Development of an Aircraft Aero-Icing Suite Using Chapel Programming Language

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Abstract

This paper presents an aircraft aero-icing simulation suite implemented using the Chapel programming language for deterministic and stochastic ice accretion in two (2D) and three (3D) dimensions. The work is performed inside the CHApel Multi-Physics Simulation software (CHAMPS) developed at Polytechnique Montreal since 2019. The solvers required to simulate the droplet trajectories, the surface thermodynamic exchanges, and the surface deformation are added to the previously implemented flow solver. The ice is accumulated in multiple layers to increase the accuracy, requiring, after each layer of ice, the generation of a new volume mesh or the deformation of the initial volume mesh. The developed structure of CHAMPS is object-oriented and takes advantage of the generic functions and types from Chapel, enabling a high growth potential and easing the maintenance requirements. The most recent addition to CHAMPS is a stochastic ice accretion framework that uses an unstructured advancing front grid method to emulate the ice growth. Stochasticity is introduced through the droplet insertion in the field during the impingement process to better represent the chaotic distribution of droplets in a cloud. Although stochastic ice accretion is not new, this paper presents an original methodology that has the advantage of conserving a valid surface mesh throughout the simulation, contrary to other non-deterministic methods from the literature. Multi-layer ice accretion results are presented in 2D and 3D for a deterministic methodology and are compared to experimental results with good agreement. It must be noted that 3D multi-layer icing simulations are scarce in the literature, so it represents in itself an original work. Single-layer stochastic icing results are provided for 2D cases only, with multiple runs for each case to show the resulting variability of the method. It can be observed that even though the stochastic simulations are performed in single-layer, the resulting ice shapes are quite similar to the experimental envelope.

Introduction

Multi-physics simulations, such as ice accretion on aircraft, require the modeling of multiple physical phenomena. The challenge arising from these simulations is that the implementation has to balance the fidelity of multiple solvers, their performances such as the computational cost, and the productivity of the team developing the software. Traditional Computational Fluid Dynamics (CFD) software usually use Fortran, C, and C++ programming languages coupled with parallel distributed memory framework to achieve high performance [13]. Libraries, as Message Passing Interface (MPI), are traditionally used to achieve the distribution across the computational nodes. The implementation

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of a parallel distributed memory framework can represent an additional challenge in terms of productivity, especially in an academic context, since the projects are limited in time [13]. The Chapel programming language is a great alternative to the traditional languages as it is natively distributed and provides a productive framework with a high-level syntax. Chapel's support of object-oriented and generic programming enables modularity in the software, as the structure can be reused in the implemented physical models.

A new CFD software named CHApel Multi-Physics Simulation (CHAMPS), which uses the Chapel programming language is developed at Polytechnique Montréal since 2019. The initial structure and performances are presented by Parenteau et al. [13]. This extended abstract presents an overview of the extension of CHAMPS for 2D and 3D ice accretion predictions over aircraft, presenting a more traditional deterministic framework and a new stochastic methodology [12]. The numerical framework in CHAMPS is firstly discussed along with the deterministic approach. Then, the most recent addition to CHAMPS, the stochastic icing method, is presented. Finally, CHAMPS icing results are compared to experimental ice shape to assess the validity of the solvers in real icing conditions.

1 CHApel Multi-Physics Simulation Framework

The framework of CHAMPS for the flow solver is well described by Parenteau et al. [13], along with its scalability and validity. The following icing framework, as well as more specific details on the Chapel's implementation, are presented in Papillon Laroche et al. [12]. The flow and droplet solutions are obtained in CHAMPS over 2D and 3D unstructured multi-zone meshes from a cell-centered finite volume scheme. RANS equations are resolved to obtained the aerodynamic field using the turbulence model from Spalart-Allmaras [18, 17] or the K - ω SST-V model [10] for closure. The droplet impingement is resolved with the Eulerian droplet equations [4].

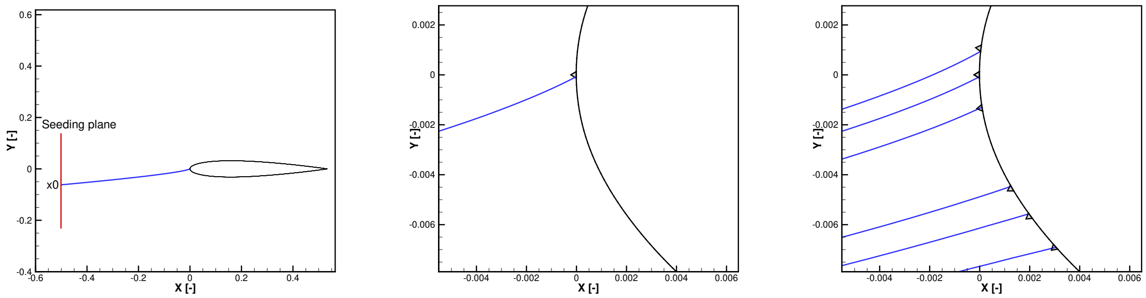
The linear solvers, gradient, and limiters in CHAMPS are implemented following a generalized structure, meaning that any method developed for a module is available in the other modules [13]. Time integration is computed with a hybrid Runge-Kutta scheme [9], a Block Symmetric Gauss-Seidel scheme, or a GMRES method. Fluxes are discretized, for the flow, using Roe [16] or AUSM [3] schemes, and for the droplet, using an upwind scheme. Gradients for the second order of accuracy are computed with the Green-Gauss or Weighted Least Square formulations [3] and the associated limiters can be obtained from the following schemes: Barth and Jespersen [2], Venkatakrishnan [21], Van Leer or Van Albada [3].

An Iterative Messinger model [23] is used to obtain the thermodynamic exchanges. Following the ice accretion map, the iced geometry is obtained by the deformation of the surface mesh via a Lagrangian method or a hyperbolic scheme [5]. The multi-layers framework in CHAMPS is enabled by a mesh regeneration with a hyperbolic mesh generation method [6] or a volume mesh deformation through a radial basis function (RBF) approach [22].

2 Stochastic Icing Approach

The stochastic approach aims to model the randomness inherent to the icing phenomenon due to the chaotic distribution of the cloud droplets, the nucleation process, and the surface irregularities. The stochastic rationale was initially introduced by Szilder [19] as the *Morphogenetic model*, and has been re-examined by Bourgault-Côté [5]. The impingement and freezing phenomena are modeled through a Lagrangian framework, i.e. the ice growth is emulated by the accumulation of individual frozen clusters of water droplets. The latter are gathered in clusters to reduce the computational costs, thus assuming that the droplets in the same cluster follow the same trajectory and freezing evolution. The workflow of the proposed approach is presented at the Figure 1 and is repeated until reaching the stop criterion, which is the mass of the accumulated ice.

In the proposed approach, ice is generated in a building block manner by accumulating ice clusters



(a) Insertion and trajectory computation

(b) Generation of an element upon impingement, zoom on the leading edge

(c) Generation of several elements, zoom on the leading edge

Figure 1: Evolution of the Stochastic Process [12]

through an unstructured advancing front algorithm, instead of on a Cartesian grid, like Szilder and Lozowski [19] and Bourgault-Côté [5]. The methodology proposed here follows the work presented in Papillon Laroche et al. [12].

2.1 Advancing Front Algorithm

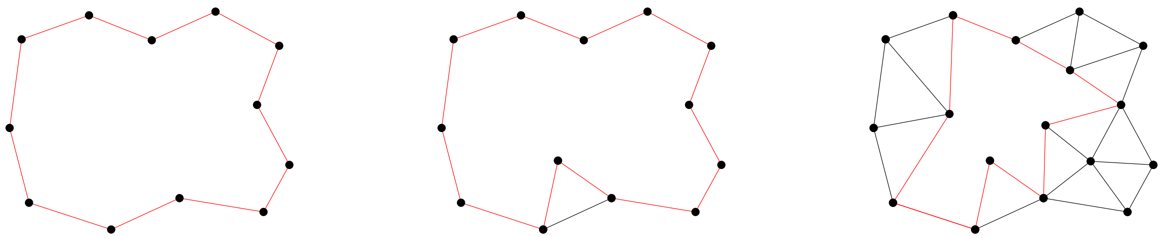
The advancing front grid generator implemented in CHAMPS follows the methods proposed by Löhner and Parikh [8], Peraire et al. [14] and Jin and Tanner [7], which are based on the dynamic generation of triangular (or tetrahedral) elements to obtain an unstructured mesh.
The steps required to complete the process are the following [12]:

1. Discretization of the boundaries, which form the initial front;
2. Generation of the next element, based on the predefined order of treatment;
   (a) Selection of an existing node or creation of a new node;
   (b) Validation of the new element (check intersections with existing elements), if invalid, return to step (2a);
3. Update of the front;
4. Repeat (2) and (3) until reaching the stop criterion.

In the proposed stochastic icing framework, the initial front is the surface mesh of the studied geometry.

2.2 Stochastic Impingement and Freezing

The impingement computation follows the process described in [12]. The droplet clusters are inserted in the field on a seeding plane upstream of the airfoil at a random seeding point (on the plane), as illustrated at Figure 1a. This initial position is obtained with a pseudo-random number (PRN) generator from the PCG family implemented in Chapel [11]. The trajectory of the clusters is then extracted from the Eulerian droplet velocity field. The process follows the method proposed by Rendall and Allen [15] to compute a droplet "streamline", which is, in fact, its trajectory. Following the insertion of the cluster in the domain, the initial cell in the RANS mesh, on which the droplet velocity field was obtained, is found to obtain the initial velocity vector of the cluster. Then, the next cell crossed by the cluster is obtained as well as its entry point, which is the closest intersection



(a) Initial front

(b) Generation of one element and update of the front

(c) Front and mesh after several iterations

Figure 2: Unstructured advancing front process. The front is represented in red [12]

Table 1: Test Cases Input Parameters

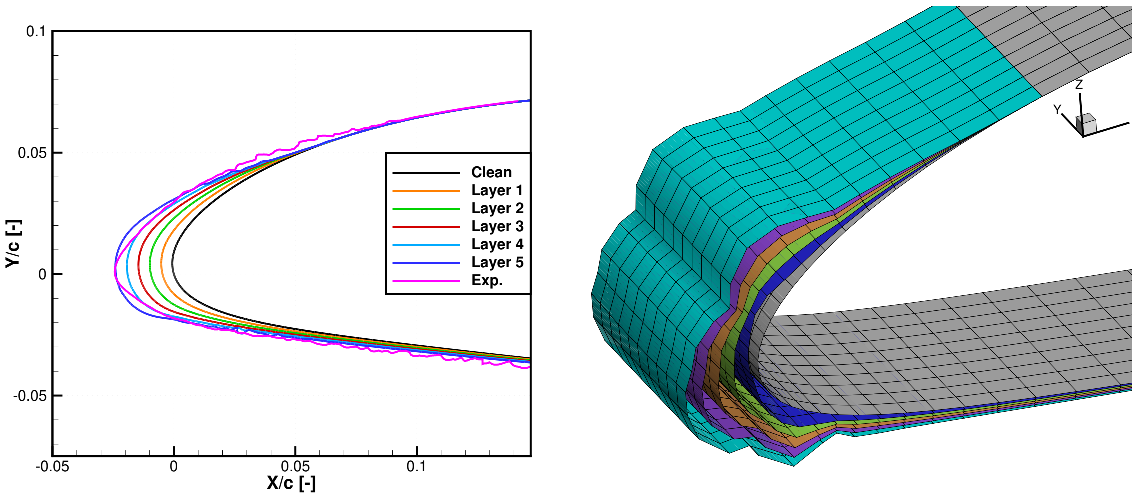
Test Case	Case 241, IPW1	Case 01, Trontin et al.
Geometry	NACA0012	NACA0012
Chord [m]	0.4572	0.5334
AoA [°]	2.0	4.0
Mach [-]	0.325	0.325
Temperature [K]	255.20	250.7
Pressure [kPa]	92.5	101.325
LWC [g/m^3]	0.42	0.55
MVD[μm]	30	20
Icing Time [min]	5.0	7.0

between the droplet velocity vector and the cell facets, downstream of the previous cell.
The trajectory computation stops when it intersects a facet of the mesh front. A new element is then generated with the advancing front algorithm, as illustrated at Figure 1b, and the process is repeated (Figure 1c) until the iced elements total mass reaches the targeted ice mass, derived from the icing conditions. Thermodynamic exchanges have yet to be computed, thus, the cluster of droplets freezes upon impact. This limits the framework to rime ice cases only.

3 Numerical Results

3.1 2D and 3D Deterministic Icing

Results for the deterministic approach are presented for the case 241 selected for the 1st AIAA Ice Prediction Workshop (IPW1) [1] and the icing parameters are presented in Table 1. Figure 3a presents the results computed by CHAMPS in 2D for five ice layers using the hyperbolic mesh generation method. Figure 3b presents the results for the same case, but in 3D, obtained with a mesh deformation method via RBF for five ice layers. The 2D geometry was extruded in the third dimension, with ten cells along a span. The RBF method was recently added to CHAMPS, thus, the method is still limited to simpler cases such as rime ice shapes, but considering the complexity of ice shapes, such simulations are not often seen in the literature.



(a) 2D rime ice

(b) 3D rime ice

Figure 3: Case 241 deterministic results from IPW1 [1]

3.2 2D Stochastic Icing

Results of the stochastic solver are presented on the rime case 241 [1] and rime case 01 of Trontin et al. [20]. Conditions are presented in Table 1.

3.2.1 Trontin's Rime Case 01

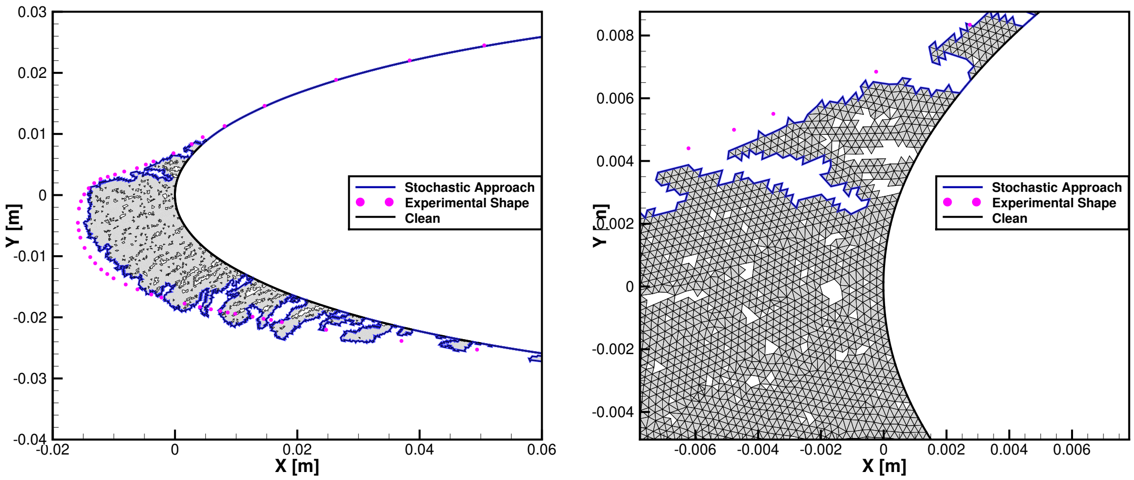
Figure 4 presents a comparison of the proposed stochastic method to the experimental results [20], showing great agreement with the experiment. A zoom of the leading edge is shown at Figure 4b, highlighting the features, like holes in the ice and ice feathers, captured by the advancing front mesh generation. These features are observed in the experiments, but cannot be model by deterministic approaches.

3.2.2 IPW1 Case 241

The stochastic approach emulates the variability observed in the experimental ice shapes. Figure 5 presents the results of ten different ice shapes, obtained from ten seeds from the PRN generator. The ten results are overlaid, with the blue scale corresponding to the likelihood of the results: the darker the area is, the most probable it is to obtain ice at this position, as presented in [12]. The impact of the stochasticity is mainly downstream of the stagnation point, especially on the lower surface where ice feathers are observed [12]. The obtained ice shapes are similar to the experimental envelope, which is the maximum combined cross-section depicted in pink [1].

4 Conclusion

An aero-icing suite, named CHAMPS, using the Chapel programming language is presented. Two approaches are proposed: i) a more traditional deterministic method in 2 and 3 dimensions, and ii) a stochastic framework in 2 dimensions. In both cases, the flow solver was previously implemented using Chapel's feature to enables productivity and modularity in the development of multiple solvers. The stochastic approach proposed uses an advancing front technique, coupled with PRN and droplets



(a) Ice Shape

(b) Zoom on the leading edge

Figure 4: 2D stochastic rime ice: Case 01 from Trontin et al. [20]

trajectories computations to obtained a stochastic ice shape. The paper presents two rime ice conditions to validate the presented methods, and the results show great agreement with the experimental ice shapes. Further works are expected to validate CHAMPS in glaze icing conditions.

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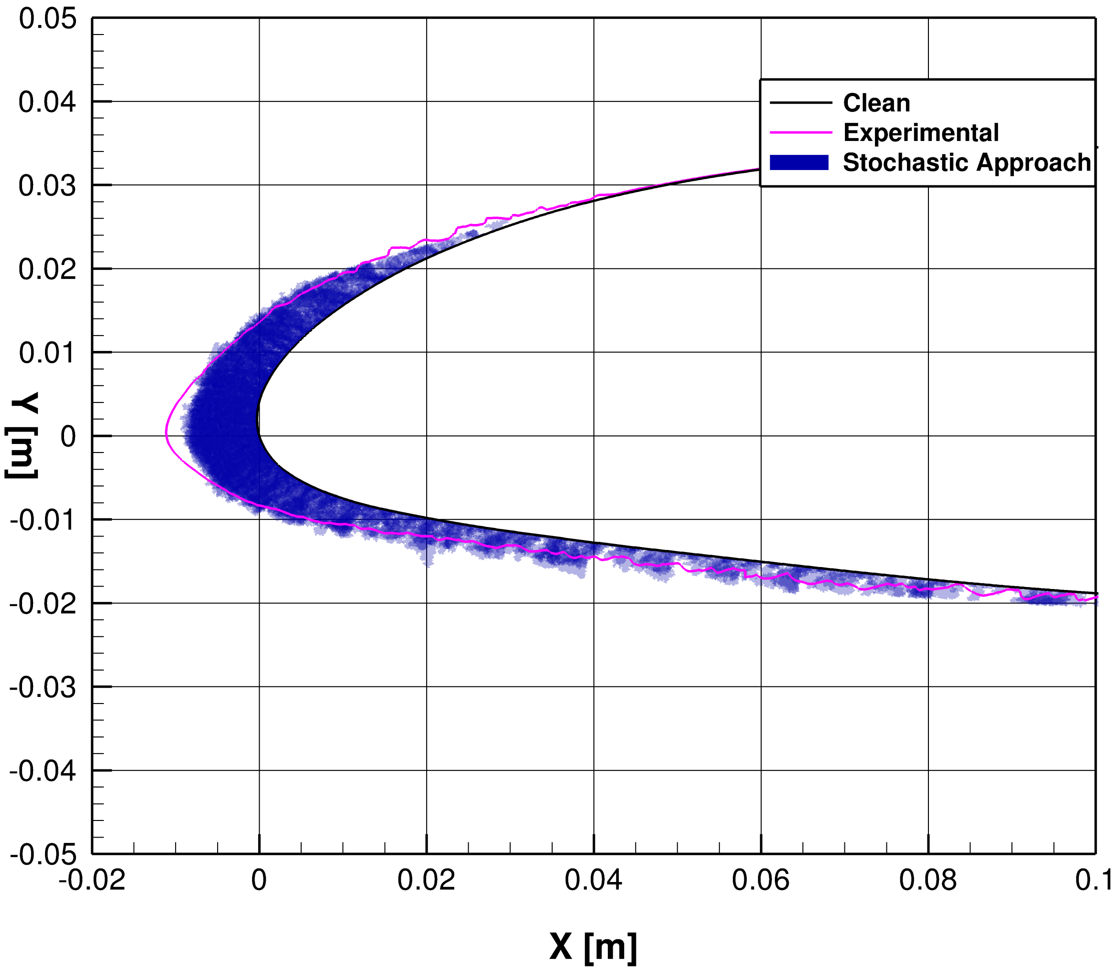

Figure 5: 2D stochastic rime ice: 10 runs of the case 241 from IPW1 [1], the bluescale represents the likelihood of the result

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