FLUCTUATING AIRFLOW IN BUILDINGS

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Fluctuating airflow through buildings are caused by temporal and spatial variations of wind-induced pressures around building envelopes. An approach using the multi-zone pulsating airflow model is introduced in this paper to study the fluctuating airflow through large openings. The approach employs the concept of aerodynamic admittance functions to modify the wind pressure spectra to represent the average fluctuating pressures over the area of opening. Theoretical solutions are compared with field experimental results from the BOUIN test-house of CSTB, France.

1. INTRODUCTION

Airflow through openings on building envelopes and internal walls is caused by the combined effects of three driving forces: wind-induced pressures, thermal buoyancy and mechanical systems. This airflow can be divided into the steady flow and fluctuating flow. The steady-state or mean airflow is caused by mean pressure differences due to driving forces. The primary unsteady variables that cause fluctuations in airflow are temporal variations in wind-induced pressures.

Fluctuating airflow through individual openings caused by the temporal variations in pressure differences can be divided into two types: the pulsating flow and the penetration of eddies. The pulsating flow results from the wind fluctuation and the compressibility of air in the building internal space. Fluctuations in the wind causes simultaneous positive or negative pressure variations at an opening, the inside air is thus either pressurized or depressurized. The eddy flow is due to the turbulence in the air stream. They create a rotational effect on the inside air. This leads to an exchange between the inside air and the outside air through openings.

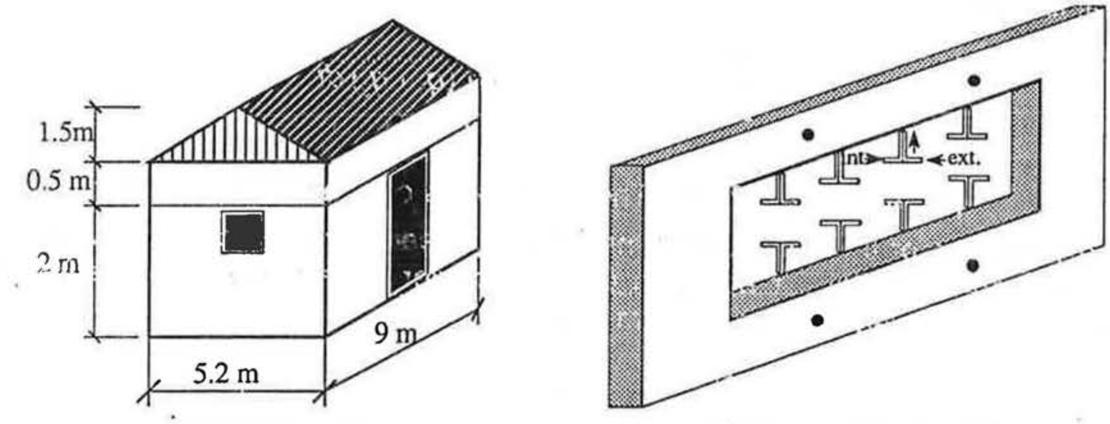
A model has been developed for predicting pulsating airflow in multi-zone buildings [1,2]. Inputs to the model include: the building airflow system (rooms, openings, and connections), the frequency characteristics of wind-induced pressures and their correlations, and output from a steady-state airflow model. In this paper, the model is extended to account for the effect of eddy flow, and is compared to field experimental data.

2. BOUIN TEST HOUSE AT FRANCE

Field experiments were conducted at France by CSTB to study single sided ventilation [3]. The test house at Bouin (Figure 1a) was a single zone building on an exposed site near the Atlantic coast. The volume of the test house was 93.6 m^3. The equivalent air leakage area of the house was measured and was less than 5 cm^2. The building was mounted on a turntable that can be rotated during an experiment.

A sharp edged slot of 40 cm width, 2.5 cm height and 1 cm thick was located on the building envelope. During the experiment, this opening was maintained to face the windward direction. The wind-induced external pressures, internal pressures, wind speed and direction and tracer gas concentration were measured simultaneously, at a rate of 10 Hz.

The wind pressure was measured close to the opening. This pressure was equal to the difference between the total pressure and the external static pressure. The pressures were also measured at eight points within the opening (Figure 1b), both inside and outside the building, allowing the direction of flow to be known locally. Full details of the site and the measurement used can found in Riberon and Villain [4].



(a) BOUIN Test House (b) Pressure Tapping Points

Figure 1. BOUIN Test House and Slot Opening

3. PULSATING AIRFLOW MODEL

In the pulsating airflow model presented in [1,2], the analysis is performed in the frequency domain. The task of calculating the pulsating airflow due to temporal variations in wind-induced pressure is decomposed into an infinite series of simple problems, each calculates the corresponding portion of airflow caused by the simple sine wave pressure at a single frequency. The total airflow is then obtained by summing up all these infinitesimal portions of airflow at single frequencies. The procedure is demonstrated in the following using the BOUIN test house as an example.

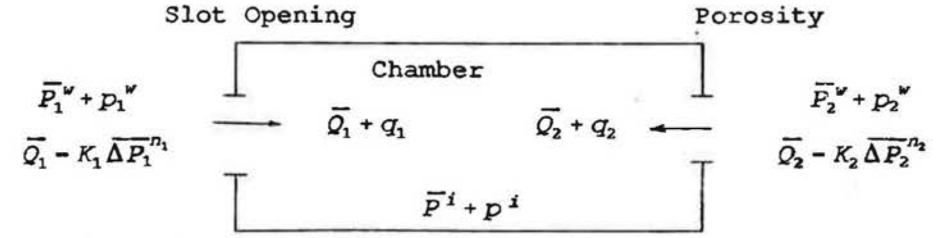


Figure 2. Modelling BOUIN House as a Two-Opening Building

The test house is modelled as a single-zone building with two openings. Opening 1 is the purpose-provided slot opening, and opening 2 represents the total leakage of the house envelope (Figure 2). In the steady-state calculation, the mass balance for this building is governed by:

$$K_1\left(\bar{P}_1^{w} - \bar{P}^{i}\right)^{n_1} + K_2\left(\bar{P}_2^{w} - \bar{P}^{i}\right)^{n_2} = 0 \tag{1}$$

For the analysis of fluctuating components in the pressures and airflow, the pressure balances for both openings results in two nonlinear governing equations:

$$\frac{\rho L_i}{A_i}\frac{dq_i}{dt} + \left(\frac{1}{K_i}\right)^{\frac{1}{n_i}}\left[\left(\bar{Q}_i + q_i\right)^{\frac{1}{n_i}} - \bar{Q}_i^{\frac{1}{n_i}}\right] = p_i^{w} - \frac{\gamma P_a}{V}\int_0^t (q_1 + q_2)\,dt \tag{2}$$

where i=1,2, same for the following equations.

The nonlinear terms in the above equations are approximated to linear relations using a statistical linearization method. Therefore, a set of linear governing equations can be obtained as:

$$M_i\frac{dq_i}{dt} + \lambda_i q_i = p_i^{w} - B\int_0^t (q_1 + q_2)\,dt \tag{3}$$

where $M_i = \rho L/A_i$ and $B = \gamma P_a/V$. The coefficients of λ_i are assigned to such values that the variances of the nonlinear terms and the linear terms in both equations (2 and 3) are the same. The linear equation (3) are Fourier transformed into the frequency domain, and converted to a matrix form as:

$$\begin{bmatrix} \lambda_1 + j\omega M_1 + \dfrac{B}{j\omega} & \dfrac{B}{j\omega} \\ \dfrac{B}{j\omega} & \lambda_2 + j\omega M_2 + \dfrac{B}{j\omega} \end{bmatrix} \begin{bmatrix} Q_1(\omega) \\ Q_2(\omega) \end{bmatrix} = \begin{bmatrix} P_1^{w}(\omega) \\ P_2^{w}(\omega) \end{bmatrix} \tag{4}$$

The transfer function matrix can be obtained as:

$$\mathrm{H}_q(\omega) = \begin{bmatrix} H_{q11}(\omega) & H_{q12}(\omega) \\ H_{q21}(\omega) & H_{q22}(\omega) \end{bmatrix} = \begin{bmatrix} \lambda_1 + j\omega M_1 + \dfrac{B}{j\omega} & \dfrac{B}{j\omega} \\ \dfrac{B}{j\omega} & \lambda_2 + j\omega M_2 + \dfrac{B}{j\omega} \end{bmatrix}^{-1} \tag{5}$$

When the spectra of wind pressures, $S_{p_1^w}(\omega)$ and $S_{p_2^w}(\omega)$, and the co-spectrum, $S^{(c)}_{p_1^w p_2^w}(\omega)$, between them are known, the spectra for the pulsating airflow can be calculated by:

$$S_{q_i}(\omega) = \|H_{qi1}(\omega)\|^2 S_{p_1^w} + \|H_{qi2}(\omega)\|^2 S_{p_2^w} - 2\|H_{qi1}(\omega)\|\,\|H_{qi2}(\omega)\|\, S^{(c)}_{p_1^w p_2^w}(\omega) \tag{6}$$

The RMS values of the fluctuating airflow are obtained through the integration of corresponding spectra over the frequency, i.e.:

$$\sigma_{q_i}^2 = \int_0^{\infty} S_{q_i}(\omega)\,d\omega \tag{7}$$

The terms λ_i and σ_{q_l} are functions of each other. An iterative procedure is employed to adjust λ_i and σ_{q_l} until both equations hold for one set of λ_i and σ_{q_l}.

By employing the mass balance of air into the zone, an equation for the internal pressure can be formed. Using the similar techniques, the transfer function between the external pressure at opening 1 and the internal pressure can be obtained as:

$$H_{p_1'}(\omega) = \left\{\frac{1}{\lambda_1 + j\omega M_1}\right\} \Big/ \left\{\frac{j\omega}{B} + \sum_{l=1,2} \frac{1}{\lambda_l + j\omega M_l}\right\} \tag{8}$$

4. MODIFIED FLUCTUATING AIRFLOW MODEL

The mean and RMS values of interested variables are displayed in Table 1. Figure 3 shows the magnitude and phase plots of the transfer function $H_{p_1'}(\omega)$ and the power spectra of the internal pressure by both experimental estimation and theoretical calculation.

Table 1. Experimental and Pulsating Airflow Model

		Experimental		Theoretical	
		Mean	RMS	Mean	RMS
Opening		$K_1=7.6771\times10^{-3}$, $n_1=0.5$		input	
Porosity		$K_2=8.3424\times10^{-4}$, $n_2=0.5$		input	
P_1^w (Pascal)		14.45	5.02	input	
P_2^w (Pascal)		-4.35	1.51	input	
Pulsating Airflow Model	P^i (Pascal)	13.60	4.53	14.23	4.72
	Q_1 (l/s)	4.93	6.24	3.60	4.72
	Q_2 (l/s)	3.02	0.59	3.60	0.66
Modified Model	P^i (Pascal)	13.60	4.53	14.23	4.50
	Q_1 (l/s)	4.93	6.24	3.60	5.17
	Q_2 (l/s)	3.02	0.59	3.60	0.66

The discrepancy between theoretical and experimental results can be attributed to that the pulsating airflow model does not consider the eddy flow due to the spatial variations of wind pressures over the opening. The pressures on the area of the opening are assumed to be simultaneously pushing in or pulling out the air through the opening at all points. In reality, however, the pressures at different points on the opening are not perfectly synchronized or correlated. There are lags between these pressures. The lags are influence by the distance between the two points, the turbulence characteristics, and eddy sizes.

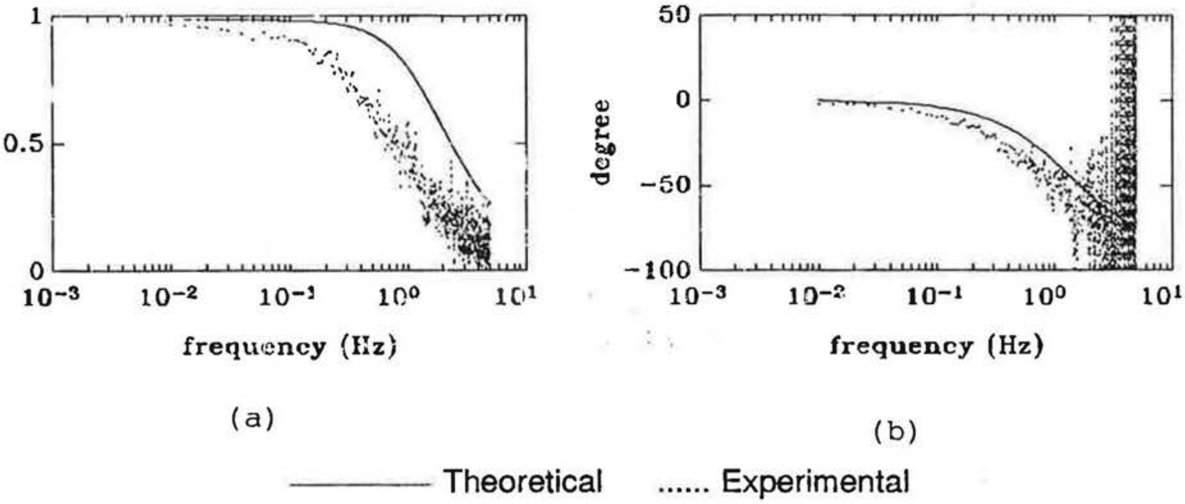


Figure 3. Results of Pulsating Model: (a) Magnitude and (b) Phase Plots of Transfer Function Between External and Internal Pressures

As a solution, a function is introduced to obtain the net effect of the imperfectly correlated pressures. Since the net force is always less than the "point" pressure (multiplied by the opening area), the function should be bounded from above by a value of 1. Because the lags are related to eddy sizes or the frequency, this function is related to the frequency. The concept of this function has been utilized in wind engineering to calculate the dynamic wind loading on building envelopes [5]. The function is referred to as an aerodynamic function.

In the proposed approach to account for the eddies in the airflow through the opening, the aerodynamic function is chosen to be the coherence function of wind-induced pressures at two representative points. Figure 4 shows the experimental estimation of the coherence function and fitting. The fitting curve will be used for later calculation.

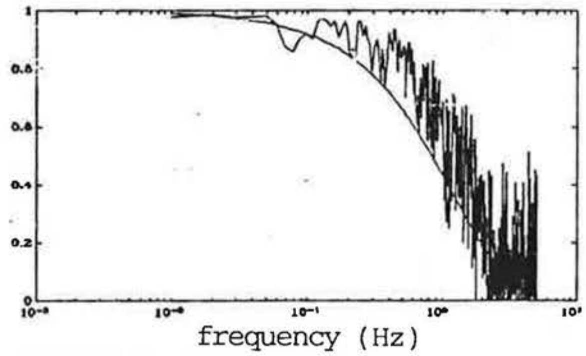


Figure 4. Coherence Function as Aerodynamic Function

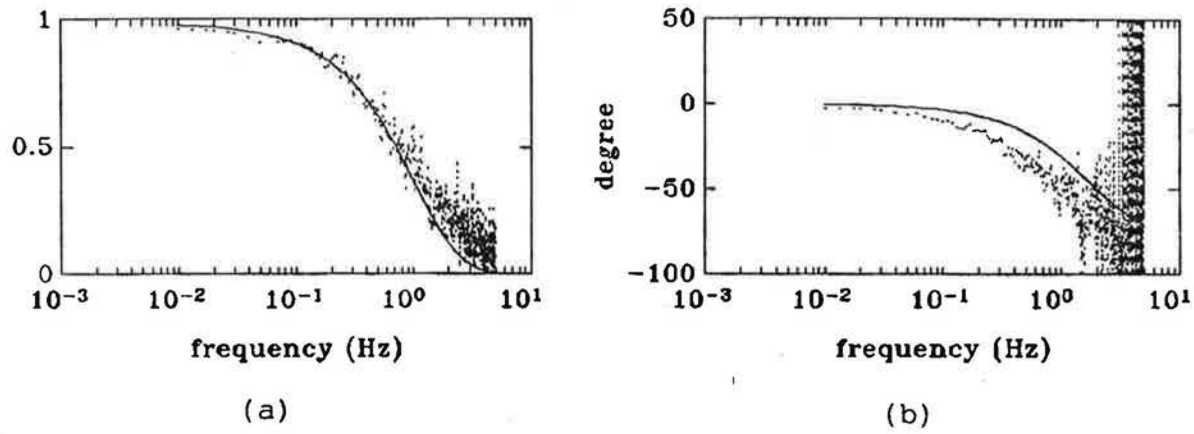
Once the aerodynamic function is obtained, the net effect should equal to the "point" value modified (multiplied) by the aerodynamic function. In the theoretic calculation the "point" force is the power spectrum of the external pressure at the opening. Therefore, the calculation will take:

$$\hat{S}_{p_1''}(\omega) = S_{p_1''}(\omega) \cdot \chi_1^2(\omega) \tag{9}$$

as the input force. A further analysis shows this is equivalent to use a modified transfer function:

$$\hat{H}_{p_1'}(\omega) = H_{p_1'}(\omega) \cdot \chi_1(\omega) \tag{10}$$

in the theoretical calculation.



———— Theoretical ...... Experimental

Figure 5. Results of Modified Model: (a) Magnitude and (b) Phase Plots of Transfer Function Between External and Internal Pressures

The comparison between experimental estimations and theoretical calculation by the modified model is shown in Figure 5. The plots shows an improvement of the modified model over the pulsating model in predicting the internal pressure spectrum. Table 1 also shows that the predicted RMS value of the internal pressure by the modified model is closer to the experimental results. The new approach also results in a larger RMS of airflow at the slot opening.

5. CONCLUSION

In accounting for the eddy airflow through building openings, an approach utilizing the concept of aerodynamic function is proposed to modified the pulsating airflow model. In this approach, the net force that is pushing in or pulling out the air through the opening is considered to be the "point" pressure multiplied by the aerodynamic function. The coherence function is chosen as the modifying function. The new approach is applied to field experimental data from BOUIN test house at France. The comparison shown the approach is very effective.

References

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