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Aerodynamic Validation of a Parametric Airfoil Description

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Tomas Melin
Fluid and Mechatronic Systems, Department of Management and Engineering, Linköping University
Research Associate
Linköping, SE-581 83, Sweden
tomas.melin@liu.se

Roland Gårdhagen
Applied Thermodynamics & Fluid Mechanics, Department of Management and Engineering, Linköping University
Assistant Professor
Linköping, SE-581 83, Sweden
roland.gardhagen@liu.se

ABSTRACT

This paper reports the aerodynamic validation of a parameterized modelling of wing profiles. The parameterization uses 4 piece-wise C1 continuous cubic Bézier curves to model the wing profile envelope. A large set of wing profiles were compared with respect to geometric and aerodynamic similarity between parametric model and point cloud representation. In particular boundary layer properties such as transition point position and drag coefficient; also the critical Mach number is compared between the two sets of wing profile modelling in order to support the conclusion that the two methods of geometrical representation are equivalent.

1 INTRODUCTION

A fundamental part of aircraft design involves wing airfoil design and optimization, establishing an outer shape of the wing, which has good aerodynamic performance for the design mission, good internal volume distribution for fuel and systems and which also serves as an efficient structural member supporting the load of the weight of the aircraft.

There are different methods for airfoil modelling used, depending on where in the design loop the work is done. In the conceptual phase a flat plate might suffice as wing profile model, while in later stages the airfoil might be selected from a database or being modifications of database airfoils. One key aspect of the data making up the airfoil is how it is stored. Several approaches to parameterization of wing profiles can be found in the literature: Airfoils can be described by point clouds as done in most airfoil libraries[1] or they could be described as mathematical functions as is the case with the NACA 4 digit libraries [2][3] and as the Joukowsky airfoils[4]. A more modern representation method is the class function/shape function transformation CST method[5]. The wing profile representation method used for this paper is the Bézier interpolation developed at Linköping University, described in [6]. The proposed parameterization allows for a very compact wing profile data format, where the position of the control points each is stored as a single digit number in a base 64 space. The entire profile can then be defined as a 13 digit number, which in the same way as the NACA 4 digits profiles, have the name is the airfoil.

This paper elaborates on the validation work for the Bézier interpolation. A large number of known wing profiles (1122) have been parameterized to test the validity of the interpolation method. The executed tests investigated geometric and aerodynamic similarity between the original point cloud representation and the Bézier curve representation. The point cloud representations of the selected airfoils came from the UIUC Online Airfoil Coordinates Database[1] and is a distributed selection of old and new, low and high speed airfoils.

2 GEOMETRIC MODEL

The airfoil's top and bottom curves are both modelled by two cubic Bézier curves in parametric form, being C1 continuous at the defined top and bottom points. The profile will also be guaranteed C1 continuous at the leading edge, whereas the trailing edge is allowed to be discontinuous to allow for a trailing edge gap. An example of the Bézier type representation of a NACA2412 profile is shown in figure 1.

Generally a four part cubic Bézier curve requires 13 control points to define the curves, giving 26 variables when both x and y coordinates are taken into account. However when symmetries and simplifications are taken into account the number of independent parameters are reduced to 15.

The employed simplifications are:
- The leading edge is always positioned at [0,0]
- The wing profile slope is parallel to the y axis at the leading edge, meaning that the leading edge control vectors have no component in the x-direction i.e. sharing x coordinate with the leading edge.
- The top most and bottom most points have slopes parallel with the x axis. The associated control vectors share the y-coordinate with their start point.
- The trailing edge has a x component of 1, and the upper and lower sides are symmetrically distributed around the x-axis.

There are also some limitations on the point clouds representation of the airfoil to model:
- The chord line must be on the x-axis. This is not the case with some historical wing profiles like the Clark-Y
- The length of chord must be one
- The trailing edge points must be symmetric in position around the x-axis
- No inflection on the forward part of the airfoil is allowed

2.1 Parameter fitting

The following method was used in order to fit a Bézier curve to the known wing profile point cloud. Firstly the point cloud was scaled, rotated and translated in order to ascertain that it fits the restrictions above. In some instances it was necessary to truncate a minute amount off the trailing edge to ensure that the trailing edge gap was vertical.

The profile point cloud was split into four segments which were then treated separately. A starting guess was generated from the known positions, slopes and curvatures of the constituent

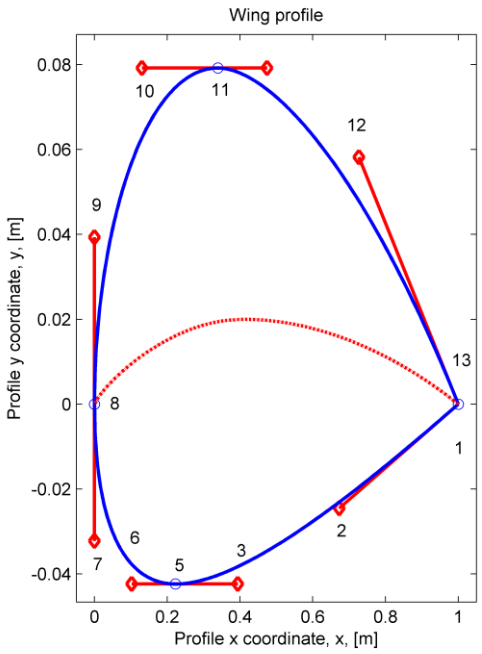

Figure 1: Bézier curves making up a NACA2412 profile

lines. A Bézier curve is expressed with the following expression (equation 1)

$$B(t) = (1-t)^3P_0 + (1-t)^2tP_1 + (1-t)t^2P_2 + t^3P_3 \qquad \text{(eqn 1)}$$

A double nested optimization loop was used. The outer loop optimized the control vector position P2 to P3 while the inner loop optimized the parameter t distribution. The objective function was to minimize the RMS error in the vertical position of the coordinate points. As the loop was nested, solving could take some time, up to 5 minutes on a desktop computer for an entire airfoil. The convergence criterion was set to RMS $\Delta Y < 10^{-4}$.

3 VALIDATION METHOD

In order to validate and verify that the proposed Bézier representation actually models the original airfoils several checks were made. Geometrically, the RMS ΔY was used as a first indicator. Additionally to the ΔY distribution, the curvature distribution, k, and the Δk, difference in curvature, distribution was examined for each airfoil. In order to have a compact reporting format, the error was reported in counts, i.e. ten-thousands (10^{-4}) rather than percent. Figure 2 show the geometrical error for the parameterization of the Whitcomb profile, while figure 3 show the error in drag and pitching moment as well as the error in transition point position for different lift coefficients.

Aerodynamically, the drag coefficient at CL=0.3 was compared between the two models, as were the pitching moment coefficient and the position of the transition point between laminar and turbulent flow. Furthermore the critical Mach number was compared between the two types of wing profile representations.

The aerodynamic study was primarily executed the XFOIL at a Reynolds number of 6 million. By collecting comparative data for a large set of profiles, a statistical analysis of the entire cohort was possible. Further verification studies were made in Fluent. The preliminary results show a good agreement between the aerodynamic properties of the point cloud representation and the parameterized

In order to ascertain that the parametric model indeed is accurately modelling the aerodynamic properties of the original point cloud airfoil, a comparative study was made using a higher order method. The aerodynamic properties of set of airfoils were analyzed using the CFD software Fluent. The computation was performed used automated grid generation with C-grids and grid convergence analysis for both the point cloud airfoils and the parameterized airfoils. The turbulence was handled with Menter's SST k-• model, developed to accurately predict separation in adverse pressure gradient flow. Skin friction

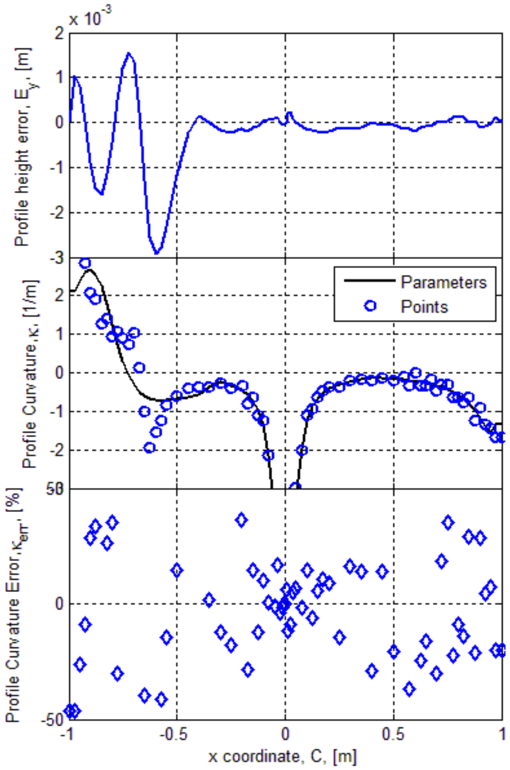

Figure 2: Geometrical errors of the parameterization of the Whitcomb profile. The large errors in curvature is attributed to poor condition of the original point cloud.

and pressure coefficient distributions at flight Reynolds and Mach number were collected together with stall angle of attack and post stall behavior.

The wing profiles CAST 10-2/DOA 2 transonic airfoil, Lockheed-Georgia C-141(a) and C5a transonic wing airfoils, were chosen for the flow simulations. A structured C-grid type mesh was constructed in ICEM CFD 15.0 (Ansys Inc., Canonsburg, PA, USA). Since moderate angles of attack were considered, i.e. no massive separation in the flow, the wall adjacent cells were placed in the logarithmic layer with a y+ of about 100. The growth rate in the wall normal direction was 1.1.

The flow simulations were conducted using Ansys Fluent 15.0 (Ansys Inc., Canonsburg, PA, USA) with the k-w SST turbulence model. A freestream boundary was employed at the outer part of the computational domain and no slip was used at the surface of the airfoil. At the freestream boundary, the Mach number along with the components in each spatial direction were specified. Second order upwind schemes were used for the convective fluxes of the momentum equations and the turbulence equations.

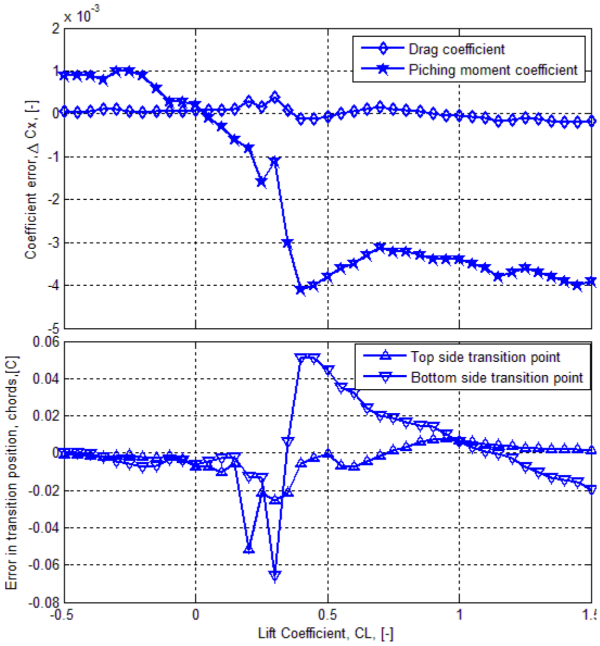

Figure 3: Aerodynamic errors of the parameterization of the Whitcomb profile.

4 RESULTS

4.1 Geometric Similarity

The geometrical similarity between the two methods of wing profile representation was investigated both on an individual level, as well as cohort statistics. The individual results were reported earlier in [6]

Figure 4 show the distribution of RMS ΔY for 1110 wing profiles. As the best fit Bézier curves were found with an iterative approach based on minimizing ΔY, there are few instances with zero error as the iterations were stopped once the convergence criterion was reached. The average error, across all profiles, was only 3 ects or 3/10000 which is regarded as a very close fit. There were some outliers with high geometrical errors, but on closer inspection these were profiles not suitable for the proposed type of parameterization to begin with.

The error, or residual, distribution with respect to curvature had a very similar shape. Although, since quite a few of the profiles in the database had an inflection point somewhere on the rear part, the error in curvature became infinite at this point.

4.2 Aerodynamic Similarity

The aerodynamic similarity between the two was also done both individually and statistically. Figure 5 shows the statistical result for the difference in drag coefficient at a lift coefficient of 0.3. The error is close to normally distributed, with a slight tendency for the Bézier curves to under predict the drag. For the 975 converged cases the average drag coefficient was 1 drag count lower for the parametric curves. This is to be expected as this profile is a lot smoother than the point cloud distribution. The standard deviation is just shy of 3 drag counts, which is about the accuracy of the Xfoil method used for prediction. As with the geometrical errors, there were some outliers where the original point cloud representation were in a poor condition.

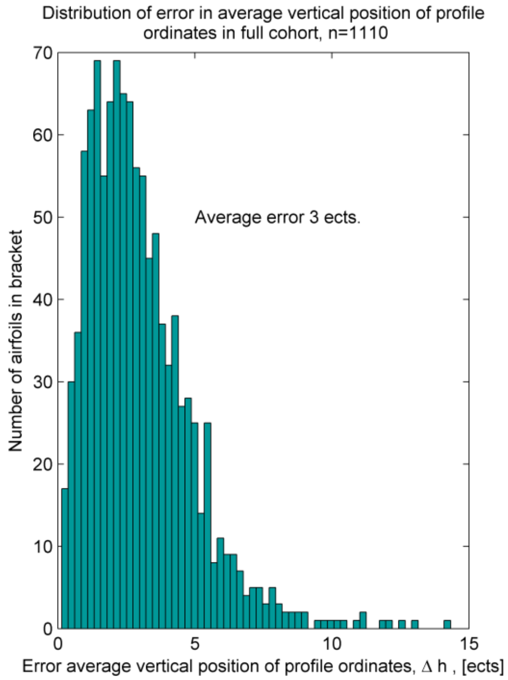

Figure 4: Distribution of absolute error in the average vertical position.

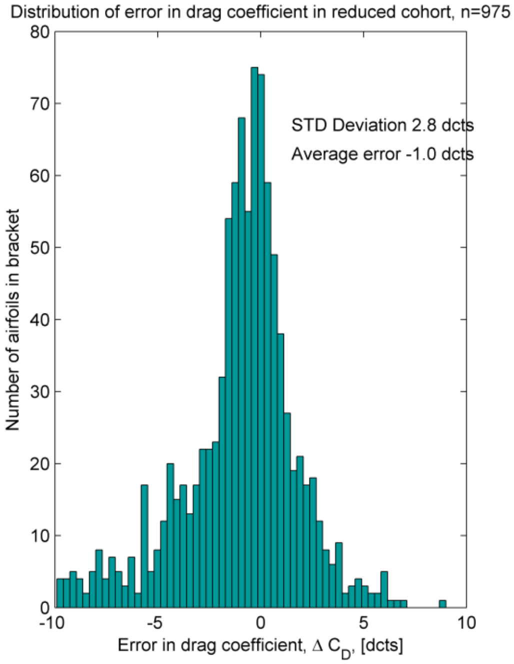

Figure 5: Distribution of difference in drag coefficient.

Figure 6 show the distribution of error in pitching moment coefficient. As the moment is taken around the c/4 point, the moment coefficient is quite sensitive to the position of the center of pressure. Still, the standard deviation was 30 counts, or 0.3%. The cohort average was just 0.4 counts, which is negligible. Figure 7 show the distribution of difference in transition point position of the upper side of the airfoil. The overall results are similar to the other aerodynamic considerations. The error is reported as position error of the point cloud value, rather than chord position. This means that for a normal transition point position on 10% of the chord, a 10% error would translate to a 1% error in chord length. The standard deviation was 4.4% with a cohort average of 1%. This is lower than the mesh resolution for most of the airfoils.

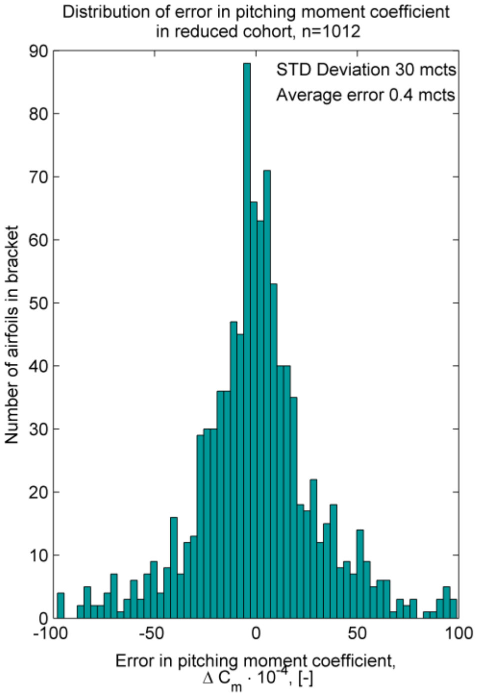

Figure 6: Distribution of error in pitching moment between the two representations.

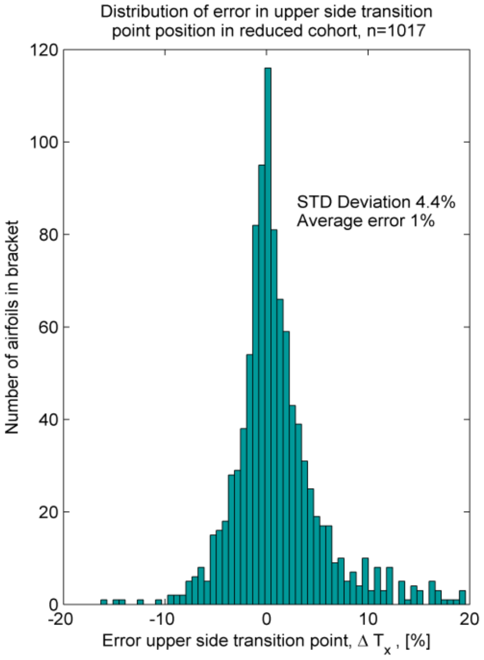

Figure 7: Distribution of error in transition point position on the upper side between the two representations

When investigating the critical Mach number for the cohort of profiles, results again followed the same trend. Figure 8 show the distribution of difference in critical Mach number. The standard deviation is 0.017 with an average of 0.002.

4.3 Higher order study

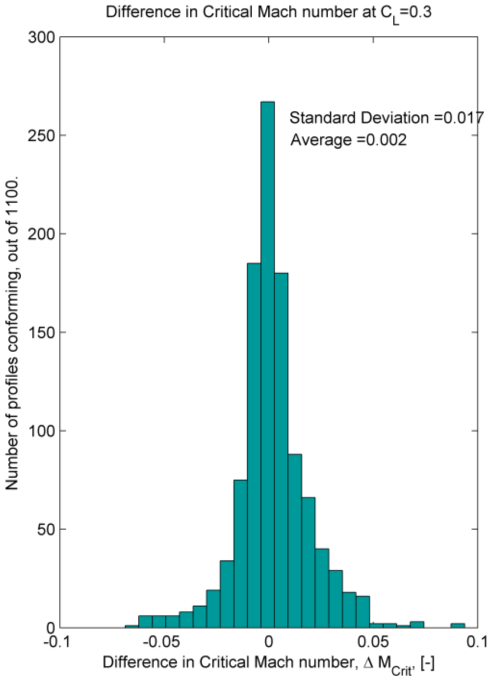

Figure 8: Difference in critical Mach

Lift and drag coefficient obtained from the reference airfoil and the corresponding parametrized airfoil created using the profile generator using Fluent are shown in Figure 9. Apparently, the drag is predicted almost identically for the two representations of each profile below as well as above the critical Mach number, i.e. even after the appearance of shock waves. For the C5a, Fig. 9a, the lift is also almost identical for the reference and parametric airfoil. As for the other two profiles, it seems to be an overestimation the lift force for the parametric profiles compared to the reference profiles, particularly in the presence of shock waves. With the good agreement for drag in mind, this suggests that the dominating drag component is friction (as expected for these small angles of attack), and that the separation point, which strongly affects the pressure distribution and hence lift, is not captured identically for the both models. This indicates that the region close to the separation point, as expected, is a crucial region and should be recreated accurately.

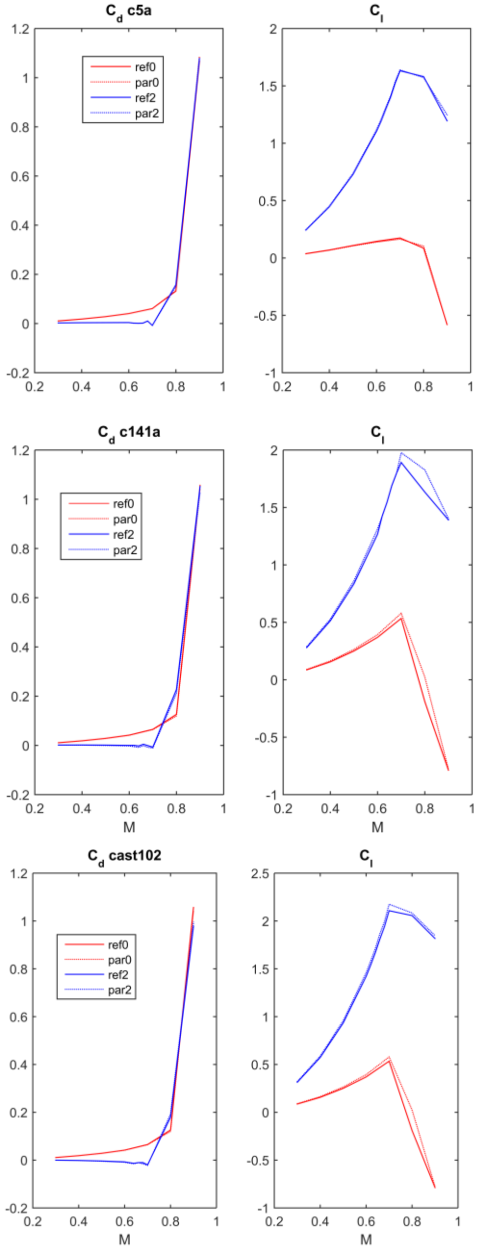

Figure 9: Mach number dependency of Lift and drag coefficients for point cloud and Bézier representations of a) C5a, b) C141a and c) CAST102 airfoil at 0 and 2 degrees angle of attack.

5 DISCUSSION

Some known airfoils are not suitable for the Bézier type of interpolation. Some rotorcraft airfoils with a flat plate extension at the trailing edge will not be modelled properly, nor will facetted airfoils for solar panel installation.

The C1 continuity at the top and bottom of the airfoil means that there might be a discontinuity in profile curvature at these points. Aerodynamically this is not ideal, but it seemed as many older wing profiles had this feature. In order to get a good agreement between the two representations, the same C1 continuity was selected for the Bézier representation. However, numerically most modern profiles still are C2 continuous on the entire upper and lower surface, as this is the best curve fit to existing point clouds.

For some point cloud profiles which needed a lot of scaling, rotation and translation on order to conform to the profile requirements, it became necessary to truncate a small portion of the trailing edge, as the upper and lower sides no longer shared the same x-coordinate. This truncation was usually in the order of 1/1000 chord length and the effects on the aerodynamic properties neglected. However, for profiles that was rotated, the zero lift angle of attack no longer will conform to older wind tunnel and computational data.

Interestingly, the Bézier based profiles did not have a better aerodynamic performance over the point cloud representations. Instead the difference between the point cloud and the Bézier representations was close to zero.

One key motivation for this work was to be able to have a wing profile representation with the same type of nomenclature as the NACA 4 digit series, where the name of the airfoil defines the geometric shape. With the parametric Bézier description this is fully possible. For example the well-known Whitcomb profile can be described, or renamed, as k1aVYk1WmX7zF8B and still retain geometric and aerodynamic similarity. Two immediate problems become evident:

1. The parametric name is not suitable for human memory recollection and
2. As the name is the shape, confidentiality might be an issue for those who need to keep the actual geometry secret.

Further studies will also investigate the similarity with stall behavior of the airfoil in the two different representation methods.

6 CONCLUSIONS

The Bézier representation of known wing profiles has been shown to yield close to identical results to their point cloud representations. The geometric similarity is very close for most of the selected airfoils as is their aerodynamic behavior. Drag coefficient, pitching moment coefficient and boundary layer transition point position are in good agreement between the two representations methods. As is the compressibility behavior.

The experienced variance is usually within the tolerances of the methods employed.

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