

Computer Modelling of Turbulent Wind Flows over Buildings

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ABSTRACT

Two computer programs have been developed to compute turbulent flows over three-dimensional rectangular surface-mounted bluff bodies and the results have been applied to wind flows over buildings. The programs solve the steady state Reynolds equation using the $k-\epsilon$ model of turbulence. The partial differential equations are solved by the use of the SIMPLE algorithm on a staggered grid.

Program WIND computes the symmetric flow field over a single rectangular building and results are compared with two wind tunnel studies carried out by others. Good agreement has been obtained. Program COMPLEX is used to compute the asymmetric flow field over a group of buildings.

INTRODUCTION

The problem of wind flows over buildings and similar structures is a practical one. It is often important to know the pressures on a building surface and the loads (and vibrations) in the building due to these pressures. It is often also important to know the wind velocities around the base of the building and in its wake.

There are presently four main ways by which wind flow patterns around buildings are found: from full scale tests, from wind tunnel tests, from calculations based on published data, and from codes of practice. Each of these has certain drawbacks and the aim of the present research is to develop and test a fifth way which overcomes most of these drawbacks: computer modelling.

Two programs are used in the calculation of the results presented in this article. Program WIND is used to compute the symmetric flow around a single prismatic obstacle where the approach flow direction is perpendicular to the front face of the obstacle. Program COMPLEX is used in the computation of an asymmetric flow around two obstacles, one of which is not prismatic; the approach flow direction is not perpendicular to the front face of either obstacle. The programs differ only in the subroutines that calculate the grid, the initial approximation and boundary conditions. Program listings are given by Paterson (1986).

These programs are totally new and are not modified versions of existing programs. The solution method adopted follows the general guidelines set out by Patankar (1980) and by Gosman and Ideriah (1976) but the detailed solution methodology has been completely reworked. There have been several attempts by other workers to compute wind flows over buildings. One attempt, using a $k-\epsilon$ model of turbulence, was made by Vasilic-Melling (1976). All other known attempts use much cruder turbulence models and few compare their calculations with experimental measurements (an exception being by Hanson, Summers and Wilson (1986)).

Comparisons of predictions with two full scale studies and two wind tunnel studies have already been reported (Paterson and Apelt, 1985, 1986). These used an earlier version of program WIND. The main improvements

in the present comparisons have been due to changes in the boundary conditions on the edges of the buildings and to changes in the post-processing of pressures.

THE MATHEMATICAL MODEL

In the computations, the time averaged Reynolds equation and the continuity equation are solved with the help of a two-equation turbulence model called the $k-\epsilon$ model of turbulence which introduces extra equations for the turbulent kinetic energy k and the dissipation of turbulent kinetic energy ϵ . These equations are presented below.

$$\begin{aligned} U_j \frac{\partial k}{\partial x_j} &= \frac{\partial}{\partial x_j} \left[\frac{\nu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right] + \nu_t \left[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right] \frac{\partial U_i}{\partial x_j} - \epsilon \\ U_j \frac{\partial \epsilon}{\partial x_j} &= \frac{\partial}{\partial x_j} \left[\frac{\nu_t}{\sigma_\epsilon} \frac{\partial \epsilon}{\partial x_j} \right] - c_2 \frac{\epsilon^2}{k} \\ &\quad + c_1 c_\mu k \left[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right] \frac{\partial U_i}{\partial x_j} \\ U_j \frac{\partial U_i}{\partial x_j} &= \frac{\partial}{\partial x_j} \left[\nu_t \frac{\partial U_i}{\partial x_j} \right] - \frac{\partial P}{\partial x_i} \quad i = 1 \dots 3 \\ \frac{\partial U_j}{\partial x_j} &= 0 \quad \nu_t = c_\mu \frac{k^2}{\epsilon} \end{aligned} \quad (1)$$

where

$U_i \quad i = 1 \dots 3$ is the fluid velocity

ν_t is the turbulent viscosity

$P = \frac{\bar{P}}{\rho} + \frac{2}{3} k$ is the augmented pressure

$k = \frac{1}{2} \overline{u_j u_j}$ is the turbulent kinetic energy

$\epsilon = \nu \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j}$ is the dissipation of energy

$c_\mu, c_1, c_2, \sigma_k, \sigma_\epsilon$ are constants

In these equations the convention of summation over repeated indices is used. There are six equations (two for the transport of turbulent kinetic energy and its dissipation, three momentum equations and the continuity equation) to be solved for six unknowns (turbulent kinetic energy and its dissipation, three components of velocity and pressure). The values used for the constants $c_\mu, c_1, c_2, \sigma_k, \sigma_\epsilon$ are the same as those recommended in the original paper by Launder and Spalding (1974).

Five of the six partial differential equations are expressed in a standard form and integrated over an appropriate control volume to produce difference equations. These are solved by a three-dimensional version of the ADI (Alternating Direction Implicit) method. In obtaining the difference equations first order hybrid upwind differencing and a staggered grid are used. The remaining equation is the continuity equation and the remaining unknown is the pressure.

The method by which the pressure is calculated is known as SIMPLE (Semi-Implicit Method for Pressure Linked Equations). Instead of solving the continuity equation directly an equation is derived for the error in the pressure. The solution of this equation

is used to correct the pressures and velocities.

In program WIND (but not in program COMPLEX) the grid is generated automatically within the program. In the initial approximation a fluid source and sink are added to the basic boundary layer flow to produce a recirculation bubble that is about as large as the building would produce. The fluid velocities within the bubble are then adjusted to replace the source and sink by a recirculating flow. The turbulent kinetic energy and the turbulent energy dissipation are calculated from the velocities. In program COMPLEX the grid is read from a data file and the initial approximation is the basic boundary layer flow.

Dirichlet boundary conditions are used on the air-air interfaces and boundary conditions on the solid boundaries are calculated by means of wall functions. These wall functions are for three-dimensional rough wall constant density flow. They are calculated from integrals of the turbulent rough wall boundary layer and are incorporated in the difference equations by modifying the source terms in those equations. Post-processing is done by separate specially developed programs.

COMPARISON WITH EXPERIMENTS BY CASTRO AND ROBINS

Castro and Robins (1975, 1977) measured velocities near and pressures on a 200 mm cube in a wind tunnel. Velocities were measured using a pulsed wire anemometer. The results selected for comparison were taken from the measurements reported in both of the above references and were limited to the case with a turbulent boundary layer approach flow with the front face perpendicular to the approach flow direction. Pressures, mean velocities and turbulence intensities are compared with computed predictions.

In Figure 1 the computed predictions of pressures on the faces of the cube are compared with the experimental measurements by Castro and Robins. In this figure the reference velocity is the velocity at the top of the boundary layer. Also shown are the computed predictions by Vasilic-Melling (1976) and some earlier predictions by the authors (Paterson and Apelt, 1985, 1986). It can be seen that the present predictions are much more accurate than those by Vasilic-Melling and are more accurate on the side and top faces of the cube than the earlier predictions by the authors. The accuracy of the present predictions of the pressures on the side and rear faces is surprisingly good but there are some differences between the predictions and measurements at the front of the top face and at the bottom of the front face.

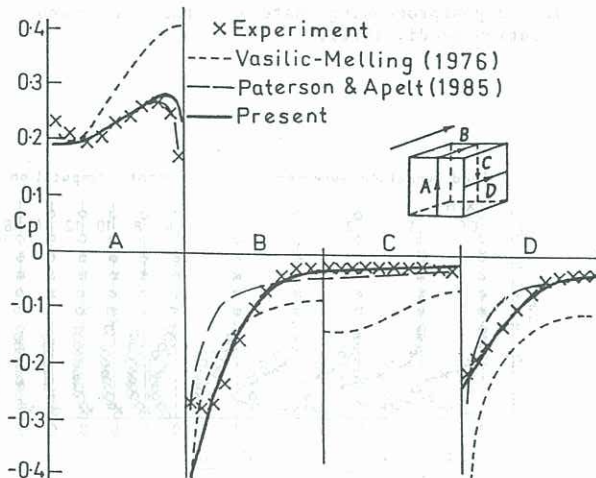


Fig. 1 Pressure on Surface of Cube

In Figure 2 predictions and measurements of the transverse profile of the longitudinal velocity are shown. This profile was taken at a height of $0.5h$ and a distance of $2.5h$ behind the cube where h is the height of the cube. Again it can be seen that the present predictions are much more accurate than those by Vasilic-Melling and are more accurate than the earlier predictions by the authors.

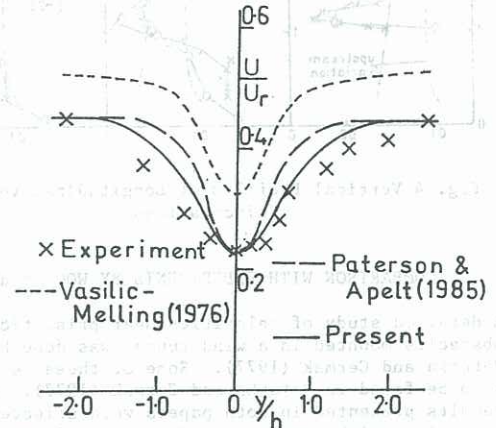


Fig. 2 Transverse Profiles of Longitudinal Velocity

Comparisons of measured and computed vertical profiles of longitudinal velocity above the cube and downstream from it are shown in Figure 3. As with pressure, the overall agreement is very good. The location $x/h = 0.5$ is the centreline of the cube. There are slight differences between measured and predicted values at $x/h = 1.5$ ($0.5h$ behind the cube) where the flow is highly turbulent and is difficult to measure and predict accurately. The length of the rear recirculation region is well predicted.

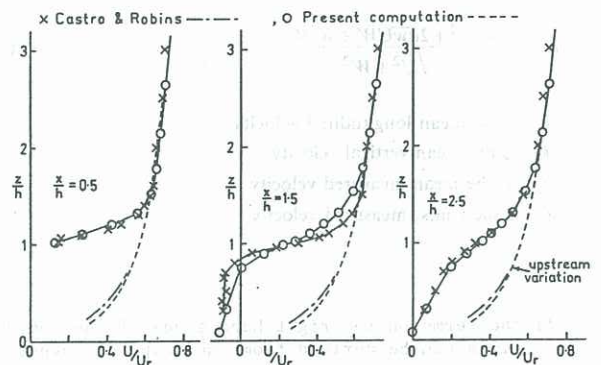


Fig. 3 Vertical Profiles of Longitudinal Velocity

Measured and computed vertical profiles of the longitudinal velocity fluctuations are shown in Figure 4. Exact agreement between the measured and computed profiles is not to be expected for two reasons. The magnitude of the velocity fluctuations upstream from the cube in the wind tunnel study is very different from that in the computer study, and the variables that are compared are different and the best that can be expected is:

$$.82 k^{1/2} \leq \overline{u' u'}^{1/2} < 1.41 k^{1/2} \quad (2)$$

Despite obvious differences, the agreement between the measured and computed profiles is quite good.

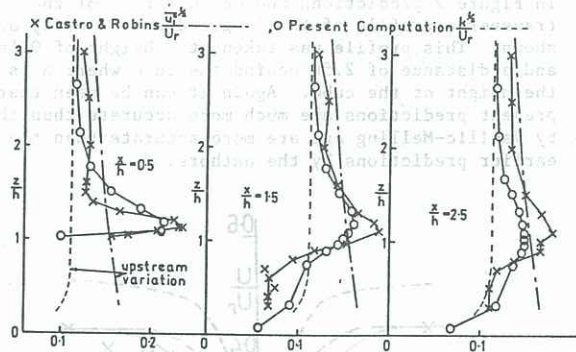


Fig. 4 Vertical Profiles of Longitudinal Velocity Fluctuations

COMPARISON WITH EXPERIMENTS BY WOO et al.

A detailed study of velocities near prismatic obstacles mounted in a wind tunnel was done by Woo, Peterka and Cermak (1977). Some of these results can also be found in Peterka and Cermak (1977). Some results presented in both papers were selected for comparison with computer predictions. Comparisons are made with mean velocities and turbulence intensities behind a block 15.9 cm by 4.9 cm by 6.5 cm in height for the case where the approach flow is perpendicular to the front face of the block.

The experimental measurements were taken with a single horizontal hot film probe and, so, are not directly related to the velocity components in the output of the computer program. However, the output from such a probe can be calculated from the computed velocity components, to second order accuracy, from the following equations.

$$U_m = \sqrt{U^2 + W^2} + \frac{u^2 + w^2}{2\sqrt{U^2 + W^2}} - \frac{u^2 U^2 + 2uwUW + w^2 W^2}{2\sqrt{(U^2 + W^2)^3}}$$

$$u' = \frac{u^2 U^2 + 2uwUW + w^2 W^2}{\sqrt{U^2 + W^2}} \quad (3)$$

U is the mean longitudinal velocity

W is the mean vertical velocity

U_m is the mean measured velocity

u' is the r.m.s. measured velocity

All the terms on the right hand sides of the above equations can be derived from the computer output.

Profiles of the mean velocity and of the turbulence intensity in the approach flow are shown in Figure 5. The turbulence intensity profile reported by Woo et al. differs from that reported by Peterka et al. Exact agreement between the measured values and computed predictions is not to be expected and the level of agreement obtained is considered to be adequate.

Vertical profiles of the mean velocity defect behind the block are shown in Figure 6. The values of x/h on this graph are based on $x=0$ being at the back of the block. Overall, the agreement is good. For $x/h = 6$ the computed prediction is too large for $z/h < 1$ and too small for $1.5 < z/h < 3$. The reason for this discrepancy is unknown.

Vertical profiles of the turbulence intensity excess are shown in Figure 7. The irregular shapes of the predicted profiles for $x/h < 4$ are probably due to the inaccuracy of the post-processing procedure.

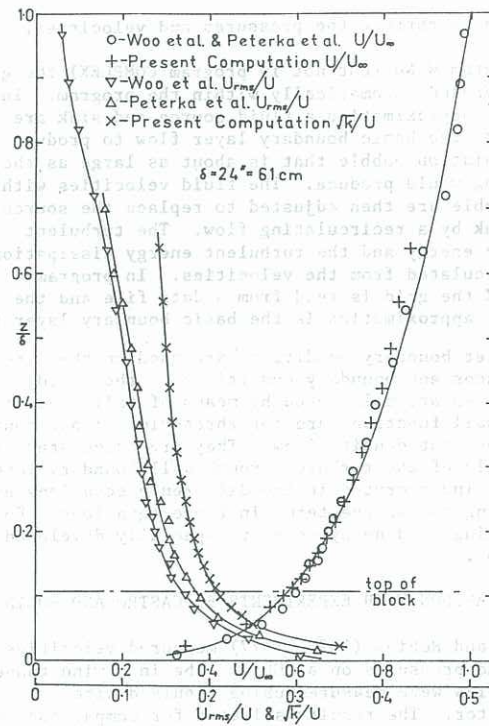


Fig. 5 Mean Velocity and Turbulence Intensity in Approach Flow

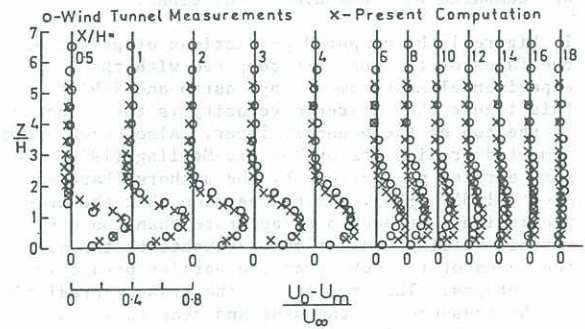


Fig. 6 Vertical Profiles of Mean Velocity Defect

Overall, the agreement is good but near the ground the computed predictions are too large and at z/h values of about two the computed predictions are too small. It is possible that better results could be obtained if the algebraic stress equations were used in the postprocessing instead of the Boussinesq equation (Rodi, 1976).

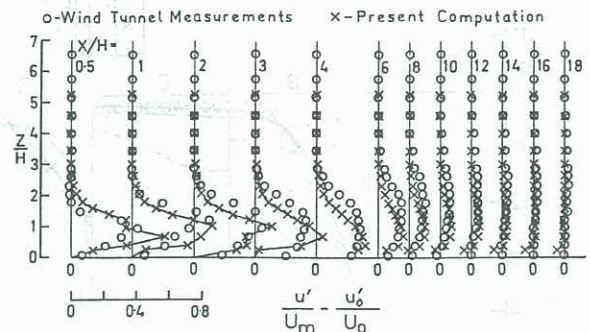


Fig. 7 Vertical Profiles of Turbulence Intensity Excess

FLOW OVER A TYPICAL BUILDING COMPLEX

Program COMPLEX has been used to compute the flow around a fictitious building complex. A plan and an elevation of the complex, with the grid layout in the vicinity of the building, are shown in Figure 8. Paths of particles released into the mean flow field upstream from the building complex are shown in Figures 9 and 10. These particle paths are also streamlines. The particles were all released at a height of two metres above ground level.

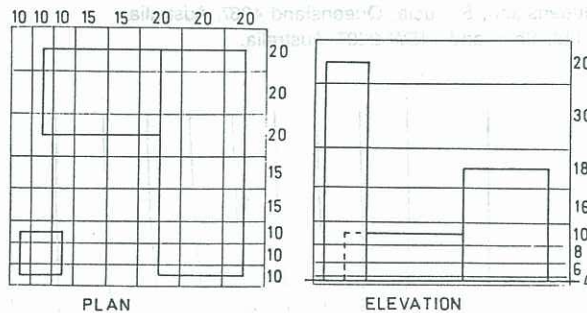


Fig. 8 Typical Building Complex

Figure 9 is an oblique top view of the building complex. Nine particles were released upstream of the building complex (lower left) and approach at an angle of 15 degrees. Three of the particles pass around the outside of the building complex; four are dragged into the recirculation region behind the main building before leaving it at the top; and two enter the recirculation region behind the front tower and are swept up to pass over the main building.

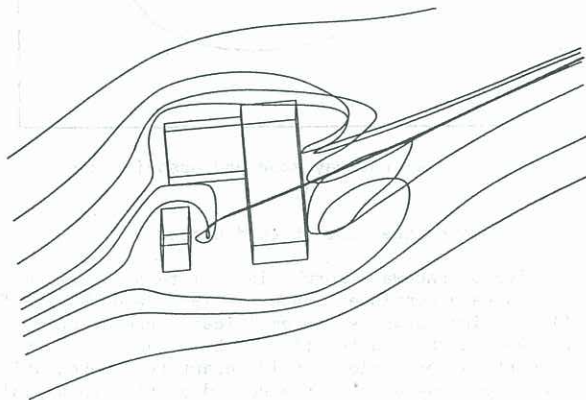


Fig. 9 Flow over Building Complex - Top View

Figure 10 is a side view of the building complex. The same nine particles have been released upstream and an extra particle has been released into the recirculation region behind the front tower. The results appear to be qualitatively correct but have not been checked against experimental data.

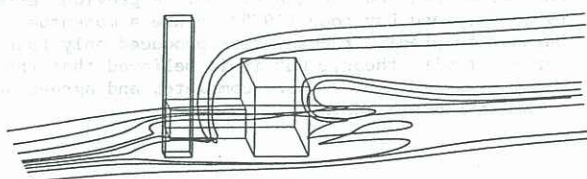


Fig. 10 Flow over Building Complex - Side View

CONCLUSIONS

It has been shown that accurate predictions of wind pressures on and velocities near buildings can be obtained by computer modelling when a $k-\epsilon$ model of turbulence is used and the equations are solved by the use of the SIMPLE algorithm on a staggered grid. It has also been shown that the solution method can be applied to the asymmetric flow over a group of buildings.

These calculations did not involve an excessive amount of computer space or time. They were carried out on an IBM 3083E and each run required less than 1.5 Mbytes of storage and 30 c.p.u. minutes processing time.

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