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Development of Deformed CAD Geometries of NASA's Common Research Model for the 6th AIAA CFD Drag Prediction Workshop

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A method for modifying the shape of digital geometry representations used in Computer Aided Design (CAD) applications according to experimental pointwise deflection data is described. In the pilot study presented here the method is applied to the CAD geometry of an aircraft wing which is deformed using measured deflections obtained from the associated wing model during a wind tunnel test. The method provides various advantages in Computational Fluid Dynamics (CFD) and other applications. Numerical grids generated on the deformed geometry yield an improved correlation of CFD results to wind tunnel data without the need for aeroelastic computations, which require coupling to a structural model. Additionally, the method is beneficial in aerodynamic optimization, where the optimized shape is usually given in the form of a CFD surface mesh or nodal deflections, which, for further processing or manufacturing purposes, need to be transferred into a CAD geometry description. The paper presents an application to NASA's Common Research Model (CRM) transport aircraft configuration, where deformation measurements from a test campaign in the European Transonic Wind Tunnel (ETW) are processed to provide deformed CAD geometries for use in the forthcoming 6th AIAA CFD Drag Prediction Workshop (DPW-6).

Nomenclature

α	=	Angle of Attack, degrees
ε	=	Wing Twist Deformation, degrees
i	=	Point Index
Ma_∞	=	Freestream Mach Number
n	=	Profile Section Index
q_∞	=	Freestream Dynamic Pressure, Pa
Re	=	Reynolds Number
T_{tot}	=	Freestream Total Temperature, K
u,v	=	Cartesian Deflection Components, m
w	=	Wing Bending Deformation, m
x,z	=	Cartesian Coordinates, m

I. Introduction

During a wind tunnel test the model is subjected to a broad variety of test conditions. The associated aerodynamic loads cause significant wing deformations which largely vary with dynamic pressure and angle of attack. The influence of these deformations on the aerodynamic properties generally cannot be neglected, in particular when testing at high Reynolds numbers or off-design conditions, and lead to discrepancies when comparing wind tunnel test data to CFD results. The usual approach to overcome these

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discrepancies is to perform aeroelastic computations which take into account the physical interaction between the outer flow field and the elastic model, but require some kind of structural model and the use of fluid-structure coupled (FSC) simulation methods.

The CAD modification method introduced here is applicable in cases where deformation data from a wind tunnel test is readily available. It uses measured wing deformations, usually provided in the form of bending and twist deflections at various spanwise locations, to generate a smoothly deformed wing surface CAD geometry from a given baseline. The approach ensures that numerical and experimental shapes, in particular the aerodynamically relevant spanwise twist distribution, are identical. Contrary to fully aeroelastic simulations a finite-element model of the wing and interpolation procedures for the transfer of aerodynamic loads onto the structural model and structural deflections back into the CFD grid are not needed. Using a deformed CAD geometry definition enables any potential user to generate his own grids using his preferred grid generating software and meshing strategies.

II. Description of the CAD modification procedure

The CAD modification procedure consists of three consecutive main steps:

1. Transformation of measured bending and twist deformations into Cartesian deflections,
2. Deformation of an auxiliary wing surface mesh using computed deflections from the first step,
3. Modification of the baseline CAD geometry based on nodal coordinates from the deformed and undeformed auxiliary surface meshes.

A. Computation of Cartesian deflections from wind tunnel deformation data

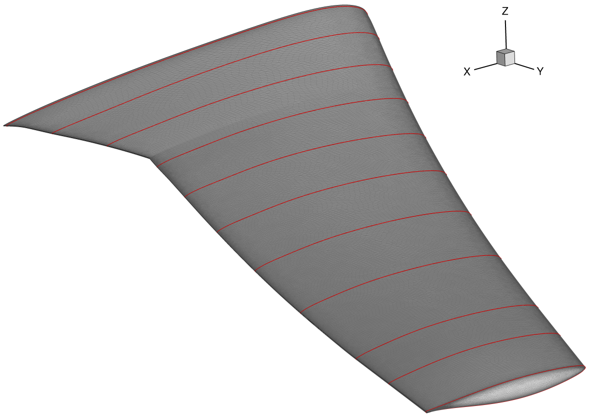
Experimental data from a wind tunnel test campaign is usually provided in the form of bending and twist deflection components at discrete spanwise locations on the wind tunnel model wing. This data format is not suitable as input for the mesh deformation algorithm used in the second step. To compute the required Cartesian deflection components, an auxiliary, unstructured, triangular wing surface mesh is generated on the given baseline CAD geometry using the commercial grid generation software Centaur^{TM}[1] and a set of spanwise airfoil sections, corresponding to the measurement locations, is extracted from this mesh, Figure 1 (a). Next, the extracted airfoil sections are relocated according to the measured twist, Figure 1 (b), and bending deflections. For twist, this corresponds to a simple rigid-body rotation around the transverse (pitch) axis, for bending, it includes both an upward and inward displacement as well as a rotation around the longitudinal axis. Including the 'real bending' instead of just an upward shear deformation ensures that wing reference area remains constant.

Deflection components $[u, v]_{i,n}$ for each grid point i along the individual spanwise sections n are computed by subtracting nodal coordinates of the relocated airfoils $[x', z']_{i,n}$ from the coordinates representing the original locations $[x, z]_{i,n}$, Figure 1 (c) (shown here for twist only). The Cartesian deflection components obtained in this way are subsequently used as control point deflections for the deformation of the auxiliary wing surface mesh.

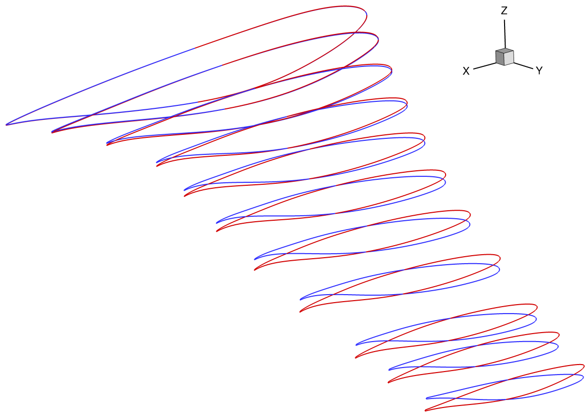
B. Surface mesh deformation

In the second step, the Cartesian deflections computed at the set of n spanwise airfoil sections are used to deform the complete surface grid. Here, an interpolation scheme based on radial basis functions (RBF),[2] available as mesh deformation algorithm within DLR's RANS flow solver TAU,[3] is applied. RBFs are particularly well suited for smooth functions like the aeroelastic deformation fields considered here. Figure 2 shows the undeformed and deformed surface meshes. Residual deflections at the wing root are evenly declined over the belly fairing surface and vanish at the fuselage-belly intersection line.

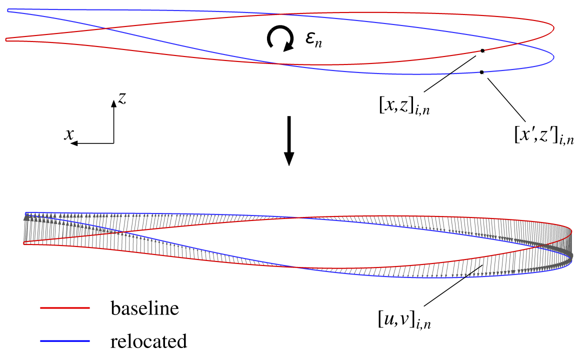
After deforming the auxiliary surface mesh nodal coordinates from grid points on the undeformed and deformed meshes, together with the associated element definitions, are exported into the bulk data format from the commercial structural analysis software NASTRAN®[4] using the GRID card format to provide nodal coordinates and the CTRIA3 card format for connectivity information.



(a) Auxiliary surface mesh and airfoil sections



(b) Slice relocation according to measured twist (not to scale)



(c) Computation of Cartesian deflections from measured twist

Figure 1. Computation of Cartesian deflections from wind tunnel deformation data.

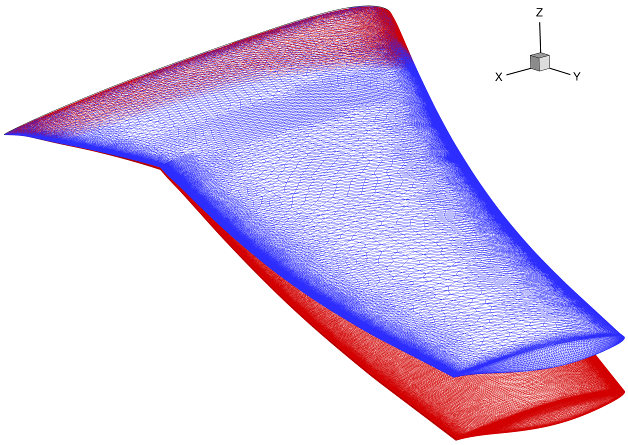
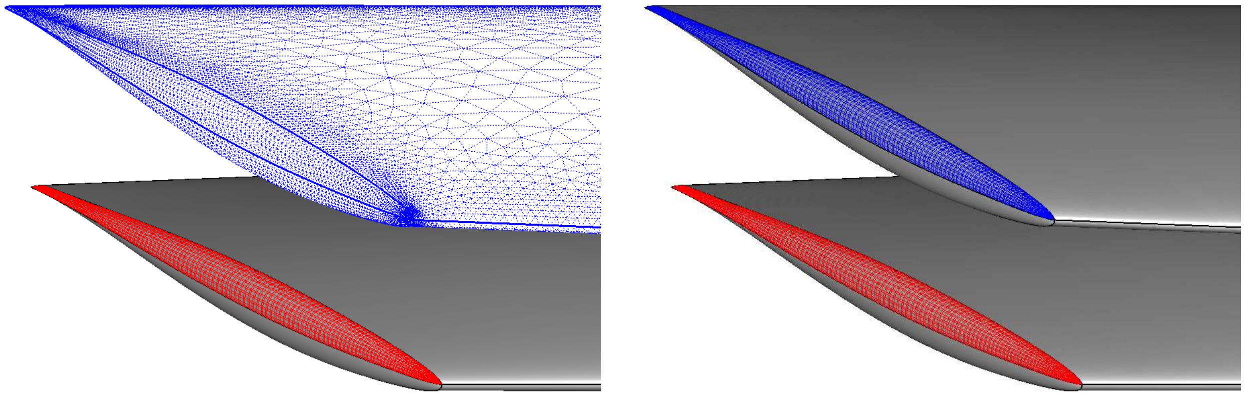


Figure 2. Undeformed and deformed surface meshes.

C. CAD modification

Finally, the baseline CAD geometry is deformed using the CAD translation tool CADfix.[5] The tool reads the bulk data files which comprise nodal coordinates from the undeformed and deformed surface meshes and converts the baseline CAD geometry given in the vendor-neutral Initial Graphics Exchange Specification (IGES) file format into the deformed shape using an advanced geometry deformation functionality. A unique feature of the deformation tool is that it does not follow the traditional approach of generating completely new curves and surfaces by a least squares fitting of the deformed mesh nodes, which is known to give poor results in regions of high curvature, such as leading edges. The approach is based on a novel NURBS based adaptive deformation algorithm that applies the mesh deformations directly to the original CAD geometry to match it to the deformed mesh. Deforming the CAD geometry (instead of fitting a new geometry) has the significant advantage of preserving any complex design intent in the original CAD, such as highly curved regions. This feature is particularly beneficial in generating a high quality deformed geometry of the wing leading edge and wing tip, as shown in Figure 3.



(a) One of the highly curved original CAD surfaces (red) at the wing tip and the deformed mesh

(b) The wing tip CAD surface after deformation (blue), showing the preservation of the original surface design

Figure 3. Deformation of the CAD geometry using the auxiliary surface mesh.

III. Application to the NASA Common Research Model

The accurate calculation of aerodynamic parameters is of significant importance during the design and analysis of an aircraft configuration. Over the last two decades, the field of Reynolds-averaged Navier-Stokes (RANS) based Computational Fluid Dynamics has significantly progressed regarding robustness, efficiency, and the capability to handle complex configurations.[6,7] Today, incremental aerodynamic coefficients of typical transonic aircraft can be calculated with acceptable accuracy, both around the cruise design point and for non-separated flows. However, regarding absolute values and increments at off-design conditions, significant challenges still exist to accurately compute aerodynamic data and model the underlying flow physics.

Based on these challenges, a working group of the AIAA Applied Aerodynamics Technical Committee initiated the CFD Drag Prediction Workshop (DPW) series[8] in 2001, resulting in five international workshops to date. Participants and committee results have been summarized in more than 120 papers.[9–13] DLR's Institute of Aerodynamics and Flow Technology is supporting DPW as a committee member and participant.[14–18]

Starting from DPW-IV, the NASA Common Research Model (CRM)[19] civil transport aircraft configuration, Figure 4, designed by NASA's Subsonic Fixed Wing Technical Working Group and by Vassberg et al.,[20] has been used as the reference geometry. Geometrical and experimental data of the model are also found on the NASA CRM web site.[19]

During the 4th and 5th workshop, exceptionally large deviations were observed between the participants computational results and experimental data, part of which were traced back to the aeroelastic deformation

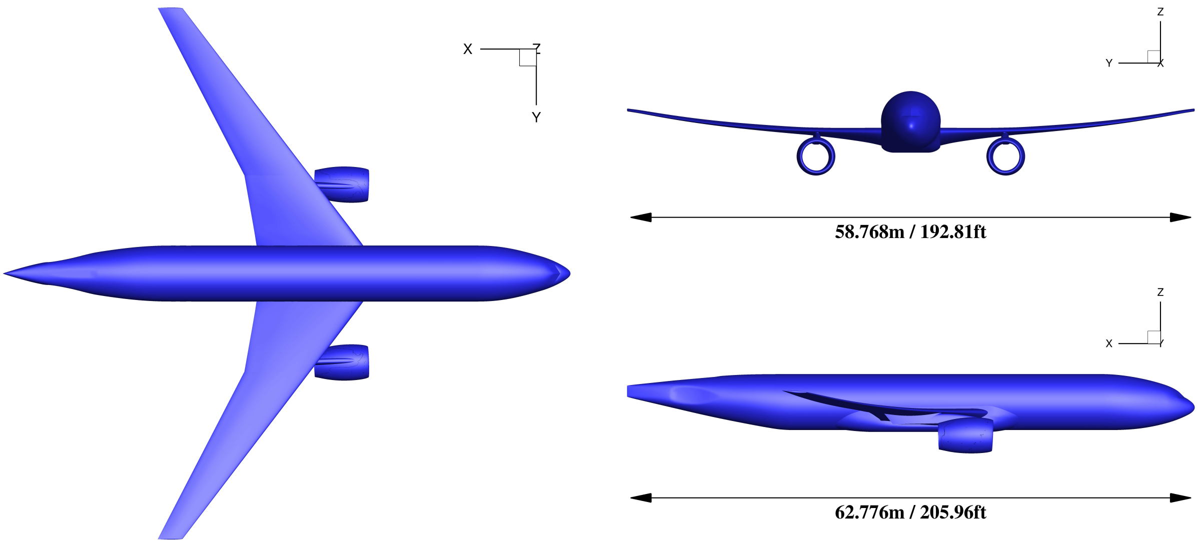


Figure 4. NASA Common Research Model, configuration including wing, body, nacelles, and pylons.

of the model wing. Following these results, NASA and DLR decided to more closely investigate aeroelastic effects by performing fluid-structure-coupled (FSC) simulations based on NASA's finite-element structural model of the CRM wind tunnel model and DLR's CFD solver TAU.[21] The study revealed a significant influence of model deformations on the overall aerodynamic properties. This implicates that the wind tunnel model adopts its built-in design flight shape only for one sole design flow condition used in conjunction with the wing's given structural stiffness. For all deviating flow conditions, e.g. varying angle of attack, Mach number, or Reynolds number, the correlation between numerical and experimental results will degrade due to varying aerodynamic loads and the corresponding model deformations.

In order to compensate for the observed effects of aeroelastic model deformations, and thus to enhance the correlation between CFD and experimental data, the DPW organizing committee has agreed to provide aeroelastically deformed CAD geometries of the CRM wing for use in conjunction with the CRM-related DPW-6 test cases.

Measured wing bending and twist deformations were taken from the Trans National Access (TNA) test campaign at the European Transonic Wind Tunnel in Cologne, Germany, as part of the European research project ESWI^{RP} (European Strategic Wind tunnels Improved Research Potential).[22] Deformation data for the flow conditions defined for the CRM test cases and the required angle of attack range was available from run no. 182, Table 1. As measured angles of attack from the data points available slightly differ from the angles required, an interpolation of measured deformations to the exact angle of attack values from the test case definitions, Figure 5, has been performed prior to applying the CAD deformation process[a].

Table 1. Flow conditions of selected reference test run from ETW test campaign.

Ma_∞	Re	q_∞	T_{tot}	α
0.85	$5{\cdot}10^6$	60,521 Pa	300 K	$2.5°, 2.75°, \ldots, 4.0°$

The auxiliary surface mesh, Figure 1 (a), needed to convert measured deflections to Cartesian deflections for mesh deformation input, has 287,000 nodes and 573,000 elements. Special attention was addressed to achieving a uniform spatial distribution of mesh points in order to ensure a smooth deformation of the resulting CAD geometries. In order to avoid any undesired distortion of the engine nacelle and pylon, these components were not included in the surface mesh for deformation. Here, a relocation according to the new wing-pylon junction line location is performed within the CAD environment.

Following the procedure described above a total of seven deformed IGES geometry files, one associated

[a]Interpolated deformation data was kindly provided by E.Tinoco, member DPW Organizing Committee.

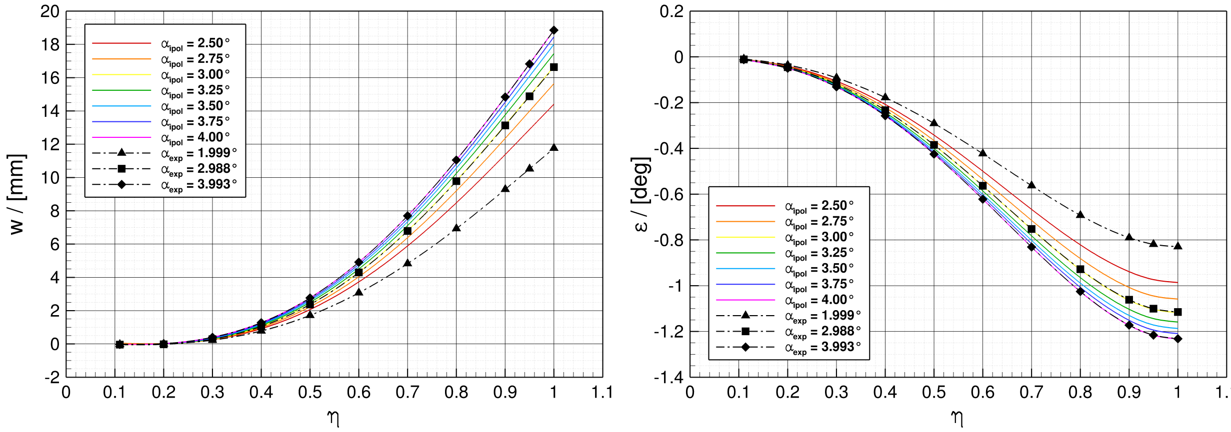


Figure 5. Measured and interpolated wing bending and twist deflections, ETW test run no. 182.

to each angle of attack required in the DPW-6 test cases, have been provided. Figure 6 shows an example of the undeformed geometry and the deformed shape for $\alpha = 4.0°$. The CAD files are available for download from the DPW website at: http://aiaa-dpw.larc.nasa.gov/Workshop6/DPW6-geom.html.

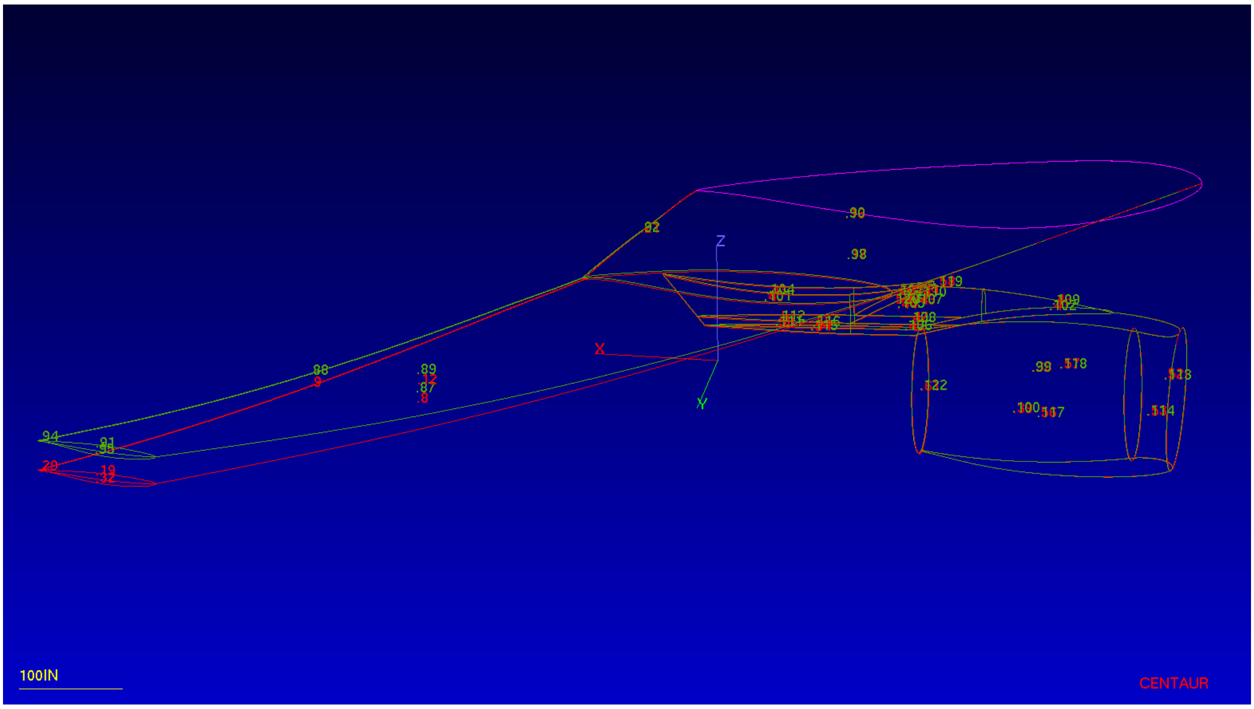


Figure 6. Undeformed (red) and deformed (green) IGES geometries of the CRM wing.

Conclusions

A novel method for using experimental deformation data to modify existing CAD geometries has been introduced. The method enables the deformation of a given baseline geometry representation according to measured pointwise deflection components. To ensure a smooth extrapolation of the pointwise input data onto the CAD surface, an RBF mesh deformation algorithm, in conjunction with an auxiliary surface mesh generated on the given baseline geometry representation, is used. Rotational deflection components, like the twist deformation of an aircraft wing subjected to aerodynamic loads, need to be transformed into Cartesian deflection components to comply to the data format required by the RBF deformation algorithm. The CAD geometry is deformed using nodal coordinates and deflection components from the auxiliary surface mesh. The method has been applied to the CAD geometry of NASA's Common Research Model transport aircraft configuration using measured deflections obtained during a test campaign in the European Transonic Wind Tunnel in order to provide deformed CAD geometries for use in the 6th AIAA CFD Drag Prediction Workshop. Using the deformed reference geometries enables participants to include the effects of model deformations on aerodynamic parameters without the need to perform aeroelastic computations.

Acknowledgments

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