AIAA 2000- 3908

FLIGHT TEST ANALYSIS OF THE FORCES AND MOMENTS IMPARTED ON A B737-100 AIRCRAFT DURING WAKE VORTEX ENCOUNTERS

Christopher L. Roberts & Sonya T. Smith
Howard University
Washington, DC

Dan D. Vicroy
NASA Langley Research Center
Hampton, VA

AIAA Atmospheric Flight Mechanics Conference
14-17 August 2000 / Denver, CO

AIAA 2000-3980

FLIGHT TEST ANALYSIS OF THE FORCES AND MOMENTS IMPARTED ON A B737-100 AIRCRAFT DURING WAKE VORTEX ENCOUNTERS

Christopher L. Roberts
Department of Mechanical Engineering
Howard University

D. D. Vicroy[+]
NASA Langley Research Center

S.T. Smith
Howard University

Abstract

Several of our major airports are operating at or near their capacity limit, increasing congestion and delays for travelers. As a result, the National Aeronautics and Space Administration (NASA) has been working in conjunction with the Federal Aviation Administration (FAA), airline operators, and the airline industry to increase airport capacity and safety. As more and more airplanes are placed into the terminal area the probability of encountering wake turbulence is increased. The NASA Langley Research Center conducted a series of flight tests from 1995 through 1997 to develop a wake encounter and wake-measurement data set with the accompanying atmospheric state information. The purpose of this research is to use the data from those flights to compute the wake-induced forced and moments exerted on the aircraft. The calculated forces and moments will then be compiled into a database that can be used by wake vortex researchers to compare with experimental and computational results.

Introduction

Aircraft travel has been a primary form of transportation over the past four decades. Due to increased air traffic, major airports are currently operating at or near their capacity limit. This has translated into increased congestion and passenger delay. As early as the 1950s, scientists have recognized this as a potential problem and sought methods to alleviate this condition. Recently, the National Aeronautics and Space Administration (NASA) has been working in conjunction with the Federal Aviation Administration (FAA), commercial airlines, and aircraft manufactures to increase airport capacity and improve safety. Several solutions have been proposed. The most feasible method is to increase the production per runway by decreasing the separation distances between aircraft during takeoffs and landings during instrument flight rules.

Depending upon the flight airspace, weather, visibility, and the aircraft's distance from clouds, Air Traffic regulations require the pilots to fly under either Visual flight rules (VFR) or Instrument flight rules (IFR). Under VFR, the pilots are responsible for maintaining safe separation distances. Under IFR, the Air Traffic Controllers (ATC) are responsible for maintaining the separation distances mandated by the FAA [1]. When conditions require an airport to operate under IFR, the airport capacity is significantly diminished. This has led to speculation that IFR separation may unnecessarily limit the operating capacity of major airports.

In order to decrease IFR separation distances, it is necessary to address the issue of a hazardous wake encounter. Wake vortices, also known as wing-tip vortices, are created when the airflow over the top surface of a wing meets the airflow over the top of the bottom wing surface. The air flowing over the top surface of the wing flow inwards towards the wing centerline; whereas, the air flowing over the under-surface of the wing flows outward towards the wing's tip. When the two airflows meet at the wing's trailing edge, they join at an angle creating clockwise and counter-clockwise rotating vortices.

Vortices are created by all classes of aircraft: Heavy (300,000lb or more), Large (between 12,500lb and 300,000lb), and Small (less than 12,500lb) [2]. When a following, lighter load aircraft encounters the wake from a heavy load aircraft, the aerodynamic load of the following aircraft is redistributed. This can result in a loss of control for the lighter aircraft and is particularly hazardous during take-offs and landings. For this reason, the FAA has set specific longitudinal separation distance guidelines to ensure that the following aircraft will

---

[+] Aerospace Engineer, Vehicle Dynamics Branch, Senior Member AIAA not encounter the wake of the heavier aircraft (Table 1).

Trailing Aircraft	Leading Aircraft		
	Heavy	Large	Small
Heavy	4	3	3
Large	5	3	3
Small	6	4	3

Table 1: U.S. Wake-Vortex Separation Standards, in nautical miles.

As more and more airplanes are placed into the terminal area, the probability of encountering wake turbulence is increased. Therefore, a better understanding of wake-vortex/aircraft interactions has to be gained before new separation guidelines can be established.

The purpose of this project is to design and implement a procedure for computing the wake-induced forces and moments imparted on an aircraft during a wake-vortex encounter. This author conducted research at NASA Langley Research Center utilizing data that was collected in a series of flight tests from 1995-1997. Information gathered in this study will be stored in a comprehensive database containing wake-vortex, atmospheric state, and wake-vortex/aircraft encounter data. The database will then be used for the comparison and validation of current and future wake-encounter simulations. Such simulation data can be used by the FAA to evaluate reduced separation guidelines.

Approach

As stated previously, NASA Langley Research Center conducted a series of flight tests from 1995-1997 with the express purpose of developing a comprehensive database consisting of wake-vortex measurements and wake-vortex/aircraft interaction data, along with the accompanying atmospheric conditions. This database would then be used for comparison and validation of experimental and computational simulations and their results. Using data from those flights, this research focused on describing the wake-vortex/ aircraft interaction by computing the wake-induced forces and moments imparted on the B737-100 aircraft.

To derive the wake-induced forces and moments (FAM_{wi}) imparted on the B737, it was necessary to use the motion and control deflections recorded onboard the aircraft. This flight data was initially put into a modified B737 simulation, whereby the FAM of the AC out of the wake's presence ($FAM_{no\ wake}$) was computed. Using the same flight data, the aircraft's forces and moments in the wake's presence (FAM_{wake}) were derived by employing a series of transformation and motion equations. The difference on the two sets of FAM yielded the wake-induced forces and moments.

$$FAM_{wi} = FAM_{wake} - FAM_{no\ wake} \qquad (1)$$

Modified Simulation

In order to compute the forces and moments (FAM) of the B737 out of the presence of the wake, it was necessary to modify a six degree-of-freedom real-life simulation of NASA Langley's Advanced Transport Operating System (ATOS) B737-100 research aircraft. The original simulation was created for the purpose of studying the major systems onboard the aircraft (engine, landing gear, pitch control, roll control, yaw control, etc.) in addition to computing the aircraft's FAM. For the purpose of this research, it was necessary to modify this simulation by isolating the FAM subroutine and determining which control state variables were required for its operation.

Validation of the modified simulation, called Wv27b, was accomplished in a two step process. The first step consisted of inputting a test case into the original simulation. This original simulation then created data files containing both the aircraft's FAM and the control state variables required for the modified simulation. The data file containing the control variables was then input into Wv27b whereby a second set of forces and moments were derived. The modified simulation was considered valid when the two sets of FAM were considered equal.

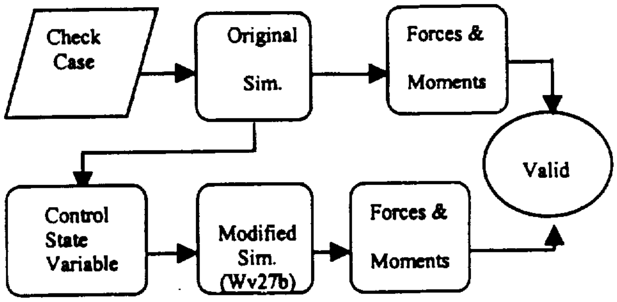

Figure 1: Modified Simulation Validation Schematic

The final procedure in computing the FAM of the B737 aircraft out of the wake's presence consisted of mapping the control state variables to the flight data variables. Using the actual flight data it was then possible to compute the forces, moments, engine thrust values, and moments of inertia of the Boeing 737-100 aircraft.

Transformation and Motion Equations

To determine the FAM of the aircraft in the presence of the wake, it was necessary to use a series of transformation and motion equations [3]. The aircraft's body force components were derived using the weight (W), longitudinal acceleration (Acc_{Lon}), lateral acceleration (Acc_{Lat}), and normal direction acceleration (F_{NZ}) data from the B737 flight data [3]:

$$F_X = (Acc_{Lon} * W) / g \qquad (2)$$

$$F_Y = (Acc_{Lat} * W) / g \qquad (3)$$

$$F_Z = (F_{NZ} * W) / g \qquad (4)$$

Converting these forces from the body axis to the stability axis, the lift (C_L), drag (C_D), and sideforce (C_Y) coefficients became

$$C_L = -((F_X - T_X) \sin\alpha - F_Z \cos\alpha) / qS \qquad (5)$$

$$C_D = ((F_X - T_X) \cos\alpha + F_Z \sin\alpha) / qS \qquad (6)$$

$$C_Y = F_Y / qS \qquad (7)$$

T_X is defined as the body axis thrust derived by the modified simulation, S is the aircraft's wing area, and q is the dynamic pressure.

The next step consisted of solving for the B737's rolling (C_l), pitching (C_m), and yawing (C_n) moments in the presence of the wake. This procedure involved computing the total moments of the aircraft in terms of the pitch rate (Q), roll rate (P), and yaw rate (R) [3]. It was also necessary to use the B737's moments of inertia (I_{XX}, I_{YY}, I_{ZZ}, I_{XZ}) derived by Wv27b:

$$M_X = P_{DOT}*I_{XX} - R_{DOT}*I_{XZ} + Q*(R*I_{ZZ} - P*I_{XZ}) - R*(Q*I_{YY}) \qquad (8)$$

$$M_Y = Q_{DOT}*I_{YY} + R*(P*I_{XX} - R*I_{XZ}) - P*(R*I_{ZZ} - P*I_{XZ}) \qquad (9)$$

$$M_Z = R_{DOT}*I_{ZZ} - P_{DOT}*I_{XZ} + P*(Q*I_{YY}) - Q*(P*I_{XX} - R*I_{XZ}) \qquad (10)$$

P_{DOT}, Q_{DOT}, and R_{DOT} represented the rate changes in the roll, pitch, and yaw rates respectively. Rewriting these moment equations in coefficient form:

$$C_l = M_X / (qSb) \qquad (11)$$

$$C_m = (M_Y + T_m) / (qSc) \qquad (12)$$

$$C_n = (M_Z + T_n) / (qSb) \qquad (13)$$

T_m and T_n were added to the preceding equations to account for the thrust contributions in the pitching and yawing moments. Converting these moments to the stability axis,

$$C_{LS} = C_l * \cos(\alpha) + C_n * \sin(\alpha) \qquad (14)$$

$$C_M = C_m \qquad (15)$$

$$C_N = -C_l * \sin(\alpha) + C_n * \cos(\alpha) \qquad (16)$$

At this point, it was now possible to derive the wake-induced forces and moments exerted on the B737 aircraft by modifying equation 2.1.1:

$$FAM_{wi} = FAM_{wake} - FAM_{no\ wake} \qquad (17)$$

$$= FAM\ E.O.M - FAM\ Wv27b \qquad (18)$$

Trim Shots

Prior to calculating the wake-induced forces and moments (FAM_{wi}), it was necessary to examine the flight data for any biases. This task was accomplished by examining the trim shots for each flight. These "trim shots" were defined as segment(s) of flight in which the aircraft is placed in a trim, or level, state of flight. Trim shots were conducted before and after each flight, at flap deflections of 15 and 30 degrees.

To determine the data bias in a particular flight, the trim shot data at a flap deflection of 15 degrees was input into the Wv27b simulation and the equations of motion. This action produced two sets of forces and moments (FAM). The differences in the two sets of FAM yielded the flight data bias at that flap setting:

$$FAM_{bias} = FAM_{E.O.M} - FAM_{Wv27b} \qquad (19)$$

This process was repeated using the trim shot data at a flap deflection of 30 degrees. Both sets of FAM_{bias} were then averaged to determine the mean flight data biases ($FAM_{M.bias}$) for the entire flight. This procedure was performed for each flight.

$$FAM_{M \cdot bias} = (FAM_{bias(15)} + FAM_{bias(30)}) / 2 \qquad (20)$$

Flight No.	CL M. bias	CD M. bias	CY M. bias
558	.008016	.003821	.002287
559	.042408	.014145	.012470
560	.018742	.002224 2410	.007097
561	.064694	-.000504	-.000203

Table 2a: Mean flight data biases

Flight No.	CLS M. bias	CMS M. bias	CN M. bias
558	-.015421	-.000031	-.001344
559	.012136	.003703	.000910
560	-.019048	.001341	.003738
561	.004717	-.000547	-.000389

Table 2b: Mean flight data biases

Once the mean flight data biases were computed, it was then possible to calculate the wake-induced forces and moments of each "event", or wake encounter, in a flight by modifying equation 18:

$$FAM_{wi} = FAM_{wake} - FAM_{no\ wake} - FAM_{M.bias} \quad (21)$$

RESULTS

The purpose of this research was to analyze the wake-induced forces and moments contained in each flight based on three criteria: flap deflection, separation distance, and flight maneuver. In order to perform these analyses, it was also necessary to calculate the FAM of each "event" in and out of the presence of the wake. The difference in the two sets of FAM, minus the $FAM_{M.bias}$, yielded the wake-induced forces and moments.

It was also necessary to determine the "age" of the wake vortex during each event. This age was defined as the time between the creation of the wake and its interception by the B737. The wake's age was computed by using a wake velocity program (Wake_Vel) described in reference [4]. As a result, the average FAM_{wi} for each event were plotted as a function of the wake's age. In addition, error bars to denote the minimum and maximum values of the average FAM_{wi}.

3.1 Flap Deflection

The first analysis performed in this research looked at the effects of flap deflection on the wake-induced forces and moments. This study was conducted using the event, or wake encounter, data from each flight to generate the wake-induced forces and moments (FAM_{wi}). The chart below lists the separation distance of each flight:

FLIGHT	Separation Distance
558	2
559	1
560	2
561	2

Table 3: Separation distances, in nautical miles.

Looking at the wake-induced rolling lift coefficient (C_{Lwi}) in figure 2, there appeared to be a clear difference in the average value in flights 558 and 559. At flap deflection of 15 degrees, the average C_{Lwi} was slightly higher. However, this pattern was not repeated in flights 560 or 561. In these flights, there was no clear distinction between 15 and 30 degrees. Similar results were demonstrated in the wake-induced drag coefficient (C_{Dwi}) and pitching moment coefficients (C_{Mwi}).

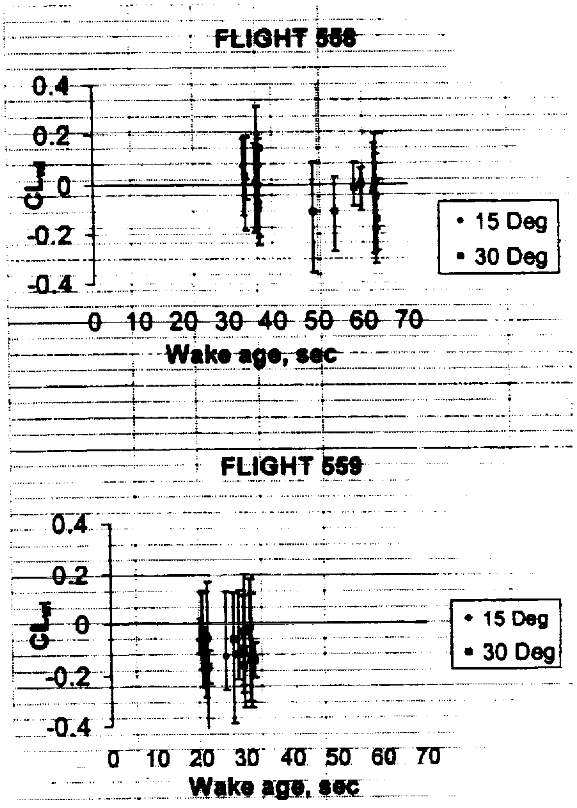

Figure 2: Wake-induced lift coefficient, based on flap deflection.

Analysis of the sideforce (C_{Ywi}), rolling moment (C_{LSwi}), and yawing moment (C_{Nwi}) yielded results which were more definite. In each flight, the averages of the forces and moments were constant for flap settings of 15 and 30.

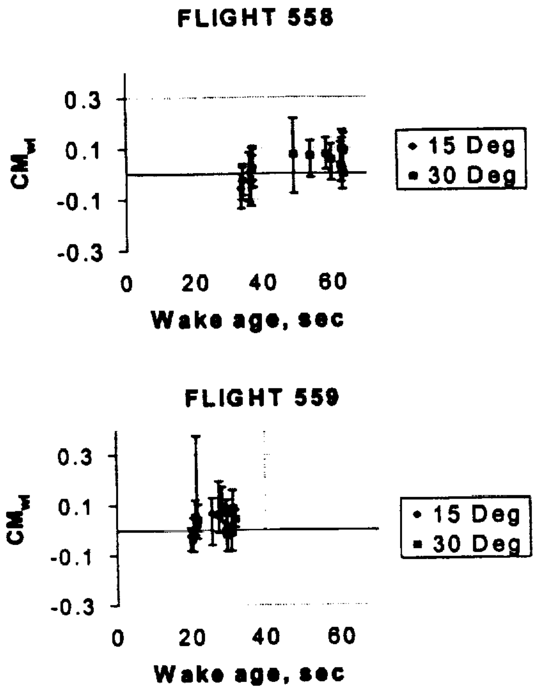

Figure 3: Wake-induced pitching coefficient, based on flap deflection.

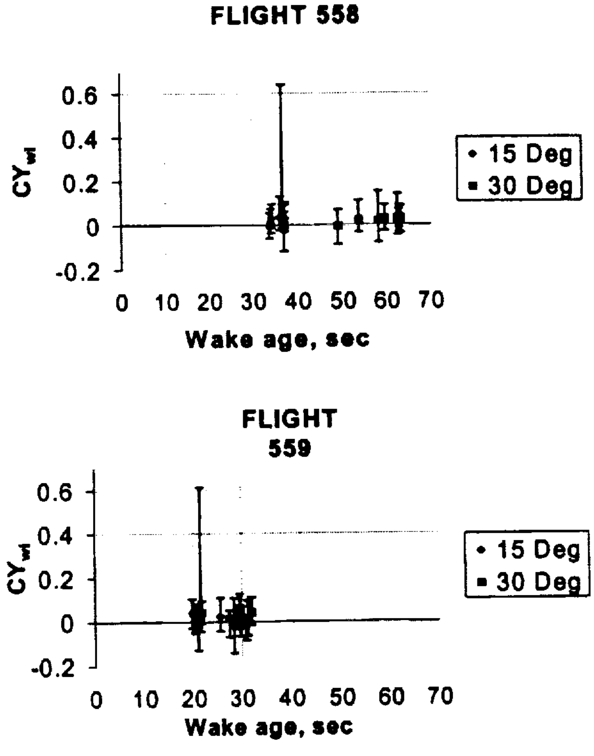

Figure 4: Wake-induced sideforce coefficient, based on flap deflection.

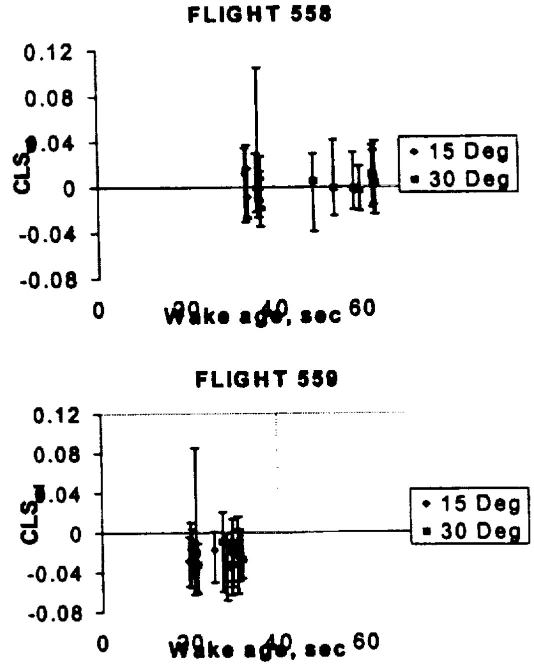

Figure 5: Wake-induced rolling moment coefficient, based on flap deflection.

Separation Distance

The second criterion analyzed in this research was that of separation distance variation. The purpose of this analysis was to determine if increased separation distances reduced the effects of the wake and vice versa. This study was conducted using the encounter data from flight 558,559,and 560 to generate the wake-induced forces and moments (FAM_{wi}). The separation distances in these encounters ranged from 1-3 nautical miles while flap deflection was constant at 30 degrees. Flight 561 was omitted from this particular analysis due to insufficient amounts of data at 3nm.

Upon analyzing the data, it was apparent that variations in these separation distances had no profound impact on some of the FAM_{wi}. In figure [6], the average wake-induced lift coefficient (C_{Lwi}) was consistent between 1nm and 2nm, ranging from –0.1 to 0.1. Similar findings were demonstrated between 2nm and 3nm in flight 560. This pattern was mimicked in the wake-induced sideforce (C_{Ywi}) and yawing moment (C_{Nwi}). For the case of the wake-induced drag coefficient (C_{Dwi}), figure [7], it was noticed that the average was consistent at 1-2nm. Yet, the average C_{Dwi} was slightly less at 3nm.

Analysis of the FAM_{wi} also provided inconclusive results in the areas of pitching and rolling moment. Looking at the wake-induced pitching moment (C_{Mwi}) in flights 558 and 560, the average initially appeared to increase slightly as the separation distance increased.

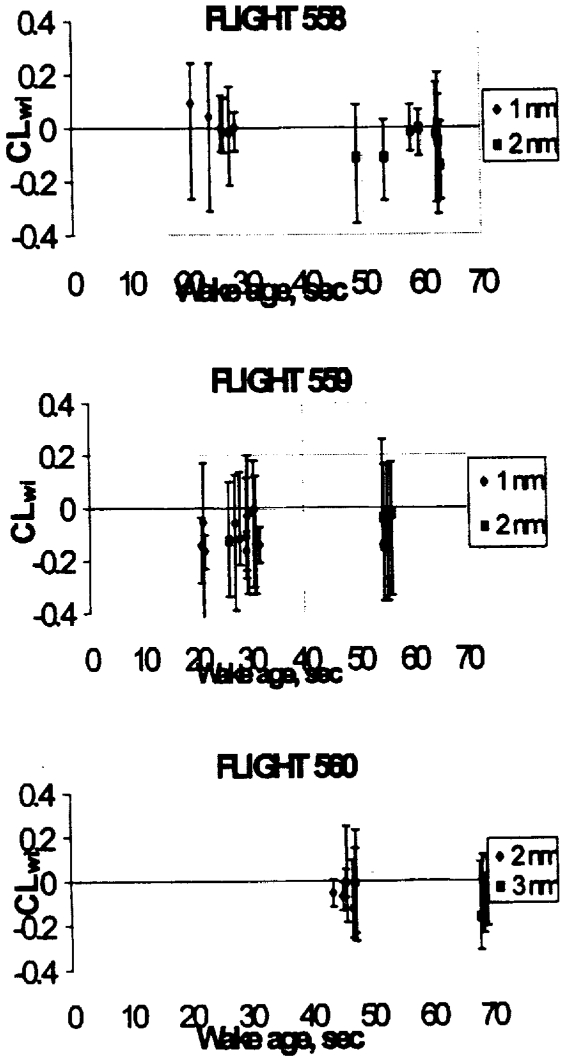

Figure 6: Wake-induced lift coefficient, based on separation distance.

In contrast, the average in flight 559 suggested that the average between 1-2nm was roughly equal, thus making the results from the other flights inconclusive. The same situation occurred in evaluation of the wake-induced rolling moment (C_{LSwi}).

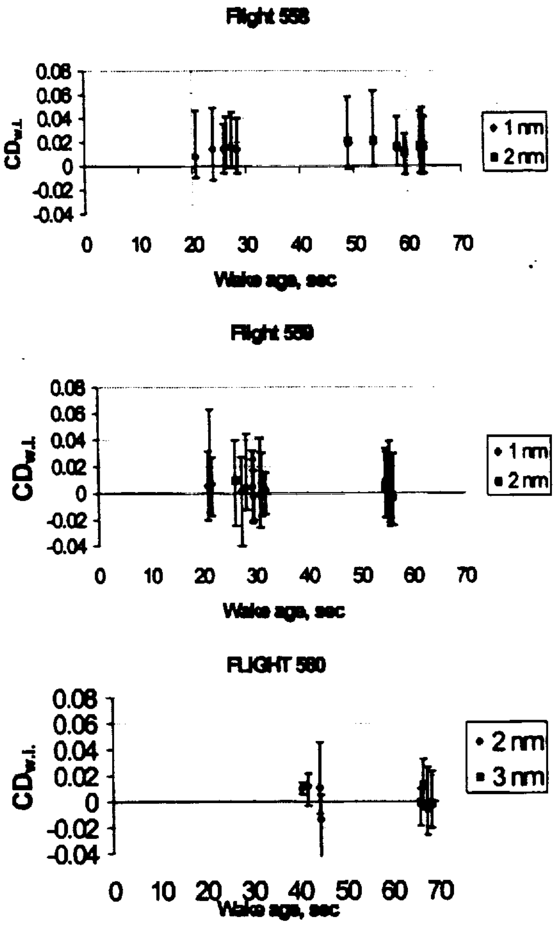

Figure 7: Wake-induced drag coefficient, based on separation distance.

Maneuver Comparison

In NASA LaRC's flight tests, the Boeing 737 executed a series of flight maneuvers, or patterns, as it penetrated the wake vortex. These patterns were defined as out-to-in (OTI), in-to-out (ITO), down-to-up (DTU), and up-to-down (UTD).

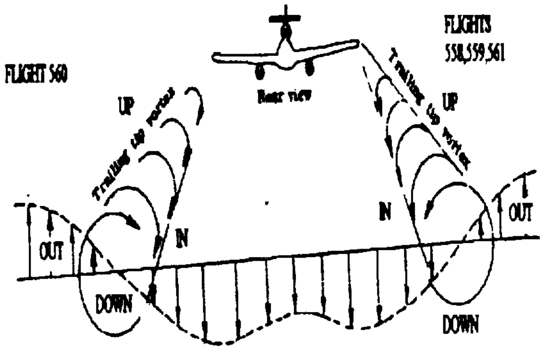

Figure 8: Description of flight maneuvers

The purpose was to determine the affects of the wake-induced forces and moments on the aircraft during these penetrations. To perform this analysis, the FAM_{wi} originated from wake encounter data taken in each flight. In these flights, the separation distance and flap deflection remained constant, allowing only the flight maneuver to change.

Flight #	Flap Deflection	Separation Distance
558	15	2nm
559	30	1nm
560	15	2nm
561	15	2nm

Table 4: Flap deflection and separation distance constants

Analysis of the wake-induced forces and moments of varying flight patterns did provide some useful information. Looking at the wake–induced lift coefficient (C_{Lwi}) in figure [9], OTI maneuvers appeared to have the largest average values in every flight. This suggested that the wake imposed more lift on the aircraft in this situation than in any other.

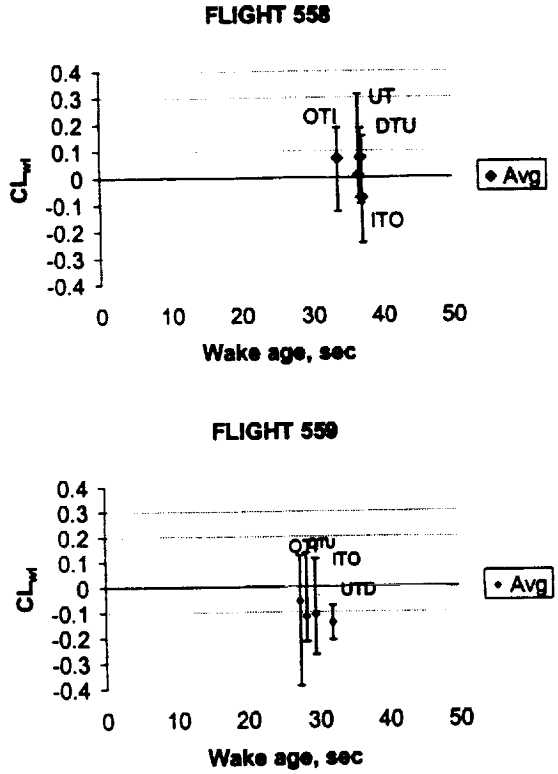

Figure 9: Wake-induced lift coefficient, based on flight maneuver.

In contrast, ITO exhibited some of the lowest averages. This is probably due to both vortices initially acting on an aircraft during this flight maneuver. OTI and ITO also seemed to display the highest degrees of disparity throughout the four flights. This translated into a large degree of upset, or turbulence, for the aircraft. Similar results were also found true for the wake-induced pitching (C_{Mwi}) and rolling moments (C_{LSwi}), figure [10].

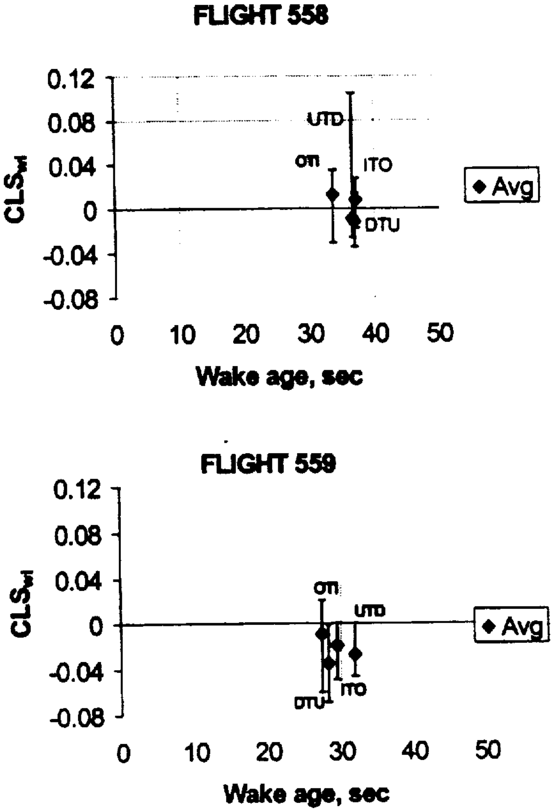

Figure 10: Wake-induced rolling moment coefficient, based on flight maneuver.

Focusing attention over to the affects of the wake-induced drag coefficient (C_{Dwi}), OTI and DTU maneuvers were found to have the lowest average values for all flights. These values usually ranged around .01. As for the wake-induced sideforce coefficient, DTU maneuvers displayed the highest degree of fluctuation between minimum and maximum average for flights 558,559 and 560. This data suggested that the aircraft experienced a noticeable sideforce, or crosswind force, when it traversed the wake from up to down. The reverse is true for flight 561, where the crosswind force was noticed when the B737 penetrated the wake in a down to up motion.

In cases involving the wake-induced yawing moment (C_{Nwi}), results were rather inconclusive. No pattern of consistency was exhibited in the average C_{Nwi} for any of the maneuvers. This pattern was repeated in each of the flights.

CONCLUSION

As previously stated, airports are becoming capacity limited. In order to alleviate this situation, it has become necessary to increase the number of operations per runway during IFR by decreasing current separation distances. In response, the NASA Langley Research Center conducted a series of flight tests from 1995 through 1997 to develop a wake encounter and wake-measurement data set with the accompanying atmospheric state information. The purpose of this research was to design and implement a procedure to calculate the wake encounter portion of that database using the flight data from those earlier flight tests. The information gathered in this study will be stored in a comprehensive database for comparison and/or validation of current and future wake-encounter simulations. This simulation data can then be used by the FAA to evaluate reduced separation guidelines.

There were three objectives to this research. Initially, the wake-induced forces and moments ($FAM_{w.i.}$) from each flight were analyzed based on varying flap deflection angles. The flap setting alternated between 15 and 30 degrees while the separation distance remained constant. This examination was performed in order to determine if increases in flap deflection would increase or decrease the effects of the wake-induced forces and moments. Next, the wake-induced forces and moments from each flight were analyzed based on separation distances of 1-3 nautical miles. In this comparison, flap deflection was held constant at 30 degrees. The purpose of this study was to determine if increased distances reduced the effects of the wake vortex on the aircraft. The last objective compared the $FAM_{w.i.}$ of each flight as it executed a series of maneuvers, or patterns, through the wake-vortex. This analysis was conducted to determine the susceptibility of one maneuver versus another in the wake's presence.

Results from the first analysis indicated that there was no difference in wake effect at flap deflections of 15 and 30 degrees. This conclusion is evidenced in the cases of C_{Ywi}, C_{LSwi}, and C_{Nwi}. The wake-induced lift, drag, and pitching moment cases yielded less conclusive results.

The second analysis compared the wake-induced forces and moments at separation distances of 1-3 nautical miles. Results indicated that there was no significant difference in the wake-induced lift, drag, sideforce, or yawing moment coefficients

The analysis compared the wake-induced forces and moments based on different flight maneuvers. It was found that the FAM_{wi} had the greatest impact on OTI and ITO maneuvers.

Plans to further this research involve a comparative analysis of these results to those obtained by Peete [5]. Her research sought to validate the strip theory and vortice lattice modeling techniques. The forces and moments of both models with their full geometry (wings, horizontal stabilizer, vertical stabilizer) were compared to the data from an experimental model. Comparisons were also performed using the partial geometry (horizontal and/or vertical stabilizer removed) of the three models to determine if the models still had an acceptable accuracy. Peete also performed a sensitivity analysis to observe the accuracy of the models if there was a 10% error in the models' input data. Another comparison which will conducted in the future will consist of using the results from a wind tunnel experiment conducted by NASA. In this case, a pilot flew a 10% scale of a B737 aircraft inside a wind tunnel. The scale model was flown at different locations with respect to the vortex whereby the forces and moment s of the encounter were recorded.

Acknowledgements

Special thanks to my advisor Dr. Sonya T. Smith. I would also like to thank D. D. Vicroy of NASA Langley Research Center for his patience, guidance, and support.

This research is supported by NASA and the Center for the Study of Terrestrial and Extraterrestrial Atmospheres (CSTEA) at Howard University.

Nomenclature

Acc	acceleration, ft/sec^2
b	wing span, ft
c	wing chord, ft
C_D	drag coefficient
C_{LS}	rolling moment coefficient
C_L	lift coefficient
C_M	pitching moment coefficient
C_N	yawing moment coefficient
C_Y	sideforce coefficient
F_{NZ}	normal direction acceleration, ft/sec^2
g	acceleration due to gravity, ft/sec^2
P	roll rate, deg/sec
Q	pitch rate, deg/sec
q	dynamic pressure, lbs/ft^2
R	yaw rate, deg/sec

S	wing surface area, ft^2
T	time, sec
T_{AS}	true airspeed, knots
T_m	thrust contribution in the pitching moment
T_n	thrust contribution in the yawing moment
T_X	thrust body axis thrust
V_{WND}	wind speed, knots
W	weight, lbs
α	angle of attack, deg
β	sideslip angle, deg
θ	pitch angle, deg
ϕ	roll angle, deg
Ψ	true heading, deg

Subscripts

A	aileron position, deg
B	reference to body axis system
bias	flight data bias
E	East direction
E.O.M	equations of motion
Lat	lateral
Lon	longitudinal
M.bias	mean flight data bias
no wake	out of the presence of the wake
wake	in the presence of the wake
wi	wake-induced component
WND	wind

Abbreviations

AC	aircraft
ATC	Air Traffic Controller
ATOS	Advanced Transport Operating System
FAA	Federal Aviation Administration
FAM	forces and moments
IFR	Instrument flight regulations
LaRC	Langley Research Center
NASA	Nat'l Aeronautics and Space Admin.
VFR	Visual flight regulations

References

1. Dunham, R.E.; Stuever, R.A.; and Vicroy, D.D.: "The Challenges of Simulating Wake vortex Encounters and Assessing Separation Criteria," AIAA Atmospheric Flight Mechanics Conference, August 9-11,1997; Monterey, CA.

2. Vicroy, D.; Brandon, J.; Greene, G.; River, R.; Stewart, E.; and Stuever, R.: "Characterizing the Hazard of a Wake Vortex Encounter," AIAA97-0055, 35th Aerospace Sciences Meeting & Exhibit, January 9-10,1997, Reno, NV.

3. Gainer, Thomas G.; and Hoffman, Sherwood: "Summary of Transformation Equations and Equations of Motion Used in Free-Flight and Wind-Tunnel Data Reduction and Analysis," NASA SP-3070, 1972.

4. Vicroy, Dan D.; Stuever, Eric C.; and Rivers, Robert A.: "Flight Reduction of Wake Velocity Measurements Using an Instrumented OV-10 Airplane," NASA TM –1999-209552, September 1999

5. Peete, Kimberly. 1999. "Model Validation for Wake-Vortex/ Aircraft Encounters."