Review of Aviation Accidents Caused by Wind Shear and Identification Methods

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ABSTRACT

According to ICAO statistics, between 1970 and 1985, there were 28 aviation accidents with 700 fatalities caused by low-level wind shear. This article reviews the unsteady weather hazards for the last three decades, relationship between the downdraft, wind shear, and the aircraft accidents related to wind shear and crosswind. Four methods are proposed to identify the intensity of wind shear: airspeed variation, flight instrument observation, unit distance of airspeed variation, and wind shear hazard factor. Furthermore, two flights are studied by these methods to validate the intensity of wind shear.

The Aviation Safety Council (ASC) of Republic of China was established in May 1998; it has conducted 18 aviation occurrence investigations, with 6 cases related to weather, 1 helicopter accident, 2 aircraft hull loss accidents, and 3 runway excursions. This article will apply the parameters of flight data recorder (FDR) to reveal the intensity of wind shear, effects of the gust wind and downdraft on the aircraft flight operations. In order to access the environmental hazard in aviation safety, three-dimensional wind field calculation of the wind shear, turbulence and gust is presented. In the future, if one can consolidate the LLWAS metrological information in some of the domestic airports, then we can further verify the practicality of the wind shear identification methods as described in this article, and to provide better wind shear alerting system to the safety community.

INTRODUCTION

Hazard to the Aircraft Caused by Turbulence

With the advanced development in aviation technology, aircraft bring on many business opportunities and convenience to transportation. However, turbulence in the atmosphere still poses a threat to aircraft. In the late 60's, the western aviation industry began to notice problems caused by (clear-air) turbulence in aircraft accidents. It was not until 1975, when a Boeing 727 aircraft crashed during landing at the JFK Airport, that the leading government investigation agency and the aviation industries commenced a systematic study on wind shear and turbulence (NTSB, 1976).

In 1975's Boeing 727 aircraft accident investigation, Fujita (1981) attributed the low-level wind shear as the cause of the accident, and an in-depth discussion on physics phenomena, space and time scale of atmospheric turbulence was presented. In 1997, ICAO formally established Low-Level Wind Shear and Turbulence Group. Its task is to circulate studies from various countries, and to formulate low-level wind shear related documents. In November 1980, the USAF amended the Military Specification on Flying Qualities of Piloted Aircraft (MIL-F-8785C), with the purpose of specifying the effects of turbulence on flying qualities of piloted aircraft (USAF, 1980). In 1981, NASA and FAA jointly promoted the project of Joint Airports Weather Study (JAWS), which focused on flying skills, flight training, and the evaluation of the low-level wind shear alert system (Woodsfield and Wood, 1983). Figure 1 shows a National Transportation Safety Board (NTSB) compiled wind speed profiles (dotted and actual lines) of wind shear related accident, which was obtained from flight data recorder (FDR). JAWS research pointed out that wind speed surrounded the accident from 6,000 ft to 12,000 ft

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changed up to 70 knots. The ladder shaped curve is wind speed profile used in flight simulators as suggested by FAA.

From 1970 to 1985, at least 28 aviation accidents were caused by wind shear, resulting in more than 700 fatalities. In 1985, FAA published an advisory circular on pilot wind shear guide (1985), to enhance pilots' skills in identifying, avoiding, and handling wind shear conditions. In 1987, FAA proposed the wind shear training guideline and related statistics (1987). The paper pointed out: avoidance is the best defense against the hazards of wind shear. A severe wind shear condition is beyond the handling ability of commercial aircraft and even highly skillful pilots.

Relationship of Downdraft and Wind shear

Wind shear can be defined as a rapid change in wind direction or speed. Wind shear could be caused by drastic changes to the following weather conditions: geographically induced, temperature inversion layer, sea and land breeze, fronts, and the most severe variation – shower and thunderstorm. The air by virga or thunderstorm, would turn the airflow downwards called downdraft, which then strikes the Earth's surface and spreads out along the boundary layer that and forms a ring vortex.

Fujita (1981) stated, the downdraft in convective mode, with wind speed over 34 knots, is called downdraft. Fujita also pointed out that when the aircraft altitude is below 300 ft, if the downdraft descend rate is above 12 ft/sec, it can also be referred as the downdraft. The spatial and temporal scales of downdraft could be broken down into two types: microburst, and macroburst. Microburst is when the horizontal scale of the outer flow is less than 4 kilometers, with a life cycle lasting 5 to 20 minutes before dissipation, and the highest wind speed up to 246 knots. Macroburst is the horizontal scale of the outer flow is over 4 kilometers, with a life cycle lasting over 20 minutes, and the highest wind speed up to 196 knots.

When an aircraft encounters downdraft (also known as unsteady airflow), due to their inability to identify its spatial and temporal features, pilots usually refer them as gust, crosswind, or wind shear to describe such air disturbance in flight. Types of wind shear disturbance to aircraft are classified into horizontal wind shear, and vertical wind shear. The horizontal wind shear could affect aircraft velocity, and can again be classified into headwind shear and tailwind shear. When wind shear occurs below 2,000 ft altitude, it is called a low-level wind shear. There are four wind shear intensity categories: light, moderate, strong and severe. Presently, the Doppler radar carried on board an aircraft has hazard F-factor and wind shear intensity scale, which act as guide to pilots.

In international airports that are prone to microburst and wind shear, a Low-Level Wind Shear Alert System (LLWAS) is usually installed to detect and forecast the (horizontal) wind shear around the airport. There are two LLWAS alerting modes: wind shear alert and microburst alert. Wind shear alert condition is when the wind speed losses 15 to 29 knots, or gains more than 15 knots; microburst alert condition is when the wind speed losses more than 30 knots. In 2001, Taipei Municipal Airport and CKS International Airport installed LLWAS, while Kaoshiung Airport will complete the installation of the Terminal Doppler Weather Radar (TDWR) in 2002.

Aviation Accidents Caused by Wind Shear

ICAO had issued a statistical report on weather related aviation accidents from 1970 to 1985. The accidents caused by or related to weather is about 30% of the fatal accident. The report states that low clouds, fog and wind are the most hazardous factors, in which gust, wind shear, and turbulence being most dangerous.

International aeronautics and meteorology society generally acknowledged that low-level wind shear is a severe hazard to aircraft during take-off, approach, and landing. Twenty-three out of twenty-eight accidents were in the epoch of approach and landing. Also, according to statistics of Aviation Safety Network (ASN) of United

States, from 1950 to 2000, there were 40 aviation accidents caused by turbulence or crosswind; and 39 wind shear or downdraft related accidents.

Until 1990, wind shear caused four major accidents (over 400 fatalities):

1. 1975.06.24: a Boeing 727 crashed during approach to the JFK international airport (115 fatalities), (NTSB, 1976);
2. 1980.07.07: a Tupolev 154B-2 crashed as it climbed from Almaty Airport at Kazakhstan (163 fatalities);
3. 1982.07.09: a Boeing 727 crashed when it encountered wind shear at 150 ft altitude during initial climb from New Orleans Airport (145 fatalities) , (NTSB, 1983);
4. 1985.08.02: a Lockheed L-1011 crashed when it encountered low-level wind shear in final approach at the Dallas Fort Worth International Airport (134 fatalities), (NTSB, 1986);

Figure 2 indicates the variety of microburst and airspeed of the accident in 1982 in New Orleans, and the aircraft encountered wind shear at 150 ft (altitude) after take-off. Accident investigation report shows the aircraft encountered downdraft from the microburst during ground taxiing and initial climb; due to the sharp loss of headwind, producing inadequate lift was produced, hence causing the crash of the aircraft.

According to ASN statistics, in the last decade (1990~2000), two major accidents were caused by wind shear (over 90 fatalities):

1. 1992.12.21: a DC-10 crashed during landing at the Faro Airport in Portugal (56 fatalities, 284 injured), (Flight Safety Foundation, 1996a);
2. 1994.07.02: a DC-9 crashed when it encountered wind shear during go around at Charlotte-Douglas Municipal Airport in North Carolina (37 fatalities, 20 injured), (Flight Safety Foundation, 1996b);

Three major accidents were caused by turbulence and crosswind (over 50 fatalities):

1. 1993.06.17: an Antonov-26 crashed when it encountered severe turbulence while cruising over Tbilis in Georgia (41 fatalities);
2. 1999.06.01: an MD-82 encountered thunderstorm and wind shear during landing at Little Rock Airport in Arkansas. Due to strong crosswind after landing, the aircraft failed to stop and crashed (11 fatalities, 134 injured) , (NTSB, 2001);
3. 1999.08.22: an MD-11 encountered severe tropical storm during landing at Chek-Lap-Kok Airport in Hong Kong. After hard landing on its right main-gear the aircraft burst into flames, and continued to roll on the runway, resulting in severe structural damage (3 fatalities, 50 injured).

Flight Data and Wind Shear Identification

We discussed the unsteady wind hazard to aircraft, relationship between downburst and wind shear, and past aircraft accidents related to wind shear. In aircraft accident investigation, the identification of wind shear is very important. Only finding the most possible causes of the flight hazards enables to improve flight safety effectively and to prevent future accidents.

In the following four sections, we will introduce four identification methods of wind shear, including airspeed variation, flight instrument recognition, unit distance of airspeed variation, and wind shear hazard factor.

Airspeed Variation

In 1987, ICAO proposed a method to measure the wind shear hazard (ICAO, 1987). This method categorizes the wind shear into four levels: light, moderate, strong and severe. The wind shear identification uses two variables; air speed variation and the proportion of air speed, as shown in Figure 3.

In April 1993, a McDonald DC-9-41 took off from Nagoya. About local time 12:44, the flight landed hard on runway 02 at Hanamaki Airport (Aviation Accident Investigation Commission of Japan, 1993). The aircraft suffered serious damage caused by impact fire. One crew and two passengers injured. The probable cause of this accident was identified as the aircraft was under severe wind speed and changing wind direction. The pilot continued approach without sufficient awareness of wind shear; and the aircraft encountered severe wind shear and suddenly sank when passing through the runway threshold. The investigation conducted the wind shear analysis by using the airspeed variation method of ICAO Circular 186. According to the variation of indicated airspeed (IAS) and pressure altitude, it was found that the aircraft encountered two severe wind shears in less than 500 feet. The metal foil based flight data recorder of the accident aircraft recorded only 5 parameters. Figure 4 illustrated the variation of airspeed and altitude of flight data below 900 feet.

Flight Instrument Recognition

The pilot wind shear guide published by FAA (1985) defines the severe wind shear as a rapid change in wind direction or velocity causing airspeed changes greater than 15 knots or changes in vertical speed greater than 500 feet per minute. This guide also introduces the wind shear recognition method for pilots during take off or landing phase to increase their awareness of the wind shear as soon as possible. The common phenomena of encountering wind shear include air speed variation greater than 15 knots, descent rate higher than 500 feet per minute, pitch attitude change over 5 degrees and glide slope indicator change more than 1 dot.

From the aspect of accident or incident investigation, this recognition method is very straightforward and effective. Using the FDR data, we can analyze the relevant parameter, for the wind shear phenomenon. For instance, the descent rate can be derived from pressure altitude or radio altitude versus time. However, if an aircraft encounters horizontal wind shear, even the airspeed change reaches just 10 knots, the related crosswind speed may be over the limit of stabilized approach for an aircraft.

Unit Distance of Airspeed Variation

The research of Peter (2000) indicated wind speed change over a distance could classify the severity of wind shear. The wind speed change（Δ Knots）over 100 feet altitude can be used to estimate the severity of vertical wind shear. There are four classifications, which include light (< 4.0), moderate (4.0 ~ 7.9), strong (8.0~11.9) and severe (≥ 12).

This method is adequate for the identification of low-level vertical wind shear. If an aircraft is at take off or landing and altitude below 1200 feet, the intensity of vertical wind shear could be estimated with the FDR data-radio altitude, wind speed and wind direction. The FDR records wind speed and wind direction derived from Inertial Reference System (IRS), with its accuracies varying from 0.25 knots to 5 knots, and about 2 degrees in pitch attitude. The bias of the IRS could be improved by proper estimation method, which is based on the three-axis acceleration data to estimate airspeed, wind speed, wind direction, and ground speed, etc.

Wind Shear Hazard Factor

An index that quantifies the wind shear threat was developed by Bowles and Hinton (1990), and is based on the fundamentals of flight mechanics and the current understanding of wind shear. This index, known as F-factor, recognizes wind shear by measuring the total energy change of an aircraft. Consider an aircraft, with weight W, altitude (H) and airspeed (V_a). Then the total energy (E_T) of the aircraft can be defined in Eq (1).

$$E_T = \left(H + \frac{V_a^2}{2g} \right) \quad \text{..(1)}$$

$$\frac{dV_a}{dt} = \frac{T}{m}\cos\alpha - \frac{D}{m} - g\sin\gamma - \dot{u}_w\cos\gamma + w_w\sin\gamma \quad \text{.......(2)}$$

Assume the aircraft is rigid, the rate of speed of the body axis could be determined in Eq (2). Equation (3) can be obtained by combined Eqs (1) and (2). The time rate of change of E_T, the aircraft's climb rate, can be equated with the aircraft energy input from the thrust (T) and drag (D). The term of (T-D)/mg is the ratio of the excess thrust; the wind shear hazard factor of F as defined in Eq. (4a), where the wind velocities are denoted as (w_x, w_y, w_z), and the rate of wind velocities are（$\dot{w}_x$, $\dot{w}_y$, $\dot{w}_z$）.

$$\dot{E}_T = \dot{H} + \frac{V_a}{g}\frac{dV_a}{dt} = V_a\left[\frac{T-D}{mg} - \left(\frac{\dot{w}_x}{g}\cos\gamma - \frac{\dot{w}_z}{g}\sin\gamma + \frac{w_z}{V_a}\right)\right]$$

$$= V_a\left(\frac{T-D}{mg} - F\right) \quad \text{..........} (3)$$

Positive F-factor reduces the total energy of an aircraft, i.e. reducing energy of climb. From Eq (4b), we know that the total energy of climb decreases when the aircraft encounters continuously increased tailwind, decreased headwind（$\dot{w}_x$>0）, and downdraft （w_z>0）. Proctor and Hinton (2000) indicated that the ratio of excess thrust for multi-engine passenger jet varies from 0.1 to 0.2. Thus, the approved F-factor value by FAA is 0.1 as the hazard threshold and 0.13 as the wind shear alert threshold.

$$F = \frac{\dot{w}_x}{g}\cos\gamma - \frac{\dot{w}_z}{g}\sin\gamma + \frac{w_z}{V_a} \quad \text{..........} (4a)$$

Assuming the flight path angle (γ) is small,

$$F \approx \frac{\dot{w}_x}{g} + \frac{w_z}{V_a} \quad \text{..........} (4b)$$

$$F \approx F_H\left(1 + \frac{\beta g H}{V_a^2}\right); \qquad F_H = \frac{\dot{w}_x}{g} \approx \frac{V_a}{g}\frac{\partial w_x}{\partial x};$$

$$\beta = 1 \quad if F_H < 0 \qquad \beta = 2 \quad if F_H > 0 \quad \text{..........} (5)$$

Wind shear hazard factor method needs all components of wind velocities and rate of wind velocities; it is very difficult to use for accident investigation. Proctor and Hinton used an approximate form as shown in Eq (5), which is also used for the airborne Doppler radar for wind shear alert. FAA has adopted the 1-km average F-factor as its hazard metric for wind shear detection systems on jet transports. On July 2, 1994, a DC-9 crashed at Charlotte-Douglas Municipal airport. NTSB and NASA conducted investigation. They used F-factor and found that the aircraft encountered severe wind shear during approach (FSF, 1996b). After the pilot decided to go around, the aircraft reached 2200 feet, then sank rapidly, and crashed at the west-north area 2000 ft away from runway 18 right. Figure 5a indicates the horizontal wind component(positive stands for tailwind）along the body axis and the vertical-wind component（positive stands for down wind）against the distance to the impact point. The headwind changed into tailwind（horizontal wind variation greater than 20 m/s）at the point about 1400 ft from the impact point. The vertical wind shear（down wind greater than 10 m/s）occurred as well. The ground based wind observation showed the headwind changed from 35 knots to tailwind of 26 knots within 14 seconds. Figure 5(b) depicts the 1-km averaged F-factor against the distance from the impact point. The F-factor rapidly changed from 0.1 to 0.25 between 1200 ft to 800 ft from the impact point.

In order to utilize the recorded FDR data to compute the three-dimensional wind velocities and the rate of change of wind velocities, it is necessary to compute the body-fixed three axis wind velocities (w_x, w_y, w_z) and the aircraft velocities（u, v, w）, by using the combination of Extended Kalman Filter and equation of motion. There were many academic researches in the past few decades. Recently, Weng et al., (2001) had success to identify accident related to wind shear.

CASE STUDY

The Aviation Safety Council (ASC) was established in May 1998; so far, ASC has conducted eighteen aviation accident and serious incident investigations, which involved 6 cases caused by weather, 1 helicopter accident, 2 aircraft hull loss accidents, 3 runway excursions.

Strong Gust Wind Affecting the Boeing 737-800 in Landing

Summary of the Serious Accident

On October 31, 2000 a Boeing 737-800, departed from Yangon Airport, Myanmar, for a flight to Chiang Kai-Shek (CKS) International Airport, Taiwan, performing a revenue flight, with 8 flight crews and 114 passengers. At local time 18:00, Taiwan was within the typhoon range. Meanwhile CKS airport suffered from heavy rain and wind. At 21:47:05, the crew executed an ILS approach on runway 05L, and runway insight at 500 feet radio altitude (RA). The flight crew disengaged the autopilot at 50 feet (RA). As the controller cleared this flight to land, he notified the weather conditions were "wind 10 degree, 21 knots, gust 34 knots, QNH1002." This aircraft was touchdown (TD) at 21:50:10. Two seconds later, the nose gear also contacted the ground. Meanwhile, both main landing gears slipped outside of runway's shoulder at 2439 feet of 05L's threshold, and then returned to the runway at 4119 feet. The nose gear remained on the runway. As the aircraft was slipping, its heading varied from 40.4 degree to 37.6 degree (aircraft's nose pointing to left side of 12.6 degree to 15.3 degree).

Probable Causes - (1) the flight crew used large maneuver on lateral control during low altitude, and this decreased the crab angle. At moment, the aircraft encountered high crosswind. (2) impaired performance resulted from heavy rain and slippery runway, the flight crew failure to maintained the directional control, and it caused the landing gears slipped outside the runway.

Aircraft Encountering the Strong Gusting Wind during landing

According to the airplane operations manual, the wind limitations for takeoff and landing are crosswind 36 knots (dry surface), tailwind 10 knots (dry and wet surface). For landing in low visibility conditions (CAT, CAT IIIA), the wind limits: headwind 20 knots, tailwind 10 knots, and crosswind 10 knots.

Both parameters of wind speed and wind direction were recorded on FDR every four seconds. Before TD of the main landing gear, the FDR data indicated that 42 knots (-12 seconds), 37.5 knots (-8 seconds), 27.5 knots (-4 seconds), and 37.0 knots (TD). Eight seconds before TD, the wind speed lost 10 knots; 4 seconds later, the wind raised 9.5 knots, and the wind direction varied from 8 degrees, to 343 degrees. Meanwhile, the angle between the aircraft's longitudinal axis and wind direction varied from 42 degrees to 57 degrees. Within the critical 12 seconds, the crosswinds were of 31 knots, 27 knots, 23.7 knots, and 36.5 knots, respectively. In the same last 12 seconds, the related headwind varied 28.4 knots, 26.1 knots, 13.97 knots, and 6.2 knots, respectively. The ground-based meteorological special observation report also depicted that wind at the central field of CKS was 10 degrees, 36 knots and gust 50 knots. Consequently, the aircraft suffered strong gusting wind during final approach from 500 feet to TD, and the wind was fluctuated about 10 knots (8 seconds before TD).

Figure 6 illustrates the time histories plots of FDR parameters (30 seconds before TD), and the wind versus radio altitude. Referring to Figure 6, before TD time, there are three major findings: (1) (30 seconds ~ 12 seconds), the average wind speed was 42 knots, and the wind direction varied from 5 degrees to 10 degrees; the draft angle 10 degrees, track angle of the aircraft 51 degrees, and the related 05L runway's heading 53 degrees. (2) (11 seconds ~ 5 seconds), wind decreased rapidly, and the flight crew applied the rough control wheel (about 32 degrees) and light rudder. The flight crew intended to recover the horizontal deviation with runway of 05L. (3) (5 seconds ~ T/D), wind increased rapidly, the wind direction changed more than 57 degrees. The flight crew applied the light control wheel from right bank to left bank. In the meantime, the left-crosswind increased and then decreased more than 10 knots, and it caused difficulty in lateral control, and induced the aircraft's track angle to 57 degrees. The pilot used 4 degrees crab angle to touchdown and that caused the aircraft slipped outside the surface of runway. Six seconds after TD, the flight crew applied the rough control wheel and rudder control for left maneuver, and it caused the nose wheel on the surface of runway and both main landing gears outside the runway. At that time, the heading was 37 degrees (-16 degrees of crab angle).

The wind speed and wind direction were also calculated from the acceleration data, ground speed and airspeed. Results during the critical 12 seconds are follows: 46.9 knots (11 seconds), 33.5 knots (8 seconds), 20.8 knots (5 seconds), and 45.9 knots (after 1 seconds of TD); crosswind varied 26.6 knots, 21.1 knots, 15.2 knots, and 3.2knots, respectively. Similarly, the headwind varied 28.3knots, 26.1 knots, 14.1 knots, and 45.9 knots, respectively. The derived wind speed with 1 second sampling was higher than the 4 second sampling data of recorded wind. Owing to the low visibility and strong gusting wing during the final approach and landing, the crosswind that the aircraft encountered was beyond its operational limit. Further analysis that emphasizes on the wind shear intensity is presented as in the following.

There are five sections of altitude below 250 feet, and it was evaluated with two methods of wind shear identification: (A) 231ft ~ 190ft; (B) 168ft ~ 131ft; (C) 98ft ~ 72ft; (D) 26ft ~ 11ft; and (E) 12ft ~ 2ft. The airspeed variation method of ICAO is used. The results indicate that the wind shear intensity ranged from strong, moderate, strong, severe, and severe, respectively. Obviously, there was airspeed loss of more than 15 knots at sections A, C and E; between sections of A –B and C-D there were tail-wind shear; section of D-E was head-wind shear, and it implies that the aircraft was losing energy. Furthermore, applying the wind shear hazard factor of F to analyze the five epochs of wind shear intensity, the results showed the F-values were 0.03, 0.05, 0.21, 0.59, and 0.48, respectively. The last three sections of C, D and E exceeded the severe wind shear alert threshold. The related horizontal F_H-values were 0.21, 0.56 and 0.48, respectively. The wind shear intensity of five sections is illustrated in Table 1. Result of airspeed variation is shown in Table 1(a); result of wind shear hazard factor was shown in Table (b).

To summarize the intensity of wind shear for this serious incident, both airspeed variation and wind shear hazard factor showed that the aircraft encountered three times of severe wind shear (below 250 feet), and airspeed variation more than 15 knots; the wind shear hazard factor indicated the severity of wind shear was almost presented on horizontal plane. It was also identified from the variation of head- and cross-wind. In addition, period of prior 8 seconds to TD, the crosswind lost 3 knots, and then gained 13 knots. This increased the difficulty of lateral control, and induced the aircraft to slip outside the surface of runway.

Downdraft affecting the de Havilland Dash- 8

Summary of the Accident

On January 15, 2001, a DASH-8-300 departed from Tainan airport at local time 10:35, performing a revenue flight, and landed at the Runway 06 of Chinmen Shangyi Airport, at time 11:13. The plane landed hard 200 feet behind the runway threshold, bounced about 1300 feet, and then contacts the ground again. Both left and right landing gears were fractured, aft bottom fuselage skin chafed open, and stopped at approximately 3,380 feet from the threshold of Runway 06. There were no injuries of the crew members and passengers.

Probable Causes - (1) Below 250 ft (RA), during aircraft approach, the flight crews encountered downdraft three times, which induced over 500 ft/min descent rate. (2) Continuation of the approach to landing five seconds prior to the first contact of the ground, the aircraft encountered downdraft again. Due to altitude limitation and crews failure to correct attitude, the aircraft landed hard then both landing gears were fractured. Contributing to the accident was the flight crew's impairment of company’s wind shear training program to enhance the situational awareness and relevant procedures of flight crews.

Aircraft Encountered Downdraft during Landing

The descent rate of the aircraft is obtained from differential of radio altitude. The aircraft suffered strong downdraft during flight through 200 ft to 150 ft RA within two seconds. Its descent rate varied from 43.0 ft/s to -19 ft/s (float), and vertical acceleration from 1.2G to 0.85G. Within four seconds, the angle of attack (AOA) varied from -2.9 degrees to 7.7 degrees. Four seconds prior to TD, the descent rate raised from 12 ft/s (59ft RA), 16 ft/s (43ft RA), 19 ft/s (24ft RA) to 28 ft/s (-4ft RA). The descent rate of previous normal flight was stabilized and maintained at 8ft/s. The results showed that the descent rate of this accident flight was higher and rapidly increased within the last 250 ft. Therefore, the accident flight sustained three times of downdraft at 200 ft, 150 ft and below 50 ft, which caused the descent rate higher and rapidly increasing.

The aircraft did not record the ground speed, wind speed and wind direction. However, one could obtain these parameters by the three-axis accelerations, and radar track data with assumptions. According to weather information recorded at Shang-Yi airport during the accident, the wind was 15 knots (40 degrees) varied to 20 knots (50 degrees). Assuming the wind was 20 knots (45 degrees) during the aircraft TD, and neglecting the effects of lateral control, we processed the acceleration data from a selected altitude to the aircraft's TD point, then validated the values of cross- and tail-wind components, and essential parameters were obtained.

Conjoining with radar data of Ma-Kung and flight data, and considering the aircraft as a rigid point mass, one could calculate the north- and east-velocity on local level coordinate system. According to the three-components of velocity, one could calculate the ground speed, track angle and flight path angle. The results showed that by assuming the initial ground speed as 285 knots at 2500 ft, then the ground speed at TD point calculated (0315:55 UTC) was less than 86.3 knots, with true airspeed 105.6 knots, and the wind speed at TD point was 19.3 knots. The results matched the assumption of tailwind. Similarly, if we assume the lateral speed was 13 knots at 2500 ft, and integrated the lateral acceleration data by every quarter second, the slide speed was 5.7 knots, which also matched the assumption of the crosswind. Based on the relationship of the ground speed equal the true airspeed plus the wind speed, one could calculate the north- and east-wind components

Five seconds before TD, the wind speed and direction were 31.5 knots, and 51.5 degrees, respectively. Two seconds before TD, both air speed and wind speed decreased about 10 knots, and its wind varied from 26.4 knots (51 degrees) to 18.3 knots (43 degrees).

According to the FDR recorded- and derived-parameters, they are indication that the aircraft suffered downdraft three times below 250 ft. The relevant parameters presented at 171 ft (change of AOA=8 degrees, descent rate=30 ft/s), 137 ft (change of AOA=6 degrees, descent rate=11 ft/s), and 43 ft (change of AOA=7 degrees, descent rate=18 ft/s), respectively. Prior two seconds of TD, the descent rate increased from 16 ft/s to 28 ft/s. At this moment, the elevator was activated from 0 degree to 20 degrees, but the aircraft was still sinking with pitch-down attitude. Figure 7 illustrated the time history plots of FDR parameters for the last 300 ft, with UTC time shown on the abscissa, and parameters of radio altitude, descent rate, vertical acceleration, attitude angles, angle of attack, and elevator shown on ordinates.

Downdraft may increase the descent rate; it could be verified from vertical acceleration, vertical wind (V_{wind}, negative value is downward wind) and change of AOA (change of positive-AOA to negative-AOA is downward wind). In addition, using wind shear identification methods to analyze the last 250 ft, we found five sections affected by downdraft: (A) 261ft ~ 254ft, (B) 254 ft ~ 182ft, (C)182 ft ~ 149ft, (D)137ft ~ 103ft, and (E)59 ft ~ 24ft, respectively.

Using the airspeed variation method proposed by ICAO, to analyze the wind shear intensity of five sections, the results were strong, moderate, moderate, moderate, and severe, respectively. Specifically, during descent through 59 ft to 24 ft, the airspeed reduced 15 knots. It could be the behavior of vertical wind shear and induced by microburst, as shown in Table 2(a). Similarly, results by using the unit distance of airspeed variation method are severe, moderate, moderate, moderate, and moderate, respectively. The relevant data was depicted in Table 2(b). Because of airspeed and wind speed decreased in the last 60 ft, both tail- and cross- wind were decreased two knots, and 8.8 knots, respectively. Therefore, unit distance of airspeed variation method is less sensitive to the response of lateral fluctuation, and is a better method to identify the tail- and head-wind shear. Furthermore, by applying the wind shear hazard factor of F to analyze the five epochs of wind shear intensity, the results showed the F-values were 0.5, 0.16, 0.07, 0.12 and 0.13, respectively. The F-factor once again has four sections of last 250 ft exceeded the wind shear alert value; the relevant data are depicted in Table 2(c).

CONCLUSIONS

This article explains the flight hazards of unsteady flow, relationship of microburst and wind shear, and reviews the wind shear and crosswind that caused accidents during the last three decades. This article presents four methods to identify the intensity of wind shear: i.e., airspeed variation, flight instrument recognition, unit distance of airspeed variation, and wind shear hazard factor of F. Two flights have been studied by these methods to validate methods to compute intensity of wind shear.

In order to reveal the environmental hazard in aviation safety, three-dimensional wind field calculation to study the wind shear, turbulence, and gust is vitally important. By identifying the cause of wind shear and intensity, it could be an index to enhance safety. In the future, one may combine low-level wind shear data from domestic airports, use them to evaluate the reliability of the wind shear identification methods, and improve in-flight wind shear alert system.

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風切造成航機失事之回顧與識別方法

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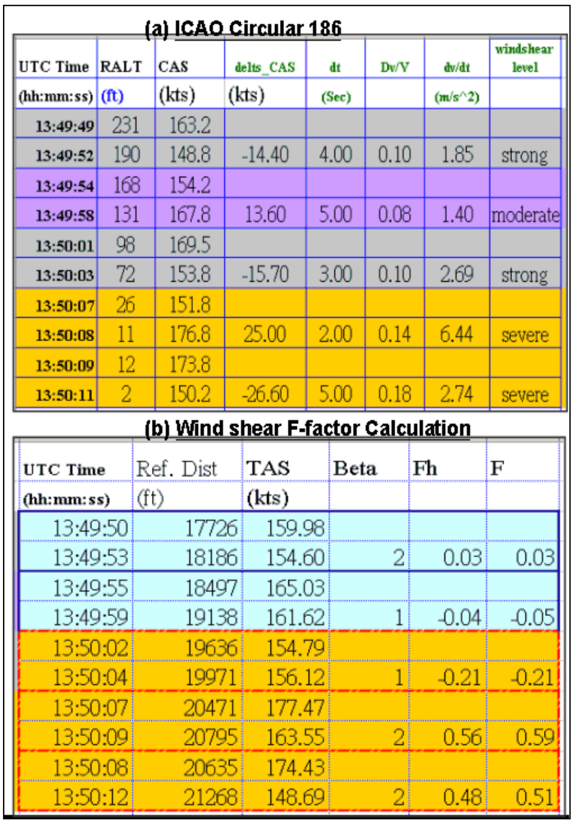
摘要

根據國際組織統計資料，西元1970年至1985年間，風切造成了至少28件民航機失事，並造成700人以上死亡。本文將回顧過去三十年來不穩定氣流對飛機之危害，下爆氣流與風切之關聯性，及風切與側風有關之飛航事故。提出四種風切識別方法：空速變化法、飛航儀表法、單位距離風速變化法與，及風切危害因子法，並應用這些方法來量化兩件飛航事故之風切強度。

自從八十七年五月行政院飛航安全委員會設立以來，共負責18件飛航事故調查工作，6件與天氣有關。其中，有1架直昇機失事墜毀，2架定翼機失事全毀，3架定翼機滑出跑道。本文應用不同的風切識別法，根據飛航記錄器所記錄之飛航資料，以探討陣風及下衝氣流對航機之影響。為了找出危害飛航安全的環境因素，針對風切、亂流及陣風等天氣情況之三維風場估算結果，識別風切之成因與強度，以作為改善飛航安全之指標。未來，若能結合部分機場的低空風切預警系統之氣象資料，則能進一步驗證本文所提之風切識別法的實用性，並且提供更安全的風切預警系統。

Table 1. Results of airspeed variation (a); results of wind shear hazard factor (b).



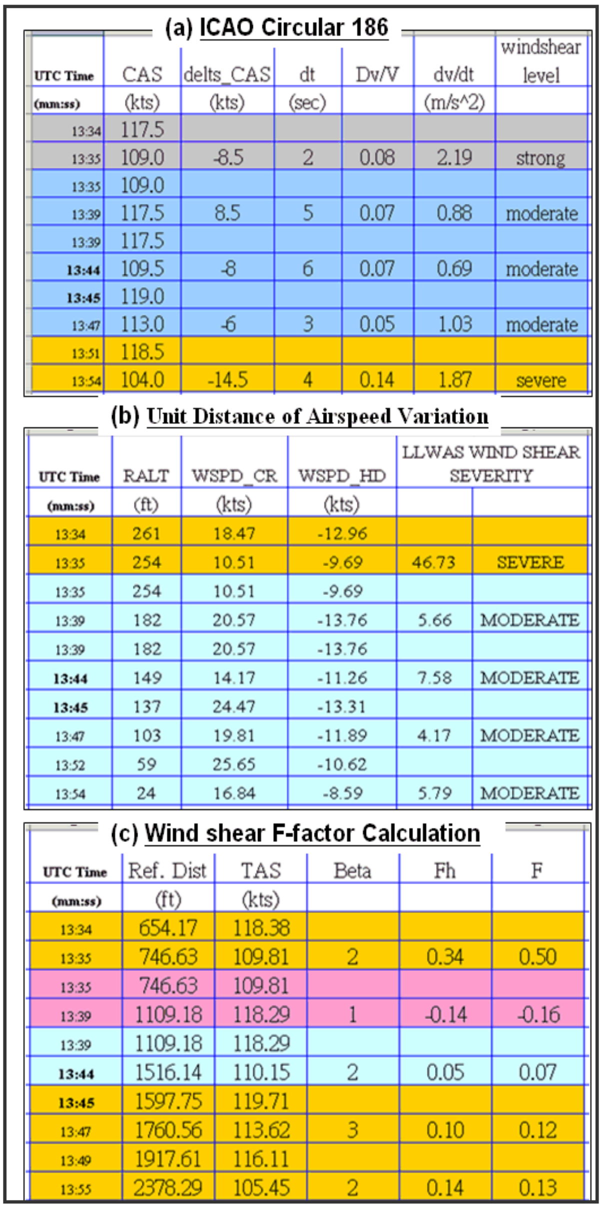
(a) ICAO Circular 186

UTC Time (hh:mm:ss)	RALT (ft)	CAS (kts)	delts_CAS (kts)	dt (Sec)	Dv/V	dv/dt (m/s^2)	windshear level
13:49:49	231	163.2					
13:49:52	190	148.8	-14.40	4.00	0.10	1.85	strong
13:49:54	168	154.2					
13:49:58	131	167.8	13.60	5.00	0.08	1.40	moderate
13:50:01	98	169.5					
13:50:03	72	153.8	-15.70	3.00	0.10	2.69	strong
13:50:07	26	151.8					
13:50:08	11	176.8	25.00	2.00	0.14	6.44	severe
13:50:09	12	173.8					
13:50:11	2	150.2	-26.60	5.00	0.18	2.74	severe

(b) Wind shear F-factor Calculation

UTC Time (hh:mm:ss)	Ref. Dist (ft)	TAS (kts)	Beta	Fh	F
13:49:50	17726	159.98			
13:49:53	18186	154.60	2	0.03	0.03
13:49:55	18497	165.03			
13:49:59	19138	161.62	1	-0.04	-0.05
13:50:02	19636	154.79			
13:50:04	19971	156.12	1	-0.21	-0.21
13:50:07	20471	177.47			
13:50:09	20795	163.55	2	0.56	0.59
13:50:08	20635	174.43			
13:50:12	21268	148.69	2	0.48	0.51

Table 2 Results of airspeed variation (a); results of unit distance of airspeed variation (b); results of wind shear hazard factor (c).



(a) ICAO Circular 186

UTC Time (mm:ss)	CAS (kts)	delts_CAS (kts)	dt (sec)	Dv/V	dv/dt (m/s^2)	windshear level
13:34	117.5					
13:35	109.0	-8.5	2	0.08	2.19	strong
13:35	109.0					
13:39	117.5	8.5	5	0.07	0.88	moderate
13:39	117.5					
13:44	109.5	-8	6	0.07	0.69	moderate
13:45	119.0					
13:47	113.0	-6	3	0.05	1.03	moderate
13:51	118.5					
13:54	104.0	-14.5	4	0.14	1.87	severe

(b) Unit Distance of Airspeed Variation

UTC Time (mm:ss)	RALT (ft)	WSPD_CR (kts)	WSPD_HD (kts)	LLWAS WIND SHEAR SEVERITY	
13:34	261	18.47	-12.96		
13:35	254	10.51	-9.69	46.73	SEVERE
13:35	254	10.51	-9.69		
13:39	182	20.57	-13.76	5.66	MODERATE
13:39	182	20.57	-13.76		
13:44	149	14.17	-11.26	7.58	MODERATE
13:45	137	24.47	-13.31		
13:47	103	19.81	-11.89	4.17	MODERATE
13:52	59	25.65	-10.62		
13:54	24	16.84	-8.59	5.79	MODERATE

(c) Wind shear F-factor Calculation

UTC Time (mm:ss)	Ref. Dist (ft)	TAS (kts)	Beta	Fh	F
13:34	654.17	118.38			
13:35	746.63	109.81	2	0.34	0.50
13:35	746.63	109.81			
13:39	1109.18	118.29	1	-0.14	-0.16
13:39	1109.18	118.29			
13:44	1516.14	110.15	2	0.05	0.07
13:45	1597.75	119.71			
13:47	1760.56	113.62	3	0.10	0.12
13:49	1917.61	116.11			
13:55	2378.29	105.45	2	0.14	0.13

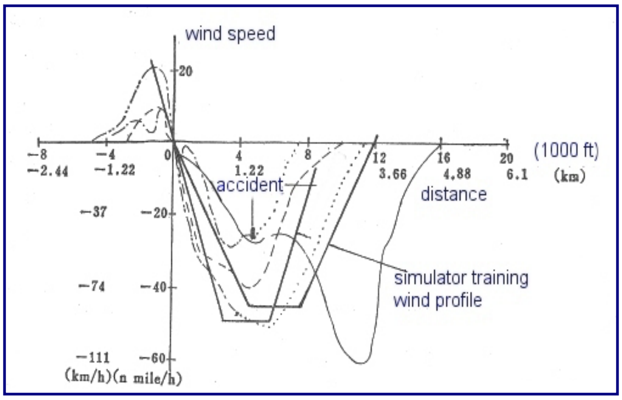


Fig.1. Wind speed profiles (dotted and actual lines) of wind shear related accident, obtained from flight data recorder (FDR), and used in flight simulators. （Source: FAA Advisory Circular, AC 00-54. Subject: Pilot Wind-Shear Guide, 1985）

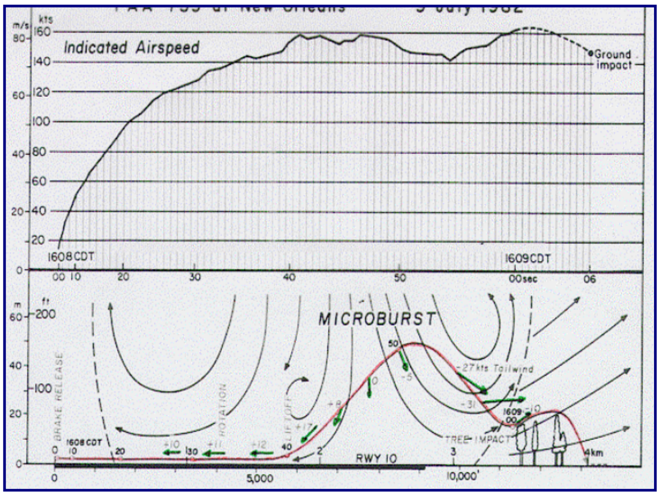


Fig.2. Variety of microburst and airspeed of the accident in 1982 in New Orleans, the aircraft encountered wind shear at 150 ft (altitude) after take-off (red indicates flight path; green indicates direction of microburst).

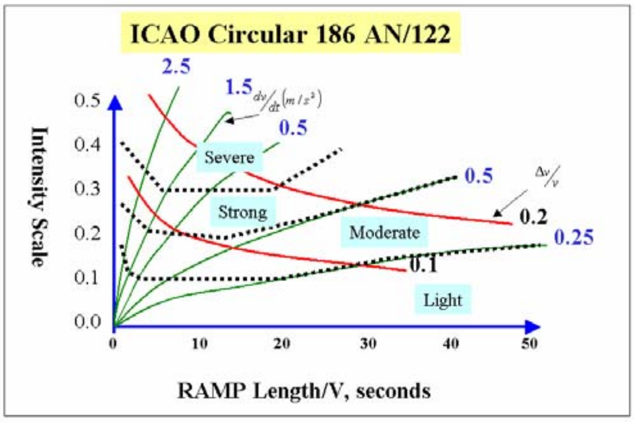


Fig.3. Wind Shear identification method- airspeed variation, published by ICAO. (Source: Fujita, 1985)

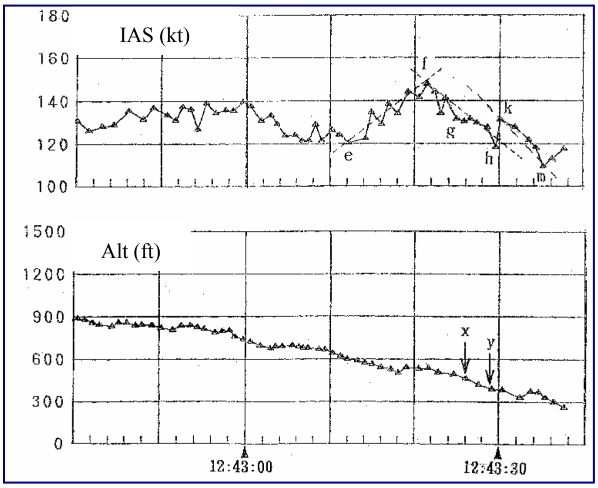


Fig.4. Variation of airspeed and altitude of flight data below 900 feet, DC-9-41 accident flight at Hanamaki Airport, Japan, 1994. （Source: AAIC Accident Investigation Report, 94-6-JA8448, 1993）

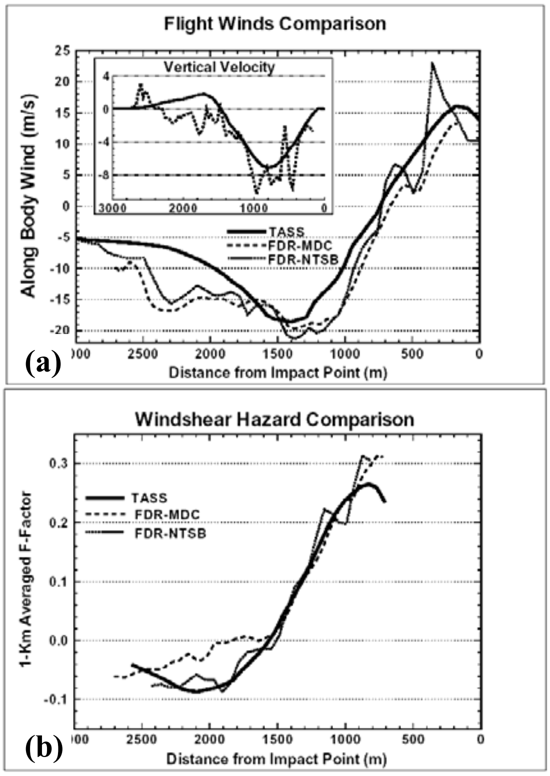


Fig.5. Horizontal wind velocity (positive stands for tailwind) and vertical wind velocity（positive stands for down wind）against the distance from impact point (a). 1-km averaged F factor against the distance from impact point (b).

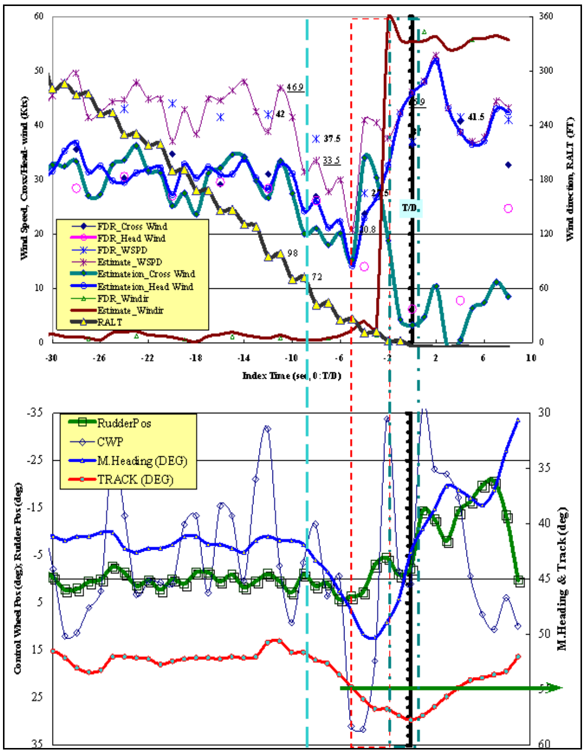


Fig.6. Time history plots of FDR parameters for the last 30 seconds

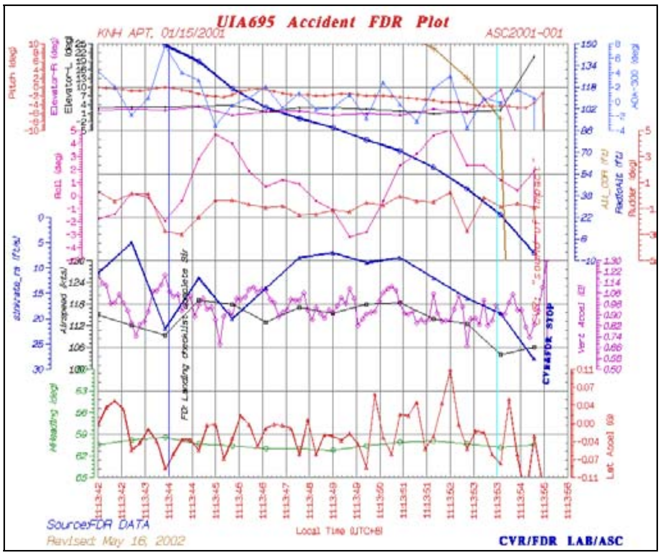


Fig.7. Time history plots of FDR parameters (below 300 ft)