INFLUENCE OF SELECTED TURBULENCE MODEL ON THE OPTIMIZATION OF A CLASS-SHAPE TRANSFORMATION PARAMETERIZED AIRFOIL

by

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An airfoil was parameterized using the class-shape transformation technique and then optimized via genetic algorithm. The aerodynamic characteristics of the airfoil were obtained with the use of a CFD software. The automated numerical technique was validated using available experimental data and then the optimization procedure was repeated for few different turbulence models. The obtained optimized airfoils were then compared in order to gain some insight on the influence of the different turbulence models on the optimization result.

Key words: *computational aerodynamics, turbulence models, optimization, genetic algorithm, class-shape transformation*

Introduction

The always increasing interest in wind turbine technology and enhancing wind turbines efficiency, cutting down air travel cost through reduction of airplanes fuel consumption, improvement of military as well as civil aircrafts performances, *etc*., creates the need for constant improvement of airfoils aerodynamic characteristics and design of new airfoils intended for narrow and highly specialized applications. In order to improve certain airfoil characteristics researchers have been using variety of different direct and inverse design optimization techniques [1-6].

Inverse design techniques are more time efficient but require detailed knowledge of the desired pressure or velocity distribution. Also it is difficult to ensure that for certain desired distribution the airfoil is going to have minimal drag. In the direct design optimization techniques the airfoils geometry is generated, then the aerodynamic characteristics are obtained through numerical simulation and finally the optimization algorithm is applied. Recently most popular methods for airfoil geometry representation are through parameterization of the airfoils shape using parametric curves with control points which are used as design variables in the optimization procedure and the PARSEC method which is designed specifically for airfoils. These allow for the geometry to be represented with only few parameters instead of large number of points.

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In the past aerodynamic characteristics of the airfoil were usually obtained using panel methods. They use Bio-Savart equations to find intensities of vortices while the surfaces are described via sources based on no-penetration boundary conditions. Boundary layer formulations are added to account for viscosity and compressibility. The advancement of computational technology increased computational resources and allowed researchers to, cost effectively, use CFD and Reynolds-averaged Navier-Stokes (RANS) equations coupled with turbulence models for aerodynamic simulations in optimization procedures. Most commonly used turbulence models today are the one equation Spalart-Allmaras, the two equations k-ε and the three and four equations shear-stress transport (SST) turbulence models and their modifications. Most authors consider several turbulence models in the validation case and choose the most suitable one for the optimization procedure. Since different turbulence models can give diverse results for the flow as well as the fact that not all turbulence models are available in different software packages, in this paper the authors have tried to see what is the difference in the resulting geometry if different turbulence models are used for the whole optimization process which, to the authors knowledge, has not yet been done.

The optimization is usually done by gradient based methods or by heuristic algorithms. Gradient based methods are fast but it is difficult for them to converge to a global optimum. Genetic algorithms (GA) are the most popular heuristic algorithms. They are bit slower than the gradient based methods but are more reliable and robust. Sometimes hybrid methods combining both types of methods might be used.

In this paper the class-shape transformation (CST) parameterization was used for airfoil representation, the analyses were made using CFD and the optimization was done by the genetic algorithm. In the analysis three different turbulence models were considered and the resulting airfoils obtained by each were compared to each other.

Numerical models

Class-shape transformation

The class-shape transformation or CST parameterization technique was developed by Boeing employee Brenda Kulfan [7-9]. It is suitable for airfoil parameterization and allows for wide spectrum of airfoil shapes with only few control points (design variables). The number of design variables influences the computational cost of the optimization and CST is therefore very useful in optimization procedures. The CST method has been extended few times in order to account for different 2-D as well as 3-D geometries.

The method is based on Bezier curves and consists of a class function that generalizes it for different geometries and an analytic shape function that defines the parameters such as leading edge radius, trailing edge boat tail angle and closure to a certain thickness. The general form for a typical airfoil can be written as:

$$\zeta\left(\psi\right)=\sqrt{\psi}\left(1-\psi\right)\sum_{i=0}^{N}A_i\psi^i+\psi\zeta_T \tag{1}$$

where $\psi = x/c$, $\xi = z/c$, $\zeta_T = \Delta\zeta_{TE}/c$.

The term $\psi^{1/2}$ provides a round nose, the term $(1-\psi)$ insures a sharp trailing edge, the term $\psi\zeta_T$ controls the trailing edge thickness while $\Sigma^N_{i=0} A_i\psi^i + \psi\zeta_T$ represents a general function for the shape between the round nose and the sharp aft end. The term $\psi(1-\psi)$ is the *class-function* and in general form is defined as:

$$C_{N2}^{N1}(\psi) = \psi^{N1}(1-\psi)^{N2} \tag{2}$$

In order for the airfoil to be a round nose and pointed aft end NACA type the values of $N1$ and $N2$ need to be 0.5 and 1.0, respectively. The shape function is consisted of a component shape function represented by a Bernstein polynomial, eq. (3), and a set of curvature coefficients $A(i)$ for a given airfoil. In eq. (3) K_i^N is the binomial coefficient.

$$S(\psi, i) = K_i^N \psi^i (1-\psi)^{N-i} \tag{3}$$

Genetic algorithm

Genetic algorithms are based on genetic processes of biological organisms. They work with population which is composed of *individuals*. Each of the individuals represents a randomly selected solution of a given problem. The individuals are most often represented with 0-1 binary chromosome scheme.

Once the algorithm is initiated it selects the fittest individuals for the next generation. Each individual is assigned a *fitness score* according to how good a solution of the particular problem it is. More precise, the individuals fitness is defined by the *fitness function*. There are different selection methods that are used in order to prevent the optimization procedure to converge to a local minimum or to a sub-optimal solution. Most popular are the *uniform*, *roulette*, *tournament*, *etc*. After selection, the individuals exchange genetic information through a *crossover* function. This produces the *offspring* or the new set of solutions. The offspring inherits characteristics from both parents. In order to preserve good genetic material that might have been lost through selection and crossover, a *mutation* function can be implemented. The mutation is randomly applied with probability of 0.001 to 0.01 percent. The procedures are repeated until convergence or a stopping criterion is satisfied.

In order to perform an optimization an *objective function* has to be defined. This is the function that is going to be optimized, the one whose minimum or maximum needs to be determined by the genetic algorithm. The objective function that was chosen in this paper is the inverse of the lift/drag ratio:

$$f_{\min} = \frac{1}{C_L / C_D} \tag{4}$$

A more comprehensive overview of the GA is given in [10-12].

Computational fluid dynamics

In order to obtain the aerodynamic characteristics of the airfoils the ANSYS FLUENT software was used for numerical simulations. FLUENT solves the mass, momentum and energy conservation equations by finite volume method [13, 14]. The fluid flow was considered as 2-D and steady while the pressure based solver was used in order to cut computational cost. The spatial discretization was of the second order.

Turbulent models that were used to determine turbulent viscosity in the validation case are: one-equation Spalart-Allmaras (S-A), two-equation standard k-ε (k-ε), k-ω SST (k-ω SST) and four-equation γ-Re$_\omega$ (trans SST).

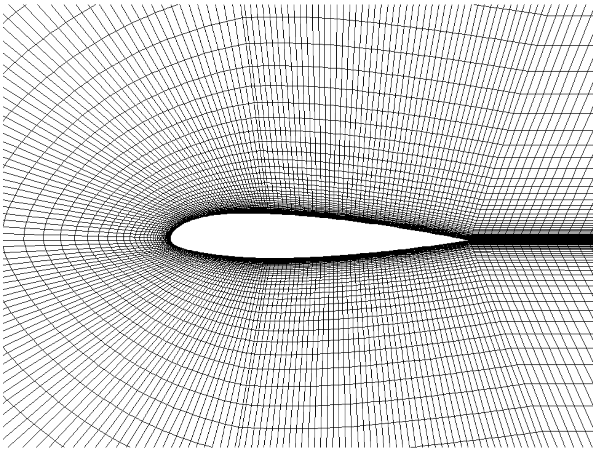

Figure 1. Computational grid

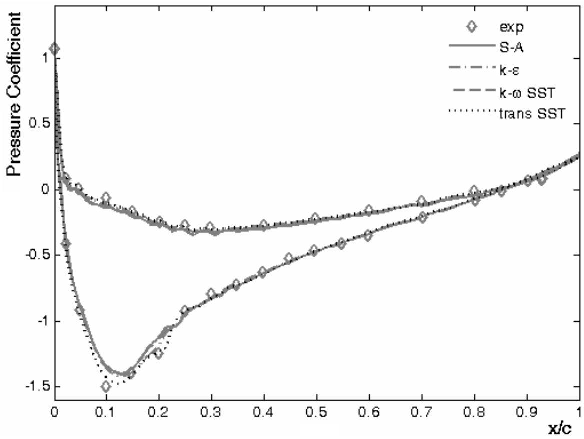

Figure 2. Pressure coefficient distribution

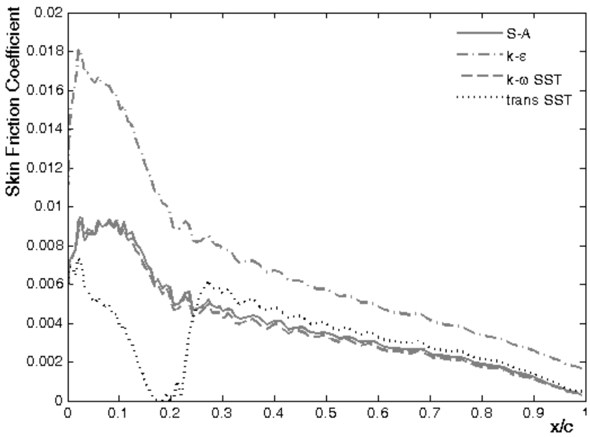

Figure 3. Skin friction coefficient distribution

Analysis

For validation purposes the NACA 23015 airfoil at $\alpha = 2^{\circ}$ angle-of-attack, Mach number M = 0.6 and freestream Reynolds number Re = $2 \cdot 10^6$ has been selected. The numerically obtained results were compared with the experimental results given in [15, 16].

The computational grid was created as structured planar with quadrilateral cells using blocking strategy where the dimensionless wall distance was set to $y^+ < 1$ (fig. 1). The blocking strategy was done in such way as to allow for easy automation of the grid generation process for different airfoil shapes. The computational domain extended from –20 to +25 chord lengths in the x-direction and from –20 to +20 airfoil chord lengths in the y-direction. A grid sensitivity study was done and it was concluded that finer mesh does not give significant differences in the results.

Comparison of the computed pressure coefficient for the different turbulence viscosity models and the experimental ones is shown on fig. 2. It can be seen that there is a good concurrence of the pressure coefficient with experimental results for all turbulence models while the best match is achieved with the use of the transitional SST.

It should also be mentioned that while all turbulence models give good results for the pressure coefficient distribution, only the transitional SST model gives good results for the drag coefficient. All other models overestimate the viscosity component and therefore the drag coefficient. This is probably due to the fact that there is a sonic point on approx. 20% of the chord length and only the transitional SST can take into account the changes in the transonic area. This can be better observed in fig. 3 where the skin friction coefficients of the airfoils upper surface obtained with different turbulence viscosity models are given. It can be seen that only the transitional SST turbulence viscosity model captures the drop in the skin friction coefficient. This accounts for the lower drag coefficient obtained with the trans SST. Unfortunately experimental results were not available for comparison. More detailed explanation of the sonic point phenomena can be found in [16].

Once the numerical methods were validated it was necessary to automate the process of generating airfoils, creating computational grid, numerical simulation and the genetic algorithm optimization procedure. Flowchart of the optimization procedure is given in fig. 4.

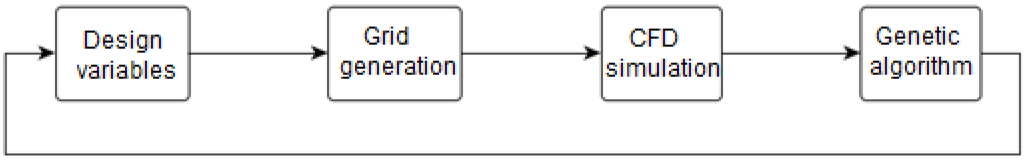

Figure 4. Procedure flowchart

Results

The optimization procedure was done by three different turbulent viscosity models. All other freestream condition parameters were left the same as on the NACA 23015 validation case. Also the optimization parameters were left the same for all three optimization procedures. This was done in order to see if different turbulent models would give different airfoil shapes as the optimal solution. The turbulence models parameters were left as the default values in Ansys FLUENT. The minimal and maximal relative thicknesses of the airfoil geometry as well as the airfoil curvature were limited in order for the results to have practically achievable meaning.

The parameterized airfoils obtained as optimal using S-A, trans SST and standard k-ε turbulence models in comparison with the NACA 23015 airfoil are shown in fig. 5. It can be seen that although small there is difference between the airfoils obtained using different turbulence models.

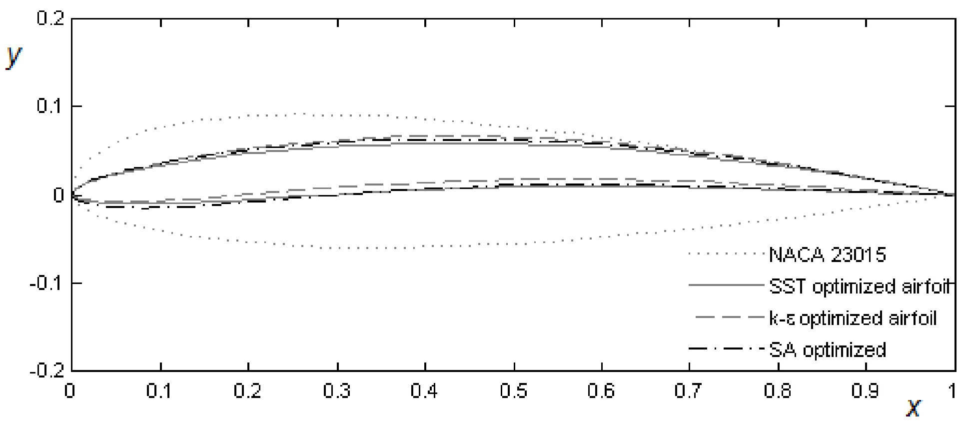

Figure 5. Airfoil shapes optimized with turbulence models in comparison with the NACA 23015

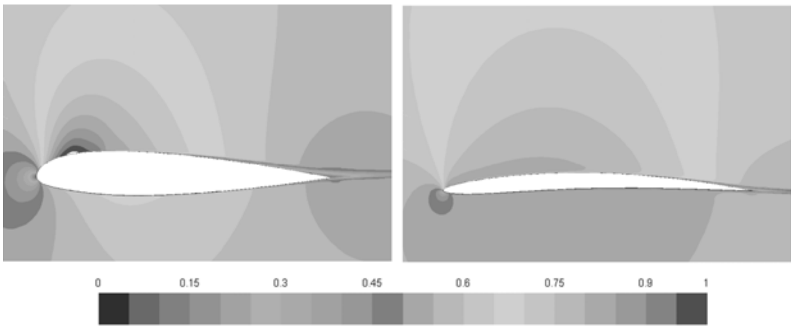

Figure 6. Mach number contours around the NACA 23015 and optimized airfoil using trans SST

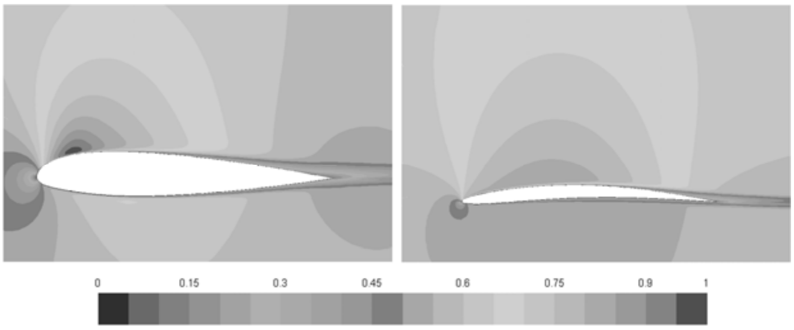

Figure 7. Mach number contours around the NACA 23015 and optimized airfoil using *k*-*ε*

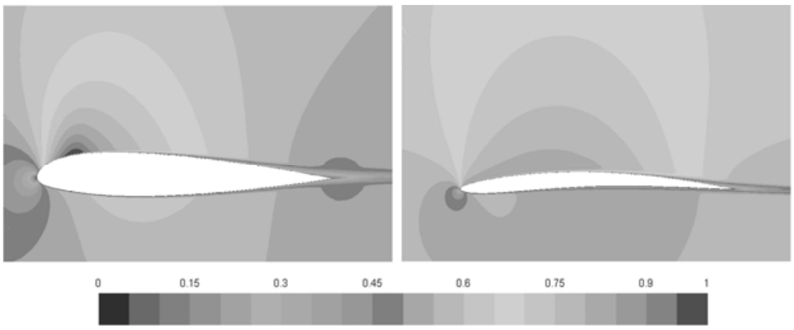

Figure 8. Mach number contours around the NACA 23015 and optimized airfoil using S-A

In figs. 6-8 the Mach number contours of the optimized airfoils are shown while in tab. 1 a comparison between the lift and drag coefficients of the NACA 23015 and the optimized airfoils obtained by different turbulent viscosity models is shown. In figs. 6-8 it can be seen that the trans SST turbulence model predicts significantly thinner boundary layer and lower turbulence level than the S-A and k-ε models.

The optimization done with the k-ε turbulence model gave as a result an airfoil with greater curvature while the one done with the trans SST turbulence model as a result gave a thinner airfoil. This is in agreement with the results given in tab. 1 where it can bee seen that the k-ε airfoil has the largest lift coefficient while the trans SST airfoil has the smallest drag coefficient.

Table 1. Comparison of lift and drag coefficients for the NACA 23015 and the optimized airfoils obtained by different turbulence viscosity models

	Spalart-Allmaras model		Standard k-ε model		Transition SST model	
	NACA 23015	Opt. airfoil	NACA 23015	Opt. airfoil	NACA 23015	Opt. airfoil
C_L	0.429	0.748	0.393	0.771	0.383	0.735
C_D	0.0130	0.0129	0.0236	0.0197	0.0086	0.0069

In order to see the effect of the turbulence viscosity model on the optimization procedure a comparative study in which all of the turbulence models are used for numerical calculation of the airfoils obtained with the optimization using different turbulence models is done. The results of this study are given in tab. 2.

Table 2. Comparison of lift and drag coefficients of the airfoils obtained with different turbulence models calculated with all of the used turbulence viscosity models

	C_D			C_L			C_L/C_D		
optimized	calculated with			calculated with			calculated with		
with	SST	k-ε	SA	SST	k-ε	SA	SST	k-ε	SA
SA	0.0095	0.0193	0.0129	0.723	0.717	0.748	75.92	37.07	57.98
k-ε	0.0088	0.0197	0.0139	0.844	0.771	0.799	95.69	39.13	57.48
SST	0.0069	0.0186	0.0125	0.735	0.675	0.714	106.52	36.29	57.03

In fig. 9 the pressure coefficients and the skin friction coefficients of the optimized airfoils obtained with the trans SST turbulence model are given.

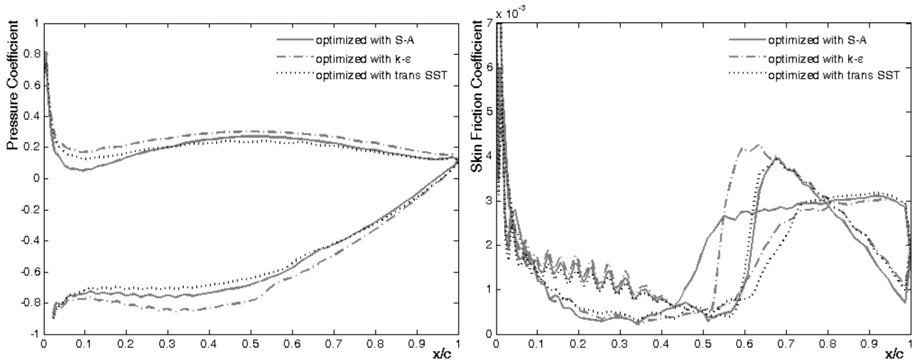

Figure 9. Pressure and skin friction coefficients for all optimized airfoils obtained with the use of transitional SST

Conclusions

Optimization of an airfoil for three different turbulent models was done. The numerical model was validated using the NACA 23015 airfoil at Mach M = 0.6, Re = 2 MRe and at $\alpha = 2^{\circ}$ angle-of-attack. The airfoil shape was parameterized using CST and then optimized with a genetic algorithm using this exact conditions. As the objective function, which was to be minimized, the inverse of the lift to ratio was chosen.

It was shown that there is a difference between the airfoil shapes obtained with different turbulent viscosity models. The trans SST turbulence model was the only one that could capture the discrepancies that occur around the sonic point in the area of transition from supersonic to subsonic flow and the corresponding thickening of the boundary layer in the validation case. The transitional SST model also seems to be the most sensitive to small geometry changes of the three which can be observed in tab. 2. The S-A and standard k-ε showed to be less sensitive to the small changes in shape. However they did create similar geometry with very small deviation than the transitional SST. Having in mind that the k-ε and the S-A in particular are a lot less computationally demanding it should be a good idea to run the optimization procedure using one of these two turbulence models after which the trans SST could be used.

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