An overview of Onera aeroacoustic activities in the framework of propellers and open rotors

Y. Delrieux

Onera. Computational Fluid Dynamics and Aeroacoustics

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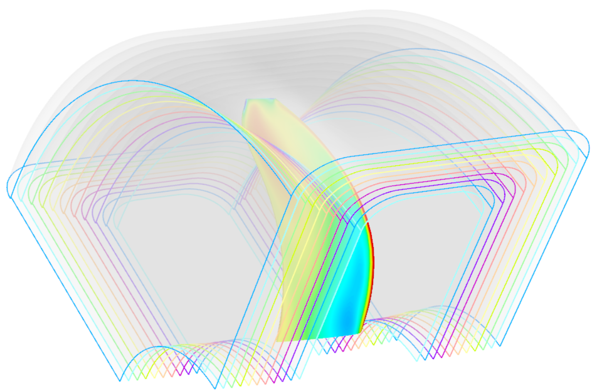

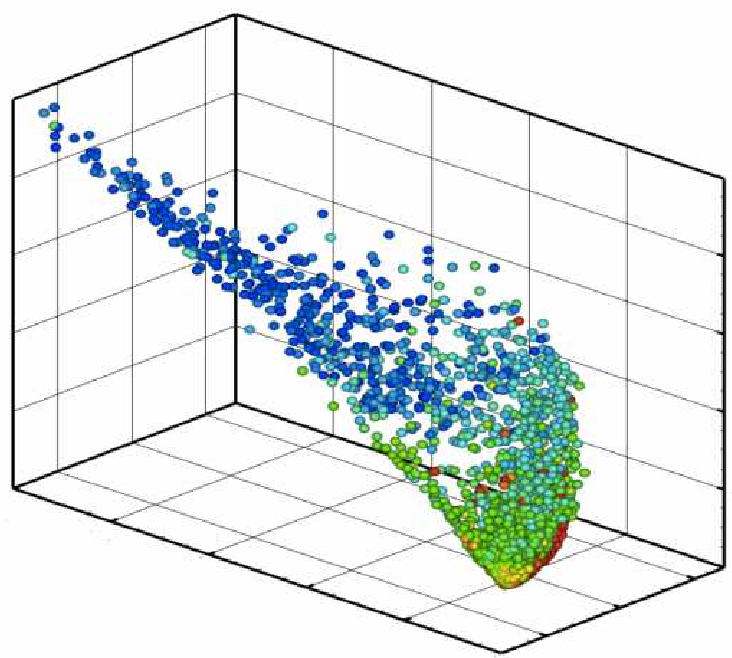

14th CEAS-ASC Workshop
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7-8 October 2010

Outline

- Introduction

- Presentation of the numerical tools for Aerodynamics and Acoustics

- Low and high speed single propellers. Numerical and experimental activities

- Counter Rotating Open Rotors.
  - CFD CAA computational chains
  - Physical insight of CROR at take off and cruise
  - CFD-CAA coupled strategies for propeller aeroacoustic simulations.

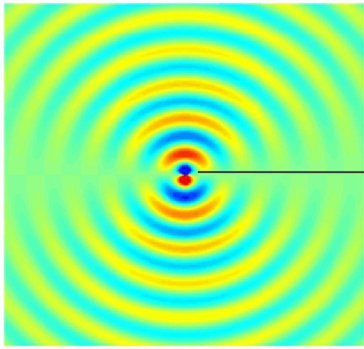
- Conclusions and perspectives

Introduction : importance of accuracy in acoustic studies of propellers and CROR

Two main challenging goals in the field of propellers and CROR simulations :

- Design accurate low-order models for **noise emission that can be run in real time** so that:
  - -air traffic agencies are able to monitor acoustic signatures of active planes
  - -blade shape optimization can be extended to take noise emissions into account
- Develop new strategies to **accurately determine the acoustic levels** associated with modern complex shapes.

In both cases, because the propeller moves with respect to the source, **acoustic levels have to be accurately determined for all angles of directivity** in order to get the accurate Sound Exposure Level (LAE).

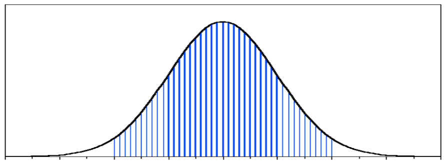


Dipole source in (slow!) motion

$$L_{AE} = 10\log_{10}\left[\sum_{k=t_1}^{t_2} 10^{L_{Ak}/10}\right]$$

where

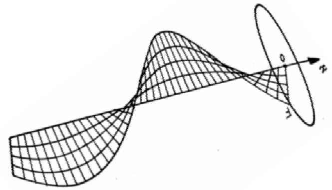
L_{Ak} = A-weighted sound pressure level [dB(A)]

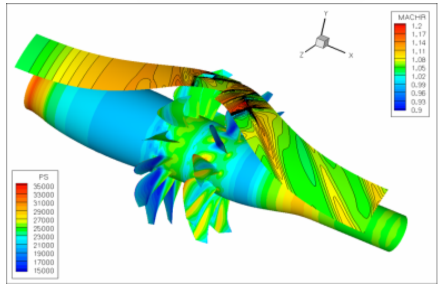


History of sound pressure level at the observer's location.

Numerical tools

<u>Aerodynamics :</u>

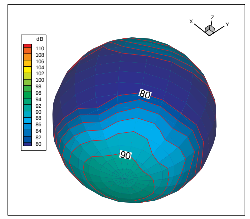




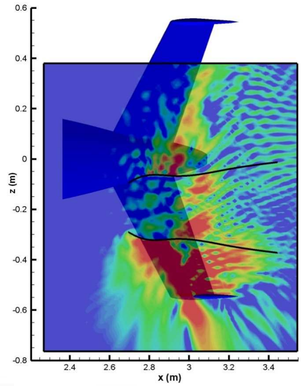
. *LPC2* : based on the Lifting Line theory, for aerodynamic and aeroacoustic performances for blades preliminary designs

. elsA : CFD code, for RANS 360° and chorochronic simulations.

<u>Acoustics :</u>



. *PARIS and KIM* : free space propagation codes, based on Kirchhoff and Ffowcs Williams & Hawkings integral formulations



. *BEMUSE* : based on the Boundary Element Method for installation effects prediction

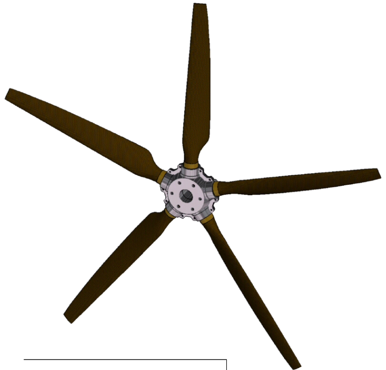
Main combinations :
elsA/KIM, MPC2/PARIS, LPC2/KIM, LPC2/BEMUSE…

Single propellers for light aircraft

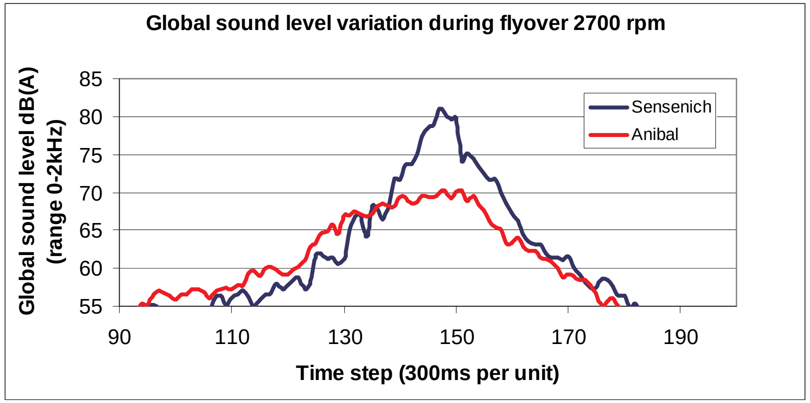
Acoustic optimization without performance loss, manufacturing and flight test

Reference prop. SENSENICH

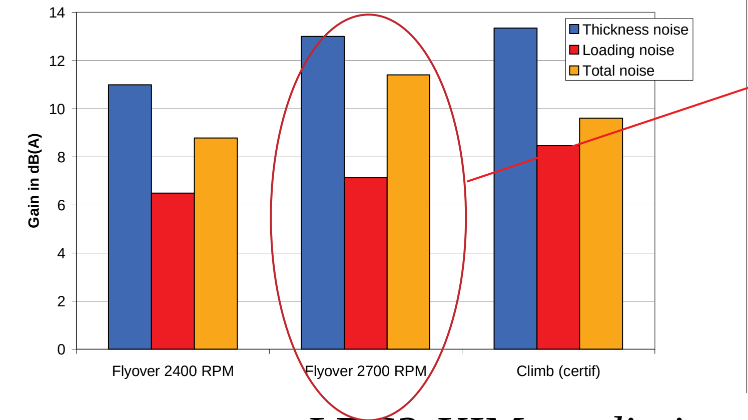
Optimised prop. ANIBAL



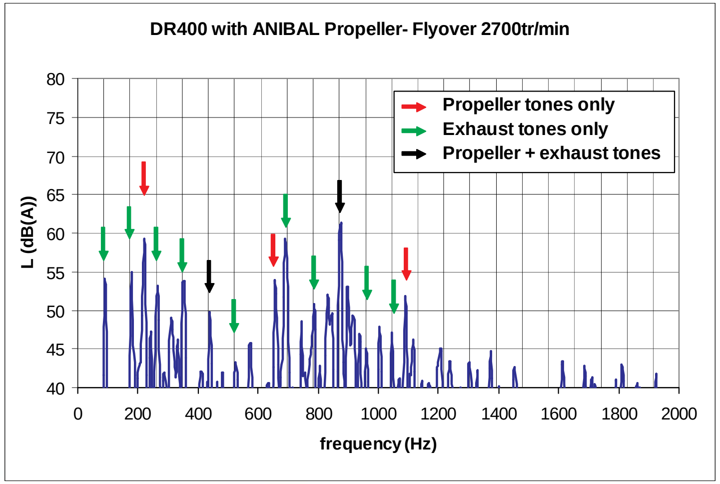
In-flight test



Noise reductions



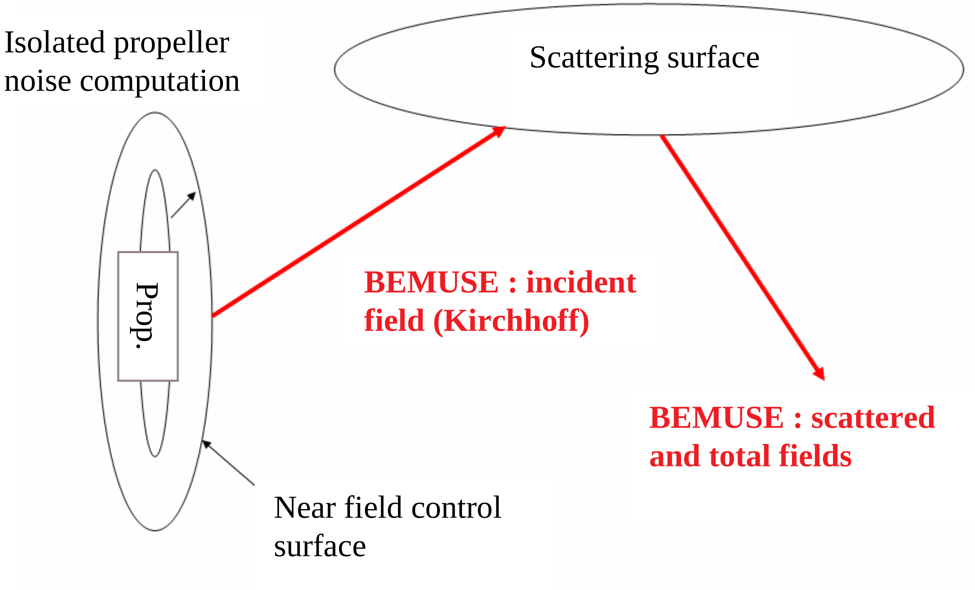
LPC2-KIM prediction

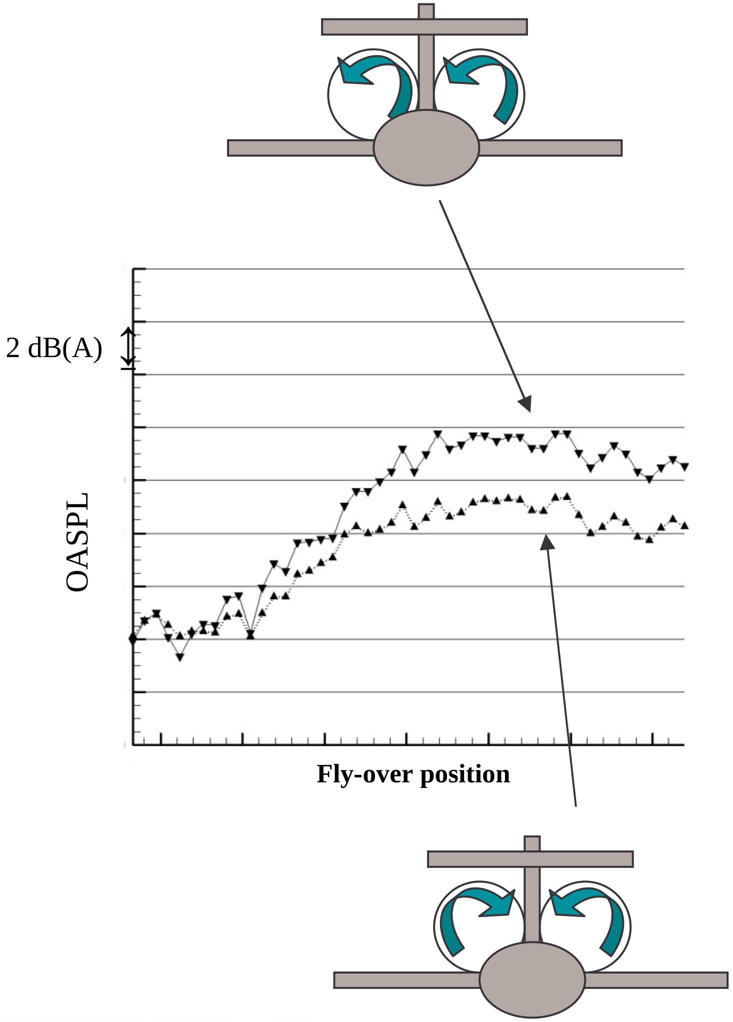


+ study of high speed propellers (CFD)

Single propellers with installation effects

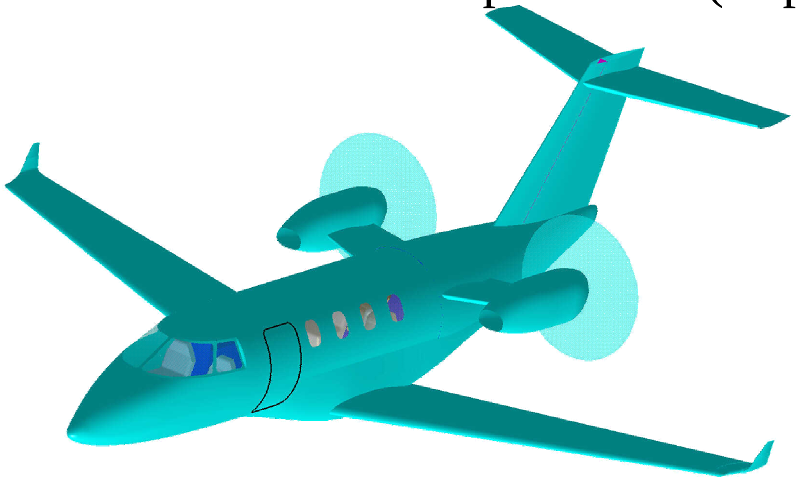
Boundary Element Method

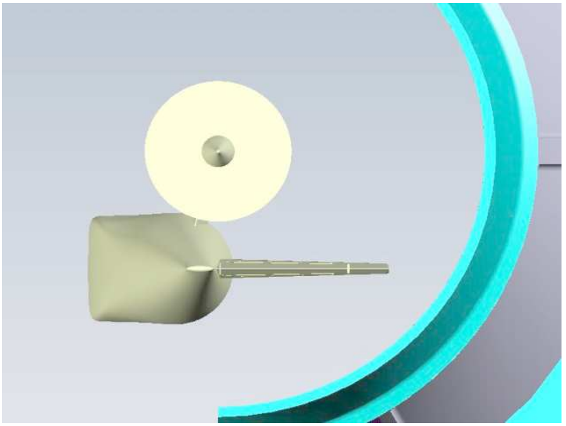


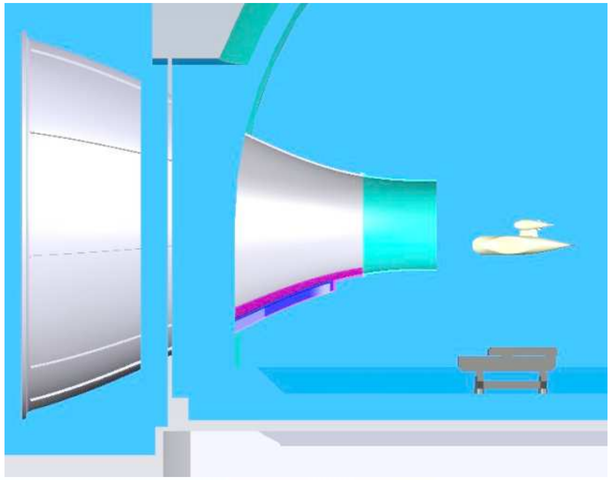


Wind tunnel experiments

Acoustic optimization of single propeller (LPC2/KIM) with optimization loop code, CFD simulations and wind tunnels experiments (Cepra 19)

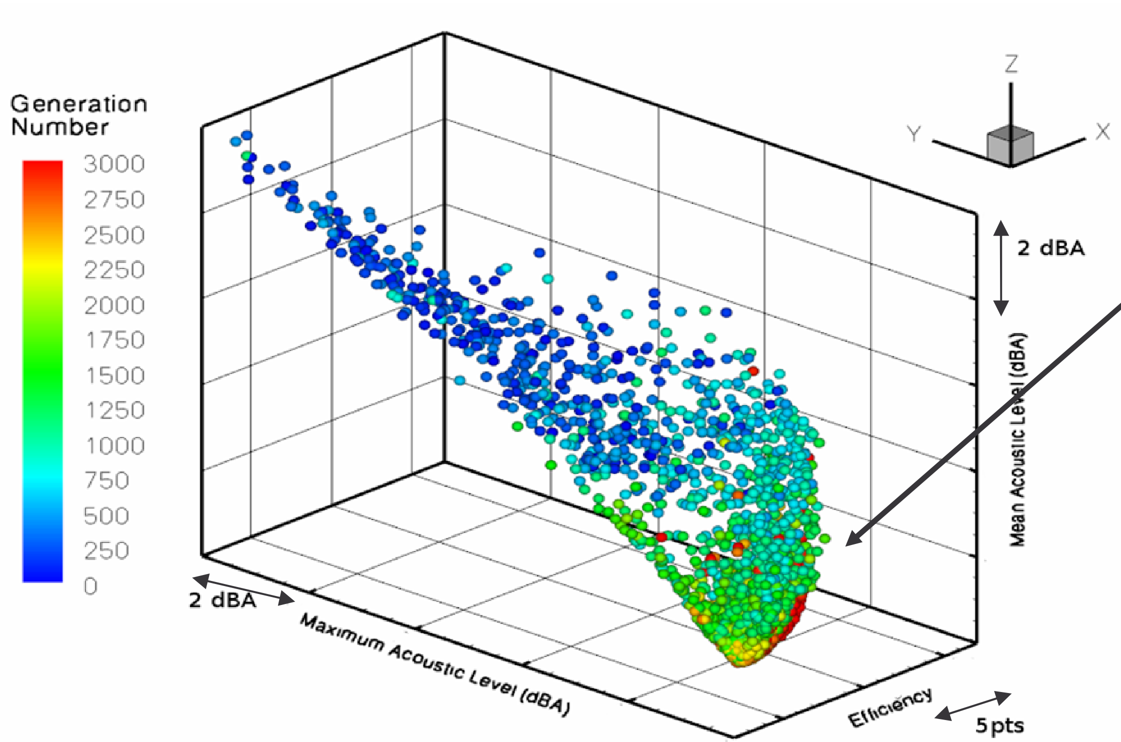






Shape optimization of single propellers using low-order models

Getting the load from Prandtl's lifting line theory is really fast (1min/individual) and enables to undertake **genetic aeroacoustic optimizations of the blade shape.**



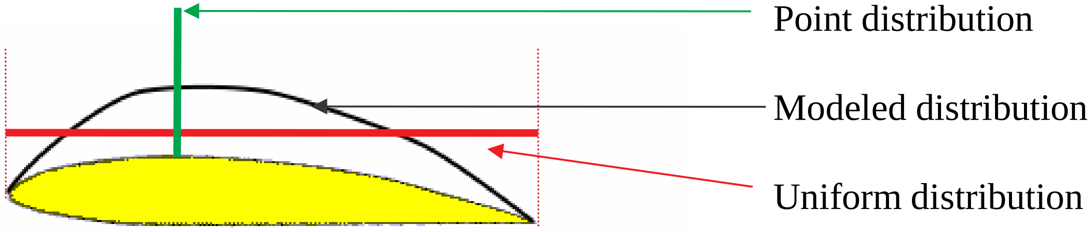
Here, **the Pareto front represents the best compromise** between lift over drag efficiency, mean and maximum acoustic emissions during take-off.

Each individual represents a unique blade geometry changing in chord, twist and sweep.

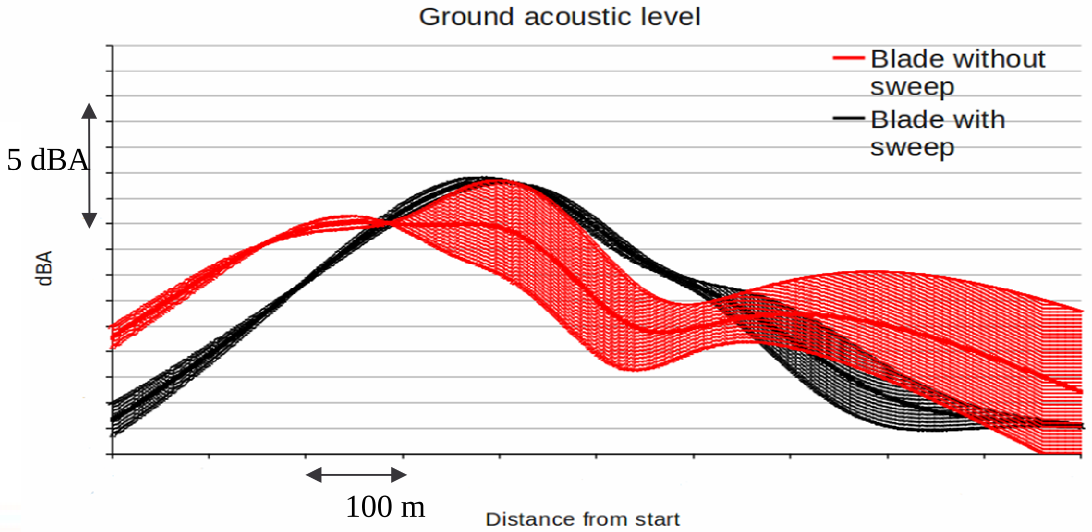
Low-order models : additional uncertainty

Yet, **even in this case, uncertainty in the result can still be present** and may hinder the quality of the results. The reason is **related to the way the mean load is distributed along the span** of the blade for acoustic computations.

In the case below, one can see that depending on the directivity angle, discrepancy as high as 5dB(A) can be observed depending on the applied model. In this case, it is therefore important to use higher order method to calibrate the distribution.

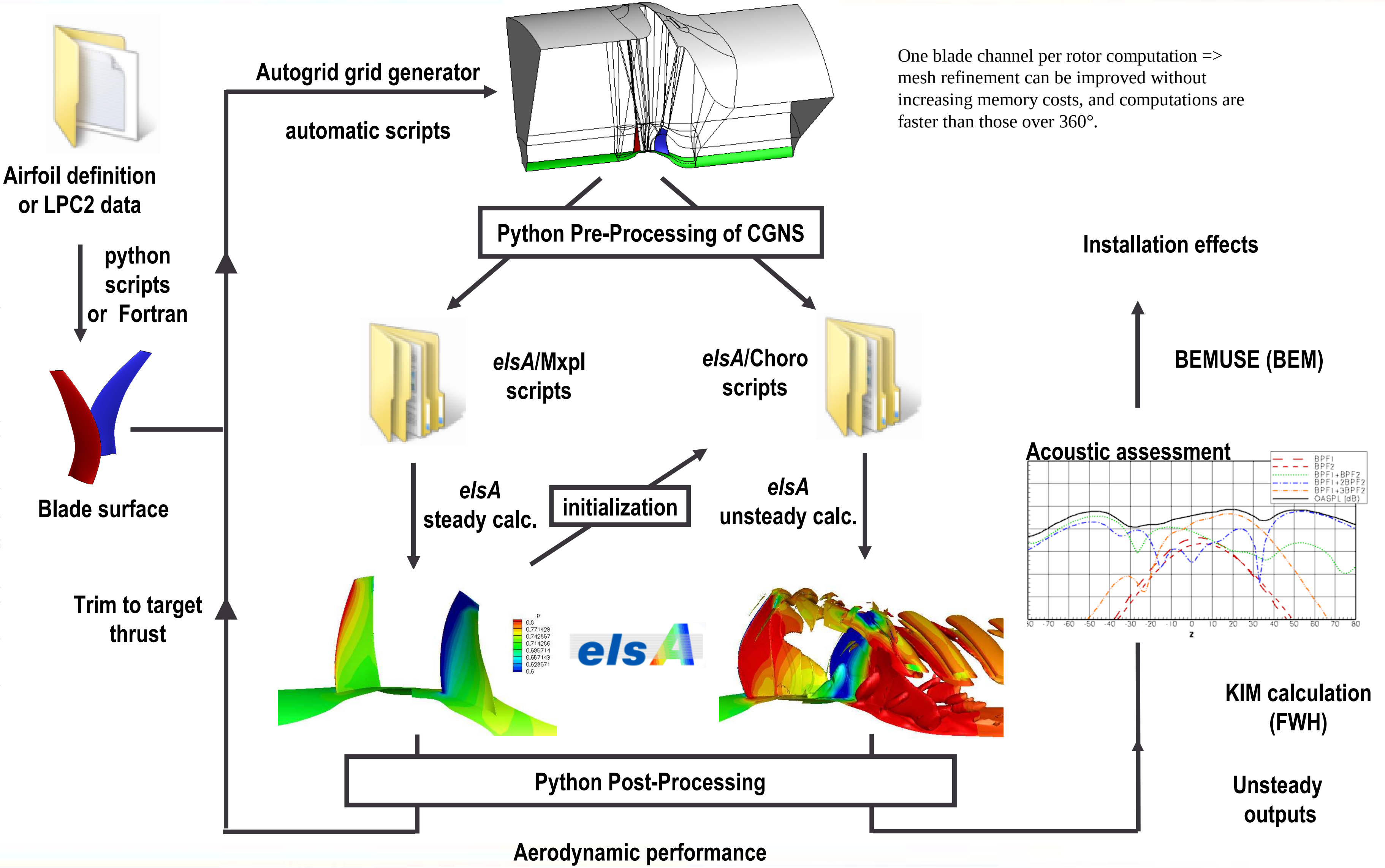


The choice of the distribution model leads to some **uncertainty in the acoustic level that can mislead the optimizer** (here the sweep's influence)



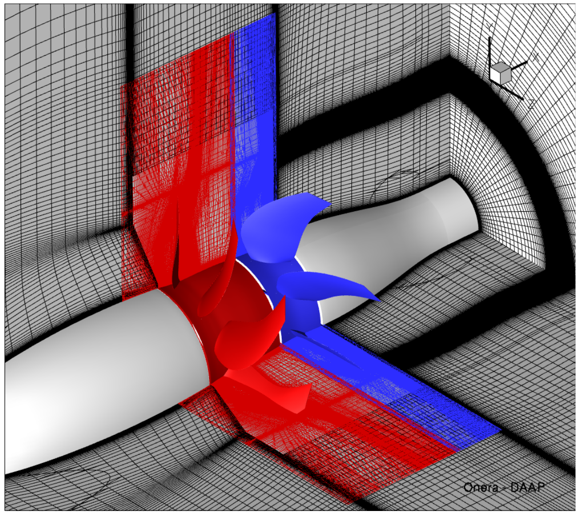
ONERA

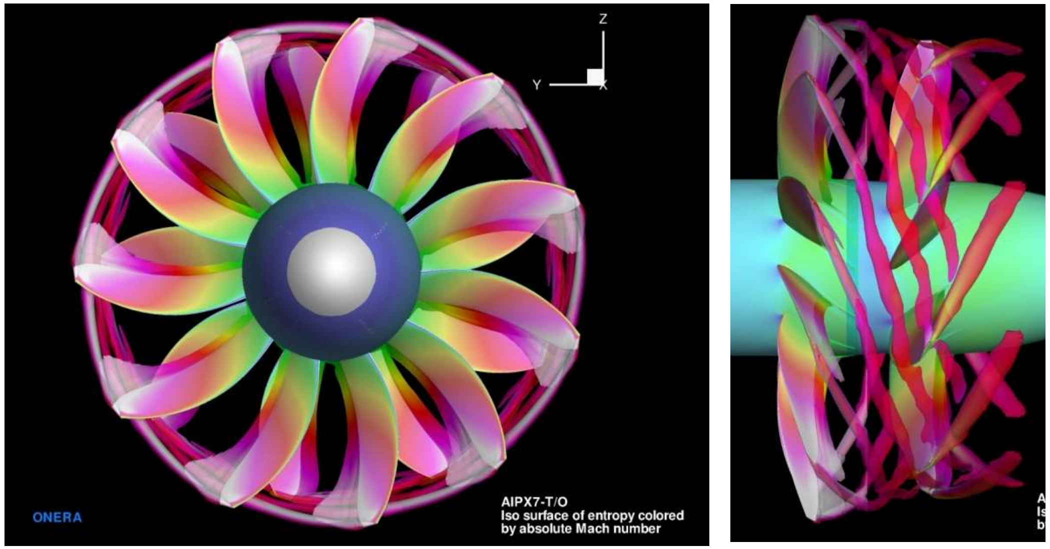
CROR aeroacoustics : Chorochronic CFD-CAA computational chain



Complete (360°) simulation of the CROR

- The objective is to set-up an open computational strategy able in a near future to compute a complete configuration for the study of installation effects
- Use of chimera strategy
- Recent applications with new computational resources (and Onera grids) give promising results:
  - NS, 50M pts, 4 rev., restitution time (80 proc Stelvio) ~ 11h (with Dψ<1°)

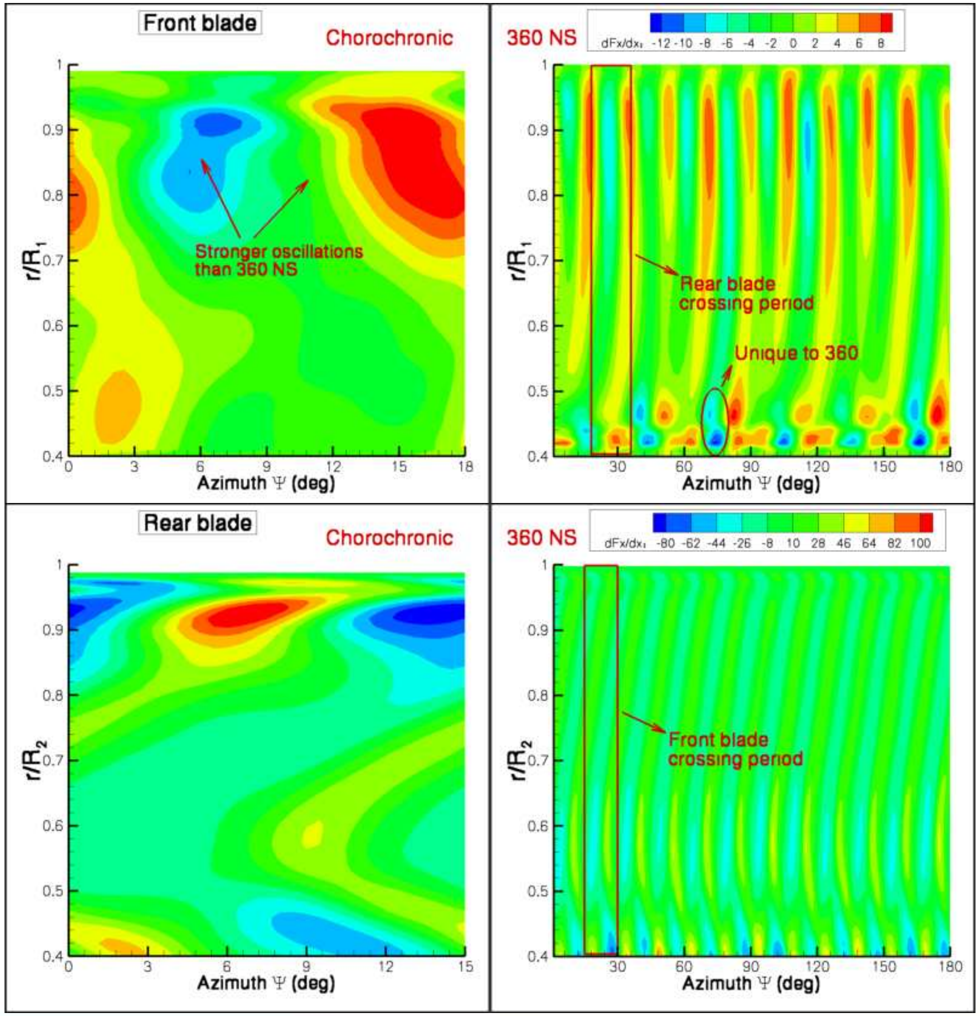




Airbus CROR Generic configuration

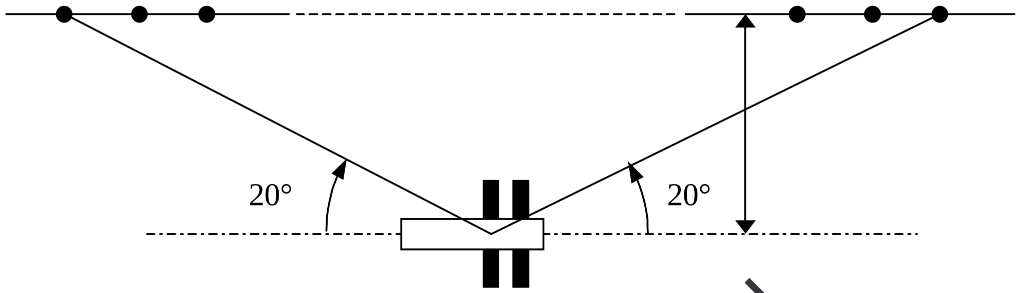
Chorochronic and 360° simulations comparison

Some non periodic phenomena may appear in the 360° computations

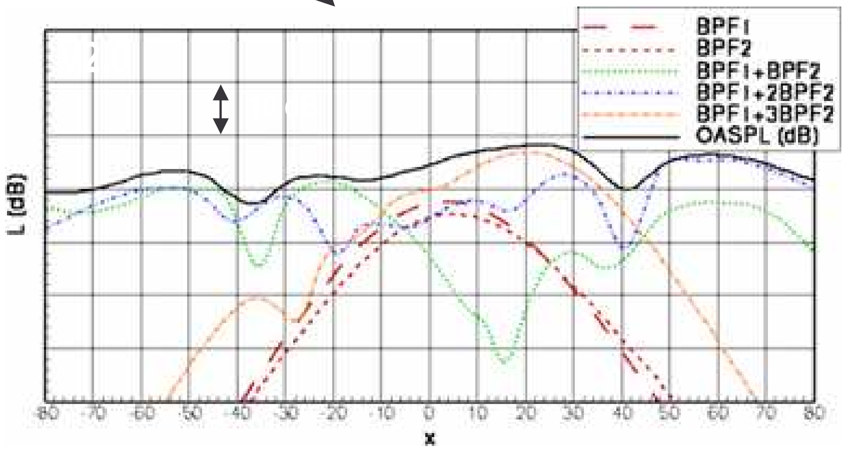


Take-off

KIM FW-H Acoustic computation

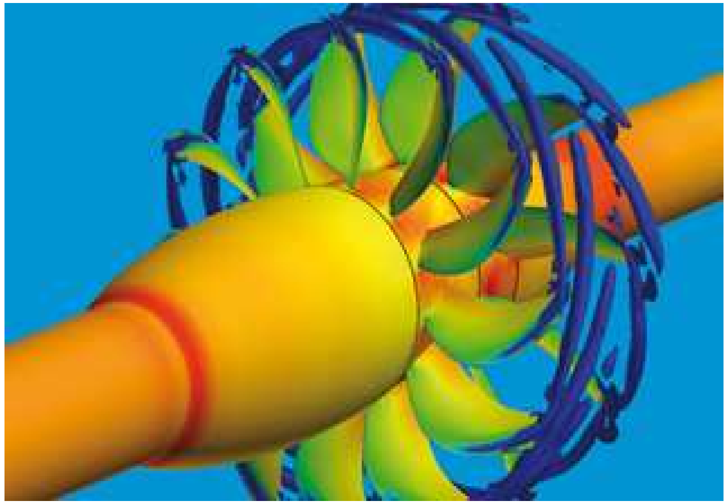


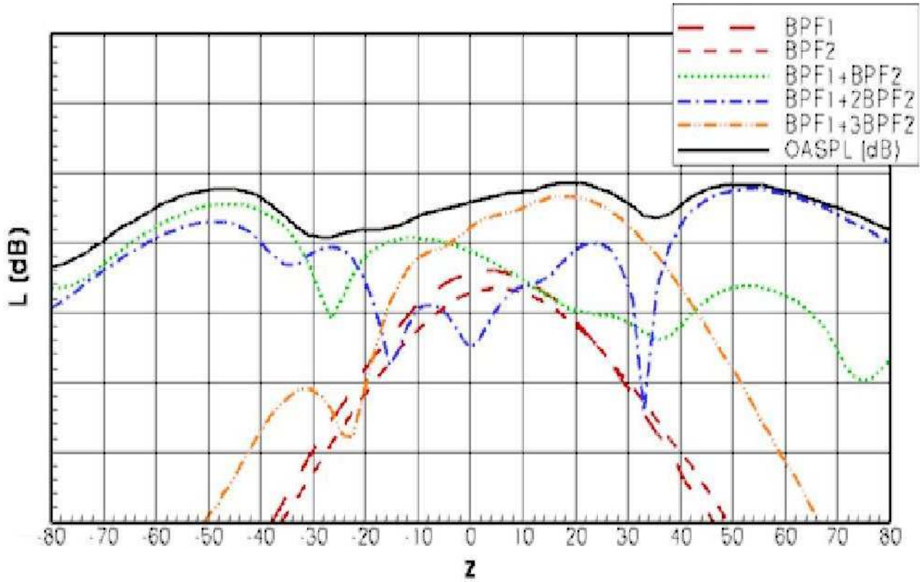
Sound Pressure Level directivities (dB)



- Eventual reconstruction from chorochronic solution
- Time-domain formulation of the FW-H equation
- Thickness and loading noise for Front and Rear propellers
- Addition of each rotor contribution
- Can take into account supersonic surfaces

CROR Aeroacoustics at take off (M ~ 0.2)



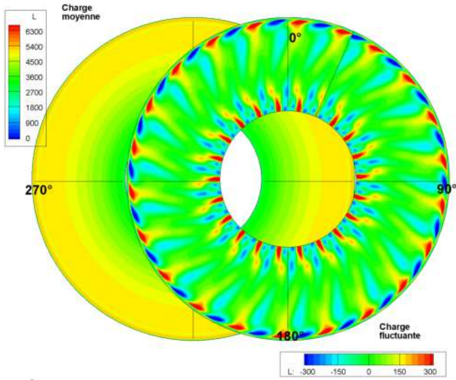


Main noise source :

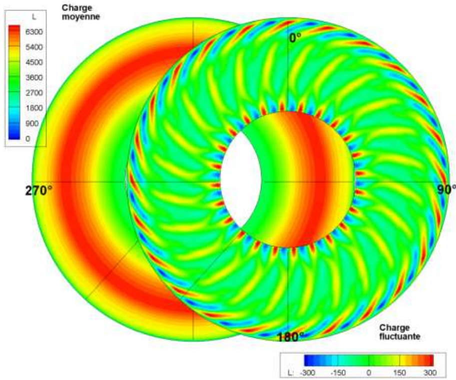
Tonal noise from blade pressure variations due to aft rotor interactions with vortices and wakes from the front one, and both rotors potential field interactions.

CFD computations are necessary and done over 360° or by using chorochronic periodicity.

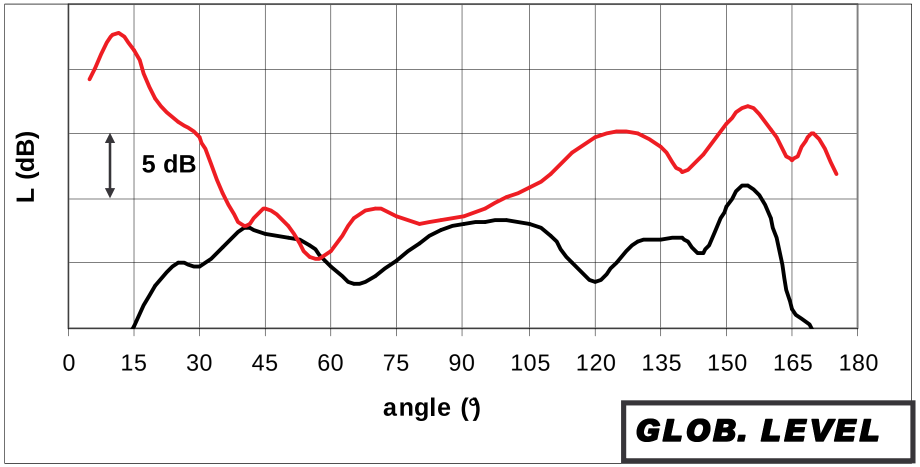
Blade pressures on one aft blade during rotation :



Geometry 1



Geometry 2



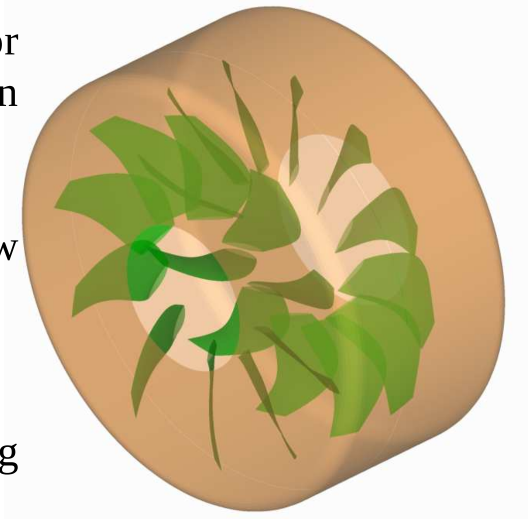
360° computation. Integration surface : blade surface.

Fluctuating loads are very weak compared to average load (<5%) but the noise level they create are of the same order than from the average load.

Two geometries with similar fluctuating loads level create very different noise directivities => very precise load prevision required.

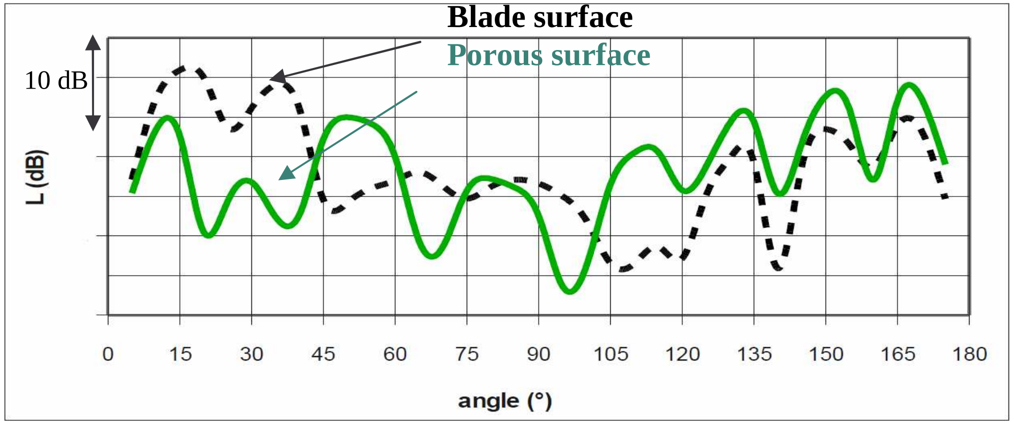
CROR Aeroacoustics at Take Off. Blade or fluid control surface

Acoustic propagation can be performed from blades pressure fields or from a porous surface. The latter is essential in transonic condition in order to capture the quadrupole sources.



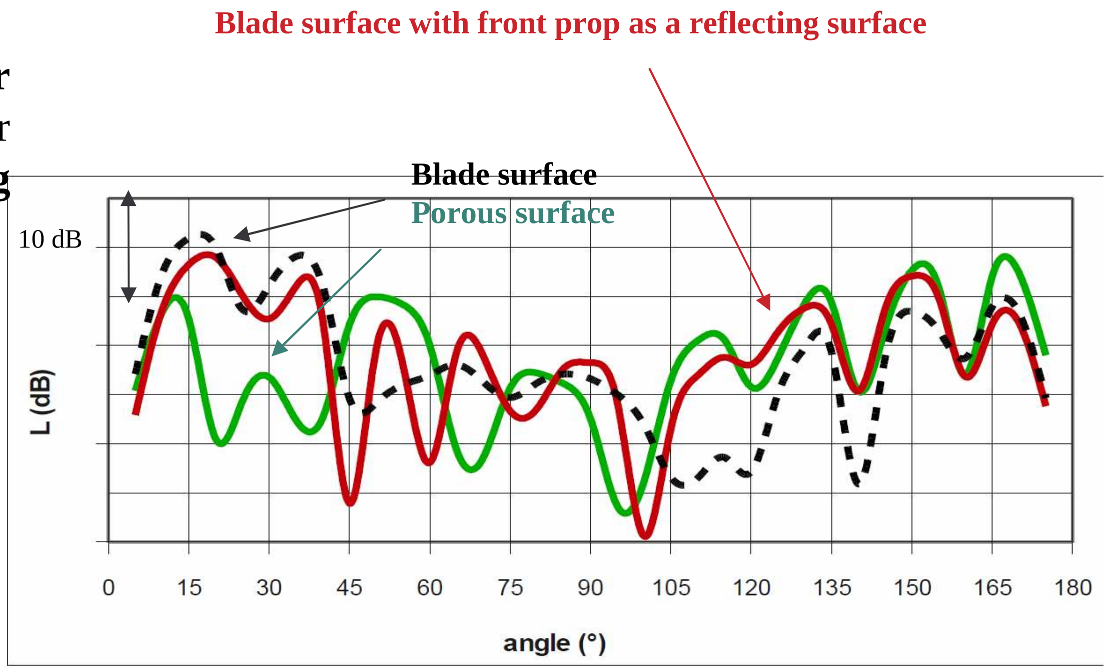
Nevertheless, even for subsonic cases the results using both methods show differences which could be due to :

- numerical dissipation of waves going backward
- non-linear propagation in the inter-rotor space due to strong gradients
- masking effects of both rotors…



Coupled strategies for CROR aeroacoustic simulations

As a test**, adding the front propeller** during the computation of the rear propeller as a static **reflecting surface does not improve the result**

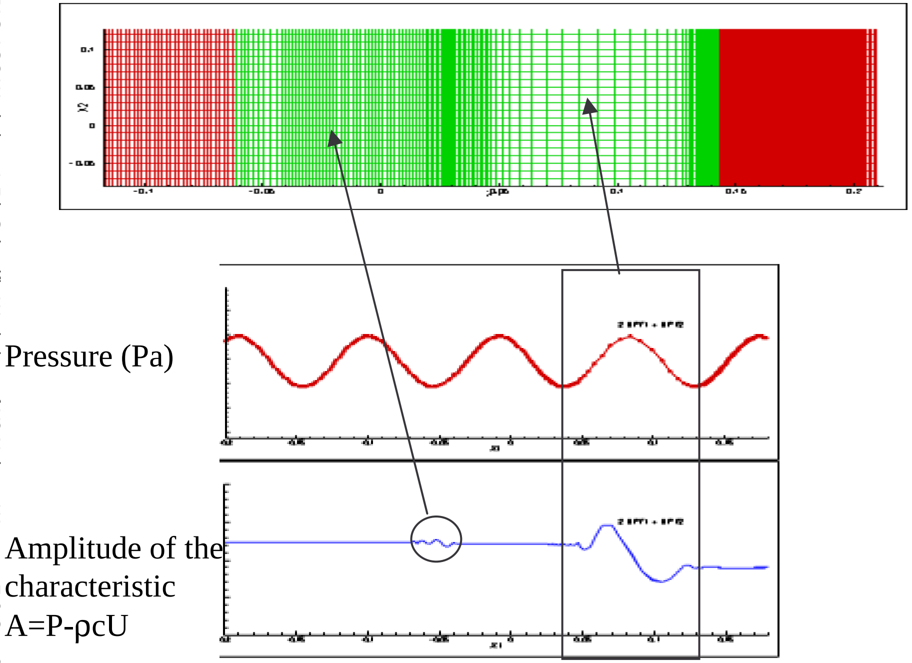


After separating or simulating these points, it seems to be on one hand a masking effect (depending on frequencies and geometry) and on the other hand an effect due the free space propagation hypothesis of code KIM (two rotors without hub do not radiate like a cylinder containing a hub and two rotors).

Coupled strategies for CROR aeroacoustic simulations

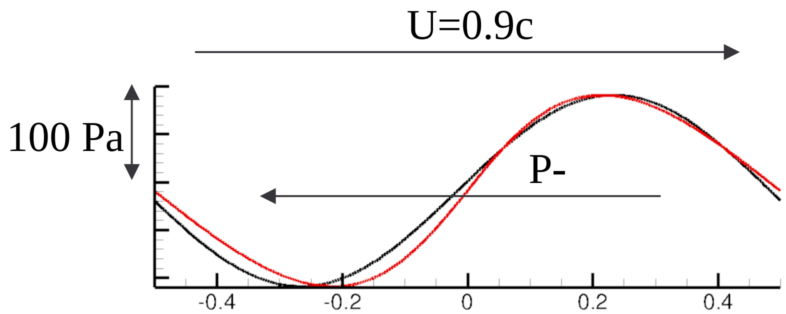
Using CFD-CAA methods, **waves can be subject to dissipation and dispersion errors** coming from a **combination of the mesh defects and the characteristics of the spatial and temporal numerical schemes.**

Usual CROR meshes show **jumps in cell size that may lead to dissipation** of the propagating waves



Courtesy: G.Delattre (private communication)

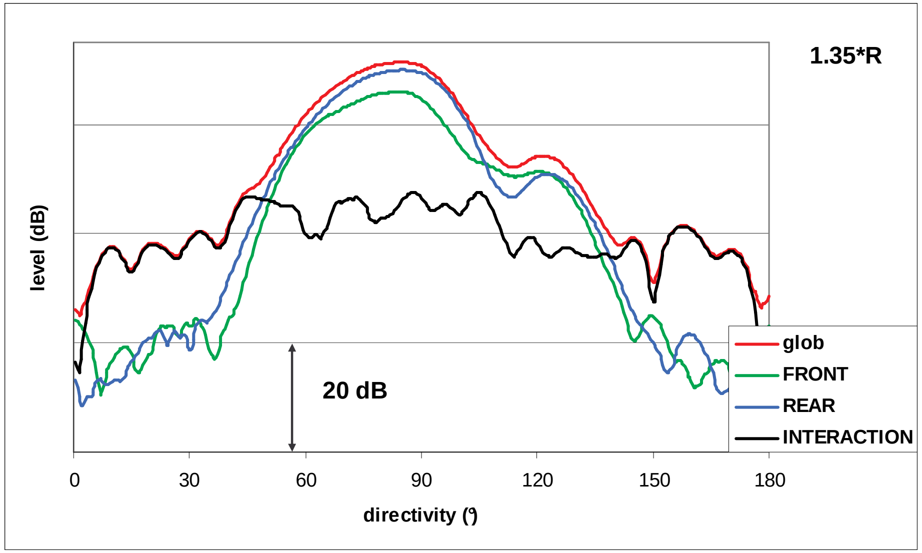
Even when spatial accuracy is ensured (here 512 pts/wavelength), **dispersion due to high mean Mach number can influence the propagation of upstream propagating waves** from the rear propeller.

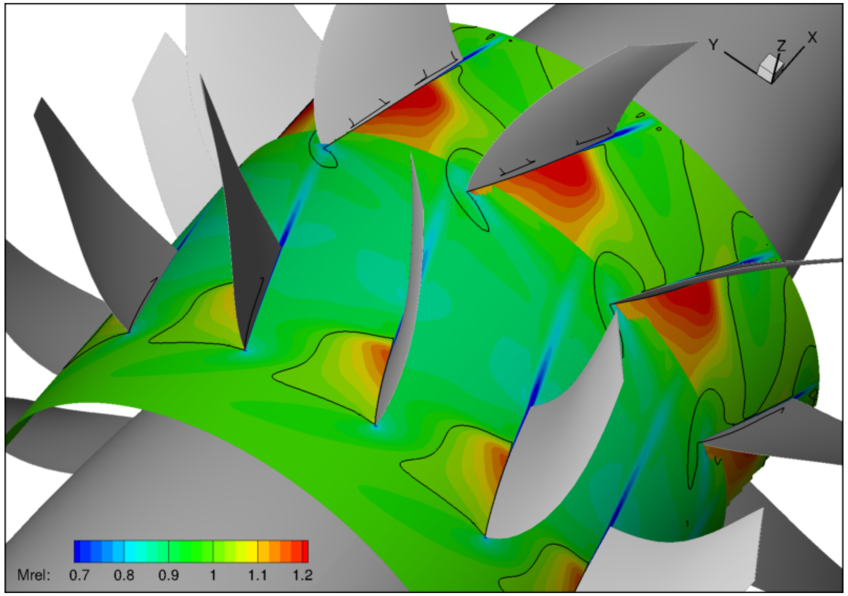


Black: analytical and initial solution
Red: acoustic wave after one wavelength convection

CROR Aeroacoustics at cruise

CROR at cruise (M ~ 0.8)

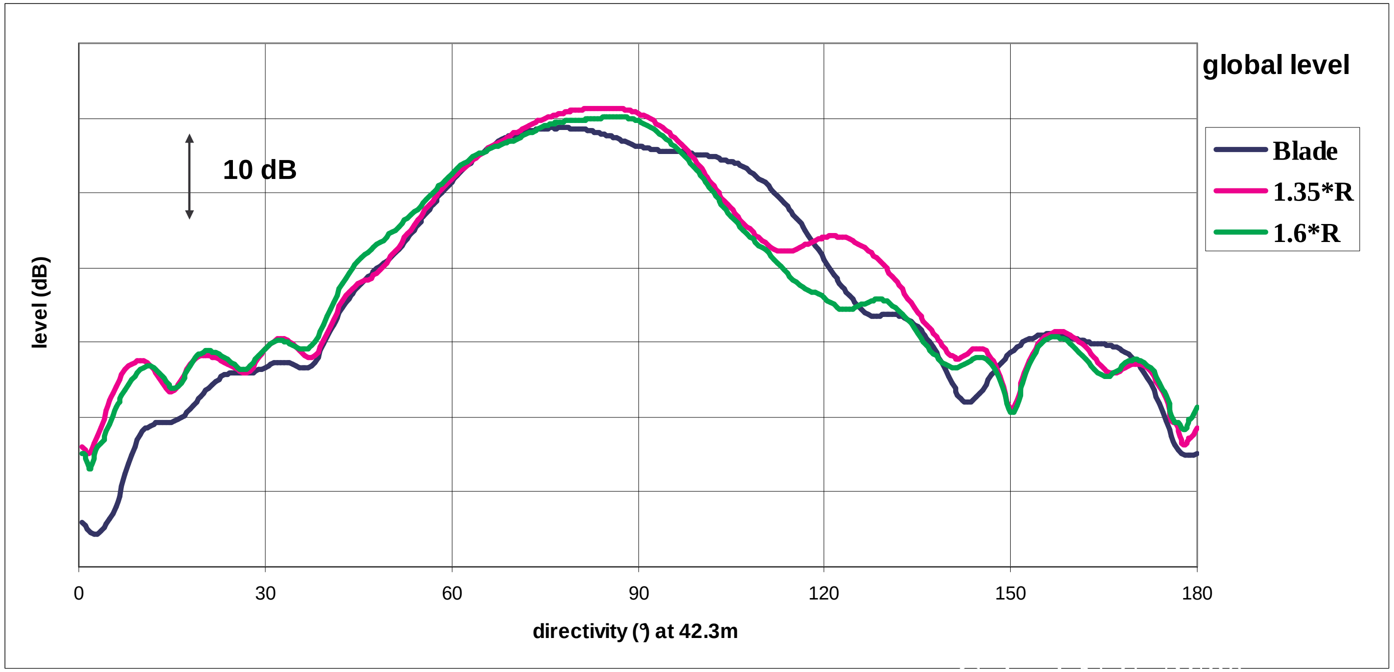




Near the rotor plane : noise sources multiple of propellers fundamentals
Upstream and downstream : Interaction noise.

Transonic flow => Shocks => Acoustics sources in the fluid => FW-H porous surfaces

CROR Aeroacoustics at cruise (M ~ 0.8). Influence of the integration surface.



The question of an optimum position for the extrapolation surface in the volume surrounding the CROR is still open and is being studied through : necessary mesh density for aerodynamic and aeroacoustic computations, acoustic sources identification and near-field non-linear propagation effects.

Assessing aeroacoustic results quality in CROR simulations

A common method to determine the quality of the results obtained by coupling CFD methods and Integral methods is to:

-interpolate CFD results on a closed surface surrounding the acoustic sources and use the integral method to get the acoustic level at a location included inside the CFD domain.

-extract the acoustic level directly from the CFD computation at this location

-compare the two results.

This method, while definitive is too restrictive.
It only proves accuracy at locations where the integral method and the CFD agree and tells nothing about other angles of directivity.

The following example is extracted from a study by Sturmer and Yin (AIAA,2010). In this case, this method only proves the accuracy of the results for absolute angles lower than 30° with respect to the blades ro tation plane.

A specific approach is to be developed for accuracy assessment!

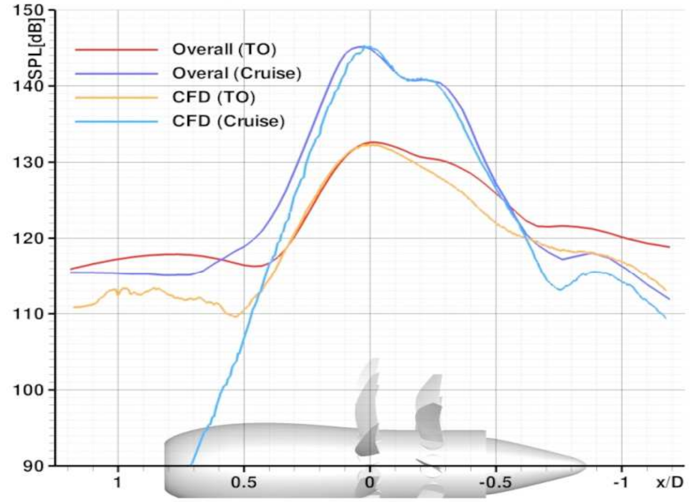
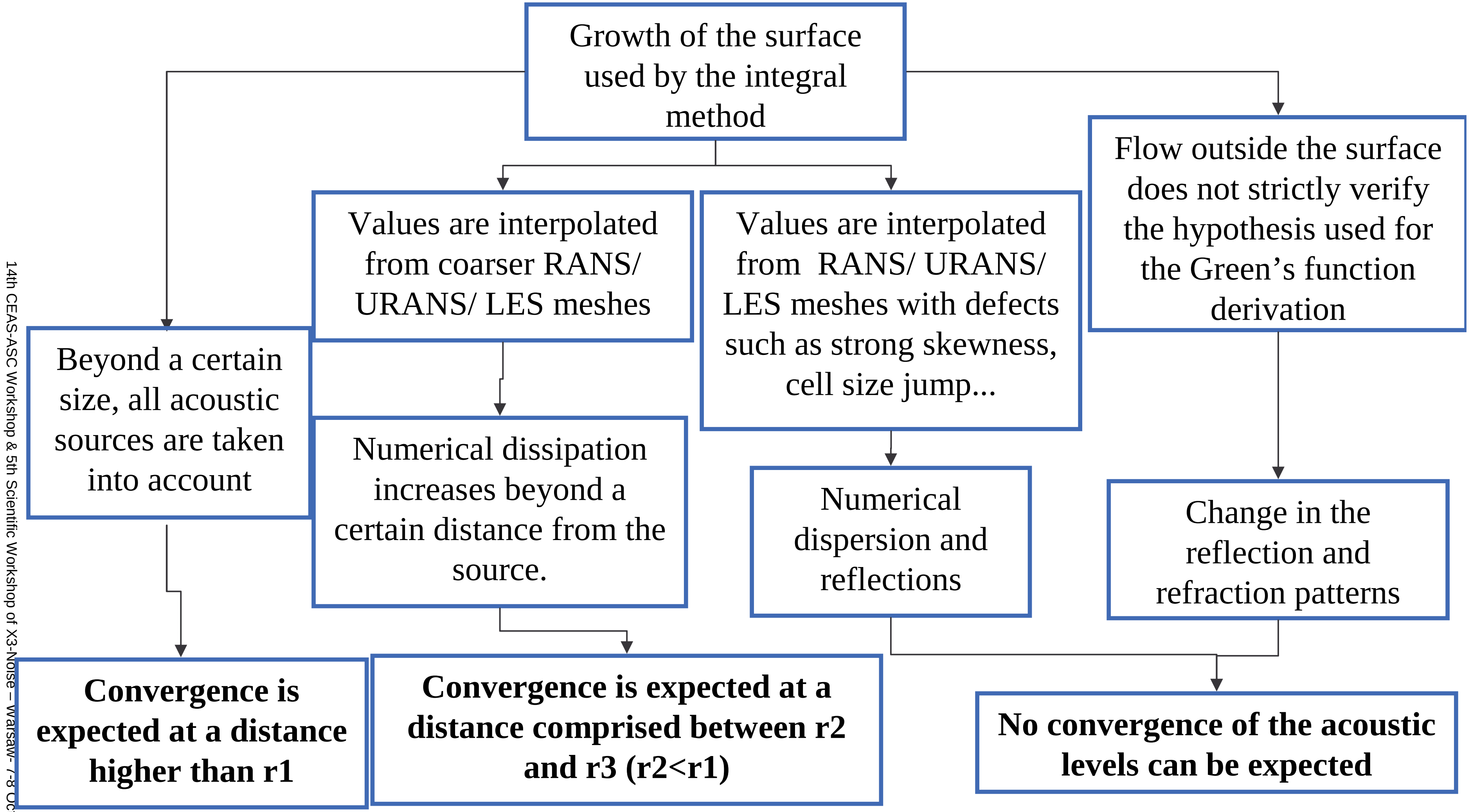


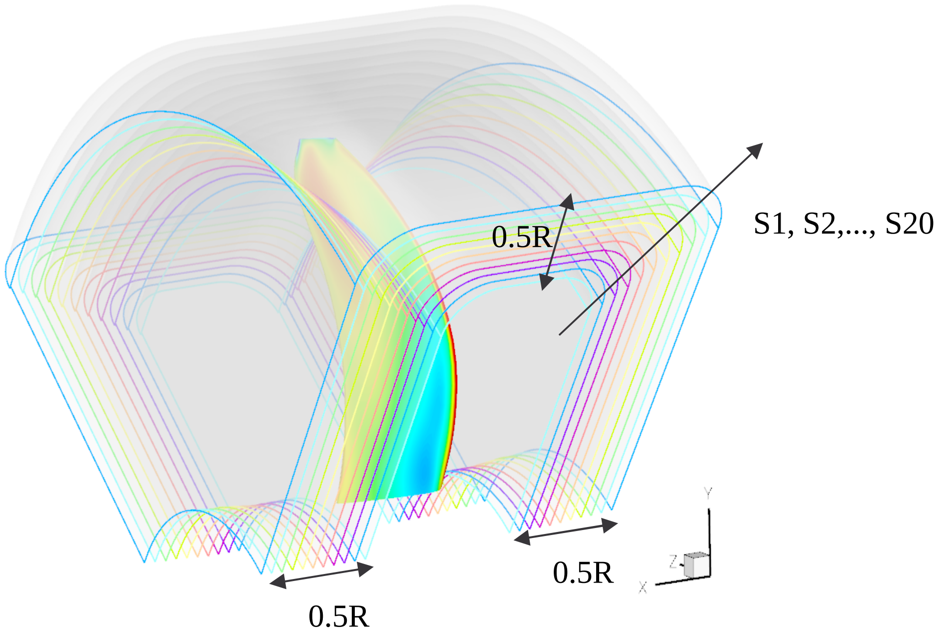
Figure 24. Comparison of nearfield polar directivities

Stuermer and Yin (AIAA,2010).

Conditions of convergence for the far-field acoustic results with respect to the control surface



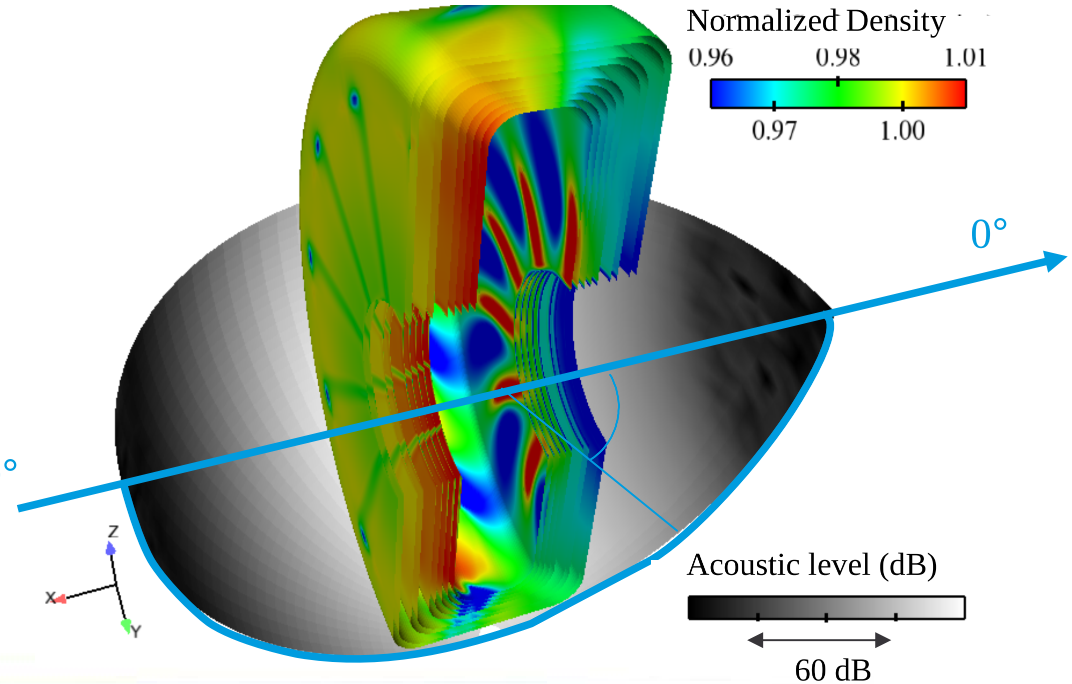
Analysis of the influence of the integration surface location on a single propeller case



A single propeller is enclosed in a growing set of closed surfaces. A steady state CFD simulation provides the input fields on the surface.

For each surface, acoustic levels are computed for all directivity angles and the maximum level for each harmonic is gathered.

What is the convergence of the far field noise results with respect to the surface location?



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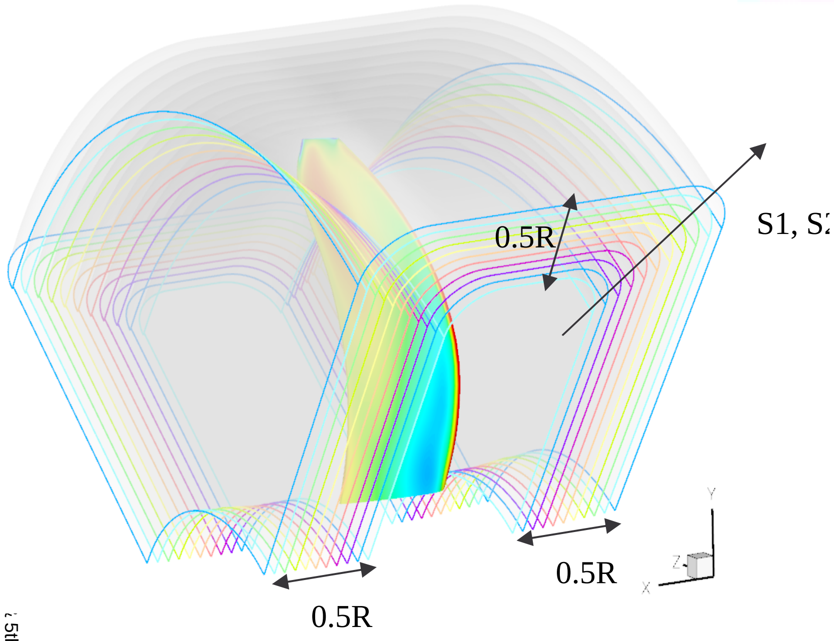
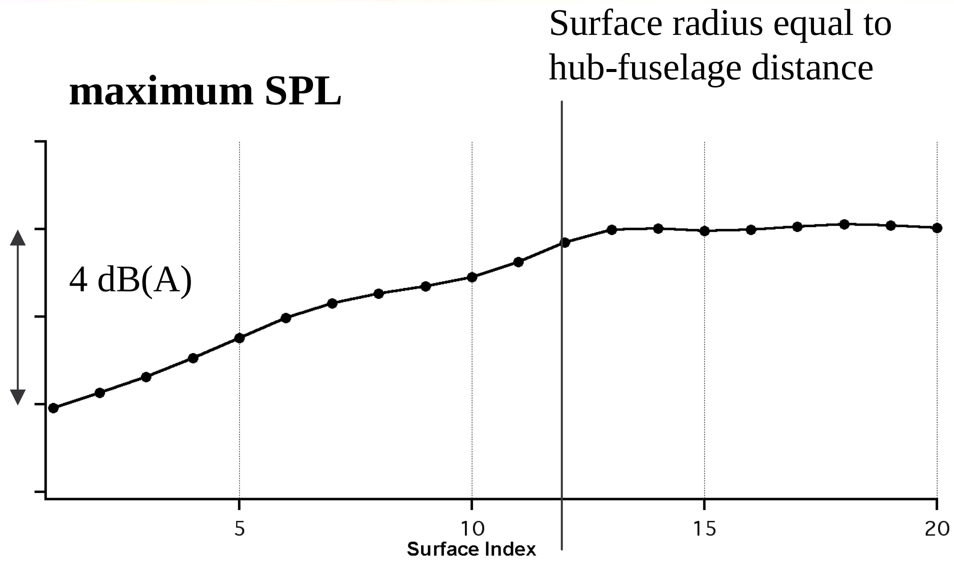
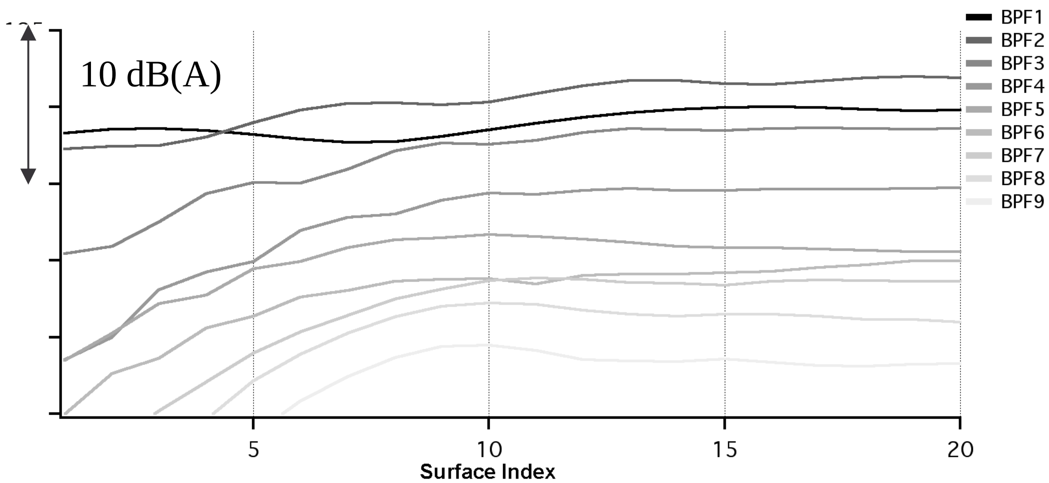
Analysis of the influence of the integration surface location on a single propeller case



maximum SPL



maximum SPL for harmonics 1 to 9

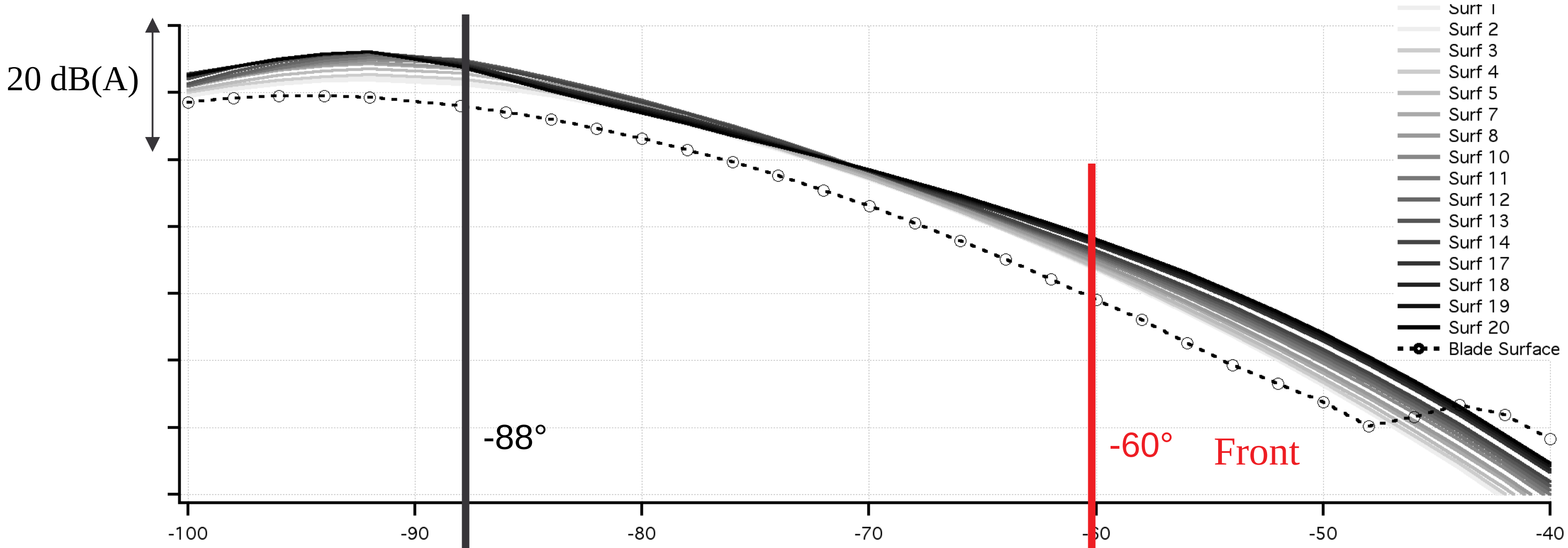


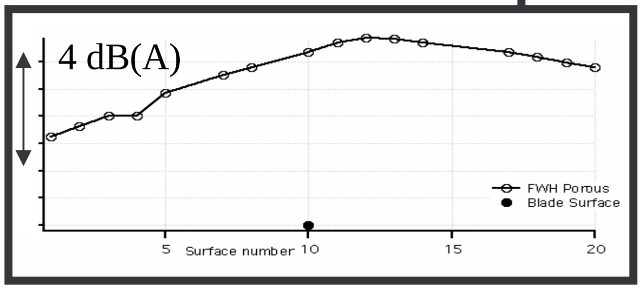
As expected, maximum acoustic levels converge toward a given value as the surface grows.

Is it the same for any given directivity angle?

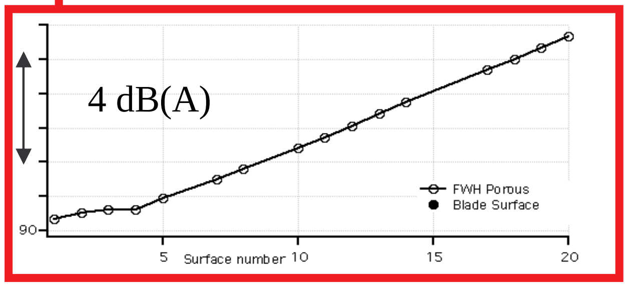
Analysis of the influence of the integration surface location on a single propeller case

Convergence of the global **front SPL** with respect to the surface position **depends on the directivity angle**





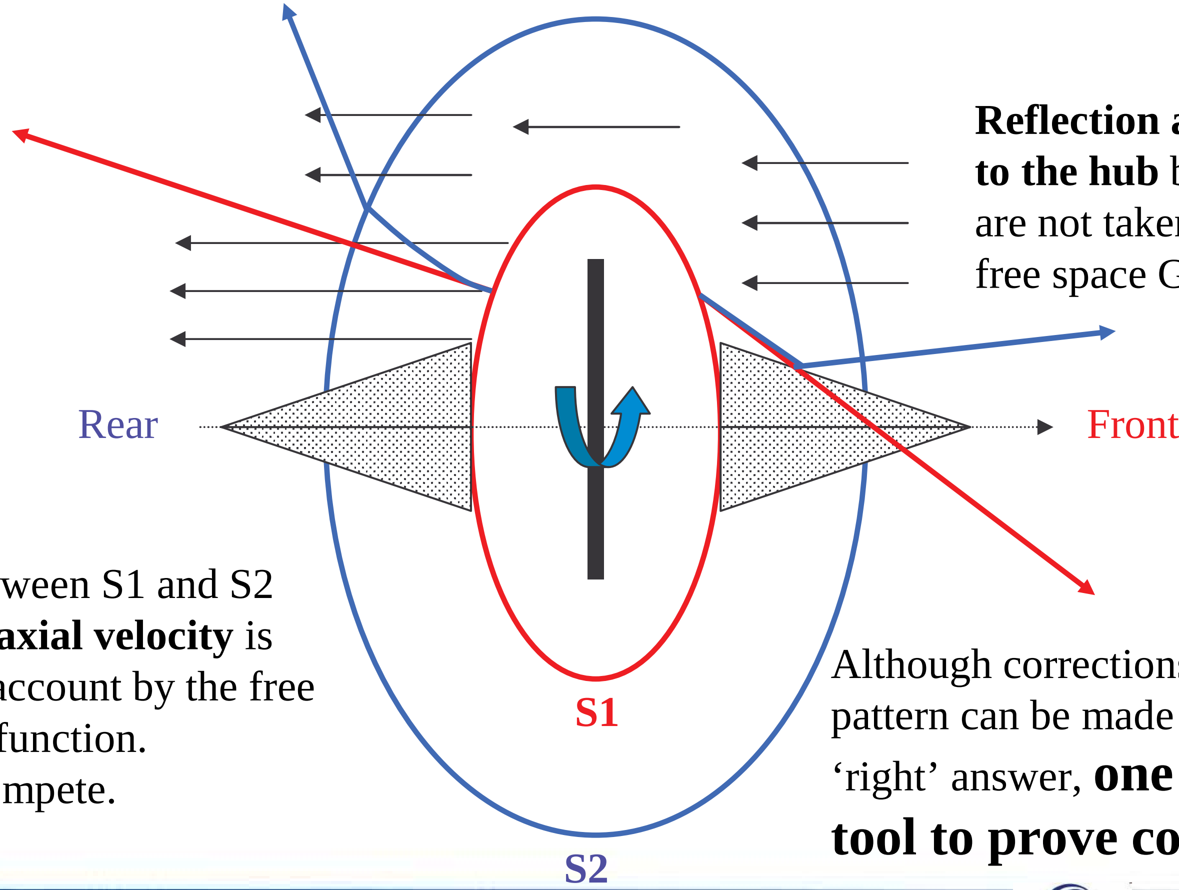
CFD results: elsA
Acoustic Integral method: KIM



Assessing aeroacoustic results quality in single propeller and CROR simulations

For some angles, the SPL continues to change although most probably all acoustic sources are long enclosed by the surface.
A possible explanation for the evolution of the SPL at a given directivity angle between large integration surface **lies in the assumptions used to derive the free space Green's function.**

Reflection and diffraction due to the hub between S1 and S2 are not taken into account by the free space Green's function

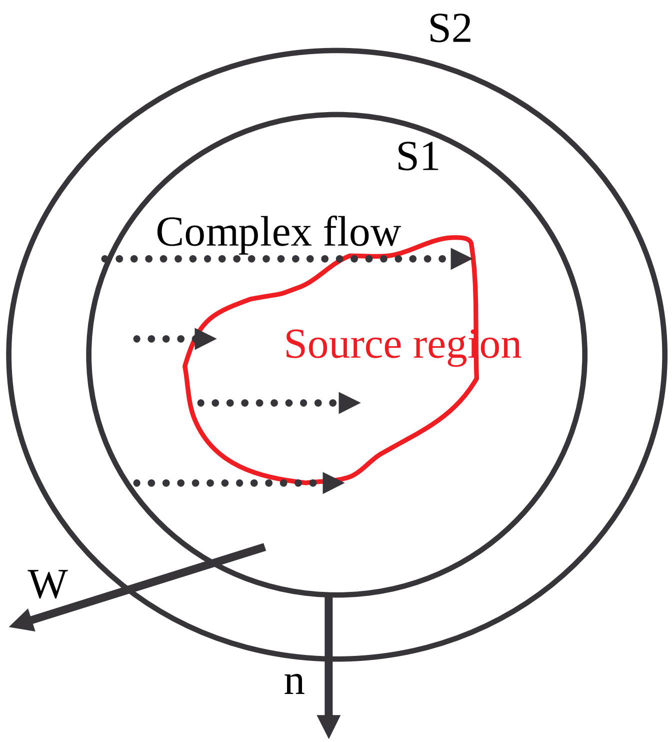


Refraction between S1 and S2 **due to higher axial velocity** is not taken into account by the free space Green's function.
Both effects compete.

Although corrections to the directivity pattern can be made to retrieve the 'right' answer, **one needs a simple tool to prove convergence**

Energetic approach for an efficient positioning of the control surface

Following many authors who have tackled this problem, **an energetic approach is proposed.**
Farassat and Farris (Forum Acusticum 1999) perfectly summarize the question at stake and the different strategies that have been pursued so far.



In propeller and CROR flows, in addition to non-uniform mean velocity, strong vorticity structures are present in the wake of the blades.
In this case, it appears that **Myers exact energy corollary is most suitable to analyze CFD results** as long as the energy transfer between vortical modes, entropy fluctuations and acoustic is negligible in the vicinity of the integration surface.

$$\frac{\partial E}{\partial t} + \vec{\nabla}.\vec{W} = S$$

if S=0 between S1 and S2, $\int_{S1} \vec{W}.\vec{n}ds = \int_{S2} \vec{W}.\vec{n}ds$

Concluding remarks

During the last 15 years, with the growing use of coupled strategies using both steady (and then unsteady) CFD and integral methods, propeller and CROR aeroacoustic studies have been able to characterize numerous innovative and complex blade shapes.

Thanks to these progress, the understanding of single propellers and CROR acoustic emission mechanisms has greatly grown.

Yet, in order to meet the next milestones mentioned earlier, assessing the quality of these methods is critical. Different approaches are being developed to deal with this issue.

Conclusion

The present objectives are :

- to answer to the remaining questions :
  - How to evaluate the effect of a vorticity impacting a porous surface on the acoustic radiation (physical or spurious effect).
  - What criterion for an effective location of the integration surface for FW-H codes.
- to propose best practices for CFD-CAA computations :
  - aerodynamic mesh suited to acoustic purpose
  - Reynolds effect to take into account the scaling effects
  - more accurate numerical scheme for CFD…
- to improve the physical insight with the goal of open rotor design :
  - noise sources localization
  - influence of the vortex and wake parameters…
- to improve the tools :
  - Green’s function accounting for inhomogeneous flows

  …