1. Introduction
Two primary prerequisites for a safe flight are stability and controllability. In addition, pilot and occupant’s comfort is of significant importance which is often referred to as handling qualities. These three aircraft design objectives will influence the design of control surfaces and create variety of design constraints. Flight stability is defined as the inherent tendency of an aircraft to oppose any input and return to original trim condition if disturbed. When the summation of all forces along each three axes, and summation of all moments about each three axes are zero, an aircraft is said to be in trim or equilibrium. In this case, aircraft will have a constant linear speed and/or a constant angular speed. Control is the process to change the aircraft flight condition from an initial trim point to a final or new trim point. This is performed mainly by pilot through moving the control surfaces/engine throttle. The desired change is basically expressed with a reference to the time that takes to move from initial trim point to the final trim point (e.g., pitch rate and roll rate).

Control of an aircraft is applied through devices are referred to as control surfaces. The control surfaces; however; are deflected by the pilot via stick/yoke and pedal. In general, control surfaces may be broadly classified into two types: conventional, and non-conventional. Conventional control surfaces are divided into two main groups (Figure 1): 1. Primary control surfaces, 2. Secondary control surfaces. The primary control surfaces are in charge of control of flight route and usually in a conventional aircraft are as follows 1. Aileron, 2. Elevator, and 3. Rudder. On the other hand, secondary surfaces are employed to reinforce primary control surfaces for minor or less important functions. Secondary control surfaces are in fact auxiliary control surfaces and are applied in special cases. These surfaces mainly include: 1. High lift device (e.g., Flap), 2. Tab, and 3. Spoiler (Figure 2).

Spoiler (sometimes called a lift dumper) essentially has three functions: 1) brake during landing, 2) assist descent to lower altitudes without picking up speed, 3) auxiliary device for roll control. Spoilers are sometimes used as aileron-substitutes, for roll-control, especially when torsional aero-elasticity is critical. Spoilers are plates/flat sheets (with no curve) on top of the
wing used to decrease lift when deflected up. By so doing, the spoiler creates a controlled stall over the portion of the wing behind it. Spoilers differ from airbrake in that airbrake is designed to increase drag without regard to affecting the wing lift.

As the name implies, a spoiler degrades the lift, so they are not utilized at high speeds. In a number of high speed aircraft, spoilers are used instead of ailerons to avoid aileron reversal. They are most effective roll controls at high speeds; and they make useful lift dampers to achieve maximum effect of wheel brakes on touch down. Sailplanes and gliders employ spoilers to steepen angles of glide by direct increase in drag and reduction of lift to drag ratio. In this Section, you will find the detail design of spoiler. The transport aircraft Boeing 747 has three different types of roll control device: inboard ailerons, outboard ailerons, and spoilers. Figure 3 illustrates the deployment of spoilers during landing for a transport aircraft.

![Figure 2. Spoiler, flap, and aileron](image)

![Figure 3. Spoiler deployment during landing](image)
Most gliders are equipped with spoilers in order to control their rate of descent and hence to adjust their angle of descent during approach for landing. For a powered aircraft (e.g., airliner); during landing operation, the deployment of the spoiler causes a considerable loss of lift; and hence more portion of the weight of the aircraft is transferred from the wing to the landing gear, allowing the wheels to be mechanically braked with much less chance of skidding. In addition, the drag added by the spoiler directly assists the braking effect (i.e., maximizing braking efficiency).

Another benefit of a spoiler is to help avoid shock cooling the engine an air-cooled piston engine (particularly for turbocharged piston engine which generally generate higher temperatures). The phenomenon of shock cooling is when the engine cools too rapidly, causing stuck valves; or deformed cylinders; or other engine problems. In a regular descent (i.e., without spoilers), airspeed is increased and the engine will be at low power, producing less heat than normal. Spoilers alleviate the situation by allowing the aircraft to descend at a higher rate; and to decelerate faster; while letting the engine run at a power setting that keeps it from cooling too quickly.

2. **Spoiler Design Guidelines**

The aerodynamic function of a spoiler is almost opposite to what a high lift device (e.g., flap) does aerodynamically. When spoilers are deployed (i.e., raised), they cause a flow separation (Figure 4); which implies a local loss of lift, and a local drag increase. In practice, a spoiler is deflected upward, while a the high lift device is deflected downward. When deflected, a spoiler decreases the wing lift (i.e., spoils); while a high lift device increases the wing lift. However, both the high lift device and spoiler will increase the wing drag. The turbulent airflow that develops behind the spoiler causes noise and vibration, which will cause discomfort to pilot/passengers.

Thus, to avoid roll reversal within the operational flight envelope, the wing structure must be designed with sufficient stiffness. The phenomenon of adverse yaw imposes a constraint on the aileron design. To avoid such an undesirable yawing motion (i.e., adverse yaw), there are a number of solutions; one of which is to employ spoiler. Spoiler is creating a wing drag such that both wing-sections drags are balanced.

The design of spoiler will influence the design of both the high lift device and aileron. Spoilers are essentially flat plates of about 10-15% chord located just ahead of the flaps. The spanwise extent of aileron depends on the amount of span required for trailing edge high lift devices. In general, the outer limit of the flap is at the spanwise station where the aileron begins. The exact span needed for ailerons primarily depend of the roll control requirements. A low speed aircraft usually utilizes about 40% of the total wing semispan for ailerons. This means that flaps can start at the side of the fuselage and extend to the 60% semispan station. Furthermore, if a small inboard aileron is provided for gentle maneuvers, the effective span of the flaps is reduced. However, with the application of spoilers, the ailerons are generally reduced in size, and the flaps may extend to about 75% of the wing semispan.
Figure 4. Spoiler aerodynamic function

If a spoiler is just for the purpose of landing deceleration, it must be close to fuselage center line (FCL) as much as possible. However, if the spoiler is only for roll control, it should be as far as possible to the fuselage center line. When a spoiler is close to the FCL, it will create small bending moment, so the structure will be lighter. On the other hand, when the spoiler is far from FCL, it will create a large rolling moment. In order to avoid any yawing moment when spoiler is deployed during landing, the spoilers must have equal area and distance to FCL on both sides of the wing sections. This symmetrical provision guarantees the aircraft straight line path during landing, since no yawing moment is produced due to drag increase and loss of lift.

In the design process of spoiler, five parameters need to be determined. They are: 1. spoiler planform area ($S_s$); 2. spoiler chord ($C_s$); 3. spoiler span ($b_s$); 4. maximum spoiler deflection ($\delta_s$); and 5. location of inner edge of the spoiler along the wing span ($b_{si}$). Figure 5 shows the spoiler geometry. In addition, the electro/mechanical mechanism to deploy the spoiler should be designed; this topic is beyond the scope of this write-up. As a general guidance, the typical values for these parameters are as follows: $S_s/S = 0.03$ to $0.10$, $b_s/b = 0.3 - 0.7$, $C_s/C = 0.10 - 0.3$, $b_{si}/b = 0 - 0.3$, and $\delta_s = 30 - 90$ degrees.

Based on this statistics, about 3 to 10 percent of the wing area may be devoted to the spoiler, the spoiler-to-wing-chord ratio is about 10 to 30 percent, spoiler-to-wing-span ratio is about 30-70 percent, and the inboard spoiler span is about 0 to 30 percent of the wing span. In addition, the spoiler may be deployed from 45 to 90 degrees upward. Table 1 illustrates the characteristics of spoiler of several aircraft.
The spoiler-to-wing-chord ratio should be about less than 30 percent. The reason lies in the availability of a flat/curved surface on top of the wing. The maximum thickness of an airfoil/wing is frequently located at about 30-40% of the chord. In addition, about 20% of the trailing edge of the wing inboard section is devoted to the trailing edge high lift device (e.g., flap). Due to the camber of an airfoil and wing, only about 30% of the top surface of the wing (behind the position of the maximum thickness) is available to a spoiler.

The regional jet airliner Bombardier CRJ200 [1] has a fly-by-wire spoiler and spoileron system, four spoilers each side, with inner two functioning as ground spoilers, outer two comprising one flight spoiler and one spoileron, both also providing lift dumping on touchdown. The twin jet airliner Airbus 320 has five-segment spoiler forward of flaps on each side of the wing, all 10 spoilers used as lift dumpers, inner six as airbrakes, outer eight and ailerons for roll control, and outer four and ailerons for gust alleviation.

<table>
<thead>
<tr>
<th>No</th>
<th>Aircraft</th>
<th>Type</th>
<th>m_TO (kg)</th>
<th>S_s/S</th>
<th>C_s/C</th>
<th>b_s/b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bombardier CRJ200</td>
<td>Regional jet airliner</td>
<td>21,523</td>
<td>0.041</td>
<td>0.07-0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>2</td>
<td>Airbus 320</td>
<td>Twin jet airliner</td>
<td>73,500</td>
<td>0.071</td>
<td>0.14-0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>Boeing 777</td>
<td>Wide-bodied jet airliner</td>
<td>299,575</td>
<td>0.054</td>
<td>0.11-0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>Airbus A400M</td>
<td>Military transport</td>
<td>126,500</td>
<td>0.06</td>
<td>0.12-0.15</td>
<td>0.3</td>
</tr>
<tr>
<td>5</td>
<td>Embraer ERJ-145</td>
<td>Regional jet airliner</td>
<td>20,600</td>
<td>0.045</td>
<td>0.09-0.13</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 1. Specifications of spoilers for several aircraft

Strategic airlift jet aircraft Antonov 124 has 12 spoilers on each wing section [1], forward of trailing edge flaps (four lateral control spoilers outboard, four glissage spoilers, and four airbrakes inboard). Twin jet freighter Boeing 767-300 has five-segment spoilers ahead of single-
slotted flaps; and two-segment spoilers ahead of double-slotted flaps. In business jet aircraft Learjet 60, spoilers are partially extended to mainly adjust descent rate.

Military transport Airbus A400M is equipped with five spoilers on each wing section [1], forward of trailing edge flaps which used for roll control, lift dumping, and also as speed brakes. Regional jet airliner Embraer ERJ-145 employs four-segment in-flight and ground spoiler [1]; where inboard spoilers are deployed 52 degrees, while outboard deployed 30 degrees.

3. Spoiler Design Requirements

In order to allow for spoilers to function effectively, the following design requirements are established:

a. Landing deceleration requirement
b. Descent rate requirement
c. Roll control requirement
d. Wing structural integrity
e. Mechanical power (force) to deflect the spoiler
f. Symmetricity about fuselage centerline
g. Bending moment at the wing root due to the spoiler deflection
h. Low cost
i. Low weight
j. Maintainability
k. Manufacturability

In the next section, design fundamentals; and the technique to determine spoiler’s parameters to satisfy the design requirements will be presented. To choose the optimum spoiler, the designer should establish and compare other design objectives. A sensitivity analysis yields the best spoiler design.

4. Fundamentals of Spoiler Design

In this section, only landing deceleration requirement is considered, other design requirements will be discussed later. An aircraft must stop within a specified distance during landing operation (after touch down). The shorter the distance, the shorter the runway, and the lower is the cost of airport construction. The main tool to meet this requirement; is the aircraft braking capability; either through mechanical brakes (i.e., brake shoes in tires), or thrust revers, or spoiler. The landing speed will be brought to zero by employing various types of deceleration.

After an aircraft touched down (Figure 6), the engine thrust gets zero (except when it is deployed as thrust reverse), so the aircraft drag (D), the brake force (FB); and friction force (Ff) will decelerate the aircraft.

There are two governing force equations that govern the aircraft motion during landing (to be more accurate; after touchdown and rotation). The first one is based on the Newton’s second law
along the x-axis. Based on the Newton’s second law, the summation of all forces generates a deceleration on the aircraft as follows:

\[ \sum F = m \frac{d}{dt} (V) \Rightarrow T - D - F_O - F_B - F_f = ma \]  

(1a)

where acceleration “a” has a negative value (so, deceleration); D is aircraft drag; \( F_B \) is the brake force; \( F_f \) is the rolling friction resistance (friction between the rotating tires and the ground); \( F_O \) is all other resisting forces (e.g., thrust reverse, or arresting gear). In addition; T is the engine thrust; and “m” is the aircraft landing mass. The engine thrust is always zero during ground roll, except when it is used as resisting force (i.e. thrust reversal). When the other resistive force is assumed to be zero, equation (1a) reduces to:

\[ -D - F_f - F_B = ma \]  

(1b)

The second one is the equilibrium of forces in the z-direction:

\[ \sum F_z = 0 \Rightarrow L + N = W \]  

(2)

where, the N is the normal force, and W represents the aircraft landing weight.

\[ W = W_L = mg \]  

(3)

where, g is the gravitational constant. The friction force \( (F_f) \) is the product of the normal force and the friction coefficient. Using equation (2), the friction force is determined by:

\[ F_f = \mu_N N = \mu_N (W - L) \]  

(4)

Table 2. Rolling friction coefficient \((\mu_G)\) for various runways

<table>
<thead>
<tr>
<th>Type of terrain</th>
<th>Dry Concrete</th>
<th>Dry Asphalt</th>
<th>Hard turf</th>
<th>Short grass</th>
<th>Long grass</th>
<th>Firm dirt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel-ground friction coefficient</td>
<td>0.03-0.04</td>
<td>0.04-0.05</td>
<td>0.05</td>
<td>0.05-0.07</td>
<td>0.07-0.1</td>
<td>0.04-0.06</td>
</tr>
</tbody>
</table>

Figure 6. Forces during landing operation
The runway rolling friction coefficient, $\mu_G$, depends on the type of terrain. Table 2 introduces the friction coefficients for different terrains. When concrete/asphalt runway gets wet (e.g., a rainy day), the friction coefficient will be reduced about 60%-90%.

The aircraft lift ($L$) during landing is obtained by the following expression:

$$L = L_L = \frac{1}{2} \rho V^2 C_{L_L} S_{ref}$$

The aircraft lift at landing is assumed to be equal to the wing-fuselage lift ($L_L$). Hence, for simplicity, the horizontal tail lift ($L_h$) is neglected.

$$L_L = L_{ref} = \frac{1}{2} \rho V^2 C_{L_{ref}} S_{ref}$$

Another aerodynamic force (drag) is obtained from the following expression:

$$D = \frac{1}{2} \rho V^2 C_{D_L} S_{ref}$$

where, $V$ denotes the aircraft linear forward speed, $S_{ref}$ represents the wing planform area, and $\rho$ is the air density at landing altitude. Furthermore, two coefficients of $C_D$ and $C_{L_{ref}}$ denote drag, and wing-fuselage lift coefficients respectively.

The landing lift coefficient (i.e., wing-fuselage lift coefficient) is determined as:

$$C_{L_{ref}} = C_{L_c} + \Delta C_{L_{spoiler}} + \Delta C_{L_s}$$

where the $C_{L_c}$ is the aircraft cruise lift coefficient at cruise; $\Delta C_{L_s}$ is the (negative) contribution of the spoiler to the wing lift; and $\Delta C_{L_{spoiler}}$ is the additional lift coefficient that is generated by the high lift device at landing configuration. The typical value for aircraft cruise lift coefficient is about 0.3 for a subsonic aircraft and 0.05 for a supersonic aircraft. The typical value for landing the high lift device lift coefficient ($\Delta C_{L_{spoiler}}$) is about 0.6 to 1.3.

The aircraft lift coefficient at cruise is obtained from:

$$C_{L_c} = \frac{2mg}{\rho C S_{ref} V_C^2}$$

where $V_C$ denotes the aircraft cruising velocity, and $\rho_C$ is the air density at the cruise altitude. The aircraft drag coefficient at landing configuration ($C_{D_L}$) is:

$$C_{D_L} = C_{D_{ag}} + KC_{L_{ag}} + C_{D_h}$$

where $K$ is referred to as induced drag factor; and is calculated by:

$$K = \frac{1}{\pi \cdot e \cdot AR}$$

The parameter “e” is the Oswald span efficiency factor; with a typical value between 0.7 and 0.95; and “AR” is the wing aspect ratio. The aircraft zero-lift drag coefficient at landing configuration ($C_{D_{ag}}$) is:

$$C_{D_{ag}} = C_{D_{ag}} + C_{D_{agL}} + C_{D_{agH}}$$
where $C_{D_0}$ is the clean aircraft zero-lift drag coefficient, $C_{D_{LG}}$ is the landing gear drag coefficient, $C_{D_{HLD}}$ is the high lift device (e.g., flap) drag coefficient at landing configuration. The typical values for $C_{D_{LG}}$ and $C_{D_{HLD}}$ are as follows:

\[
C_{D_{LG}} = 0.006 \text{ to } 0.012 \\
C_{D_{HLD}} = 0.007 \text{ to } 0.014
\]

The author’s note [3] on “Aircraft Drag Coefficient” presents the technique to determine both landing gear drag coefficient, and the high lift device drag coefficient.

The parameter $C_{D_s}$ represents the spoiler drag coefficient. The spoiler helps the landing operation with a dual role: 1. Increase the aircraft drag directly. 2. Increase friction indirectly. The aircraft drag increase due to spoiler deflection is very similar to the aerodynamic drag of a thin plate, since the spoiler may be assumed as a thin plate. Hence, the drag model of a spoiler introduced here, is fairly accurate, but the contribution model of the spoiler to the wing lift; presented in this section, is not very accurate and is an approximate.

A thin plate perpendicular to the flow has a drag coefficient of about 1.9 based on its frontal area [2]. Thus, the spoiler drag coefficient with a planform area of $S_S$; and a deflection of $\delta_s$ is determined from:

\[
C_{D_s} = 1.9 \sin(\delta_s) \frac{S_S}{S_{ref}}
\]

The spoiler planform area is simply the product of the spoiler span ($b_s$) and spoiler mean chord ($C_s$):

\[
S_S = b_s C_s
\]

Mathematically, the contribution of the spoiler to the aircraft lift ($\Delta C_{L_s}$) is hard to be modelled. The following is an approximation for this contribution:

\[
\Delta C_{L_s} = -C_{L_c} \frac{b_s}{b}
\]

For an accurate result, the reader is encouraged to conduct a wind tunnel test; or utilize a CFD model. In equation 16, the ratio “$b_s/b$” is the spoiler-to-wing-span ratio. The negative sign in this equation illustrates the spoiling nature of a spoiler.

The brake force ($F_B$) is produced through wheels via either internal-shoe (or drum) brake, or disk brake. In both cases, a friction force against the rotation of wheels is created. When the pilot pushes the pedals, a constant pressure (e.g., hydraulic) is applied over the area of the friction pad. Hence, the friction force is a function of type of pad materials (i.e., coefficient of friction); the contact area; and the pressure applied over the rotating wheel.

This process, absorbs the kinetic energy of the wheels, and creates heat energy; and it is concurrently dissipated. To adjust the brake force, the brake temperatures are displayed in the pilot cockpit; so the pilot will adjust his/her pedal force accordingly. The pad limit temperature will avoid melting the tire wheel; and brake pad. The kinetic energy is absorbed during slippage
of a brake, and appears as heat. Table 3 provides the coefficient of friction [4] of some friction materials for brakes.

<table>
<thead>
<tr>
<th>No</th>
<th>Brake Pad Material</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cermet</td>
<td>0.32</td>
</tr>
<tr>
<td>2</td>
<td>Sintered metal</td>
<td>0.29-0.33</td>
</tr>
<tr>
<td>3</td>
<td>Rigid molded asbestos</td>
<td>0.35-0.41</td>
</tr>
<tr>
<td>4</td>
<td>Woven asbestos yarn and wire</td>
<td>0.38</td>
</tr>
</tbody>
</table>

*Table 3. Coefficient of friction ($\mu_B$) of some friction materials for brakes*

The detail analysis of the brake system is beyond the scope of this note. So, the brake force is modeled as the product of aircraft weight (at landing; $W_L$) and the coefficient of friction ($\mu_B$) of brake pad.

$$F_B = k_1 \mu_B W_L$$

(17)

where $k_1$ represents the percentage application of the full maximum brake power. A maximum energy stop (max braking force) will heat up the brakes and wheels a lot, and may lead to blown tires, or even fires. In a normal operation, there's no need to employ the maximum stopping power of aircraft. It would be generally harmful to do so, unless absolutely necessary. Due to safety precaution, landing gear configuration, and the type of brake system, the parameter $k_1$ may vary between no use (i.e., 0%) and full application (i.e., 100%) (i.e., $0 < k_1 < 1$).

It is emphasized again that; this section considers only the landing deceleration requirement. For the landing distance calculation ($S_L$), we use the basic governing equation for an accelerated (indeed; decelerated) linear motion from a Physics textbook:

$$V_2^2 - V_1^2 = 2ax$$

(18)

where $V_1$ denotes the initial velocity, $V_2$ denotes the final velocity, “$a$” as acceleration (here deceleration), and $x$ is the distance traveled. In our case (i.e., landing), the $V_1$ is the velocity of aircraft at the end of rotation (not shown in Figure 7); and after the touch down ($V_L$), $V_2$ is zero (full stop); and “$x$” is the ground distance of the landing run; $S_G$ (Figure 7).

$$-V_L^2 = 2aS_G$$

(19)
The acceleration is defined as the time rate of change of velocity:
\[ a = \frac{dV}{dt} \tag{20} \]

Velocity (or speed) is defined as the time rate of change of displacement:
\[ V = \frac{dS}{dt} \tag{21} \]

If we combine these two and cancel “\(dt\)” from both sides, we have:
\[ a \cdot dS = V \cdot dV \tag{22} \]

So, the ground roll or ground run \((S_G)\) is determined through the integration of:
\[ S_G = \int \frac{V}{a} \, dV \tag{23} \]

By substitution of the equation 1b into equation (23), and applying the integral limits; we have:
\[ S_G = \int_{V_L}^{v_f} \frac{-mV}{D + \mu N + F_B} \, dV = \int_{0}^{v_f} \frac{mV}{D + \mu(W - L) + F_B} \, dV \tag{24} \]

where \(V_L\) is the landing velocity. The velocity is a function of the stall speed, and the aircraft type:
\[ V_L = k_2V_S \tag{25} \]

where \(k_2\) represents a safety factor, and the typical values for \(k_2\) are as follows:
- 1.1-1.15 for fighters
- 1.2-1.3 for large transport aircraft
- 1.15-1.2 for GA aircraft

After substitution of the required elements, and an algebraic step, we will have:
\[ S_G = \int_{0}^{v_f} \frac{mV}{2 \rho V^2 S(C_{D_k} - \mu G C_{L_k}) + \left(\mu_G + k_1 \mu_B\right)mg} \, dV \tag{26} \]

When all required elements of equation 26 are substituted, the integration can be performed to solve for landing ground run \((S_G)\). This integration can also be solved directly using a mathematical or engineering software package. But, we introduce a simplified solution. This integration can be modeled as:
\[ S_G = \int_{0}^{v_f} \frac{V}{A + BV^2} \, dV \tag{27} \]

where
\[ A = \left(\mu_G + \mu_B\right)g \tag{28} \]
\[ B = \frac{1}{2m} \rho S \left(C_{D_k} - \mu G C_{L_k}\right) \tag{29} \]

The solution for the integration of (26) from standard mathematical handbooks [5] is obtained:
\[ S_G = \frac{1}{2B} \ln \left[ \frac{A + BV_L^2}{A} \right] \]  

(30)

where A and B are substituted from (28) and (29). With this substitution, the result would be

\[ S_G = \frac{1}{2} \frac{1}{m} \ln \left[ \frac{(\mu_G + k_i \mu_b)g + \frac{1}{2m} \rho S(C_{D_k} - \mu_G C_{L_k})V_L^2}{(\mu_G + k_i \mu_b)g} \right] \]  

(31)

or

\[ S_G = \frac{m}{\rho S(C_{D_k} - \mu_G C_{L_k})} \ln \left[ 1 + \frac{\rho S(C_{D_k} - \mu_G C_{L_k})V_L^2}{2(\mu_G + k_i \mu_b)mg} \right] \]  

(32)

In the design of a spoiler, the only two unknowns in this equation (32) are the aircraft drag coefficient, and the lift coefficient; both of which are functions of the spoiler geometry. The application of these equations and concepts will be provided in the next section.

5. Spoiler Design Steps

In this section, the spoiler design steps only to satisfy the landing deceleration is considered, other design techniques will be presented later.

In order to design a spoiler, the following parameters must be given:

- the desired ground distance of the landing run; \( S_{GL} \)
- aircraft zero lift drag coefficient
- high lift device zero lift drag coefficient
- landing gear zero lift drag coefficient
- induced drag factor (K)
- wing area
- wing span
- fuselage diameter
- landing velocity at touchdown
- aircraft cruise lift coefficient
- aircraft type
- landing altitude
- additional lift coefficient that is generated by the high lift device at landing configuration
- type of runway
- brake force

At the end of the design process, the following spoiler variables are determined:

- spoiler planform area (\( S_s \))
- spoiler chord (\( C_s \))
- spoiler span (\( b_s \))
- maximum spoiler deflection (\( \delta_s \))
- location of inner edge of the spoiler along the wing span (\( b_{si} \)).
There is no unique design technique; the following is a working technique based on the systems engineering approach:

**Step 1.** Select an initial value for the spoiler maximum deflection. It is recommended to begin with 90 degrees.

**Step 2.** Select an initial value for the spoiler-to-wing-span ratio ($b_s/b$). It is recommended to begin with a value of 40 percent.

**Step 3.** Calculate the aircraft lift coefficient at cruise is obtained using equation (9):

$$C_{Lc} = \frac{2mg}{\rho C_{\text{ref}} S_{\text{ref}} V_C^2} \quad (9)$$

**Step 4.** Calculate the contribution of the spoiler to the aircraft lift ($\Delta C_{L_s}$) using equation 16:

$$\Delta C_{L_s} = -C_{Lc} \frac{b_s}{b} \quad (16)$$

**Step 5.** Calculate the landing lift coefficient (as equal to wing-fuselage lift coefficient) using equation (8):

$$C_{L_L} = C_{L_{\text{eq}}} = C_{Lc} + \Delta C_{L_{\text{sepL}}} + \Delta C_{L_s} \quad (8)$$

**Step 6.** Calculate the landing velocity ($V_L$) using equation 25:

$$V_L = k_2 V_S \quad (25)$$

**Step 7.** Calculate the required aircraft drag ($C_{D_L}$) to meet a desired landing ground run, using equation 32:

$$S_G = \frac{m}{\rho S(C_{D_L} - \mu_G C_{L_L})} \ln \left[ 1 + \frac{\rho S(C_{D_L} - \mu_G C_{L_L}) V_L^2}{2(\mu_G + k_1 \mu_B) mg} \right] \quad (32)$$

**Step 8.** Calculate the contribution of the spoiler to the aircraft drag ($\Delta C_{L_s}$) using equation 10 and 12.

$$C_{D_L} = C_{D_{\text{eq}}} + KC_{L_{\text{wef}}}^2 + C_{D_s} \quad (10)$$

$$C_{D_{\text{eq}}} = C_{D_{\text{eq}}} + C_{D_{\text{eqG}}} + C_{D_{\text{eqID, L}}} \quad (12)$$

**Step 9.** Calculate the required spoiler area ($S_S$) using equation 14:

$$C_{D_s} = 1.9 \sin(\delta_s) \frac{S_S}{S_{\text{ref}}} \quad (14)$$

**Step 10.** Calculate the required spoiler chord ($C_S$) using equation 15:

$$S_S = b_s C_S \quad (15)$$

**Step 11.** Check to see if the spoiler-to-wing-chord ratio is less than 40 percent; if not, go back to step 2 and increase the spoiler span.
Step 12. Calculate the resulting deceleration to meet the landing requirement using equation 19:
\[-V_L^2 = 2aS_{gl}.\]  
(19)

Step 13. Select an initial value for the spoiler inboard spoiler location (b_s/b). It is recommended to begin with the value equivalent to the ratio of fuselage width to wing span; D_f/b; (i.e., ratio of the inboard spoiler span to the wing span). This implies that the spoiler begins at the edge of the fuselage along the wing span.

Step 14. Determine the mechanical force required to deploy (raise) the spoiler. The technique is not covered here. This force will be used to design the mechanism to deflect the spoiler.

Step 15. Compute the additional drag created by spoiler when deployed.

Step 16. Calculate the bending moment (at the wing root) created by the spoiler deflection.

Step 17. Calculate the overall manufacturing cost to employ this spoiler (i.e., spoiler, plus extension mechanism).

Step 18. Optimize the spoiler by varying the spoiler parameters (e.g., span, deflection) to minimize a design requirement (e.g., cost/weight). In this step, a number of iteration is necessary to come up with the best spoiler. For instance, if the spoiler deflection is changed, go to step 1; or if the spoiler-to-wing-span ratio is changed, go to step 2.

Step 19. Using a CFD software; or a wind tunnel test; determine the aerodynamic performance (i.e., ΔC_L, ΔC_D) of the spoiler to validate the theoretical results.

Step 20. If the spoiler has other roles such as roll control, examine the performance of the spoiler for other design requirements, and modify accordingly.

6. Example

Problem statement: A subsonic business twin-jet aircraft (similar to a Boeing 717) has a take-off mass of 50,000 kg and a wing area of 93 m². Other characteristics of the aircraft are as follows:

\[V_c = 438 \text{ KTAS (at 34,000 ft), } V_s = 108 \text{ KEAS}, \ C_{Do} = 0.018, \ C_{Do,\text{flap}} = 0.008, \ C_{Do,\text{flap}} = 0.007, \ AR = 9, \ e = 0.85, \ ΔC_{L,\text{flap}} = 1.3, \ k_2 = 1.2\]

The aircraft is required to land at an 950 m dry asphalt runway (the distance after touchdown and rotation), during the landing operation at sea level altitude. Design a spoiler to meet this requirement. The aircraft is equipped with a brake with Cermet pad and the percent application of 50% (i.e., k_1 = 0.5).

Solution: (A MathCad file is used)
\[ m_1 := 50000 \text{ kg} \quad S_1 := 93 \text{ m}^2 \quad \Delta C_{\text{flap}} := 1.4 \quad C_{L_{\max}} := 2.8 \quad \mu_G := 0.04 \]

\[ b := 28 \text{ m} \quad e_1 := 0.8 \quad \text{AR} := 5 \quad C_{\text{DoC}} := 0.011 \quad \Delta C_{\text{DLG}} := 0.00 \quad \Delta C_{\text{Dflap}} := 0.00 \]

\[ K_1 := \frac{1}{\pi e_1 \cdot \text{AR}} = 0.042 \quad \mu_B := 0.3 \quad S_G := 950 \text{ m} \quad k_1 := 0.5 \quad k_2 := 1.2 \]

\[ V_s := 108 \text{ knot} \quad \rho_o := 1.225 \text{ kg m}^{-3} \]

\[ V_C := 438 \text{ knot} \quad \rho_c := 0.000766 \text{ slug ft}^{-3} \]

\[ \delta_s := 90 \text{ deg} \]

\[ 1) \quad \delta_s := 90 \text{ deg} \]

\[ 2) \quad b_s := 0.4b = 11.2\text{ m} \]

\[ 3) \quad C_{Lc} := \frac{2m_1g}{\rho_c S_1 V_C^2} = 0.526 \]

\[ 4) \quad \Delta C_{Ls} := -C_{Lc} \frac{b_s}{b} = -0.21 \]

\[ 5) \quad C_{LL} := C_{Lc} + \Delta C_{\text{flap}} + \Delta C_{Ls} = 1.616 \]

\[ 6) \quad V_L := k_2 V_s = 129.6\text{ knot} \]

Given \[ C_{DL} := 0.14 \]

\[ 7) \quad S_G = \frac{m_1}{\rho_o S_1(C_{DL} - \mu_G C_{LL})} \ln \left[ 1 + \frac{\rho_o S_1(C_{DL} - \mu_G C_{LL}) V_L^2}{2(\mu_G + k_1 \mu_B) m_1 g} \right] \]

\[ C_{DL} := \text{Find}(C_{DL}) \quad C_{DL} = 0.223 \]

\[ 8) \quad C_{\text{DoL}} := C_{\text{DoC}} + \Delta C_{\text{DLG}} + \Delta C_{\text{Dflap}} = 0.033 \]

\[ C_{Ds} := C_{DL} - C_{\text{DoL}} - K_1 C_{LL}^2 = 0.081 \]

\[ 9) \quad S_s := \frac{C_{Ds} S_1}{1.9 \sin(\delta_s)} = 3.985\text{ m}^2 \quad \frac{S_s}{S_1} = 0.043 \]

\[ 10) \quad C_s := \frac{S_s}{b_s} = 0.356\text{ m} \quad C_1 := \frac{S_1}{b} = 3.32 \text{ in} \quad \frac{C_s}{C_1} = 0.107 \]
Thus, the spoiler will have the following geometry:

\[ \frac{S_s}{S} = 4.3\%; \quad \frac{b_s}{b} = 40\%; \quad \delta_s = 90 \text{ degrees}, \quad \text{and} \quad \frac{C_s}{C} = 10.7\% \]

It is interesting to examine other alternatives. For instance, two other acceptable options are:

**Option 2:**
If \( \frac{b_s}{b} = 40\% \); and \( \delta_s = 70 \text{ degrees} \) are selected, the spoiler will need to have the following geometry:

\[ \frac{S_s}{S} = 4.6\%; \quad \text{and} \quad \frac{C_s}{C} = 11.4\% \]

**Option 3:**
If \( \frac{b_s}{b} = 50\% \); and \( \delta_s = 90 \text{ degrees} \) are selected, the spoiler will need to have the following geometry:

\[ \frac{S_s}{S} = 4.5\%; \quad \text{and} \quad \frac{C_s}{C} = 9.1\% \]

The rest of the design and optimization is left to the interested reader. To choose the optimum spoiler, one must consider and compare other design objectives such as the manufacturing cost, mechanical force required to deploying (raising) the spoiler, and bending moment due to the spoiler deflection. A sensitivity analysis will result in the best spoiler design.

**References**

1. Jackson P., Jane’s All the World’s Aircraft, Jane’s information group, 2006-2007