Terminology and Classification of Deformation Models in Engineering Surveys

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Abstract

The deformation of an object is the result of a process. According to the current trends in engineering surveying, the analysis of deformations intends to figure out the dynamics of this process. Apart from the geometrical changes observed, the basis of the investigations is to incorporate the causative forces and the physical properties of the body. In its entirety, the body, the influencing forces and the resulting deformations are considered a dynamical system. Thus in our days „Geodetic Deformation Analysis“ means „Geodetic Analysis of Dynamic Processes“. The tools to do so, are made available by neighbouring disciplines like the sciences of mechanics, filter and control engineering and systems theory. Especially systems theory provides the terminology and classification of models for an up-to-date deformation analysis in the above sense. The essence of the paper is the description of the deformation models in accordance with systems theory.

1. Introduction

The traditional task of deformation analysis is the investigation of movements and displacements of an object with respect to space and time. Driven by the development of measuring and analysis techniques and the need of interdisciplinary approaches for solutions, the goal of geodetic deformation analysis is nowadays to proceed from a merely phenomenological description of the deformations of an object to the analysis of the process which caused the deformations, i.e. to incorporate the causative forces and the physical properties of the body under investigation. In its entirety, the body, the influencing forces and the resulting deformations are considered a dynamical system. Thus „Geodetic Deformation Analysis“ means „Geodetic Analysis of Dynamic Processes“ with the consequence that engineering surveying has to understand to a certain degree the dynamics of the processes the object monitored is involved in. The surveying engineer is forced to talk to his colleagues of neighbouring disciplines like mechanics, filter and control engineering and systems theory, to understand their technical language and thinking and to make them acquainted with his expertise. Ideally the terminology should be standardised and be understood by everyone involved.

A generally accepted systematisation of technical terms for an up-to-date deformation analysis in the above sense is provided by systems theory.

2. Systematisation of Deformation Models

In systems theory dynamic systems are characterised by input signals (cause), transmission through the system (transfer process) and output signals (response). An object to be monitored can be considered a dynamic system, if acting forces (internal and external loads) are regarded as input signals which lead to geometrical changes (displacements and distortions) as output signals.

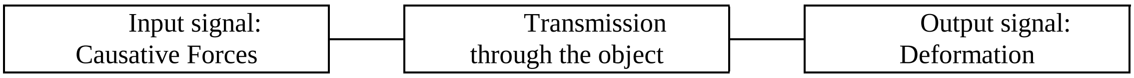

Figure 1 Deformation as an element of a dynamic process

Changes of input signals release a time-dependent process of adaptation of the system with the consequence that the reaction of the output side is delayed: a dynamic system has a memory. This is the general case. Special cases are the following:

- Dynamic systems: the acting forces create the dynamic process in the above mentioned sense. Dynamic systems can be distinguished with respect to the factor time. There are two kinds of dynamic systems:
  a) dynamic systems as such react as in the general case: the deformations as the output signal are a function of time and (varying) loads;
  b) static system are in equilibrium. They react immediately to a change of the causative forces: the new state of equilibrium is taken without time delay. The deformations are a function of (varying) loads only.
- Systems which are not subject to acting forces are called autonomous. These systems can nevertheless be in motion. There are two kinds of autonomous systems:
  a) kinematic systems are in motion, but the motion can be described as a function of time;
  b) random walk systems are in motion, but the motion is random, a function of time cannot be established.

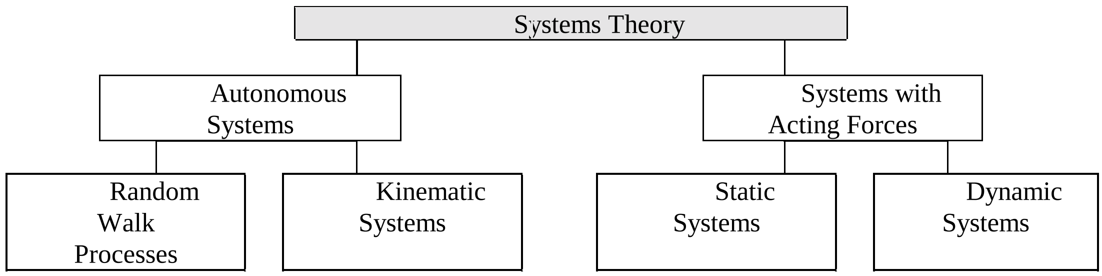

Figure 2 Hierarchy of systems in systems theory (Heunecke 1995, Welsch 1996)

The main purpose of systems theory is to find pertinent mathematical descriptions of the behaviour of systems. This is called system identification. From the geodetic point of view the goal is supported by geodetic deformation analysis, if this means the analysis of processes by geodetic means. The analogy of the hierarchy of systems and models for deformation analysis is obvious.

Congruence or identity models, the classical geodetic approach in deformation analysis, allow a purely geometrical comparison between two states of an object represented in the space domain by a number of characteristic points (object points) without explicitly regarding "time" and "loads". The first step of analysis is to examine the geometrical identity of an object on the basis of statistical tests. Deformations detected are then analysed as either local, regional or global. Local deformations are in many instances single point movements, regional or global deformations can be generalised and described by rigid body movements, affine distortions or other approximation functions.

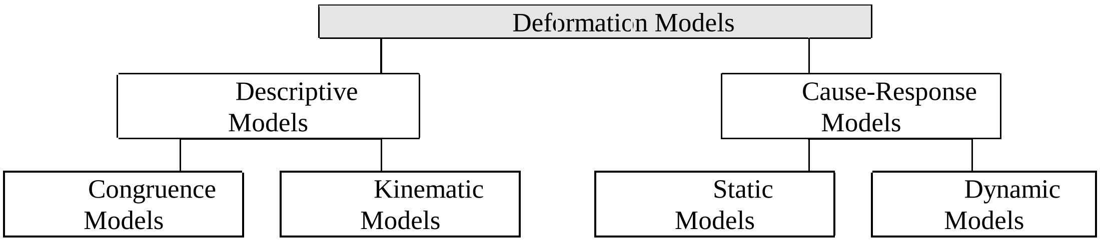

Figure 3 Hierarchy of models in geodetic deformation analysis (Heunecke 1995, Welsch 1996)

The intention of kinematic models is to find a suitable description of point movements by time functions without regarding the potential relationship to causative forces. Polynomial approaches, especially velocities and accelerations, and harmonic functions are commonly applied.

A static model describes the functional relationship between loads as causative forces and geometrical reactions of an object without regarding time aspects. The object has to be sufficiently in a state of equilibrium during the observation epochs. The behaviour between the epochs remains unknown and is not of interest in a static model.

Subject of dynamic modelling is a pertinent description of the behaviour of an object with respect to time and forces. A dynamic model integrates the capabilities of static and kinematic models.

Deformation Model	Congruence Model	Kinematic Model	Static Model	Dynamic Model
Time	no modelling	movements as a function of time	no modelling	movements as a function of time and loads
Acting Forces	no modelling	no modelling	displacements as a function of loads	
State of the Object	sufficiently in equilibrium	permanently in motion	sufficiently in equi- librium under loads	permanently in motion

Figure 4 Classification of deformation models (Heunecke 1995; Heunecke, Pelzer 1998)

3. Dynamic Models

Dynamic models are the most general and comprehensive models because they describe the reality of a dynamic system completely. There are two categories within the class of dynamic systems: parametric and non-parametric ones. Other terms are structured or state vs. attitude models, or theoretical vs. experimental process analysis, or model vs. operational approach. The feasibility of setting up a physical-mathematical model for the transmission of input to output signals through the object is decisive for the distinction.

Another classification can be made with respect to the number of input and output signals, resp. There are single input – single output (SISO), multiple input – single output (MISO) and multiple input – multiple output (MIMO) systems and models (Heunecke et al., 1998):

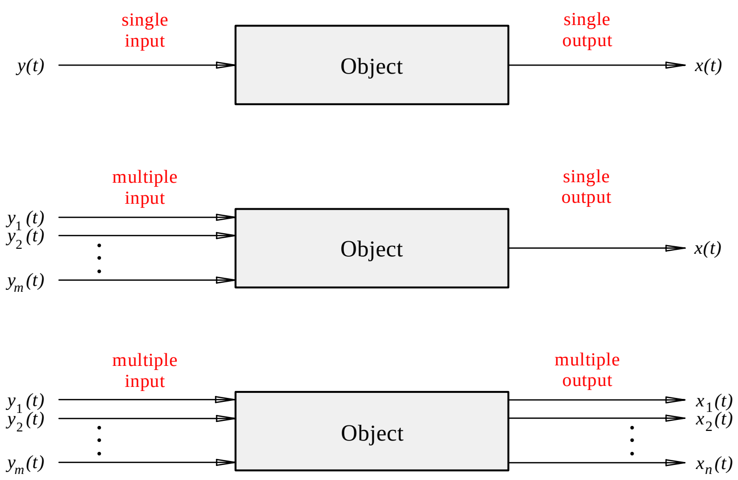

Figure 5 SISO-, MISO- and MIMO-systems

3.1. Parametric Models

If the physical relationship between input and output signals, i.e. the transmission or transfer process of the signals through the object or – in other words - the transformation of the input to output signals, is known and can be described by differential equations, then the model is called a parametric model. The parameters of the model are the ones, which interpret the dynamic process in a physical way. The systems identification is carried out in a so-called “white box” model.

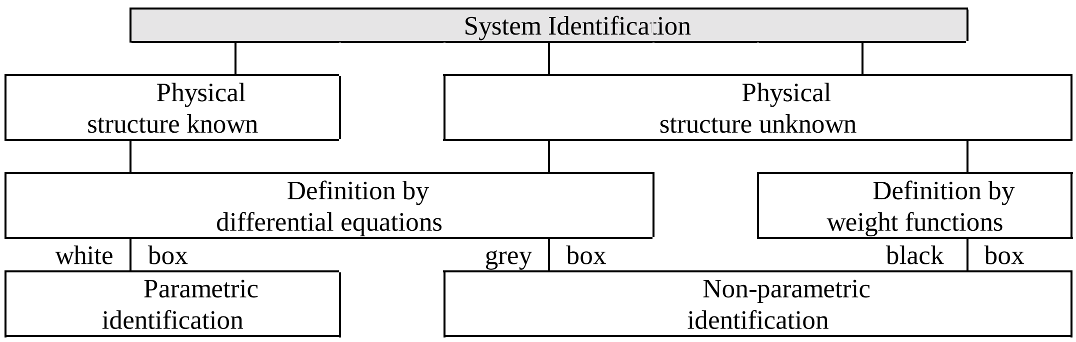

Figure 6 Methods of system identification (Heunecke 1995, Welsch 1996)

3.2. Non-Parametric Models

If there is no way of modelling the physical structure of a system, the relationship between input and output signals can be formulated only in the sense of regression and/or correlation analysis. System identification means then the determination of the regression/correlation coefficients. Commonly these coefficients are called parameters, too, although they are not the parameters of the process under investigation; they relate rather the input signals to the output signals without any physical significance. These non-parametric models are therefore also called “black box” models.

The most general description of non-parametric models is a set of partial differential equations. In the case of a SISO model it is given by an ordinary differential equation which can be established (Ellmer 1987, Welsch 1996) by the approach

$$\begin{aligned} & a_q \frac{d^q x}{dt^q} + a_{q-1} \frac{d^{q-1} x}{dt^{q-1}} + \ldots + a_1 \frac{dx}{dt} + a_0 x = \\ & b_p \frac{d^p y}{dt^p} + b_{p-1} \frac{d^{p-1} y}{dt^{p-1}} + \ldots + b_1 \frac{dy}{dt} + b_0 y \end{aligned} \quad . \qquad (1)$$

If one proceeds from the differential to a difference equation, the model is also known as the so-called ARMA (autoregressive moving average) model:

$$x_k = a_1 x_{k-1} + a_2 x_{k-2} + \ldots + a_q x_{k-q} + b_0 y_k + b_1 y_{k-1} + \ldots + b_p y_{k-p} \, . \qquad (2)$$

The unknown coefficients a_k and b_k are the parameters to be estimated in the identification procedure. The boundary values q and p represent the continuance of the memory: at time t_k the model recollects all the input and output events back to those boundaries.

Characteristic for this elementary non-parametric model is the fact, that for $q > 3$ and $p > 0$ a physically meaningful model structure gets lost, although the coefficients have to be regarded as functions of the material and design parameters of the system. For $q > 3$ and $p > 0$, however, the parameters can physically be interpreted. In this case the model is a “grey box”.

The ARMA-model consists of a recursive and a non-recursive part:

$$x_k = \sum_{i=1}^{q} a_i \, x_{k-i} + \sum_{j=0}^{p} b_j \, y_{k-j} \quad . \qquad (3)$$

For $p = 0$ the model is autoregressive: the actual observation x_k is considered a linear combination of the past observations and the present system input y_k. For $q = 0$ the model becomes non-recursive: the actual system output is a linear combination of the present and the past system inputs. The coefficients b_j can then be regarded as the factors of a regression analysis.

For continuous observations the representation of the non-recursive (linear) model is the convolution integral (Strobel 1975)

$$x(t) = \int_0^\infty g(\tau) \; y(t-\tau) \; d\tau \qquad (4)$$

where $g(\tau)$ is the so-called weight function which plays - as above - the role of regression analysis parameters.

For the treatment of non-linear models the so-called VOLTERRA-model (Wernstedt 1989) has been developed:

$$x(t) = \int_0^\infty g_1(\tau_1)\; y(t-\tau_1)\; d\tau_1 + \int_0^\infty\int_0^\infty g_2(\tau_1\tau_2)\; y(t-\tau_1)\; y(t-\tau_2)\, d\tau_1\, d\tau_2 + \textit{higher order terms.} \tag{5}$$

In the discrete case model (4) and model (5) can be written in form of a summation or multiple summation equation, respectively (Pfeufer 1988).

Recently new analysis techniques have been adopted from control engineering: neural networks and fuzzy logic have been used to set up models for the identification of input-output systems (Heine, 1999).

The non-parametric models can be applied to a great variety of systems and processes.

4. Computation Techniques

4.1. Lumped and Distributed Parameters - Finite Elements

If with parametric system identification only the time dependence rather than the local or spatial variation of the process is considered, the system can be defined by lumped parameters. Ordinary differential equations are sufficient in this case. If with parametric system identification apart from the time dependence also the local variation of the process is considered, the system has to be defined by distributed parameters. This leads to partial differential equations. If these differential equations are set up for restricted areas only, they can be replaced by ordinary differential equations which are, however, effective only within the respective restricted areas. This procedure is called local discretisation. A numerical method is realised by the Finite Element Method (FEM) which is today the standard computation method for any kind of structural problems in civil engineering and in many other engineering sciences.

4.2. Time Series Analysis

Time series analysis as such is another method of system identification. The most significant information to be calculated in the time domain of a time series is its expectation value and the auto-covariance function which informs of the variance of the process observed. Comparing the input and the output time series by calculating the cross-covariance function, one obtains information about the correlation of the two time series and whether the reaction of the system is delayed with respect to the input signal (phase shift).

If one applies FOURIER-transformations to switch from the time to the frequency domain, characteristic frequencies of the process can be detected. The output signal comprises only frequencies which are also contained in the input signal. Consequently, frequencies which are in the output but not in the input signal, can give clues that there may be more than the investigated factors influencing the system.

Time series analysis as such has a wide range of applications (Kuhlmann 1996). In most cases of non-parametric system identification time series *x(t)* and *y(t)* are the data basis for the investigations.

4.3. KALMAN-Filtering

KALMAN-Filtering is the most popular and universal estimation tool for MIMO-system identification and can be applied to all kinds of models in Figure 4. The essential idea can be explained as follows. On the one side there is the theory how the object is to be modelled by differential equations. These equations are called system equation. On the other side there are measurements monitoring the real behaviour of the object. The measurements are formulated as the so-called observation equation. KALMAN-Filtering is a technique to combine both equations by least squares adjustment in order to gradually improve the identification of the system.

A KALMAN-Filter (Heunecke 1994, 1995) contains several groups of information $\boldsymbol{Y}$: the previous output signal, commonly referred to as the state vector $\boldsymbol{x}_k$; the (deterministic) input quantities, in KALMAN-Filtering called $\boldsymbol{u}_k$; some disturbance quantities $\boldsymbol{w}_k$, and the monitoring observations of the new state $\boldsymbol{l}_{k+1}$. The respective covariance matrices are included:

$$\boldsymbol{Y} = \begin{vmatrix} \boldsymbol{x}_k \\ \boldsymbol{u}_k \\ \boldsymbol{w}_k \\ \boldsymbol{l}_{k+1} \end{vmatrix}; \quad \boldsymbol{\Sigma}_{\boldsymbol{YY}} = \begin{vmatrix} \boldsymbol{\Sigma}_{\boldsymbol{xx},k} & \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{\Sigma}_{\boldsymbol{uu},k} & \boldsymbol{O} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{\Sigma}_{\boldsymbol{ww},k} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{O} & \boldsymbol{\Sigma}_{\boldsymbol{ll},k+1} \end{vmatrix}. \tag{6}$$

The theoretically predicted transition from the state $\boldsymbol{x}_k$ at time t_k to the state $\boldsymbol{x}_{k+1}$ at time t_{k+1} is modelled in the system equation

$$\overline{\boldsymbol{x}}_{k+1} = \begin{vmatrix} \boldsymbol{T}_{k+1,k} & \boldsymbol{B}_{k+1,k} & \boldsymbol{C}_{k+1,k} \end{vmatrix} \cdot \begin{vmatrix} \boldsymbol{x}_k \\ \boldsymbol{u}_k \\ \boldsymbol{w}_k \end{vmatrix}. \tag{7}$$

For the combination of the predicted state $\overline{\boldsymbol{x}}_{\boldsymbol{k}+1}$ with the observations $\boldsymbol{l}_{k+1}$, a GAUSS-MARKOV model is formulated:

$$\begin{vmatrix} \overline{\boldsymbol{x}}_{k+1} \\ \boldsymbol{l}_{k+1} \end{vmatrix} = \begin{vmatrix} \boldsymbol{I} \\ \boldsymbol{A}_{k+1} \end{vmatrix} \hat{\boldsymbol{x}}_{k+1} - \begin{vmatrix} \boldsymbol{v}_{\overline{x},k+1} \\ \boldsymbol{v}_{\boldsymbol{l},k+1} \end{vmatrix}, \quad \boldsymbol{\Sigma}_{\boldsymbol{YY},k+1} = \sigma_0^2 \begin{vmatrix} \boldsymbol{Q}_{\overline{\boldsymbol{xx}},k+1} & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{Q}_{\boldsymbol{ll},k+1} \end{vmatrix}. \tag{8}$$

Using the so-called gain-matrix

$$\boldsymbol{K}_{k+1} = \boldsymbol{Q}_{\overline{\boldsymbol{xx}},k+1} \boldsymbol{A}_{k+1}^T (\boldsymbol{Q}_{\boldsymbol{ll},k+1} + \boldsymbol{A}_{k+1} \boldsymbol{Q}_{\overline{\boldsymbol{xx}},k+1} \boldsymbol{A}_{k+1}^T)^{-1} = \boldsymbol{Q}_{\overline{\boldsymbol{xx}},k+1} \boldsymbol{A}_{k+1}^T \boldsymbol{D}_{k+1}^{-1} \tag{9}$$

which is one of the characteristic matrices of KALMAN-Filtering. The most important results representative for time t_{k+1} can be comprehended by a vector $\boldsymbol{X}$:

$$\boldsymbol{X} = \begin{vmatrix} \boldsymbol{d}_{k+1} \\ \hat{\boldsymbol{x}}_{k+1} \\ \boldsymbol{v}_{\overline{x},k+1} \\ \boldsymbol{v}_{\boldsymbol{l},k+1} \end{vmatrix} = \begin{vmatrix} -\boldsymbol{A}_{k+1} & \boldsymbol{I} \\ \boldsymbol{I} - \boldsymbol{K}_{k+1} \boldsymbol{A}_{k+1} & \boldsymbol{K}_{k+1} \\ -\boldsymbol{K}_{k+1} \boldsymbol{A}_{k+1} & \boldsymbol{K}_{k+1} \\ \boldsymbol{Q}_{\boldsymbol{ll},k+1} \boldsymbol{D}_{k+1}^{-1} \boldsymbol{A}_{k+1} & -\boldsymbol{Q}_{\boldsymbol{ll},k+1} \boldsymbol{D}_{k+1}^{-1} \end{vmatrix} \cdot \begin{vmatrix} \overline{\boldsymbol{x}}_{k+1} \\ \boldsymbol{l}_{k+1} \end{vmatrix}. \tag{10}$$

The innovation $\boldsymbol{d}_{k+1}$ is the difference between the predicted and the measured reaction of the object. It can be analysed to verify and to enhance gradually the system identification (Heunecke 1995).

The algorithm can be used whenever a system equation can be established. In a congruence model the system equation degenerates to the prognosis of identical co-ordinates on the base of the differential equation $\dot{\boldsymbol{x}} = \boldsymbol{o}$; deterministic input quantities are not modelled. A kinematic approach is given by $\ddot{\boldsymbol{x}} = \boldsymbol{o}$, the state vector contains co-ordinates, velocities and accelerations. KALMAN-Filtering in deformation analysis is mainly applied to static or even dynamic models with system equations set up by the Finite Element Method.

5. Two Examples

Due to lack of space, only two typical examples will be given in the following.

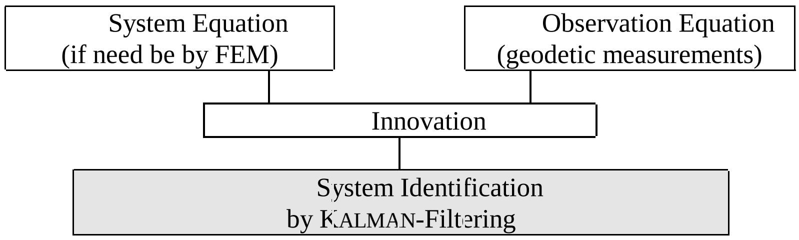

Figure 7 Substance of KALMAN-Filtering (Heunecke 1995)

5.1. Parametric Static Model of a Pylon

The diurnal variation due to solarization of the 55m-pylon of a suspension bridge (see Figure 8) across the Elbe river, Germany, was to be monitored Heunecke 1996). The task was solved theoretically by calculating the bending line caused by the horizontal temperature gradient owing to the insolation. The temperatures were hourly measured at a specific height inside the pylon shaft. The real bending line was observed by geodetic measurements (tachymeter and inclinometer observations). In terms of KALMAN-Filtering the result was the system and the observation equation of the pylon (compare Figure 7). It turned out that the theoretical and the real bending lines were different, see Figure 9, however, not significant (10 mm at the top of the pylon). The discrepancy represents the innovation. It was assumed that the temperature gradient) $\Delta\vartheta$ = 10.5 K and the expansion coefficient α = 11.5·10^{-6}/1K which were introduced as material parameters into the calculation of the theoretical bending line were not fully adequate. Applying (adaptive) KALMAN-Filtering techniques the two material parameters were included in the estimation algorithm leading to a full agreement of the theoretical bending line with the real one ($\Delta\vartheta$ = 9.8 K, α = 10.5·10^{-6}/1K).

Resumé: The investigation of the diurnal variation of the pylon is just an example for an advanced deformation analysis which leads to a better understanding of the whole deformation process. The perspectives are evident.

5.2. Non-Parametric Input-Output Model of a Turbine Foundation

The following example discusses the reaction of the foundation pillars of a large turbo engine due to temperature variations (Ellmer, 1987). Due to irregularities and major gaps during the data acquisition of the temperature and deformation measurements, in a first step interpolation and approximation procedures were applied to the time series in order to achieve equispaced data which are required for the analysis models. In a second step FOURIER transformations were used to get preliminary information on the behaviour of the system. The last step relates the temperature changes to the deformations by a SISO identification model which considers the fact that temperature changes effect the foundation pillars over a longer period of time. This model is given by equation (3) which is restricted, however, to the estimation of the non-recursive parameters b_0, ... , b_p only, where p stands for the memory-length. The solution includes 30 significant parameters b_k. This model is able to demonstrate that most of the deformations can be explained by the recorded temperature variations.

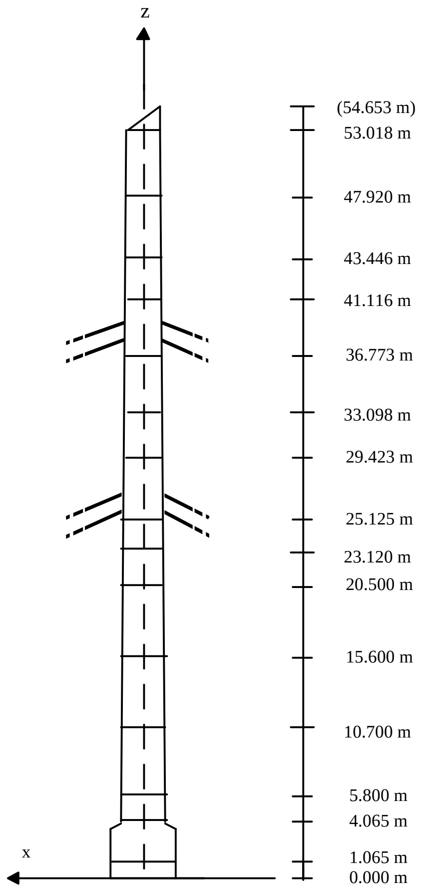

Figure 8 Pylon of a bridge, subdivided into finite elements

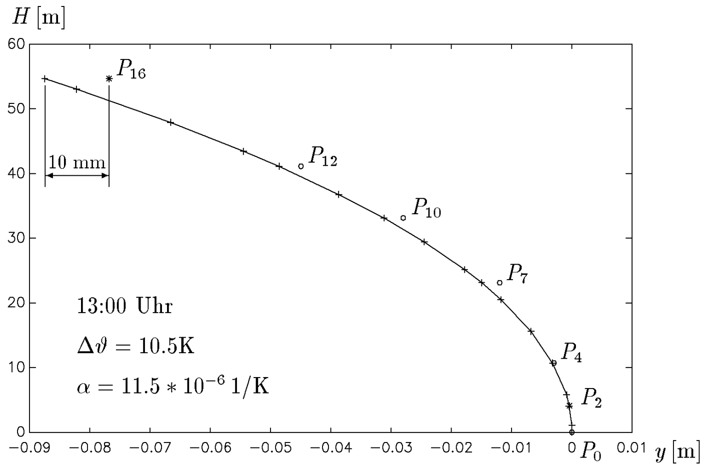

Figure 9 Theoretical (+) and real (P_i) bending lines. The discrepancy could be removed by estimating and adapting the material parameters with KALMAN-Filtering

Figure 10 depicts the reaction of all the pillars of the turbine table to an input impulse of 1 K immediately after the impulse, after 4 hours and after 3 days. The point of this sort of non-parametric system identification is that the model describes the reaction of the object to be monitored in a "black box" manner. It is meaningful, because it relates input signals (temperature variations as physical causative forces) to output information (deformations of the pillars). It does not contain, however, any information about the structure or at least the significant material parameters of the system which could make evident why the system reacts as it obviously does.

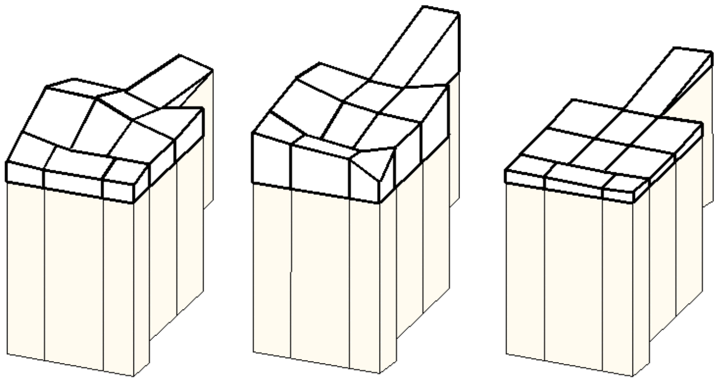

Figure 10 Deformation of the table plate as caused by a unit impulse of 1K

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Similarity of Meaning: Classification of the Lexical Items page 127 in the Thematic Field â€œEnvironment and Ecologyâ€ The Link Between Metaphorical and Non-Metaphorical page 148 Terms. 4.Â Representation of the Terminological Concept: Special Vocabulary Classification.33. 1.5.1. Terms of scientific and technical domain. 35 1.5.2.Â These principles have been integrated in the study course â€œTerminology and Terminographyâ€; the author has designed the textual model of contemporary scientific and technical text, in which various levels and dimensions of a text are mutually linked. It enables to study application of terms of the thematic field â€œenvironment and ecologyâ€ in different types of the modern texts According to the current trends in engineering surveying, the analysis of deformations intends to figure out the dynamics of this process. Apart from the geometrical changes observed, the basis of the investigations is to incorporate the causative forces and the physical properties of the body. In its entirety, the body, the influencing forces and the resulting deformations are considered a dynamical system. Thus in our days â€žGeodetic Deformation Analysisâ€œ means â€žGeodetic Analysis of Dynamic Processesâ€œ.Â @inproceedings{Heunecke2001TerminologyAC, title={Terminology and Classification of Deformation Models in Engineering Surveys}, author={Otto Heunecke and W. Welsch}, year={2001} }. Otto Heunecke, W. Welsch. Published 2001.