THERMOMECHANICAL TRANSFER FUNCTIONS AND CONTROL OF A MACHINE TOOL COOLING SYSTEM

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Nowadays the cooling systems are more than ever applied into the structure of a machine tool, but unfortunately there are no efforts being made in the control of the cooling systems, which doesn't allow complete utilisation of their possibilities. This paper presents active cooling control (ACC) system, based on thermal transfer functions, which was experimentally tested on an inbuilt cooling jacket of a machine tool electrospindle.

Keywords
Thermomechanical transfer function, thermal error, machine tool

1. Introduction

The frequency transfer function describes the link between the output (response) and the input (excitation) of a dynamic system in the frequency domain. If the system is linear the transfer function is constant. The transfer function is commonly used in the analysis of analog electronic circuits or mechanical system, but its application on thermomechanical system is relatively new phenomenon [Fraser 1998a], [Fraser 1998b].

Thermomechanical transfer function (TTF) contains the nature of the heat transfer principles, thus the calibration of the empirical parameters is simpler and the model is in addition more reliable with untested inputs, because the data is forced to conform to the same principles as the real process. At the same time the results are obtained by two orders of magnitude faster [Fraser 1998a]. These parameters make thermomechanical TF very suitable for real-time modelling and diagnostics of thermal and thermo-mechanical systems. Terminology used for TTF is described in [Hornych 2007].

2. Principle of the active cooling control method

The essence of the new control method of the cooling system is to remove/add exact amount of heat from/to the structure in order to minimize its thermal error caused by non-stationary heat sources.

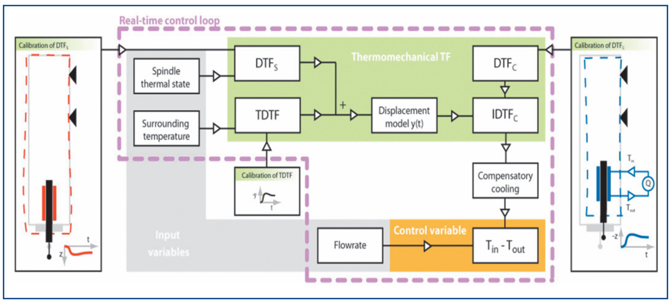

Figure 1. *Scheme of the active cooling control*

The thermal error is generally unknown. Therefore firstly the error must be estimated from the main factors acting on the thermomechanical system (surrounding temperature, inner heat sources etc.) using a TF model.

If the goal is to minimize the thermal error, the cooling system must cause deformation, which is right opposite to the thermal error. This can be done with an inverse DTF of the cooling system (IDTFC), which enables to recalculate compensatory deformation into cooling (see Figure 1).

3. Experimental verification

The presented ACC was tested on an inbuilt cooling jacket of electrospindle CYTEC (z axis – power of a 18kW, torque 70Nm and maximal revolution 15000 rpm) on machine tool MCFV 5050 LM (see Figure 2) for a high speed cutting.

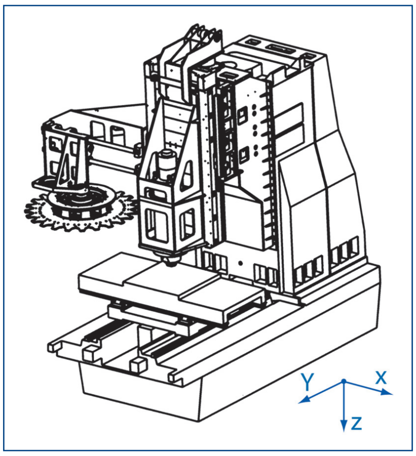

Figure 2. *Tested machine tool 5050 LM*

a. Calibration of the cooling system

The spindle was cooled by a known amount of heat and its deformational response was measured at the same time (see Figure 3). The link between cooling and deformation can very well represented with eight-parametric DTFC, which is defined in frequency domain as:

$$\Delta_C(s) = \frac{A \cdot a \cdot b}{(s+a)(s+b)} + \frac{B \cdot c \cdot d}{(s+c)(s+d)} + \frac{C \cdot e}{(s+e)}$$

where A = 0.36 μmW-1, B = 0.4 μmW-1, C = 0.05 μm.s.W-1,
a = 1/3560 s-1, b = 1/3555 s-1, c = 1/10000 s-1,
d = 1/10010 s-1, e = 1/2100 s-1.

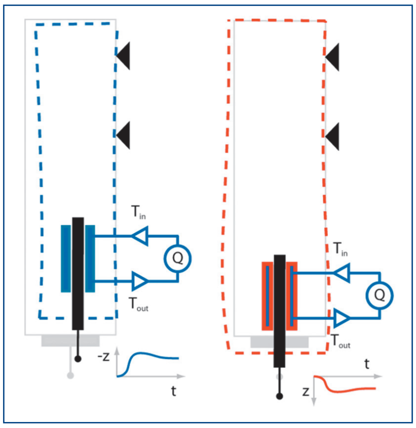

Figure 3. *Calibration of the cooling system (left) and the spindle (right)*

b. Calibration of the spindle electromotor

A general calibration of the spindle electromotor is very complicated due to very complex thermal behaviour. Therefore only one regime of the spindle (position control mode) was chosen for the experimental verification of the ACC. In order not to cause any damage due to overheating, the spindle was cooled (see Figure 3) with known amount of heat. The complete deformational response of the spindle was given by a sum of measured deformational response and a fictive deformation of the cooling system, which is calculated with already identified DTFC (see Figure 4). Then the deformational response of the spindle can be very well approximated with six-parametric DTFS, which is defined in frequency domain as:

$$\Delta_S(s)=\frac{A\cdot a\cdot b}{(s+a)(s+b)}+\frac{B\cdot c\cdot d}{(s+c)(s+d)}$$

where A = 225 μm, B = -40 μm, a = 1/4800 s-1, b = 1/4850 s-1, c = 1/18000 s-1, d = 1/18100 s-1.

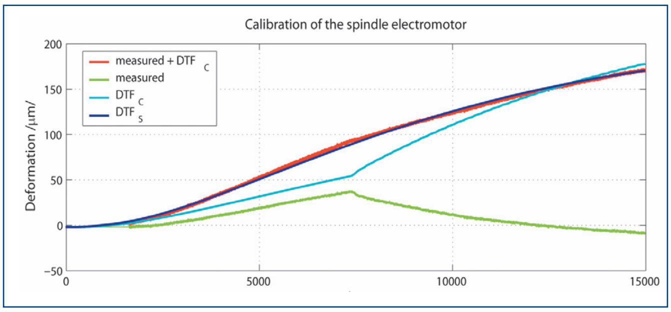

Figure 4. *Calibration of the spindle electromotor (position control mode)*

c. Active control of the cooling system

The active control of the cooling system is described by Figure 1 (TDTF was neglected). The demand on the cooling system is to compensate the thermal error, which is modelled with DTFS (Figure 7 – red) in the real-time. This is realizable with inverse form of DTFC specifying the exact cooling (Figure 5 – red), in order to achieve the desired deformation in the real-time.

Real removed heat (Figure 5 – blue) shows oscillatory character due to temperature of the coolant. If the difference between real (Figure 5 – blue) and ideal (Figure 5 – red) is integrated (Figure 6), the agreement between real and ideal cooling is proven.

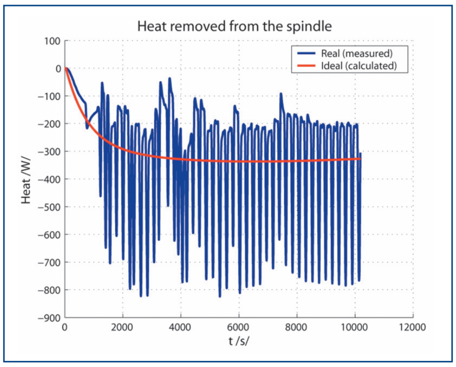

Figure 5. *Removed heat from the spindle*

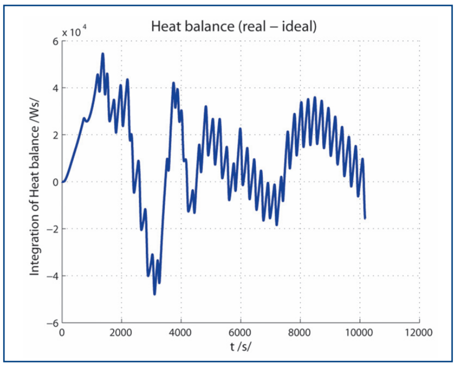

Figure 6. *Heat balance*

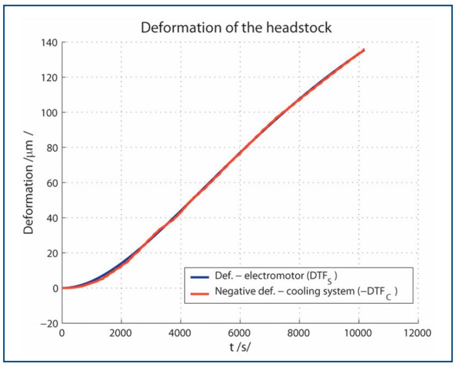

Figure 7. *Deformational balance*

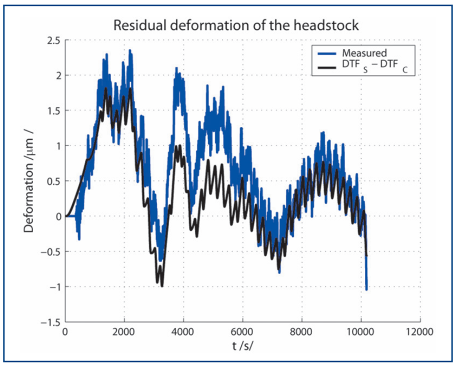

Figure 8. *Residual deformation; measured and calculated*

4. Conclusion

The TF model of spindle thermal error (DTFS – Figure 7 – red) shows very good agreement with deformation caused by cooling system (DTFC – Figure 7 – blue). The difference between these two models (Figure 8 - black) is compared with measured residual thermal error of the headstock (Figure 8 - blue).

The resultant residual thermal error remained within the range ± 3 μm (2 % of maximal thermal error) and the method shows possible improvement to ± 1 μm (Figure 8).

Acknowledgements

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