Basic Aircraft Configuration Design Rules

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Unified Engineering

Nomenclature

x, y	longitudinal, spanwise positions
S	reference area (wing area)
b	wing span
c	average wing chord $(= S/b)$
$\mathcal{R}$	wing aspect ratio
C_L	lift coefficient
Υ	wing dihedral angle
β	sideslip angle
ϕ	bank angle
R	turn radius
S_h	horizontal tail area
S_v	vertical tail area
ℓ_h	horizontal tail moment arm
ℓ_v	vertical tail moment arm
$\mathcal{R}_h$	horizontal tail aspect ratio
V_h	horizontal tail volume coefficient
V_v	vertical tail volume coefficient
B	spiral stability parameter
α	angle of attack
V	velocity

Role of Simple Design Rules

Aircraft must have a certain amount of inherent stability and controllability to be flyable. It is therefore important to consider these characteristics when designing a new aircraft. Accurate evaluation of the stability characteristics of any given aircraft is a fairly complicated process, and is not well suited for preliminary or intermediate design. Fortunately, we have alternative criteria which give reasonable estimates and are vastly simpler to apply.

The criteria involve basic dimensions, shown in Figure 1. Longitudinal x locations are typically

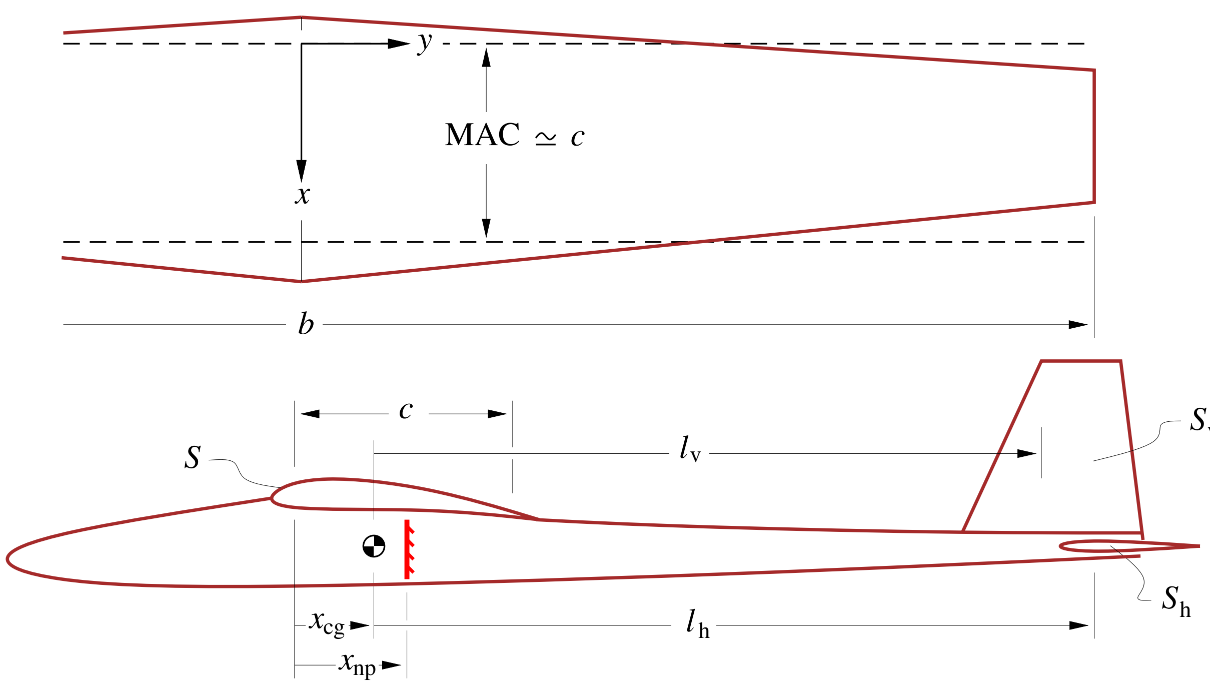

Figure 1: Lengths, areas, and angles used in simple stability criteria.

measured relative to the leading edge of the wing's *Mean Aerodynamic Chord*, or MAC, which is the root-mean-square average chord. For most wings this is very nearly equal to the simple-average chord c.

The ℓ_h and ℓ_v tail moment arms are the distances between the Center of Gravity (CG) and the average quarter-chord locations of the horizontal and vertical tail surfaces. The criteria which will use these dimensions are estimates, so it's acceptable to estimate the CG position and to "eyeball" the tail average quarter-chord locations when measuring ℓ_h and ℓ_v.

Center of Gravity Position

An aircraft's horizontal tail size and position, and the CG position are the dominant factors controlling the aircraft's *pitch stability*, which is the tendency to automatically maintain an angle of attack and airspeed. The basic effects of moving the CG position are:

Decrease x_{cg}/c	(move CG fwd.):	increased stability; more resistance to α and V changes.
Increase x_{cg}/c	(move CG back):	decreased stability; less resistance to α and V changes.

There is one particular CG position which gives *neutral* stability, which is called the *Neutral Point* (NP). This is shown as x_{np} in Figure 1. The degree of pitch stability or instability is traditionally specified by the *Stability Margin*, sometimes also called the *Static Margin*.

$$\text{S.M.} = \frac{x_{np} - x_{cg}}{c} \tag{1}$$

Figure 2 illustrates the natural behaviors of an airplane after a pitch disturbance, for different values of S.M. The unstable behavior occurs when S.M. is negative, i.e. when the CG is behind the NP. Because pitch instability makes the aircraft very difficult or impossible to control, the NP position is considered to be a practical *aft CG limit*.

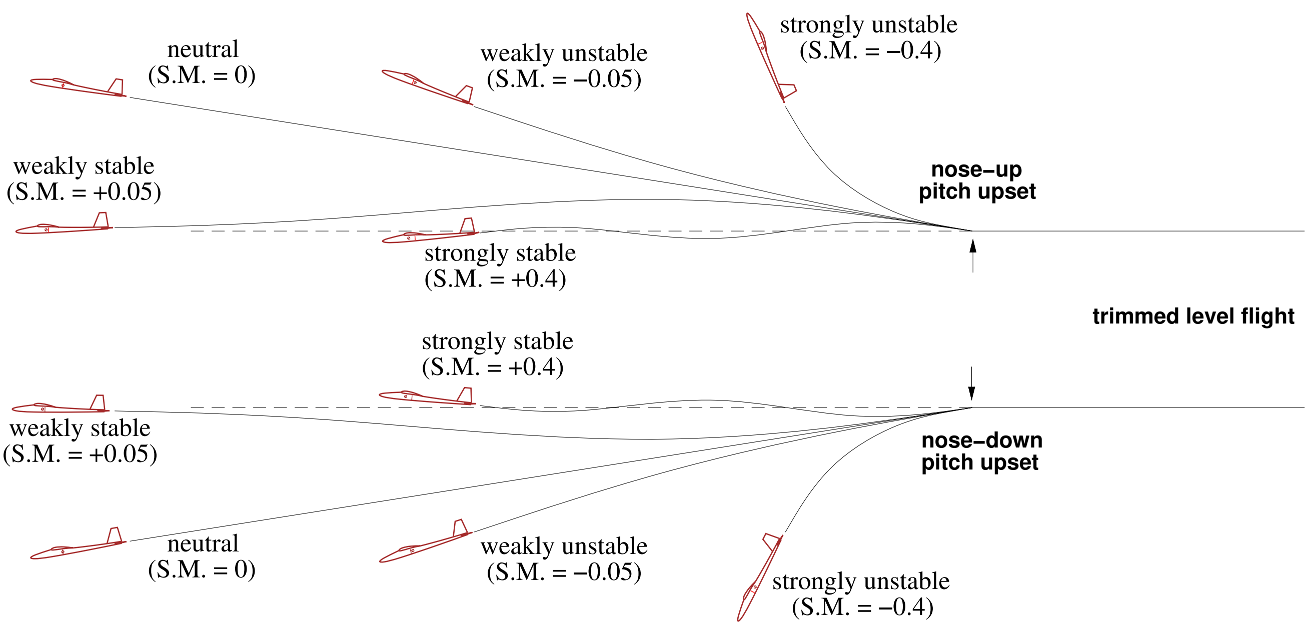

Figure 2: Natural aircraft responses to a pitch disturbance, for different amounts of pitch stability.

Making the S.M. strongly positive by moving the CG far forward will give plenty of pitch stability and a strong resistance to pitch upsets, but it also has undesirable side effects. One large drawback of a large S.M. is that it causes large (and annoying) pitch trim changes with changing airspeed. Figure 3 shows the flight paths of airplanes with different nonnegative S.M., immediately after an airspeed increase caused by a power increase. The straight-ahead acceleration of the weakly stable or neutral airplane is more desirable for the pilot.

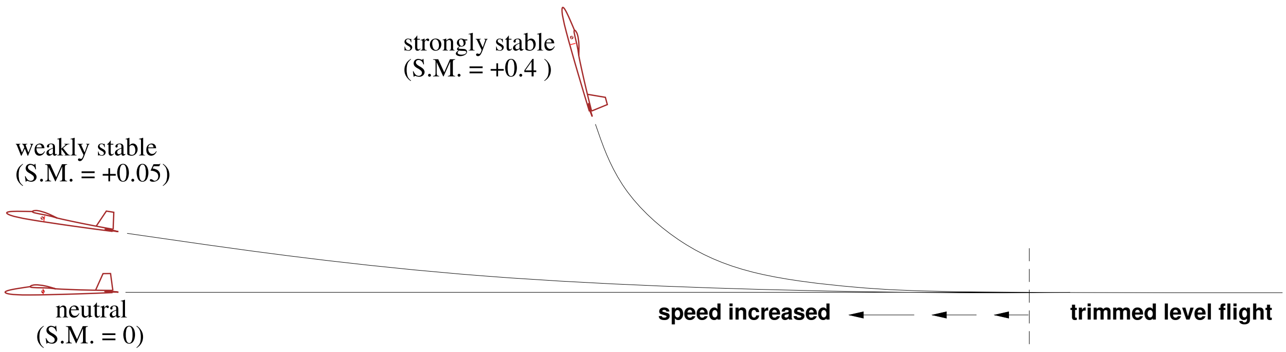

Figure 3: Pitch-up behavior from an airspeed increase, for large and small Static Margin.

More specifically, the strongly stable airplane shown in Figure 3 requires a relatively large elevator angle change commanded by the pilot to restore it to level flight. Figure 4 compares the situation for the strongly and weakly stable airplanes. In effect, a large positive S.M. degrades the *pitch trim authority* of the elevator, since large trim deflections are needed to maintain level flight in response to airspeed changes.

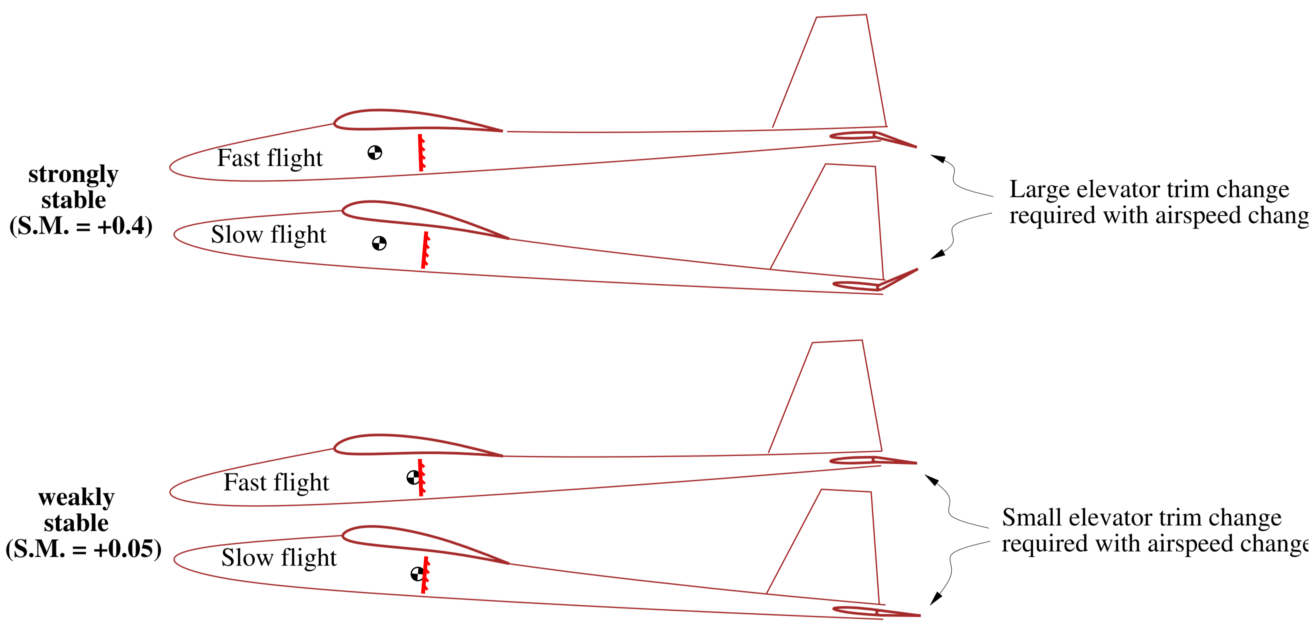

Figure 4: Elevator trim adjustment with changing airspeed, for large and small Static Margin.

This situation illustrates the benefit of reducing the S.M., by positioning the CG closer to the NP. However, if the CG is positioned behind the NP, the airplane will now have a negative S.M., and be unstable in pitch to some degree, with the results illustrated in Figure 2. This makes it difficult or even impossible to fly. In general, the small positive S.M. suggested by rule (2) is the ideal situation.

$$\boxed{S.M. \;\equiv\; \frac{x_{\rm np} - x_{\rm cg}}{c} \;=\; +0.05 \ldots +0.15} \tag{2}$$

Horizontal Tail Sizing Criteria

The Neutral Point location $x_{\rm np}$ is primarily controlled by size of the horizontal tail and its moment arm from the CG. A measure of this tail effectiveness is the *horizontal tail volume coefficient*:

$$\mathrm{V_h} \;\equiv\; \frac{S_{\rm h}\,\ell_{\rm h}}{S\,c} \tag{3}$$

A well-behaved aircraft typically has a $\mathrm{V_h}$ which falls in the following range:

$$\boxed{\mathrm{V_h} \;=\; 0.30 \ldots 0.60} \tag{4}$$

If $\mathrm{V_h}$ is too small, the aircraft's pitch behavior will be very sensitive to the CG location. It will also show poor tendency to resist gusts or other upsets, and generally "wander" in pitch attitude, making precise pitch control difficult.

The $\mathrm{V_h}$ also directly affects the NP location $x_{\rm np}$, which can be estimated by the following expression.

$$\frac{x_{\rm np}}{c} \;\simeq\; \frac{1}{4} \;+\; \frac{1+2/AR}{1+2/AR_{\rm h}}\left(1 \;-\; \frac{4}{AR+2}\right)\mathrm{V_h} \tag{5}$$

The derivation of this formula is beyond scope here, but it is straighforward to evaluate for any aircraft configuration.

Wing-Tail Configuration Layout

In the configuration-design stage, an airplane is treated as some collection of masses m_i, each having its own center of gravity at some location x_i, where $i = 1 \ldots n$ is the mass index. The center of gravity location of the entire collection is then given by

$$x_{\rm cg} \;=\; \frac{1}{m}\sum m_i\,x_i \tag{6}$$

$$m \;=\; \sum m_i \tag{7}$$

where the sums run over the mass index i, and m is the total mass.

The center of gravity calculation (6) can be combined together with the neutral-point estimate (5) to allow the static margin to be calculated from (1). These calculations can be implemented in a spreadsheet or a simple program, with the information flow shown in Figure 5.

Such a spreadsheet or program allows an iterative layout of an aircraft configuration which has the required static margin. Specifically, the mass locations x_i are adjusted until the resulting S.M. has the specified value, typically within the range given by rule (2). Simultaneously, the tail area $S_{\rm h}$ is also adjusted as needed to obtain the target $\mathrm{V_h}$ value as given by rule (4).

Vertical Tail Sizing Criteria

The primary role of the vertical tail is to provide *yaw damping*, which is the tendency of yaw oscillations of the aircraft to subside. The vertical tail also provides *yaw stability*, although this

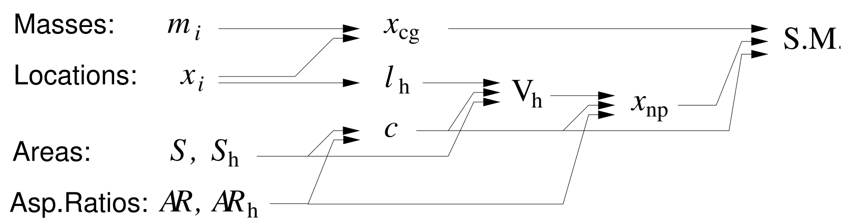

Figure 5: Calculation of horizontal tail volume V_h and Stability Margin S.M. from airplane masses and geometry parameters.

will be almost certainly ensured if the yaw damping is sufficient. One measure of the vertical tail's effectiveness is the *vertical tail volume coefficient*:

$$V_v \equiv \frac{S_v \, \ell_v}{S \, b} \tag{8}$$

Most well-behaved aircraft typically have a V_v which falls in the following range:

$$\boxed{V_v = 0.02 \ldots 0.05} \tag{9}$$

If V_v is too small, the aircraft will tend to oscillate or "wallow" in yaw as the pilot gives rudder or aileron inputs. This oscillation, shown in Figure 6, is called Dutch Roll, and makes precise directional control difficult. A V_v which is too small will also give poor rudder roll authority in an aircraft which uses only the rudder to turn.

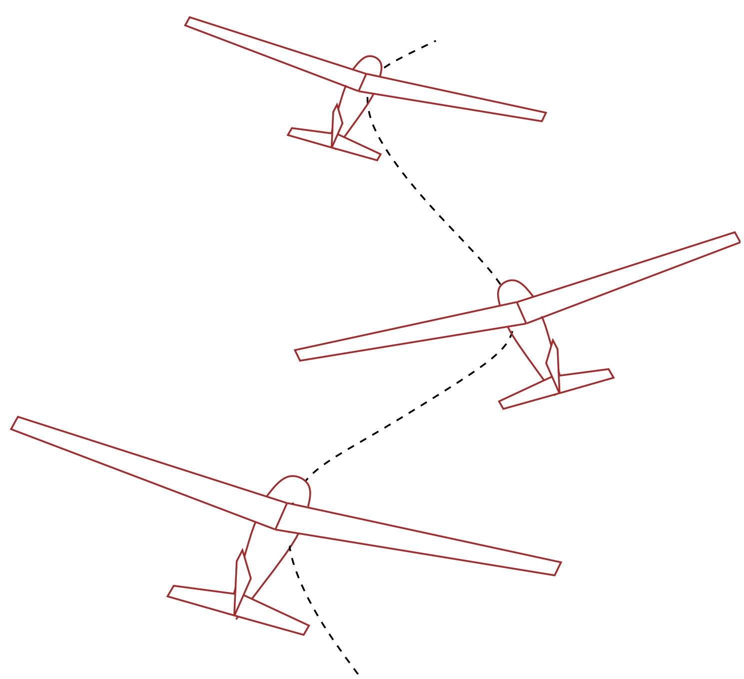

Figure 6: Dutch roll oscillation tendency from insufficient vertical tail volume.

Picking suitable V_h and V_v values for any new aircraft design is partly a matter of experience. One common approach is to simply duplicate the V_h and V_v values of an existing aircraft which is known to have good stability and control characteristics.

Dihedral Sizing Criterion I – Spiral Stability

The *dihedral angle* of the wing, denoted by Υ in Figure 1, provides some degree of natural spiral stability. A spirally-unstable aircraft tends to constantly increase its bank angle at some rate, and therefore requires constant attention by the pilot. Conversely, a spirally-stable aircraft will tend to roll upright with no control input from the pilot, and thus make the aircraft easier to fly. Figure 7 compares the two types of behavior.

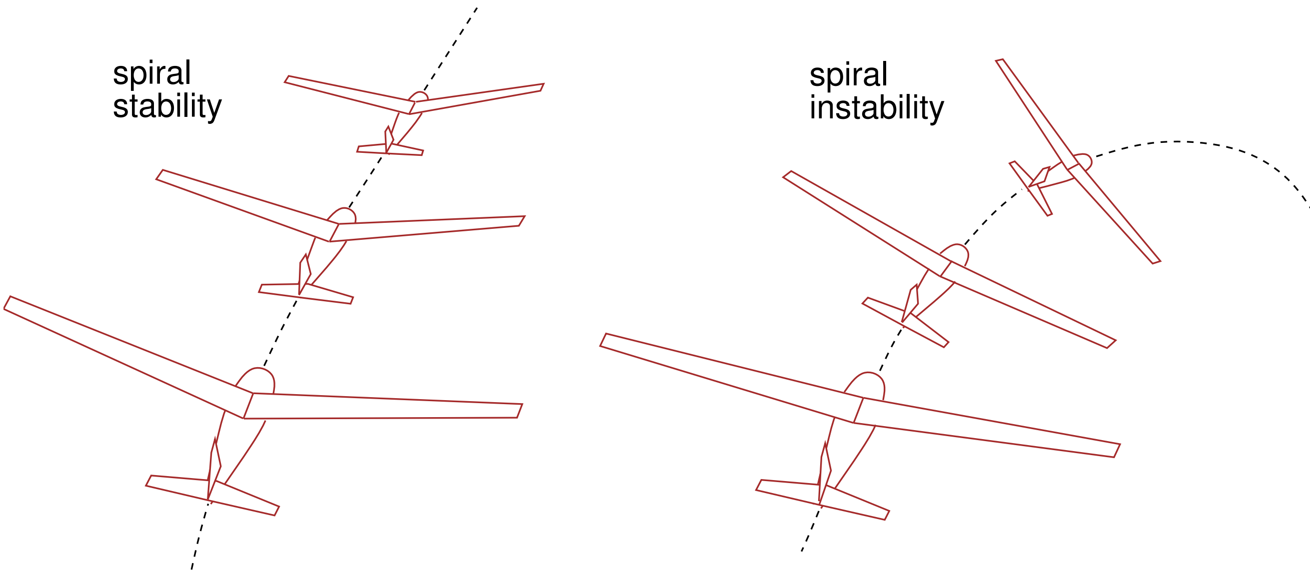

Figure 7: Two types of hands-off flight behavior starting from a banked orientation. Spiral instability results in a steepening of the bank angle, while spiral stability results in a return to zero bank angle.

Whether an aircraft is spirally stable or unstable can be determined via the spiral parameter B (named after its originator Blaine Rawdon, from Douglas Aircraft):

$$B \equiv \frac{\ell_v}{b} \frac{\Upsilon}{C_L} \qquad (\Upsilon \text{ in degrees}) \tag{10}$$

$$\boxed{\begin{array}{llll} B & > & 5 & , \text{ spirally stable} \\ B & = & 5 & , \text{ spirally neutral} \\ B & < & 5 & , \text{ spirally unstable} \end{array}} \tag{11}$$

The main parameter which is used to adjust B in the design phase is the dihedral angle Υ, since its other parameters ℓ_v, b, C_L are typically dictated by other design considerations.

Spiral stability is not a hard requirement, and most aircraft are in fact spirally unstable. Level flight is then ensured either by the pilot, or by a wing-levelling autopilot, provided the instability is slow enough. RC aircraft which can fly stably hands-off must be spirally stable, although a small amount of instability ($B = 3 \ldots 4$, say) does not cause major difficulties for an experienced pilot.