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An Analysis of Aerodynamic Design Issues of Box Wing Aircraft

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Abstract

The potentials 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 aerodynamics 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 makes it very attractive as a future airliner. 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.

Index terms— box-wing, biplane, lift distribution, best wing system, aerodynamic efficiency, downwash.

1 I. Introduction

he need to reduce the negative impact of airline operations on the environment led to renewed interests in unconventional designs such as the Blended Wing Body and Joined/Box-wing concepts. The Joined/Box-wing aircraft configuration attracted the attention of researchers due to its claimed merits of reduced structural weight and low induced drag (1). The potentials 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 configuration. 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%, nitrous oxide emissions by 75% and minimize noise by 42Db (2).

Wolkovitch (1) carried out extensive research on the Box-Wing aircraft configuration following Munk's (2) and Prandtl's (3) earlier work. Wolkovitch (1) 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, aerofoil issues, aerodynamic considerations and optimization.

It is essential to state that even though the terms Joined Wing and Box-Wing are used interchangeably in literature, the two concepts are not necessarily the same as could be seen from Figures **??** and 2. In Box-Wing aircraft, both wings form a closed non-planar design, 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

2 II. Box Wing Theory

Prandtl's (3) '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 (3) 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 (**??**). Accordingly, Prandtl (4) 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 end-plates is exposed to outward pressure while the bottom parts experience inward pressure. Figure **??** shows a front view schematic of 2 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 (5). 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 pollutants emission leading to reduced environmental impact.

Figure 4 depicts the effect of wing gaps on induced drag of a biplane as provided by Prandtl (3). 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 increase and practicability of the design. Lift Distribution on a Biplane Figure **??**: Using Munk's (3) 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 (5). 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 (5) posits that Prandtl's (4) 'Best Wing System', if applied to conventional aircraft configuration, could reduce induced drag by up to 20-30% based on a h/b ratio of 10-15%. Frediani (5) 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 (5) 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.

3 III. Airfoil Issues

According to Wolkovitch (1), airfoils used in the vicinity of Box-Wing aircraft inter-wing joints must consider the induced flow curvature. Consequently, the use of natural laminar flow airfoils was recommended (1). Subsequently, Addoms (4) corroborated this finding by proposing that biplane configurations must employ airfoils with remarkably different camber than those of a monoplane. This is because using monoplane airfoils on biplanes induces premature separation, leading to a low maximum lift coefficient. Wolkovitch (1) thus advocates reduce the unsupported column length of the aft wing, thereby decreasing drag and structural weight. Frediani (5) corroborated Wolkovitch 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 (5) to design a Joined/Box-Wing configuration to harness the aerodynamic benefits of Frediani's (5) aft-wing/twin fin design.

4 IV. Aerodynamic Concepts and Considerations

Bagwill and Selberg (7) advanced that positively staggered Joined-Wing aircraft are more aerodynamically efficient than 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 staggering refers to the reverse configuration. Mamla and Galinski (8) agree with Bagwill and Selberg (7) on the superior aerodynamic efficiency of positively staggered joined wing aircraft over negative stagger. However, Smith and Jemitola (8) 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 (8) study showed that the negatively staggered arrangement benefits from the use of the tail fin to maximize the wing's vertical separation. In contrast, positively staggered arrangement provides comparable aerodynamic benefit but with significant mass penalties and directional stability issues. In a similar vein, Wolkovitch (1) 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-Wings aircraft design. Wolkovitch (1) thus concluded that twin fins of approximately 60 degrees dihedral **??**) 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 centres of gravity of the airframe, engines, fuel and, payloads were carefully manipulated so they are located at approximately the same position. In a related study, Demasi (9) 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 (9) established that closedwing systems (like biplanes) have practically the same induced drag as c-wings. This result is similar to what Kroo (12) obtained in his investigation of non-planar wing concepts.

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Burkhalter et al. (??3) 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 semi-empirical 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 could be used without loss of accuracy.

Corneille's (11) conducted a wind-tunnel experiment to compare the aerodynamic performance of a 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 (1), Prandtl (4), and Frediani (5). However, just like those studies, Corneille's (11) focused only on the aerodynamic performance of the Box-Wing Aircraft over Conventional Aircraft and neglected other disciplines. Since aircraft is a complex mix of multiple disciplines including aerodynamics, structures, and stability and control; there is the need to investigate the combined effect of some of these disciplines on a configuration to arrive at a holistic conclusion. Consequently, Jansen et al. (??2) 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. Jansen et al. (12) Study highlights the difficulty in developing a Joined Wing Aircraft with optimal multidisciplinary characteristics.

Nangia and Palmer (??6) analyzed the effects of forward-swept outboard wings on a Joined/Box-Wing aircraft. They observed that a forward-swept outboard wing produces favourable lift distribution on the forward and aft wing through a forward placement of the Centre of Pressure. Yechout et al. (18) 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 Wings 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. Yechout et al. (18) Study concludes that a wing gap of 4.75 inches and a decalage angle of -1.5 degrees will create optimal configuration for higher lift coefficients and a shallower drag polar. However, it was observed that Joined-Wing configurations create negligible performance advantage over a monoplane. ??halid and Golson (18) undertook an aerodynamic analysis of a Box-Wing configuration for an unmanned aircraft system using computational fluid dynamics. ??halid and Golson (18) varied the winglet height to wing span ratio parameter from 5% to 25%. The Study finds 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. ??halid and Kumar (19), however find that varying the airfoil, winglet height and aspect ratio resulted in a significant increase in lift to drag ratio relative to the baseline design. Specifically, the model with a 30% winglet to wing span ratio generated the highest increase in aerodynamic efficiency, equivalent to 15% increase in lift to drag ratio, when compared to a cantilever model. ??arcala et al. (20) 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 (21). 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 (21). Nonetheless, the flow separates at a higher angle of attack on the rear-wing relative to the fore wing as highlighted in Frediani's (5) work.

Gagnon and Zingg (22) 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-wing span ratio of about 0.2 creates up to 43% less induced drag than its 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' (22).

Balaji et al (23) 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' (23).

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 (23).

Bagwill and Selberg (24) investigated twist and cant angles of the tip fins of Box-Wing aircraft. The results from the study conformed to Wolkovitch's (1) 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 (24) This discovery was corroborated by Nangia et al. (25) in a study to investigate the effect of high aspect ratio on Joined-Wing aircraft. Nangia et al. (25) find 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 (26) study 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 (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.

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

Gallman et al (**??**7) performed a synthesis and optimization for a medium-range Joined-Wing transport aircraft. They developed a program to model joinedwing 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 Joined/Box-wing aircraft is deficient in field performance owing to a low maximum lift capability.

Gallman et al (27) showed that 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 performance aircraft. Gallman et al. (27) 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. (27) attributes the significant increase in direct operating cost of Joined/Box-Wing aircraft to the poor field performance characteristics of the configuration. The Box Wing aircraft exhibits poor field performance characteristics due to its limited capacity to generate maximum lift in take-off mode.

7 VI. 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 conventional cantilever aircraft concept, it is quite challenging to obtain optimal multidisciplinary performance improvement on the Box Wing Aircraft. Notwithstanding, the less radical departure of the concept from 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. [1] [2]

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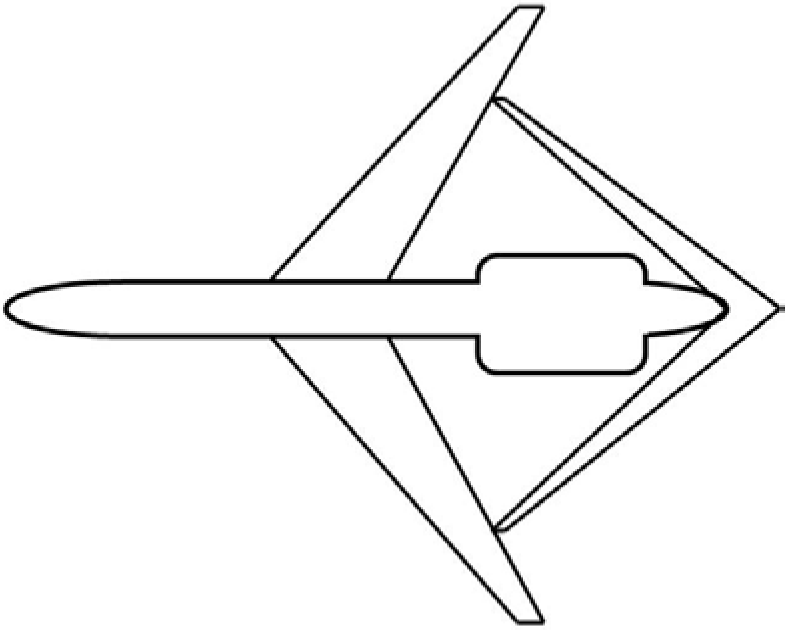

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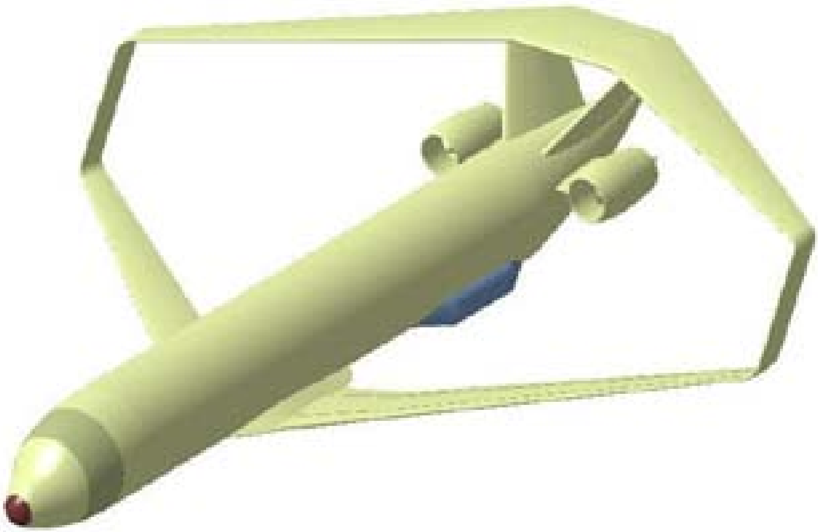

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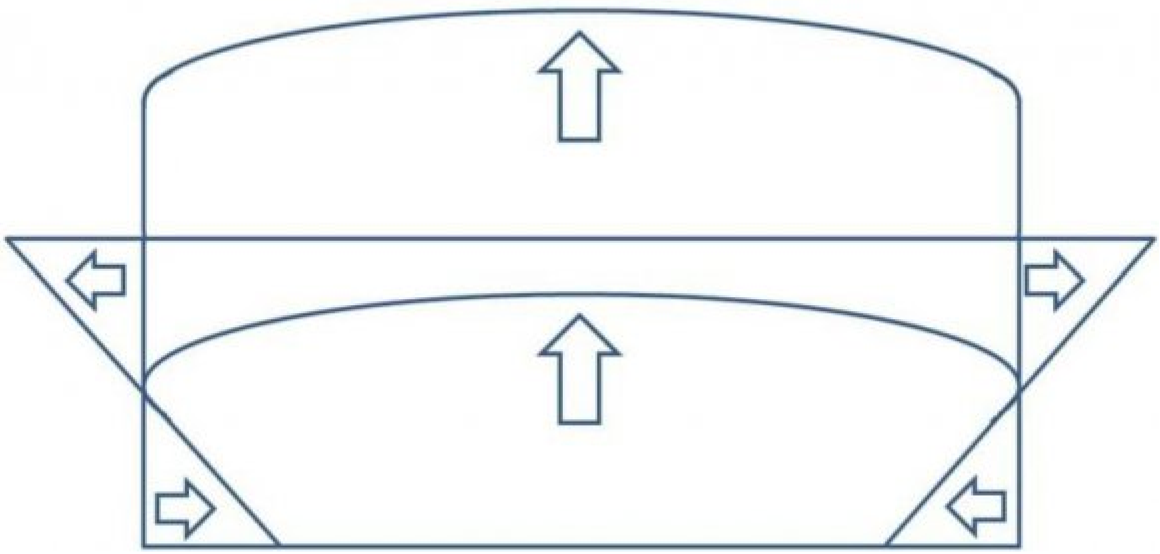

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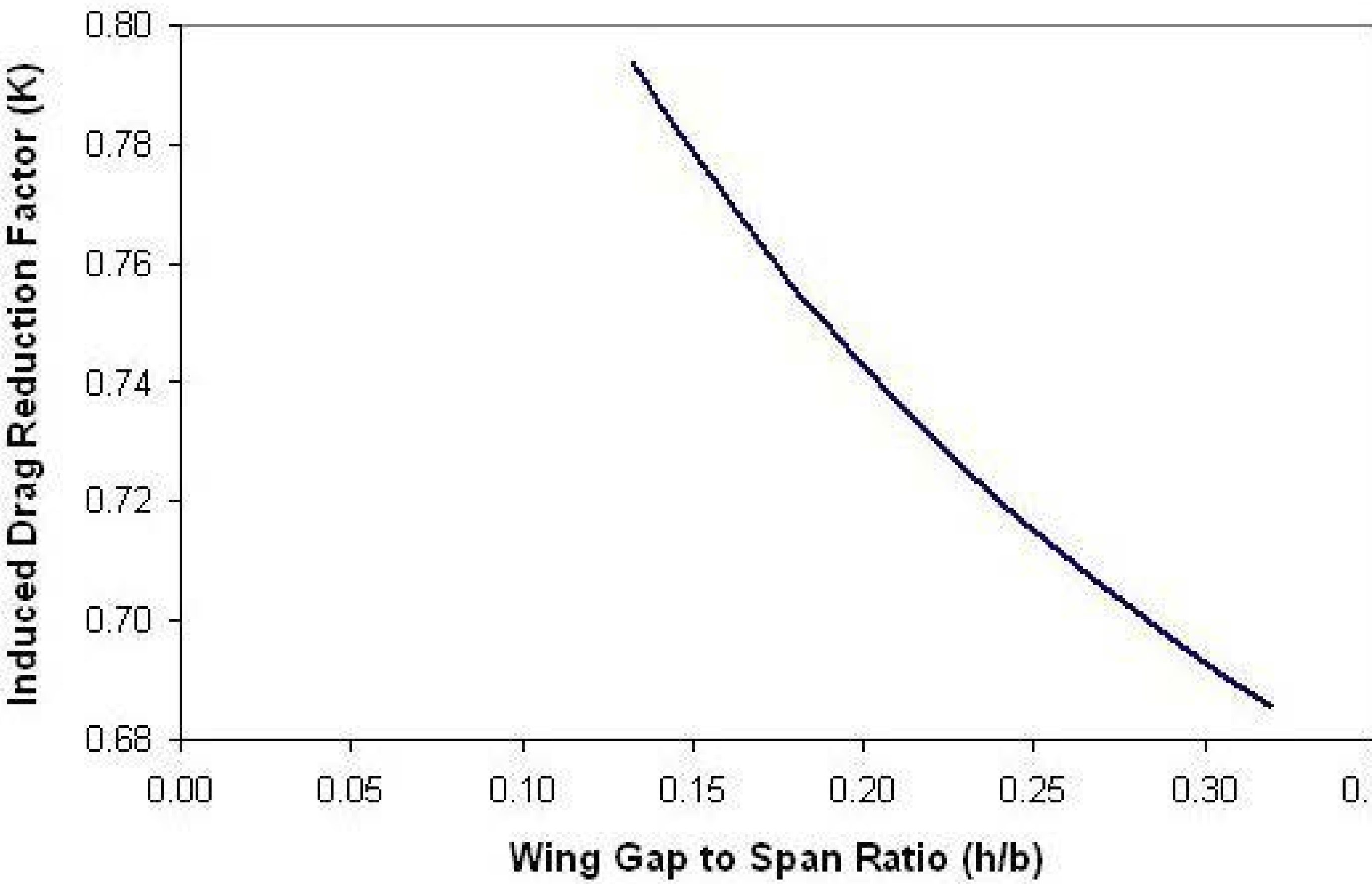

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Figure 4: Figure 5 :

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