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Trim Analysis of Box Wing Aircraft

Paul O Jemitola* and Paul P Okonkwo

Air Force Institute of Technology, Nigerian Air Force Base, Kaduna, Nigeria

Abstract

Computational studies at the conceptual design level were performed to investigate the longitudinal trim of a Box wing aircraft. The analysis was intended to show the points in the envelope at which the aircraft could be trimmed longitudinally. A similar analysis was performed on an equivalent conventional cantilever aircraft. The results suggests that further optimization is required for the Box wing as its trimmable flight envelope is smaller than that of an equivalent conventional cantilever aircraft.

Nomenclature

AoA: Angle of Attack [deg]; OEM: Operating Empty Mass [kg]

Introduction

AIRCRAFT configurations such as the Box wing and Joined wing, studied by Wolkovitch [1], Kroo, et al. [2], Nangia, et al. [3] and Henderson and Huffman [4] have elicited renewed interests in unconventional configurations. The attraction of unconventional aircraft configurations like the Box and Joined wing aircraft lies in their reduced induced drag with potential for improved fuel efficiency and hence reduced direct operating costs. The Box wing is derived from biplane configurations and has been investigated by Prandtl [5], Munk [6] and recently Frediani [7] and Balaji, et al. [8]. The superior aerodynamic efficiency of Box wing designs over conventional configurations is well covered in their studies. Frediani's [7] study of the Box wing hinted that the Box wing aircraft's longitudinal trim should be practicable. It was therefore instructive to investigate the longitudinal trim of Box wing aircraft and how it compares to an equivalent conventional cantilever aircraft. The object of trimming is to bring the forces and moments acting on the aircraft into a state of equilibrium; a condition when the axial, normal and side forces, and the roll, pitch and yaw moments are all zero [9].

Reference Aircraft Description

Box wing aircraft

The baseline Box wing aircraft used in this work is derived from a conceptual design study of a medium range Box wing aircraft carried out in Cranfield University and outlined in Smith and Jemitola [10]; see Figure 1. It is a 4000 nautical mile range

***Corresponding author:** *Paul O Jemitola, Air Force Institute of Technology, Nigerian Air Force Base Kaduna, Kaduna, 800001, Nigeria*

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Figure 1: Box wing aircraft.

Figure 2: Conventional aircraft.

Box wing airliner with a maximum take-off mass of 127760 kg and wing span of 37.6 m. The fore and aft wing gross areas are 118.32 m^2 each. The wing gap, measured at the wing tips, is 8.0 m while the fore and aft wing sweep angles are 40 and -25 degrees respectively. Overall fuselage length is 46 meters and maximum diameter is 5.6 m.

Conventional cantilever wing aircraft

As a basis for comparison and to validate the method-ology, a conventional cantilever wing aircraft similar to the B767, and obtained from Jemitola [11] was studied, see Figure 2. It is also a 4000 nautical mile range airliner but with a maximum takeoff mass of 136000 kg and wing span of 47.0 m. The wing gross area is the same as the sum of the fore and aft wing areas of the baseline Box wing aircraft at 236.64 m^2, while the wing sweep angle is 30 degrees. Overall fuselage length is 46 meters and maximum diameter 5.6 m.

Methodology

Longitudinal trim involves the simultaneous adjustment of elevator angle and thrust to give the required airspeed and flight path angle for a given airframe configuration. Equilibrium is achievable only if the aircraft is trimmable while the control actions required to trim depend on the degree of longitudinal static stability. Since longitudinal flight conditions are continuously varied, it is very important that trimmed equilibrium is possible at all conditions. For this reason, considerable emphasis is given to ensuring suitable longitudinal static stability that will enable sufficient trim control. Because of their importance, static stability and trim are often interpreted to mean longitudinal static stability and trim.

The trim analysis described in this paper was performed following the procedure shown in Figure 3. Accordingly, mass statements from the reference aircraft were used to produce the mass and cg situations of both aircraft and subsequently the aircraft inertia statements. As outlined in Bruhn [12], the inertia of each aircraft's component was first of all determined about its own centroidal axis then about the axes of the aircraft. For this conceptual level investigation, only the inertia statements for both aircraft at *OEM* plus 33% payload were produced for the

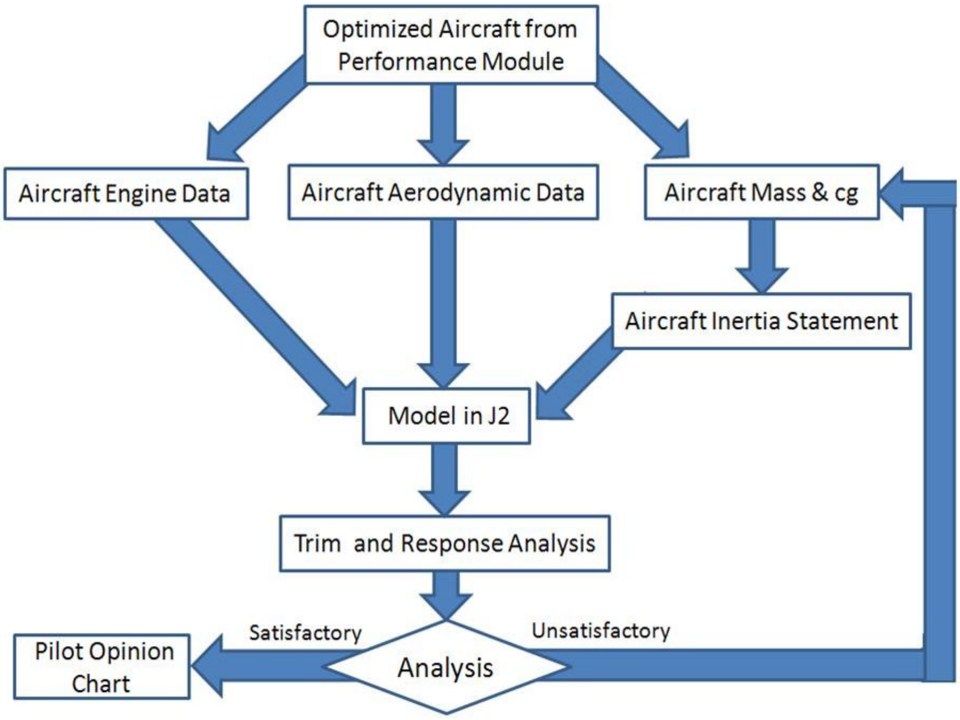

Figure 3: Trim evaluation schematic.

investigation. Aerodynamic data were generated for the reference aircraft from empirical and analytical methods. The data required were:

1. Fore wing lift coefficient variations with *AoA* (Angle of Attack) and elevon deflection.

2. Aft wing lift curve slope variation with *AoA* and elevator deflection.

3. Fore wing trim drag variation as a function of *AoA* and elevon deflection.

4. Aft wing trim drag variation as a function of *AoA* and elevator deflection.

5. Aircraft pitching moment as a function of aft wing *AoA* , elevator and elevon deflection.

Serials 1 to 5 above were initially computed using methods given by Roskam [13], ESDU74011 [14] and ESDU89029 [15]. However due to the complexity and volume of computations required, Javafoil [16] was used after the initial set of computations. Javafoil [16] is a software based on the potential flow and boundary layer theory and used for the aerodynamics analysis of airfoils and aircraft models. The results from Javafoil [16] were in agreement with hand calculations.

The engine data required were thrust as a function of mach number, altitude and engine throttle setting. These were computed using methods given by Yechout, et al. [17].

The values of the foregoing computations for the Box wing and conventional aircraft were used to build the aircraft models in J2 aircraft dynamics software [18] as a prelude to the trim analysis. J2Universal software [18] suite is a tool kit that can be used to perform trim analysis of an aircraft. It utilizes strip theory to automatically calculate total aerodynamic coefficients and derivatives. J2's algorithms are almost entirely based on work by Roskam [19]. Trim and response analyses were thereafter performed and the results analyzed.

Trimming Analysis

Trimming analysis was performed for the Box wing and conventional aircraft models with a representative 33% payload. The analysis was performed for several points within a speed range of 0 to 240 m/s and altitude range of 0 to 31,000 ft. Trimming devices used were the elevators for the conventional aircraft and the elevators and elevons (elevator on the forward wing) for the Box wing. The Box wing's elevator and elevon work in opposition. The elevon's convention is opposite that of the elevator meaning up is positive and down is negative. The sign conventions used are shown in Figure 4 [20].

Trim analysis - conventional aircraft

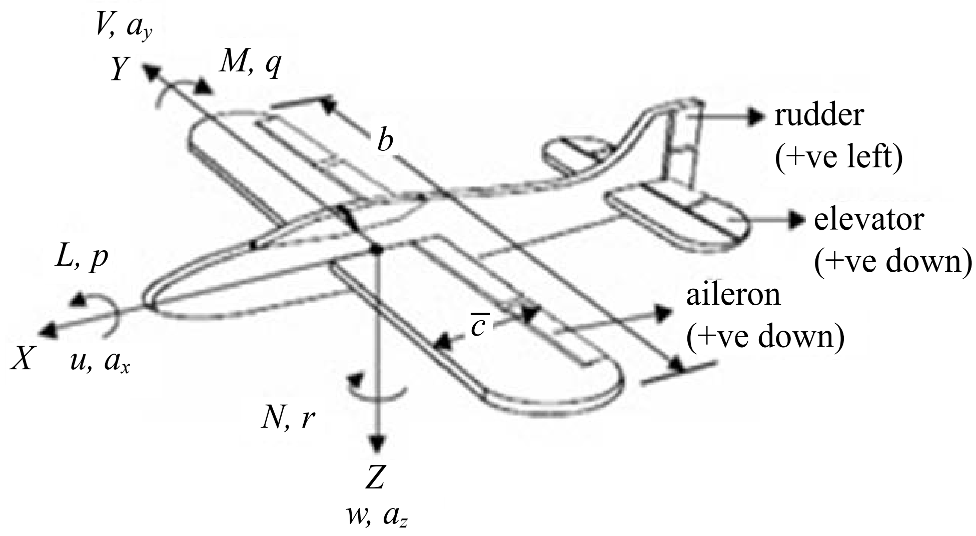

Figure 4: Axes and sign conventions [20].

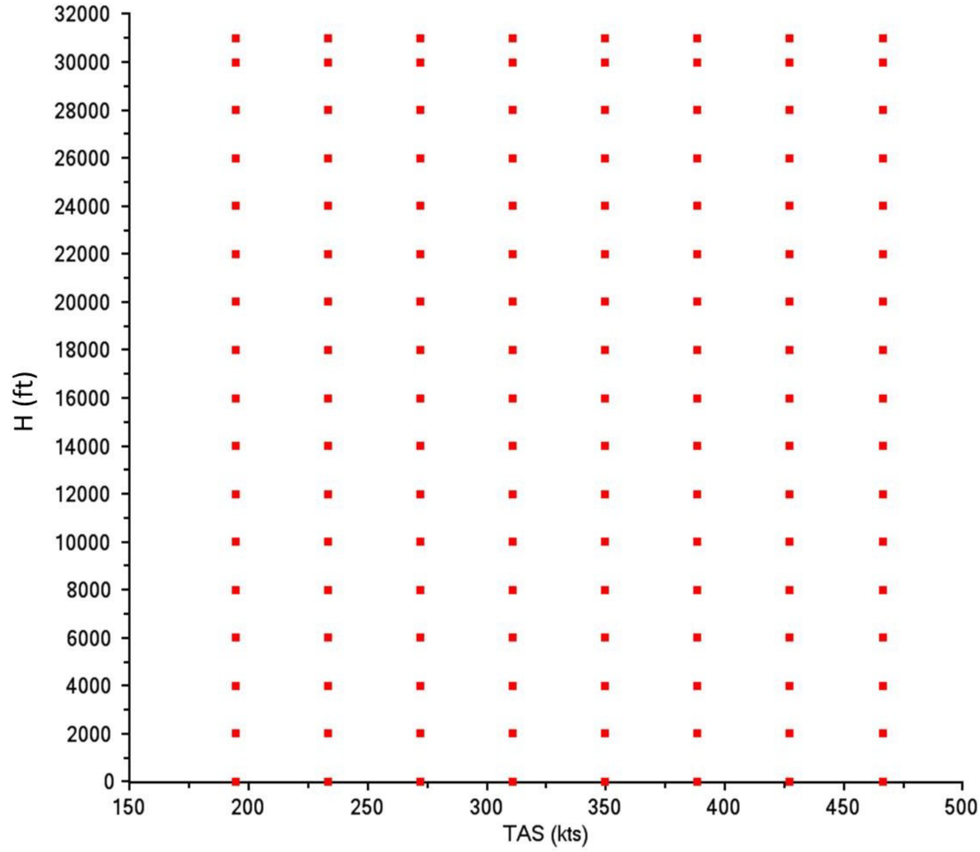

Figure 5: AoA and elevator deflection achievable.

Figure 5 is a graph of the trimming analysis for the conventional cantilever wing aircraft. On the y-axis on the left is the aircraft's angle of attack in degrees while on the y-axis on the right is the elevator deflection angle also in degrees. The x-axis displays the true air speed of the vehicle in kts. The speed range displayed is that for which the aircraft is flyable at any altitude, i.e above stall speed . The angle of attack is indicated by the red square dots while the elevator deflection is represented by the blue circular dots. Multiple dots on the same speed mark represents different altitudes. Figure 5 shows that as speed increases, the angle of attack of the aircraft reduces from a maximum of about 16 de-

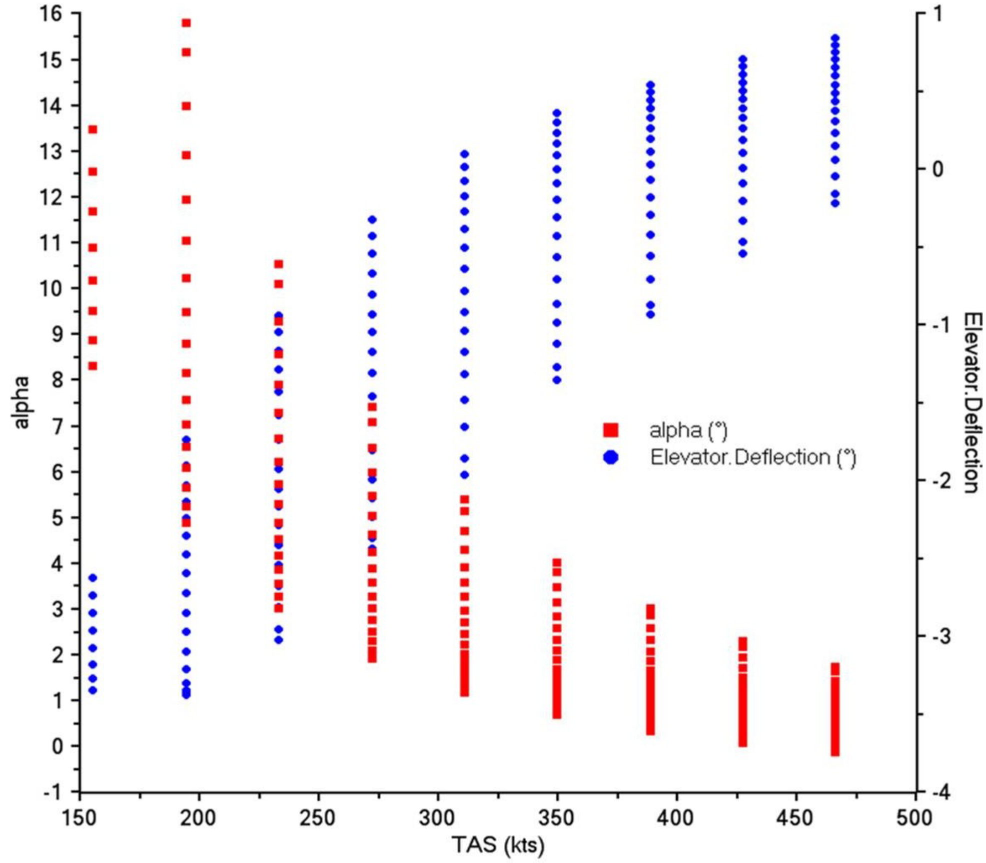

Figure 6: Flight envelope.

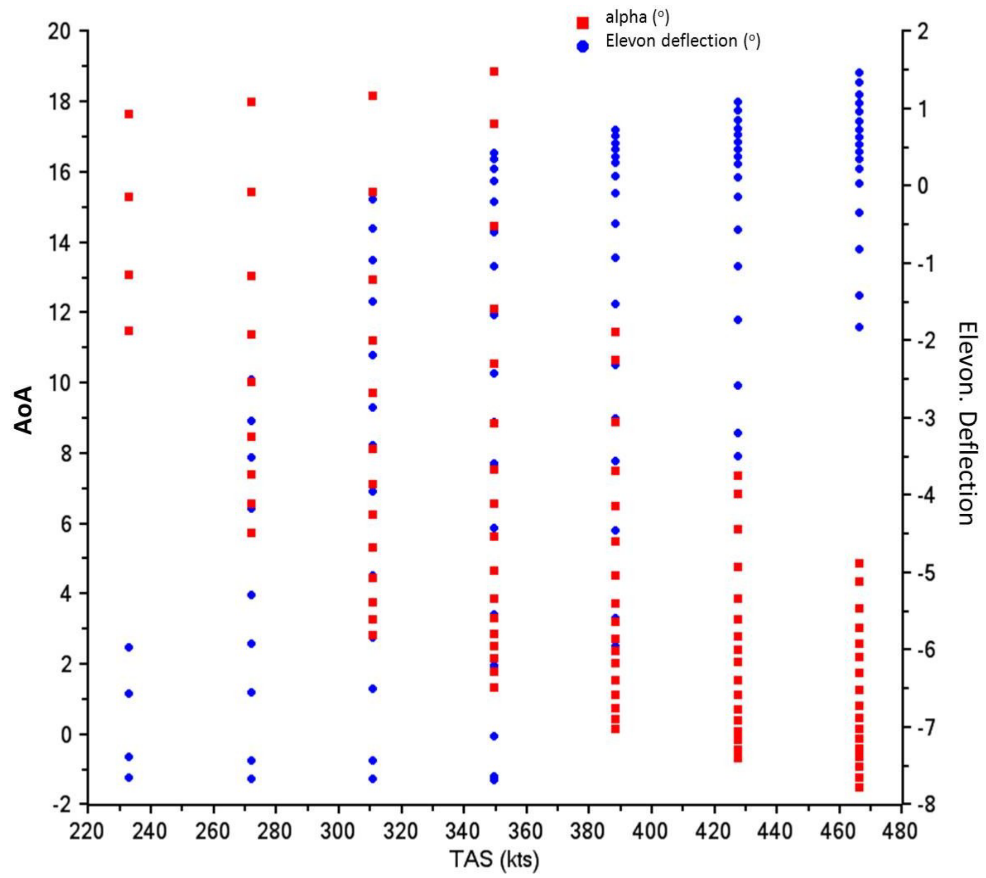

Figure 7: Box wing AoA and elevon deflection deflection.

grees at 200 kts to -0.5 degrees at about 460 kts. The elevator deflection on the other hand increases from a minimum of -3.4 degrees at 150 kts to about 0.8 degrees at 460 kts. The trend of the angle of attack and the elevator is opposite each other and this is what occurs in practice. Additionally, the range of elevon and elevator deflections are within the acceptable limits of ± 20-25 degree specified by Sadraey [21].

The points in the envelope at which the model can be theoretically trimmed is shown graphically in Figure 6. On the y-axis is altitude in feet and on the x-axis is true air speed in kts. Thus, this model cannot be trimmed at speeds below 170 knots in altitudes from 0 to 31,000 ft.

Trim analysis - box wing aircraft

Figure 7 shows the trim analysis conducted for the Box wing aircraft. The left y-axis shows the angle of attack in degrees while the left y-axis shows the elevon deflection in degrees. The x-axis shows the true air speed in kts. The red square dots indicate the angle of attack and the blue circular dots the elevon deflection. The trend in this graph is not as obvious as in the graph of Figure 5. However, the red square dots show a reduction in angle of attack with increase in air speed from about 18 degrees at 230 kts to -1.5 at 460 kts. The elevon deflection, indicated by the blue circular dots, shows its movement from about -7 degrees at 230 kts to 1.5 degrees at speed.

Figure 8 shows the same trim analysis conducted for the Box wing aircraft but here the left y-axis shows the angle of attack in degrees while the left y-axis shows the elevator deflection in degrees. The x-axis shows the true air speed in kts. The red square dots indicate the angle of attack and the blue circular dots the elevator deflection. Here, the elevator deflection is from about 4.5 degrees at 230 kts to -1.6 degrees at speed. The red square dots (angle of attack) show a reduction with increase in air speed from about 18 degrees at 230 kts to -1.5 at 460 kts.

Figure 9 shows the trends of the elevon and elevator with increase in air speed. The left y-axis shows the elevon deflection in degrees while the y-axis shows the elevator deflection in degrees. The x-axis shows the true air speed in kts. The red

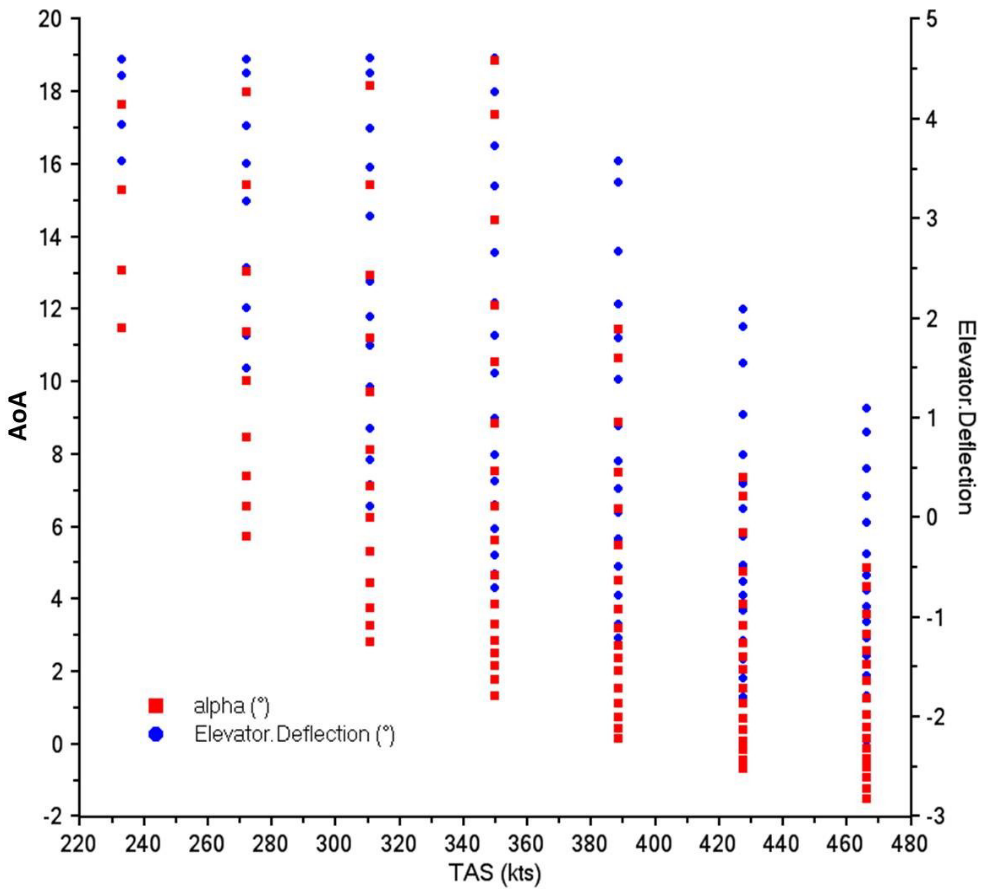

Figure 8: Box wing AoA and elevator.

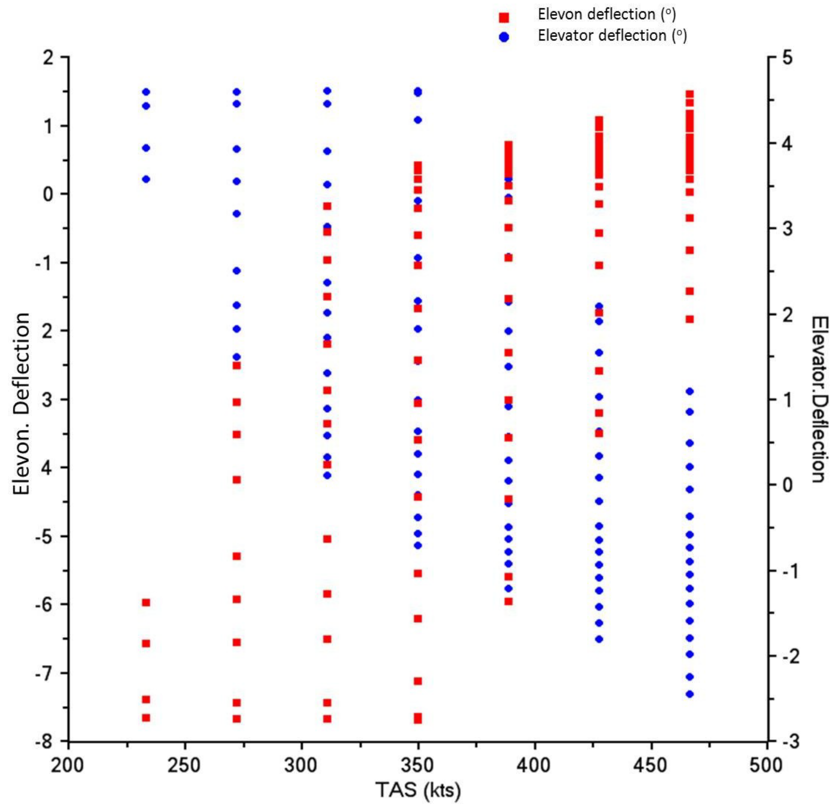

Figure 9: Box wing elevon and elevator deflection achievable.

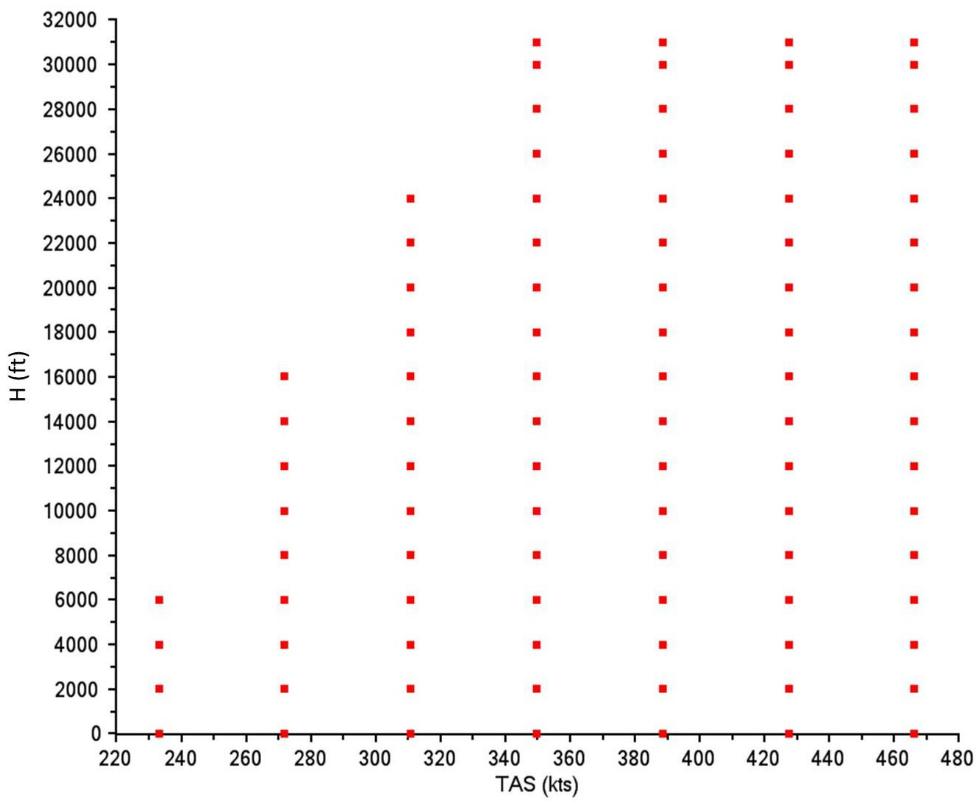

Figure 10: Box wing flight envelope.

Table 1: Aircraft parameters at mach 0.8 31,000 ft.

Type	*AoA*	Wing/Fore wing *AoA*	Elevon	Tailplane/Aft wing *AoA*	Elevator
	(^{o})	(^{o})	(^{o})	(^{o})	(^{o})
Conventional	1.70	2.94		1.12	-0.22
Box	1.68	-1.32	3.1	2.10	-5.13

square dots indicate the elevon and the blue circular dots the elevator deflection. Clearly and as already elucidated, the elevon and elevator move in opposite directions and the trends are opposite. As airspeed increases, the elevon moves from negative to positive within a range of -7.8 degrees to 1.4 degrees, while the elevator moves from 1.7 degrees to -2.5 degrees.

Figure 10 shows the points in the envelope at which the model can theoretically be trimmed. On the y-axis is altitude in feet and on the x-axis is true air speed in kts. Thus, this model cannot be trimmed at speeds below 230 kts. Additionally, at 230 kts the referenced Box wing aircraft can only be trimmed at altitudes below 6000 ft. At 270 kts, the aircraft can be trimmed at altitudes below 16,000 ft. At 310 kts the model can be trimmed only below 24,000 ft. From 350 kts upwards the model can be theoretically trimmed from zero altitude to 31,000 ft. This indicates that the trimmable range of altitu for a Box aircraft increases with increase in airspeed. Additionally, a comparison of the data shown in Figure 10 with Figure 6 indicates that the trimmable flight envelope for Box wing aircraft is much smaller than the equivalent conventional aircraft.

For greater illustration, both aircraft were compared while cruising at 31,000 ft at Mach 0.8; see Table 1. Both aircraft were cruising at about the same angle of attack but while the conventional aircraft's wing had a positive angle of attack the Box wing's fore wing had a negative angle of attack. At the tailplane and aft wing both had positive angle of attacks.

The fact that for the Box wing aircraft the fore wing is at a *'low'* angle and the aft wing is at *'high'* angle conforms with Bell's [22] analysis that the rear wing induces an upwash on the forward wing which in turn induces a downwash on the rear wing. Thus, the fore wing's negative angle of attack is to compensate for the increased angle of attack caused by the upwash induced on it by the aft wing. Similarly, the aft wing's *'high'* angle of attack is to compensate for the reduced angle of attack induced on it by the downwash from the fore wing.

The trim drag of the conventional aircraft with an elevator angle of -0.22° would be much lower than that of the Box wing with elevon and elevator angles of 3.10° and -5.13° respectively. This suggests that further optimization is required for the Box wing as the high trim drag obtained from this simulation could reduce the main attraction of this configuration over conventional aircraft configuration.

Conclusion

The longitudinal trim of a Box wing aircraft requires more control surface deflection and therefore higher trim drag than the equivalent conventional aircraft. Furthermore, the flight envelope under which the Box wing aircraft can be trimmed is limited. A more detailed investigation of this situation is recommended for future studies to sustain the advantages of the Box wing aircraft over conventional configuration.

Acknowledgments

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