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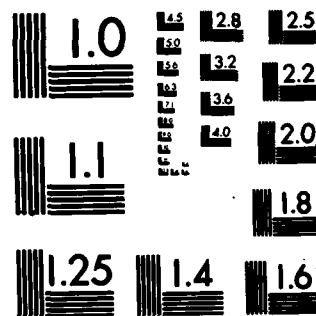
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by

Jan Staszek

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PROBLEM OF VORTEX TURBULENCE BEHIND WINGS (II)

Jan Staszek, M.S. Eng.

This article describes the formation and propagation of wake turbulences behind wings until their disintegration. Their influence on airport traffic and on aircraft flying into the disturbed region is explained. Some research methods and the possibilities to counteract the negative effects are also described. The data presented in the article lead to conclusions regarding aircraft design and usage, as well as the necessity to continue theoretical and experimental research.

Research at the airports

The disintegration and dissipation of the vortices is the research subject which has scientific and operational implications. The scientific problems encompass the nature and formation of instabilities, the influence of external disturbances, and the interaction of vortex pair. The operational aspects contain the understanding of vortex disintegration mechanism which can lead to their controllable artificial dissipation. The problem of avoiding the vortex regions can be solved only by a thorough understanding of their motion and dissipation, and, consequently, means of their localization. It is, therefore, a very complex and difficult task.

As a result of research, a special radar installation was constructed to test - using two similar methods - the air flow behind the aircraft (Fig. 18).

In the first method, molecules reflecting radar radiation are introduced into the vortex to determine the formation, propagation and disintegration of the disturbance through analysis of the reflection record. Silver iodine in an acetone solution is combusted in special burners to achieve radar echo from

reflecting molecules.

In the second method vortex regions are observed in snow conditions where water crystals produce radar echoes. Precise measurements of the speed of the turbulence, its inside diameter and that of the whole vortex are undertaken with the use of equipment similar to that used for measuring car speeds.

Good results were obtained with both methods despite fears that the observed data would be distorted by centrifugal forces. The distortion of the vortex by the device producing the reflective molecules to achieve radar echo, which was fixed at the tip of the wing, was not determined; however, this distortion does not seem to be significant.

The application of a Doppler laser system to the survey of the vortex, led to similar results as the radar methods.

In the middle of 1969 the Boeing Corporation did comparative tests to define the behavior of the wing vortex behind B-747 and B-707 airplanes. The CV-990 and F-86 were also tested. This included landing approaches to determine ground interference on the wing turbulence. These tests concluded that dynamic influences of the turbulence on preceded airplanes was, in fact, the same. This resulted in the deduction that Jumbo Jets, as well as Hercules planes did not cause a new, or special hazard. This opinion should be considered very carefully since the aim of the tests was to enable the introduction of B-747 planes and the tests did not include smaller airplanes and those of lower surface loading on the wing.

It was also concluded that altitude differences between the planes of 300 m is sufficient to protect the following

machine from the influence of the turbulence zone of the preceding one. The turbulence pair is lowered down only a certain height, which is not more than 270 m., before complete disintegration. On landing approach, strong vortices were not noticed which resulted in the conclusion that the disturbed region in the vicinity of the air strip is relatively mild.

As far as displacement of disturbances at the airport is concerned, it was observed at landing approach as well as during take-off that at a cross-wind speed of 9 km/h (2.5 m/s) the turbulence deflects towards both sides in relation to the direction of the wind. However, at the cross-wind speed of 3 m/s, both wing vortices are completely drifted by the wind, as is shown in the enclosed diagram (Fig. 19).

It was not assumed that such a mild wind can influence the turbulence region of significantly high energy to that extent. This is also an important realization for agricultural planes carrying out crop dusting operations over the fields. This factor was insufficiently considered during analysis of the distribution of chemicals across a treated strip, as well as during crop dusting itself. During these operations, not the direction of the wind, but the longest direction of the field, was considered as the decisive element in crop dusting techniques. Proper distribution of chemicals can be achieved only when the crop dusting is done with the wind.

Fig. 20 shows the accidents in 1972 considering the relationship between the mass of the preceding and following aircraft and the distance between them. Five out of eighteen accidents described were caused by wing vortices behind a B-747. Considering the extent to which the airport operations are preoccupied with this aircraft, it results in a five-times

higher hazard than with smaller airplanes. Taking into account that three accidents happened at the horizontal distance of 9,000 m., and only one at 10,800 m., the latter was introduced in March 1974 as the obligatory distance behind B-747 aircraft. At the same time the pilots were reminded of the necessity to avoid wing vortices behind big and heavy aircraft. Since that time no serious accidents have occurred.

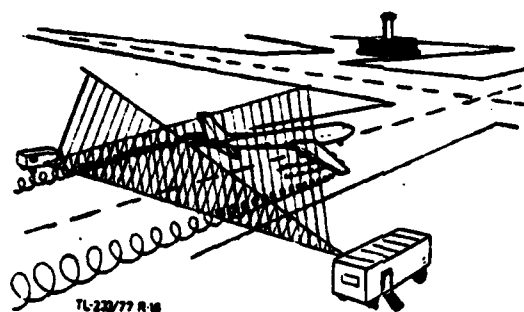


Fig. 18 The application of laser to localization of turbulence

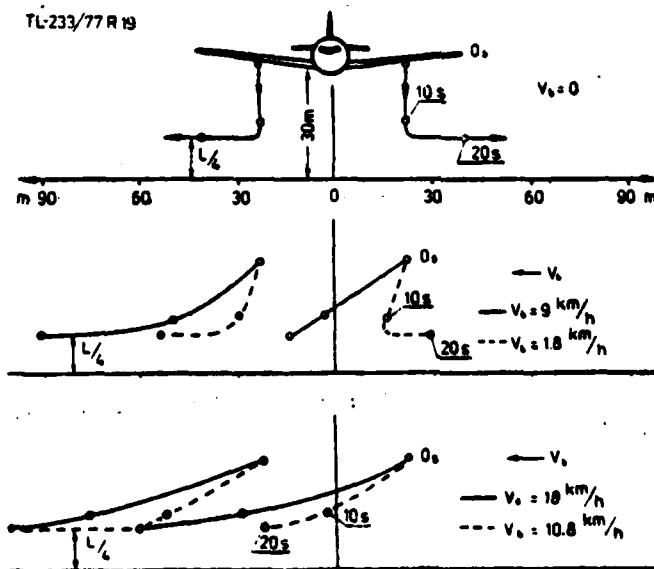
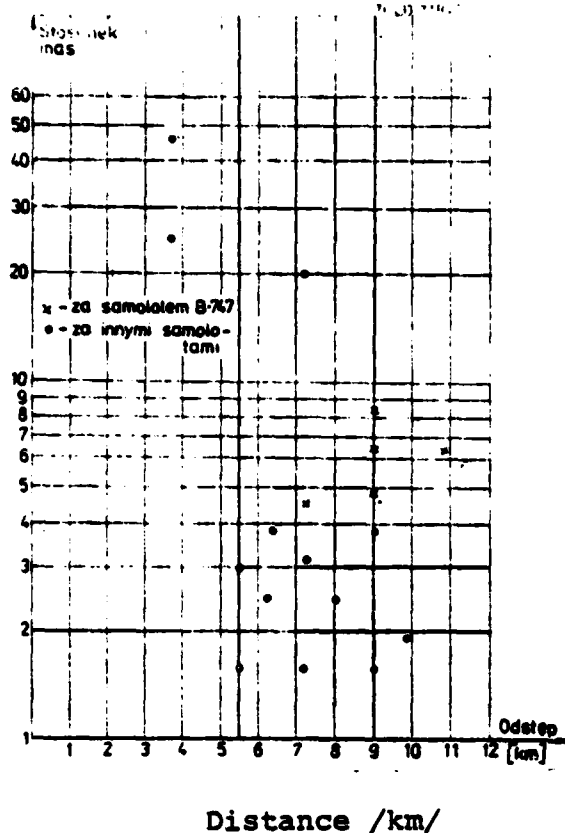


Fig. 19 The influence of the cross-wind on turbulence displacement near the ground.



Relation between masses

x behind the B-747

o behind other aircraft

Fig. 20 Accidents in 1972

The possibility of cases in which landing or departing aircraft might be endangered by the meeting of turbulence zones produced by the preceding plane should be eliminated in order to work out the parameters for the air traffic controllers and to increase the flight safety and comfort of the passengers. This can be achieved by keeping the proper distance in air traffic and the proper procedure for different planes.

To simplify the task it has been presumed that the preceding plane has greater dimensions and mass than the following one and that the division of categories is influenced by two

basic parameters:

- wingspread of the following plane (which follows the preceding one), and
- surface loading of the preceding plane producing the turbulence zone which is hazardous to the following plane.

Proposed division into two categories is presented in Fig. 21. The borderline is approximately at 35 tons total mass of the plane.

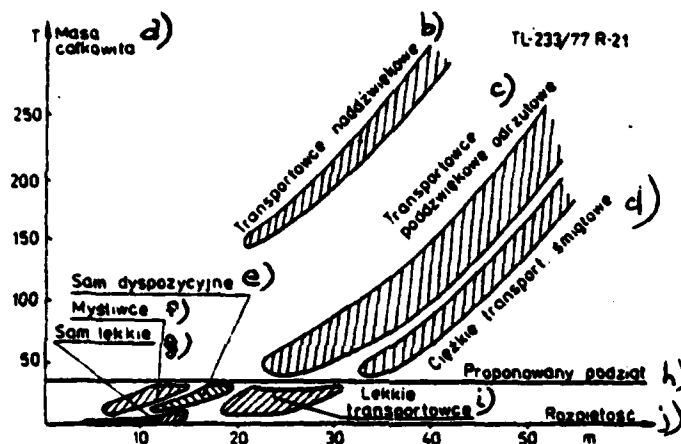
Fig. 22c shows schematically the danger zone on landing approach. Usually the following plane does not fly in or below the disturbed area. It should be noticed that the plane can meet the disturbances at the height which is equal to $1/4$ or $1/2$ of the wingspread of the preceding plane. That should give the pilot a sufficient amount of time to react and to regain the balance of the plane when these turbulences are not too great.

Since the stability of the vortices and their vertical position are a function of the wind velocity component perpendicular to the runway, suitable precautions and procedures should be applied when this component does not exceed 9 km/h. Then one of the vortices can remain over the runway for up to 5 minutes.

When a small aircraft takes off behind a large plane from the same place (the beginning of the runway), the possibility of meeting strong disturbances is rather small since, as a rule, a small plane has significantly smaller take off length and a larger take off angle. A small light aircraft meets only moderate turbulence, and when it banks it is protected from the stronger vortices which occur in the last phase of heavy plane take off (Fig. 22b). The situation when a small plane finds itself under

the flight path of a large preceding aircraft (Fig. 22a) may happen when they take off from opposite points on a runway (if there is no wind), and, therefore, this situation should always be avoided.

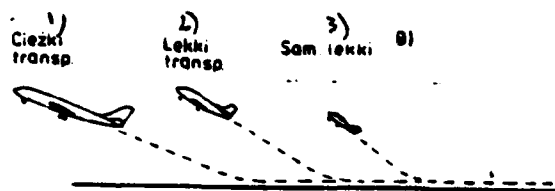
The research indicates that the safe distance between two successive aircraft is 5 km during take off and 8 km during landing. This does not apply to B-747 and C-5A planes, for which the corresponding distances are 8 and 11 km.



- a) Total mass, b) Supersonic transporters, c) Conventional jet transporters, d) Heavy propeller transporters,
- e) Executive aircraft, f) Fighters, g) Light aircraft,
- h) Proposed division, i) Light transporters, j) Wing spread

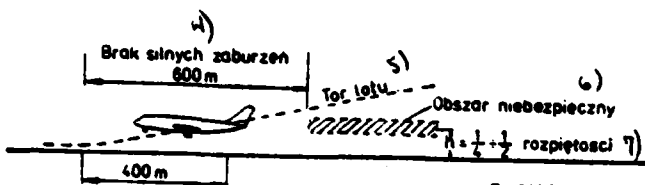
Fig. 21 Proposed division of categories

A) Danger



- 1) Heavy transport
- 2) Light transport
- 3) Light aircraft
- 4) No strong disturbances
- 5) Flight Path
- 6) Dangerous zone
- 7) of wing span

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Turbulence damping and dissipation

Turbulence damping and dissipation

The majority of the proposed devices speeding up the turbulence disintegration were based on the idea of bringing instability into the vortex structure. Usually they applied

symmetrical oscillations of flap and aileron displacements which caused changes in inside diameters of the vortices and in their actual pressure. Such active conceptions, however, are not very attractive since they cause vibration, fatigue, wear, decrease of power output, etc. They also require safety devices in case of system damage and they can have a negative effect on plane control and maximum lift coefficient. (Fig. 23).

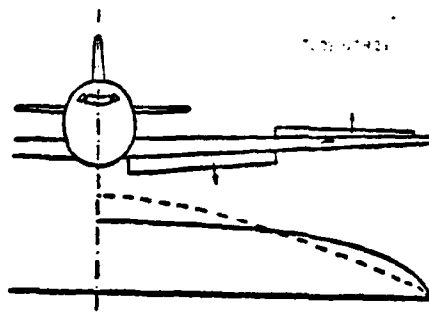


Fig. 23 The disturbance of vortex stability by oscillational control surface displacement

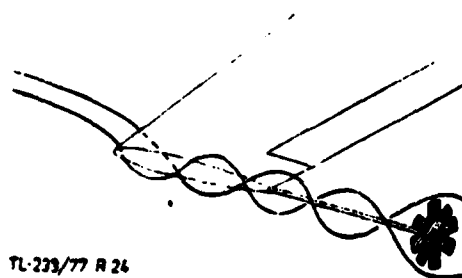


Fig. 24 The application of splines

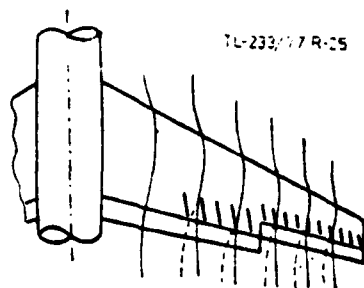


Fig. 25 The application of vortex generators

The other method intended to bring the instability into the vortex system is wavelike flight which causes temporary changes in the supply of energy to the vortices by changes in the wing loading. This cannot be done, however, with passenger aircraft.

Therefore, the most important thing in research aimed at lowering the intensity of vortices is to modify their structure before whirling up. This results in enlarging their inside diameter and engaging the greater mass of air which rotates at lower speeds.

Fig. 24 shows so-called splines - the example of an effective, though less practical installation. They are fixed at both sides in the vortex axis at a distance of one chord behind the wing. The device is very primitive and causes great drag because two splines cause the same drag as the stalled propeller of a four engine aircraft. It has been proven, however, that vortex disturbances can be weakened.

The tests performed in a water tank with a model of a B-747 equipped with splines attached to the wing tip proved that

the rotational speed of the vortices was decreased four times. Tests performed during flight with a DC-4 aircraft (preceding) and a Piper-Cherokee showed that the distance between these two planes can be reduced from 5,400 m to 450 provided that half of the possible aileron displacement is used to control the Piper-Cherokee. Similar tests were performed with a model of Lear Jet towed behind a B-747 model in a water tank and the moment transferred to the following plane was measured indirectly. It was proved that - when converted to real conditions (in full scale) - at a distance of 2,700 m behind a B-747 plane this moment was half as small as without the splines.

Another method to influence the formation of a wake turbulence is to modify the vortex sheet to diminish its energy. The method applies a row of plates (usually triangular) attached to the wing surface near the trailing edge. They are mounted at such an angle to the direction of the local airflow as to deflect the airstreams and cause in the local vortex leaving the trailing edge a circulation reversed to the airflow which would have existed without the deflector plates (Fig. 25). The best solution would be, of course, to get such an airstream deflection that when leaving the trailing edge the streams are parallel to each other at a maximum span of the wing spread. This disturbs the formation of vortices on the trailing edge and the feeding of the edge vortex with the energy from the whirling vortex sheet. In practice we can only come close to such a solution and the results achieved till now are not encouraging. The tests in a water tank showed that the use of such angled vortex generators with a B-747 plane in a smooth configuration (covered flaps and landing gear) diminished the maximum contact speed to about one quarter at the distance of 4,300 m (in scale 1:1). Fig. 26 shows the decrease of the coefficient of the banking moment with the different ratios between the wing spread of the

following aircraft and the preceding one relative to the plane without the vortex generators. Similar tests were performed with a B-747 aircraft which had its flaps opened for landing and it was proven that vortex generators were not effective. It makes their application useless since at landing they are most necessary.

Spoilers in their version shown in Fig. 27 were tested by NASA with a B-747 in a water tank and proved very efficient: at a distance of 2.7 km the banking moment transferred to a Lear Jet aircraft was diminished five times and half of the possible aileron displacement was sufficient to maintain equilibrium. This is a substantial difference in comparison to the present minimum permissible distance of 10,8⁰⁰~~88~~ m. Spoilers can be easily designed in a retractable version and this seems a very interesting possibility for the future. It can be noted here that during initial tests of the spoilers in other versions or displacements their influence on vortices was not sufficiently effective. At a smooth wing configuration the effect was positive, whereas the results were not satisfactory with open flaps and wheels down.

In search for methods to diminish the intensity of vortices many studies and tests were made on the influence of a wing tip deflected down towards the energy of the disturbed area.

They came down to the following conclusions:

- at the wing tip deflection angle of 90° two separate vortices are formed: one at the wing tip, and the other at the place of deflection;
- the maximum energy of a whirled edge vortex decreases ----- when deflection increases from 0° to 110° ;

- maximum energy of the whirled vortex in a place of deflection is increasing with the increasing deflection angle from 20° - 110° ;
- circulation distribution in both vortices is similar and can be defined by general functions based on Navier-Stokes equation;
- load distribution along with wing spread is qualitatively sufficient for localization and energy of whirled vortices;
- deflection angle of about 90° results in the smallest figure in speed values induced in a complex vortex system as a whole.

The disadvantage of this concept is that wing tips deflected down are inconvenient at landing and take off (Fig. 28).

Wing tips and even flap tips are very important as far as the formation of vortices behind the wings is concerned. The vortex leaving the wing tip is the cause of non-parallel airflow and the core which accumulates the energy of the whole vortex sheet. The decrease of the edge wake has a great impact on the formation and the energy of the whole vortex behind wings. The research made by The Sikorsky Corporation on wing tip shape showed that the ogive form presented in Fig. 29 was the most effective one in decreasing the vortex. The tests proved that the use of such a tip can decrease the speed on the vortex core circumference up to one fourth. It seems that even a triangular tip would result in a substantial improvement.

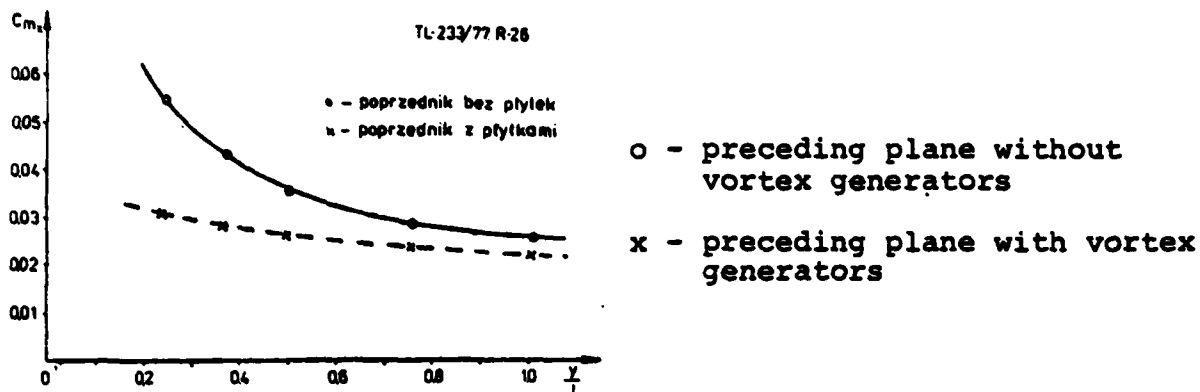


Fig. 26 Diminishing of the moment M_x depending on the ratio of the wing spread of the following aircraft to the wing spread of the preceding aircraft

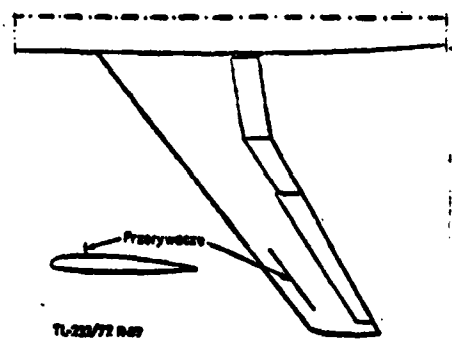


Fig. 27 Spoiler placement

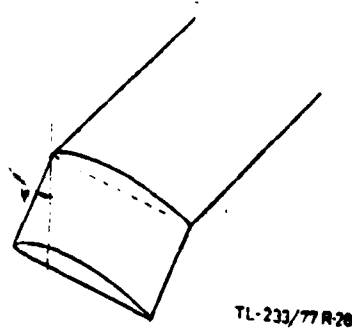


Fig. 28 Wing deflection

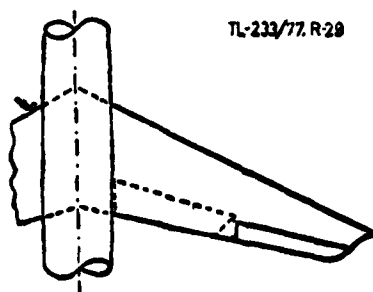
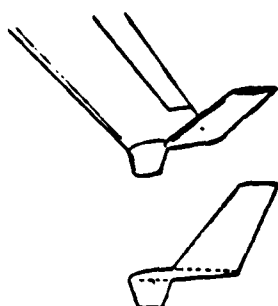
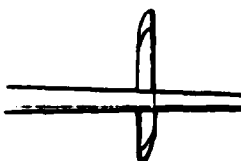
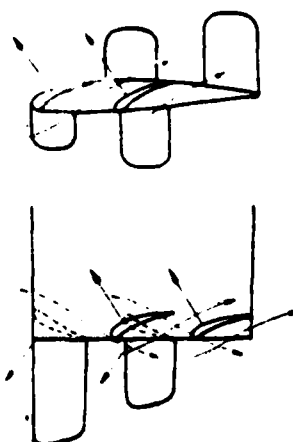


Fig. 29. Ogive Wing tips



TL-233/77 R-30

Fig. 30 Whitcomb winglets



TL-233/77 R-31

Fig. 31 Set of winglets for wake dissipation

Surfaces on wing tips, winglets (Fig. 30), proposed by Whitcomb to diminish the induced drag proved to be effective in decreasing the vortex energy. It seems more effective, however, to use the shaping vortex - which will appear anyway - to decrease the induced drag of the wing by putting some winglets at a certain angle in different planes, as shown in Fig. 31. The total induced drag of the wing can then be decreased by deflecting the airstreams to make them more parallel to the wing plane of symmetry. At the same time these winglets would give a resultant aerodynamic force directed towards the front which would decrease the wing drag. Such winglets will affect the shaping edge vortex by causing its greater turbulence and diminishing the contact speeds of the vortex core circumference due to the increase of its diameter. The functioning of such winglets joins the concepts of splines, Whitcomb winglets, and modified wing tips.

The possibilities to modify the ground influence on vortex behavior were also analyzed. This can be done by evacuating air from above the runway. Such evacuation "removes" the base and

so enables the displacement of vortices not horizontally aside *a conceptual diagram shows two of more slots* but rather downwards to suction slots along the runway. The channels draining evacuated air are joined to a suction system.

Computer simulation of such a diagram shows the following features of this concept:

- the most effective situation is created when there is no wind and when the vortex is very strong as the one formed during take off of a B-747. Under such conditions the wake - which is shifting by its own induced motion - is very vulnerable to suction;
- the least effective conditions are at "soft" vortex of great turbulence and diameter and at a wind speed above 9 - 10 km/h;
- air speed in the slots in the order of magnitude 3 m/s is sufficient to evacuate the vortex located 30 m above the ground in 70 s. This speed above the runway is at the order of magnitude 0.3 m/s;
- a total power requirement at the slots with measurements of $0.3 \times 3 \cdot 10^4 \text{ m}^2$ is 1.500 kW. When the outlet is equal to one third of the slot section an increase of power does not substantially affect the time necessary to evacuate the vortex;
- this concept has additional advantages since the suction system can be used for snow removal from the runway and for ground fog clearing.

Concluding remarks

The formation of vortices behind the wings is a rewarding field of research and it still contains many questions which have not been answered so far. The role of the boundary layer, the disturbances during the formation of the vortex sheet, the effect of wing angle, shape, and loading on the development of wakes, and the dimensioning of vortex parameters in relation to time,

space and wing geometry will possibly comprise - after their more detailed understanding - a base for their future control and manipulation.

Vortex manipulation depends on the understanding of the character of the flow of the vortex center connected with the formation of disturbances. It also depends on the development of equipment and technology to shape this flow. A great deal of attention should be paid to the process of vortex formation, namely the action against the whirling of the vortex sheet until it creates one strong edge vortex.

To define the real density of a vortex is a separate important problem since there is no doubt that atmospheric conditions, its stability, and the turbulence level have a substantial influence on the behavior, duration, and dissipation of the disturbed area.