An Efficient Approach to Simulating Ice Accretion on 2D and 3D Airfoils

Prof. Marco E. Biancolini[1] and Dr. Corrado Groth[2]
University of Rome "Tor Vergata"
Via Politecnico 1, 00133, Rome, Italy

Abstract

Accurately predicting collection efficiency and ice accretion requires a tight coupling between the water/ice particle trajectories, the aerodynamics and the thermodynamics. Being able to efficiently link the numerical simulation with the geometrical change that it implies can be a paramount. A study was carried using a radial basis function approach within a detailed CFD analysis loop to demonstrate the ability to dynamically morph an aircraft wing profile to realistic ice shapes in both 2D and 3D. Two 2D airfoils (NACA0012 and GLC305) and one extruded airfoil profile (based on NACA0012) were used and six complete ice shapes based on the LEWICE 2.0 validation manual were applied performing CFD simulations at clean, intermediate and complete accretion stages to investigate the effect on aerodynamic lift and drag.

[1] Assistant Professor, Department of Enterprise Engineering, biancolini@ing.uniroma2.it

[2] PhD Candidate, Department of Enterprise Engineering, corrado.groth@students.uniroma2.eu

Introduction

Flying in icing atmospheric conditions can be a serious safety problem. Ice build-up generally occurs when supercooled droplets impinge on aircraft surfaces, most commonly the engine and the windward face of the wings, causing a variation in the overall vehicle fluid dynamics.

Ice accretions can increase the drag force and decrease the lifting characteristics of the airfoil, so more power and a greater angle of attack is required to maintain flight conditions. Wing Icing causes not only stall to occur at lower attack angles, but an uneven ice distribution that can diminish dangerously the vehicle manoeuvrability.

In-flight icing has been responsible for more than 819 deaths and 583 plane crash in a 19 years span period between 1982 and 2000 in the USA only. Understanding and studying the icing problem is then of capital importance, and an ice accretion analysis has thus became a must during the design process. Ice build-up can be investigated by means of flight tests, wind tunnels or numerical simulations. Flight tests are the most realistic and the most expensive too, so they are used in certain conditions only or in the final stage of the analysis. Wind tunnels can recreate exact ice shapes, but the control over the dimensionless parameters can be very hard. Computational fluid dynamics by the other hand is widely used because it's a low cost alternative than can simulate relatively good the whole icing process, allowing to change instantly an infinite number of related parameters. Although historically NASA and DERA were the main contributors to the numerical models development, nowadays there are several different accretion models from all the major international agencies, such as Lewice (NASA), Trajice2 (DERA), Capta (ONERA), Multi-ice (CIRA) and fensap-ice (NTI).

A typical icing accretion model consists of two main modules that work seamlessly together. The first one deals with the droplets trajectory, and determines the collection efficiency distribution over the whole body. The second one computes a thermodynamic analysis to establish, given the collection efficiency, the ice thickness in any given point. Results from the accretion model can be then used to model a new shape in the analysis environment used for the fluid dynamic simulation. There has therefore to be a direct connection between the ice accretion model and the CFD solver, that can be used cyclically to compute back the flow field for the collection efficiency determination of the new configuration. Being able to generate a high quality grid in the shortest time possible is a major challenge as it is a possible bottleneck of the whole ice accretion analysis in terms of both time and quality.

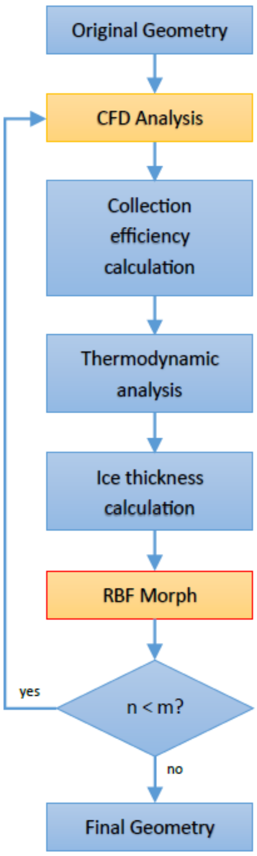

Figure 1 – Proposed workflow

Tools description

Radial Basis Functions (RBF) are powerful mathematical functions able to interpolate, giving the exact values in the original points, functions defined at discrete points only (source points). The interpolation quality and its behaviour depend on the chosen radial basis function. In the field of mesh morphing radial basis functions find their natural application. Using RBF can be indeed modified the displacement at discrete points, and interpolated congruently every nodal position of the grid in a mesh independent fashion, as it deals with points positions only.

Radial Basis Functions are the ideal tool for the grid generation problem in an icing application. Instead of having to rebuild the mesh at every step to take into account new ice layers, the new shape can be obtained imposing the displacement required by the accretion model to the source points, and morphing accordingly the wing shape and the fluid domain using RBF. An important amount of time and computational resources can be saved integrating the RBF morpher into the work flow.

LEWICE 2.0 is an extensively tested ice accretion computer code developed by NASA that includes an analytical thermodynamic model for the freezing evaluation of the supercooled droplets. The final ice shape can be modified varying the atmospheric and meteorological parameters such as velocity, pressure, temperature, liquid water content, relative humidity, droplet diameter.

Proposed workflow

The workflow proposed in this paper, using ANSYS Fluent for the CFD analysis and RBF Morph for the morphing task, is displayed in Figure 1. The original Mesh geometry is used for the CFD analysis in the first step only: droplet trajectories and water volume content are then computed for the collection efficiency calculation. The results are used as inputs for the thermodynamic analysis that allows the ice thickness evaluation for every point of the surface. Finally translating ice thickness into nodal displacement allows to morph the interested domain using RBF Morph, generating the new iced geometry that can be used as a starting point for a new calculation cycle. The process can be executed cyclically for the number of step required.

To put the focus on the interested task and to showcase the ability of the RBF morpher, the process has been simplified eliminating the need for an accretion model. Six complete ice shapes were indeed taken from the LEWICE 2.0 validation manual and fed directly into RBF Morph, simulating the ice accretion model working output.

Original airfoil geometries

Two 2-D clean wing geometries were used in this study. The NACA0012 profile has been widely used in icing tests over the years, and the GLC305 is representative of a business jet aerofoil. To be able to compare properly the results from the different accretion runs was chosen to maintain the initial grid as similar as possible both in the NACA0012 and in the GLC305 related cases. A single mesh of a NACA0012 2D wing was then used as a starting point for all the simulations and, to assure the needed uniformity, radial basis functions were used when needed to change its shape into a GLC305 profile. While the NACA0012 profile was used for the first simulation, the GLC305 aerofoil was involved as a starting geometry in the remaining five.

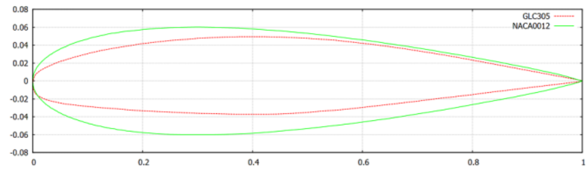

Figure 2 – GLC305 and NACA0012 airfoil profiles

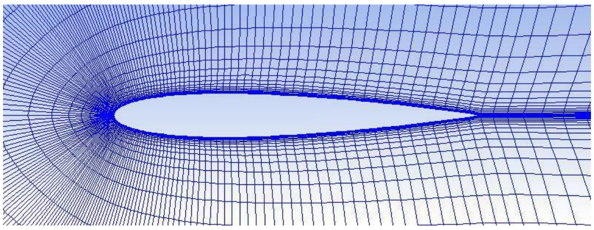

Figure 3 – NACA0012 clean grid

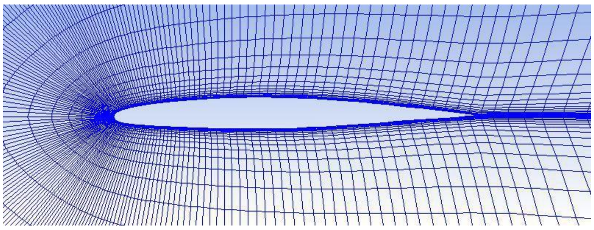

Figure 4 – GLC305 clean grid obtained through NACA0012 morphing

Numerical setup

Even if in the case in study the icing shapes were already known in advance, source nodes displacements were given at steps, to simulate with a better accuracy the RBF morpher working inside the workflow and receiving only the information relative to the current calculation cycle. In the absence of the real accretion model ice build-up was simulated, without loss of generality, linear. Point displacements, in the RBF Morph environment, can be expressed as a relative distance in the independent axis directions or in the surface normal direction. Almost every ice accretion code already express the new ice layer thickness for every node along the surface normal, so the accretion code-RBF Morph coupling is particularly eased. To maintain finally the remaining portion of the domain geometry unaltered, a zero motion was imposed to the inlet and outlet boundaries source points using the included surfs option of RBF Morph.

To complete the workflow and to have a better insight into the behavior of the iced geometries, every profile was examined and studied in ANSYS Fluent. The two dimensional cell domain is composed by 9800 quadrilateral elements. With the exception of the wing profile, a Pressure far-field boundary condition was imposed to the inlet (c profile) and to the outlet (right border in Image 5). Simulations were carried using a pressure based double precision k-epsilon (two equations) turbulence model, modelling air after an ideal gas

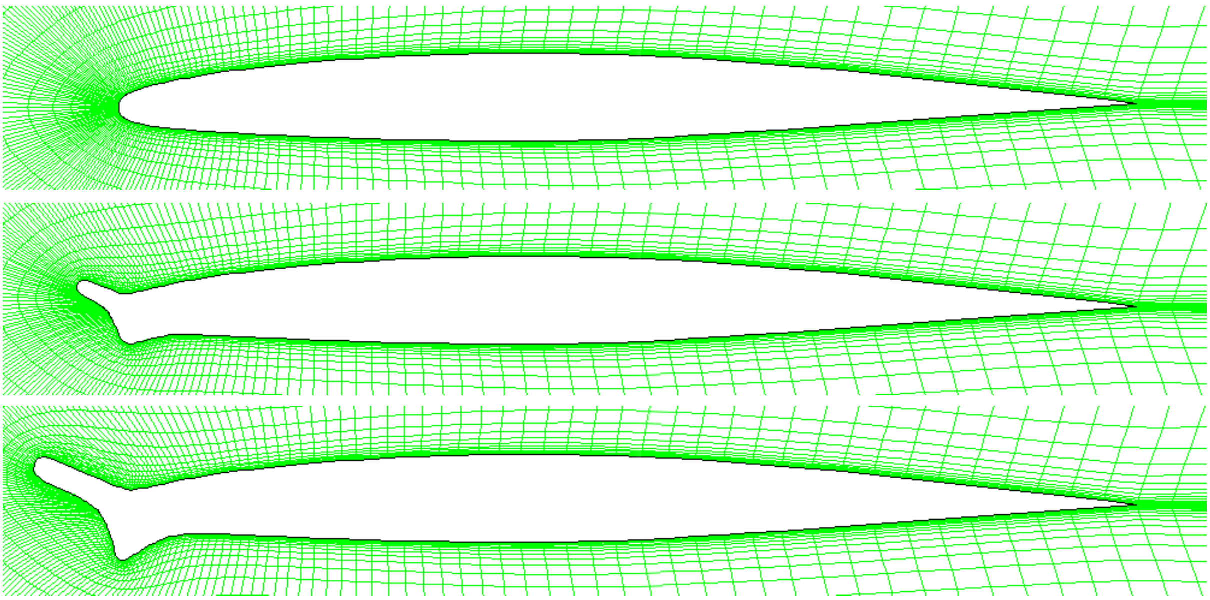

Figure 5 - clean, intermediate and complete accretion on a GLC305 geometry

with a Sutherland viscosity behavior. To couple pressure and velocity was used a SIMPLE scheme, and second order upwind spatial discretization were used for density, momentum, turbulent kinetic energy, turbulent dissipation rate and the energy equations.

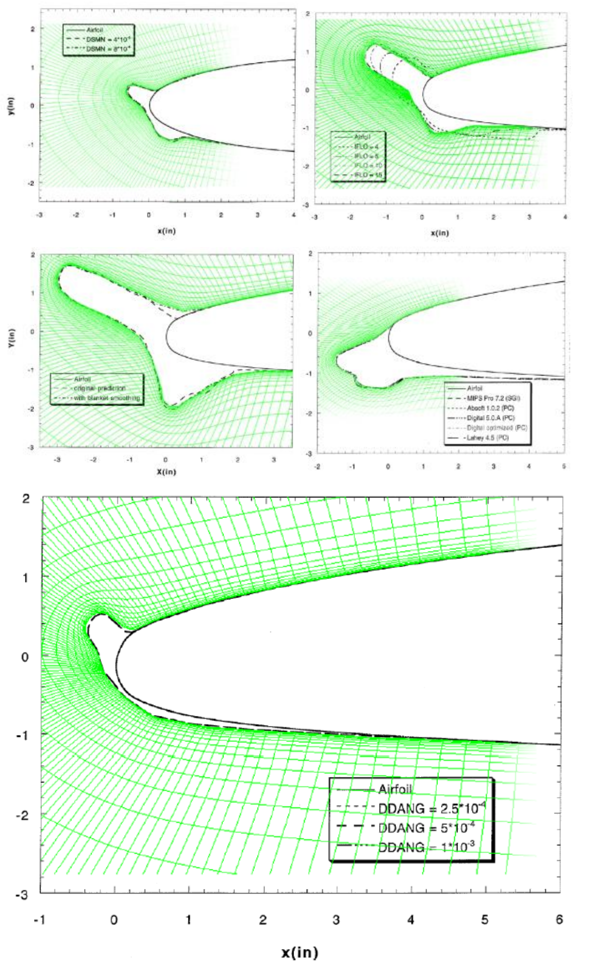

Figure 6 – Completely accreted grids for the literature profiles

2D Benchmark

As demonstrated in Figure 5 the morphing action preserved grid quality during the accretion even for the most complex shapes. Grids for the completely accreted geometries are shown in Figure 6. CFD results were calculated for a 0.6 Mach flight and drag, lift and full polars were plotted for a 0-14 deg angle of attack range. Clean wings were investigated as well as intermediate and final stages of ice accretion. As expected ice accretions are generally responsible for an increasing of the drag force and a decreasing of the lift coefficient, as an effect of the early flow separation introduced by the deteriorated geometry. Pressure coefficients for the wing were calculated for clean and completely iced profiles for a 2 deg angle of attack. In Figure 7 the Cp curve and the full polar are displayed for run 1.

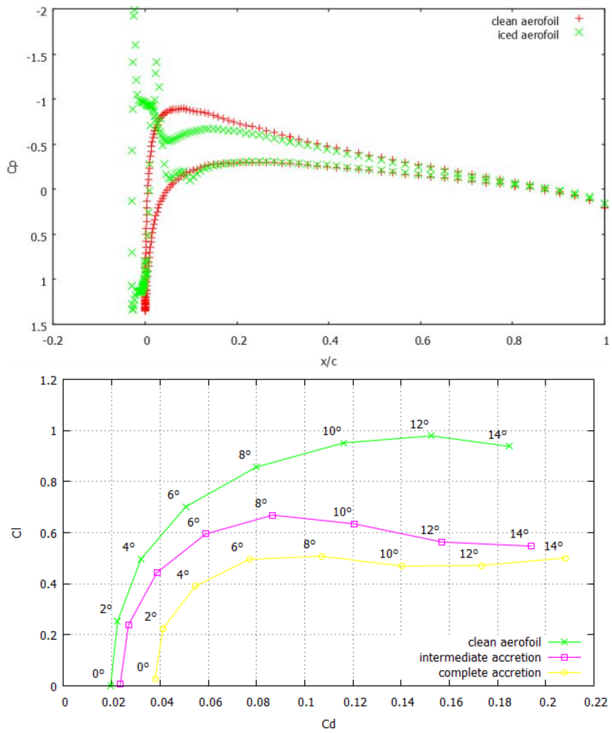

Figure 7 - Cp curve for clean and iced airfoil (baseline angle) and full polar for run 1

3D Benchmark

To demonstrate the feasibility of the already proposed icing analysis workflow for a 3D scenario, RBF Morph was tested at first in simple 3D evolutions of the 2D benchmarked cases. A clean 3D grid of the NACA0012 airfoil profile was extruded from the two dimensional mesh obtaining the GLC305 profile through the mesh morphing of the 3D NACA0012 geometry, following the same practice already adopted for the two dimensional case. Final 3D grids are composed by 98000 hexaedral cells and 110825 nodes each.

Considering that there is a profile symmetry along the third dimension the ice shape – the result of an ice accretion model – will remain unchanged along the span. Being the 2D and 3D results identical, CFD analysis weren't carried, but

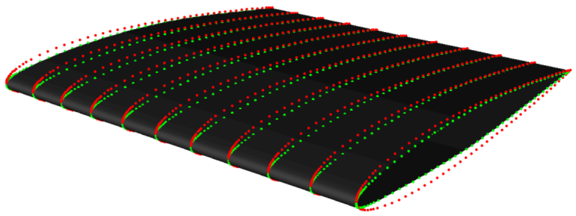

Figure 8 – clean GLC305 airfoil profile (green dots) obtained by means of mesh morphing of a NACA0012 wing profile (red dots).

accretion was reproduced anyway to demonstrate the 3D mesh update capability. Ice build-up was simulated linear, and completed for the same amount of steps needed for the 2D case. The time employed by RBF Morph raised from 0.1 s for the 9800 cell 2D problem with 200 source points to 6 s for the 98000 cell 3D case with 2200 source points. For a similar industrial application (snow accretion on trains) the RBF Morph technology allowed to control a volume mesh of 14 million cells using about 250000 source points in 6 minutes. In Figure 9 a morphed 3D profile at final step of accretion is shown with a section of the volume mesh.

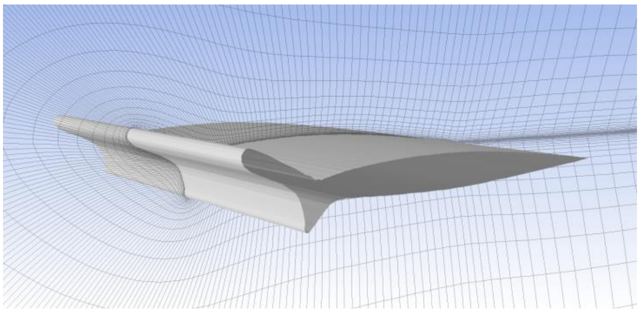

Figure 9 – morphed 3D profile at final step of accretion

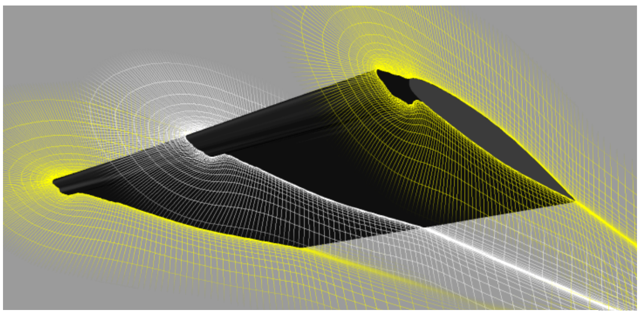

Figure 10 – Mixed accretions and grid sections at 0, 0.5 and 1 span

To finally test RBF Morph in a more challenging environment and to prove its ability to update the mesh in a complex three dimensional context, was carried a further benchmark with the ice buildup evolving in the three directions, achieving the variable accretion along the span imposing two different ice shapes at the wing extremities. Final results are shown in Figure 10.

Further development

In partnership with Piaggio Aero Industries and D'Appolonia, and in the RBF4AERO[3] European funded project framework, the proposed approach was successfully applied for an icing test case on a NACA0012 2D geometry using ice geometrical data from a Piaggio in-house accretion code with different icing conditions. The RBF4AERO project aims at developing an integrated numerical platform and methodology to efficiently face the most demanding challenges of aircrafts design and optimization, including FSI and icing simulations for both 2D and 3D cases. In Figure 11 a complete accretion for a NACA 0012 profile with 0 degree AoA and 0.15 g/m^3 LWC after a 45 minute simulation is shown.

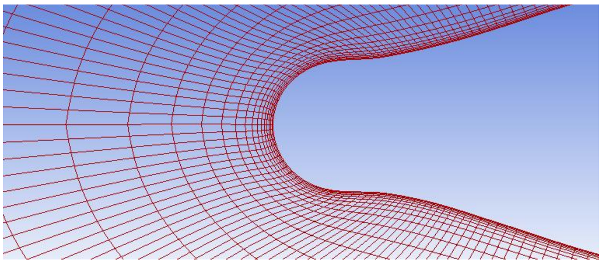

Figure 11 - 45 min accretion on a NACA0012 with 0 deg AoA

Further studies, in cooperation with ANSYS India, are being carried by implementing the proposed approach in an automatic workflow using a 2.5D ice accretion model exploiting the ANSYS Fluent Eulerian wall film capabilities developed by ANSYS.

Conclusion

In this paper an icing application of mesh morphing by means of Radial Basis Functions is presented. Being able to regenerate a modified grid in the shortest amount of time is critical when dealing with an ice accretion model, as it is required cyclically at every step by the accretion model itself.

RBF morphing provides the ability to morph the wing profile assuring both speed and quality,

[3] http://www.rbf4aero.eu/

allowing to define the displacement of the interested nodes only.

Integrating an RBF morpher into the icing analysis process, allows optimizing efficiently the workflow in terms of both time and quality.

Acknowledgements

Presented study is part of scientific cooperation between our University and ANSYS India. We would like to express our gratitude to Ajay Parihar and Hemant Punekar for the definition of the benchmark problem and to Robert Harwood, ANSYS Aerospace and Defense Industry director.

Part of this work was also financially supported by the RBF4AERO project funded by the EUs 7th Framework Programme (FP7-AAT, 2007 - 2013) under Grant Agreement no. 605396. We would like to thank Giorgio Travostino and Gabriele D'Agostini from Piaggio Aero Industries and Emiliano Costa from D'Appolonia for their kind support.

References

1. Wright, W. B., Rutkowski, A. (1998). Validation Results for LEWICE 2.0. NASA CR 208690.
2. Biancolini M E (2011). Mesh Morphing and Smoothing by Means of Radial Basis Functions (RBF): A Practical Example Using Fluent and RBF Morph. In: Handbook of Research on Computational Science and Engineering: Theory and Practice (2 vol). p. 347-380, doi: 10.4018/978-1-61350-116-0.ch015.
3. Biancolini M E, Cella Ubaldo (2012). Coupled CFD-CSM Aeroelastic Analysis of a Full Aircraft Model and Comparison to Experimental Data. JOURNAL OF AIRCRAFT, ISSN: 0021-8669
4. Gadebusch, J. A. (2012). "Computational 3D icing results for scaled DLR-F6 Geometry" AIAA Journal, Vol. 2, pp. 911-927.
5. Bragg, M. B., Broeren, A. P., & Blumenthal, L. A. (2005). Iced-airfoil aerodynamics. Progress in Aerospace Sciences, 41(5), 323-362.
6. Gent, R. W., Dart, N. P., & Cansdale, J. T. (2000). Aircraft icing. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 358(1776), 2873-2911.