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SUBTOPIC : Comparison of building thermal response model reduction methods

Experimental building application

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INTRODUCTION

With the development of data processing facilities, the digital modelling of thermal response systems now makes it possible to implement ever more powerful calculation codes, characterising increasingly detailed physical phenomena. The latter are generally obtained from spatial discretization like finite element, nodal method or other, which takes increasingly memory and execution-time.

In spite of the technological advances made in data processing tools, ever faster calculation times are sought: The purpose of this paper is to show the possibility of using a small dimension model, whose main features are its execution speed and reliability compared with a detailed higher order model used as a reference.

This is the role of model reduction methods which are used to design a so-called reduced model, from an initial detailed model, while retaining most of the information needed to process a given problem.

A model which can be easily run on a PC, but which provides highly accurate results, can then be made available to users.

This study will compare three techniques (Marshall, Michaïlesco, Moore) derived from three major reduction families. The field of application involves the thermal response modelling of single-area buildings; attention will be given, in particular, to local behaviour in natural climates, in other words, with exposure to solar flux and outside temperature.

After describing the three methods, the results obtained from the detailed models produced by the CLIM2000 software and validated by real simulations involving experimental cells, will then be given.

1. DESCRIPTION OF THE REDUCTION TECHNIQUES USED

Model reduction techniques were originally proposed by automation experts. Much synthesis work ([10], [11]) have already been carried out in this area. Two types of techniques are basically involved :

- identification reduction techniques which are based on input/output data (Ref [9]),
- direct reduction techniques which use equations extracted from detailed codes (Ref [1],[2]).

The techniques that will be discussed here are direct reduction techniques. These techniques are suited to the development of codes run on PCs as they only require the description of buildings. Indirect reduction techniques, on the other hand, require inputs and outputs.
These techniques are very fast. They also allow parametric studies to be carried out. To change a parameter, the model admittedly has to be reduced again. This virtually instantaneous operation is, however, completely transparent for the user.

These techniques include 3 main families :

- truncation reduction techniques,
- optimisation reduction techniques,
- mixed techniques (truncation followed by minimisation).

Three techniques will be applied in this study : Marshall, Michaïlesco and Moore. Being iterative, optimisation techniques do not fully meet PC calculation code requirements and will hence not be considered here. This paragraph describes the principle of these methods.

1.1. Base change

It should first and foremost be remembered that these techniques are based on the detailed model equation system.
This system must be expressed in state form in order to be able to be used by these techniques. An approximation of the field of temperatures T with inputs U can be expressed by the state equation (1) through spatial discretization of the study domain. The model outputs (Y) complete the model in the thermal base.

$$\begin{aligned} \dot{T} &= AT + EU \\ Y &= HT + DU \end{aligned} \quad (1)$$

The purpose of the base change is to express this system in a simpler form of base.
Two bases are commonly used : the balanced base and modal base.

1.2. Moore's method

This is a truncation in the balanced base. Moore developed this method in [4] and [6].
The first stage of this method is a transition in the balanced base. Through truncation, only the most controllable and most observable state components of the system are conserved.

The truncation principle is as follows : the initial system (1) is expressed in the following form:

$$\begin{bmatrix} \dot{X}_d \\ X_f \end{bmatrix} = \begin{bmatrix} A_{dd} & A_{df} \\ A_{fd} & Aff \end{bmatrix} \times \begin{bmatrix} X_d \\ X_f \end{bmatrix} + \begin{bmatrix} E_d \\ E_f \end{bmatrix} \times U$$

$$T_s = \begin{bmatrix} H_d H_f \end{bmatrix} \times \begin{bmatrix} X_d \\ X_f \end{bmatrix} + D \times U$$

The d suffix corresponds to the dominant modes (from the observability and controllability standpoint) and the f suffix corresponds to the weak modes.

Once truncated, the system becomes :

$$\begin{bmatrix} X_d \end{bmatrix} = \begin{bmatrix} A_{idd} \end{bmatrix} \times \begin{bmatrix} X_d \end{bmatrix} + \begin{bmatrix} E_{id} \end{bmatrix} \times U$$

$$TS = \begin{bmatrix} H_{id} \end{bmatrix} \times \begin{bmatrix} X_d \end{bmatrix} + D_i \times U$$

Modified Moore's method : The method used in our building thermal response applications does not correspond exactly to the Moore technique : it requires the static gain to be conserved as well.

1.3. Marshall's and Michaïlesco's methods

These methods are more commonly used in thermal response than Moore's method. We consequently do not propose to give details of their operation.

They both begin by a transition in the modal base.

- Marshall's method is a truncation in the modal base. It only conserves the modes with the highest time constants.
- Michaïlesco's method (Ref [3], [8]) is a truncation in the modal base in accordance with an energy criterion. After truncation, the reduction error is minimised (it is classified in the so-called "mixed" techniques). From the conserved modes, a selection is made of those for which the output error is minimum as defined by the L2 standard.

2. DESCRIPTION OF STUDIED MODELS

2.1. **Modelled building**

The modelled building is an experimental cell located on the Commissariat à l'Energie Atomique's site in Cadarache (France).

This building was chosen because it has several advantages :

- This cell was designed to favour solar contributions : the window area is large (2.26m²) and it faces South. This allowed us to test the behaviour of reduced models with a dominant solar flux input.
- It is a realistic building : its construction and shape are representative of a typical building.

Note : The graphs shown below do not indicate experimental results. Indeed, the purpose of this study is not to validate reduced models. The validation phase involves the knowledge model and was carried out independently of model reduction. We have merely taken advantage of validated and hence realistic knowledge models.

Furthermore, the reduced model cannot give better results than the knowledge model. The reduced models are consequently only compared against the knowledge model.

2.1.1 Experimental site

The site is characterized by the following data: latitude 43° 39' 18" N and longitude 5° 46' 21" E. The altitude is 268m. The front wall faces South. The albedo equals 0.3. And finally this site is considered to be in a rural environment.

2.1.2 Description of cells

These are rectangular shaped cells on top of a crawl space with an antic above. The geometrical characteristics and materials are given in the diagrams and table below :

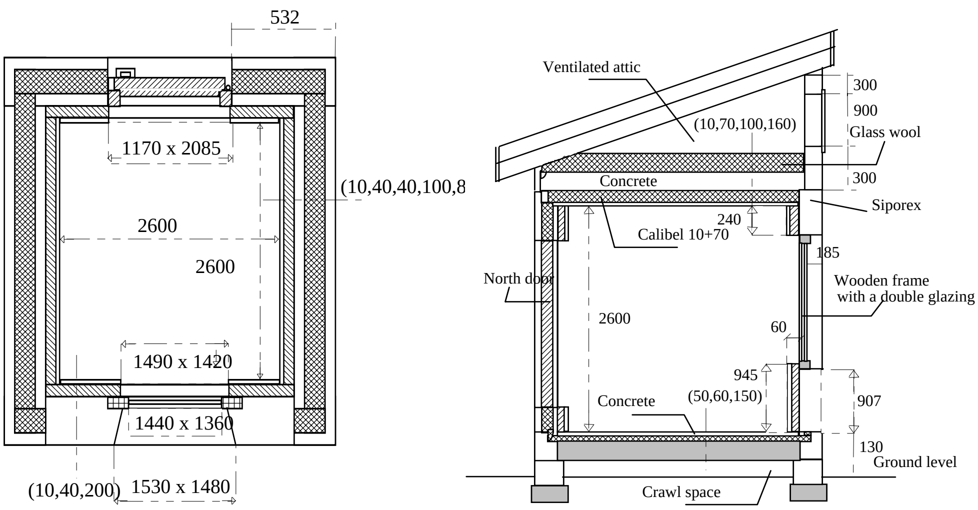

Fig. 1: Geometric description of cells

Material	Thermal conductivity (W/m.K)	Density (kg/m3)	Specific heat (J/kg.K)

Concrete	1.75	2400	880
Expanded polystyrene	0.038	15	1200
Plaster	0.35	850	800
Steel	5000	7800	502
Polyurethane	0.029	10-80	1380
Wood	0.16	800	2093
Glass	1.16	2490	830
Glass wool	0.042	200	670

Table 2: Characteristics of materials

2.2. Detailed model

The detailed model was developed with CLIM2000 code, EDF's building thermal response software. As we are in this case interested in the behaviour of reduction methods for models with solar flux in buildings, several types of solar modelling have been considered in the detailed code :

- **Without solar path** : the whole solar flux is absorbed by the floor
- **With solar path** : the solar flux transmitted by the windows is distributed along the walls inside the cell by means of a geometrical calculation : the calculation of the window's projection, in the direction of the sun's rays, on the walls. This calculation is performed at each time step. In this model, the solar flux is immediately absorbed by the wall exposed.
- **With solar path and with reflection** : this is the same model as previously. The first reflection of the solar flux on the walls is, however, taken into account.

The assumptions made for this model are as follows:

- The exchanges are considered as one-dimensional.
- Inside convection and radiation phenomena are globalized.
- Window pane inertia is neglected.

These are 56th order models (approximately 10 nodes per wall). The observed output is the inside air temperature. It should also be noted that the mesh topology of this model was designed to handle one hour demands.

Demands: The model inputs are of two types:

- solar flux driving the model in a frequency range up to 2E-4 Hz.
- an outside temperature varying at lower frequencies (up to 2E-5 Hz).

This classification of demands into two families according to the energy of signals in each frequency range, makes us opt for two reduced models:

- Model 1: Effect of outside temperature on inside air temperature.
- Model 2: Effect of solar flux on inside air temperature.

In this study, we are going to take model 2 as an example since demands are faster and it is consequently more difficult to reduce it.

2.3. Development of reduced models

The reduced model was developed using EDF's MATRED software. This software, developed with E.N.P.C-GISE (Ref [5]), allowed us to test and evaluate the various methods described above.
The detailed models are supplied to MATRED in state form. The approach used to reduce our models is indicated below.

Reduced model objectives

The reduced model objective is to simulate the variation in the air temperature inside the cell over a heating period. The reduction error variance will hence be of interest. The reduced model order must also remain low to obtain short simulation times on averaged sized IBM-PCs.

Reduction order choice

Before reducing models, MATRED indicates a reduction relative error range for a given problem, as a function of the method order.
It can be seen that good reduced models can be obtained from the 3rd order onwards, for the models studied. Our models will consequently be reduced to this order.

3. RESULTS AND ANALYSIS

The conclusions we reached on completion of the comparison of direct reduction methods are indicated in this paragraph. These conclusions were reached on the single-area building described above.

The results relate to the analysis of the air temperature difference between the knowledge model and the reduced models. The variation of these models against time is plotted below:

Marshall, Michaïlesco - Moore comparison

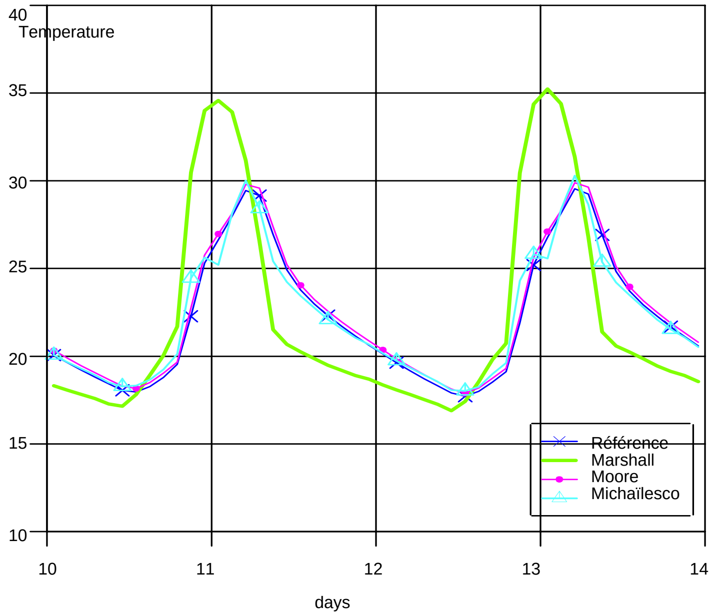

Fig. 3: Comparison of reduction techniques

In this case, it can be seen that the Moore method is the closest to the reference model. Marshall does not give very good results and Michaïlesco is closer to the reference.

<u>Note</u> : the graphs relative to the models without solar path and with solar path and reflection, behave in the same way.

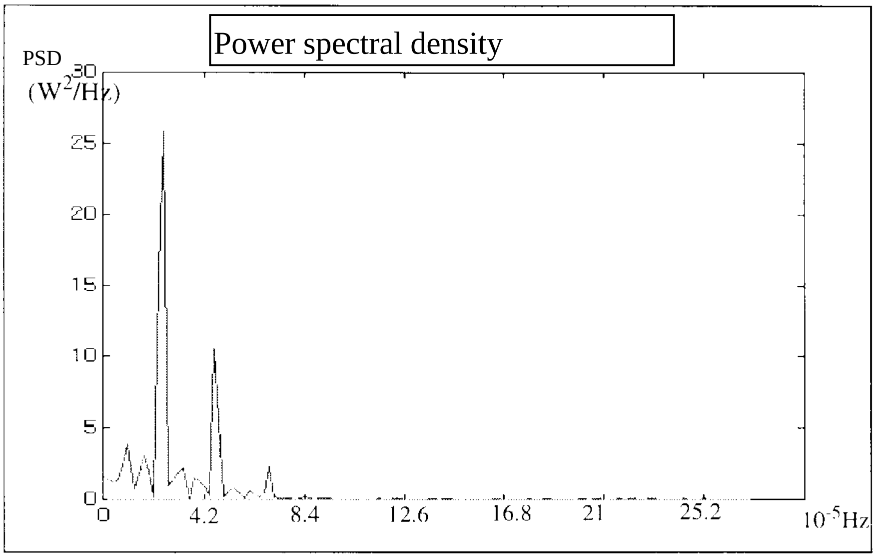

Fig. 4: Solar flux spectral characteristics

It can be seen that most of the signal is located between 10^{-5} and $3 10^{-5}$ Hz. It is in this frequency band that we are going to observe the reduced model's behaviour in relation to the reference model.

Tools are available for comparing the reduced model against the reference model from the frequency standpoint. This involves the Bode diagram plotted below :

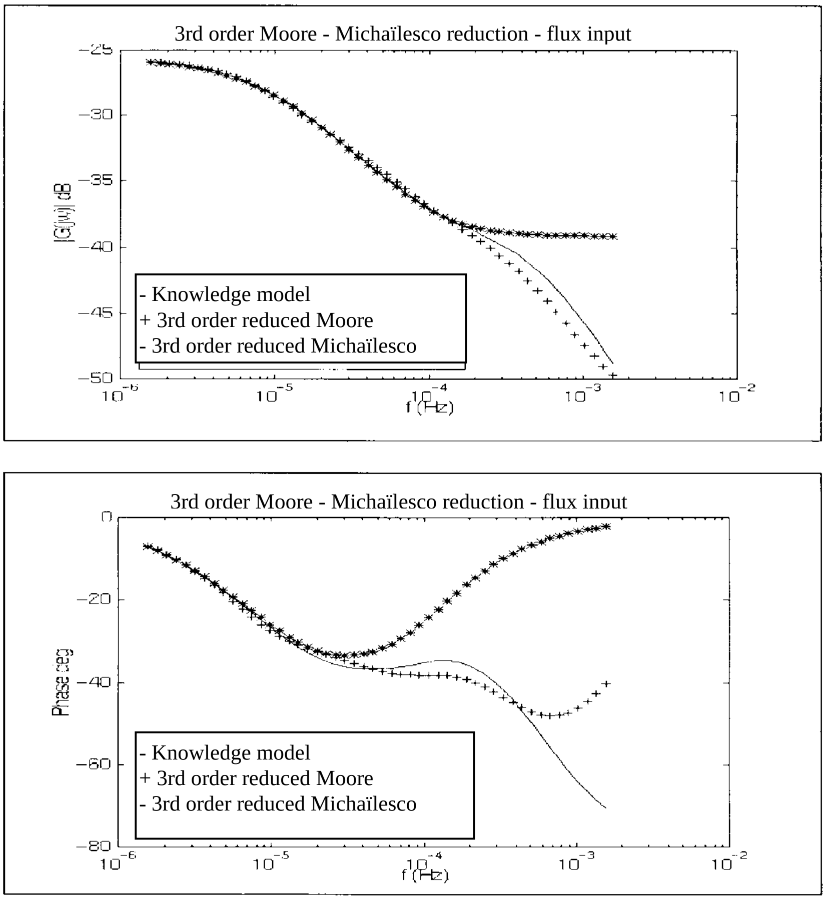

Fig. 5: Location of methods in the Bode diagram

These diagrams first show us that the reduced models considered are valid over a frequency band covering the demand frequency band. This accounts for the good results obtained by the Moore and Michaïlesco methods. For the phase, the Moore method remains correct over a larger frequency band. This may explain the better behaviour of this method.

3.1.3. <u>Comparison of models with and without solar path</u>

We have seen that the deductive evaluation provided the same graph plots and the same conclusions for models with and without solar path. The same conclusions are also reached, when the results concerning reduction methods are examined. It is still the Moore method which is closest to the knowledge model.

The improved solar modelling in the detailed models hence does not affect the behaviour of reduction techniques. The increased number of inputs consequently does not disturb our models in this case.

CONCLUSION

In this comparative study of model reduction techniques in the field of thermic’s building, we have noticed the interest of the Moore’s technique for our applications of simulations on PC.

We explained and observed the behaviour of a variant of this Moore method, taking into account the conservation of static gain. It was seen that this 3rd order method is the one which provided the best results in the case of single-area buildings (with an initial size of 56 for the cells studied), with solar flux and outside temperature as inputs. These results are, moreover, very close to those provided by the detailed model.

This analysis, conducted on single-area buildings, should be extended to multi-area buildings. To facilitate this work on more complex models, deductive evaluation techniques will be developed. The expected result should make it possible to establish the relative positions of the various methods without the need for simulation phases.

BIBLIOGRAPHIE

[1] DEQUE F., PALOMO E., BONNEFOUS Y., OULEFKI A.
Techniques numériques de réduction de modèles linéaires à partir de modèles de connaissance - Synthèse appliquée à la thermique du bâtiment, Note EDF HE - 14/95/037, 1995

[2] DEQUE F.
Techniques numériques de réduction de modèles linéaires - Etat de l’art, Note EDF/DER/HE 14/94/024, 1994

[3] A. EL BIYAALI, J.J. ROUX, R. YEZOU
Application de la réduction de modèles aux singularités thermiques de bâtiments, Revue Générale de Thermique, Octobre 1994

[4] MOORE B.C.
Principal component Analysis in linear systems : Controllability, Observability, and model reduction. IEEE Transactions on automatic control, Vol. AC-26, n°1, February 1981

[5] DEQUE F.,PALOMO E., BONNEFOUS Y.
Guide de prise en main du logiciel MATRED, note EDF HE14/96/014, 1996

[6] LAUB A. J.
Computation of « balancing » Transformations, Proc JACC, Vol. 1, paper FAS-E, 1980

[7] DECOSTER M., VAN CAUWENBERGHE A.R.
A comparative Study of Different Reduction Methods (Part 1-2) Journal A, vol. 17, n°3, 1976, pp 58-74, pp 125-135

[8] BERTRAND P., DUC G., MICHAILESCO G.
Recent developments in model reduction. RAIRO - APII 1985, Vol 19, pp 131-146

[9] PETIT D.
Systèmes thermiques diffusifs. Modélisation de leur comportement par identification de modes dominants. Revue générale de thermique n°373, pp 302-311, Juin