DRAG OF A BLUFF BODY IMMERSED IN A ROUGH-WALL BOUNDARY LAYER

TRAINÉE D'UNE PLAQUE MASSIVE IMMERGÉE DANS UNE COUCHE DE SURFACE TURBULENTE SUR UNE PAROI RUGEUSE

by

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Abstract

Experiments have been carried out in a wind tunnel on two kinds of two-dimensional roughness arrays and on one array of three-dimensional roughness with a turbulent boundary layer growing over the arrays.

The drag coefficient on an individual element has been measured by pressure tapping as its height was varied relative to the average height.

For the two-dimensional cases some general forms for the drag coefficients have been found.

The results for the three-dimensional case show some general trends but more work needs to be done.

Glossary of terms.

u - mean velocity at a distance y from some datum.

Δu - velocity decrement of rough-wall layer compared with smooth wall layer

U_τ - friction velocity = $\sqrt{\tau/\rho}$

τ_o - wall shear stress

ρ - density of air

δ - boundary layer thickness

U_1 - free stream velocity

C_{D_1} - drag coefficient based on U_1

C_D - drag coefficient based on some velocity located above building

$C_{D\tau}$ - drag coefficient based on U_τ

k - scale of the roughness

h - height of building

A - aspect ratio (breadth to height ratio)

ν - kinematic viscosity

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g - gap between buildings

ε - distance below building crests to effective origin for boundary layer

λ - pitch of buildings in an array

M - characteristic constant for roughness

K - Karman constant (= 0.41)

x - the fetch - that is, streamwise distance measured from origin of boundary layer

ς - a surface drag parameter $\left(= U_W / \sqrt{D/\lambda\rho} = \frac{U_W}{U_\tau}\right)$

u_W - wall velocity at crest of buildings found by extrapolation

Y - distance from ground level

w - streamwise width of building

N - characteristic constant for roughness

1. Introduction

One of the main problems with the prediction of drag on buildings is to gain information and understanding of the flow about buff bodies immersed in turbulent boundary layers. Basic work along these lines has proceeded at the University of Melbourne over the last twelve years.

Stevens, Joubert and Robertson (1961) discussed wind forces on tall buildings and in particular, experimental results of pressure distributions on a model of a tall building and compared these results with standard codes of practice. Joubert, Stevens and Perry (1962) reported experimental results on the effect of aspect-ratio on wind forces on building models. It was shown that frontal aspect-ratio is the more important variable and the effect of increasing the horizontal side dimension is conservative.

Perry and Joubert (1963) classified rough wall boundary layer action in terms of wall variables and the roughness geometry. A general method was developed for measuring the local boundary layer characteristics using the properties of the wake and aligning the velocity profile in the logarithmic region to be a straight line thus establishing the roughness function, $\Delta u/u_\tau$. This allows the origin of the log law to be found which has always been a difficulty with rough walls. The roughness used in these experiments was all two-dimensional of square cross-section.

Good and Joubert (1968) studied the form drag of a two-dimensional bluff plate immersed in a turbulent boundary layer.

Prior to this work it was generally assumed that bluff bodies produce constant drag coefficients. Even when the bodies were immersed in turbulent boundary layers, workers such as Plate (1964), Hoerner (1965) and Nash & Bradshaw aimed at finding correlating parameters which would give constant coefficients. Good & Joubert found that the drag coefficient depended greatly on boundary layer variables such as the thickness, δ, and friction velocity U_τ which existed at the same streamwise position in the flow as the bluff plate when the plate was not there.

For zero pressure gradient layers the drag coefficient based on the shear velocity is given by

$$C_{D_\tau} = \frac{D}{\frac{1}{2}\rho U^2 h} = f\left[\frac{h\,U_\tau}{\nu}, \frac{h}{\delta}\right]$$

(where h is the bluff plate height) and for small $\underline{h}$ a "wall similarity" law of the form

$$C_D = f\left[\frac{h\,U_\tau}{\nu}\right]$$

was found.

The deviations from wall similarity for the drag coefficient, due to effects of the outer-flow variables were found to depend on h/δ only. This can be expressed by a "drag-defect law",

$$C_D\ (h) - C_D\ (\delta) = f\left[h/\delta\right]$$

which is analogous to the well known "velocity defect law" for zero pressure gradient layers.

When isolated three-dimensional bluff plates immersed in turbulent boundary layers are considered, the problem becomes more complicated.

Hoerner in his book (1965) presents the effects of aspect-ratio on the drag of bluff plates placed in uniform unbounded streams. The curve is symmetrical about $A = 1$ and is almost independent of Reynolds number. The drag coefficient is fairly insensitive in the range $\frac{1}{4} < A < 4$.

Quite different effects can be expected when one edge of the plate is attached to a wall and the incident stream is no longer uniform. For one thing the effect of aspect-ratio can no longer be symmetrical. Also the parameter h/δ can be expected to play an important part.

For small values of h/δ a correlation scheme similar to the two-dimensional results, should apply.

$$C'_{D_\tau} = \frac{D}{\frac{1}{2}\rho U_\tau^2 hb} = f\left[\frac{h\,U_\tau}{\nu}, \ h/\delta\ , \ A\right]$$

and for small h/δ

$$C_D = f\left[\frac{h\,U_\tau}{\nu}\right]$$

Preston tubes depend on this relation and are known to work.

For large h/δ, the alternative correlation

$$C_{D_1} = f\left[h/\delta\ , \ U_\tau/U_1\ , \ A\right]$$

may be useful. However this is outside the usual range of building dimensions.

Some experimental results presented in this manner, are given by Joubert, Stevens, Good, Hoffmann and Perry (1968) and are included in figure 9.

It appears that in the range 1 to ∞, aspect-ratio has a small effect on the drag coefficient, whereas the parameter h/δ has a considerable effect.

Unlike the work considered so far, the majority of real situations are involved with bluff bodies immersed in rough-wall turbulent boundary layers. Furthermore, these bodies are not always isolated and may sometimes form part of an array.

This paper first discusses an array of two-dimensional bluff bodies and second an array of three-dimensional bluff bodies.

2. Array of two-dimensional bluff bodies.

Such an array forms the roughness elements of a rough wall turbulent boundary layer.

Perry, Schofield and Joubert (1969) classified roughness into two kinds: "k" type where the roughness function $\Delta u/U_{\tau}$ depends on the scale of the roughness k and "d" type where the roughness function depends, for flow in a pipe, on the pipe diameter d. For the case of zero pressure gradient boundary layer flow it appears that d can be replaced by δ, the boundary layer thickness.

Again, two-dimensional square cross-section roughness was used. The resistance of the rough wall was found from very detailed measurements of the pressure distributions on the front and rear faces of the elements. Part of the experiment involved finding the errors in resistance due to misalignment of the crests of the elements.

These results have application to flow across large industrial plants or housing estates. By re-analysing them into terms more related to the drag on buildings they may shed some further light on the problem of wind resistance.

Suppose it is desired to find a drag coefficient of the n^{th} building counted from the first upwind building as shown in figure 1.

The undisturbed wind profile approaching the building site is represented as a boundary layer of thickness δ_o and whose thickness does not change appreciably with streamwise distance. Above the site, an inner boundary layer of thickness δ develops and it is within this layer that the original layer is perturbed from its distribution of velocity. The outer layer is so thick that its presence has small influence on the new development.

For the "d" type roughness shown in figure 2, the ratio g/h is small enough (<1) to enable fairly stable vortices to be set up in the gaps between the buildings.

The thick streamlines stagnate near the top corner of the building and a typical profile of pressure difference across an individual building is shown in figure 3. Note the peak pressure near the top.

It has been found that the location and value of this peak pressure and hence the drag, depends critically on how the stagnation streamline behaves. This stagnation streamline moves about due to the turbulence structure in the boundary layer above the buildings, hence the dependence of the roughness function on the outer flow variable δ.

Drag coefficients of individual buildings, when based on the velocity measured immediately above them and lying within the new inner boundary-layer, will depend on the turbulence structure and hence will depend on the fetch x. This is another example of a drag coefficient of a bluff body which is not constant.

If the wind profile above the array is measured relative to some origin located $\mathcal{E}$ below the building crests, then a logarithmic distribution may be found by plotting u versus log Y and by trial and error subtracting distances $(h - \mathcal{E})$ from Y until a straight line is produced (see figure 4).

It was found for this array that $\mathcal{E} \propto \delta$ and $\delta \propto x$ and the constants of proportionality depend entirely on the parameter λ/h for a fixed building shape. The drag coefficient $C_D = D/\frac{1}{2}\rho u^2 h$, where D is the drag per unit run of building and u is a velocity measured Y above the ground, is given by

$$C_D = \frac{2\lambda/h}{\left[\frac{1}{K} \cdot \ln\left(\frac{Y - (h-Mx)}{Mx}\right) + \xi\right]^2} \qquad \text{for } Y < 0.2\delta, \ \delta \gg h$$

which is the approximate outer limit of log law. K is the Von Karman constant $\simeq 0.41$ and $\xi = u_w \Big/ \sqrt{D/\lambda\rho}$

The velocity u_w shown in figure 2 is found by extrapolating the log profile to the crest of the buildings. The constant M depends only on λ/h and w/h and so does the constant ξ.

For $Y \gg \delta$, C_D becomes constant.

$$C_D = H\left[\lambda/h, \ w/h\right]$$

This constant drag coefficient, independent of the fetch x, is obtained only if $Y = h$ or if $Y > \delta$. The latter position for measuring the reference velocity is not always practical. It is then possible to find a drag coefficient by following the described procedure, although it is necessary to know the wind profile over some height of the building line.

Another feature of the "d" type roughness is that any misalignment of the crests of the buildings can cause large changes in their drag.

Figure 5 shows the effect of a building being Δh higher than the general building line. Figure 6 shows the dramatic change in the drag.

For the "k" type array, $g/h > 1$ and the vortices between the buildings become unstable. With the change in the flow pattern the drag law changes suddenly. The drag coefficient of individual buildings are now insensitive to both the turbulence structure in the boundary layer above and any small misalignment of the building crests. For $\Delta h/_h = 2\%$ changes in drag are undetectable. Again it is found that

$$C_D = \frac{2\lambda/h}{\left[\frac{1}{K}\ln\left[\frac{Y - (h - Nh)}{Nh}\right] + \xi\right]^2} \qquad \text{for } Y < 0.2\delta \text{ and } \delta \gg h.$$

Here N is a constant dependent only on λ/h and w/h as is ξ. Unlike the previous case, if C_D is based on some reference velocity at a distance $Y < 0.2\delta$, then provided Y is some standard factor times h, then

C_D is constant and is independent of the fetch. On the other hand if $Y > \delta$, which means that C_D is based on U_1, then C_D is an extremely complicated function of the fetch. This problem has been solved by Rotta (1962) but involves the use of charts and there are difficulties in determining an effective origin for the fetch. The variation of C_D versus fetch for $Y > \delta$ is shown in figure 7.

This "k" type array would occur in practice more often than the "d" type and it is fortunate that a constant drag coefficient does have meaning for this two-dimensional roughness in a turbulent boundary layer with an easily measured velocity close to the building line.

3. Three dimensional bodies on rough walls.

Some preliminary experiments have been conducted with a bluff model at a set position in a three-dimensional roughness field. The field was composed of 3" cubes spaced 6" apart transversely and 9" apart longitudinally, with all the cubes lying on diagonal lines (i.e. there was a 3" lateral stagger from one transverse row to the next.).

The pressure-tapped model was 3" wide x 1¼" deep and its height could be varied from zero to 10½" above the ground. It was positioned in place of a cube on the centre-line of the wind tunnel, 10 feet from the leading edge of the field. The field was placed on the floor of the wind tunnel at the University of Melbourne, the floor being 3'6" wide. The field extended 3'0" beyond the model position.

The velocity profile was measured above the position of the model and is shown plotted semi-logarithmically in figure 8. The results are shown below and the Reynold's number of the tests may be found using a velocity of 60 ft/sec. in standard air.

Table I.

	$A = b/h$	C_{P_1} Windward	C_{P_1} base	C_{D_1}	h/δ
1	10	-0.02	-0.16	0.14	0.02
2	5	-0.02	-0.16	0.14	0.04
3	3.3	-0.03	-0.16	0.13	0.05
4	2.5	0	-0.18	0.18	0.07
5	1.7	0.04	-0.21	0.25	0.1
6	1.3	0.04	-0.21	0.25	0.13
7	0.95	0.08	-0.23	0.31	0.18
8	0.8	0.08	-0.25	0.33	0.22
9	0.6	0.1	-0.3	0.41	0.3
10	0.52	0.2	-0.35	0.55	0.34
11	0.43	0.2	-0.42	0.62	0.4
12	0.38	0.25	-0.46	0.71	0.46
13	0.35	0.3	-0.54	0.84	0.59
14	0.29	0.4	-0.6	1.0	0.61

Note that all quantities have been measured relative to the ground (e.g. δ = 16"). The accuracy of the absolute values could not be guaranteed to better than ± 10% and therefore can only show the trend of results.

The plot of the drag coefficient against aspect-ratio is shown in figure 9.

The parameter h/δ may be an important variable in this rough wall study as it was for the smooth wall. However, as it was not varied independently this point needs checking by further experiments.

All that can be said is that the results show the same trends as the smooth wall case and it may be possible after further work to deduce some laws of behaviour.

There is one other aspect worth mentioning, namely the effect of the upstream roughness in shielding the bluff model when h is less than the average roughness height (region of $A > 1$ on figure 9) which results in a low drag coefficient. Wind codes could well allow for this reduction.

4. Conclusions.

1. For the type of two-dimensional roughness array with unstable vortices between the elements, the drag coefficient on an individual element is constant and independent of the fetch when it is based on a velocity measured above the element at a spacing some multiple of the element height provided this measuring lies within the logarithmic portion of the velocity profile.

2. When the gap between the elements is decreased to the stage where stable vortices are formed between the elements, then the drag coefficient defined before is no longer constant but depends on the fetch. A constant drag coefficient can be found for this case by using the free stream velocity.

3. When the height of the individual element rises slightly above the average height of the array, then the drag coefficient increases very rapidly and vice versa. This is only true for the arrangement with stable vortices between the elements.

4. An experiment on a three-dimensional bluff body in an array of three-dimensional roughness showed that the drag coefficient varied with changes in both h/δ and aspect-ratio. More experiments are required to clarify the interaction.

5. References.

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10. Stevens, L.K., Joubert, P.N. and Robertson, B.D. Wind forces on tall buildings. Symposium on the design of high buildings, University of Hong Kong, Golden Jubilee Congress, 1961.

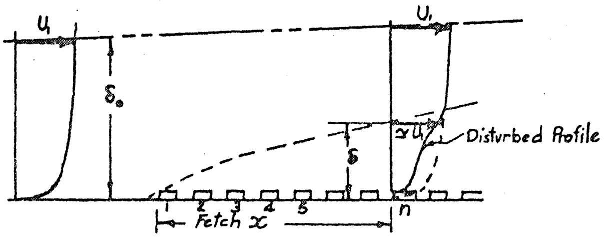

Fig. 1. Inner boundary layer growth over an array of roughness elements.

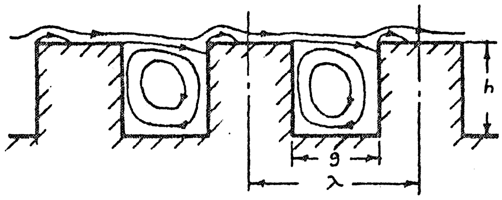

Fig. 2. "d"-type roughness array showing stable vortices.

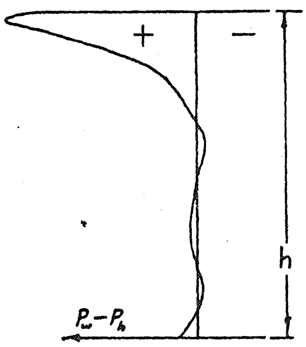

Fig. 3. Pressure pattern on individual element in a "d"-type array. P_w = windward pressure. P_b = base (leeward) pressure.

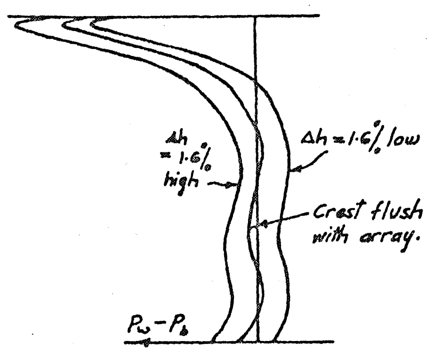

Fig. 5. Effect of crest misalignment on pressure pattern on individual element in a "d"-type array.

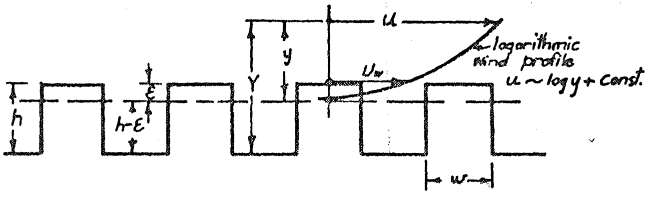

Fig. 4. Figure showing roughness geometry and its relation to the origin for the outer flow.

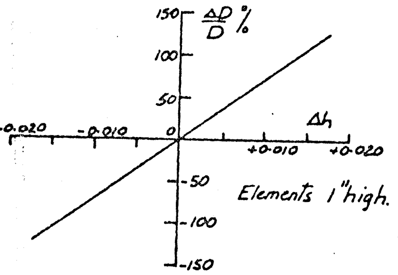

Fig. 6. Variation in drag due to element misalignment in a "d"-type array.

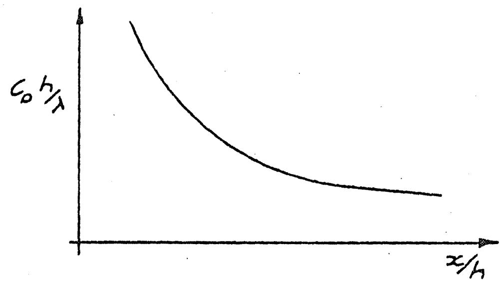

Fig. 7. Variation of drag coefficient based on free-stream velocity for an individual element in a "k"-type array.

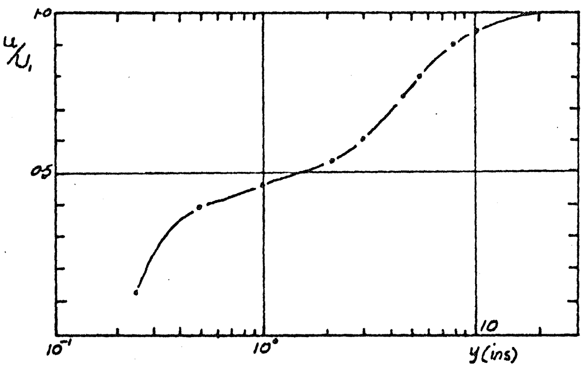

Fig. 8. Velocity profile recorded on top of a 3 inch bluff body in a three-dimensional array.

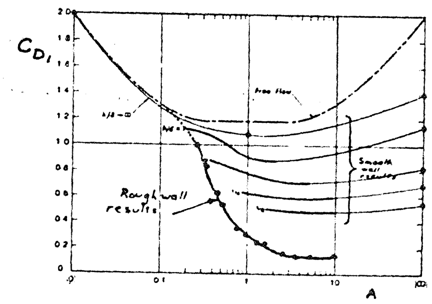

Fig. 9. Results of three-dimensional bluff body in roughness array compared with body immersed in smooth wall boundary layer after Joubert et al (1968).