Chapter 2 Aircraft Center of Gravity

2.1. Introduction

The precise location of the aircraft *cg* is essential in the positioning of the landing gear, as well as for other MDO applications, *e.g.*, flight mechanics, stability and control, and performance. Primarily, the aircraft *cg* location is needed to position the landing gear such that ground stability, maneuverability, and clearance requirements are met. Given the fact that none of the existing conceptual design-level *cg* estimation procedures has the degree of responsiveness and accuracy required for MDO applications, a new approach is formulated to provide a reliable range of *cg* locations that is better suited for MDO applications.

The connection between the landing gear and the *cg* has become even more critical with the adoption of advanced control systems. As pointed out by Holloway[10] in 1971, and illustrated here in Fig. 2.1, once the aft *cg* limit is no longer based on stability but on the ability to generate the required nose down pitching moment, the wing tends to move forward relative to the *cg* and the landing gear may "fall off" the wing. Thus, the tip-back angle may become an important consideration in determining the aft *cg* limit. Sliwa identified this issue in his aircraft design studies.[11]

2.2. Current Capabilities

Although not expected to determine the location of the aircraft *cg*, current aircraft sizing programs, as typified by Jayaram *et al.* [12] and McCullers [13], do provide some rudimentary estimates. These codes use estimated component weights obtained from statistical weight equations, and either user-specified or default component *cg* locations to arrive at the overall aircraft *cg* location. However, as demonstrated by Chai *et al.* [14], the lack of responsiveness and accuracy have rendered current approaches inadequate for MDO application.

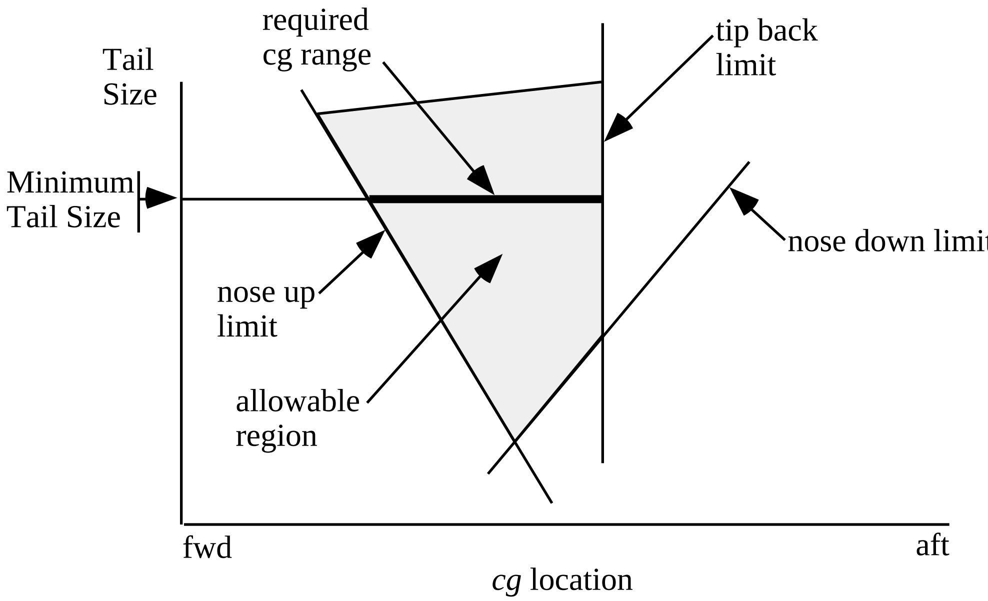

Figure 2.1 Typical tail sizing chart with tip back limit becoming the aft cg limit for relaxed static stability aircraft (after Holloway, *et al.*, [10]).

The lack of responsiveness is attributed to the fact that each aircraft component is assigned a specific location within the airframe. Typically, these approaches do not estimate the operational range of cg locations. The *cg* location is a complicated function of the configuration, loading, and fuel state, with an allowable range limited by a number of operational factors [15]. Although a range of *cg* locations can be established by varying the configuration, equipment arrangement, and payload and fuel states individually, the process is difficult. The accuracy limitations arise because the codes assume that the user has the experience and knowledge required to make adjustments to the component weight and *cg* estimates. Unfortunately, this approach is not suitable for use in automated procedures required in MDO.

Evidently, what is needed is a new approach which is capable of establishing a maximum permissible *cg* range for a given configuration. This available *cg* range can then be compared with the desired operational *cg* range obtained from performance, control, and operational requirements. If the desired *cg* range is within the available cg range, the concept is viable and can be balanced. If not, the configuration must be changed, either by the designer or an MDO procedure if an automated process is being used.

2.3. Alternate Method

Component location flexibility at the conceptual design phase is actively exploited as a means to improve the responsiveness and accuracy of current *cg* estimation procedures. In the proposed procedure, aircraft components are assigned a range of *cg* locations based on the geometry, as well as physical and functional considerations, associated with each component. By arranging the *cg* of the components at their fore- and aft-most limits, the maximum permissible *cg* range of a particular layout can be established. This *cg* range can then be used by an MDO procedure to determine the forward and aft aircraft *cg* limits required to meet performance and stability and control considerations. Adjusted for uncertainty, this maximum permissible *cg* range can be used as a constraint for the operational *cg* range during the optimization.

2.3.1. Establishment of Component CG Range

The assignment of component *cg* range is based on the geometry, planform, and the type of components involved. In the case of the primary components, *e.g.*, fuselage, wing, and empennage, the location of these items remains relatively unchanged once the concept is frozen. Consequently, the *cg* range is expected to be centered near the volumetric center of the component and is unlikely to shift too much. For ease of identification, the primary components will be referred to as the *constrained* items.

As for secondary components, *e.g.*, equipment and operational items, the location of each component varies from one aircraft concept to another, depending on the philosophy and preference of the airframe manufacturer. Note that as long as the stowage and functionality constraints are not violated, these components can be assigned to any available space throughout the aircraft due to their compactness. Consequently, the corresponding *cg* range is defined by the forward and aft boundaries of the stowage space within which the item is located. Accordingly, these components are termed the *unconstrained* items.

Although the payload and passenger amenity, *i.e.*, furnishings and services, are confined within the cargo holds and cabin, operational experience has shown that the *cg* location of these items varies according to the loading condition and cabin layout as specified by the airlines, respectively. Similarly, the *cg* location of the fuel varies as a function of time as the fuel is being consumed during the duration of the mission. Given the added freedom in terms of the loading pattern, these components are also classified as *unconstrained* items.

2.3.2. Generic Component Layout

The proposed aircraft component *cg* ranges are listed in Table 2.1 and represented graphically in Fig. 2.2. The ranges are based on the layout of existing commercial transports [16 and 17] and can be modified to accommodate any unique layout of the aircraft concept under consideration.

The locations of the front and rear spar for the wing and empennage are dictated by space required for housing the control surfaces and the associated actuation systems, where values of 15 and 65 percent chord, respectively, are typically used. As in the conventional cantilever wing and empennage construction, the majority of the structure, *i.e*., bulkheads, ribs, and fuel tanks, are located between the front and rear spars. Thus, it can be expected that the *cg* of the wing is most likely to be located between the two, along the respective mean aerodynamic chords (*mac*). In addition, given the physical arrangement of the fuel tanks, the *cg* of the fuel and the fuel system can be expected to be located near the same vicinity.

Table 2.1 Generic component location for conventional civil transports

Component	**Type**	**Component *cg* range**
Wing	Constrained	Between fore and aft spars along wing *mac*
Fuselage	Constrained	40 to 50 percent fuselage length
Horizontal tail	Constrained	Between fore and aft spars along horizontal tail *mac*
Vertical tail	Constrained	Between fore and aft spars along vertical tail *mac*
Engines/Nacelles	Constrained	45 to 60 percent engine length
Nose gear	Constrained	Between fore and aft wheelwell bulkheads
Main gear	Constrained	Between fore and aft wheelwell bulkheads
Fuel system	Unconstrained	Between fore and aft spars along wing *mac*
Hydraulics	Unconstrained	Between fore and aft wing spars along aircraft centerline; Between aft pressure bulkhead and tip of tailcone

Electrical system	Unconstrained	Between forward pressure bulkhead and nose wheelwell; Between fore and aft wing spars along aircraft centerline
Avionics	Unconstrained	Between forward pressure bulkhead and nose wheelwell
Instrumentation	Unconstrained	Between forward pressure bulkhead and nose wheelwell
Environmental	Unconstrained	Between fore and aft wing spars along aircraft centerline
Flight control	Unconstrained	Between aft spar and trailing-edge along surface *mac*
Auxiliary power	Unconstrained	Between aft pressure bulkhead and tip of tailcone
Furnishings	Unconstrained	45 to 60 percent cabin length
Services	Unconstrained	45 to 60 percent cabin length
Passengers	Unconstrained	45 to 60 percent cabin length
Cargo	Unconstrained	45 to 55 percent forward and aft cargo holds
Fuel	Constrained	Between fore and aft spars along wing *mac*; Between fore and aft wing spars along aircraft centerline

The *cg* of the fuselage depends on the structural arrangement of the pressure bulkheads, frames, and the aft-body taper ratio. Other factors include local structural reinforcement around the landing gear wheelwells, cargo holds, and the layout of the cabin, *e.g.*, a forward upper-deck as found on the Boeing Model 747 or a double-decker as found on the proposed ultra-high-capacity transports. Taking these factors into consideration, the proposed procedure assumes that the *cg* of the fuselage is most likely to be located between 40 and 50 percent of the fuselage length.

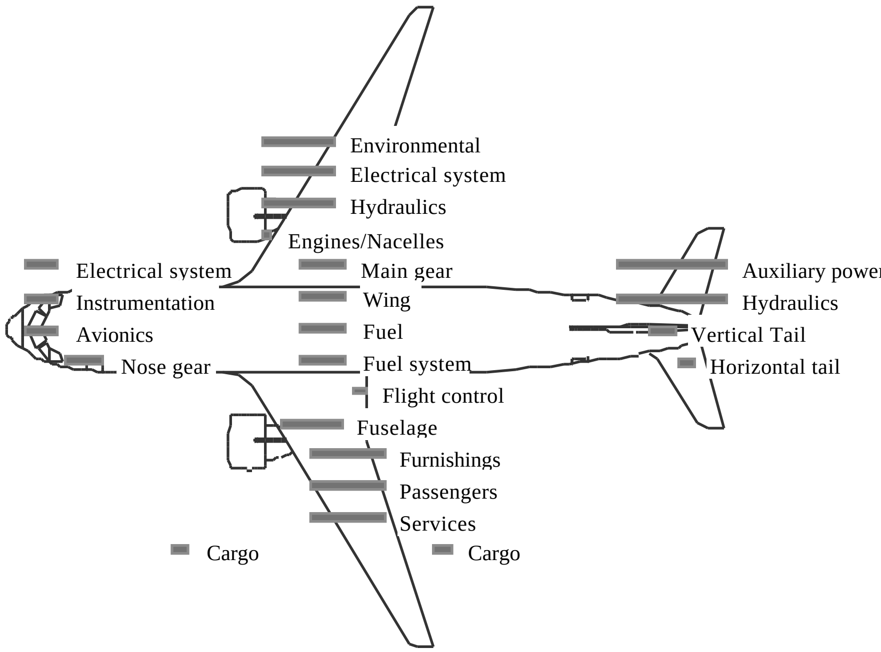

Figure 2.2 Ranges of available component *cg* locations

The *cg* of the engine group varies according to the dimensions of the engine, nacelle, and engine pylon. To account for weight-affecting factors such as compressor fan diameter, the shape of the nacelle, thrust reverser and pylon structure arrangement, forward and aft *cg* limit of 45 and 60 percent of the length of the engine, respectively, were assigned.

Regardless of the configuration of the landing gear, the *cg* of the landing gear will be confined between the landing gear wheelwells in flight. Thus, the forward and aft *cg* limits of the landing gear are assumed to coincide with the forward and aft stowage volume boundaries of the nose and main assembly wheelwells.

Hydraulics is divided into the wing and empennage group, with the weight proportional to the ratio of the respective control surface area to the total control surface area. The wing group is assumed to be located beneath the wing torsion box, which results in a *cg* range that is defined by the fore and aft wing spars along the aircraft centerline. On the other hand, the *cg* range of the empennage group is limited to the space behind the aft pressure bulkhead. Besides providing the stowage volume for the empennage hydraulics, the tail cone space also houses the auxiliary power unit.

Similarly, flight controls are divided into the wing and empennage group, with the weight proportional to the ratio of the local control surface area to the total control surface area. The proposed procedure assumes that the weight of the leading-edge control surfaces is negligible and that the trailing-edge control surfaces are in the retracted position. Thus, the *cg* of the flight controls are bounded by the rear spar and the trailing edge of each surface, along the respective *mac*s.

The electrical system is divided into the battery and generator groups, assuming that the weight is distributed evenly between the two. The battery group is to be located between the forward pressure bulkhead and the nose wheelwell, although it can also be located in the cavity between the nose wheelwell and the forward cargo hold. The generator group is to share the wing-body fairing cavity as being used to stow the wing hydraulics, *i.e.*, under the wing torsion box. Due to functionality constraints, avionics and instrumentation are assumed to be located in the same compartment which houses the batteries. Similarly, environmental control packs are to share the wing-body fairing cavity with the electrical generator and wing hydraulic groups.

Given that the aircraft is fully loaded, the *cg* of the furnishings, services, and passengers is limited to between 45 and 60 percent of the cabin length. This assumption takes into account the distribution of the passengers and the corresponding arrangement of the furnishings and passenger services in different cabin layouts. To accommodate the variable nature of the cargo loading operation, which is affected by the type and weight of the baggage and bulk materials, forward and aft *cg* limits of 45 and 55 percent, respectively, of both forward and rear cargo holds were assigned.

2.3.3. Validation of Analysis

A simple spreadsheet software, where the component *cg* range data as presented in Table 2.1 are stored and a macro is defined for calculation purposes, is created to establish the forward and aft limits of the permissible aircraft *cg* range. A detailed description of the spreadsheet can be found in Chapter Nine. The Boeing Models 737, 747, 767, and

McDonnell Douglas DC-10 were used to validate the proposed *cg* estimation procedure as outlined above. Estimated component weights were obtained from ACSYNT(AirCraft SYNThesis) [12] and used for all four aircraft, while component *cg* ranges were determined using the generic layout as detailed in the previous section. Essentially, the four aircraft are treated as conceptual aircraft. The objective here is to determine if the maximum permissible *cg* range as established by the new approach can enclose the actual operational *cg* range. Actual [18] and estimated aircraft *cg* ranges determined using the spreadsheet are listed in Table 2.2, both sets of data are shown in Fig. 2.3 for ease of comparison.

Table 2.2 Aircraft *cg* range

Aircraft	**Estimated, % *mac***	**Actual, % *mac***
B737 (forward/aft)	0.0/68.0	12.0/30.0
B767 (forward/aft)	-4.0/67.0	11.0/32.0
DC10 (forward/aft)	-7.0/46.0	8.0/18.0
B747 (forward/aft)	4.0/63.0	13.0/33.0

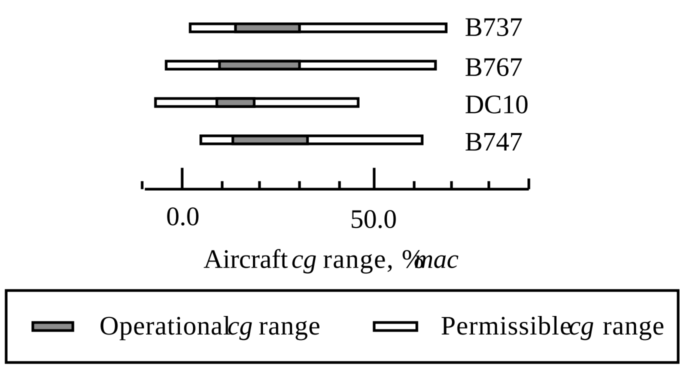

Figure 2.3 Actual and estimated aircraft *cg* range comparison

As shown in Fig. 2.3, the new approach is capable of producing a permissible aircraft *cg* range that brackets in the actual operational *cg* range for all four aircraft. In addition, the estimated *cg* range offers a generous margin at either end-limit of the band representing the actual operational *cg* range. Since both the weight and location of the components are based on statistical information, the margin would ensure that the operational *cg* range remains within the obtainable range even when the uncertainty is included. Evidently, the proposed *cg* estimation procedure is able to meet the flexibility and reliability requirements that are essential for MDO applications.