SEPARATED AND UNSTEADY FLOWS IN AERONAUTICS: RESEARCH AT THE UNIVERSITY OF BRISTOL

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I. Introduction

The aerodynamics of aeronautics to most people is probably synonymous with the aerodynamics of streamlined shapes. By contrast aerodynamics outside of aeronautics may well conjure up a picture of a non-uniform airstream approaching a building, creating an unsteady, separated flow. That these pictures are misleading would be known to most of those connected with aeronautics - aircraft do develop separated, unsteady flows, and outside of aeronautics there is interest in aerodynamic efficiency and smooth attached flows. Until comparatively recently, however, the need in aeronautics has been to increase aerodynamic efficiency, and virtually all major research topics seem to have been related to steady, smooth flows; the problems connected with separated and unsteady flows (e.g. wing stall, or buffeting in bomb bays) have, by contrast, usually been tackled on an ad hoc basis, without very much emphasis being given to understanding why the flow was as it was.

Recently the picture has been changing - separated and unsteady flow problems are arising more frequently in aeronautics, together with a need to obtain a more fundamental understanding of the behaviour of the air.

At the University of Bristol, in the Department of Aeronautical Engineering, considerable experience has been built up in the field of 'Industrial Aerodynamics', particularly by Lawson (Reference 1 and Figure 1) in work relating to the aerodynamics of buildings and other structures. The flows have usually been separated and unsteady, and perhaps in part because of this experience the Department has become increasingly interested in separated and unsteady flows in aeronautics.

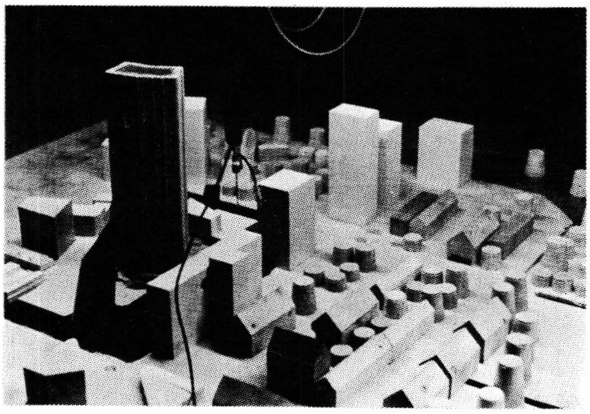


Figure 1. Typical Wind Tunnel Model of a Building Complex.

This paper discussed the range of separated and unsteady flow problems now of interest in aeronautics, aims to show the breadth of interest in this field at Bristol, and in particular to present certain results and conclusions stemming from work that the authors have been involved in.

In order to discuss the various problems the important parameters first need to be identified - these may relate to the flow or to the geometry involved.

The flow condition can be described as:-

(a) Uniform or non-uniform; this relates to the approaching stream with uniform implying constant velocity across the stream and with no change with time. Non-uniform might refer to the velocity changing across the stream (a windshear) or to turbulence in the approaching stream.

(b) Attached or separated; this relates to the flow behaviour over the surface of interest.

(c) Steady or unsteady. Unsteady is taken to mean a flow condition where the changes in flow pattern with time are large, where the rate of change of a surface position has a strong influence, or where history (lag) effects are important. Steady is taken to refer to cases where the flow is unchanging with time, or where the essential features of the flow can be explained by reference to steady flow - i.e. can be termed 'quasi-steady'.

Various combinations of these are possible, and these are best illustrated by a Venn diagram, as shown in Figure 2(a).

The geometry of the surface under consideration is obviously of great importance, but in order to discuss and compare the various problems it is convenient to consider not so much the geometry of the surface as the way the surface is changing with time. Discussion is therefore centred around:-

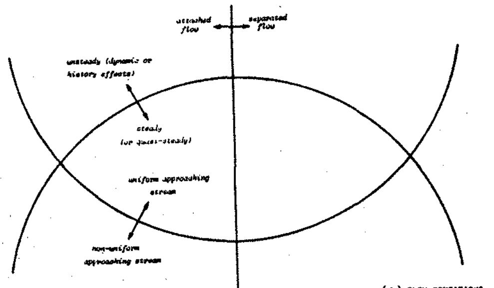
(a) Fixed surfaces ; i.e. no change of geometry with time.

(b) Rigid body movement ; i.e. change of orientation but not of shape.

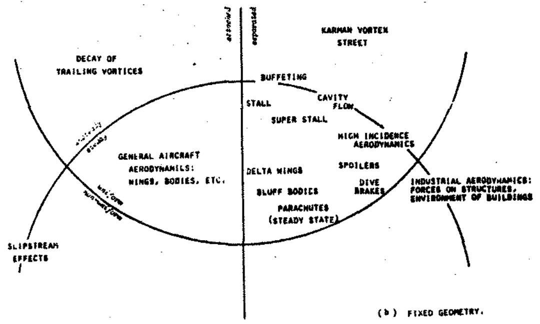
(c) Elastic distortions ; these might range from small slow deformations to gross or extremely fast shape changes.

(d) Propulsion ; the power unit of aircraft introduces a further dimension to the range of problems.

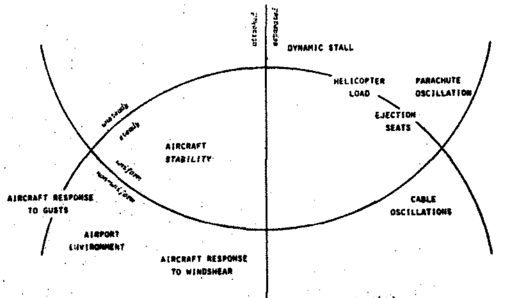
Separated and unsteady flows are conveniently discussed in the following sections under these



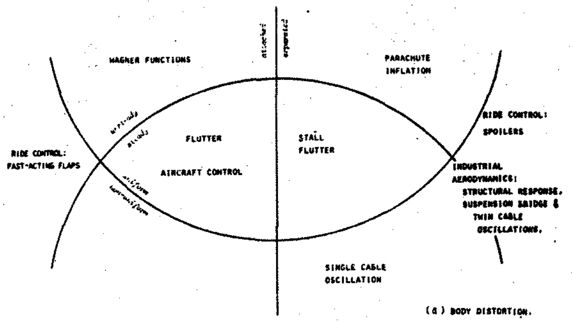
(a) FLOW CONDITIONS



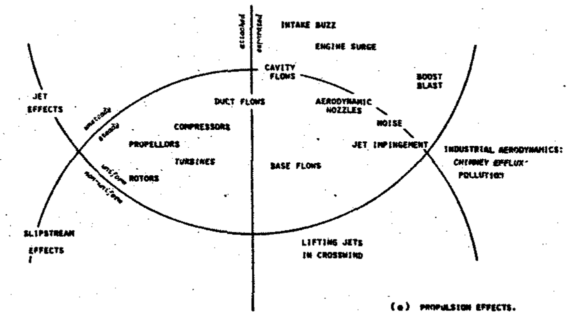
(b) FIXED GEOMETRY.



(c) RIGID BODY MOTIONS.



(d) BODY DISTORTION.



(e) PROPULSION EFFECTS.

Figure 2. Venn Diagrams of Areas of Interest.

headings. It should, however, be appreciated that this is a simplification, with any one topic having some aspects that fall in one section and some in another. Reference is made, as appropriate, to research outside of aeronautics, to the various aspects of industrial aerodynamics. Research topics of particular interest at Bristol are indicated by **, with a quoted reference. Topics that have at some time interested us but to a lesser extent, (for example as the subject of an undergraduate project), are indicated by *.

Reference may be made to Figures 2(b) to 2(e), that summarise the topics discussed in Venn diagrams, covering respectively

2(b)	Fixed Geometry
2(c)	Rigid Body Motions
2(d)	Body Distortions
2(e)	Propulsion Effects.

2. Steady Separated Flows around Fixed Shapes

Flow separation occurs naturally with bluff shapes, and in the early days of aeronautics attention was concentrated on reducing separation by avoiding bluff and using streamlined shapes. These shapes can of course generate separation at large incidences, and investigations of conventional aerofoil stall have been made from earliest days, complicated, as is so often the case, by Reynolds Number effects. More recently the 'super stall' has been a subject for investigation, with the effectiveness of the tail-plane being seriously impaired by the separated flow from a stalled wing.

With swept or delta wings the flow separation that leads eventually to stall can start at a low incidence as a leading edge separation and develop into a complex but stable pattern with strong vortices sitting above the upper surface. Various problems may arise with such separated flow patterns; one unusual one relates to the possibility of ice ridges forming on the upper surface of slender delta wings**. Ice is normally expected to form on the leading edges of wings, and in these localised areas appropriate anti-icing measures can be concentrated. Model tests on delta wings had showed that ice could be formed on the upper surface, with the strong vortex pattern bringing the super cooled water droplets down onto that surface. With an aircraft such as Concorde anti-icing measures over large areas of the upper surface would be extremely difficult to arrange, and investigations to establish the extent of the problem were obviously necessary. Model tests in normal icing tunnels tend to be unreliable in one respect: correct scaling is difficult, leading to pessimistic predictions on windward surfaces and optimistic on leeward surfaces. In an attempt to represent more nearly the full scale trajectories of the water droplets experiments were performed in a water tunnel, using small glass beads to simulate the water droplets (Reference 2). The tests indicated low ice levels, but were in themselves inconclusive. Parallel to the experimental work, however, an alternative approach was tried based on a minimum of experimental results. A surface flow visualisation picture of the upper surface of the Concorde wing was taken, flow directions extracted, and local flow characteristics

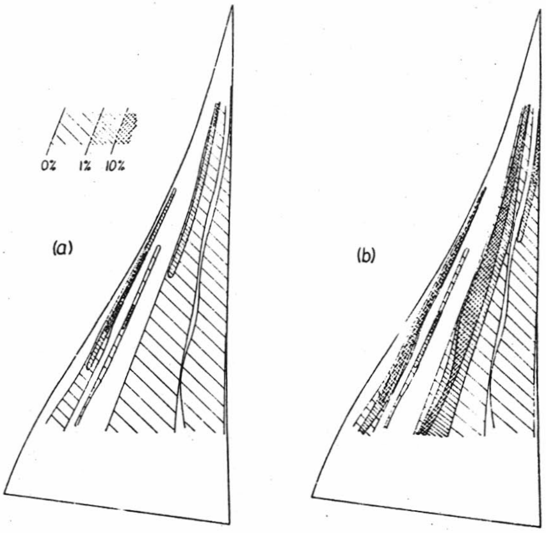


Figure 3. Typical Theoretical Results for Concorde Wing.
(a) 0%, 1% and 10% contours, 20 micron
(b) 0°, 1% and 10% contours, 40 micron.

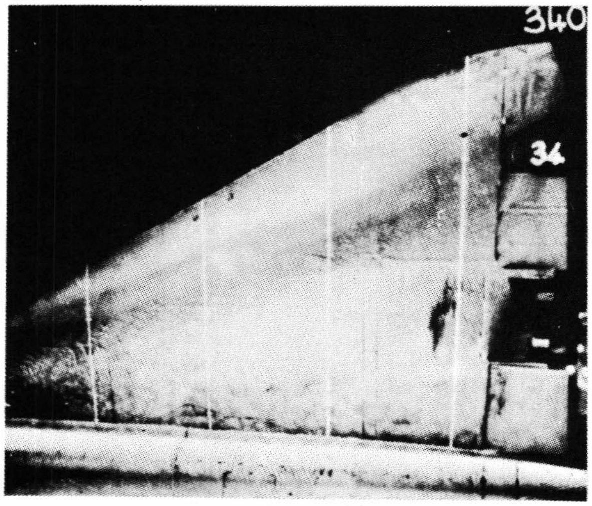


Figure 4. Concorde - Icing Pattern from Large Scale Tunnel Tests.

in the vicinity of the surface deduced. Particle trajectories and associated ice formation were computed. Computed results (presented in reference 2) are shown in Figure 3, and can be seen to compare well with results obtained on a large scale Concorde model in the Modane wind tunnel (Figure 4).

The main components of aircraft are usually streamlined, although for some aircraft the fuselages may be comparatively bluff, with flow separations possibly extensive, and with the aerodynamic characteristics somewhat unpredictable. This may be the case for some light aircraft designed for certain roles, some conventional helicopters, and certainly for some mini-helicopters now being developed. Aeronautical interest in the aerodynamic characteristics of bluff shapes* is therefore now growing. Figure 5 shows some results obtained for an axisymmetric shape with elliptic cross-section. All force components vary in an irregular way with attitude. The discontinuities can be related to the changing pressure distributions and positions of separation with change of attitude. Separation, and hence the aerodynamic characteristics, is unfortunately also dependent on Reynolds Number and turbulence level, and is also affected by protruberances, representing smaller components of an aircraft. In connection with this type of problem further investigations into the behaviour of 3-dimenlsional boundary layers are being made*.

Smaller components of an aircraft may develop separated flows; some, such as spoilers or dive brakes, rely on the flow separation for their effectiveness.

Outside of mainstream aeronautics separated flows are also evident. One good example is the parachute where again effectiveness depends on the separation. Parachute design used to be an art, with designs proven by ad hoc testing; now design is tending to be more scientific, with a need for a more fundamental understanding of the aerodynamics.

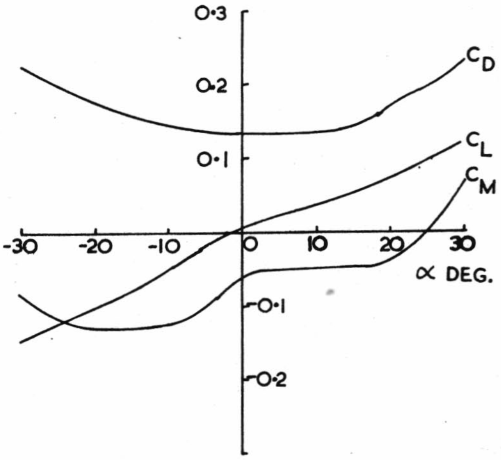


Figure 5. Lift and Drag Coefficients for an Ellipsoidal Shape.

3. Flow Instabilities for Fixed Shapes

Variations with time of a flow pattern around a body would almost seem to be the rule rather than the exception. The variation may be due to some unsteadiness in the flow, or to the body moving in some way. The classic case of an unsteady flow generated by a fixed shape is of course the Karman Vortex Street, shed behind a circular cylinder within a certain range of Reynolds number. The oscillating pattern can be related to that past an impulsively started cylinder* where the flow is initially attached and then, as the flow separates, a pair of vortices grows. The vortices are initially symmetric, but in time an asymmetry, or instability, develops, with the asymmetry leading to forces that exaggerate the asymmetry. Eventually one vortex separates, the asymmetry then changing until the other vortex sheds, starting the street of vortices. This unsteadiness is closely related to a steady flow past certain three dimensional shapes.

A slender delta wing at incidence develops a pair of attached vortice above its upper surface. In similar manner a slender cone will generate a pair of vortices. A slender body with conical nose will develop vortices over the nose, but the vortices will leave the body further downstream, usually in an unsymmetric manner with other vortices being generated and shed again further downstream. The pattern may be steady, in that it may be unchanging with time, but can be viewed as completely analogous to the Karman Vortex Street in two dimensions, with a cross section through the pattern looking very much like the Karman Street. In effect variation with time in the one case can be compared with variation along the body in the other. This pattern is particularly pronounced over incidences ranges that are usually rather large for aircraft, but may well be encountered by missiles when manoeuvring after launch. The implication of an unsymmetric flow pattern is that forces and moments out of the plane of symmetry can develop and for this reason investigation is necessary**. Hunt at Bristol has obtained interesting results for various shapes (e.g. Reference 3). A diagram of a typical flow pattern is shown in Figure 6. Results were obtained through some 360 pressure points, and an example of integrated pressures giving local side forces is shown as Figure 7.

The flow is not, in fact, always steady but can switch between one pattern and its mirror image, with dwell times being somewhat different, presumably due to small differences in surface conditions. Hunt has shown that the switching is produced by external disturbances, particularly free stream turbulence and model vibration. Recent results with a very rigid model under very low turbulence conditions have shown that switching can be eliminated but that the flow still contains some inherent unsteadiness.

Similar asymmetrics have been noted on very slender wings at high incidence, although with wings another phenomenum - that of vortex 'bursting' - is perhaps of greater interest.

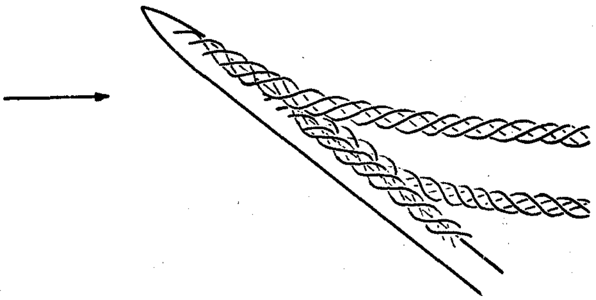


Figure 6. Vortex Pattern Behind an Inclined Cylinder.

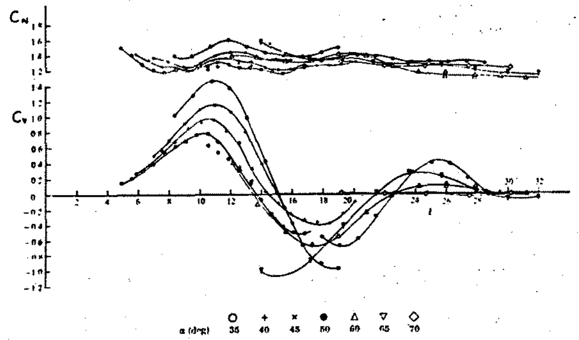


Figure 7. Experimental Normal and Sideforce Coefficients for a 3 Calibre Ogive Nose at a Reynolds Number of 1.1 × 10^5.

Another form of vortex instability is also now attracting considerable attention. The trailing vortices from large aircraft can be considered as small but quite powerful horizontal tornadoes. Small aircraft running into them can easily be thrown upside down - an extremely hazardous situation when close to the ground, the situation, unfortunately, that is most likely to occur where the tracks of planes are close on take-off or landing. The vortices can take a considerable time to decay, although instabilities that help to dissipate the vortices do occur, and can perhaps be encouraged. Studies of vortex breakdown have been made* (e.g. Oon, Reference 4), and, more recently, possible means of alleviating the situation.

4. Quasi-Steady Flows

When a variation in time of a flow pattern is due to the body moving in some way, the movement may be a 'rigid body' motion, with the body simply changing its orientation relative to the stream, or to some elastic deformation of the body. In either case it is frequently possible to represent the flow with sufficient accuracy by assuming that the flow is that appropriate to the instantaneous position and shape of the body. This is the simplest approach in the aeroelastic work in aeronautics for attached flow past wings.

This quasi-steady approach can also often be used as a means of examining, or predicting, instabilities in separated flow situations, and one good example is the aerodynamic excitation of cable spans** (e.g. Reference 5). A span can develop pendulum style oscillations in the critical Reynolds Number range, where the relatively low velocity but high drag when moving downstream puts more energy into the cable than is taken out by the relatively high velocity but low drag when moving upstream (see Figure 8). Other modes of oscillation can arise through lifting forces developed when the wind crosses the strands of a yawed cable at different angles on upper and lower surfaces, with the two flows separating at different positions.

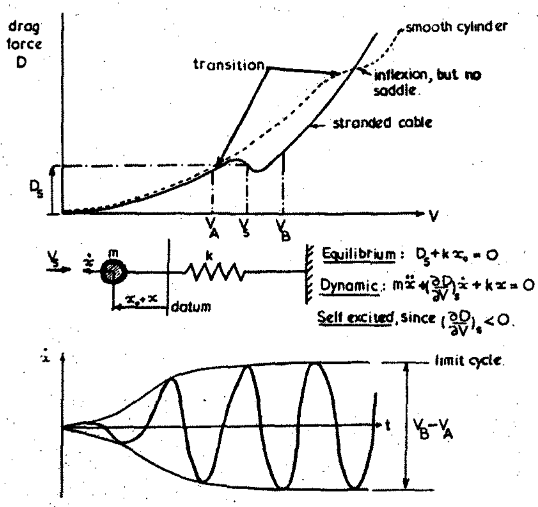


Figure 8. Drag Saddle on Certain Stranded Cables Gives Rise to Negative Aerodynamic Damping.

The wake induced flutter of one cable oscillating in the wake of a fixed windward neighbouring cable may be explained by recourse to quasi-steady aerodynamic assumptions. Flutter boundaries thus computed agree to within a few per-cent with actual ones determined in wind tunnel dynamic tests (Reference 6). Figure 9 illustrates the mechanism of wake induced flutter.

In aeronautics this approach may also explain observed phenomena. Ejection seats are bluff shapes whose orientation to the local stream direction changes with time*. The aerodynamic forces show subtle variations that can largely be related to the growth and decay of separated flow regions stemming from various parts of the seat or occupant, and this is illustrated in Figure 10. These 'steady' forces are used in calculations of

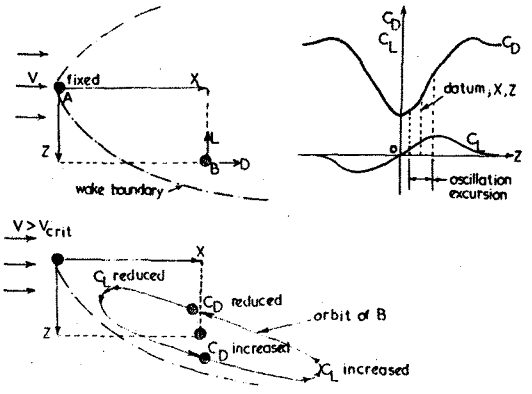
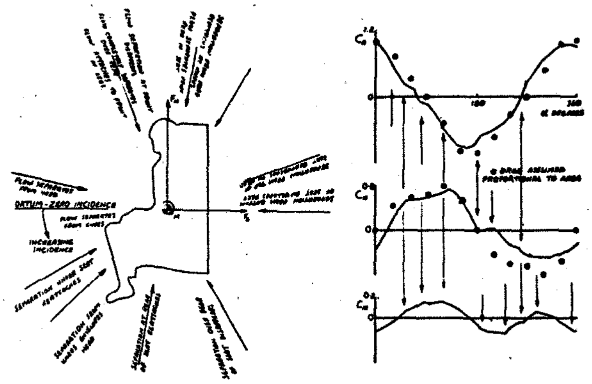


Figure 9. Wake Induced Flutter. (Position-Dependent C_D and C_L Support Orbital Motion).



THE ARROWS ON THE LEFT CORRESPOND TO THOSE ON THE RIGHT, INDICATING INCIDENCES AT WHICH THE CURVES HAVE A CHANGE OF SLOPE. THE COMMENTS ARE APPROPRIATE TO INCIDENCE INCREASING AND INDICATE APPROXIMATE DIRECTIONS FOR WHICH DISCONTINUITIES MIGHT BE EXPECTED.

Figure 10. Typical Steady Force Coefficients for an Ejector Seat.

seat trajectory, and in many cases this 'quasi-steady apprach is sufficient. There is, however, some indication that 'dynamic' or history effects may be important during emergence or at high rates of seat rotation.

5. Dynamic Effects for Rigid Shapes

By no means all of the flow characteristics around rigid shapes that are changing orientation can be explained by the quasi-steady approach. History, or lag, effects can be pronounced. One of the best known is the dynamic stall of a wing, where the flow remains attached when incidence is rapidly taken through the normal stall incidence - but having stalled, when incidence is decreased the separated flow does not reattach until below normal stall incidence. This hysterisis effect can be the mechanism by which energy is fed into an oscillation, creating a dynamic instability (i.e. stall flutter). A similar effect can be

Wind

observed in tests on suspension bridge sections[*].

A somewhat similar situation can occur in three dimensions with a fully inflated parachute - when oscillations, or a 'coning' motion may be sustained by a separation that changes with time. In some cases a separation may be unstable, possibly due to shock wave/boundary layer interaction at high subsonic Mach number, and 'buffeting' may result.

A more complicated example in aeronautics is that of bluff shapes suspended beneath helicopters. Such loads can obviously move easily relative to the helicopter (if slung on a single cable), and several dramatic cases bear witness to the fact that aerodynamic excitation is not only possible but extremely probable, curtailing the helicopter performance. Studies of this problem[**] have been made at many establishments. In some cases ad hoc tests have been performed; in others static aerodynamic characteristics have been established and a quasi-study approach used. This latter approach has been shown to have its limitations, and at Bristol (Reference 7) attention has been focused on dynamic, or history, effects. The simple 20' x 8' x 8' container shape has been studied, with the main results being obtained via pressure measurements while the shape was being inexorably oscillated in various modes. The results showed pronounced dynamic effects, as illustrated in the helium bubble sequence for a pitching oscillation, shown in Figure 11. The same effect is also illustrated in the loop diagram (Figure 12) where yawing moment is presented against yaw angle. The differences between the curve while angle is increasing and that while angle is decreasing is a dynamic effect, with a clockwise loop corresponding to an input of energy and an anticlockwise loop to an extraction of energy - or a damping. These effects, and others, have been explained by using a simple conceptual mathematical model of the pressure variations within a separation bubble whose geometry changes with container attitude (Figure 13). The basic assumption is one of a constant pressure in the bubble, falling to zero at the rear edge, and with other assumptions relating to the size of bubble and variations with time. In some cases the history effect may lead, in any one configuration, to changes in dynamic stability with modest variations in forward speed. In one case (container broadside-on to the stream at equilibrium) the stability in yaw changes from negative at low speeds to positive at moderate speeds, and back to negative at high speeds. In another case static stability and dynamic instability at small angles changes to static instability and dynamic stability for larger angles.

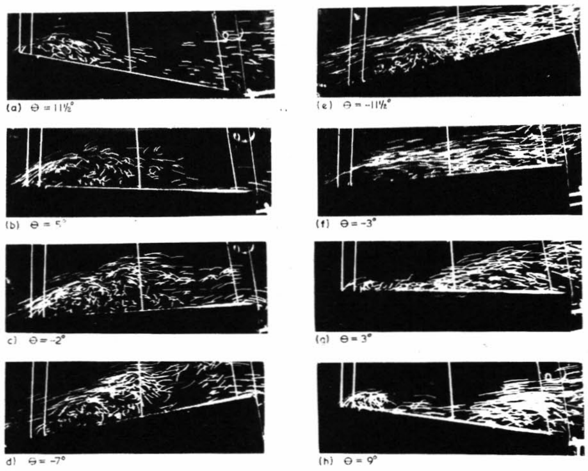

(a) $\Theta = 11\frac{1}{2}^\circ$ (b) $\Theta = 5^\circ$ (c) $\Theta = -2^\circ$ (d) $\Theta = -7^\circ$ (e) $\Theta = -11\frac{1}{2}^\circ$ (f) $\Theta = -3^\circ$ (g) $\Theta = 3^\circ$ (h) $\Theta = 9^\circ$

Figure 11. Helium Bubble Unsteady Flow Sequence for a Pitch Oscillation of ± $11\frac{1}{2}^{\circ}$, and Frequency Parameter 1.94.

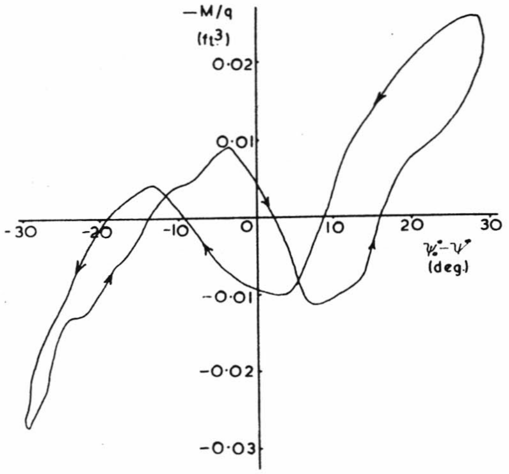


Figure 12. Loop Diagram of Yawing Moment vs. Yaw Angle for a Container in Steady Yawing Oscillation.

6. Dynamic Effects for Elastic Bodies

Further complexity comes from the change of geometry as seen by the flow being not simply a change of orientation but a distortion of the body. The distortion, caused by the aerodynamic forces, brings elastic forces into play - and the study becomes that of aeroelasticity. A full examination of the aerodynamic excitation of suspension bridges requires knowledge of both the aerodynamic and elastic forces. Similarly for a full analysis of cable oscillation. The latter becomes even more complicated for the case of multiple cables, e.g. twin conductors[**] (Reference 8). Here the relative position of the cables is important, the leeward being affected by the wake of the windward. Several dynamic effects are important, the most obvious being the lag due to the wake taking a finite time to travel from the windward to the leeward cable. One important dynamic effect, unnoticed in any previous studies, was revealed by the use of a simple mathematical model; viz, reduced aerodynamic damping in vertical motion through a sheared flow.

In aeronautics, the whole of the usual aeroelastic investigations for conventional aircraft and helicopters might be considered to fall within this section. Most effects, viz flutter,

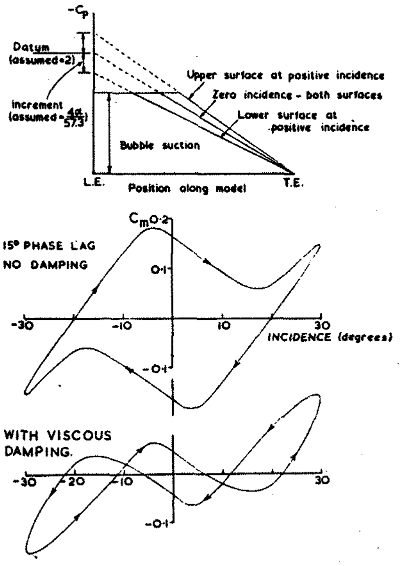


Figure 13. Mathematical Model - Loop Diagram for Steady Yawing Oscillation.

divergence, control reversal and elastic distortion effects on stability, are treated using inviscid flow theory. Divergence, reversal and stability effects are static phenomena and thus simple aerodynamics suffices. Flutter is sometimes treated on a quasi-study basis, but usually allowance is made for frequency parameter (lag) effects via the Theodorsen function. Some phenomena involve hysterisis - e.g. stall fullter of wing tips - and in some cases where a local rate of change of incidence is large enough history or lag effects can be important. These effects are often expressed in terms of Wagner or Kussner functions - particularly when dealing with aircraft response to atmospheric turbulence.

7. Dynamic Effects for Rapidly Changing Shapes

When a body changes its orientation or its shape fast enough there is a noticeable lag in the flow as it adjusts to the new boundary conditions. For conventional wings, the form of variation is usually expressed as 'Wagner' functions, as previously indicated. This lag can become important where rapid response is looked for, as with CCV's (Control Configured Vehicles) where DLC (Direct Lift Control) may be desirable as a more rapid means of adjusting lift, perhaps for ride control in turbulent conditions. Normally control is obtained by change of attitude of the aircraft - this however becoming progressively more difficult as aircraft (and inertia in pitch) become larger. DLC may be obtained either by using fast acting flap type control surfaces - or, with less effort, by the use of spoilers*. Some detail of the way in which the force follows the motion for spoilers is required - this not, for example, necessarily the same for spoiler being extended to spoiler being retracted.

Outside of mainstream aeronautics two problems are of particular interest. The first, already mentioned in Section 4, pertains to ejection seats*. Typical seat trajectories may often be calculated using the quasi-study approach; for high rotation rates, however, or during seat emergence when the shape as seen by the air is changing rapidly, dynamic effects may be pronounced.

The second case, is that of the inflating parachute**. The worst design case for parachutes is that corresponding to peak load, and this occurs during the inflation period, often before the parachute first reaches its normal flying diameter. Depending upon the geometry of the parachute, and the conditions under which it is deployed, the factor by which the peak load exceeds the final steady load may be from 10 to 15. Precise knowledge of this factor is obviously important during design of a parachute - or, looked at from a different point of view, an understanding of the flow mechanism during inflation may make it possible to avoid excessive loading. Investigation of the aerodynamics of parachutes during the opening phase has been the subject of research by Lingard (Reference 9) at Bristol. He has deployed model parachutes in water and in air, varying parameters to represent a large range of full scale conditions. Flow fields have been recorded photographically, using polystyrene beads in water or helium bubbles in air; Figure 14 shows a typical photograph from a water test, where the camera is stationary relative to the water. Information from the film is extracted and stored on computer for analysis. A print out of some of this data in diagram form is shown in Figure 15, where here the viewpoint is stationary relative to the confluence of the parachute lines. The upper diagram represents conditions during an inflation, the lower conditions approaching steady state. Interesting observations have been made:- during the inflation, for example, separation is very restricted and only a narrow wake may result - encouraging for the mathematical model being developed. Force measurements during inflation have also been recorded, and correlation parameters suggested. Figure 16 shows a typical set of results collapsed onto a single curve by suitable choice of correlation parameter.

8. Non-Uniform Approaching Stream

In all previous sections it has been implied that the approaching stream is uniform; this may, however, not be the case. In industrial aerodynamics**, e.g. the work of Lawson at Bristol (Reference 10) the approaching stream is rarely uniform. Air approaching a building has been affected by the terrain upwind, such that mean velocity increases with height and an intensity and spectra of turbulence is added. Interest may centre on the environment of the building (pedestrian comfort, pollution), on whether there is adequate structural strength and/or stiffness, or on the effect that a new building may have on existing buildings. The requirements for tests in this field are:-

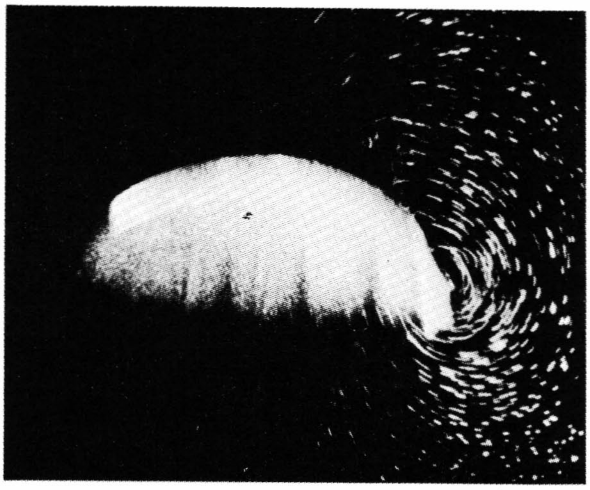


Figure 14. Photograph of Polystyrene Beads During Parachute Inflation in Water.

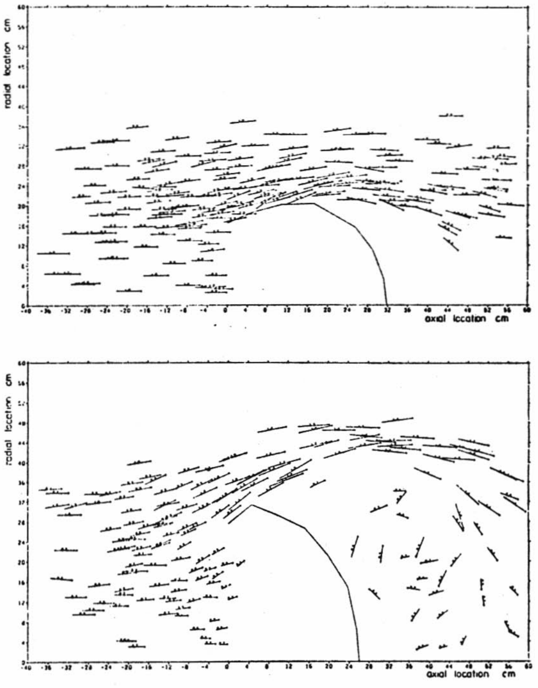


Figure 15. Typical Flowfield Vectors for a Model Parachute in a Wind Tunnel.
(a) during inflation
(b) approaching steady state.

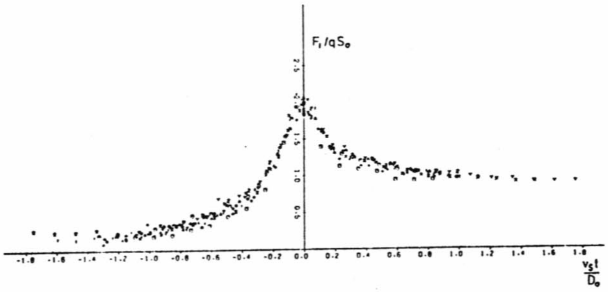


Figure 16. Drag Coefficient Against Non-Dimensional Time for a Model Parachute.

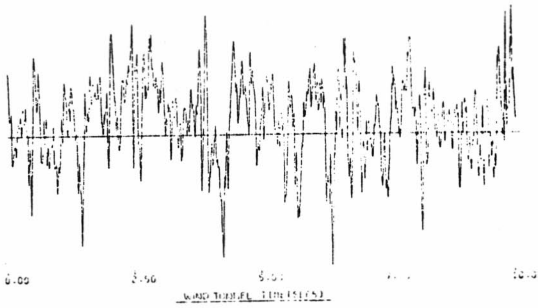


Figure 17. Variation of Pressure with Time.

(1) wind tunnels where the approaching stream can be made to represent different atmospheric conditions (mean velocity profile and turbulence spectra),

(2) a means of sampling and recording information at a high rate (this may be pressures from pressure transducers, velocities via hot wire anemometers, and possibly forces via strain gauges, e.g. Figure 17),

(3) novel techniques in the design and building of models.

In contrast to most aerodynamic work in aeronautics the amount of data stemming from tests in industrial aerodynamics is large - a day's testing may conceivably result in some 5 million bits of data, to be sampled, compared, and correlated.

Non-uniform streams may also be developed within the flow - in the case of twin conductor cables mentioned in Section 6 the wake from the windward cable becomes a non-uniform stream approaching the leeward. Also, when turbulence is introduced into the free stream**, the separation points on the windward cable move aft producing a different wake structure and hence modified flutter boundaries for the leeward conductor (Reference 11). It is found however that these turbulence effects on flutter can be assessed accurately by means of quasi-study theory in which the steady aerodynamic forces on the leeward cable in turbulent free stream flow are used.

Problems involving non-uniform streams also arise in aeronautics, although perhaps with a different emphasis. A turbulent atmosphere can give an uncomfortable ride to passengers. The response of any aircraft to turbulence* needs to be assessed, although a quasi-study approach will often be sufficient. This leads on naturally to studies of how the 'ride' might be improved** (Reference 12) either by the use of conventional control surfaces or by the 'direct lift control' mentioned in Section 7.

Closer to the ground other problems can arise. Particular atmospheric conditions can lead to extreme wind shear, which, when encountered by an aircraft*, can lead to extremely hazardous conditions. Also during take-off and landing turbulence created by wind flowing past very large buildings in the vicinity of runways (e.g. hangers)* can create dangerous conditions. Similarly the changing pattern of air flow over a pitching deck of an aircraft carrier may create problems for a pilot just when there is little room for error.

9. Relating to Propulsion

The final group of separated and unsteady flow problems of interest in aeronautics is that relating to the power unit, whether piston, turbojet, ramjet or rocket, - or with propellors or rotors.

Propellors and rotors leave wakes (slipstreams) that will usually impinge on other parts of the aircraft, sometimes with adverse effects. Parts of a rotor may have low efficiency due to separated flow - e.g. the hub, or the inboard parts of the rotor blades when travelling downwind. Also in forward flight conditions are changing continuously on each blade element.

Turbojet installations comprise intake, engine, nozzle, together with a certain amount of secondary ducting. The intake may suffer from engine surge, from instabilities in shock wave patters (buzz), or need careful attention given to the flow through any auxiliary doors*, in any secondary ducting or to the separated flow in any cavities*. The nozzle, if of convergent/divergent form may have internal separations when running over expanded, certainly so if it is in the form of an aerodynamic nozzle. If the exhaust does not completely fill the base area of the aircraft or missile (and in practice it is unlikely to do so completely) there will be flow separation in the base area.

Problems associated with power units may be clear of the power unit itself (see also propellors and rotors above). Jets too close to (for example) the fuselage of an aircraft can suck themselves onto the surface and/or the unsteady conditions in the edge of the jet can cause damage to local structure. If angled to the flow** the effect on the main stream flow can be enormous, the jet impeding the flow somewhat in the manner of a bluff body, although with the shear layer of the jet acting in a manner very different from the boundary layer on a solid body. This type of problem is connected with VTOL aircraft in particular, and has been of some interest at Bristol. The first major investigation was by Tipping (Reference 13) who studied the flow around a jet issuing from a flat surface that was aligned with the stream. Later work looked at a two dimensional jet, with current interest centreing around circular but non-uniform jets.

Jets may also impinge on surfaces, creating flows that have some separated or unsteady features. With VTOL aircraft re-injestion of exhaust air may create problems*. With missiles the blast from a missile at launch creates a transient flow pattern* that can cause problems on adjacent launchers. The local flows may also warrant detailed investigation; the impingement of the jets on the launcher or the ground have led to a close investigation of the flow from supersonic jets on surfaces of various shapes**. Hunt at Bristol has been responsible for a number of studies (e.g. Reference 14). While the flows are essentially steady, they generate separated flows on the leeward side of any surface they hit, these separations varying with the geometry and hence varying the forces. Separated flows have, surprisingly, also been identified within the complicated shock pattern formed on the windward surface.

10. Concluding Remarks.

We have tried in this paper to indicate the increasingly wide range of separated and unsteady flow problems occurring in aeronautics, pausing to discuss in a little detail those of some interest to us at Bristol. There is a growing need for more work in this field - both experimental and theoretical but there would seem to be some dangers in both approaches if embarked upon without sufficient thought.

Experiment is essential - the field is very complex and theory cannot supply the answers - but too much ad hoc testing can be very wasteful. To supply an answer to a very particular problem may be useful - but in the broader field more carefully designed experiments are desirable. The mathematical approach is also of great use but again, much time can be wasted. To achieve adequate accuracy with theory, starting with the basic equations, and making due allowance for the flows being separated and unsteady, can be extremely difficult.

The best approach would seem to be an appropriate combination of both theory and experiment. We believe it necessary to obtain as full an understanding of the physics of the situation as possible first (the experimental approach), and to then formulate mathematical models taking account of the physics (a theoretical approach). This approach has, in our experience over the past two decades, often led to a simple mathematical model which is much more useful than anything obtained purely from experiment or from theory.

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