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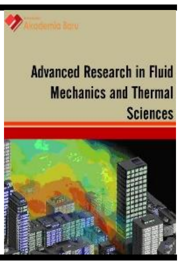

Experimental Study and Thermal Modeling (Linearization of Nonlinear System) of Building: Southwest Algeria Case

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ABSTRACT

In this article, a physical model of the building by thermoelectric analogy was developed. A detailed and simplified nonlinear model was obtained. Experimental data were collected at the laboratory site with a weather station equipped with a computer to measure the external and internal climatic variables. A linear approach was then implemented on this nonlinear model to prepare it for controlling of the building's internal microclimate. After the two linearization methods were used, linearization by indirect Lyapunov method and a modal simplification of the original nonlinear system were conducted. Validation, calculation and simulation were performed under the MATLAB/Simulink environment.

Keywords:
thermal model; thermal building; identification; experimental study; linearization

1. Introduction

The rapidly growing world energy use has already increased concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts. The International Energy Agency (IEA) has gathered frightening data on energy consumption trends [1-4]. During the last few years (1984-2004) primary energy had grown by 49% and CO_2 emissions by 43%, with an average annual increase of 2% and 1.8%, respectively [5-7].

Taking a closer look at various sectors, the residential sector consumes the most energy 43%, followed by the transport sector (36%) and the industry sector (21%). More detailed figures are outlined in Table 1 below [8].

In terms of energy consumption, the residential sector is the biggest consumer in Algeria, representing 38.1% of the national consumed energy. Other important sectors are the tertiary sector (20.93%) and the manufacturing industry (17.83%) [5, 9].

For this reason, there exist interest to control thermal buildings, keep thermal comfort and reduce energy consumption.

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Table 1
Final energy consumption in Algeria in 2012 and 2013 by sector [10]

Sector	Change in %
Residential	+9.0
Transport	+3.9
Industry	+3.7

There is a wide variety of software that could offer the possibility to create thermal models for climatic conditions of buildings so that it would be possible to simulate it, and control climatic conditions to be compatible with occupants. MATLAB/Simulink is one of the effective software that has advance possibility to design thermal models for the climatic conditions of buildings.

In regard to the growing concerns of sustainable development, the building sector must meet two essential requirements, which are control impacts on the external environment, and ensure healthy and comfortable indoor environments. In fact, physiology, physics, psychology, and sociology are all areas that will intervene, to a certain extent, in the definition of thermal comfort [11, 12].

The problems that arise are how to control this system, and which modeling is good in giving the effective command? Therefore, a better control of this thermal system requires a good model [13-15].

Modeling, which is an important phase in the control, will be developed by using thermoelectric analogy [16, 17]. With the law of nodes and meshes, we obtained nonlinear physical models. Then a manual parameter identification phase to minimize the error between measured and model-calculated values will be used.

2. Experimental Setup and Procedure

2.1 Meteorology Data

In practice, the outside temperature, solar flux, and wind speed are the most influential weather variables on thermal behavior of building and are provided by the weather station at Bechar University, which offered a wide range of climatological data from monthly to yearly schedules.

The data to be processed were recorded at the meteorological station of the research laboratory. The measurements were made with a time step of 10 min and included several data, such as the speed and direction of the wind or humidity and external and internal temperature of the laboratory. The solar flux received by the building was composed of two parts, which were diffuse flux, depending on the state of the sky (presence of clouds); and direct flow (a component whose contributions are the most considerable).

To define a single temperature for a given building poses a problem due to the heterogeneity of heating or air conditioning systems of each room, the variability of desired degree of comfort in different rooms and difficulty of defining a temperature of one room, particularly in the presence of irregular phenomena (opening of windows for example). An example of research laboratory equipped with a temperature probe was considered.

In practice, it is the comfort level of an occupant that takes precedence. This is why different studies were interested in the temperature felt. Whether it is indoor temperature or sensed temperature, there is a question on the number of thermal zones to consider according to the uniformity or not of comfort degree desired in a room. In the context of this study, the mono-zone case was considered; a single temperature was defined according to the temperature inside. The richness of the input data made it possible to ensure a good identification of the studied model.

2.2 Experimental Device

To study the thermal behavior and energy of building in the chosen model, some sensors were used to record the external and internal conditions of the building. The research laboratory at the studied university has an area of 416 m² (Figure 1). The temperature measurement was carried out by using a PT100 probe (accuracy ± 0.1 °C) located in the middle of the building. Radiation by using pyranometers (accuracy of ± 5 W/m2) on the roof of building, and a wind speed per cup anemometer (start threshold = 0.5 m/s) was located on the roof of the building. All these measurements were recorded in 10 min. [18].

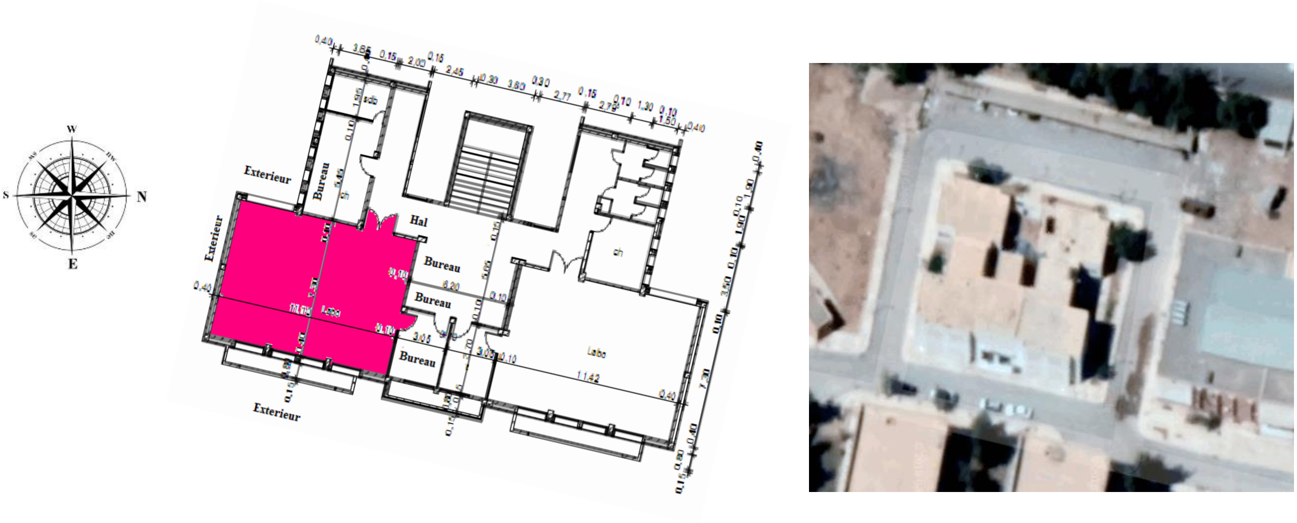
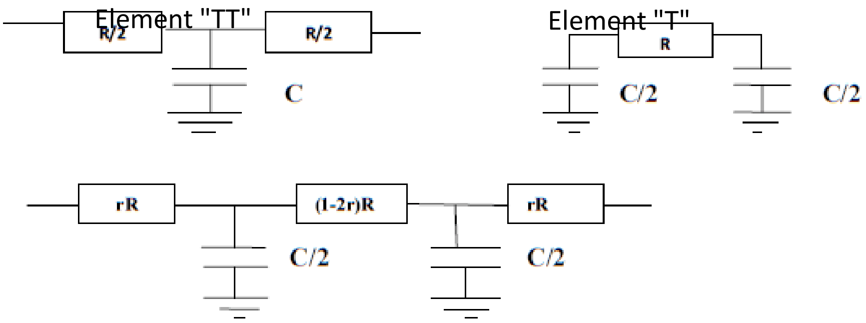


Fig. 1. Laboratory plan [19]

2.3 Aggregate Capacity Method

The thermal analogy with electrical conduction can be used to interpret the discretized structure obtained as a series of "RC" circuits, where the resistance and capacitance are those of a slice of a wall. When the number of elements is small, this approach is known as "aggregate capacity". Individual RC cells may be "T", "TT" or have a more general structure, as shown in the Figure 2.



Generalized element

Fig. 2. Aggregate capacity method [20, 21]

2.4 Nonlinear Detailed Thermal RC Model of Building

If all internal facades of the laboratory, as well as the windows and adjacent offices as a single envelope were considered, a detailed and complicated model will be obtained. A 9-state model and 36 parameters developed with the 2R1C (TT) method model are shown in Figure 3.

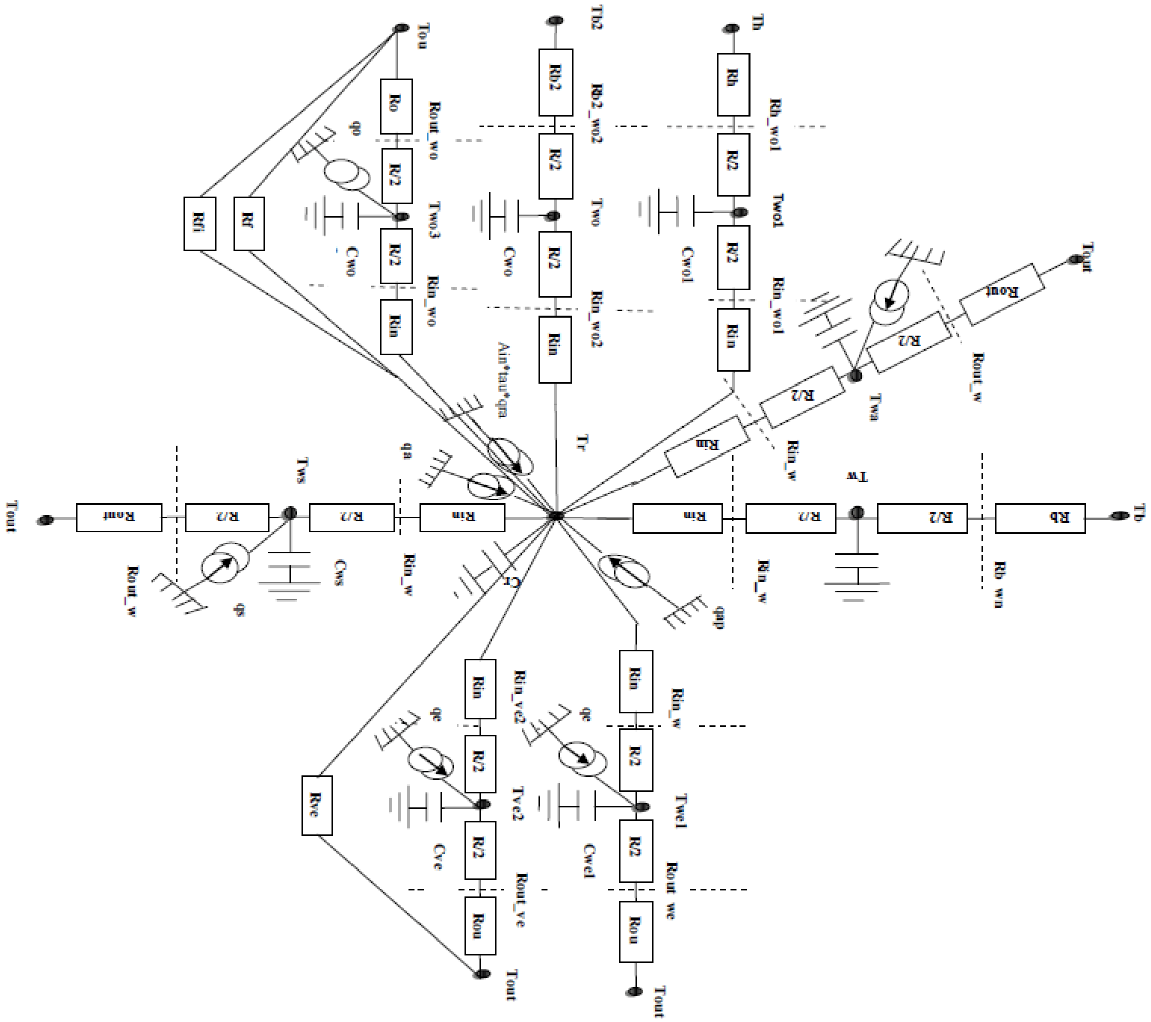


Fig. 3. Detailed thermal RC model

$$\frac{dT_{wn}}{dt} = \frac{1}{C_{wn}} \times \left(\frac{(T_b - T_{wn})}{R_{b_{wn}}} + \frac{(T_r - T_{wn})}{R_{in\_wn}} \right) \tag{1}$$

$$\frac{dT_{ws}}{dt} = \frac{1}{C_{ws}} \times \left(\frac{(T_{out} - T_{ws})}{R_{out\_ws}} + \frac{(T_r - T_{ws})}{R_{in\_ws}} + q_s \times q_{rad} \right) \tag{2}$$

$$\frac{dT_{wa}}{dt} = \frac{1}{C_{wa}} \times \left(\frac{(T_{out} - T_{wa})}{R_{out\_wa}} + \frac{(T_r - T_{wa})}{R_{in\_wa}} + q_a \times q_{rad} \right) \tag{3}$$

$$\frac{dT_{wo1}}{dt} = \frac{1}{C_{wo1}} \times \left(\frac{(T_h - T_{wo1})}{R_{h\_wo1}} + \frac{(T_r - T_{wo1})}{R_{in\_wo1}} \right) \tag{4}$$

$$\frac{dT_{wo2}}{dt} = \frac{1}{C_{wo2}} \times \left(\frac{(T_{b2} - T_{wo2})}{R_{b2\_wo2}} + \frac{(T_r - T_{wo2})}{R_{in\_wo2}} \right) \tag{5}$$

$$\frac{dT_{wo3}}{dt} = \frac{1}{C_{wo3}} \times \left(\frac{(T_{out} - T_{wo3})}{R_{out\_wo3}} + \frac{(T_r - T_{wo3})}{R_{in\_wo3}} + q_{o3} \times q_{rad} \right) \tag{6}$$

$$\frac{dT_{we1}}{dt} = \frac{1}{C_{we1}} \times \left(\frac{(T_{out} - T_{we1})}{R_{out\_we1}} + \frac{(T_r - T_{we1})}{R_{in\_we1}} + q_{e1} \times q_{rad} \right) \tag{7}$$

$$\frac{dT_{we2}}{dt} = \frac{1}{C_{we2}} \times \left(\frac{(T_{out} - T_{ve2})}{R_{out\_ve2}} + \frac{(T_r - T_{ve2})}{R_{in\_ve2}} + q_{e2} \times q_{rad} \right) \tag{8}$$

$$\frac{dT_r}{dt} = \frac{1}{C_r} \times \Bigg(\frac{(T_{wn} - T_r)}{R_{n\_r}} + \frac{(T_{ws} - T_r)}{R_{s\_r}} + \frac{(T_{out} - T_r)}{R_{a\_r}} + \frac{(T_{wo1} - T_r)}{R_{o1\_r}} + \frac{(T_{wo2} - T_r)}{R_{o2\_r}} + \frac{(T_{wo3} - T_r)}{R_{o3\_r}} + \frac{(T_{out} - T_r)}{R_{fh}} + \frac{(T_{out} - T_r)}{R_{fwin}} + \frac{(T_{we1} - T_r)}{R_{e1_r}} + \frac{(T_{ve2} - T_r)}{R_{e2_r}} + \frac{(T_{out} - T_r)}{R_{ve2}} + q_{ac} + t_{auwin} \times A_{win} \times q_{app} \Bigg) \tag{9}$$

2.5 Simplified RC Thermal Model

In this case, only the 3 middle branches were considered, one for external facades without windows and no openings, another for the external facades symbolizing the windows, and a final facade delimited by adjacent offices and highs (Figure 4). Only 11 parameters were obtained.

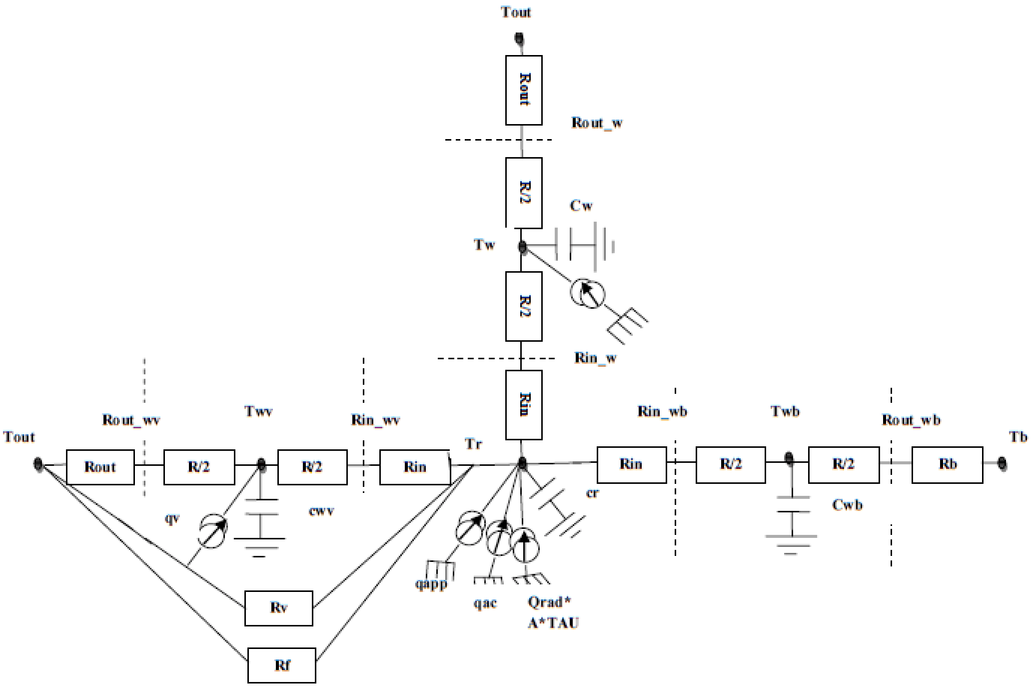


Fig. 4. Simplified RC thermal model

The differential equations of the thermoelectric model with 3 branches according to the law of electricity are

$$\frac{dT_w}{dt} = \frac{1}{C_w} \times \left(\frac{(T_{out} - T_w)}{R_{out\_w}} + \frac{(T_r - T_w)}{R_{in\_w}} + q \times q_{rad} \right) \tag{10}$$

$$\frac{dT_{wb}}{dt} = \frac{1}{C_{wb}} \times \left(\frac{(T_b - T_{wb})}{R_{b\_w}} + \frac{(T_r - T_{wb})}{R_{in\_wb}} \right) \tag{11}$$

$$\frac{dT_{wv}}{dt} = \frac{1}{C_{wv}} \times \left(\frac{(T_{out}-T_{wv})}{R_{out\_w}} + \frac{(T_r-T_{wv})}{R_{in\_wv}} + q_v \times q_{rad}\right) \tag{12}$$

$$\frac{dT_r}{dt} = \frac{1}{C_r} \times \left(\frac{(T_w-T_r)}{R_{in\_w}} + \frac{(T_{wv}-T_r)}{R_{in\_wn}} + \frac{(T_{wb}-T_r)}{R_{in\_wb}} + \frac{(T_{out}-T_r)}{R_f} + \frac{(T_{out}-T_r)}{R_v} + q_{ac} + t_{auwin} \times A_{win} \times q_{app} \times q_{rad}\right) \tag{13}$$

3. Validation Results of the Obtained Models

Given the large number of parameters to be identified, it can be seen that the error between the temperature calculated by the detailed model and the measured one was too big, as shown in Figure 5. Therefore, this system was not considered.

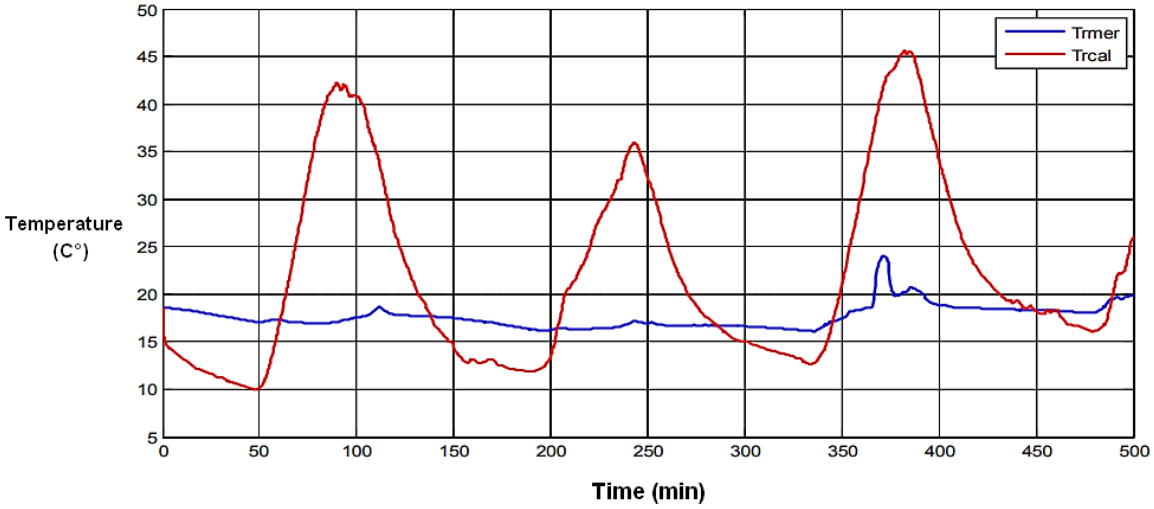


Fig. 5. Evolution of temperatures of detailed model during March 2018

The other states calculated by the model are given in Figure 6

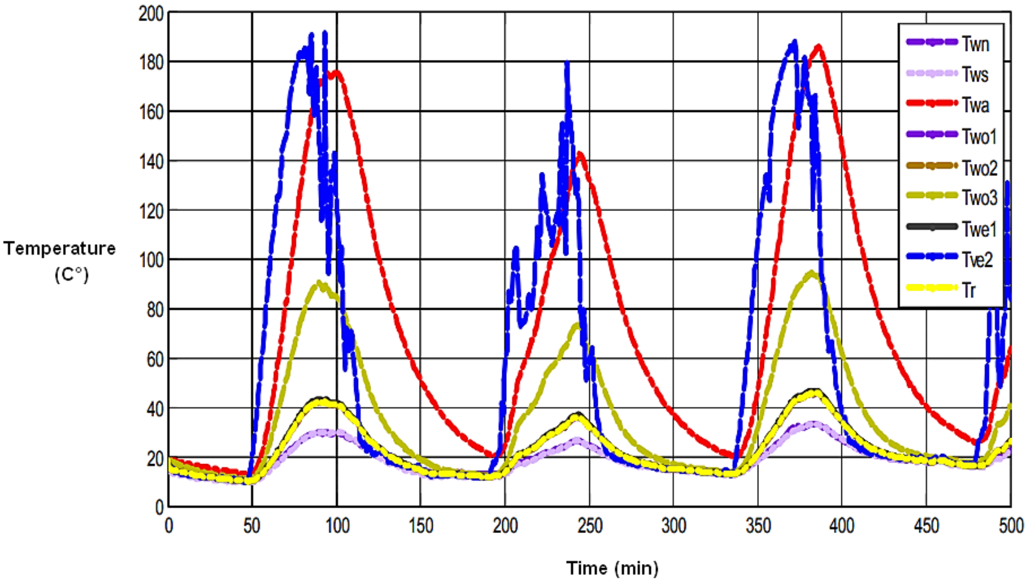


Fig. 6. The states calculated by the detailed nonlinear model

It can be seen that these states are in a natural way where the effect of the day and the night are visible on the figure.

3.1 Simplified Nonlinear Model of the Building

The temperatures calculated by the simplified nonlinear model and measured within the local building are given in Figure 7.

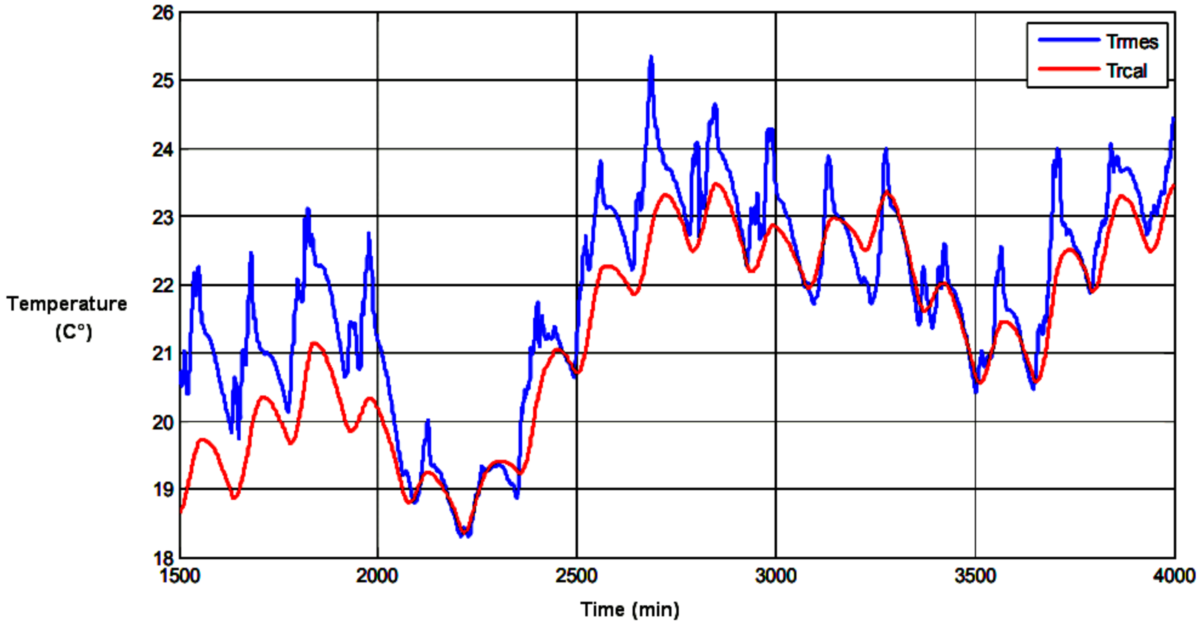


Fig. 7. Evolution of temperatures of simplified nonlinear model during the month of March 2018

It is clear that there is a certain agreement between the measured and calculated values by the simplified model (Table 2), and the error takes the maximum values up to 2 °C.

Table 2
Identified parameters of the simplified nonlinear model

Identified parameters	Value	Identified parameters	Value	Identified parameters	Value
a	1	Rinwv	5×10-3	Cw	640
b	480	A	25.75	Cwb	640
Rw	20	Av	36.5	Cwv	640
Rinw	2×10-5	alphaw	0.25	Cr	3×105
Routw	5×10-2	alphav	0.75	Rv	10-3
Rinwb	5×104	q	6.94	Twin	0.1
Routwv	5×10-10	qv	27.37	Awin	9.25

3.2 Linearization of Thermoelectric RC Models of the Building

Because of the wind stress presence in the determination of the leakage resistance (R_f) the obtained models were nonlinear.

As the detailed thermal RC model was too complex, so the choice to work with the simplified nonlinear model with identified parameters was made.

3.2.1 Linearization by the indirect Lyapunov method (Taylor)

The state representation of the simplified model is defined as follows

$$\frac{dX_1}{dt} = \frac{1}{C_w}\left[\frac{-X_1}{R_{out\_w}} + \frac{X_4 - X_1}{R_{in\_w}}\right] + \frac{1}{C_w}\left[\frac{U_1}{R_{out\_w}} + qU_1\right] \tag{14}$$

$$\frac{dX_2}{dt} = \frac{1}{C_{wb}}\left[\frac{-X_2}{R_{out\_wb}} + \frac{X_4 - X_2}{R_{in\_wb}}\right] + \frac{1}{C_{wb}}\left[\frac{U_2}{R_{out\_wb}}\right] \tag{15}$$

$$\frac{dX_3}{dt} = \frac{1}{C_{wv}}\left[\frac{-X_3}{R_{out\_wv}} + \frac{X_4 - X_3}{R_{in\_wv}}\right] + \frac{1}{C_{wv}}\left[\frac{U_3}{R_{out\_wv}} + q_v U_1\right] \tag{16}$$

$$\frac{dX_4}{dt} = \frac{1}{C_r}\left[\frac{X_1 - X_4}{R_{in\_w}} + \frac{X_1 - X_4}{R_{in\_wv}} + \frac{X_1 - X_4}{R_{in\_wb}} - \frac{X_4}{R_f} - \frac{X_4}{R_v}\right] + \frac{1}{C_r}\left[U_3(2 + 10U_6) + \frac{U_3}{R_v} + U_5 + U_4 + tauA_{win}U_1\right] \tag{17}$$

3.2.1.1 Calculus of operating points

The operating states points were

$$X_1 = 7.\,10^{-4}.U_1 + 5U_3(40U_1 + 10^{-4}U_2 + 6.\,103U_3 + 5U_4)(10U_6 + 2\,) + 8.3210^{-4}U_5 \tag{18}$$

$$X_2 = 5U_2 + 5.\,10^{-6}U_3 + (4.\,10^5 + 6.\,10^3U_2 + 0.006U_3 + 5.\,10^{-6}U_4)(10U_6 + 2) + 8.\,10^{-11}U_5 \tag{19}$$

$$X_3 = 7.\,10^{-8}\,.U_1 + 5U_3 + (9.\,10^{-5}U_1 + 10^{11}U_2 + 6.\,10^3U_3 + 5.\,10^{-7}U_4)(10U_6 + 2) + 5U_5 \tag{20}$$

$$X_4 = 5U_3(39.31.\,U_1 +.\,10^{-4}\,.U_2 + 6.\,10^{-3}\,.U_3 + 5U_1)(10U_6 + 2) + (10U_6 + 2) + 8.\,10^{-4}U_5 \tag{21}$$

Since there were only 4 equations and 10 unknowns, 6 fixed values from the data files were taken and the remaining 4 unknown states were calculated. The coordinates of the points are given in Table 3.

Table 3
The equilibrium points of the linearized model

Balance points	X_{1e}	X_{2e}	X_{3e}	X_{4e}	U_{1e}	U_{2e}	U_{3e}	U_{4e}	U_{5e}	U_{6e}
Numerical value	18.57	20.73	18.5	18.56	28.7	20.37	20.4	45	0	2.4

3.2.1.2 Jacobean matrix calculation

The values of the matrices A, B, C, D of the system depend on the operating point

$$q = (Xe\,, Ue) = (X_{1e}\,, X_{2e}\,, X_{3e}\,, X_{4e}\,, U_{1e}\,, U_{2e}\,, U_{3e}\,, U_{4e}\,, U_{5e}\,, U_{e6}\,) \tag{22}$$

The state matrix is

$$A = \begin{bmatrix} -78.12 & 0 & 0 & 78.12 \\ 0 & -0.03 & 0 & 3.12\times10^{-8} \\ 0 & 0 & -3.12\times10^{6} & 0.31 \\ 0.2 & 8.10^{-11} & 8.10^{-4} & -0.2 \end{bmatrix}$$

and the control matrix is

$$B = \begin{bmatrix} 0.01 & 0 & 7.8\times10^{-5} & 0 & 0 & 0 \\ 0 & 0.03 & 0 & 0 & 0 & 0 \\ 0.04 & 0 & 3.12\times10^{6} & 0 & 0 & 0 \\ 3.7\times10^{-6} & 0 & 0.004 & 4\times10^{-6} & 4\times10^{-6} & -2.8\times10^{-6} \end{bmatrix}$$

The output to control is the temperature inside the building, therefore

$$C = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$$

D = 0

3.2.2 Linearization by elimination of weak modes method

Based on the modal analysis algorithm of MATLAB function, the previous linearized of Order 4 model was reduced to Order 2 state space model as follows

$$\begin{cases} X = A_r X + B_r U \\ Y = C_r X + D_r U \end{cases}$$

with

$$A_r = \begin{bmatrix} -0.004788 & 0.000759 \\ 0.0002996 & -78.31 \end{bmatrix}$$

$$B_r = \begin{bmatrix} 0.0004519 & -6.945.10^{-10} & -0.06919 & -5.766.10^{-5} & -5.766.10^{-5} \\ -0.005025 & -6.312.10^{-5} & 0.002198 & 1.862.10^{-6} & 1.862.10^{-6} \end{bmatrix}$$

$$C_r = \begin{bmatrix} -0.0692 & 0.005485 \end{bmatrix}$$

$$D_r = \begin{bmatrix} -2.33\times10^{-11} & 2.209\times10^{-9} & -2.458\times10^{-10} & 8.631\times10^{-50} & 8.63\times10^{-15} \end{bmatrix}$$

The preceding Figure 8 shows that the linear system of Order 4 and reduced Order 2 were confused and equivalent.

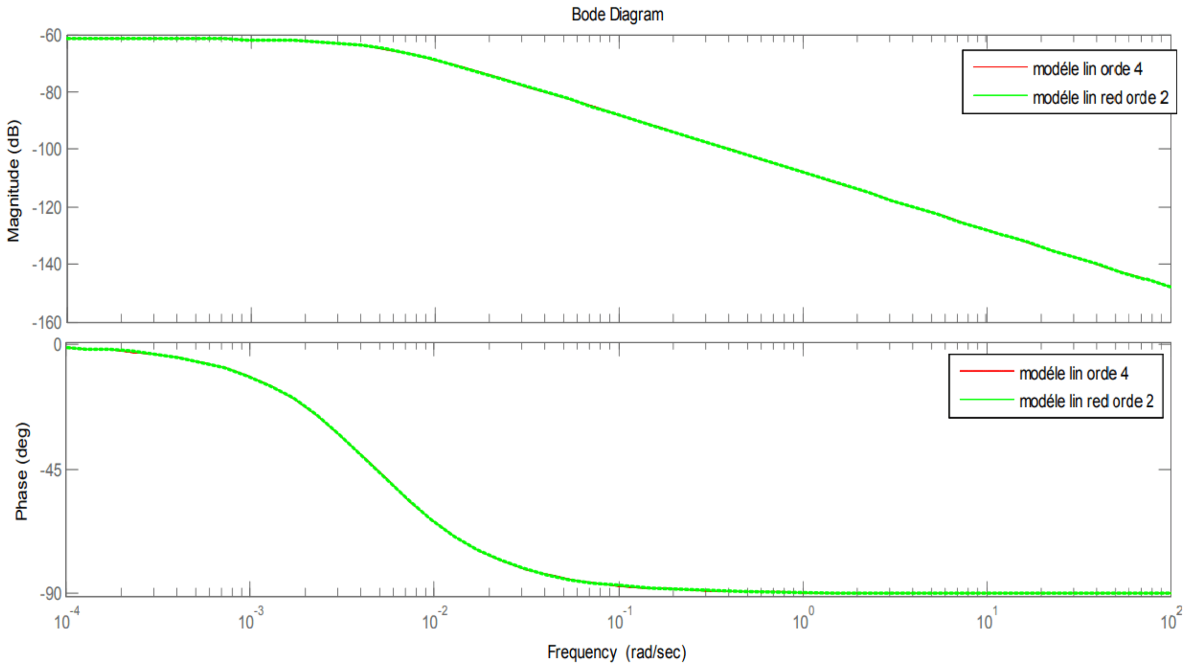


Fig. 8. Bode diagram of the linear system of Order 4 and reduced Order 2

3.3 Analysis of the Reduced Linear System

3.3.1 Stability

The map plot of the system's poles and zeros were on the left half-plane, so the system has a stable nature, as can be seen in Figure 9.

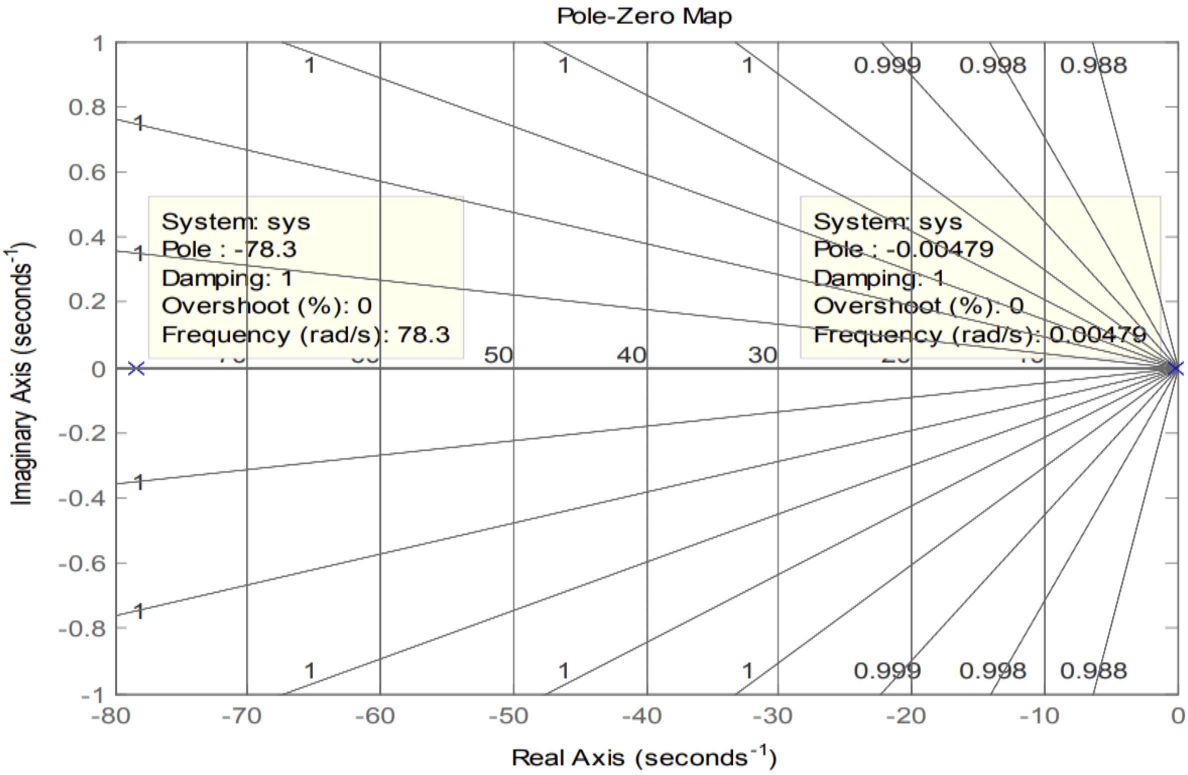


Fig. 9. Poles plot and zeros of the reduced linear system

3.3.2 Commandability

To enable control, the system must be controllable, and hence Kalman's commandability criterion was used.

$$\mathfrak{G} = [B_r \quad AB_r A^2 B_r A^3 B_r]$$

$$\mathfrak{G} = \begin{pmatrix} -5.10^{-4} & 0 & -6.10^{-2} & -10^{4} & -10^{-4} & 0 & 0 & 3.10^{-4} & 0 & 0 \\ -5.10^{-3} & 10^{-4} & 22.10^{-3} & 0 & 0 & 0.3935 & 49.10^{-3} & -0.1721 & -10^{-4} & -10^{-4} \end{pmatrix}$$

The rank of this system is

$rang\ (\mathfrak{G}) = 2$

Therefore, the system is completely controllable.

3.3.3 Observability

According to Kalman's criterion of observability

$$\mathcal{O} = \left(\begin{bmatrix} C \\ \cdots \\ CA \\ \cdots \\ \vdots \\ \cdots \\ CA^{n-1} \end{bmatrix} \right)$$

$$\mathcal{O} = \begin{bmatrix} -692.10^{-2} & 55.10^{-3} \\ 3.10^{-3} & -0.4296 \end{bmatrix}$$

The rank of this system is

$rang\ (\mathcal{O}) = 2$

Therefore, the system is completely observable.

Linearization of the nonlinear thermal model by the Lyapunov method and by modal approximation was established. Linearization by modal approximation was adopted and analyzed to have at the end a reduced linear system of Order 2.

4. Conclusion

In this article, the laboratory building was considered as a case study. At first, a physical modeling over a period of five days was done in March 2018, the results of the identification were acceptable.

Then the linearization stage of the nonlinear physical model was proceeded with modal approximation and indirect Lyapunov method.

After calculating the equilibrium points and Jacobean matrix, the first stable linear model was obtained because it had eigenvalues with a negative real part. This system was not completely controllable and observable; hence, it was not used to control the internal local environment. A third linear, fully controllable and observable model was obtained by modal simplification of the second approximate linear model, which gave better control results. Simulation results obtained and implemented on MATLAB/Simulink were significantly better for the reduced linear Order 2 system.

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