SIMULATION OF DYNAMIC ENVELOPE COMPONENTS THROUGH SYSTEM IDENTIFICATION PROCEDURES

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ABSTRACT

Together with the definition of innovative plant and envelope technological solutions for buildings, many simulation tools (models) have been developed to make the design choices easier. However the definition of analytical structures able to describe the characteristics of building components installed under real conditions is still difficult. The paper presents some experiences made by ITC. They have been carried out by using System Identification techniques to simulate and predict the performances of various components analysed also through experimental campaigns under real conditions. To this end, parametrical black-box models have been identified and validated. Apart from the physical and dimensional characteristics of the building, they allow to describe it through equations that consist of simple polynomials whose variables are represented by inputs and outputs.
The application of the models has allowed to obtain meaningful results, as regards the prediction of the behaviour of the studied components also with a very limited knowledge of their characteristics. They need repeated identifications each time the external environment's dynamics change. But as the analytical structure is quite simple and they don't need too long monitoring periods, the identification can be efficaciously automated, like in the presented cases.

KEYWORDS

System Identification, simulation, prediction, dynamic envelope.

INTRODUCTION

The paper presents the results of some experiments and analyses carried out on dynamic envelope systems. In particular, the attention is focused on the survey approach that, together with an experimental phase, used simulation techniques and prediction analyses through System Identification procedures. In fact the experimental data were used to identify analytical models with two different aims: the simulation of the various studied systems extending the analyses to periods whose experimental data were not available; predictions about the variables, allowing to optimize the regulation and the control.
The analysed systems were: two typologies of dynamic façade, a passive double-skin dynamic system, a hybrid opaque dynamic component.
The scheme of Figure 1 (left) shows the characteristics of the two typologies of the tested dynamic façades: type A with an aluminium external shield, type B with fibre-cement panels.
The double-skin dynamic system (Figure 1, centre) was conceived starting from the idea of combining the working modes of the dynamic systems with the ones of solar chimneys.
In particular, a dynamic behaviour was expected with different modes that could be selected through the opening and/or shutting of appropriate shutters located in the external façade, in addition to the aerator and the shutters in the internal skin. The solar chimney integrated in the

system consisted of the space between a TIM (Transparent Insulation Material) panel in the lower part of the system and the wall behind it, that represented the massive store element.

Figure 1: The studied systems

The hybrid envelope dynamic component (Figure 1, right) basically consisted of a dynamic multi-layer element in the lower part and an energy management module in the upper one, that managed the air flows of the system's air-space in an automated and autonomous way, thanks to photovoltaic panels. The component's behaviour was controlled on the basis of three temperatures (of the internal, external air and of the air in the air-space), acquired by appropriate sensors and processed by the regulation logic software, implemented on an electronic board. Depending on the acquired values, the behaviour of the dynamic component was either natural or forced, thanks to fans and shutters located in the central part of the management module, where the air from the air-space was conveyed.

THE EXPERIMENTATION

The two typologies of dynamic façade studied were set and tested on one of ITC's experimental buildings. In particular the attention was focused on the evaluation of the air temperature in the internal environments of the building and in the air-space of the façades under different climatic conditions.
The passive system was tested under real conditions, set on a test-cell (Figure 1, centre). The analysis was made by comparison with a traditional system, by also assessing the energy contribution of the double-skin component. The experimental program was adapted to the results obtained from time to time, focusing the analyses to better understand the dynamics that developed in the system's air-space. In fact some changes were introduced in the system concerning both its dimensions and the materials used, to understand the contribution of individual elements to the global efficiency of the system.
The thermo-energy analyses on the opaque dynamic component were carried out within a research that started from the design and the realization of the prototype. After a first validation in laboratory and on real-scale setups (the out-door test-cells) aimed at optimizing the system's performances, ended with a final validation on the optimized systems carried out in an experimental building (Figure 1, right).

APPLICATION OF THE SYSTEM IDENTIFICATION TECHNIQUES

The research objective was to define a tool without knowing the physical-geometrical characteristics of the systems, even thought such knowledge was however used to choose the input variables. The System Identification techniques allow to build mathematical models of dynamic systems of purely analytical kind (black box), based on measured data. Such techniques can be applied to a wide variety of mathematical structures, among which the

parametric models and, in particular, the ones defined as ARMAX (Auto Regressive Moving Average with eXogenous inputs). The analyses carried out for the case studies described refer to the structure ARX, a simplification of the mentioned ARMAX, because the obtained results were not considered dissimilar to the ones obtained with the complete structure.
In general a dynamic linear model in the ARX form can be symbolically described as follows:

$$y(t)+a_1 y(t-1)+...+a_{na} y(t-na)=\sum_i b_i u_i(t-nk_i)+...+b_{nbi} u_i(t-nk_i-nb_i+1)$$

The output (y) is partly determined from the input (u_i) considered at various (nb_i) previous steps starting from delays (nk_i) assigned during the identification phase and partly from other inputs of the system, which are not rendered explicit. Such dependence is defined by parameters “a” and “b”. The phase identified as “identification” of the analytical model consists of the research, through appropriate mathematical procedures, of the numerical values of the parameters that give the best agreement between the model output and the measured one.
To choose among different tested mathematical structures, a series of analyses are available; in the cases presented here, the model was chosen on the basis of the best fitting calculated as the percentage of the output’s variations correctly simulated by the model.
In defining the independent (input) and dependent (output) variables the two problems of simulation and prediction were distinguished. For what concerns the prediction, the output of the parametric model could be used as input of a regulation logic, most likely fuzzy logic particularly suitable for complex systems like the analysed envelope components.

RESULTS

The dynamic façades

In the case of dynamic façades tested on the experimental building, the application of the System Identification procedures regarded the analysis of the temperature that the air reached in their air-space, depending on the materials’ characteristics, the façade exposure, etc.
Figure 2 shows the graph of the measured and simulated output related to the identification period. In the case on the left side of Figure 2 the simulation is made by removing the mean.
The characteristic polynomial identified in the considered case appeared as follows:

$$\mathbf{Tg}(t) = 1.4132\cdot\mathbf{Tg}(t-\tau) - 0.6011\cdot\mathbf{Tg}(t-2\tau) + 0.0055\cdot\mathbf{I}(t-2\tau) + 0.2796\cdot\mathbf{Te}(t-2\tau) - 0.0655\cdot\mathbf{Te}(t-3\tau) + 0.2246\cdot\mathbf{Te}(t-4\tau) + 0.0533\cdot\mathbf{Te}(t-5\tau) - 0.3677\cdot\mathbf{Te}(t-6\tau)$$

As it may be noticed, the influence of the first input (solar radiation) to determine the temperature in the air-space is limited by the low value of its coefficient (0.0055) if compared with the algebrical sum of the coefficients related to the output and to the second input. In fact the identification algorithm of the SI tool-box shows a bad correlation between solar radiation and air-space temperature owing to nocturnal periods, when there is no solar radiation.

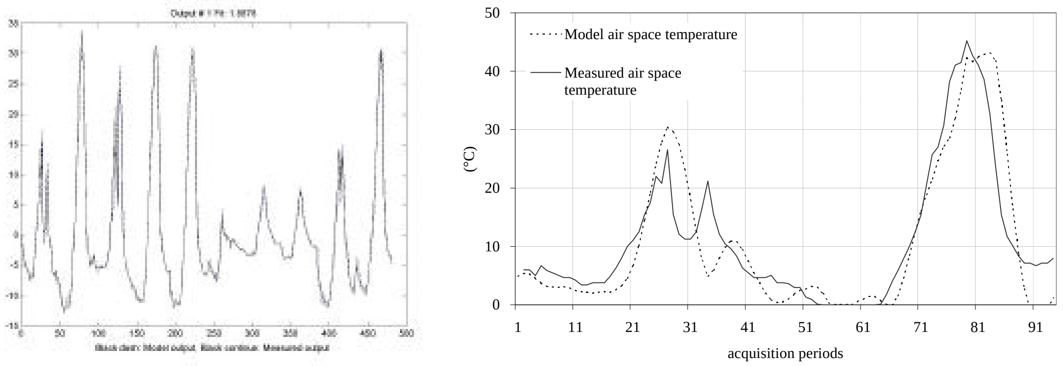

Figure 2: Simulations made considering as previous output the measured (left) and the simulated (right) ones.

For this reason the coefficient linking solar radiation with the temperature rise in the air-space was recalculated (from 0.0055 to 0.115), on the basis of the data collected by monitoring. In this way, also for pure simulations, that is when the trend of the temperature in the air-space wasn't known a priori (fresh data), appreciable results were obtained (Figure 2, right).
Having identified the analytical model, the simulations were made, by assuming different conditions of external temperature and solar radiation, finding the corresponding trend of the temperature in the air-space and its maximum value, as reported in Table 1.

Table 1: Summarizing table of the simulations made through the mathematical model

max solar rad. (W/m^2)	max ext. temp. (°C)	max air-space. temp. Tg (°C)
125.2	9.9	16.7
461.3	12.5	34.8
525.6	10	43.6
659.3	14	56.9

The temperature trend in the air-space related to the solar radiation is an indicator of the correct behaviour of the dynamic façade system studied; in fact a high air-space temperature means good energy contribution in winter, an improvement of indoor comfort through humidity exhausting, breaking of the thermal wave and exhausting of part of the indoor sensible and latent heat during the summer.

The passive system

Two models were identified, related to two different kinds of analysis:

- considering consumption as output, two system's configurations, having different air-space thickness, were compared;
- considering the air-space temperature as output, a model was defined to predict such variable, to define a control logic of the devices characteristic of the system, in the prospect of a possible future automation, that could turn it into an hybrid system.

The identifications result is the following:

Consumption with air-space of 12 cm	$\mathbf{C}(t) = -0.1442\cdot\mathbf{C}(t-\tau) + 0.1100\cdot\mathbf{C}(t-2\tau) + 0.2638\cdot\mathbf{C}(t-3\tau) + 0.1408\cdot\mathbf{C}(t-4\tau) - 0.02402\cdot\mathbf{C}(t-5\tau) - 0.0006766\cdot\mathbf{I}(t-\tau) - 0.000258\cdot\mathbf{I}(t-2\tau) + 0.0003363\cdot\mathbf{I}(t-3\tau) - 0.02836\cdot\mathbf{Te}(t-3\tau) + 0.02081\cdot\mathbf{Te}(t-4\tau) - 0.01329\cdot\mathbf{Te}(t-5\tau) + 0.02237\cdot\mathbf{Te}(t-6\tau) - 0.02056\cdot\mathbf{Te}(t-7\tau)$
Consumption with air-space of 8 cm	$\mathbf{C}(t) = 0.6343\cdot\mathbf{C}(t-\tau) + 0.4646\cdot\mathbf{C}(t-2\tau) - 0.08599\cdot\mathbf{C}(t-3\tau) + 0.08887\cdot\mathbf{C}(t-4\tau) - 0.1609\cdot\mathbf{C}(t-5\tau) - - 0.0001716\cdot\mathbf{I}(t-\tau) - 0.0004236\cdot\mathbf{I}(t-2\tau) + 0.0005732\cdot\mathbf{I}(t-3\tau) - 0.01138\cdot\mathbf{Te}(t-3\tau) + 0.06941\cdot\mathbf{Te}(t-4\tau) + 0.06315\cdot\mathbf{Te}(t-5\tau) - 0.05615\cdot\mathbf{Te}(t-6\tau) + 0.01444\cdot\mathbf{Te}(t-7\tau)$
Air-space temperature (gap= 8cm)	$\mathbf{Tg}(t) = 1{,}838\cdot\mathbf{Tg}(t-\tau) - 0.976\cdot\mathbf{Tg}(t-2\tau) + 0.1088\cdot\mathbf{Tg}(t-3\tau) + 0.02463\,\mathbf{Tg}(t-4\tau) - 0.009642\,\mathbf{Tg}(t-5\tau) + 0.002495\,\mathbf{I}(t-\tau) - 0.002003\,\mathbf{I}(t-2\tau) + 0.004876\,\mathbf{I}(t-3\tau) - 0.004628\,\mathbf{I}(t-4\tau) - 0.0003243\,\mathbf{I}(t-5\tau) + 0.07869\,\mathbf{Te}(t-\tau) - 0.0711\,\mathbf{Te}(t-2\tau).$

In this case the solar radiation data used for the identification were filtered, subtracting the mean of only the positive values from the series of values, calculated over the whole experimental period. Such filter procedure was needed in order not to overestimate, during the identification phase of the model parameters, the solar contribution when the solar radiation was high, that is when its trend presented high values in very restricted periods (peaks).
The models obtained were validated with "fresh" experimental data, obtaining meaningfully positive confirmations, that is to say fittings with a fair correspondence between simulated and measured values.
The simulations were carried out considering some days chosen as "typical days", whose characteristics are reported in Table 2.

Table 2: The meteorological characteristics of the "typical days"

typical day	**max ext. temp. (C°)**	**sum degree-hours** $\sum_{i=1}^{24}(T_{rif} - T_{iext})$ **(C°)**	**max solar rad. (W/m^2)**	**total radiant energy (Wh/m^2)**
1	14.0	350.55	742.6	4802
2	10.0	340.87	525.8	1895
3	12.5	297.15	461.3	1725
4	9.9	349.55	125.2	441
5	19.6	230.06	656.9	4251
6	25.4	124.71	684.2	4585

In order to compare the two configurations of the system, the same orders and delays were used in the identification phase of the analytical models. Table 3 reports the results, that is the daily energy consumption in the typical days related to the two configurations and the obtained percentage saving.

Table 3: Results of the simulations on the double-skin passive system

typical day	**consum. air-space 12 cm (kWh/day)**	**consum. air-space 8 cm (kWh/day)**	$R = \frac{C_{12} - C_8}{C_{12}} x 100$
1	11.90	8.60	27
2	10.63	7.80	26
3	7.37	5.30	28
4	7.42	6.74	9
5	7.81	4.83	38
6	6.00	4.03	32

It's evident from the table that the configuration with a less thick air-space presents lower consumption, in every climatic condition. The solar captation efficiency could then be improved both with the passive operation of the system, and through appropriate mechanical ventilation devices or an automatic management of the components (screening elements, shutters for the communication between indoor and outdoor environments, ...). Such automation could take place by using in the regulation logic the outputs of the prediction model of the air-space temperature trend.

The comparison between the first three typical days and the fourth points out how fundamental the solar radiation is to trigger the dynamic phenomena of the system, underlining the importance of the design choices, in this case the air-space thickness. In fact with very low solar radiation, the system shows a similar behaviour in the two configurations; the consumption was in fact determined nearly only by the static insulation, that is the same in the two cases. For what concerns the last two typical days, it must be specified that they are characteristic of climatic conditions rather far from the ones used for the models' identification, and the results must be therefore carefully considered. In fact System Identification techniques allow, experimental data series of adequate length having been acquired, to identify and simulate the system rather quickly, allowing several comparisons. On the other hand, as parameters are purely analytical, the system physical nature must be introduced with a particular care, in particular during the identification phase (as described above) and results must be read with a critical eye, without neglecting the characteristics of the analysed system.

The opaque dynamic system

The results of two simulations have been compared, considering as output the energy consumption needed to keep the internal temperature at 20°C in the test cells with the innovative dynamic component and with the reference one.
The objectives of the application of the ARX parametric model were:
- the prediction of the energy consumption in the two cells;
- the quantification of the expected energy saving.

The result of the identification in the two cases, innovative dynamic component (1) and reference component (2) is the following:

1) $\mathbf{C}(t) = 0.0174 \cdot \mathbf{C}(t-\tau) + 0.1876 \cdot \mathbf{C}(t-2\tau) + 0.2252 \cdot \mathbf{C}(t-3\tau) - 0.0067 \cdot \mathbf{Te}(t-2\tau) - 0.9649 \cdot 10^{-3} \cdot \mathbf{I}(t-\tau) + 0.3316 \cdot 10^{-3} \cdot \mathbf{I}(t-2\tau) + 0.2406 \cdot \mathbf{I}(t-3\tau)$

2) $\mathbf{C}(t) = 0.0307 \cdot \mathbf{C}(t-\tau) + 0.3124 \cdot \mathbf{C}(t-2\tau) + 0.25 \cdot \mathbf{C}(t-3\tau) - 0.0056 \cdot \mathbf{Te}(t-3\tau) + 0.0012 \cdot \mathbf{Te}(t-4\tau) + - 0.0077 \cdot \mathbf{Te}(t-5\tau) + 0.0037 \cdot \mathbf{Te}(t-6\tau) - 0.1120 \cdot 10^{-3} \cdot \mathbf{I}(t-3\tau)$

Once the model was identified, a series of simulations were carried out, with the data of the typical days before mentioned (Table 2). By applying the identified model to the two components, parameter R was obtained, as index of the energy saving that could be obtained with the innovative system compared with the reference one. Table 4 reports the results.

Table 4: The obtained results.

Typical day	**1**	**2**	**3**	**4**	**5**	**6**
R (%)	46	36	35	31	44	47

The attainable energy saving is proportional to the solar radiation; in fact in the first three typical days an energy saving of about 35% up to 46% was estimated; in the 4th day with a very low solar radiation, which does not allow the characteristic dynamics of the tested component trigger, the obtainable energy saving is lower.
The application of the model, carried out considering the 1st, 5th and 6th typical days, has instead underlined that the energy saving of the system does not seem to depend in a meaningful way on the external temperature.
The analysis made through the application of the mathematical model confirmed what resulted from the experimental tests, that is a meaningful energy contribution of the studied system even under not particularly meaningful conditions of solar radiation. In fact from the experimental data a 40% saving in terms of energy contribution was obtained, a result which is close to the one calculated through the models.

CONCLUSIONS

Firstly, it must be underlined how System Identification techniques can contribute in analysing complex systems like the envelope components described without having to formalise an “exact” physical-technical description of the energy flows that develop thanks to the operation of the dynamic systems itself.
Furthermore, there is the chance to use the identified analytical systems to make predictions, to be combined with regulation fuzzy logic to control the components’ operation. The analytical model would therefore be periodically identified as the data related to the variables chosen as input are collected.
If the system presents particularly complicated nonlinearities, that can be neither schematized with the analysed dynamic systems nor formalized from the physical point of view, other kinds of parametric models have to be considered. Among these models, Artificial Neural Networks (ANN) could be a solution, as more structured, self-learning analytical black-box models.