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Contents

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List of Symbols

C_L	lift coefficient
M	Mach number
c	local chord
d	defect
I	cost functional
η	non-dimensional spanwise length
$\bar{H}$	shape factor of the boundary layer
N	non-linear operator
$\mathbf{x}$	vector representing wing geometry
$\mathbf{p}$	vector representing pressure distribution
$\mathbf{e}$	error
ν	iteration counter
p	pressure
p_t	target pressure
B_W	wing surface

INVERSE AERODYNAMIC SHAPE DESIGN FOR IMPROVED WING BUFFET-ONSET PERFORMANCE

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ABSTRACT

The paper describes the re-design of a wing/fuselage aircraft configuration in transonic flow with the objective to improve the buffet onset boundary in terms of lift coefficient C_L at a cruise Mach number of 0.8. This re-design is done by prescribing a pressure distribution on the wing surface that implies a higher C_L at the buffet-onset boundary. The inverse problem refers to the computation of a wing shape that produces the prescribed pressure distribution. A defect correction approach is applied for solving the re-design problem, where an inverse design methodology for isolated wings in inviscid flow is combined with viscous flow analysis code for wing/body configurations. The defect correction makes use of the design code SYN87 for isolated wings in inviscid flow and the analysis code MATRICS-V for wing/fuselage configuration in viscous flow. Computational results are shown for improvement of the buffet-onset performance of a wing/fuselage configuration at the design Mach number of 0.8.

KEYWORDS

Inverse method, aerodynamic design, shape optimization, buffet-onset, viscous-inviscid interaction, optimal control

INTRODUCTION

Transonic buffet is an unsteady flow phenomenon that occurs when transonic shock waves induce a certain type of flow separation. Figure 1 gives an illustration of buffet flow around a circular-arc wing section as computed by the NLR's ENFLOW CFD system [4]. Each picture represents instantaneous Mach contours. The upper left picture shows an incipient flow separation induced by the shock wave near the trailing edge on the lower surface. As this lower surface flow separation gets larger as indicated in the upper right picture, the lift on the airfoil changes with the effect of moving the shock wave upstream and reducing the shock strength. This reduction in turn allows the flow to re-attach as shown in the lower left picture. Finally, as the lower surface flow attaches, the shock wave starts to form

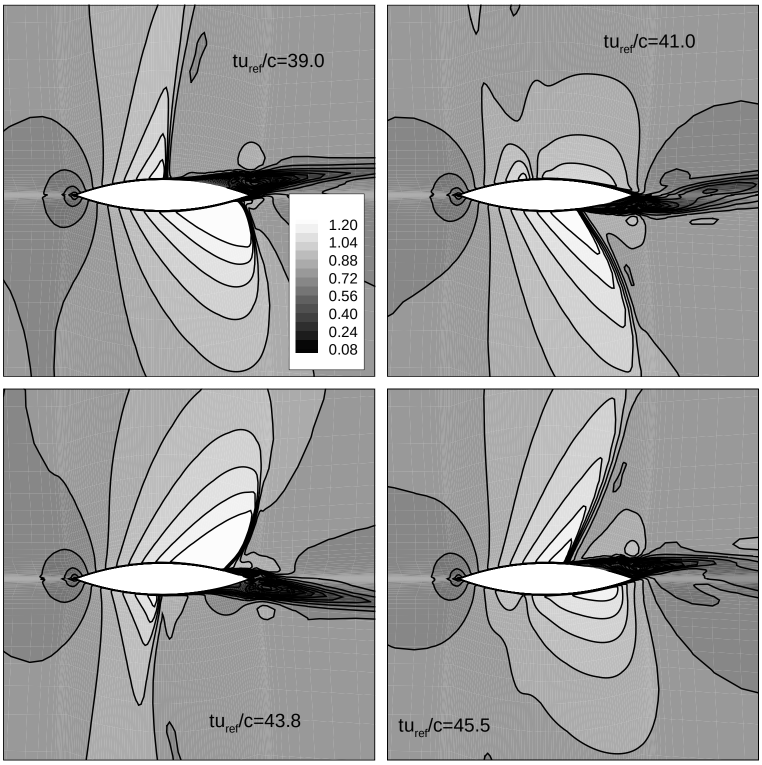


Figure 1: Buffet flow around a circular-arc wing section computed by ENFLOW (Ref. [4]).

again at the trailing edge with increasing strength until it induces another flow separation. The process repeats itself forming a self-sustained oscillation. The same flow mechanism occurs at the upper surface with a phase shift of 180 degrees.

The oscillatory aerodynamic loads and structural deformations associated with buffeting flow lead to a so-called buffet-onset boundary, defined by a curve on the C_L-M plane, where C_L and M are the lift coefficient and Mach number, respectively. Below this curve, the aircraft operational conditions are considered to be free from buffet. The certification requirement states that $C_{L,buffet} \geq 1.3 C_{L,cruise}$.

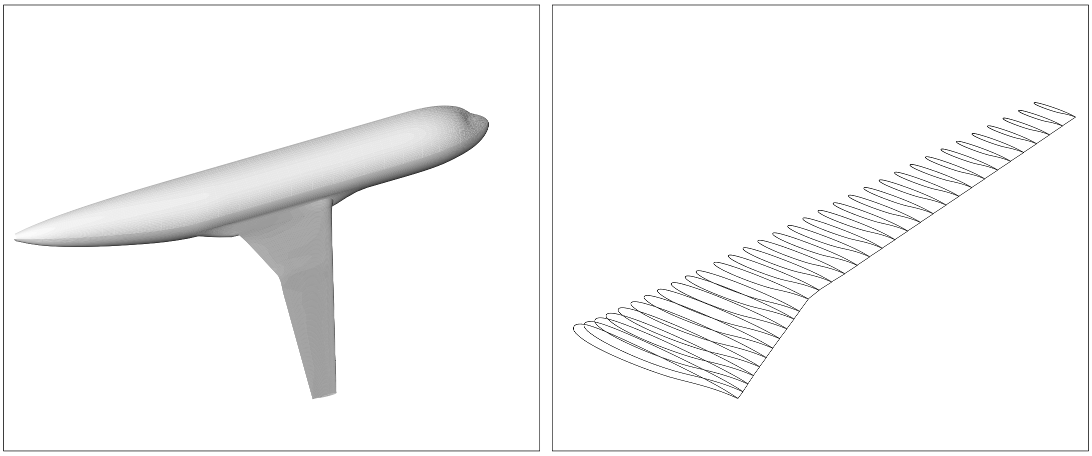
The present re-design concerns the improvement of the buffet-onset performance in terms of C_L at the design Mach number. This re-design is done by prescribing a pressure distribution on the wing surface that implies a higher C_L at the buffet-onset boundary. The inverse problem to be described refers to the computation of a wing shape that produces the prescribed pressure distribution.

The flow associated with the buffet-onset boundary is dominated by turbulence and strongly unsteady. To deal with such a flow directly in a design procedure would entail the use of a flow analysis tool based on the time-accurate Reynolds-averaged Navier-Stokes equations, that is capable of resolving the unsteadiness. Such a direct approach for designing three-dimensional bodies such as wings is unnecessary. In the present study, the inverse problem will be solved using defect correction which is a well-known approach in numerical analysis. This approach is based on the code SYN87 (Refs. [3],[5]) for isolated wing design in inviscid flow, in combination with the code MATRICS-V (Ref. [6]) for the analysis of a wing/fuselage configuration in viscous flow.

This paper is organized as follows. First, the design problem will be described, comprising the definition of the existing geometry and the flow conditions, and the flow analysis for the existing geometry. This analysis is followed by a description of the design algorithm with explanation on the defect correction approach. Subsequently, computational results are demonstrated and conclusions are drawn in the last section.

BUFFET BOUNDARY ANALYSIS OF EXISTING CONFIGURATION

Figure 2 shows the existing wing/fuselage configuration and the wing sections. This configuration represents a typical civil transport aircraft with transonic cruise speed. The design point Mach number has been specified as $M = 0.8$. The Reynolds number of 3.0×10^6 typical for wind tunnel measurement is used for the viscous flow computations, with the laminar to turbulent boundary layer transition specified at 30% and 7% of local chord on the lower and upper surface of the wing, respectively.



(a) Half wing/fuselage configuration. (b) Wing sections along the span.

Figure 2: Existing wing/fuselage configuration.

The existing wing/fuselage configuration is analyzed with respect to its aerodynamic characteristics using MATRICS-V, which is a computational aerodynamics code for drag prediction to support the design of jet transport aircraft. MATRICS-V is based on full-potential flow in quasi-simultaneous interaction with boundary-layers on the wing. Flows with considerable separation can be modeled by MATRICS-V. This feature allows one to compute the off-design aerodynamic boundaries, such as the buffet-onset boundary.

The buffet-onset boundary is determined based on the boundary layer parameter indicating shock-induced flow separation and the extent of the flow separation along the wing span that normally leads to buffet. Figure 3 shows the distribution of the boundary layer shape factor $\bar{H}$, (denoted as Hbar in the figure), for different values of C_L at the design Mach number $M = 0.80$, where η and x/c are the non-dimensionalized length on the wing in the spanwise and chordwise directions, respectively. The criteria for buffet-onset is that the maximum value of $\bar{H}$ indicating shock-induced flow separation is larger than or equal to 3.3, and that this flow separation occurs over more than 25% of the wing span. In Figure 3 on the left, $\bar{H}$ reaches a maximum value of $\bar{H}_{max}$ at around $x/c = 0.5$ corresponding to a location near the shock wave. On the right, the figure shows the spanwise distribution of $\bar{H}_{max}$. In order to determine the buffet-onset boundary, the curves are interpolated for the C_L value that corresponds to $\bar{H}_{max} \geq 3.3$ covering 0.25 of η. This interpolation gives $C_L \approx 0.56$ at the buffet onset boundary. The objective in the present study is to re-design the wing shape by means of an inverse design methodology such that the C_L value at the buffet-onset boundary is increased, while keeping the planform fixed.

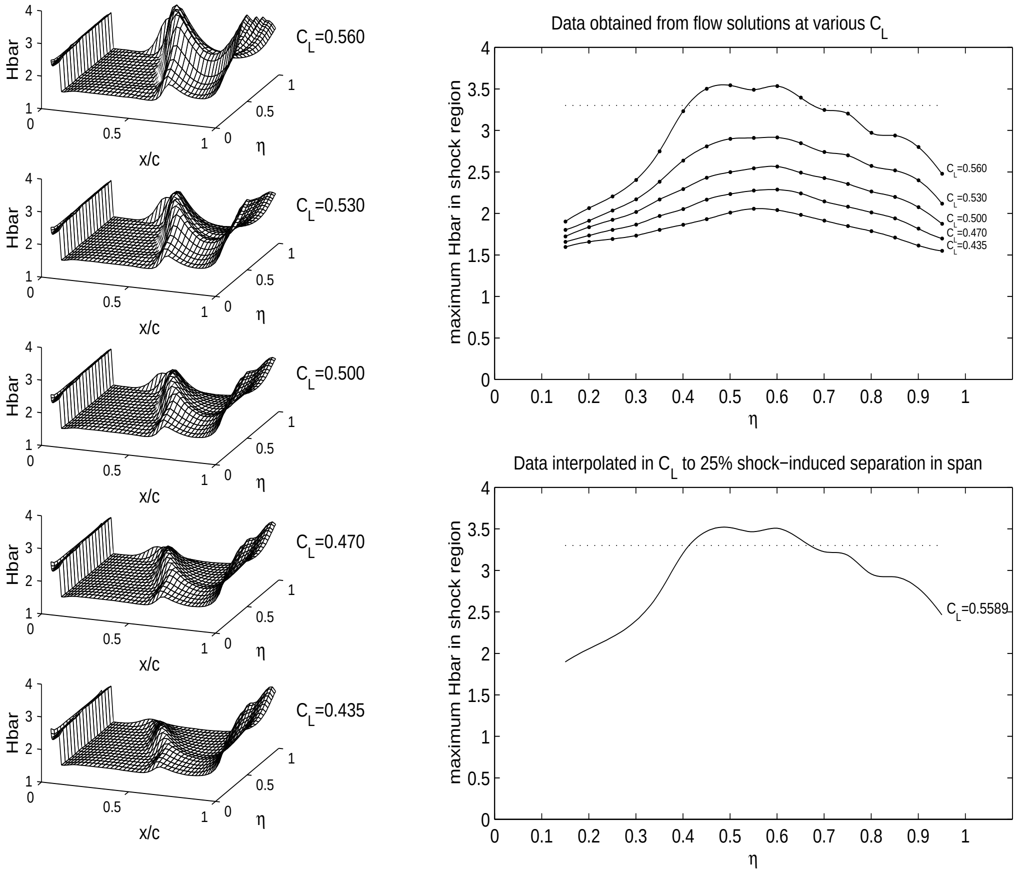


Figure 3: Buffet-onset boundary of the existing wing/fuselage configuration.

DEFECT CORRECTION APPROACH

In order to explain the defect correction approach (Refs. [2], [1]), the following system can be considered:

$$\mathbf{p} = N\mathbf{x}, \tag{1}$$

where N is a non-linear operator applied to a control variable $\mathbf{x}$ resulting in a state variable $\mathbf{p}$. In the case of a flow analysis such as that described in the preceeding section, N, $\mathbf{x}$ and $\mathbf{p}$ can be considered as representing the code MATRICS-V for the analysis of wing/fuselage configuration, the wing geometry and the pressure distribution, respectively, with $\mathbf{x}$ specified. Re-designing the wing geometry by prescribing a target pressure distribution can thus be interpreted as solving the system (1) for $\mathbf{x} = \mathbf{x}^*$ with a given $\mathbf{p} = \mathbf{p}_t$:

$$\mathbf{x}^* = N^{-1}\mathbf{p}_t. \tag{2}$$

For a current approximation $\mathbf{x}^\nu$ of $\mathbf{x}^*$, the defect can be defined as:

$$d(\mathbf{x}^\nu) = N\mathbf{x}^\nu - \mathbf{p}_t. \tag{3}$$

The error of $\mathbf{x}^\nu$ with respect to $\mathbf{x}^*$ is written as:

$$\mathbf{e}^\nu = \mathbf{x}^\nu - \mathbf{x}^*, \tag{4}$$

which can be expressed as:

$$\mathbf{e}^\nu = N^{-1}(\mathbf{p}_t + d(\mathbf{x}^\nu)) - N^{-1}\mathbf{p}_t = N^{-1}d(\mathbf{x}^\nu). \tag{5}$$

In the defect correction approach, the error $\mathbf{e}^\nu$ is estimated by $\tilde{\mathbf{e}}^\nu$ by means of an approximate inverse operator $\widetilde{N}^{-1}$:

$$\tilde{\mathbf{e}}^\nu = \widetilde{N}^{-1}d(\mathbf{x}^\nu). \tag{6}$$

In view of equation (3), the above equation can be worked out to yield:

$$\tilde{\mathbf{e}}^\nu = \widetilde{N}^{-1}N\mathbf{x}^\nu - \widetilde{N}^{-1}\mathbf{p}_t. \tag{7}$$

A new iterate is determined as follows:

$$\mathbf{x}^{\nu+1} = \mathbf{x}^\nu - \tilde{\mathbf{e}}^\nu. \tag{8}$$

The new geometry can be substituted into equation (7), forming an iterative procedure until convergence is achieved.

In the present study, however, instead of following the iterative procedure, a one-step approach has been chosen, involving only one N and two $\widetilde{N}^{-1}$ operations, and one geometry update. In this one-step approach, $\mathbf{p}_t$ in the right hand side of equation (7) is replaced by its approximation $\widetilde{\mathbf{p}_t}$, and equation (7) is written as:

$$\tilde{\mathbf{e}}^o = \widetilde{N}^{-1}N\mathbf{x}^o - \widetilde{N}^{-1}\widetilde{\mathbf{p}_t}, \tag{9}$$

where $\mathbf{x}^o$ represents the existing wing geometry.

In the present study, the approximate inverse operator $\widetilde{N}^{-1}$ is represented by the code SYN87 for geometry design of wing-alone configuration in inviscid flow modeled by the Euler equations. In dealing with the geometry design, the minimization of the following cost functional is considered:

$$I = \frac{1}{2}\int_{B_W}(p - p_t)^2 dS \tag{10}$$

where p_t is the target pressure, p is the pressure of the current geometry, and B_W refers to the wing surface. The iterative solution method for the minimization of the functional is based on optimal control theory using the wing geometry as the control. In each iteration a variation of the wing shape is considered. These variations will cause variations of the actual pressure and consequently variations in the cost functional (10). Each iteration requires the solution of an adjoint problem for the co-state variable which is defined using the flow solution for the current geometry.

The pressure distributions coefficient C_p on the wing sections of the wing-alone configuration in inviscid flow (representing a result of $\widetilde{N}\mathbf{x}^o$) is depicted in Figure 4 at the design Mach number and at a lift coefficient of 0.56 slightly above the buffet-onset lift coefficient. These inviscid flow wing-alone pressure distributions can be compared with the results of MATRICS-V for the wing/fuselage configuration in viscous flow ($N\mathbf{x}^o$) shown in Figure 5. A comparison suggests that the effect of the wing/fuselage interference as well as the effect of the boundary layer is large. In spite of this large effect, it will be shown that use of the approximate inverse operator $\widetilde{N}^{-1}$ in the defect correction approach can lead to improvement of the existing wing.

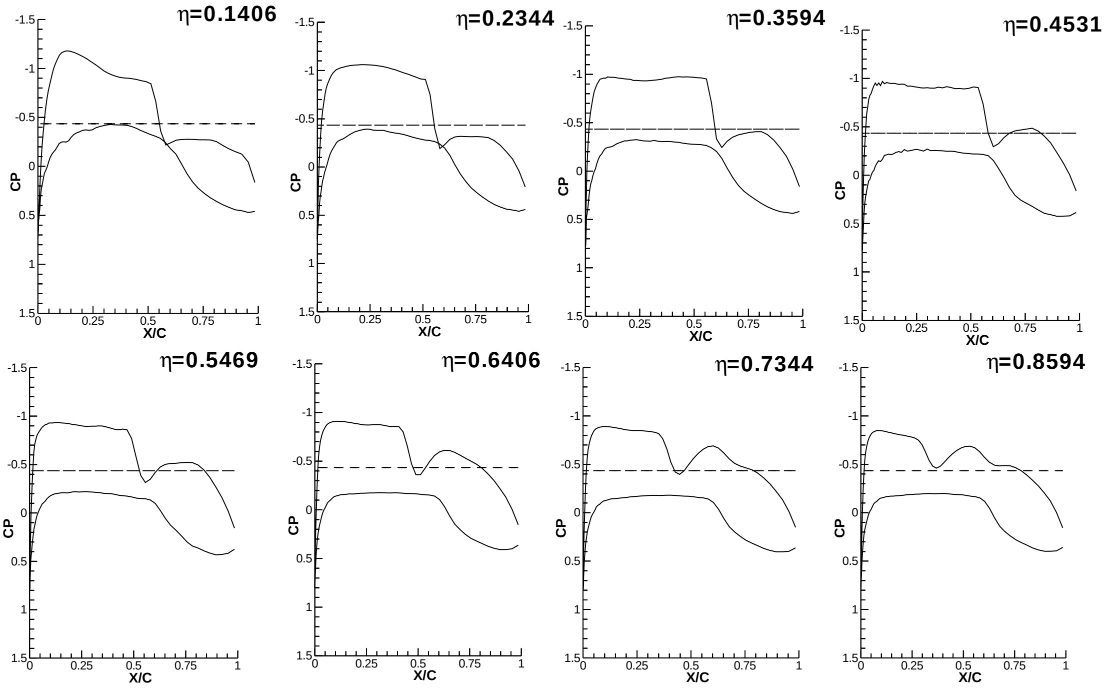


Figure 4: C_p distribution on the isolated wing in the inviscid flow at $M = 0.8$ and $C_L = 0.56$ (*dashed line indicates the* $M = 1$ *level in* C_p).

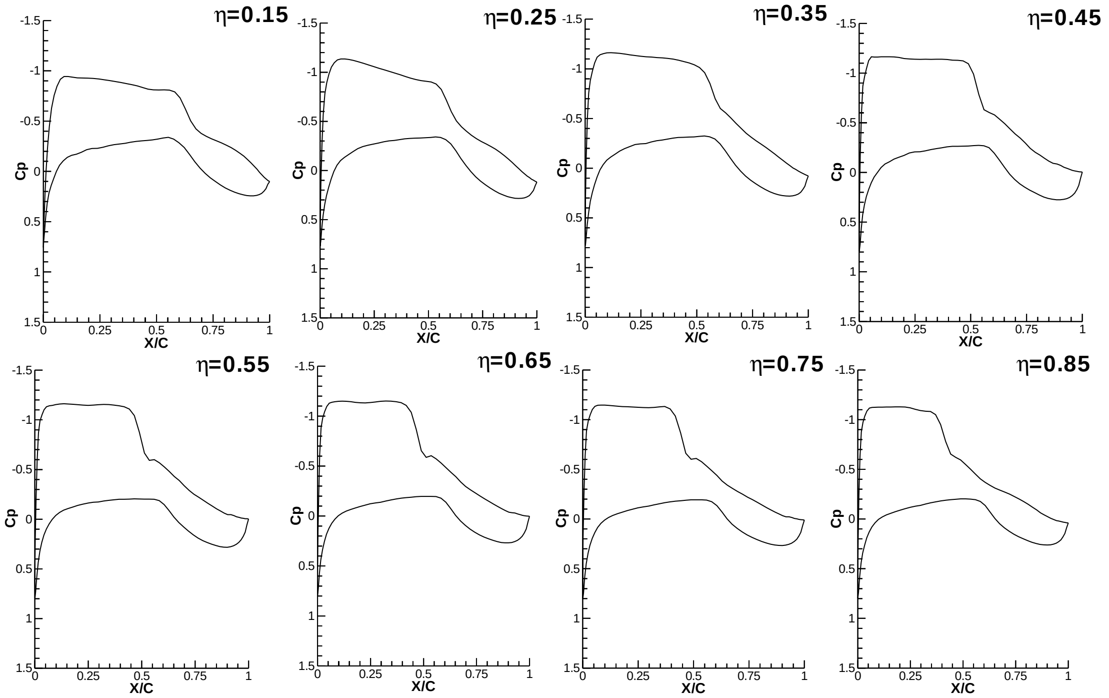


Figure 5: C_p distribution on the wing of the wing/fuselage configuration in the viscous flow at $M = 0.8$ and $C_L = 0.5655$.

The first term in the right hand side of equation (9) represents a geometry design using SYN87, with the target pressure distribution obtained from the viscous analysis of the current wing/fuselage configuration using MATRICS-V. The resulting wing-alone geometry,

$$\widetilde{\mathbf{x}}^o = \widetilde{N}^{-1}N\mathbf{x}^o,$$

can be considered as a baseline geometry simulating the viscous effect and fuselage effect.

A flow analysis for the geometry $\widetilde{\mathbf{x}}^o$ in inviscid flow gives an inviscid pressure distribution $\widetilde{\mathbf{p}}$. In order to determine $\widetilde{\mathbf{p}_t}$, $\widetilde{\mathbf{p}}$ is modified such that improvement with regard to buffet-onset performance is implied. After $\widetilde{\mathbf{p}_t}$ is specified, another geometry design using SYN87 (the second term in the RHS of equation (9)) is required in order to obtain $\widetilde{\mathbf{e}}^o$. The redesigned geometry is finally obtained from

$$\mathbf{x}^r = \mathbf{x}^o - \widetilde{\mathbf{e}}^o, \tag{11}$$

which can be analyzed using MATRICS-V with respect to improvement of the buffet-onset boundary in terms of C_L.

COMPUTATIONAL RESULTS

In order to be able to simulate viscous effects with reasonable success, i.e. to perform $\widetilde{N}^{-1}N\mathbf{x}^o$ in equation (9), the flow about the wing should be fully attached over the whole surface. Therefore, at the design Mach number $M = 0.8$, the highest lift coefficient for which the flow meets this requirement has been determined and is found to be $C_L = 0.52$. The corresponding pressure distribution is referred to as the current pressure distribution.

The resulting baseline geometry ($\widetilde{\mathbf{x}}^o$) produces an inviscid pressure distribution ($\widetilde{\mathbf{p}}$), shown in Figure 6 along with the current (viscous) pressure distribution. The deviation around the shock wave can be attributed to the fact that the inviscid flow model produces sharp (discontinous) shock waves and therefore cannot match the pressure of the shock wave boundary layer interaction with the lower gradient. This local mismatch is compensated by deviations at other locations in order to achieve the same C_L. Regardless of the discrepancies, the pressure distributions shown represent a minimum deviation, where the obtained baseline wing geometry can be considered as simulating both the viscous displacement effect and the fuselage effect.

The inviscid pressure distribution is modified as follows: (i) the chordwise distribution is altered such that the local lift coefficients are increased, (ii) the pressure jump at the shock wave is decreased so as to get a weaker shock wave, and (iii) a less adverse pressure gradient is applied aft of the shock wave. The modification is performed bearing in mind that it should eliminate the shock-induced flow separation without implying a flow separation in the trailing edge region. This modification leads to a pressure distribution representing $\widetilde{\mathbf{p}_t}$ in equation (9).

The geometry design for $\widetilde{\mathbf{p}_t}$ leads to the redesigned wing ($\mathbf{x}^r$), which is analysed for $M = 0.8$ and $C_L = 0.52$ with the fuselage present. It has been observed that the value of $\bar{H}_{max}$ is significantly reduced except in the region near the trailing edge. It is noted that in the geometry design algorithm the trailing edge is not allowed to move and, in order to avoid "fish-tail" geometries, a rather severe constraint is applied to the geometry close to the trailing edge. As a consequence, the wing geometry in the trailing edge region can hardly change during the inverse design process. The situation is dealt with by a careful manual modification of the trailing edge region of the redesigned wing, while preserving the improvement that has been achieved in other areas of the wing, such as in

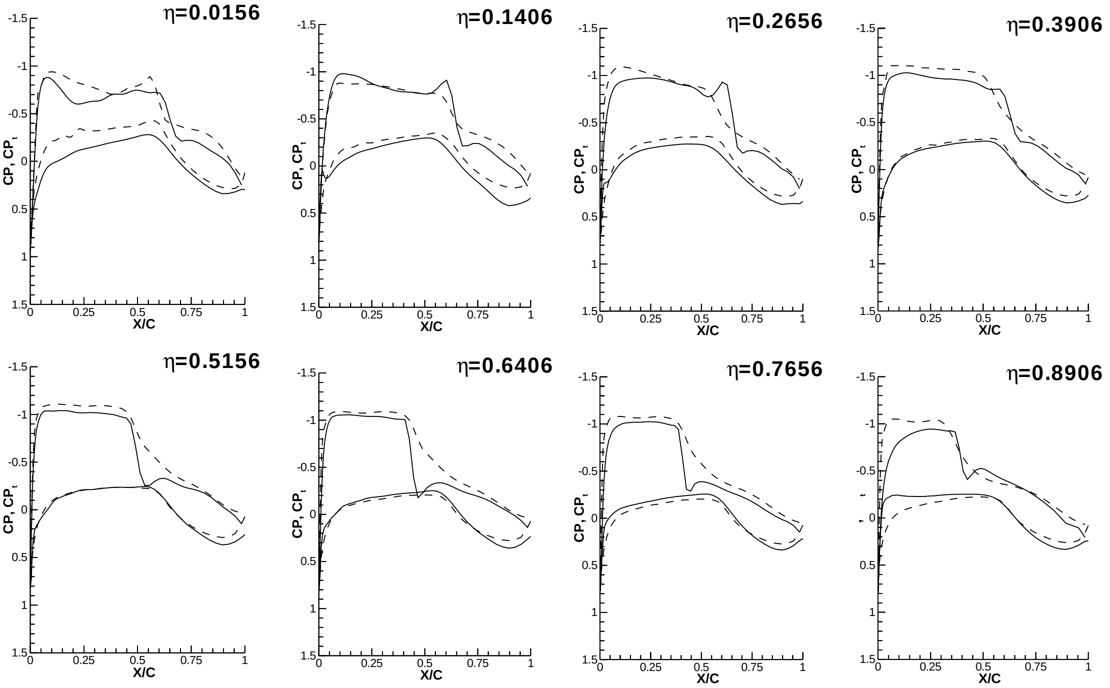


Figure 6: C_p distribution of the inviscid flow at $M = 0.8$ and $C_L = 0.52$ simulating the C_p distribution of the viscous flow around the wing/fuselage configuration (*solid line= inviscid; dashed line= viscous/target*).

the region near the shock wave. After this modification, the chordwise distributions of $\bar{H}$ of the redesigned and existing wings are shown in Figure 7, where improvement in terms of $\bar{H}_{max}$ is demonstrated. Figure 8 gives a comparison between the pressure distributions, which indicates reduction in the shock wave strength. Figure 9 shows the geometries of the wing sections. As an improvement in terms of $\bar{H}_{max}$ has been achieved by the redesigned wing for $C_L = 0.52$, it has to be verified whether this implies a higher C_L at the buffet onset boundary. The buffet onset boundary is searched for by performing MATRICS-V computations sequentially in a way similar to that leading to Figure 3. The buffet-onset boundary was found to be corresponding to $C_L \approx 0.62$. Compared with $C_L \approx 0.56$ of the existing wing, the redesigned wing represents about 10% improvement of the buffet onset performance for the wing/fuselage configuration.

CONCLUSION

A redesign procedure has been formulated for improvement of the buffet-onset boundary of a wing/fuselage aircraft configuration. The procedure is based on a standard defect correction approach, formulated in terms of the wing pressure distributions. It has been found that design aimed at increasing C_L at the buffet-onset boundary can be done effectively using the flow condition with a lower value of C_L at which the flow separation has not yet occurred. It is concluded that the present defect correction approach opens the possibility of using a low fidelity tool for geometry corrections, in combination with a high fidelity tool for flow analysis, for solving inverse design problems of complex configurations. In this respect, research in the future can be carried out to investigate the applicability of the approach for more complex configurations such as those incorporating engine nacelles.

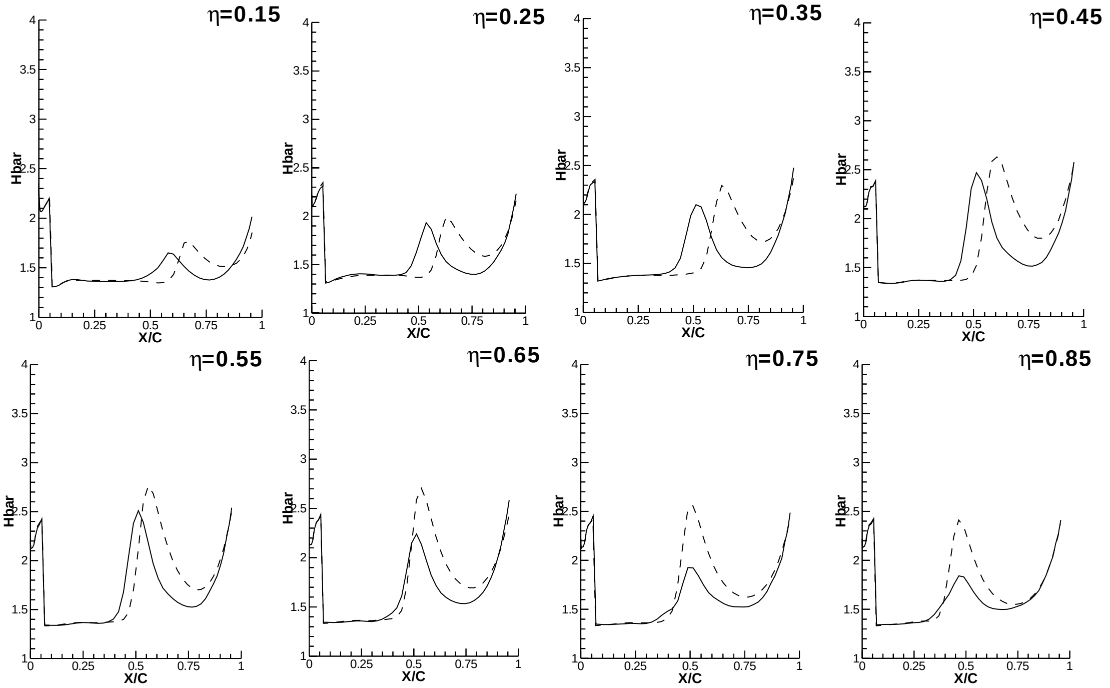


Figure 7: $\bar{H}$ distributions on the existing and redesigned wings of the wing/fuselage configuration for $C_L = 0.52$ (*solid line= redesigned; dashed line= existing*).

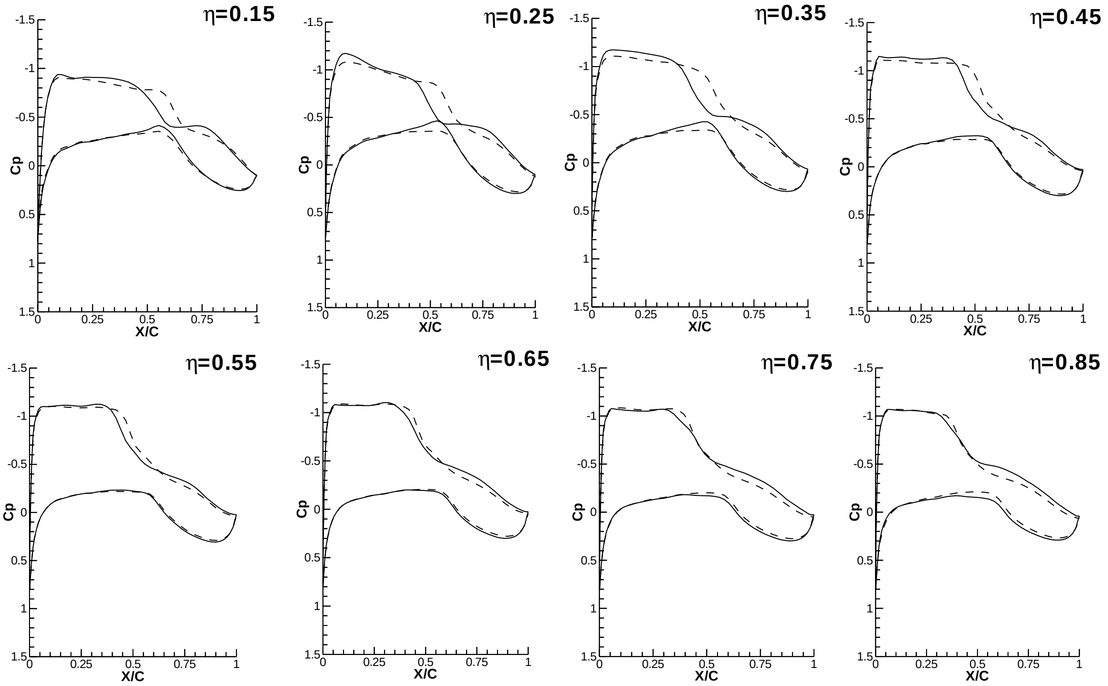


Figure 8: C_p distributions on the existing and redesigned wings of the wing/fuselage configuration for $C_L = 0.52$ (*solid line= redesigned; dashed line= existing*).

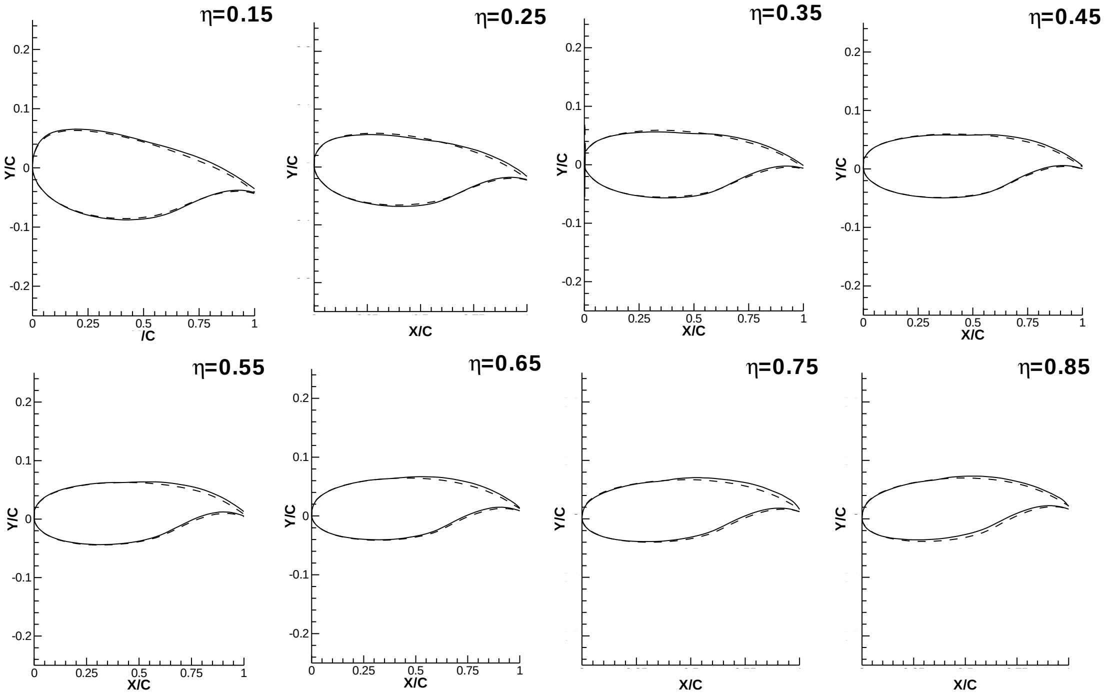


Figure 9: Geometries of the existing and redesigned wings (*solid line= redesigned; dashed line= existing*).

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