RECENT EXAMPLES ON DESIGN AERODYNAMICS FOR TRANSPORT AIRCRAFT

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Abstract

Discussed in this paper are some of the results in Design Aerodynamics research for civil transport aircraft. An iterative inverse-direct design software for airfoils and wings has been upgraded for more accuracy, reliability and user-friend-ness. The design modification of a supercritical wing has been conducted effectively with the present method to remove a partial-span separation induced by un-equal strength shockwave at higher cruise Mach numbers. DTE wing concept is investigated numerically and experimentally, being demonstrated as a good candidate to supercritical wing modifications for stretched version aircraft. GA approach could reasonably provide optimized positions for the high-lift system, while indicating also interesting flow mechanism. Fuselage after-body flows and drag values are strongly connected with major geometry parameters, the NS analysis of the after-bodies helps to validate the engineering method and its software developed in this work, increasing the database and displaying the flow details.

1. Introduction

The dramatic re-construction of the passenger aircraft manufacturers and the market share of their products in the last decade demonstrate the dominant role of the modern design technology and scientific research in this severe competitive industry. The goals of the Design Aerodynamics for transport aircraft are still to increase the aerodynamic efficiency, the flight safety and the environmental friend-ness.

The CFD methods, one of the main tools besides ground and flight tests, have been used for more complicated configurations like engine integration and 3D high-lift systems [1], while the reliability being kept carefully validated. The inverse design methods, due to their demonstrated engineering applicability, have been continuously studied and even combined with optimization codes for optimizing their target pressure distributions [2][3]. Numerical optimization approach, as one of the promising candidates for the future multi-disciplinary design, is undertaken intensive research in its effectiveness and robustness [4][5]. More quiet flows and more innovative concepts are always under investigation.

In this paper some of the recent research activities on Design Aerodynamics for civil aircraft are discussed, which include:

- Upgrade of a CFD 2D/3D Transonic Design software. The accuracy of the inverse method is improved by introducing an additional higher-order upwind term; the integration of more accurate direct codes extends the function and overall accuracy of the software; and the on-screen interface helps to operate the software in the way of most popular commercial codes.
- A supercritical wing modification with the upgraded software.

- Study of the Divergent Trailing Edge (DTE) wing concept for the stretched passenger jets application.
- 2D high-lift system optimization research by combining the Genetic approach (GA) with an accurate Euler + Boundary layer code MSES.
- Development of an engineering method and software for airplane after-body design, together with flow analysis by a NS solver for validation and geometry parameter study.

The methods, software and expertise developed in this paper are found satisfactory and applicable.

2. Upgrade of a CFD Design Software

An iterative residual correction method being developed for transonic airfoil and wing designs and used for many years has been again modified in order to: **a.** further improve the convergence in the supersonic regime and **b.** upgrade the accuracy of the complete tool to the same lever of the modern direct solvers. The software of this method, TDTDTD (Two-Dimensional Three-Dimensional Transonic Design), is composed of two inverse codes and a number of 2D/3D direct flow solvers which are closely coupled to generate the airfoil and wing geometries with their pressure coefficient (Cp) distributions converging to the designer prescribed Cp targets. This software is responsible for the low speed and transonic airfoil, wing and wing/body design and analysis.

2.1 Modification of the inverse method

The 2D and 3D inverse methods had been developed based on the “iterative residual correction” principle of Takanashi [6], and been modified through the research and applications [7] [8] [9] by:

- Deriving the closed form integral representations to replace all the numerical integrations used in the original method, in order to increase the accuracy and enhance the stability of the algorithm;
- Finding out and implementing a special formulated supercritical weighted smoothing function to improve the convergence in the supersonic flow area and also around the shocks;
- Utilizing the numerical matrix condition analysis to ensure the correct meshing over the wing planforms;
- Investigating a direct-viscous-iteration principle to realize the design in viscous flow conditions, which is very essential for generating transonic and laminar flow configurations correctly.

These modifications have made this inverse method much practical in engineering applications.

A different approach to enhance the supersonic convergence was introduced to the same method in DLR [10] and the effect has been verified by a validation study [11]. In order to make the current TDTDTD software more reliable and robust, both 2D and 3D inverse codes are further modified based on the DLR approach.

This modification intends directly to increase the accuracy of the governing equation. It has been reached by introducing a higher order term to the Potential Equation of the inverse method:

$$\Delta\phi_{xx}+\Delta\phi_{yy}+\Delta\phi_{zz}=\frac{\partial}{\partial x}\underbrace{\left[\frac{1}{2}\left(\phi_x+\Delta\phi_x\right)^2-\frac{1}{2}\phi_x^2+\Delta X\Delta\phi_{xx}\left(1-\phi_x-\Delta\phi_x\right)\right]}_{\chi^*} \tag{1}$$

Where the third part in χ^* is the new higher order term, which is calculated in the form of upwind operators and would be effective only in hyperbolic regimes.

From this more accurate equation, the whole inverse solution procedure has been re-derived and FORTRAN codes re-programmed. Validation of the new modification is done by 2D and 3D design and re-design examples in both sub-critical and supercritical cases.

Because the additional term appears only in the right-hand side of the final equations, the inverse computation time is almost not affected. The convergence along the supersonic roof and near the strong shocks has been found very satisfactory, as shown in Fig. 1 for a 3D wing design case.

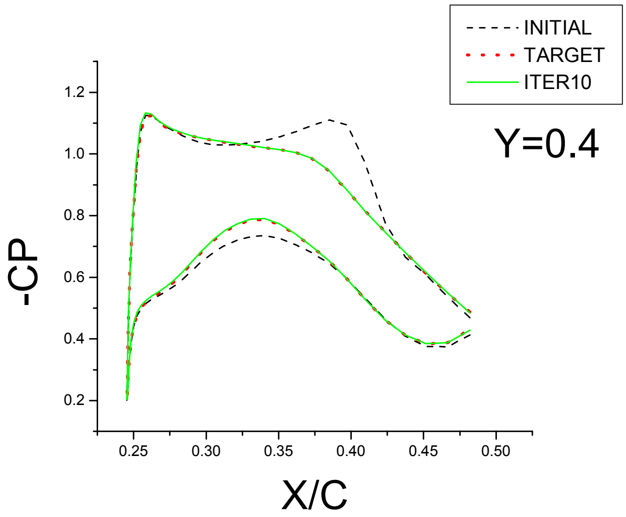


Fig. 1. Comparison of the designed, target and initial Cp distributions of a wing section at 0.4 semi-span, M=0.79

2.2 The upgrade of the analysis codes

One of the most important features of this iterative method is that it brings the inverse design to the same accuracy of the direct analysis methods coupled into the system, so the upgrade of the entire CFD tool could be done by integrating the above inverse codes with 2D/3D Euler/NS solvers of the modern CFD. Due to the very small number of the direct-inverse iterations needed to reach the target pressure distribution, the design by Euler/NS has become engineering practical.

Recent integration of modern analysis codes into the TDTDTD software includes:

- A reliable 2D airfoil analysis code MSES [12] for turbulent and laminar airfoil designs.
- A reliable 3D Full Potential + Boundary-Layer code for the wing designs with the presence of the real fuselage and the wing/fuselage fairing.
- A 3D Aero-elastic code (Full Potential + Boundary-Layer + Finite Element structure deformation analysis) to realize the aerodynamic/structural integrated design of transport wings. In this design process, the wing geometry is corrected in each of the inverse-direct iterations by taking both viscosity and elasticity into account. When the wing Cp distributions converge to the target, the software generates instead of the theoretical rigid wing, but the final tooling wing geometry, in principle.
- A 3D Euler/Navier-Stokes Solver with both structured and unstructured grid capacity is coupled into the design iteration for more complicated wing/body configurations, and the wing designs with the presence of the engine nacelles.

2.3 The on-screen operation interface

- An on-screen target Cp editing software based on Visual Basic and Windows platform has been developed. The design engineer could easily modify the wanted target Cp distributions with the mouse, as shown in Fig. 2 for a wing section.

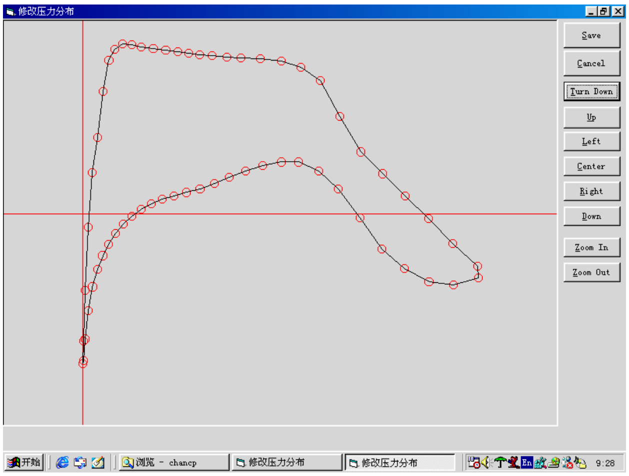
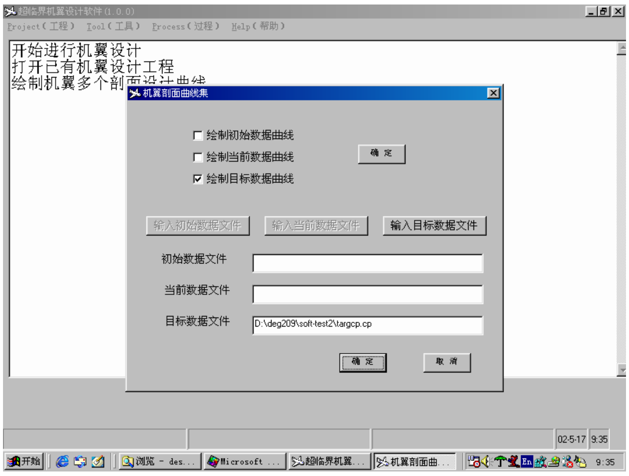


Fig. 2. Target Cp on-screen modification code

- A software interface based on the Visual Basic is constructed which includes the pre-processing, inverse and direct codes selection, target Cp modification, initial geometry preparation, flow parameter input, iteration display, convergence display and post-processing by 2D/3D plot software. This intends to operate the software as convenient as most of the commercial CFD/FEA codes (Fig. 3).



开始进行机翼设计
打开已有机翼设计工程
绘制机翼多个剖面设计曲线

☐ 绘制初始数据曲线
☐ 绘制当前数据曲线
☑ 绘制目标数据曲线

初始数据文件
当前数据文件
目标数据文件 D:\deg209\soft-test2\targcp.cp

Fig. 3. A display of the operating interface of the TDTDTD software (Chinese Version)

Design examples with each of the above codes combinations suggest that this upgrading has greatly extended the design capacity of the TDTDTD software, brought it to the high standard of the up-to-date direct methods, and provided a practical and user friendly 2D/3D design and analysis CFD package.

3. Example of a Wing Design Modification

One of the design examples with the above upgraded software is a supercritical wing for a hundred-seat passage jet. The wing was designed considering the influence from the fuselage and the wing/body fairing, as shown in Fig. 4.

One of the sample wings had a part-span separation at higher cruise Mach number 0.81. Examining the flow at design Mach number 0.78, the boundary layer thickness at this span position is already higher than its inboard and outboard neighborhood, the isobars are not straight enough. It is clear that this local separation is induced by the non-equal strength of the shockwave when the Mach number increases. This problem has been quickly solved by re-prescribing the Cp distribution near that span area with the equal-isobar principle, and running the design method a few more iterations, as shown in Fig. 5.

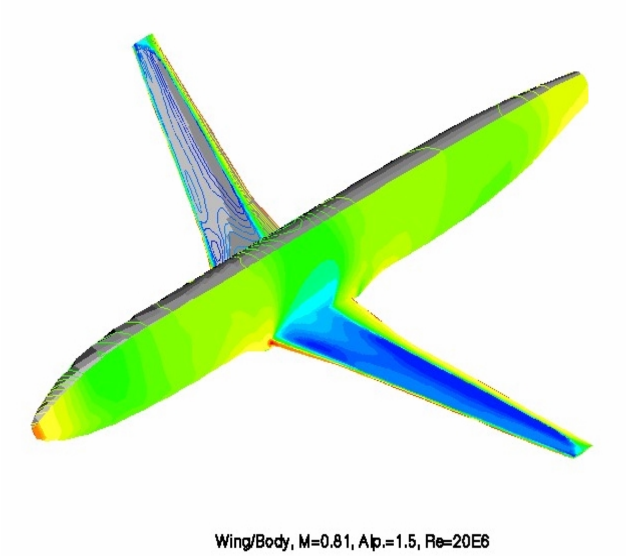


Fig. 4. Cp Contour and isobars of a sample wing at higher cruise Mach number 0.81

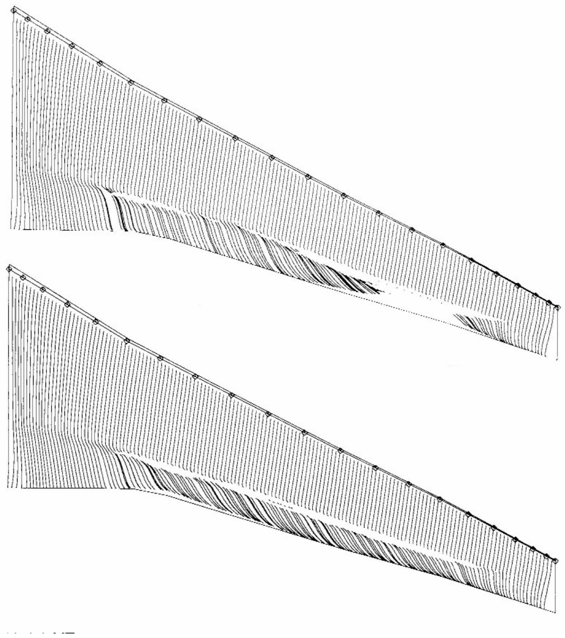


Fig. 5. Modified design (lower) of the sample wing towards the removal of the part- span shock induced separation (upper)

4. Divergent Trailing-Edge (DTE) Wing

The common practice to provide additional lift for stretched passenger aircraft derivatives has been to increase wing areas or to use winglets.

To increase the wing area involves the redesign of the whole wing and sometimes the center wing box and the center fuselage, too. Examples include a well-known rear-fuselage-mounted twin-engine jet modified by inserting extended inboard and outboard wing span-sections. Even though great efforts on redesign, re-test and manufactory tooling change spent, the aerodynamic efficiency of the larger wing was not increased enough because of the original classic wing sections unchanged. Sometimes, for conventional wings, to change into a completely new supercritical wing, with the wing planform and the wing-fuselage joint section unchanged might be a better choice, as numerically studied for a wing-mounted twin-engine jet configuration in [8]. The modern digitalized production procedure could help to reduce the cost of the new wing.

To use the winglets is relatively a simple way, but the design, test, structure modification and the maintenance will draw additional concerns. Aerodynamically it is no more than reducing the additional induced drag when the wing has to work at higher than design lift coefficient CL in the stretched airplane.

DTE airfoil has the advantage of the minimum structure and manufactory expense, while provides additional lift and supercritical characteristics to an existing wing. The idea has been discovered from the Cp behavior of different trailing edge geometry, when calculated with CFD codes like BGKJ. The benefit of using the DTE concept to modify a conventional transport wing has also been demonstrated by Henne [13]. DTE effectiveness for supercritical wings has been studied in Europe, too.

It is certain that the DTE airfoil will increase the absolute pitching moment, which means more balance drag.

In this paper, it is supposed that a supercritical wing should be modified with minimum expense for a stretched passenger jet. The baseline airfoil should then operate at M=0.73 and CL=0.80, instead of CL=0.65 for the original design. Based on the above analysis and considering that the stretching of the fuselage could provide larger pitching balance momentum, the DTE concept is studied here.

The design software used is the same as the above discussed. The final change of the trailing edge to the original airfoil, NPU-SP7, is plotted in Fig. 6. The new geometry, named BUAA-DT5 has the relative trailing edge thickness 0.7%, compared with the original value 0.5%. The corresponding increase of the base-drag 0.0003, according to [13], is considered acceptable. At CL=0.80, the DT5 has 0.4 degree less incidence, a weaker shock and a slightly increased lift to drag ratio L/D, compared with the original, based on the MSES computation as shown in Fig. 7. CFD analysis also shows postponed drag-rise and acceptable pitching moment.

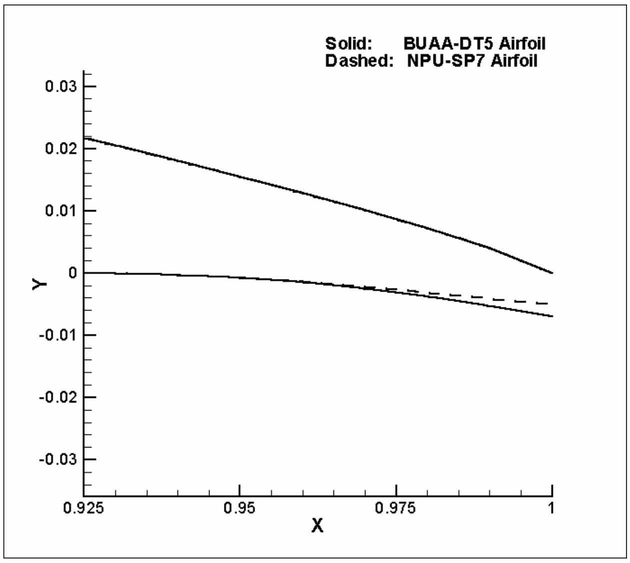


Fig. 6. Comparison of the trailing edges of the DT5 and the original SP7 airfoils

Both airfoils are tested in a 0.6x0.6 m^2 high-speed wind tunnel of CARDC. Fig. 8 is a comparison of the measured and computed Cp distributions, suggesting that the analysis results from MSES are accurate and reliable. Fig. 9 is the comparison of the measured L/D plot, a 9.2% L/D increase is obtained in the required operating lift CL=0.8, while a 9.0% stronger absolute pitching moment is also measured, under the test Reynolds number with fixed transition.

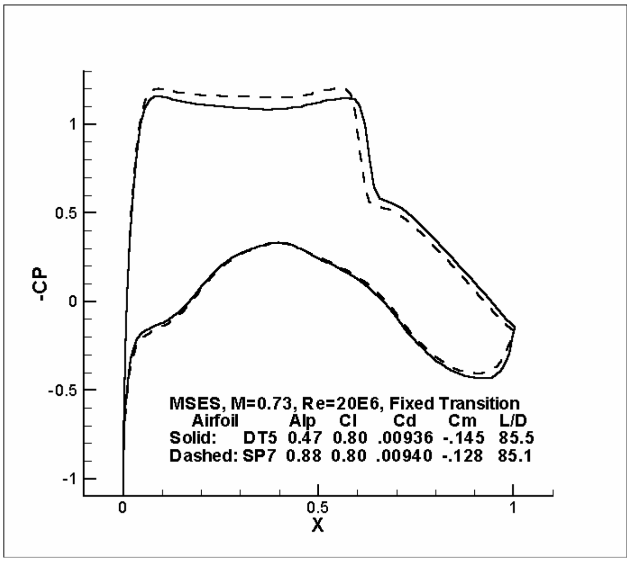


Fig. 7. Comparison of the DT5 and SP7 airfoils: Calculated pressure distributions and the aerodynamic coefficients

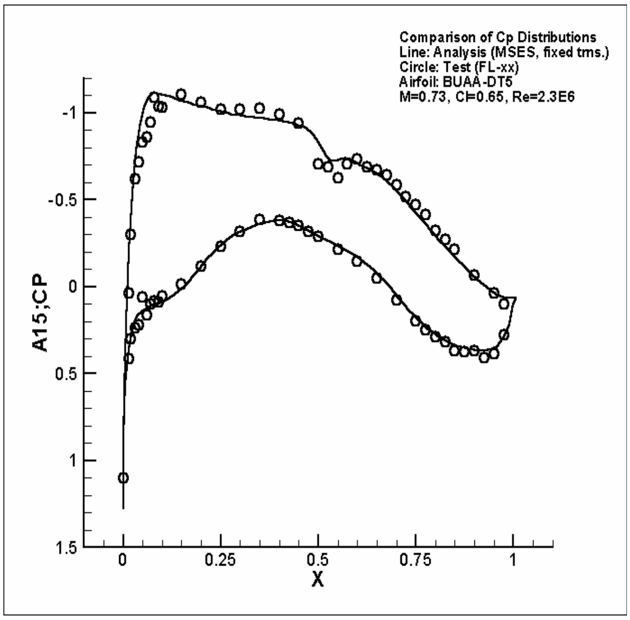


Fig. 8. Comparison of the calculated and measured Cp distributions of the DT5 airfoil

This 2D investigation demonstrates that the DTE wing sections could provide necessary lift with minimum structure and manufacture changes and acceptable additional pitching moment, which might be a solution for stretched-fuselage passenger jets originally equipped with supercritical wings.

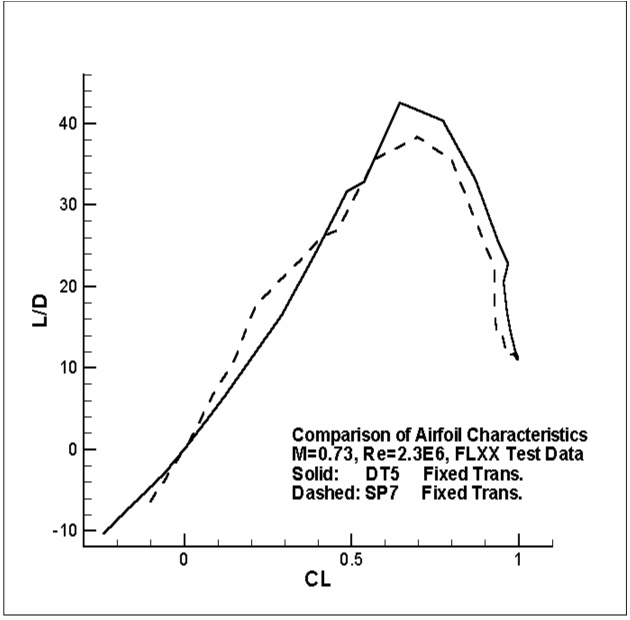


Fig. 9. Comparison of the DT5 and the SP7 airfoils: measured L/D curves

5. High-Lift System Optimization

Successful high-lift system design could greatly increase the take-off and landing performance of an airplane, reduce structure complexities and control the flow separation noise. Because of the multi-parameter and multi-freedom nature, high-lift system design becomes a most suitable topic for numerical optimization methods. A powerful CFD tool could, in this process, not only provide better design and better understanding of the flow in the system, but also reduce the experimental work substantially.

As a chapter of a degree work [14], the Genetic method (GA) has been used to couple with the MSES code for the 2D high-lift system optimization.

This method is also applied to the design investigation of the systems and the flow mechanism analysis study.

One of the design cases with the GA approach is shown in Fig. 10, where the NLR-7301 configuration is used. The objective is the lift alone; the contours of both main airfoil and the flap are unchanged; the flap deflection angle is fixed at 10^{o}. The flow condition is M=0.25,

$\alpha=8^{o}$ and Re=2.5E6. The flap movement is indicated by the center of its leading edge, and a large enough allowed moving area is specified. There are 60 members in each Genetic generation and the mesh around the flap and in the slot is refined.

It could be seen from the figure that the flap first moves backward and little down, then moves up and slight backward. The optimized position is obtained after 6 generations. It could be seen that the flap dose not move far away from the main, even though the large space allowed.

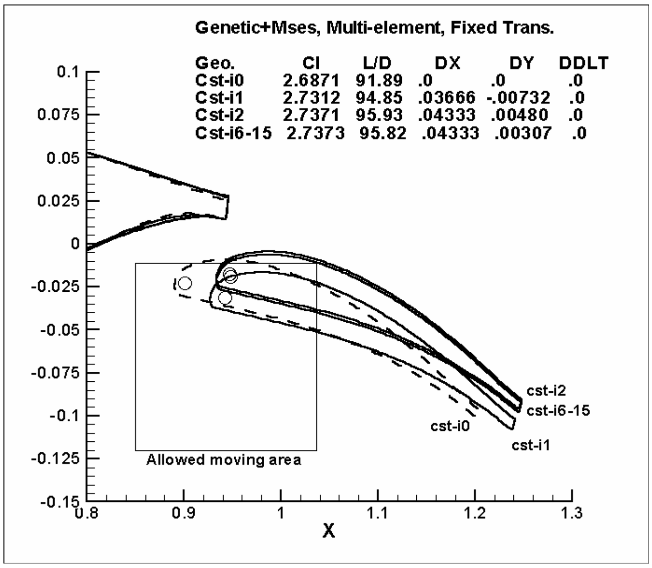


Fig. 10. GA results of a high-lift system optimization case

Further investigation by separating the lift increments of the main and the flap in this and other cases indicates the following:

- When the flap moves back, the lift increases as expected, without suffering additional drag;
- When the flap moves up, the lift of the main wing increases, because the blocking of the slot increases the circulation of the main, but reduces the lift of the flap;
- When the flap moves down, more flow moves through the gap so as to increase the lift of the flap while reduce the lift of the main.

6. After-Body Design Research

The main parameters defining the geometry of a fuselage after-body are the upswept angle, the contraction ratio, the fineness ratio and the flatness.

As the first step, a computerized engineering aerodynamic estimation method has been developed and corresponding software constructed, for a fast drag assessment during the after-body preliminary design phase. This is an on-screen interface in VB platform, similar to the 2D/3D design software shown in Fig. 2 and 3. This method is theoretically based on some of the drag calculating equations and a database.

The second step involves the NS computations of different after-body configurations. The purpose of the flow analysis is both to modify the accuracy of the above engineering method, by correcting the equations and increasing the database, and to provide better understanding of the after-body flow mechanism.

The computation models are a passenger jet fuselage with different after-bodies, and another two fuselages of existing airplanes. Structured grid and k-ε models are used in the computation. Fig. 11 shows the flow patterns over an after-body with large upswept angle. The flow concentration could be recognized which generates vertices in the wake.

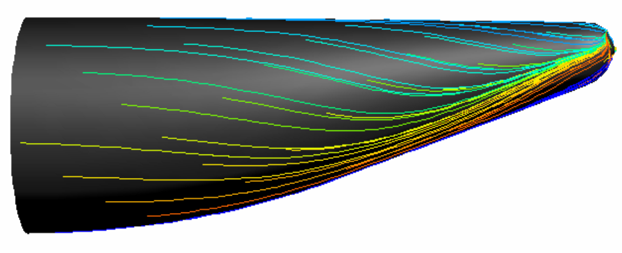


Fig. 11. Computed flow pattern over an after-body surface

The results show that the pressure drag coefficient increases rapidly with increasing upswept angle and contraction ratio, respectively. The friction drag coefficient increases with increasing after-body fineness ratio. The more the after-body flatness, the more the pressure drag. The wave drag coefficient increases with increasing upswept angle at transonic speed.

Good coincidence of the engineering and CFD results with known test data has been verified. The engineering software will be further modified with the wind tunnel measurements of the fuselage models.

7. Conclusions

- Design Aerodynamics research for civil transport aircraft plays an important role in the competitive products development.
- The upgrade of the TDTDTD software has made it a more accurate, reliable and user-friendly design tool.
- The design modification of a supercritical wing could be conducted effectively with the present method and the isobar principle.
- DTE wing concept is found a good candidate to supercritical wing modifications for stretched version aircraft, which could provide additional lift without suffering drag rise, feature minimum structure and production change and acceptable pitching moment increment.
- GA approach could reasonably provide optimized positions for the high-lift systems, and indicate interesting flow mechanism that may advise the flap system design.
- After-body flows and drag values are strongly connected to the main geometry parameters, the engineering method developed in this paper aims to provide designers with a fast assessment tool, while the NS analysis helps to validate the engineering software, increase the database and display the flow details.

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