An improved method for transport aircraft for high lift aerodynamic prediction

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ABSTRACT

The aim of this work is the development of a methodology to predict lift characteristics for transport aircraft in the whole flight envelope, useful in the preliminary aircraft design stage. The purpose is an attempt to improve the classical methodologies for wing load distribution and lift prediction, considering the airfoils aerodynamic characteristics until stall and post stall conditions during the process, and modifying 2D characteristics in case of high lift devices to take into account 3D effects introduced by the devices themselves. The method is a modification of Nasa Blackwell procedure, capable to predict wing stall aerodynamic characteristics for both clean and flapped configuration. As far the high lift devices effect is concerned, the improved method works substituting clean airfoil aerodynamic characteristics with the flapped aerodynamics ones, and introducing a correction to evaluate the 3D effects induced by high lift devices geometrical discontinuities. The results of the developed method have been compared with CFD and experimental data showing good agreement, making available a fast and reliable method, useful in preliminary aircraft design.

KEYWORDS: *Aircraft design, high lift aerodynamic, transport aircraft, span lift coefficient distribution,* extended lifting-line theory*.*

NOMENCLATURE

α – Angle of attack
α_{0L} – Zero lift angle of attack
AR – Aspect ratio
b – Span
C_l – Local 2D lift coefficient
C_L – 3D lift coefficient
$C_{L,max}$ – Maximum lift coefficient
C_{L0} – Lift coefficient at zero angle of attack
c_k – Kink chord
c_r – Root chord
c_t – Tip chord
Λ_{LE} – Sweep at leading edge
η – Non-dimensional station along semi-span
η_{in} – Flap/Slat inner station
η_{out} – Flap/Slat outer station
h – Altitude
M – Mach number
MAC – Mean aerodynamic chord
Re – Reynolds number
S – Surface
Y – Dimensional station along semi-span

1 METHOD

1.1 Basic concepts

In the conceptual design stage, high lift characteristics are estimated using simple semi-empirical approaches such as those suggested in classical aircraft design handbook of Roskam, Torembeek, Nicolai and Sforza [1] to [4]. These methodologies start from the knowledge of the airfoil aerodynamic characteristics and then they simply estimate wing lift curve through charts based on wing geometrical parameters.
Other methods are based on the lifting line theory [5] [6] and they estimate the wing lift curve by integration of the wing span loading. To obtain the span loading, the generic lifting surface is represented by a system of vortex that defines a velocity field [7].
The lifting line theory had substantial success in predicting lift and drag of conventional wings. However, it cannot properly handle swept wings, so several methods have been developed to deal with swept wing such as Weissinger [8][9] or Nasa Blackwell [10]. According to these methods, the wing is divided into straight elements, each one modelled by a horseshoe vortex with control points located at the three-quarter-chord line and the bound vortex located at the one-quarter-chord line. Considering the influence factors of these "master points" on the "control points", these methods can consider different real wing geometries. Vortex methods are usually coupled with stall path calculations to appreciate the maximum lift coefficient [11] to [14]. This approach leads to quite accurate results, but it does not consider for the airfoil and wing characteristics close to stall and post stall conditions.
Furthermore, although these methods are usually fast and quite accurate for a wing in clean configuration, they are not applicable with high lift devices. On the other hand, CDF analyses lead to more accurate results, with an increased computational time. Moreover, wing with high lift devices aerodynamic characteristics are usually computed, during the preliminary design through semi-empirical methodologies [1][2][3], based on spread sheets and charts. These semi-empirical methods allow to calculate some increments due to high lift devices, which must be applied on the clean lift curve. Obtained results are very preliminary, and they only lead to a rough estimation of high lift device effects, based on few geometrical parameters of these devices (span, chord extension). Moreover, these methodologies are not able to evaluate the aerodynamic effect produced by a designed high lift design system, also simply considering the two-dimensional effects of a properly high lift system. As a matter of fact, nowadays, the preliminary design of a such system, involves a lot of two-dimensional aerodynamic analyses and optimization based on CFD calculations, which can be very useful to reliably estimate the 3D aerodynamic characteristics.
The present work introduces a simple procedure, completely embedded into an executable software, that allows to calculate aerodynamic coefficients on a wing with or without high lift devices deflected.
In recent years, the Design of Aircraft and Flight technologies (DAF[1]) research group of the University of Naples has growth knowledge and experience in developing, testing and validating several approaches and methodologies concerning aircraft design field. In particular, an improved approach with regard to the vertical tail plane design and sizing was accomplished by means of CFD calculations [18][19]. This methodology was also applied to size the vertical tail plane of a new twin-engine commuter aircraft [21], then was validated through wind tunnel tests [21], and made available into the AGILE consortium during the DC-1. Another methodology, regarding the design of the fuselage and the prediction of its aerodynamic characteristics, was developed through CFD-RANS calculations performed on several fuselage geometries suited for regional transport aircraft [22]. All these methodologies were collected into a Java-based framework for aircraft preliminary design and optimization[13][14][15], and they are available and used in the distributed MDO system formulated during the DC-1[24].

1.2 Modified stall path

This method modifies the load distribution obtained using the Nasa Blackwell method, which is reliable in the linear range of lift curve.
The proposed method follows these logical steps (see Fig. 1). First, the wing semispan is divided into n control/vortex points (usually 50). Each of these n points will correspond to an intermediate airfoil with its own lift characteristic.

[1] www.daf.unina.it

1. For each angle of attack the lift distribution using the classical Nasa Blackwell method is evaluated. This allows to obtain the C_l inviscid distribution.
2. For each of n points along the semispan the local value of Cl is obtained starting from the known distribution.
3. With this local value of C_l, it is possible to enter in the 2D linear lift coefficient chart obtaining the local angle of attack of the airfoil.
4. Using this angle of attack, it is possible to enter in the real lift curve of the airfoil obtaining the local C_l which takes into account viscous effects.
5. In this way a new lift distribution along the semispan, which considers the two-dimensional non-linearity, is obtained.
6. This new lift coefficient distribution causes a new distribution of induced angle of attack which produces, in turn, a new Cl distribution. So, an iterative process from step 4 to 6 is necessary.
7. The wing C_L is obtained integrating the final lift distribution.

Stall condition is achieved in the process in correspondence of the reduction of lift coefficient distribution integration. A flow chart of this method is proposed in Fig. 1

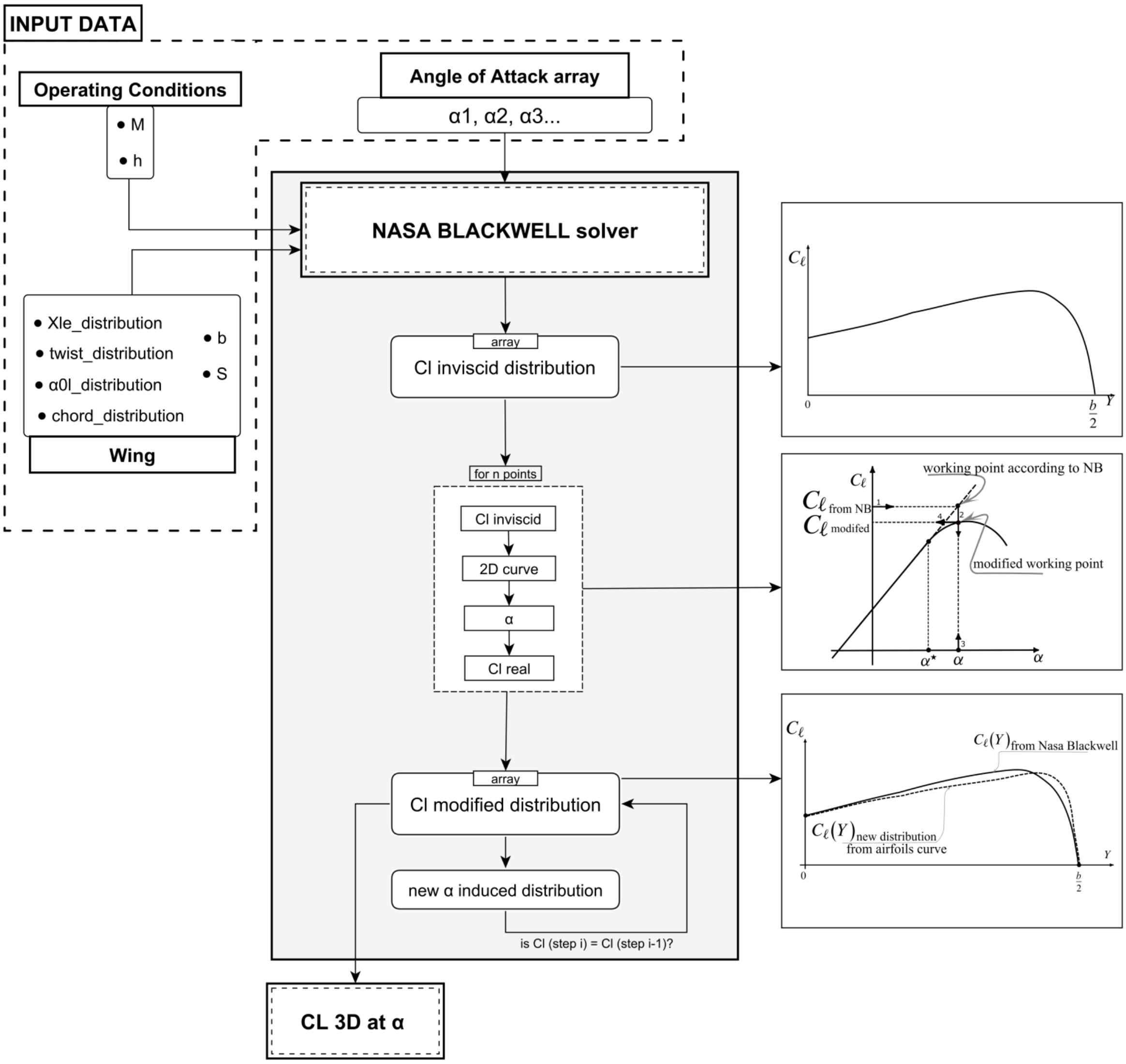


Figure 1: Improved method flow chart.

1.3 Modified Stall path with high lift devices

To predict the aerodynamic characteristics of the wing with the high lift devices, some useful semi-empirical methods are available in the literature [1] [2] [3]. The guideline that is followed is to analyze separately the trailing-edge and the leading-edge devices effects, evaluating the changes in aerodynamic characteristics of airfoils to extend these to entire wing. These semi-empirical methods allow to calculate some increments due to high lift devices, which must be applied on clean lift results. The improved method, introduced in this work, aims to enhance classical vortex methods (using, in particular, the Nasa-Blackwell one), to consider the two following aspects:

- Lifting surfaces equipped with high lift devices (flaps and slats)
- Non-linear trait of lift curve

Following, there will be underlined how these two facts are processed in the improved method.

Presence of high lift devices

To consider the presence of high lift devices, the method works substituting the clean airfoil aerodynamic characteristics with the flapped ones, obtaining a new wing planform and applying the Nasa Blackwell method to this new lifting surface. In particular the substituted parameters are the following:

- Chord distribution
- α_{0l} distribution
- X_{LE} distribution

To obtain these new distributions, chords increases are evaluated by semi empirical methods, as well as the new leading-edge distribution, while as far α_{0l} is concerned, the method needs input values which can be obtained from previous high fidelity 2D analyses (e.g. CFD).
It is important to highlight that the planform used to make the lift coefficient non-dimensional, is the real surface and not the modified one.

Non-linear trait of lift coefficient curve

Vortex methods are usually coupled with stall path calculations to appreciate the maximum lift coefficient. Inspired by this approach, the method presented in this paper, works modifying the 2D distribution of $C_{l,MAX}$ considering that the presence of high lift devices modifies also the aerodynamic characteristics of sections close to these devices as shown in Fig. 3. Ascertain that, it has been necessary to modify the 2D $C_{l,MAX}$ distribution (i.e. airfoils $C_{l,MAX}$ distribution).
To achieve the new $C_{l,MAX}$ distribution, the $\Delta C_{l,MAX}$ function has been evaluated know the wing planform using the following process

1. For each angle of attack of an array of α_W, two Cl distribution are evaluated: the clean one with the classical Nasa Blackwell method, and the modified one with the presence of high lift devices, using the method presented before
2. For each station along the semispan, the function ΔC_l is evaluated between these two distributions
3. For each station, the effective angle of attack is calculated thanks to the evaluation of the distribution of the induced angle of attack
4. Corresponding to α_{stall} of each station, it now possible to know the related α_W and it is possible to calculate the $\Delta C_{l,MAX}$

In this way, it is possible to obtain for each station j, the new $C_{l,MAX}$ with high lift devices effects with the formula proposed in Eq. (1).

$$C_{l_{\max,hl}}\Big|_j = C_{l_{\max,clean}}\Big|_j + \Delta C_l\left(\eta, \alpha_W(\alpha_s|_j)\right) \tag{1}$$

This new distribution of the maximum lift coefficient for each station, is the reference for the modified stall path method for a lifting surface with high lift devices. A flow chart of this method is proposed in Fig. 2.

The importance of the development of this method is related to a concrete contribution that DAF group has to provide within AGILE European project [23] under request made by DLR as project leader.
In particular, each one of the 19 AGILE partners can provide several services which cover one or more aircraft design fields and UniNa has been chosen as low speed aerodynamics specialist to provide tools able to evaluate low speed aircraft performance. Thanks to the development of this method will be possible to give the required contribution to the AGILE consortium during the third year of the project

(Design Campaign 3) providing a tool characterized by a level of fidelity higher than methods based on semi-empirical formulas and so improving the set of methodologies on which the Multidisciplinary Design Optimization (MDO) chain will be based [24]. The improve methodology and calculations will be stored in an executable file which will be integrated in the MDO chain through RCE software[25] to contribute to the design of some innovative aircraft configurations.

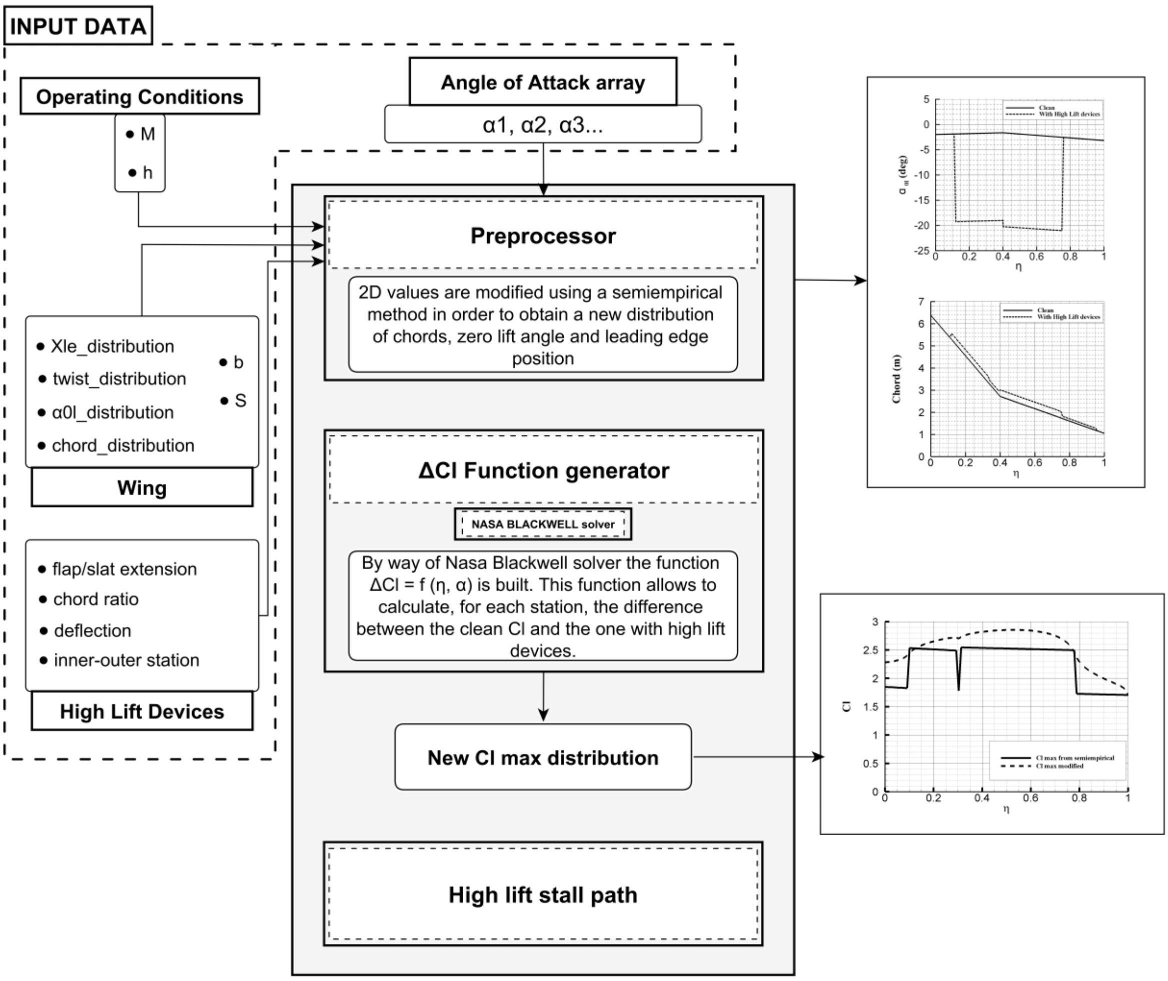


Figure 2: Method for C_{Lmax} evaluation for a wing with high lift devices. Flow chart.

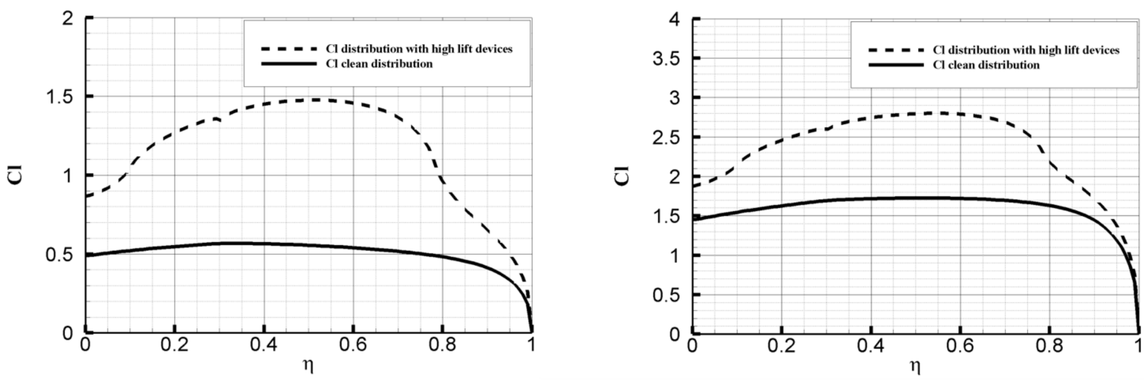
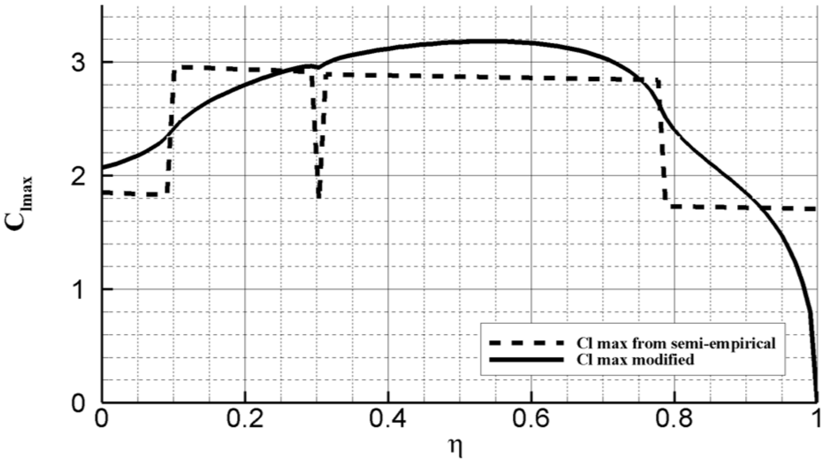


Figure 3: Cl distribution comparison with (performed by the improved method) and without high lift devices (performed by Nasa- Blackwell method) for a wing with S=105 m^2, AR=12, and with two fowler flaps deflected of 15°. α = 2° left, α = 14° right.



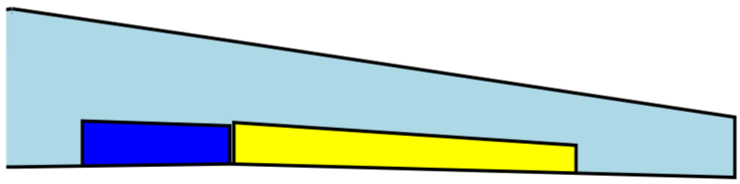


Figure 4: Cl_{max} distribution comparison from semiempirical method and from improved one for a wing with S=105 m^2, AR=12, and with two fowler flaps deflected of 15°.

2 APPLICATIONS

To validate the method, several analyses have been performed. The results have been compared with experimental data of a swept wing studied by Koven and Graham [16] and get again by [2], whose main data are summarized in Table 1 and in Table 2.

2.1 Clean configuration

As far the clean configuration is concerned, as mentioned before, Weissinger or Nasa Blackwell methods are usually coupled with stall path calculations to appreciate the maximum lift coefficient. Results of these two methods are shown in Fig. 5 and they have been obtained using two tools for aircraft preliminary design: ADAS [15] which implements Weissinger, considering only the linear trait, and the java library JPAD [12] to use the Nasa Blackwell method coupled with stall path.

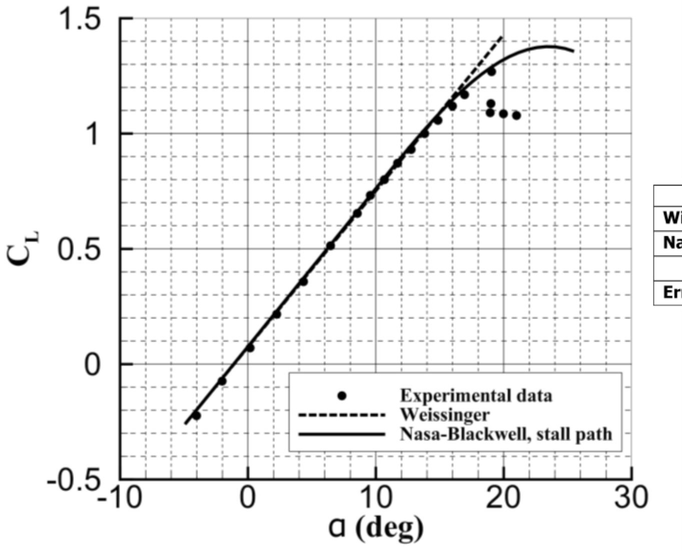
Table 1: Main analysis data

Operating Conditions	Value
Re	6800000
M	0.13

Table 2: Main wing data

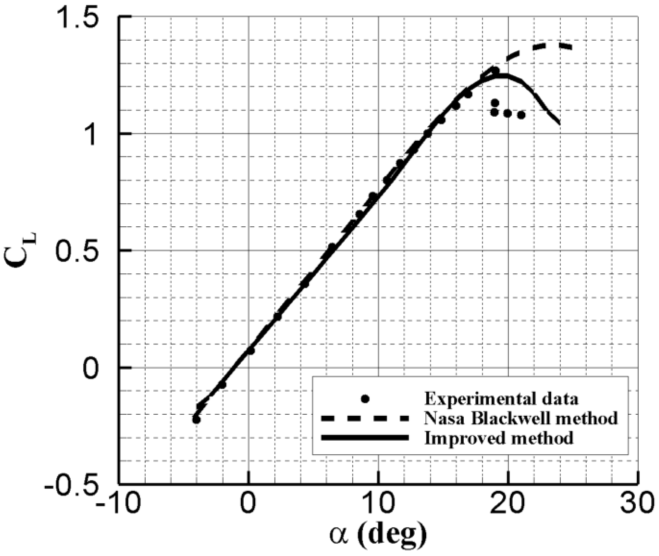
Wing Data	Value
C_r	1.42 m
C_t	0.71 m
Λ_{LE}	37.2°
S	6.83 m^2
b	6.40 m

As it is possible to see in Fig. 5, these approaches lead to quite accurate results but they do not consider, for the airfoil and wing, characteristics close to stall and post stall conditions.



	α_{stall} (deg)	C_{Lmax}
Wind tunnel	19.05°	1.27
Nasa Blackwell	23.33°	1.38
Err (%)	18.34%	8.66%

Figure 5: Lift coefficient curve evaluation with classical methods, comparison. Error in high lift values.



	α_{stall} (deg)	C_{Lmax}
Wind tunnel	19.05°	1.27
Improved method	20°	1.25
Err (%)	4.98%	1.57%

Figure 6: Lift coefficient curve evaluation, comparison between classical Nasa Blackwell method and improved one. Error in high lift values.

To apply the improved method, whole airfoils lift characteristics need to be used as input data. These characteristics can be assumed from airfoil databases (wind tunnel tests, Handbook, etc.) or from high fidelity numerical analyses (CFD). In the present application, the airfoil aerodynamic characteristics come from CFD Navier-Stokes aerodynamic analyses. The proposed method allows to achieve high accuracy in a short computational time. In fact, as shown in Fig. 6, the percentage error is less than 5% both for α_{stall} and for C_{Lmax}.

2.2 Wing with high lift devices

The second test cases concerns the configuration with high lift devices (as shown in Figure 7), whose data are summarized in Table 3. The proposed improved method works modifying the 2D input values useful in the calculation of lift coefficient distribution (Fig. 8).

Table 3: Main high lift data

High lift device data	Value
Type	Double slotted
Flap Chord ratio	0.25
Flap deflection	48.85°
Inner station	0.018
Outer station	0.5

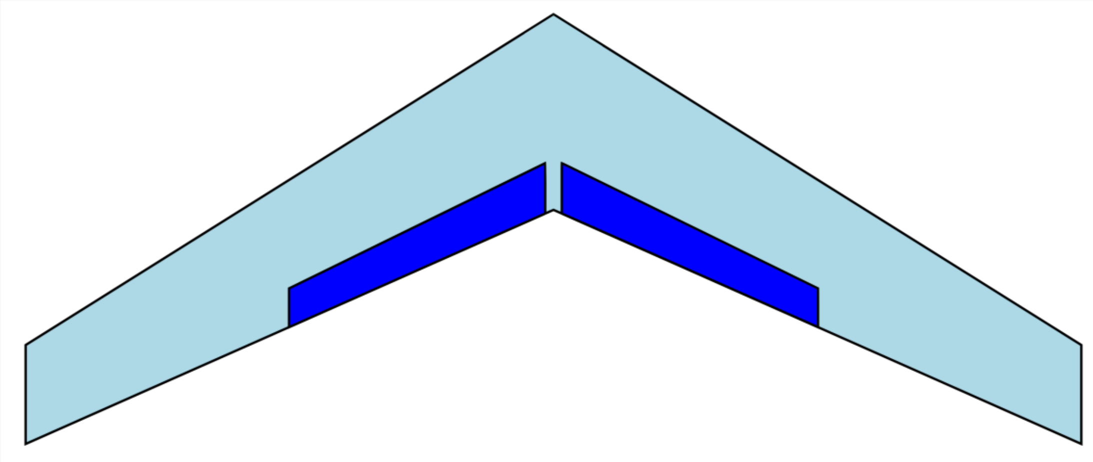


Figure 7: Wing planform modelling with high lift devices.

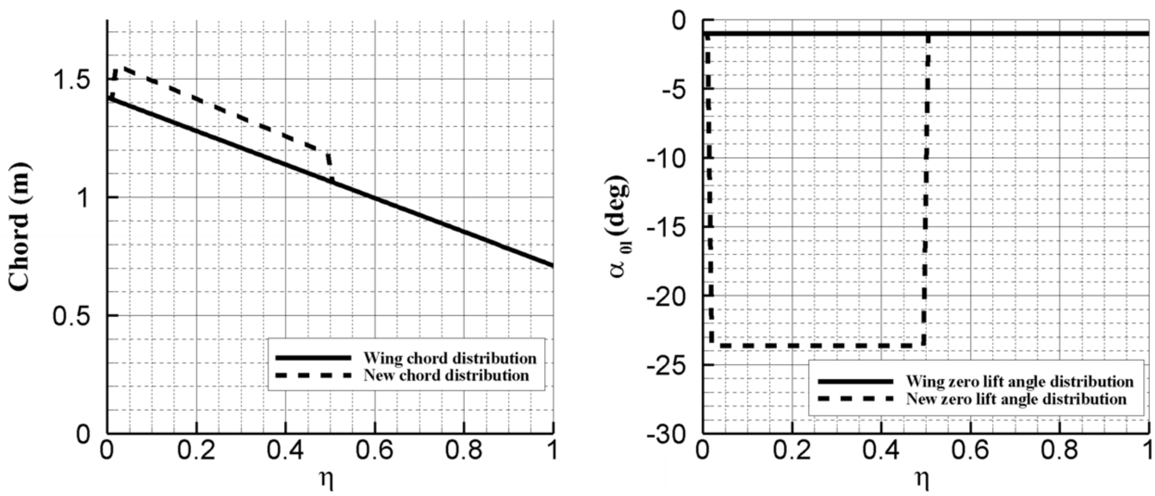


Figure 8 : Wing input data modification.

Starting from these new input data it is possible to evaluate the lift coefficient distribution with high lift devices effects (Fig. 9). The method calculates the function that allows to define the new $C_{l,max}$ distribution with high lift devices, which differs from the semi-empirical one especially in the zones without devices close to the flap (Fig. 10). Using this new $C_{l,max}$ distribution it is possible to perform the stall path method even for the wing with high lift devices (Fig. 11 and Fig. 12).

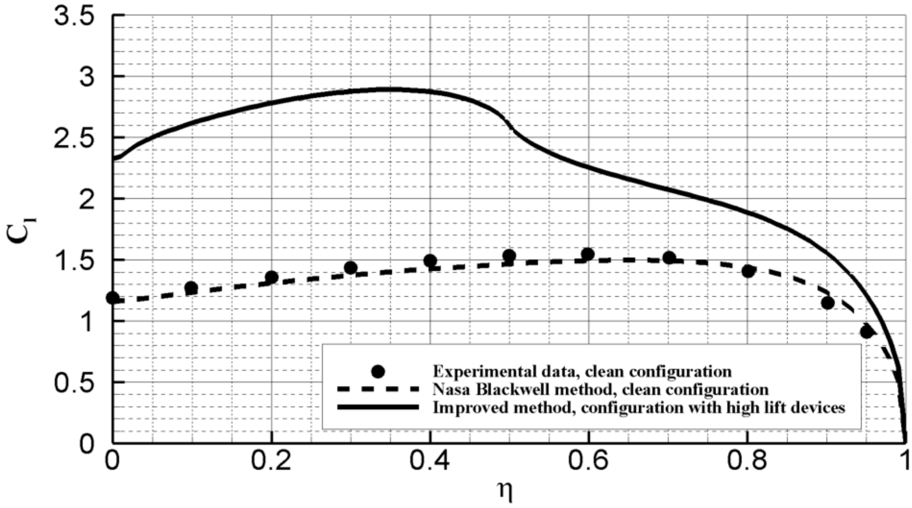


Figure 9: Inviscid lift coefficient distribution at α = 18.7°, comparison.

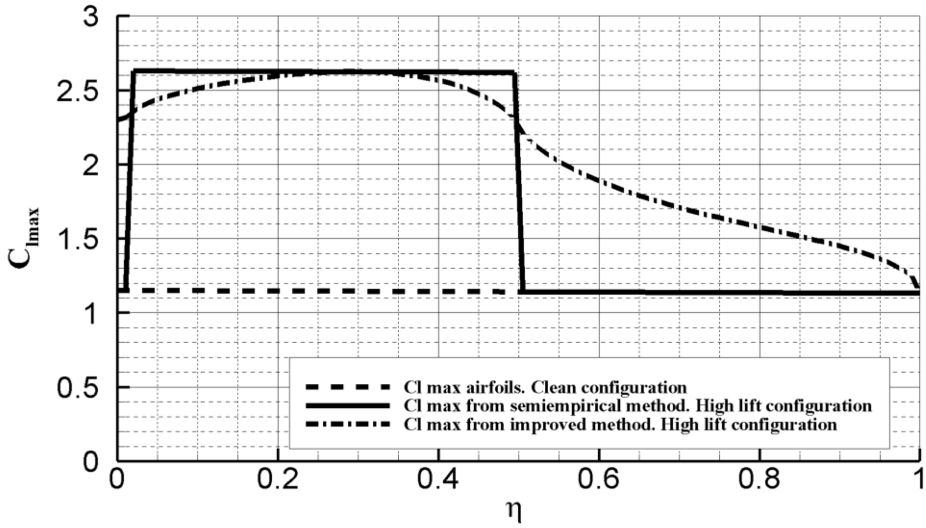


Figure 10: C_{lmax} airfoils distribution. Methods comparison.

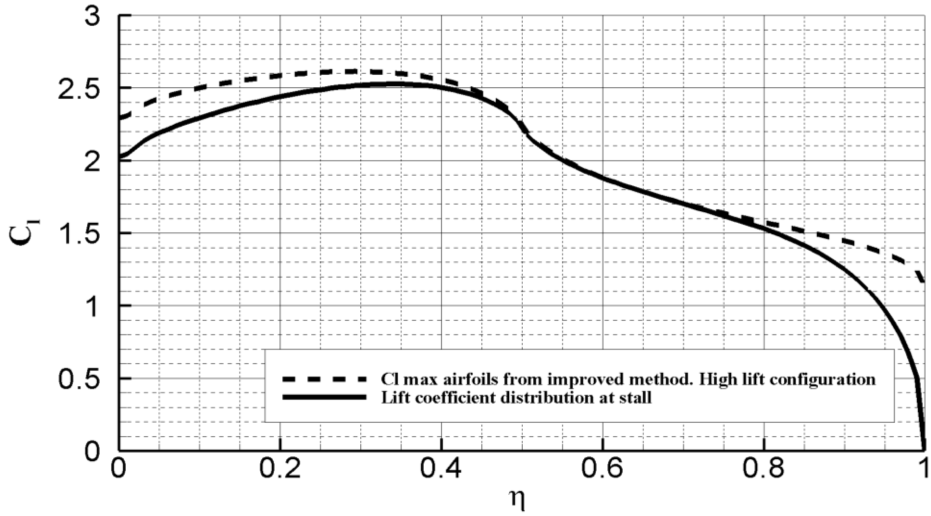
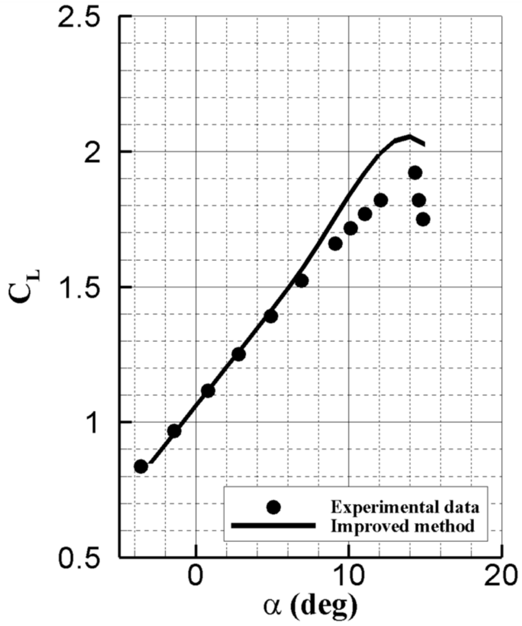


Figure 11 : Improved method, stall path with high lift devices.

Concerning the lift coefficient distribution and the stall zone, further analyses have been performed to develop and validate the method. In Fig. 13 and in Fig. 14 it is possible to note that the improved method allows to define the right stall zone along the semispan. The CFD and analytical analyses have been performed on a wing whose main data are described in the figure caption. As it is possible to see in the figures below, the stall zone is the same both with the improved method and with CFD analysis.



	α_{stall} (deg)	C_{Lmax}
Wind tunnel	14.3°	1.92
Improved method	14.05°	2.05
Err (%)	1.75%	6.7%

Figure 12: Wing lift coefficient, methods comparison.

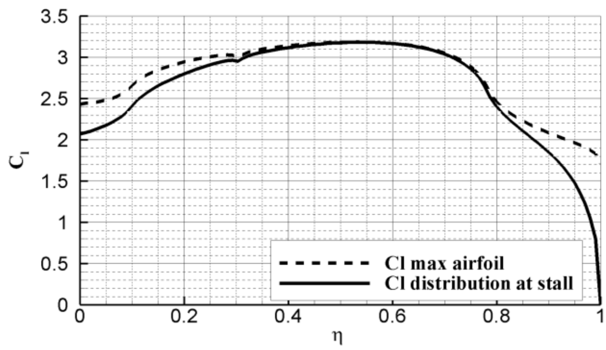


Figure 13: C_l distribution calculated with improved method for a wing with S=105 m2, AR=12, and with two fowler flaps deflected of 15°.

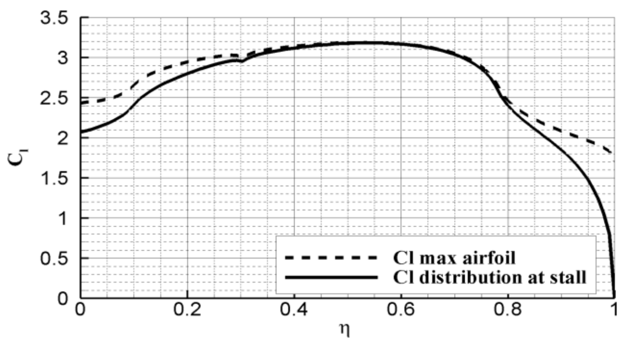


Figure 14: Cl distribution calculated with CFD for a wing with S=105 m2, AR=12, and with two fowler flaps deflected of 15°.

CONCLUSIONS

In this paper, an improved method to estimate the lift curve and the lift distribution has been presented. The method allows to obtain reliable analyses (error is lower than 7%), fast (less than 5 seconds for a complete analysis) and easy to use. However, it needs of reliable 2D curves obtained with high fidelity methods. The method structure and the results obtained from a case study has been showed in order to verify the code effectiveness to perform aerodynamic analyses. UniNa DAF research group is currently working on further improvement on the method, especially on $C_{l,max}$ distribution along semispan evaluation. In particular, authors are studying how obtain the 3D lift curve for a wing with high lift devices through 2D curves with an iterative process that allow to modify an inviscid vortex-lattex method.

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