine of Z axe ball screw. This engine is situated at the top of the frame. The used way of cooling is insufficient. Chilling of screw ball bearings and engine flange should be an appropriate measure too. Another reason is that the ordinary heat exchanger works only at that time, when a temperature gradient between coolant and ambient is lumping. But a direct connection to an industrial cooler is not suitable. Contemporary cooling systems can't hold coolant temperature in enough narrow range. This affects thermal amplitude of a machine frame. Problem is the uncontrolled distribution of a cooling achievement into the particular cooling lines and the independent work of a SW thermal drifts compensation. The controlled heat stabilization of machine tools could be a way to improve their accuracy. But it is necessary to solve above mentioned problems.

5 Acknowledgements

This research has been supported by the Czech Ministry of Education grant No. 1M6840770003.

6 References

[1] J. Y. Ahn, S. C. Chuang, Journal of Engineering Manufacture, Vol. 218 (2004), pp. 1667-1681.
[2] J. Bryan, Ann. CIRP 39-2 (1990), pp. 645–656.
[3] J. Braasch, Accuracy of Feed Drives, Heidenhain Info, Vol. 6 (2000).
[4] Horejš, O. Proceedings of ThETA 2007, Université francais D'Egypt (2007), Paper No.61., p. 213-217.