Proposal JTI-CS-2009-2GRC-01-002

SUMMARY REPORT

Project acronym: LAMBLADE

Project title: Development and provision of a numerical model to solve laminar turbulent boundary layer transition and boundary layer velocity profiles for unsteady flow conditions

Project reference: 267567

Programme Acronym: CLEAN SKY

Period covered: from 1/01/2011 to 31/07/2012

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Context

The Clean Sky Green Rotorcraft ITD focuses on innovative rotor blades and engine installation for noise reduction, lower airframe drag, diesel engine and electrical systems for fuel consumption reduction and environmentally friendly flight paths. In this framework the research consortium is aiming at the development of laminar blades (producing lower drag) able to provide the greatest possible reduction in fuel consumption. This aim requires the capability to understand the physical processes occurring in an unsteady laminar boundary layer and model the transition from laminar to turbulent flow.
Unfortunately, there is a general lack of reliable analytical and numerical methods apt to predict transition in unsteady flow conditions. Our understanding of transition in unsteady laminar boundary layers is in fact much less advanced than that in boundary layers over fixed wings for which several models already exists (both in two and three dimensions).
Moreover, for rotor blades in particular, both rotation and cyclic pitching must be properly taken into account, since these effects may contribute in a relevant way to the transition scenario.

Objectives

In this context, the proposal JTI-CS-2009-2-GRC-01-002 was entirely dedicated to the development of the necessary theoretical and numerical models to predict transition and compute the laminar base flow quantities in unsteady conditions, like those occurring on blades of rotorcrafts undergoing hover and forward flight. The objective of the project, as required by the GRC Consortium, was to develop theoretical and numerical tools able to:

1) Compute the main boundary layer quantities for unsteady flow conditions.

2) Perform stability analysis using the multiple-scale technique and the ray theory for the evaluation of the laminar flow region on the blade.

All the delivered codes were required to take as inputs the three components of the external velocity, usually provided by an inviscid flow solver.

Methodology / Work performed

In order to reach the proposed objectives, a theoretical analysis has been initially performed to derive the minimal set of equations apt to describe the behavior of an unsteady boundary layer under the effects of rotation and cyclic pitching (see figure 1). With the appropriate choice of the coordinate system, it was concluded that the appropriate equations to consider for the calculation of the base flow characteristics are the classical 2D unsteady boundary layers equations with the addition of an Ekman term. In the limit of an infinite blade, this system can be simplified using a similarity assumption. The resulting equations have a parabolic character when viewed with respect to each of x and t separately, so that a backward Euler discretization (first or second order) remains the tool

of choice as for the steady case. The numerical solution of these equations, however, faces several additional difficulties.
The greatest challenges were related to the treatment of stagnation points and the occurrence of separation. In order to deal with the first problem, the inversion of the

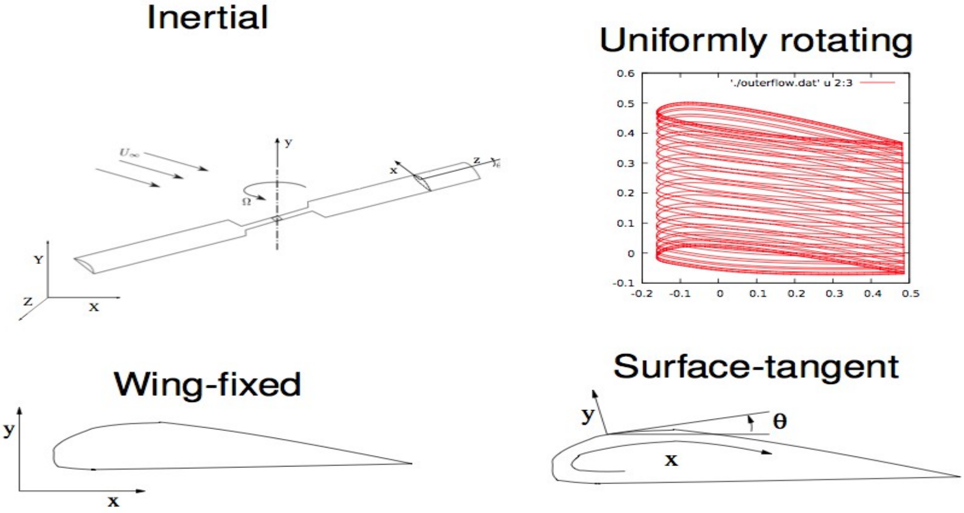

Figure 1

upwind direction in proximity of the stagnation point showed to be vulnerable to numerical inconsistencies. In particular, the problem occurs when a conservative formulation is used. In order to avoid this problem, the convective form of the equations was used. On a similar level of difficulty, the problem of separation required a specific study. The main problem here is related to the occurrence of a moving singularity, which delimits the region of existence of the solution. In order to deal with such difficulty, an innovative numerical technique was adopted, consisting of a particular discretization based on a diagonal stencil studied to avoid crossing the singularity. Its detection is performed numerically by checking where in space the system of equations becomes singular.
The resulting discretized equations are solved with a classical marching procedure starting form the stagnation point, where the solution is obtained in an iterative way by sweeping back and forth across the stagnation point.
Once the numerical scheme for the unsteady boundary layer was ready, both for the 2D and the 2.5D case, the focus of the research moved to the transition prediction issue. The transition analysis developed in this project is based on linear theory and highly relies on the multiple scale approach. This technique is based on the possibility to represent the disturbance in the form of a rapidly oscillating perturbation whose phase is governed by the eikonal (or Hamilton-Jacobi) equation. This is a first order partial differential equation whose solutions are the so-called characteristic lines or rays. Integrating the system of equations with given initial conditions selects a particular ray, which, in general, is a trajectory in the complex X plane. The amplification of the disturbance between two points can be calculated considering rays connecting the two specific locations. However, several difficulties arise from the complex trajectory formulation, such as:

• the integration cannot be marching. Every streamwise position x requires a new boundary-value problem
• the calculation of complex rays requires the base flow to be known for complex values of time.

This problem was solved introducing the real-path approximation. According to Fermat variational property, the phase integral has an extremum for given initial and final x and t, with the integration path corresponding to a solution of the ray equations. The error in the N factor results small if the path deviates slightly. By applying this principle, since the initial and final points are real, we can move the whole path from complex time to real time. This is analogous to using the stationary-phase as opposed to the saddle-point approximation of an integral. The transition can now be predicted with the classical e^N method. The numerical solution of the ray equations has been implemented in a way such that the same computational grid is used for the base flow and the transition analysis. As past experiences have shown, in fact, sharing the same computational grid avoids large errors caused by the interpolation procedures.

Results

Using the theory exposed above, two codes have been developed, both written in C language and respectively named “ubl” and “timeray” (see figure 2 for a block diagram). For both command-line help is provided.

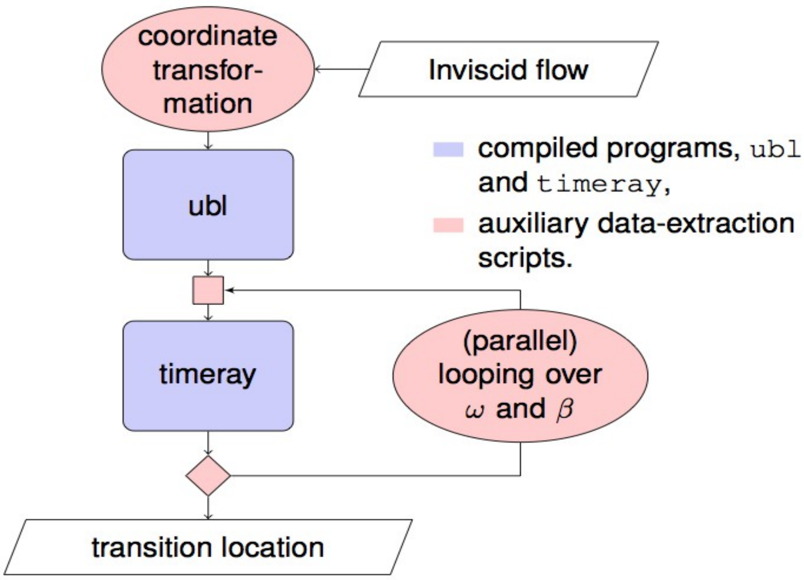

Figure 2

The “ubl” code, calculates an unsteady, 2D or 2.5D boundary layer given the external inviscid flow at the wing surface. If the inviscid flow data are specified to be time periodic, the solution is iterated in time until a time-periodic state is attained.
The “timeray” code calculates the instability amplification along a single ray (characteristic line) in space-time, given the output of “ubl”, a starting time, the frequency and the wavenumber of the perturbation. Calculating multiple rays and finding the worst possible case just involves invoking “timeray” multiple times in a (possibly parallel) driver program or script.
Two drivers, both in compiled form and as Octave scripts, are provided to facilitate the transition analysis:
a) “obcycle” runs “timeray” on a grid of different frequencies ω and wavenumbers β, producing data suitable for a surface plot.

b) “timecycle” optimizes the values of ω and β in order to find the maximum N factor (or minimum x where a given N factor is attained). It does so in parallel for several input times, so as to generate a transition-position versus time plot (see figure 3 for an example). Several tests in CIRA showed that such tools may be efficiently used to perform parametric studies on transition prediction over rotor blades.

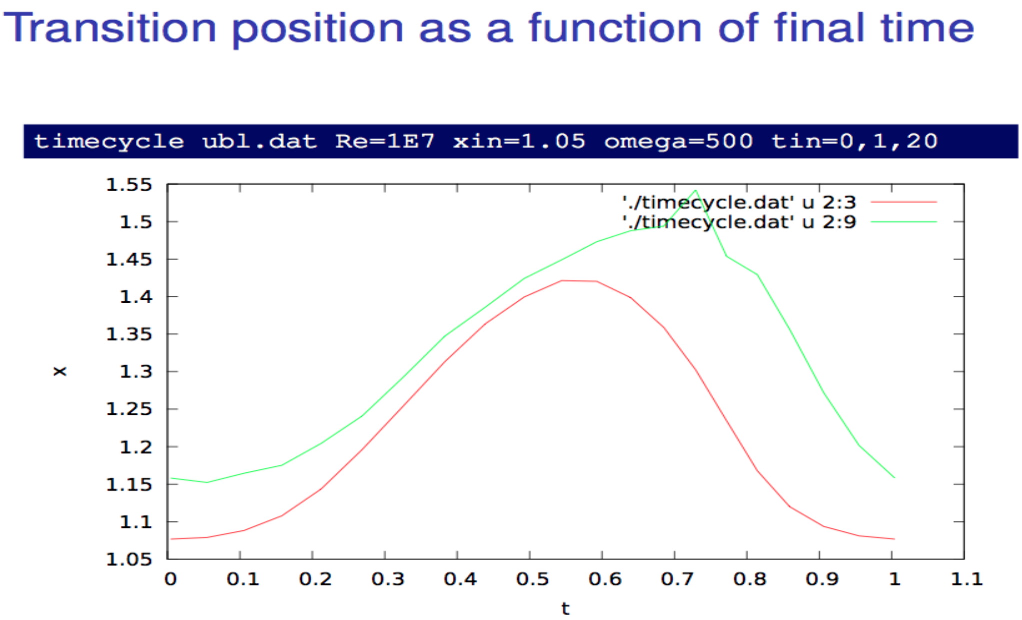

Figure 3

Conclusions

The LAMBLADE project has shown the effective possibility to develop theoretical and numerical tools apt to study the transitions on boundary layers developing on the blade of helicopters or others engines. The detailed studies performed during the project have highlighted the existence of several issues related to the nature of the equations and their discretization which need to be properly accounted for in order to correctly model the transition process. The solution of these problems provided a deeper understanding of physics involved in the boundary layers and transition processes which may be useful in the design of a laminar blade. Both for the 2D and 2.5D cases, the delivered tools proved to be suitable to perform parametric studies for the blades design and show that a transition prediction analysis based on ray theory is possible and indeed efficient. No theoretical or computational difficulty is foreseen in extending the present numerical tools to a completely 3D flow. Challenges will not be trivial but the experience gained from the present work is expected to be sufficient to overcome them. Writing an unsteady, 3D transition-prediction code is a feasible task.
The greatest obstacle may perhaps be the trivial one that all the input and output files will have one additional dimension and the time required for computation (and data analysis) will increase accordingly. While writing an unsteady 3D transition-prediction code is a feasible task, the additional cost in both computer and human time of applying such a code may probably only be justified for particularly complex geometries of the body over which transition is to be predicted.

Outcome

1. 2D approach report
2. 2.5D approach report
3. 3D feasibility report
4. Codes: ubl, timeray, obcycle,timecle; source code and manual