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Accurate Induced Drag Prediction for Highly Non-Planar Lifting Systems

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Abstract

The impact of wake model effects is investigated for two highly non-planar lifting systems. Dependent on the geometrical arrangement of the configuration, the wake model shape is found to considerably affect the estimation. Particularly at higher angles of attack, an accurate estimation based on the common linear wake model approaches is involved.

Introduction

Induced drag is an inviscid phenomenon, preventing a practical but accurate experimental investigation. Its impact on flight performance is profound. For a commercial aircraft during cruise flight, induced drag accounts for approximately 40% of the total drag [9]. The ability to predict the induced drag with high accuracy by means of computational methodologies is therefore particularly important. Within conceptual wing design, induced drag is preferably estimated by computational approaches based on linear potential-flow theory. This is related to their ability to deliver reliable and computationally inexpensive induced drag estimates for planar systems of limited geometric complexity.

Referred to highly non-planar lifting systems (i.e. box wing configuration), this cannot generally be presumed. The reason for this is primarily given by the applied wake model, not necessarily providing an appropriate surrogate of the actual trailing vortical flow phenomena. In this context, first-order impact is introduced by the incorrect body-fixed wake placement, neglecting the geometrical relation of the angle of attack and the effective height-to-span ratio, a key design parameter for highly non-planar concepts. A review of existing potential-based methodologies confirms this wake approach as common engineering practice. Higher-order effects related to the roll-up and deflection of the true force-free wake are considered to be significant for these systems [10]. The peculiarity of both effects is influenced by the geometrical arrangement of the lifting system, which are particularly the height-to-span ratio and the longitudinal staggering. Although the decisive relevance of the wake model for these systems has been mentioned by Kroo [10] and further evidence for its importance can be derived from the wake substitution concept [15], a self-contained analysis addressing these aspects has not yet been conducted.

The present study therefore aims to quantify the impact of the trailing wake model on an accurate induced drag prediction for highly non-planar lifting systems. The dependency of trailing wake effects on key design parameters and the angle of attack is estimated exemplarily for a biplane and box wing configuration.

Computational Methodology

This work employs a standard vortex-lattice method (*AVL*) [6], a multi-lifting line formulation (*LiftingLine*) [8], a lifting-surface technique (*FreeWake)* [3], a higher-order panel method (*PanAir*) [1] and a commercial CFD-code (*STAR CCM+*) [4] to evaluate induced drag and associated quantities. Selected techniques are considered to sufficiently cover the range of existing inviscid computational methodologies for this purpose. A disquisition on present potential-based methodologies and their conceptual originalities is presented in Schirra et al. [13, 14]. Assets and drawbacks related to the wake model approach, the discretization and estimation technique are conveyed. *AVL* and *LiftingLine* make use of the body-fixed wake model whereas a streamwise representation is employed in *PanAir*. The force-free wake shape is computed by means of a time-stepping approach in *FreeWake*.

The Euler-based simulation (*STAR CCM+*) provides the most comprehensive inviscid flow model, but is computationally expensive and considered for the purpose of validation. This methodology does actually not employ a wake model. The true (force-free) wake shape is generally included as a part of the solution. A farfield approach [5] has been adapted from Bourdin [2] and implemented to circumvent issues related to the induced drag estimation based on surface pressure integration. Suggestions given by Vos et al. [16] were recently added. Selected methodologies have been successfully validated using as set of planar reference systems [7, 12, 14].

Lifting Systems

Two highly non-planar lifting systems are investigated. Major geometric characteristics of the planform are chosen to be equivalent among both systems (aspect ratio Λ=3.0, taper ratio λ=1.0 and chord length c=1.0m). All lifting surfaces are untwisted and represented either by singularity sheets without camber, or in case of the panel method (*PanAir*) by thin and symmetric airfoil sections. The right hand section of the box wing planform is exemplarily depicted in figure 1.

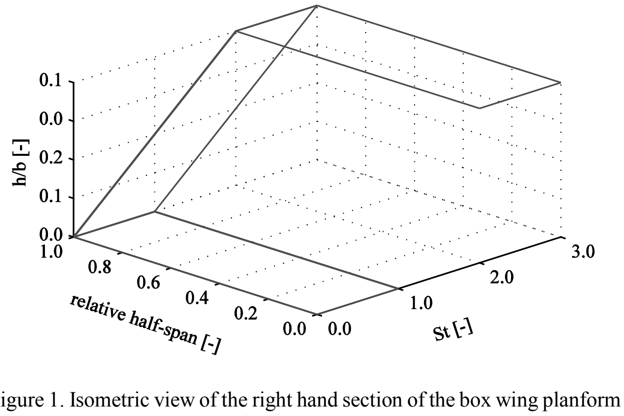

Figure 1. Isometric view of the right hand section of the box wing planform for a height-to-span ratio of h/b=0.20 and a staggering factor St=2.0.

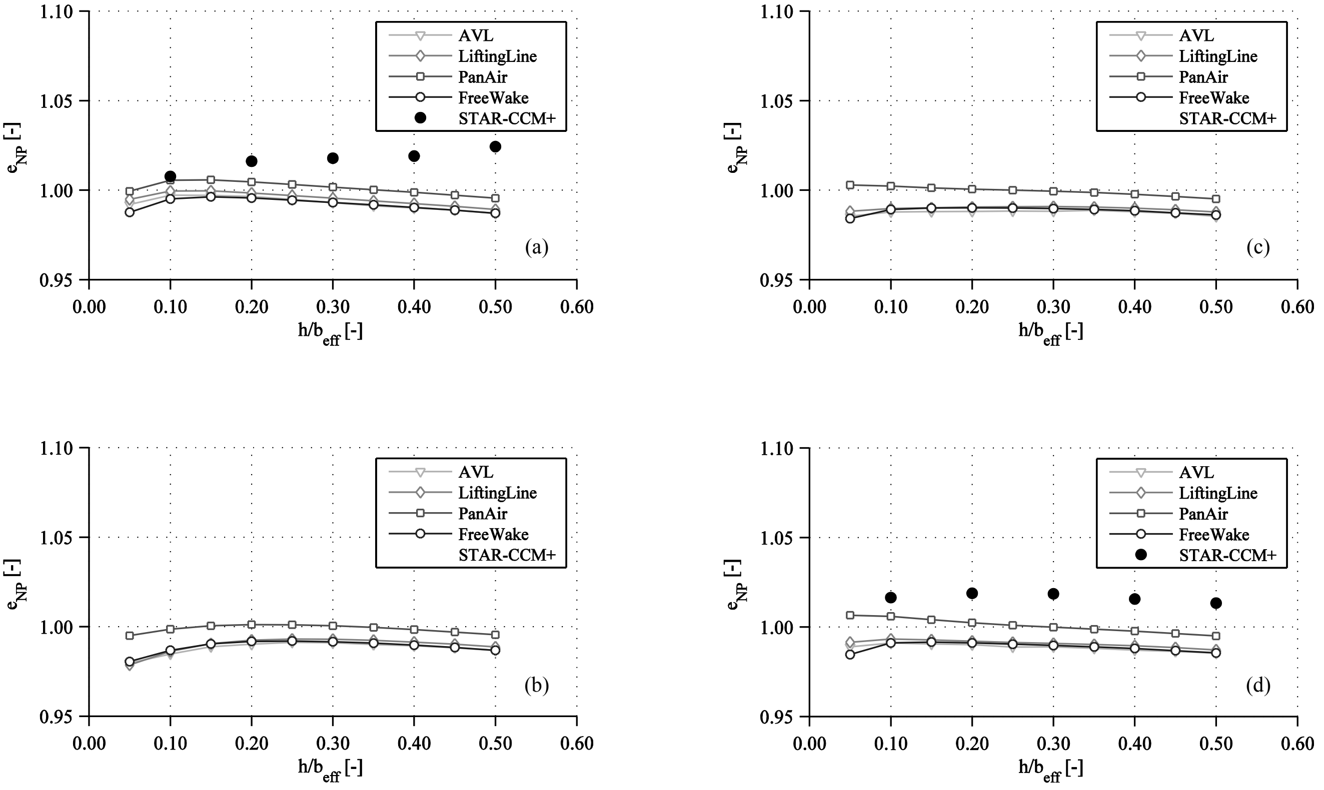

Figure 2. Computed non-planar span efficiency factors for the biplane configuration for the staggering factors: (a) St=0.0; (b) St=1.0; (c) St=2.0; (d) St=3.0.

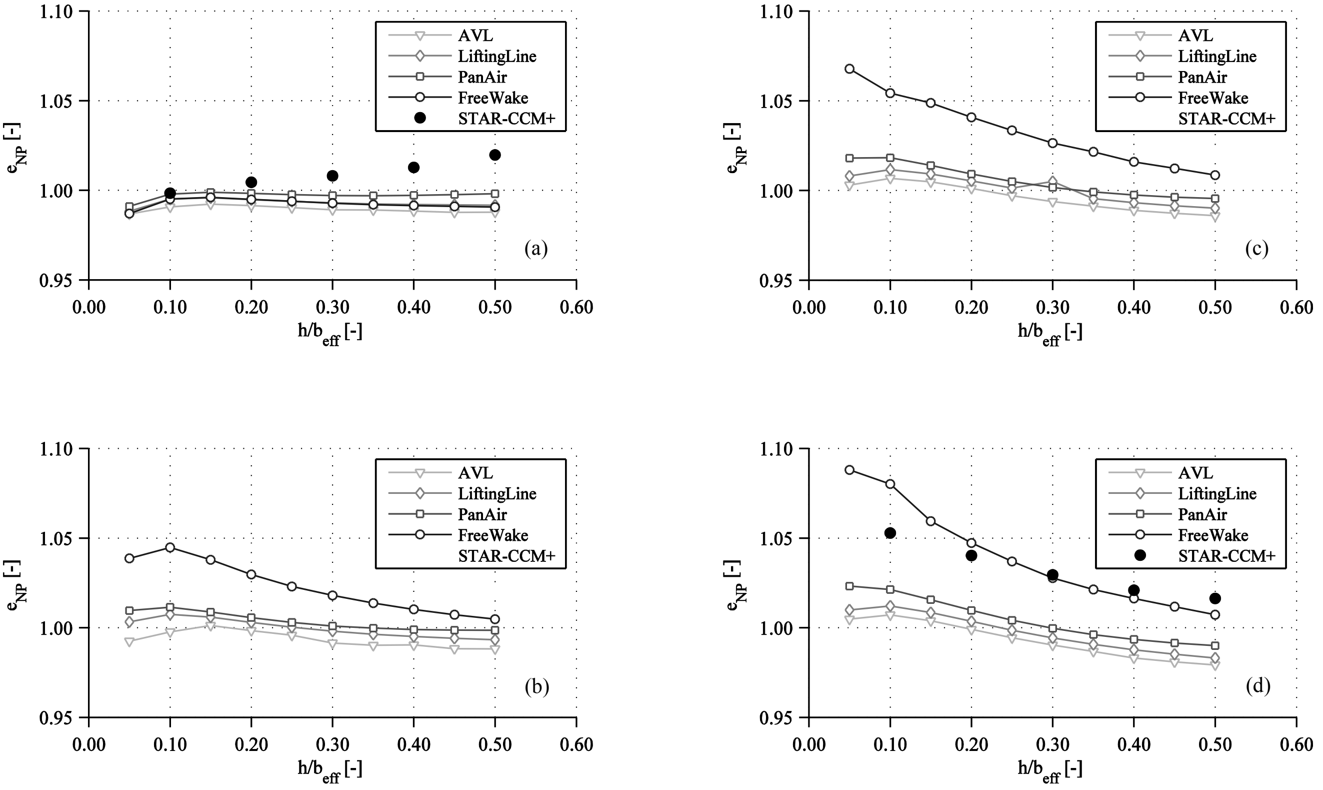

Figure 3. Computed non-planar span efficiency factors for the box wing configuration for the staggering factors: (a) St=0.0; (b) St=1.0; (c) St=2.0; (d) St=3.0.

Computational Results and Discussion

Variation of the Key Design Parameters

The study is conducted at a freestream Mach number of $M_\infty=0.01$ and at an angle of attack of $\alpha=4.0°$. Grid sensitivity studies were performed for each methodology in advance. Based on potential-methodologies, computed non-planar span efficiency factors e_{NP} for the biplane configuration are presented as a function of the effective height-to-span ratio for different staggering factors in figure 2. The non-planar span efficiency factor is defined as the span efficiency of the system relative to the optimum efficiency according to the biplane theorem for equal height-to-span ratio [11].

$$e_{NP} = \frac{e}{e_{OPT}} \tag{1}$$

The effective height-to-span ratio is the relative aerodynamic vertical gap as it is seen by the incoming flow velocity vector. It is corrected for the influence of the angle of attack. Euler-based estimates (*STAR-CCM+*) are given for selected staggering factors. Overall, an excellent agreement among potential-based methodologies (wake models) is achieved independent on the staggering factor involved. The largest relative deviation between potential-based methodologies is found to constitute less than 1%. First-order impact due to the body-fixed wake placement (*AVL, LiftingLine*) does not affect the solution considerably, as good accordance with the force-free wake representation (*FreeWake*) is given. It can be assumed that this is related to the relatively small angle of attack. Based on potential-methodologies, higher-order wake effects are not found to be significant. A dependency on both key design parameters, the height-to-span ratio and the longitudinal staggering, cannot be determined. With regards to the unstaggered system, Euler-based non-planar span efficiency factors (*STAR-CCM+)* are in reasonable agreement with potential-methodologies for small height-to-span ratios. Noticeable inconsistencies are encountered for larger vertical gaps. The source of this has not been verified yet, but is not supposed to be related to higher-order wake effects. An evaluation with respect to the wake substitution concept is employed to provide reasoning for this assumption. As the trailing edges are unswept, a partition surface may be introduced directly downstream of each trailing edge, replacing the force-free wake by a streamwise projection. Thereby any higher-order effect is removed as well. It can be shown that this procedure can be performed successfully with very minor impact (if at all) on the induced drag of the system [15]. Non-linear wing-wake interactions can hence be neglected. Moreover, as both lifting elements are not physically connected to each other and incorporate a relative large vertical separation it is hypothesized that a partition surface can be introduced for each lifting surface individually. Higher-order wake effects for any non-zero staggering are therefore also not likely to exist.

For the box wing configuration, non-planar span efficiency factors are depicted in figure 3 for different staggering factors. Euler-based estimates are provided for selected staggering factors. Referred to the unstaggered system (St=0.0), the result is equivalent to the biplane configuration. Good agreement is given among employed potential-methodologies. The incorrect body-fixed wake placement (*AVL, LiftingLine*) does not impact on the estimation; higher-order wake effects can be neglected. Euler-based estimates (*STAR-CCM+)* show acceptable consistency with potential-methodologies for low up to medium height-to-span ratios. Discrepancies in the range of 2-3% are encountered for larger vertical gaps similar to the biplane configuration. For any non-zero longitudinal staggering larger deviations are evident. Although potential-methodologies relying on the body- or freestream-fixed wake model (*AVL, LiftingLine, PanAir*) predict a similar characteristic development of the efficiency with varying height-to-span ratio, deviations between them are slightly more pronounced than for the unstaggered case. The non-planar span efficiency exhibits a distinct dependency on the height-to-span ratio in general, which is especially true for estimates based on the force-free wake model (*FreeWake*). Foremost in the range of low to medium height-to-span ratios (which are of most practical interest), a significant difference between estimates based on force-free and straight wake (either body or freestream-fixed) is evidently given. Considering a staggering factor of St=3.0, the largest relative deviation between body- or freestream-fixed wake model estimates (*AVL, LiftingLine, PanAir*) and the efficiency factor associated with the force-free wake approach (*FreeWake*) is found to constitute approximately 8%. Higher-order wake effects are assumed to cause this deviation in computed span efficiency. The extent of these non-linear wing-wake interactions is dependent on the height-to-span ratio and the staggering as well. The longitudinal separation does apparently promote this effect. With regards to Euler-based results (*STAR-CCM+*), reasonable agreement is given with force-free wake estimates (*FreeWake*). For small height-to-span ratios, efficiency factors predicted are diminished by about 2% compared to the force-free wake result, whereas for larger vertical gaps the trend is reversed. The impact of higher-order wake effects predicted by the force-free wake model is considered to be reasonably confirmed. However, results may have been distorted for larger height-to-span ratios similar to the unstaggered case.

Referred to the wake substitution concept an individual wake replacement in the vicinity downstream of the trailing edge is not feasible. Lifting surfaces are physically connected, postponing substitution to the most downstream extremity of the entire system. In contrast to the staggered biplane configuration, large portions of the force-free wake remain. Non-linear wing-wake interactions impacting on the span efficiency are likely to exist. This emphasizes the plausibility of the present result.

Variation of the Angle of Attack

The study is performed for a box wing configuration with a fixed geometric arrangement (h/b=0.20, St=3) at a freestream Mach number of $M_\infty=0.01$. The angle of attack is varied in one degree increments from $\alpha=1.0°$ to $\alpha=10.0°$. Computed non-planar span efficiency factors are depicted in figure 4 as a function of the angle of attack. Dependent on the employed methodology (wake model), essential differences arise in the estimation, especially for larger angles of attack. Predictions relying on the body-fixed wake model (*AVL, LiftingLine*) indicate an almost proportional correlation of the span efficiency and the angle of attack. Efficiency factors computed by means of the freestream-fixed wake model (*PanAir)* show an inverse dependency. Compared to the body-fixed wake model (*AVL, LiftingLine*), the span efficiency factor is generally lower. The maximum relative deviation amounts approximately 10%. Estimates based on the body-fixed wake model (*AVL, LiftingLine*) must be considered to be distorted by first-order

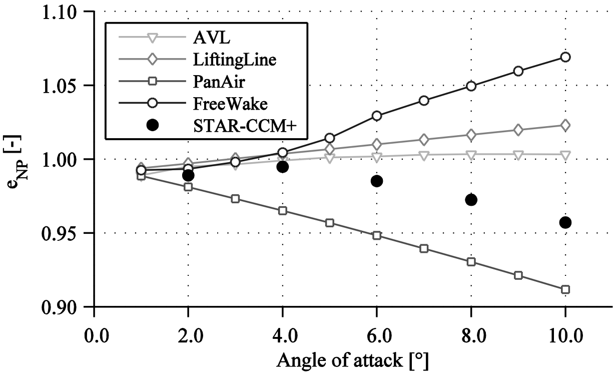

Figure 4. Non-planar span efficiency factor as a function of the angle of attack for the box wing configuration.

impact due to inappropriate wake placement. Besides the influence of erroneous farfield velocities, this wake positioning neglects the correlation of the height-to-span ratio and the angle of attack. For the present case of a positive staggering factor (rear wing above front wing) the effective height-to-span ratio theoretically diminishes, as the system is progressively inclined to the freestream velocity vector. As indicted by equation (2), the optimum span efficiency factor e_{OPT} is proportional to the height-to-span ratio [11]. The approximation is valid for a box wing configuration.

$$e_{OPT} \cong \frac{1 + 0.45\frac{h}{b}}{1.04 + 2.81\frac{h}{b}} \qquad (2)$$

Consequently, if the (effective) height-to-span ratio decreases, the span efficiency is meant to reduce as well. This cannot be resolved by *AVL* or *LiftingLine* based on the body-fixed wake model. In contrast to that, estimates predicted by *PanAir* can account for this effect due to the freestream-fixed placement. In the light of the implemented wake model this result is correct within linear flow-theory. Span efficiency predictions based on the force-free wake estimates (*FreeWake*) grow substantially with the angle of attack. Highest span efficiency is achieved at maximum angle of attack. The largest relative deviation towards the streamlined wake approach (*PanAir*) amounts 17%. Although non-linear wing-wake interactions are likely to gain impact as the angle of attack increases, predictions based on *FreeWake* are considered to be erroneous for larger angles of attack. The source of this error is currently investigated. However, reasonable consistency with Euler-based results (*STAR-CCM+)* is evident for lower angles of attack. Interestingly, the body-fixed estimates (*AVL, LiftingLine*) also match the Euler-based predictions with good accuracy for low angles of attack. Assuming that the distortion by farfield velocities on the Trefftz plane estimation is limited, this may be explained by analyzing the trajectories of the employed wake models. For small angles of attack and in the immediate vicinity downstream of the lifting element the force-free wake is closely aligned with the trailing edge bi-sector. In the present case, this coincidences well with the body-fixed wake. Although this placement neglects the correlation of the height-to-span ratio and the angle of attack, the flow conditions near the trailing edge are apparently modelled quite accurately in this particular case. Euler-based non-planar span efficiency factors differ considerably from the freestream-fixed values (*PanAir*) for any angle of attack. This provides indication for the existence of higher-order wake effects and partially confirms results for small angles of attack based on the force-free wake model (*FreeWake*). It is again emphasized, that the wake aligned with the freestream velocity vector is accurate within linear flow-theory. The maximum relative deviation towards the body- or freestream-fixed wake model constitutes about 3%-7%.

Conclusion

The impact of wake effects on an accurate induced drag prediction was investigated for two highly non-planar lifting systems. Dependent on the geometrical arrangement of the lifting system higher-order wake effects are found to considerably affect the estimation already at low angles of attack. Implications based on the wake substitution concept served as an argumentation baseline and emphasized the present result. First-order impact due to wake placement can be neglected. At larger angles of attack an accurate estimation is involved, wake model effects become significant. Force-free and drag-free wake model underestimate the induced drag; the streamlined wake model predictions are considered to be conservative. Euler-based results confirm the existence of higher-order wake effects for the entire angle of attack range. To enable accurate induced drag estimation at higher angles of attack an Euler-based approach is apparently required.

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