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INFLUENCE OF WAKE-VORTEX TURBULENCE ON THE FLIGHT SAFETY

1. INTRODUCTION

The powerful aerodynamic swirl, which is produced behind an aircraft in flight and stays in free atmosphere for some time, is called a vortex. Every aircraft in flight generates a certain degree of wake-vortex turbulence, whose intensity depends on the weight of the aircraft, airspeed, shape and span of the wings. The heavy and clean (retracted wheels and wing mechanism) aircraft at low airspeeds generate the most intensive wake vortex. Pilots know that flying into wake vortex of a preceding aircraft is accompanied by various unpleasant occurrences which can in certain cases even endanger the flight safety.

Military aircraft often fly in groups or close formations, and military pilots pass special training for such flying. However, there is a growing necessity for the civil air personnel as well to know more and more about hazards of flying into a wake vortex, including both the pilots and the flight controllers in order to enable them to determine the minimum distance between the two aircraft and the minimum safety time interval between repeated takeoffs and landings.

The intensity of air traffic in the airspace surrounding airports has been greatly increased, so that civil aircraft more and more often fly in "formation". At the Frankfurt airport, for example, there are three runways and about 1000 takeoffs and landings daily, so that during "peak hours" about 74 aircraft per hour take off (one takeoff every 48.6 seconds), and at the same time on the parallel runway up to 50 aircraft per hour land. This means that the civil aircraft fly practically one after another. The Frankfurt airport was in 1996 the seventh in the world regarding the number of passengers. At the Heathrow airport in London is a similar and even more critical situation with 16 million passengers more traffic than Frankfurt, and regarding the number of passengers it is the fourth in the world. At both airports the number of passengers is increasing (5.2-8.7%) and they plan to increase the number of takeoffs and landings. To what extent is the increase in traffic intensity possible regarding the significance of the wake vortex and the accompanying effects, how to recognise and react to the momentary destabilisation of the aircraft, i.e. how to determine the separating distance and provide the minimum interval between the aircraft in order to maintain the basic flight safety?

2. STUDY OF VORTEX TURBULENCE

The vortex turbulence endangers greatly the flight safety, due to the increase of traffic intensity, especially the frequency of starting and ending flight operations and the introduction of heavy structure weight aircraft (over 300,000 lb_f MTOW according to the FAA classification).

The U.S. NTSB (National Transportation Safety Board) study on research carried out between 1983 and 1993, registered 51 aircraft accidents caused by (probable cause) vortex turbulence, out of which about 40 aircraft were substantially damaged or destroyed.

The UK has the most extensive data on consequences of vortex turbulence, with 501 accidents registered in the period between 1982 and 1990 at the London Heathrow airport. The English researchers have discovered two separate blocks of altitudes within which the majority of incidents is concentrated. The first block is the altitude between 100 and 200 ft (30.5-61 m) above runway threshold, and the second one between 2000 and 4000 ft (610-1220 m).

The cause of accidents in the latter block is attributed to the pilot error in lining up for the interception of the localiser. The same research have also shown that the aircraft B-747 and 757 have the highest incident proportion in generating vortex turbulence, and the most frequently involved i.e. caught are the aircraft DC-9, B-737 and BAC-111.

In French studies of vortex turbulence and the consequences of flying into wake-vortex, the concluding finding emphasises that in all the cases the wind did not exceed 8 kt (NM/h).

The concluding suggestions of all the previous research done stress the measures of increasing the aircraft separation as the main effect of reducing risk of incident i.e. the intensity of turbulence acting on the aircraft in-trail, as well as to preventive criteria of aircraft weight, flight control procedures and pilot training.

3. THE ETYMOLOGY OF WAKE-VORTEX TURBULENCE BEHIND AN AIRCRAFT

The way in which turbulent wake is generated behind the aircraft in flight is very complex, and it is affected by:

1. the free aerodynamic vortices formed by circulation, which are caused by airflow around the airfoils (the wings) when there is lift;
2. the exhaust air jet discharged from a reaction engine;
3. the turbulent field of air resulting from the flow of viscous air in the boundary layer on the airframe surface;
4. the secondary turbulence caused by the local unsteady airflow around the aircraft elements (interference at joints - wing and fuselage), so that the streamlines get separated at certain parts of the structure.

According to the theory of potential airflow, which explains also the forming of the induced drag, without circulation (Γ) there is no lift at an aerodynamic body in real fluid. Supposing there is viscous fluid in the boundary layer which determines the fluid circulation, Prandtl showed at the beginning of the 20th century (1905), that lift per span unit is directly proportional to circulation and that a wing can be replaced by a hypothetical vortex system around the wings and trailing vortices at wing tips (Figure 1).

The air downwash, i.e. descent, produced by trailing vortices at wing tips and the bound vortex along the wing, provide a flexible model which enables mathematical calculation of any given distribution of downwash or lift at the wing. The movement of aircraft and the change in pressures produced by flying, cause a large mass of air to flow around the aircraft flying surfaces. The circular airflow is steady, which in fact determines the duration of vortex flow behind the aircraft in flight, dissipating eventually due to the viscosity of air. It is well known that such circulation is closely related to the vortex motion. Every vortex produces an even airflow, whose particles move without rotating around the boundary layer of the vortex. Within this area there is the vortex core, where the particles flow along the circle, at the same time rotating around their axes. Figure 3 presents the basic features of the turbulent wake behind a flying aircraft, on the control panels A-B-C along the aircraft and panels D-E-F behind the aircraft.

The exhaust airflow behind a reaction engine at the nozzle outlet of diameter *D* shows high jet axis velocity (V_m) and significant kinetic energy (Fig. 3-A). Unlike circulation of aerodynamic airflow of trailing vortices, the air mass in the jet current behind the engine is relatively small, and therefore disappears rather quickly. Thereby its diameter increases and the axis velocities become reduced.

At the distance L_m, which equals about 25-50 diameter behind the exhaust nozzle of diameter *D* (even with afterburner) the influence of that flow is practically non-existent (Fig. 3-B).

The air that has passed through the boundary layer, after flowing around aircraft surfaces, generates the lower turbulent wake (Fig. 3-A). Its structure reminds of the reactive current from the engine, with the speed opposite in sign. Having a much lower ki-

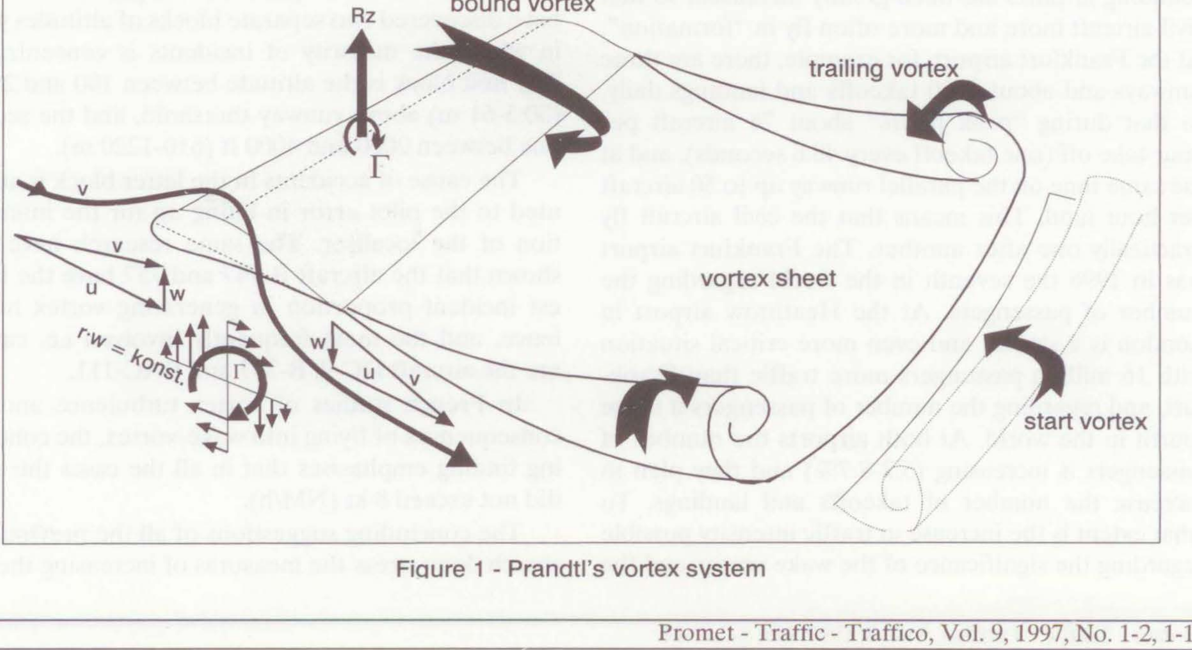

Figure 1 - Prandtl's vortex system

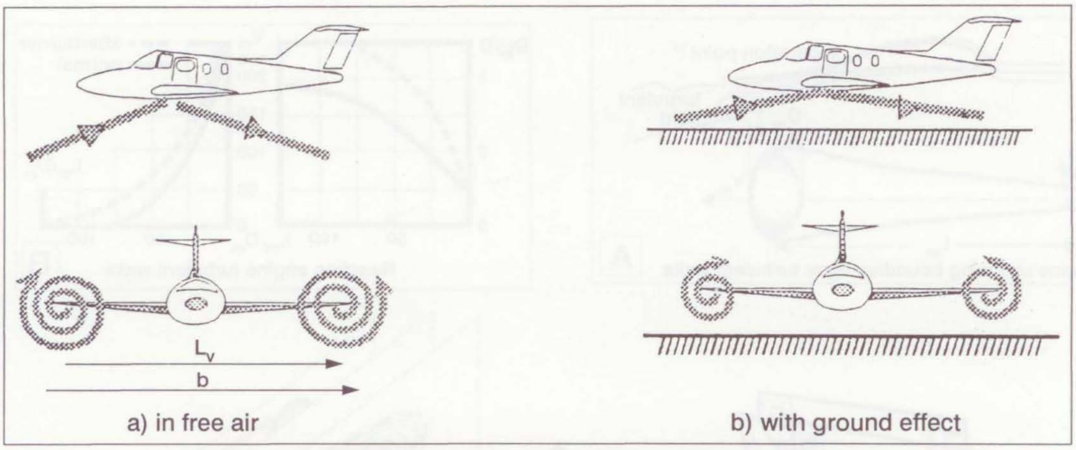

Figure 2 - Circulation and deflection of the free aerodynamic vortex

netic energy than the reaction current, the lower turbulent flow disappears in the close vicinity of the aircraft.

The tendency is to eliminate the turbulence and vortex motion generated by interference of airflow around the airfoils, i.e. at the joints of certain aircraft elements (e.g. wings and fuselage), already during design itself by appropriate shaping (aerodynamic channels). However, even if not eliminated, this is certainly only a minor air mass and minor vortical intensity, which are not a decisive factor in aircraft turbulent wake.

Therefore, it can be concluded that the main cause of wake-vortex turbulence behind a flying aircraft lies in the forming of *aerodynamic trailing vortices* that are generated due to the circulation around the airfoils. Trailing vortices caused by the flow around the wings, interact and thus form the "vortex plaits" (vortices). Usually a vortex pair forms behind the wing. The vortices of each pair have a circulation which is equal in magnitude and opposite in sign (direction) (Fig. 2 and Fig. 3-D).

The vortex circulation is calculated according to the following formula:

$$\Gamma_0 = R_z/\rho V L_v$$

where:

R_z – is lift force

ρ – is air density

V – is airspeed

L_v – is span between the vortex axes

b – is wing span

Prandtl also found out that the hypothetical cross section of air mass, which is deflected in downwash makes a circular form, whose diameter is proportional to the wing span:

$$A = \Pi b^2/4$$

whereas the induced angle of downwash (Fig. 3-C) is in the function of lift:

$$\alpha_i = C_z S/\Pi b^2$$

where:

C_z – is lift coefficient

S – is wing surface

The span between the vortical axes is determined by the layout of airflow along the wing span, which depends on the shape of the wings (planar view) and the angle of attack. With most wings, which have no break lines at the leading edge, at mean angles of attack, the relative spacing $L_v' = L_v/b$ is *0.8* (Fig. 2). The increase in airflow around the central part of the wing, reduces the spacing between the swirl axes to $L_v' = 0.72 - 0.75$. This is especially the case with swept and delta wings at high angles of attack, and with wings with varying geometry at low and medium angles, as well as with devices for changing the airflow round the wings (flaps, spoilers, etc.), if they are positioned within the span and do not change the planar shape of the wings. With aircraft that have swept thinner wings, the load is relatively taken off the fuselage so that usually another inner vortical pair is formed. The vortices of the inner pair (secondary) have a relatively low circulation that is opposite in direction to the basic outer free pair. The profile of the radial velocities of the free vortex pair is presented by a schema in Figure 3-F.

The field along the vortical axis where the velocity increases from 0 to w_{max} is called the vortex core. The radius of this core (r^*) behind the rectangular wings is between 0.01 and 0.02 of the wing span b and practically does not depend on the angle of attack. Behind swept-winged aircraft at low angles of attack, the relative radius ($r' = r^*/b$) is somewhat bigger (0.015-0.025), and at higher angles of attack it increases (0.04-0.06). The range of variable velocities within and near the vortex core is accompanied by

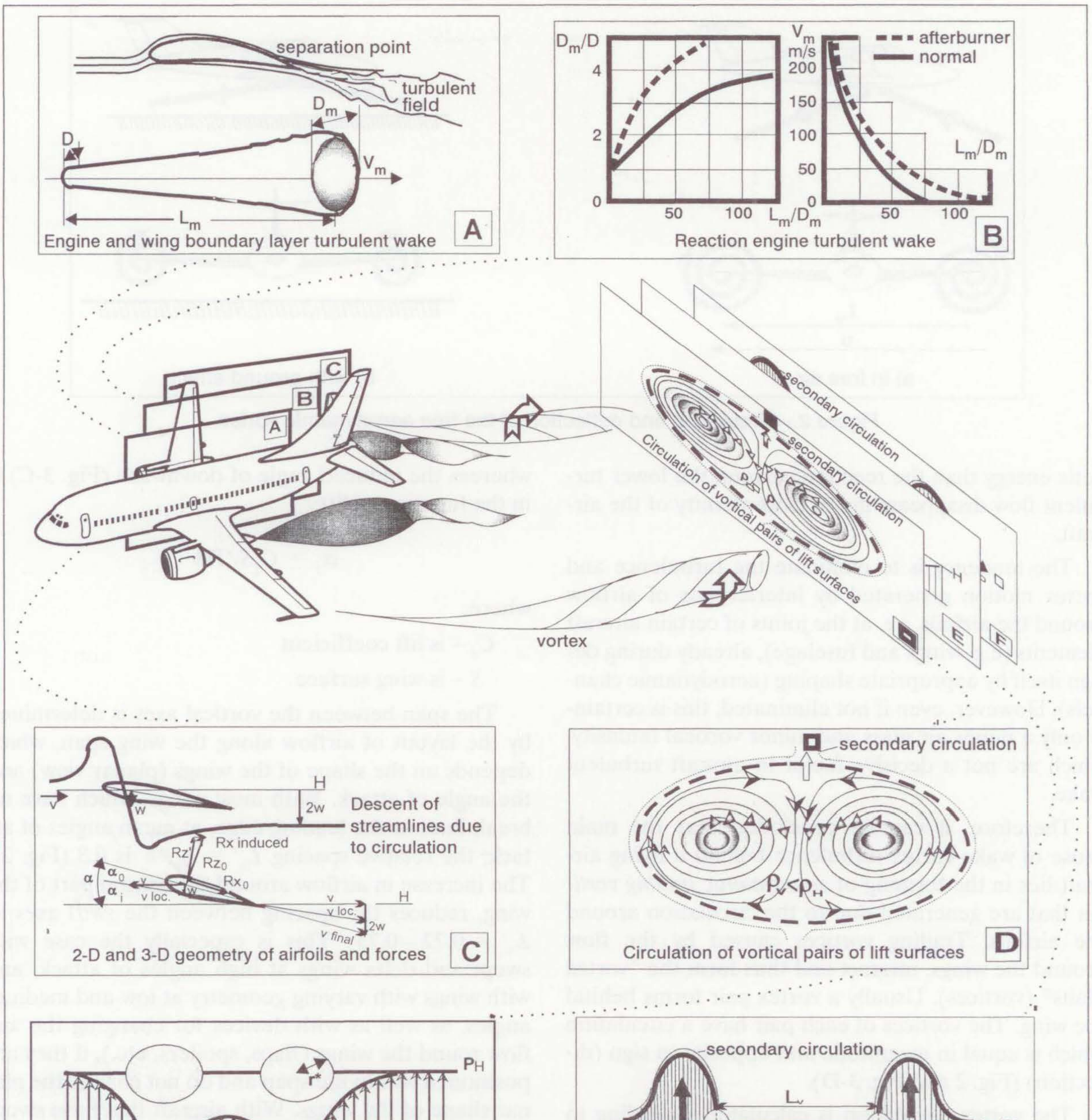

Figure 3 - The features of the aircraft turbulent wake

the variation in pressure. By increasing the velocity (w), if measured from the outer layer towards the core, the pressure decreases, which corresponds to the Bernoulli's principle. Within the core, the pressure is even further reduced, and reaches its minimum in the vortical axis (Fig. 3-E).

4. PARAMETERS OF WAKE-VORTEX TURBULENCE

The basic part of wake-vortex turbulence consists of the vortices. Their structure is fixed and their axes almost parallel.

The change of parameters along the wake is determined by gas dynamic processes. It has already been mentioned that the rate of circular motion around every vortex acts on the trailing vortices and causes downwash by velocity:

$$w = \Gamma_0 / 2\Pi L_v$$

If this velocity was constant, the downwash in time dimension would look like a straight line. However, practice has shown that the downwash rate is reduced with time, and later it floats. The floating is explained by the complexity of the wake caused by the following physical processes: within the range of vortex downwash (pair), an isolated field is formed which separates the air from the environment by a closed line of flow (Fig. 3-D). This area is called "*the atmosphere of wake-vortex turbulence*". In cross-section it has the shape of an ellipsis and is usually considered as the wake edge. Depending on the downwash rate, the pressure in the surrounding atmosphere rises, resulting in wake density. This causes the rise in wake temperature, which becomes higher than the ambient temperature. Difference in temperature, with same pressures causes differences in density ($\rho_v - \rho_H < 0$) resulting in centrifugal force F_c which slows down the downwash (Fig. 3-D). Since the pressures within the wake and in the surrounding atmosphere are equal, due to the difference in air densities (disturbed barothropy) at the wake edge secondary swirling is generated, which is directed towards reduction of vortical circulation and velocities in the outer flow zone. The downwash depends on the initial velocity w_0, the downwash time, and its being heated by reaction engine exhaust gases. The heating increases the difference in density and slows down the downwash, increasing at the same time the secondary swirling which in turn reduces the vortical circulation.

The change in atmosphere parameters in relation to the ISA conditions, i.e. the temperature gradient (dT/dH), the existence of the random vertical wind component along the wake, and the change in circulation (Γ_0) caused by fluctuations of the aircraft angle of attack in relation to a certain mean value, result in uneven downwash.

The less the downwash, the longer the duration of the vortical circulation. The rate of downwash (ΔH), regardless of the aircraft type, practically does not exceed 250-300 m. Furthermore, the turbulent wake always moves opposite from the lift force (Fig. 3-C). Therefore, during manoeuvring of the aircraft after leaving the vertical plane, the wake, apart from downwash also moves within the horizontal plane. With the overload manoeuvre the turbulent wake intensity is increased in proportion to the loading factor n.

Gradual decay of the vortices due to air viscosity causes also the reduction of the maximum radial velocities (w) and increase of the conditioned vortex core radii (r^*). The turbulent wake decay with manoeuvring aircraft is most often significantly affected by the instability of the vortex pair. This instability is reflected in the increase of the initial small deformations of vortical axes, where their certain parts (sectors) join together and thus the regularly formed stream disappears. The initial deformations occur because of the turbulent velocity fluctuation within the vortices, and in rough atmosphere because of turbulence as well. The difference in velocities and the increase in deformations result over a period of time in the occurrence of wave-like form of the vortical axes, with variable wave length. The rate of deformation increase depends on the relative wave length ($\lambda' = \lambda / b$) and the relative core radius (r^*). The regular symmetric structure of the aerodynamic flow starts to be disturbed with increase in axes deformation until their subsequent joining. This occurs over the period: $t = t' \cdot L_v^2 / \Gamma$, where t' is the duration of the symmetric wake structure. The value of L_v^2 / Γ determines the time of joining, which is explained in the following way: the amount of deformation is obviously equal to $L_v / 2$. The vortex deformation rate is proportional to the circulation Γ_0 (to the radial velocities within the vortex) and inversely proportionate to the span L_v. In this way, the time of joining equals the relation of the path and velocity, and is proportionate to L_v^2 / Γ. The proportion coefficient is mainly determined by the extent of the vortex deformation. The increase of the relative radius of the vortex core increases the zone of turbulence, and at the same time increases also the initial deformations of vortical axes, which reduces the relative duration (t') of the symmetric wake structure.

The turbulence of the surrounding atmosphere at low altitudes, due to wind, also increases the initial vortical deformations. If the other conditions remain the same, this increase depends on the relative radius (r^*). With aircraft that have rectangular thinner wings, the wind has more influence on the duration of disturbing the symmetric structure of a wake, than with aircraft that have not such thin wings and a greater r^*. In other words, the more "compact" the turbulent vortex, the easier it is diverted and drifted by the wind.

5. THE EFFECT OF DESTABILISING FORCES AND MOMENTS ON THE AIRCRAFT IN-TRAIL

By flying into wake-vortex turbulence of the preceding aircraft, the airflow around the aircraft changes as well. The angles of attack of some aircraft elements change, as well as the slip angles. All this results in a redistribution of pressures on the aircraft surface and generates sudden unsteady aerodynamic

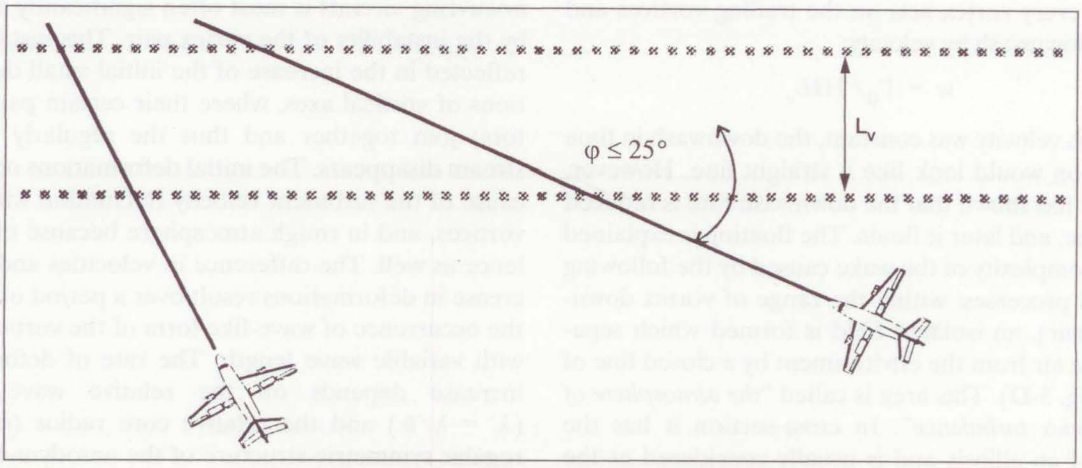

Figure 4 - The angle of crossing a turbulent wake

forces and moments which disturb the aircraft path. This destabilising movement is determined by the intensity and direction of the turbulent flow, duration of its acting on the aircraft, and by the way in which the pilot operates the control stick.

It should be stressed that the intensity of turbulent wake is many times greater with "heavier" category aircraft, i.e. aircraft with greater specific load (weight per unit of flying surface G/S), such as transcontinental aircraft Boeing 747, Boeing 757, Airbus 320, etc. The hazard of flying into wake vortex behind an aircraft lies primarily in the fact that it is *invisible*, and that it contains high intensity turbulent flow which causes major, unexpected and uncontrollable evolutions of the aircraft in it.

When an aircraft crosses the turbulent aerodynamic wake at a very high angle (Fig. 4), it stays in it for less than a tenth of a second, and the effect of the wake-vortex turbulence occurs in the form of gust load, which practically does not change the basic flight parameters.

The influence of wake-vortex turbulence, whose structure has already been disturbed due to instability (lower intensity), occurs as tossing in the turbulent air, regardless of the angle at which the aircraft enters the airflow and does not endanger the flight safety. Most dangerous is when the aircraft crosses wake-vortex turbulence of the preceding aircraft at low angles ($\varphi < 25°$). It usually happens during takeoff or landing, and in military flights in close formations when flying in the same path, with shorter time intervals. Besides, the aircraft can even fly into its own turbulent vortex flow when taking sharp turns.

In order to simplify the explanation and for better understanding, it will be assumed that the aircraft is flying parallel with the turbulent aerodynamic wake at different positions in relation to it (Fig. 5 - positions A - B - C - D).

When the aircraft is on the outer part of the turbulent wake, the lift component of the radial vortex velocity w acts on its wing as a whole, which causes the increment of the lift force (ΔR_Z) on the wing, and the variable force component causes the rolling moment M_x which tosses the aircraft out of the aerodynamic wake (Fig. 5 - Aircraft B). Analogue airflow occurs also on the stabilisers. These additional lift forces (ΔR_z and ΔR_{zHS} - of the wings and horizontal stabiliser) result in the pitching moment M_y when the stable aircraft tends to dive nose down. In the presented figures the aircraft does not fly higher than wake-vortex turbulence, so that the vertical stabiliser is above the wake. The velocity component w on the vertical stabiliser generates additional lateral force ΔR_{zVS} directed sideways towards the vortex. It generates the additional rolling moment M_{xVS}, but of low intensity, opposite in direction to the moment generated on the wing and horizontal stabiliser, but contributes considerably to the turning moment M_z which tends to toss the aircraft out of the wake.

Slight descent of the aircraft in relation to wake-vortex turbulence (Fig. 5 - Aircraft A) results in invariability of forces and destabilising moment on the wing and the horizontal stabiliser, but acts on the vertical stabiliser and changes the sign of direction, i.e. results in an additional force ΔR_{zVS} which turns the nose of the aircraft towards the vortex by turning moment M_z and rolling moment M_x outside the vortex wake.

With aircraft that have swept and delta wings, when flying parallel on the outer side of the vortex, the same changes occur as with other aircraft, but the variable lift component acts on the wing elements located at the distance dx in relation to the centre of gravity (CG), resulting in additional pitching moment ΔM_y, especially with wings swept at a greater degree (Fig. 5 - Aircraft E).

When the aircraft approaches the wake, the constant component of the lifting airflow changes and becomes unstable. Therefore, at first a rise can be noticed in the additional lift force ΔR_z and moments

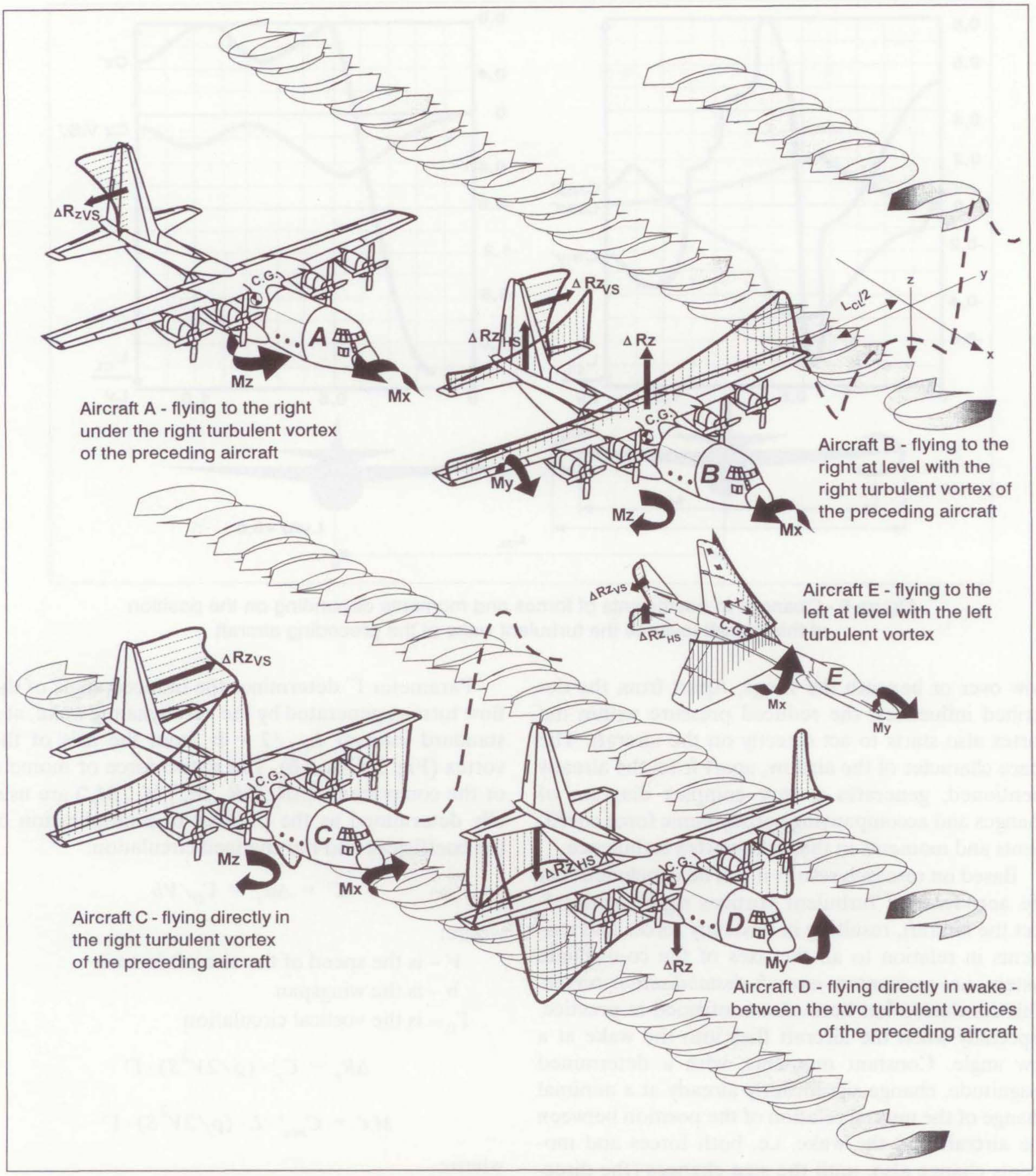

Figure 5 - The influence of wake-vortex turbulence on the lift and stabilising surfaces of the aircraft

ΔM_x and ΔM_y, which then start to decrease. The rolling moment M_x undergoes the greatest changes. By changing the sign, it starts to roll the aircraft sideways into the aerodynamic wake. It is felt the most when the aircraft fuselage nears the vortex (Fig. 5 - Aircraft C). The additional moment M_{xVS}, which is generated on the vertical stabiliser, can reduce or increase the effect of the moment of the resulting rolling moment M_x. This depends on how much the vertical stabiliser is above wake-vortex turbulence.

When the aircraft approaches the wake symmetry level, the rolling moment M_x is again reduced at the expense of the downwash, and the lift force is also reduced. The pitching moment M_y occurs (Fig. 5 - Aircraft D), which reaches the maximum when the aircraft fuselage is exactly in the middle between the turbulent vortices.

Figure 5 shows the vortices as straight lined. In reality, the aircraft flying in the wake also influences them, deforms them, so that the vortices, deformed,

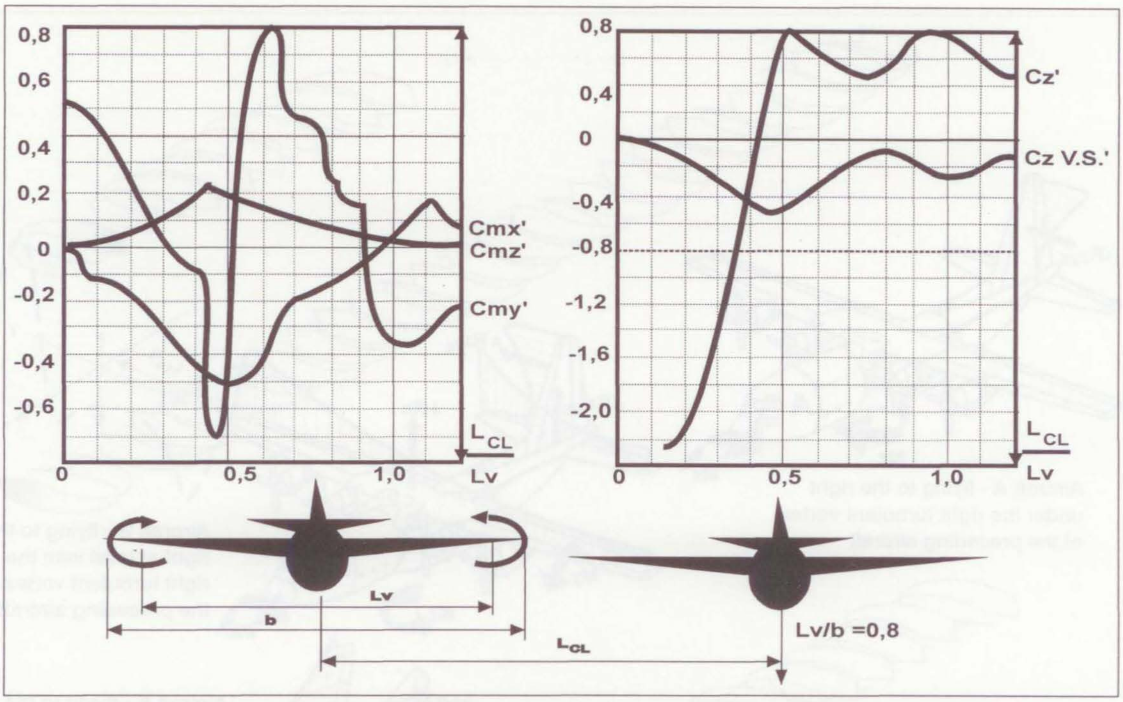

Figure 6 - Changes in coefficients of forces and moments depending on the position of the aircraft towards the turbulent wake of the preceding aircraft

flow over or beneath the wings. Apart from the described influences, the reduced pressure within the vortex also starts to act directly on the aircraft. The space character of the airflow, apart from the already mentioned, generates a very complex diagram of changes and accompanying aerodynamic force coefficients and moments in the wake-vortex turbulence.

Based on research results it can be concluded that the aerodynamic turbulent vortices significantly affect the aircraft, resulting in unsteady forces and moments in relation to all the axes of the co-ordinate system, i.e. *momentary aircraft destabilisation occurs*. This conclusion has been also confirmed in practice, especially when the aircraft flies into the wake at a low angle. Constant moments, with a determined magnitude, change significantly already at a minimal change of the mutual relation of the position between the aircraft and the wake, i.e. both forces and moments change also, until the sign changes (the direction of acting).

The interrelation of the aircraft and the aerodynamic wake determines also the direction and the magnitude of the additional forces and moments. Figure 6 shows the changes in coefficients of these additional forces and moments (C_z', C_x', C_{mx}', C_{my}', C_{mz}') depending on the position of the aircraft and wake-vortex turbulence. In order to obtain their absolute value, they have to be multiplied by the changed circulation parameter around the flying surfaces, i.e. by the changed induced angle of attack of the airflow.

Parameter Γ' determines the induced angle of the flow turning generated by the aerodynamic wake, at a standard interval $L_{CL}/2 = b$ from the axis of the vortex (Fig. 3-C and 6). The entire force or moment or the components (ΔR_x, ΔR_z, M_x', M_y', M_z') are usually determined as the product of multiplication of the coefficient and the changed circulation:

$$\Gamma' = \Delta\alpha_i' = \Gamma_0/Vb$$

where:

V – is the speed of the aircraft in-trail

b – is the wingspan

Γ_0 – is the vortical circulation

$$\Delta R_z = C_z' \cdot (\rho/2V^2S) \cdot \Gamma'$$

$$Mx' = C_{mx}' \cdot L \cdot (\rho/2V^2S) \cdot \Gamma'$$

where:

L – is the arm of force acting from the centre of gravity CG

In Figure 6 the clockwise moments have a positive value. The aircraft inertia moment in relation to the longitudinal axis is as a rule much lower than the inertia moment in relation to other axes, so that the effect of aerodynamic wake is most significantly noticed in the form of angular velocity of rolling, since other moments have the same order of magnitude.

If, for example, a smaller aircraft flies into wake-vortex turbulence of an aircraft with a big wingspan, then it is affected by a limited part of the area of disturbed velocities. In the outer border of the wake, the rolling moment M_x is reduced due to the reduced disturbance of the field, and the pitching moment M_y is increased due to the velocity *w* and its acting on the stabiliser. Analogue to this, the rolling moment M_x is significantly increased near the vortices.

High magnitudes of the additional destabilising forces and moments acting on the aircraft in-trail, even during a short flight through wake-vortex turbulence, bring about significant changes in the aircraft flight parameters. The hazard is, on one hand, in the acting intensity of the aerodynamic wake, and on the other hand, in the limited possibilities of the pilot and the aircraft to counteract. The lower the instrumental speed in the wake, the greater the hazard to flight safety, which happens in approaching landing.

Flying at low speeds involves *higher angles of attack* (another flight regime), logically diminishing the lift force and coming very near to the stalling point. This reduces the efficiency of the control mechanisms (control surfaces), so that in order to counter the destabilising moments (which do not depend on the speed) the controls lag may be lacking. Therefore, flying into an aerodynamic wake is *most dangerous during takeoff and landing*. Flying into wake-vortex turbulence occurs as a rule unexpectedly for the pilot, and they experience it as a momentary failure of flight controls. When the aircraft in wake inclines, the vertical component of lift force is reduced, and as a result the aircraft starts losing height. This loss of height is often even increased due to aerodynamic forces caused by the turning of the aircraft, as a result of additional aerodynamic moments. In manoeuvring the aircraft with overload, flying into wake-vortex turbulence is accompanied by elimination of overload, and then the breakdown of lift is also possible.

Significant changes of flight parameters, whose origins are not clear at the beginning, cause the pilot to counteract by reflex, but always with a delay. The actual delay period of commands is limited by the operating speed of the control system and often does not match the required one. Therefore, counteracting wake-vortex turbulence is not efficient, and most often the cause for the uncoordinated flight of the aircraft is discovered only after leaving the wake. The loss of height at low altitudes is the most dangerous, during takeoff and landing.

In case of flying into turbulent wake of a "heavy" aircraft (with a great G/S), which is affected by the rolling moment M_x, the hazard is in exceeding the allowed angle of attack. However, practice has shown that pilot's operating of control commands on heavy aircraft in order to stabilise the given flight regime even in wake-vortex turbulence, is essentially efficient. Furthermore, the destabilising influence of wake vortex turbulence is very efficiently countered by the auto-pilot. At the regime of stabilising an angular position of the aircraft the auto-pilot efficiently maintains the stability when flying into a vortex. This can be explained by the fact that when flying through a wake with the auto-pilot switched on, the duration of non-countered destabilising moments is reduced. Thereby, the lesser inertia of the auto-pilot, and the greater range of angles controlled by the auto-pilot, the greater flight stability is insured.

6. THE INFLUENCE OF WAKE-VORTEX TURBULENCE ON TAKEOFF SAFETY OF THE AIRCRAFT IN-TRAIL

The greatest hazard to aircraft flight safety, confirmed in practice, is wake-vortex turbulence of the preceding aircraft during takeoff and landing operations, when the time intervals between the aircraft are short. The essence of hazard lies in the overlapping trajectories (paths) of the flight during these phases, and the flight at low altitudes, and at low speeds, when the efficiency of flight commands is significantly reduced, so that sometimes there is not enough delay period available for countering the resulting forces and moments. The flight safety is most affected by the possibility of loss of height and the possibility of exceeding the angles of stall, due to the additional disturbance of streamlines, which can result in lift breakdown and stalling of the aircraft.

In order to increase the safety during takeoffs or landings in high intensity traffic, i.e. to eliminate the possibility of flying into wake-vortex turbulence, it is necessary to know the time of its decay and the direction in which it moves through the air.

What are the specific features of a turbulent vortex during takeoffs and during landings? The greatest influence on the motion and duration of wake-vortex turbulence during these flight phases is exerted by the *ground effect*. It disturbs the symmetry of flow around the vortex and eliminates the downwash (Fig. 2 and 7). If the vortex is fixed, the air dissipation is reduced, so that excessive air builds up on one side of the vortex along with the increase in pressure, and on the opposite side there is lack of air with reduction in pressure. Such nature of these processes allows the vortex to remain fixed and it starts shifting above ground from left to right (Fig. 7). The physical basis for such behaviour is that there will be a lack of velocity component of a trailing vortex on both sides of the reflexive surface, which causes the vortex to move above ground (starting vortex) just like the two trailing ones in the atmosphere (the vortex and its reflection in free space). The movement of the vortices during takeoff i.e. landing is best considered through

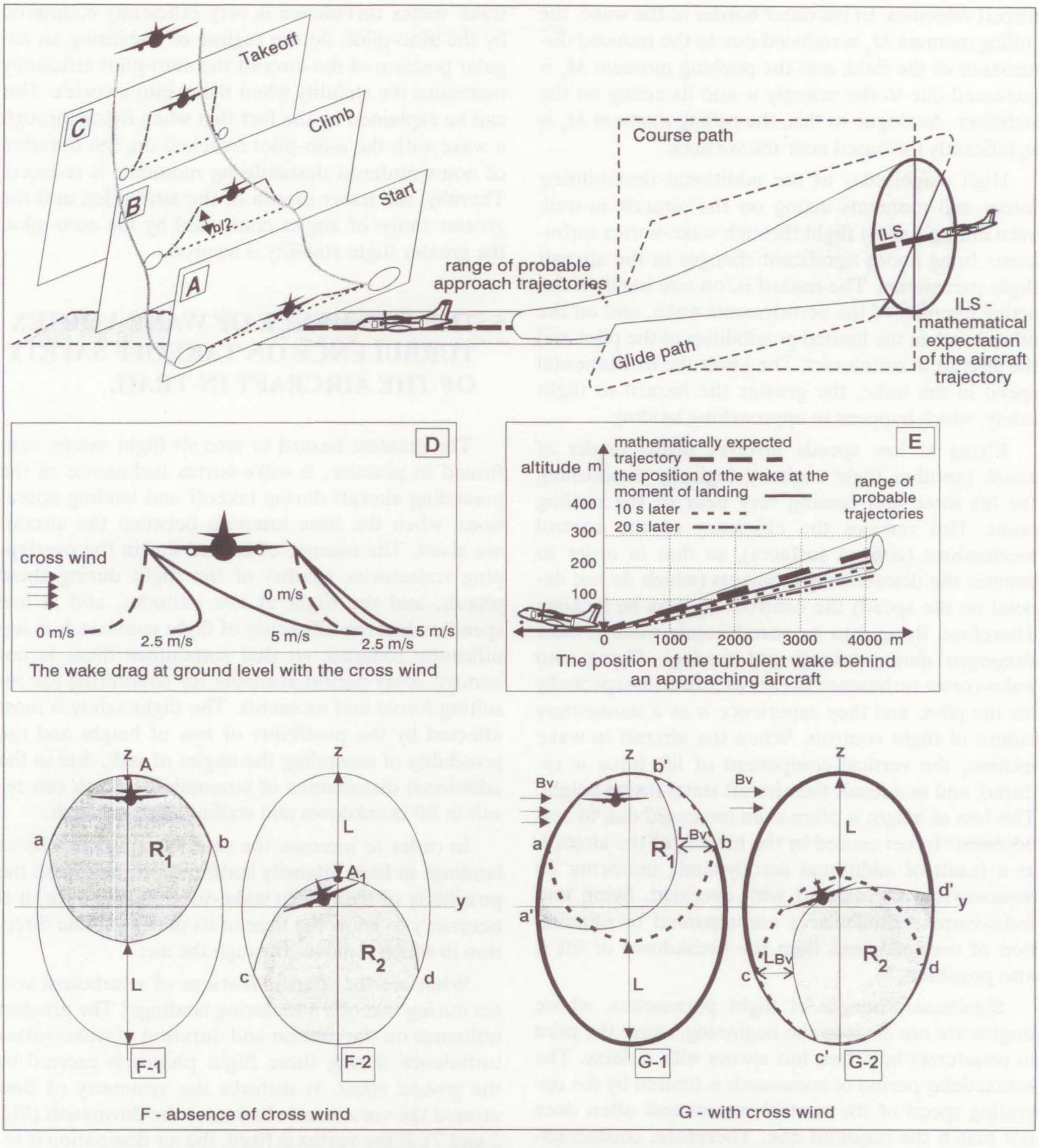

Figure 7 - the position of the turbulent vortex in relation to the aircraft trajectory

a range of vertical cross-sections - control planes (Fig. 7 A-B-C).

During the initial run of the takeoff and immediately upon taking off, all the way until the aircraft reaches the altitude proportional to half of its wingspan, the vortices practically shift only horizontally, and the distance between them increases. During further climbing and moving further away from the ground, the vortices descend in the beginning due to interaction, and move still further away from one another which reduces the interaction and slows down the downwash. By nearing the ground the horizontal velocity component rises (Fig. 7-B) and the vortices start to move parallel to the ground at the altitude which is approximately equal to half of the wingspan. During takeoff of heavy category aircraft, sometimes the vortex flows may be noticed also on the sides, which is nothing else but repeated vortex caused by their shifting at ground level.

Regardless of the vortex dissipation, the probability of flying into it is rather high since aircraft trajectories in takeoff and landing are almost the same.

Therefore it is necessary that the *takeoff intervals are longer than the duration of wake-vortex turbulence*. The causes for aircraft instability in wake-vortex turbulence during takeoff i.e. landing, are the same as during other phases of the flight. The only difference is that the role of the second bound vortex (free atmosphere) is taken on by its reflection. Because of this, at the end of the initial run and immediately upon takeoff (when the wake altitude above ground is less than half of the wingspan) the vortex instability develops very quickly. With climbing, the ground effect gets reduced due to the second vortex. Beginning at an altitude that is approximately equal to double the wingspan, the regular structure of the vortex is disturbed according to the laws that have been already explained. With speeding up and moving away from the ground, the vortical circulation is reduced, the development of instability is slowed down and the duration of the regular structure of wake-vortex turbulence is increased.

The wind, regardless of its direction, increases the development of instability and causes the vortices to dissipate more rapidly. This has to be taken into account when determining and selecting the minimal allowed separation distances between takeoffs i.e. landings. Cross wind carries the vortex out of the takeoff trajectory. However, regardless of the constant velocity of the cross wind, the vortex moves unsteadily (Fig. 7-D). Thus, cross wind blowing at a velocity of 2-2.5 m/s only slows down the vortex drift. Therefore, it is possible in such conditions to reduce the takeoff interval only to the value determined by the quicker dissipation of the regular wake structure due to atmosphere turbulence. At wind velocities higher than 3-5 m/s the drift is greater and the wake puts practically no limit on the minimal takeoff intervals.

7. THE INFLUENCE OF WAKE-VORTEX TURBULENCE OF THE PRECEDING AIRCRAFT ON FLIGHT SAFETY DURING APPROACH AND LANDING OPERATIONS

The physical characteristics of the turbulent airflow (vortex) behind each aircraft, which generates significant moments of inclination and vibrations and causes major overload, have been studied and explained. However, this has not stopped aircraft from flying into wake-vortex turbulence of the preceding aircraft. As mentioned earlier, the little spare altitude and airspeed, high angles of attack which diminish the efficiency of flight controls, are additionally burdened by a distinct lack of time necessary to correct the landing operations. In such conditions the rate of descent, the aircraft configuration, the engine operating regime change, the intensity of radio-communication increases, and as a rule, the crew is exposed to increased psychological and physical efforts. The crew on a ship sails from rough seas into a calm port. For an aircraft crew, the "sailing into" a port is the most critical phase of the flight. The simplest way to avoid flying into wake vortex is to increase the landing intervals, but at some airports this is contrary to the landing requirements of a huge number of aircraft within a given period of time (high traffic intensity). In order to assess the probability of flying into wake-vortex turbulence it is necessary to be well acquainted with the vortex characteristics. The most important elements are the downwash duration and rate.

The pilots know from experience that Boeing 757 generates an especially strong vortex, i.e. that certain aircraft types leave a significantly intense and long-lasting vortex behind. The smaller and lighter planes leave a 30-60 sec. wake, whereas the wake behind heavy category aircraft lasts for 2-5 minutes. The vertical velocity of vortex downwash (w) can range from 1 - 5 m/sec., depending on the aircraft type, its approaching and landing speed, overload etc. One should also be acquainted with the range of possible trajectories during approaching to land (Fig. 7), which is designed for every airport on the basis of the accepted standards, according to the altitude and direction in several cross-sections, beginning from the end of the IV. turn all the way to the touchdown point. It is necessary to determine the probability of flying into the wake vortex of the preceding aircraft in order to ensure the safety of landing.

8. THE PROBABILITY OF FLYING INTO TURBULENT WAKE OF THE PRECEDING AIRCRAFT

First, the mathematically expected duration of wake-vortex turbulence in the range of possible trajectories is determined, assuming that the pilot's errors during descent are random variables that are negligible. The duration of turbulent wake in the given range of trajectories is also a random value that is calculated by the formula:

$$t = (H_s - H_{min})/V_{sil} = \Delta H/w$$

where:

H_s – is the actual altitude of aircraft in the given control cross-section

H_{min} – is the altitude of the lower boundary of the considered cross-section in relation to the ground in the given control cross-section

w – is the vertical velocity of the wake descent

In this formula ΔH is a random value, and the velocity w is given for the certain type of aircraft and configuration in landing. These speeds are constant values. In case the criterion of accuracy is a strict one, it should be considered that the velocity w is reduced with time, so that the average value w_{sr} is used. If the probable characteristic altitudes of the control cross-section are known, the time can be determined during which wake-vortex turbulence will remain within the given control cross-section. The mathematical expectation of that duration is determined according to the following formula:

$$m_t^* = (m_{ts} - H_{min}) / w_{sr}$$

where:

m_t^* – is the mathematical expectation of the period in which the turbulent vortex will remain within the given control cross-section

m_{ts} – is the mathematical expectation of the landing trajectory within the given control cross-section

w_{sr} – is the mean vertical velocity of the turbulent vortex downwash.

The calculations show that during alignment for landing from a circle, the mathematically expected duration of the wake within the range of expected trajectories m_t^* changes, from 26 sec at the point of alignment to 46 sec. at the point of final approach, for 96% of final approach trajectories (after coming out of the IV. turn). Regarding the trajectory, as the aircraft approaches the runway, m_{ts} is increased from 40% at the point of starting the alignment, to 70% at the point after the IV. turn. Assessing the probability of flying into turbulent vortex of the preceding aircraft is based on certain hypotheses.

The aircraft is considered as a point (centre of gravity - CG) so that the aircraft trajectory is the path from the centre of gravity. Errors (deviations) from the trajectory of the final approach are subjected to normal law of errors - asymmetry and excess are not negligible. The pilot flies in the final approach without assessing the position of the preceding wake, which is correct. The deviations are greater in relation to the glide path because of the changing aircraft configuration in approach (extending of the landing gear, flaps, etc.) and angle of attack, whereas the errors regarding course are slighter. At greater distances the aircraft dimensions are much smaller in relation to the dimensions of ellipsis of the expected deviation, and its semi-axis is at the distance of 4 km greater than 120 m. The dimensions of ellipsis at the distance less than 1 km are almost identical to the dimensions of the aircraft flying into wake-vortex turbulence. For the analysis example one can take any of the ellipsis of the range of the possible trajectory deviation, where the first aircraft passes through the shaded area R_1 (Fig. 7 G-1), and the aircraft in-trail through R_2 (Fig. 7 G-2). If the first aircraft flew beneath the line a-b, the wake-vortex turbulence would for the given time interval t leave the ellipsis of the expected trajectory deviation (it would descend lower for the distance $L = w_{sr} t$), so that the in-trail aircraft could fly into wake-vortex turbulence only below line c-d. Though, if the first aircraft flew through the ellipsis at the highest point A (Fig. 7 G-1), the wake-vortex turbulence would descend by the value L, and flying into it would be possible in the area of point A_1 (Fig. 7 G-2).

Furthermore, it is known that the cross wind moves the vortex sideways. If the wind velocity is known, Bv, the value of its drag (shift) from the o-z axis can also be determined:

$$L_{Bv} = B_V t_s$$

where

L_{Bv} – is the linear drag of the wake along axis

B_V – is the wind velocity

t_s – is the landing time interval.

Area R_1, bordered by line a'-b' and shaded, through which the first aircraft would have to fly so that the in-trail aircraft would fly into its wake, is reduced (Fig. 7 F-1). Area R_2, bordered by line c'-d' (Fig. 7 F-2) will move due to wind and decrease in relation to area R_2 in the absence of wind. The increase of the cross wind velocity reduces the probability of flying into wake-vortex turbulence of the preceding aircraft. At a certain magnitude of the cross wind B_v and the given landing interval t_s, the area R_2 can find itself outside the ellipsis of the expected range of differing trajectories.

Calculating the probability of flying into wake-vortex turbulence of a preceding aircraft at different landing intervals t_s and wind velocity B_v are presented graphically in Figures 8 and 9. The values of landing intervals t_s have been presented in seconds on the abscissa, and the probability of flying into wake-vortex turbulence on the ordinate, under the condition of distance to the preceding aircraft, i.e. from runway where the preceding aircraft landed. The diagram in Figure 8 shows the probability of flying into wake-vortex turbulence, depending on the interval of repeated landings t_s and various distances from runway, i.e. behind the preceding aircraft, in absence of cross wind. At interval of 10 sec. at the distance of 4 km from the runway threshold, i.e. the preceding aircraft, the probability is 0.035, and at a distance of 600 m it amounts to 0.1, which means that 10 out of 100 aircraft in such conditions will fly into wake-vortex turbulence of the preceding aircraft. It is obvious that the probability of flying into wake-vortex turbulence increases with the shortening of the interval between repeated landings.

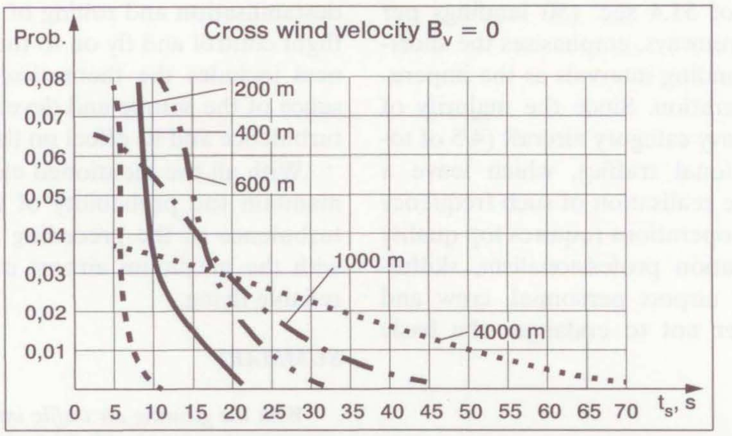

Figure 8 - The probability of flying into wake-vortex turbulence of a preceding aircraft at a distance of up to 1 km in the absence of cross wind - B_v=0

The probability of flying into wake-vortex turbulence in absence of wind at a distance of 1,000 m and for the landing interval t_s of 40 sec. is 0 (Fig. 8), whereas for a shorter landing interval t_s of 20 sec. it amounts to 0.03, which in practice means that out of 100 aircraft in the final approach, three can fly into wake-vortex turbulence of the preceding aircraft. With an even greater shortening of the landing interval t_s to 5 sec., the probability increases to 0.062, i.e. six aircraft may fly into wake-vortex turbulence of the preceding aircraft.

The probability of flying into wake-vortex turbulence is most affected by the wind. By neutralising the vortices, it not only diminishes the intensity of the vortex into which an aircraft has flown, but also carries it out of the range of probable trajectories. So, for example, at wind velocity B_v of 4 m/sec. at a distance of 1,000 m and landing interval t_s of 12 sec., the probability of flying into wake-vortex turbulence of the preceding aircraft is 0 (Fig. 9). In other words, the interval of repeated landings at which it would be possible to fly into wake-vortex turbulence will be reduced 3.33 times compared to the same distance in absence of wind. That is, the results show how the probability of flying into wake-vortex turbulence of the preceding aircraft at interval of 20 sec. and at a distance of 1,000 meters is reduced from 0.036 in absence of wind to almost 0 at the wind velocity of 2 m/sec. (Fig. 9).

The probability calculation with the given hypotheses is valid also for the VFR (visual flight rules) and for IFR (instrument flight rules) approach. Aircraft fitted with sophisticated equipment for CAT III (auto-landing category) and new generation aircraft, fly-by-wire with digital control technique and GPS (global satellite navigation) land exactly according to ILS trajectory (instrument landing system), so that the range of differing trajectories even at greater distances from runway, is small or coincides with the aircraft dimensions. Such matching of the trajectories reduces the probability of flying into wake-vortex turbulence of the preceding aircraft and contributes to the flight safety since the vortex leaves the range of ellipsis by downwash.

The example of the Frankfurt airport with an exceptionally dense traffic and tendency of passenger traffic increase of 8.7%, which already has a takeoff interval of 48.6 sec. (more than 70 takeoffs per hour)

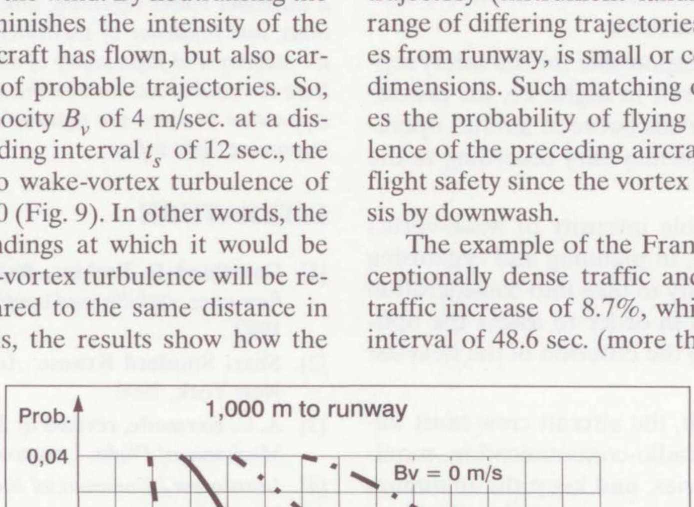

Figure 9 - The probability of flying into wake-vortex turbulence of the preceding aircraft with cross wind velocity of B_v at 1 km to runway

and landing interval of 51.4 sec. (50 landings per hour) on two parallel runways, emphasises the shortening of takeoff and landing intervals as the imperative for successful operation. Since the majority of operations involves heavy category aircraft (4/5 of total traffic is international traffic), which leave a strong wake vortex, the realisation of such frequency of takeoff and landing operations requires top quality planning and organisation professionalism, skilfulness and accuracy of airport personnel, crew and flight control, in order not to endanger the basic flight safety.

9. CONCLUSION

The wake vortex hazard for the flight safety is most frequent during takeoff and landing operations, which are in segments of flying operations, due to low airspeed, low altitude, controls lacking efficiency and high angles of attack, the most critical ones anyway. At airports with a high intensity of in- and outgoing aircraft it is necessary to determine time separation between subsequent landings and takeoffs in such a way that the probability of flying into a wake-vortex turbulence of the preceding aircraft is minimised. This condition should be provided for already in planning, calculating and defining the approach chart of an airport, with the already existing specific microclimatic conditions, wind, airflow in free atmosphere or overcoming possible barriers.

The flight control is responsible for the safety separation between the aircraft in flight, i.e. for providing minimum safety intervals between aircraft operations, and the calculations may vary according to the current winds.

Because of the variable intensity of wake-vortex turbulence and its decay, in planning and organising the air traffic it is necessary to take into consideration also the types of aircraft in order to assess the optimum sequence regarding the criterion of the heaviest category in takeoff.

During final approach, the aircraft crew must follow very attentively the radio-communication, monitor the range of trajectories, and keep the minimum separating distance. If a crew, nevertheless, flies into wake-vortex turbulence of the preceding aircraft, they have to be ready to counter the momentary destabilisation and rolling of the aircraft, inform the flight control and fly on to the next circle. The readiness includes the theoretical knowledge of the essence of the source and development of wake-vortex turbulence and its effect on the aircraft.

With all the mentioned elements, it is possible to maintain the probability of flying into wake-vortex turbulence of the preceding aircraft at a minimum, with the maximum airport utilisation, and safe and reliable flying.

SUMMARY

With the growing air traffic intensity, at some airports we are more often faced with the fact that aircraft land or take off one after another. Since every aircraft leaves a turbulent vortex behind, which acts unexpectedly and is destabilising for the aircraft flying into it, the flight safety in such repeated landings and takeoffs becomes questionable. Determining the minimum safety time interval between the repeated operations becomes imperative and a limiting factor for some airports with high air traffic intensity. Unlike military flying, where crew is trained to fly in a group, in civil air traffic the crew is not trained for such flying and on top of it mostly operate on large aircraft, which produce very strong turbulent vortex. Additional sophisticated equipment in new modern aircraft improves navigation, communication and steering of the aircraft, but does not insure it from flying into an invisible turbulent vortex. This paper discusses the vortex generation, its nature and factors that influence its intensity and duration. The paper also deals with a model of calculating the probability of flying into a turbulent vortex regarding time interval of repeated operations, and influence of sophisticated equipment installed, on the stability and flight safety of an aircraft. Conclusion underlines the need to standardise the minimum safety time interval separation between the repeated operations, with the aim of improving flight safety.

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