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CONDITIONS OF GENERATION AND METHODS OF DAMPING THE INLET VORTEX OF A TURBOJET ENGINE

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16. Abstract

An aeromechanical analysis of the generation of an inlet vortex in a turbojet engine is presented. Methods for the prevention of vortex generation and methods of vortex damping are described.

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CONDITIONS OF GENERATION AND METHODS OF DAMPING THE INLET VORTEX OF A TURBOJET ENGINE

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One of the basic problems in using turbojet engines is protecting /5* their airflow ducts against damage caused by foreign objects being introduced along with the free intake jet. The significance of this problem consists in economic concerns, regard for the safety of pilots, and under the conditions of military aviation in addition, in the factor of combat readiness. In the publications in the periodical literature concerned with this problem, as well as in TLiA [Technical Aviation and Astronautics], authors have sought the theoretical and experimental principles of the aeromechanics of the pollution of the intake jet resulting from the formation of inlet vortices and as a result of these studies, they have suggested applied protective means. The lack of a full understanding of the sophisticated problematics has motivated this undertaking up to the present time. The solution to this problem requires, in the first phase, studies of the process of the generation of inlet vortices, and it would be on the basis of this knowledge that it would be possible to determine the conditions that must be fulfilled in order to excite an inlet vortex, and in the same way, to describe then the method for damping them.

The Process of Generating an Inlet Vortex

We must keep in mind that a free inlet or intake jet under conditions of windlessness at the airport may be modelled as a potential irrotational flow. The form of the stream lines in this flow characterizes the existence, due to the ground effect, of a stagnation stream line, that is, the existence of a stream line which terminates in contact with the ground at a stagnation point. The velocity at this point is zero, and at the same time, it is the midpoint of increasing radial flow within

*Numbers in the right margin indicate pagination in the foreign text.

the limits of the intake jet over the airport runway, as has been shown by theoretical and experimental studies [2, 8].

The process for generating an inlet vortex arises with the interaction of the free intake jet with the potential vortex. In the general case, a potential vortex arises in the environment of a free intake jet (Fig. 1b), when the wind is blowing with a determined velocity gradient. This potential vortex can be modeled as a circular vortex with the known equations for the velocity potential and the stream function:

$$\varphi = \frac{\Gamma}{2\pi} \operatorname{arctg} \frac{y}{x}; \quad \psi = \frac{\Gamma}{2\pi} \ln \sqrt{x^2 + y^2}$$

and the equation for induced velocity according to Biot-Savart:

$$v = \frac{\Gamma}{4\pi} \int_L \frac{\sin \alpha}{r^2} dL$$

The position of the potential vortex is dependent on the direction angle and the average wind velocity. With specific values for these, the potential vortex takes up a position in which the stagnation point, together with its lines, is located in the center of the vortex. At the instant when this situation has come about, the process leading to the occurrence of an inlet vortex commences. In the first sequence (if for the sake of analysis we take the process under discussion here as a group of serial phenomena appearing one after the other), there follows a folding of the radial flow towards the stagnation point together with the potential vortex. The effect of this may be modeled in the form of a vortex sink flow generated by the superposition of the potential circular flow and the potential sink flow at the stagnation point. The equations for the velocity potential and the stream function for the vortex sink flow have the following form:

$$\varphi = \frac{1}{2\pi}(Q \ln r + \Gamma\theta); \quad \psi = \frac{1}{2\pi}(Q\theta - \Gamma \ln r)$$

and the stream line is described by the equation:

$$r = C \exp Q\theta/\Gamma$$

The stream lines for the vortex sink flow are shown in Fig. 2.

The potential circular vortex changes into a vortex sink flow only during the initial phase, which corresponds to the normal interval for the occurrence of radial flow. The remainder of the potential circular flow phase persists without change. As a result of the folding of the movements of the progressive free intake jet as well as the movements of the rotational potential vortex sink flow and the potential vortex, a screw motion occurs, forming an inlet vortex with its core formed on the basis of the center of the potential vortex. The situation of the external region characteristic for the potential vortex is completely taken up by the transitional region. It is formed by the elements of the jet flowing into the core of the vortex along spiral paths; it is in this screw motion that the vortex enters into the engine intake. A photograph showing an intake vortex formed during tests carried out is shown in Fig. 3, and a model of the flow structure of

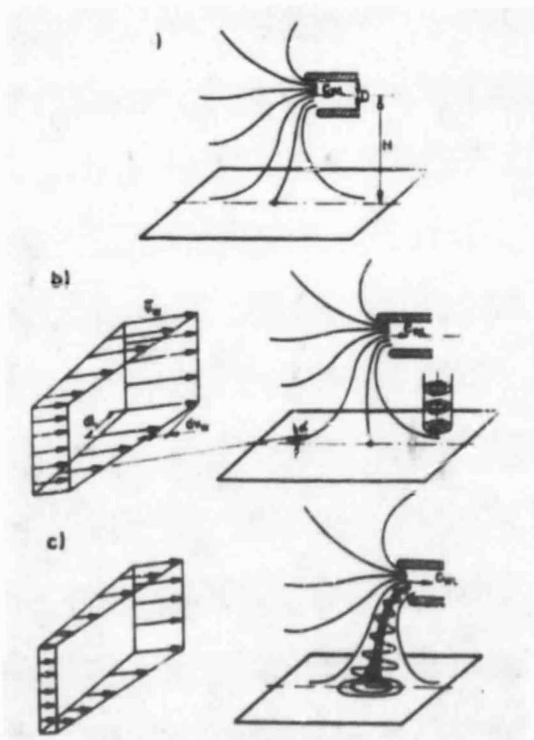

Fig. 1. The process of generating an inlet vortex: (a) the free irrotational intake jet; (b) potential circular vortex in the environment of the free intake jet, formed under the influence of wind with a velocity gradient; (c) free intake jet with vortex.

the inlet vortex is shown in Fig. 4. This figure illustrates also the existence of a boundary layer of atmospheric air with thickness δ. In

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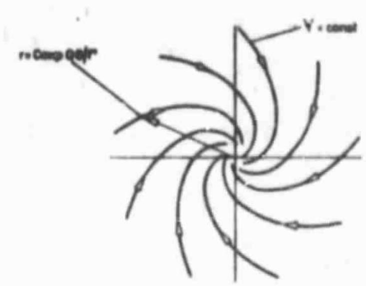

Fig. 2. Stream lines for the vortex sink flow.

Fig. 3. Inlet vortex shown with the aid of smoke.

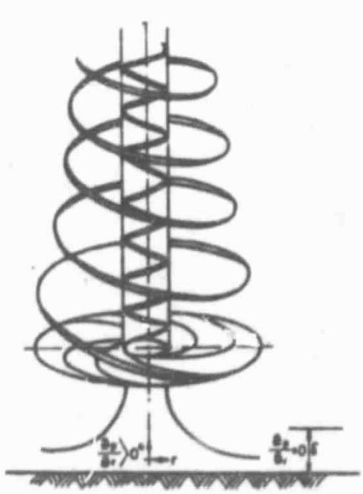

Fig. 4. Model of the flow structure of an inlet vortex.

this boundary layer, there ensues a disturbance in the equilibrium of the system of forces originating from inertia and the pressures as a result of the mechanical energy dissipation of the vortex. In consequence of this, a secondary flow arises in the boundary layer in a direction corresponding to the radial pressure gradient. This flow additionally strengthens the inlet vortex core. It is the foot of the core, in which the lowest pressure arises in the radial direction, that has a sucking effect on dirt; it may even suck up foreign objects embedded in the runway surface [8, 10] and introduce them into the engine duct along with the intake jet. At the same time, the portion of the vortex which executes a spiral movement over the runway tears foreign objects out of it. The foreign objects that come into the region of the increased velocity of the free jet in this way flow along with it into the engine's air flow duct (Fig. 5). The absence of a diffusion effect on the inlet vortex is a result of the continuous interaction between the free intake jet and the penetrating atmospheric air, and it is the fulfillment of these conditions that generates an inlet vortex.

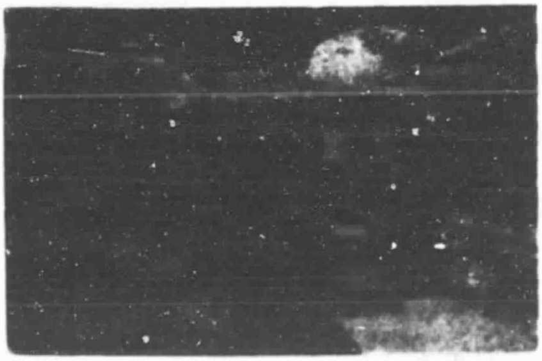

Fig. 5. The influence of an inlet vortex on modelled foreign objects covering a runway.

The process presented here for the generation of an inlet vortex has made possible the description of the set of its criteria. It is possible to understand it in the form of characteristic ratios of magnitudes connected to the interaction between the free intake jet and its environment. The criterial significance of these ratios consists in the fact that they have threshold values, which when exceeded, present no more possibility of generating an inlet vortex, and thus no longer the possibility of introducing foreign objects into the inlet. It should be emphasized that there exists a set of criterial ratios which can at the same time take values lower than the threshold ones and thus ensure the conditions for generating an inlet vortex. The set of these criteria is the Rossby number, Ro, the ratio of wind velocity* to the intake jet, as well as the ratio of the distance of the inlet window from the runway to the linear dimensions of the window. These phenomena for generating a vortex are considered in the following.

In order for air circulation in the environment of a free intake jet to be possible, it is necessary that, for a given velocity characterizing the free jet, there be a determined velocity gradient in the surrounding air across a section not shorter than the linear dimensions of the inlet window. It is possible to take the average velocity at one section of the jet, for example at the inlet window, as the velocity characterizing the intake jet, c_{WL}. It turns out that the most suitable criterion for the range under consideration is the Rossby number from the theory of atmospheric movement, which when adapted to the conditions of the analysis being performed here has the form:

$$Ro = \frac{c_{WL}}{wD}$$

where $w = dv_W/dL$, the wind velocity gradient (Fig. 1b); D, the linear dimension of the intake window, for example the geometric diameter or hydraulic diameter of the intake window. In order for a potential vortex to be conducted into the environment of a stagnation stream line, it is necessary that there be a proportional relationship between the value and direction of wind velocity and the velocity of the free intake jet across the section chosen in it. This may be estimated by means of the ratio of wind velocity to the mean jet velocity v_W/c_{WL}. Depending on the value of this ratio, the potential vortex changes its position with respect to the stagnation point on the runway surface. It turns out that the velocities of the vortex blowing away from the vicinity of the stagnation point depend to a great extent on the direction of wind flow upstream (from the point of view of the airplane's motion on the runway). The greatest velocities for the vortex's movement away from the stagnation point occur in the interval of directions from the frontal

*As "wind velocity," the direction and value of the velocity of the wind with respect to the motion of the airplane on the runway should be understood.

to oblique-frontal. It is possible to explain this in terms of the connection between the form of the tail of the free jet on the runway, as it becomes the set of all stagnation points, and the path of the movement of the potential vortex away from the stagnation point, that is, the segment required for the passage of the potential vortex beyond the stagnation region.

The possibility of exciting an inlet vortex in conjunction with a free intake jet with a potential vortex must also depend on the distance H of the jet axis from the runway surface at a given linear dimension for the inlet window. With an increase in the distance H, the pressure gradient in the free jet in the direction normal to the runway surface decreases, and subsequently the possibility of interaction of this jet with the potential vortex decreases. The criterial form of the ratio under examination is defined as the ratio of the distance H to the diameter D (Fig. 1a).

The conditions for generating an inlet vortex and determining its criterial numbers determines the basic methods for the aeromechanical protection of the intake jet against foreign bodies. In general, these consist in preventing the generation of an inlet vortex, or in damping one.

The Prevention of the Generation of an Inlet Vortex /7

In the work cited [2], it is suggested that a potential vortex may be prevented from arising due to the wind by blowing streams of air, tapped from the engine compressor, into the stagnation region.* In the work cited [10], it has been suggested that during the operation of the airplane on the runway, the value of the ratio v_W/c_{WL} may be maintained above threshold values by applied control of the engine rotational velocity. In the present work, however, it is suggested that the cited goal may be achieved by using a deflector mounted in the intake window (Fig. 6). The role of a deflector is to lift the free intake jet off the runway

*This method has already found practical application in several passenger aircraft with engines slung underneath the air foil (or presently being designed).

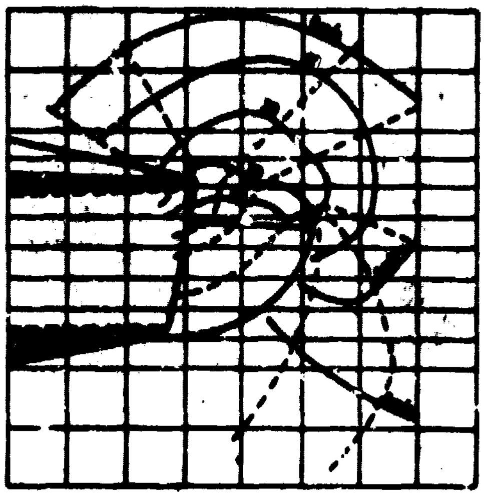

Fig. 6. The structure of the suction spectrum for the intake jet through an intake with a deflector attachment.

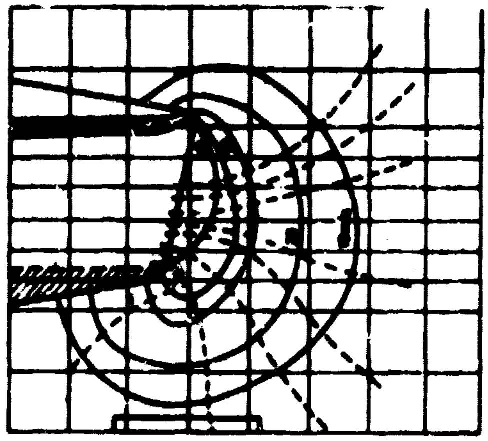

Fig. 7. The structure of the suction spectrum for the free jet through an inlet with a screen (irrotational jet).

surface (without lifting the inlet); this would make it impossible, in light of the third-named criterion, to generate an inlet vortex. If the structure provides for adequate raising of the free intake jet, it will be impossible for an inlet vortex to be generated, despite its excitation by wind, with a least advantageous velocity gradient, that is, with a Rossby number less than its threshold value. This kind of wind may cause a vortex movement in the stagnation region, but it cannot develop into an inlet vortex as a result of the lack of interaction under the conditions discussed above on the part of the elevated free intake jet.

Damping the Inlet Vortex

This method consists in reducing the intensity of the inlet vortex so that its influence on foreign bodies lying on the runway will not be harmful for the inlet. It has been suggested that this method may be realized by introducing a screen or latticework (Fig. 7) between the inlet and the runway surface as a damper for inlet vortices. The screen causes damping on inlet vortices (Fig. 8) by slowing down its angular velocity due to the dissipation of its energy as it passes through the screen. As a result of this moderation, the inlet vortex loses its drawing capacity and its ability to tear loose foreign objects of the surface of the runway. The unique dimensions of the screen should be optimalized with regard to its weight and makeup within the design system of the engine inlet. At the same time, from the point of view of ease of design in the screen attachment, it is necessary that its placement be optimalized as close as possible to the inlet, keeping in mind the fact that the effectiveness of the damping of the inlet vortex differs in relation to the distance of the screen from the runway.

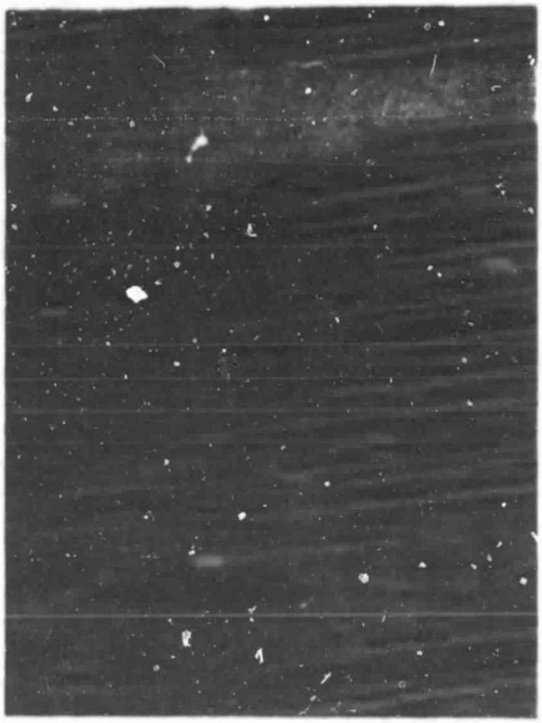

Fig. 8. Studies of the effect of a screen on an inlet vortex.

The attachments proposed (a deflector and a screen) have the advantage that they may be retained during flight.

From measurements carried out, it emerges that the introduction /8 of a screen into an irrotational intake jet in no substantial manner interferes with its velocity field (Fig. 7); this is connected with the shortness of the screen, as well as with its placement in a region that is still weak with respect to the aerodynamic activity of the intake jet. However, a deflector has substantial effects on the velocity field, but they are in accordance with its design (Fig. 6). The profile of a deflector should be carefully chosen with respect to its substantial effects on overall pressure loss in the inlet jet.

From the review presented here, to which could be added the concrete propositions of other scientific-research centers both here and abroad, it may be seen that at the present it is a matter that lies within the disposition of the designers of the ever-increasing numbers of means for protecting the intake jet against fouling from off the runway surface. The selection and development of these kinds of means depends on their maturity and design and applications experience, as well as on the specifics of engine inlet operation, which are determined by the inlet type, shape, inlet control, as well as by the means of accommodating the inlet to the air foil design.

At the least, however, the basic means for protecting against foreign objects remains in maintaining the operational and movement areas for the aircraft at the airport in a state of cleanliness. It turns out that with regard to these matters, it is also necessary that there be some care for the technical state of the runway surface. The products of wear from off the artificial runway surface are potential foreign objects, and the drawing action of an inlet vortex accelerates the process of surface wear. In addition, it is not only the state of cleanliness of the runway surface, but also its technical condition that should be considered among the kinds of basic engine protection against foreign objects.

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