A METHOD TO VERIFY CALCULATION OF TRANSIENT HEAT CONDUCTION THROUGH MULTILAYER BUILDING CONSTRUCTIONS

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ABSTRACT

Validation and verification of building simulation programs and load calculation programs is of continuing interest. Dynamic thermal behavior data, including conduction transfer function (CTF) coefficients, thermal response factors and periodic response factors, are used to calculate transient heat conduction through building constructions. Computational inaccuracy sometimes occurs in calculating CTF coefficients and response factors. In this paper, a method for verification of the CTF coefficients and response factors over the whole frequency range is introduced. This method is based on the equivalence of dynamic models for a linear system and the frequency characteristics of building transient heat transfer models. Polar diagrams and error criteria are proposed to verify the CTF coefficients and response factors. Some examples are given to demonstrate the methodology.

INTRODUCTION

Conduction heat transfer through the building envelope is one of the principal components of space cooling/heating loads and energy requirements. Models for transient heat transfer through building constructions are important parts of building energy and HVAC system simulation programs. In current building simulation programs such as DOE-2, TRNSYS and EnergyPlus (Crawley et al., 2001; Strand et al., 2001), as well as space cooling load calculations (ASHRAE 2001), the dynamic thermal behavior data of building constructions including thermal response factors, conduction transfer function (CTF) coefficients or periodic response factors are calculated by various algorithms, and then utilized in conjunction with weather data to calculate the heat flow through the constructions. The accuracy of the dynamic thermal behavior data directly affects the accuracy of the building load and/or energy calculations.

Various methods, such as the direct root-finding method (Stephenson and Mitalas, 1971; Hittle and Bishop, 1983), Seem's method (Seem et al, 1989), finite difference method (Burch et al., 1992), state space method (SSM) (Jiang, 1982), time-domain method (TDM) (Davies, 1997) and frequency-domain regression (FDR) method (Wang and Chen, 2003) may be employed to calculate the dynamic thermal behavior data in building simulation programs. However, there are various potential factors such as too big of an iteration step, low calculation precision, unconverged computational results, the limitation of calculation methods, etc., which may lead to incorrect results in calculating the dynamic thermal behavior data. In the direct root-finding method, for an example, there are risks to miss several roots in numerically searching, especially in case where two adjacent roots are close together. This may lead to incorrect results (Hittle and Bishop, 1983). As pointed out by Spitler and Fisher (1999), computational inaccuracy sometimes occurs in calculating the dynamic thermal behavior data. Therefore, the accuracy and reliability of the dynamic thermal behavior data should be verified after they are worked out.

For whole building energy simulation programs, analytical verification tests have been developed for the fabric heat conduction models (Rees, et al., 2002; Bland, 1992). Steady-state conduction tests are designed to find the response to a steady difference in dry-bulb temperature between the inside and the outside surfaces a building wall or roof with significant thermal resistance and a multilayer construction. Transient conduction test cases have been developed to test the response to either step changes in the driving external dry-bulb temperature or sinusoidal external boundary conditions, while holding the inside dry-bulb temperature is held constant. The sinusoidal boundary condition test only checks the response at a single frequency. The work described in this paper tests the response over a range of frequencies.

A conventional verification check for the dynamic thermal behavior data is to check whether or not they give the correct heat transfer in steady-state. For CTF coefficients,

$$\sum_{k=0} a_k \Big/ \sum_{k=0} d_k = \sum_{k=0} c_k \Big/ \sum_{k=0} d_k = \sum_{k=0} b_k \Big/ \sum_{k=0} d_k = U \qquad (1)$$

For thermal response factors,

$$\sum_{j=0}^{\infty} X(j) = \sum_{j=0}^{\infty} Y(j) = \sum_{j=0}^{\infty} Z(j) = U \quad (2)$$

For periodic response factors,

$$\sum_{j=0}^{23} X_P(j) = \sum_{j=0}^{23} Y_P(j) = \sum_{j=0}^{23} Z_P(j) = U \quad (3)$$

The above relationships are valid for the case when frequency $\omega = 0$, but do not address the accuracy for dynamic thermal behavior.

Weather data can be expressed in the form of summation of the mean value signal ($\omega = 0$) and sinusoidal excitation signals of various frequencies through Fourier expansion. As equations (1)-(3) only cover the case where $\omega = 0$, it is highly desirable to have a method for checking the entire range of frequency response.

In this paper, a method for verification of dynamic thermal behavior data within the entire range of frequency response, based on the equivalence of dynamic models and the frequency characteristics of linear systems, is presented.

THEORY AND METHODOLOGY

Equivalence of dynamic models for a linear system

The dynamic behavior of a linear system can be described by various dynamic models, such as differential equations, *s*-transfer functions, *z*-transfer functions, state-space models, etc. The differential equation of a linear system can be transformed into *s*-transfer function or state-space model by applying Laplace transforms. On the other hand, the frequency characteristics of a linear system can be used to measure the equivalence among the various dynamic models describing the system. Therefore, if the frequency characteristics of a linear system can be obtained accurately and the frequency characteristics of various dynamic models for the system can also be worked out, the equivalence between the frequency characteristics of the system and its dynamic models can be employed to evaluate the correctness of the dynamic models. The polar diagrams for a linear system, i.e., the curve depicting the frequency characteristics of the system, can be used as visual aids to judge whether or not the dynamic models are consistent with the described system.

Transmission matrix of heat conduction through a multilayer construction

The transmission matrix of transient heat conduction through a multilayer construction has in detail been described in previous papers (Wang and Chen, 2003; Chen, 2000, 2001). Most building walls consist of more than three layers, including the surface air films[1] on both sides. The heat conduction through a building construction can be regarded as a one-dimensional and isothermal process, and each layer of the building construction as homogeneous and isotropic. Considering a solid construction with *n* layers, the relationship between the temperature and the heat flow on both sides can be expressed as equation (4).

$$\begin{bmatrix} T_i(s) \\ q_i(s) \end{bmatrix} = \begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} \begin{bmatrix} T_o(s) \\ q_o(s) \end{bmatrix}, \quad (4)$$

where, $T(s)$ and $q(s)$ are the Laplace transforms of temperature and heat flow, respectively. Subscripts i and o indicate the inside and outside surfaces of the construction, respectively. The matrix $\begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix}$ is the total transmission matrix, which is the product of the transmission matrices of all layers, including the surface air films on both sides, as shown in equation (5).

$$\begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} = \begin{bmatrix} A_i(s) & B_i(s) \\ C_i(s) & D_i(s) \end{bmatrix} \begin{bmatrix} A_1(s) & B_1(s) \\ C_1(s) & D_1(s) \end{bmatrix} \cdots \begin{bmatrix} A_n(s) & B_n(s) \\ C_n(s) & D_n(s) \end{bmatrix} \begin{bmatrix} A_o(s) & B_o(s) \\ C_o(s) & D_o(s) \end{bmatrix}, \quad (5)$$

where, $\begin{bmatrix} A_k(s) & B_k(s) \\ C_k(s) & D_k(s) \end{bmatrix}$ ($k = 1, 2, \cdots, n$) is the transmission matrix of the k^{th} solid layer. The elements of the transmission matrix of the k^{th} layer can be given in the hyperbolic functions of Laplace variable .

$$A_k = D_k = \cosh(L_k \sqrt{s/a_{mk}}) \quad (6)$$

$$B_k = -R_k \sinh(L_k \sqrt{s/a_{mk}}) \big/ (L_k \sqrt{s/a_{mk}}) \quad (7)$$

$$C_k = -L_k \sqrt{s/a_{mk}} \sinh(L_k \sqrt{s/a_{mk}}) \big/ R_k, \quad (8)$$

where L, R and a_m ($= \lambda/\rho C_P$) are the thickness, thermal resistance and thermal diffusivity of the corresponding layer, respectively. λ, ρ and C_P are thermal conductivity, density and specific heat, respectively.

The total transmission matrix can be rearranged to express the surface heat flows as response and the surface temperature as excitation:

$$\begin{bmatrix} q_o(s) \\ q_i(s) \end{bmatrix} = \begin{bmatrix} -G_X(s) & G_Y(s) \\ -G_Y(s) & G_Z(s) \end{bmatrix} \begin{bmatrix} T_o(s) \\ T_i(s) \end{bmatrix} = \begin{bmatrix} -A(s)/B(s) & 1/B(s) \\ -1/B(s) & D(s)/B(s) \end{bmatrix} \begin{bmatrix} T_o(s) \\ T_i(s) \end{bmatrix} \quad (9)$$

where, $G_X(s)$, $G_Y(s)$ and $G_Z(s)$ are the transfer functions of the outside, across and inside heat conduction of the construction, respectively. These transfer functions characterize the dynamic thermal behavior of the construction.

[1] The surface air films may or may not be included in the dynamic thermal behavior data. In the case of the heat balance method, they are not. In the case of the transfer function method and the radiant time series method, they are.

Theoretical frequency characteristics of a multilayer construction

The matrix elements $A(s)/B(s)$, $1/B(s)$ and $D(s)/B(s)$ are the transfer functions of outside, across and inside heat conduction of a multilayer construction, respectively. They are all complicated transcendental hyperbolic functions, especially for the construction of more than two layers. Substituting $j\omega$ ($j=\sqrt{-1}$) for s into equation (9), one can obtain the complex functions $G_X(j\omega)$, $G_Y(j\omega)$ and $G_Z(j\omega)$, which are called the theoretical frequency characteristics of outside, across and inside heat conduction, respectively, and describes the dynamic thermal behavior of the construction. They are all denoted as $G(j\omega)$. These frequency characteristics are complex functions and are generally characterized by their amplitude $\psi(\omega)=|G(j\omega)|$, which is the absolute value of $G(j\omega)$ and phase lag, $\phi(\omega)=\arctan\dfrac{imag(G(j\omega))}{real(G(j\omega))}$, where $real(G(j\omega))$ and $imag(G(j\omega))$ are the real and imaginary components of $G(j\omega)$, respectively. When $\omega=0$, $\psi(0)=|G(0)|=U$, where U is the thermal transmittance or U-factor of the construction.

In practice, if the thermal and geometric properties of materials in each layer are given, it is easy to obtain exactly the three theoretical frequency characteristics by applying matrix multiplication in the frequency domain. The calculation approach is as follows. At first, the matrix elements for each layer of the multilayer construction are calculated at N frequency points ($s_k=j\omega_k$, $k=1,2,\cdots,N$) by equations (6)–(8). Secondly, the total transmission matrix at each frequency point is obtained by applying matrix multiplication as in equation (5). Finally, the three frequency characteristics with N frequency points are established using equation (9). And the polar curve $G(j\omega)$ can be plotted on polar diagram for showing the transient heat conduction characteristics of the calculated construction.

In short, the set of amplitudes and phase lags developed with this procedure may be compared graphically to those determined with CTF coefficients, thermal response factors, or periodic response factors, as discussed in the next section. For internal quality assurance purposes, it is desirable to have a quantitative, non-graphical comparison. A criterion for these purposes is proposed in the subsequent section.

FREQUENCY CHARACTERISTICS OF MODELS BASED ON DYNAMIC THERMAL BEHAVIOR DATA

In this section, procedures for obtaining the amplitude and phase lag characteristics from each type of thermal behavior data -- CTF coefficients, thermal response factors, and periodic response factors – are given.

CTF coefficients

Here, the conduction transfer function of across heat conduction through a construction is taken as an example to discuss. If the CTF coefficients for a building construction are worked out by a computational method as b_0, b_1, b_2, …; d_0, d_1, d_2,…, then the conduction transfer function can be expressed in a ratio of two polynomials of z^{-1} as follows.

$$\tilde{G}_Y(z)=\frac{b_0+b_1z^{-1}+b_2z^{-2}+\cdots}{d_0+d_1z^{-1}+d_2z^{-2}+\cdots}, \qquad (10)$$

where z is unit time delay operator, $z=e^{s\Delta\tau}$; s is Laplace variable, $\Delta\tau$ is the time interval of discretization (generally, for transient heat conduction calculation of building constructions, $\Delta\tau=3600$ seconds).

Substituting $e^{j\omega\,\Delta\tau}$ for z into equation (10), $\tilde{G}_Y(\omega)$ gives the frequency characteristics of the conduction transfer function -- its amplitude $\tilde{\psi}(\omega)=|\tilde{G}_Y(j\omega)|$, and phase lag, $\tilde{\phi}(\omega)=\arctan\dfrac{imag(\tilde{G}_Y(j\omega))}{real(\tilde{G}_Y(j\omega))}$. For N frequency points ($z_k=e^{j\omega_k\Delta\tau}, k=1,2,\cdots,N$), the polar curve $\tilde{G}_Y(\omega)$ can be plotted together with the theoretical frequency characteristics of the construction on polar diagram. The agreement of the polar curves between the theoretical and conduction transfer function's frequency characteristics provides an intuitive judgment for the correctness of the CTF coefficients.

The procedure to verify the CTF coefficients of external and internal heat conduction for the construction is exactly the same as described above. Also, for the case when the frequency variable $\omega=0$, equation (10), i.e., when $z=e^{j\omega\Delta\tau}=1$, $\tilde{\psi}(0)=\tilde{G}_Y(1)=\sum_{k=0}b_k\Big/\sum_{k=0}d_k$. In other words, $\sum_{k=0}b_k\Big/\sum_{k=0}d_k=U$ as given in Equation (1). This check is therefore applicable to the case at the frequency point of $\omega=0$, but not to the frequency range of $\omega>0$.

Thermal response factors

The thermal response factors for a building construction are the time series of heat flow through the construction under the excitation of a unit triangular temperature pulse input. The response factor series can also be expressed in the form of a *z*-transfer function model. The ratio of the

Z-transform for the obtained thermal response factors, $Y(k)$ ($k = 0,1,2,\cdots$) to that of a unit triangular temperature pulse excitation is another form of z-transfer function for the building construction as equation (13), which is the z-transfer function based on thermal response factors.

$$\hat{G}_Y(z) = \frac{Z[Y(k)]}{Z[\theta(\tau)]} = \frac{\sum_{k=0}^{\infty} Y(k) z^{-k}}{1} = \sum_{k=0}^{\infty} Y(k) z^{-k} \quad (13)$$

Substituting $e^{j\omega\Delta\tau}$ for z into equation (13), $\hat{G}_Y(\omega)$ gives the frequency characteristics of the z-transfer function based on the cross thermal response factors. Its amplitude is $\tilde{\psi}(\omega) = \left|\hat{G}_Y(j\omega)\right|$, and phase lag is $\tilde{\phi}(\omega) = \arctan\frac{imag(\hat{G}_Y(j\omega))}{real(\hat{G}_Y(j\omega))}$. For N frequency points ($z_k = e^{j\omega_k\Delta\tau}$, $k = 1,2,\cdots,N$), the polar curve $\hat{G}_Y(\omega)$ can be plotted together with the theoretical frequency characteristics of the construction on polar diagram. Again, this gives some intuitive judgment as to the correctness of the thermal response factors.

The procedure to verify the thermal response factors X and Z of external and internal heat conduction through a construction is exactly the same as above. According to equation (13), when the frequency variable $\omega = 0$, i.e., when $z = e^{j\omega\Delta\tau}$ =1, $\tilde{\psi}(0) = \hat{G}_Y(1) = \sum_{j=0}^{\infty} Y(j)$. This is equivalent to Equation (2).

Periodic response factors

The periodic response factors are easily worked out from the thermal response factors and the CTF coefficients of a building construction through simple calculation (Spitler, et al. 1997; Spitler and Fisher, 1999; Chen and Wang, 2005). If the thermal response factors and the CTF coefficients of a construction can be obtained and their accuracy can be assured by the above verifying method, then the periodic response factors obtained from the thermal response factors and z-transfer coefficients are surely correct. That is to say, the correctness of the periodic response factors for a construction can be evaluated by assessing the accuracy of its thermal response factors or CTF coefficients through the above method. Thus, there is no need to separately develop a verifying approach for the periodic response factors.

ERROR CRITERION TO EVALUATE ACCURACY

Visual observation of the polar curves on Bode diagrams is helpful in assessing the accuracy of the dynamic thermal behavior data. However, it is useful to have a single quantitative measure, for which we propose the following error criterion:

$$E = \frac{1}{U}\sqrt{\frac{1}{N}\sum_{k=1}^{N}[\psi(\omega_k) - \tilde{\psi}(\omega_k)]^2} \times 100\% \quad (14)$$

where, $\tilde{\psi}(\omega_k)$ and $\psi(\omega_k)$ are the amplitudes of the frequency characteristics of the model based on dynamic thermal behavior dada and the theoretical frequency characteristics of a construction at frequency point ω_k, respectively. N is the number of the calculated frequency points within the concerned frequency range and U is the total thermal transmittance or U-factor of the construction.

The error criterion employs a percentage error to measure the quantitative disparity between the models based on dynamic thermal behavior data and theoretical frequency characteristics of a construction. It is ratio, in percent, of root mean square error to the total thermal transmittance of the construction. The smaller the percentage error, the more accurate the dynamic thermal behavior data.

EXAMPLE AND ANALYSIS

Two multilayer walls are taken as examples to illustrate the present verifying method. One is a brick/cavity wall. Another is ASHRAE wall group 37, which is a very heavyweight wall described in the ASHRAE Handbook (1997). Both polar diagrams and error criterion are employed to assess the accuracy of the dynamic thermal behavior data of the constructions – thermal response factors and CTF coefficients. The evaluated frequency range is [10^{-n_1} , 10^{-n_2}], where n_1=8~10 and n_2=3. In the calculation of frequency characteristics, N frequency points are generated in the frequency range with equal logarithmical spacing (i.e., $\omega_k = 10^{-n_1+(k-1)(n_1-n_2)/(N-1)}$, ($k = 1,2,\cdots,N$)). Thus, the number N of points evaluated is $9(n_1 - n_2) + 1$.

A brick/cavity wall

A brick/cavity wall is described in Table 1. Its CTF coefficients is provided by time-domain method (Davies, 1997) and listed in Table 2. Its CTF coefficients and the first 96 thermal response factors are also provided by FDR method, respectively.

The theoretical frequency characteristics and the frequency characteristics of conduction transfer functions and the z-transfer function based on thermal response factors are evaluated for the brick/cavity wall within the frequency range [10^{-8}, 10^{-3}], shown in polar diagrams as Figure 1. The comparison of the polar curves indicates that the frequency characteristics of all transfer functions agree perfectly with the theoretical frequency of the wall. The percentage errors E_{TDM} and E_{FDR} of the CTF coefficients provided by time-domain method and FDR method are both 0.16%. The percentage error of the first 60 thermal response factors has reached 0.16%. The results show that both the time-domain method and FDR method have high accuracy for this construction. The percentage errors E_{24}, E_{36}, E_{48}, E_{60} and E_{90}, of the first 24, 36, 48, 60 and 90 thermal response factors are 5.04%, 0.93%, 0.23%, 0.16% and 0.16%, respectively. The results indicate that the first 36 thermal response factors provide sufficient accuracy for calculating the heat gain through the brick/cavity wall using thermal response factors, and a point of diminishing returns is reached between the 48th and 60th terms.

Table 1
Details of a brick/cavity wall

Description	Thickness and Thermal Properties				
	L ,mm	λ ,Wm^{-1}K^{-1}	ρ ,kgm^{-3}	C_P , J kg^{-1}K^{-1}	R ,m^{2}KW^{-1}
Outside surface film					0.060
Brickwork	105	0.840	1700	800	0.125
Cavity					0.180
Heavyweight concrete	100	1.630	2300	1000	0.06135
Inside surface film					0.120

Table 2
CTF coefficients of the brick/cavity wall

k	0	1	2	3	4	5	$\sum$
$b_k{}^*$	0.000178	0.013915	0.043475	0.018078	0.001052	0.000006	0.076704
$b_k{}^\#$	0.000179	0.013915	0.043460	0.018036	0.001034	0.000005	0.076628
$d_k{}^*$	1.000000	-1.619841	0.724516	-0.064305	0.001542	-0.000006	0.041907
$d_k{}^\#$	1.000000	-1.620834	0.726131	-0.065025	0.001594	0.000000	0.041866

Note: * — FDR method, # — Time-domain method (Davies 1997)

ASHRAE wall group 37

Harris and McQuiston (1988) worked out the CTF coefficients b_k and d_k for sets of 41 wall and 42 roof constructions intended to span the complete range of constructions used in North America. These coefficients were first provided in Imperial units. Subsequently, they were adopted by ASHRAE and published in the 1989, 1993 and 1997 editions of the *ASHRAE Handbook—Fundamentals* in SI units. Wall group 37 is described in Table 3 in SI units. Its CTF coefficients provided by ASHRAE Handbook are given in Table 4. It was found that the ratio of $\sum b_k \Big/ \sum d_k$ does not agree with the actual thermal transmittance or U factor of the wall (Spitler and Fisher, 1999). In fact, the deviation of the ratio from the actual U factor or thermal transmittance of the wall reaches 30%.

By using the FDR method, the CTF coefficients and the first 144 thermal response factors of wall 37 are calculated, respectively. The frequency characteristics of the two conduction transfer functions and the z-transfer function based on thermal response factors are evaluated and compared with the theoretical frequency characteristics of the wall within the frequency range [10^{-8}, 10^{-3}]. Their polar diagrams are shown in Figure 2.

The comparisons shown in Figure 2 indicate that the polar curves for the CTF coefficients and thermal response factors provide by FDR method have good agreement with the theoretical curves of wall 37. However, there are great deviations between the polar curves of the CTF coefficients provided by ASHRAE and the theoretical curves of the wall. The error criterion, E_{FDR} between the theoretical frequency characteristics and the frequency characteristics for the CTF coefficients provided by the FDR method is 0.04%. The percentage error, E_{ASHRAE} between the theoretical frequency characteristics and the frequency characteristics of the CTF provided by ASHRAE Handbook is 23.19%. Furthermore, the percentage error $E_{FDR-144}$ between the theoretical frequency characteristics and the frequency characteristics of the z-transfer function based on thermal response factors provided by FDR method is 0.04%.

This example also illustrates that the FDR method can provide dynamic thermal behavior data – CTF coefficients, thermal response factors and periodic response factors with sufficient accuracy for calculation of transient heat conduction through a range of building constructions.

CONCLUSIONS

Various causes may lead to incorrect dynamic thermal behavior data used in building simulation and dynamic space cooling/heating load calculation.

Various dynamic models of a linear system should be equivalent. The agreement of frequency characteristics of the dynamic models can be employed to measure their equivalence, correctness and reliability. The theoretical frequency characteristics of transient heat conduction through a construction can be calculated easily and accurately. The agreement between the frequency characteristics of the models based on dynamic thermal behavior data and the theoretical frequency characteristics of the construction can be used to evaluate their correctness and reliability. The polar diagrams for the dynamic models and theoretical frequency characteristics are visual aids to judge whether or not the dynamic thermal behavior data is correct. The proposed error criterion, which represents the ratio of the root mean square error over a range of frequencies, may be used to assess the accuracy of the dynamic thermal behavior data. Two examples have demonstrated the verification of dynamic thermal behavior data using the polar diagrams and the percentage error. The method is both comprehensive and reasonably easy to implement.

Table 3
Details of ASHRAE wall group 37

Description	Thickness and thermal properties				
	L, mm	λ, $Wm^{-1}K^{-1}$	ρ, kgm^{-3}	C_p, $Jkg^{-1}K^{-1}$	R, m^2KW^{-1}
Outside surface film					0.060
Face brick	100	1.332	2000	920	0.076
L.W. concrete block (filled)	300	0.138	300	837	2.203
Insulation	85	0.043	90	837	1.939
Plaster or gypsum	20	0.727	1600	837	0.026
Inside surface film					0.120

Table 4
CTF coefficients of ASHRAE wall group 37

k	0	1	2	3	4	5	6	$\sum$
b_k^*	0.000009	-0.000026	0.000032	0.000022	0.000158	0.000174	0.000030	0.000400
$b_k^\#$	0.000000	0.000000	0.000001	0.000031	0.000146	0.000196	0.000088	0.000462
d_k^*	1.000000	-3.409664	4.770703	-3.568588	1.552839	-0.389444	0.045927	0.001772
$d_k^\#$	1.000000	-3.177600	4.004600	-2.563300	0.890480	-0.167640	0.016379	0.002919

Note：* – FDR method, # – Provided by ASHRAE Handbook (1997)

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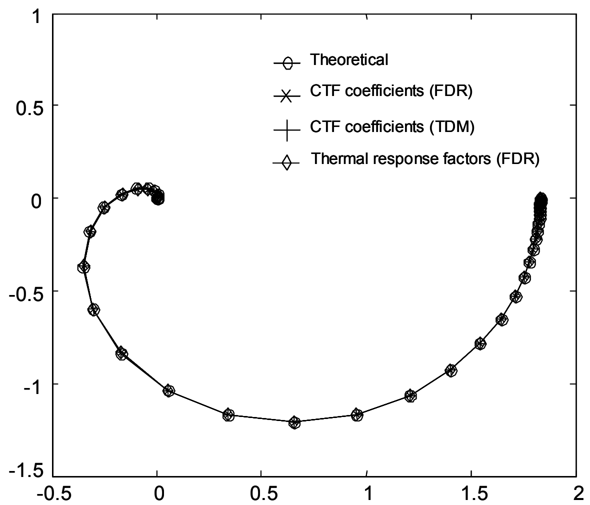

Figure 1 Polar diagram of frequency characteristics for the brick/cavity wall

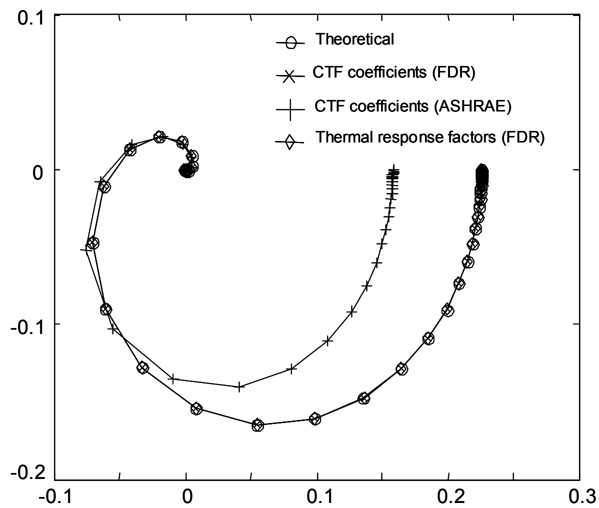

Figure 2 Polar diagram of frequency characteristics for ASHRAE wall group 37