NATURAL VENTILATION AIR CHANGE RATES CONSIDERING ATMOSPHERIC TURBULENCE

Marques da Silva, Fernando ;Saraiva, Jorge G.
LNEC - NDA, Av. do Brasil 101, 1799 Lisboa Codex, Portugal
Tel : 351-218443862 ; Fx : 351-218443025 ; e-mail : fms@lnec.pt ; jsaraiva@lnec.pt

ABSTRACT

The estimate of actual air change rates considering atmospheric turbulence is introduced. The starting point is the spectral description of turbulence - Kaimal spectrum was used in order to consider the height above ground. A set of *synthetic* wind velocity series are generated, out from a modified spectrum. The procedure considers an aerodynamic transfer function (a filter) where peculiar and cut-off frequencies are determined by the general dimensions of the building and of the external openings, *i. e.,* the turbulent scales of interest. For each opening is furthermore possible to generate different but correlated time series, the correlation coefficient being defined through the relative position of the openings, considering the appropriate scales of turbulence.

A first set of results derived from a time step to step run of VENTIL - an integral model for NV estimates - using the *synthetic* wind velocity series shows that a fine accurate estimate of the air change rate is now possible. The relation between rms ACH value and the turbulence intensity becomes evident. Further developments will look upon a frequency analysis of these results.

1. The wind representation

In order to estimate air change rates (ACH) in a Natural Ventilation (NV) process the common practice refers to the local average wind velocity at a level corresponding to the one of wind tunnel's reference height when evaluating the façade pressure coefficients (CP).

This is a very simplified wind velocity model with clear limitations to cope to the reality specially when significative turbulence intensities are present. Pressure is related to the square of the velocity, and is the effective source for air mass flow through openings. So it becomes evident that average ACH could be well out of real values when only a mean velocity is considered.

A possible solution is to deal with a representative wind velocity time series where atmospheric turbulence is introduced. The way to achieve it is to consider the spectral representation of the wind turbulence – spectrum – and reversing the usual calculation procedures generate wind velocity time series matching the original turbulent properties present on the spectrum.

1.1 The wind turbulence

The most common way to describe the instantaneous velocity U, on a turbulent flow consists on adding a fluctuating component u, to the mean velocity $\overline{U}$, and $U = \overline{U} + u$. Mean velocity and turbulence intensity, I

$$I = \frac{\sqrt{\overline{u'^2}}}{\overline{U}}$$

allows to describe a flow like the atmospheric boundary layer (ABL) as represented by a turbulence intensity and a vertical mean velocity profiles.

Turbulence might also be seen as a set of *eddies* – image of highly rotational portions of fluid with angular frequency $\omega=2\pi n$ (*n* being the frequency) or a wave number $k=2\pi/\lambda$ (with the wave length $\lambda=U/n$), continuously changing both in space and time – carried by the mean flow, as proposed by G. I. Taylor. Wind velocity fluctuations are then explained as *eddy* contributions to the mean flow.

It is widely accepted that the conceptual *eddy* is kept unchanged on it's path – what is usually known as *frozen turbulence* – and that *eddies* verify the Kolmogorov's hypothesis: isotropy for the smaller (higher frequency) and energy dissipative – no preferential direction meaning that only viscosity matters; and that an inertial range exists (lower frequencies) where the rate of energy transfers is important but independent of viscosity.

Eddy sizes are evaluated through the scales of turbulence – nine scales altoghether corresponding to three directions with three fluctuating components each - that may be defined as for each direction, namely that of the flow, after considering the *frozen turbulence* hypothesis,

$$L_u^x = \frac{U}{\overline{u_i'^2}} \int_0^\infty R_u(\tau)\, d\tau$$

$R(\tau)$ being the autocovariance function for u(x, t) and (x, t ± τ).

The relation between the integral scales of the alongwind component for the three directions is $L^x_u \approx 3\, L^y_u$ and $L^x_u \approx 2\, L^z_u$. It may also be stated that $L^x_u = C\, z^m$ where *C* and *m* are dependent on the terrain roughness [11] and *z* is the elevation above ground level.

The turbulence frequency content represented as a power spectral density function (spectrum) of each particular frequency or wave number, trough a Fourier transform of the velocity frequencies. For the ABL the most common spectra used are the ones developed by Davenport and more recently by Kaimal who introduced the elevation dependency, figure 1, and defined by,

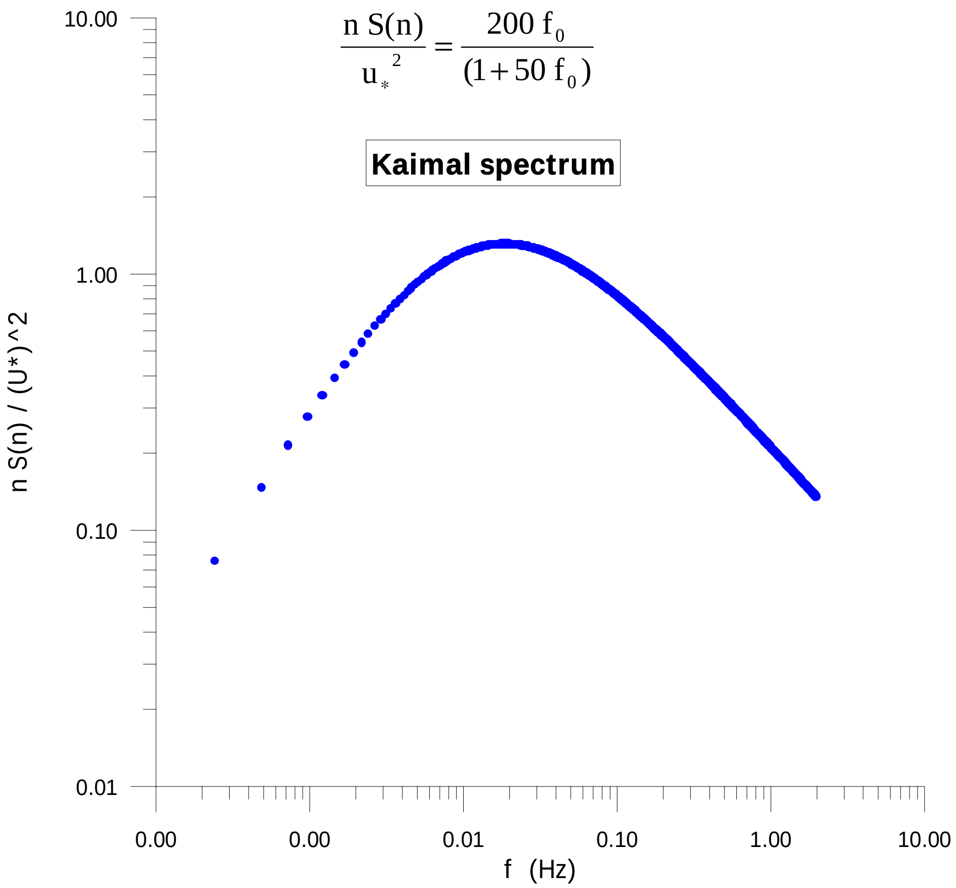

Figure 1 – Kaimal spectrum

where u_* is the friction velocity ($=\sqrt{\tau_0/\rho}$), τ_0 being the surface shear stress and ρ the fluid density) and f_0 is the Monin parameter ($= n\,z\,/\,\overline{U(z)}$)

1.2 The generation of *synthetic* wind series

These spectral representations being "universal", in the sense that they represent a large number of observations, may be used to revert the process (inverse Fourier transform) and generate wind velocity time series with the statistical properties of the ones observed in Nature.

The procedure to generate these *synthetic* wind series is based of the method of Shinozuka [12] and the procedure developed by Carvalhal [12] based on the evaluation of the inverse Fourier transform (IFT) of the spectrum. It consists basically on a weighted sum of sinusoidal waves, the contribution from each one coming from the spectral intensity of the corresponding frequency and the phase being randomly coosed.

Estanqueiro [12] changed some details of the procedure in order to generate wind time series for the wind power case. The generation of correlated series is not based on a random "perturbation quantum", as established by Shinozuka in order to avoid repeated series, but, instead, on the high sample rate of the frequency domain of the spectrum. The model also uses a fast IFT procedure (IFFT) allowing the referred high sample rates within a rapid calculation process. The generated series have zero mean value that should be added the local mean wind velocity.

For the purpose of this work this last procedure was adapted for the particular case of buildings. The integral scales are dependent on the ABL wind profile, terrain roughness and building overall dimensions, cut-in depends also on building overall dimensions and cut-off frequencies on opening dimensions. In what concerns to the correlated series some changes have been introduced due to the specificity of each case.

1.3 The actual model

The model first define a Kaimal spectrum adapted to the terrain and building specifications. Out of this spectrum a reference wind time series (WTS) for the elevation corresponding to the conditions of CP evaluation is established, fig. 2.

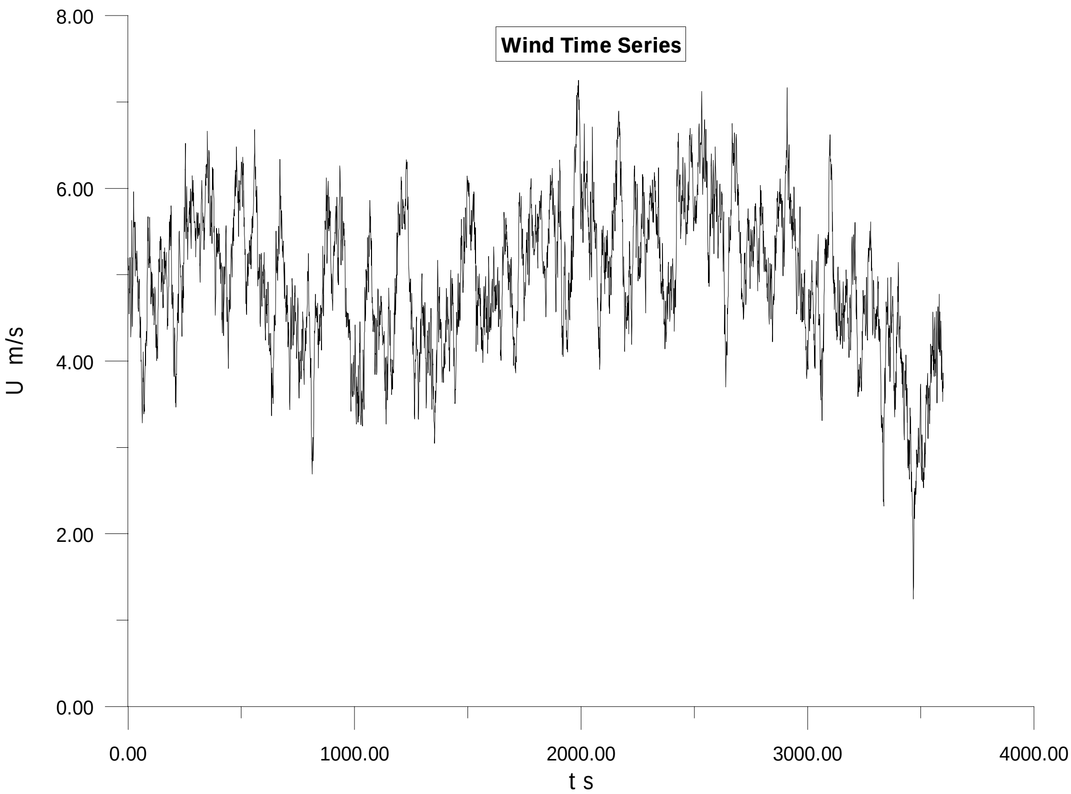

Figure 2 – Reference wind time serie

Front facade openings must consider the presence on a different but correlated WTS. The correlation coefficients are estimated according to the work of Wacker and Plate [9] and if any particular value shows to be at least 0.8 it is assumed that the reference WTS may be used.

For the facades under separation conditions Gusten [6] showed that the spectrum of pressure fluctuations was quite similar to the one at the front facade. Keeping in mind that CP values are obtained using a non disturbed wind velocity reference; that it is pressure that promotes ventilation, and; considering the *frozen turbulence* hypothesis, it was assumed that the WTS reaching those openings was the reference one delayed of the time necessary for the mean wind velocity to carry it from front facade.
An estimate of a NV process for a building with a number of internal spaces is characterised by the knowledge of the flow velocity through any opening and the pressure, temperature and density variation for each one of the spaces.

VENTIL assembles a set of non linear equations allowing to achieve that target:
- A mass balance equation for each space and the overall building. In addition flow velocities for any opening of connecting spaces must cancel;
- A momentum balance equation (Bernoulli eq.) for each opening;
- An energy balance equation for each space, and;
- The perfect gas law.

This set of equations is solved for each time step considering the appropriate wind velocity of each external opening.

2. Results

Two side by side identical industrial buildings was used as an illustration of the model application and capabilities. The choice of those buildings is justified by the fact that a scale model had previously been tested on wind tunnel under different boundary layers and it's pressure coefficients measured and was also used for previous models [4,13,14].

The buildings main features are (Fig. 1): planform area of 1600 (=80*20) m^2; volume of 10144 m^3; one external opening on each side (30 m^2) and one at each roof summit (30 m^2), and one communicating opening (15 m^2), fig. 3. The wind blows at 5 m/s (eaves height) normal to the façade with a turbulence intensity of 25%. The outside temperature is 15ºC. There's a small heat source of 3500 W on the leeward building. It was considered an ABL, the power law exponent being α=0.22, with a roughness coefficient established as 0.0075.

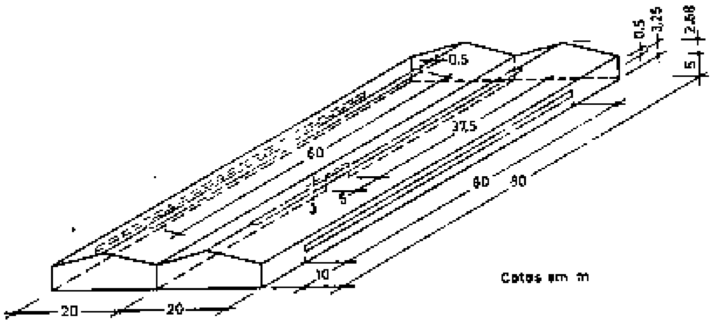

Figure 3 – Buildings layout and dimensions

Figures 4, 5 and 6 shows the one minute plot of the used WTS, equivalent hour ACH and internal pressure coefficients.

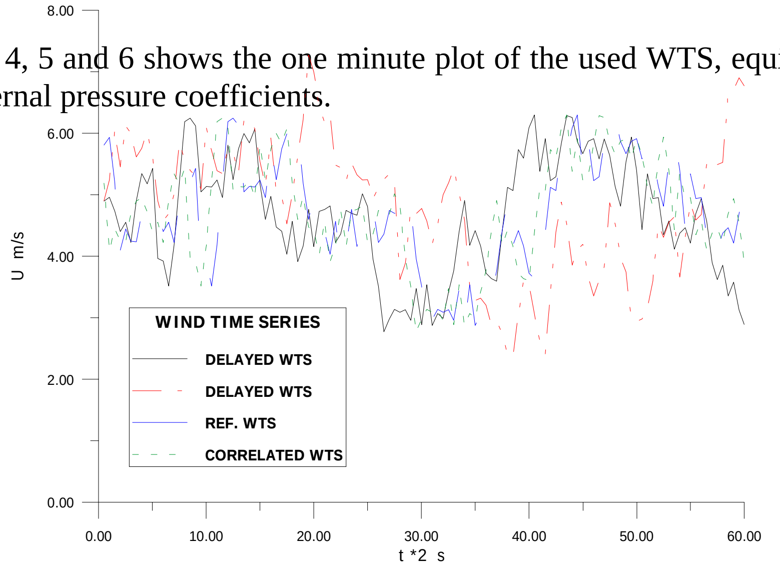

Figure 4 – Wind time series

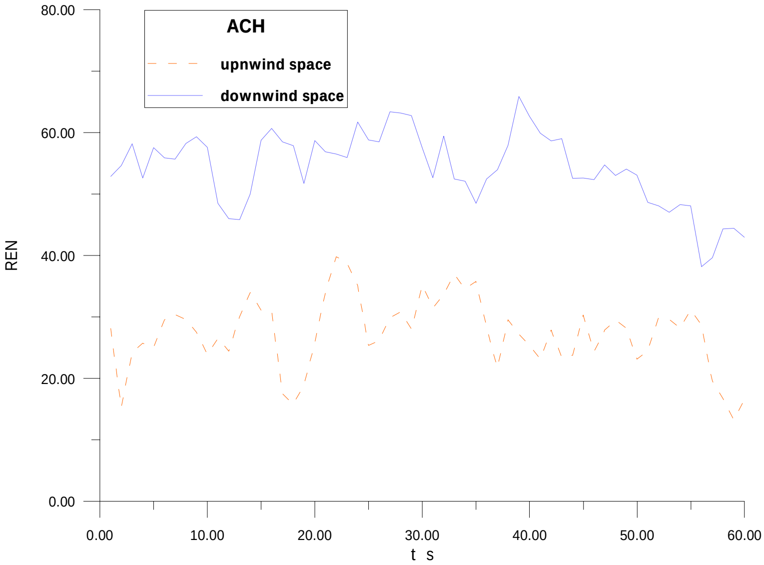

Figure 5 – Equivalent hour ACH time series

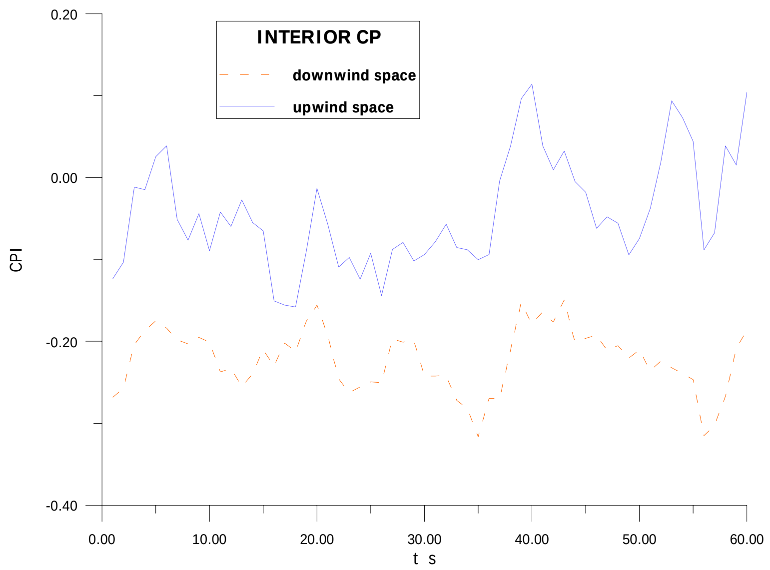

Figure 6 – Internal pressure time series

The final average hourly ACH is 52 for the upwind space and of 42 for the downwind space. These values clearly exceed both the ones evaluated using the mean wind velocity (26 and 14 respectively) and the evaluated through the model that considers the only the turbulence intensity added to the mean value of velocity (35 and 18 respectively). The former model considers that eddies influence the whole building at the same time. In fact this influence depends on both the building and eddy dimensions what could explain the difference. Also, and yet to be clarified, is the velocity/pressure conversion model because the rapid distortion theory of turbulence states that there is no time, for a "square dependence", the relation being linear.

Another aspect needing further development is the analysis of internal space pressures that do not adapt instantaneously to the mass flow entering or leaving the space. A damping effect could occur changing the ACH dynamic rates.

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