

# Simulation of Jet Blast Effect on Landing Aircraft

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In this paper, we describe a computer simulation of the jet blast effect on an aircraft landing on an orthogonal runway. A phenomenological jet blast model is first presented, followed by a study of its effect on a landing aircraft passing through the blast region. The jet blast issued from the departing aircraft in motion is simplified as a cosine function, specified by peak velocity and width. The jet blast velocity is assumed to cause an additional sideslip velocity for the landing airplane, whose value is subsequently modified accordingly to the coupled governing flight dynamics equations. Numerical simulations are conducted for two different landing aircraft under the control of an automatic landing system.

## INTRODUCTION

The impact of jet blast from a departing aircraft on the control authority of another aircraft landing on an orthogonal runway has long been a concern in the aviation community (Figure 1). In addition, severe material damages and personnel injuries can occur, should the characteristics of jet blast not be taken into account in aircraft operations

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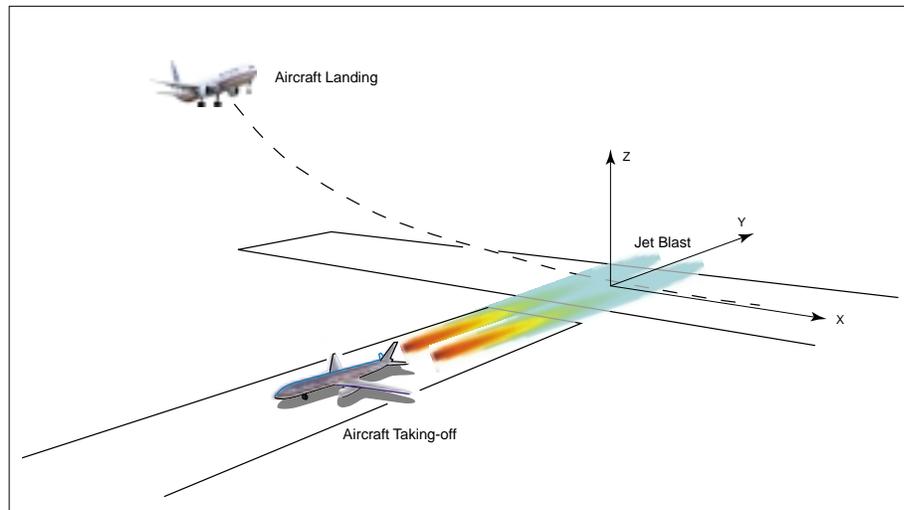


Figure 1: Configuration of jet blast.

[Anon., 1955; Anon., 1999; FAA, 1989; Jones, 1970; Christiansen, 1975; Struck *et al.*, 1989; Rudis *et al.*, 2000]. The introduction of aircraft equipped with newer and higher thrust engines into carriers, and the growing desire to increase capacity while maintaining safety in airport operations, prompted a resurgence of interest in examining the jet blast issue. A recent effort to quantify jet blast is summarized in Rudis *et al.* [2000].

The fluid dynamics of engine exhaust from various nozzle configurations has been studied theoretically and experimentally by many researchers [Groesbeck *et al.*, 1977; Smith, 1998; Zaman, 1998 and 1999]. However, to the authors' best knowledge, the behavior of an aircraft landing through a jet blast has not been addressed, nor has the time required for a landing airplane to avoid harmful disturbance been established. These are not only safety issues in air traffic control, but also economic considerations for aircraft and airport operators.

In connection with these concerns, it is desirable to have a numerical model for assessing the effect of various jet blast levels on landing aircraft for the type of runway configurations shown in Figure 1. As an example of its application, if a predictive tool can be integrated into operational analysis, rational guidelines may be issued on throttle management for the departing aircraft.

## JET BLAST VELOCITY MODEL

A detailed simulation of the jet exhaust field behind the aircraft is beyond the scope of the present study and deemed unnecessary. How-

ever, from existing literature on jet studies and jet blast field data, it is possible to formulate a simple phenomenological model for the current simulation effort as follows. A representative large aircraft consists of multiple engines. The high-speed exhaust flow from each engine is initially compressible and at high temperature. However, each exhaust would ultimately become an incompressible and isothermal jet in the far field, which may be as short as 25 exit nozzle diameters downstream in some cases [Zaman, 1989 and 1999]. Regardless of the degree of compressibility in the jet flow, with the exception of the first few nozzle diameters (i.e., the “potential core” region), velocity decay as a function of downstream distance in the far field has been experimentally characterized to be of exponential nature<sup>1</sup>. Concurrently, the radial profile of the axial velocity at a given location beyond the potential core is found to resemble a bell-shape. Meanwhile, there would be a merger of the exhausts in the far field. With the presence of the ground, as in the current case, the jet wake system would curve slightly upward, compared with its counterpart in free space, but still preserve the described general behavior.

Using a twin-engine transport as an example and in light of the previous descriptions, a first order approximation to model its jet blast distribution while maintaining physical relevance may simply be superimposing the far-field velocity profiles of two isolated jets. For example, for a departing twin-engine jet such as the Boeing 757, 767 or 777, assuming that center-to-center distance of the engines is  $2d$ , the jet blast velocity is then given by

$$V_y(x, y, z) = \{G(x - d, y, z) + G(x + d, y, z)\} e^{-\lambda_o y} \quad (1)$$

where  $G$  is the radial distribution of axial velocity from an isolated jet, and  $\lambda_o$ , expressed as

$$\lambda_o = \frac{1}{\Delta y} \ln \frac{V_1}{V_2} \quad (2)$$

describes the rate of the velocity decay downstream of the aircraft, where  $V_1$  and  $V_2$  represent the peak axial velocities along jet axes measured at positions 1 and 2 separated by  $\Delta y$ . As an example,  $G$  is taken as the zero-th order Bessel function of the first kind and the decay factor is calculated for a Boeing 777 from field data [Rudis *et al.*, 2000]. The resulting decay factor is  $\lambda_o = (380 \text{ ft})^{-1}$  and the value is used to simulate the jet-wake of a static Boeing 777. Figure 2 shows the simulated velocity distributions according to equation (1) and  $\lambda_o = (380 \text{ ft})^{-1}$ .

The approach is extended to simulate the axial velocity for a departing aircraft. Assuming that the acceleration of the departing aircraft

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<sup>1</sup>Jet engine and noise data from Boeing Company Airplane Group Reports, “Airplane Characteristics for Airport Planning,” 1969–1995.

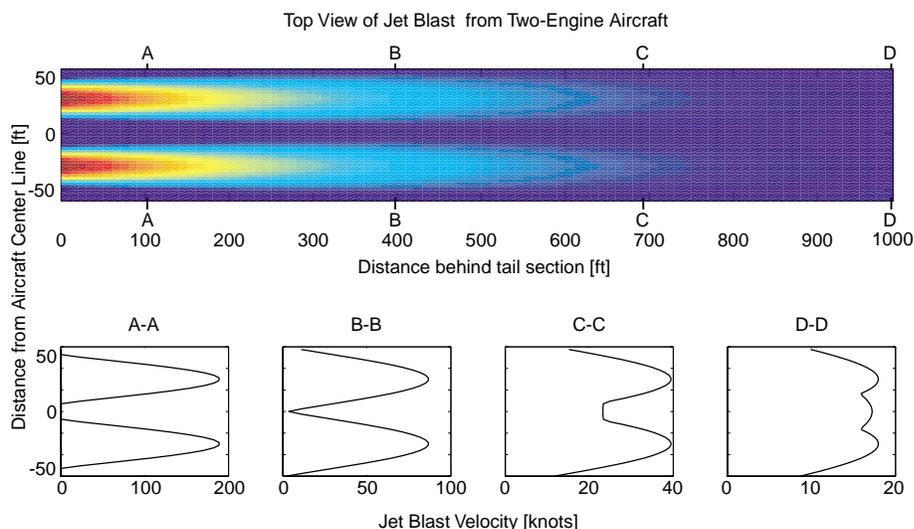


Figure 2: Simulation of the axial blast velocity beyond the tail section of a twin-engine jet (Boeing 777).

(Boeing 777) is  $a$   $\text{ft/s}^2$ , then the axial peak velocity of blast above the background cross wind in terms of time is given by

$$V_m(t_w) = V_M e^{-\lambda_o a (t_w - t_s)^2 / 2}, \quad \text{for } t_w > t_s \quad (3)$$

where  $t_w$  is the waiting time starting from the time of thrust of the departing aircraft,  $t_s$  is the time for jet blast to reach its maximum, and  $V_M$  is the axial peak velocity of jet blast at an initial far field measurement location, in this particular case [Rudis *et al.*, 2000], at 760 feet from the departing aircraft at waiting time  $t_w = t_s$ . Using the same value of  $\lambda_o$  and letting  $V_M = 22.3$  knots,  $t_s = 2$  sec, and  $a = g/4$ , where  $g = 32.19$   $\text{ft/s}^2$  is the acceleration of gravity, the function  $V_m(t) + V_b$  is plotted in Figure 3 for the background crosswind  $V_b = 15$  knots. The similarity of the simulated results in Figures 2 and 3 to published field data is noted. Therefore, the outlined approach is considered as a viable first order approximation in modeling the jet blast, and is adopted in this paper.

## FLIGHT MODEL FOR LANDING AIRCRAFT

The flight mechanics equations governing the lateral and vertical motion of a landing aircraft are given in vector-matrix form by [McLean, 1990]

$$\frac{d}{dt} X_H = A \cdot X_H + B \cdot e \quad (4)$$

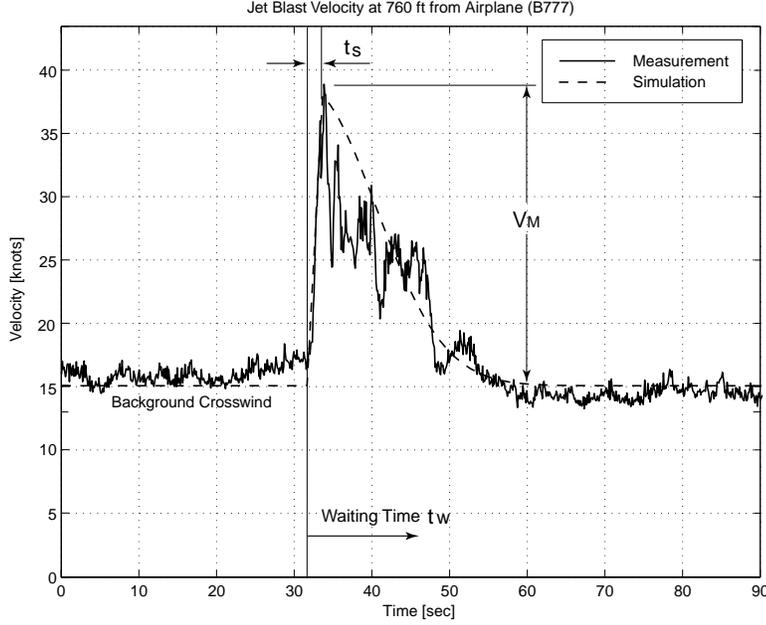


Figure 3: Comparison of simulation result with measured data: Decay of jet blast velocity at 760 ft from a twin-engine jet (Boeing 777) taking off with the acceleration  $a = g/4$ .

$$\frac{d}{dt}X_V = C \cdot X_V + D \cdot f \quad (5)$$

$$e = G_H \cdot X_H \quad (6)$$

$$f = G_V \cdot X_V \quad (7)$$

where  $A$ ,  $B$ ,  $C$ , and  $D$  are aerodynamic and stability characteristic matrices, and  $G_H$  and  $G_V$  are characteristic matrices for automatic flight control. The state vector for the aircraft's lateral movement as described in (4) is defined as

$$X_H = [\beta \ p \ r \ \varphi \ \psi]^T \quad (8)$$

where  $\varphi$  and  $\psi$  are the perturbations of roll (bank) and yaw angles, respectively, and the superscript  $T$  represents transpose. The bank and yaw angular rates are given by  $p = \frac{d\varphi}{dt}$  and  $r = \frac{d\psi}{dt}$ , respectively. The sideslip angle is written as  $\beta = \frac{v}{V_L}$  for small  $v$ , where  $v$  is the perturbation of sideslip velocity and  $V_L$  is the aircraft landing speed. The state vector for vertical movement in (5) is written as  $X_V = [u \ w \ q \ \theta]^T$ , where  $u$  and  $w$  are the perturbations of forward and vertical velocities, respectively.  $\theta$  is the perturbation of pitch angle, and  $q$  is the rate of  $\theta$ , i.e.,  $q = \frac{d\theta}{dt}$ .

In equations (4)–(7), the unknown vectors are  $X_H$  and  $X_V$ , and they are functions of time. To obtain a solution numerically, the differential equations (4) and (5) are changed to difference equations by the approximation  $\frac{d}{dt}X_{H,V} \approx (X_{H,V}^{n+1} - X_{H,V}^n)/\Delta t$ , where  $\Delta t$  is the time step for each iteration and  $n$  is the sequence number of iteration. The time is discretized as  $t_n = n\Delta t$  where  $n = 0, 1, 2, \dots$ . The lateral and vertical displacements are the time integral of  $\beta V_L$  and  $u$ , respectively. The matrices  $A$ ,  $B$ ,  $C$ ,  $D$ ,  $G_H$ , and  $G_V$  are given for specifying different types of aircraft and automatic flight control system. For example, the matrices  $A$  and  $B$  for a Boeing 747 jumbo jet are as follows [McLean, 1990]:

$$A = \begin{bmatrix} Y_v & 0 & -1 & g/V_L & 0 \\ L'_\beta & L'_p & L'_r & 0 & 0 \\ N'_\beta & N'_p & N'_r & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\stackrel{B747}{=} \begin{bmatrix} -0.089 & 0 & -1 & 9.81/V_L & 0 \\ -1.33 & -0.975 & 0.327 & 0 & 0 \\ 0.168 & -0.166 & -0.217 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (9)$$

$$B = \begin{bmatrix} 0 & Y_{\delta_R}/V_L \\ L'_{\delta_A} & L'_{\delta_R} \\ N'_{\delta_A} & N'_{\delta_R} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \stackrel{B747}{=} \begin{bmatrix} 0 & 1.07/V_L \\ 0.227 & 0.0636 \\ 0.0264 & -0.151 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (10)$$

where  $Y_\alpha = \frac{1}{m} \frac{\partial F_y}{\partial \alpha}$ ,  $L_\alpha = \frac{1}{I_{xx}} \frac{\partial N_x}{\partial \alpha}$ , and  $N_\alpha = \frac{1}{I_{zz}} \frac{\partial N_z}{\partial \alpha}$ ,  $L'_\alpha = L_\alpha + \frac{I_{xz}}{I_{zz}} N_\alpha$ , and  $N'_\alpha = N_\alpha + \frac{I_{xz}}{I_{xx}} L_\alpha$ , in which  $m$  is the mass of aircraft,  $F_y$  is the external force in the sideslip direction,  $I_{xx}$ ,  $I_{xz}$  and  $I_{zz}$  are aircraft moments of inertia,  $N_x$  and  $N_z$  are the torques, and the subscript  $\alpha$  denotes  $v$ ,  $\beta$ ,  $p$ , *etc.* In (4) and (7), the control vector is  $e = \begin{bmatrix} \delta_A \\ \delta_R \end{bmatrix}$ , where  $\delta_A$  and  $\delta_R$  are aileron and rudder deflections, respectively.

The stability derivatives are approximately given by  $Y \propto 1/\ell$ ,  $L \propto 1/\ell^2$ , and  $N \propto 1/\ell^2$ , where  $\ell$  is the linear scale factor for different size of aircraft that are similar in shape to a Boeing 747 ( $\ell = 1$ ). Therefore, for a landing aircraft with scale factor  $\ell$ , the aerodynamic matrices are

approximated as

$$A = \begin{bmatrix} -0.089/\ell & 0 & -1 & 9.81/V_L & 0 \\ -1.33/\ell^2 & -0.975/\ell^2 & 0.327/\ell^2 & 0 & 0 \\ 0.168/\ell^2 & -0.166/\ell^2 & -0.217/\ell^2 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (11)$$

and

$$B = \begin{bmatrix} 0 & 1.07/(\ell V_L) \\ 0.227/\ell^2 & 0.0636/\ell^2 \\ 0.0264/\ell^2 & -0.151/\ell^2 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}. \quad (12)$$

Notice that the “scaled” aerodynamic matrices roughly represent aircraft with scaled size, and may be useful in the absence of actual data.

### JET BLAST EFFECT ON LANDING AIRCRAFT

The jet blast generates an additional sideslip velocity  $V_y$ , which combines with the original sideslip velocity,  $v$  as shown in Figure 4. Therefore, the total sideslip angle can be written, approximately, as

$$\beta' = \frac{v + V_y}{V_L} = \beta + \frac{V_y}{V_L}. \quad (13)$$

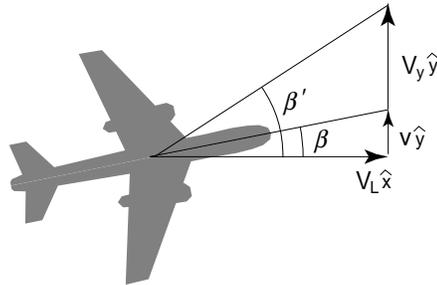


Figure 4: Effect of jet blast on sideslip angle for landing aircraft.

At distances larger than 760 ft from the departing aircraft, the blasts from the two engines merge into one and the cross-section size is assumed as  $L$ . For an aircraft landing on the orthogonal runway with respect to the runway for the departing aircraft, the jet blast exposure time,  $T$ , can be estimated using the jet blast cross-section size,  $L$ , and the aircraft landing speed,  $V_L$ , namely,  $T = L/V_L$ . To facilitate investigation of the

behavior of landing aircraft response, we simplify the merged jet blast velocity  $V_y$  exposed on the landing aircraft as a cosine function shown below

$$V_y(x, t_w) = \begin{cases} \frac{V_m(t_w)}{2} \left[ 1 + \cos \left( 2\pi \frac{x}{L} \right) \right] + V_b, & -L/2 < x < L/2 \\ V_b, & \text{otherwise} \end{cases} \quad (14)$$

where  $V_b$  is the background crosswind, the landing aircraft is assumed to be at the same altitude as the jet blast, i.e.,  $z = 0$ ,  $V_m(t_w)$  is the axial velocity of jet blast given by equation (3),  $t_w$  is the waiting time, and  $L$  is the cross-section size of the jet blast at the landing aircraft. In numerical simulations, a jumbo jet (Boeing 747) and a smaller airplane (with the scale factor  $\ell = 0.3$ ) are considered for the landing aircraft. The departing aircraft is assumed to be a Boeing 777 and its jet blast width  $L = 328$  ft. The peak velocity,  $V_m$ , of the jet blast is related to the waiting time,  $t_w$ , as defined in Figure 3. For example, the waiting time corresponding to a very mild jet blast velocity  $V_m = 4.5$  knots is about 16 seconds.

## NUMERICAL RESULTS

In the simulation, the landing aircraft is assumed to have flown perpendicularly into the blast and has one second recovering time before touching down on runway. Figure 5 illustrates the effect of a mild jet blast acting on a jumbo jet (Boeing 747) near touchdown, showing the jet blast velocity measured on the landing aircraft in time (jet blast exposure), and the corresponding sideslip acceleration in terms of  $g$ .

Figure 6 shows the corresponding vertical and lateral movements of a jumbo jet landing in the presence of jet blast. The peak displacement at touchdown in comparison with the situation without jet blast is about 0.7 ft, and the aircraft cannot recover the lateral displacement within one second before touchdown. Note that the disturbance of altitude is not visible, due to the fact that the blast blows laterally.

Figure 7 contains plots of the angular perturbations (pitch, bank and yaw) and sideslip velocity of the jumbo jet subjected to the same blast level. The pitch angle near touchdown is increasing as is expected, when the landing aircraft is in the flare mode. The figure shows that the bank angle disturbance is around  $0.2^\circ$ . Notice that the jumbo jet can respond quick enough to recover for the bank angle, yet the yaw angle and sideslip velocities, although small, cannot be completely recovered.

Simulations are also conducted for a smaller aircraft, with the scale factor  $\ell = 0.3$ . Figure 8 shows that the smaller aircraft has a larger sideslip acceleration in reaction to the jet blast.

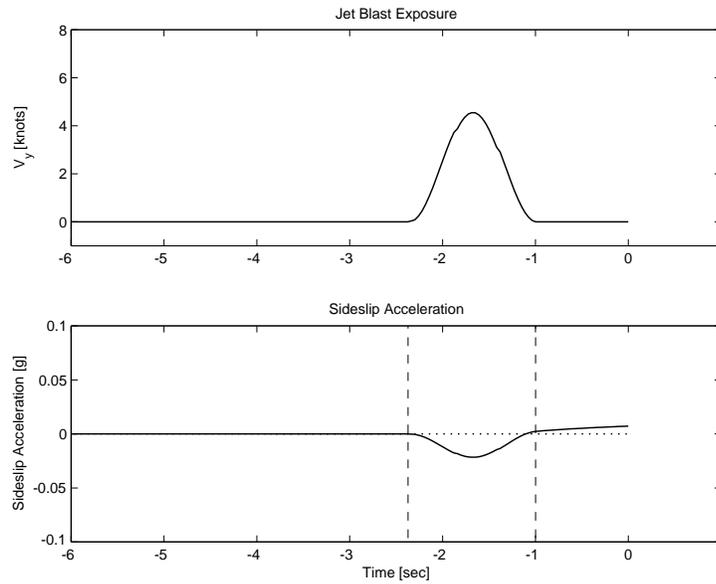


Figure 5: Jet blast velocity exposure on a jumbo jet (Boeing 747) and resulting sideslip acceleration. Peak velocity of jet blast is  $V_m = 4.5$  knots which corresponds the waiting time of 16 sec. Time zero refers to the moment of touchdown.

As indicated in Figure 10, although the maximum yaw angle and sideslip velocity disturbances for the smaller aircraft are larger than those for the jumbo jet during jet blast exposure, the final values at touchtown are smaller, suggesting the smaller aircraft may recover these displacements in a shorter time. Consistently, as shown in Figure 9, the lateral displacement of the small aircraft is larger than that for the Boeing 747 shown in Figure 6.

Figures 11–14 are the plots for the lateral displacement and angular variations in terms of waiting time for jumbo jet and smaller aircraft. The circle points indicate the maximum values during jet blast exposure, and the cross points are the values at touchdown. The figures show that, for all plots, smaller aircraft have larger displacement than jumbo jets (Boeing 747). However, the smaller aircraft can respond faster to recover the displacement introduced by the blast. For the particular jet blast profile used in this paper, it shows that the waiting time should be larger than 20 seconds to avoid noticeable disturbance for the landing aircraft. The 20-second waiting time corresponds to 4 knots jet blast peak velocity in this case. Since the jet blast profile vs. time could vary greatly for different types of aircraft, power settings, and meteorological conditions, it would be more consistent to monitoring jet blast peak velocity instead of waiting time for landing/departing air traffic control.

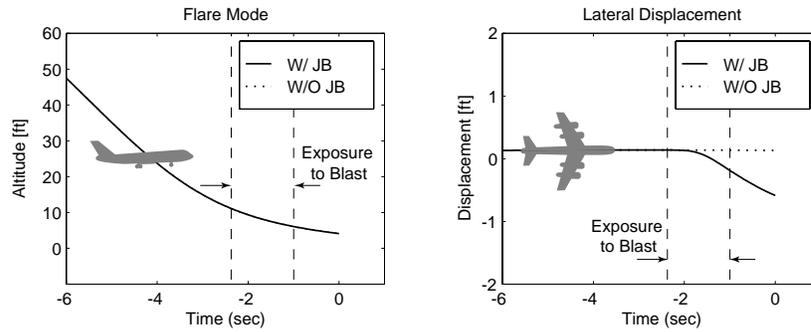


Figure 6: Vertical and lateral displacement of a jumbo jet (Boeing 747) in the presence of jet blast with peak velocity  $V_m = 4.5$  knots.

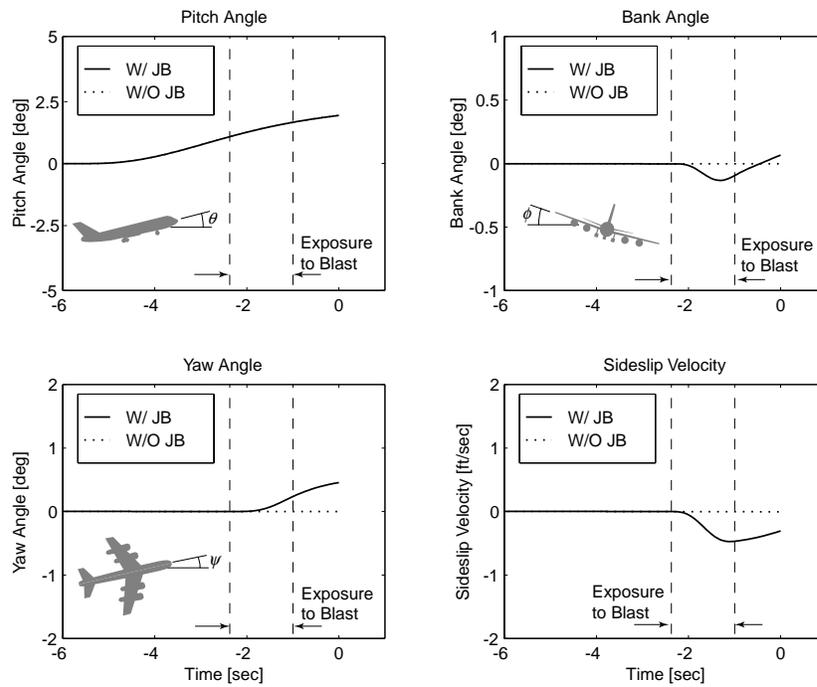


Figure 7: Angular and sideslip velocity perturbations of a jumbo jet (Boeing 747) in the exposure of jet blast with peak velocity  $V_m = 4.5$  knots.

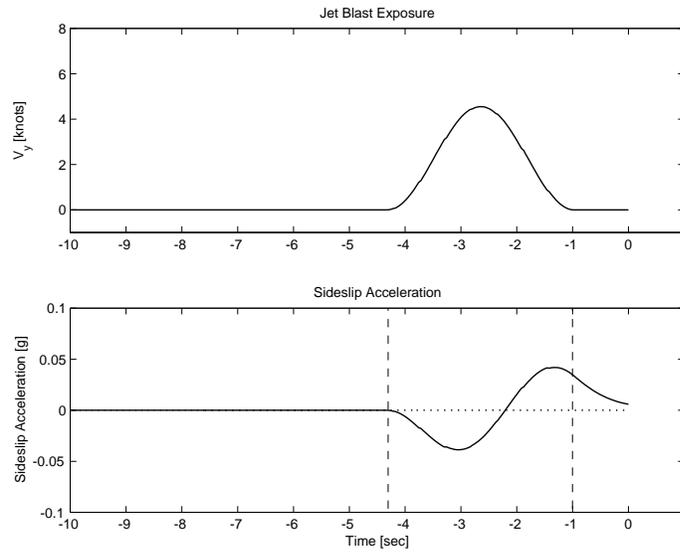


Figure 8: Jet blast velocity exposure on smaller aircraft and resulting sideslip acceleration. Peak jet blast velocity is  $V_m = 4.5$  knots.

## CONCLUSIONS

Based on the simulation results, the jet blast may cause large disturbances for a landing aircraft at a short waiting time, even though the jet blast exposure is short ( $1 \sim 2$  sec). Compared to a larger aircraft, a smaller aircraft would be more prone to these disturbances. However, some displacements, such as yaw angle and sideslip velocity at touchdown, could be smaller for a smaller landing aircraft because it takes less time to recover. It is found from the simulation that, based on the specific jet blast profile, the waiting time must be more than 12 sec to keep the lateral displacement at touchdown less than 5 ft for a small aircraft. However for the jumbo jet (Boeing 747), the maximum lateral displacement is always smaller than 5 ft regardless of the waiting time. Since the jet blast profiles in terms of time are very different for particular circumstances, it is difficult to obtain a standard minimum waiting time applicable to all aircraft so as to optimize traffic flow and safety. It is therefore suggested to use continuously measured jet blast *peak velocity* to determine the waiting time deemed safe for the landing aircraft.

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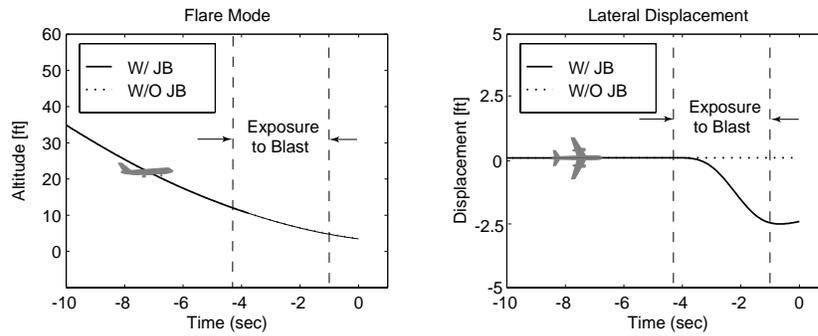


Figure 9: Vertical and lateral displacement of a smaller aircraft in the presence of jet blast with peak velocity  $V_m = 4.5$  knots.

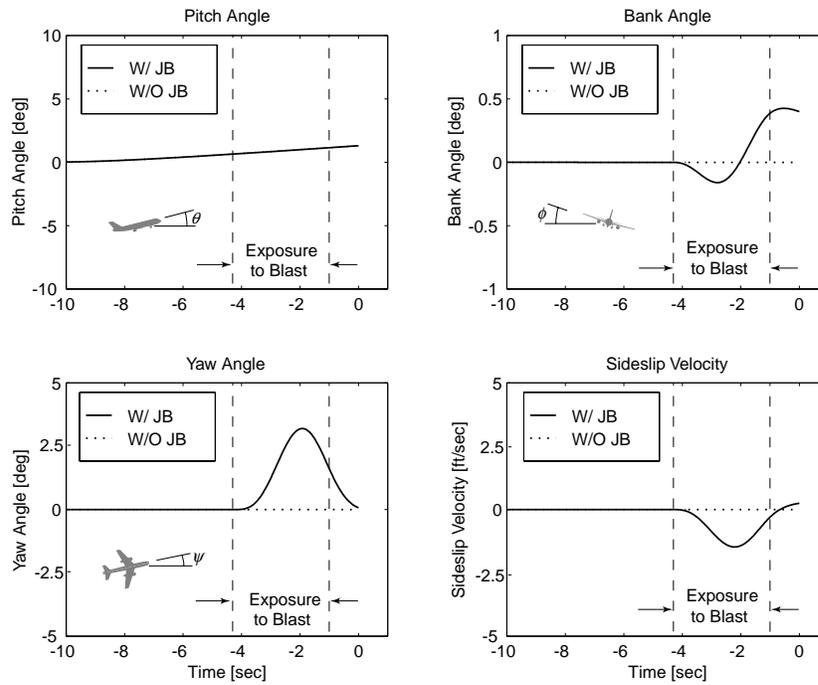


Figure 10: Angular and sideslip velocity perturbations of a smaller aircraft in the presence of jet blast with peak velocity  $V_m = 4.5$  knots.

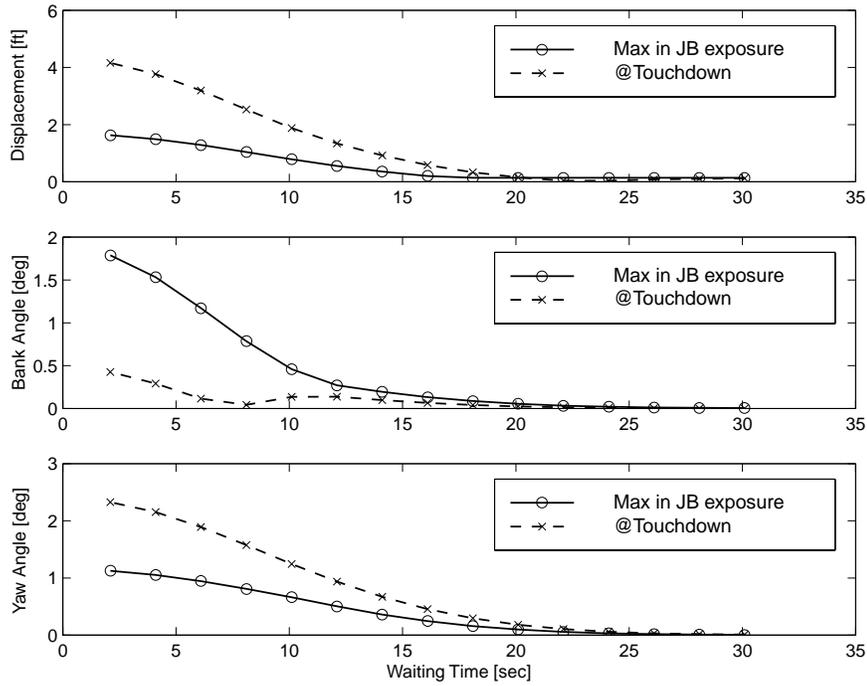


Figure 11: Disturbance of a jumbo jet (Boeing 747) at touchdown vs. waiting time.

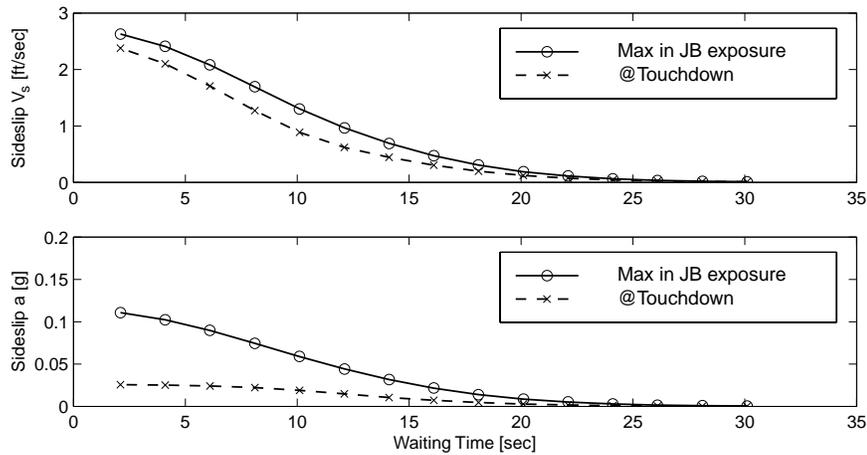


Figure 12: Disturbance of a jumbo jet (Boeing 747) at touchdown vs. waiting time.

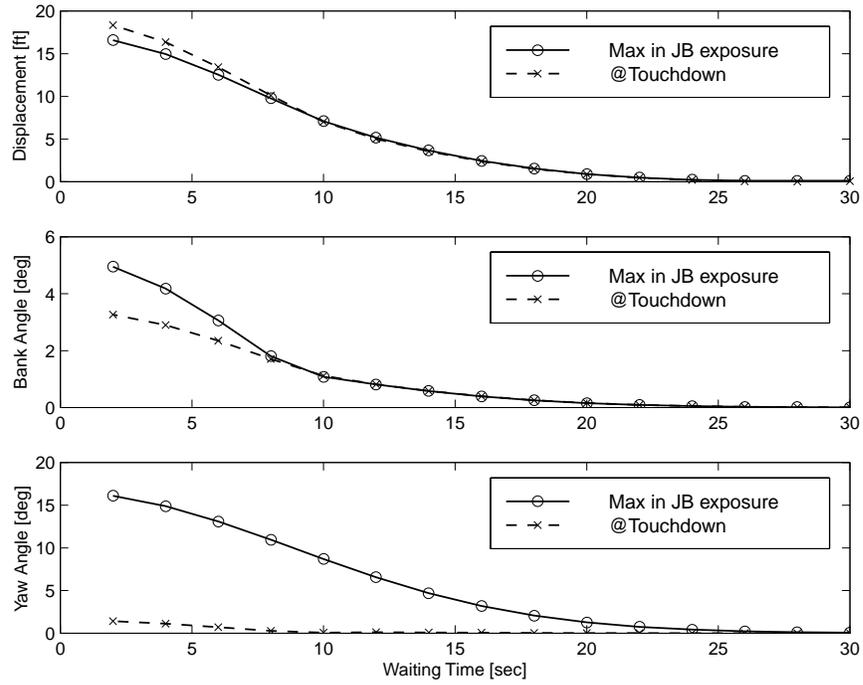


Figure 13: Disturbance of a smaller aircraft at touchdown vs. waiting time.

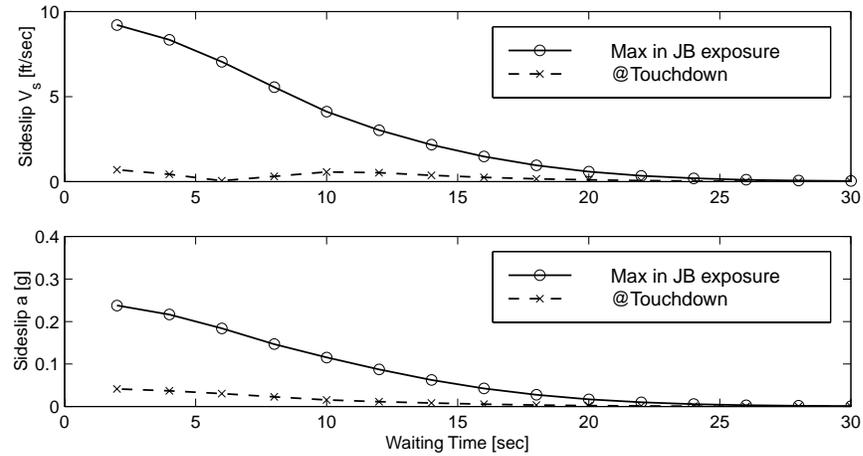


Figure 14: Disturbance of a smaller aircraft at touchdown vs. waiting time.

## ACRONYMS AND SYMBOLS

|                                |   |
|--------------------------------|---|
| $a$                            | acceleration of departing aircraft                                    |
| $A, B, C, D$                   | aerodynamic and stability characteristic matrices                     |
| $B747$                         | Boeing 747  |
| $\beta, \beta'$                | sideslip angle and modified sideslip angle by jet blast, respectively |
| deg                            | degree  |
| $\delta_A$                     | aircraft aileron deflection   |
| $\delta_R$                     | aircraft rudder deflection  |
| DOT                            | Department of Transportation  |
| FAA                            | Federal Aviation Administration                                       |
| ft                             | feet  |
| $g$                            | acceleration of gravity   |
| $G$                            | axial velocity distribution of jet blast on a radial plane            |
| $G_H, G_V$                     | characteristic matrices for automatic flight control                  |
| $L$                            | cross-section size (width) of jet blast                               |
| $\ell$                         | scale factor  |
| $\lambda_o$                    | factor of jet blast velocity distribution in radial direction         |
| $L'_\beta, N'_\beta$           | stability derivative in terms of $\beta$                              |
| $L'_{\delta A}, N'_{\delta A}$ | stability derivative in terms of $\delta A$                           |
| $L'_{\delta R}, N'_{\delta R}$ | stability derivative in terms of $\delta R$                           |
| $L'_p, N'_p$                   | stability derivative in terms of $p$                                  |
| $L'_r, N'_r$                   | stability derivative in terms of $r$                                  |
| $\psi$                         | yaw angle   |
| sec                            | second  |
| $t_s$                          | the time for jet blast to reach its maximum                           |
| $t_w$                          | waiting time  |
| $\theta$                       | pitch angle   |
| $u$                            | perturbation of aircraft forward velocity                             |
| $v$                            | perturbation of aircraft sideslip velocity                            |
| $\varphi$                      | bank angle  |
| $V_b$                          | background crosswind  |
| $V_L$                          | aircraft landing speed  |
| $V_m$                          | peak velocity of jet blast on a radial plane                          |
| $V_M$                          | axial peak velocity of jet blast at distance 760 ft and $t_w = t_s$   |
| $V_y$                          | jet blast longitudinal velocity                                       |
| $w$                            | perturbation of aircraft vertical velocity                            |
| $X_H$                          | aircraft lateral state vector   |
| $X_V$                          | aircraft vertical state vector  |
| $Y_{\delta R}$                 | stability derivative in terms of $\delta R$                           |
| $Y_v$                          | stability derivative in terms of $v$                                  |

**REFERENCES**

- Anon. (1955), *A Preliminary Study of the Effect of Jet Blast or Wake on Other Aircraft*, Beech Aircraft Corp., Wichita, KS.
- Anon. (1999), *Engine Thrust Hazards in the Airport Environment*, Aero Magazine, No. 6, The Boeing Company, Seattle, WA.
- Christiansen, G. H. (1975), *Jet Blast Fence Investigation at John F. Kennedy International Airport*, FAA-RD-75-121/FAA-NA-75-36.
- FAA Airport Design Advisory Circular (1989), *The Effects and Treatment of Jet Blast*, AC 150/5300-13, Sep. 29.
- Groesbeck, D. E., R. G. Huff, and U. H. Vongahn (1977), *Comparison of Jet Mach Number Decay Data with a Correlation and Jet Spreading Contours for a Large Variety of Nozzles*, NASA-TN-D-8423, pp. 631–650.
- Jones, D. N. (1970), *Introduction of Jet-Engine Exhaust and Trailing Vortex Wakes*, Air Weather Service Technical Report 226, Scott AFB, IL.
- McLean, D. (1990), *Automatic Flight Control Systems*, Prentice Hall International (UK) Ltd, Herfordshire, UK.
- Rudis, R. P. and A. C. Daskalakis (2000), *Jet Blast Test Program*, Data B7770804B, DOT-VNTSC-RSPA-00-01, Volpe National Transportation Systems Center, Department of Transportation, Cambridge, Massachusetts.
- Smith, M. W. (1998), “Application of a planar doppler velocimetry system to a high reynolds number compressible jet,” *Proceedings of the 36th AIAA Aerospace Sciences Meeting and Exhibit*. AIAA 98-0428, Reno, Nevada.
- Struck, J. K. and Barile, A. J. (1989), *Aircraft Jet Engine Blast Effect on Par-56 Runway Threshold Lamp Fixtures*, DOT/FAA/CT-89/4.
- Zaman, K. B. M. Q. (1998), “Asymptotic spreading rate of initially compressible jets experiment and analysis,” *Physics of Fluids*, 10 (10), pp. 2652–2660.
- Zaman, K. B. M. Q. (1999), “Spreading characteristics of compressible jets from nozzles of various geometries,” *J. of Fluid Mechanics*, 383, pp. 197–228.

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