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Dynamic thermal characteristics of opaque building components. A proposal for the extension of EN ISO 13786

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Abstract

In order to dynamically characterise the opaque components of a building envelope subject to sinusoidal loadings in steady periodic regime conditions, the use of nondimensional periodic thermal transmittance is proposed. Such a parameter allows for the evaluation of the decrement factor and time lag that the heat flux undergoes while crossing the wall and the efficiency of the heat storage. For non-sinusoidal loadings, dynamic characterisation is obtained by the decrement factor, defined as the ratio between energy in a semi period entering the indoor environment and entering the wall and as the ratio between maximum heat fluxes entering the environment and the wall, and as the ratio between the minimum heat fluxes. These parameters allow to determine the heat storage capacity of the component, the maximum heat flux in summer and winter conditions and their time lags. The defined dynamic properties were calculated considering two commonly used walls and surrounding conditions that are representative of the effective operative conditions.

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Keywords: steady periodic regime, harmonic method, building wall, time lag, decrement factor

1. Introduction

The dynamic characterization of a building component is obtained through parameters that identify its behaviour when it is subjected to loadings that are variable in time. The reference Standard is EN ISO 13786 [1], which considers a steady periodic regime as the thermal regime, realized by means of a sinusoidal oscillation of temperature or heat flux on one or both of the component faces. The formulation in matrix terms of the thermal exchange between the indoor and outdoor environment, presents the clear advantage of creating relations for the calculation of periodic thermal transmittances, that consent the evaluation of the decrement factor and the time lag, of the periodic thermal

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Nomenclature

C	steady areal heat capacity [J/(m^2 K)]
G	specific air flow rate [kg/(m^2 s)]
h	heat transfer coefficient [W/(m^2 K)]
t	time [s]
U	steady thermal transmittance [W/(m^2 K)]
α	absorption coefficient [-]

admittances and of the areal thermal capacities.

In the recent literature, the study of the dynamic thermal properties of walls has been the subject of increasing interest. Numerous studies have been conducted for multilayered walls in a periodic regime in order to evaluate the influence of the thermophysical properties of the materials, of their position in the stratigraphy, of the orientation of the wall, of the external surface optical properties, of the humidity, of the natural ventilation heat flux and of the thickness of the insulating layer on the decrement factor and time lag [2-5]. In general, such parameters are evaluated with reference to temperature oscillations on both the internal and external side of the wall using numerical techniques to solve the analytical equations. In these studies, the determination of the dynamic thermal properties is carried out simplifying the real loading trends or by not considering the contemporaneous presence of the internal and external loadings. In the studies conducted, the outdoor environment is schematised, at times, using a sinusoidal oscillation of external air temperature, or of sol-air temperature. In such conditions, the dynamic behaviour of the walls depends exclusively on the geometry and thermophysical properties of the layers. Many others, in order to take into consideration the non-sinusoidal trend of the response propose more parameters, in terms of decrement factor and time lag, for dynamic characterisation. In particular, Sun et al. [6] correlate the dynamic properties to the Increasing Stage (IS) of the external loading. If reference is made to the real trend of the loadings, the dynamic parameters strongly depend on the considered loadings. Gasparella et al. [7] proposed corrections to the periodic thermal transmittance in order to evaluate the decrement factor and the time lag of a wall subjected to the action of the sol-air temperature. Oliveti et al. [8] introduced nondimensional periodic thermal transmittance to evaluate decrement factor and time lag that the heat flux undergoes in crossing the wall when the real trends of absorbed solar radiation, of the external air and of the sky temperature act contemporaneously. In all the conducted studies, the presence of radiant loadings on the internal surface and of convective heat fluxes due to the presence of sources and due to the ventilation, is not considered. Currently, the response of a wall to the single action of a periodic internal radiant loading is evaluated by the surface factor [9] while the periodic heat admittance is used to evaluate the convective heat flux produced on the same surface by the periodic variation of the internal air temperature. The dynamic parameters are greatly influenced by the loadings that operate within the environment and it is necessary to consider both the internal and external loadings in order to correctly identify them.

In this work the dynamic characterisation of the opaque components, subject to sinusoidal loading, is rendered more general through the use of nondimensional periodic thermal transmittance defined as the ratio between the heat flux entering the environment and the conductive heat flux that penetrates the wall at the interface with the outdoor environment. Heat flux use is present in the literature and has been used by Jin et al. [10] for the dynamic study of walls through a finite difference method. The heat flow across the wall causes oscillations of the internal air temperature and is directly related to the cooling/heating load and to the thermal comfort of the cavity.

In sinusoidal conditions, the nondimensional periodic thermal transmittance allows to determine the decrement factor and time lag that the heat flux is subjected to in crossing the wall and the instantaneous capacity of heat storage [7]. The heat fluxes are evaluated considering the external surface as subject to the simultaneous action of the external air temperature, of the absorbed solar radiation and of the apparent sky temperature. Indoors, the surrounding conditions are of continuous heating or cooling regime, or with nocturnal attenuation, with surface heat exchange evaluated by means of surface heat transfer coefficient. Any contributions due to short wave absorbed radiative heat flux, in part generated by the solar radiation that enters through the glazed surfaces, and also due to ventilation air flow rate, as well as to internal convective heat fluxes due to sources, are considered.

The dynamic characterisation for loadings that do not have a sinusoidal trend, due to the different tasks that the wall executes, is obtained using several parameters. The decrement factor is calculated as the ratio between energy in a semi period entering the indoor environment and penetrating the wall, to evaluate the thermal storage capacity of the wall, and as a ratio of heat fluxes, considering the maximum and minimum peaks in a period. The decrement factors of the maximum and minimum heat flux peak, the relative time lag, and the steady heat flux values allow for the identification of maximum thermal loads that are transferred in the wall in both winter and summer conditions. Time lags are calculated with reference to the maximum and minimum heat flux peaks. We used the methodology created for the calculation of the dynamic parameters of some walls subject to real surrounding conditions on the external surface, and indoor continuous air-conditioning conditions and with nocturnal attenuation, in the absence and presence of a shortwave radiative heat flux absorbed on the internal surface.

2. Methodology

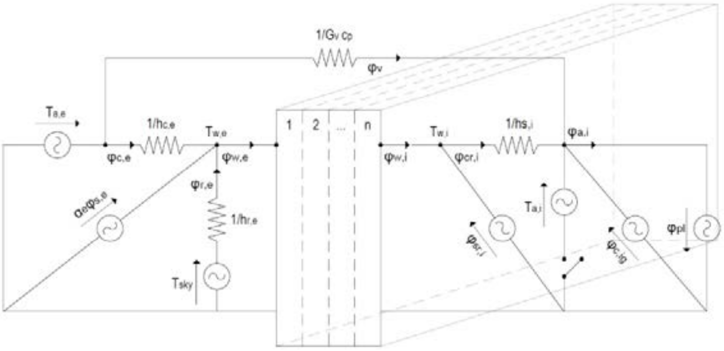

Figure 1. Equivalent electrical circuit of a multilayer wall subject to external loadings air temperature $\widehat{T}_{a,e}$, apparent sky temperature $\widehat{T}_{sky}$, absorbed solar radiation $\alpha_e\widehat{\varphi}_{s,e}$, and the internal loadings, namely air temperature $\widehat{T}_{a,i}$, shortwave radiative heat flux $\widehat{\varphi}_{sr,i}$, ventilation heat flux $\widehat{\varphi}_v$, convective heat flux due to sources $\widehat{\varphi}_{c,ig}$, and convective heat flux supplied by the plant $\widehat{\varphi}_{pl}$.

The wall subject to the joint action of the external and internal loadings was schematized with the equivalent electrical circuit in Figure 1, that refers to the sinusoidal periodic regime, which was resolved with the method of superimposition of causes and effects. In the hypothesis that a thermal quantity $f(t)$ is periodic, it can be expressed, in an analytical form, through a Fourier series expansion:

$$f(t) = \bar{f} + \sum_{k=1}^{n} |f_k| \mathrm{sen}(k\omega t + \psi_k) \tag{1}$$

In which $\bar{f}$ represents the mean value, $|f|$ the amplitude, ω the pulsation, ψ the argument of the k-th harmonic and n the number of harmonics. With reference to a generic harmonic, represented by means of the associated complex phasor, the equations of external and internal surface balance and the transfer matrix $[Z]$ from surface to surface of the component, determined according to the EN ISO 13786 standard, leads to the matrix expression linking the temperature oscillating $\widehat{T}_{a,i}$ and the heat flux $\widehat{\varphi}_{a,i}$ in the indoor environment with the external loadings $\widehat{T}_{sky}$, $\widehat{T}_{a,e}$ and $\alpha_e\widehat{\varphi}_{s,e}$ and with the internal loadings $\widehat{\varphi}_{sr,i}$, $\widehat{\varphi}_v$ and $\widehat{\varphi}_{c,ig}$:

$$\begin{aligned}
\begin{bmatrix} \widehat{T}_{a,i} \\ \widehat{\varphi}_{a,i} \end{bmatrix} &= \begin{bmatrix} 1 & -\dfrac{1}{h_i} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \left\{ \begin{bmatrix} \dfrac{h_{r,e}}{h_{r,e}+h_{c,e}} & \dfrac{h_{c,e}}{h_{r,e}+h_{c,e}} & -\dfrac{1}{h_{r,e}+h_{c,e}} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \widehat{T}_{sky} \\ \widehat{T}_{a,e} \\ \widehat{\varphi}_e \end{bmatrix} + \begin{bmatrix} \dfrac{\alpha_e\widehat{\varphi}_{s,e}}{h_{r,e}+h_{c,e}} \\ 0 \end{bmatrix} \right\} + \begin{bmatrix} -\dfrac{\widehat{\varphi}_{sr,i}}{h_i} \\ \alpha_i\widehat{\varphi}_{s,i} + \widehat{\varphi}_v + \widehat{\varphi}_{c,ig} \end{bmatrix} \\
&= \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \end{bmatrix} \begin{bmatrix} \widehat{T}_{sky} \\ \widehat{T}_{a,e} \\ \widehat{\varphi}_e \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} \dfrac{\alpha_e\widehat{\varphi}_{s,e}}{h_{r,e}+h_{c,e}} \\ 0 \end{bmatrix} + \begin{bmatrix} -\dfrac{\widehat{\varphi}_{sr,i}}{h_i} \\ \widehat{\varphi}_{sr,i} + \widehat{\varphi}_v + \widehat{\varphi}_{c,ig} \end{bmatrix}
\end{aligned} \tag{2}$$

In the preceding relation, $\widehat{\varphi}_{e}$ is the heat flux that penetrates the wall at the interface with the outdoor environment, obtained through the thermal balance equation on the external surface. Matrix [A] represents the product between the internal surface heat transfer matrix, the heat transfer matrix of the wall and the external surface heat transfer matrix; [B] is the product of the first two. By substituting the expression of $\widehat{\varphi}_{e}$ in system of equations (2), obtaining from the first equation of the system $\widehat{T}_{w,e}$ and substituting the latter in the second equation of the system, we obtain the relation linking the heat flux that is ceded to the internal air to the internal and external loadings:

$$\widehat{\varphi}_{a,i} = \left(-\frac{h_{r,e}}{h_{r,e}+h_{c,e}}\frac{1}{A_{13}}\right)\widehat{T}_{sky} + \left(-\frac{h_{c,e}}{h_{r,e}+h_{c,e}}\frac{1}{A_{13}} + G_v c_p\right)\widehat{T}_{a,e} + \left(-\frac{h_{r,e}}{h_{r,e}+h_{c,e}}\frac{1}{A_{13}}\right)\alpha_e\widehat{\varphi}_{s,e} + \left(1+\frac{A_{23}}{A_{13}h_i}\right)\widehat{\varphi}_{sr,i} + \left(\frac{A_{23}}{A_{13}} - G_v c_p\right)\widehat{T}_{a,i} + \widehat{\varphi}_{c,ig} \tag{3}$$

The expression of the heat flux that penetrates the wall from the external side is obtained by substituting $\widehat{T}_{w,e}$ in the external surface balance equation:

$$\widehat{\varphi}_{e} = \left(-\frac{A_{11}}{A_{13}}\right)\widehat{T}_{sky} + \left(-\frac{A_{12}}{A_{13}}\right)\widehat{T}_{a,e} + \left(-\frac{1}{\left(h_{r,e}+h_{c,e}\right)}\frac{B_{11}}{A_{13}}\right)\alpha_e\widehat{\varphi}_{s,e} + \left(\frac{1}{A_{13}h_i}\right)\widehat{\varphi}_{sr,i} + \left(\frac{1}{A_{13}}\right)\widehat{T}_{a,i} \tag{4}$$

The difference between the oscillating heat flux entering the wall (Eq. 4) and the heat flux transferred to the internal air (Eq. 3) gives the variation of the internal energy of the wall per unit time $\Delta\widehat{U}$. The generic complex parameter Y, that multiplies the loadings in the Eqs. (3) and (4), provides the contribution, in amplitude and argument, to the calculation of heat flux $\widehat{\varphi}_{e}$ or $\widehat{\varphi}_{a,i}$ or of the variation of internal energy $\Delta\widehat{U}$ per unit time, consequent to the unitary periodic variation of the relative internal or external loading. Once the phasors associated with the thermal quantities for each harmonic have been calculated, it is necessary to return them to the time domain for the successive composition of the harmonics. The total fluctuating component of a thermal quantity is obtained by adding the oscillating contributions, of different pulsations, of the single phasors. The effective trend of the thermal quantity is obtained by adding the relative steady component to the total fluctuating component.

3. Dynamic characterization of the wall with sinusoidal loadings

The contemporaneous presence of several temperature and heat flux loadings on the external and internal surfaces, differing from the schematisation provided for by EN ISO 13786, requires the use of heat fluxes entering and exiting the wall, expressed by means of Eqs. (3) and (4), for dynamic characterisation. With reference to a generic harmonic k, when the heat flux penetrates from the outdoor towards the indoor environment, the ratio between the internal heat flux and the external heat flux is the external side nondimensional periodic thermal transmittance:

$$\tau_{ei} = \frac{\widehat{\varphi}_{a,i}}{\widehat{\varphi}_{e}} = \frac{Y^{i}_{sky}\widehat{T}_{sky} + Y^{i}_{a,e}\widehat{T}_{a,e} + Y^{i}_{s,e}\alpha_e\widehat{\varphi}_{s,e} + Y^{i}_{s,i}\widehat{\varphi}_{sr,i} + Y^{i}_{a,i}\widehat{T}_{a,i} + \widehat{\varphi}_{c,ig}}{Y^{e}_{sky}\widehat{T}_{sky} + Y^{e}_{a,e}\widehat{T}_{a,e} + Y^{e}_{s,e}\alpha_e\widehat{\varphi}_{s,e} + Y^{e}_{s,i}\widehat{\varphi}_{sr,i} + Y^{e}_{a,i}\widehat{T}_{a,i}} \tag{5}$$

Such a parameter, in addition to depending on the complex Y parameters, which are a function of the thermophysical properties, of the internal and external surface heat transfer coefficient and of the oscillating period, also depends on the loadings. In the particular case of constant internal air temperature, when the internal radiant $\widehat{\varphi}_{sr,i}$ and convective $\widehat{\varphi}_{c,ig}$ fluctuating contributions are equal to zero, and in absence of ventilation heat flux, transmittance τ_{ei} is reduced to the ratio between the periodic thermal transmittance and the external side periodic thermal admittance calculated according to EN ISO 13786 [8]. Parameter τ_{ei} is a phasor and allows for the definition of decrement factor $f_{ei} = |\tau_{ei}|$ and time lag $\Delta t_{ei} = (T/2\pi)\arg(\tau_{ei})$ that undergoes the external heat flux $\widehat{\varphi}_{e}$, associated with the generic harmonic, in crossing the wall. Being sinusoidal quantities, f_{ei} describes both the attenuation undergone by the energy entering the wall in a semi period and that which the maximum and minimum heat flux peaks undergoes. Similarly, the time lag Δt_{ei} represents the time lag both between the maximum heat flux peaks and between the minimum peaks. The ratio between the energy stored per unit time and the external heat flux entering the wall defines the external side periodic thermal storage efficiency $\varepsilon_{ei} = \Delta\widehat{U}/\widehat{\varphi} = 1 - \tau_{ei}$ [8]. In the case of transfer from the indoor to the outdoor environment, the internal side nondimensional periodic thermal transmittance is calculated as the ratio between the external heat flux and the internal heat flux.

4. Dynamic characterization of the wall with non-sinusoidal loadings

In the presence of non-sinusoidal loadings, the global nondimensional periodic thermal transmittance $\boldsymbol{\tau_{G,ei}}$ (Eq. 5) are not phasor and cannot be used to define the global attenuation of the heat flux that enters the wall and the global time lag between the internal heat flux and the external heat flux. The identification of the dynamic behaviour of the wall is obtained using several dynamic parameters, with the aim of dynamically characterising the wall in energy terms and in terms of heat flux. The decrement factor, in terms of energy, is defined as the ratio between the energy in a semi period entering and exiting the wall, and in terms of heat flux, as the ratio between the maximum heat flux peaks entering the environment and entering the wall, and as the ratio between the minimum heat flux peaks. In terms of heat flux, it is necessary to consider both the decrement factor of the maximum peak and of the minimum peak in order to identify, according to the direction of the stationary, the heat flux peak in summer conditions and in winter conditions. In formulae:

$$f_{g,ei} = \frac{\int_0^P \left|\sum_{k=1}^{n} \widetilde{\varphi}_{i,k}\right| dt}{\int_0^P \left|\sum_{k=1}^{n} \widetilde{\varphi}_{e,k}\right| dt} \quad (6a) \qquad f_{g,ei}^{max} = \frac{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{i,k}\right)_{max}}{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{e,k}\right)_{max}} \quad (6b) \qquad f_{g,ei}^{min} = \frac{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{i,k}\right)_{min}}{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{e,k}\right)_{min}} \quad (6c)$$

The time lag of the maximum and minimum heat flux peaks, that intervene respectively in the summer and winter behaviour of the wall, are defined by the relations:

$$\Delta t_{g,ei}^{max} = t_{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{i,k}\right)_{max}} - t_{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{e,k}\right)_{max}} \quad (7a) \qquad \Delta t_{g,ei}^{min} = t_{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{i,k}\right)_{min}} - t_{\left(\sum_{k=1}^{n} \widetilde{\varphi}_{e,k}\right)_{min}} \quad (7b)$$

Similar relations can be obtained referring to the internal side. The calculation of the preceding parameter values requires the use of all the harmonics. A sufficiently accurate calculation can be obtained considering a limited number of harmonics for the evaluation of the internal heat flux and the external heat flux.

5. Application of the calculation procedure

The hourly climatic data were generated with Trnsys 17 software [11] and used to define the day type through monthly average hourly values. The dynamic parameters were calculated considering a brick wall (U=0.95 W/(m^2K); C=971.2 kJ/(m^2K)) and a hollow wall (U=0.67 W/(m^2K); C=328 kJ/(m^2K)), with southern orientations and with different stratigraphy and thermophysical properties situated in Turin (TO) and Cosenza (CS). The case of the south facing vertical wall is of great interest since the incident solar radiation in the heating period is greater than that in the cooling period. Externally, the loadings considered were obtained through a Fourier series expansion starting from monthly average hourly values of the external air temperature, of the apparent sky temperature and of the absorbed incident solar radiation. Inside, we considered two surrounding conditions corresponding to winter heating and summer cooling in both continuous regime (cont) and with nocturnal attenuation (att), in absence (abs) and in presence (pre) of short wave radiant contributions on the internal surface. In the calculation of the internal surface radiant load, the contribution of solar radiation and light sources was taken into consideration. Internal convective heat fluxes due to sources and to ventilation were not considered since they not depend on the wall dynamic properties. The monthly values of the decrement factors and time lags, calculated with Eqs. (6a), (6b) and (6c) and (7a) and (7b), for walls 1 and 2, are summarized through the respective average values in summer and in winter. Overall, 16 heat exchange configurations were considered. The average values in summer of the decrement factor of the maximum heat flux peaks as a function of the relative time lag are reported in Figure 2a. Figure 2b reports the average values in winter of the decrement factor of the minimum heat flux peaks as a function of the relative time lag. Figure 2c shows the values of the decrement factors defined in energy terms in winter and summer.

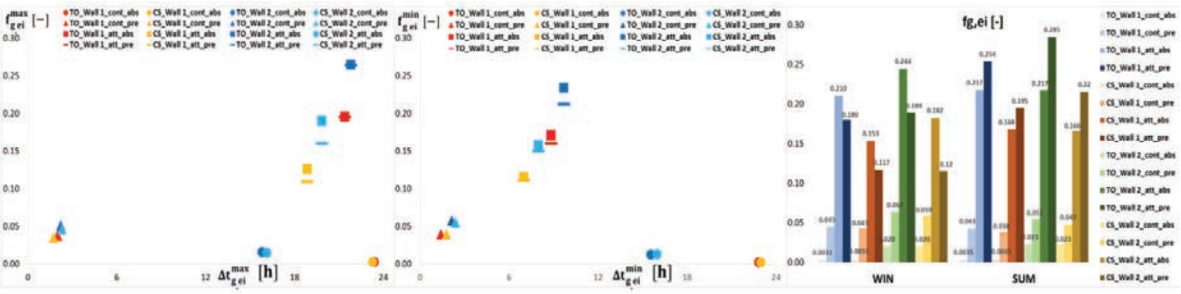

Figure 2. Decrement factors and time lags in continuous regime and with nocturnal attenuation, in the absence and presence of internal radiant loads for walls 1 and 2 in Turin and Cosenza a) Average values in summer of the decrement factor of the maximum heat flux peak $f_{g,ei}^{max}$ as a function of the maximum heat flux peak time lag $\Delta t_{g,ei}^{max}$; b) Average values in winter of the decrement factor of the minimum heat flux peak $f_{g,ei}^{min}$ as a function of the minimum heat flux peak time lag $\Delta t_{g,ei}^{min}$; c) Average values in winter and in summer of the energy decrement factor $f_{g,ei}$.

These results offer the possibility of distinguishing the behaviour of the wall in summer and winter in relation to the air-conditioning regime and to the considered surrounding conditions.

6. Conclusion

In sinusoidal conditions, the dynamic characterisation of the walls can be improved using nondimensional periodic thermal transmittance that describes the behaviour of the wall taking into account several internal and external loadings of different amplitudes. Such a parameter, defined by means of the heat flux which is transferred through the wall, allows the determination of all the dynamic characteristics. In non-sinusoidal periodic conditions, the proposed decrement factors and time lags describe dynamic behaviour in relation to the real trend of the internal and external loadings and furthermore allow for a distinction to be made between summer and winter. The best value of the dynamic thermal characteristics of the wall depend on the type (office or residential) and operation (continuous or intermittent) of the building zone, on the desired indoor temperature level as well as the temperature swings tolerance, on effects of ventilation heat flux and internal convective heat fluxes due to sources, on the presence or absence of air-conditioning units, on the existing glazing surface (extension and type) and on the surrounding outdoor environment.

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