

Methodology for analyzing thermal responses in buildings. Proposal and application

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ABSTRACT

Thermal evaluation of buildings involves different variables and parameters. The different models of thermal analysis and evaluation of buildings vary depending on the input data needed, the mathematical models used, the accuracy of results and the scope of the evaluation. A phenomenological global approach is a possibility for simplifying detailed models considering specific purposes, i.e. improving thermal characteristics for retrofitting.

In previous works, a simple method was proposed to describe the global thermal response of buildings through measured data from outdoor temperature and solar radiation, obtaining a good description of the indoor temperature in buildings. In this work, we extend the previous method in order to incorporate in the analysis the effects of outdoor relative humidity. This dynamical analysis is carried out in the frequency domain. The typical amplitude patterns obtained from the thermal responses give an approximated characterization of the building behaviour at each frequency.

When the building behaviour is analyzed under different climatic conditions, it is shown that humidity and solar radiation are complementary variables to outdoor temperature, able to improve the description of the thermal response under the same climatic conditions. However the main result of this contribution is that solar radiation and humidity are not able to characterize the thermal behaviour under different seasonal conditions. Only the outdoor temperature is a relevant variable for calculating a response that can characterize completely the global thermal behaviour of the buildings all year around.

1. INTRODUCTION

One of the main problems in sustainable architecture is the description of the thermal behaviour of buildings. This problem is handled with some sophisticated software, applied in most cases in public buildings or high-class residential homes. Many models have been developed in order to calculate the building performance, with different accuracy level and also different scopes. However, in developing countries the construction of large sets of small homes for working class people almost never received the corresponding care on the thermal comfort facts. Detailed behaviour models often require a considerable amount of input data, resources and hard work. These requirements are in relation to the resulting accuracy needed for specific purposes and for the output quality required (Sonderegger, 1978; Athienitis et al., 1990; Casanovas et al., 1993; and many other authors).

The use of simplified models, introducing few representative data, enables one to obtain an approximation of buildings global thermal response. Some of the predicting simplified models of building behaviour are described and applied by Givoni et al. (2001) and Krüger et al. (2001 and 2004). The predicted formulas used need few climatic parameters, and the formula that represents the building behaviour is obtained from indoor and outdoor temperatures measured during other periods. Good results can be obtained with this model. The disadvantage is that a new formula is needed for each building.

In general, simplified models could be a good alternative form to analyze the thermal response, in order to give some insight on the modifications needed to improve the thermal

comfort of, for example, economic houses, without detailed analysis for different environmental conditions. A phenomenological approach to describe the behaviour of buildings has been proposed by analyzing the buildings response to specific environmental variables (Marincic et al., 2001, 2002, and 2003). In this simple model, a global building response obtained from monitoring data is used to describe the building behaviour. A correlation filter was applied to the obtained results, in order to minimize noise from data and to improve the interpretation of them.

In many developing countries the same architectural project of house is built in many different climates, varying from hot dry and hot humid to temperate. It is well known, that several variables affect the type of climate and also the thermal comfort of the people indoors. Some of them are relative humidity and solar radiation. We want to know if these variables, combined with outdoor temperature, can improve the characterization of the thermal response of a building. Here we extend the thermal response method (Marincic et al., 2001, 2002 and 2003) in order to consider the role of outdoor humidity and solar radiation in the thermal behaviour.

2. METHODOLOGY

It is well known that buildings present periodic

variations in their internal temperatures and also the changes in the weather conditions are periodic. Thus frequency seems to be a better independent parameter than time in order to describe the thermal response in buildings. In the following we will use the term *dynamic response* referring to a *frequency dependent response*. These dynamic global responses allow one to have an adequate description of the thermal behaviour of constructed buildings. Thus, these responses are defined in the frequency domain and we are looking for thermal responses assuming the indoor temperature of a building as a consequence of changes in the climatic and internal variables. One of the main problems in this approach is the selection of the relevant frequencies in the responses, able to characterize the building behaviour. This was solved using a correlation function for the independent and dependent variable in the frequency domain (Marincic et al., 2001, 2002 and 2003).

Our mathematical proposal is based on the fact that thermal behaviour of buildings is in high proportion a consequence of the time variations of the weather conditions. Our approach assumes that this behaviour can be described by global building thermal responses (R). The schematic idea is presented in Figures 1a and b. We consider all the climatic variables (radiation, outdoor temperature, relative humidity, wind, etc.) acting on the building which has been de-

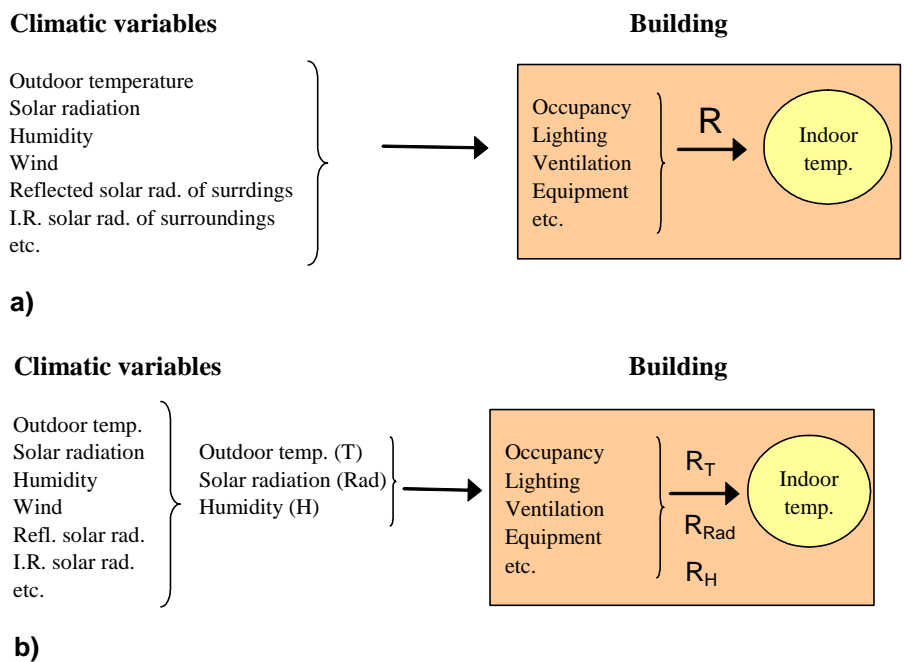


Figure 1: Schematic idea of thermal response R in buildings.

signed considering some architectonic characteristics and internal variables (shading, orientation, lighting, time of occupancy, ventilation, etc.) in order to obtain the best thermal conditions indoors, mainly indicated by the indoor temperature (see Fig 1a). Here it is important to mention that the internal variables have been over-passed selecting a representative place to measure the indoor temperature (Marincic et al., 2002). Depending on the type of climate, several climatic variables can have a great impact on the indoor temperature. In the present work, to characterize a very varying climate such as the desert climate, we have considered, apart from outdoor temperature, humidity and solar radiation in a combined form (complementary to outdoor temperature), as seen in Figure 1b. We want to know, under different weather conditions of the same climate, which variables are needed to determine the thermal response.

In the following paragraphs we describe briefly the methodology.

First in our approach, the climatic variables intervening as inputs and output of the thermal system are expressed as functions of frequency, using in this case the Fourier Transform. Actually the inputs are the external temperature and relative humidity, the output is represented by the indoor temperature in the building. We obtain the building responses due to outdoor climatic variables in two steps: first we calculate the temperature response according to Eqn. (1):

$$F_T = T_{in} / T_{out} \quad (1)$$

where T_{in} is the indoor temperature as a function of frequency, T_{out} is the outdoor temperature as a function of frequency, and F_T is the building thermal response. In the following, capital letters will indicate functions in the frequency domain, i.e. Fourier Transform functions. F_T depends on frequency and is a complex function with real and imaginary parts. However, expression (1) has the inconvenience that if T_{out} has a range with small values and the response F_T will be very high introducing mathematical artifacts. This was avoided by the use of a cutoff value based on the correlation function C between spectra variables (Fourier transformed functions) as in Marincic et al. (2001):

$$C = T_{in} * T_{out} \quad (2)$$

If we define C_f as the correlation function,

which contains only the relevant data greater than a cutoff value “a”, i.e.

$$C_f = \begin{cases} C & \text{if } C > a*0.05 \\ 0 & \text{if } C < a*0.05 \end{cases}$$

With this correlation, we can construct a 0-1 function as $|C_f|/|C|$ (where $| \cdot |$ indicates the modulus of the complex value) keeping the information where there is an important correlation between the indoor temperature and the outdoor temperature. The value “a” was selected from the average of the two maximum correlation values without considering the zero frequency value (as was proposed in Marincic et al. (2001)). Thus we have a filtering function of the most relevant frequencies, namely:

$$F_{Tf} = F_V * |C_f| / |C| \quad (3)$$

F_{Tf} is the expected thermal building response containing only higher correlated values. Clearly this procedure has an error less than 5%, because of the selection of the cutoff frequencies of this parameter.

In this way we can obtain the indoor temperature using the inverse Fourier Transform:

$$F_{Tf} * T_{out} \quad (4)$$

However, we are unable to introduce the humidity. In order to consider its effect we perform the following procedure. First we subtract expression (4) from T_{in} and we obtain a response for this difference in terms of the humidity, H , namely

$$F_{Hf} = (T_{in} - F_{Tf} * T_{out}) / H * |C_{Hf}| / |C_H| \quad (5)$$

where

$$C_H = (T_{in} - F_{Tf} * T_{out}) * H \quad (6)$$

and

$$C_{Hf} = \begin{cases} C_H & \text{if } C > h*0.05 \\ 0 & \text{if } C < h*0.05 \end{cases}$$

with “h” calculated in the analogue form as “a” in the temperature response case. In this way the reconstructed temperature T_{recon} is obtained directly from the inverse Fourier transform of

$$T_{recon} = F_{Tf} * T_{out} + F_{Hf} * (T_{in} - F_{Tf} * T_{out}) \quad (7)$$

We have followed the same procedure using as output variables the temperature and the solar radiation, obtaining another T_{recon} , due to the mentioned variables.

With this procedure, we analyze building under different climatic conditions. In the next section we describe the analyzed system.

3. APPLICATION

In order to describe the calculation steps and the results, we have selected one example from several analyzed case studies. The monitored building is a single floor urban dwelling, constructed with break walls and not insulated concrete roof. This is a very traditional construction type in Mexico during eighties. The selected measured room was scarcely ventilated during the 9-days monitored periods. The local climate is hot-dry, with high temperature swings during day and the whole year. No air conditioning was used during these periods.

First step was to obtain the combined thermal response to reconstruct the indoor temperature using the same outdoor climatic conditions (according to (5) and (7)). We present the results applying as output climatic variables three different combinations: temperature and humidity, temperature and radiation, and only temperature. We compare the measured indoor temperature and the reconstructed indoor temperature depending on the outdoor variables used, in Figure 2.

In order to look for a thermal response able to characterize a specific thermal condition (for example, one specific season), the combination between outdoor temperature (most relevant) and one climatic variable more, such as humidity or solar radiation, demonstrate to be the best option to represent a specific pattern of climatic

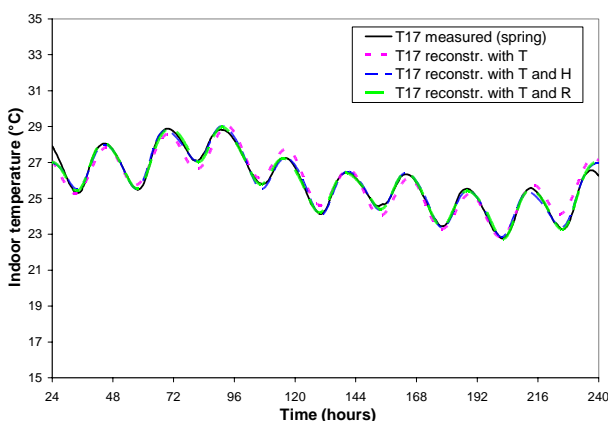


Figure 2: Reconstructed indoor temperatures using the combined thermal responses and the same outdoor climatic conditions.

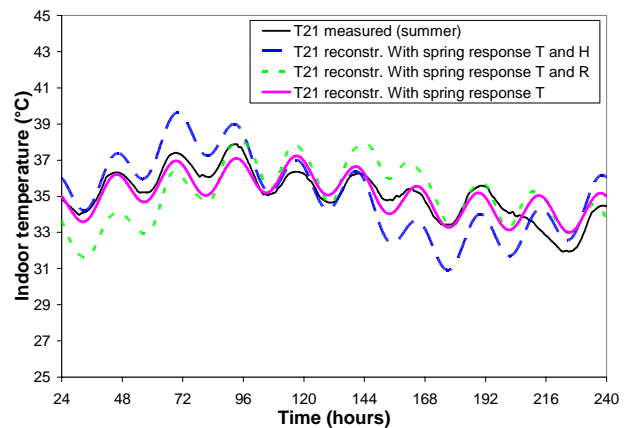


Figure 3: Reconstructed indoor temperatures using the combined thermal response, applied to other climatic conditions.

variations (see Fig. 2).

In most cases, the characterization of climatic patterns in different weather conditions during the year, has major utility. Thus, once obtained the combined thermal response for one specific climatic time series, according to Eqn. 1 to 6, it is applied to other different climatic conditions (for example, another season), in order to predict the indoor temperatures at that time (Eqn. 7).

Only the thermal response calculated with the outdoor temperature has an acceptable agreement with the measurements (see Fig. 3). In order to characterize the thermal behaviour all around the year, only the external temperature seems to contain the complete information. The correlation between other outdoor variables such as humidity and solar radiation with the indoor temperature is different under different climatic conditions and this distorts the results.

It is necessary to remark, that because of mathematical restrictions, the initial conditions (0-frequency amplitude and phase) are lost after the Fourier-transform. Thus, for the reconstruction of the indoor temperatures, the 0-frequency amplitude is added, by means of adding (positive or negative value) a constant in the temperature time series.

For the above case study, we compare the responses corresponding to two different climatic conditions, in order to understand the influence of the outdoor variables on the internal temperature in the frequency domain (see Figs. 4 to 6).

As it is shown in Figures 4 to 6, comparing the temperature responses of two climatic conditions with those responses obtained with com-

bined variables, the responses with only temperature as outdoor variable agree better, this is the reason because we have obtained better results in the reconstruction of the indoor temperature, as shown in Figure 3.

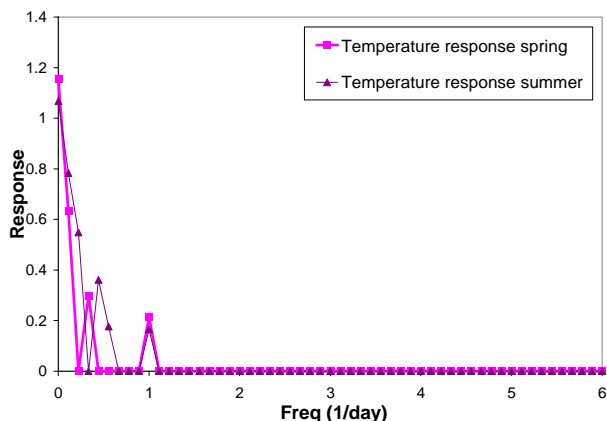


Figure 4: Amplitude responses due to outdoor temperature calculated with two climatic data sets.

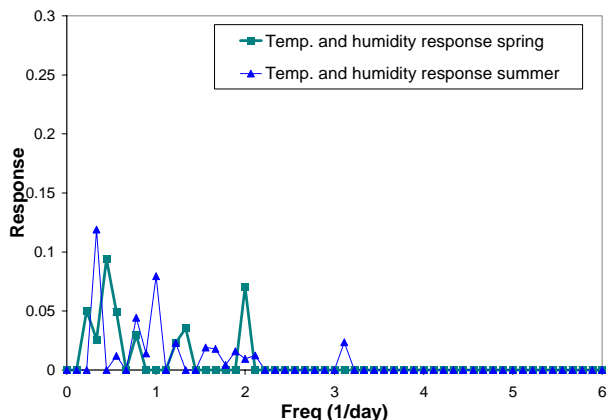


Figure 5: Amplitude combined responses due to outdoor temperature and relative humidity calculated with two climatic data sets.

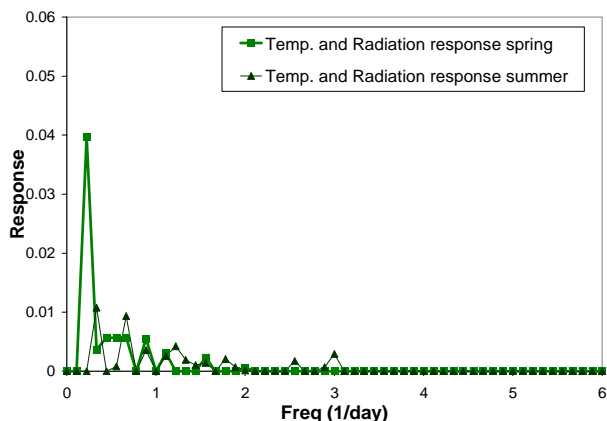


Figure 6: Amplitude combined responses due to outdoor temperature and solar radiation calculated with two climatic data sets.

Table 1: Deviation in the reconstruction of indoor temperature with different outdoor variables as input. Values in **bold** are the most accurate.

OUTDOOR VARIABLE	SAME CLIMATIC CONDITIONS(°C)	DIFFERENT CLIMATIC CONDITIONS(°C)
T_{out}	0.40	0.70
$T_{out} + H$	0.16	1.37
$T_{out} + R$	0.14	1.35

4. RESULTS INTERPRETATION

In this work we want to verify if the combined response (temperature and humidity or temperature and solar radiation) can help to improve the accuracy of the model.

Results at Table 1 show that dealing with specific climatic conditions (for example, the same season), the correlation between humidity or solar radiation patterns and indoor temperature seem to be constant and thus more predictable. That means, that both can give complementary information in the characterization of the thermal building behaviour, apart from outdoor temperature. This situation is not necessary the same in other season. In this case, the correlation between outdoor humidity or solar radiation, and indoor climatic patterns changes too much and is no more good for intervening in the building response, able to characterize the building.

Correlations between outdoor and indoor temperature spectra seem to change less under different climatic conditions, and that means that outdoor temperature is more suitable as data for the calculations. The effects of outdoor temperature patterns on the indoor temperature are the most predictable, showing in this case a deviation of 0.7 °C in the indoor temperature, between reconstructed and measured. The high oscillations of the outdoor variables in hot dry climates (daily and in several days- periods) must be taken into account to interpret the deviations.

Analyzing the different responses, the correlation between outdoor and indoor temperature is more relevant at low frequencies, as can be seen in Figures 4 to 6, where the amplitude of the filtered response has the most significant values between the daily and the 0-frequency. The accuracy in the low frequency range has in most cases more impact on the accuracy of the recon-

structed temperature. This fact has more significance also in the building characterization, because buildings used to “filter” most of the high frequencies of the outdoor variables (such as those produced by solar radiation, wind, etc), changing them into lower frequencies of the indoor temperature. Temperature measurements during relative short monitoring period, such as those of our case, were able to detect these relevant amplitudes of the thermal response. This is another good reason to use outdoor temperature as input for calculations.

5. CONCLUSIONS

One of the most important conclusions is that the use of the correlation filter in the building response is fundamental in order to interpret the results of measurements that always contain noise. The advantage is that only the relevant amplitudes of the thermal response are considered. Taking into account that the simplified methodology presented needs few parameters as input, to obtain a global thermal building characterization all around the year, the accuracy in results is quit acceptable for having a rough idea of the thermal performance of the building.

The selection of the most relevant outdoor variable is also important for the accuracy of the thermal characterization. From the analyzed example and from other case studies not presented here, we can conclude that for two different climatic periods, solar radiation and humidity seem not to have a relevant impact (alone) on building thermal response. Radiation and humidity are able to give complementary information to improve thermal response for one specific climatic condition. Under different climatic conditions, their correlation patterns with indoor temperature change, and because of this, they are not suitable to predict the building behaviour. The correlation between outdoor temperature and indoor temperature patterns is more constant all around the year and is more appropriate for characterizing the thermal building behaviour and for predicting the indoor temperature. Outdoor temperature contains time constants that are independent from the other mentioned variables, and is the best choice for characterizing building thermal behaviour. The temperature response includes amplitudes at several-days frequencies (low frequencies) that

can be detected in relative short monitoring periods (more than a week, depending on weather changes).

The presented methodology is a very simple prediction tool, which can roughly characterize the thermal behaviour of a building. The accuracy of the methodology has not been proved for other climates, like hot humid, but it seems to have great possibilities to be used for example in housing developments, particularly economic houses, which have very similar designs and construction and are located in many different climates in developing countries, for improving their thermal performance.

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