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An Analysis of Aerodynamic Design Issues of Box-Wing Aircraft

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Abstract

The potential of the joined/box-wing aircraft as an environmentally friendly airliner that is capable of meeting current and future emission thresholds led to the investigation of this concept. This study reviews the evolution and current trends in the aerodynamic design of the box-wing aircraft with specific emphasis on box-wing theory, airfoil characteristics, and aerodynamic issues of the box-wing aircraft. The study was undertaken to highlight the distinct features of the box-wing configuration which make it very attractive for future airliners. The study reveals that the box-wing aircraft possesses a significant aerodynamic advantage over conventional aircraft. The box-wing aircraft configuration is also a less radical departure from the conventional concept. It thus could be developed with existing tried-and-tested aircraft design technologies, methodologies, and processes. Hence this article is a commentary that highlights the enormous potential of the box-wing aircraft and the need for further studies in this research domain.

Keywords: box wing, biplane, lift distribution, best wing system, aerodynamic efficiency, downwash

I. Introduction

The need to reduce the negative impact of airline operations on the environment has led to renewed interest in unconventional designs such as the blended wing body and joined/box-wing concepts. The joined/box-wing aircraft configuration has attracted the attention of researchers due to its claimed merits of reduced structural weight and low induced drag (Wolkovitch, 1986). The potential for improved fuel efficiency and reduced direct operating costs were other reasons that motivated researchers to investigate the aerodynamic concepts of the box-wing configuration. Though the blended wing concept claims to have some of the preceding advantages, the joined/box-wing aircraft configuration offers lower design risk than the blended wing body concept because it is not a completely radical departure from conventional aircraft configurations. These considerations influenced the National Aeronautics and Space Administration to award a contract to Lockheed Martin to investigate the box-wing aircraft configuration. The contract required Lockheed Martin to examine the box-wing claims of being able to reduce fuel burn by 40% and nitrous oxide emissions by 75% and minimize noise by 42 dB (Munk, 1923).

Wolkovitch (1986) carried out extensive research on the box-wing aircraft configuration following Munk's (1923) and Prandtl's (1924) earlier work. Wolkovitch (1986) viewed the joined/box-wing aircraft configuration as a highly integrated concept that connects structural and aerodynamic properties in novel ways. This paper discusses the aerodynamic design issues of the box-wing aircraft with emphasis on the box-wing theory, airfoil issues, aerodynamic considerations, and optimization.

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It is essential to state that even though the terms joined wing and box-wing are used interchangeably in the literature, the two concepts are not necessarily the same as can be seen from Figures 1 and 2. In box-wing aircraft, both wings form a closed nonplanar design, and produce equal amounts of lift, whereas, for the classical joined-wing aircraft, the fore wing produces approximately 80% of the total lift. This paper focuses on the novel aircraft concept that has fins linking the tips of the fore and aft wings together in what is appropriately called a box-wing aircraft.

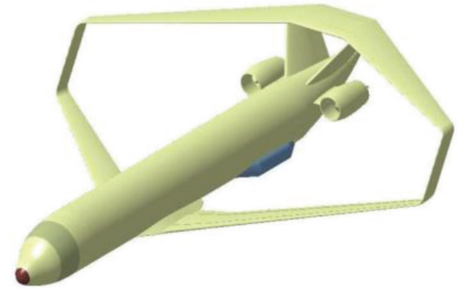

Figure 2. Lift distribution on a biplane.

II. Box-Wing Theory

Prandtl's (1924) "best wing system" states that a closed rectangular lifting system produces the least possible induced drag for a given span and height. In making this assertion, Prandtl (1924) established that all biplanes have less induced drag than their equivalent monoplane with equal spans. The study further highlighted that biplane drag decreases as the wing gap increases (Addoms & Spaid, 2014). Accordingly, Prandtl (1924) posits that the ideal arrangement for minimum induced drag is a closed biplane with equal lift distribution and total lift on each wing. In this arrangement, the top of the endplates are exposed to outward pressure while the bottom parts experience inward pressure. Figure 3 shows a front view schematic of two lifting surfaces with equal spans joined at the tips thus positioning the ideal pressure distribution on the endplates. As the gap between the wings increases, trailing-edge vortices are reduced, thus lowering induced drag (Frediani, 2005). The lower induced drag makes the box-wing configuration an attractive proposition for reducing the environmental impact of aviation. This is because induced drag accounts for a significant portion of the total drag count of a commercial flight. Hence, reduced induced drag lowers fuel burn and minimizes pollutant emission leading to reduced environmental impact.

Figure 4 depicts the effect of wing gaps on induced drag of a biplane as provided by Prandtl (1924). In the plot, the horizontal axis represents the wing gaps while the vertical axis represents the induced drag. The plot illustrates the inverse proportional relationship between the induced drag and wing gap. This implies that the lower the wing gap, the higher the reduction in induced drag. For example, for a wing gap/span (h/b) of 0.25, the induced drag is about 71% of an equivalent monoplane with the same aspect ratio while a wing gap/span (h/b) of 0.15 gives an induced drag reduction of almost 80% (78%). Consequently, a closed biplane arrangement produces the greatest reduction in induced drag. However, this aerodynamic benefit is relative as there is an attendant increase in wing mass and issues with the practicability of the design.

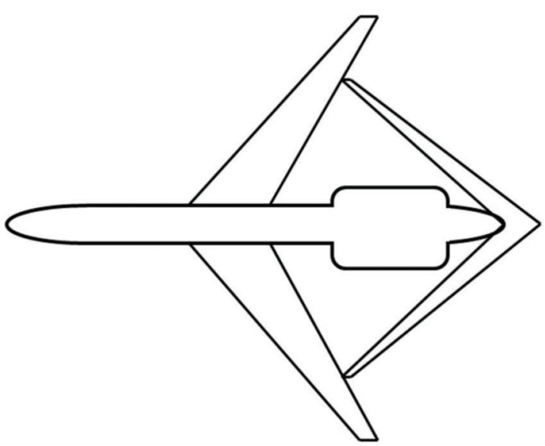

Figure 1. A sketch of the joined-wing aircraft.

Using Munk's (1923) equivalence theorem, Prandtl's theory can be extended to a staggered wing arrangement. Munk's equivalence theorem states that given a constant lift distribution, the total induced drag of any multiplane system is unaltered if any of the lifting elements is moved in the direction of motion. However, by staggering the wings, the induced flow between the wings changes. The forward wing experiences an upwash while the aft wing is subjected to a downwash. This results in the decrease of the lift-curve slope of the aft wing relative to the fore wing when the airfoil sections and angles of attack (assuming no fuselage is present) are equal (Frediani, 2005). Consequently, one of the major challenges of developing the box-wing aircraft is the difficulty in optimizing the design to obtain equal lifts on the wings.

Combining the Prandtl best wing system and the Munk equivalence theorem, Frediani (2005) posits that Prandtl's best wing system, if applied to a conventional aircraft configuration, could reduce induced drag by up to 20–30% based on an h/b ratio of 10–15%. Frediani (2005) further established that for a box wing or "Prandtl plane," the aerodynamic efficiency obtained is strongly linked to the ease of creating a stable aircraft with equal lift distribution on the wings. Additionally, Frediani (2005) determined that induced drag accounts for approximately 43% of the total aircraft drag during cruise flight in still air. Thus, a decrease in induced drag provides design benefits such as reduced aircraft weight and thrust requirements. This would ultimately minimize the negative impact on the environment. These findings led to widespread interest in the box-wing aircraft.

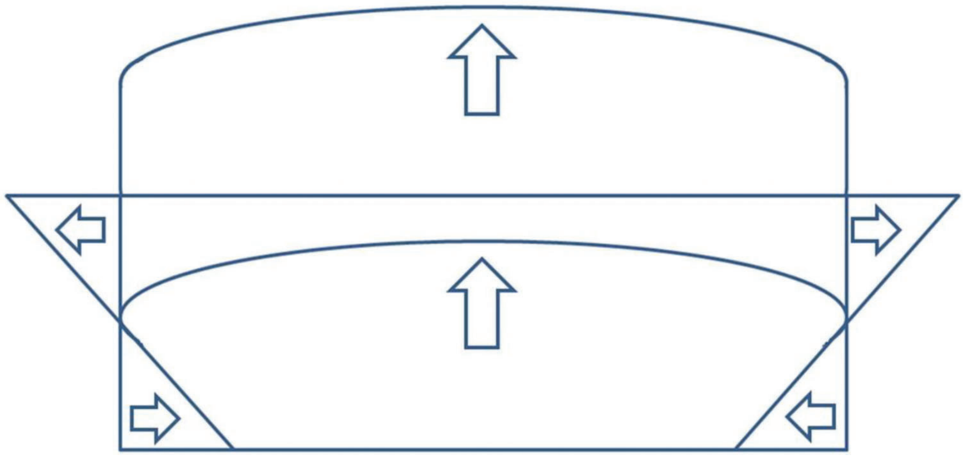

Figure 3. Definition of the airfoil + two-dimensional flap system.

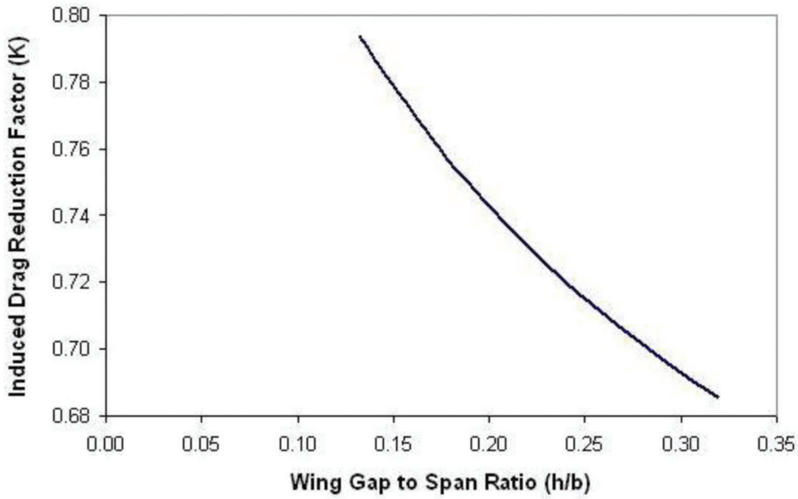

Figure 4. Effect of wing gap on induced drag reduction.

III. Airfoil Issues

According to Wolkovitch (1986), airfoils used in the vicinity of box-wing aircraft interwing joints must consider the induced flow curvature. Consequently, the use of natural laminar flow airfoils was recommended. Subsequently, Addoms and Spaid (2014) corroborated this finding by proposing that biplane configurations must employ airfoils with markedly different camber from those of a monoplane. This is because using monoplane airfoils on biplanes induces premature separation, leading to a low maximum lift coefficient. Wolkovitch (1986) thus advocates for the design of tailormade airfoils by exploiting the advanced state of current airfoil design technology.

In a similar vein, Wolkovitch (1986) revealed that because the effective depth of a beam, *d*, of a joined/box wing is primarily determined by the chord of its airfoils, as sketched in Figure 5, their thickness is a significantly less important consideration. This finding justified the adoption of thin airfoils for joined/box-wing aircraft design. Wolkovitch (1986) thus concluded that twin fins of approximately 60° dihedral reduce the unsupported column length of the aft wing, thereby decreasing drag and structural weight. Frediani (2005) corroborated Wolkovitch's views on the use of twin fins for joined/box-wing aircraft when he disclosed that the aerodynamic channel created by the top of the rear fuselage, aft wing under-surface, and the twin tail enhance the aerodynamic efficiency of the concept. These discoveries influenced Bernardini and Frediani (1999) to design a joined/box-wing configuration to harness the aerodynamic benefits of Frediani's (2005) aft-wing/twin-fin design.

IV. Aerodynamic Concepts and Considerations

Bagwill and Selberg (1986) advanced that positively staggered joined-wing aircraft are more aerodynamically efficient than those with negatively staggered joined wings. Positive stagger refers to an arrangement where the higher wing is placed in front of a lower aft wing, while negatively

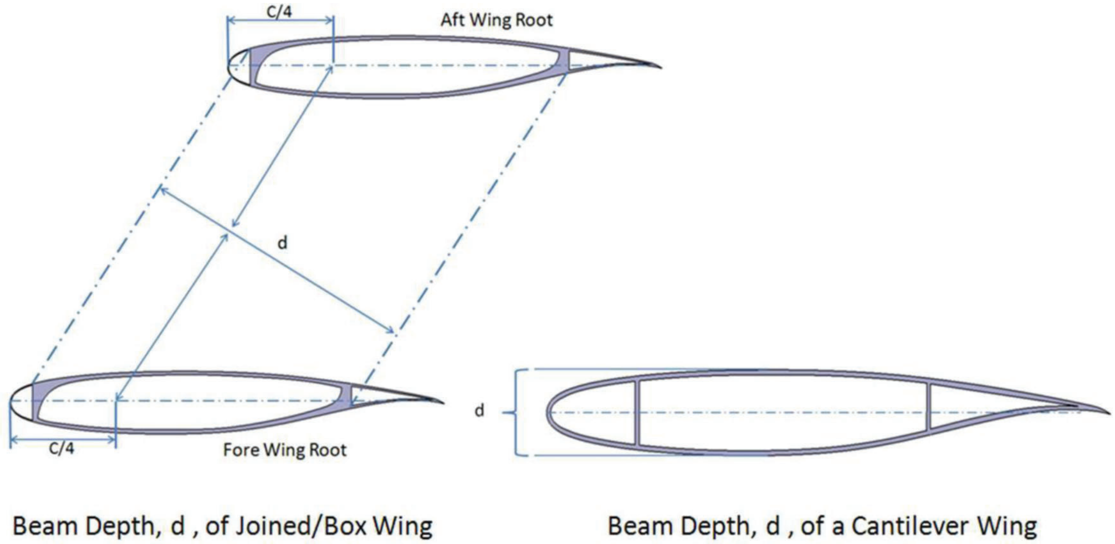

Figure 5. Effective wing depth, *d*.

staggering refers to the reverse configuration. Mamla and Galinski (2009) agree with Bagwill and Selberg (1986) on the superior aerodynamic efficiency of positively staggered joined-wing aircraft over negative stagger. However, Smith and Jemitola (2009) highlighted the beneficial influence of a maximized vertical separation between the fore and aft wings on a negatively staggered joined-wing arrangement. For a medium-range airliner, Smith and Jemitola's (2009) study showed that the negatively staggered arrangement benefits from the use of the tail fin to maximize the wing's vertical separation. In contrast, the positively staggered arrangement provides comparable aerodynamic benefit but with significant mass penalties and directional stability issues.

Schikantz and Scholz (2022) undertook a study that examined the conflicting requirements of obtaining aerodynamic efficiency and static longitudinal stability for the box-wing aircraft. They stated that to ensure the stability of their model, the fore wing lift coefficient was increased thereby increasing the ratio of the fore and aft wing lift coefficients. Furthermore, the centers of gravity of the airframe, engines, fuel, and payloads were carefully manipulated so that they are located at approximately the same position. In a related study, Demasi (2007) investigated the conditions for a minimum induced drag of closed-wing systems and c-wings using the lifting line theory and small perturbation acceleration potential. Applying numerical and analytical solution methods, Demasi (2007) established that closed-wing systems (like biplanes) have practically the same induced drag as c-wings. This result is similar to what Kroo (2005) obtained in his investigation of nonplanar wing concepts.

Burkhalter et al. (1992) investigated the downwash effects for joined-wing aircraft using experimental and theoretical aerodynamic approaches. The study revealed that there is only a 12% difference between the experimental and the semiempirical methods. This suggests that there will be no need to develop new methodologies for designing the box-wing aircraft. This is because existing design and analysis methods have proven that they can be used without loss of accuracy.

Corneille (1999) conducted a wind-tunnel experiment to compare the aerodynamic performance of joined-wing and conventional aircraft. The study finds that the joined-wing configuration is aerodynamically superior to conventional cantilever wing aircraft. This finding agrees with the results from previous studies by Wolkovitch (1986), Prandtl (1924), and Frediani (2005). However, just like those studies, Corneille (1999) focused only on the aerodynamic performance of the box-wing aircraft over conventional aircraft and neglected other disciplines. Since an aircraft involves a complex mix of multiple disciplines including aerodynamics, structures, and stability and control, there is a need to investigate the combined effect of some of these disciplines on a configuration to arrive at a holistic conclusion. Consequently, Jansen et al. (2010) performed a single-discipline aerodynamic optimization and multidisciplinary aero-structural optimization of nonplanar lifting surfaces. For the aero-optimization, both the box-wing and joined-wing aircraft were optimal. However, when aero-structural optimization was performed, only the conventional configuration with a winglet was optimal. The study of Jansen et al. (2010) highlights the difficulty in developing a joined-wing aircraft with optimal multidisciplinary characteristics.

Nangia and Palmer (2006) analyzed the effects of forward-swept outboard wings on a joined/box-wing aircraft. They observed that a forward-swept outboard wing produces favorable lift distribution on the forward and aft wing through a forward placement of the center of pressure. Yechout et al. (2008) embarked on an aerodynamic evaluation and optimization of a joined-wing concept model aircraft. They used general engineering rules of thumb and a University of Missouri biplane design to optimize the performance of joined-wing aircraft. The authors varied the negative decalage angle and the taper ratio to less than one. Additionally, they increased gap, decreased the wing sweep, and decreased the stagger. The study concluded that a wing gap of 4.75 inches and a decalage angle of -1.5° will create optimal configuration for higher lift coefficients and a shallower drag polar. However, Yechout et al. (2008) observed that joined-wing configurations have negligible performance advantages over a monoplane.

Khalid and Golson (2014) undertook an aerodynamic analysis of a box-wing configuration for an unmanned aircraft system using computational fluid dynamics. They varied the winglet height to wingspan ratio parameter from 5% to 25%. The study found that a 15% winglet-to-wingspan ratio gave the highest lift-to-drag ratio while a taper ratio of 0.4 provided the highest lift-to-drag ratio. Khalid and Kumar (2014), however, found that varying the airfoil, winglet height, and aspect ratio resulted in a significant increase in the lift-to-drag ratio relative to the baseline design. Specifically, this study revealed that a box wing with KC-135 airfoil sections produced a 20% increase in lift-to-drag ratio over a cantilever wing aircraft in cruise conditions. Additionally, varying the winglet height of the resulting box-wing aircraft from 5% to 35% of span in steps of 5% yields a 5% increase in *L*/*D* over the baseline box wing and 15% higher *L*/*D* than the reference cantilever wing at winglet height equal to 30% of span. However, varying the aspect ratio showed negligible improvement in aerodynamic efficiency, with only the −5% aspect ratio model showing comparable results to the baseline box-wing model. Consequently, the study established that the optimal geometry of a box wing is composed of KC-135 winglets with winglet height equal to 30% of span, and 0% aspect ratio.

Barcala et al. (2014) studied the aerodynamics of an unmanned aircraft system of box-wing configuration at low Reynolds numbers through a wind-tunnel experiment. By varying the positions of the wings along the fuselage and the sweepback angles of the wings, significant differences in aerodynamic efficiency were found. This result indicates that the relative positions of the wings affect the aerodynamic efficiency of the box-wing configuration (Jger et al., 2015). Another observation from this study is the late separation of flow on the fore wing at high angles of attack as the angle of attack is increased (Jger et al., 2015). Nonetheless, the flow separates at a higher angle of attack on the rear wing relative to the fore wing as highlighted in Frediani's (2005) work.

Gagnon and Zingg (2015) undertook a study to minimize the drag of a box-wing aircraft configuration using high-fidelity aerodynamic optimization. The study finds that box-wing aircraft with a tip fin height-to-wingspan ratio of about 0.2 creates up to 43% less induced drag than the conventional counterpart. This aerodynamic benefit was derived from the inherent characteristics "of Box Wing Aircraft to redistribute its optimal lift distribution with almost no performance degradation" (Gagnon & Zingg, 2015).

Balaji et al. (2016) explored different aerodynamic issues in the design of the box-wing aircraft using a wind tunnel. Experimental results revealed a decrease in drag due to "the overall reduction in the downwash of the complete system" (Balaji et al., 2016). In addition, the study established that adding an endplate to a lifting system further reduces the downwash thereby increasing the effective span and thus the aerodynamic efficiency of the box-wing aircraft (Balaji et al., 2016).

Bagwill and Selberg (1996) investigated twist and cant angles of the tip fins of box-wing aircraft. The results from the study conformed to Wolkovitch's (1986) findings. These studies suggest that careful selection of twist and cant angles of a box wing aircraft, at higher aspect ratio, provides a greater increase in the lift-to-drag ratio compared to a conventional cantilever-wing aircraft (Bagwill & Selberg, 1996). This discovery was corroborated by Nangia et al. (2003) in a study to investigate the effect of high aspect ratio on joined-wing aircraft. Nangia et al. (2003) found that joined/box-wing aircraft generate lower induced drag as well as higher wing stiffness compared to conventional cantilever aircraft.

In terms of stalling characteristics, Bell et al. (2008) revealed that the rear wing of a joined-wing aircraft induces an upwash on the forward wing which then initiates a downwash on the rear wing. According to Bell et al. (26), the higher angle of attack on the fore wing of a joined/box-wing aircraft ensures that it stalls before the rear wing. This prevents deep stall, thereby improving stalling characteristics of the box-wing aircraft. Accordingly, the joined/box-wing configuration exhibits safer stall characteristics than a conventional aircraft. This was corroborated by Singh et al. (2020) who established that the box-wing aircraft has $+6^\circ$ delay in stall angle, implying a lower stalling speed, compared to a monoplane wing.

Another aerodynamic phenomenon associated with the box-wing aircraft was highlighted by Cipolla et al. (2019). The study which was part of the PARSIFAL (PrandtlPlane Architecture for the Sustainable Improvement of Future Airplanes) project established that increasing the wing loading of a box-wing aircraft in subsonic conditions increases the lift-to-drag ratio. However, in transonic flight, higher values of wing loading lead to drag rise conditions thus diminishing the aerodynamic efficiency of the box wing. Similarly, Frediani et al. (2020) state that box-wing aircraft show severe compressibility effects at the tip of the forward wing and the onset of large flow separation at a relatively small incidence. This reduces the maximum achievable lift while producing a strong drag rise. Strong compressibility effects were also observed at the intersection between the fin and the upper wing while wave drag behavior in the high transonic regime became pronounced at increasing Mach number above 0.8. This influenced the choice of Mach = 0.79 for the cruise speed of the PARSIFAL airplane. Furthermore, this study highlights that the damping-in-pitch is derived from the rotary contribution associated with the pitch rate, while the acceleration contribution due to the incidence rate is almost negligible.

In a related study, Frediani et al. (2019) carried out two- and three-dimensional CFD analyses to design a flap system for the prototype of an innovative light amphibious airplane based on the box-wing configuration known as the IDINTOS. The flap system composed of Fowler flaps (FF) on the front wing and plain flaps (PF) on the rear wing was conceptualized, as shown in Figure 6.

Following CFD and wind-tunnel analyses, Frediani et al. (2019) established that the best aerodynamic performance is obtained at xFF = 0, while the optimal vertical distance (zFF) depends on the selected section owing to its strong influence on maximum CL. Furthermore, the study shows that stall occurs at CL values higher than in conventional airplanes. This creates a significant negative pitching moment, thus reaffirming the anti-stall characteristics of the box-wing aircraft.

Frediani et al. (2019) also discovered that elevator deflections between 5° and 15° degrees have minimal effect on CL, providing a near perfect pitch control without transient lift variation when properly designed counter-rotating elevators are employed. Frediani et al. (2019) subsequently concluded that due to the intrinsic anti-stall characteristic and the presence of control surfaces on both wings, the PrandtlPlane is less prone to maneuvering errors. The two counter-rotating elevators on both wings permit pitch variation by pure couple while the FF on the front wings lowers the stall speed. This increases maneuvering precision thereby enhancing safety in all flight conditions especially when the aircraft is close to the ground.

Other findings from the Frediani et al. (2019) study include that winglets provide a 6–10% reduction in total drag and show good anti-stall behavior due to flow separation on the front wing creating a negative pitching moment which opposes the onset of stall as the angle of attack rises beyond 10°. Indeed, as the angle of attack rises between 10° and 15°, the lift coefficient decreases with angle of attack and eventually becomes null when maximum CL is reached, up to alpha = 24, thus indicating a smooth stall behavior in low-speed conditions. This study also revealed that the pitch damping moment is about three times higher than that for a conventional airplane. The beneficial effect of this characteristic on longitudinal stability enables the PrandtlPlane configuration to avoid "porpoising" instability. This could be valuable in cruise flight conditions, thus increasing both safety and flight comfort.

V. Effect of Optimization on Aerodynamic Characteristics of Joined/Box-Wing Aircraft

Gallman et al. (1993) performed a synthesis and optimization for a medium-range joined-wing transport aircraft. They developed a program to model joined-wing transport aircraft and measured their overall performance in terms of direct operating cost. The program predicted the aerodynamic interaction between the lifting surfaces and the stresses in the statically indeterminate structure. Aerodynamic forces were determined using a vortex lattice model of the complete aircraft in a LinAir program. Viscosity and compressibility were then added to compute compressibility drag while inextensible theory was used to simulate fully stressed lifting surface structures. The study revealed that a joined/box-wing aircraft is deficient in field performance owing to a low maximum lift capability.

Gallman et al. (1993) showed that a joined-wing aircraft is cheaper to operate than an equivalent conventional transport. Additionally, they opined that an in-depth study of wing sweep, flap span, and elevator span provides further gains in the aerodynamic performance of a joined-wing aircraft. Gallman et al. (1993) posit that any design changes that reduce the tail sweep angle would likely improve the performance of a joined-wing aircraft. They identified take-off field length and horizontal-tail buckling as the critical design constraints for joined/box-wing aircraft. Gallman et al. (1993) attribute the significant increase in direct operating cost of joined/box-wing aircraft to the poor field performance characteristics of the

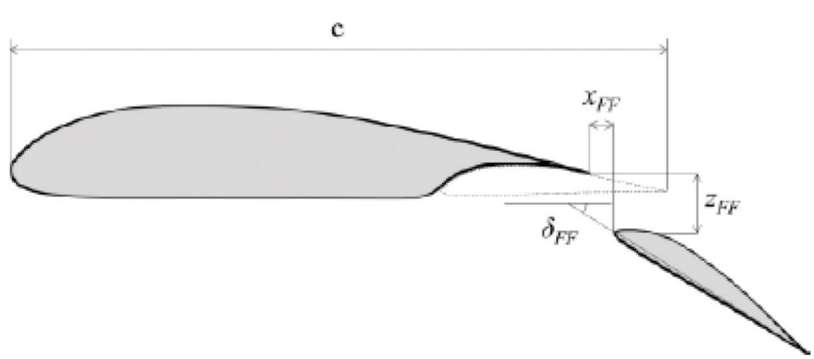

Figure 6. A sketch of the box-wing aircraft.

configuration. The box-wing aircraft exhibits poor field performance characteristics due to its limited capacity to generate maximum lift in take-off mode.

Andrews and Perez (2018) compared the performance of box-wing and conventional aircraft designed for representative regional-jet missions using multidisciplinary analysis and optimization. The parametric study varies the stagger of the wings, the height-to-span (*h*/*b*) ratio, and the relative area of the fore wing in cruise condition subject to static longitudinal stability, trim, and maneuverability constraint. The stagger of the wings, the height-to-span ratio, and the relative area of the fore wing were varied as 0.5–2.0, 0.125–0.5, and 0.4–0.6 respectively.

Using the SNOPT optimizer implemented in the pyOpt framework, Andrews and Perez (2018) identified that box-wing aircraft with large stagger and a height-to-span ratio of at least 0.25 have higher aerodynamic efficiency than conventional tube and wing aircraft. The study also revealed that aerodynamic efficiency increases with increasing area ratio, higher stagger, and rising height-to-span ratio up to 0.5. The best aerodynamic efficiency of 23.64 for box-wing aircraft was obtained with area ratio of 0.5, height-to-span ratio up to 0.5, and at the highest value of stagger. However, beyond a height-to-span ratio of 0.5, there is a decreased aerodynamic efficiency due to greater effect of resulting higher wetted area.

Stagger affects the lift-to-drag ratio of the aircraft when trim constraints are imposed. Since this study imposed a positive static margin of 7% on the design, the center of gravity is positioned ahead of the aerodynamic center of the aircraft. This creates a negative pitching moment that is counteracted by varying the lift generated by the fore and aft wings thus nullifying the assumptions of Munk's stagger theorem. Increasing stagger thus increases the effective moment arm of each wing while neutralizing the pitching moment imposed by the stability requirement.

Overall, Andrews and Perez (2018) recommend an area ratio of 0.4–0.5, increasing stagger to the maximum value possible to reduce the impact of the trim constraint on the lift-to-drag ratio, and raising the height-to-span ratio to maximum 0.5 to obtain an optimal box-wing design that provides the best aerodynamic efficiency over conventional concepts while satisfying stability and trim requirements. Although a box-wing aircraft often has a lower span than a conventional cantilever-wing aircraft designed for similar missions, it would require a larger planform area if it is required to carry all mission fuel in the wings. This will increase the skin-friction drag and thus the wing weight, thus nullifying the aerodynamic advantage of the design over conventional cantilever-wing aircraft.

Carini et al. (2020) described the application of high-fidelity Reynolds-averaged Navier–Stokes computations and Euler-based workflow to the analysis and optimization of a box-wing aircraft. The study established that induced drag accounts for about 43% of the total drag of a box-wing aircraft in cruise condition. The study further revealed that the maximum aerodynamic efficiency of a box-wing aircraft is obtained close to the cruise design point, at approximately CL = 0.4 with a value of 24.1 for an isolated lifting system and approximately 19.4 for the full PrandtlPlane configuration. Also, the Oswald efficiency (e) is always greater than 1, with $e = 1.28$ for the full PrandtlPlane at zero degree angle of attack. However, the maximum value of e is not obtained at the maximum aerodynamic efficiency conditions but at approximately CL = 0.55.

VI. Structural Dynamics and Aeroelasticity

Fazelzadeh et al. (2018) investigated the structural dynamics and aerodynamic loading of a two-dimensional box-wing model using aeroelastic governing equations derived from Lagrange's equations and aerodynamic forces obtained from the Theodorsen quasi-steady aerodynamic model. The study reveals that increasing winglet stiffness and angles will decrease the flutter speed of a box-wing aircraft. In addition, increasing the winglet angle decreases the stability domain of the airplane. Similarly, there is an increase in flutter speed and frequency with altitude and the wing bending stiffness while increasing the wing length decreases the flutter speed and frequency. Furthermore, both plunge and pitch-effective stiffness coefficients are reduced by increasing the wing length. Wing chords and the length ratio between the front and rear wings have a negligible effect on the flutter speed of a box-wing aircraft but flutter frequency is increased by decreasing the wing's chords.

Similarly, Ghasemikaram et al. (2021) studied the flutter characteristics of a three-dimensional box-wing aircraft using the Wagner unsteady model to simulate the aerodynamic force and moment on the wing and Hamilton's variational principle. The study investigated the effects of winglet tension stiffness, wing sweep, and dihedral angles, as well as the aircraft altitude on the flutter velocity and frequency. The study reveals that the physical and geometrical properties of the front and rear wings as well as the winglet design have significant influence on box-wing aeroelastic stability. Additionally, the flutter boundary is extended by increasing the skin thickness and adding tip tanks. The study showed that adding 20% thickness to the front wing and 10% to the rear wing increased the flutter speed to the maximum value. However, the front wing dihedral angle exerts no significant influence on the flutter boundary.

Increasing the sweep angles expands the flutter stability boundary, especially for large sweep angles but does not significantly change the flutter frequency. Also, there is an increase in flutter speed at high altitudes and large sweep angles, but the flutter frequency remains almost constant for large sweep angles. The sweep angle only has a minor influence on the flutter speed at a given chord ratio.

However, increasing the chord ratio enhances the flutter speed and frequency. Also, increasing the bending rigidity ratio, at high winglet stiffness, does not affect the flutter speed but it decreases the flutter frequency. However, increasing the torsional rigidity ratio significantly decreases the flutter speed and frequency. Additionally, increasing the semi-span initially reduces the flutter speed and then it remains constant while decreasing the flutter frequency. On the other hand, increasing the winglet tension stiffness decreases the flutter speed but does not change the flutter frequency. Winglet design significantly influences box-wing flutter boundary resulting in maximum flutter speed at an optimum winglet stiffness ($K = 0.2$). Large increase in the winglet stiffness would, however, minimize the flutter velocity, while increasing the box-wing span reduces the flutter speed and frequency.

Cavallaro et al. (2019) investigated the aeroelastic response of a prototype 250-seat, 6000nm, 230-ton box-wing aircraft to discrete symmetric gust, in order to obtain an insight into the structural design of such configuration. Using the DYNRESP code tool, the dynamic response of the flexible free–free aircraft was obtained for several gust parameters and two points in the envelope. The study showed that the response with the largest deformations was encountered at the sea-level condition with the largest gust gradient. Furthermore, the gust-induced lift deforms the wings (flap-up) and moves the whole aircraft upward. This also reversed the flapping motion (flap-down) even though the aircraft is still moving upward. The study further highlights that only marginal areas of the structure undergo higher stresses at chosen response instants than those observed on the reference limit load (load factor of 2.5) condition. In a related study, Cavallaro et al. (2021) examined the dynamic aeroelastic behavior of box-wing aircraft comprising the flutter and post-flutter regimes, including limit cycle oscillations. The study highlights that the front wing produces a destabilizing aeroelastic effect since it extracts energy from the flow. However, the most active region in this energy exchange is the tip. Nonetheless, most low-speed flutters or instabilities could be minimized by adding dampers to the hinge line and using mass balancing.

In another study, Cavallaro et al. (2016) revealed that the overconstrained structural system and the mutual aerodynamic interference of box-wing aircraft increase the complexity of the aeroelastic response. For a 250-seat PrandtlPlane with an aluminum structure, flutter is associated with a coalescence of two elastic modes, characterized by a classic upward bending of both wings, and an out-of-phase bending of the two wings and tilting of the lateral joint. Analyses show that energy is injected into the structure mainly at the tip of the front wing, close to the aileron. Nonetheless, flutter is greatly minimized when composite materials are employed. Cavallaro et al. (2016) also disclosed that increasing fuselage mass promotes a body freedom flutter (BFF) when pitching inertia is fixed. Conversely, fixing fuselage weight and varying moment of inertia creates BFF followed by pitching and elastic mode frequencies leading to increased flutter speed associated with BFF until the instability is diminished.

The coupled lateral-directional flight dynamic and aeroelastic behavior of a box-wing airplane using an *ad hoc* in-house framework was studied by Bombadieri et al. (2019). The study which employed the doublet lattice method unstable aerodynamic solver for aerodynamic analysis established that the flutter speed increases slightly due to the elastic–rigid interaction. However, low flutter speed is primarily due to the different shapes and frequencies of elastic modes relative to a fixed-in-space model. Notwithstanding, the rigid–elastic aerodynamic interaction provides a slightly beneficial effect on the onset of flutter.

VII. Computational Tools for Aerodynamic and Aeromechanical Design and Analysis

Salem et al. (2021) described the development of two computational design tools for the conceptual aerodynamic design and aeromechanical analysis of the box-wing airplane. The tools are AEROSTATE and THELMA. The AEROSTATE tool implements a constrained aerodynamic optimization procedure using low-fidelity aerodynamic solvers to enable large amounts of design information to be obtained in a short time. AEROSTATE is implemented in MATLAB and uses the AVL as the aerodynamic solver while implementing the mixed-optimization strategy. The mixed-optimization strategy combines sequential quadratic programming as the local optimizer and LocalSmooth as the global optimizer to obtain the optimal design variables that provide global minima. The design variables are the chord, twist angle, dihedral, sweep angle, and longitudinal leading-edge positions of lifting surfaces and span.

The AEROSTATE tool is used to minimize the induced drag subject to pitching moment, lift coefficient, stability derivatives (CM_alpha and CL_alpha), and neutral point constraints. The results indicate that the aerodynamic design of the lifting system is a trade-off between flight mechanics (stability, trim) and aerodynamic performance (lift-to-drag ratio). Additionally, the study finds that the ratio between the front wing and rear wing loading is a critical parameter for the design of box-wing aircraft. Specifically, the front wing needs a higher wing loading relative to the rear wing to satisfy stability and trim requirements. Consequently, this study recommends a ratio in the range of 0.5–0.8 between the rear-wing loading and the front-wing loading to ensure feasible stability and trim design space.

THELMA (Tool for High-lift and Movable surfaces Analysis) is a tool for the conceptual sizing of control surfaces and high-lift systems of the PrandtlPlane in the approach trim and take-off conditions and the aeromechanical analysis of a box-wing aircraft in ground effect. Using the tool, Salem et al. (2021) highlight that the design and deflection of the front wing flap influence the low-speed performance characteristics of the box-wing aircraft such as C_{LMAX}, approach speed, and take-off runaway length while the design and deflection of the flap on the rear wing are mainly related to pitch equilibrium concerns. Nevertheless, the rear wing flaps must be designed so that it is never critical to stall so as to avoid unacceptable problems of unstable stalling.

VIII. Conclusion

The investigation of aerodynamic design issues of the joined/box-wing aircraft highlights the aerodynamic efficiency of the concept and the complex interactions of several disciplines within the configuration. The joined/box-wing aircraft shows improved aerodynamic efficiency compared to a conventional cantilever-wing aircraft due to lower induced drag. However, it suffers from poor field performance and greater complications in structural design. Additionally, this study revealed that while the box-wing aircraft offers improved aerodynamic advantage over the conventional cantilever aircraft concept, it is quite challenging to obtain optimal multidisciplinary performance improvement for the box-wing aircraft. Notwithstanding, the less radical departure of the concept from the conventional configuration enables the use of existing analysis tools for the design of the box wing. This makes the box-wing aircraft concept an attractive prospect for aircraft designers in the quest to reduce the environmental impact of aviation.

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