JOURNAL OF AIRCRAFT
Vol. 33, No. 4, July–August 1996

Airport Jet Plume Zone Mapping

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A software package, which maps the jet plume zones for a jet aircraft during airport ground operation, has been developed. The method generates an airport plume zone map by predicting plume velocity contours (for a selected jet plume velocity level, e.g., 35 mph) as a function of the aircraft geometry and engine power setting. The velocity contours are then superimposed on a predigitized airport map. A standard normalized velocity contour plot, which is unique to each airplane configuration, is used to quickly determine the plume velocity contour for an engine power setting and a computer graphics program is used to display an airport plume zone map on the computer screen. The method is general and is applicable to any airplane configuration. The purpose of this article is to introduce an airport plume zone mapping tool to the airplane design and operation groups.

Nomenclature

A = total cross-sectional area of engine nozzles
D = diameter of a round jet
T = thrust setting for a single engine
U = jet velocity
ρ = ambient density of air

Subscripts
c = centerline
h = head wind
ref = reference
0 = initial mean velocity of a jet

Introduction

WITH the increase in air travel and the growing volume of air cargo, development of new aircraft, even larger than the present Boeing 747, is now being considered. A large aircraft requires more engine power and this implies more or larger engines. Already, some current high-bypass-ratio jet engines produce a thrust of almost 100,000 lbf per engine. This is almost twice the power of the engine presently on the Boeing 747.

At a crowded airport, increased operation of high-power engines is a concern because of the potential damage that jet blast can cause to ground crew, cargo equipment, terminal buildings, and small aircraft nearby. The erosion of unprotected soil adjacent to runways and taxiways is another potential problem. Jet blast damage and erosion can occur while an aircraft is in ground service (idling, breakaway, and takeoff) along a taxiway or a runway. If the plume velocity distribution downstream of airplane engines is known, jet blast damage caused from dynamic pressure can be prevented and the safe distance between airplanes on a taxiway can be determined.

Because of these potential problems, accurate jet plume prediction is becoming increasingly important. Numerical analysis of jet plumes first became possible with the development of three-dimensional parabolized Navier–Stokes codes in the mid 1970s. These analyses, combined with two-equation turbulence models that were under development at that time, provided the first numerical capability to analyze complex three-dimensional jets. These analyses were originally developed to study the performance of lobed mixers,[1] but were soon applied to the analysis of three-dimensional jets[2] and jet plumes[3] of, ultimately, all Boeing airplanes. This is the basis for the jet plume data generally included in airport planning documents.

At present, the jet plume data supplied in Airport Planning Documents[4,5] is limited to idle, breakaway, and takeoff power settings. To obtain information at other engine power settings requires a new calculation, or a crude approximation based on the available data.

When this jet plume analysis procedure was originally developed, a typical jet plume calculation required the full capabilities of the largest available mainframe computers and was generally run as an overnight job. Advances in computer hardware, an improved physical understanding of the jet plume decay process, and the development of sophisticated interactive graphics tools have now completely changed that situation. The work described in this article gives the project engineer, sitting at a workstation, the capability to interactively move an image of an airplane around a map of an airport and to study the behavior of the jet plume for different locations of the airplane and different engine power settings. Not only has the time for the jet plume calculation been reduced to a matter of seconds, the accuracy and reliability of the calculation has also been significantly improved.

The objective of this article is to introduce a computerized method of predicting and mapping an airport plume zone (velocity contours with a selected plume velocity level, e.g., 35 mph) during the ground operation of an aircraft.

Approach

The airport jet plume zone mapping method is based on a combination of a standard normalized velocity contour plot and computer graphics animation techniques. The jet plume analysis method, a standard normalized velocity contour plot, and the animation techniques are described in order.

Analysis Method

The jet plume of an airplane is calculated by numerically solving the parabolized form of the Navier–Stokes equations for mass, momentum, and energy, coupled with a two-equation k-ε turbulence model. Wall functions are used to reduce mesh requirements in the near-wall region. The equations and the numerical procedure used to solve them, together with the required boundary conditions, are described in detail in Refs. 1 and 2. The initial conditions for velocity and total temperature,

Received Oct. 18, 1995; revision received Feb. 19, 1996; accepted for publication Feb. 26, 1996. Copyright © 1996 by the authors. Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.

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at the nozzle exit, were obtained using a proprietary one-dimensional engine cycle analysis code that was run for the particular engine under consideration.

To simplify the overall calculations, the development of the individual jets are generally calculated separately until they start to interact with each other or the ground. Since the jets in this region are essentially axisymmetric, this part of the analysis can be run as a two-dimensional calculation. These calculations were run using a two-dimensional version of the three-dimensional code that was used for the main calculation.

A two-dimensional axisymmetric analysis is conducted near the nozzle by simulating the primary and fan flow mixing over a short distance downstream of individual engines to prepare the initial boundary conditions for the three-dimensional analysis. The axisymmetric solution for each engine is then interpolated onto the first plane of the three-dimensional solution domain. For example, in the jet plume analysis of a four-engine airplane, two sets of an axisymmetric solution, which represent the two inboard engines, are interpolated to the first plane of a three-dimensional marching solution domain. The three-dimensional solution is carried out to the axial location of the two outboard engines. Finally, two axisymmetric jets representing the outboard engines and the three-dimensional solution of the inboard engines are interpolated to a new three-dimensional starting plane to carry out the three-dimensional solution up to the axial distance of interest. A three-dimensional flowfield is analyzed by a plane-by-plane parabolic marching solution scheme covering a sufficient downstream distance until the peak jet velocity decays to a velocity magnitude of interest (typically 35 mph). The size of the computational mesh in the plane normal to the marching direction is adjusted to accommodate the growth of jet diameter with downstream distance. Figure 1 illustrates the front views of typical predicted jet velocity contours at four different axial stations downstream of the inboard engines of a four-engine jet airplane, which clearly shows the mixing and velocity decay of multiple jets with axial distance.

The analysis was first validated for individual axisymmetric jets by detailed comparisons between numerical calculations and experimental data, using model scale data, available in the literature, and data from special tests on full scale engines. Figure 2 shows the comparison of predicted and measured centerline velocity decay for a round jet vs downstream distance.[6]

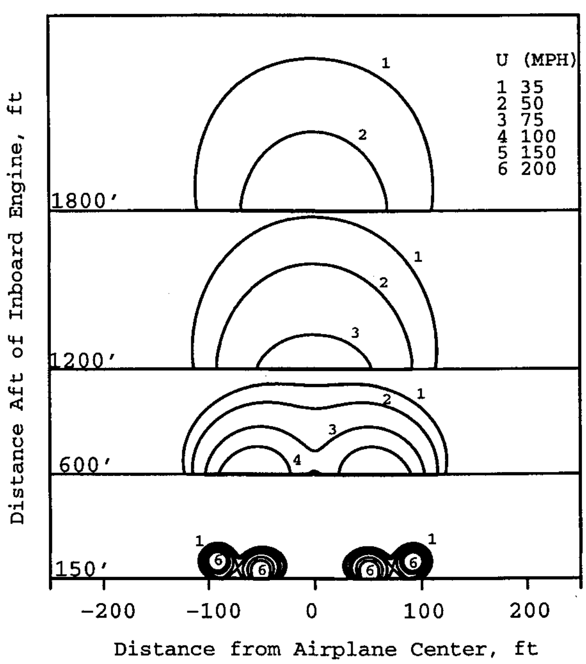

Fig. 1 Predicted jet mixing and velocity decay downstream of a four-engine airplane.

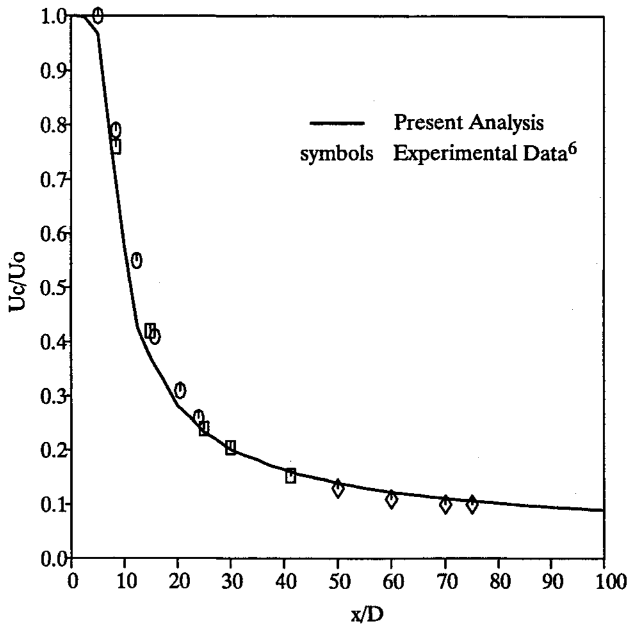

Fig. 2 Comparison of the predicted and the measured centerline velocity decay for a round jet.

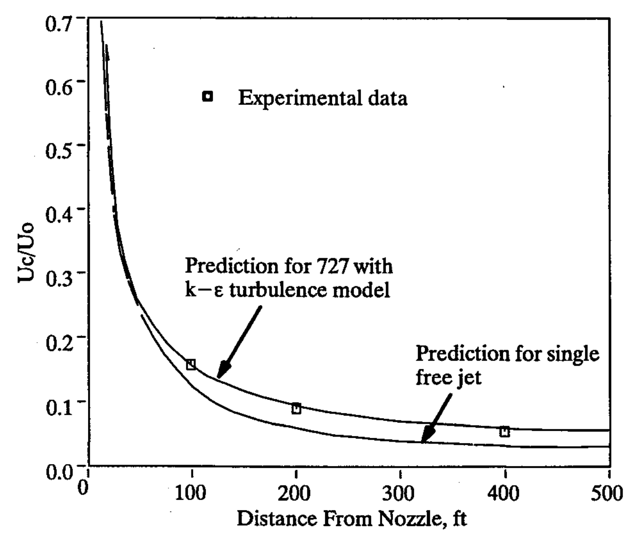

Fig. 3 Jet velocity decay for the 727 jet engine exhaust installation.[3]

As shown, the jet properties predicted using the present analysis method agree very well with the experimental data. The validation of the analysis using experimental data for actual jet plume from a commercial jet airplane is shown in Fig. 3. Measurements were made behind a Boeing 727 airplane for a number of different power settings. Figure 3, taken from Ref. 3, shows the good agreement that was obtained between the numerical calculations and experimental data.

Velocity Normalization

A problem with the original calculation was that an accurate jet plume calculation, in common with other computational fluid dynamic calculations, requires the selection of an appropriate computational grid for the calculation. This grid is dependent enough on details of the flow that it is difficult for the nonexpert to run such calculations reliably, and this has limited the use of these analyses. As is well known, the downstream development of a turbulent jet, far from the nozzle exit, becomes independent of detailed flow conditions at the nozzle exit and is determined only by the momentum flux of the jet. Because of this, suitably normalized velocity fields of subsonic jets can all be collapsed to a single plot, see, for example, Ref. 6. While this is not strictly true for the more complex jet plume flow behind an airplane, detailed flow calculations have demonstrated that the actual flowfield can be approximated well enough for most applications by a normalized plot of the velocity and temperature fields. Normalized plots of the calculated velocity fields downstream of a single- and a four-engine airplane for idle, breakaway, and takeoff thrust levels are shown in Figs. 4 and 5. The ground plane is included in all calculations and, as can be seen from Figs. 4 and 5, the normalized plots are almost identical. The velocity used to normalize these data is given by

$$U_{\mathrm{ref}} = \sqrt{T/\rho A} \tag{1}$$

Here T is the engine power setting, A is the total area of both the primary and the fan nozzles, and ρ is the ambient air density.

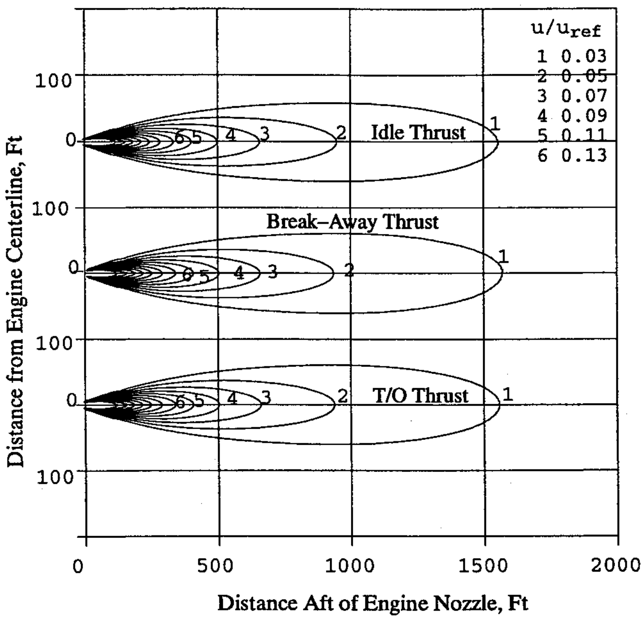

Fig. 4 Comparison of normalized velocity contours at different engine power settings for single-engine operations.

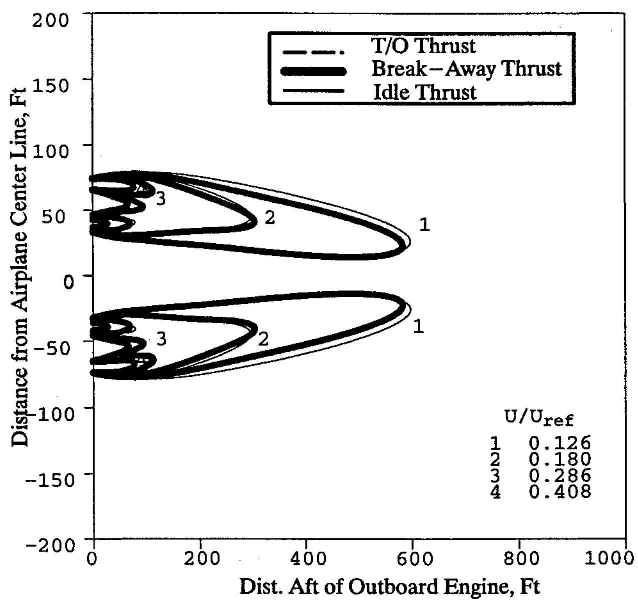

Fig. 5 Similarity of normalized velocity contours at different engine power settings for four-engine operation.

Standard Normalized Velocity Contour Plot

The existence of scaling independent of power setting for single and multiple jets from a given exhaust nozzle geometry allows the generation of a standard normalized velocity contour plot. To generate a standard normalized velocity contour plot, a three-dimensional jet plume analysis is required per airplane configuration at the maximum engine power setting once. Predicted velocities are normalized with respect to a reference velocity. Next, predicted three-dimensional velocity data are projected onto a plane through the loci of peak jet velocity. This projected two-dimensional normalized velocity contour plot as a function of the distance aft of engine and the lateral distance from airplane centerline is defined as a standard normalized velocity contour plot. An example of normalized velocity contour plots for a two- and a four-engine airplane configuration, is shown in Figs. 6 and 7. The use of this scaling minimizes the computational work required to achieve a plume zone map. A standard normalized velocity contour plot can be used to determine a velocity contour of interest over an entire range of engine power. If an engine power setting is given, the reference velocity can be calculated using Eq. (1), and a plume zone associated with a selected absolute plume velocity of interest can be determined from the standard normalized velocity contour plot using the estimated velocity ratio U/U_{ref}.

The effect that interaction of the individual jets has on the characteristics of the overall jet plume depends on the particular airplane configuration. At one extreme, when the engines are tightly clustered, like the three engines on a Boeing 727, the jets will interact strongly a short distance behind the airplane and, except at very low power settings, the jet plume will behave as if it were generated by a single nozzle. In this case, the size of the jet plume will be determined primarily by the total thrust and will be relatively insensitive to whether this thrust was generated by a single engine or by some combi-

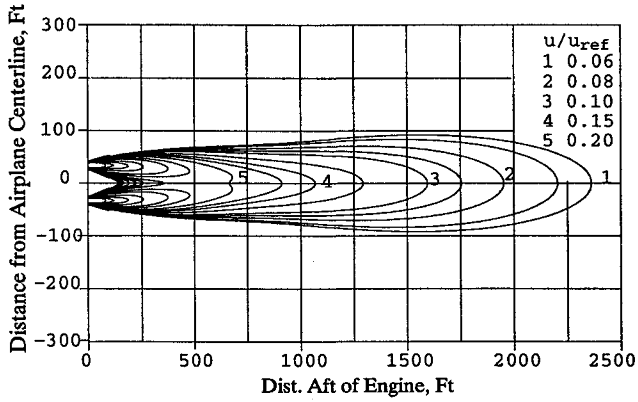

Fig. 6 Standard normalized velocity contour plot for a twin-engine airplane model.

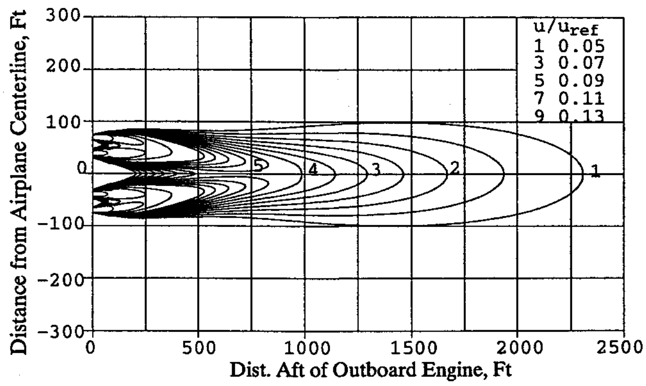

Fig. 7 Standard normalized velocity contour plot for a four-engine airplane model.

nation of all three engines. At the other extreme, if the engines on a two-engine airplane, for example, are mounted far enough apart so that there is little interaction between the jets, then each jet will decay independent of the other. In this case, the downstream extent of the jet plume will be determined by the thrust of the individual engines rather than the total thrust. This situation leads to the shortest overall jet plume for two-engine operations; but one needs to remember that if one of the engines is now shut down, as is sometimes done during taxiing, the length of the jet plume, for a given total thrust level, will be increased by about 40%, since the total thrust is now being generated by a single engine. The characteristics of the jet plumes of most airplanes fall somewhere between these extremes, with little interaction between the individual jets at low power settings and increasing interaction as the thrust level is increased.

Airport Plume Zone Mapping

Normalized jet plume velocity contour plots are now generated, for each airplane, from a three-dimensional jet plume analysis at the maximum engine power setting. Once the plots are available, the project engineer can calculate the jet plume for a particular engine power setting by simply scaling the standard plots. What makes this procedure particularly attractive and easy to use is the availability of sophisticated computer graphics tools.

The software used for airport plume zone mapping is X/Motif window based graphics software package. The project engineer can choose a jet plume velocity and a thrust level for an airplane position. Upon entering this input a plot is generated of the jet plume that is attached to the selected airplane. Several airplane positions with different thrust levels may be chosen, and with a linear interpolation, a smooth animated playback will be created. The movements of the airplane and the plume along a chosen path over a digitized map of an airport can be observed by playing this animation.

The present airport plume zone mapping tool displays the locations of plume zones relative to airport terminal buildings and the other airplanes parked nearby. The airport map and airplane configuration database are generated using a digitizer and a translator to convert the digitized data into CAD data. The software was developed for Silicon Graphics, Inc. (SGI) workstations using the SGI graphics libraries. However, it can be extended for use on other workstations and personal computers.

Results

Figure 8 shows one of the interactive user input windows. The input data required to use the software are the airplane configuration, the velocity contour level of interest (default = 35 mph), the coordinates along a taxiway, and the history of engine power setting along the taxiway.

Figure 9 shows three airplanes on a digitized map of Chicago O'Hare Airport. All three airplanes have displayed a 35-mph jet plume velocity and one plane also has a 75-mph jet plume velocity contour.

An example plume trace along a taxiway in O'Hare Airport is shown in Fig. 10. A trace of plume zones for the chosen 35-mph velocity contours was displayed along a taxiway. In this map, the engine power settings were gradually increased from an idle to a medium engine power. The map shows the locations of plume zones for a range of frames relative to airport buildings and the other airplanes parked nearby.

The capability of checking jet plume interaction with other airplanes nearby is shown in Fig. 11.

Current Development

So far, the discussion has been limited to situations where wind effects can be ignored. In practice, however, there is generally some wind present and a consideration of these effects raises a number of difficulties that are not present for the simple flow.

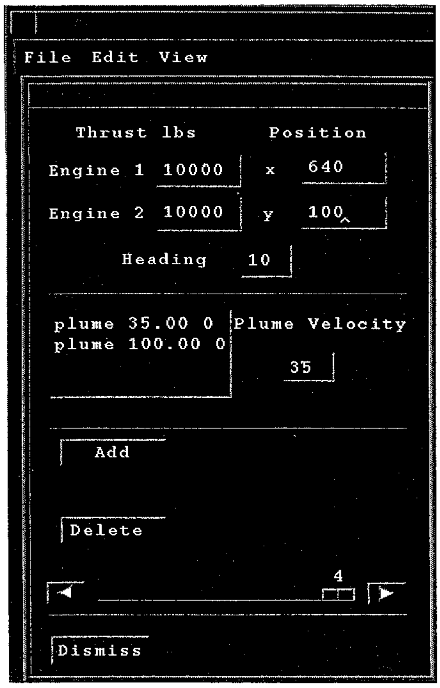

Fig. 8 Interactive user input window.

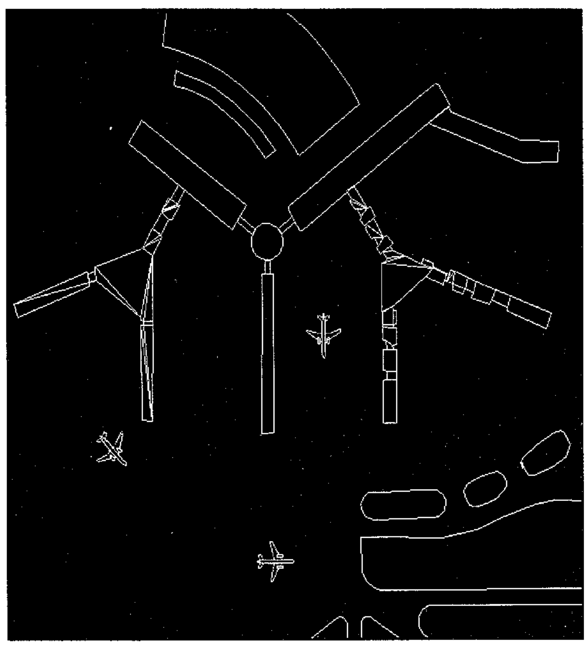

Fig. 9 Airport map (Chicago O'Hare Airport).

The first difficulty is associated with a clear definition of the flowfield to be analyzed. Typically, the magnitude and direction of the wind change continuously, both in space and time. Although it is possible to accurately monitor wind conditions at a particular point in an airport, the wind conditions encountered by an individual airplane will generally differ from those at the monitoring station, and from those encountered by other airplanes at the same airport.

In addition, to accurately analyze the jet plume development in the presence of a wind with arbitrary magnitudes and direction implies the use of a full three-dimensional Navier–Stokes analysis, as opposed to the parabolic analysis that is currently being used. This would substantially increase analysis costs and would probably not be practical for most applications considering the significantly long solution domain required to contain a jet plume.

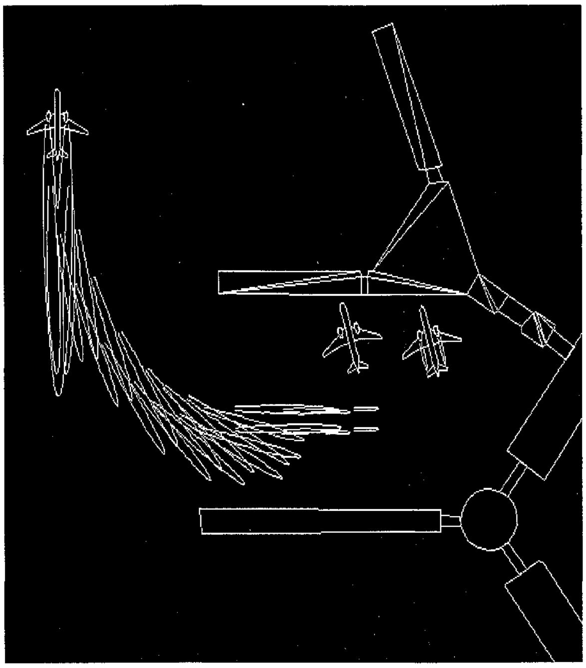

Fig. 10 Trace of plume zones for a twin-engine airplane.

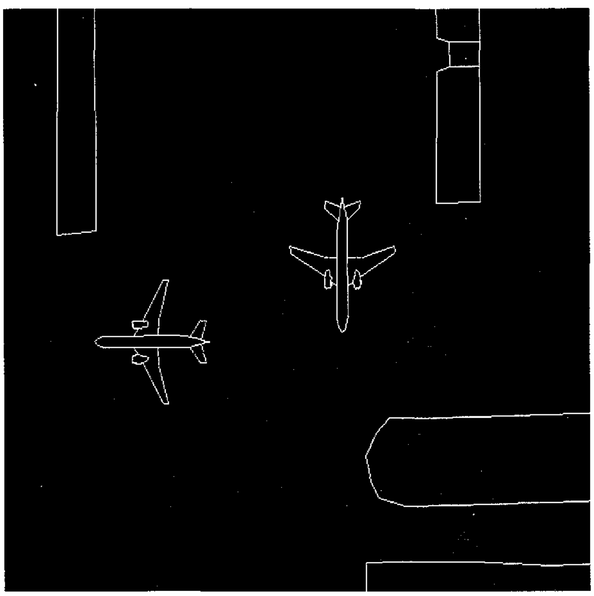

Fig. 11 Jet plume interaction with other airplanes.

There is also the problem of developing a consistent definition for the hazard zone itself. At present, the hazard zone is generally defined as the zone enclosed within a specific velocity contour, typically 35 mph. Such a definition would obviously not be valid in situations where the wind velocity itself might be greater than 35 mph.

As should be clear from the previous discussion, including the effects of wind on the development of a jet plume complicates the analysis considerably. Nevertheless, if interest is limited to relatively low velocities, and subject to the recognition that estimates of these effects will always necessarily be approximate, a relatively simple extension of the previously described analysis can be used.

Although true self-similarity does not appear to exist, even for simple freejets, in the presence of steady crossflow, these flows do appear to be approximately self-similar if the ratio of the jet to crossflow momenta is greater than 10 (Ref. 7). Since the deflection of the jet is determined primarily by the ratio of the jet to crossflow momenta, it has been demonstrated[7] experimentally that this parameter can be used to scale the data, as long as the jet momentum is an order of magnitude larger than the momentum of the crossflow. It is expected that this will also be true for the complete jet plume.

The effects of head- and crosswinds on jet plume zone for a twin-engine airplane model are shown in Figs. 12 and 13, respectively. In these analyses, the wind direction was assumed uniform and steady. Figure 12 indicates that increasing head wind extends the plume zone. Figure 13 shows that an increase in crosswind speed shortens the length of a plume zone in the downstream direction, but widens the plume zone in the lateral direction. An investigation to determine aircraft ground operation limits on windy days is under way.

It is believed that a head wind and a crosswind are the conditions that will tend to give the largest increase in the size of the hazard zone.

These calculations all assume a steady external flow. In practice, the situation is considerably more complex than this because the jet plume is actually interacting with a thick three-dimensional boundary layer. These analyses should, therefore,

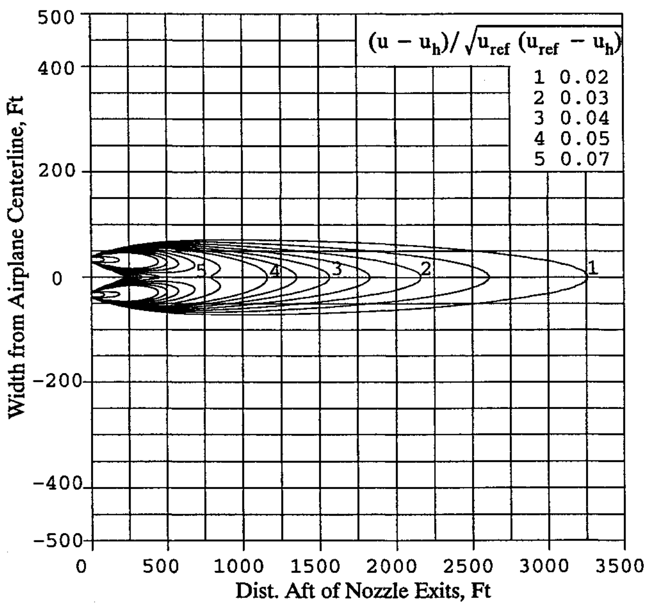

Fig. 12 Effect of head wind on standard normalized velocity contours for a twin-engine airplane.

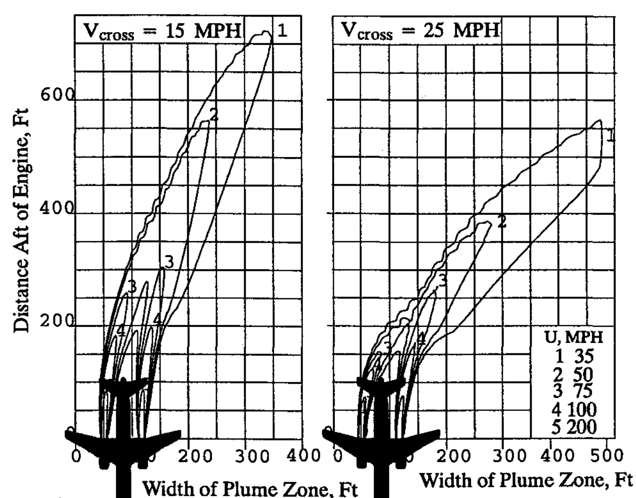

Fig. 13 Effect of crosswind on jet velocity contours for a twin-engine airplane model.

be regarded as a preliminary estimate of the effects of wind on the decay of the jet plume.

Conclusions

A computerized airport plume zone mapping method that is useful for ground operation studies for a given airport has been developed and demonstrated. This method is based on the combination of the standard normalized plume velocity contour plot technique and computerized graphics animation techniques to display the jet plume zones within an airport. The following conclusions can be drawn based on the present study:

1) The plume zone mapping tool can be used by airlines and airports to ensure safe ground operation of an airplane and for airport design and planning.

2) The mapping process is easier to use, more accurate, and dramatically cheaper and faster than the old process.

3) A standard normalized velocity contour plot can be generated as a function of engine power for an airplane model and then used to determine the plume zones associated with a selected velocity level over an entire range of engine power setting.

4) Preliminary results suggested that a plume zone with a selected plume velocity level becomes longer and wider because of the effects of a head- and a crosswind, respectively. More work is required to effectively include the wind effect into the airport plume zone mapping tool.

Acknowledgment

The authors thank Gerald C. Paynter of The Boeing Company for valuable discussions and comments on the subject of this article.

References

[1]Birch, S. F., Paynter, G. C., Spalding, D. B., and Tatchell, D. G., "Numerical Modeling of Three-Dimensional Flows in Turbofan Engine Exhaust Nozzles," *Journal of Aircraft*, Vol. 15, No. 8, 1978, pp. 489–496.

[2]Barton, J. M., and Birch, S. F., "Numerical Modeling of a 7-Tube Nozzle/12-Lobe Moxer Jet Flow," *AIAA Journal*, Vol. 19, No. 3, 1981, pp. 259, 260.

[3]Tjonneland, E., and Birch, S. F., "Application of Viscous Analyses to the Design of Jet Exhaust Powered Lift Installations," *Engineering for Power*, Vol. 102, No. 3, 1980, pp. 626–631.

[4]"Advisory Circular," U.S. Dept. of Transportation, Federal Aviation Administration, A/C 150/5300-13, Sept. 2, 1989.

[5]"767 Airplane Characteristics—Airport Planning," Boeing, D6-58328 Rev. F, Feb. 1989.

[6]Rodi, W., "Review of Experimental Data of Uniform Density Free Turbulent Boundary Layers," *Studies in Convection*, Vol. 1, edited by B. E. Launder, Academic, London, 1975.

[7]Keffer, J. F., and Baines, W. D., "The Round Turbulent Jet in a Cross-Wind," *Journal of Fluid Mechanics*, Vol. 15, Pt. 4, 1963, pp. 481–497.

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