PASLINK AND DYNAMIC OUTDOOR TESTING OF THERMAL AND SOLAR PROPERTIES OF BUILDING COMPONENTS

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ABSTRACT

The PASLINK test facilities and analysis procedures aim to obtain the thermal and solar characteristics of building components under real dynamic outdoor conditions. Both the analysis and the test methodology have evolved since the start of the PASSYS Project in 1985. A programme of upgrading the original PASSYS test cells has improved measurement accuracy. The emphasis has moved from steady state to dynamic methods with shorter test durations yielding improved information and more accurate results. Dynamic test procedures aim to de-couple the different thermal processes within the test cell in order to obtain separation between the thermal transmission and the solar aperture of a component. In parallel with improvements in test methodology, software tools have been developed to enable the identification of the component characteristics and statistical information on the accuracy from the dynamic test data. The PASLINK Network has implemented quality procedures and promoted the development of participants’ expertise in the design, preparation and execution of tests and the analysis of test data.

Keywords: Test cells, thermal and solar properties, dynamic testing, parameter identification

1. INTRODUCTION

One of the fundamental aims of PASLINK Network (www.paslink.org) is the development and improvement of test methods and analysis procedures to obtain the thermal and solar characteristics of building components under real dynamic outdoor conditions. PASLINK evolved from the European PASSYS Project (Passive Solar Components and Systems Testing) which began in 1985, as an endeavour to increase the confidence in energy conscious and passive solar building products and evaluation techniques. The PASSYS project was focussed on the test cell facility (Figure 1) as a means to determine the performance of passive solar building component to inform building design and simulation tools. The advantages of the test cells are that they provide a well-controlled, realistic room sized environment without occupancy effects.

The test methodology and analysis methods in the early days of PASSYS were based around steady state evaluations. However, as the project progressed it became increasing clear that both dynamic test and analysis methods were required to deliver high quality performance characteristics for building components tested with real climatic boundary conditions. In parallel, a programme of upgrading the original PASSYS test cells was accomplished to improve measurement accuracy. The PASLINK Network has 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.
2. THE STEADY STATE METHODOLOGY

From the viewpoint of the building designer the main (steady state) performance characteristics of interest are the heat loss coefficient or thermal transmission coefficient \((UA\text{-value})\) and the total solar heat gain factor or solar transmittance \((gA\text{-value})\) of a component. These parameters are defined as follows.

- \(UA\) is the heat flow rate in the steady state divided by the temperature difference between the surroundings on each side of the system or component \((W/K)\).

- \(gA\) is the heat flow rate leaving the component at the inside surface, under steady state conditions, caused by solar radiation incident at the outside surface, divided by the intensity of incident solar radiation on the component \((m^2)\).

The component’s ability to accumulate heat, e.g. expressed as some thermal capacity \((C)\) and the thermal coupling with the indoor environment may also be of relevance, particularly where the transmission of solar radiation is concerned, as part of integrated building design.

Unfortunately, the determination of these parameters is not obvious. Whilst many passive solar systems are quite simple concepts, the thermal processes involved are very complex. Moreover, the performance will depend on the relative area, orientation and position of the component, the influence of the building's thermal mass, the presence of different heat sources, etc. The primary task in any experiment is to isolate these factors and to understand both the performance of the component, as well as its interaction with the building and its occupants.

In general, neither the heat loss, nor the solar heat gain through the component, can be measured directly because of the simultaneous operation of a variety of heat transfer mechanisms, such as free convection, thermal radiation, short wave solar radiation and conduction. Therefore, an indirect measurement is needed, based on the measurement of the net heat flow through the building component. The test cells are well suited to measure this quantity.

For a steady-state situation, the heat balance of the test room (Figure 2) may be expressed as follows.

\[
Q_{psc} = P_{hc} - (UA)_{tre} \times \Delta T_{tre} 
\]

\[(1)\]

- where \(Q_{psc}\) is the net heat loss from the test room through the component to the outside (unknown);
- \(P_{hc}\) is the sum of heating power injected and cooling power extracted from the test room (measured);
- \((UA)_{tre}\) is the UA-value of the test room envelope (from calibration);
\(- \Delta T_{tr,e}\) the temperature difference across the test room envelope between the internal and external surface, with temperatures \(T_{tr,i}\) and \(T_{tr,e}\), respectively (measured).

Note: as a rule, the service room temperature is kept equal to the test room temperature; otherwise, the heat exchange through the partition wall is added as a separate term in the equations.

\[
\begin{align*}
Q_{psc} &= \left( U A \right)_{psc} \times \Delta T_{psc} - \left( g A \right)_{psc} \times G_{psc} \\
&= \frac{Q_{psc}}{\Delta T_{psc}} \times \frac{G_{psc}}{\Delta T_{psc}} \\
&= \frac{Q_{psc}}{\Delta T_{psc}} - \frac{G_{psc}}{\Delta T_{psc}} \\
&= \left( U A \right)_{psc} - \left( g A \right)_{psc} \\
&= Y \\
Y &= \frac{Q_{psc}}{\Delta T_{psc}} - \frac{G_{psc}}{\Delta T_{psc}}
\end{align*}
\]

A graphical \((X,Y)\) plot, with \(X = Q_{psc}/\Delta T_{psc}\) and \(Y = G_{psc}/\Delta T_{psc}\), gives the linear relationship:

\[
Y = \left( U A \right)_{psc} - \left( g A \right)_{psc} \times X
\]

where \((UA)_{psc}\) is the intercept of the curve with the \(Y\)-axis and \((gA)_{psc}\) is the slope of the curve (Figure 3). In principle only two distinct measurement points are needed to yield the characteristics. With more points the \(UA\)- and \(gA\)-values are obtained by regression analysis (least square fit), as illustrated in Figure 3.
Whilst the steady state method is a straightforward, simple measurement technique, there are critical disadvantages. Equations 1-4 are only valid for steady-state conditions. Since the tests are carried out under real, dynamic conditions, the steady-state equations are only acceptable if integrated values are considered over a long enough period to minimise the dynamic effects. The possible effects of short-term weather variations on the system's characteristics are ignored; e.g., variation of cloud cover, sun position, outdoor temperature, etc. The method also yields no information on the dynamics of the system: e.g., thermal capacitance, time constants, etc. Given the inertia of the test cell and of some highly insulated and/or heavy mass building components, an integration period of several weeks may be required. This is illustrated in Figure 4 which is similar to Figure 3, but here the integration period per point in the graph is only 24 hours instead of 10 days. The daily average heat loss through the component is strongly influenced by the history of the previous days. This history is ignored in the steady-state analysis. This is revealed by the spread of points in the graph and the low slope of the regression line.

The latter phenomenon is typical of the influence of heat accumulation on the steady-state analysis: there is a high probability for a day with a relatively high heat loss to be followed by a day with a lower heat loss; the influence of the previous day tends to depress the high heat loss value downwards. The converse situation arises on days with net heat gains. As a consequence, both the UA- and the gA-values are underestimated. Similarly, the regression line in Figure 3, based on ten days average values, may also be influenced by dynamic effects.

Whilst longer experiments may be considered as necessary to achieve results with sufficient accuracy, a consequence of this approach can be that the range of variation in the test results reduces; with a longer integration period, all the points tend to the long-term average value, and it becomes more difficult to apply a
regression analysis. This can be overcome by improving the test strategy: e.g. operate test room for a period with a high set-point temperature, followed by a similar period with a low set-point, and/or by using a shading screen during part of the test to obtain artificially low incident solar radiation levels. Improvements can also be made by introducing a heat accumulation term (‘capacity’) in the regression analysis. From such a rudimentary first order dynamic model, it is not too great a step to a more powerful analysis method in which the full dynamic information is retained: parameter identification. Coupled with the latter, the use of dynamic test sequences can reduce the test period and improve accuracy.

3. DYNAMIC TESTING AND PARAMETER IDENTIFICATION

By applying parameter identification, dynamic effects due to heat accumulation are properly taken into account, whilst the steady state properties are derived from a short dynamic test sequence.

3.1 The method

With the parameter identification approach, a transient mathematical model of the test cell including the component is assumed. The parameters of the model (e.g. resistances, capacitances and heat flow admittances) comprise the dynamic and steady-state thermal and solar properties of the system.

Initially guesses of the parameter values are made. The output of the actual test (for instance: the test room temperature as a function of time) is compared with the output which the model produces for the same conditions (input). In the case of the test cell, the main input variables are the outdoor temperature, the solar radiation and the heating power as functions of time. By statistical analysis of the deviations between the model and measured outputs, the parameter values are adjusted in order to improve the agreement.

With adjusted parameter values, the whole process of comparison of test and model output, followed by the statistical analysis is repeated until optimum agreement is reached (Figure 5). This iterative process is carried out with the aid of specialised software tools.

The parameter identification technique has characteristics in common with linear regression analysis. In regression analysis, the set of parameters (coefficients) of the model is found by an analytical calculation procedure. But if the model is more complex or non-linear, there is no analytical solution.

An example of the iteration process is given in Figure 6. This figure shows the measured output variable as a function of time, plus the following calculated output:

1) At the first iteration step (based on guessed parameter values) there is a strong deviation from measured output;

![Figure 5. Parameter identification principle.](image-url)
2) After $n$ iterations, with successively improved parameter values there is less, but still significant deviation from measured output;

3) At the end of convergence, with best fit parameter values, there is minimum deviation from measured output.

Note: Figure 6 shows that the best fit is not a perfect fit: the model of the system may be an imperfect representation of the real system.

![Schematic illustration of the iterative parameter identification process.](image)

The parameter identification method is particularly suited to dynamic test conditions, which result from varying outdoor conditions and the large inertia of the test cell and many components. It is not necessary to wait until dynamic effects have been cancelled out, as in the case of the steady-state method with long integration periods. On the contrary, the dynamic effects are explicitly taken into account in the analysis. Consequently the test duration can be much shorter.

On the other hand, parameter identification requires the right choice of software tools to obtain statistical information on the reliability of the identified parameters along with the identified parameter values. The reliability may be affected by measurement errors and 'model' errors and by correlation between parameters.

The choice of an adequate dynamic mathematical model of the system is another major consideration. Extensive attention has been given to the choice of suitable models for test cell and components.

### 3.2 Model of test room and test component

Generally, lumped parameter models have been chosen for the evaluations. Such a model can be visually represented as a network of thermal resistances (R) or conductances ($H=1/R$) and thermal capacitances (C), with heat flows from external sources (e.g. heating power, solar radiation) connected to specific points (nodes). The complexity of the model can vary between a very simple single node model (first order RC-model), to a multi-node model with a high number of resistances, capacitances and connections with external heat flow sources. Alternatively, autoregressive methods using black box or ARX models have been used.
The main requirements for an appropriate model for the test room and the test component are as follows.

− The model should be able to accurately reproduce the steady-state and dynamic thermal processes.

− It should allow the separation of the physical properties, i.e. the heat loss rate through envelope should be distinct from the heat loss rate through the test component, or the heat loss rate from the solar energy transmittance (solar gain). One should be able to relate the identified physical properties with definitions in international standards.

− It should not be too detailed, in the sense that it leads to 'over parameterisation', i.e. the situation in which some of the parameters cannot be identified because of strong correlation with other 'free' parameters in the model.

− It should preferably allow for prior knowledge to be used.

− It should preferably allow the option of adding specific non-linearities, such as a specific thermal resistance changing with temperature or with wind velocity, or solar transmittance changing with solar and sky conditions.

By adopting these requirements the model created should be 'transparent', i.e. a model in which the main elements of the heat balance in the test room and the separate components are recognised.

Figure 7 shows the three different branches of the model of test room/service room and component used within the test cell. The branches connect at the test room air node.

Figure 8 represents a typical model of the test cell with component. In this model it is assumed that part of the solar radiation penetrates directly into the test room (e.g. by transmission through a window in the test component) and is absorbed (admittance factor $a_1$) at the indoor surface of the test room envelope (at $T_{tr,i}$). At the same time it is assumed that part of the solar radiation is also absorbed (admittance factor $a_2$) at the external surface of the test component (between $H_{psc4}$ and $H_{psc3}$); the latter leads to an indirect contribution to the heat balance in the test room. Of course, the true relations are more complicated, comprising direct thermal radiative coupling between the indoor facing surfaces of the test room envelope and the test component, for instance.

As a rule, in the course of the evaluation of the identification results, the models are reduced in complexity, to suppress apparent high correlation between specific individual parameters. This can be simply done by 'freezing' specific parameters to their initial values, i.e. removing these from the list of parameters which are to be optimised in the fitting process, e.g. in the case of two resistances in series without significant thermal capacity between them. Of course, any available a priori knowledge of the model and its parameters may be used to decrease the number of free parameters which have to be fitted to a minimum. On the other hand, one should realise that a best fit model is not necessarily a complete physical model in every detail.
3.3 Software development

The co-operation within PASSYS led to the development of two identification packages, MRQT and CTLSM, which typify two alternative approaches to parameter identification.

MRQT uses as a criterion the least square deviation between the measured and calculated output over the whole (or selected part of the) test period (Output Error Method - OEM). The minimisation procedure is the Marquardt-Levenberg method. MRQT now forms the basis for LORD, which has a graphical user interface and is able to use either OEM or PEM. Whilst LORD has been tailored to the specific requirements of the PASLINK Network for the analysis of test cell experiments, it is simple to create R-C models of many thermal systems. It is also possible to specify variable resistances and capacitances which may be (non-linear) functions of input variables such as wind speed and temperature.

CTLSM is a stochastic method which takes into account uncertainties in both the measurements and calculations (Prediction Error Method - PEM). CTLSM has evolved into CTSM (Continuous Time Stochastic Modelling). It is well suited for modelling both non-linear and non-stationary systems. CTSM has been used for estimating and identifying physical systems, like the heat dynamics of an entire building, the thermal characteristics of walls, the dynamics of a heat exchanger, the dynamics of radiators and thermostats.

The MATLAB environment using IDENT has also been used, particularly with Box-Jenkins, ARMAX and FIR models.

The most recent tools are able to provide improved statistical information on their output, which enables greater confidence in their results.
3.4 Test control strategy

A successful identification is contingent on applying the correct test strategy. The main requirements are as follows.

− The test sequence should contain low and high frequency variations, to allow the identification of both steady-state and dynamic properties;
− It should de-couple the temperature signals and the intensity of solar radiation, to allow the identification of the physical characteristics as separate properties;
− It should yield a sufficient signal-to-noise ratio, in particular in the low frequencies, because of the priority given to the accuracy in the identification of the steady-state properties.

The temperature difference between internal and external conditions and the incident solar radiation are normally highly correlated. De-coupling can be achieved by applying a maximum variation in the test, for example, there should be a maximum of variation of the internal temperature, which can be obtained by having a plant input which is not dependent on the solar gain, in order to derive distinct UA- and gA-values.

The priority given the steady-state properties requires a sufficiently strong signal with several repeats of the largest time constant of both the test cell and the component system.

The signal should ensure that temperature differences are much larger than the uncertainties on the measured temperatures. In a pessimistic scenario, this uncertainty may be as high as 1K, due to various types of non-uniformity which normally occur under real conditions, both in the indoor and the outdoor environmental temperatures.

The requirements can be met by a test which contains a sufficiently long period (a few days) with high heating or cooling power in the test room and a period of similar length with low power, with power levels chosen such as to yield a temperature variation of the order of 20K.

For the dynamic characteristics, it is required that variations cover the range of frequencies corresponding to the range of characteristic time constants of the system, e.g. 20 minutes to 50 hours.

Finally, in order to isolate the component’s characteristics from the heat balance in the test cell, it is necessary to carry out a calibration test on the test cell without the test component.

Based on these requirements, a general test procedure was developed which is appropriate for different types of components and widely varying weather conditions [1] as follows

− 1.5 days Initialisation with constant low power (e.g. 50W circulation fan) into test room;
− 1.5 days constant low power into test room;
− 1.5 days constant high power into test room;
− 3.5 days pseudo-random on/off power into test room (the dynamic part as shown in Figure 9).

This sequence may be followed by a validation sequence:

− 2 days medium power;
− 4 days low power.

In the case of moderate weather conditions or a component with low solar gains, heating power is used. In the case of high outdoor temperatures and/or high solar gains, the cooling system is used instead. The power levels are determined from the estimated free float temperature of the test room which would occur for average outdoor temperature and incident solar radiation conditions and fan power only. The aim is to maximise the temperature difference between the low power part and the high power part of the sequence by at least 10K, but preferably 20K.
3.5 Quality procedures

Testing and analysis carried out within the PASLINK Network are underpinned by common quality procedures and training exercises to develop expertise in the application of analysis software. The IQ-Test Project [2], coordinated by PASLINK, has consolidated this approach with a view to a broader market for performance evaluation using the tools and facilities of the network. The results of inter-site comparisons carried out during IQ-Test, reported by Baker [3], showed good agreement between teams.

4. CONCLUSIONS

The PASLINK Network of outdoor test facilities is able to accurately determine the thermal and solar characteristics of building components over the range of European climates by applying appropriate dynamic test procedures and parameter identification techniques, supported by common quality procedures and training.

Dynamic test methods, whilst enabling shorter test durations to be implemented, can be optimised to maximise information on the component or system. The test cell facility allows the full dynamic behaviour of a building component to be estimated under real outdoor conditions. Characterisation of performance by parameter identification gives more confidence in the results compared to steady state test methods and analysis.

REFERENCES