

# Adaptive transonic wings – a new challenge in designing and testing

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## Abstract

Proposed are new approaches to the design and testing of adaptive transonic wings for civil aircraft. Due to the extraordinary sensitivity of the adaptive wings to the flight mode, testing them at low Reynolds numbers, typical for non-cryogenic wind tunnels, can lead to incorrect conclusions both with respect to the optimal geometry of the base wing and to the choice of optimal settings of the adaptive elements. The application of cryogenic wind tunnels solves this problem, but multiparameter testing of numerous adaptation options requires huge time and finance consumption.

This paper proposes a new test method for determining the optimal configuration of an adaptive trailing edge, which can be used in conventional wind tunnels. The cornerstone of the new methodology is the concept of “equivalent” wings, which, by definition, in a wind tunnel have a pressure distribution identical to that of a real wing under flight conditions. Thus for defining “equivalent” wing geometry, the use of inverse method is necessary. It is shown that the simplest “brute force” optimization procedure is very rational for solving this inverse task, since physical considerations suggest that the geometry of the real and equivalent wings has noticeable differences only near the trailing edge due to different displacement thicknesses of the boundary layer under wind tunnel and flight conditions. Therefore only two geometry variations per each wing section are sufficient for correct formulation of optimization problem.

A design of a large half model is proposed to test the applicability of the “equivalent” wing concept for both fundamental problems of correct tunnel-to-flight extrapolation and definition of the optimal settings of adaptive elements.

## 1. Introduction

One of the promising modern directions in the field of civil aircraft aerodynamics assumes an introduction of the so-called adaptive wings. Adaptive wings can minimize aerodynamic drag by alternating their geometry depending on the flight condition thus achieving peak performance without too steep shortfalls at off-design regimes. In addition wing adaptation may give an extension of the flight envelope without buffeting thus providing better operational flexibility of an aircraft.

Despite a fairly long history of attempts to introduce “variable wing camber” concept on civil transports [1-4], only recently Boeing and Airbus implemented rather simple adaptive drooped hinge flap systems which combine both cruise adaptive functions with common high-lift generating properties on their wide-bodies B787 [5] and A350 [6].

But even in such a simplified case several new challenges arise in designing and testing of adaptive transonic wings. At designing an additional freedom in geometry variation results in a challenge of choosing flight envelope points (M, Cl) and their ranking (weights). Optimal trailing edge deflections are not known a priori and in fact depend on the chosen final wing geometry (and geometric-kinematic realization of camber variation, of course), i.e. successive optimal design procedure is necessary for an adaptive wing geometry determination and trailing edge deflections refinement.

Another challenge concerns the procedure of optimal flap deflections determination. Modern supercritical wings are very sensitive to the Reynolds number effect at cruise but adaptive wings are even more sensitive at peak performance. Owing to this high sensitivity the geometries of optimal wings at subscale and full-scale conditions do not coincide and optimal settings of adaptive flaps do not coincide as well.

Finally, local geometry features may also affect the results, that is large scale semispan models are preferable for the flaps deflection optimization task. Strictly speaking even this procedure does not guarantee an optimal choice of an airplane adaptive geometry but the possibility of doing that in the real flight is at least disputable.

This article discusses both of the aforementioned aspects of designing and testing adaptive wings, but with a large bias towards the second aspect.

Successive optimal design procedure is proposed for adaptive wing geometry determination. It is concluded that this procedure converges to optimal solution.

Earlier proposed by the authors was a concept of “equivalent” wing for simulating flight flow conditions in a wind tunnel at much less Reynolds number [7]. The geometry of the “equivalent” wing differs from the basic one near the trailing edge only, thereby modeling the effect of different boundary layer displacement thicknesses at flight and wind tunnel conditions.

Here the concept of “equivalent” wing is suggested also for the problem of optimal adaptive flap settings selection. Calculations show that optimal flap deflections are identical for the basic wing at flight conditions and for the “equivalent” wing at wind tunnel conditions. Special research half-model with detachable wing rear parts is constructed to investigate the applicability of the “equivalent” wing concept for both problems.

## 2. Description of the adaptive technologies demonstrator model

The following requirements were imposed on the model-demonstrator of the adaptive technologies:

- aerodynamic behavior should be similar to the real transonic wing;
- model should provide the maximum possible range of Reynolds number during wind tunnel tests;
- absolute thickness of the wing sections should allow the use of removable tail parts;
- deformations of the model when tested with different dynamic pressures should not lead to significant manifestations of aero elastic pseudo-effects.

The above requirements are met by a semispan model with small aspect ratio and low sweep (Figure 1). The leading edge sweep angle is chosen equal to  $\chi = 20^\circ$ , taper ratio equals  $\eta = 2.5$ , half-span equals 2 meters. In order to reduce the cost of the model the fuselage was taken directly from the half-model of MC-21-200, previously tested in the same wind tunnel T-128. The mean aerodynamic chord (MAC) of the model equals 0.743 m, which makes it possible to vary Reynolds number from  $Re \approx 3$  mln at underpressure in the wind tunnel contour to  $Re \approx 21$  mln (de facto flight  $Re$  number for narrow bodies) during pressurization up to 2 atmospheres. With such a difference in dynamic pressure the washouts of the wing will not differ more than  $\Delta\phi = 0.11^\circ$  at the tip; thus, if necessary, small corrections to the aerodynamic characteristics can be introduced.



Figure 1: The adaptive technologies demonstrator semispan model (on the left) and the MC-21-200 half-model (on the right)

Three removable tail parts along span are assumed on the wing, starting at 65% of the chord on the upper surface and at 75% of the chord on the lower surface. Different tail parts can correspond to both an adaptive trailing edge of the real wing and the trailing edge of an “equivalent” wing, reflecting different boundary layer thicknesses at flight and wind tunnel conditions.

The aerodynamic surface of the half-wing was designed using our routine multi-criterion optimization procedure [8] at nine different flow regimes in the vicinity of the basic point  $M = 0.8$ ,  $Cl = 0.45$  at  $Re = 21$  million. To estimate aerodynamic characteristics the domestic code BLWF-56 was used. It is based upon iterative quasi-simultaneous strong viscous-inviscid interaction of external potential flow and a boundary layer on lifting surfaces. The solution of transonic flow over an entire airplane is provided within half a minute on modern PC. Thanks to small CPU time requirement and also to the built-in automatic procedure of grid generation not demanding direct intervention of the user the BLWF code is widely used in TsAGI and other world aviation centers for designing efficient aerodynamic configuration of commercial transports.

The calculated drag polars of the configuration at maximal Reynolds number  $Re = 21$  mln are shown in Figure 2.

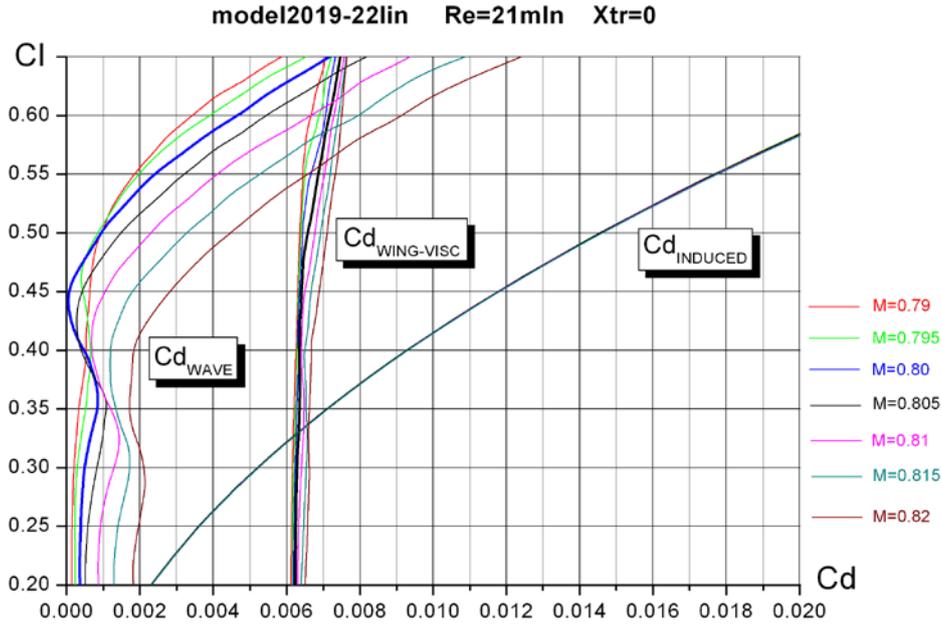


Figure 2: Calculated drag polars of basic configuration at  $Re = 21$  mln

It can be seen that practically shockless regime is realized at  $M = 0.8$ ,  $Cl \approx 0.445$ . The pressure distribution over the wing at this mode is shown in Figure 3. A very weak shock wave is observed only near the section  $\bar{Y} = 0.85$ . At the same time, there is a considerable wave drag both at large  $Cl$ 's and at smaller ones, in the latter case it is caused by a double shock wave due to the excessive camber of the wing profiles. Such nonlinear behavior of the wave drag polar often appears when design Mach number is chosen higher than usual [9]. As will be shown in the next section wave drag at small  $Cl$ 's can be significantly reduced by decambering of the trailing edge. In addition, camber reduction allows significant shift of the high-speed drag rise boundary.

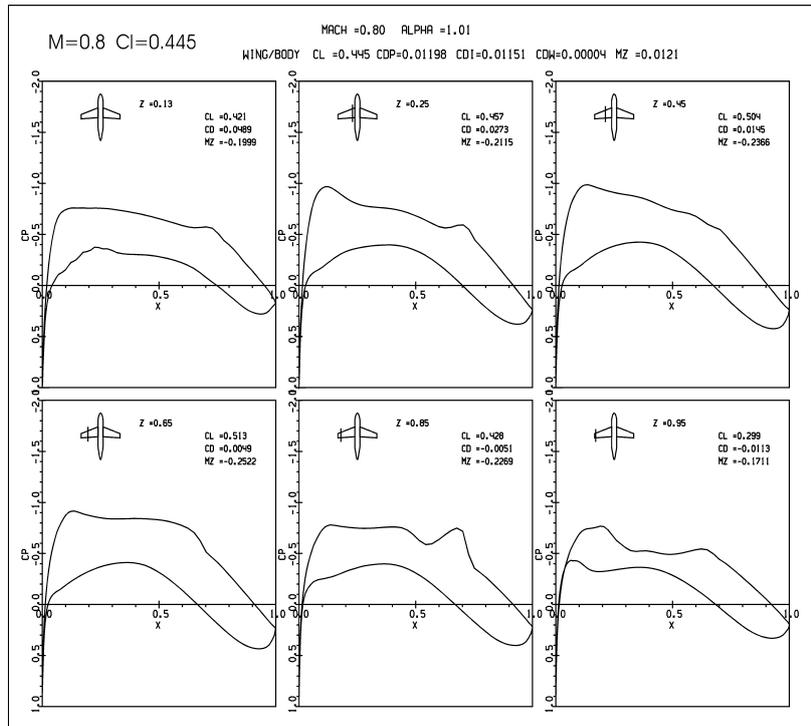


Figure 3: Calculated wing pressure distributions at  $M = 0.8$ ,  $Cl = 0.445$ ,  $Re = 21$  mln

In principle, the base wing has to be designed with regard to subsequent deflections of the adaptive flaps. Here, the same successive optimal design procedure can be used as in [10], although they considered subsonic laminar two-dimensional airfoil with a smooth bend of the tail. Optimal tail deflections for different flight modes are defined for the base profile, then their values are smoothed to eliminate “noisy” behavior (see [3]), after that “frozen” and the new optimization is performed with fixed flap settings. For the new obtained airfoil, the optimum flap angles are determined again etc., up to convergence. Certainly, final wing geometry depends on the selected flight envelope points ( $M$ ,  $Cl$ ) and their ranking, as well as on the chosen geometric-kinematic realization of camber variation. Especially important issue is attributed to the flap hinge line position relative to supersonic region location. One of the dangers that await the designer is the re-expansion at the hinge line caused by surface discontinuities. To avoid this in [1, 2], for example, a special aerodynamic design technique for an adaptive wing with a choice of basic airfoil geometry designed for moderate  $Cl$  was proposed.

In this article, the sequential optimization of the base wing was not applied. This is due to the fact that the model assumes the utilization of various adaptation options for the trailing edge. However, in contrast to [1, 2], the base wing was tuned to increased  $Cl$ 's, since the flap upward deflection is in our opinion less dangerous as regard to the development of shock waves and flow separation.

Drag polars at wind tunnel Reynolds number  $Re = 5.25$  million with fixed transition are shown in Figure 4. It can be seen that induced drag does not change, whereas profile drag increases according to well-known empirical relationships. At the same time considerable differences exist in the wave drag polars as compared with those in Figure 2. For example, wave drag increases from 9 counts to 18 counts at ( $M = 0.8$ ,  $Cl = 0.5$ )-regime, on the contrary wave drag decreases from 9 counts to 5 counts at ( $M = 0.8$ ,  $Cl = 0.36$ ) and from 21 counts to 13 counts at ( $M = 0.82$ ,  $Cl = 0.3$ ).

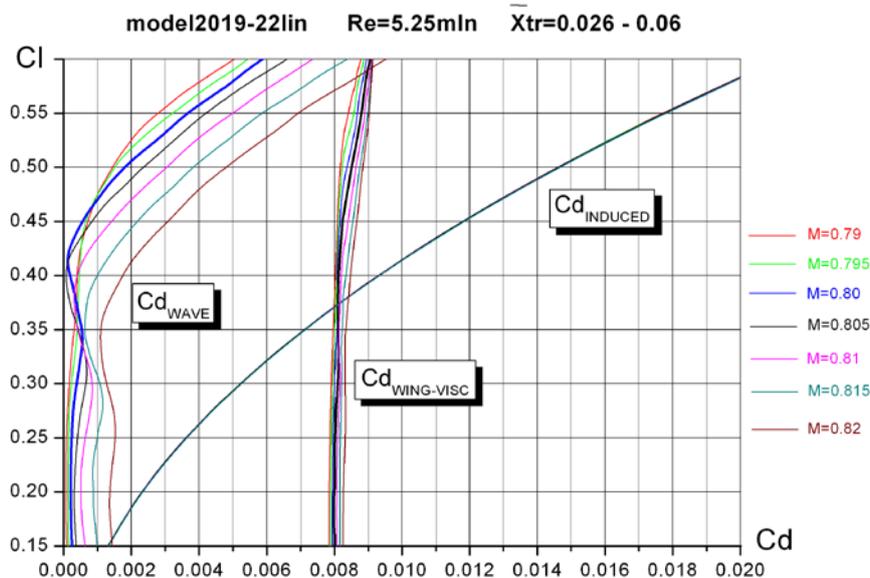


Figure 4: Calculated drag polars of basic configuration at  $Re = 5.25$  mln

In standard techniques of tunnel-to-flight extrapolation it is supposed, as a rule, that flow behavior does not vary with increasing Reynolds number, therefore wave and induced drag components are accepted identical, and only profile drag is corrected; besides for the real airplane some parasitic drag is added. Corrections to the wave drag values are applied sometimes, but in fact they are based usually on the assumptions that aerodynamic characteristics at increasing Reynolds number do not worsen and may even improve somewhat due to separation phenomena weakening (see Figure 5 from [15]). Such approach is more or less correct for subcritical flows. Unfortunately, it is not valid for the advanced supercritical optimized wings which are very sensitive to Reynolds number value even at cruise. Strong shock movement is typical at small change of cruise regime and/or the geometry of an effective “liquid” contour, that is, the wave drag may even grow significantly with increasing Reynolds numbers to flight values as in our second and third cases.

Maximal possible Reynolds number  $Re \sim 10$ - $15$  mln in non-cryogenic wind tunnel may be achieved with the help of semispan models [11], but even such high values are not “sufficient” for solving the problem of choosing the optimal trailing edge deflection angles with satisfactory accuracy. A number of examples of such discrepancies can be found in the literature [12-14]. Ultimately, this misalignment of characteristics at flight and wind tunnel conditions had become one of the main reasons for the construction of cryogenic wind tunnels, first in the US – NTF, and then in Europe – ETW.

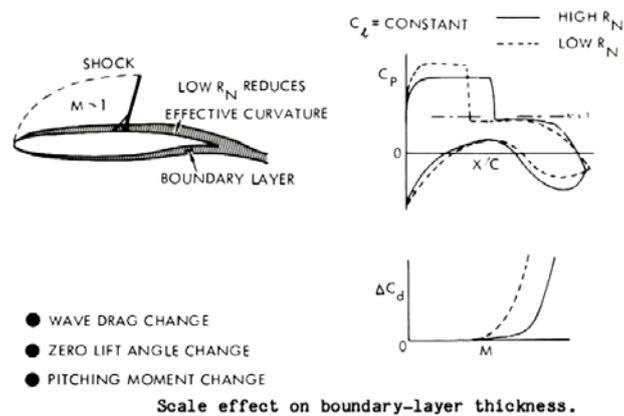


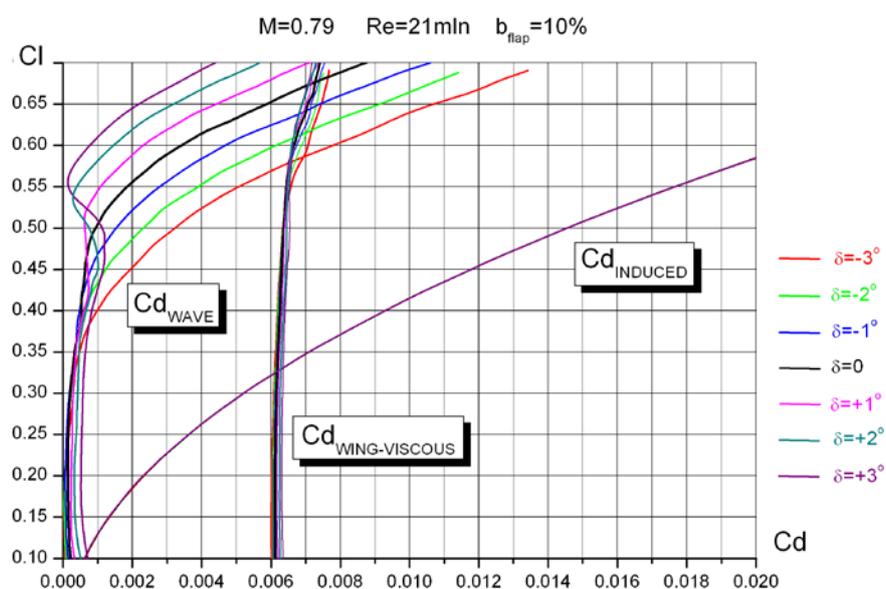
Figure 5 from [15]

### 3. Enhancement of the flight envelope by adaptive trailing edge flaps

To illustrate the possibility of expanding the flight envelope by adapting the trailing edge simple rotary flaps (tabs) with axes at 90% of the wing chord were considered. Although such tabs require additional control mechanisms, nevertheless they satisfy the request of remoteness of the rotation axis from supersonic zones. Adaptive drooped hinge flap systems like that used on the B787 & A350 will also be reviewed on a demonstration model, and possibly others. Comparison of span segmented flaps deviations and flap deviations as a whole showed that more complicated option does not provide significant advantages. Perhaps this is due to the chosen planform of the demonstrator's wing, in any case, for a real wing, this statement needs additional verification.

The effect of the deviation of adaptive flaps on the wing polar at different Mach numbers is shown in Figure 6. It can be seen that with a smaller Mach number  $M = 0.79$ , it is advantageous to tilt the flap down to reduce the drag at large  $Cl$ 's. In the higher speed mode  $M = 0.81$  and more, the main profit can be obtained at small  $Cl$ 's by moving the flap up. Finally, at the design Mach number  $M = 0.8$ , it is possible to obtain a monotonically better envelope of the drag polar compared to the base wing by deflecting the flap in different directions depending on  $Cl$ .

Flap deflection maximally affects the wave drag value. At negative deflection angles the wing profile drag also decreases as well as the pitching moment, and that will give an additional benefit as to the balance drag. At very high speed mode ( $M = 0.82$ ), the base wing has a strong shock-induced separation, while an upward deviation of the trailing edge restores an attached flow.



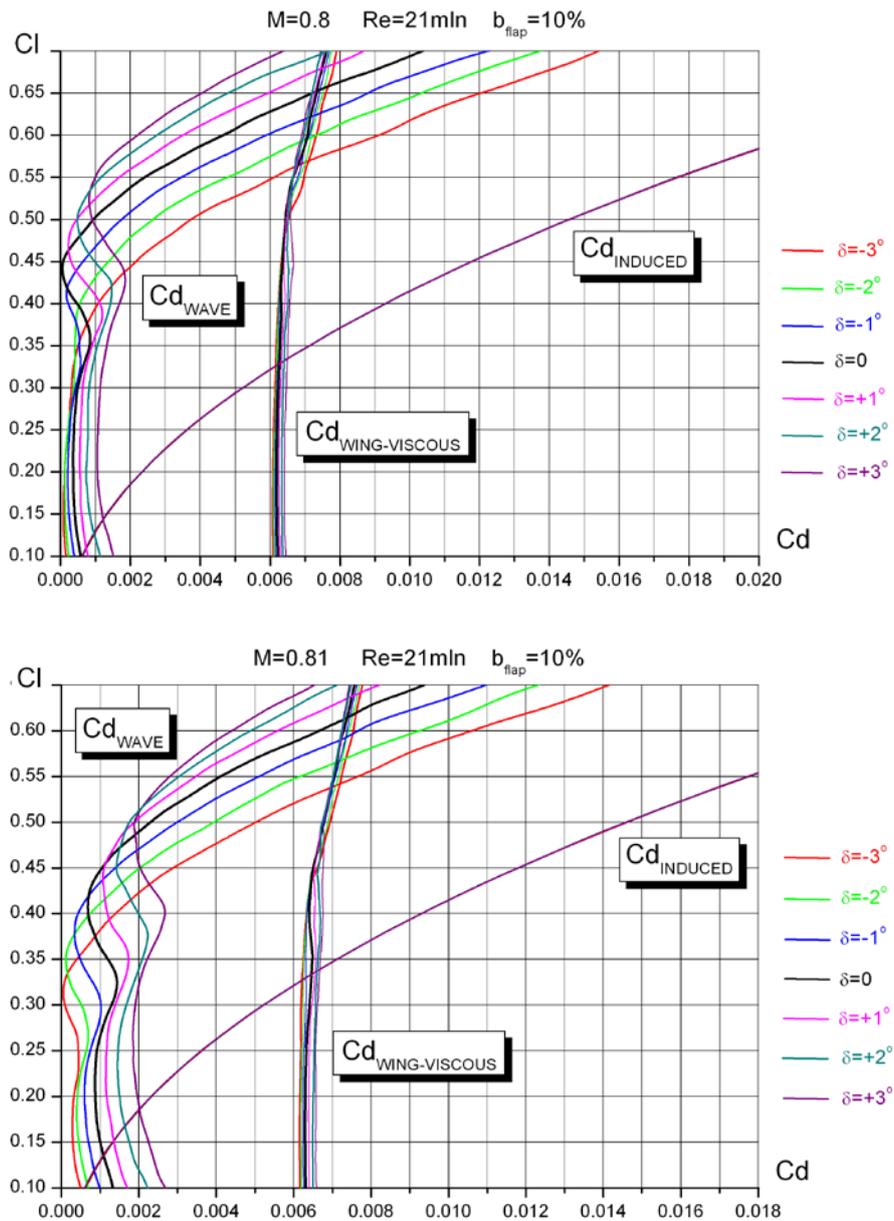


Figure 6: Calculated polars for different adaptive flap settings

#### 4. The equivalent wing concept

We shall name an “equivalent wing” such a wing which has the same distribution of pressure, as the original one, but under other conditions. Hence, for construction of equivalent wings it is necessary to use an inverse method. The concept of equivalent wings is not new. Numerous authors suggested this idea in the past for simplified modeling of the flow features in question. In this work the concept of equivalent wings is offered to be used for modeling a flow at flight Reynolds numbers. In fact, all the techniques of modeling full-scale conditions according to Blackwell [15], Haines [16], Green [17] and others are based on the following principle: *close distributions of displacement thickness of a boundary layer, i.e. close forms of an effective “liquid” contour => close distributions of pressure => close levels of wave drag and similar character of profile drag*. The concept of equivalent wings bases on the same principle, but without the first link since close distributions of pressure are achieved by definition.

Different variants of inverse method exist nowadays, which are intensively used for aerodynamic design purposes [8]. One option is to solve an inverse problem by direct optimization procedure, minimizing the difference between the prescribed and the resulting pressure distribution. The method is not very effective as compared with other approaches, why earlier it received the name of “brutal force” approach. Curiously enough, the “brutal force”

method is the most elegant solution to the problem of constructing an equivalent wing! This is due to the fact that the difference in the pressure distribution on the wing at different Reynolds numbers is caused by the different distribution of the boundary layer thicknesses near the trailing edge. Therefore, only two variations of the geometry on the upper and lower surfaces near the trailing edge of each wing section are sufficient to solve the optimization problem. In our case, the base wing was built on 7 sections along span, thus we used 14 variable parameters. The exact form of the geometry variations is not fundamental; in general they should alter the Kutta-Zhukovsky condition. Having tried several different options, we came to the conclusion that good results are obtained by using the following two variations: a bend of the whole tail part following cubic parabola and a deepening of the lower surface that regulates the rear loading. Variations do not affect the main part of the wing  $\bar{X} < 65\%$  on the upper surface and  $\bar{X} < 75\%$  on the lower surface.

Optimization is carried out at a fixed angle of attack, minimizing both the discrepancy of the pressure distribution and, in part, the discrepancy of  $C_l$  and  $C_m$ . An arbitrary number of flow regimes may be chosen for optimization. Calculations show (and it became a pleasant surprise for the authors) that equivalence of the wings “tailored” at one mode (for example,  $M = 0.8$ ,  $C_l = 0.5$ ) is kept then practically in all the range of cruise flight for pressure distribution as well as for the wave drag. However, we carried out multiregime optimization at several different flow regimes for the guaranteed small deviation of the equivalent wing behavior from the prototype.

For formation of the equivalent wing №1 the Reynolds number was considered corresponding to half an atmosphere in wind tunnel contour  $Re = 5.25$  mln, transition was fixed at the 6% on the tip section, the transition line being parallel to the leading edge. Target pressure distributions were taken from the eight basic wing flow regimes at  $Re = 21$  million ( $p_0 = 2$  atm). A comparison of the pressure distributions of the base and obtained “equivalent” wing at ( $M = 0.8$ ,  $C_l = 0.5$ )-mode is shown in Figure 7. It can be seen the perfect match, except for a small neighborhood of the trailing edge. The pressure distribution over the basic wing at  $Re = 5.25$  mln is also shown in the figure by a dashed line. Wave drag in this case is almost twice as high as with full-scale  $Re$  number (18 counts vs 9.5 counts). Wave drag of the equivalent wing at this mode equals the same 9.5 counts.

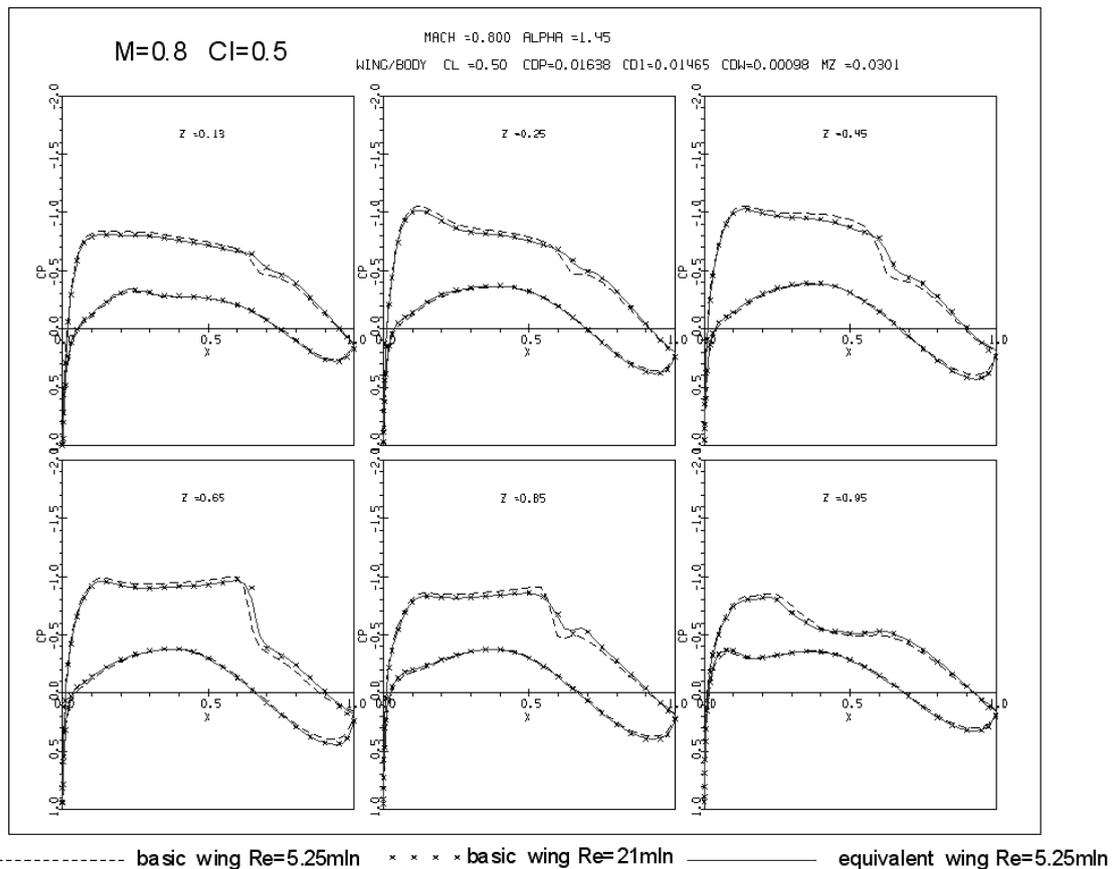


Figure 7: Comparison of the pressure distributions of the base and obtained “equivalent” wing

Comparison of the half-span airfoil geometries with vertical expanded scale is given in Figure 8.

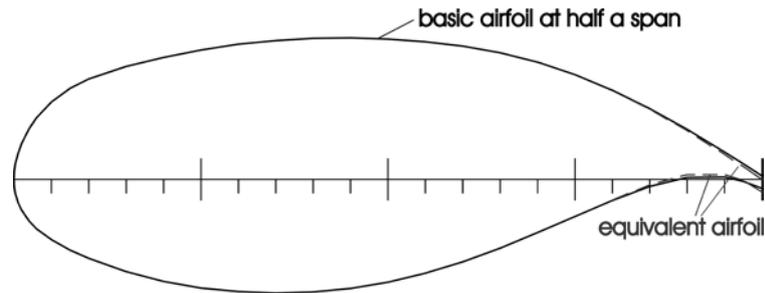


Figure 8: Comparison of basic wing section (solid contour) with the equivalent one (dash)

The polars are compared in Figure 9. Polars of induced drag coincide perfectly, the difference in wave drag does not exceed 1-2 counts, and notable difference exists only in the viscous drag of the wing, whose shift due to different Reynolds numbers corresponds to the known empirical dependencies.

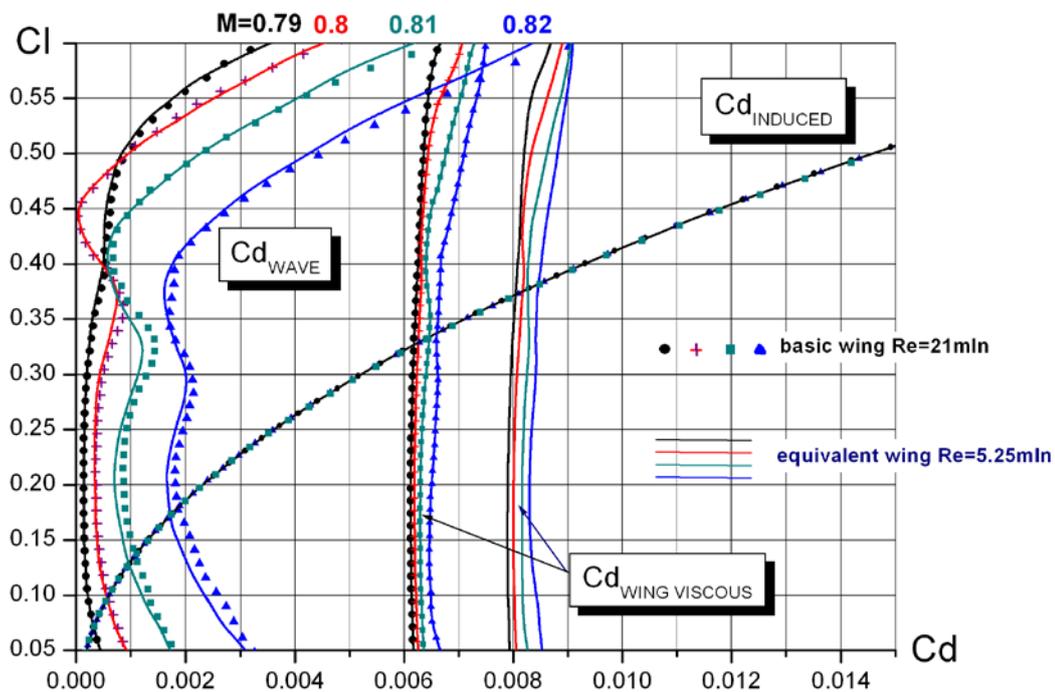


Figure 9: Comparison of drag components of the basic wing and the equivalent wing №1

Thus, in the broad sense, the proposed concept [7] suggests experimental studies in the wind tunnel of an “equivalent” wing in addition, if not to replace a geometrically similar model. It is natural, that lift, pitching moment and induced drag of an equivalent and an initial wing behave similarly in view of similarity of pressure distribution. As angle of attack also coincide, the lift of the horizontal empennage and, hence, trim drag is identical. Thus, testing equivalent wings makes the procedure of tunnel-to-flight extrapolation simpler and more straightforward because it is necessary to recalculate only the profile drag of all elements of configuration, as in usual standard techniques. For the sake of justice it is necessary to note that it is not a trivial task yet. In addition, one more restriction should be taken into account; it is a demand of unseparated flow around an equivalent wing at wind tunnel Reynolds numbers. To test the limits of applicability of the approach, an equivalent wing №2 intended for a smaller Reynolds number  $Re = 3.15$  million is supposed to test on the demonstrator model. Calculations fulfilled show that the accuracy of the equivalent wing №2 in regard to modeling prototype behavior is of the same order as of the wing №1.

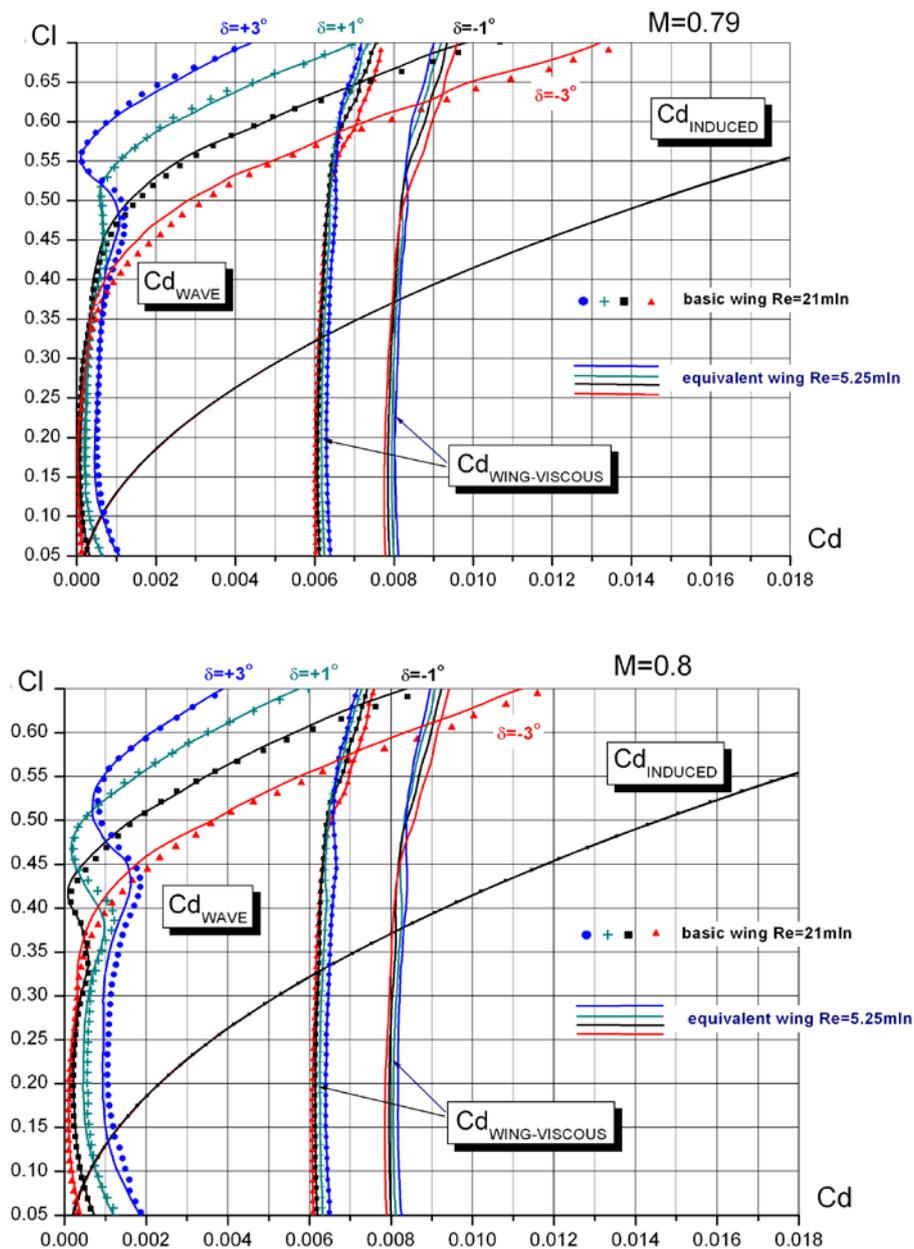
The conclusion about the equivalence of  $C_l$ ,  $C_m$ ,  $C_{d_w}$  values does not depend on the accuracy of a computational method, and bases on the healthy physical assumption that at close distribution of pressure total aerodynamic characteristics will be close as well. Equivalence of wing aerodynamic characteristics is not influenced with changes of geometry, for example with installation of an engine nacelle or with changing wing-fuselage fairing though distributions of pressure and value of wave drag may change considerably.

## 5. Adaptive trailing edge flaps for equivalent wings

The identity of the pressure distribution and total aerodynamic characteristics of the base wing and the “equivalent” one (at different Reynolds numbers!) gives reason to hope for the same effect for the adaptive flaps deflection.

Let us apply for the equivalent wing the same type of pivoting tabs with a chord of 10%. The calculated polars for the “equivalent” wing with deflected tab at  $Re = 5.25 \text{ mln}$  are compared with those for the basic wing at  $Re = 21 \text{ mln}$  in Figure 10. Again, the induced drag is the same, the difference in wave drag does not exceed 1-3 counts even for extreme deflections  $\delta = \pm 3^\circ$ . It is rather tolerant value because at of-design flight regimes the shift of drag polars due to one degree flap rotation is of the order of 10 counts. It is highly unlikely, that for the real plane the flap deflections with the discrete step less than half-a-degree will be tuned up.

Thus, it is shown that the problem of choosing the optimal flap deflection under flight conditions can be solved under non-cryogenic wind tunnel conditions (at much smaller Reynolds number!) if an “equivalent” wing is tested instead of the base wing. The most suitable is the use of a large half-model, where the designer can more accurately simulate the real geometry of flaps, spoilers and other local elements. Even for a wide-body aircraft, the difference in  $Re$  number will be no more than four times, that fully allows the use of the “equivalent wing” concept.



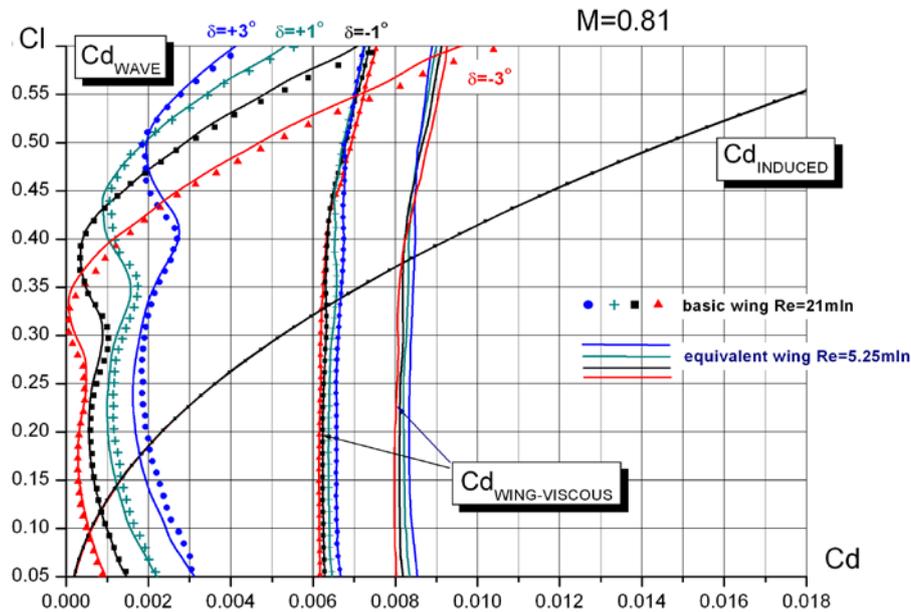


Figure 10: Comparison of drag components of the basic wing and the equivalent wing №1

## Conclusions

Three fundamental new challenges arise in designing and testing of adaptive transonic wings for next generation aircraft. At designing an additional freedom in geometry variation results in challenge of choosing flight envelope points ( $M$ ,  $C_l$ ) and their ranking (weights). Optimal trailing edge deflections are not known a priori and in fact depend on the chosen final geometry (and geometric-kinematic realization of camber variation, of course) that is successive optimal design procedure is necessary for an adaptive wing geometry determination and trailing edge deflections refinement.

Another challenge concerns the procedure of optimal flap settings determination. Modern supercritical wings are very sensitive to Reynolds number effect at cruise but adaptive wings are even more sensitive at peak performance. The utilization of the “equivalent wing” concept is suggested by the authors for the optimal adaptive flap settings to be defined. Calculations show that optimal flap deflections are identical for the basic wing at flight conditions and the “equivalent” wing at wind tunnel Reynolds number. Special research half-model with detachable wing rear parts is constructed to prove the applicability of the “equivalent” wing concept for solving both fundamental problems: the tunnel-to-flight extrapolation of wing aerodynamic characteristics and the optimal adaptive flap settings definitions.

Finally, local geometry features may also affects the results, that is large scale semispan models are preferable for the flaps deflection optimization task. Strictly speaking even this solution does not guarantee an optimal choice of adaptive geometry but the possibility of doing that in the real flight is at least disputable.

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