

Parametric Identification of Thermal Deformations Using Adaptive Kalman-Filtering Techniques

Andreas EICHHORN, Austria

Key words: Dynamic temperature loads, thermal bend, non-stationary heat flow, adaptive Kalman-filtering, identification of “white box”-model

SUMMARY

The investigation of the progress of thermal deformations as consequence of dynamic temperature loads is an important task in civil and in mechanical engineering. Typical fields of interest are slim buildings under sun exposure and the computational compensation of thermal influences in the heating and cooling phases of machine tools. Within these applications, the determination of the thermal bend resulting of only one-sided influencing heat sources is of central importance. Its quantification with a physically justified structural model enables the prediction and close-to-reality simulation of bending procedures under time-variable loads.

Using a structural model the description of thermal deformations requires the knowledge of the progress of the spatial temperature distribution inside the regarded object. Consequently the collection of representative temperature data can be considered as a central task. In many cases the sensors can only be placed at the objects surface or in its outside layers. The high-grade nonlinearly spatial temperature gradient is then supposed to be linear which causes significant model errors. The minimization of these errors requires the modelling of the heat flow inside the object.

In this paper a dynamic temperature deformation model based on non-stationary temperature processes is presented. The model was developed for the investigation of the effect of one-sided thermal loads on bar-shaped bodies (i.e. slim towers in civil engineering and robot arms in industrial manufacturing). Using additional temperature measurements the experimental identification of the material parameters is realised by means of adaptive Kalman-filtering. In lab tests with an aluminium column the estimation of thermal diffusivity succeeds with a deviation of only 0,2%. Control measurements are showing that the identified model can be used to predict the columns thermal bend with a mean deviation smaller than 10 mgon. Consequently the deformation model is suitable for the precise prediction and close-to-reality simulation of thermal deformations under variable loads. Future activities are especially planned for industrial applications.

Parametric Identification of Thermal Deformations Using Adaptive Kalman-Filtering Techniques

Andreas EICHHORN, Austria

1. MOTIVATION

The registration and investigation of thermal deformations is of large interest in the range of industrial manufacturing, especially in applications linked with robots. As an example, the reproducible accuracy of the TCP (= tool center point) of a typical welding robot can be specified with 0.01 mm. In Richter (1998) it is shown that thermal induced displacements may reach magnitudes up to 0.5 mm. Consequently thermal effects represent significant sources of error.

The development of constructive and compensatory methods to reduce thermal influences on robots and machine tools is the subject of numerous work in the last years (i.e. Overbeck 1992, Richter 1998, Bonse 1999). Especially in the case of computational compensation methods the realistic calculation of the expected deformations of single components or kinematic chains is an important task. It requires the quantification of the relationship between temperature measurements (system input quantities) and the resulting deformations (system output quantities). The goal is to derive correction factors for the system control (see Figure 1).

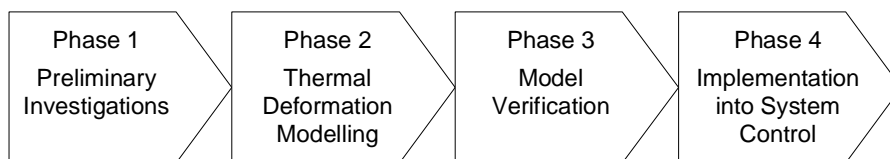


Figure 1: Process chain for computational compensation of thermal influences (referring to Richter 1998)

Another field of interest is provided by civil engineering. In deformation analysis of slim buildings and structures, one problem is the separation of the influence of thermal and mechanical loads (e.g. sun and wind). Considering bridge suspension towers or other types of towers temperature effects may reach magnitudes in the range of some dm. As a typical example the Stuttgart TV tower can be stated. On a summer day the maximum deflection caused by sun exposure amounted up to 1,5 dm in a height of 160 m.

The realistic calculation of thermal deformations requires the collection of a representative spatial temperature distribution inside the structure. In many applications temperatures can only be measured on the surface or in the outside layers. If thermal effects are quantified with static Finite Element models (FEM) the distribution is usually assumed to be stationary and linear. In this case a low thermal conductivity of the material (e.g. concrete) leads to

significant model errors (see Figure 2). The minimization of these errors requires a view based on the fundamental laws of heat flow.

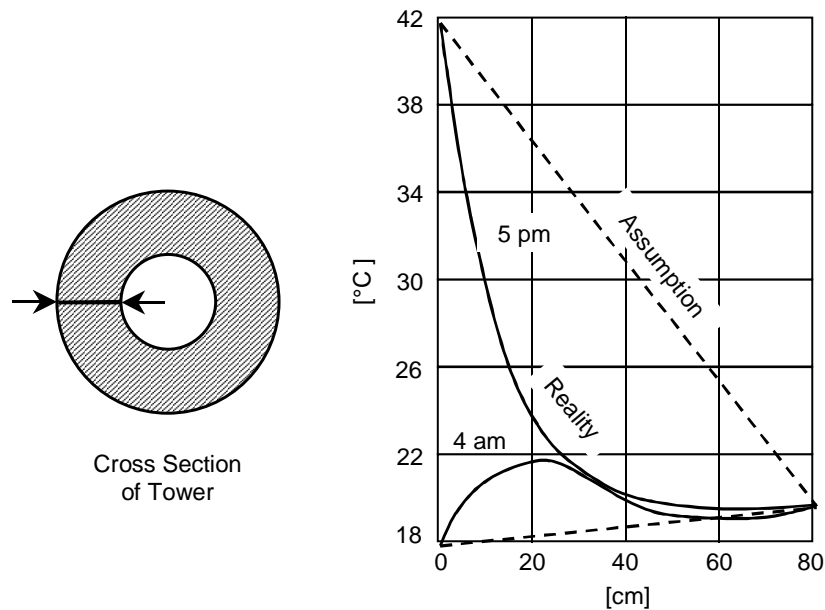


Figure 2: Nonlinear radial temperature distribution in TV tower (Reichmann 1984)

In the field of research “Identification of Dynamic Systems” investigations concerning analysis and modelling of heat flow and thermal deformations are effected at the “Institute for Applications of Geodesy to Engineering” (IAGB, University of Stuttgart). One emphasis is set in the range of industrial applications: development and parametric identification of heat flow and deformation models for the realistic prediction and computational compensation of the thermal bend. As special study objects the frequently occurring class of bar-shaped bodies (i.e. robot arms, etc.) was selected. The interface to mechanical engineering is realised by the exchange of experience with the “Institute for Machine Tools” (IFW, University of Stuttgart).

2. MODELLING AND IDENTIFICATION TASK

2.1 Definition of the Investigation Objectives

Investigating the bend as one main thermal deformation quantity of bar-shaped bodies the following objectives are defined (see also Figure 3):

- Development of a parametric non-stationary heat flow model which is suitable to predict or simulate the influence of one-sided dynamic thermal loads in the heating and cooling phases of machines.
- Flexible modular extension (“user function”) to a parametric deformation model for the precise prediction and computational compensation of the thermal bend.
- Identification of unknown relevant material parameters using adaptive Kalman-filtering.

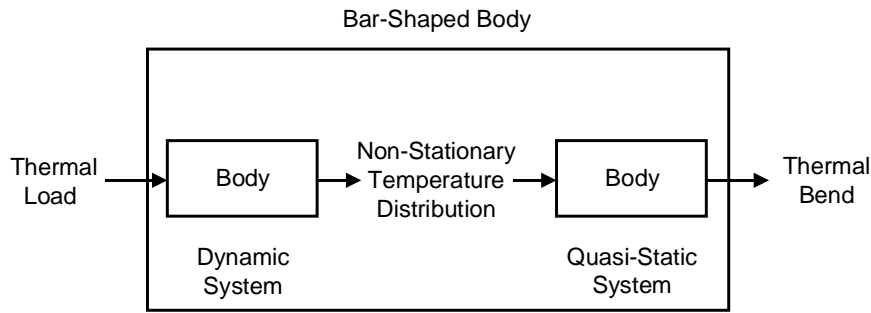


Figure 3: Causal relationship between dynamic temperature loads and thermal bend

The decision to use a physically justified structural model (“white box”-model) is motivated by the variety of possibilities concerning prediction and simulation of the deformation process (Welsch and others 2000). Especially in the case of time-variable thermal loads significant deviating from system calibration “white box”-models are suitable for the calculation of realistic output quantities (Eichhorn 2004).

2.2 Experimental Application

As shown in Figure 4 the experimental investigations of the thermal bend are realised by a thin-walled aluminum column with a height of 1,5 m and a diameter of 0,15 m. Its base is fixed connected to the ground. The one-sided external heat source applies heat energy on a longitudinal profile of the column. The main deformation quantity is represented by the columns bend in the (x, z) vertical plane.

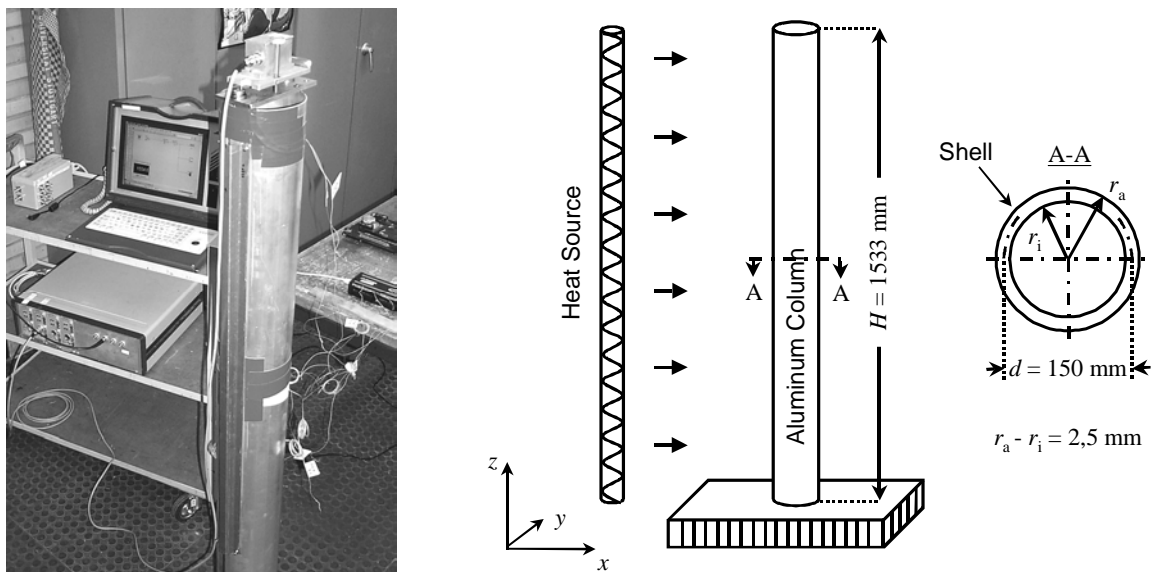


Figure 4: Lab test with aluminum column and external heat source

The usage of an aluminum column as study object is motivated by the following reasons:

- The tubular column and its temperature distribution are representative for bar-shaped machine elements. In one more abstract sense also slim towers may be regarded as columns (see Figure 2 and Pelzer 1974).
- Aluminum has a high thermal conductivity which enables the experimental creation and observation of dynamic temperature processes in an appropriate time.
- The in principle well known homogeneous and isotropic material parameters can be used to evaluate the identification results.
- The thin-walled structure is suitable for the realisation of representative measuring points to verify the modelled progress of the bodies temperature distribution.

The relevant range for the columns surface temperature is defined from room temperature with 293 K (≈ 20 C) up to approximately 400 K. It covers the variations of thermal influences on machine tools (Richter 1998).

3. THERMODYNAMIC FUNDAMENTALS

To provide a deterministic model for the non-stationary heat flow (= ‘temperature model’) the column is divided into several vertically arranged circular shell segments (see Figure 5a). Inside a single segment the heat flow is assumed to be homogenous in its cross section A and to have a one-dimensional dispersion along the shell in a (x, y) plane (see Figure 5b). Because of the thin-walled structure the radial dispersion is neglected. Deviations from these assumptions are treated as model disturbances.

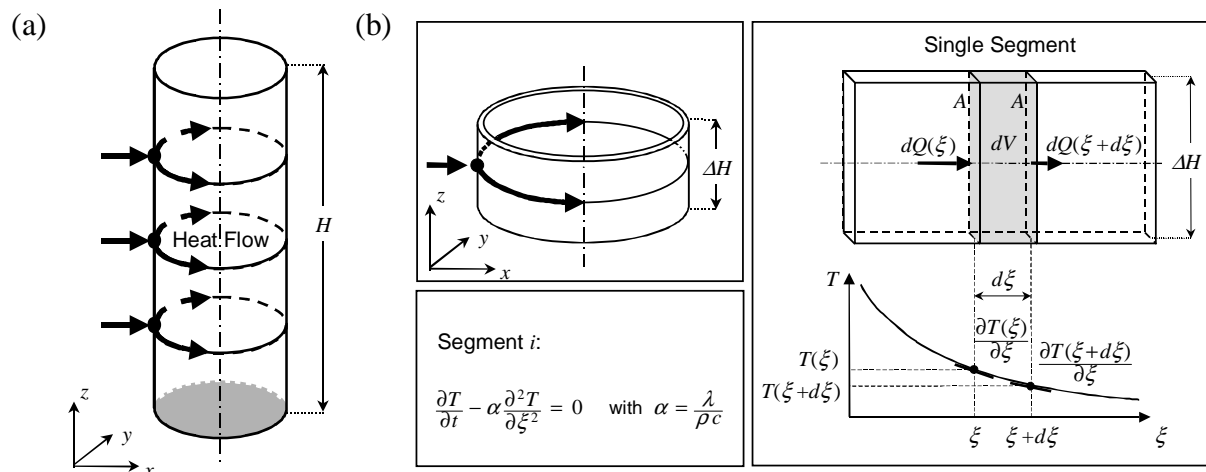


Figure 5: Modelling of the heat flow in single shell segments

Using Fourier's law of heat flow describing the relationship between the transported heat quantity and the associated temperature gradient (see Figure 5b, i.a. Janna 2000) the non-

stationary temperature distribution which is representative for a segment can be quantified by a homogenous linear partial differential equation of 2nd order (= 2nd order PDE).

In (1a) $T_i(\xi, t)$ describes the local and temporal progress of the temperature distribution (see also Figure 6). The material parameter α is the thermal diffusivity consisting of thermal conductivity λ , density ρ and specific heat capacity c . The specification of the initial and boundary values (1b) with $T_{0,i}(\xi)$ as ‘initial temperature distribution’ and $T_{u,i}(t)$ as ‘boundary temperature’ enables the solution of (1a).

$$(a) \quad \frac{\partial T_i}{\partial t} - \alpha \frac{\partial^2 T_i}{\partial \xi^2} = 0 \quad \text{with} \quad \alpha = \frac{\lambda}{\rho c} \quad ; \quad i = 1 \dots s \text{ segments} \quad (1)$$

$$(b) \quad \begin{aligned} T_i(\xi, t = t_0) &= T_{0,i}(\xi) && 0 < \xi < L && \text{initial values} \\ T_i(\xi = 0, t) &= T_i(\xi = L, t) = T_{u,i}(t) && t \geq t_0 && \text{boundary values} \end{aligned}$$

In Figure 6 it is shown that $T_{u,i}$ is injected by the external heat source and can be assumed as system input quantity. The temperature distribution represents the state of the system.

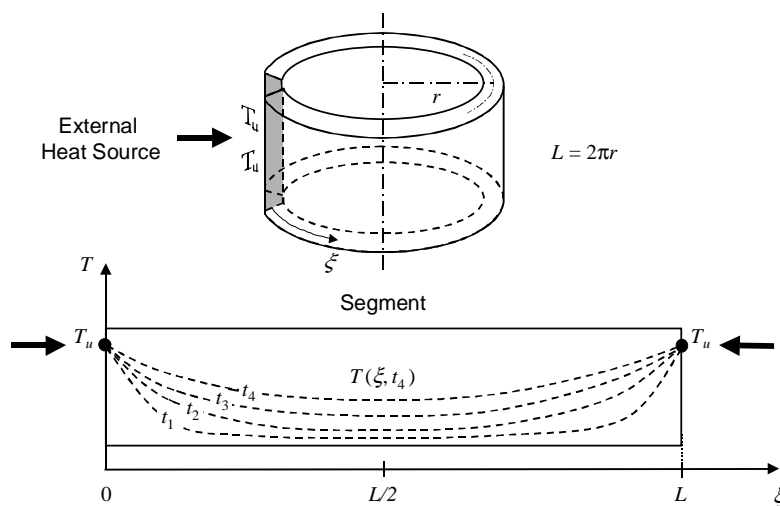


Figure 6: Definition of initial and boundary values

4. DEVELOPMENT OF AN ADAPTIVE KALMAN-FILTER

Using suitable temperature measurements the calibration of the temperature model (1) is realised by adaptive Kalman-filtering. It includes the optimal adaptation of the initial temperature distribution $T_0(\xi)$ and the thermal diffusivity α to reality.

4.1 System and Measuring Equations

The integration of the temperature model into the recursive system equations of a discrete Kalman-filter (i.e. Gelb and others 1974) is realised by a piecewise solution of (1) using the Laplace-transformation (i.e. Föllinger 1986).

The temperature process is represented in discrete time t_k and by n equidistant sampling points ξ_i . The resulting n discrete temperatures $T(\xi_i, t_k)$ represent the temperature state of the shell segment at t_k and define the first part of the filters state vector \mathbf{x} :

$$\mathbf{x}_{\text{Temp}}^T(t_k) = (T(\xi_1, t_k), T(\xi_2, t_k), \dots, T(\xi_n, t_k)) \quad (2)$$

The identification of the material parameter α requires the adaptive extension x_p of the state vector:

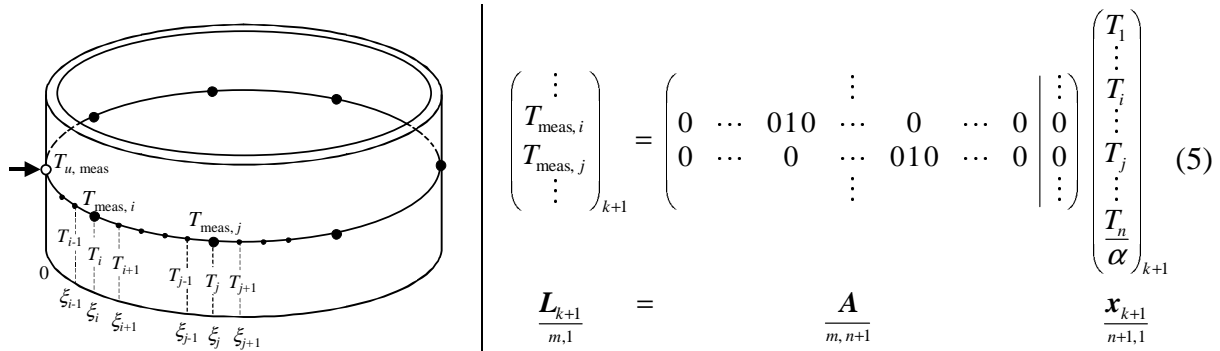
$$\mathbf{x}_k^T = (\mathbf{x}_{\text{Temp}, k}^T \mid x_{p, k}) = (T_{1, k}, \dots, T_{n, k} \mid \alpha_k) \quad (3)$$

The structure of the disturbed system equations of the adaptive Kalman-filter are shown in (4). On the right side the first hypermatrix represents the ‘extended transition matrix’ for \mathbf{x} , the second matrix the ‘extended coefficient matrix of correcting variable’ for u (= injected boundary temperature T_u) and the third matrix the ‘extended coefficient matrix of disturbing variables’ \mathbf{w} and w_p .

$$\begin{aligned} \begin{pmatrix} \frac{\tilde{\mathbf{x}}_{\text{Temp}, k+1} - \bar{\mathbf{x}}_{\text{Temp}, k+1}}{n, 1} \\ \frac{\tilde{x}_{p, k+1} - \bar{x}_{p, k+1}}{1, 1} \end{pmatrix} &= \begin{pmatrix} \frac{\mathbf{T}_{k+1, k}}{n, n} & \frac{\mathbf{T}_{p, k+1, k}}{n, 1} \\ \mathbf{O} & \mathbf{E} \end{pmatrix} \begin{pmatrix} \frac{\tilde{\mathbf{x}}_{\text{Temp}, k} - \hat{\mathbf{x}}_{\text{Temp}, k}}{n, 1} \\ \frac{\tilde{x}_{p, k} - \hat{x}_{p, k}}{1, 1} \end{pmatrix} \\ &+ \begin{pmatrix} \frac{\mathbf{B}_{k+1, k}}{n, 1} \\ \mathbf{O} \\ \frac{\mathbf{O}}{1, 1} \end{pmatrix} \begin{pmatrix} \tilde{u}_k - u_k \\ 1, 1 \end{pmatrix} \\ &+ \begin{pmatrix} \frac{\mathbf{S}_{k+1, k}}{n, q} & \frac{\mathbf{T}_{p, k+1, k}}{n, 1} \\ \mathbf{O} & \mathbf{E} \end{pmatrix} \begin{pmatrix} \frac{\mathbf{w}_k}{q, 1} \\ \frac{w_{p, k}}{1, 1} \end{pmatrix} \end{aligned} \quad (4)$$

The stochastic influence of the model disturbances \mathbf{w} was empirically evaluated in preliminary investigations of the column. The quantity w_p is the stochastic part of a ‘random walk’-process (i.e. Chatfield 1982) disturbing the material parameter α .

The measuring equations contain direct measurements of state quantities in selected measuring points:



4.2 Stochastic Model

The stochastic model of the Kalman-filter is represented by discrete noise processes. Assuming no temporary and crosscorrelations the following covariance matrices are defined (see also Heunecke 1995):

$$\frac{\Sigma_{LL^*, k+1}}{n+m+q+3, n+m+q+3} = \begin{pmatrix} \frac{\Sigma_{\hat{x}\hat{x}, k}}{n+1, n+1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ & \frac{\Sigma_{uu, k}}{1, 1} & \mathbf{0} & \mathbf{0} \\ & & \frac{\Sigma_{w^*w^*, k}}{q+1, q+1} & \mathbf{0} \\ \hline & & & \frac{\Sigma_{LL, k+1}}{m, m} \end{pmatrix} \quad \text{with} \quad \frac{\Sigma_{w^*w^*, k}}{q+1, q+1} = \begin{pmatrix} \frac{\Sigma_{ww, k}}{q, q} & \mathbf{0} \\ & \frac{\Sigma_{w_p w_p, k}}{1, 1} \end{pmatrix} \quad (6)$$

5. IDENTIFICATION AND PREDICTION RESULTS

5.1 Identification of the Material Parameter

To create a suitable experimental design for the estimation of the thermal diffusivity α only a cut-out of the aluminum column is used (see Figure 7). The single circular shell segment is assumed to fulfill the thermodynamic behaviour defined in Section 3.

The procedure enables the creation of a sufficient thermal load step to measure the systems step response. Disturbance influences (e.g. convective heat exchange caused by air flow) can be minimized and accessible measuring points can be guaranteed.

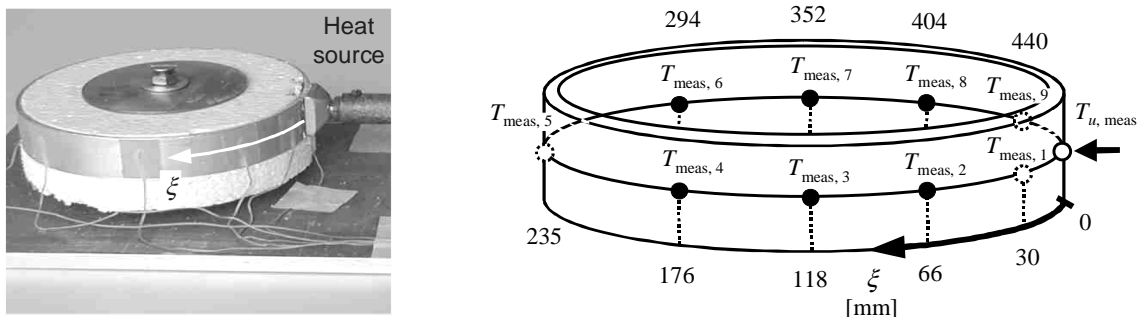


Figure 7: Experimental design and measuring points

The optimal distribution of measuring points is detected analyzing the algebraic correlations between the observable temperature state quantities x_{Temp} and the non-observable material parameter x_p in the system equations of the Kalman-filter. In Figure 8 it is shown that the maximum correlations are localized within a symmetrical range around the injected boundary temperature T_u . Consequently the temperature measurements are carried out in this area with $T_{meas,1} - T_{meas,3}$ and $T_{meas,7} - T_{meas,9}$. Three additional control measurements are realised by $T_{meas,4} - T_{meas,6}$. The correcting variable is collected by $T_{u,meas}$ (see Figure 7). As sensors Nickel-chromium-nickel thermocouples (external accuracy $s_T \approx 0,4$ K) are used with a measuring frequency of 0,5 Hz.

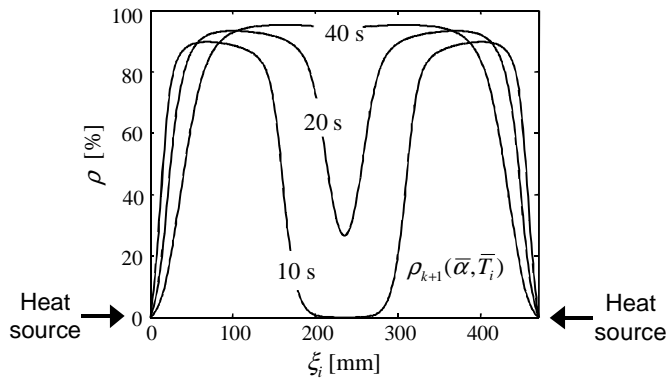


Figure 8: Selection of optimal measuring points by correlation functions

In Figure 9 the filter results for the thermal diffusivity and its standard deviation are presented. Starting from a bad initial value it is shown that the estimation of α converges to the theoretical value for pure aluminum with a final deviation of 0,2%. Its standard deviation has a level compatible with these results.

Using a spectroscopic material analysis for additional verification the columns material can be specified as aluminum alloy AlMgSi0,5 (see Kammer 1995). Depending from its unknown portion of magnesium and silicon the theoretical thermal diffusivity is located in a narrow tolerance band (see Figure 9). The adaptive Kalman-filtering enables to restrict this tolerance to its upper limit.

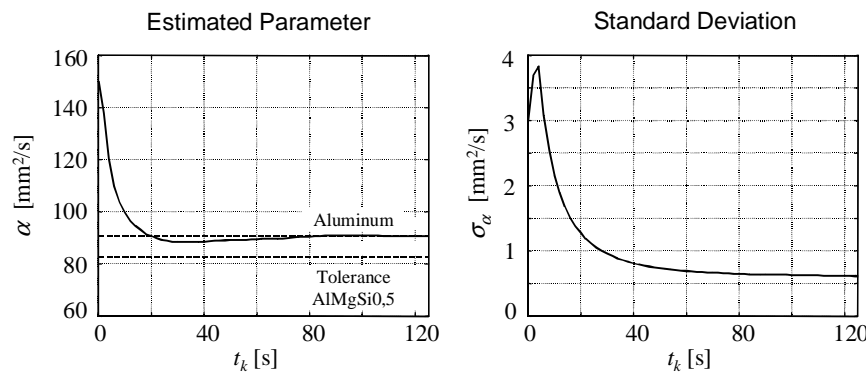


Figure 9: Estimated thermal diffusivity and its standard deviation

5.2 Verification of the Calibrated Temperature Model

The verification of the calibrated temperature model is realised on the aluminum column itself. In Figure 10 the basic principle of verification is shown. Measuring only the system input quantity T_u the calibrated temperature model (represented by the system equations of the Kalman-filter with the identified thermal diffusivity $\hat{\alpha}$) can be used to predict the local and temporal progress of the non-stationary temperature distribution of a shell segment. These predictions are evaluated by comparison with real temperature measurements. In order to receive representative results the system input is varied significantly from calibration.

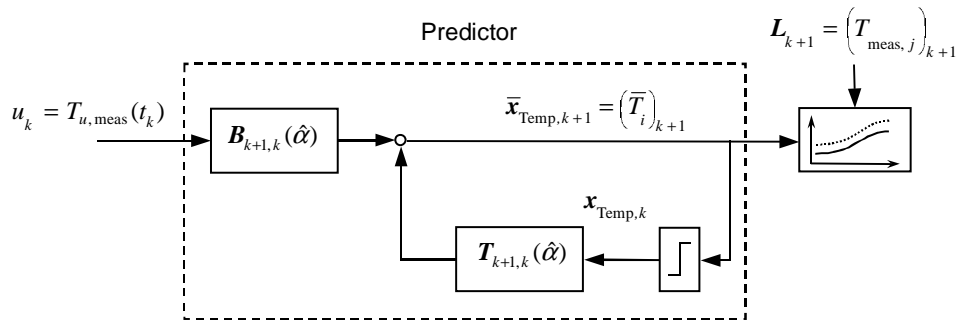


Figure 10: Principle of verification for a shell segment

The practical transfer of the temperature model to the column is realised by its discretisation into three identical segments (bottom, middle and top segment, see Figure 11). Starting from constant room temperature (≈ 293 K) the progress of the temperature distribution is predicted for each segment. In Figure 11 predictions and control measurements are compared in selected points ξ_5 and ξ_8 .

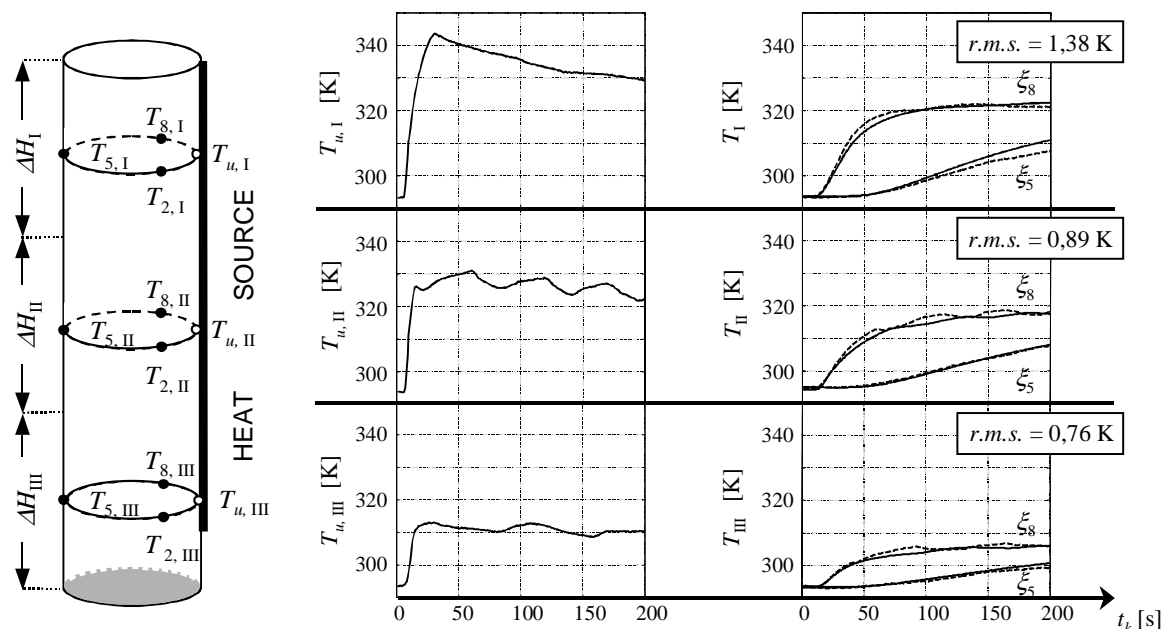


Figure 11: Comparison of measured (---) and predicted (—) temperature progress

In a heating phase of 200 s the mean deviations (*r.m.s.*-values) between prediction and control measurements derived in the bottom and middle segment are within the 3σ -range of the thermocouples. In the top segment increasing convective disturbances cause a rise up to *r.m.s.* = 1,4 K. Altogether the calculated temperature progress can be evaluated as close-to-reality and the calibrated temperature model as verified.

Figure 12 shows the predicted non-stationary temperature distribution for the middle segment with a resolution of $\Delta\xi = 1$ mm and $\Delta t = 1$ s.

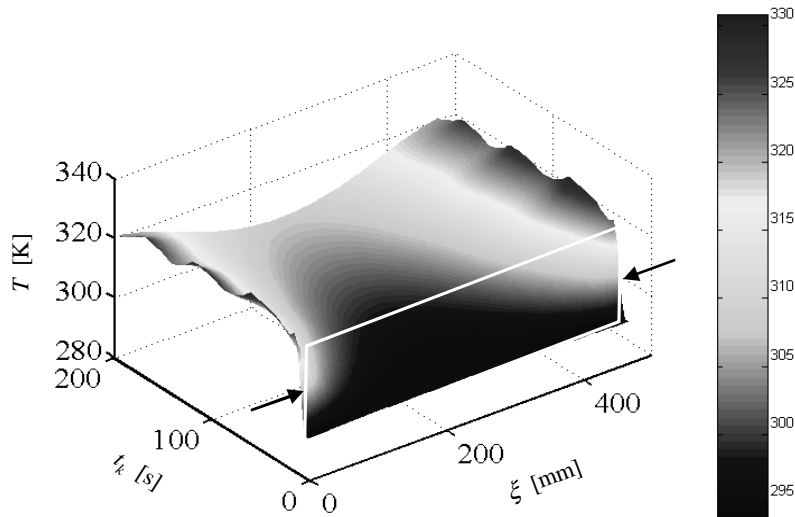


Figure 12: Predicted non-stationary temperature distribution in middle segment (II)

6. EXTENSION TO A DEFORMATION MODEL

To receive a thermal deformation model the deformation part is regarded as a specific “user function” (Heunecke 1995) combining the temperature state quantities with relevant deformation (output-)quantities. This strategy enables the flexible extension of the calibrated temperature model with a “deformation module” depending on the material properties of the column.

The creation of the deformation module for one-sided thermal loads requires the definition of geometrical quantities representing the thermal bend. Introducing a circular arc as idealised bending line the inclination φ of the column is suitable for (simple) modelling and the practical realisation of precise control measurements for verification (see Figure 13).

The assumption of a circular arc as bending line is connected with some simplifications concerning the thermoelastic behaviour of the column. One main simplification is neglecting the thermal bending stress caused by the non-linear temperature distribution (i.e. Timoshenko / Goodier 1985). The admissibility of this measure in the case of a thin-walled aluminum tube was proved in preliminary investigations (Eichhorn 2004).

With α_T specifying the temperature extension of aluminum the deformation module can be quantified using the well known formula for slim structures (Pelzer 1974, see Figure 13b):

$$\varphi(t_k) = \frac{H \alpha_T \Delta T(t_k)}{d} = \frac{H \alpha_T (T_u(t_k) - T(\xi_5, t_k))}{d} \quad (7)$$

In (7) ΔT is the temperature difference between the thermal loaded and the opposite side of the column. It can be substituted using the injected boundary temperature T_u (system input) and the temperature state quantity T_5 in ξ_5 (see also Figure 11). The right side of (7) specifies the algebraic relation between the temperature model and the deformation module.

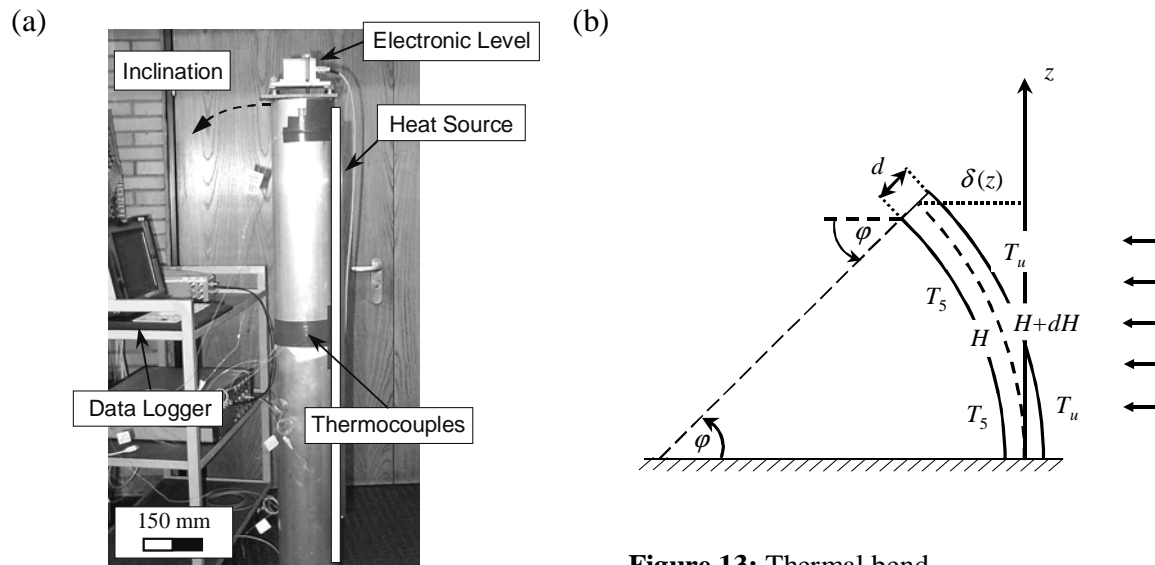


Figure 13: Thermal bend

In Figure 14 the functional architecture for the prediction of the thermal bend is presented. The measured temporal progress of the system input $T_u(t_k)$ and the calibrated temperature model enable the prediction of the temperature distribution of the column (see Section 5.2).

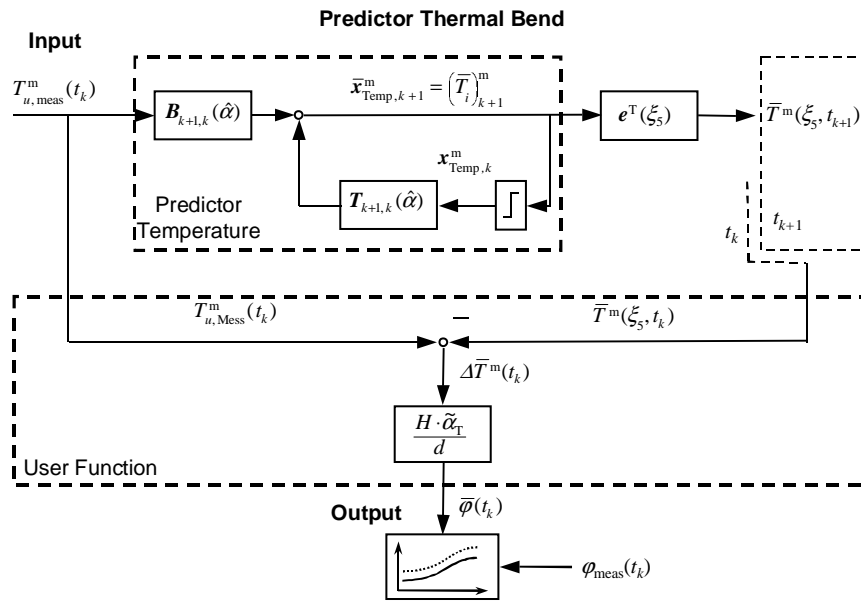


Figure 14: Predictor for thermal induced inclination

The opposite temperature state quantity $T_5(t_k)$ is separated and used for the prediction of the inclination $\varphi(t_k)$. The system output is verified by comparison with the measured inclination. For the measurements the electronic level Q-flex 1400 (from Honeywell) is adapted to the top of the column (see Figure 13a).

Figure 15 shows the comparison of the predicted and measured inclination φ for a heating phase of 200 s. The discretisation of the temperature model is conform with Figure 11. It is obvious that the progress of the predicted inclination has a good conformity with the measured inclination.

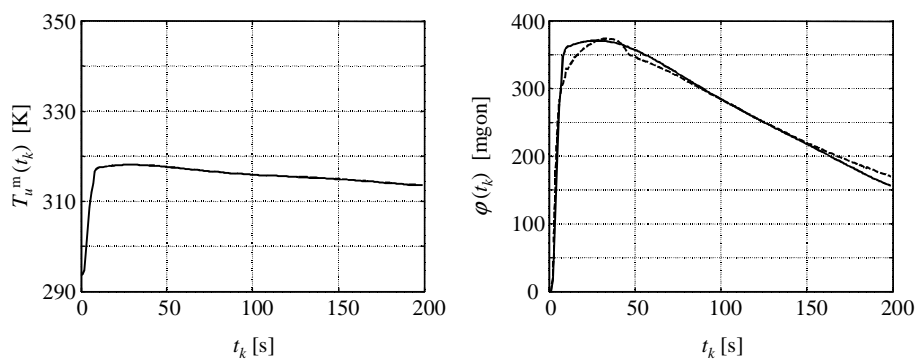


Figure 15: Comparison of measured (---) and predicted (—) inclination

The mean deviation between predictions and measurements is $r.m.s. = 10$ mgon (see Table 1) which corresponds to a relative error of 2,5% (referred to maximum inclination). This result can be evaluated positive for applications in the field of computational compensation with specified relative errors in a range of 1 or 2%.

Table 1: Conformity between predicted and measured inclinations

Variation of α	-10%	-5%	-4%	$\hat{\alpha}$	+4%	+5%	+10%
<i>r.m.s.</i> [mgon]	12,7	10,1	9,9	10,0	11,7	12,3	15,9

In Table 1 it is also shown that the best fit is achieved within a range of approximately $\pm 4\%$ ($\approx \pm 3\sigma_\alpha$) around the identified value of the thermal diffusivity α . This result is an additional indicator for the successful identification of the material parameter and its compatibility with the deformation module.

The predicted inclinations $\varphi(t_k)$ can be used to calculate the deflections $\delta(t_k)$ of the top of the column (see Figure 13b). According to Pelzer (1974) the algebraic relation is defined as:

$$\delta(t_k) = \frac{H^2 \alpha_T (T_u(t_k) - T(\xi_5, t_k))}{2d} = \frac{H}{2} \varphi(t_k) \quad (8)$$

The conversion of the inclination progress into thermal induced deflections $\delta(H, t_k)$ is shown in Figure 16.

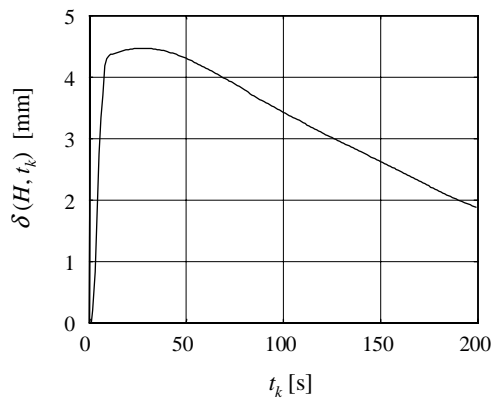


Figure 16: Predicted deflections δ of the top of the column

7. CONCLUSIONS

Comparing the predicted and measured thermal induced inclination the efficiency of a dynamic structural deformation model is demonstrated. One main advantage is the independency of varying thermal loads, of course only within the range of validity of the physical assumptions. The achieved accuracy in calibration and prediction provides a very promising base for future computational compensation methods in industrial manufacturing. There's of course still room for improvement investigating the influence of the convective heat flow and the distribution of the thermal stresses. Using an adaptive Kalman-filter a very efficient tool is provided to consider these quantities by deterministic and stochastic methods.

The calibrated deformation model is suitable for close-to-reality simulations. Specifying only the progress of the injected boundary temperatures $T_{u,i}$ the system output (inclination φ or

deflection δ) can be calculated by the computer model. This allows the investigation of a wide spectrum of thermal influences without additional experiments.

It is also planned to transfer the non-stationary heat flow model and its identification to slim buildings. Dynamic FEM topologies with similar basic ideas are in use in civil engineering (i.e. Reichmann 1984). The identification of the material parameters is still a problem.

REFERENCES

- Bonse, R. (1999): *Thermisches Last-Verformungsverhalten von Werkzeugmaschinen*. RWTH Aachen, Berichte aus der Produktionstechnik, Band 14/99, Aachen
- Chatfield, C. (1982): *Analyse von Zeitreihen*. München Wien, Carl Hanser Verlag
- Eichhorn, A. (2004): *Ein Beitrag zur parametrischen Identifikation von dynamischen Strukturmodellen mit Methoden der adaptiven Kalman-Filterung*. Doctoral thesis, University of Stuttgart, IAGB, in preparation
- Föllinger, O. (1986): *Laplace- und Fourier-Transformation*. Heidelberg, Hüthig Verlag
- Heunecke, O. (1995): *Zur Identifikation und Verifikation von Deformationsprozessen mittels adaptiver KALMAN-Filterung (Hannoversches Filter)*. Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Nr. 208, Hannover
- Janna, W. S. (2000): *Engineering Heat Transfer*. London New York, CRC Press
- Kammer, C. (1995): *Grundlagen und Werkstoffe*. In: Aluminium-Zentrale-Düsseldorf (Eds.): Aluminium-Taschenbuch, Band 1, Düsseldorf, Aluminium-Verlag
- Overbeck, T. (1992): *Beitrag zur Steigerung der Leistungsfähigkeit von Horizontal-Knickarm-Robotern*. Technische Universität Hamburg-Harburg, AWA Fortschrittsberichte, Band 4, Hamburg
- Pelzer, H. (1974): *Bewegungen hoher Türme*. In: Vermessungswesen und Raumordnung, Heft 36, 345 – 354.
- Richter, F. (1998): *Erfassung und Ausgleich thermisch bedingter Verformungen an Industrierobotern*. Universität Stuttgart, Berichte aus dem IfW, Band 12, Stuttgart
- Timoshenko, S. P. / Goodier, J. N. (1985): *Theory of Elasticity*. Singapore, McGraw-Hill Book Company
- Welsch, W. M. / Heunecke, O. / Kuhlmann, H. (2000): *Auswertung geodätischer Überwachungsmessungen*. In: Möser, M. / Müller, G. / Schlemmer, H. / Werner, H. (Eds.): Handbuch Ingenieurgeodäsie, Heidelberg, Wichmann Verlag

BIOGRAPHICAL NOTES

Andreas Eichhorn

Since 2003: University Assistant at Institute for Geodesy & Geophysics, Engineering Geodesy, Vienna University of Technology, Austria

1996-2002: Research assistant at IAGB, University of Stuttgart, Germany

1990-1996: Studies in geodesy, University of Karlsruhe, Germany

Selected professional experience:

- At present project member: "Knowledge based analysis of landslides (EU-project)"
- 3 years project member: "Analysis of dynamic deformation processes" (IAGB and IFW)
- 1 year project member: "Car navigation" (IAGB, DaimlerChrysler)
- 3 years project manager: "High precision DTM calculation" (IAGB, DaimlerChrysler)

Memberships: German Association of Surveyors (DVW), IAG Working group 4.2.2

CONTACTS

Andreas Eichhorn

Institute for Geodesy & Geophysics, Engineering Geodesy

Vienna University of Technology

Gusshausstr. 27-29 / E128/3

1040 Vienna

AUSTRIA

Tel. + 43 1 58801 12842

Fax + 43 1 58801-12894

Email: aeichhor@pop.tuwien.ac.at

Web site: <http://info.tuwien.ac.at/ingeo>