Wing tip vortices of cyclonic proportions

The designers and operators of jumbo jets are becoming increasingly concerned about the hazards created by the wing tip trailing vortices continuously shed by these aircraft when in flight. Several fatal accidents have resulted in the past few years due to an aircraft encountering the trailing vortices of another. The hazard exists because of the sheer size of these vortices and the high swirl velocities contained in them. For example, swirl velocities of the order of ±18.3 m/sec may be found in the vortices shed by a C5-A Galaxy one and a half miles astern or 30 sec. after the aircraft's passage. Swirl velocity is directly related to vortex strength which in turn varies directly with aircraft lift coefficient and inversely with aircraft velocity. This is just the wrong combination that one encounters in the approach–departure corridor of an airport. From an operational point of view, therefore, undesirable restrictions must be placed on airport traffic by reducing air traffic density and thus limiting the number of take-offs and landings when the jumbos are around; a practice currently followed around the world.

For example, the CAA (Civil Aviation Authority) of Great Britain requires air traffic controllers to try to keep at least 4 nautical miles between two Boeing 747s, 5 nautical miles between a Boeing 747 and a Boeing 727, and 8 nautical miles between a Boeing 747 and a light executive jet in the approach corridor of an airport.

Such separation distances are believed to be conservative and are based on worst case scenarios. If separation distances could be reduced enough, without compromising flight safety, to allow one extra aircraft landing per hour at busy airports in Europe and the USA, several million dollars of revenue per year per airport could be generated.

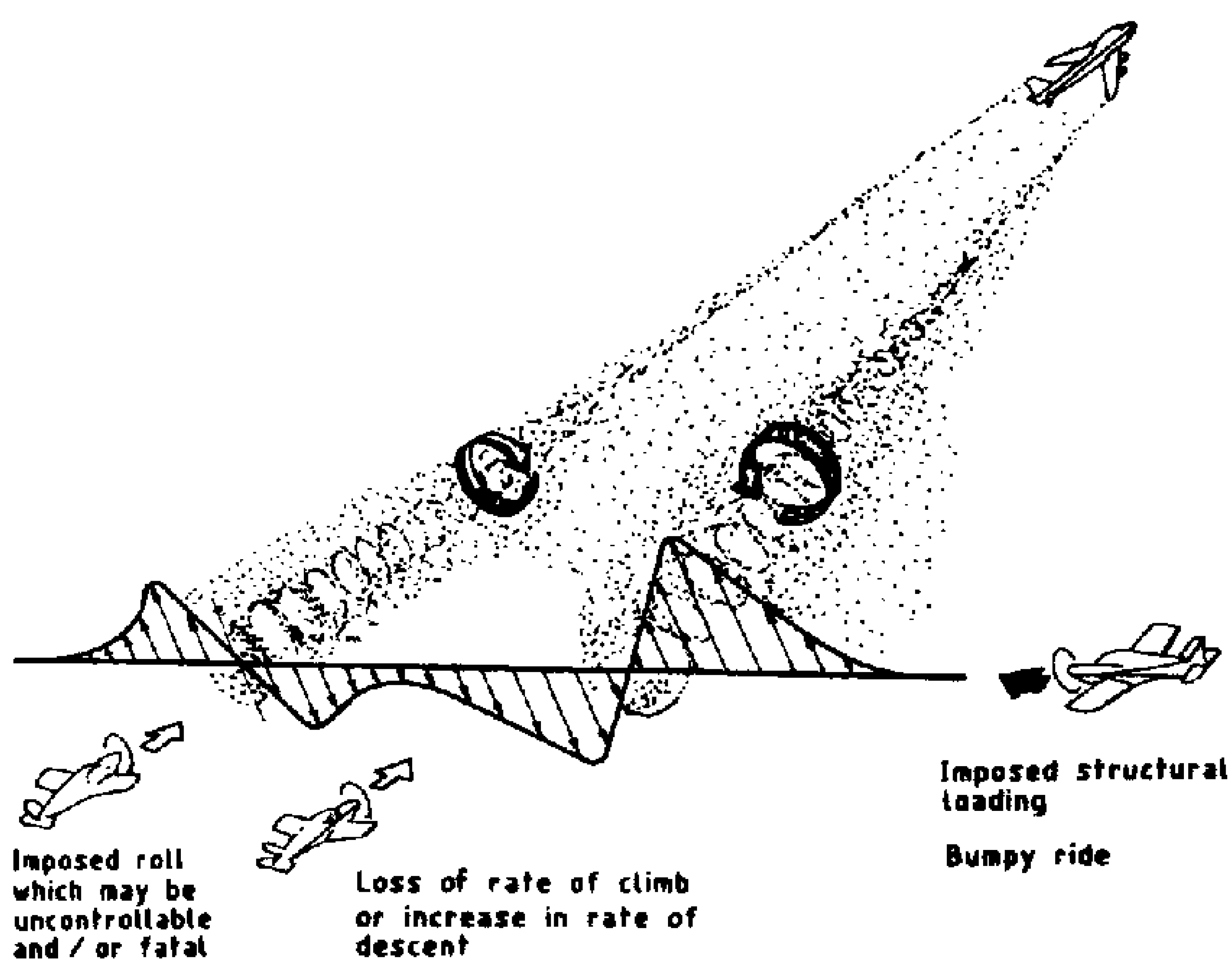
However, the airport vicinity is not the only problem area. Jumbo vortices shed under cruise conditions are no less hazardous since encountering aircraft will meet them under high dynamic pressure conditions. Thus, even under cruise conditions heavily used corridors, like the Atlantic crossing, must be carefully monitored and aircraft widely spaced to prevent accidents.

Some idea of the type of hazards an aircraft encountering jumbo vortices will face may be gained from Figure 1. Briefly, they are: (1) an aircraft penetrating the core of a vortex would experience imposed rolling moments, (2) an aircraft subject to the downwash would experience a loss in rate of climb or an increase in the rate of descent, and (3) if the penetrating aircraft approaches perpendicular to the vortex system, as shown in the figure, for example, structural loads would be imposed. In addition, a bumpy ride is almost certain to result. The hazard level increases as the follower aircraft size and/or its distance from the jumbo decreases. Present day jumbo jet tip vortices are perfectly capable of structurally destroying or causing total loss of roll control to any non-jumbo category following aircraft if they stray sufficiently close to the jumbo. For example, a Boeing 737 can experience total loss of roll control within a couple of miles of a Boeing 747.

In any future transportation scenario, jets of even larger size compared to today's are expected to operate in large numbers and therefore the trailing vortex problem demands a solution. In the past, investigators have proposed various gadgets to be fitted at the wing tips that would destroy the tip vortices at a rate faster than its natural decay. These have included the addition of end plates, a body of revolution, flow through a nacelle or an engine at the wing tip, the use of drooped tips, downstream injection into the vortex core, a wing tip mounted upstream facing jet, porous wing tips, wing tip drogue chutes, a crossed blade (X-pattern) turbine fixed immediately behind the wing tip (locked or free to rotate), and fences placed near the wing tip above and below the wing to produce a swirl counter to vortex swirl.

These experimental investigations and others that continue to be made are motivated by the well-known observed fact that when objects are inserted into swirling vortex type flows, their subsequent influence may alter the flow structure significantly to the extent of causing their breakdown and decay. However, none of these devices, except the crossed blade turbine, have met with a degree of success that would justify their drag penalties, heavy power requirements, or engineering complexity.

The crossed blade turbine seems to show some promise. In flight tests on a four-bladed prototype turbine mounted on a NASA owned Piper PA28RT's wing-tips it was found that, apart from



After Lee-6 H, *Aeronautical Journal*, September 1975.

effectively dissipating the spiraling vortices, there is a favourable aerodynamic drag reduction of almost 6 per cent. It is also estimated that a similar device when mounted on a Boeing 747 type of aircraft could mean drag reductions of about 4 per cent, a result significant enough to catch the attentions of aircraft designers and operators. A likely side-benefit from such a turbine, if allowed to rotate, is that power may be harnessed to generate electric, hydraulic, or pneumatic power, for example, to meet peak-load requirements. Otherwise, the turbine would remain static for maximum drag benefits.

On the other hand, predominantly aerodynamic solutions to the problem have also been proposed. Two broad approaches appear to be emerging from these investigations. In the first, the wing spanwise lift distribution is sought to be altered by deflected flaps to produce centres of high shed vorticity so that the wing wake attempts to roll up into several vortex cores. In this way it is hoped that the individual vortices will be weaker compared to the present tip vortices and that their mutual interaction will quickly cause the vortices to destroy themselves in a Crow type instability or by vortex bursting, thereby alleviating the wake hazard to a following aircraft. The motivation for such studies has come in large measures from the theoretical work of Vernon Rossow of NASA Ames in the early seventies. However, such spanwise wing lift distributions produce large increments in the induced drag and the mutual interaction mechanisms by which the vortices are supposed to destroy themselves are neither well-understood nor do they appear to be controllable to any satisfactory degree. In the future, if this method does become feasible, it is likely to be restricted in its use to the approach/landing phase only because of the induced drag penalty.

In the second, aerodynamic control surfaces (e.g. flaps, spoilers, etc.) are to be programmed to automatically generate an unsteady pressure distribution on the wing while maintaining constant lift so as to produce an unsteady wake. Limited flight and wind tunnel tests based upon this general approach indicate that a critical frequency exists at which, if the control surfaces are oscillated, they could cause a marked decrease in vortex dissipation time. However, such a concept requires careful evaluation from at least two points—excitation of aircraft structural modes due to control surface oscillations and passenger comfort as affected by an oscillating longitudinal acceleration field created by changes in the induced drag. A practical application of the concept will, in all probability, be restricted to aircraft embodying CCV (control configured vehicle) technology.

While these various methods of alleviating the wake hazard are being explored, a fair amount of wind tunnel, water tank, and flight data have been accumulated to investigate the roll-up process and the mechanisms of vortex decay.

Aircraft vortices do not lend themselves easily to tests. In wind tunnels and water tanks, difficulties arise due to small available test section lengths, improper simulation of Reynolds number causing an imbalance of inertia forces to viscous forces in the vortex core, vortex meandering, probe and tunnel wall interference, etc. Since vortex cores may become very sensitive to obstacles placed in their path, laser velocimetry techniques are in increasing use. Reliable flight test data on vortices are difficult to obtain due to a general lack of quiescent atmospheric conditions, difficulty of positioning chase aircraft, data contamination due to atmospheric stratification and turbulence, and unknown effects of aircraft propulsive systems. However, some valiant attempts to probe the vortices in flight have been made by the FAA (Federal Aviation Administration) of the USA using the NAFEC (National Aviation Facilities Experimental Center) Vortex Flight Test Facility in 'Tower-Fly-By' experiments. The NAFEC Facility consists of a 42.67 m tower instrumented with an array of hot film anemometers, coloured smoke dispensers, and meteorological instrumentation past which aircraft, whose vortices are to be probed, fly. The interference created by the tower remains an undetermined factor, and the data must be corrected for ground effects.

The available experimental data have provided some clues to aircraft wake behaviour. In the classical situation where two tip vortices develop, it appears that the vortical wake is completely contained within the viscous wake, and regions of high total pressure loss also are associated with high streamwise vorticity. Most, but perhaps not all, of the shed vorticity roll up into two roughly axisymmetric vortex cores. On the basis of maximum tangential velocity in the vortex, there appear to be two characteristic flow regions. A plateau region whose downstream extent depends upon the span loading and angle of attack, shows an almost constant maximum tangential velocity followed by a decay region in which the maximum tangential velocity decreases with downstream distance (roughly as the inverse one-half power). Axial velocity measurements show that both enhancements and defects are possiblle and vary in magnitude with downstream distance. Depending upon the spanwise loading, additional rolled-up vortices may develop downstream of the wing trailing edge in which case the vortices, including the tip vortices, may interact in several ways (e.g. merge, rotate around one another, etc.) to an ultimate decay. Atmospheric turbulence, winds, jet exhausts, multiple vortex formations, etc. all enhance the decay rate of the vortices.

Inevitably, researchers are also looking into means of detecting and tracking vortices to avoid them if not prevent them. These means have included a variant of radar, called the lidar, to locate and measure the velocities in the vortices; a sodar, originally designed to detect wind shear, that uses acoustics principles of sound detection and ranging; a laser system; and Doppler radars. But none have matured where they can be used with confidence. The difficulty is that of picking the turbulent core of a vortex which is less than 10 m across at long ranges. But even if the detection problem is sorted out, there is the problem of presenting this information to air traffic controllers who are, in any case, tied up with watching radar screens and communicating with pilots.

Rajendra K. Bera, National Aeronautical Laboratory, Bangalore