Inlet Vortex

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A sink type flow located near a solid boundary will form a vortex if the circulation in the fluid near the sink is not zero. One end of the vortex will attach to the solid boundary at the stagnation point; the other end passes through the sink attaching to a surface beyond the sink or extending to infinity. This type of flowfield, called an inlet vortex, commonly appears at the engine inlet of a gas turbine propelled aircraft. Identical flows have also been observed at the inlets of open-circuit wind tunnels. The formation of a vortex at the inlet of a gas turbine engine is a nuisance, because of the tendency of the vortex to lift objects from the surface where the objects can be drawn into the inlet and cause severe damage to the compressor blades. The vortex also causes a transient distortion in the flowfield, which can be a hindrance to wind-tunnel studies. This paper describes work conducted at The Boeing Company to study the conditions necessary for existence of the inlet vortex and develop techniques to prevent the formation of the vortex.

I Introduction

THE character of a gas turbine is such that it is very susceptible to damage from debris that is taken in through the inlet and presented to the compressor blades. Some estimates indicate that more than 50% of all gas turbines removed from aircraft have suffered damage because of the ingestion of a foreign object. The objects causing engine damage vary in size from small grains of sand or dirt to nuts, bolts, and rocks 1-in. diam or larger. (One instance even involved a moose but this was not wholly attributed to the topic of this paper!)

The cause of this damage has been of concern to aircraft operators and manufacturers for some time, and numerous schemes to reduce the chances of foreign object damage have precipitated over the past years. Among these ideas, the two most obvious were 1) to keep the runways, taxiways and parking ramps clean of all objects and 2) to filter the air entering the gas turbines to remove all the debris that could cause damage. The first idea requires manpower and machinery to sweep or vacuum airport facilities on some regular basis; an extremely expensive operation. A scheme to filter the inlet air has not yet been developed which will produce an acceptable loss in total pressure or flow distortion compatible with the gas turbine requirements. (A commercial jet airplane will suffer a 15% to 40% loss in payload, depending on the specific airplane, at cruise conditions because of a 2% loss in inlet recovery.)

II Previous Work

Critical examinations of the problem by Klein,[1] Rodert and Garrett,[2] and Miroshnichenko[3] have shown that the ingestion of objects into the inlet of a gas turbine can be attributed to a vortex that forms between the inlet and the ground. Figure 1 is a photograph of the vortex that formed at the inlet of the aircraft gas turbine being run on a test stand. The vortex core is visible because of condensation of moisture from the atmosphere as a result of the high velocities and low pressure existing near the core. The vortex is usually not visible to the naked eye; the condensation in the core occurs only during a rainy or foggy day when the atmosphere is close to saturation.

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Other studies by Colehour[4] and Graue[5] have shown that ingested objects do not necessarily follow the path of the vortex into the inlet. Instead, it seems that a particle on the ground will be ejected upward and out of the vortex as the vortex core passes over the object on the ground plane. The object is then entrained in the inlet flowfield and carried into the inlet. This is a significant point because on large bypass ratio engines the vortex appears to enter the inlet in the region of the fan. If an ingested object remained in the vortex core it would likely pass through the fan blades and cause less significant damage. However, it seems that objects lifted from the ground by the vortex may enter any part of the engine including the compressor stages, which are less tolerant to ingestion. Slow motion films of vortex initiated ingestion shows objects entering gas turbine inlets at various locations including the bypass doors. A photograph of a aircraft gas turbine ingesting 1-in. diam rocks (Fig. 2) gives an indication of the type of dispersion that can exist. It should be noted here that the inlet vortex is not always present. Its existence depends on the presence of circulation in the air being drawn into the inlet. Without the vortex, ingestion into the inlet is not likely because the velocities in the ground plane are too small to lift particles of significant size into the high-velocity region of the flowfield. The conditions necessary for the existence of the vortex and the fluid mechanics involved will be discussed in more detail in the following sections.

Recognition of the ingestion potential of the inlet vortex has produced several schemes for ingestion control. A flat plate mounted forward and beneath the lower lip of the inlet and parallel to the ground plane was intended to provide a debris-free surface, to which the vortex could attach and also act as a deflector for objects approaching the inlet from the ground. Contrary to all intentions, this tea-tray arrangement does not raise the vortex stagnation point off the ground; instead, the vortex will form to the side of the

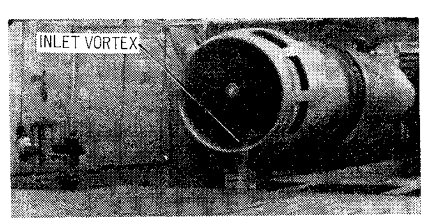

Fig. 1 Typical inlet vortex (visible because of moisture condensation in the vortex core).

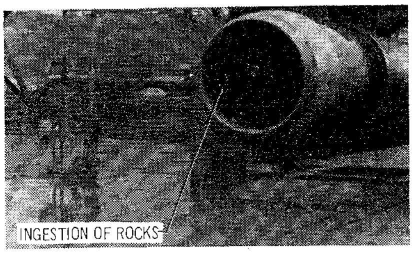

Fig. 2 Rock ingestion on an aircraft gas turbine inlet.

tray. Some instances have been observed with two vortices, one on each side of the tray.

A patented idea[6] suggests using a series of small air jets mounted on the wings and fuselage of the aircraft to blow debris away from the path of the inlets. Such a system could use air bleed from one of the gas turbine compressor stages. Another blowing technique[7] utilizes a jet of air mounted beneath the lower lip of the inlet and directed at the point on the ground plane where the vortex stagnation point forms. The jet impinging on the ground plane at the stagnation point creates a radial flow component directed out from the stagnation point opposing the radially inward flow created by the inlet, thus not allowing the concentration of angular momentum necessary for existence of the vortex. The difficulty with this latter technique is in determining the location of the stagnation point. Experimental studies of the inlet vortex have indicated it to be a transient phenomenon dependent on the conditions in the surrounding air. Efforts to stabilize the position of the stagnation point were not successful. Thus, it appears that the jet cannot always be aimed at the stagnation point, and therefore continuous suppression of the vortex does not occur. Also, any blowing technique which uses a jet of air to impinge on the ground plane near a gas turbine inlet can create an ingestion problem by lifting debris from the surface where it can be entrained by the flow into the inlet.

III Fluid Mechanics of the Flow

The mechanics of the flow that give rise to an inlet vortex are quite complex in nature. The existence of a vortex at the inlet of a gas turbine engine is dependent on the conditions in the ambient air surrounding the engine inlet. If the ambient air is quiescent or has a uniform velocity, a vortex will not be formed at the engine inlet. A vortex can form at the inlet only if the ambient air contains circulation. (A commonly held attitude that the rotation of the gas turbine rotor is responsible for the vortex is unfounded and in error.) No complete analytical solution exists for this problem at present. It is possible, through the use of existing methods and observations, to construct a useful flow model that can aid in the understanding of ingestion initiated by the inlet vortex.

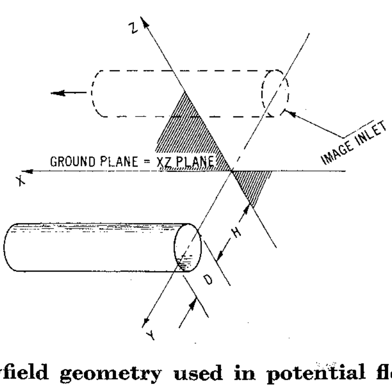

Fig. 3 Flowfield geometry used in potential flow study.

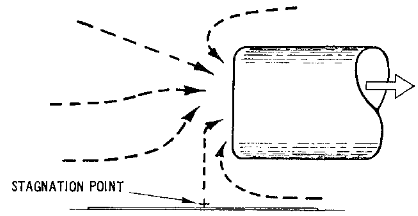

Fig. 4 Potential flow streamlines for sink flow with quiescent ambient conditions.

It is helpful in this case to divide the flow into a nonviscous potential flow and a viscous flow. The viscous flow affects the regions near the ground and in the core of the vortex; the potential flow governs all other parts of the flowfield.

If the flow is assumed inviscid and incompressible the complete three-dimensional flowfield can be studied using the method of Rubbert et al.[8] To study the potential flow, a simplified flow model was chosen with the geometry as shown in Fig. 3.

The first flow model of interest is a simple sink flow near a ground plane with quiescent ambient conditions. The flow along the ground plane is radial with the only variation being slightly higher velocities beneath the sink due to interference effects. The streamline pattern for this flow calculated with potential flow theory is shown in Fig. 4. Of interest here is the radial nature of the flow along the ground and the stagnation point on the ground plane below and slightly ahead of the inlet. Also of interest are the velocities along the ground plane in the region below the inlet. Figure 5 presents computed ground plane velocities along the X axis for an $H/D = 0.75$ (H/D is the ratio of the minimum height of the inlet highlight above the ground plane to the inlet highlight diameter). As can be seen, the velocities are quite low; the lowest velocities occurring in the region of the most intense observed ingestion activity. Although it is obvious at this point that potential flow does not completely describe the real flow, some additional information can be obtained by this technique.

Of particular importance is the case where some ambient wind condition exists. The potential flowfield calculated for a moderate head wind is shown in Fig. 6. As can be seen, the stagnation point moves slightly to the rear. Potential flow theory indicates the stagnation point tends to move in the ambient flow direction. A sufficiently high-head

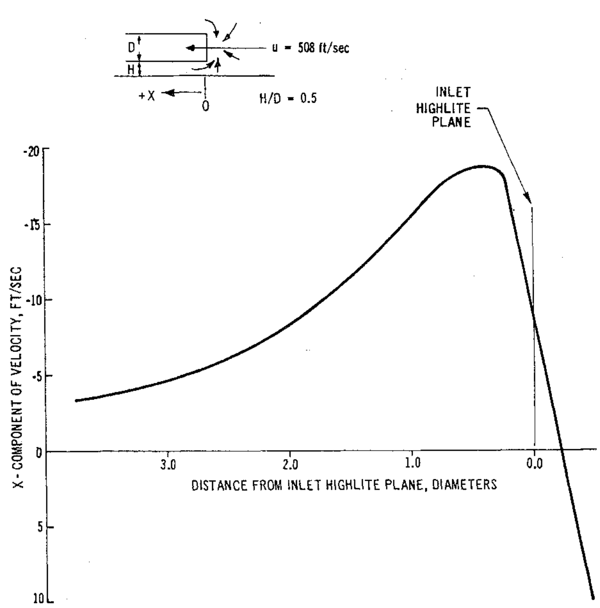

Fig. 5 Ground plane velocities parallel to the inlet axis, $H/D = 0.75$.

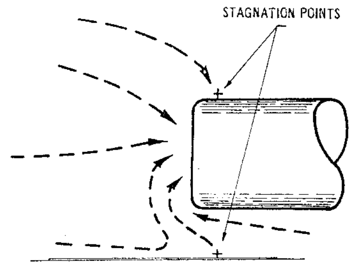

Fig. 6 Potential flow streamlines with a moderate headwind.

wind can remove the stagnation point from the ground plane as shown in Fig. 7. (The head wind required to remove the stagnation point for the conditions of Fig. 5 is 19 fps.)

It is also possible to add an irrotational vortex to the flowfield; this is done three-dimensionally using the method of Rubbert et al.[8] Both the location and strength of the vortex must be specified. For a potential vortex, the velocity varies inversely with radius; its behavior can be described by the following relation:

$$V = \Gamma/r$$

Γ is a constant (the vortex strength), V is the tangential velocity, and r is the radius from the center of the vortex. The primary value of the exercise is in noting the difference between flows with and without a vortex present. The main difference occurs in the region near the stagnation point beneath the inlet where the local velocity behaves as a potential vortex.

Although this flow model produces high-tangential velocities beneath the inlet, a careful study of the flow indicates that the magnitude of the vertical component of velocity is the same as for a potential sink flow alone. Colehour[4] measured ground plane static pressures near an inlet model. A comparison of the two potential flow studies, with the velocities obtained from these measured ground plane static pressures, indicates that the magnitudes of the local velocities fall between the two potential flow cases as shown on Fig. 8.

This discrepancy in the theoretical and measured velocities and the fact that particles can be ingested requires consideration of the viscous portion of the flow. The potential flow results permit deduction of a fairly complete flow model in the region of the ground plane. The potential flow provides a radial or nearly radial flow that moves toward a stagnation point beneath the inlet. A boundary layer is also developed along the ground plane. If it is assumed that a vortex flow is superimposed on the above situation, a tangential velocity component is developed above the ground plane boundary layer. The vortex also impresses a strong radial pressure gradient on the ground plane with pressure decreasing toward the center of the flow. Outside the boundary layer, radial equilibrium exists because the tangential momentum just balances the radial pressure gradient. However, in the ground plane boundary layer this tangential momentum is partially dissipated through viscous effects, whereas the impressed pressure gradient is undiminished. Thus, a radial flow is induced in the boundary layer along the ground. Evidence in support of this flow model can be found from experimental work with vortex tubes. Kendall[9] presents measurements of the boundary layer on the end wall of a vortex tube; a sample of this data is presented in Fig. 9. This

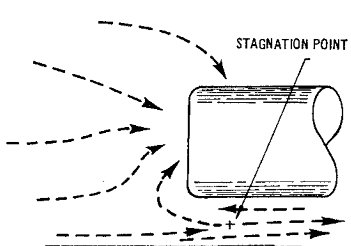

Fig. 7 Potential flow streamlines with headwind sufficiently large to remove the stagnation point from the ground plane.

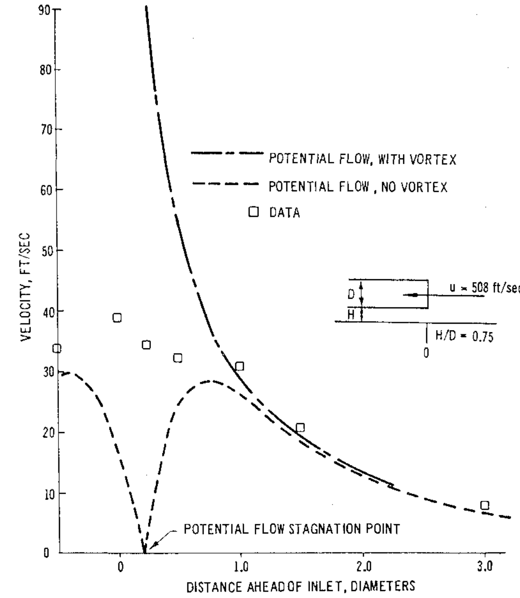

Fig. 8 Comparison of measured ground plane velocities with potential flow velocities, $H/D = 0.75$.

flowfield is similar to the inlet vortex in that a vortex is attached to a plane surface. The profile measured by Kendall clearly shows the radial flow in the end wall boundary layer. It is also interesting that the peak radial velocity occurs deep in the boundary layer, close to the stationary surface.

Observations[4,5] of the behavior of particles in the region where the vortex joins the ground plane indicate that vigorous vertical velocities exist very close to the ground plane. Unfortunately, quantitative measurements of these velocities have not been obtained to date, but using the aforementioned observations, a model of this flow can be assumed. This suggested model is shown in Fig. 10. The radial flow in the boundary layer moves toward the vortex interaction point and then, apparently, abruptly turns up the vortex core. Qualitative evidence is also presented by Kendall,[9] which indicates high axial velocities in the vortex core.

Using the flow model shown in Fig. 10, the two aspects of flow mentioned at the beginning of this section can be explained: 1) the flow that is responsible for ingestion results from viscous effects, and the critical region for ingestion is the point where the vortex joins the ground plane boundary layer; and 2) the measured velocities in the ground plane are

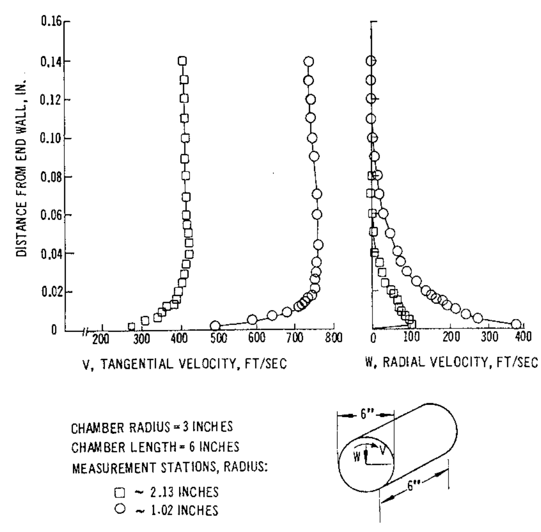

Fig. 9 Tangential and radial boundary-layer profiles on the end wall of a vortex tube.

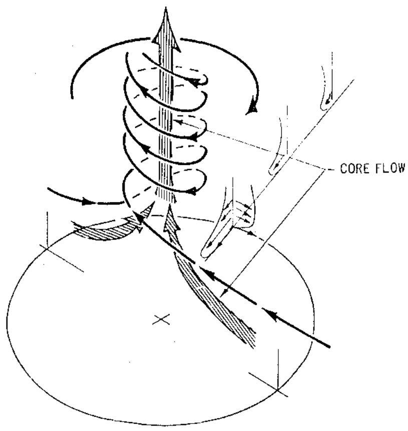

Fig. 10 Inlet vortex flow model.

larger than the potential sink flow calculation but less than the potential vortex calculation. This results from modification of the flow near the vortex axis by viscous effects as shown by Kendall.[9]

An experimental program was carried out by the authors using a small scale inlet and flow visualization to indicate flowfield behavior. Titanium tetrachloride ($TiCl_4$), used as the flow visualization agent, was placed on the ground plane about the inlet. The moisture in the air combined with the titanium tetrachloride to produce a dense white smoke, which was entrained by the inlet flowfield thus, allowing the flow to be observed. Other regions of the flowfield could be observed by saturating a cotton string with $TiCl_4$ and placing it in the flow. This produced a thin sheet of smoke for studies above the ground plane. These observations of the flow tended to confirm the following: 1) Some external disturbance that introduces circulation into the inlet-flowfield must be present before a vortex will form; 2) Ambient winds move the stagnation point as previously indicated but do not produce a vortex if the wind is uniform; 3) A vortex can occur with the inlet located several inlet diameters from the ground plane if circulation is introduced into the flowfield; and 4) Stability of the vortex decreases as inlet height increases.

IV Vortex Suppression Methods

Based on the understanding of the flow presented in the previous section it is possible to proceed with an attempt to suppress the vortex formation without a complete mathematical description of the flow. Two different classes of methods will be described: the first describes a method suitable for aircraft use; and the second class could be used on a ground test rig, or almost any other situation where a sink flow exists and a vortex causes problems.

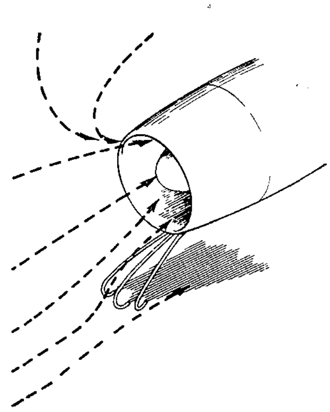

Fig. 11 Streamline of inlet flowfield with vortex suppression.

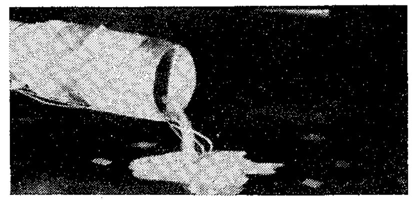

Fig. 12 Flow visualization study of inlet vortex on small scale test.

Aircraft Application

For aircraft applications, use is made of predicted behavior of the vortex under head wind conditions shown in Figs. 6 and 7. An effective way of eliminating the vortex is by producing a head wind in front of the inlet such that the flow of Fig. 7 is maintained. Providing a head wind would be rather difficult; however, the region that is critical is a rather small area beneath the inlet, and a local head wind in this region can be produced. The method that proved most effective in small scale flow visualization tests used small aft blowing air jets for this purpose.

The jets were placed about $\frac{1}{2}$ an inlet diameter ahead of the inlet and approximately $\frac{1}{8}$ of an inlet diameter off the ground. The action of the jets entrains the surrounding flow and ejects it to the rear, such that it is effectively removed from the inlet flowfield. This prevents the formation of the vortex by destroying, locally, the radial flow necessary for the concentration of angular momentum. Although some radial flow will persist outside of this region, the critical region where the flow converges to a point has been removed and no vortex can form.

The flowfield generated by the inlet and the blowing jets is shown in Fig. 11. Figures 12 and 13 are two photographs from these tests showing, respectively, the flow without and with the ejector blowing. As can be seen, the flow from the ground to the inlet is virtually eliminated by the ejector action of the vortex suppression jets. A large number of blowing configurations were examined; the arrangement shown in Fig. 11 was considered the most successful with respect to cross-wind and tail-wind conditions. The important characteristics of this vortex suppressor are: 1) The blowing jet should be directed rearward; 2) The jets should be placed as close to the ground as practical; 3) Blowing jets should be ahead of the ground plane stagnation point for all appropriate conditions (i.e., tail wind); a distance of $\frac{1}{2}$ an inlet diameter was found to be adequate in the tests previously described; and 4) A fan shaped jet parallel to the ground plane is desirable; this shape of jet can be generated by 3 or more small nozzles. Mass flow requirements for a device such as this will be of the order of $\frac{1}{2}\%$ of the total mass flow through the inlet.

Other Inlet Vortex Flows

As indicated previously, vortices will form at the inlets of other sink type flowfields; for example, a test stand mounted gas turbine and the bellmouth of the inlet of an open circuit

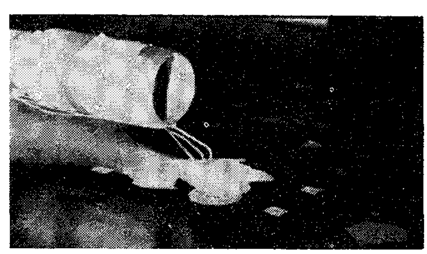

Fig. 13 Flow visualization study of vortex suppression with aft blowing scheme on small scale test.

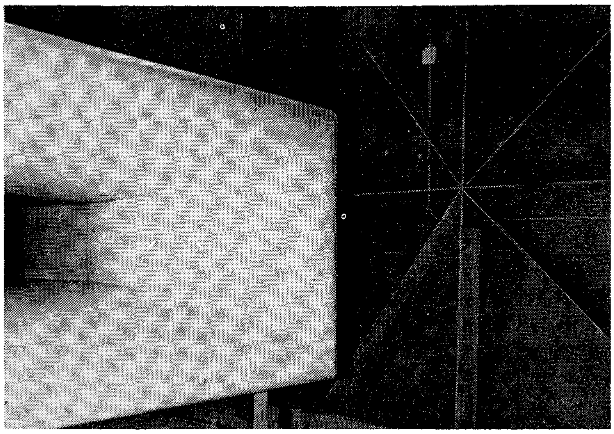

Fig. 14 Wind-tunnel bellmouth with asterisk vortex suppressor mounted on adjacent wall.

wind tunnel. These flows are identical to that at the inlet of an aircraft gas turbine; however the fact that the installations are stationary affords the opportunity to use a less involved method of vortex suppression. Obviously, a gas turbine mounted on a test stand should not be subjected to the ingestion problems of an aircraft. It is a simple chore to keep a test stand area free of debris and thus eliminate the ingestion hazard. The same is true for wind-tunnel inlets where ingested particles can cause damage to instrumentation. Vortex suppression on stationary installations is usually desirable to reduce the flow distortion, which can be the casue of erratic data in wind-tunnel studies. Vortex distortion in the inlet of stationary gas turbine installations has been blamed for excess noise radiating from the engine inlet and for causing engine surge. (This appears to be speculation; no conclusive data, to the authors' knowledge, is available to substantiate the noise or surge theories.)

Currently, several techniques are in use for vortex suppression on gas turbine test stands. One method employs a grid of 1-in. to 2-in. squares constructed of 1-in. wide steel strips. The grid, usually about two-inlet diam square, is located between the lower lip of the inlet and the ground plane. The authors' experience with a similar grid on a small scale test did not indicate complete suppression of the vortex. Rather, the grid acted more as a flow straightener with the vortex forming beneath the grid. If the grid is placed close to or on the ground plane, the vortex forms on top of the grid.

The most effective means of vortex suppression for both stationary gas turbines and wind-tunnel inlets is a Tee or asterisk shaped fence as shown on Fig. 14. The intersection of the arms is placed on the wall or ground plane in the vicinity of the observed vortex stagnation point. The rotational flow near the ground plane cannot form a stagnation point because of the fence.

Instead, the flow is forced to separate from the ground plane and flow up into the inlet without forming a vortex. The various arms of the fence also disturb the circular flow in the ground plane, thus inhibiting vortex formation. An asterisk fence has been used by The Boeing Company on both wind-tunnel and gas turbine applications, and has proven to be an adequate measure for vortex suppression.

One other technique was found practical for suppression of a vortex which formed between the bellmouth of a wind tunnel and an adjacent wall. This involves ventilating the wall in the vicinity of the vortex stagnation point with a series of small holes (Fig. 15). The flow induced through the wall will cause the flow along the wall to separate from the wall; thus preventing a stagnation point from forming. By preventing the stagnation point from forming, the concentration of angular momentum necessary for the existence of the vortex does not occur.

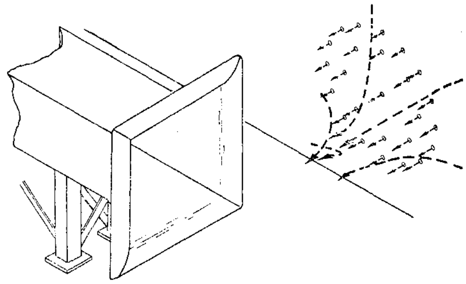

Fig. 15 Ventilated wall for vortex suppression.

V Summary

The discussion presented herein describes the fluid mechanics of the vortex that can exist at the inlet of an aircraft gas turbine. The condition necessary for the existence of the vortex, and the mechanism for particle ingestion into the inlet was deduced from a potential flow analysis and flow visualization studies of the flowfield. The aft ejector blowing[10] technique described is the most effective method of vortex suppression tested. This scheme has been certified by The Federal Aviation Administration and is currently being used on commercial transports in gravel runway service. Several less involved methods of vortex suppression have been described for stationary applications. Each of these methods seem equally effective where the facilities for ejector blowing are not available or compatible with the application.

References

[1] Klein, H., "An Aerodynamic Screen for Jet Engines," Paper 676, 1962, Institute of the Aeronautical Sciences.

[2] Rodert, L. A. and Garrett, F. B., "Ingestion of Foreign Objects into Turbine Engines by Vortices," TN 3330, Feb. 1955, NACA.

[3] Miroshnichenko, A. I., "The Vortex at the Inlet of an Air Intake," (in Russian), *Samoletostroenie I Technika Vozdushnogs Flota*, No. 12, 1967, pp. 128–129.

[4] Colehour, J. L., "A Study of Foreign Particle Ingestion for a 747 Type Inlet," Document D6-23238, Aug. 1969, The Boeing Company, Seattle, Wash.

[5] Graue, R. W., "Particle Ingestion Tests of a JT3D Engine with a Movable Ground Plane," unpublished data, The Boeing Company, Seattle, Wash.

[6] Wiles, W. F., British Patent 898,417 granted June 6, 1962 to Rolls Royce Ltd.

[7] Klein, H. J., "Vortex Inhibitor for Aircraft Jet Engines," U. S. Patent 2,915,262 granted Dec. 1, 1959 to Douglas Aircraft Corp., Santa Monica, Calif.

[8] Rubbert, P. E., et al., "A General Method for Determining the Aerodynamics Characteristics of Fan-In Wing Configurations," D-6-13476-1, Nov. 1967, The Boeing Company, Seattle, Wash.

[9] Kendall, J. M. Jr., "Experimental Study of a Compressible Viscous Vortex," TR No. 32-290, June 1962, Jet Propulsion Laboratory, C.I.T., Pasadena, Calif.

[10] Colehour, J. L. et al., "Vortex Preventing Method and Apparatus for Aircraft Jet Engines," U.S. patent pending.