Wake Vortex Encounter Research

Jeffrey M. Wilson
The University of Kansas
Langley Aerospace Researchers Summer Scholar

Robert A. Stuever
NASA Langley Research Center
Hampton, VA

Research and Technology Group
Flight Dynamics and Control Division
Vehicle Dynamics Branch

Abstract

The National Aeronautics and Space Administration (NASA) is conducting research to improve airport capacity by reducing the separation distance between aircraft. The limiting factor in reducing separation distances and improving airport capacity is the wake vortex hazard. The ability to accurately model wake vortices and predict the outcome of a vortex encounter is critical in developing a system to safely improve airport capacity. This is the focus of the wake vortex research being done at NASA Langley Research Center (LaRC). This paper will concentrate on two topics. The first topic is the control system developed for the Boeing 737 freeflight model in support of vortex encounter tests to be conducted in the 30- by 60- foot tunnel at NASA Langley Research Center later this year. The second topic discussed is the limited degree of freedom (DOF) trajectory generation study that is being conducted to determine the relative severity of a multitude of paths through a wake vortex.

Introduction

While the number of aircraft in the world fleet is projected to more than double by the year 2015, many of the world's major airports are already capacity limited.(1) The National Aeronautics and Space Administration (NASA) is currently conducting research to enable safe improvements in the capacity of the nation's air transportation system. One part of the NASA research program is the Terminal Area Productivity (TAP) Program. This program is responsible for conducting the necessary research to support the Federal Aviation Administration (FAA) and the aviation industry in safely achieving fair weather airport capacity in instrument meteorological conditions. The TAP Program is subdivided into four elements: Air Traffic Management, Aircraft-Air Traffic Control Systems Integration, Low-Visibility Landing, and Reduced Spacing Operations.

The Reduced Spacing Operations element is responsible for conducting research on reducing the in-trail spacing distance between airplanes. Improvements in landing frequency by reducing in-trail spacing distances have the potential to increase system capacity by 10-15%.(2) The limiting factor in reducing the spacing distances is the wake turbulence phenomena. The wake of an aircraft is characterized by two counter-rotating vortices that are spaced at a distance of slightly less than the aircraft span. Another aircraft encountering one of these vortices could either be mildly perturbed or catastrophically upset. The degree of upset is dependent on a number of factors including relative sizes of the aircraft.

The current aim of the wake vortex research program at NASA Langley Research Center (LaRC) is to create a methodology that will allow researchers to accurately model wake vortices and characterize the hazard posed by them. The purpose of this hazard characterization research is to relate the potential vortex hazard to sensor observable quantities. A sensor based system designated as Aircraft Vortex Spacing System (AVOSS) will then be developed to predict, detect, track, and quantify wake vortices.(3) Hazard analyses will be applied to determine if an aircraft could safely penetrate a vortex that has been detected in the approach corridor. This report will discuss the development of a freeflight model control system and the trajectory generation study conducted at LaRC as part of the wake vortex research program.

Freeflight Model Control System

As part of the wake vortex research program, tests will be conducted to determine the dynamic effects of flying a Boeing 737 within the wake of another aircraft. In one test, a scale model of the Boeing 737 aircraft will be flown behind a simulated second aircraft within the test section of the 30- by 60- foot tunnel at LaRC. Control laws were developed for the Boeing 737 freeflight model based on the control system for the Boeing 737-100 at LaRC. The control laws represent the Boeing 737 for eight candidate approach flight conditions in which the flap settings and airspeed vary. Aerodynamic data for each of the eight flight conditions were obtained for the state-space matrices from a Boeing 737 simulation database. Actuator models, maximum control surface deflections, and yaw damper models were obtained from Boeing documentation. A SIMULINK file was then created to analyze the dynamics of the full scale aircraft. The control laws for the full scale aircraft were scaled down to the model size using Froude number scaling as explained by Wolowicz, et al.(4) The model control system was then analyzed to ensure dynamic similarity existed between the model and the actual aircraft.

Trajectory Generation Study

The purposes of the trajectory generation study were twofold. The first objective was to determine the validity of using simple and approximate planform and mass characteristics to predict the severity of vortex encounters. The primary advantage of using such relatively simple techniques is the ease of which the study could be applied as a means of hazard prediction for the entire commercial fleet. The second objective of the study was to obtain a database about the severity of a vortex-induced upset for a multitude of paths through a wake for several follower-generator aircraft pairs.

For this study, a MATLAB simulation was developed based on simplified math models of aircraft. Generator aircraft were assumed to have elliptic spanwise lift distributions. Using the known characteristics of vortices shed from aircraft with ellipitic spanwise lift distributions, the wake vortices of the generator aircraft were then modeled by an accepted vortex velocity-distribution. Strip theory was used to calculate the aerodynamic forces and moments induced on the follower aircraft by the vortices. Explicit solutions for the induced lift and rolling moment coefficients were obtained from Tatnall by integration of the strip theory equations.(5) Using the induced lift and rolling moment coefficients, Bowles determined the equations of motion of the follower aircraft in the wake of the generator aircraft.(6) With these equations, the simulation could be altered to allow the follower aircraft either one degree of freedom (DOF), roll, or three DOF, roll and translation along the Y and Z axes.

To simulate the decay of actual vortices with time in the atmosphere, the wake vortices in the vortex encounter simulation were decayed linearly with non-dimensional time. This vortex decay model is based on worst case situation of tower fly-by data in research conducted by Greene. (7)

In the simulation runs completed for this report, the Boeing 737 was used as the follower aircraft. In previous vortex encounter simulations, the follower-generator span ratio was determined to be a key parameter in predicting the severity of a vortex encounter. Accordingly, generator aircraft were selected to represent a range of follower to generator span ratios. The selected ratios were 0.5 (Boeing 747 as the generator aircraft), 1.0 (Boeing 737), and 2.0 (Learjet 60). An additional aircraft pair with a span ratio of 0.7 was analyzed. This span ratio represents the Lockheed C-130 as the generator aircraft and was selected since the C-130 is a candidate vehicle for flight experiments.

Each simulation run consisted of 99 passes through the generator wake in which each pass differed in the lateral and vertical approach angles. The lateral approach angles selected were -20° to 20° in 5° increments. The vertical approach angles used were -10° to 10° in 2° increments. The Boeing 737 began each pass two generator spans away from the location of maximum induced rolling moment in the wake and aimed for this location. The pass ended when the follower aircraft was once again two generator spans away from the location of maximum rolling moment. Simulation runs will be completed for cases in which the follower aircraft will have no roll control power and full roll control power.

After the data is collected, a sensitivity analysis will be conducted for a nominal approach condition. The objective of the analysis is to evaluate the relative importance of certain parameters in determining the outcome of a vortex encounter. This information will be useful in hazard prediction.

Trajectory Generation Study Results

The trajectory generation study was not completed at the time this report was written. Sample 1 and 3 DOF results of a Boeing 737 encountering the wake of a Boeing 747 are available and will be discussed presently. These results are for the follower aircraft with no roll control inputs.

Figure 1 is a series of plots which contain the results of a 1 DOF penetration of the location of maximum rolling moment. The penetration occurs at the FAA specified separation distance of 5 nautical miles for this aircraft combination. The encounter shown in Figure 1 occurs when the Boeing 737 is on a 4° glideslope in the approach flight condition. The plot in the upper right corner indicates the follower aircraft reaches a maximum bank angle of -243°. The plot on the middle right shows that the maximum induced roll rate is -58 °/sec. These results are unrealistic but are explained by the fact that since the penetration occurs a such a slow rate, the aircraft is allowed to remain inside the vortex for a considerable period of time. Furthermore, the follower aircraft is constrained to only roll. As will be seen in Figure 2, if the aircraft would have had additional degrees of freedom, the magnitudes of the vortex induced perturbations would have been smaller.

Figure 2 contains the 3 DOF results for the same initial trajectory as in Figure 1. As can be seen in the plot in the upper left corner, the follower aircraft is removed from the intended path and is driven over 200 feet off course. It is apparent from the plot in the lower left that the aircraft is also accelerated downward. If this dangerous situation had occurred, the follower aircraft could have potentially crashed. At the very least, the aircraft would have been forced out of the approach corridor and would have had to execute a 'go-around'. It should also be noted that the bank angle and roll rate perturbations are smaller that the 1 DOF values but nonetheless result in unacceptable passenger comfort levels.

Once the trajectory generation study is completed, the data will be analyzed to determine a criteria for the estimating the potential of a wake vortex upset on a given trajectory. A worst case trajectory for a vortex encounter will then be determined.

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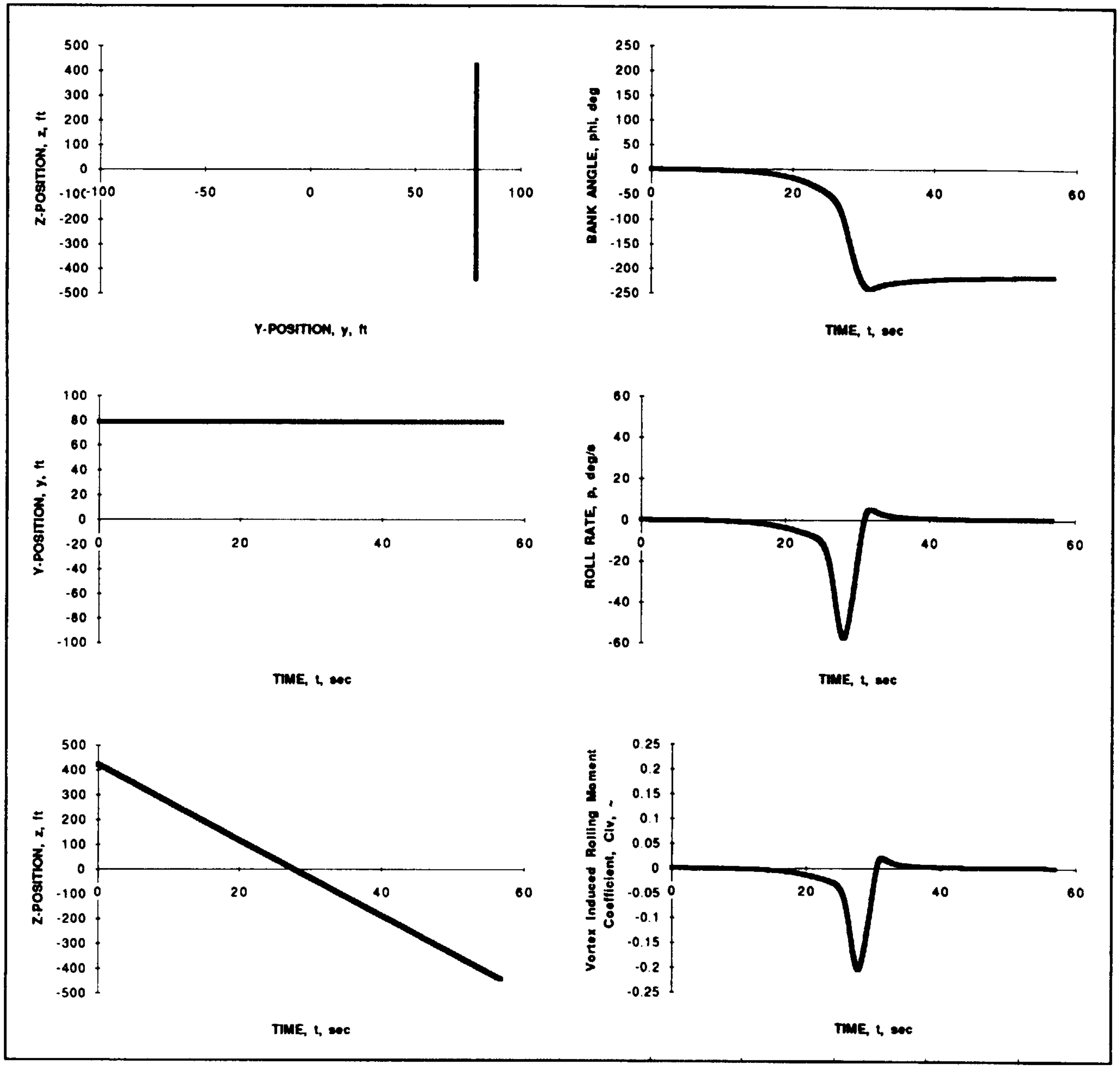

Figure 1. One Degree of Freedom Data of a Boeing 737 Encounter with a Boeing 747 Wake Vortex

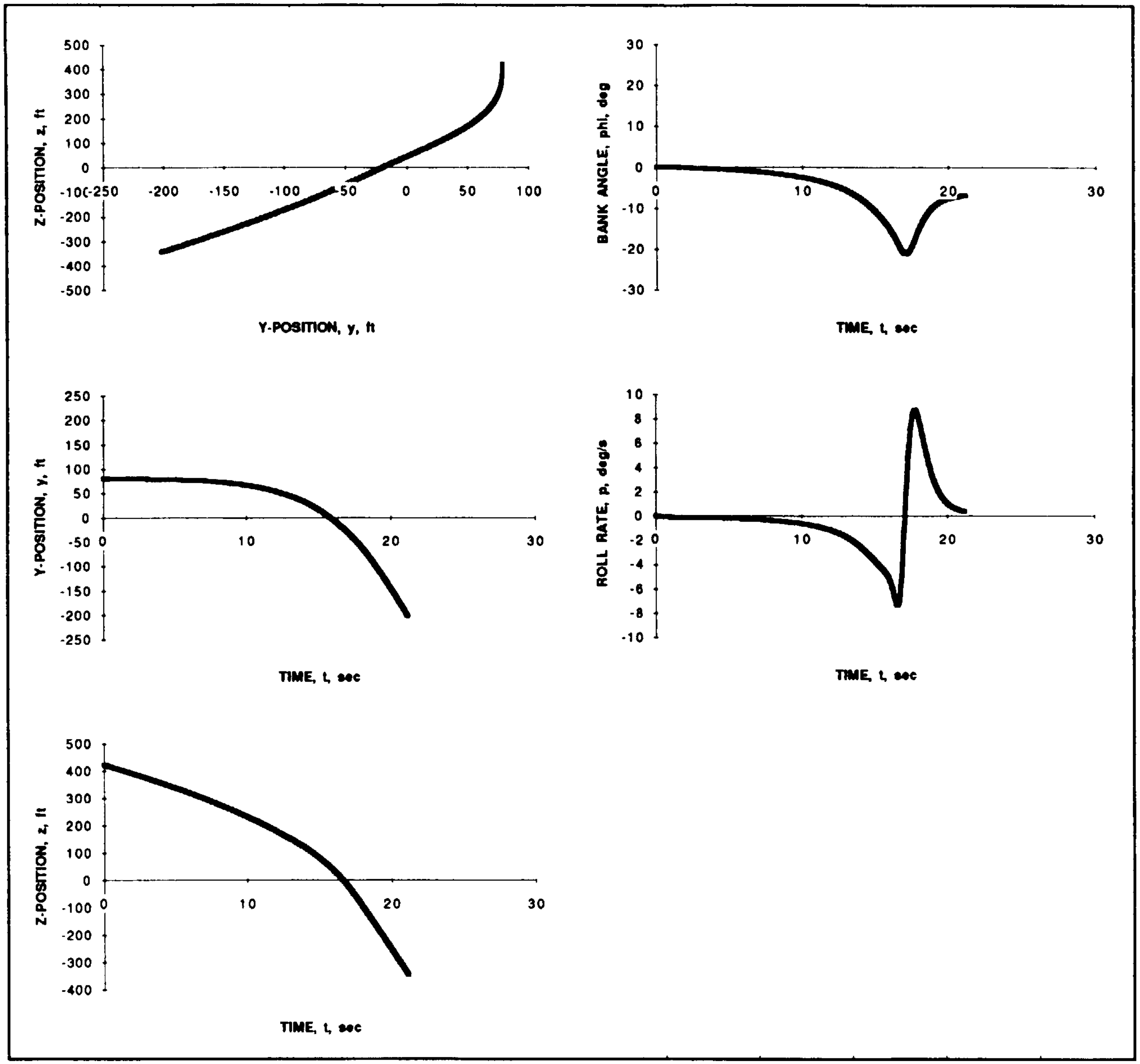

Figure 2. Three Degree of Freedom Data of a Boeing 737 Encounter with a Boeing 747 Wake Vortex