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Correlation of Fluctuating Wind Pressures on a House

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SUMMARY In this paper, wind tunnel measurements of the covariance and correlation coefficients of the fluctuating panel pressures, for ten panels along the centre line of an isolated single storey house in rural terrain, are presented. The model used was a 1/50 scale model of a typical single storey tropical style house. The covariance data is used to calculate structural loads such as total uplift, drag, and overturning moment.

1 INTRODUCTION

During recent years more attention has been paid to the determination of wind loads on domestic houses using turbulent boundary layer wind tunnels. In virtually all such studies, design loads have been based upon point measurements of the fluctuating pressures. The fluctuating wind pressures are caused both by upwind "freestream" turbulence and by "local" turbulence generated in the separated flow regions around the body.

Structural load parameters (such as uplift and bending moments) are dependent upon a spatial integral of pressure and it is possible to estimate *mean* values of structural parameters based upon the measured spatial variation of mean pressure. However, fluctuating peak and r.m.s. values of structural parameters cannot be evaluated from the individual point properties of the pressures acting over the area of influence. In order to estimate structural load r.m.s. and peak values it is necessary to obtain information of the joint properties of the relevant point pressures.

Some approaches which have been used to measure r.m.s. and peak structural loads are:

(i) Direct measurement (e.g. Jancauskas and Sharp (1977))- The structural property of interest can be directly measured using, for example, strain gauge techniques. This is the most straightforward approach but is limited in that only a few loads can be measured at one time and measurement of many types of loads (e.g. truss member forces) would prevent severe practical difficulties.

(ii) Electronic/digital combination of point pressures. (Davenport et al (1977,1978))- The weighted sum of all pressures contributing to a structural load is monitored and the statistical properties can be measured directly. This method allows great flexibility in the choice of structural load examined but requires a new run for each parameter to be measured. The method also necessitates large numbers of pressure transducers and, where digital combination is used, fast acquisition and on line processing rates are necessary to achieve suitable frequency response.

(iii) Pneumatic averaging (Stathopoulos (1975)) - Pressures from a number of points are manifolded into a single output pressure which is the average of the input pressures, thus allowing a single pressure transducer to be used to measure a spatially averaged pressure. By varying the concentration of pressure taps channeled to a manifold it is possible to include unequal weighting effects. It may also be possible to introduce weighting by the use of varying diameters of connecting tube though this possibility has not yet been explored.

(iv) Covariance matrix method - To employ this method the entire covariance matrix for the fluctuating pressures from a grid of taps is measured. Once obtained, this matrix can be used to estimate a wide range of r.m.s. structural parameters. In order to reduce the size of the covariance matrix it is possible to combine the pneumatic averaging technique described in (iii) over panel sections of model area to produce spatially averaged pressures. The covariance matrix relating these section pressures may then be used to estimate various peak and r.m.s. structural loads. This approach allows considerable flexibility in the type of structural parameter examined, while necessitating the use of only two pressure transducers.

In this paper, the computation of peak overall loads for a central bay of a domestic house in rural terrain is carried out using the covariance matrix techniques as described in (iv), above.

2. EXPERIMENTAL

2.1 Wind Tunnel

The boundary layer wind tunnel used for this work is of the open circuit type with a 2.5 m wide by 2 m high cross section and a 13.5 long working section. The tunnel is powered by a 45 kVA electric motor driving a 2.4 m diameter, five bladed, fixed pitch, fan through a five speed gear box.

A detailed description of the design and performance of this wind tunnel has been given by Holmes (1977).

2.2 The Model

The model tested was a 1/50 scale model of a tropical style low-set house with 10° roof pitch, eaves and gable overhangs (See Fig 1)

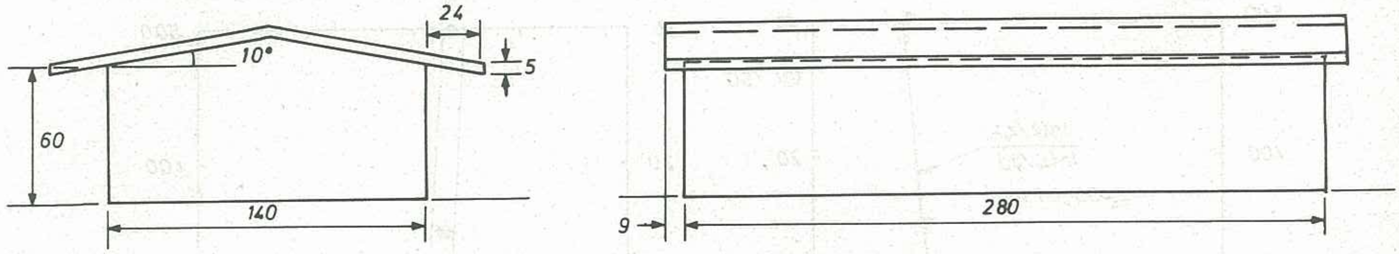

Figure 1 Dimensions of house model

This model geometry was used in a previous study by Best and Holmes (1978). The model was constructed from 5 mm "perspex" sheet. Pressures were measured over a central band across the model (see Fig 2). Only the wind direction normal to the long wall of the building was considered.

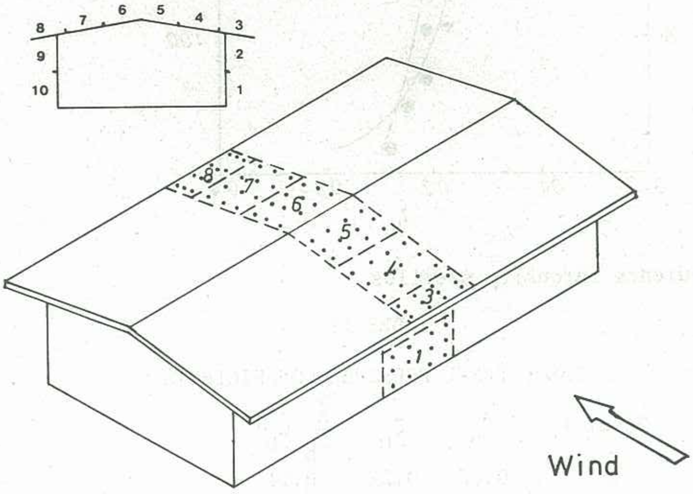

Figure 2 Panels and pressure tap grids

The pressure taps were made by inserting short lengths of 1.6 mm external diameter hypodermic tubing into holes drilled through the roof and walls. The band of interest was divided into 10 panels each containing 12 pressure taps (Fig 2). The group of 12 taps within each panel was connected by 50 mm lengths of 1.5 mm internal diameter vinyl tubing to a common manifold, which was, in turn connected via a 450 mm length of 1.5 mm vinyl tubing, containing two restrictors, to a "Scanivalve" pressure scanning device. In this way a fluctuating pressure representative of the average pressure over a panel could be measured. The validity of this technique is discussed in Section 3.

2.3 Instrumentation

Pressure measurements were made using Setra 237 capacitance-type pressure transducers mounted within 48 port "Scanivalves". A T.S.I. linearised constant temperature anemometer (Type 1054B) in conjunction with a T.S.I. hot film probe was used to measure wind velocity. All measurements were recorded using a PDP/8-E mini-computer which was also used to control the panel referenced by each "Scanivalve".

2.4 Boundary Layer Simulation

The simulation of a 1/50 scale rural terrain boundary layer has been discussed previously, (Holmes (1977)) and was achieved using a 300 mm high fence in combination with carpet on the floor upwind. This arrangement gives good agreement with full scale velocity and turbulence intensity profiles for a full scale roughness length of 35 mm (See Fig 3).

The longitudinal turbulence spectrum (not shown), is shifted to the high frequency end by a factor of about two when compared with the curve suggested by the Engineering Sciences Data Unit (1974). There is evidence to suggest that this should have little influence on mean or r.m.s. coefficients e.g. Davenport and Surry (1974).

3 PNEUMATIC AVERAGING

Results from work at the University of Western Ontario, reported by Stathopoulos (1975), have demonstrated the validity of pneumatic averaging techniques. Previous work at James Cook University by Perkins (1979) suggested the tubing lengths and arrangement to be used. The setup was checked in the following way.

For the case of two panels, numbered 3 and 4 in Fig 2, the entire covariance matrix for the individual pressure taps was measured. These two panels were chosen as the most severe pressure gradients existed in that region of the roof. Using the techniques described in sections 4 and 5 of this paper, the expected properties of pneumatic averages of the test panels were computed. Table I shows a comparison of expected statistical properties versus the properties measured using pneumatic averaging.

TABLE I

Parameter	Value based on Individual taps	Value measured using pneumatic averaging
$\bar{C}_{p_3}$	-1.21	-1.07
$\bar{C}_{p_4}$	-0.55	-0.47
C'_{p_3}	0.36	0.33
C'_{p_4}	0.18	0.16
$\dot{C}'_{p_3}$	0.26	0.23
$\dot{C}'_{p_4}$	0.18	0.12
r_{34}	0.67	0.69
$\dot{r}_{34}$	0.00	0.12

The comparison is reasonable when it is realized that this is the worst case situation, and that, if

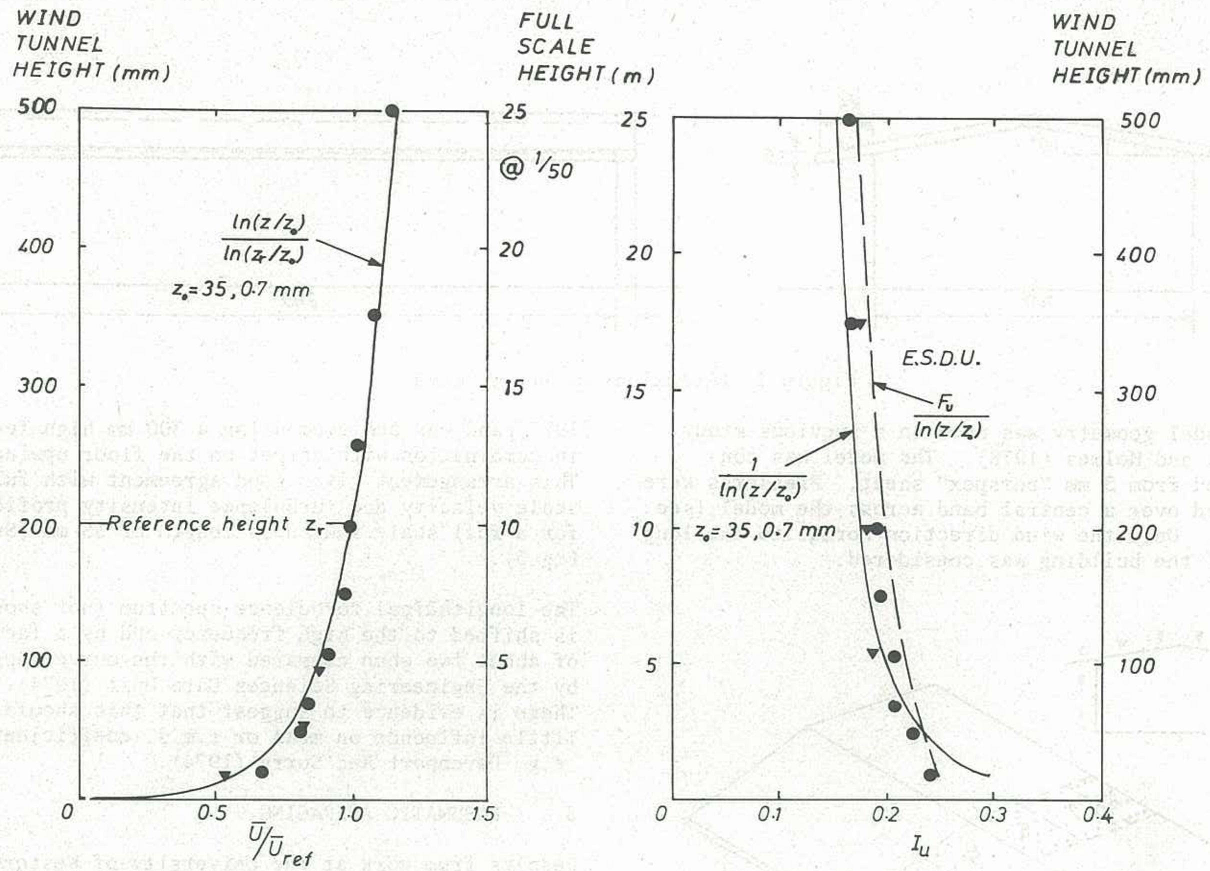

Figure 3 Mean velocity and turbulence intensity profiles

necessary, it would be possible to improve accuracy by using more panels in areas of high pressure gradient.

4. RESULTS

For each panel the mean and r.m.s. pressure coefficient and the r.m.s. value of the rate of change of pressure were measured, using a sampling time of 20 seconds at a rate of 500 samples per second. The coefficients are defined as follows:

Mean pressure coefficient, $\bar{C}_p = \dfrac{\bar{p} - p_{ref}}{\frac{1}{2}\rho \bar{u}_h^2}$

R.M.S. pressure coefficient, $C_p' = \dfrac{\sqrt{\overline{p'^2}}}{\frac{1}{2}\rho \bar{u}_h^2}$

and derivative pressure coefficient,

$$\frac{h.\dot{C}_p'}{\bar{u}_h} = \frac{\sqrt{\overline{\dot{p}^2}}}{\frac{1}{2}\rho \bar{u}_h^3} \cdot h$$

The values measured for these coefficients are given in Table II.

The mean and r.m.s. coefficients in Table II are consistent with previous point pressure measurements on a similar model (Best and Holmes (1978)).

As well as these individual measurements the complete cross-correlation matrices of fluctuating pressure and fluctuating pressure derivatives were measured:

TABLE II

BASIC PANEL PRESSURE COEFFICIENTS

Panel #	$\bar{C}_p$	C_p'	$\frac{h}{\bar{u}_h}\dot{C}_p'$
1	0.55	0.22	0.11
2	0.66	0.28	0.16
3	-1.07	0.33	0.23
4	-0.47	0.16	0.12
5	-0.54	0.15	0.10
6	-0.60	0.17	0.08
7	-0.32	0.10	0.07
8	-0.20	0.07	0.07
9	-0.12	0.07	0.06
10	-0.11	0.05	0.04

Cross correlation, $r_{ij} = \dfrac{\overline{p_i' p_j'}}{\sqrt{\overline{p_i'^2}}\sqrt{\overline{p_j'^2}}}$

Derivative cross correlation, $\dot{r}_{ij} = \dfrac{\overline{\dot{p}_i' \dot{p}_j'}}{\sqrt{\overline{\dot{p}_i'^2}}\sqrt{\overline{\dot{p}_j'^2}}}$

where the subscripts refer to panels i and j.

As both [r] matrix and the [$\dot{r}$] matrix are symmetric with the diagonal elements equal to one, they can be shown as a single matrix whose upper triangle comprises the r_{ij} terms and whose lower trangle comprises $\dot{r}_{ij}$ terms. Table III gives such a matrix containing the measured values.

Note that the correlation coefficients for the derivatives are considerably lower in magnitude than those for the pressure fluctuations themselves - this reflects the higher frequency content of the derivatives. Negative correlations occur between the windward wall and roof pressures; this is to be expected as the roof pressures will tend to *fall* (suctions rise), when the windward wall pressures *increase*. Another interesting feature is the higher observed correlation coefficient for the roof panels 3 and 5 (or 6), compared with that for 3 and 4. This has been observed previously by Stathopoulos, Davenport and Surry (1978) for a flat roof, and can be explained by the reattachment of the flow on to the roof.

TABLE III

$[r]$ and $[\dot{r}]$ MATRICES

	1	2	3	4	5	6	7	8	9	10
1	1.0	.95	-.61	-.18	-.47	-.54	-.32	-.12	.02	.00
2	.76	1.0	-.63	-.14	-.48	-.55	-.38	-.18	-.07	-.03
3	-.43	-.48	1.0	.69	.78	.73	.70	.57	.47	.45
4	.01	.00	.12	1.0	.66	.51	.63	.62	.53	.55
5	.03	.01	.25	-.09	1.0	.95	.90	.74	.57	.55
6	.01	.01	.16	.10	.13	1.0	.92	.73	.55	.56
7	.06	.03	.14	.15	.16	.31	1.0	.90	.76	.74
8	.07	.06	.10	.15	.19	.28	.37	1.0	.89	.88
9	.11	.06	.12	.18	.22	.37	.39	.42	1.0	.98
10	.08	.05	.11	.16	.19	.35	.36	.39	.72	1.0

r

$\dot{r}$

5 APPLICATION

5.1 Theory

At time t, the value of structural parameter η, which depends upon the pressures according to influence coefficients β_i over a number of panels (N), of area A_i, is given by:

$$\eta(t) = \sum_{i=1}^{N} \beta_i A_i p_i(t) \tag{1}$$

Hence,

$$\eta(t) = \tfrac{1}{2}\rho \bar{u}_h^2 \sum_{i=1}^{N} \beta_i A_i C_{pi}(t) \tag{2}$$

The time averaged mean of $\eta(t)$, $\bar{\eta}$ is given by:

$$\bar{\eta} = \tfrac{1}{2}\rho \bar{u}_h^2 \sum_{i=1}^{N} \beta_i A_i \bar{C}_{pi} \tag{3}$$

The variance can be shown to be (Best and Holmes (1978)):

$$\overline{\eta'^2} = \sum_{i=1}^{N} \sum_{j=1}^{N} \overline{p_i' p_j'} \beta_i \beta_j A_i A_j$$

$$= \left[\tfrac{1}{2}\rho \bar{u}_h^2\right]^2 \sum_{i=1}^{N} \sum_{j=1}^{N} r_{ij} C_{pi}' C_{pj}' \beta_i \beta_j A_i A_j \tag{4}$$

writing this in matrix form:

$$\overline{\eta'^2} = \left[\tfrac{1}{2}\rho \bar{u}_h^2\right]^2 \{\beta\}^T [\grave{}A\lrcorner][\grave{}C_p'\lrcorner][r][\grave{}C_p'\lrcorner][\grave{}A\lrcorner]\{\beta\} \tag{5}$$

where $\{\beta\}$ is the vector of influence coefficients
$[\grave{}A\lrcorner]$ is the diagonal matrix of panel areas
$[\grave{}C_p'\lrcorner]$ is the diagonal matrix of panel pressures
$[r]$ is the matrix of panel cross-correlation coefficients

Define $[F] = [\grave{}A\lrcorner][\grave{}C_p'\lrcorner][r][\grave{}C_p'\lrcorner][\grave{}A\lrcorner]$ (6)

where $[F]$ becomes a force coefficient covariance matrix which remains constant for a given geometry and terrain type:

$$\overline{\eta'^2} = \left(\tfrac{1}{2}\rho \bar{u}_h^2\right)^2 \{\beta\}^T [F] \{\beta\} \tag{7}$$

The above expression (7) can be used to calculate the variance of a number of structural parameters simply by changing the vector of influence coefficients, $\{\beta\}$, for each case.

In a similar way $[\dot{F}]$ can be defined as a derivative force coefficient covariance matrix:

$$[\dot{F}] = [\grave{}A\lrcorner][\grave{}\dot{C}_p'\lrcorner][\dot{r}][\grave{}\dot{C}_p'\lrcorner][\grave{}A\lrcorner] \tag{8}$$

whence $\overline{\dot{\eta}^2} = \left(\tfrac{1}{2}\rho \bar{u}^2\right)^2 \{\beta\}^T [\dot{F}] \{\beta\}$ (9)

If $\eta(t)$ can be assumed to be a Gaussian process (which should be a fair assumption when η depends upon a number of well separated regions because of the Central Limit Theorem), the peak values expected during time T_R can be shown to be (Davenport (1964)):

$$\eta_{peak} = \bar{\eta} \pm g \sqrt{\overline{\eta'^2}} \tag{10}$$

where g is a peak factor given by :

$$g = \sqrt{2 \ln \nu T_R} + \frac{\gamma}{\sqrt{2 \ln \nu T_R}} \tag{11}$$

and where γ = Euler's constant = 0.5772

ν is the process cycling rate $= \dfrac{\sqrt{\overline{\dot{\eta}^2}}}{2\pi \sqrt{\overline{\eta'^2}}}$ (12)

The above relationships have also been derived by Leicester and Hawkins (1978).

5.2 Examples

Using equations (3), (7), (9), (10), (11) and (12) from the previous section, the peak values of the overall lift, drag and overturning moment acting on the central bay of the house have been computed.

Table IV gives the influence coefficient vectors for these parameters. The effect of wind pressures under the eaves has been included by introducing dummy panels 2a and 9a which are assumed to be acted upon by pressures fully correlated with panels 2 and 9 respectively.

The results of the calculations are summarised in Table V. The calculations have been carried out for the full scale house, for which the bay width is 2.5 m, and for a mean velocity $\bar{u}_h$ of 30 m/s.

The gust factor, representing the ratio of the peak to the mean, is about 2.0 for lift and overturning moment, although the drag fluctuations have a somewhat higher value, probably due to the dominance of the well-correlated windward wall pressure fluctuations. It is interesting to

TABLE IV

INFLUENCE COEFFICIENTS

Panel #	β_L	β_D	β_M
1	0	1.000	.750
2	0	1.000	2.250
2a	.985	-.174	6.775
3	-.985	.174	-6.775
4	-.985	.174	-5.271
5	-.985	.174	-3.556
6	-.985	-.174	-3.091
7	-.985	-.174	-1.378
8	-.985	-.174	.127
9a	.985	.174	-.127
9	0	-1.000	-2.250
10	0	-1.000	-.750

TABLE V

CALCULATIONS OF OVERALL LOADS

	Lift	Drag	Overturning Moment
Mean Value (kN or kN.m)	7.42	2.40	39.7
R.M.S. Fluctuating value (kN or kN.m)	1.97	0.91	11.0
Cycling rate, ν (Hz)	0.66	0.82	0.76
Peak Factor, g (T_R = 10 minutes)	3.63	3.68	3.66
Peak Value (kN or kN.m)	14.56	5.76	80.1
Gust Factor, G ($= \frac{\text{Peak}}{\text{Mean}}$)	1.96	2.40	2.02

compare these values with those inherent in the procedures of the Australian wind loading Standard (SAA (1975)). It can be shown (Holmes (1976)), that the gust factor for overall loads implicit in the Standard is the *square* of the gust factor for the upwind velocities. At the eaves height of the house considered here, this gust factor is about 2.5-3.0. The higher value from this source is consistent with the generally conservative nature of the Standard.

The above procedure can be applied to other structural parameters of importance in design, such as tiedown loads on roof trusses or column loads.

6 CONCLUSIONS

A rational method of estimating peak overall structural loads has been described, which takes account of the correlation of pressures on a building, and is suitable for a small computer or even hand calculation. The measurement of the required pressure data can be carried out using most boundary layer wind tunnel facilities, and a single set of aerodynamic coefficients can be used to compute any number of different structural effects. The use of pneumatic averaging reduces the complexity of the measurement procedure as well as the final calculations making both operations more time-efficient.

7 ACKNOWLEDGEMENTS

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