MECHATRONIC APPROACH IN MODELING, IDENTIFICATION AND CONTROL OF THERMAL DEFORMATION OF QUILL

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The demands on machining accuracy have been increasing lately and therefore research of thermal behaviour of machine tool structures is crucial for successful manufacturing. Generated heat diffuses into the structure of the machine tool components. This process is affected by heat sinks such as heat transfer on the surfaces and cooling systems. Meanwhile the heat warms up the structure of the machine tool and thermal dilatation deforms it. This deformation subsequently affects machining accuracy in a negative way. Different systems are used to eliminate the thermal error, but their efficiency depends on the quality of the thermal machine tool model. This article brings up new approach in the thermal modelling, which combines thermal transfer function modelling and Matlab® tools such as Matlab system identification toolbox® and Matlab® Simulink®.

Keywords
machine tool, quill, thermal error, thermal transfer function, identification, control, Matlab®

1. Introduction

The transfer function (TF) is commonly used in the analysis of analog electronic circuits or mechanical systems. Its application on thermo-mechanical systems is relatively new phenomenon [Barta 2007], [Barta 2008].

Transfer functions describe the link between the output (response) and the input (excitation) of dynamic system in the frequency domain [Barta 2007]. Matlab® provides all tools necessary to identification, modeling and control. See the figure bellow.

Experiment
(calibration measuring)
↓
Matlab® Workspace
(elaboration of measuring data into suitable form)
↓
Matlab System Identification toolbox
(identification of transfer function)
↓
Matlab® Simulink®
(modeling and control)

Figure 1. *Scheme of Matlab® application.*

The modeling of thermo-mechanical systems using TF is faster and reaches sufficient quality of the model in comparison with other methods (e.g. FEM), [Barta 2007]. Therefore the model is suitable for real-time modeling, control and diagnostics of thermo–mechanical systems.

This article brings up new approach in the thermal modeling, which combines thermal transfer function modeling and Matlab® tools. This approach is experimentally tested on a quill.

2. Experiment description

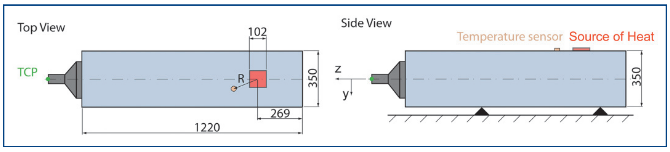

Figure 2. *Scheme of the quill.*

The experiment was performed on an empty closed quill. There was situated a resistivity heater plate with power input (Q) (Fig. 2) which was the main cause of quill thermal deformations [Barta 2008].

The aim of experiment was to measure thermal deformation response on the heat source and subsequently to build up the TF model (i.e. model established on thermal transfer functions) which would be with good agreement with thermal deformations of the quill tool center point (TCP). About the experiments see the table below.

Table 1. Summary of measuring apparatuses	
Measuring frequency	60 sec.
Measuring apparatus	Lion Precision
Sensors	capacitive contactless
Measuring error of 95% of all measured data	1%

The TFs were calibrated in the first part of experiment and in the second part they were tested by comparisons with real (measured) thermal-deformations in y direction. An idea of composition of the complex control model of quill thermal deformations is below.

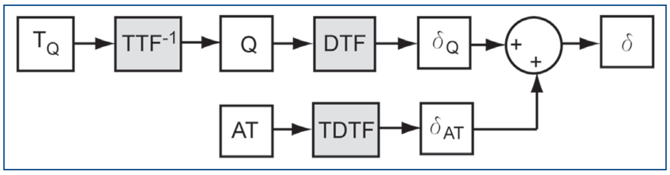

Figure 3. *Scheme of complex control model.*

Thermal TFs are called according to their physical interpretation. Deformational TF (DTF), temperature TF (TTF) and its inversion (inv. TTF) and temperature–deformational TF (TDTF) [Barta 1990], [Barta 2007], [Barta 2008] will be used. Determination of a heat source is sometimes complicated. This problem is included inv. TTF describing dependence between the temperature measured close to the heat source (T_Q) and the heat source. Then this T_Q and the ambient temperature (AT) are the only inputs into this model.

3. Calibration

Calibration is the first step to assemblage of a model of a thermal-mechanical system.

3.1. Options of TDTF calibration methods for ambient temperature

Identification of thermal behavior of the quill (or machine tool) needs to determinate response to a pure heat source without any AT disturbance. Determination of AT thermal deformation is challenge of this chapter. The next expression serves for better imagination.

$$\delta_y - \delta_{yAT} = \delta_{yQ}$$
$$\delta_y - T_A . E(s)_{yi} = \delta_{yQ}; \quad i = I, II, III \qquad (1)$$

Where δ_y is measured deformation with two components, the deformation caused by the heat source δ_{yQ} and by AT δ_{yAT}. Subtraction of AT deformational component from the measured one is necessary for obtain a δ_{yQ}. The former component is multiply of a measured

AT T_A and TDTF $E(s)_{yi}$ established from ETVE (Environmental Temperature Variation Error) in frequency domain. Those tree methods (I, II, III) of TDTF determination will be shown later. In addition to that this article contains a new approach to assignation of the TDTF without any ETVE experiment (from these ways will be chosen the optimal one for the complex model).

Next figure reflects the time behavior of AT during ETVE experiment (without any other heat source).

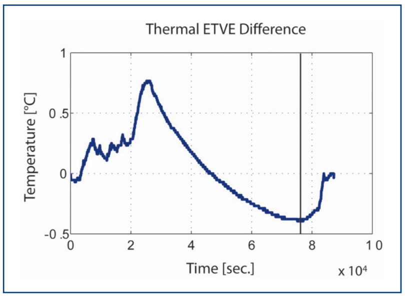

Figure 4. *Ambient temperature during ETVE.*

The TDTF can be determined by several conventional ways:

- TDTF model I as 0th function type [Barta 2008];
- TDTF model II from the whole ETVE behavior;
- TDTF model III from a short end ETVE behavior.

3.1.1. TDTF model I as 0th function type

The influence of AT is supposed much lesser than from the heat source. For that reason can be used a simplest TF namely exponential TF [1]. TDTF in this example for y direction may be consequently in the form of below:

$$E_{yI}(s) = \frac{K_1}{1+T_1 s} \qquad (2)$$

with parameters $K_1 = -3$ m.W^{-1}, $T_1 = 100$ sec.

3.1.2. TDTF model II from the whole ETVE behavior

Identifications of TFs are performed with the help of Matlab System Identification Toolbox® (Ident). Input u(t) and output y(t) of the import time-domain data have to follow the form of columnar vectors of the same length. Starting time is zero.

By using the Estimate parametric models is generated a suitable TF. The Approximate Models are ARX, OE (a linear difference equations that relate the input u(t) to the output y(t)) [Ljung].

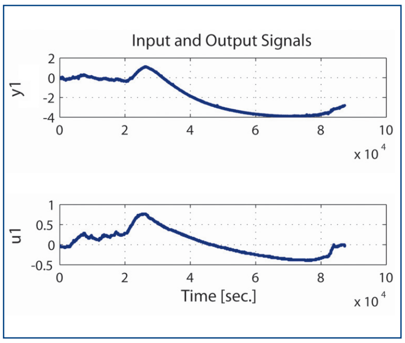

Figure 5. *Input and output signals to Ident.*

The whole behavior from Figure 4 is used as input. Output is only thermal deformation caused by AT (in y-axes).

Next figure presents the approximation TF model (pale blue curve) with the behavior of measured values. In the legend of the figure is displayed the percentage of the output variations that is reproduced by the model (so-called fit). A higher number means a better model. The precise definition of the fit is in [Ljung].

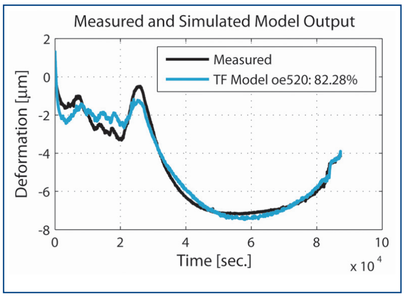

Figure 6. *Time plot of ETVE and Measured and simulated ETVE model with the fit value in Ident.*

Expression of TF isn't unnecessary to show further. Here are both numerator and denominator of 5th degree and they have homothetic form like equation (2). Symbol of this AT-TDTF is E_{yII}.

Influence of measured AT to thermal deformations is unambiguous. Behavior of thermal deformation is decreasing with increasing AT till about 2,5x10^4 sec. Curves are decreasing further or their trends are the same. This has an adverse influence to substitution quality (a control is possible to do in LTI Viewer in Ident work space, where is shown the step response, impulse response, Bode diagram of TF etc.). For this reason identification from a short end of measured AT (and its response) will be carried out.

3.1.3. TDTF model III from a short end ETVE behavior

The short end is visible on Figure 4 (cut off by horizontal line). Configuration of TF with a TF model substitution quality is shown in Figure 7.

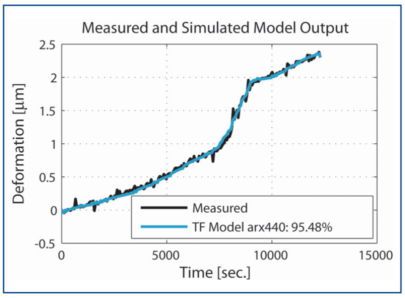

Figure 7. *Measured and simulated ETVE short end model with the fit value for y deformation.*

Numerator and denominator are of 4th degree. Name of the function is E_{yIII}.

3.2. Options of DTF calibration methods in y direction

Calibration of this system is given by measuring and approximated deformational response, caused by the unit step heat source Q. The deformational response is filtered according to equation (1). For the quill calibration measurement was used the source of unit thermal excitation of magnitude 90 W with the time step like in the Figure 8.

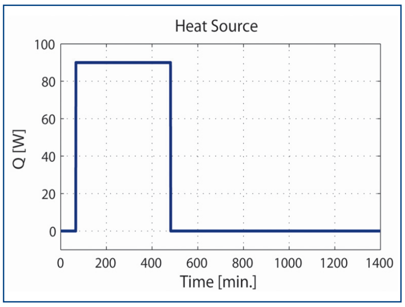

Figure 8. *Heat source for calibration measurement.*

Both the heat source influence and AT are included in measured thermal deformation (response). The ways to filter AT influence and determinate DTF are:

- from TDTF model I;
- from TDTF model II;
- from TDTF model III;
- DTF and TDTF model IV as a result of double input into 'Ident'.

The AT measured on a day of calibration measurement is visible on the figure below (its influence will be very small).

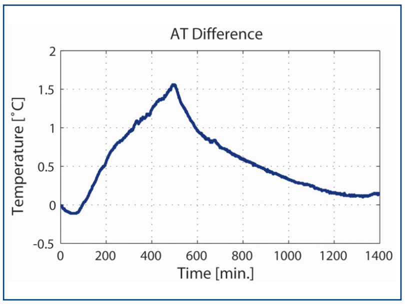

Figure 9. *Difference of ambient temperature measured on a day of measurement.*

The second term in the expression (1) represents a thermal deformation caused by AT which is necessary to subtract from the whole thermal deformation of the quill (methods I, II and III). The behavior of resultant thermal deformation after subtraction (equation (1)) shall be smoother than that before [Barta 2008].

The Ident offers the possibility of more input to the time domain import data in form of a matrix with column dimension equal to number of inputs. Output is still the only one. ETVE experiment is unnecessary to determine the TDTF. The second component of TF is directly DTF.

The inputs are the heat source Q and measured AT on a day of measurement (Fig. 9, Fig. 10). The result is one TF represented of three components (instead of currently two) B1(s), B2(s) and A(s) which are describing as heat source (B1(s)) as AT influence (B2(s)).

The Figure 10 depictures part of deformations caused by AT which affects the whole quill deformation for the models I – IV.

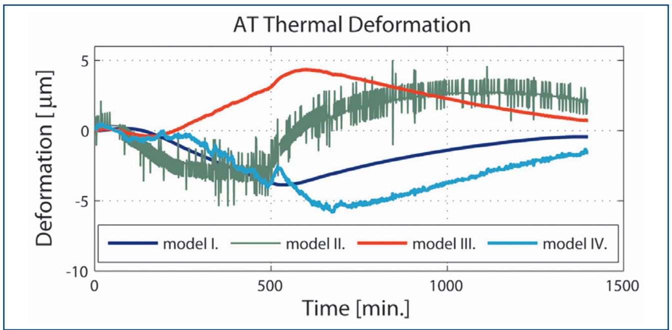

Figure 10. *Thermal deformation caused by AT for TDTF models I – IV.*

3.3. Calibration of TDTF and DTF

The AT influence was very small in this example (compare deformation in Fig. 10 and Fig. 12). For that reason is used the unconventional method IV for the final determination TDTF and DTF.

But the Ident is only a tool and for its complication it requires a critical view over the model approximation quality. Some eventuality is to check the LTI (Linear Time Invariant) step response [[Ljung]]. That's a response of TF model to a step change of the input value. The return to a stabilize state in comparison with a real prediction is the initiation to selection. The LTI view for the selected model IV is in the next figure. That's probably entirely good conforming to the stabilization demand.

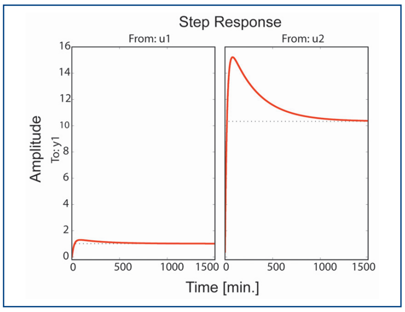

Figure 11. *LTI step response to choice method of TDTF and DTF determinate.*

Next Figure 12 shows y-axes deformation system output (the measured deformation response to the heat source and AT actions). The TF replacement and the fit value are represented too.

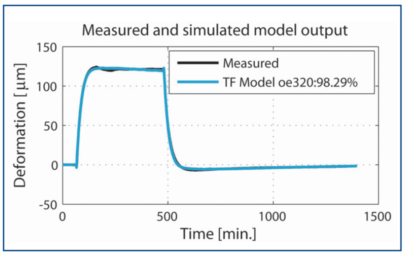

Figure 12. *Measured and simulated double input model with the fit value.*

Equation of the DTF is then expressed as:

$$\Delta_y(s) = \frac{B1(s)}{A(s)} \qquad \Delta_y(s) = \frac{K_2 + K_3 s + K_4 s^2 + K_5 s^3}{T_2 + T_3 s + T_4 s^2 + s^3} \qquad 3)$$

and the used TDTF:

$$E_{yIV}(s) = \frac{B2(s)}{A(s)} \qquad E_{yIV}(s) = \frac{K_6 + K_7 s + K_8 s^2 + K_9 s^3}{T_2 + T_3 s + T_4 s^2 + s^3} \qquad (4)$$

with parameters K_2 = 0,0001065 m.W^{-1}, K_3 = 0,04279 m.W^{-1}, K_4 = –0,00769 m.W^{-1}, K_5 = –0,01453 m.W^{-1}, K_6 = 0,001081 m.W^{-1}, K_7 = 0,5127 m.W^{-1}, K_8 = 0,5118 m.W^{-1}, K_9 = 0,1279 m.W^{-1}, T_2 = 0,0001046 min., T_3 = 0,03288 min., T_4 = 0,6899 min.

3.4. Source identification

The last step to assemblage the complex TF model of the quill is to find suitable TTF describing the heat source. The input to the time domain import data in Ident is known heat source. The output is temperature measured close to that (T_Q) with AT subtracted. This new TF is necessary to inverse for obtain inv. TTF and for the heat source approximation. The heat source behavior is the same as in Figure 8. On the figure below the AT, the temperature measured close to heat source and their difference are depicted.

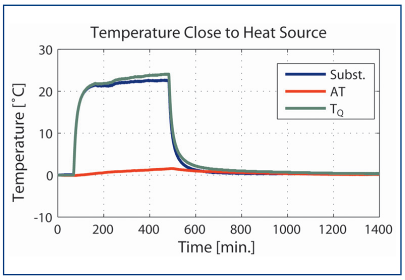

Figure 13. *Temperature measured close to heat source and AT.*

The TTF is provided in Matlab system identification toolbox® like others TFs. TF model is 220 with the fit value equal to 98,18 %.

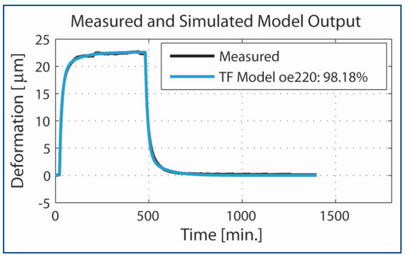

Figure 14. *Measured and simulated source identification with the fit value.*

Mathematical expression of that is:

$$\Gamma_y(s) = \frac{K_{10} + K_{11}s + K_{12}s^2}{T_5 + T_6 s + s^2} \qquad (5)$$

with parameters K_{10} = 0,0002567 m.W^{-1}, K_{11} = 0,01629 m.W^{-1}, K_{12} = 0,008079 m.W^{-1}, T_5 = 0,001022 min., T_6 = 0,09112 min. The inversion of TTF will be provided in Matlab® Simulink®.

4. Simulation

Complex model of the quill thermal deformation behavior is assembled in Matlab® Simulink® with used the bock diagrams.
Simulation is carried out using another real measured data (AT and temperature close to heat source) with different step heat source from the calibration. Thermal deformation in y direction and all temperature are known. So the verification during simulation is allowed too. The figure of inputs is below.

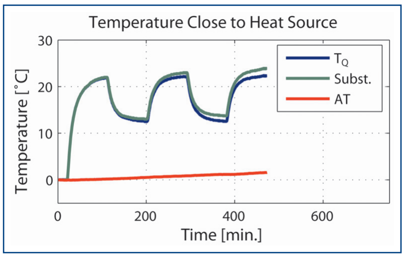

Figure 15. *Temperature measured close to heat source, AT, simulation inputs.*

The Simulation model contains outputs in the form of behavior differences of measured and computed thermal deformation and known and computed heat source (these known behaviors are used the verification – see below). The inversion of TTF is realized by simple reversal of numerator and denominator of equation (5) in appropriate block. All used TFs are defined in the previous chapters. The Transfer function blocks are picked up with the gray background and a Scope block is the chart output. See scheme below.

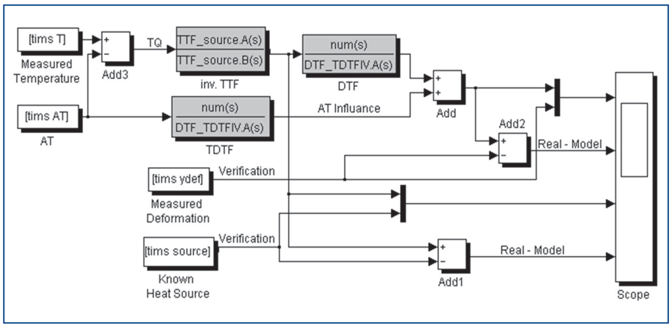

Figure 16. *Complex thermal model of the quill in Simulink®.*

Scheme in Figure 16 is corresponding more or less with the scheme in Figure 3. In addition to that the former has the verification which is realized in the form of subtraction between the measured and the computed values.

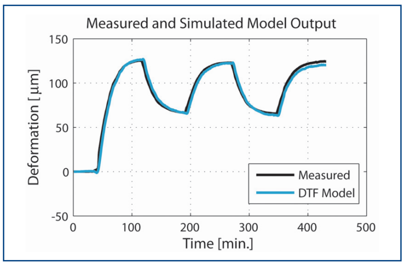

Figure 17. *Measured and simulated behavior of the quill thermal deformation from the Simulink® control simulation.*

Graph illustration of thermal deformation behavior and its TF approximation (for y direction of course) is in Figure 17 (output of the Simulink® Scope).

The DTF model deviation from measured data is shown in the next one.

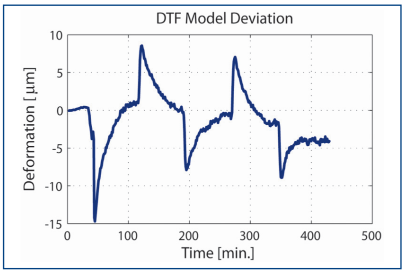

Figure 18. *Difference between DTF model and measured deformation.*

And the same for the heat source of this example is in the next figures.

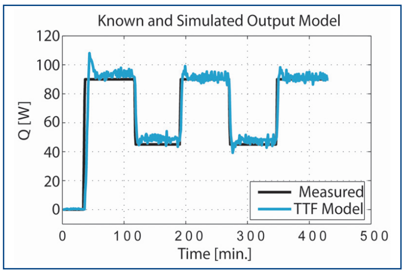

Figure 19. *Known and simulated behavior of the heat source from the Simulink® control simulation.*

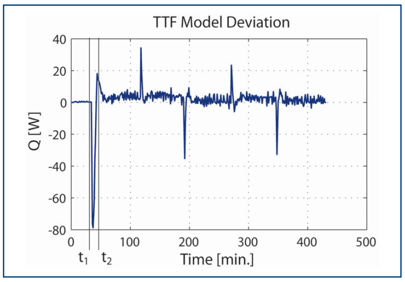

Figure 20. *Difference between TTF model and known heat source.*

The high deviation points (one point is lying in the interval <t_1,t_2> (in Figure 20)) are caused by a time delay between the excitation and the response. This problem could be solved by placing sensor closer to the heat source.

5. Conclusion

This article describes a simple method of identification and modeling of the machine tool thermal deformation behavior with using

Matlab® tools. Creation of the quill TF model was reached with the calibration measurement for determination of TFs and the temperature measured close to the heat source with AT in addition as the model's inputs. Matlab® modeling gets around problems with ETVE determination (chapter 3.2) and the TF inversion (for example) [Barta 2008].

The AT influence to the quill thermal deformations wasn't so intensive to show quality of TDTF determination methods, however, the AT influence cannot be generally ignored. Different behavior of TFs was obtained by different modeling methods but the research of some AT behavior and its part in thermal deformations is subject of future development.

Further possibilities to exploit Matlab tools summarized in the article are in a control of the thermal behavior of various thermo – mechanical systems which will minimize the thermal error.

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