VOLUME I
PERFORMANCE PHASE

CHAPTER 8
TAKEOFF & LANDING PERFORMANCE

JANUARY 1993

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8.1 INTRODUCTION

A very important part of the testing of any aircraft is the takeoff, landing, and operation near the ground. Takeoffs and landings are greatly dependent upon pilot judgement and technique and, therefore, are subject to considerable variation for any given aircraft and set of conditions. Because of this largely unpredictable variable, the pilot, it is neither possible nor practical to make exact prediction or correction of takeoff and landing performance. It is only possible to estimate the approximate capabilities of an aircraft within broad limits. Consequently, we will consider takeoff and landing performance from a general point of view, considering only the major variables and making some assumptions concerning the lesser variables.

The major purpose of these tests are development and/or verification of pilot techniques, forming performance estimates for the flight manual, and verifying compliance, or lack of compliance, with contractual guarantees or military specifications or FAA requirements. Besides normal takeoffs and landings, a complete series of tests will include refused takeoffs (high speed aborts), crosswind operations, wet/icy runway tests, barrier tests, and engine out operations.

This chapter will not cover the specifics of such parameters as refusal speeds, minimum control speeds, or critical runway lengths, since these will be covered in detail during the "engine out" phase of instruction.

8.2 TAKEOFF THEORY

8.2.1 METHOD OF DEVELOPMENT

The mechanics of the takeoff will be examined in two phases, the air phase and the ground phase. The air phase is normally considered that portion of flight from leaving the ground until reaching an altitude of 50 feet AGL. In rare cases, it may be possible to stabilize at a constant climb speed before reaching 50 feet, in which case, the air phase of operation may be broken into a transition phase and a steady state climb phase. For most high performance aircraft, the transition to a steady climb speed will not be completed before reaching 50 feet, even for a maximum climb angle takeoff. The ground phase begins at brake release and ends when the aircraft first becomes airborne.

This chapter will develop equations that can be used to study the effects of various factors that influence takeoff performance. The assumptions required to achieve workable equations make the equations unusable for predicting takeoff performance but do not make them invalid for analysis and correction.

8.2.2 FORCES (GROUND PHASE)

In addition to the usual forces of lift, weight, thrust, and drag, an aircraft on takeoff roll is affected by additional resistance. This resisting force includes wheel bearing friction, brake drag, tire deformation, energy absorbed by the wheels as they increase rotation speed, etc. This force will become smaller as the weight on the wheels is reduced and can be mathematically expressed as μ (W-L). Typical values of μ, the "coefficient of resistance" range between .02 and .05 for a dry concrete runway. The forces acting on the aircraft during the ground roll are illustrated in Figure 8.1.

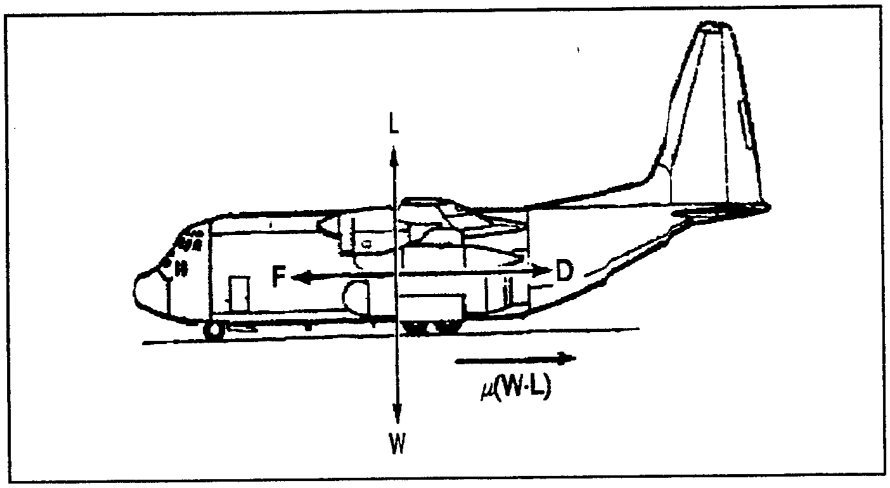


FIGURE 8.1. TAKEOFF ROLL FORCES

Note that this depiction of forces includes the assumption that engine thrust is parallel to the runway. For aircraft with engines mounted at an angle, the horizontal component of thrust is not reduced significantly until the angle becomes quite large. The vertical component of thrust from inclined engines reduces the effective weight of the aircraft. The mass of the aircraft, however, must be computed using the actual weight.

8.2.3 GROUND ROLL EQUATION

Setting the work done equal to the change in energy, we can write

$$\int_0^{S_g} F-D-\mu\,(W-L)\,ds=\frac{W}{2g}\,(V_{T.O.}^2-0) \tag{8.1}$$

where S_g is the total ground distance and $V_{T.O.}$ is the ground speed at liftoff. None of the terms under the integral are constant during the roll, and an exact evaluation is virtually impossible. If, however, we make the assumption that the entire quantity remains constant at some average value, the integration is simple and the expression becomes

$$F-D-\mu\,(W-L)_{avg}S_g=\frac{W}{2G}V_{T.O.}^2 \tag{8.2}$$

or

$$S_g=\frac{WV_{T.O.}^2}{2g[F-D-\mu\,(W-L)]_{avg}} \tag{8.3}$$

At first glance, this assumption appears gross but further examination of the individual forces shows it to be reasonable. Engine thrust decreases slightly as speed increases. A jet engine may enter ram recovery prior to liftoff and realize an increase in thrust over that at lower speed. Propeller thrust will decrease throughout the takeoff roll. Aerodynamic lift and drag increase during the roll in direct proportion to the square of the airspeed. If the aircraft attitude is changed considerably at rotation, both lift and drag will increase sharply. The coefficient of resistance, μ, and the aircraft gross weight remain nearly constant. These variations in forces for a turbojet aircraft are shown graphically in Figure 8.2.

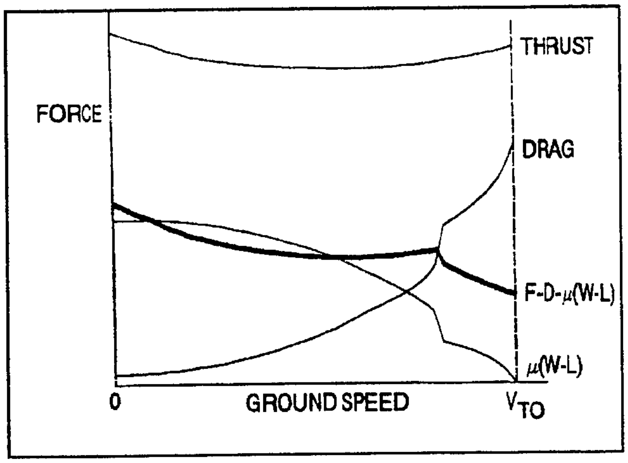


FIGURE 8.2. VARIATION OF FORCES DURING TAKEOFF GROUND ROLL

For a propeller aircraft, the thrust curve will show a greater decrease, while the shape of the drag and wheel force curves will not change. In general, the excess thrust (the vector sum of all three forces) at liftoff will be about 80% of its initial value for a jet aircraft and 40% for a propeller aircraft. In either case, test data show that use of the actual excess thrust at 0.75 $V_{T.O.}$ as the average value in Equation 8.3 gives reasonable results.

8.2.4 SHORTENING THE GROUND ROLL

Equation 8.3 shows that ground roll can be shortened very effectively by lifting off at a lower speed, since the distance increases with the square of the takeoff speed. Looking at the problem from the standpoint of minimizing the ground roll, the aircraft should be lifted off at $C_{L,max}$. However, the aerodynamic drag created by this technique may reduce the excess thrust to an unacceptable level. In extreme cases, rotation to $C_{L,max}$ may reduce the excess thrust to zero or negative values, a definitely unacceptable situation. If sufficient total thrust is available to overcome the drag penalty, high lift devices such as slats and flaps can provide a higher available lift coefficient.

A second approach to decreasing S_g is through increasing the total thrust available, F. This can be done either by operating the engine above its maximum rated power, such as by water injection, or by use of an auxiliary engine such as JATO (Jet Assisted Take Off), RATO (Rocket Assisted Take Off), etc. Thrust augmentation is of maximum value if it can be used throughout the takeoff roll. If it is limited to a time shorter than that required for takeoff, then it is of interest to find whether the augmentation should be used early or late in the ground roll.

Since the energy gained equals the work done, limited augmentation is most efficient if used where the work done is a maximum. If the augmentation provides an increase in thrust,

ΔF, for a fixed time, Δt, during which distance, ΔS, is traveled, then $\Delta S = V \ \Delta t$ and the work done will be

$$\text{work done} = \Delta F \times \Delta S = \Delta F \times V \, \Delta t \qquad (8.4)$$

Both ΔF and Δt are fixed by the limitations of the augmenting engine. The pilot can obtain maximum gain by making V as large as possible. For minimum ground roll, therefore, limited thrust augmentation should be fired late, such that it will burn out or reach its time limit just as the aircraft becomes airborne.

Excess thrust during the takeoff roll is also dependent on aircraft angle-of-attack through both the drag term itself and the inclusion of lift in the wheel force term. We can determine the best angle of attack to maximize excess thrust by finding the optimum value of C_L.

$$F_{ex} = F - D - \mu (W-L) \qquad (8.5)$$

Recall that

$$D = C_D \, qS$$

$$L = C_L \, qS$$

and

$$C_D = C_{D_P} + \frac{C_L^2}{\pi A R e}$$

Substituting into Equation 8.5

$$F_{ex} = F - \left(C_{D_P} + \frac{C_L^2}{\pi A R e}\right) qs - \mu \left(W - C_L qs\right) \qquad (8.6)$$

Differentiating with respect to C_L

$$\frac{\partial F_{ex}}{\partial C_L} = \frac{2C_L}{\pi ARe} qS + \mu qS \tag{8.7}$$

Setting the right side of Equation 8.7 equal to zero, the velocity term (q) drops out and the value of CL for maximum excess thrust is constant at

$$C_{L_{opt}} = \frac{\mu \pi ARe}{2} \tag{8.8}$$

This lift coefficient is quite small for most aircraft and obviously results in extremely long takeoff distance if held throughout the roll.

The optimum technique would be to establish the angle of attack that corresponds $C_{L,opt}$ in Equation 8.8, maintain that until the speed permits liftoff at the maximum practical C_L available, and then rotate the aircraft to the liftoff attitude.

It should be pointed out that this technique is very seldom used. The inherent danger of overrotating, lack of elevator power, crosswind effects, and possible aircraft stability problems usually override any gain achieved. However, most aircraft are configured so that in the taxi attitude, the wing is near the optimum angle of attack for minimizing the total resistance throughout the takeoff roll.

8.2.5 AIR PHASE EQUATION

The equation for ground distance covered between liftoff and 50 feet altitude is obtained similarly to the ground roll equation, except that the wheel force no longer exists. However, a potential energy term must be included:

$$\int_0^{S_a} (F-D)\, ds = \frac{W}{2g} (V_{50} - V_{T.O.}^2) + 50W \tag{8.9}$$

where S_a is the air phase distance and V_{50} is the ground speed at 50 feet. If we make the same assumption concerning excess thrust, Air distance for a given weight would obviously be minimum for a constant speed climb at maximum cess thrust.

$$S_a = \frac{W\frac{(V_{50}^2 - V_{T.O.}^2)}{2g} + 50}{(F-D)_{avg}} \tag{8.10}$$

Maximum excess thrust occurs at the speed for minimum drag (max L/D). Most aircraft, however, lift off at airspeeds much slower than that for max L/D. In most cases, the gain due to an increase in excess thrust realized by accelerating prior to the initial climb is more than offset by the increase in distance due to the large kinetic energy change required. The number of variables involved, particularly if time-limited thrust augmentation is included, makes definition of a single "best" technique impossible.

8.3 LANDING THEORY

8.3.1 GROUND DISTANCE EQUATION

The forces acting on an aircraft on landing roll can be depicted similarly to those shown in Figure 8.1 for takeoff. Low power settings and the increase in μ, the coefficient of resistance, due to brake application result in excess thrust less than zero. The equation for landing ground roll is also quite similar to the takeoff equation.

$$\int_0^{S_g} [F-D-\mu(W-L)]\, ds = \frac{W}{2g}(0 - V_{TD}^2) \tag{8.11}$$

Where V_{TD} is the ground speed at touchdown. The required integration is accomplished using the same assumption. Equation 8.11 becomes

$$S_g = \frac{WV_{T.O.}^2}{2g[F-D-\mu(W-L)]_{avg}} \tag{8.12}$$

8.3.2 SHORTENING THE LANDING ROLL

Touchdown speed is obviously one of the most important determinants of distance required to stop. Besides weight and speed at touchdown, landing roll can be influenced by all the factors in the excess thrust term. Thrust should be reduced to the minimum practical, and reverse thrust, if available, should be employed as soon as possible after touchdown. The logic for early application of reverse thrust is the same as for thrust augmentation on takeoff. Additional drag, whether from increased angle-of-attack or deployment of a drag chute, is most effective in the initial part of the landing roll for two reasons. Not only is a given force most effective at high speed, the force itself is greater due to its dependence on V^2. Runway surface condition, as well as the mechanical design of the brakes themselves, can cause the value of μ to vary over a considerable range.

Our assumption of constant excess thrust is not unreasonable since the attitude of the aircraft remains relatively constant. It gets a bit shaky, however, if nose-high aerodynamic braking is followed by maximum effort wheel braking. This technique is, for some aircraft, the recommended procedure for minimum landing roll. The question arises as to the most advantageous point to transition from one braking mode to the other. The relative magnitudes of the forces involved are shown in Figure 8.3. Note that μ_2, with brakes applied, is much greater than μ_1, which is the same as takeoff resistance. For minimum stopping distance, aerodynamic braking should be employed only as long as it provides a greater decelerating force than maximum wheel braking. An equation can be developed for the appropriate speed at which to make the transition using Equation 8.6 evaluated for both conditions. Unfortunately, the form of the resulting expression does not allow generalization of results.

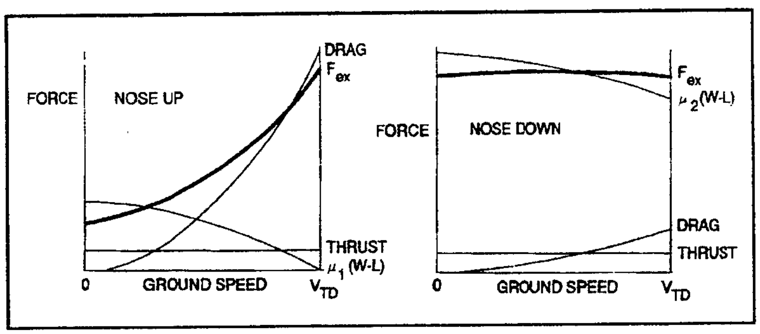


FIGURE 8.3. VARIATION OF FORCES DURING LANDING ROLLOUT

8.3.3 AIR DISTANCE EQUATION

The landing air distance equation is developed in the same manner as the takeoff equation.

$$S_a = \frac{W\left(\frac{V_{TD}^2 - V_{50}^2}{2g}\right) - 50}{(F-D)_{avg}} \tag{8.13}$$

Rearranging signs for consistent form,

$$S_a = \frac{-W\left(\frac{V_{50}^2 - V_{TD}^2}{2g}\right) - 50}{(F-D)_{avg}} \tag{8.14}$$

Examination of Equation 8.14 shows that air distance is minimized if touch-down speed is maintained throughout the final descent (no flare!) and a high drag/low thrust configuration (steep glide path) is used. The structural integrity of the aircraft becomes the limiting factor.

8.4 CORRECTIONS TO STANDARD CONDITIONS

Now that a number of equations are available, we can use them to determine the effects of nonstandard conditions on actual takeoff performance. Remember, the equations were developed for this purpose, and cannot be used to predict exact performance.

8.4.1 WIND

The wind correction is normally the first to be applied. The velocity in Equation 8.3 is ground speed at liftoff, since this defines the energy level required. The aircraft, however, flies according to its airspeed that can be considerably different from ground speed in significant winds. Since ground speed and true airspeed are equal in a no wind situation, the ground speed required with wind is

$$V_{T.O._W} = V_{T.O.} - V_W \tag{8.15}$$

where V_w is positive for a headwind, and includes only the component of wind velocity parallel to the runway. From Equations 8.3 and 8.5

$$S_{g_w} = \frac{W}{2g} \frac{V_{T.O._w}}{F_{ex_{avg_w}}} \tag{8.16}$$

where the subscript w indicates parameters in the wind environment. Substituting Equation 8.15 into Equation 8.3

$$S_g = \frac{W(V_{T.O._w} + V_w)^2}{2gF_{ex_{avg}}} \tag{8.17}$$

Dividing Equation 8.17 by Equation 8.16

$$\frac{S_g}{S_{g_w}} = \frac{F_{ex}}{F_{ex_{avg}}} \frac{(V_{T.O._w} + V_w)^2}{V_{T.O._w}^2} \tag{8.18}$$

$$S_g = S_{g_w} \frac{F_{ex_{avg_w}}}{F_{ex_{avg}}} (1 + \frac{V_w}{V_{T.O._w}}) \tag{8.19}$$

The difference in excess thrust due to wind is difficult to determine, but has a significant effect on takeoff roll. An empirical relationship has been developed which works well for steady winds less than 10 knots. This relationship provides the following equation for correction of wind effect:

$$S_g = S_{g_w} (1 + \frac{V_w}{V_{T.O._w}})^{1.85} \tag{8.20}$$

Equation 8.20 does not account for gusts, which might have considerable effect if occurring near liftoff speed. For this and other reasons it is often required that winds be kept below 5 knots before takeoff data will be accepted. For the air phase an exact determination of wind velocity is even more difficult. The correction, however, is quite simple, based on the fact that change in distance caused by wind is $\Delta S = V_w t$.

$$S_a = S_{a_w} + \Delta S \tag{8.21}$$

8.4.2 RUNWAY SLOPE

If we define runway slope angle θ as positive downhill, we can obtain a correction equation by adding a potential energy term to Equation 8.2 (subscript sl indicates sloping runway parameters).

$$F_{ex_{avg}} S_{g_{sl}} = \frac{W}{2g} (V_{T.O.}^2) - W S_{g_{sl}} \sin\Theta$$

(8.22)

$$S_{g_{sl}} = \frac{W V_{T.O.}^2}{2 g S_{g_{sl}}} - W \sin\Theta \tag{8.23}$$

Solving for S_g,

$$S_g = \frac{S_{g_{sl}}}{1 - \frac{2 g S_{g_{sl}}}{V_{T.O.}^2} \sin\Theta} \tag{8.24}$$

The relationship is such that a fairly large slope is required before data will be significantly affected. Low thrust-to-weight aircraft with relatively low takeoff speeds (trash haulers) will be affected more than high thrust-to-weigh, high wing loaded (fighter) aircraft.

8.4.3 THRUST, WEIGHT, AND DENSITY

Atmospheric conditions will affect the thrust available from the engines as well as changing the true airspeed required to fly a given weight at the standard lift coefficient. As the weight changes, the airspeed required to fly at that C_L will also change. The analysis of these effects results in extremely complex expressions, and sophisticated computer operations are required for their evaluation.

Empirical relationships have been developed which provide reasonably accurate results. For jet aircraft, the expressions are (subscripts s and t refer to standard day and test day parameters, respectively):

$$\frac{S_{g_s}}{S_{g_t}} = \left(\frac{W_s}{W_t}\right)^{2.3} \left(\frac{\sigma_t}{\sigma_s}\right) \left(\frac{F_{n_t}}{F_{n_s}}\right)^{1.3} \tag{8.26}$$

$$\frac{S_{a_s}}{S_{a_t}} = \left(\frac{W_s}{W_t}\right)^{2.3} \left(\frac{\sigma_t}{\sigma_s}\right)^{0.7} \left(\frac{F_{n_t}}{F_{n_s}}\right)^{1.6} \tag{8.27}$$

The accuracy of these equations depends very heavily on the determination of net engine thrust, F_n. Equations developed from thrust stand data are normally used.

For turboprop aircraft with constant speed props, the correction equations are:

$$\frac{S_{g_s}}{S_{g_t}} = \left(\frac{W_s}{W_t}\right)^{2.6} \left(\frac{\sigma_t}{\sigma_s}\right)^{1.9} \left(\frac{N_t}{N_s}\right)^{0.7} \left(\frac{P_{a_t}}{P_{a_s}}\right)^{0.5} \tag{8.28}$$

$$\frac{S_{a_s}}{S_{a_t}} = \left(\frac{W_s}{W_t}\right)^{2.6} \left(\frac{\sigma_t}{\sigma_s}\right)^{1.9} \left(\frac{N_t}{N_s}\right)^{0.8} \left(\frac{P_{a_t}}{P_{a_s}}\right)^{0.6} \tag{8.29}$$

where N is propeller rpm.

8.4.4 PILOT TECHNIQUE

Individual pilot technique is probably the factor causing the greatest variation in takeoff data. Unfortunately, it cannot be quantified and mathematical corrections are impossible. Some of the factors which can significantly affect takeoff performance are:

1. Speed and sequence of brake release and power application.
2. The use of nose wheel steering, differential braking or rudder deflection for directional control.
3. The number and amplitude of directional control inputs used.
4. Aileron and elevator position during acceleration.
5. Airspeed at rotation.
6. Pitch rate during rotation.
7. Angle of attack at liftoff.

8.4.5 LANDING DATA CORRECTIONS

The corrections of landing data to standard day are basically identical to the methods used in takeoff. The wind correction equations and runway slope correction are identical to takeoff performance. The equation for thrust, weight, and density will be the same if reverse thrust is used, but may be simplified if idle thrust is used by setting $Fn_t = Fn_s$.

Then

$$S_{g_s}=S_{g_t}\left(\frac{W_s}{W_t}\right)^2\left(\frac{\sigma_t}{\sigma_s}\right) \tag{8.30}$$

$$S_{a_s}=S_{a_t}\left(\frac{W_s}{W_t}\right)^{\left(2+\frac{h_v}{H_v+50}\right)}\left(\frac{\sigma_t}{\sigma_s}\right)^{\frac{h_v}{h_v+50}} \tag{8.31}$$

where h_v is the kinetic energy change during the air phase

$$h_v=\frac{V_{50}^2-V_{TD}^2}{2g} \tag{8.32}$$

Experience has shown the weight correction to be valid only over a very small range. In order to obtain data over a wide range of gross weights, a large number of tests must be conducted at carefully controlled weight near pre-selected standard weights.

Pilot technique is even more important in landing data than in takeoff data. Data scatter will result from variations in:

1. Power handling during approach, flare, and touchdown
2. Altitude of flare initiation
3. Rate of rotation in flare
4. Length of hold-off time
5. Touchdown speed
6. Rapidity of initiation of braking (aerodynamic and/or wheel)
7. Use of drag chute and/or reverse thrust
8. Brake pedal pressure

8.5 FLIGHT TEST

Takeoff and landing tests are important portions of the flight test program for any aircraft. Generally, during the course of a flight test program, all takeoffs and landings will be recorded for data purposes whenever weather and other factors permit; in addition, a number of test missions may be devoted entirely to takeoffs in various configurations, refused takeoffs, and landings in various configurations, all done at various gross weights.

More than any other tests, takeoffs and landings are affected by factors which cannot be accurately measured and properly compensated for. It is only possible to estimate the capabilities of the airplane within rather broad limits, relying on a statistical average of as many takeoff and landing maneuvers as possible to cancel residual errors.

Dedicated takeoff and landing tests are typically delayed during the development flight test phase of a new aircraft. This is mainly due to the fact that these tests take a fair amount of support and time to perform. Except for basic initial data taking and safety considerations, the delay is due to higher priority of other airframe and systems tests. A minimum amount of initial tests in the takeoff and landing phase are performed to clear the aircraft envelope and "spot check" estimated performance. The bulk of the more hazardous takeoff and landing tests are performed downstream of the initial development flight test phase when more opportune test resources and airframes are available. It is the responsibility of the program manager to ensure that adequate flight test data is available in this area prior to critical phases of aircraft development such as operational deployment.

8.5.1 HIGH SPEED TAXI TESTS

Since the takeoff precedes the landing of an aircraft, it is logical that takeoff tests precede landing tests. However, because the possibility of a refused takeoff is always present, high speed taxi tests are normally conducted prior to actual takeoff or landing tests because certain parameters must be determined which are important to both.

The parameters normally determined from high speed taxi tests are thrust transients, drag, and rolling coefficient of friction. Tests must be conducted on surfaces of different composition and under wet and dry conditions. Aircraft should also be tested at several gross weights and in all configurations within the aircraft's mission capability.

Some braking tests would also be conducted as part of the high speed taxi tests. However, full braking effectiveness can only be evaluate during refused takeoff or actual landing tests.

8.5.2 TAKEOFF TESTS

In a takeoff performance test, ground roll distance and air distance to clear a 50 foot obstacle must be determined. Effort must be made to determine optimum rotation speeds for different gross weights and aircraft configurations. Runway composition and condition must again be considered.

In the event of an unplanned refused takeoff, knowledge of the parameters determined during high speed taxi tests is very beneficial.

Planned refused takeoff tests must be conducted to determine stopping distances and braking capability with the aircraft in the three point attitude. The controllability of the aircraft and operation of the antiskid system (if installed) must be assessed.

8.5.3 LANDING TESTS

A typical landing test is broken down into several phases. The importance of the parameters determined during the high speed taxi tests cannot be overemphasized.

The initial phase of a landing test would be to determine the air distance from 50 feet above the ground to touchdown. Methods of determining this distance are contained in Reference 8.3. Other than determination of the air distance, the particulars of this phase of the test are more pertinent to handling qualities of the aircraft during landing approach.

Once the aircraft has touched down, stopping distance and brake effectiveness must be evaluated. Stopping distance is, once again, a function of the type of surface and condition of the surface.

Braking effectiveness is a function of brake energy, temperature, and aircraft weight. Weight variation up to the maximum energy capability of the brake system should be explored, keeping a careful record of degradation of braking effectiveness due to temperature increase. Brake wear must also be recorded to determine intervals at which brake system components must be replaced to prevent hazardous landings.

The effects of aerodynamic braking and other methods of reducing ground roll distance, i.e., thrust reversing and drag chute, should also be determined. If the aircraft is equipped with an arresting hook, tests must be made to ensure that the aircraft can withstand the structural loads during an arrestment and still be stopped safely and effectively.

One last area that has a definite effect on landing characteristics is crosswind. Once again the airborne phase of this particular test is more pertinent to flying qualities testing. The ground handling characteristics of the aircraft during takeoff and landing rollout and taxiing must be evaluated to determine the effects of crosswinds up to the maximum crosswind component acceptable for the aircraft.

8.5.4 SAFETY

The importance of safety during conduct of all high speed taxi, takeoff, and landing tests cannot be overemphasized. These tests are all classified as hazardous. The danger of losing control of the aircraft is ever present. During braking tests, elevated temperatures may cause overheating of the brake system or even fire. Therefore, safety must be considered during the initial test planning, and proper safeguards should be ensured throughout the test program.

8.5.5 DATA RECORDING METHODS

Data recording during takeoff and landing tests is divided into two categories:

1. External Data - Ground roll, distance to 50-foot height, ground speed and acceleration, runway temperature, ambient pressure, and runway wind conditions.

2. Internal Data - Power parameters, V_i, H_i, T_i, EGT, etc. The most desirable method of recording internal data is by use of on board instrumentation; however, limited hand recorded data can be taken.

External data is usually recorded by a phototheodolite which yields distance, velocity (ground speed), and acceleration as shown in Figure 8.4.

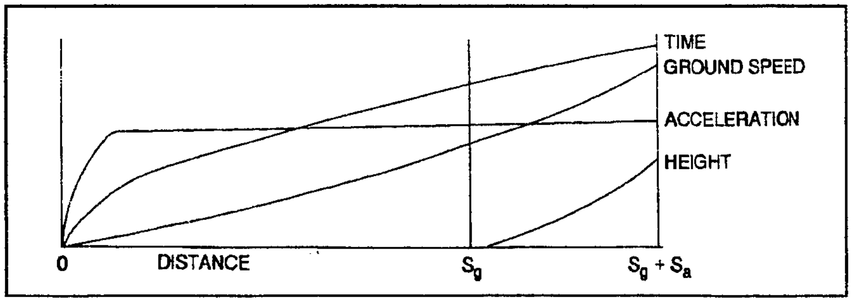


FIGURE 8.4. TAKEOFF DATA

The theodolite data will normally be in the form of printed digital readouts which can be used to develop plots similar to those in Figure 8.4.

If a phototheodolite is not available, the pilot can estimate ground roll and total distance to a 50-foot height. Distance can be estimated by reference to runway markers and edge lights. (The lights at Edwards AFB are 200 feet apart). If takeoff roll is started abeam a light, ground distance can usually be judged within +/- one light. Air distance determination by pilot estimate is at best a rough approximation and probably almost useless. Not only is it difficult to determine distance down the runway, it is virtually impossible to accurately judge 50 feet altitude.

Temperature, ambient pressure, and wind velocity and direction should be monitored continuously at the runway. This information may be supplied as part of the technical support data; however, the pilot should record the same information as a cross-check and back up. The pilot should always attempt to estimate takeoff performance by reference to runway markers even with theodolite coverage to provide an additional means of correlation and cross-check.

8.5.6 STANDARDIZATION TECHNIQUE

The large amount of data scatter introduced by pilot technique was discussed in Sections 8.4.4 and 8.4.5. Although this scatter can never be eliminated, it can be minimized by as much standardization of technique as possible among members of the test team. Items which can be standardized include:

1. Throttle setting prior to brake release
2. Throttle technique at/immediately after brake release
3. Control positions during acceleration
4. Airspeed at rotation

5. Rate of rotation
6. Aircraft attitude at liftoff
7. Gear and flap retraction points

These are by no means the only items to be considered. The degree of standardization available and the effect on data scatter will vary considerably between different aircraft types.

8.5.7 SUMMARY

Takeoff and landing tests are an important part of the performance testing of any aircraft. The large number of variables involved, especially the strong influence of individual pilot technique, results in a vast amount of data scatter and a very low degree of repeatability. A large number of data points are required to accurately predict the actual capabilities of the aircraft.

8.6 FLIGHT TEST TECHNIQUES (TAKEOFF DATA)

1. Determining best takeoff speed

   a. Engineering estimates best speed

   b. Start with high IAS and work down

   c. Determine takeoff roll for each IAS

   d. Limitations

      (1) Tire limit speeds

      (2) Tail dragging

      (3) Acceleration after takeoff
      (4) Aircraft control

   e. A good technique (F-15): rotate to a predetermined pitch attitude and let the aircraft fly off when it is ready

      (1) Easier to control attitude than IAS

      (2) Equates to angle of attack

(3) Avoids problems associated with high angle of attack

2. Data collection

a. Determine OAT, PA, wind, weight

b. Determine takeoff roll and takeoff speed

(1) Takeoff and landing tower: photographs the aircraft form one or two towers, records time and angle. The film is processed and exact angles and times determined. The data reduction program gives distance, height, and ground speed vs time. Takeoff point may be determined by noting when height increases or by a visual marking system or tone. With only one tower tracking, the aircraft must be on the centerline of the runway. Accuracy is to within 10 ft.

(2) Pilot determined: Note start and end of takeoff roll and IAS at liftoff. In this case, position and instrument errors must be known to compute TAS at liftoff. Accuracy: difficult to beat +/- 200 ft and 2 KIAS.

3. Error Sources

a. IAS and distance estimation

b. Position error correction

c. Pitch attitude/angle of attack. For consistent data, you must compute the correct takeoff speed for your weight and takeoff at that speed.

d. Fuel weight: fuel density may vary from 6.3 to 6.5 lbs/gal(3%). This corresponds to a weight error of over 100 lbs for the T-38 (more for larger air raft). Normally, aircraft are weighed after refueling to determine exact weights.

e. Technique: the biggest error source

(1) Application of takeoff thrust

(2) Brake release/use of brakes for directional control

(3) Rotation speed and weight

(4) Gear/flap retraction

(5) Climb-out angle

f. Runway surface

g. Wind shear/crosswind. Normally, takeoff data is not taken if the wind in greater than 10 kts.

B. Landing Data

1. Determine best landing speed

a. Same procedures: start fast and work down

b. Limitations

(1) Stall/controllability

(2) Tail dragging

(3) Gear sink rate limits

(4) Flare requirements

(5) Air distance vs ground distance

(6) Brake energy limits

2. Data collection: same as takeoff

3. Error sources

a. Conditions at 50 ft; IAS, flight path angle, etc.
b. Ground effect: varies with wind, temperature

c. Technique

(1) Flare height and rotation rate

(2) Power reduction

(3) Aero vs wheel braking

(4) Max braking technique

(5) IAS at touchdown; more important than on the spot

(6) Control deflection after touchdown (stick full back, etc)

4. Landing tests are usually planned as a function of energy

a. Determine desired touchdown energy

b. Plan fuel weight vs airspeed

c. Plot landing roll vs energy at touchdown

5. Considerations

a. Max brake energy

b. Wheel cool-down period

c. High speed taxi vs landing tests

d. Full stops vs touch and go

e. Considered hazardous tests

C. Wet Runway Tests

1. Determine stopping distance in 3-point attitude for various touchdown energies

2. Determine aero braking effect using various pitch attitudes

3. Determine "best" technique

4. Considerations

a. Actual RCR; difficult to plan for, may change during test

b. Effects of splashed water in inlets

c. Definitely hazardous

D. RTO Testing

1. Description: accelerate to some speed, then stop with maximum braking

2. Data: Explain refusal speed

3. Procedures

    a. Normally done with high speed taxi tests

    b. Start with low airspeeds and work up

    c. Data from takeoff/landing tests may be used here, if weights are high enough

4. Considerations

    a. Delay time from perceiving a problem to applying brakes

    b. Max brake energy (usually at a high gross weight)

    c. Time consuming (test, cool down, refuel)

    d. Aero vs wheel braking

    e. Wet vs dry runways

    f. Hazardous; uses a bunch of runway (normally down on RWY 04)

E. Engine Out Tests

1. Vm_c (multi-engine): explain

2. Engine-out performance tests

    a. Data: Explain SETO speed, critical engine failure speeds. To be able to take off, the ground distance at engine failure plus the ground distance during the reaction time plus S_g must be less than the runway length

    b. Procedures: Combine engine-out takeoff roll data with results of two-engine and RTO tests

F. Crosswind Tests

1. Primarily for controllability evaluation; determine crosswind limits

2. The problem:

   a. Touchdown: wing-low or crabbed

   b. On the runway: can you keep it there?

      (1) Wet runway: drifts down wind

      (2) Dry runway: drifts up wind for a directionally stable aircraft

3. Limits (different for different aircraft)

   a. Gear side loads

   b. Rudder power

   c. Aileron control

4. Examples

   U-2: very directionally stable, can't lower a wing, limited by rudder power

   F-15: lateral control problems

      a. Aileron into the wind causes ARI rudder inputs
      b. Soft struts caused aircraft to rock back and forth
      c. Solution: disable ARI on the ground, use stiffer strut
      d. Also affected by pitch attitude

5. Considerations

   a. Wet vs dry runway

   b. Hard to pre-plan a crosswind

   c. Lakebeds normally used

G. Barrier Test (not much knowledge around)

1. Data

   a. Max engagement speeds/energy

b. Off-center control problems: may lead to lateral rocking/overturn (A-7)

c. Stores effects; interference

2. Procedures

a. Start on-center, on low weight

b. Work to high weight on-center

c. Start off center at medium weight: light weights may make worse lateral control problems

d. Instrumentation

(1) Use onboard ground speed if available

(2) Hook load strain gages

(3) Photo coverage prior to and at engagement

e. Facility at South Base

3. Considerations

a. Hook bounce

b. Hook failure vs cable failure

c. Cable whip vs steady loads

d. Type of cable vs load onset (function of weight)

e. Considered hazardous

8.7 SUMMARY

Data reduction to standard conditions

Development of charts

Flight test techniques

Data requirements

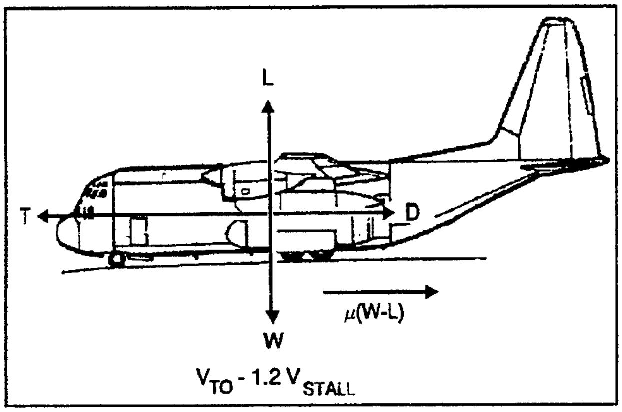
Limitations

Considerations

8.8 **PROBLEMS** (Optional - Not required for class)

8.1 Certain simplifying assumptions may be made to the takeoff problem with very little loss of accuracy. Consider the following aircraft during takeoff roll:

T/W = 0.80
CD = 0.02 + .2 CL2
CL Z 0.1
m = 0.04
W = 40,000 lbs
S = 550 ft2



a. Assuming that the acceleration is constant over the takeoff ground run, show that

where

$$a=\frac{dV}{dt}$$

b. Using 3SF = ma, derive an expression for the average acceleration during the ground run.

c. Using the data given above at sea level, calculate a value for each term in the equation for acceleration. Assume V_{avg} = 100 KTAS.

d. Observe the quantities found in Part c: which of these can be eliminated from the equation with only a small loss in accuracy?

e. Show that a good 1st order approximation for takeoff ground run may be expressed as

$$S_g = \frac{1.44}{g\rho C_{L_{max}}} \left(\frac{W}{S}\right) \left(\frac{W}{T}\right)$$

f. Using the approximation of Part e: answer the following questions. Assume all other conditions remain the same.

1. Calculate the ratio of takeoff distances for an aircraft at a gross weight of 55,000 lbs to one of 35,500 lbs.

2. Calculate the ratio of takeoff distances for an aircraft at sea level to one at 6,000 ft. Use standard day conditions. Do not neglect the change in thrust.

3. Calculate the ratio of takeoff distances for an aircraft in a cruise configuration

where: $C_{L_{max}} = 0.9$

to one with takeoff flaps,

where: $C_{L_{max}} = 1.6$

4. Calculate the ratio of takeoff distances for a day when the temperature is 20 20F to a day when it is 90 20F. The atmospheric pressure in both cases is sea level standard day. The effect of temperature change upon the thrust output of the engine is not easily determined. Use the assumption that there is approximately a 25% decrease in thrust for a 70° temperature increase.

8.10 BIBLIOGRAPHY

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