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A Comparison between Transonic Wind-Tunnel and Full-Scale Store Separation Characteristics

J. F. Reed* and W. H. Curry†
Sandia Laboratories, Albuquerque, N. Mex.

Nomenclature

a = speed of sound
C_F = static aerodynamic force coefficient
g = acceleration of gravity
l = length
m = mass
M = Mach number
p = static pressure
V = velocity
V_e = ejection velocity
W = weight
γ = ratio of specific heats of air
λ = scale factor, l_f/l_m
ρ = air density

Subscripts

f = full scale
m = model scale

Introduction

STORE separation characteristics from the parent aircraft can best be determined in a wind tunnel either by utilizing a trajectory-following mechanism which successively iterates the forces and moments on the store in the aircraft flow field and computes new locations for the store,[1] or by actual release of scaled stores from the aircraft model.[2] Black[3] discusses some of the advantages and disadvantages of each method. For example, it would be extremely difficult to simulate a rocket launch by the actual release method, whereas a release condition that created very large angular excursions would be nearly impossible for a trajectory follower to duplicate. The intent of this Note is to outline the two scaling methods usually employed in wind-tunnel free-flight store separation testing, to describe the anomalies and limitations of each, and to show the resulting good correlation between wind-tunnel and full-scale test results.

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* Staff Member, Experimental Aerodynamics Division, Aerothermodynamics Projects Department. Member AIAA.

† Supervisor, Experimental Aerodynamics Division, Aerothermodynamics Projects Department. Associate Fellow AIAA.

Scaling Laws[4–9]

In any reduced-scale wind-tunnel test involving store separation, it must be assumed that the flowfield around the aircraft is scaled and that the force field acting on the model is directly scalable to full scale without corrections for Reynolds number or Mach number. In addition, the weights and moments of inertia of the store models must be properly scaled. According to incompressible theory, the two parameters to be considered are Froude number V^2/lg and the ratio of store density to air density, $m/\rho l^3$. This implies that full-scale performance may be simulated in the wind tunnel by setting

$$V_m = \frac{1}{(\lambda)^{1/2}} V_f; \quad \left(\frac{W}{\rho}\right)_m = \frac{1}{\lambda^3}\left(\frac{W}{\rho}\right)_f$$

and

$$\left(\frac{I}{\rho}\right)_m = \frac{1}{\lambda^5}\left(\frac{I}{\rho}\right)_f$$

Considering the significant scaling effect on velocity, a direct application of this method to the compressible case does not appear reasonable. Simulation of Mach number in addition to Froude number and density ratio imposes a completely impractical restriction upon the testing procedure. Theoretically, retention of the three parameters can be accomplished by at least two methods. One method involves scaling the velocity of sound in the test medium as follows: $a_m = 1/(\lambda)^{1/2}a_f$. This cannot be achieved in a conventional wind tunnel because of the resulting low stagnation temperature required. The second method is to impose upon the model an artificial gravitational field[10] equal to the scale factor times the normal gravitational field, that is, $g' = \lambda g$, or to accelerate the airplane model away from the store at the same rate.[11] For typical scale factors of 10 to 20, this is usually impractical.

It is apparent then that some theoretical anomalies must exist in the scaling aspect of practical experimentation. One approach, which has shown promise in the case of ejected releases, is to retain density ratio and duplicate the freestream Mach number, that is,

$$(W/\rho)_m = (1/\lambda^3)(W/\rho)_f; \quad (I/\rho)_m = (1/\lambda^5)(I/\rho)_f$$

and

$$M_m = M_f$$

This has been arbitrarily called "light" scaling. Indications are that, with sufficient ejection, the correct pitch oscillation and an approximate trajectory will be obtained in the immediate neighborhood of the aircraft. Ejections causing a store vertical velocity at release of about 30 fps are considered sufficient.

Another method, used for example by Rainey,[2] places most emphasis on the trajectory of the center of gravity. Assuming a simulated flowfield in the vicinity of the scaled carrier, it is theorized that a scaled trajectory will be obtained, in the normal gravitational field, if the pitch oscillation at release is small. Scaling factors considered are freestream Mach number and the ratio of static aerodynamic force to gravity force, that is,

$$M_m = M_f \text{ and } \left(\frac{C_F(\gamma/2)pM^2l^2}{mg}\right)_m = \left(\frac{C_F(\gamma/2)pM^2l^2}{mg}\right)_f$$

It can then be shown that model weight and inertia are established by the relationships

$$(W/p)_m = (1/\lambda^2)(W/p)_f \text{ and } (I/p)_m = (1/\lambda^4)(I/p)_f$$

This has been arbitrarily called "heavy" scaling.‡ Analysis

‡ Note that in "heavy" scaling, static pressure p is the appropriate parameter rather than density ρ.

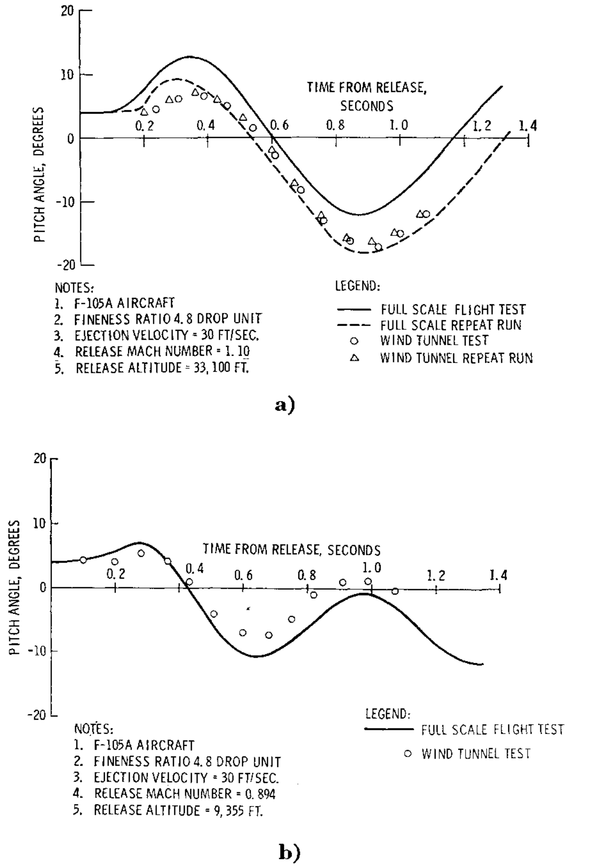

Fig. 1 Comparison between wind-tunnel and full-scale drop tests using the "light" scaling method.

of the method reveals that the linear and angular velocities of the model will be deficient by a factor of $1/(\lambda)^{1/2}$ of the values needed for correct simulation. The model test results therefore imply "too vertical" a drop and underdamping in the event of significant pitch at release. With heavy scaling, however, the nonejected case can be at least partially investigated. It is probably adequate, for example, in the case of severe initial pitch oscillation, to determine configurational modifications that would alleviate this condition.

Experimental Investigation

Two wind-tunnel programs were conducted by Sandia Laboratories utilizing the Cornell Aeronautical Laboratory 8-ft Transonic Wind Tunnel. These programs included ejected release of Sandia-designed store models from the bomb bay of a 6.56% model of the F-105 aircraft using "light" scaling, and free drops of another store configuration from the bomb bay of a 7.5% model of the B-47 aircraft using heavy scaling. The release conditions in the wind tunnel closely simulated those in the full-scale tests.

Figures 1a and 1b show correlation on ejected releases of a blunt-nosed, fineness-ratio 4.8 store from the F-105 bomb bay. The full-scale, flight-test data were acquired from wing-mounted motion picture cameras and have an estimated accuracy of $\pm\frac{1}{2}°$. Wind-tunnel data were obtained by reading strobe pictures of the release with an estimated accuracy of less than $\pm\frac{1}{4}°$. As can be seen, correlation between wind tunnel and full scale appears to be within the repeatability of the full-scale data.

As previously mentioned, the gravitational field in the tunnel is improperly scaled in light scaling. In this test it was 15.25 times too low. This error can be neglected if the stores are ejected at sufficient velocity, since gravity will not affect the vertical separation in the immediate vicinity of the aircraft nearly so much as will the ejection velocity. For example, in this case (V_e = 30 fps), at a vertical separation of 10 ft full scale, only about 13% of the separation is caused by gravity with the remaining 87% caused by ejection velocity. Thus, light scaling, when ejection velocities are sufficient to use it, produces slightly conservative store separation characteristics. The scaling error in separation distance will decrease as the ejection velocity is increased.

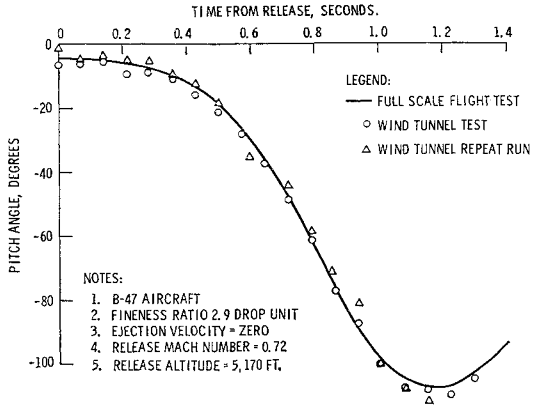

Fig. 2 Comparison between wind-tunnel and full-scale drop tests using the "heavy" scaling method.

Figure 2 shows the correlation between free flight and wind tunnel for a free drop of a blunt-nosed, fineness-ratio 2.9 store from the B-47 aircraft using heavy scaling. The severe nose-down pitch at release was caused by an adverse flow condition in the bomb bay of the B-47. (This condition was subsequently alleviated.) The full-scale data were obtained by integrating the rate gyro output telemetered from the store, and thus are probably somewhat more accurate than data read from film. The wind-tunnel data were again obtained from strobe pictures. The excellent agreement shown is even more striking because the pitching rate and thus pitch damping are known to be too low when heavy scaling is used. Heavy scaling should produce best agreement for low pitch rates.

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Flow of a Circular Jet into a Cross Flow

P. T. Wooler*
Northrop Corporation, Norair Division, Hawthorne, Calif.

Nomenclature

C_D = jet cross-flow drag coefficient
d_0 = jet exit diameter
E = jet entrainment parameter
$g(m)$ = arbitrary function of m
m = U_j/U
t = time
U = cross-flow velocity
U_j = jet exit velocity
X,Z = jet centerline coordinates
α,β,γ = exponents in Eq. (4)

In recent years there has been considerable interest in the aerodynamics of aircraft having the capability of vertical or short takeoff and landing (V/STOL). One method for achieving V/STOL is to use lift engines or fans so that an important aerodynamic problem is to determine the flowfield due to a jet exhausting at right angles into a uniform cross flow. A number of methods for predicting this flowfield have been put forward.[1–5] In the majority of these methods it is necessary to know the position of the jet centerline, and empirical formulae have been used to define the jet path. When a detailed analysis of the jet cross-flow interference problem is made, it is usually not possible to obtain an expression for the jet centerline in closed form.

One expression for the jet centerline has been determined in Ref. 6. This expression shown in Eq. (1) was obtained by considering jet entrainment of cross-flow fluid and the blockage effect that the jet has on the cross flow.

$$\frac{X}{d_0} = \frac{\pi(C_D + 2E)}{8E^2}\left[\exp\left(\frac{4E}{\pi}\cdot\frac{Z}{md_0}\right) - \frac{4E}{\pi}\cdot\frac{Z}{md_0} - 1\right] \quad (1)$$

The expression of Eq. (1), valid for moderate values of m, has the interesting property that it implies X/d_0 = function (Z/md_0). It is the purpose of this note to show that this functional relationship is valid for large values of m.

Let us consider the flow of a circular jet exhausting at right angles from a plane wall into a uniform cross-flow. If $m \gg 1$, the three-dimensional steady problem may be investigated by considering a related two-dimensional unsteady problem. In this case at time $t = 0$, the jet is replaced by a distribution of line vortices perpendicular to the wall. The strengths of these vortices are chosen so as to represent the flow of a uniform stream U around the jet which is represented as a solid boundary. At time $t = 0$ the vortices are allowed to move as free vortices, and their subsequent motion represents the jet deformation under the influence of a cross-flow.

Now t is related to the jet exit velocity U_j and the distance Z perpendicular to the wall by the expression $Z = U_jt$. Also, the displacement of the jet centerline X will be a function of U, t, and d_0, that is,

$$X = \text{function } (U,t,d_0) \quad (2)$$

or

$$X = \text{function } (U, Z/U_j,d_0) \quad (3)$$

Writing this function in series form,

$$X = \sum_{\alpha=-\infty}^{\infty} \sum_{\beta=-\infty}^{\infty} \sum_{\gamma=-\infty}^{\infty} U^\alpha \left(\frac{Z}{U_j}\right)^\beta d_0{}^\gamma \quad (4)$$

Then dimensional considerations imply that $\beta = \alpha$, $\gamma = \alpha + 1$ so that

$$\frac{X}{d_0} = \sum_{\alpha-\infty}^{\infty} \left(\frac{Z}{d_0}\cdot\frac{U}{U_j}\right)^\alpha \quad (5)$$

Then

$$X/d_0 = \text{function } (Z/md_0) \quad (6)$$

This functional relationship is verified in Table 1 using data obtained from Ref. 7. Plotting the data of Table 1 in the form log X/d_0 vs log(Z/md_0), shown in Fig. 1, it has been possible to find a simple form for the equation of the jet centerline. This equation

$$(X/d_0)^2 = 7(Z/md_0)^5 \quad (7)$$

also may be written in the form

$$X/m^{5/3}d_0 = 7^{1/2}(Z/m^{5/3}d_0)^{5/2} \quad (8)$$

Williams and Wood[5] have pointed out that certain similarity laws will hold if the equation for the jet path can be expressed in the form $X/g(m)d_0$ = function $[Z/g(m)d_0]$, in which $g(m)$

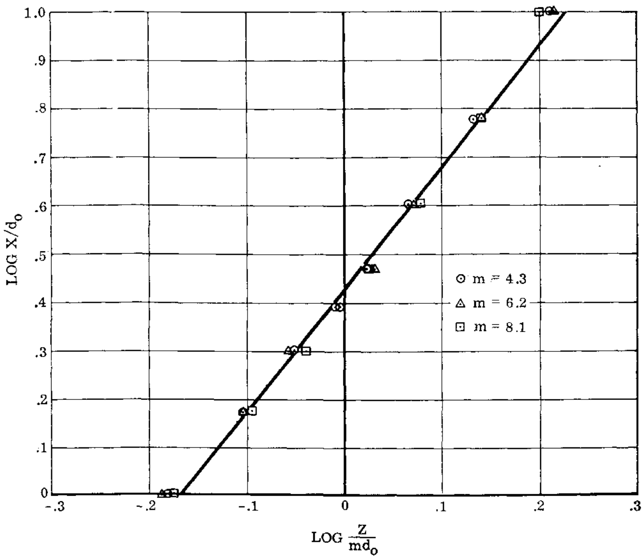

Fig. 1 Correlation of jet centerline data.

Table 1 Tabulation of experimental data (Ref. 7)

X/d_0	m = 4.3	6.2	8.1
	Z/md_0		
1	0.66	0.65	0.67
1.5	0.79	0.79	0.80
2	0.89	0.88	0.91
2.5	0.98	0.99	0.99
3	1.06	1.06	1.07
4	1.17	1.18	1.19
6	1.36	1.39	1.38
10	1.63	1.64	1.60

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* Engineering Specialist, Structures Research and Technology. Member AIAA.