Wind Shear and Vortex Wake Research in UK. 1982

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1.0 INTRODUCTION

The Royal Aircraft Establishment, Bedford (RAE) has been actively involved in research on both Wind Shear and Vortex Wakes, for many years (REF 1,2,3 & 4). The years 1982 and 1983 will see the successful completion of many of the recent programmes which have already led to major steps forward in our understanding of both wind shear and vortex wake and their impact on aircraft. This increased understanding is reflected in the development of systems and advice to help pilots, and in providing rational scientific methods to assist in advising Certification Authorities and all those interested in improving flight safety.

Wind Shear and Vortex Wakes are related in that they both are invisible enemies of aircraft in the form of large disturbances in the atmosphere and both cause major accidents. They are considered separately in this report, as is the similar problem of building wakes at airports.

During the late 1970's a considerable volume of research on wind shear was initiated by the American FAA following the Boston, New York and Denver accidents to civil airliners. Similar work was also started in the UK. This research resulted in useful advice to pilots about wind shear; better attempts by the meteorologists at forecasting wind shear conditions; and some useful ideas for wind shear measurement and warning systems. By 1980, there were still three major research tasks outstanding:

a. Worldwide measurements to give reliable estimates of probability and details of the forms of large wind shears.

b. Developments of real-time wind shear measuring systems for ground or airborne use.

c. Establishing relationships between measured wind shear and the potential hazard to an aircraft, or class of aircraft.

Without results from these three areas, it is difficult for Certification Authorities to suggest workable requirements, or for avionics companies to provide adequate display information for pilots. The RAE have established programmes in all three areas in collaboration with UK industry and the United Kingdom CAA. The work and some highlights from the results are presented in this note. It is worth noting that progress towards installing suitable equipment in aircraft and at airports will be very slow if Certification Authorities do not make any requirements. Until this year, these authorities could claim with considerable justification that:

a. Suitable proven equipments for wind shear measurement did not exist;

b. Improved training seemed to reduce accidents from wind shear.

These arguments, together with the political and economic climate, effectively stalled any possibility of producing requirements. Although the political and economic climate has not changed, the situation on both (a) and (b) is now very different. Several systems for measuring and displaying wind shear information have now been tested in flight, particularly in the UK. Also, the tragic New Orleans accident and the Air India B-747 accident at Bombay, have dramatically highlighted the continuing menace of wind shear.

Turning to Vortex Wakes: the RAE withdrew from all Civil Vortex Wake experiments in 1977, although some reports continued to be published as interesting events arose, such as incidents in cruising flight (REF 4), or as further analysis of existing data was completed (REF 5 & 6). However, in 1981, an RAF F4 (Phantom) aircraft crashed in a formation landing and early in 1982, an RAF Hawk Trainer also crashed. The RAE advised, and the Boards of Enquiry agreed, that Vortex Wake encounters were very likely causes of both accidents. Several flight measurements of vortices were made to verify this, using the unique fast response flow measurement probe on the RAE HS-125 research aircraft. From these measurement and past experiments in the USA and UK, the RAE have developed a relatively simple and rational method of assessing potential vortex hazard, and identifying the relative susceptibilities of various military and civil aircraft. The main lessons from this work are described in this note and should provide both civil and military authorities with a means of assessing separation requirements for existing and proposed new aircraft, such as the proposed B-747 development and, at the other extreme, the new Ultra Light aircraft.

The third topic addressed is Building Wake Turbulence. At some airports, such as London (Heathrow), constraints on space have led to the construction of large aircraft maintenance buildings near the runways. At Heathrow, the buildings of the British Airways Engineering Base are South of the last kilometre of the approach to Runway 28R. Pilots are warned to expect large wind changes on this approach in SW winds of 15 kt or more. Plans to construct more large buildings are in hand for Heathrow and other airports, but we have as yet no means of assessing their potential hazard in any objective way. A joint programme between the RAE and Bristol University is addressing this problem and is described in this note.

2.0 WIND SHEAR PROGRAMME

This section describes the work on:

a. Wind shear measurements

b. Hazard level determination

c. Wind shear detection and display systems.

2.1 Wind Shear Measurements

2.1.1 Airline Flight Data Recordings

All major airlines in the UK, and airlines in several other countries, but not including the USA, use continuous flight data recording to monitor system health (especially engines) and provide information on operating events to improve operating techniques and flight safety. These records contain a wide range of flight situation parameters and in 1978, the RAE approached British Airways (BA), with the support of the CAA, with a proposal to use such records to obtain wind shear measurements. The programme was agreed and, following an initial trial period in Summer 1980 (1205 landings, REF 7 & 8), a programme of analyzing the final 2 mins of every landing of BA B-747 aircraft for about 12,000 landings started early in 1981. At September 1982, data from 9000 landings had been analyzed.

The programme has three aims:

a. To provide statistics on the probabilities of encountering severe wind shear at individual airports in a worldwide route structure;

b. To provide examples of large wind shear to improve our understanding of the forms of shear and the associated aircraft behavior;

c. To prove the usefullness of the Discrete Gust Analysis methods (REF 9) in detecting wind shear and provide a method for routing application at British Airways.

Initially, the flight data are processed at BA to extract head wind, cross wind, aircraft heading, and height data at one-second intervals for the 2 mins before touchdown. British Airways process these data through a simple wind shear identification programme and identify:

a. Landings where the shear magnitude exceeds a predetermined threshold, which are called alerts;

b. Landings where a combination of wind and aircraft heading change will give a significant apparent wind shear when considering only head wind changes. These are not checked for alerts but head wind, cross wind, aircraft heading and height are passed to the RAE;

c. Landings where more than 20% of the data has lost synchronization is rejected at BA.

British Airways pass to RAE the head wind and height data for all landings, other than those identified with (b) and (c) above. At the RAE, the data are subjected a series of checks to reject all runs with suspect data, after visual inspection, and to check the validity of all the runs with events at the 5% probability level or less. The alert threshold is set at about the 1.5% probability level.

The wind shears (and turbulence) are identified using the Discrete Gust Analysis Method (REF 9) developed at the RAE by J. G. Jones. This is used to identify particular patterns in the head wind data: In this case, single and double ramps (Figure 1). These are filtered to identify the length of the ramp as well as its size.

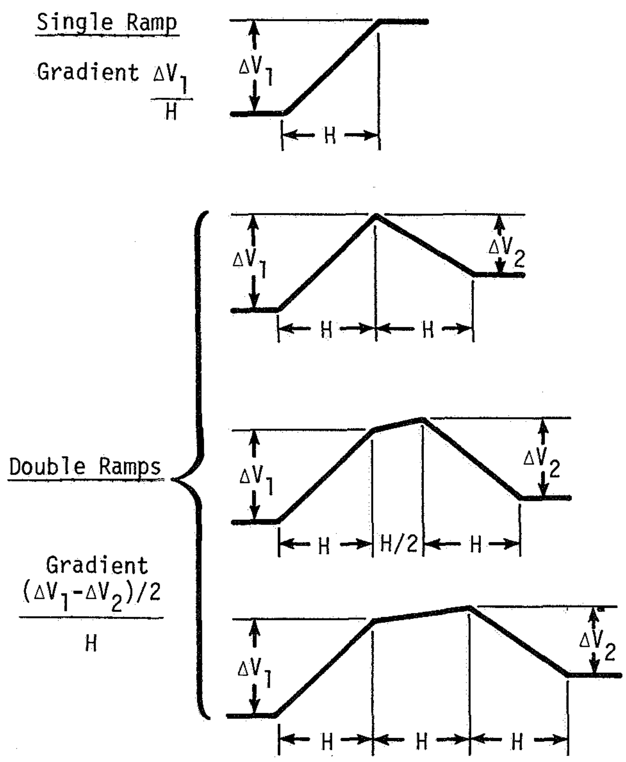


Figure 1. Wind Shear Patterns

Typical data after 9135 landings at a total of over 70 airports around the world is shown in Figure 2. The cumulative probability plots show a remarkably consistent relationship with an exponential distribution form (straight line on the log-linear plots). The data include both turbulence and isolated wind shears. This consistency means that extrapolation to predict the severity of wind shears at the 10^{-7} probability level for landing can be readily justified. For a single ramp 600 m long, which has been suggested as a critical length in ICAO discussions, the 1 in 10^7 landings case is likely to be a shear of about 27 knots. Also the data show that the longer shears of about 600 and 1200 m can be normalized when plotted as (Speed Change/(Ramp Length)$^{1/3}$ so that shear at other lengths can be predicted readily, e.g., at 1500 m shear length the 1 in 10^7 landings case is likely to be a shear of 37 knots.

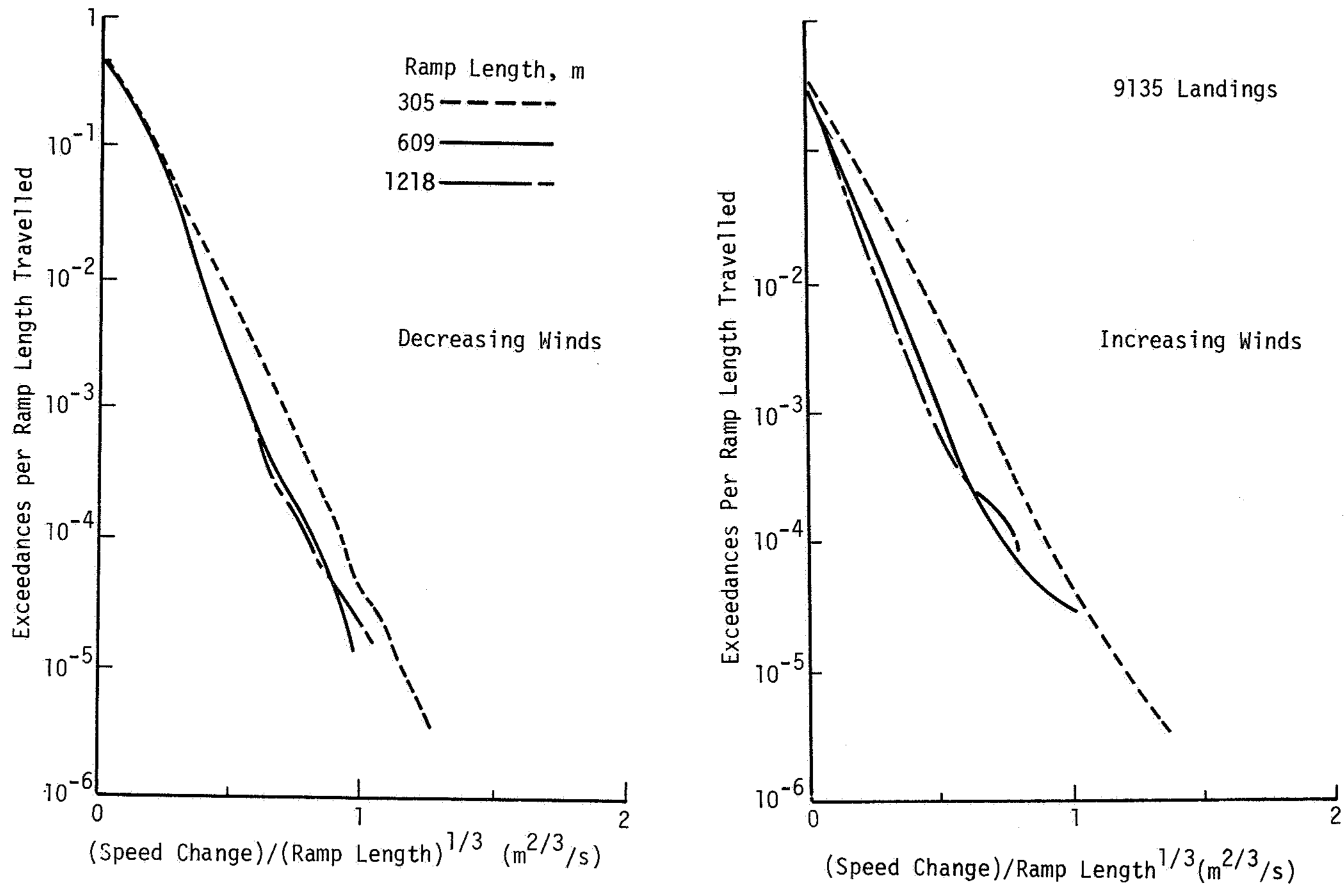


Figure 2. Cumulative Distribution of Single Ramps (British Airways Records)

Data for individual airports and both single and double ramps of 600 m are shown in Figure 3, and cover a wide range of conditions in terms of airport latitude, topography, time of day, etc. There are significant differences in the level

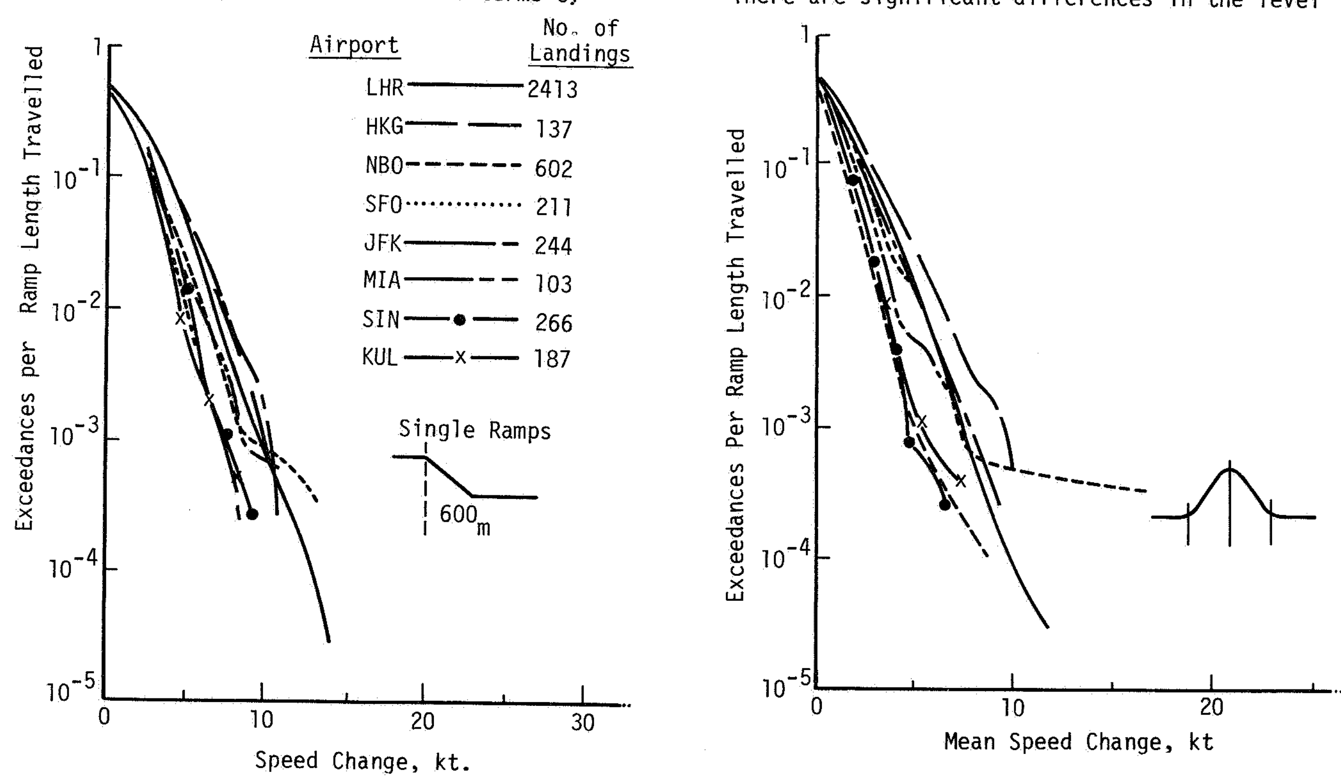


Figure 3. Cumulative Distributions of Single and Double 600 m Ramps at a Selection of Airports

of activity at different airports, but, despite the much smaller sample sizes, the general form of the distributions are well established. Airports with significant thunderstorm activity are covered very adequately as the data includes late afternoon and early evening landings at Kuala Lampur and Singapore, which have very high probabilities of thunderstorms. The rate is almost one a day in the most active months (Oct./Nov.). The data also cover Miami in the USA, which has quite a high probability of thunderstorms, although only about half that at Singapore. These three airports are included in Figure 3, but are all relatively inactive.

One other aspect being studied from the statistics is the distribution of wind shear with height above ground. The data are grouped into approximate height bands between 0, 250, 500, 1000 and 1500 feet for different airports. The results have yet to be fully assessed; but, as the hazard from wind shear is greater as the available decision height decreases, the data will improve the estimation of the worst cases.

The statistical data is already proving valuable in helping the RAE to advise the Hong Kong authorities on possible wind shear hazards at proposed sites for a new airport.

Examples of head wind variations with various types of wind shear encountered are shown in Figure 4 (data from REF 7). The two largest events recorded up to August 1982 are shown in detail in Figure 5 (Melbourne) and Figure 6 (Anchorage). In Figure 4, there are examples of a low-level jet at San Francisco (16.6 kt in 4s), a sorm front at Calcutta (13.6 kt in 4s), an on-shore wind at San Francisco (12.8 kt in 16s), and a mountain wake at Hong Kong (Double ramp of average 10.7 kt and 4s each ramp).

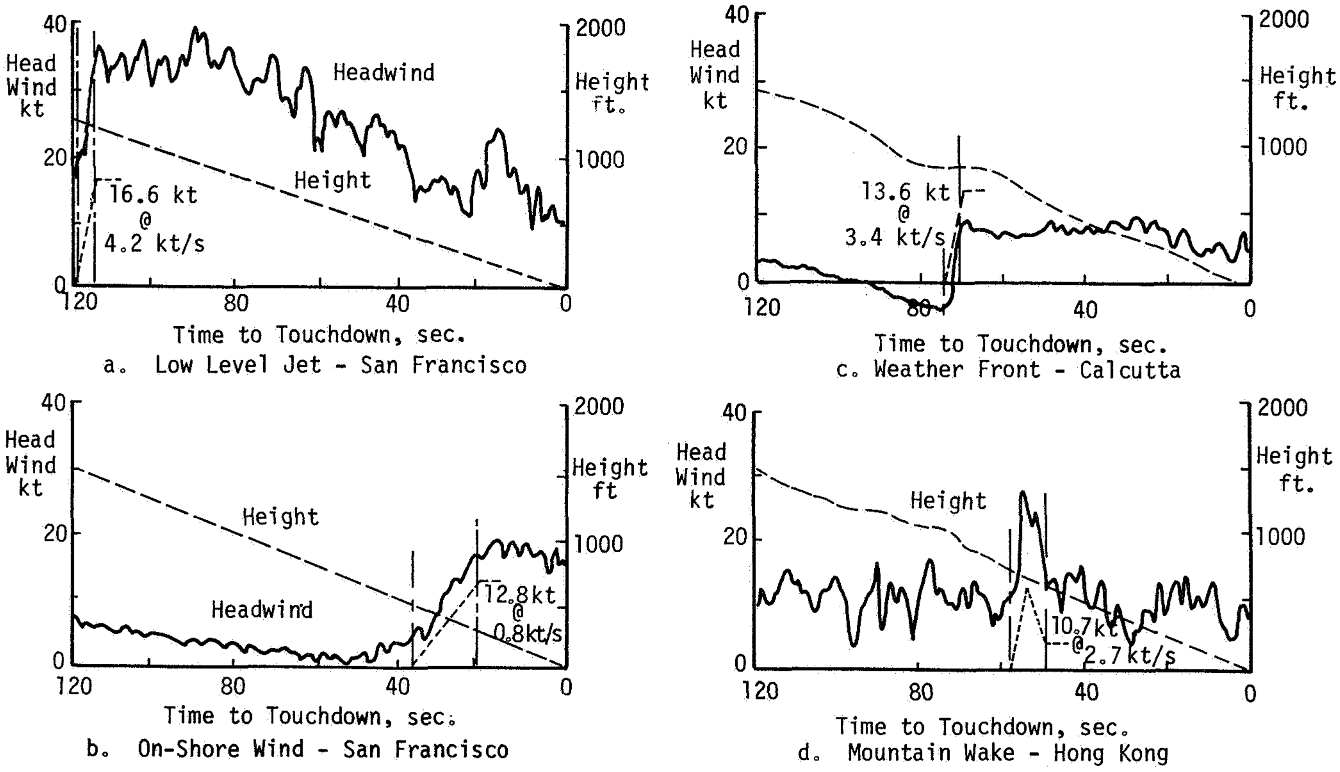
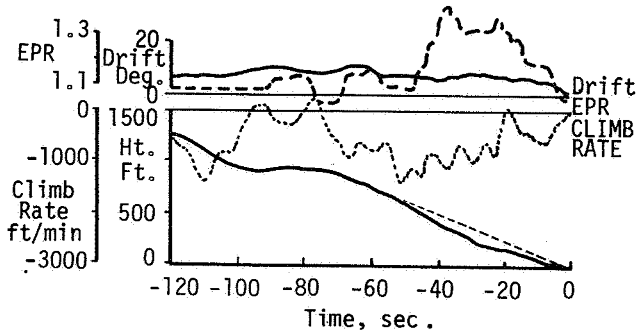
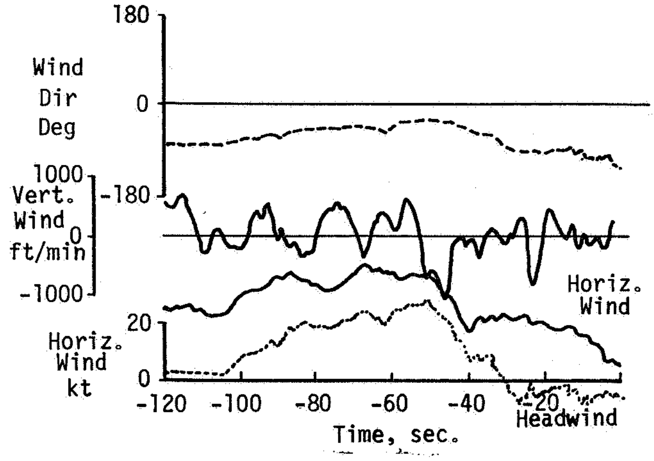


Figure 4. Wind Shear Measured from British Airways Flight Data

The event at Melbourne, Figure 5, demonstrates the effectiveness of the calculation of vertical as well as horizontal winds and shows an event starting with a 1000 ft/min downdraught and about 35 kt loss of head wind. The pilot applied thrust to a level that would normally give level flight but this was only sufficient to stabilize descent rate at slightly more than normal for an approach. The aircraft finally recovered when the wind shear ended and the aircraft was about 150 ft above the ground. The other major event at Anchorage, Alaska, was of a similar magnitude and the pilot overshot. (Note that the Ground Proximity Warning System (GPWS) operated 1 or 2 seconds after the pilot decided to overshoot.)

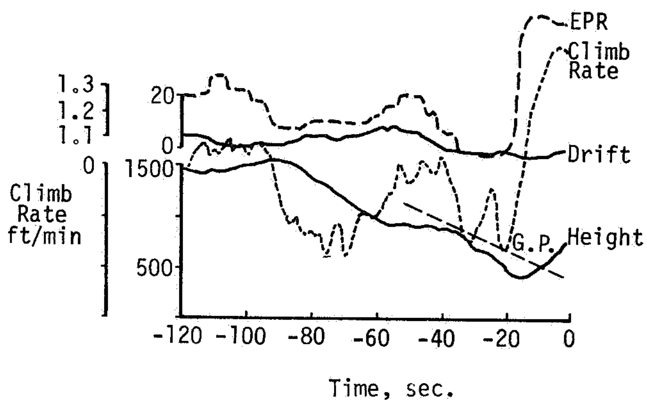


a. Aircraft

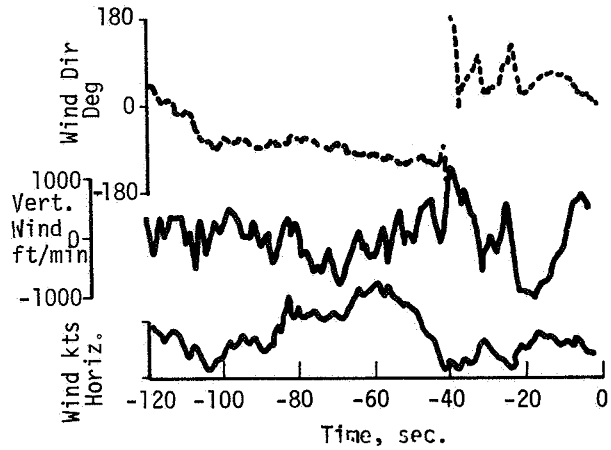


b. Winds

Figure 5. Wind Shear at Melbourne



a. Aircraft



b. Winds

Figure 6. Wind Shear at Anchorage

The routine collection of BA data will end in March 1983, as any significant extension of the statistical data base would be both uneconomic and, in view of the orderly nature of the results to date, unnecessary. The NLR, Holland, have been involved in a similar data collection programme from KLM Aircraft (REF 10 & 11), but without the assistance of discrete gust methods were unable to test and summarize their data readily. Following publication of REF 7 & 8, they are now programming the RAE method so that the data from KLM and BA can be compared directly. There are about 8000 landings and take-offs during 1978 in the KLM data and a further period of data collection is expected in 1983. This data will be exchanged with the RAE data.

Collection of large events from BA is expected to continue beyond March 1983 under the CAA's special event programme CAADRP. The RAE will provide programme advice and a consultance service.

2.1.2 Thunderstorm Wind Shear

Quite a few of the major aircraft accidents from wind shear have occurred in winds associated with thunderstorms. In the Summer of 1982, the US National Center for Atmospheric Research (NCAR) and the University of Chicago organized an extremely successful programme around Denver, Colorado - the Joint Airport Weather Studies (JAWS) Project (REF 12) - to investigate the structure of thunderstorms and their winds. The RAE were fortunate to be invited to participate with the HS-125 research aircraft (Figure 7).

The RAE HS-125 was in Colorado for three weeks in June/July 1982, and flew 34 experimental sorties of which 16 were flights in thunderstorm winds at heights between 1000 and 3000 ft above ground level. The other flights covered a variety of related tasks. The RAE programme was supported by funds from the UK Department of Industry, UK Ministry of Defense, CAA, Smiths

Industries plc., US NCAR, Marconi Avionics plc., Ferranti plc., and Signal Processors Ltd.

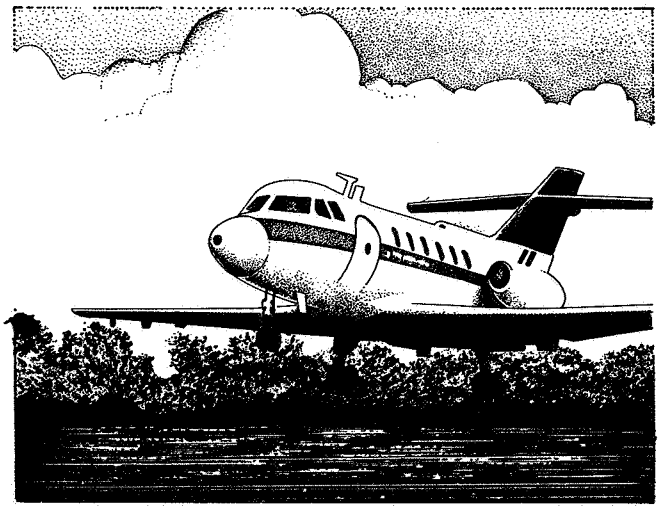


Figure 7. RAE HS-125 Research Aircraft

In addition to its basic instrumentation to measure turbulence, including wind shear, in three axes at frequencies up to about 20 Hz (a minimum wavelength of 6 m at typical speeds used for JAWS flights), the RAE HS-125 was unique among the participating aircraft in having a wind shear detection and display system fitted... the Smiths Industries 2 pointer VS/ERO (Vertical Speed/Energy Rate Indicator). It also carried the detection elements for two other systems, viz:

a. Laser True Airspeed System (LATAS), which detects wind shear several hundred metres ahead of the aircraft;

b. Marconi AD660 Doppler Velocity Sensor, which could be used as the basis of a ground speed/airspeed display.

These systems are discussed in a later section.

The editing and analysis of the JAWS flights is proceeding and an example of one of the more dangerous microburst events is shown in Figure 8. The primary microburst pattern has smaller events on either side. The main event sees the head wind increase by about 25 kt following the initial dip of 8 kt. It stays at a mean of about 25 kt for 5.5 seconds and then falls by 35 kt followed by an increase of 18 kt. The final action is a smaller drop of 10 kt. The main event covered a distance of about 2.2 km, or about 30 - 35 seconds of flight time at normal jet transport aircraft approach speeds. Calculation of the downdraught is not yet complete but the mean flight incidence remains constant whereas the pitch attitude increases by about 3 degrees. This indicates a downdraught of about 1200 ft/min. The flow was also very turbulent and produced normal acceleration changes of +/-1g at the speed of

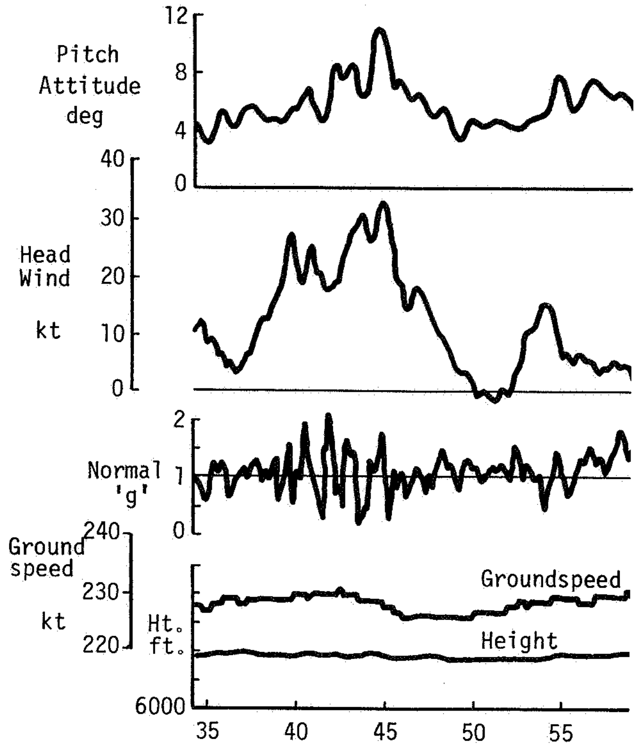


Figure 8. Thunderstorm Microburst - JAWS Project RAE HS125 - Flight 792, Run 3.

250 kt CAS used for the flight tests. Full analysis of events such as these will provide a detailed understanding of the form of one of the more dangerous forms of wind shear by identifying not only its magnitude, but also its development and decay. From this should come a better understanding of the meteorological conditions likely to cause microbursts.

In marked contrast to the turbulence in a microburst, flight in the vicinity of intense precipitation, including 3 cm diameter hail, was generally in calm air. Wind data for these flights are being analyzed as are the results for thunderstorm fronts and general outflows with wind changes of 30 - 40 kt, which often included significant updraughts on which the HS-125 could almost soar at idle thrust.

The data from the JAWS project will give a better description of some of the worst shears that nature can produce, which will be of great value for use in wind shear simulations to develop detection and display systems. Also, by studying wind shear events at airports on the BA B-747 routes, it may be possible to estimate the probabilities of encountering a significant microburst.

2.2 Hazard Levels

At first glance, it may seem strange that there is still no straightforward way of estimating the potential hazard to an aircraft of a given variation of horizontal and vertical wind (wind shear). There is general agreement that the height excursion from the intended flight path is a measure of the potential hazard and, as this is a greater hazard near the ground, it is best considered as a fraction of the height available.

The difficulty in relating such height losses to a given wind shear lies in the length of wind shears, e.g., the 30 or so seconds taken to pass through the microburst of Figure 8 at approach speeds. During a time interval of this length control actions will be taken in both pitch and thrust by either a pilot or an automatic control system. The control response will have a significant, even dramatic, effect on the height excursions. This is clearly illustrated when the stick (and throttle) fixed response of REF 13 is compared with piloted simulation (REF 14) through the same wind shear. In the first case, the usually lightly damped long period (Phugoid) response is excited, whereas in the piloted case, it is almost totally suppressed. Also in the first case, very large height oscillations occur which are largely absent from the piloted case. Pilots respond well to motion with periods longer than a second or two, and the Phugoid is typically of 30-40 seconds period; so the above result should not be very surprising.

Piloted simulator studies have been used for many tests. However, such simulation introduces a much wider number of variables than simplified analytical methods, so it is highly desirable to establish a suitable analytical method for assessing susceptibility to wind shear. This method should then be tested using piloted simulation.

For any analytical method, the form of pitch and throttle control has to be defined from the start. One simple pitch control mode considered by the author is flight with constant pitch attitude. This is not unreasonable as it is pilots' control of pitch attitude which modifies the Phugoid and introduces the concept of speed (or flight path) stability. The basic longitudinal motion is modified to a pair of exponential modes. One is mainly a well-damped incidence response and the other is mainly a lightly-damped speed response. Figure 9 shows some typical responses with pitch constraint and without any throttle action. The single ramp head wind change results in an almost constant height rate. The double ramp downburst (single ramp downdraughts are very unlikely as the mean vertical wind is zero) produces a loss of height.

Actual maximum height deviation will depend on the thrust response function, or a reversal of the wind shear (or both). It is this dependence of height deviation on pitch and thrust control functions and wind shear pattern, which makes it difficult to find generally accepted ways of relating the potential hazard to the wind shear.

However, the use of pitch constraint seems a promising starting point, as do the wind shear patterns identified by discrete gust methods. Current research at the RAE is investigating various throttle control modes suggested by study of throttle activity on BA B-747's and other aircraft.

It is hoped that this work will identify the most important aircraft characteristics (e.g., speed, stability, thrust margin, minimum drag speed), and wind shear characteristics (e.g., speed change, length). Aircraft can then be categorized in groups with similar susceptibility to shear. This will also give a basis for presenting the most useful information to pilots.

This study should be completed during 1983, including tests of various features in a piloted simulation. It is the most important aspect of wind shear yet to be resolved as, without it, it is very difficult to establish how to use wind shear data to help pilots, other than through generalized warnings.

2.3 Wind Shear Detection and Display Systems

These systems can be divided into two groups:

a. Ground based sensors

b. Airborne sensors

To be a viable commercial proposition and, perhaps even to be considered as acceptable for complying with any Aviation Authority requirements, any system must provide continuous information of value to pilots and, for ground based systems, air traffic controllers. This information cannot be wind shear, as the significant events are rare; and, because rapid response is essential when wind shears occur, it is vital that pilots and air traffic controllers have confidence in the system. This can only be earned by long experience of receiving correct (and useful) information without "soft" failures prior to its first genuine significant wind shear indication. Thus, it is vital when designing systems to consider first their value in normal operating conditions. Having done this, then the price must be made acceptable.

In addition, the author has always considered that any airborne display system must be prominently located on (or perhaps close to) the primary flying display and provide continuous analogue information during all flights. The idea of a wind shear warning system without an associated analogue display is impractical. Real events are very rare. This means that protection

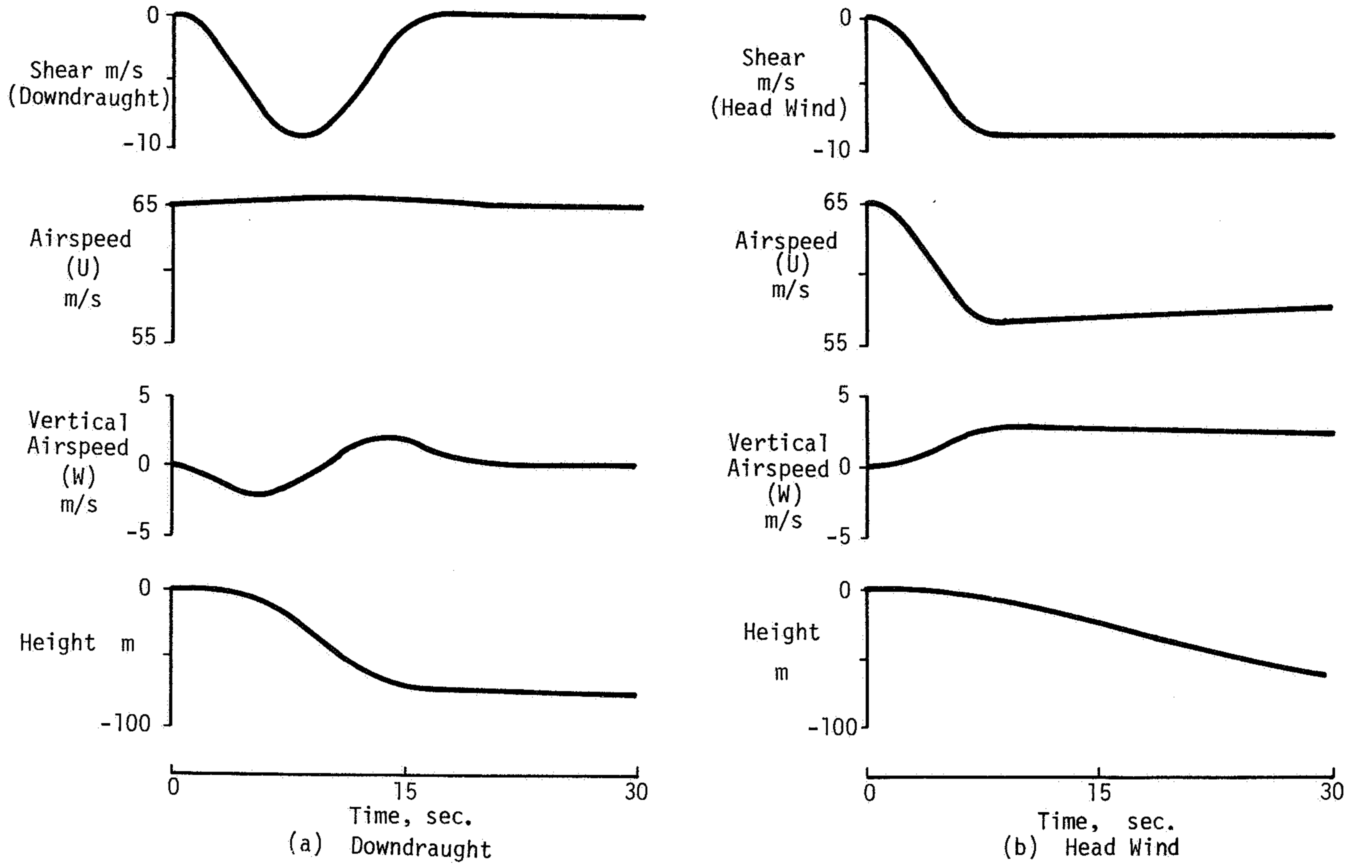


Figure 9. Response to Wind Shear with Pitch Constraint

against nuisance events is very difficult without introducing a lot of smoothing with associated lags in producing the warning. Delays have a dramatic effect on height loss, which is approximately proportional to delay squared.

Thus, 'warning only' systems are likely to be either too late or generate a lack of confidence because of nuisance warnings so that pilots need to crosscheck with other instruments before responding. This creates further delay.

In the following discussion on detection and display systems, brief mention will be made of known systems, but only the UK activities will be duscussed in any detail.

2.3.1 Potential Flight Path/Energy Rate Displays

These are the only type of airborne display that are commercially available and they are advertised by the following three companies: Safe Flight, Inc., USA, SFENA, France, and Smiths Industries plc, UK. The author only has experience with the Smith Industries system, which is the two-needle VS/ERI (REF 15). Potential Flight Path Displays offer similar capabilities and are most easily provided on Electronic Displays (Head Up or Head Down).

The basic principle of these systems is to establish the rate of change of energy, E, where

$$dE/dt = V_{True}(dV_{True}/dt) + gdH/dt$$

To compensate for lags in the air data system when the aircraft is responding to thrust, or flight path changes, a pair of accelerometers (normal and longitudinal) are fitted, and resolution of these into flight path axes required measurements for estimates) of incidence angle. The rate of change of energy can be displayed as the flight path that will be attained if no throttle action is taken to counter the situation.

Various possibilities exist for displaying the information but they are essentially either a situation display of the potential flight path (or potential climb rate), or a throttle director. Of the various systems, only the Safe Flight System is a throttle director, the others are situation displays. The situation displays have the advantage of improving thrust management as they can be used to indicate excess thrust as well as wind shear. Potential flight path is probably more useful as it is associated with the Attitude Display, ADI, which together with the Airspeed Indicator (ASI), are the most actively scanned instruments during take-off and landing. However, the Vertical Speed (VSI) is part of the primary flying instruments and a good location if the ADI cannot be modified. This is where the Smiths Industries and SFENA displays are located.

The Smith Industries VS/ERI is shown in a nominal thunderstorm microburst (downdraught) situation in Figure 10. It has been tested on piloted simulators (REF 15) and flown in a BA Tristar, a Britannia Airways B-737, the RAE BAE 1-11, which has advanced electronic displays, and on the RAE HS-125. In all simulated wind shear cases, the pilots found that the VS/ERI gave their first indication of wind shear and this is supported by a few encounters with moderate shears in the flight trials. However, there is some criticism of using the VSI for the display because many pilots do not usually include it in their primary scan.

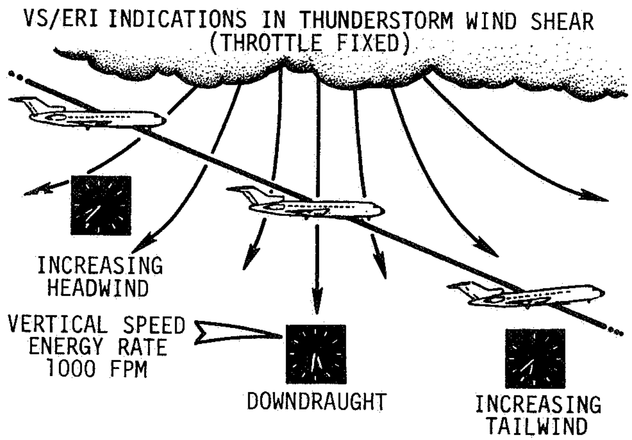


Figure 10. Expected Response of the Smiths Industries' 2 Pointer VS/ERI in a Thunderstorm Microburst

A time history of the response of the Smiths Instrument in the microburst of Figure 8 is shown in Figure 11. This shows the Energy Rate needle responding directly to the rate of change of airspeed. The VSI needle does not respond to the downdraught in this case because the pilot increased pitch angle to compensate. All these types of instruments have a lag in response to wind shear as they must calculate the rate of change of speed. In the Smiths VS/ERI, this lag to shear is about 1.6 sec. Note that: (1) The lag is only about 0.6 sec because the accelerometer terms provide compensation for rates of change of velocity relative to the earth, but not for shears, which affect airspeed with little effect on ground speed; (2) The lag is made greater in Figure 11 by the increase in pitot-static system lag with altitude, as Denver is over 5000 feet above sea level and hot. No scale is shown on the difference between the two needles as the tests in Figure 11 were flown at

It is interesting to note that the difference between the two needles in the microburst is must greater when the speed loss occurs. If

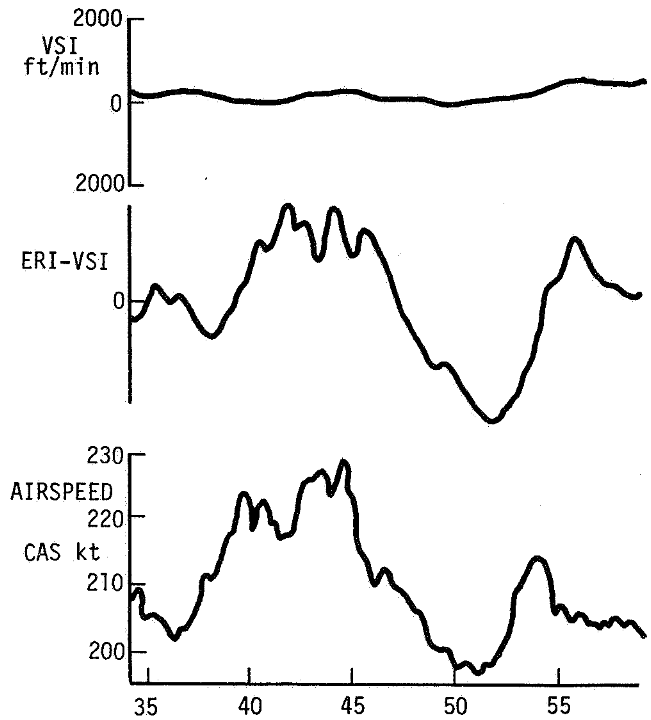


Figure 11. 'JAWS' Microburst Response of Smiths Industries' 2 Pointer VS/ERI

throttle had been used in response to the split between the needles, then a decrease in thrust would not be demanded until the speed was about 15 kt above datum (Datum = 025 kt) but an increase is called for while still 3 kt ABOVE datum. This fortunate response is largely due to the steeper gradient of velocity (dV/dt) near the centre of the microburst, where V is also greatest. Thus giving a much faster response in the midst of the microburst.

2.3.2 Groundspeed/Airspeed Displays

The principle of this system is that the hazard from wind shear is reduced by maintaining the highest airspeed compatible with a safe touchdown groundspeed. This principle is generally confirmed by the RAE studies of hazard levels. Thus, instead of flying approaches on airspeed relative to a target threshold speed, they can be flown to keep the lower of either airspeed or equivalent groundspeed above the target speed. In the more usual case with a head wind at touchdown, this will lead to higher than usual airspeeds on the approach.

In the case of a microburst (Figure 8), the use of this groundspeed/airspeed method would inhibit the normal reaction to reduce thrust as airspeed increases because the groundspeed hardly changes and will be the lower speed. Thus, a higher airspeed is maintained to help cope with the downdraught.

The main complications with this system arise when high head winds push the approach airspeed up to flap limiting speeds. If flap angle is reduced, then the speed safety margin falls. In most cases, it would seem best from a performance point of view to keep airspeed below the flap, limiting speed even if it means that the groundspeed falls below the target speed. However, this could be a poor philosophy to adopt if the instrument is to have a clearly defined role as an indicator of minimum speeds.

The head wind variation in the microburst (Figure 8) is a direct indication of the difference that would be seen between the two needles of a 2-pointer ASI. Positive head wind would place the groundspeed lower than the airspeed pointer.

The information on any ASI can be improved by using a laser system, such as the LATAS which looks ahead of the aircraft, as the airspeed source.

The airspeed/groundspeed display does not give any information on downdraughts, which will appear as a transient decrease in normal acceleration and a subsequent increase in descent rate, but it has the advantage of being located on the airspeed indicator which is continuously monitored during both take-off and landing.

2.3.3 Laser Airspeed Systems

Laser systems measure airspeed by Doppler analysis of reflections from minute particles (aerosols) in the atmosphere. These particles have an extremely rapid response to airspeed changes and can thus be used as a direct measure of airspeed in a region remote from the laser equipment. Two main types of laser are available:

a. Pulsed systems which use time gating to establish the range and short pulse duration (typically 1-2 microseconds) to obtain range resolution. These systems can operate to quite long range and the size of the optical aperture relates to the amount of backscattered signal received. Range resolution is constant at about 300 m.

b. Continuous Wave (CW) focused systems where the beam is focused to a waist at remote point to give a maximum level of illumination and thus the greatest signal returns from that point. The sharpness of this focusing is greatest at short range and with a larger optical aperture. Range resolution can be very fine, but increases rapidly at long ranges, and optical aperture is determined by the resolution and maximum range required.

The choice between the two systems depends on whether 300 m range resolution is adequate, and the maximum range required. Research in the UK has concentrated mainly on the CW focused systems. The general principles of the system are shown in Figure 12. The weak return signal is rapidly converted to a Doppler Spectrum and successive spectra integrated to give very clearly defined spectra. For low altitude wind shear detection, a few hundred integrations are usually adequate and an output data rate of more than 100 samples a second can be obtained.

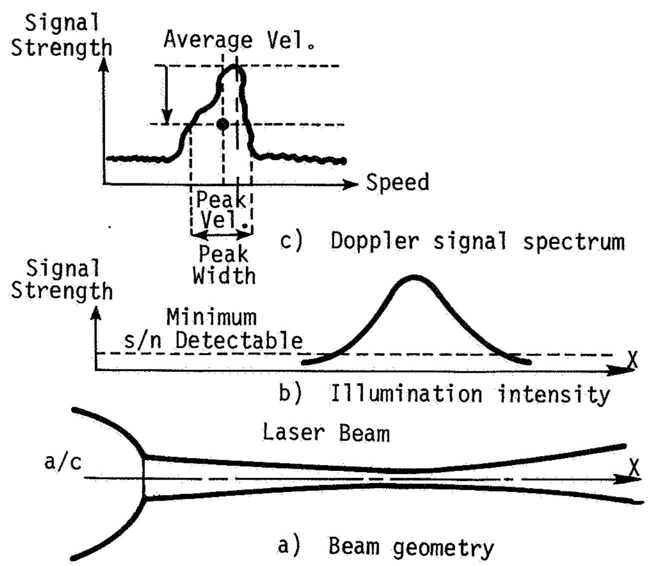


Figure 12. Principles of a CW Focussed Laser Anemometer

One useful feature of CW laser signals is information on the spread of airspeeds over a larger range which is given by the minimum and maximum velocities. With this data, it is possible to distinguish real shear from turbulence. Figure 13 shows the RAE/RSRE LATAS airborne laser system signals recorded in the microburst of Figure 8, and the width of the peak of the velocity spectra clearly identifies the real shears. The difference between the laser and the aircraft true airspeed is a direct measure of the shear gradient over 250 m (about 4 seconds of flight time at normal approach speeds). These shear gradients have values of around 4 kt/sec (2 m/s/s) at approach.

The RAE in close collaboration with the Royal Signals and Radar Establishment (RSRE), who have been responsible for the development of the optics and signal processing equipment, have tested both ground based and airborne CW laser systems. Both systems use eye-safe carbon dioxide lasers

The main aims of the research programme have been to establish the character of laser wind signals and the essential features required in production versions for regular use at airports or in aircraft.

2.3.3.1 Ground Based System

A ground based system (Figure 14) was tested at RAE, Bedford, and the results compared well with more conventional anemometer data. Power Spectra and Discrete Gust Analysis of these data confirmed that the laser system was a reliable source of wind information. The system used 30 cm diameter reflecting telescopes, was monostatic and had an output power of 5 watts. It was used satisfactorily out to ranges of about 1 km.

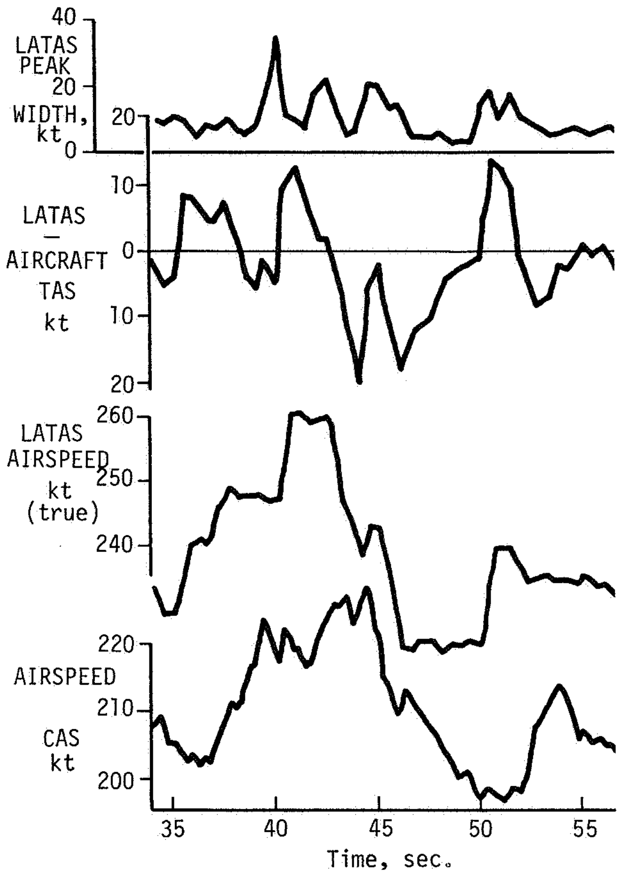


Figure 13. 'JAWS' Microburst Response of RAE/RSRE 'LATAS' System

Any ground based system for airport use would need to make wind measurements from about 0.5 km to 6 - 10 km and preferably with a full 360 deg azimuth scan. The measurements could then be used to give air traffic continuous wind information for all landing and take-off points, and also identify any wind shear development. Measuring both its magnitude and its track relative to landing and take-off paths.

The main problem with operating at such long ranges with a CW system is the large size of the optical aperture required which is about 1-2 m diameter. This could be expensive, although full visible wavelength accuracy is not required, and, in theory, there may be a limit to the effective aperture size, despite the geometric size, because of the effects of small scale turbulence. There is not appropriate experimental data to confirm this limit on effective aperture, but, if the present estimates are correct, it may not be possible to use apertures greater than about 1 m diameter. The author views this theoretical limit with some scepticism as:

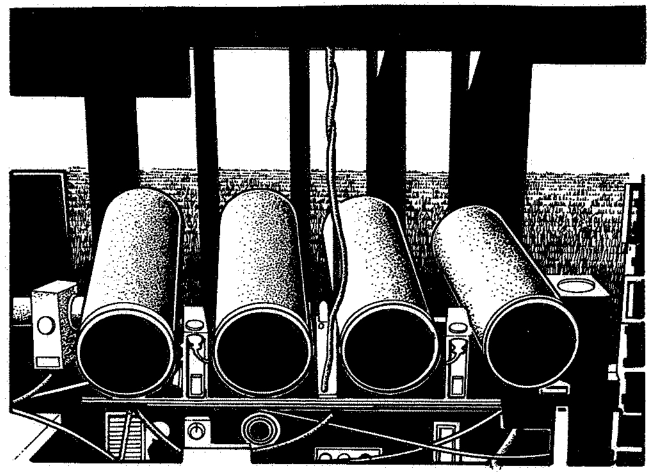


Figure 14. Ground Based Laser Airspeed System

a. The theoretical data is only supported by experimental results from bi-static systems with the beam only a few feet above an arid surface, and

b. Other limitations on laser effectiveness have proved less of a constraint than theoretical estimates would suggest.

However, until tests can be made to see whether such a limit on effective aperture exists, it will be difficult to persuade commercial companies to invest in the development of an airport system based on CW lasers. Pulsed lasers do not rely on focusing for range definition and may be more suitable for a ground based system. However, as yet there has not been a detailed evaluation of a pulsed system against other wind measuring systems.

2.3.3.2 Airborne System

An airborne system (LATAS), Figure 15, (REF 16), has been flying in the RAE HS-125 for about two years and is proving very successful and reliable for measuring airspeeds at remote points up to about 300 m ahead of the aircraft. As Figure 13 shows, this gives extra vital seconds of warning of wind shear. The system uses CW optics made by RSRE and a 3-watt waveguide carbon dioxide laser manufactured by Ferranti. Based on earlier experience, the critical areas for reliability were expected to be the laser, the optical train and the germanium window used to transmit the infrared beam. In the event the lasers have been operating for periods of up to six months without any attention, the optics have not required any adjustment at all, except after laser changes, and the front surface of the germanium window, with its special protective coating is unmarked after 2 years of flight trials, which included flight in soft hail. Figure 16 shows the state of the surrounding paint, which was pitted down to the metal, after flying in heavy rain and soft hail. The window surface is unharmed. Reliability of this level from prototype experimental equipment argues very well for a reliable commercial development.

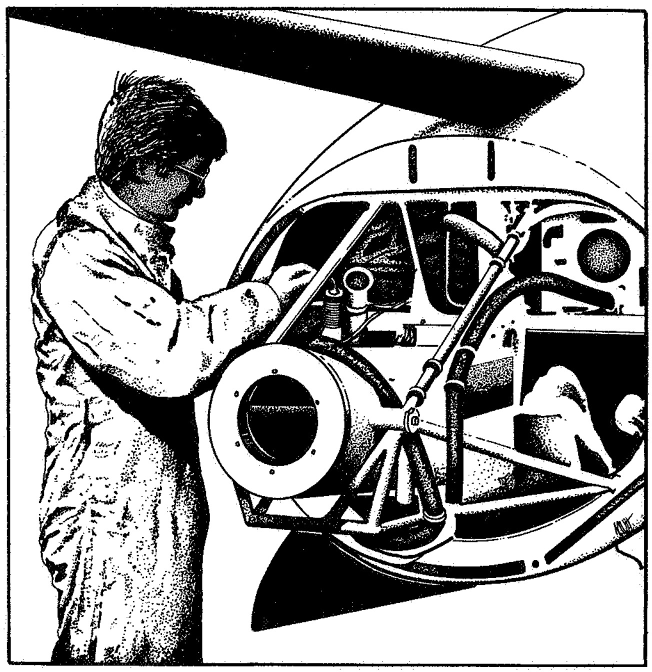


Figure 15. Airborne Airspeed Laser System (LATAS)

The only real obstacle to commercial development is finding a suitable incentive for airlines to purchase such a system. This requires either that the unit earns its keep by saving aircraft operating costs, or that airworthiness requirements call for such a system to be fitted. The

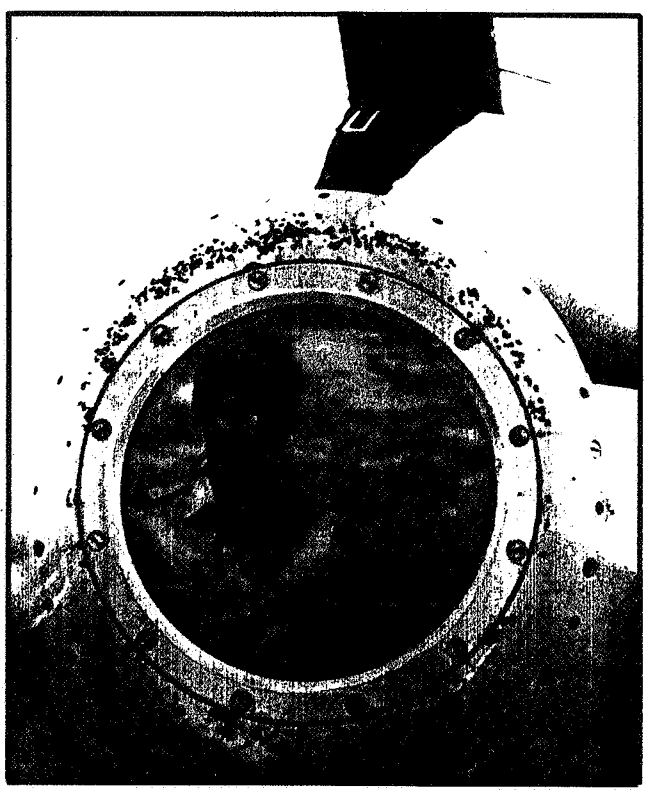


Figure 16. Effect of Hail on Germanium Window

research programme in the UK is addressing possible features that could produce savings in operating costs. Such as:

a. an efficient autothrottle sensor which is responsive to significant shear with negligible lag and yet able to ignore short period turbulence;

b. a control system for tyre spin-up that accurately measures both ground and tyre speed;

c. a sensor for active ride smoothing and/or gust load alleviation control systems which provides adequate lead.

For this last application the system has to function at all heights, and great advances have been made in obtaining reliable signals in very low backscattering conditions at high altitude. Figure 17 shows an example of the signal to noise ratio measured in a climb to 43000 ft pressure altitude. To give some relationship between this data and visibility, it should be noted that the quite high signal to noise ratio at low altitude corresponded to a visibility of about 70 nm. The system is not yet able to obtain a usable signal in all conditions at high altitudes, although there are no problems near the ground.

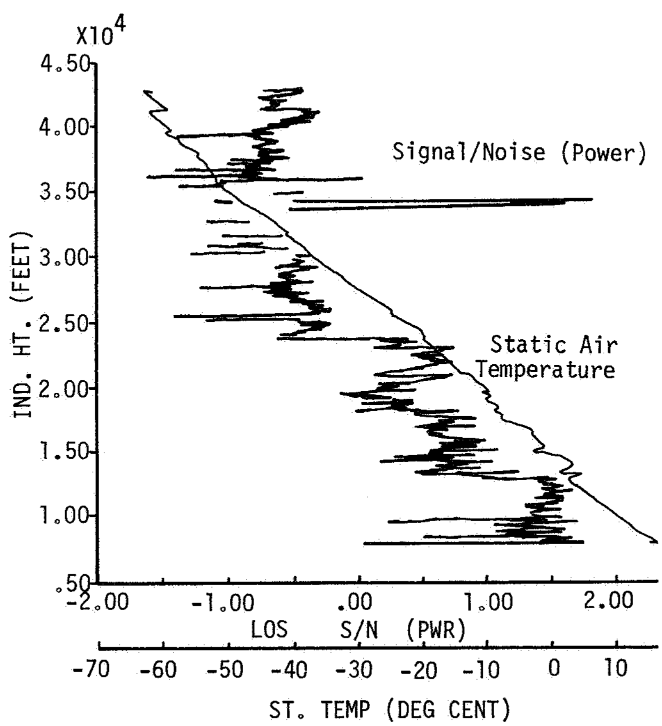


Figure 17. Example of Variations in Backscatter and Air Temperature With Height (RAE/RSRE LATAS)

The system also has uses for special test purposes. The data of Figure 17 can be converted directly into backscatter coefficient, and these data are needed to assist in the design and evaluation of proposed earth satellite laser systems for global wind measurements. Another application is for accurate determination of static pressure errors on aircraft. The true static pressure can be calculated by measuring total pressure, which is usually unaffected by the aircraft flowfield, and total temperature, as well as the true airspeed ahead of the aircraft. This can be compared with the pressure measured by the aircraft static pressure system. The laser system could be mounted in place of a radar for these tests and frees the aircraft to obtain pressure error data under any flight conditions without ground based ranges, trailing cones or calibration aircraft.

The next stage of wind shear research with the LATAS system is to develop and test various laws and simple displays using a 2-pointer ASI and/or a Fast/Slow indicator on the ADI. These will be flown on the HS-125 and also assessed on larger aircraft in the RAE, Bedford, piloted flight simulator. So far the LATAS signals have been displayed only to the pilot on rudimentary meters mounted on the cockpit coaming.

3.0 VORTEX WAKES

Vortex wakes are another invisible hazard to aircraft, mainly during take-off and landing, although some encounters in cruise have also been found (REF 4).

The RAE has been actively involved in research in this field (REF 3,4,5 & 6), although no new experimental work has been done since 1977. That is, until recently, when two military accidents, one to a fighter and the other to a jet trainer, highlighted the need for methods of assessing hazard levels for a wider range of aircraft than the civil transport group. To support these studies, some further vortex wake measurements were made in flight using an RAE designed very fast response airflow sensor on the HS125. The sensor is a five hole conical yawmeter with surface mounted transducers and has a response time lag of about 1 millisecond. The response when enclosed in a balloon, which was then burst, is shown in Figure 18. The response is

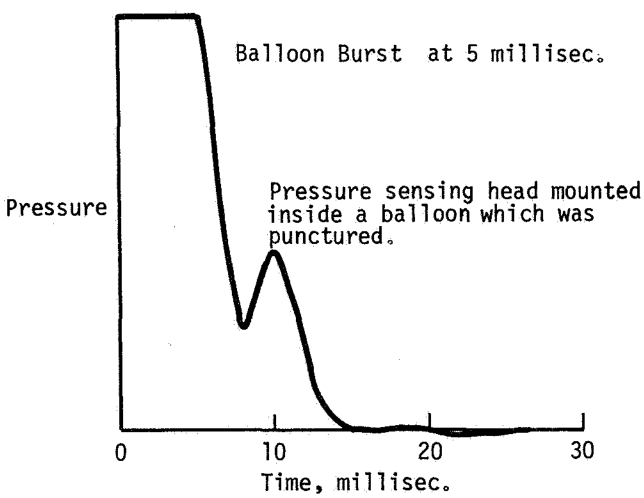


Figure 18. Response of the RAE 5-Hole Airflow Sensor To A Balloon Burst

so fast that the initial pressure resonances following the bursting of the balloon are clearly identified. An example of one of the vortex measurements is shown in Figure 19. The definition of the vortex structure with data at every 5 cm is quite remarkable.

Assessment of hazard levels needs three main inputs:

a. Information on Vortex structure;

b. A means of relating this structure to the roll control capability of the encountering aircraft;

c. Criteria for acceptable roll disturbance.

3.1 Vortex Structure

When trying to estimate the probable vortex induced velocities for advice to the accident investigators on the two military aircraft accidents, the author found two main difficulties. First the two most generally used relationsihps between tangential velocity, vorticity and radius were not very suitable and secondly there were difficulties in establishing the probable core radius, i.e., the radius to the peak tangential velocity.

The two most commonly used equations for vortex structure have been

$$V = \frac{(K/R)}{2\pi(r/R)} \left\{ 1 - e^{-1.256\ (r/R)^2} \right\}$$

which was developed by Squires (REF 17 & 18), and

$$\frac{V}{V_c} = \frac{1}{(r/R)} \left\{ 1 + \ln\ (r/R) \right\}$$

from Kuhn and Nielson (REF 19),

where V = tangential velocity

K = vorticity

R = core radius

r = radius

V_c = maximum V (i.e., at core radius)

These two models are compared in Figure 20 at unit peak velocity. When compared with measured vortices, the Squires model contains more of the total vorticity inside the core and this results in a more rapid fall in velocity outside the core. However, the model does relate velocities to the total vorticity. The Kuhn and Nielson model is quite a good fit to experimental data around the core diameter and outside it, but unfortunately it is not related to total vorticity. Indeed at large distances from the core the vorticity tends to infinity. This is not problem when fitting experimental data, but it does make it very difficult to use when estimating vortices from an initial

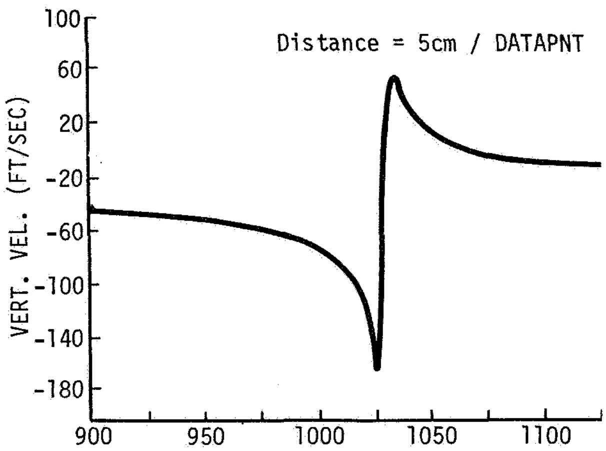


Figure 19. Flight Measurement of Vortex Velocity Using the RAE Fast Response Air Data Sensor

knowledge of total vorticity. The author has therefore developed a model (Figure 20) which matches the experimental data as well as the Kuhn and Nielson model and is related to total vorticity, viz

$$V = \frac{2(K/R)}{\pi^3(r/R)} \left\{ \tan^{-1} 1.392\ (r/R) \right\}^2$$

Having defined a suitable formula, it is then necessary to derive values of total vorticity, K, and core radius, R, so that a velocity distribution can be defined. Various methods are discussed in REF 20. Except in rare cases, it is not worthwhile using the more sophisticated methods, and the author of this paper normally uses

$$K = P \left\{ L/(\rho b V_t) \right\}$$

where P = ratio of centreline lift per unit span

L = total lift

ρ = air density

b = wing span

V_t = aircraft true airspeed

P is chosen as $4/\pi$ (= 1.27) for cruise configurations (elliptic lift distribution), or 2 for landing configurations (triangular lift distribution).

Estimation of radius is less well-defined as the growth depends strongly on the level of turbulence in and close to the vortex. However, the worst case is the slowest growth and experimental evidence (REF 21) suggests that Owen's formula, which is incorporated in Squires Vortex Formula and predicts growth proportional to the square root of vortex age, is reasonable up to the point where the two main vortices start to interact.

After this point, the experimental evidence (REF 22) suggests that the radius remains constant and the vorticity reduces linearly with time. (Actually, the vorticity is redistributed

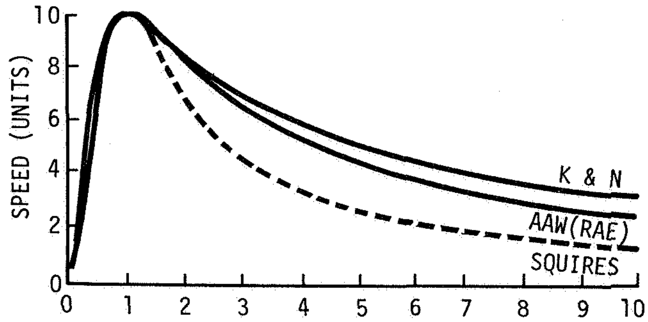


Figure 20. Comparison of Vortex Models

from the main vortices into small eddies.) REF 22 indicates that the changeover occurs when (d Lift Coefficient/(b Aspect Ratio)) is 9.6. It may be coincidental that with the author's vortex formulae, this occurs when the total induced velocity at the point midway between the pair of vortices is equal to the tangential velocity at the core radius. The separation between the vortex centres is then about 9 vortex radii. Figure 21 shows the form of the three vortex models for twin vortices at this separation.

For typical civil transport aircraft on the approach, the changeover occurs at about 2-3 nm. Thus, normal separation requirements (REF 23), which are 3 nm or more, all relate to the region where the vorticity is decaying.

3.2 Vortex Strength

Vortex strength is a relative feature in the context of aircraft operations and is defined here as the ratio of vortex induced rolling moment to the maximum roll control moment of the encountering aircraft. Studies at the RAE

$$\text{VORTEX STRENGTH} = \frac{(K/D)_g}{(p_{MAX} \cdot b)_e}\, f \left\{ \frac{b_e}{D},\ \text{Taper} \right\}$$

where D = vortex diameter(= 2R)

p_{MAX} = maximum roll rate suffices

g = generating aircraft

e = encountering aircraft

The size and shape function for the usual case of twin vortices (Figure 21) is found, Figure 23, to be only weakly dependent on b_e/D for aircraft of the same span as the generating aircraft ($b/2R$ = 9) down to about 20% of that span ($b/2R$ = 1.8), and for most normal values of taper ratio between 0.3 and 1.0.

Thus

$$\text{VORTEX STRENGTH} \propto (K/D)_g/(p_{MAX}b)_e$$

This can be evaluated using the vortex equations discussed in the previous section and the approximate relationship for transport aircraft (Figure 23) that

$$b_e \text{ (metres)} \approx \left\{ \text{MTOW} \right\}_e^{1/3}$$

and becomes

$$\text{VORTEX STRENGTH} \propto \left\{ \frac{WA}{\rho C_L} \right\}^{1/2} \Big/ \left\{ p_{MAX} \text{MTOW}^{1/3} \right\} \Big/ d$$

where MTOW - maximum takeoff weight

W - weight

A = aspect ratio

C_L = lift coefficient

d = separation between aircraft

If a general rule for categorizing aircraft is required, then ρ C_L and p_{MAX} are approximately the same for most transport aircraft, and many long-range aircraft tend to have both a higher ratio of maximum take-off weight (MTOW) to maximum landing weight (MLW) and higher aspect ratio, A. Thus, the simplest relationship is

$$\text{VORTEX STRENGTH} \propto (\text{MTOW})_g^{1/2}/(\text{MTOW})_e^{1/3}$$

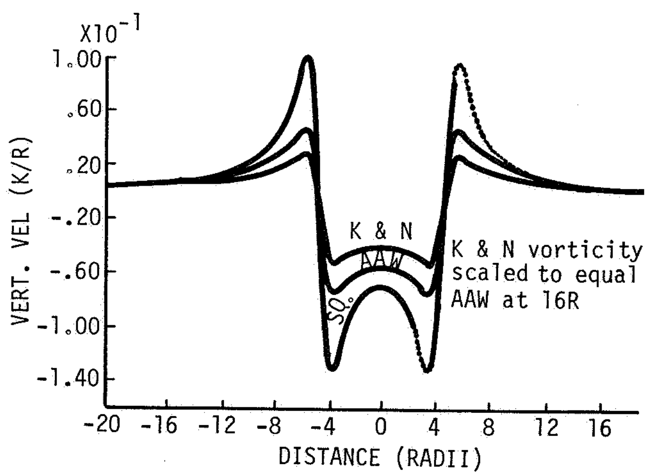


Figure 21. Twin Unit Vortices (K=R=1) at 9R Separation.

The range of (MTOW)g/(MTOW)e are plotted against recommended separation distances in Figure 24 (a) for CAA and Figure 24 (b) for ICAO. The CAA recommendations are generally grouped in a way which agrees with the above weight relationship. Although it would seem that a weight

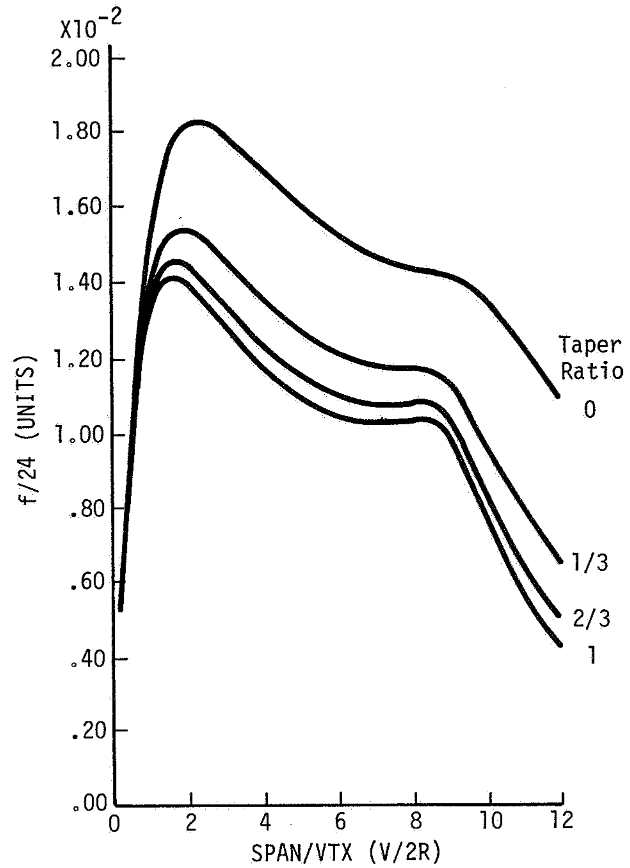


Figure 22. Vortex Strength: Size and Shape Function, f, at 9R Separation

grouping for aircraft below about 7000 kg would be useful especially for separation from the Heavy group. Also it looks as though the top of the Heavy group may be somewhere around the present maximum of about 380000 kg. The ICAO recommendations do not fit the weight relationship so well. In particular there are insufficient groups and the separation between the Heavy and Light groups would seem to be too low.

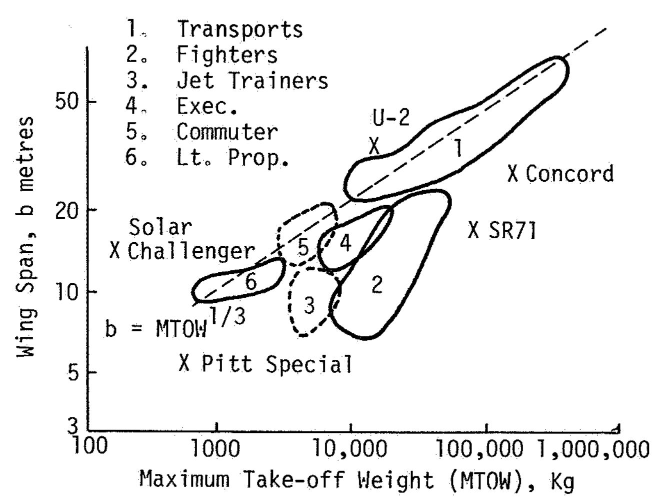


Figure 23. Aircraft Weights and Wing Span

3.3 Vortex Strength Criteria

The data of Figure 24 also gives indications of a possible relationship between Vortex Strength and Separation Distance. The CAA recommendations are based on practical experience of vortex wake encounters reported at London (Heathrow) over many years. REF 24 indicates the general philosophy, which is to reduce severe incidents to about 15 in 100,000 landings, which is expected to be equivalent to an accident rate of about 1 in 10^7 landings.

It is possible to work back from the relationship between separation distance and the weight factor to find the approximate value of Vortex Strength (i.e., ratio of induced rolling moment to roll control power) that the relationship implies. This is found to be about 0.7 for the CAA (or about 1.0 for ICAO) recommendations. The CAA criteria for a severe event is more than 30° of bank; thus, the equivalent for ICAO would be more than 45° of bank.

3.4 Discussion

The practical experience that led to the CAA recommendations for separation distances relate well to the theoretical estimates and show that the RAE estimation methods form a rational basis for assessing susceptibility to vortex induced roll. In general, it seems appropriate to categorize aircraft by MTOW as at present, and then use more detailed calculations to identify the few exceptions to the general groupings. An obvious example is Concorde, whose low aspect ratio would place it in a lower category than its weight would suggest. This is supported by the results of earlier tests by the RAE (REF 3), which showed that the Concorde wake did indeed decay much more rapidly than other transport aircraft.

Another conclusion from the theoretical equations is that military fighter and jet trainer aircraft are no less susceptible to vortex wakes than transport aircraft of the same weight. This

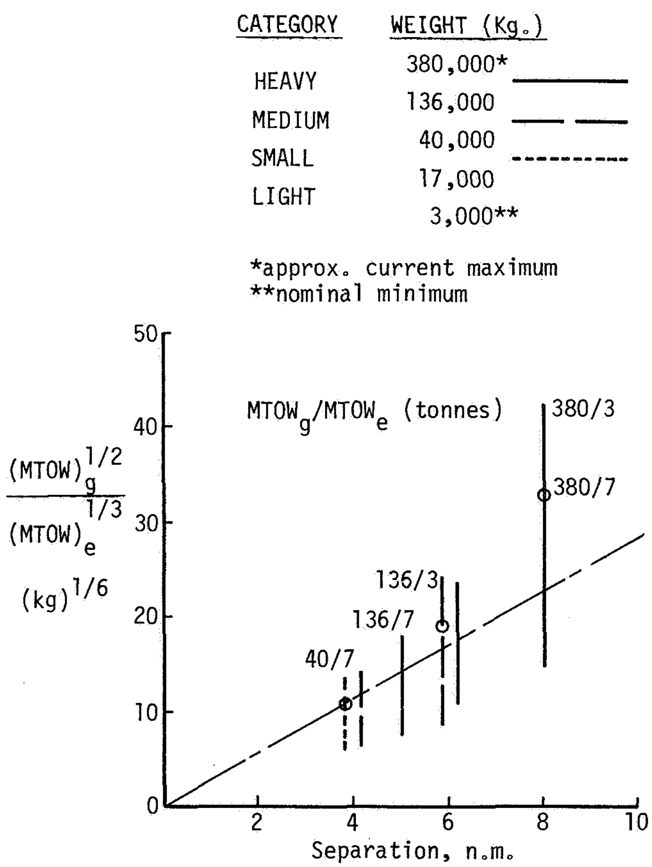


Figure 24 (a). UK CAA Separation Recommendations (AIC 81/1981)

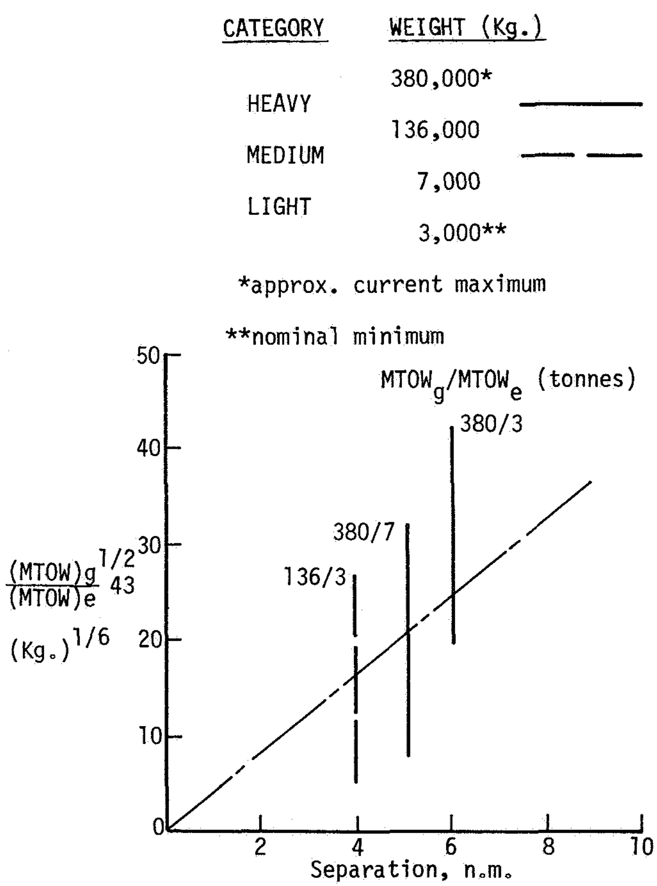


Figure 24 (b). ICAO Separation Recommendations (10 Aug. 1978) has surprised most military pilots who felt that their extra manoeuverability in roll would give them more protection. However, although the maximum roll rates on the approach are about twice as high as transport aircraft, the span of the military aircraft is about half. Thus, the critical term (b p_{MAX}) is about the same.

4.0 BUILDING WAKES

Building wakes are related to both wind shear and vortex wakes. The increasing pressure to build on airport land to provide maintenance facilities for large aircraft and new terminals has produced situations such as the large airline engineering base alongside the final kilometre of the approach to runway 28R at London (Heathrow) Pilots landing on this runway are warned 'Turbulence likely below 300 ft near threshold 28R in strong S/SW winds'. This applies generally in winds of more than 15 kt.

The RAE are asked to advise the CAA on the acceptability of proposed new large buildings at many UK airports, but have been unable to give any positive guidance so far. There are basically two problems:

a. a need for theoretical or model test methods to assess the character of the building turbulence, and

b. relating turbulence characteristics to aircraft disturbances.

The second area is being addressed by the work to establish hazard levels for wind shear.

The first is the subject of joint research activities by Bristol University Aeronautical Engineering Department and the RAE. The first stage of the work showed that building wake turbulence in simulated natural turbulence can best be described as discrete eddies shed in a random fashion. The size and probability of encountering eddies being a function of the building, wind strength and natural turbulence. As the wind velocities are varying in space in a form that is related to the building geometry, it means that the frequently used Taylor's hypothesis cannot be applied. This hypothesis says that the distribution of velocities is the same if the observer is stationary and the wind brings the turbulence past him or if the observer moves through the turbulence (in an aircraft).

It was, therefore, decided that meaningful tests could only be made by traversing the wake of the building along a typical aircraft path and at the same order of speed. A series of such traverses would then allow the distribution of turbulence and the probability of encountering large distrubances to be determined. The main experiment is on a model of the Heathrow site in the Bristol University Building Research Wind Tunnel. This is being compared with a more limited set of data obtained from flights by the RAE HS125 at Heathrow. The Heathrow conditions will also be used as a guide to levels of acceptability, as it would be undesirable to create any turbulence worse than the level at Heathrow.

The data from these experiments will be available in 1983 and it should then be possible to establish test methods and criteria for assessing proposals for large buildings at, or near, airports.

5.0 CONCLUDING REMARKS

This review of research in the UK on two of the more significant invisible enemies of aircraft, particularly during landing or take-off, has described the main features of the wind shear programme; the results from a recent vortex wake study, and the status of a study of airport building wakes.

The wind shear programme is aimed at providing relevant advice on aircraft certification implications, and developing suitable systems to provide information to pilots to make it possible for them to penetrate wind shear with safety. The three main elements of the programme are:

a. Worldwide measurements of wind shear from regular airline flights and special trials with the RAE HS-125 research aircraft;

b. Assessment of potential hazard to aircraft from wind shear;

c. Development of systems to give the pilot information on wind shear.

These are expected to reach a point during 1983 when fundamental research will be sufficiently complete to provide the basis for certification and design of automatic control systems, such as autopilot, autothrottle, and autoland, and also for the development and production of wind shear detection and display systems. At this point, most of the RAE research effort will be transferred to other basic research tasks. The Establishment will continue to provide its usual consultancy service to the CAA and UK Industry.

The study of vortex wakes following the accidents to a military fighter and a jet trainer aircraft has led to the development by the RAE of a rational method for assessing the potential hazard for a given encounter, and also for categorizing aircraft into convenient groups. No further work is planned, although the recent study was unexpected. The study does highlight the benefits of flexible research facilities such as the HS125, which can respond rapidly to such unexpected needs.

The building wake programme is also reaching a point where it may be possible to establish criteria for acceptability, and corresponding test procedures for assessing new building proposals.

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