BRAKE SYSTEM DESIGN AND THEORY

Aircraft brake systems perform multiple functions. They must be able to hold the aircraft back at full static engine run-up, provide adequate control during ground taxi operations, and be able to effectively stop the aircraft during landing and roll-out. We will look at each of these functions separately.

1. ABILITY TO HOLD THE AIRCRAFT AT FULL STATIC RUN-UP

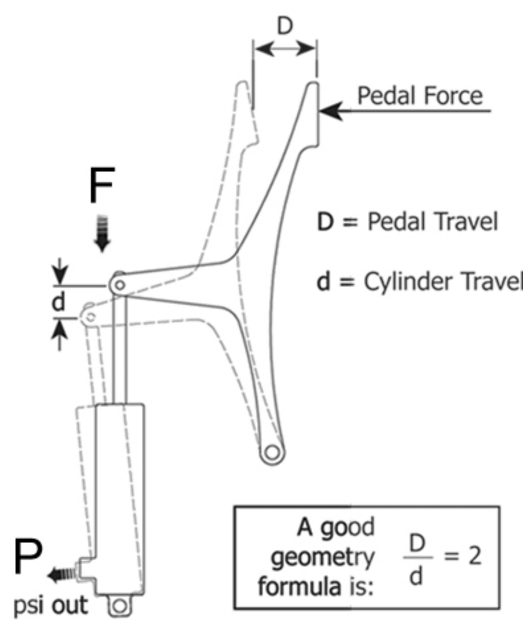
The thrust produced by the engine(s) is opposed by the retarding force (F_T) caused by the friction between the tire and the ground surface as seen in the diagram below. In order to hold the aircraft back at full static engine run-up, the retarding force must be equal to or greater than the thrust produced by the engine(s).

Simply put, the brake system must provide adequate torque on the wheel(s) to accomplish this. Several factors contribute to this — the brake pedal geometry, master cylinder piston diameter, brake caliper piston diameter, effective radius of the brake disc and the rolling radius of the tire.

Let's begin with the brake pedal and master cylinder. The main function of the brake master cylinder is to provide adequate brake system hydraulic pressure — typically between 400 psi and 600 psi for a modern disc brake type system.

The brake system pressure (P) produced is P=F/A where F is the force applied to the brake master cylinder piston, and A is the area of the master cylinder piston. Most modern aircraft use a master cylinder piston with a diameter of 5/8". When a force (F) on the master cylinder of 150 lbs is applied, an adequate pressure of approximately 500 psi will result.

To achieve this force, a general rule-of-thumb is to design the brake pedal geometry to have a 2 to 1 ratio of pedal travel to brake cylinder travel. For example, 1" of pedal travel will result in 1/2" of cylinder travel. A pedal force of about 75 pounds will result in an adequate 500 psi pressure to the brake caliper using a standard 5/8" piston diameter master cylinder.



When a brake system is unable to hold the aircraft back at full static engine run-up, it is often the fault of the brake pedal geometry not exerting adequate force on the brake master cylinder.

Now let's look at the brake caliper. The brake caliper applies a clamping force (N) on the brake disc that is equal to the total area of the brake caliper piston(s) multiplied by the pressure (P) in the brake system.

The retarding force (F_B) on the brake disc is equal to twice the clamping force (N) times the coefficient of friction (μ) of the brake linings (pads). This is twice because the friction force is acting on both sides of the brake disc.

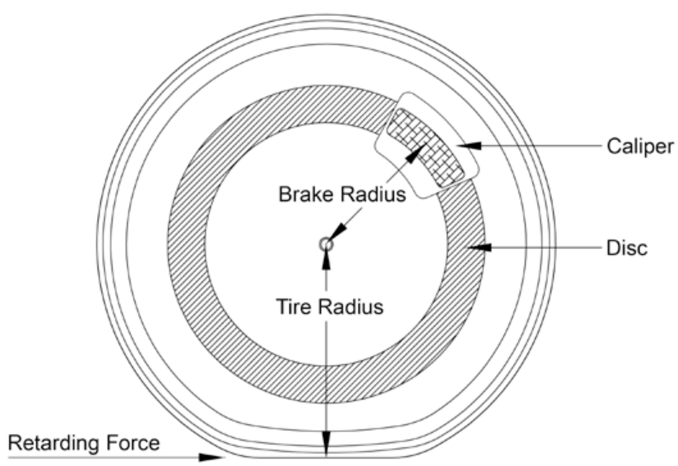
$$F_B = 2PA\mu = 2N\mu$$

P = Brake System Pressure
A = Total area of the caliper piston(s)

This results in a retarding torque (moment) of the brake disc about the axle equal to the retarding force of the brake (F_B) times the effective brake radius (distance between the axle and center of the brake lining) of the brake disc (R_D).

$$M_B = F_B \text{ x } R_D$$

The diameter of the tire plays an important role in the ability of the brakes to hold the aircraft back at full static engine run-up. The relationship between the effective brake radius and the tire's rolling radius can be seen in the diagram below.



The moment about the axle of the brake must be equal to that of the tire which means that the retarding force on the tire (F_T) times the rolling radius of the tire (R_T) must be equal to the retarding force of the brake (F_B) times the effective brake radius (R_B).

$$F_T \times R_T = F_B \times R_B \qquad \text{or} \qquad F_B = F_T \times \frac{R_T}{R_B}$$

It is important to realize the importance of the ratio of the tire radius to that of the brake radius (R_T/R_B). The retarding force of the brake (F_B) is directly proportional to the rolling radius of the tire. If the rolling radius of the tire doubles, then there must be a corresponding doubling of the brake retarding force. This is an important consideration when installing large diameter tires.

Putting it all together. As you can see, there are a lot of variables that enter into designing a brake system that is able to hold the aircraft back at full static engine run-up without being so strong that ground handling is compromised by powerful brakes that are overly sensitive.

If the brakes are unable to hold the aircraft back at full static engine run-up, there are several remedies — some easier than others.

First, is the brake system producing enough hydraulic pressure? This can be remedied by improving the brake pedal geometry, or by installation of a brake master cylinder with a smaller piston diameter. Master cylinders with a 9/16" piston bore diameter produce 19% more pressure, and those with a 1/2" piston bore diameter produce 36% more pressure compared with master cylinders with a standard 5/8" diameter piston.

Second is the brake caliper. Increasing the total area of the brake caliper piston area directly increases the force applied to the brake disc. This can be accomplished by installation of a brake caliper with larger diameter piston(s) or with a brake caliper with multiple pistons.

Third is installation of a brake disc with a larger effective brake radius. Usually this is impractical for multiple reasons.

Finally is consideration of the radius of the tire. Unless large diameter tires are required or desired, braking effectiveness will increase proportionally with a decrease in tire size.

2. GROUND TAXI OPERATIONS

It is important that the brakes are able to control the aircraft during ground taxi maneuvers without having to apply excessive brake pedal pressure or being overly sensitive. Important considerations are the geometry and location of the brake pedals and the pressure produced by the master cylinder.

The brake pedals should be installed in such a manner as to be conveniently operated by the pilot.

If excessive brake pedal pressure is required during taxi maneuvers, or if the brakes are overly sensitive, it is the result of the brakes producing too little, or too much torque. Refer to the above section for possible solutions.

3. ABILITY TO STOP THE AIRCRAFT DURING LANDING

First is our old friend, the torque produced by the brake disc. This torque must be adequate to decelerate the aircraft at a rate of 10 ft/sec^2 during landing, and 6 ft/sec^2 during a rejected take-off. Typically, if a brake system is able to hold the aircraft back at full static engine run-up, it will meet this criteria.

A landing aircraft has a certain amount of kinetic energy which is reduced to zero when the aircraft comes to a stop. The brake system converts a major part of this kinetic energy to heat energy which is absorbed by the heat sink portion of the brake disc. The larger the mass of the heat sink, the more heat energy it is able to absorb. A well designed brake system will provide adequate disc mass without excessive weight.

You can calculate the kinetic energy required for each main wheel with brakes of your aircraft with the following formula.

$$K.E. = \frac{0.0443WV^2}{N}$$

W = Design landing weight in pounds,
V = Brakes-on speed in kts, and
N = Number of main wheels with brakes

As you can see, the most important variable is the brakes-on speed. There is little you can do about the aircraft weight or number of main wheels with brakes, but the required kinetic energy increases with the square of the brakes-on speed. Be cautious of high approach speeds or downwind landings.

You should consult the kinetic energy rating of the wheel and brake assembly to see if it is adequate for your aircraft and type of operation.

If the aircraft has a brake disc with too small of a heat sink, the heat generated by the friction between the brake disc and the brake linings may cause the temperature of the brake linings to rise to a level that causes "brake fade". This effect occurs at about 1,000^{O}F for most general aviation, light weight aircraft that use organic brake linings.

The use of metallic linings increases this critical temperature. However, as with most things, there is a trade-off. Metallic linings have a lower coefficient of friction requiring greater system pressure, increase the wear of the brake disc, they tend to "grab" and are often "squeaky".

During operations requiring repeated use of the brakes, it is important to let them cool before subjecting them to demanding applications. If the heat sink portion of the brake disc is not allowed to cool, it will begin the braking process at an elevated temperature and may well exceed the critical temperature causing "brake fade".

This is also an important consideration for aircraft with non-steerable nose or tail wheels. Long taxi operations, especially in a crosswind, can heat the brake disc to a very high temperature, leaving little or no room for additional heat to be absorbed before reaching its critical temperature.

4. SEATING OF NEW BRAKE LININGS

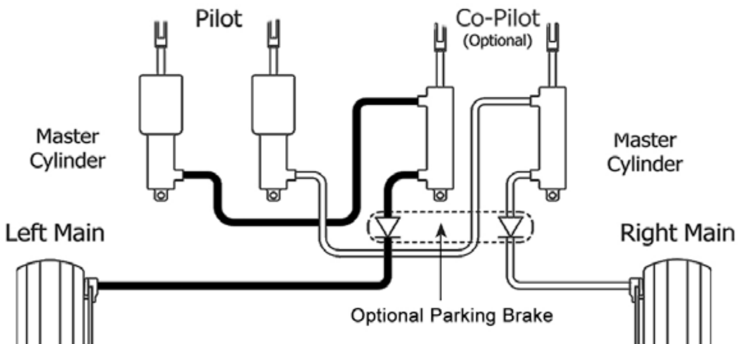
A thin glaze must be created on the brake lining surface for the brake linings to have maximum efficiency. This glaze is produced by heating the pads to a high enough temperature to sufficiently post-cure the resins in the pad. Once this glaze is formed, it will be maintained by normal operations.

There are many ways to accomplish this, but enough energy in the form of heat must be produced between the brake linings and discs so that a lining temperature of 600° to 700°F is reached. A common method is to taxi with a moderate power setting, keeping the taxi speed slow by dragging the brakes. The brakes should be allowed to cool between "break-in sessions" because the heated pads have a lower coefficient of friction and could result in potential hazards due to reduced braking.

The pilot will notice a significant difference in braking effectiveness once the linings have been “seated.” The best test to determine if the linings have been seated is the ability to hold the aircraft back at full static engine run-up.

5. BRAKE SYSTEM DESIGN

Illustrated to the right is the hydraulic portion of a typical aircraft brake system. In the illustration, the master cylinders on the pilot side incorporate an integral reservoir. Whether you use a master cylinder with integral reservoir, or remote reservoir, the most upstream component must be a reservoir.



Typical Brake System Installation

It is critically important that the installation allows the brake cylinder piston rod to fully extend when no load is applied.

6. BLEEDING THE BRAKES

Insure that you are using the proper fluid. Most modern systems use MIL-H-5606 (MIL-PRF-5606) hydraulic fluid or its newer replacements: MIL-PRF 83282 and MIL-PRF-87257. All of these fluids are miscible and can be used with each other. These fluids are compatible with Buna-N (Nitrile) O-Rings.

The most efficient method of refilling and removing air from the system is to fill from the bottom up.

1. Remove the vent plug from the brake system reservoir to allow the air to escape from the system.
2. Connect a clean hydraulic pressure source such as a hydraulic hand pump to the bleeder valve on the lower end of the brake caliper.
3. Open the bleeder valve one-half turn.
4. Pump hydraulic fluid into the system observing the level in the brake system reservoir. When the reservoir is nearly full, tighten the bleeder fitting and remove the hydraulic pressure source.
5. Replace and tighten the brake system reservoir vent plug.
6. Apply pressure to the brake pedal to ensure that you have a "hard pedal" and that there are no leaks. You may have to pump the brake pedal several times to remove any remaining air from the system.
7. If a "soft pedal" condition exists, repeat the above steps.