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# The Prospect ahead

P. R. Owen

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# The prospect ahead

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The exacting nature of the problems of architectural aerodynamics and some of the difficulties of obtaining an accurate solution to them from laboratory experiments are described. Among the latter is the uncertainty associated with scale effect, which requires for its resolution more observations of the flow patterns about, and measurements of the wind pressures on, actual buildings and structures. The possibility of constructing a special wind tunnel is also mentioned.

A dual approach to aerodynamic research is advocated: such that work in large wind tunnels, with complicated architectural models and elaborate simulation of the atmospheric wind, proceed in parallel with investigations on a simpler scale. The latter should concentrate on fundamental aspects of bluff body flows; particularly their unsteady components, their interaction with shear and turbulence in the approaching stream, as well as their dependence on the shape of the body, on any vibration it may exhibit and on its interference with neighbouring bodies. Examples are given of some of the subtle and surprising features of such flows.

The architect is invited to specify the accuracy he requires of aerodynamic data and is urged to regard the wind-tunnel test, with full representation of the atmospheric wind and its turbulent structure, as a routine element in the design process.

## 1. INTRODUCTION

If an attempt is made to amalgamate the themes and ideas presented during the past two days, the result is a definition of architectural aerodynamics that is forbidding in its complexity. For, in its most general terms, architectural aerodynamics is concerned with the flow, under the influence of the Earth's rotation, of a turbulent, sheared, thermally stratified fluid about a bluff body or group of bodies which can be man-made or part of the natural topography. To make matters more difficult, the bodies may deform and oscillate under the imposed wind loads: and the wind itself, capable of only a statistical description, has a structure that is strongly influenced by the nature of the ground, especially that upstream of the bodies in question.

On listing the parameters involved—such as the Reynolds number, Richardson number, the wind shear parameter and the non-dimensional frequencies associated with the unsteadiness of the wind and the characteristic modes of oscillation of the body or structure—it quickly becomes apparent that there can be no precise answer to the problem available from laboratory experiments.

I must emphasize the word 'precise' in that seemingly depressing statement, for I believe that upon it hinges the future aerodynamic prospect and the challenge it contains.

In the first place we recognize that, taken literally, the need for a precise answer leads to an absurd situation. To every building, every chimney, every embankment, every bridge, every hill, every set of atmospheric conditions, there belongs a distinct pattern of airflow; and it is inconceivable that the architect's thirst for precision is so unquenchable as to persuade him to erect a full-scale test structure as a preliminary to his final design. Recourse to the laboratory and the acceptance of some degree of approximation are essential.

If, then, the wind tunnel is to be regarded as the primary means of obtaining information about new designs, two statements are called for which, it is to be hoped, will converge in time. The

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one, from the architect, is the degree of accuracy he requires; the other, from the aerodynamicist, is the accuracy he believes his wind tunnel to achieve.

Neither statement has, to my knowledge, yet been given unequivocally; nor is it likely to be the same for all situations, since the quality of the information required to determine the effect of a building on the flow in its environment, of the kind described in the paper of Mr Wise, may be coarser than that needed to evaluate the pressures exerted by the wind on the fabric of the building and their influence on its structure. Until the demands of the architect are put in quantitative terms, the aerodynamicist will continue to regard his experimental work critically, *perhaps over-critically*; at the same time, he will seek to establish the reliability of his measurements by comparing them with full-scale data. Unfortunately, there are insufficient of those available to enable even such a crucial matter as the effect of Reynolds number to be assessed.

## 2. The need for full-scale measurements

The first challenge therefore is for more full-scale measurements of the time-dependent wind loads on buildings and other forms of structure: as so many speakers at this meeting have emphasized. They should be comprehensive with regard to the area of the building explored and to the range of atmospheric conditions encompassed and ought, if possible, to include a reference measurement of the upstream flow; above all, they must be reliable. Experiments of this kind have been made, and are still in progress in this country, by the Central Electricity Generating Board and by the Building Research Station (Newbury, Eaton & Mayne 1968); but more are needed not only to establish the accuracy of the wind tunnel but to reveal phenomena that might be obscured by operating an experiment at a reduced geometrical scale. A similar treatment of *flow patterns* around buildings has been urged by Dr Hunt. Coupled with this need for full-scale information, it appears to be fashionable to claim that there is the equally difficult one for more data on the turbulent structure of the wind itself, especially that over cities where it comes under the influence of buildings and distant topographical features; I shall comment on that claim presently. But it has to be acknowledged that such measurements are protracted and costly. In the meantime, one is compelled to work with the tools available in the laboratory.

## 3. Dual approach to wind-tunnel experiment

The approach to wind-tunnel experiment seems to lie in two distinctly stated, none the less interacting, directions. The first, aimed at acquiring data of immediate practical value to the architect, involves the use of the largest wind tunnels available and the elaboration of technique in order to reproduce as accurately as is necessary geometrical detail of the structure and its environment, its elastic properties, and the known features of the atmospheric wind. The second, which might well be accomplished with simpler apparatus, is to study the fundamental character of the flow about bluff bodies; its unsteady components and the way in which it is influenced by other bodies and by the turbulence and shear in the approaching stream.

This fundamental attack is not suggested for its scientific merit alone. A deeper understanding of the subtleties of bluff body flows, if only on a qualitative basis, will surely be of value to the architect in providing him with a warning of the problems he is likely to encounter and of those forms of design he should avoid.

The ease with which such objectives can be stated does not conceal the difficulties involved in

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achieving them, and the rest of this talk will be devoted to listing some of the problems facing the aerodynamicist. For that purpose, it will be convenient to separate broadly questions concerned with the environment from those concerned with the evaluation of wind loads.

## 4. Environmental problems

Environmental problems fall into two main classes: the dispersion of effluent and the influence of topography or buildings on the flow about other buildings or people or over neighbouring terrain.

The wind-tunnel study of the behaviour of effluent discharged from chimneys in open country, in the detail sufficient to provide design information, as opposed to scientific information, presents serious difficulties if atmospheric conditions other than the neutrally stable are to be considered: as Dr Craxford and Dr McCormick acknowledge in their papers. For, even in neutral conditions an attempt must be made to simulate the mean streamlines of the wind and its spectrum of turbulence: and both depend on the nature of the terrain surrounding the chimney and exposed to its plume, as well as the terrain far upstream from it. In that last respect, Panofsky (1969) has drawn attention to spectral measurements made in the United States of atmospheric turbulence over cities. They suggest the existence of energetic motions on a scale, in the direction of the wind, of the order of kilometres. They presumably arise from mesoscale topographical irregularities: in which case there seems to be little prospect of generating them in wind tunnels. The inclusion of a *temperature profile* adds to the difficulty, especially if an attempt is made to simulate the important practical situation in which a stable atmosphere layer is formed above an unstable one at a moderate distance from the ground. While, in principle, such a temperature inversion might be produced in a suitably large wind tunnel, it invites speculation about the constraint imposed by the wind-tunnel walls; for, if a gross non-uniformity is imposed on a wind-tunnel stream, motions will be generated on a scale comparable with the dimensions of the tunnel working section: and such motions may have no counterpart in a real atmosphere. In addition, experiments of this kind with temperature stratified flows cannot reproduce correctly both Richardson number and Reynolds number simultaneously, unless a fluid different from the actual full-scale fluid is used.

However, there is at least one problem of chimney effluent discharge which merits study on a smaller scale, where one would be prepared to sacrifice dynamical similarity to physical insight. It is the behaviour of a naturally buoyant or forced plume in a cross-wind. In common with the classical aeronautical problem of a jet in a cross-wind, its physical details are still elusive. The crucial question is: what is the fluid dynamical mechanism causing the plume to turn from the vertical into the wind? Following that, one is led to inquire into the consequences of the secondary motions developed as a result of the bending of the plume on its mixing with the surrounding air. Although semi-empirical formulae for the plume's trajectory exist, one would feel more confident in applying them to a variety of situations if the physics of the phenomenon were better understood. After all, the effective chimney height—that is to say, the height to which the plume rises under the action of buoyancy and its own momentum—is a sensitive initial condition in an estimate of the subsequent dispersion of the plume and its concentration on reaching the ground.

After injecting this isolated problem into the discussion, I should like to return to the question of wind-tunnel technique: in particular, the simulation of wind profile and turbulent structure

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and their dependence on the details of the terrain—but excluding those on a very large scale. The question is central to the problem of experiments in architectural aerodynamics and appears in relation both to environmental and loading measurements. If there were some archetypal wind structure the problem could be resolved economically, once for all, by the use of vortex generators and distributed roughness of the kind successfully developed and explored by Armitt & Counihan (1968); Counihan (1969) at the Central Electricity Research Laboratories: an extension of the pioneering work of Jensen & Franck (1963). For they devised a method of reproducing not only the mean velocity profile but important constituents of the turbulent structure of the lower part of the atmosphere very rapidly in a wind tunnel, thereby dispensing with the need for a long working section of the type found in the tunnels at the University of Western Ontario and the Colorado State University. However, Armitt's and Counihan's work was confined to the neutrally stable atmosphere over flat, rural territory: a reasonable environment in which to generate electricity. Other wind profiles and turbulence spectra, and perhaps even temperature profiles, could be produced by this technique, but in complicated ground conditions, such as an urban area or hilly country, a difficulty at present lies in knowing *precisely* what atmospheric properties one is required to simulate. Here, if precision is necessary, one must return to the plea for further meteorological data. But the important point for the architect to note is that, where meteorological data are available or become available, Armitt & Counihan have provided a powerful method of reproducing them in the wind tunnel.

It seems then that I have again followed the fashion of the meeting in demanding more information about turbulence from the meteorologist. Now, there are many good reasons for encouraging more turbulence measurements in the atmosphere, but I confess to what is seemingly a heresy in believing that those given at this meeting are not among the most pressing. Surely, the requirements of the architect, irrespective of whether his question is one of environment or of wind loading, are principally for data on *extreme* values of wind speed, the aerodynamic consequences of which might be evaluated on a quasi-stationary basis. To be sure, it would be helpful to know how such extreme winds are distributed with respect to height during the period of their existence, so that the shear appropriate to them may be represented in the wind tunnel: possibly, their distribution of velocity is more nearly uniform than that of the mean wind. But, apart from such information about the energetic meso- and macro-scale components of the wind under neutral and unstable atmospheric conditions, I find it difficult to justify the requests being made to the meteorologist for data covering the entire turbulent spectrum. Sufficient data, of the kind described in the paper by Dr Pasquill, are already available about the micro-meteorological spectrum to construct a wind-tunnel stream which will provide measurements, satisfactory to the architect, of the unsteady forces on his structure and the fluctuating-pressures exerted on cladding. If that structure and its environment are so sensitive to the exact form of the atmospheric turbulence spectrum at a particular place over some specified period of time, it invites the speculation that there is something inherently unsatisfactory about the design methods being used. In any case, supposing the data were required by the aerodynamicist in order to specify the kind of turbulence he injects into his wind tunnel stream, and if he generates that stream in order to measure the response to it of a *tall* building or chimney, a limit on the accuracy he can achieve is imposed by the absence of any representation in the wind tunnel of the geostrophic turning of the wind with increasing height: for the change in the direction of the wind between levels of the order of 100 m apart is appreciable; some 2 or 3°.

What these arguments suggest is first, a careful appraisal of existing meteorological data,

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possibly including a justifiable demand for more data on those components of the wind that are to be embodied in a design criterion; and secondly, the acceptance of some standard model structure of the small-scale components of atmospheric turbulence, which is then modified in a wind-tunnel experiment by the appropriate representation of local terrain: whether that be urban or rural.

In the problem of modelling a flat, urban area, the procedure consistent with the preceding suggestion is to reproduce some broad set of meteorological conditions which are then refined by the detailed representation of buildings in the neighbourhood of the one in question, as described by Mr Lawson. However, two problems present themselves: what is the extent of the neighbourhood to be represented, and in what detail? When the building is much taller than its neighbours, Mr Lawson, in his paper, has suggested *an* answer—the accurate modelling of surrounding buildings for an extent of $1\frac{1}{2}$ times the building height in all directions—but I am sure that he would agree that the question still requires careful consideration and might not even be capable of answer in terms of a universal recipe. As to the degree of detail with which small-scale features are reproduced on the model, it is not clear that geometrical accuracy is necessarily always desirable. Recognizing that model experiments are usually performed at Reynolds numbers of the order of one-hundredth or smaller of those at full-scale, local Reynolds numbers on parts of the model may be so diminished as to lead to the blurring of the influence of its fine geometry on the flow as a whole, owing to the action of viscosity. Some judicious geometrical distortion might be desirable.

Of course, not all environmental problems involve concentrated building complexes; examples of the influence of isolated buildings or of embankments on objects exposed to their wakes have been given by Dr Hunt and Mr Price at this meeting. Equally, not only machines or human beings are sensitive to their environment: so too are plants and insects and, in that respect, there are close points of contact between the architect and the agriculturist. For instance, the flow through a crop or forest has certain features in common with the flow through a densely populated urban area, although the former is affected by aero-elastic phenomena which are absent from the town; and the problem of protecting vehicles from snow or high winds by means of embankments is similar to the agricultural problem of providing shelter to plants by means of windbreaks. This latter involves another interesting environmental question. In Denmark and the Soviet Union, the careful planning of windbreaks has led to substantial increases in crop yield; of around 20 % in barley, potatoes and sugar and more than 50 % in millet grown on the steppes of Russia. At the same time, insects too find the shelter of windbreaks attractive, and experiments by Dr Lewis of Rothamsted (1967) have shown that the concentration of insects in their lee may be as much as thirty times that in an unimpeded airstream. Sometimes the insects are benign, but at others they may be pests which destroy the very crop the windbreak is intended to protect.

In excusing this digression, I must point out that it provides *one* example of where the nature of the response to environment, if not the reason for it, is fairly well established. The situation with regard to human beings is less successfully identified; indeed, according to Mr Lawson, little more is known than that humans differ in their reactions to wind and microclimate, and his suggestion for a systematic study of those subjective responses appears to be well justified.

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## 5. Wind-loading problems

I now propose to turn to the subject of laboratory experiments on actual designs in relation to wind loading which, in the light of the dual standard of precision I suggested earlier, might incline one to look critically at the accuracy achieved by the wind tunnel. I previously mentioned the danger of being over-critical: I shall try to avoid it and simply list the broad problems which in my view require further exploration.

But, first of all, I think it fair to pay tribute to those involved in architectural aerodynamics for having, within a relatively short period, succeeded in refining experiment and our physical understanding of many of the flow interactions with which the subject abounds. It is not so long ago that not very meaningful experiments were performed in small wind tunnels with nominally uniform airstreams; the degree of sophistication both in technique and instrumentation is now becoming immense and that achievement must in part be due to the architect's rapid appreciation of the importance of aerodynamic phenomena whose complexity at first sight might have seemed terrifying. I hope that this meeting has done nothing to increase that terror.

Certain questions remain: the effects of Reynolds number, especially on flows in which boundary-layer separation is not controlled by salient edges, the extent of the neighbourhood of a building or structure that requires representation in an urban model, the degree of detail that it is necessary and meaningful to reproduce to a faithful geometrical scale, and the fidelity with which the higher modes of deformation of an elastic structure should be reproduced in an aeroelastic experiment.

### (*a*) *Unsteady force measurements*

Apart from the first, which requires full-scale data, these are largely questions of experimental technique. The broader prospect for the future seems to be an emphasis on the measurement of unsteady pressures and forces and their relation to structural response. The reason lies in the evolution of structural design and fabrication towards buildings possessing lower weight and stiffness as well as lower structural damping; the latter, in particular, leading to a more sharply peaked frequency response and higher resonant magnification. At the same time, thin, shell-type, concrete structures, such as cooling towers, exhibit a sensitivity in their tensile stress fields to circumferential gradients in pressure: and fluctuations in the pressures lead to corresponding stress fluctuations. The difficulty of avoiding a resultant transitory tensile stress in the fabric is made more acute by the trend towards lighter construction and therefore smaller dead-load compression.

Moreover, the fundamental natural frequency of oscillation of modern structures often lies deeply within the spectrum of the turbulent fluctuations in a moderate wind. In other words, the force fluctuations produced by the energetic turbulent components of the wind may be centred on frequencies *lower* than the structure's natural frequency. Now, an increase in windspeed has two effects. First, the dominant forcing frequency increases approximately in proportion to the windspeed, thus approaching more closely the fundamental frequency of the structure. Secondly, the magnitude of the loading increases roughly in proportion to the square of the windspeed. The resulting effect on the structure is therefore to produce an amplitude response that increases with windspeed *faster* than its square. This result has environmental consequences too, because it implies that accelerations and their time rates of change, to which the occupants of a swaying building are subjected, also increase rapidly with windspeed.

The practical importance of the problem of measuring fluctuating forces and pressures, to-

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gether with their effect on the dynamics of the structure, inclines one to encourage aerodynamic work on perhaps a smaller scale and with simpler models than those used in architectural design investigations, in order to study the fundamental nature of the flows that give rise to them. That work can be broadly classed under the heading of 'bluff body flows'. I firmly believe that more effort can and should be devoted to it; and the aerodynamicist can be assured that he will find it a rewarding subject.

### (*b*) *Bluff body flows*

The key problems of bluff body flows, as I see them, accepting the global importance of the study of vortex wakes, have five main elements: the effect of turbulence in the approaching stream, the effect of mean shear in that stream, the consequences of a variation in the cross-section of the body with height, the modification to the flow when the body vibrates and the interference between neighbouring bodies.

The interaction between turbulence and a body has been studied experimentally by Vickery (1965), Bearman (1969) and others, and theoretically by Dr Hunt. Hunt's researches surely provide an impressive example of the application of fluid mechanical theory to an architectural problem and draw attention to one of the key mechanisms governing the interaction: namely, the distortion of the vorticity associated with the smaller scale turbulent eddies. But profound as they have been, the theories do not supercede experiment: on the contrary, they provide a stimulus to it.

If we make the physically convenient distinction between large scales of turbulence and small scales of turbulence compared with a dimension of the body, its width say, evidently the larger turbulent eddies in their encounter with the body give rise to a flow possessing the main features of a quasi-steady flow of an irrotational stream about the same body, but complicated by possessing an essentially three-dimensional character. The behaviour, on the other hand, of the small eddies endowed with greater vorticity is dominated by the distortion they undergo as the main stream is constrained to flow around the body. At the same time, the pressure fluctuations associated with those eddies may be expected to be correlated over small regions of the body surface, whereas the larger eddies give rise to more extensively correlated pressure fields, hence to significant fluctuations in the overall force on the body. A difficulty arises in visualizing, on the basis of this simple argument, what happens to turbulent eddies of comparable size to that of the body; for, as Bearman (1969) has pointed out, and as is evident from the figure presented in the paper by Dr Hunt, certain effects on the turbulent velocity fluctuations in their approach to the body are in competition when the eddies are respectively large and small. Here, then, is one area for further experiment and a challenging computational problem.

These remarks apply principally to the flow over the front of the body. Another aspect of the interaction explored experimentally by Dr Bearman (1969) calls for further exploration; it is the effect of the main stream turbulence on the mixing characteristics of the shear layers springing from the points of boundary-layer separation leading, in the case of a flat plate, to a *lower* pressure on its base and a *higher* mean drag than occur in a smooth stream; or as found by Vickery (1966) on a prism of square cross-section, to which the shear layers can re-attach, a *higher* base pressure and a *lower* mean drag. However, the influence of turbulence on a bluff body is not confined to the drag; fluctuating side forces are also developed, and they, in turn, imply fluctuating circulations. When the body possesses a sharp trailing edge, like an aeroplane wing, the problem is made determinate by the Kutta–Zhukovski condition; but precisely what controls the magnitude of the side-forces on a *bluff* body is not understood.

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Nor is turbulence in the approaching stream the sole source of complication. Even when that stream is smooth, a peculiar phenomenon occurs in the wake behind a non-cylindrical body, as was discovered by Gaster (1969). He found that the frequency of vortex shedding from a body which tapered along its length depended on the local diameter, such that the *Strouhal number* was constant over the length of the body. He also observed that the shedding process was modulated by a low frequency oscillation unrelated to any dimension of the body, and he attributed this to the fact that vorticity was being shed at different rates along the length of the body.

A similar behaviour was revealed by Maull's (1969) experiments on the flow past flat plates lying normal to a sheared stream. Again, the rate of vortex shedding appeared to be consistent with a constant Strouhal number, in this case, referred to the local undisturbed velocity of the stream; and observations of the flow by means of smoke showed that the vortices in the wake of the body were skewed, convoluted and formed into loops.

This essentially three-dimensional character of a vortex wake has long been recognized in the ostensibly simpler flow of a uniform stream past a circular cylindrical body and accounts for the restricted spanwise distances over which the pressure fluctuations are well-correlated on the surface of a rigid cylinder. The most recent observations have been described by Gerrard (1966).

When, however, the incident stream is sheared, or the body is non-cylindrical, an obvious question is: what modification to the vortex shedding process is likely to ensue if the body is free to vibrate? Indeed, that question may well be extended to include *all* flows involving vortex shedding, for as the work of Professor Parkinson has shown, an oscillation of a body in a uniform stream has the effect of improving the correlation between shedding from different parts of the span: which is a physically more attractive explanation of the phenomenon hitherto described by Scruton as 'negative aerodynamic damping' and which has the consequence of a rapid build-up of amplitude of an oscillation with increase in windspeed. A similar effect might be produced by the interference between neighbouring bodies.

One could readily extend the list of basic aerodynamic problems and include those to which Professor Mair & Dr Maull, Dr Hunt, and Professor Etkin drew attention in their papers. We might include too the problem of the flow about the free end of a body and its influence on the mean and fluctuating loads exerted on a tall building or structure. And we could bear in mind that the experimental possibility of examining the details of the flow in a strongly fluctuating separated region has recently improved enormously by the development of a pulsed hot-wire instrument by Dr Bradbury of the Aeronautics Department at Imperial College. That instrument is able to discriminate between forward flow and reversed flow, which an ordinary hot-wire cannot, and, again unlike the ordinary hot-wire, its accuracy is unimpaired by large intensity fluctuations.

But I think that I have said enough both to justify further fundamental aerodynamic studies and to emphasize their interest and difficulty. But lest it be thought that the subject is always complicated by turbulent interactions and by non-uniformities in the airstream and in the shape of the body, taken both separately and in combination, I should finally like to mention one basic result which was obtained in Japan by Nakaguchi, Hashimoto & Muto (1967) in their study of the drag on a two-dimensional block of progressively increasing thickness in a uniform wind: an apparently primitive problem.

Now, the drag coefficient for a thin flat plate normal to a stream is 2.0. The drag coefficient on a thicker block of square cross-section has also been found to be 2.0. With increase in thickness to twice the width of the block, the drag coefficient falls to 1.5. One can therefore imagine a

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plausible curve drawn through these points; it would have a flat portion between thickness/width ratios of zero and unity and then fall. However, Nakaguchi explored the region between zero and unity in a wind tunnel at a modest Reynolds number. He found that as the ratio increased from zero, so did the drag coefficient, reaching a value as high as 2.8 for a thickness a little greater than one-half the width of the plate, and then falling steeply.†

The reason for this behaviour demands, and is receiving, further attention; but I mention the observations here to underline the unexpected quality some of the apparently most simple architectural aerodynamic problems may exhibit.

## 6. THE PROSPECT AHEAD

I must now acknowledge the title of this talk and attempt to sum up very briefly the prospect ahead. That prospect will be dominated by the responsiveness of the architect, the town planner, the transport engineer and the structural designer to the new knowledge being accumulated about aerodynamic phenomena: as well as by the willingness of the aerodynamicist to cooperate with them. From what we have heard at this meeting from Lord Holford, the response is informed and vigorous: it is evident too that the cooperation of the aerodynamicist is secure. Both promise the evolution of future architectural forms and structural designs different from those to which we have been accustomed. We might perhaps find, in urban planning, sculptured windbreaks as part of the architectural landscape and an atmosphere free from noxious contaminant; in building design, possibly even a re-evaluation of old forms in terms of their aerodynamic performance: for I suspect that a flying buttress provides an effective air-brake, and the collonade possesses the useful property of refracting the flow through it! On a more serious level, it is not inconceivable that such devices as vortex generators, flow deflectors, spoilers and screens could, in the hands of the architect, take on a functional beauty and permit him some measure of control over the flow around his buildings. In the process, he might succeed in eliminating those regions of high wind near the corners of buildings, which not only impede the pedestrian but immerse him in a miniature dust and debris storm; and he might also examine the interaction between external and internal aerodynamics in relation to the environmental problems of heating and ventilation.

The aerodynamic contribution will be, broadly speaking, of two kinds. In the first place, there will be a continuing and, one hopes, intensified study of particular architectural models in wind tunnels of the type outlined in the paper by Mr Scruton & Dr Rogers, and elaborated in the paper by Dr Hunt and the contribution from Dr Amitt, with emphasis on the detailed representation of the wind and its effect in producing unsteady pressures and forces on elastic structures. Such experiments will progressively contribute information about the patterns and properties of airflow generated about individual buildings and building complexes, but the growth of knowledge can be hastened and made more complete by investigations on a less ambitious scale. Those investigations of the fundamental character of bluff body flows form the second kind of contribution to architectural aerodynamics and may in the long run, be as decisive as the first in suggesting new shapes and forms to the designer.

Finally, I must repeat the plea to the architect to state the accuracy he requires of his aerodynamic data. I do this to restore a measure of impartiality to my argument, because I have

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† The ratio of thickness to width at which the maximum drag coefficient occurs is approximately that at which galloping instability can first develop on a prismatic block as its thickness is increased, according to the observations presented by Professor Parkinson in his paper.

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been at pains to catalogue the deficiencies in *aerodynamic* knowledge. Other matters contain their mysteries too: the magnitude of structural damping, the mechanical behaviour of foundations, the consequences of cumulative damage to which Dr Chilver has drawn attention in his paper, and even the structural properties of certain materials. Above all, there is the delicate question of selecting the appropriate windspeed and gust intensity to the formulation of a design criterion. In the light of those uncertainties perhaps the wind tunnel, in its modern form, can be too harshly judged and I am therefore led to make a further suggestion. While recognizing the convenience of working to a code of practice and applauding the efforts that are continually made to revise that code, the complexity of architectural aerodynamics and the surprising flow phenomena being revealed imply that there can at present be no effective substitute for the carefully performed wind tunnel test as *a routine* preliminary to a new design: in spite of the delay it introduces into the design process, as deplored by Dr Kerensky.

By 'carefully performed', I am referring to tests which include the proper simulation of the atmospheric wind, such as those regularly performed in this country by the Central Electricity Research Laboratories, in Canada by Dr Davenport and, in Denmark, by Professor Jensen. The deficit in Reynolds number will remain a problem: whether the uncertainty associated with it can be reduced by the construction of a special, large wind tunnel or by much more extensive full-scale experiment is a question to be resolved on economic grounds.

But whichever course is adopted in the long run, an improvement in the technique of aerodynamic experiment, in our understanding of the intricacies of bluff body flows and in the architect's qualitative knowledge of their consequences will be achieved by that intensive wind tunnel study *which demand alone can stimulate.*

In saying this, I am perhaps too overtly displaying my own aeronautical background, in which the wind tunnel has long been accepted as a design tool and both its scope and limitations firmly recognized. At the same time, I might be inviting the rebuke that the high development costs of aeroplanes are a conspicuous feature of their inception. What is not so often stated is that those costs are not just bound up with technological innovation, but represent the price which must be paid for safety. Safety in architecture is surely just as precious; it can hardly be expected to be purchased cheaply.

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