

An Overview of Box Wing Aircraft Aerodynamics and Performance

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ABSTRACT

The aeronautical industry has been facing significant economic and environmental challenges in regards of fuel consumption. Non-planar aircraft configurations are found to be one of the alternatives that can overcome these issues. They are found to increase aerodynamic performance by reducing drag, in turn reducing fuel consumption. One such design is the box wing configuration. This paper reviews various aspects of box wing configuration developed through the past years. This paper gives an overview of lift distribution over box wing aircraft. It also provides insight on various geometric parameters affecting the aerodynamic performance and stability of box wing configuration.

Keywords—Box wing, induced drag, Prandtlplane

Nomenclature

h -height
b -span
nm - Nautical miles
h/b – height to span ratio
e - Oswald's factor
 C_L - Lift Coefficient
 C_D - Drag Coefficient
NACA - National Advisory Committee for Aeronautics
CFD - Computational fluid dynamics
L/D Ratio - Lift to drag ratio
AR - Aspect ratio
DOC - Direct operating cost
USD - United state dollars
C.G - Center of gravity

I. INTRODUCTION

Rising fuel prices and environmental concerns are some of the main challenges faced by the aviation industry. A reduction in fuel consumption would resolve these issues by reducing of pollutant emissions. A reduction in the amount of fuel consumed by the aircraft can be accomplished by minimizing the aerodynamic drag. This can be achieved via better technologies, fuel alternatives, light-weight materials or hybrid propulsion systems. However, a change in the aircraft design itself can also lead to a more efficient aircraft than an existing conventional one. Hence, unconventional aircrafts seem to be of great interest for the future generations of civil aviation industry. One such unconventional design is non-planar wing configuration. Various types of non-planar wing configurations are shown in figure 1.

Non-planar aircraft configurations provide a notable benefit to the aerodynamic efficiency of an aircraft by lowering its induced drag in comparison to conventional aircrafts of the same span and lift. Different non-planar wing designs have been proposed in the past. Their main difference leading to different aerodynamic characteristics arises due to the variations in the lifting surface geometries. One such possibility is the box wing aircraft also known as 'Prandtlplane'.



Figure 1: Taxonomy of various non-planar lifting surfaces [1]

Box wing design is a type of bi-planar configuration, which consists of two wings having the same span, connected at their tips through a vertical fin. The vertical distance between the two wings is termed as the height of the box wing. The relative positioning of the aerodynamic center of the fore wing with respect to the aft wing in the direction of the flow is known as stagger. These geometric parameters are depicted in Figure 2. Along with the above mentioned parameters, variations in the area, taper, sweep and twist of the fore wing, aft wing and the connecting tip fin provide numerous possibilities for box wing designs. An innovative configuration such as the box wing is able to provide a real step-change in the overall performance of the aircraft. The possibility of conceiving an aircraft that reduces drag without considerable changes to its geometry is due to the particular design of the lifting system of the box wing configuration and its aerodynamic superiority.

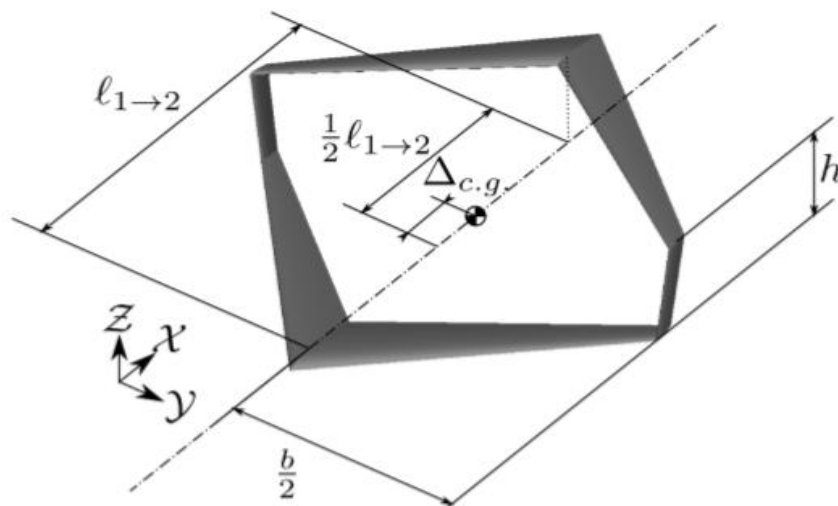


Figure 2: Box wing aircraft schematic. Stagger is represented as $l_{1 \rightarrow 2}$ and the height is represented as h [1].

A. Concept of Drag

Drag is the aerodynamic force that resists an aircraft's motion through the air. Mathematically drag is defined as:

$$D = \frac{\rho V^2 S C_D}{2}$$

(1)

Where; ρ = Density, V = Velocity, S =

Surface Area and C_D = Drag Coefficient

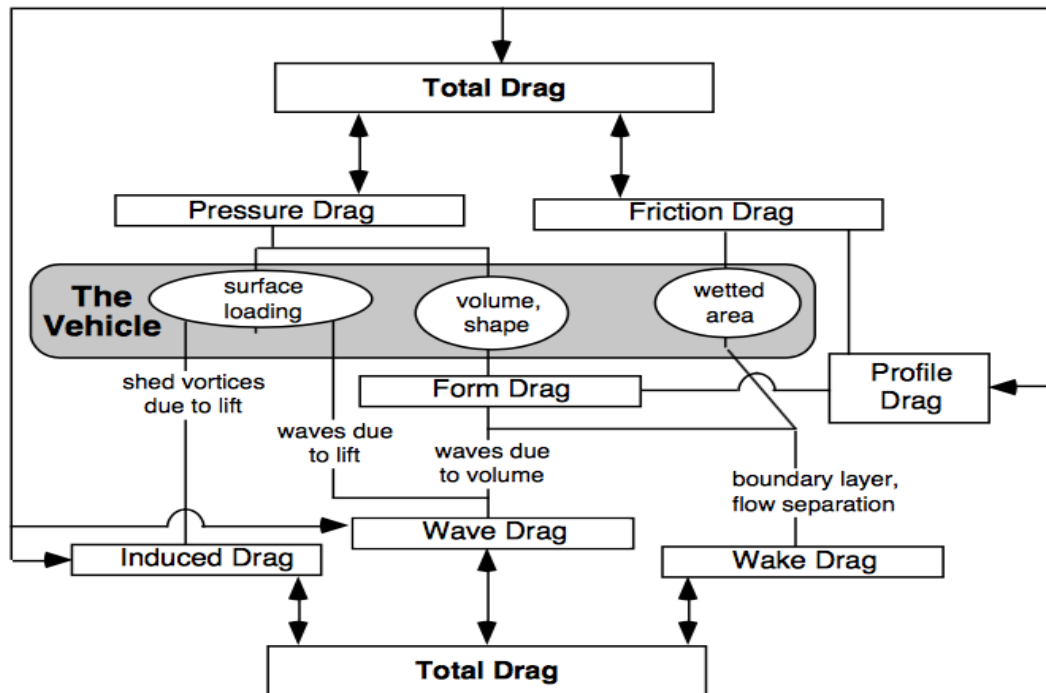


Figure 3: Types of drag

Mathematically, this can be written in coefficient form as:

$$C_D = C_{Dp} + \frac{C_L^2}{\pi \cdot AR \cdot e} + \Delta C_{Dc} \quad (2)$$

Where; C_D = Coefficient of Drag, AR = Aspect Ratio, e = Oswald's constant, C_{Dp} = Parasitic drag (Which consists of pressure drag, skin friction and interference drag associated with viscosity).

C_L = Design lift coefficient accounting for induced drag

ΔC_{Dc} = Change in drag due to compressibility effects when the aircraft flies at transonic conditions.

The total drag of an aircraft is the summation of the profile drag, the induced drag and the wave drag. The profile drag is due to the shape of the aircraft moving through the air, the skin friction due to the aircraft surface and the interference due to the flow over various parts of the aircraft body. Wave drag is a result of shock waves formation on the aircraft body which is thus greatly dependent on the speed of the aircraft. The induced drag is caused by the generation of lift on the lifting surfaces and is a major contributor to the total drag force.

B. Induced Drag

Lift on an aircraft is generated due to the pressure difference between the upper and lower surface of the wing. As shown in figure 4, this pressure difference results in formation of circular patterns of air flow at the wing tips, resulting in wingtip vortices. This vortex system in return produces a down wash effect on the wing and thereby changing its effective angle of attack. Thereby the force on the wing obtains an additional component opposite to the direction of the aircraft motion, which contributes to the drag force.

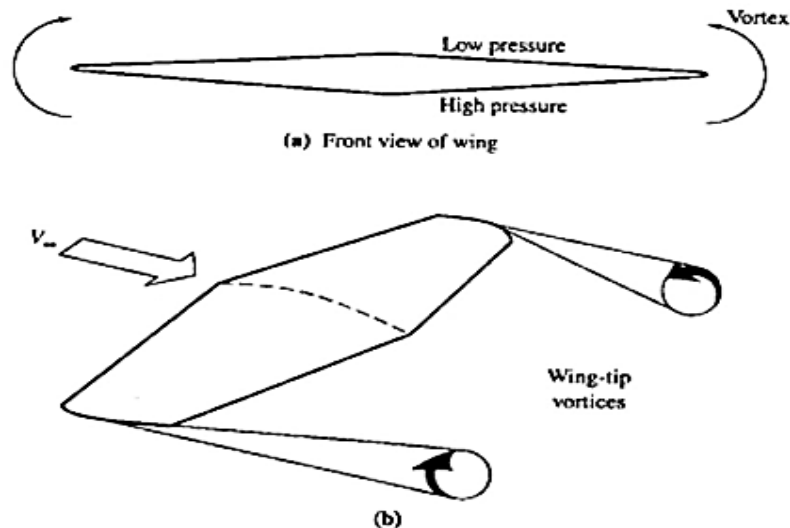


Figure 4: Wing tip vortices [1]

This drag force affects various performance parameters of an aircraft such as increasing the required thrust or decreasing its endurance. It also increases the amount of fuel consumed without any beneficiary results. Thus, induced drag needs to be reduced with only negligible effect on the lift generated for an aircraft to operate at an increased overall efficiency. This was the cause that led to the design of Prandtlplane.

II. PRANDTL BEST WING SYSTEM

In 1924, Ludwig Prandtl presented in his paper the concept of best wing system based on the biplane design. He concluded that the biplane having two wings of the same span has lesser drag than an equivalent monoplane. Moreover, minimum induced drag can be achieved if the wings form a closed system with the tip fin connecting the fore wing and the aft wing, as shown in figure 5.

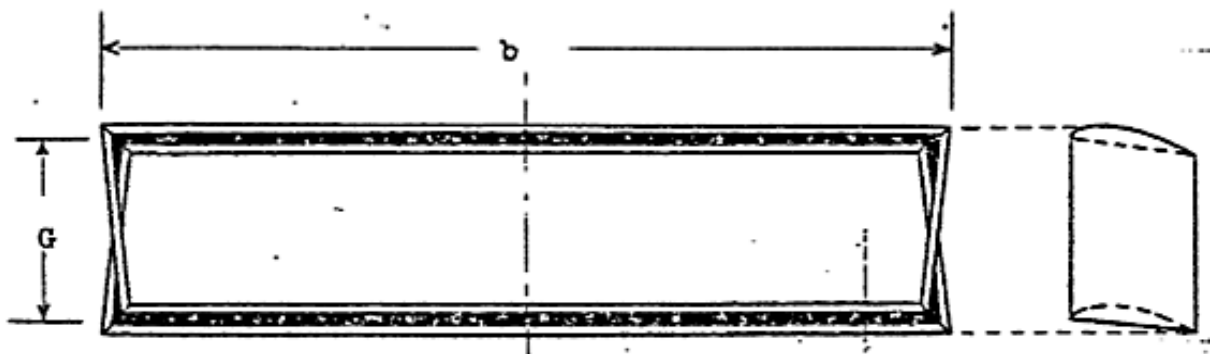


Figure 5: Prandtl's best wing system, front and side views [2]

The total induced drag in a biplane design is the summation of the induced drag by each of the wing component and the flow interference due to the downwash effect generated between the lifting components [2].

$$D_b = D_{11} + D_{22} + 2. D_{12} = \left\{ \frac{1}{\pi \cdot q} \left[\frac{L_1^2}{b_1} + \frac{L_2^2}{b_2} + 2 \cdot \sigma \frac{L_1 L_2}{b_1 b_2} \right] \right\} \quad (3)$$

Where: D_b is the drag induced for a biplane

D_{12} is the component of drag induced by wing 2 on wing 1

q is the free stream pressure

L_1 is the lift on wing 1

b_1 is the wing span of wing 1

σ is the mutual interference coefficient

III. BOX WING AERODYNAMICS

The box wing aircraft design was first presented by Ludwig Prandtl in 1924. It was observed that biplanes have lesser induced drag than the equivalent monoplane and the least drag is achieved when both upper and lower wings have the same span.

A. Lift distribution

In a box wing configuration, the loading on the fore wing and aft wing is an elliptical lift distribution with constant circulation and along the vertical fin the circulation decreases linearly.

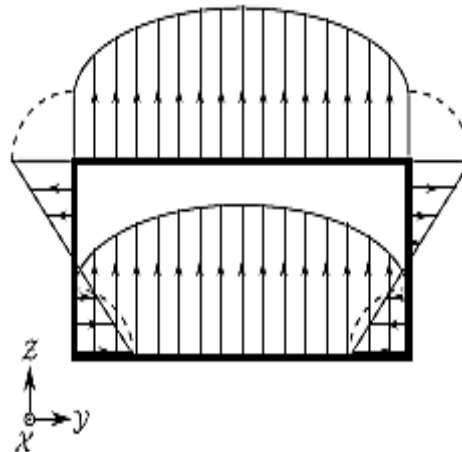


Figure 6: Span wise lift distribution on a box wing, adapted from Prandtl [2]

According to Prandtl, in the best wing system, the upper portion of the vertical segment is subject to outward pressure and the lower portion is subjected to inward pressure. As the vertical distance between the fore wing and aft wing increases, the load distribution varies and becomes more uniform and the system becomes more efficient. This is because the forces acting on the vertical segments reduce the trailing vortices, which would otherwise appear at the wing tips if they were not connected.

B. Stagger

Munk dealt with various aspects of non-planar wing systems in his NACA document. The variation of interference drag on each wings of a biplane with the changing stagger was shown in his study. It was seen that induced drag of the non-planar wing system would be the same when the circulation for all elements in the wing systems remained constant. This means that the induced drag is not dependent on the relative horizontal positioning of the lifting surface as long as the total circulation for each surface is kept constant. This came to be called as Munk's stagger theorem and this is of great importance in studies regarding reduction of induced drag [3].

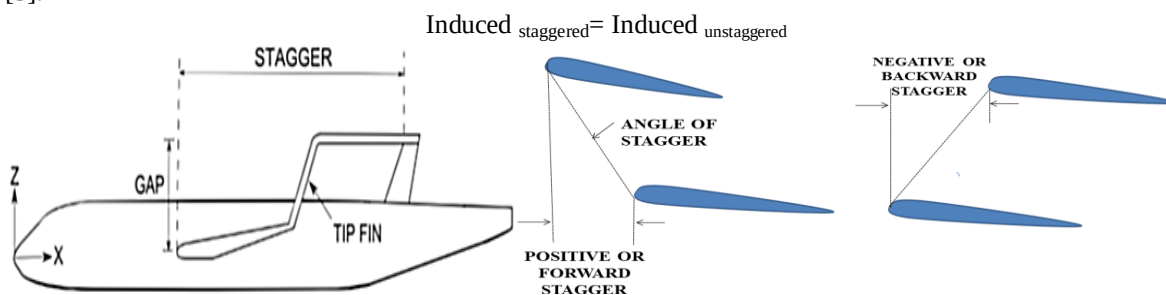


Figure 7: Stagger in a biplane aircraft

By applying Munk's stagger theorem for the box wing configuration, it is seen that the induced drag of the configuration is not dependent on the stagger between the fore wing and the aft wing. This implies that the fore wing and the aft wing can be placed at any position horizontally as long as the lift circulation on the two wings is kept constant.

However, recent studies have shown results that contradict this theorem. A parametric study showed that increasing positive stagger (shown in figure 7) improved the aerodynamic performance of the box wing configuration. As the stagger increased, the effect of the downwash on the aft wing and upwash on the fore wing reduced. And due to increase in the length of the moment arms, trim can be achieved with lesser change in incidence [4].

C. Drag reduction

Till recent times, the box wing design was an improbable configuration for commercialized aircrafts as the structural supports resulted in a huge amount of parasitic drag. However, development in the field of composite materials made these designs a more plausible solution to improving aircraft performance.

The box wing configuration offers better aerodynamic performance due to improvement in L/D ratio, as it has lower drag compared to that of conventional aircraft, as can be seen from Figure 8.

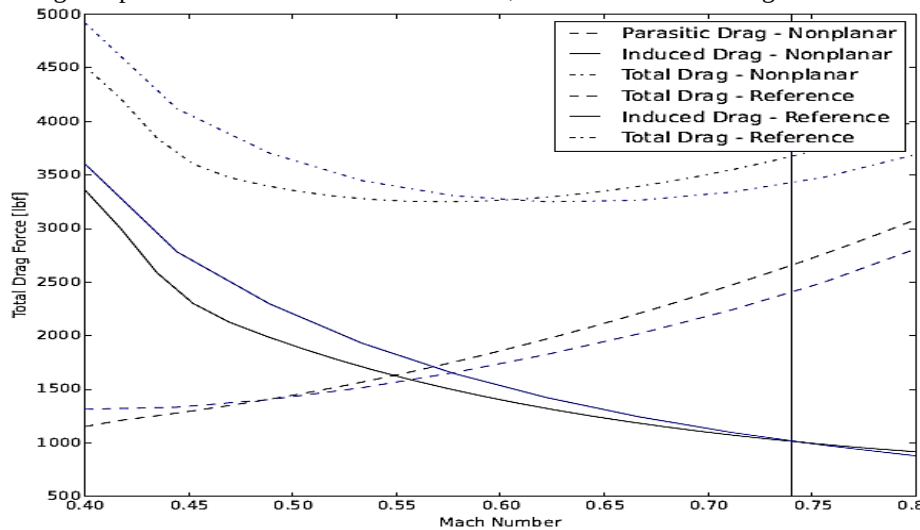


Figure 8: Drag breakdown for conventional and non-planar aircraft [5]

Induced drag reduction would result in a direct decrease in operating costs and also a reduction in noise and emissions levels. It comprises of around 43% of the total drag. Therefore, any reduction in the induced drag will lead to improvement in the efficiency of the overall aircraft design. A box wing configuration also offers a fuel burn reduction of up to 5%, thus reducing fuel cost [6].

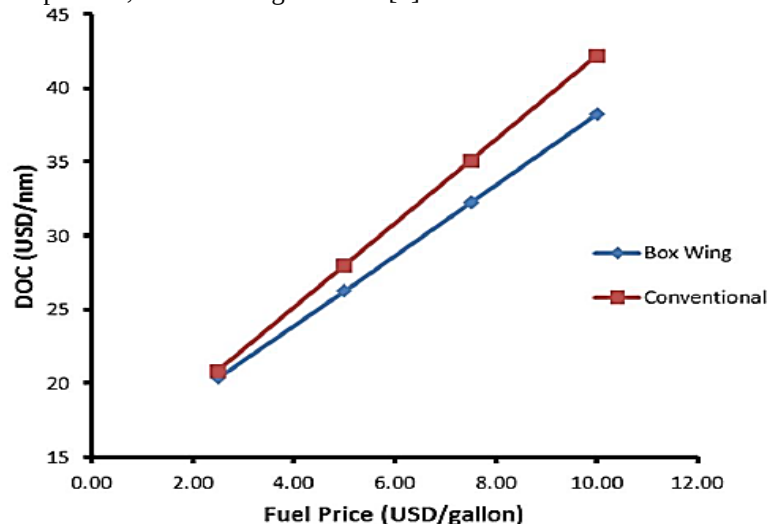


Figure 9: DOC/nm trend with fuel price for conventional and box wing aircraft [6].

D. Height to span ratio

The topological design of non-planar lifting surface configurations was explored in [7]. It was observed that ignoring the effects of compressibility and parasitic drag, a box wing design with maximum allowed height separation between its lifting surfaces would provide the optimal wing configuration. This height separation in biplanes is normally referred to as “Gap”. It is usually expressed with the help of height to span ratio, h/b , which is a characteristic feature of box wing configuration. It is one of the primary factors that influence the induced drag of this wing configuration. In [8] a parametric analysis was done from which it was concluded that, aspect ratio and height to span ratio are crucial geometric parameters for a box wing design. For height to span ratio less than 0.2, it was found that aspect ratio is a significant parameter in the induced drag reduction. As taper ratio increases higher values of h/b offer less induced drag. But, the taper ratio (λ) also increases the tip fin viscous drag.

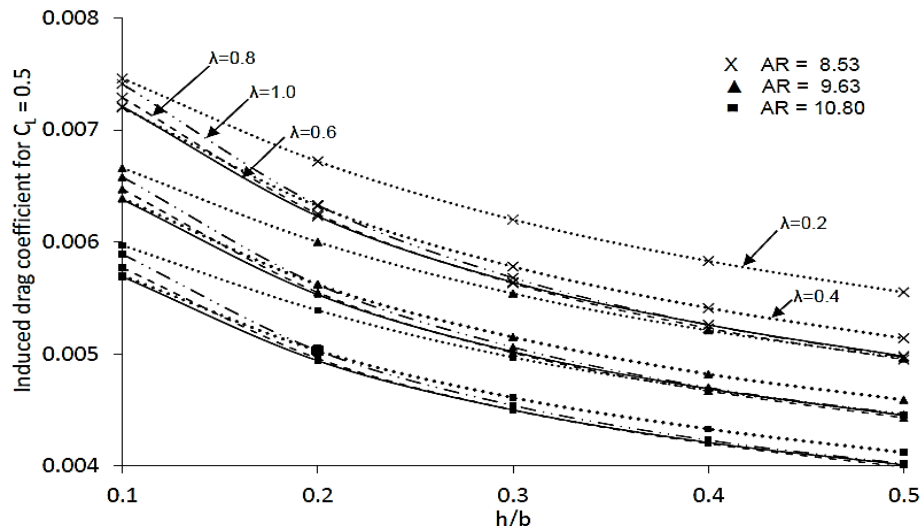


Figure 10: Induced drag versus height to span ratio, as obtained in [8]

Reference [9] concluded from CFD analysis of box wing configuration that a height to span ratio of one gives optimum induced drag for various flight conditions. This was reasoned to be due to the fact that as the vertical distance between the fore wing and aft wing increases, wetted area added to the wing increases. But, for h/b ratios of around 0.5, it was seen that the increase in height actually began to deteriorate the designs' aerodynamic performance. Thus h/b ratio of 0.5 is considered to be the maximum practical value for the box wing configuration. Biplane mutual interference factor was also seen to be one of the factors which influence the reduction in induced drag as h/b ratio increases, as shown in Figure 11. A reduction in biplane interference factor would in turn lead to a reduction in induced drag [2].

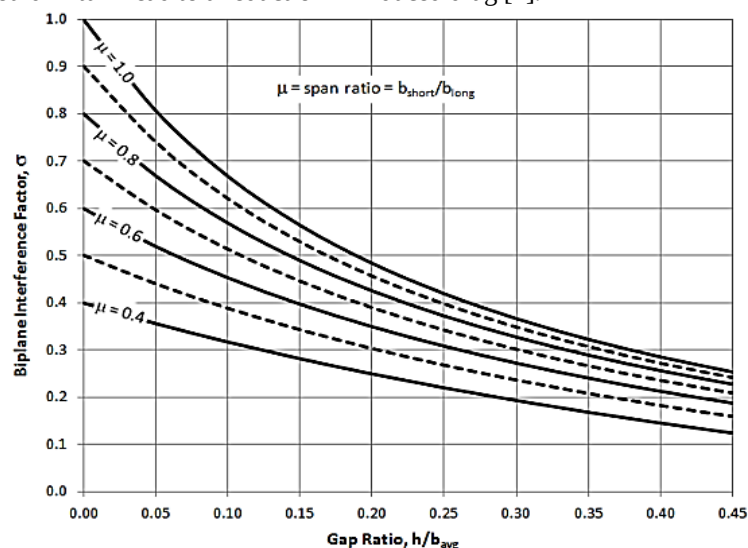


Figure 11: Prandtl's biplane interference factor as function of the gap and span ratios [10]

IV. BOX WING STABILITY

Schikanz and Scholtz studied the conflict between aerodynamic stability and performance of box wing aircraft. It was seen that for a stable design of box wing configuration, its optimum aerodynamic performance could not be achieved [11]. However, it was seen that the stability requirements imposed a very small aerodynamic penalty [4].

The variations in the wing area have a very negligible effect on the L/D ratio, which allows for the modification of the location of the neutral point for the stability without any considerable impact on the aerodynamic performance [12]. Reference [13] provided results based on the analysis of the box wing configuration's longitudinal cruise stability which showed that the box wing design remained stable and trimmable over a range of center of gravity positions and fuel loadings.

V. CONCLUSION

The box wing configuration has continued to be a topic of interest for aerodynamic research as it provides a potential solution for the improvement of the overall efficiency of an aircraft. To improve this overall efficiency of the box wing aircraft to its optimum value, it is important to consider the parameters like stagger, height to span ratio and also stability aspects as explained in the paper. It was concluded that increasing the height to span ratio of the box wing design increased its aerodynamic efficiency. The effect of other mentioned parameters on the box wing aircraft's performance was also studied. A significant reduction in induced drag for the box wing aircraft was observed. This, in turn, contributed to the reduction in fuel consumption. Hence, box wing aircraft will be a step towards green aviation.

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