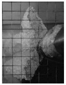
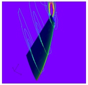
Modeling icing using cartesian grids, penalization & level sets

Héloïse Beaugendre

IMB Institut de Mathématiques de Bordeaux - INRIA Sud-Ouest MC2
`Heloise.Beaugendre@math.u-bordeaux1.fr`

November 5, 2009





with CARPEiNTER team and François Morency (ETS, Canada)

Institut de Mathématiques de Bordeaux

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

INRIA

centre de recherche BORDEAUX - SUD OUEST

Icing has several negative effects

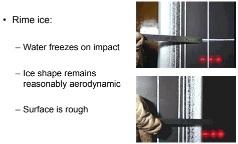
- Aircraft performance degradation

  Incidents & Accidents: substantial reduction of engine performance and stability, reduction in maximum lift and stall angle, increase of drag, eventually mechanical damage caused by ice-shedding.

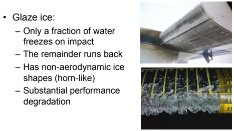
- Wind turbine performance degradation

  Diminution of the power output: increase of drag, complete loss of production, mechanical dammages: overloading, increased fatigue, damage or harm caused by uncontrolled shedding of large ice chunks.

We are interested in modeling ice accretion and especially we will focus on ice-shedding.



- Rime ice:
  - Water freezes on impact
  - Ice shape remains reasonably aerodynamic
  - Surface is rough



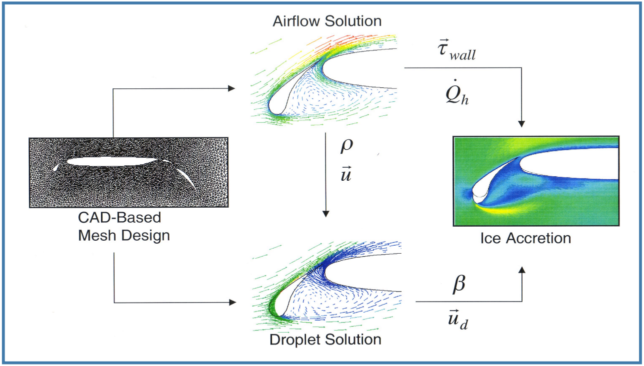
- Glaze ice:
  - Only a fraction of water freezes on impact
  - The remainder runs back
  - Has non-aerodynamic ice shapes (horn-like)
  - Substantial performance degradation

Modeling ice accretion

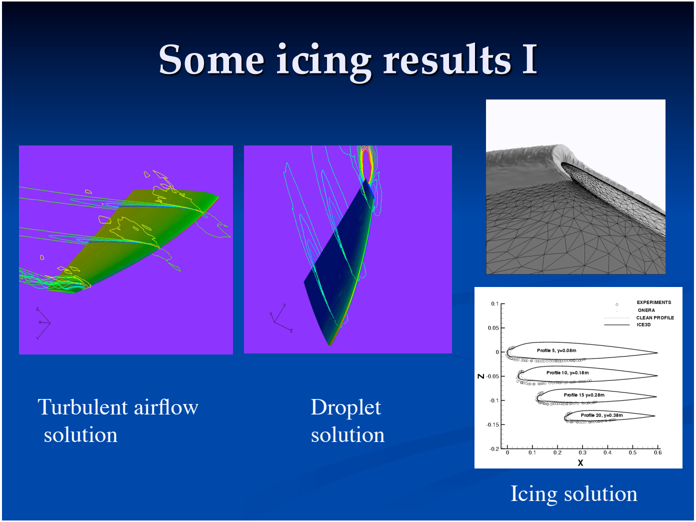
- Three contributing factors:

  the aerodynamic flow field, the water droplet trajectories, the thermodynamic ice accretion process

- Previous validated approach:



Helicopter blade



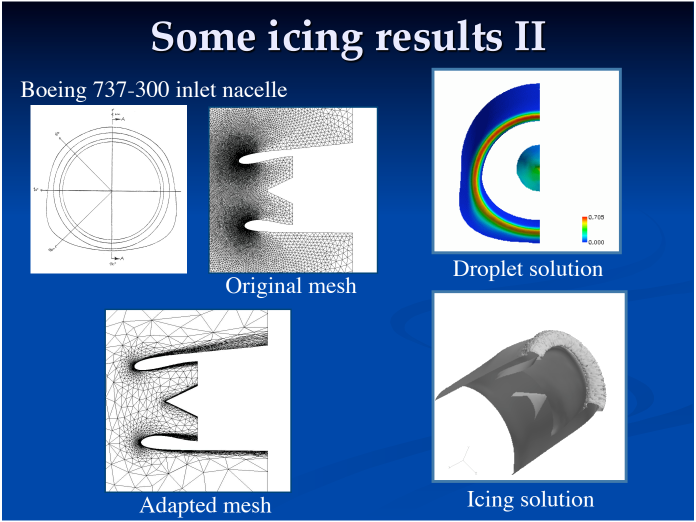
Some icing results I

Turbulent airflow solution

Droplet solution

Icing solution

Boeing inlet nacelle 737-300



Some icing results II

Boeing 737-300 inlet nacelle

Original mesh

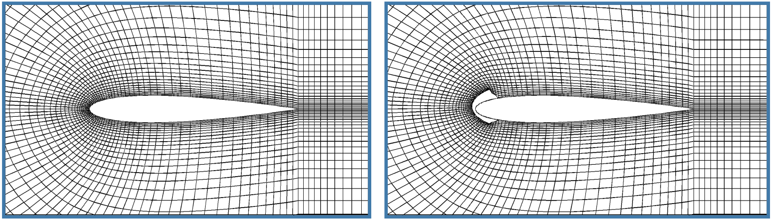
Droplet solution

Adapted mesh

Icing solution

Drawbacks: remeshing might be required

ALE displacement of grids to account for ice accretion



Can not handle big displacements: **remeshing is needed**

The proposed approach

- Cartesian grids
  - bypass the meshing issue in complex geometries
  - allows extensions to higher order accuracy in a natural and simple way
- Penalisation
  - an efficient alternative to explicitly impose boundary conditions
  - body fitted meshes can be avoided
  - making multi fluid/multi physics flows easy to set up and simulate
- Level sets
  - describe the geometry in a non-parametric way
  - geometrical and topological changes due to physics and in particular icing are straight forward to follow

Flow model

The fluid velociy is extended inside the solid body and we solve the unsteady incompressible N-S flow equations with a penalization term to enforce rigid motion inside the solid.

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)\, u - \nu \nabla^2 u + \frac{1}{\rho} \nabla p = \lambda \chi_s (\bar{u} - u) \tag{1}$$

coupled with the incompressibility condition

$$\mathrm{div(u)} = 0 \tag{2}$$

Flow model

Taking the vorticity formulation of (1) gives

$$\frac{\partial \omega}{\partial t} + (u \cdot \nabla)\,\omega = (\omega \cdot \nabla)\,u + \nu \nabla^2 \omega + \lambda \nabla \times [\chi_s(\bar{u} - u)] \qquad (3)$$

This system has to be complemented by the usual system giving the velocity in terms of the vorticity

$$\nabla \times u = \omega \qquad (4)$$

VIC scheme

The VIC is an example of hybrid vortex methods, see [1] & [2]:

- non linear advection is computed by tracking the trajectories of the Lagrangian particles through a set of ODEs,
- an Eulerian grid is adopted to solve efficiently the velocity field and diffusive term.

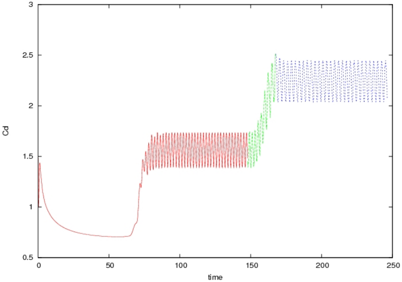
Further numerical simulations have been done using Federico Gallizio's code [2] modified to account for

- ice accretion first
- ice-shedding trajectories in a second time

[1] M. Coquerelle, G.-H. Cottet (2008) : A vortex level set method for the two-way coupling of an incompressible fluid with colliding rigid bodies. *Journal of Computational Physics* **227** pp. 9121-9137.
[2] F. Gallizio (2009) : Analytical and numerical vortex methods to model separated flows. *Ph.D. thesis*

Ice accretion on cylinder

Ice is growing on a cylinder (Re= 550 not realistic).



Drag increase due to the ice shape.

Moving Bodies with a fixed velocity

Axial turbine Re=10000.

Interaction of an incompressible fluid with a rigid body

Method : same as in ref [1]
The calculation of the rigid motion $\bar{u}$ is obtained by averaging translation and angular velocities over the solid S_i

$$\bar{u} = \frac{1}{|S_i|} \int_\Omega \chi_{s_i} u dx + \left(J^{-1} \int_\Omega \chi_{s_i} u \times (x - x_G)\, dx \right) \times (x - x_G) \quad (5)$$

Each body-fluid interface is captured by a level set function. These level set functions are advected by a rigid motion.
Algorithm:

1. Solve (3) without penalization and compute $\bar{u}$ using (5).
2. Solve (3) with penalization using $\bar{u}$.

[1] M. Coquerelle, G.-H. Cottet (2008) : A vortex level set method for the two-way coupling of an incompressible 'uid with colliding rigid bodies. *Journal of Computational Physics* **227** pp. 9121-9137.

Ice-Shedding

Numerical simulation at Re=550

Achieve realistic simulations

Aim: achieve realistic simulations with applications in aeronautics and wind turbine indusrty.
Possible only if the three contributing factors:

- the aerodynamic flow field (module 1),
- the water droplet trajectories (module 2),
- and the thermodynamic ice accretion process (module 3)

are as accurately modeled as possible.

Aerodynamic flow field (module 1)

- Add turbulence models to achieve realistic simulations (Re numbers are around 10^6 for both application)
  - Turbulent simulations on cartesian grids for moving bodies?
  - grids size ?
  - law of the wall?
  - algebraic turbulence models (Baldwin-Lomax, Cebeci-Smith) but what about U_e usually done with panel methods or Euler solutions?
  - no idea for vortex method?
- Increase precision with penalization method
  - need second order to predict friction on the wall and heat fluxes.
  - need accurate Neumann boundary conditions.

Droplet trajectories (module 2) & thermodynamic process (module 3)

- Module 2 : looks like Euler equations with source termes
  2 sets of equations : mass conservation and momentum conservation.
- Module 3 : Requires some care (Messinger formulation, shallow water equations form)

Ice-shedding

- Try to propose a breaking law
- What about solving in the ice?