DESIGN OF MULTI-LIFTING SURFACES AT TRANSONIC FLOW

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Abstract

The aerodynamic design method for a single lifting surface based upon the iterative residual correction principle is developed for designing multi-lifting surfaces, an aerodynamic design code based on this method is extended and coupled with the advanced aerodynamic analysis codes in order to be able to design multi-lifting surfaces. Using such an aerodynamic design software system, a canard wing configuration is studied and designed. The method and software developed within this work has significant practical value for aircraft design.

1 Introduction

The goals of design aerodynamics for transport aircraft are still to increase the aerodynamic efficiency, the flight safety and the environmental friendliness. 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.

The three-surface aircraft (TSA) with an additional third wing in the forebody region of the aircraft, the "canard", represents a concept for future large transport aircraft. The study of new TSA configurations shows the relevance and further improvement which is still required for the pre-design and detail design aerodynamic tools. The aerodynamic forces acting on the wing and the canard (or horizontal tail plane) are influenced by the mutual interference between the two lifting surfaces. Therefore these surfaces should be taken into account in the design procedure.

In this paper a multi-surface aerodynamic design code based on the inverse method, which developed from the iterative residual correction principle and for designing multi-lifting surfaces, is extended and coupled with advanced aerodynamic analysis codes in order to be able to design multi-lifting surfaces. Basically mesh generation, CFD-analysis and inverse design modules have been coupled and are used iteratively in an automated way. As the design code is completely independent of the analysis code, in order to apply this method for complex three-dimensional geometries, like multi-lifting surface configurations, and to ensure a great accuracy of the design solution for the subsonic and transonic flow regime, two different CFD software systems, one is an Euler/Navier-Stokes solver based on unstructured meshes including the CAD modules MegaCads, the mesh generation module CENTAUR and the CFD module TAU of DLR, the other is a Cartesian multi-grid Euler solver MGAERO of NPU, are chosen as CFD analysis solver.

A two surface configuration including the canard and the wing of the model of the DLR "Three Surface Aircraft" project was used in this paper as test case for the two surface design case.

2 Methods

2.1 Iterative Residual Correction Method

The aerodynamic design method for a single lifting surface based upon the iterative residual correction principle is developed for designing multi-lifting surfaces. For the two surface case, the three-dimensional full potential equation can be written in terms of the perturbation velocity potential $\Delta\phi$. In scaled form and with transformed coordinates, the three-dimensional full potential equation, the pressure difference between the specified and the calculated pressures ΔC_P and the geometry correction function Δf are given by the following equations:

$$\Delta\bar{\phi}_{\bar{x}\bar{x}} + \Delta\bar{\phi}_{\bar{y}\bar{y}} + \Delta\bar{\phi}_{\bar{z}\bar{z}} = \frac{\partial}{\partial\bar{x}}\left[\frac{1}{2}\left(\bar{\phi}_{\bar{x}} + \Delta\bar{\phi}_{\bar{x}}\right)^2 - \frac{1}{2}\phi_x^{\;2}\right] \tag{1}$$

for the first lifting surface:

$$\Delta\bar{\phi}_{\bar{z}}\left(\bar{x},\bar{y},\pm 0\right) = \frac{\partial}{\partial\bar{x}}\Delta\bar{f}_{1\pm}\left(\bar{x},\bar{y}\right),$$

$$\Delta C_{p1\pm}\left(\bar{x},\frac{\bar{y}}{\beta}\right) = -2\frac{\beta^2}{K}\Delta\bar{\phi}_{\bar{x}}\left(\bar{x},\bar{y},\pm 0\right), \tag{2}$$

for the second lifting surface:

$$\Delta\bar{\phi}_{\bar{z}}\left(\bar{x},\bar{y},\bar{H}\pm 0\right) = \frac{\partial}{\partial\bar{x}}\Delta\bar{f}_{2\pm}\left(\bar{x},\bar{y}\right),$$

$$\Delta C_{p2\pm}\left(\bar{x},\frac{\bar{y}}{\beta}\right) = -2\frac{\beta^2}{K}\Delta\bar{\phi}_{\bar{x}}\left(\bar{x},\bar{y},\bar{H}\pm 0\right). \tag{3}$$

with the transformed variables ($\bar{x},\bar{y},\bar{z}$) and

functions $\bar{\phi}$ and $\bar{f}$ given by:

$$\bar{x} = x\ ,\quad \bar{y} = \beta y\ ,\quad \bar{z} = \beta z\ ,\quad \bar{H} = \beta H\ ,$$

$$\bar{\phi}\left(\bar{x},\bar{y},\bar{z}\right) = \frac{K}{\beta^2}\phi\left(x,y,z\right)\ ,$$

$$\bar{f}_{i\pm}\left(\bar{x},\bar{y}\right) = \frac{K}{\beta^2}f_{i\pm}\left(x,y\right)\ ,\ \left(i = 1,2\right).$$

The subscripts 1 and 2 correspond to the first and second lifting surface respectively, the subscript ± indicates the upper and lower surfaces of the wing, H corresponds to the difference of the normal position between the two surfaces. Furthermore

$\beta \equiv \sqrt{1 - M_\infty^{\;2}}$, with M_∞ the freestream Mach number.

$K \equiv \left(\gamma + 1\right)\cdot M_\infty^{\;2}$ is a transonic similarity parameter, γ is the ratio of specific heats.

The derivation and numerical treatment of these formulas for the multi-lifting surface case are the same as those for the single surface case in the references [3][4][5][6][7][8].

2.2 Design Process

The procedure of the iterative residual correction method does not require any restrictions on the formulation or numerical solution scheme of the analysis code. The only requirement needed for the flow solver is the output of the calculated pressure distribution on the corrected wing surface, since the design code is completely independent of the analysis code. Therefore any type of analysis code for a three-dimensional transonic wing with or without body can be employed with the present procedure.

In order to apply this method for complex three-dimensional geometries, like multi-lifting surface configurations, and to ensure a great accuracy of the design solution for the subsonic and transonic flow regime, an Euler/Navier-Stokes solver based on unstructured meshes or a Cartesian multi-grid Euler solver were chosen as CFD analysis solver. Since the geometry corrections are based on the transonic small perturbation potential equation while the pressure distribution is obtained by the solution of the Euler/Navier-Stokes equation an iterative correction procedure is required.

2.3 Basic Modules

As mentioned before, there are several different modules in the design process using different programs or software tools. In the investigation of DLR, we decided to use a CFD solver based on unstructured hybrid meshes. It is advantaged that the mesh generation for complex configurations becomes relatively easy compared to a structured mesh generation, however the coupling between the CFD solver and the design tool requires more elaborate interpolation tools.

- CAD Processing. The CAD process is used in order to generate the geometric model for the unstructured mesh generation. In this work, the MegaCads[9][10][11] software which has been developed by DLR for CAD processing and mesh generation was used. For the case considered in this work the required input for MegaCads is a structured surface mesh for wing and canard. Output is the geometric model, which defines wing and canard with trimmed surface panels.
- Mesh Generation. After the generation of the geometric model by MegaCads, an unstructured mesh generation software CENTAUR[12] was used in the following step. Setupgrid is the first module of CENTAUR for the definition of the boundaries and other useful information for the unstructured mesh generation. Another important module of CENTAUR is Makegrid. The function of Makegrid is to generate the surface and spatial unstructured mesh. In CENTAUR sources can be used in order to control the cell spacing. This means that sources can be added to the places where higher mesh quality is required. An important and useful module in CENTAUR is Movegrid. Supposing that a spatial unstructured mesh has been generated by CENTAUR and that the correction of surface is small compared to the original one, Movegrid can be used for the generation of a new mesh for the corrected surface. It is unnecessary to generate a new full spatial mesh from the very beginning. Using Setupgrid instead, the original unstructured mesh can be transferred to the new one using the boundary change information. The Movegrid module of CENTAUR is useful especially for the design case, since during the process of the iterative residual correction, in each design step the change of surface geometries is very little and needs several design iterations to get the final result. Without Movegrid, in every design step a new mesh has to be generated from the beginning, leading to much more computing time. Using Movegrid, there is only some transfer work between the original mesh and the new one. The computing time required for Movegrid is 1/4 or even less of that for Makegrid. The limitation of using Movegrid is that geometry changes must be small enough, otherwise the transfer will fail or the new mesh will be of poor quality.
- CFD Analysis. TAU[13][14][15], an achievement of DLR, is an Euler/Navier Stokes solver based on unstructured meshes. It is used in the design process of this work as the CFD analysis module. It works with a finite volume scheme using central or upwind spatial discretization and uses a Runge-Kutta scheme for time integration. It includes several convergence acceleration techniques such as multigrid, local time stepping, enthalpy damping and implicit residual smoothing.
- Interpolation. As mentioned before, a data transfer module is required for the design process in order to interpolate the calculated pressure distribution from the unstructured mesh to the structured one. This interpolation module uses some TAU libraries to get the useful information from the unstructured mesh. It is based on similar interpolation tools developed in [16]. In this work it was adapted and extended to multi-lifting surface applications.
- Inverse Design. This module is the inverse design module of the design procedure, which uses the developed

iterative residual correction principle and treats a design project of two lifting surfaces such as canard and wing or wing and tail plane by taking into account the influence between those two surfaces.

An important prerequisite for developing the overall design code is the coupling of these different computer programs, proven to be operative as single modules. This means that the interfaces between these programs have to be elaborated. Furthermore, since the design involves a chain in which these different components are used iteratively an efficient and robust function of the complete chain has to be developed and tested. The different computer modules are written in different computer languages and work on the same or different computer platforms. For the design chain to be operative for unstructured meshes not only the results of the different modules have to be transferred through the interfaces but also the data transfer has to guarantee an sufficient accuracy of the geometric resolution of the lifting surfaces in each step of the design chain. The coupling of the different modules in this inverse design system is similar to the one developed by R. Wilhelm[16] for the design of isolated and wing mounted engine nacelles.

For the design investigation in NPU, which using AMI's MGAERO as the CFD module, there are three modules: MGAERO, Interpolation and Inverse Design in the design procedure, since the MGAERO contains the functions of mesh generation and CFD calculation.

As the iterative residual correction method needs the design process to run for several times, a UNIX shell script has been written to process the overall design method in an automatic way using different computer platforms.

3 Example

A two surface configuration including the canard and the wing of the model of the DLR "Three Surface Aircraft" project was used in this work as test case for the two surface design case. Fig. 1 shows the geometric model of such a two surface configuration.

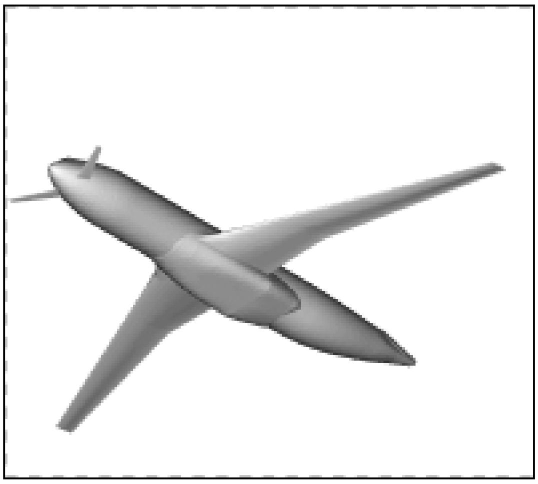

Fig. 1. Canard wing configuration of EuroTSA

The design Mach number for this configuration is M_∞=0.85 corresponding to modern transport aircraft cruise conditions.

For the design cases studied here, the pressure distribution of the transonic wing without canard was used as the design target with the aim and to design a new wing with the same pressure distribution as the original transonic wing, but under the influence of the canard. The target and initial pressure distribution of the canard remain the same, which means that after the design process the canard maintains the same aerodynamic character as before. This kind of design work is useful in the practice of aircraft design. Suppose there is a given conventional configuration aircraft with wing and tail plane, due to the influence of an installed canard the aerodynamic character of the wing changes compared to the case without canard. If the wing shall retain the original aerodynamic character (case without canard), a simultaneous canard and wing design is required.

Fig. 2 shows pressure distribution at wing section with or without the influence of the canard. The figure shows that with the canard influence the pressure distribution show large difference, therefore the simultaneous design of the two surfaces is useful.

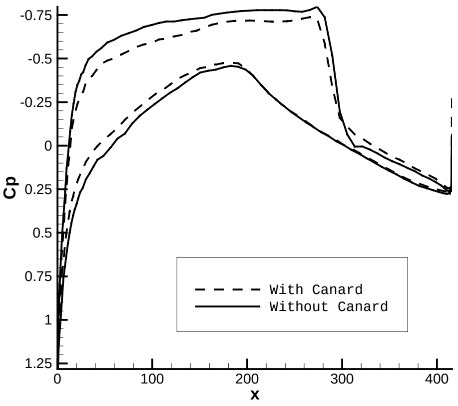

Fig. 2. Pressure distribution of main wing root section （2Z/b=0.00）

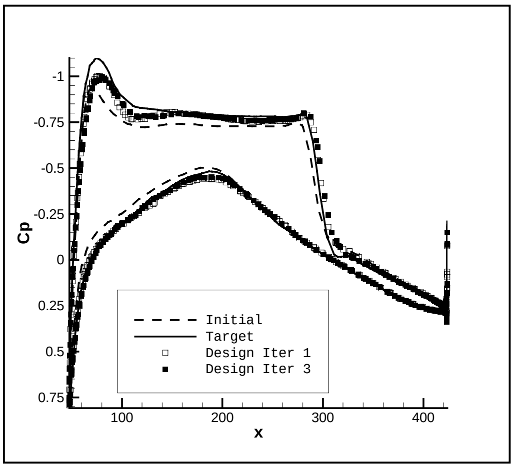

Fig. 3. Design process: Pressure distribution of main wing section （2Z/b=0.154）

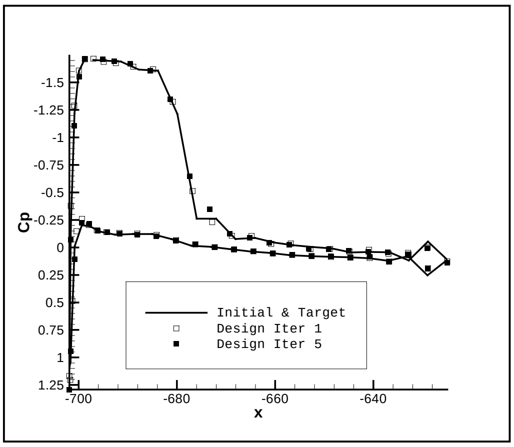

Fig. 4. Design process: Pressure distribution of canard section （2Z/b=0.0）

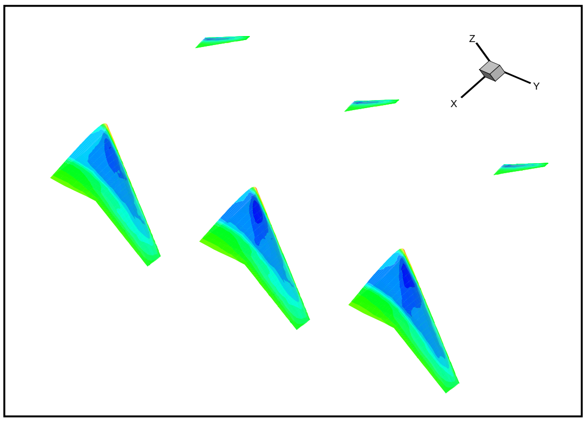

Fig. 5. Contour of pressure of canard configuration (from left to right: Initial, Target and Design result)

Fig. 3 and Fig. 4 show some results of the design case using CENTAUR and TAU.

Fig. 5 shows the result of the same design case but using MGAERO as the CFD analysis module.

4 Conclusions

In this work a multi-surface aerodynamic design code based on the inverse method is extended and coupled with advanced aerodynamic analysis codes in order to be able to design multi-lifting surfaces. Basically mesh generation, CFD-analysis and inverse design modules have been coupled and were used iteratively in an automated way.

The results of the two surface design concerning the canard and wing configuration show:

- For the first design iterations the pressure distributions of all sections for the wing approach the target, this means the design method and software worked well. The pressure distributions for the canard remained nearly unchanged at all during the design iterations, as expected in the beginning.
- After several design iterations, the pressure distributions for the wing sections converged but was unable to fix target exactly, which means that the applied design target is physically impossible, i.e. the wing can not retain

the same pressure distribution as in the wing alone case in the presence of the canard influence.

- The results obtained also show that surface smoothing procedure is necessary and very sensitive to the design results in the design process, which also influence the convergence of design.
- Using different meshes and CFD software, we get nearly the same design result, so the design work is independent of the CFD analysis method and software.

The method and software developed in this work is of significantly practical value for aircraft design but it still needs to be modified and tested.

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