Wake turbulence vortices

On 1969, the Federal Aviation Administration supervised a program to provide more information on wake turbulence and wake vortices. The results confirmed that wake turbulence and wake vortices are real flying hazards. These hazards became clearer on flying safety as well as on passengers safety. Aircraft characteristics as weight and wingspan and climate changes of wind, air pressure and air density alter wake turbulence. Avoidance of wake turbulence is the joint responsibility of air traffic controllers and pilots. Scientific research to develop better sensors and electronic equipment to detect wake turbulence will help in avoidance of wake turbulence. The scope of this thesis is to spotlight the meaning of wake turbulence, the mechanisms of formation, the hazards and how to avoid them.

Introduction

On November 12, 2001, American Airline flight 587 and Airbus A300-600 crashed minutes after taking off from Kennedy international Airport. The accident resulted in killing 250 passengers. This accident revived attention to the problem of wake turbulence. A wake is the region of turbulence immediately behind a solid body running in air or fluid. It is the result of the flow of air or fluid around that body. In every day life, one notices turbulence on many occasions. When flies a kite on the beach facing the wind, the way the kite flies in the air becomes unsteady as it suffers turbulence. On air travel, one usually hears the word turbulence associated with fastening seat belts.

There is no universally accepted definition of the word turbulence, but it can be described as a disordered behavior of fluid or air in space and time.

Turbulent motion is a difficult subject in physics and science and has a wide range of applications.

Wake turbulence has several types among which, wing tip vortex and jet wash are the most important. Jet wash points to the huge amounts of rapidly moving gases coming out of the jet engines. It is turbulent yet for a short time. Wake vortex is the dangerous part as it stays in air for few minutes after the passage of an airplane.

The aim of the present work is to discuss, briefly, mechanisms, hazards, and local weather effects on wake turbulence and how to avoid hazards of wake turbulence.

Wake turbulence: What does it mean? (Hoffren, 2007)

All aircrafts in flight create wake turbulence, the heavier the plane the stronger the turbulence. ICAO (Document 9426, November 2000), used wake turbulence to describe the effect of two rotating air masses produced behind the wing tips of a big aircraft. Wake vortex (vortices) describes the nature of air masses. Wake vortices are two counter rotating air masses. They are generated when the airplane takes off the ground and fade away when it touches the ground again. The wake vortex circulation is upward, outward and around the wing tips. Flow turbulence is three-dimensional and time dependant. It contains irregular eddies and enhances mixing, diffusion and dissipation. Flow turbulence, however, is not random because of the underlying determinant nonlinear mechanisms.

The two most important reasons to decide turbulence are: 1) any flow that is modeled as two-dimensional is laminar but not turbulent. 2) A flow that can be studied using the potential flow theory is not turbulent. Thus we have two types of airflow; laminar (nonturbulent) and turbulent flow. However; the classification is not that clear-cut as there is a shadow area at the boundary layer between the two flows. An example is the flow in the boundary layer over a flat plate may be laminar or turbulent. For some distance behind the plate, the flow remains laminar. The boundary layer turns turbulent depending mainly of the state of the external flow.

This transition, however, does not occur instantly, and the border between laminar and turbulent flow is difficult to draw. Second, it is difficult to predict the area where this change takes place. A more complex example is the flow behind a cylindrical body. The wind induced flow separates and forms an alternating pattern of vortices (Von Karman vortex street). Here, the whole three-dimensional flow field appears erratic, however; there are smaller, clearly turbulent eddies superimposed on the large-scale vortices. Thus turbulence becomes more complex. This clarifies the difficulty in drawing general borders around turbulence.

How wake turbulence is created? (Choroba 2006 and FFA 90-23F 2002)

Air turbulence results form convection currents caused by the sun heating the ground and therefore, the air mass near it. This hot air rises by convection and is replaced by cooler air from higher masses. In windy days, we experience the scene of flying pieces of paper and light objects in eddy forms between high buildings. Obstruction to wind flow causes this kind of turbulence. In a flying aircraft; this occurs when flying over mountains, if two air masses with different speeds or directions are near enough, wind shear results. This turbulence is mostly affected by climate conditions of temperature and air pressure. An aircraft passing through air creates wake turbulence. There are many types of wake turbulence, among which the turbulence created by the wings and ailerons during take off (wake vortices) is the most important. Other types are; jet engine or propeller wash and jet blast (stream turbulence created during flying). Aircraft weight, its air speed and the distance between wing tips (wing span) determines the intensity of wake turbulence.

- *Generation of wake vortex:* For an aircraft to take off (lift up), there should be a pressure difference over both wing surfaces (upper and lower). During take off, the high pressure area is under the wing surface and the low pressure area is over the wing. These pressure gradients are the main cause for generating a wake vortex. Air from the high pressure area (under the wing) flows around the wing tip to the area of low pressure (above the wing); this is known as rollup. Thus the wake vortices are composed of two air masses generated from the wing of aircraft. The mass generated from the left wing rotates in a clockwise direction and that generated from the right wing rotates in an anticlockwise direction. Multiple vortices occasionally develop with the use of ailerons or with aircrafts with multiple flaps. These multiple vortices combine in a wake vortex generated for each wing. Like a hurricane, a wake vortex consists of a core surrounded by an area of circularly rotating wind. The surrounding area is much larger than the core (100 feet to few inches respectively). The speed of air is maximum in the core area, while in the surrounding area if fades as we go the periphery. Wind energy created by a vortex is maximum only few feet of the center (as it suffers vortex decay), however; pilots should keep at least 100 feet from the vertex core of the preceding craft.

- *Wake vortex decay:* It means how strong the wake vortex is at a distance that equals 10 to 15 times the wing span of an aircraft. Wake vortex persistence depends mainly on meteorological factors such as ground factors, the nearer the ground the more persistent vortices are. Wind speed, where light cross-wind drifts the vortices whereas atmospheric turbulence causes the vertices to decay more rapidly, and direction and stability of atmospheric factors (temperature, pressure). Technical causes to affect vortex decay are maneuvering and inter-wing span, the shorter the span, the more violently generated vortices.
- *Characteristics of wake vortices:* Knowing how wake vortices behave and their characteristics should enlighten pilots on how to avoid them. Wake vortices are generated from the moment an aircraft takes off. The direction of circulation of a wake vortex is upwards and outwards around the wing tips in a clockwise direction at the left wing tip and anticlockwise atthe right wing tip i. e. counter rotating vortices. Aerodynamically, such counter rotating vortices are unstable in term of wavelength. This has an impact on the far field wake (the region where atmospheric factors significantly affect wake vortices) aerodynamics. Wake turbulence resulting from bigger aircrafts is more severe and

persists longer. On landing, as the wake vortices decay, they take a more lateral direction. Crosswind affects the speed and direction of the wake vortices whether upwind or downwind. Tailwinds also affect the vortices of the preceding aircraft.

Hazards of wake turbulence

Hazards of wake turbulence on an air flight are classified into three main categories: 1- Effects on the aircraft. 2- Passenger injury and 3- Is wake turbulence an obstacle to increased capacity of airports and the frequency of air travel?

- *Effects of wake turbulence on aircraft:*
- Induced roll: It is the most serious effect during take off and landing, when there is little altitude or speed for recovery. The ability of an aircraft to oppose induced roll depends on wingspan and counter control responsiveness. According to the reported angle, wake turbulence is one of three categories, namely: 1- severe: the reported roll angle is more than 30 degrees. 2- moderate: the reported angle is between 10-30 degrees; and 3- mild: where the reported angle is less than ten degrees. Severity of induced roll depends on other causes like direction of facing the turbulence, point of encounter and distance from the creating aircraft (Puri and Saravanan, 2005).
- Structural stress (structural failure): Stress is the damage that affects the structural integrity of an aircraft, thus affecting its performance during a flight. According to the Federal Aviation Administration (FAA) regulations, Building aircrafts should meet higher stresses than would

be ordinarily met during flights. Air turbulence is among the calculated stress; however, thunderstorms may create turbulent air speeds that would represent an uncalculated stress and may cause serious damage to the aircraft. (Retrieved from).

- Altitude loss near the ground. Altitude change may occur because of wake turbulence. It happens when an airplane is flying slowly as during take off or landing creating a wake turbulence behind that may affect a closely following plane. This is one reason of limiting time and distance spacing between departing and arriving planes. Thunderstorms especially those creating powerful unexpected downdrafts may cause wake disturbances that seriously affect planes flying nearby. How serious the effects of sudden altitude changes induced by wake disturbances can be; depends mainly on aircraft weight and at which distance the aircraft is. The lighter the aircraft the more serious the consequences are. The nearer to the ground the more tragic accidents may occur irrespective of the aircraft weight (Retrieved from).
- Wind changes near the ground . Turbulent airspeed does not affect an aircraft speed significantly. From an aerodynamic perspective, the relative speed of the aircraft to the speed of wind around it is what matters. This produce the raise needed to keep it flying. Safety is compromised when the aircraft is near to the ground during a sudden change in wind speed as that created by a preceding departing or arriving airplane. This results in a change of course right off the runway end (Retrieved from).

- *Passenger injury.* Passenger injury because of wake turbulence can be either physical or psychological. Physical injuries occur when an airplane flies an area of low pressure or an area of air moving downwards (air pump). Moving passengers or those who are not fastening their seat belt. In which case falling or trauma induced by sudden movement of the body, because of inertial lag, may range from mild to severe and may affect other passengers as well. Falling of loose objects may also cause physical injury to passengers. Psychological fears or worsening of psychological disorders depend mainly on the passenger attitude and to what extent he or she is affected by the sudden airplane movement caused by wake turbulence. Passenger behavior is also affected by culture which dictates his or her behavior (Proceedings of AvKiwi Seminar, 2006).
- *Wake turbulence as an obstacle to increased airports capacity and travel frequency:* This is not a direct wake turbulence flight hazard but represents an economic issue since airports are important portals for national and international trade. Meeting the increased demand on air travel as well as a keeping safety parameters are another challenge, especially where the demands for air transport could double or even triple by 2025. Factors which determine airports capacities and abilities to adjust to increasing numbers of flight are many. A common cause for flight delay is flight spacing and separation distances to be maintained between aircrafts as safety procedures against possible accidents that wake turbulence may cause. The report of the national research council, 2008 stated that the main objective of wake

turbulence research is to improve safety. This has successfully created wake vortex separation criteria. The query is how to reduce flight delays because of wake turbulence disturbances without compromising the safety criteria. The main condition to achieve this is to agree on a defined hazard boundary to properly calculate spacing distance and time that produces increased airports capacities and achieve increased travel frequency.

Weather effects on wake turbulence (Choroba 2006 and Veillette 2002)

Different atmospheric weather conditions influence both the flow and decay of wake turbulence. Before going into the details, we need to know what is atmosphere; and in which layer aircrafts fly. Atmosphere is that sheet of gas mixture (air) that covers earth. It consists of four layers; troposphere, which is the nearest layer to earth surface. The weather changes that we know (wind, temperature, humidity…) occur in that layer. The second layer is stratosphere; most jet aircrafts fly in this area because climatic conditions are stable. The next layers are mesosphere and thermosphere (where space shuttles fly). Thus, it is expected that weather conditions significantly affects flying aircrafts when they are in the troposphere layer i. e. during take off and while gaining the course altitude and when descending to the landing destination. It is, also, stated that the ability to predict sudden changes occurring in stratosphere is limited till now. The wind pattern in stratosphere is rather complicated, yet aircrafts face less resistance and strong thunder storms do not occur in this layer (Charlton and Polvani, 2007).

1- Wind effects on wake vortex: In stratosphere, the wake vortex is coherent (consistent), smooth and uninterrupted by ailerons (wing flaps) as it is generated from the smooth wing surfaces. Another factor that affects wake vortex in high altitude is the absence or minimal atmospheric turbulence. Atmospheric turbulence is one reason for the decay of wake turbulence. Its absence enables wake vortex created to remain coherent. In FFA database, 43% of accidents caused by wake turbulence occurred when wind speed was between three to 10 knots. Vortex stretching or tilt of wake vortex may be caused by atmospheric turbulence, convection or other aircraft jet stream or vortices. If a wind changes its speed or direction over a short distance, creating a wind gradient difference, this is called wind shear. Wind shear can be either horizontal (with weather fronts) or vertical, in which case the vortex decay is delayed causing increased time and distance spacing. More seriously, the vortex may bounce back or suddenly come to a halt depending on whether the vortex is in the same or opposite direction of rotation of a vertical wind shear. In FFA database, 7% of the accidents occurred on parallel runways or on runways close enough to parallel runways. The reason for this is cross wind which significantly delays the vortex decay time. Moreover; cross winds causes the wake vortex to travel longer distances.

Over large water surface areas, the land and sea breeze has some impact on winds. The warmer temperature, because of increased solar radiation and the relatively weaker wind in low altitudes, at tropical shores result in sea breeze. The effect of sea breeze diminishes with increasing altitudes. This sea-land air circulation cycle occurs in temperate countries during late spring and summer. Temperature gradients over large lakes produce a similar phenomenon called the lake-land breeze.

Obstruction to wind flow by mountains and hills results in deformation of airflow. Eddies and upward and downward current of air in this nearly closed space (drafts) are formed. As a result; wind direction changes significantly in mountains areas. When there is a series of mountains (e. g. Rocky Mountains), the wind may be kept behind and is deflected to run parallel to the mountains series. More seriously; if there a breach area within the series, the wind may rush through it with considerable speed (similar to the tunnel effect). Local areas of distorted airflow can produce the mountain wave. Mountain waves have three main characteristics: a) Perpendicular in direction, b) of increasing speed and c) the lens shaped cloud heralding its presence.

2- Air pressure: Since air has a mass, it is attracted by gravity. Therefore; it has weight. The pressure exerted by the weight of an air column over an area is air pressure. It is logic, then, to assume that the higher the altitude the lower the air pressure. The average air pressure at sea level is 17. 4 pounds per square inch, and for every 1000 feet increase in altitude air pressure decreases by 1 inch of mercury. How this affects flying? Aircraft lift results from the flow of air below, above and around the wings. If air pressure is decreased, then more speed is needed to obtain enough pressure around the wings for take off. This means longer ground run and therefore longer run ways. Changes in temperature, in high altitudes, changes air density which in turn results in change in air pressure. This produces vertical and horizontal winds and air currents which will alter wake turbulence distance, direction and decay (FFA 2003).

3-Temperatur, humidity and air density: It is defined, as density of any other gas or liquid, as the mass of air per unit volume. Therefore; it is affected by air pressure, air temperature and humidity. The air column resembles a compressed spring, when released it expands and occupies a bigger volume. In the case of an air column, this means it becomes less dense. Thus an air column at low pressure contains a smaller number of air molecules i. e. a smaller mass of air. Pressure is not the sole factor affecting air density. Air density is inversely proportional to temperature. Temperature and pressure decrease in high altitudes, this should produce contradicting effects on air density. However; decrease in pressure with increasing altitude is more rapid than decrease in temperature, so change in pressure has a superior effect on air density than the change in temperature (FFA 2003). This argument applies if the air is dry, which is not the case because atmosphere contains a certain amount, whatever small it is, of water vapor. Since water vapor is lighter than dry air, warm and humid air masses are less dense than cold and dry masses. So air pressure, temperature and humidity collectively, through their effect on air density, have a significant effect on aircraft performance.

The interaction of air pressure (through its effect on air density), temperature and humidity control air stability. A stable atmosphere is one that makes vertical movement difficult and can reduce the effects of or even cause small vertical movements to disappear. Higher temperature and increased humidity result in unstable atmosphere. In this climate, thunderstorms are more liable to occur.

How to avoid the hazards of wake turbulence

(Pilot and Air Traffic Controller Guide to Wake Turbulence)

Prevention or minimizing the hazards of wake turbulence is the outcome of hard work and commitment of air traffic controllers and pilots. The development of electronic systems and sensors to detect or predict wake turbulence is a great step forwards. The research conducted in the US is more advanced and inclusive to most aspects of the problem than those conducted in Europe and Canada.

- *Air traffic controller responsibility:* Air traffic controllers are responsible for the avoidance of wake turbulence hazards till the point of time when pilots assume visual responsibility for avoidance. Their role is to issue wake turbulence cautionary advisories as well as information regarding direction, height and the position of heavy aircrafts. The issue these advisories to aircrafts which are not radar vectored but known to be behind another heavy aircraft; aircrafts which were radar vectored but discontinued to be so and to aircrafts which accept visual approach. There is flexibility in judging; as air controllers can give cautionary advises to any aircraft which they judge wake turbulence may have a hazardous effect on. The main responsibility of tower controllers is runway separation for departing or arriving aircrafts to an airport. Longitudinal separation criteria depend on the weight of the preceding aircraft, runways used whether same, parallel or intersecting. The direction of take off or descent whether opposite or in the same direction of the preceding aircraft, vertical separation distance between the two crafts, displaced landing threshold and local climate especially surface wind direction and speed also play a role in determining longitudinal separation criteria. There are numerous reports on aircraft separation criteria, the slight variation in estimation depend on the report objective avoiding accidents created by wake disturbances or totally avoiding wake disturbance. Air traffic controllers rely on pilots to communicate with them freely if they believe that visual responsibility might endanger the course of departure or landing.

- *Pilot responsibility:* Varies with each flight phase. During take off and landing; if the pilot recognizes a possible factor to increase life span of wake vortex of the preceding aircraft, he should ask for take off delay for few minutes. The pilot must ensure that his take off route will be higher or at least to maintain take off upwind of the preceding (leading) aircraft route. During cruise; the seat belt on sign should be declared when in the vicinity of another aircraft. Always check spacing with nearby aircrafts. During approach, the pilot is to make sure that he is on the runway path and not above it; this will keep the effect of his aircraft wake turbulence apart from following aircrafts. On landing, whenever possible, pilots are to design landing beyond the point of touchdown of the preceding aircraft.

Conclusion

All aircrafts leave a wake behind them while flying taking the form of two rotating wake vortices. The strength, time they last and the distance they travel depend mainly on the weight of the aircraft, atmospheric winds, air density flying speed and wingspan. Minimizing this problem is essential for travel safety as well as for increasing airport capacities as main portal for trade and travel. It is the responsibility of air traffic controllers and pilots. The rule of thumb remains the best way to avoid the hazards of wake vortices is to avoid the areas where they are created.

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