Dynamic Analysis Methods and Modelling. Application to Energy Performance Assessment

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ABSTRACT

The application of system identification techniques to the energy performance assessment of buildings and building components requires a high level of knowledge of physical and mathematical processes. This factor, combined with the quality of the data, the description of the monitoring procedure and test environment, together with the experience of the user of the analysis software itself, can produce varying results from different users when applying different models and software packages. Past international system identification competitions (1994 and 1996) demonstrated the spread in results that can be expected regarding the application of different models and techniques to the same benchmark data. The PASLINK network has attempted to consolidate and strengthen knowledge and expertise of system identification techniques within the grouping by organising lectures and workshops and also to ensure that data analysis meets minimum quality levels.

This presentation highlights the milestones in the development of practical software tools, defining data series for training and selected practical case studies. As an example discussed will be the spread in results obtained during the previous competitions to that obtained during the recent workshops carried out by the PASLINK network, following ten years of networking activities in the field. The objective was to identify the extent to which these activities have strengthened the position of the individual teams working in the field and to identify the areas where quality assurance is met and where further improvements can be made.

In order to maintain the quality in analysis and modelling work a third system identification competition has been organised.

Keywords: Dynamic analysis, modelling, energy performance, buildings, building components

APPLICATION AREAS

The test methodology and analysis methods in the early days of the PASLINK network (PASSYS I and II projects) were based around steady state evaluations. However, as the project progressed it became increasingly clear that both dynamic testing and analysis methods were required to deliver high quality performance characteristics for building components tested in real climates [3]. During the '90's the PASLINK Network moved away from the original philosophy of prescribed common equipment to one of agreed quality procedures for testing which includes the calibration of instrumentation and the test cells, and also data processing and analysis. This paper describes the developments that have taken place in dynamic testing driven by the research activities of the PASLINK Network and reviews the historical development of the test and analysis procedures currently in use. Energy performance concerning buildings, can be divided in three research areas:

Building components (such as bricks, window systems, insulation material, wall components). The experimental conditions are well-known and the experiment is optimised to investigate one dependent parameter. Often these experiments are performed in laboratories (hot-box and guarded hot-plate experiments).

Test cells**.** The European outdoor test facility created under the PASSYS project offers to industry the possibility to perform research on complete building wall components under real climate (including effects of phenomena like rain, wind and sunshine) and well controlled conditions. Specific tools have been developed to analyse the obtained data.

Real buildings**.** A complex situation appears when occupied buildings have to be analyzed. The behaviour of the occupants can not be controlled (opening windows) and additional techniques have to be used for the analysis of the data. Interaction of simulation tools based on physical properties and system identification techniques are under investigation. However when carefully applied, system identification could offer the way for the energy labelling of buildings.

AN OVERVIEW OF ANALYSING SOFTWARE

During the last 20 years the development of computing hardware and software a huge advancement has made been made in assessing specific characterisation of energetic behaviour of buildings and building components (see also reference [4]). Computer technology has made calculation as well as monitoring of thermal processes in buildings much easier than ever before. However the implementation of hardware and software tools and the proper design of experiments requires a certain skill. During 20 years of international research dedicated to energy characterisation of buildings and components through several EU funded projects expertise has been made available. In 1994 the PASLINK EEIG focused on outdoor testing, analysis and modelling of buildings and components. The development of dedicated software tools to identify thermal parameters from physical systems has gone hand in hand with the fast development of computing hardware. Software tools like CTSM [11], LORD [10] or the SIT in the MATLAB environment [5] are good examples. Also modelling software tools like TRNSYS and ESP-r show a similar progress and user friendly interface. System identification techniques have been developed in order to assist researchers in obtaining a better and more accurate knowledge of the thermal characteristics of building components [4]. System identification is the field of modelling dynamic systems from experimental data (see also [1]). A good academic book is given in reference [2]. A dynamic system has a number of input variables, u(t), it is affected by disturbances N(t), and it has output signals y(t). The general form of a dynamic system is shown in Figure 1.

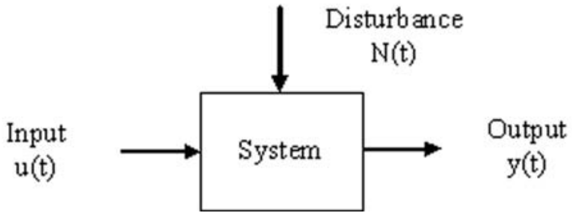

Figure 1. General form of a dynamic system

System identification is applied by the following procedure:

1. An experiment is performed by exciting the system and regular observing its input and output signals over a specific time interval.
2. These signals are recorded for subsequent “information processing”.
3. A parametric model is developed to process the recorded input and output sequences. Several models can be applied.
4. An appropriate form of the model is determined (typically a linear differential equation of a certain order).
5. A statistically based method is used to estimate the unknown parameters of the model.

For reasons of clarity the following terms, tools, methods and models will be introduced briefly.

A *model* is a mathematical description of a physical system or process. By definition it is a simplification of the reality. Models can be categorized in different ways. A list of possible models to be used is the following:

- thermal models or lumped parameters models
- state-space models
- modal models
- linear regression models
- frequency domain models
- neural network models

A *method*, here a system identification technique, consists of two major parts: the mathematical model (e.g. an ARMAX model) and the routine to estimate the parameters by a specific algorithm (e.g. least squares method). Minimization is used in the context of minimizing the difference between measured and corresponding data obtained from the model. Optimization is used in the context of optimizing the mathematical parameters of the model to fit the data obtained from the model with the measured data.

A *tool* is a sophisticated software program which allows the user to a method in a user friendly way. It is a ready-to-use product. Often these type of tools come with pre-processing routines and statistical information about the identification process and accuracy of the estimates. The selection and creation of models is one of the items which is simplified in a graphical way. Toolboxes are popular among researchers. It offers the freedom of the creation of own methods using reliable algorithms and routines. The system identification toolbox in MATLAB [5] is a good example of such an environment.

The following six points can be distinguished in the general approach of solving the problem of energy performance assessment using identification techniques.

1. design the experiment. In a first phase the experiment must be designed taking into account the objective, all available physical knowledge and all possible errors must be reduced to a minimum.
2. perform the experiment. The duration of the experiment must be long enough to fulfill all objectives. Special attention needs to have the interval for data acquisition. Collect data
3. pre-processing. Check for irregularities by having a global look at the data. This can be achieved in different ways. One way is to plot some of the important input signals. Another way is to apply the average method and to examine statistical information of the data.
4. analysis by estimation. Choose and apply a model and method that you are familiar with. Determine model structure. There are several ways to classify models, methods or tools.

- available software; general purpose software like MATLAB, MathCad, programming languages and mathematical libraries.; some examples of special purpose software are given below.

- categories in prediction or output error method, deterministic or stochastic.
- the minimization criteria. Least Squares Method (LSM) and the Maximum Likelihood (ML).

5. post-processing of the results. The most important is the validation of the applied model. Criteria that can be used for that purpose can be the following (in [4], Norlen, 1993):

1. Fit to the data Residuals are 'small' and 'white noise'
2. Reliability Same results with different data
3. Internal validity Cross-validation; The model agrees with other data than those used for estimation
4. External validity Results are in general not in conflict with previous experience
5. Dynamic stability From a steady state, the response from a temporary change in an input variable fades out
6. Identifiability Model's parameters are uniquely determined by the data
7. Simplicity The number of parameters is small

Special attention needs to have the conversion from mathematical parameters into the required physical ones. This is often a cause for problems, misunderstanding and errors.

6. feedback should be made in every phase of the process. Is the model accepted? It is advisable to apply more than one method to get a better understanding of the whole problem. Common sense should always be used and all available physical knowledge should be applied whenever possible.

Based on the experience from the analysis of test cell data a closer look on the properties will be given. In general two types of criteria for parameter identification can be distinguished:

the Prediction Error Method (PEM) and the Output Error Method (OEM)

The OEM is a special case of the PEM when takes the following formula in consideration:

$$Q(t) = G(q)u(t) + H(q)e(t) \quad \text{when} \quad H(q) = 1$$

The Prediction Error Method

PEM (e.g. CTSM, linear models) based on statistical models finds parameters by minimising the error between a k-step (usually k=1) ahead prediction and the measured output. Some characteristics are:

- more sensitive to high frequency parameters
- too optimistic on low frequency (steady state) parameters
- disturbed if residuals are auto correlated

The Output Error Method (OEM)

Simulation or Output Error Method (e.g. MRQT, LADY) based on deterministic models finds parameters by minimising the error between simulation and measurement over a whole test period. Some characteristics are:

- more sensitive to low frequency parameters
- too optimistic confidence intervals if residuals (here simulation errors) are auto correlated
- but due to inertia these are "always" auto correlated
- the application of a correction factor in the minimization algorithm.

one can ask if different types of parameters need different correction for auto correlation?

APPLICATION

Over the past decade the interest in renewable energy has increased. Analysis of complex dynamic energy flow systems that contain non-linear processes needs a skill. Considering the built environment, the focus has been mainly on utilising solar energy with promising developments in the integration of photovoltaic (PV) technology in buildings. Building Integrated Photovoltaic (BIPV) systems combine other functions of the building envelope with electricity generation. Examples include the following.

- External shading devices containing PV cells.
- Roofing tiles, directly replacing traditional pitched-roof materials and also being placed on low-sloped roofs in some climates.
- Rainscreen cladding and curtain walling.
- Ventilated facades where PV is used as the external cladding element. The larger part of the incident solar radiation on the PV elements is converted into sensible heat, which results in a warming-up of the PV elements, which may reduce their electrical efficiency. Ventilating the cavity behind the PV limits the temperature rise, and the warm air may be used for ventilation pre-heat in winter, or driving natural ventilation in summer. Such systems may be termed hybrid-PV components.
- Dynamic ventilated window systems

As part of the building envelope the impact of any construction element on the whole building performance must be considered and in case of PV panels the electrical performance as well as. Various projects have investigated the impact of BIPV on building performance. The PV-Hybrid-Pas project [www.paslink.org] was concerned with thermal performance evaluation of hybrid-PV components (with both natural and forced ventilation), as well as the measurement of electrical performance under real climate conditions, using the PASLINK outdoor test facility. A number of case studies are discussed on the PASLINK web-site.

THIRD SYSTEM IDENTIFICATION COMPETITION

A series of case studies for estimation techniques for the energy performance characterisation of buildings and building components

OBJECTIVE

The objective of the third competition is to further develop knowledge of system identification applied to thermal performance assessment in the built environment.

INTRODUCTION

After the success of the first competition [6 and 7] in 1994 and the second one [8] in 1996, the organisation has prepared a third challenging one, involving data from in situ measurements and real experimental set-ups. The previous competitions show that a number of methods and techniques exist and how inventive researchers can be to solve the physical problem of thermal behaviour. The most important conclusion has been that one needs a certain level of skill using system identification techniques, to perform well. The PASLINK network has organised over the last couple of years several workshops and courses to bring the knowledge to the people and to further improve the tools [9]. The implementation now of the Energy Performance of Building Directive requires adequate calculation and modelling tools and this is the main reason that a third competition has been organised. The application of system identification techniques to the energy performance assessment of buildings and building components requires a high level of knowledge of physical and mathematical processes. Similar problems arise in most observational disciplines, including physics, biology, and economics. As an outcome of the DAME-BC project (funded by DG-RESEARCH) the DYNASTEE network has brought knowledge from different disciplines together to work on this subject.

This new challenge has been organised to help clarify the conflicting claims among many researchers who use and analyse building energy data and to foster contact among these persons and their institutions. The intent is not to declare winners, but rather to set up a format in which rigorous evaluations of techniques can be made. In all cases, however, the goal is to collect and analyse quantitative results in order to understand similarities and differences among the approaches. Moreover participation to this competition will offer material for training and self study.

Research on energy savings in buildings can be divided in to three major areas:

1) building components,

2) test cells and unoccupied buildings in real climate and

3) occupied buildings.

Three competitions were planned along this line, of which the present competition concerned with real data from buildings components will be the third and last one. The present competition is concerned with four different cases for estimation and prediction including real data from a retrofitted wall, an occupied house, an urban area and a solar chimney. Participants are free to submit results from any number of cases. Since all cases deal with experimental data, detailed description is accompanying the data however basic knowledge about the practical energy flows is required.

The data and description for all four cases is available from 1st of July 2007. The submitted results will be evaluated at regular interval, 3 to 4 months, starting from September 2007. Because there are natural measures of performance; a rank-ordering will be given and published on the internet. The best contributions will be selected for publication in the SIC III book provided that the submission is before 1st of May 2008. The SIC III book is planned to be published in Spring 2009.

BRIEF INTRODUCTION TO THE SIC III CASES

The *first* case is concerned with the monitoring of a wall in a house constructed in the 1990’s to assess its thermal performance before and after the installation of cavity-fill insulation. The wall as-built is poorly insulated compared to current standards, with a lightweight concrete block and a cavity providing the insulation. Filling the cavity with insulating material should improve thermal performance, resulting in lower energy consumption and better comfort for the occupants. As a real case study it would be interesting to assess the thermal resistance improvement and the moment of filling the cavity.

The *second* case concerns an occupied residential house and is a modern (constructed in 1994) two storey single family house with one common wall and the whole envelop insulated (including the roof space). The walls are well insulated and all windows are double glazed. It has been monitored during two heating seasons. In addition the ventilation losses are monitored using PFT techniques.

The *third* case considers the modelling of the heat consumption in a large district heating systems, called VEKS (Vest-Egnens KraftvarmeSelskab). This system actually covers about half of the Copenhagen area. VEKS is a transmission company (established in 1984) supplying surplus heat generated from combined heat and power (CHP) plants to 19 local district heating companies at Western part of Copenhagen. The purpose of this case study is to investigate time series of measured heat production in the VEKS district heating system, and to establish models for predicting the heat consumption one to several hours ahead.

The system considered for the *fourth* case study is a solar chimney constructed and monitored at the LECE (Laboratorio de ensayos Energéticos para Components de la Edificación), from CIEMAT in Tabernas (Almería, Spain). Natural ventilation plays an important role as passive energy saving strategy, regarding cooling of buildings in this climate. Solar chimneys are some of the most useful systems that make use of this strategy. The tests have been carried out in real size and dynamic outdoors weather conditions.

The full description and data for analysis can be downloaded from www.dynastee.info

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