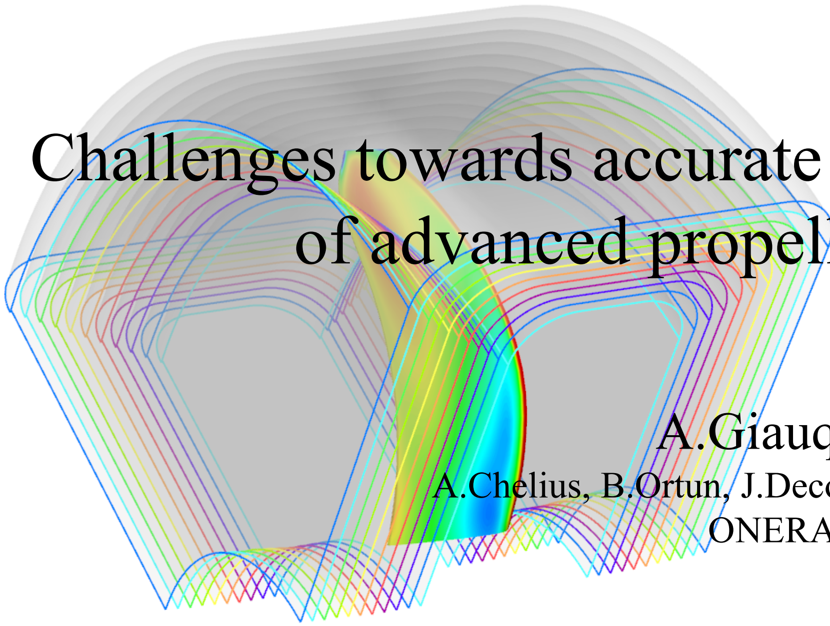
Challenges towards accurate and reliable acoustic studies of advanced propellers and open rotors



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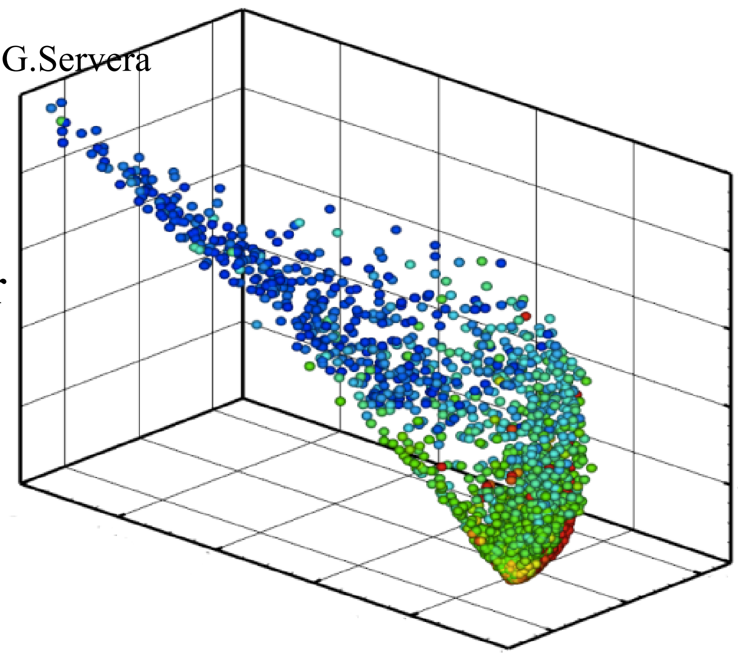

Trilateral Seminar
Svetlogorsk
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Outline

Why accuracy in acoustic studies is still a challenge?

Low order models and shape optimization:

- Interest and limitations of low-order models for aeroacoustic studies of propellers.
- Additional source of uncertainty using low-order models

Coupled strategies for single propeller and CROR aeroacoustic simulations:

- An example of common methods used to assess accuracy
- A different approach to accuracy assessment: growing surface set technique
- Discussion
- Fluctuating energy approach

Concluding remarks

Importance of accuracy in acoustic studies of propellers and CROR

Today's acoustic researchers and engineers in the field of propellers and CROR simulations often pursue one of the following two main challenging goals:

-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

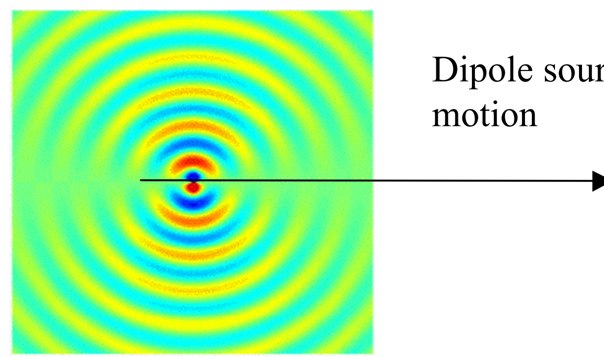
-Develop new strategies to **accurately determine the acoustic levels** associated with modern complex shapes.

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).

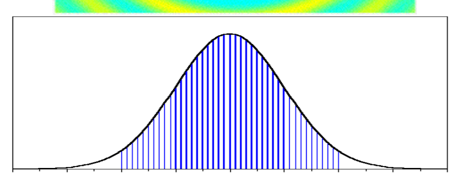
$$L_{AE} = 10\log_{10}\left[\sum_{k=t_1}^{t_2} 10^{L_{Ak}/10}\right]$$

where

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



Dipole source in (slow!) motion



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

Why accuracy in acoustic studies is still a challenge?

As mentioned by many authors, **acoustic energy is (really) small.**

The typical noise level for a (not so) modern small propeller-driven plane lies around 85dB during take off at approximately d=200m.
If one assumes a naive dipole-type noise source, the total acoustic power comes to
$\Pi = (|Pmax|*d)^2*8\pi/(3\rho c) \sim 100W$, which represents at most 0.02% of the total engine power!

Given these figures, **CFD Methods transporting total energy and used for acoustic studies therefore need some extreme care when dealing with the numerical errors in terms of dissipation and dispersion.**

In this context, Direct Noise Computation (ex:Bogey, Bailly, ICENCE, Shanghai, 2008) is the most promising technique. Yet, ensuring the required level of accuracy with complex geometries remains an opened topic.

Therefore URANS or LES technique is often used and CFD domains are truncated so that integral methods take over after a few meters. Yet, at this location, the actual radiating pressure wave only has an amplitude of a few Pa (or less!) which is a thousand times smaller than the mean aerodynamic pressure gradients that drive the flow.

Acoustic sources: Low-order models for single propellers

Propeller noise can be separated into three main type of sources:
-**Monopole thickness noise**, related to the displacement of air due to the rotation of the blades
-**Dipole load noise**, related to the steady and unsteady pressure distribution on the blade profiles
-**Quadrupole noise**, related to flow features such as shock, turbulence and wake interactions.

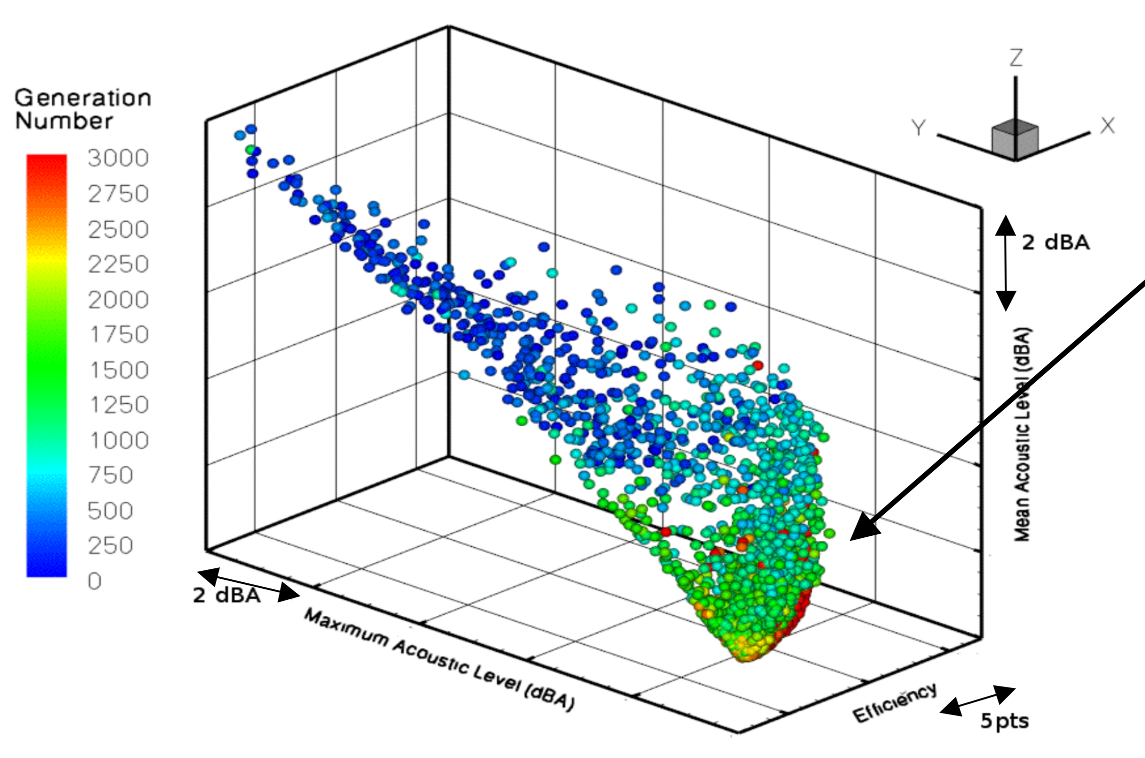
This order decomposition is at the origin of today's fast acoustic analysis methods for propeller noise studies.

If the quadrupole noise can be neglected and
incoming flow is assumed stationary in the blade frame for each angular position, **Prandtl's lifting line theory can be used** to get the load.

Note that the incoming flow does not have to be homogeneous and therefore **(some) installation effects can be investigated** through azimuthal and/or radial velocity fluctuations.

Low-order models and shape optimization for single propellers

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.**

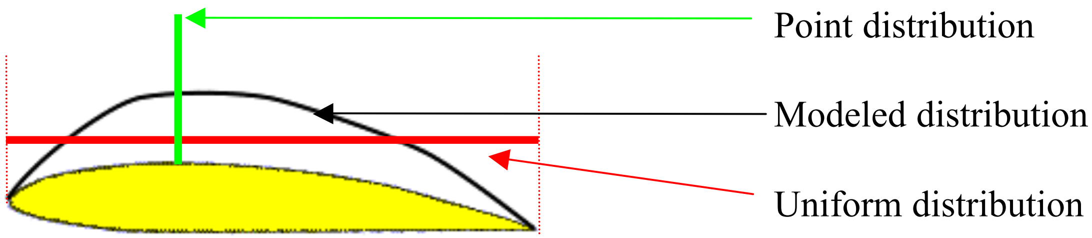


Here, **the Pareto front represents the best compromise** between lift over drag efficiency, mean and maximum acoustic emissions during take-off.

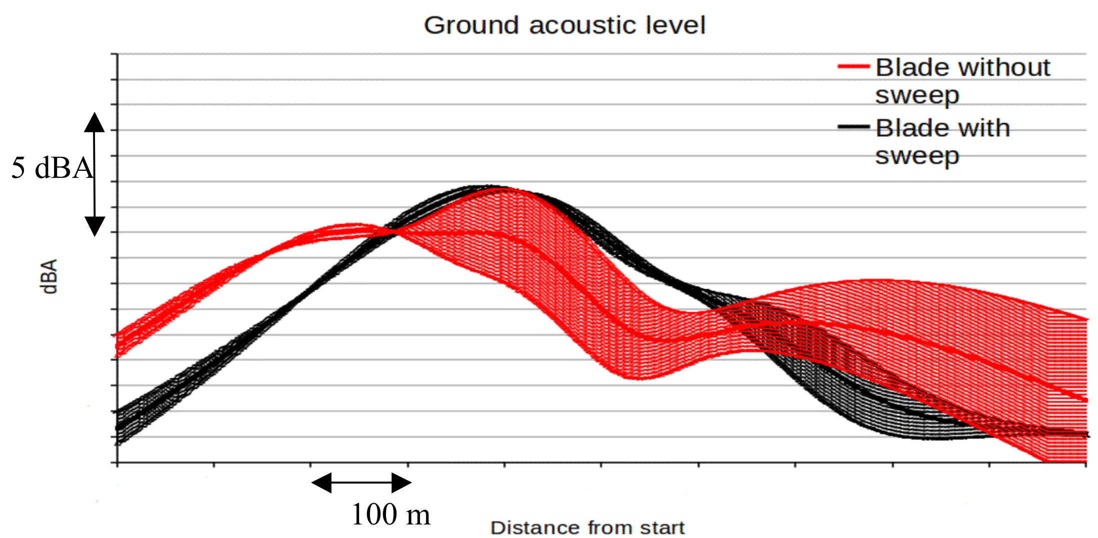
Each individual represents a unique blade geometry changing in cord, twist and sweep.

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 cord** for acoustic computations.



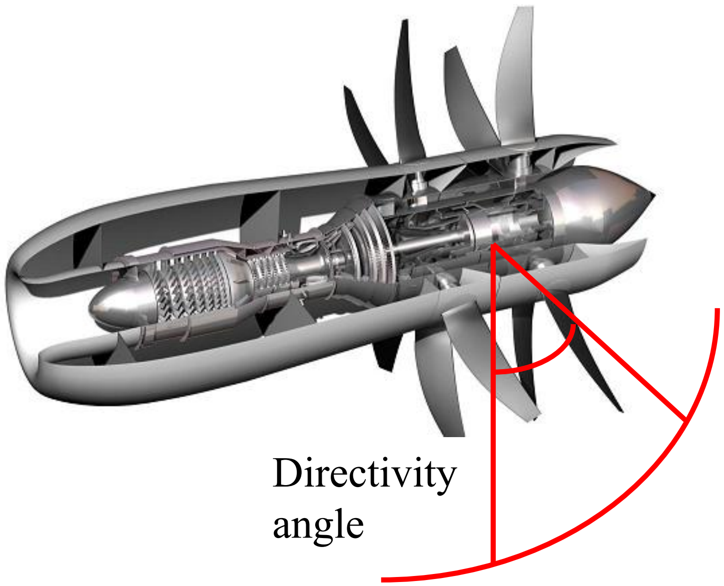
Prandtl LPC2
FWH KIM

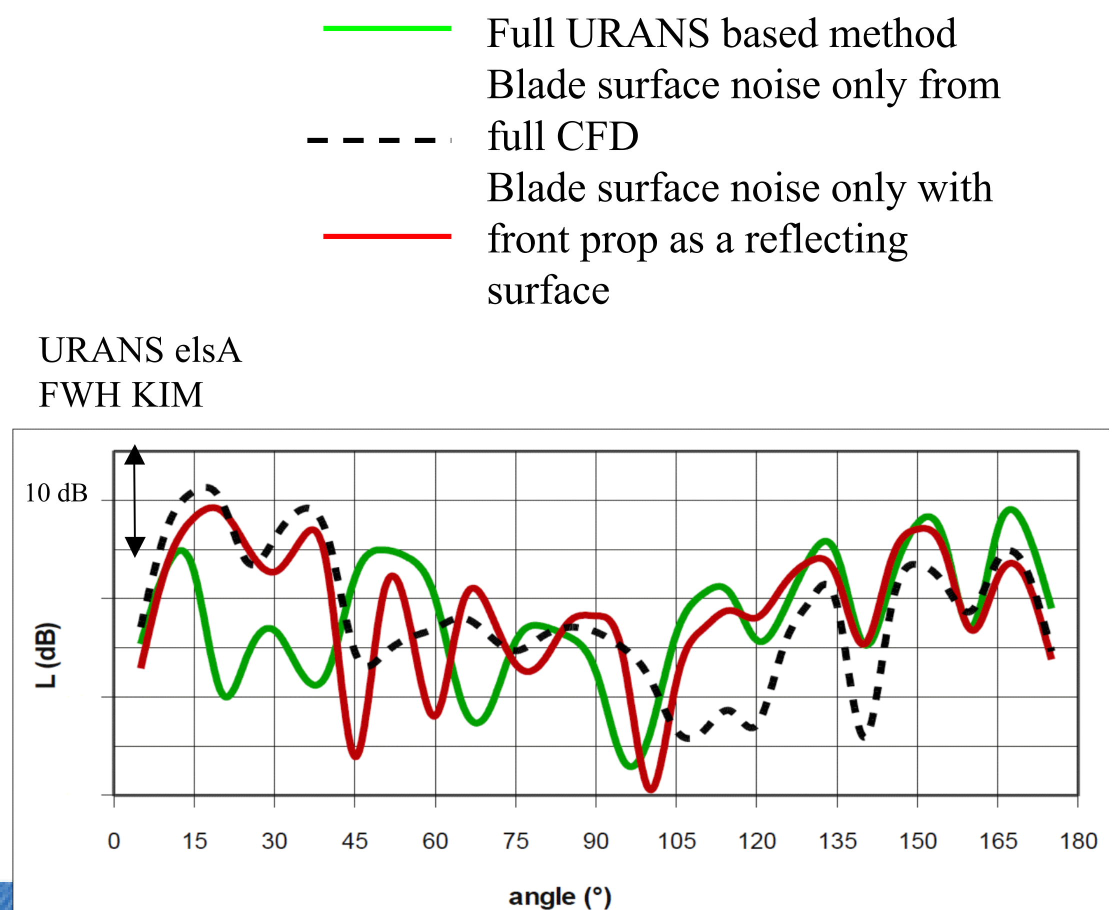


The choice of the distribution model leads to some **uncertainty in the acoustic level that can mislead the optimizer** (here the sweep's influence)

Coupled strategies for CROR aeroacoustic simulations

CROR acoustic studies show that maximum **acoustic levels are often related to the interaction frequency**. The directivity pattern of this particular harmonic of the common but opposed rotation speed **cannot be accurately reproduced if quadrupole sources are not taken into account.**





Adding the front propeller during the computation of the rear propeller as a static **reflecting surface does not improve the result**

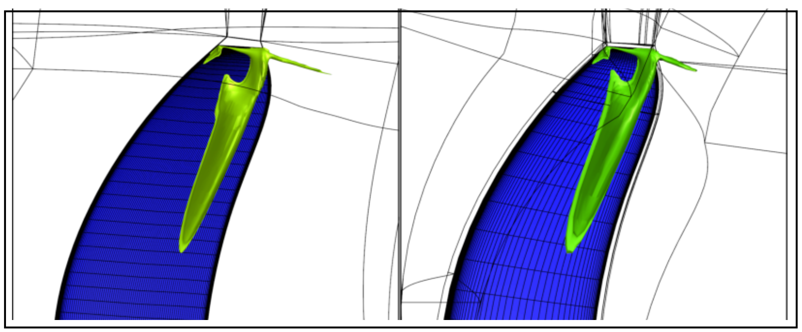
Coupled strategies for CROR aeroacoustic simulations

Given these results, it appears that full **CFD coupled with Integral methods is today the only method a priori able to correctly reproduce the noise levels and directivity patterns of modern CROR** with complex geometry.

Using this methodology with second order schemes, two aspects have to be treated with caution:

1.**The acoustic sources in the volume have to be most accurately discretized.**

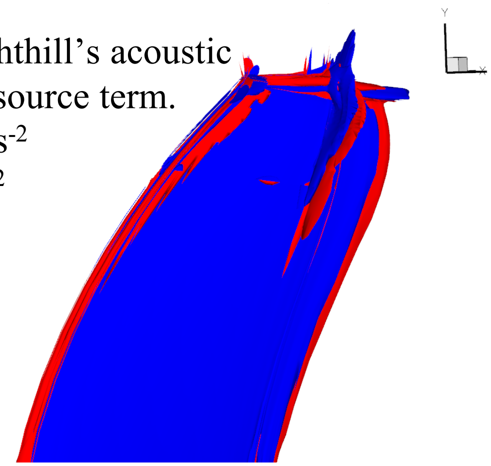
Different grid resolutions provide almost identical shock structures.



Visualisation of the shock
Iso-surface of velocity (M=1)

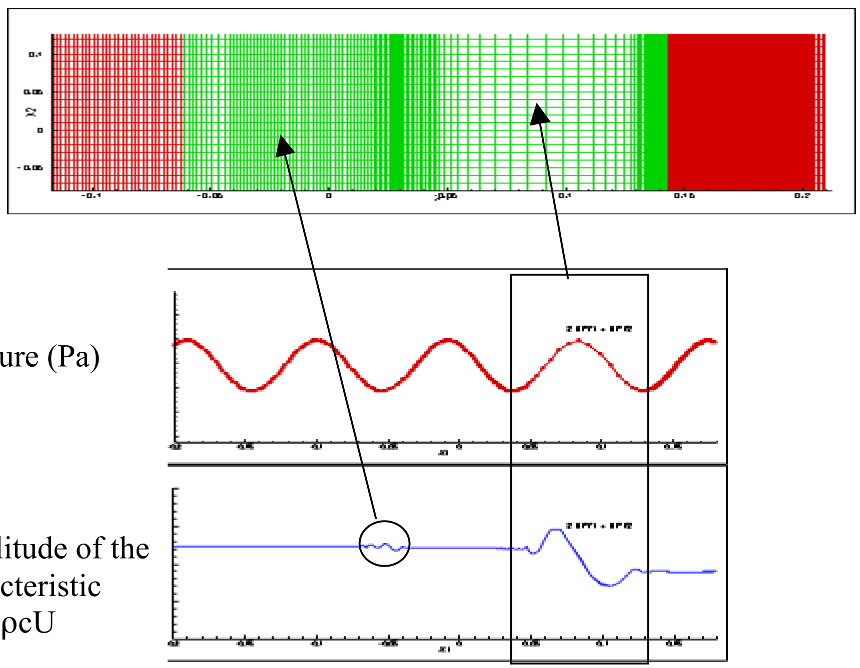
Yet, acoustic emission results from a subtle balance of locally extremely sharp and large source terms

Iso-surface of Lighthill's acoustic analogy equation source term.
Blue: -10^{7} kg.m^{-3}.s^{-2}
Red: 10^{7} kg.m^{-3}.s^{-2}



Using this method, **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 lead to dissipation** of the propagating waves

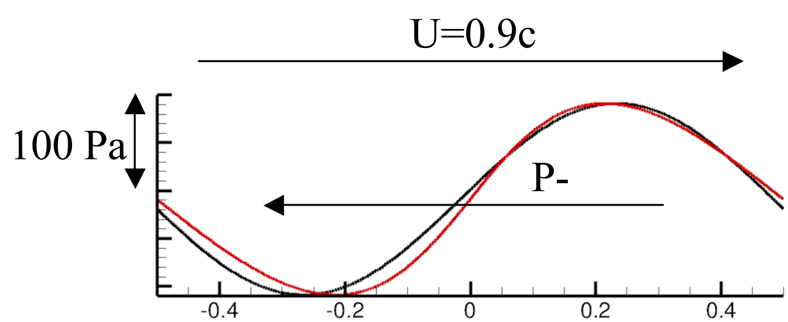


Pressure (Pa)

Amplitude of the characteristic $A=P-\rho c U$

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

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 Stuermer 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 rotation plane.

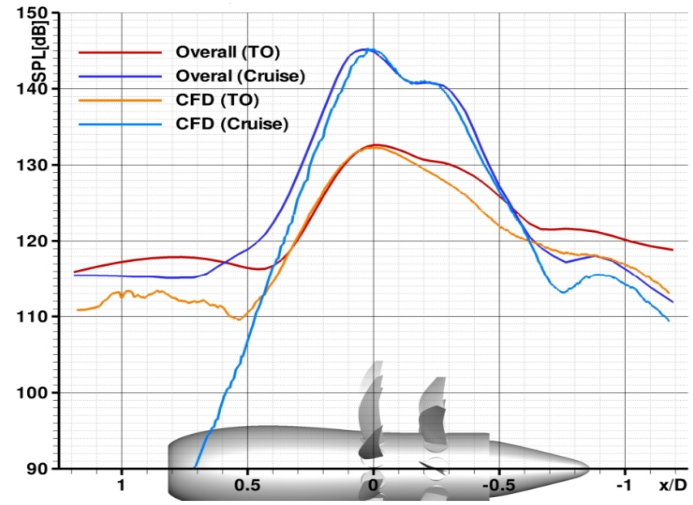


Figure 24. Comparison of nearfield polar directivities

Stuermer and Yin (AIAA,2010).

A specific approach is to be developed for accuracy assessment!

Ideal scenario for convergence

Growth of the surface used by the integral method

↓

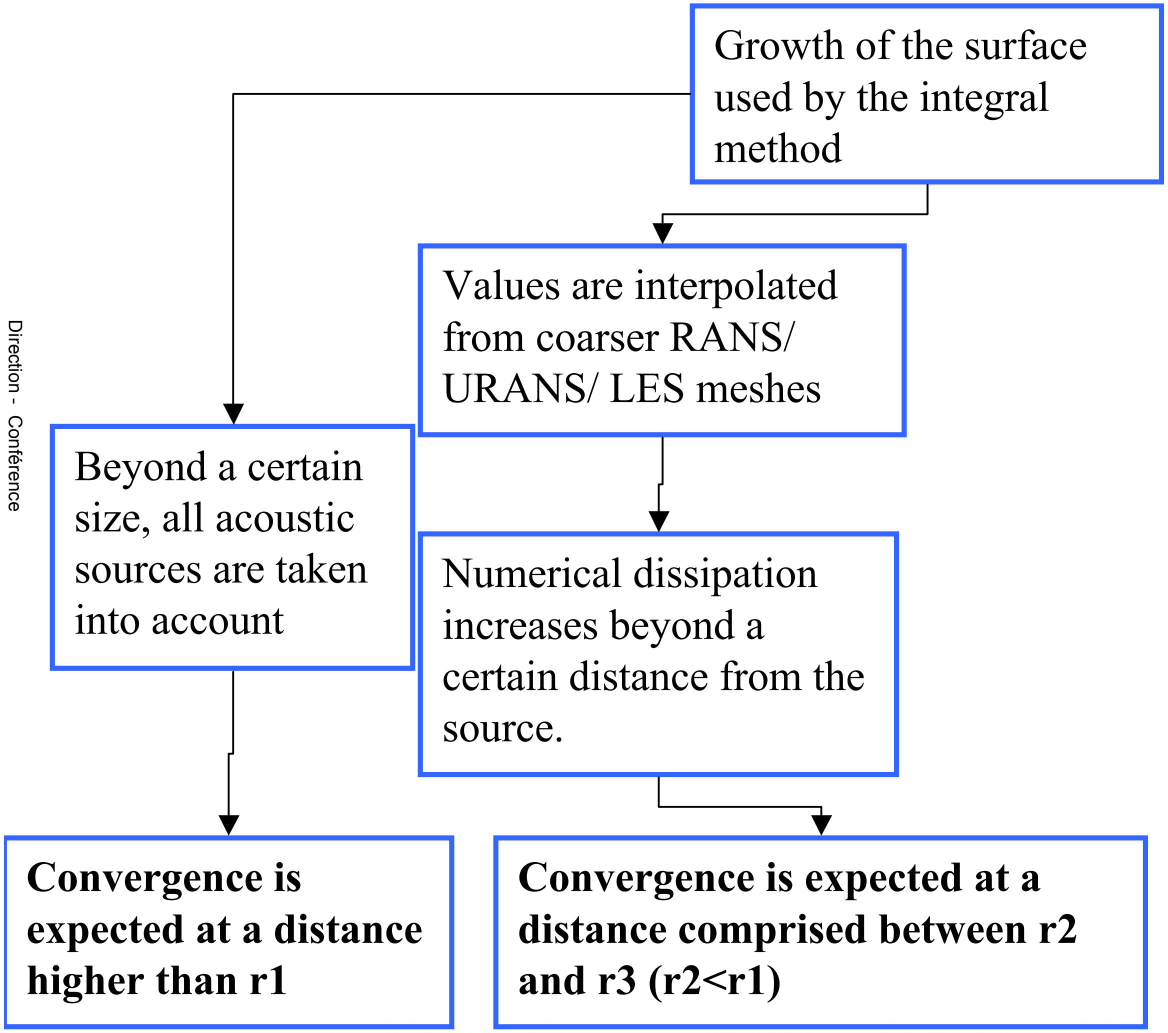
Beyond a certain size, all acoustic sources are taken into account

↓

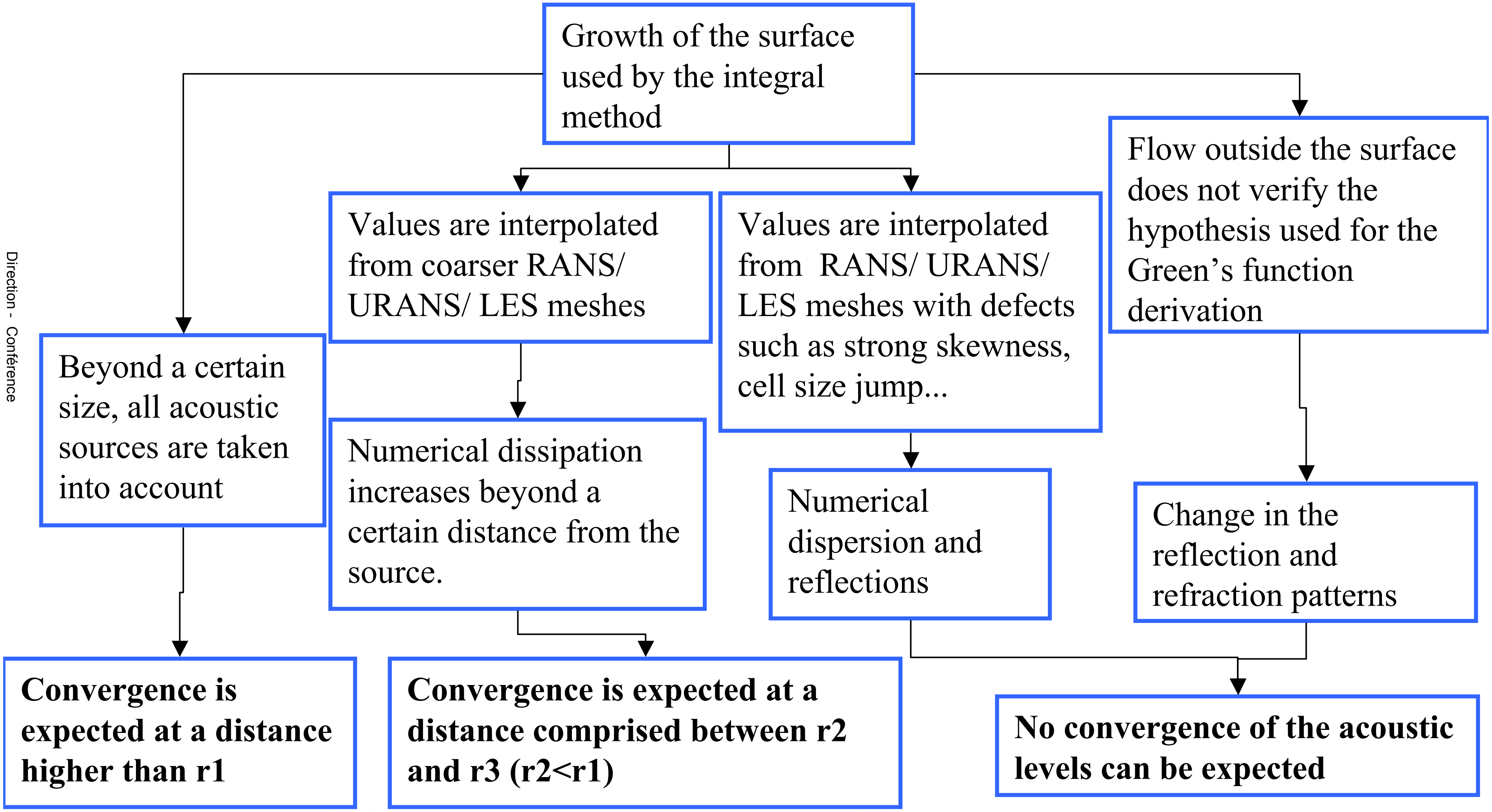
Convergence is expected at a distance higher than r1

A different approach to accuracy assessment

Realistic scenario for convergence

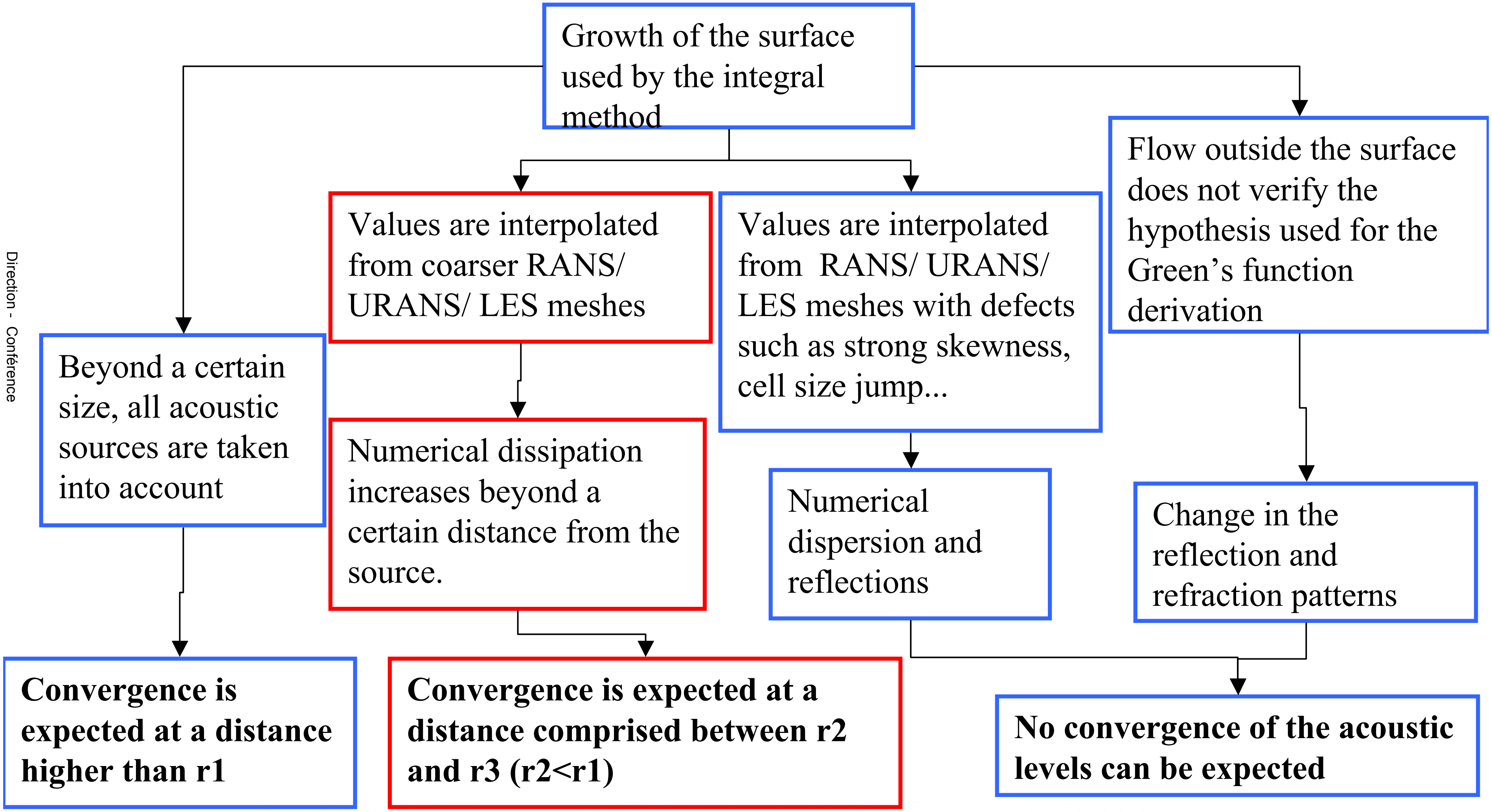


Worst case scenario for convergence

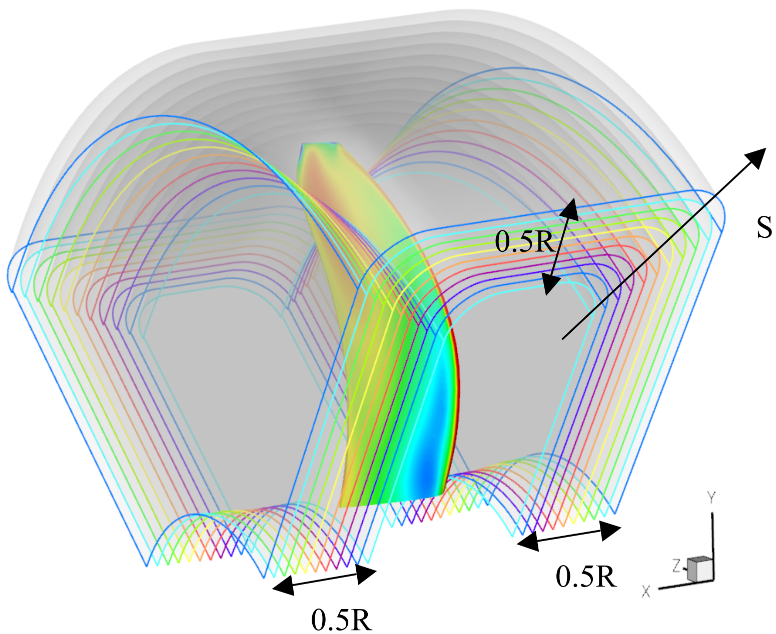


A different approach to accuracy assessment

This is where you want your computation to be

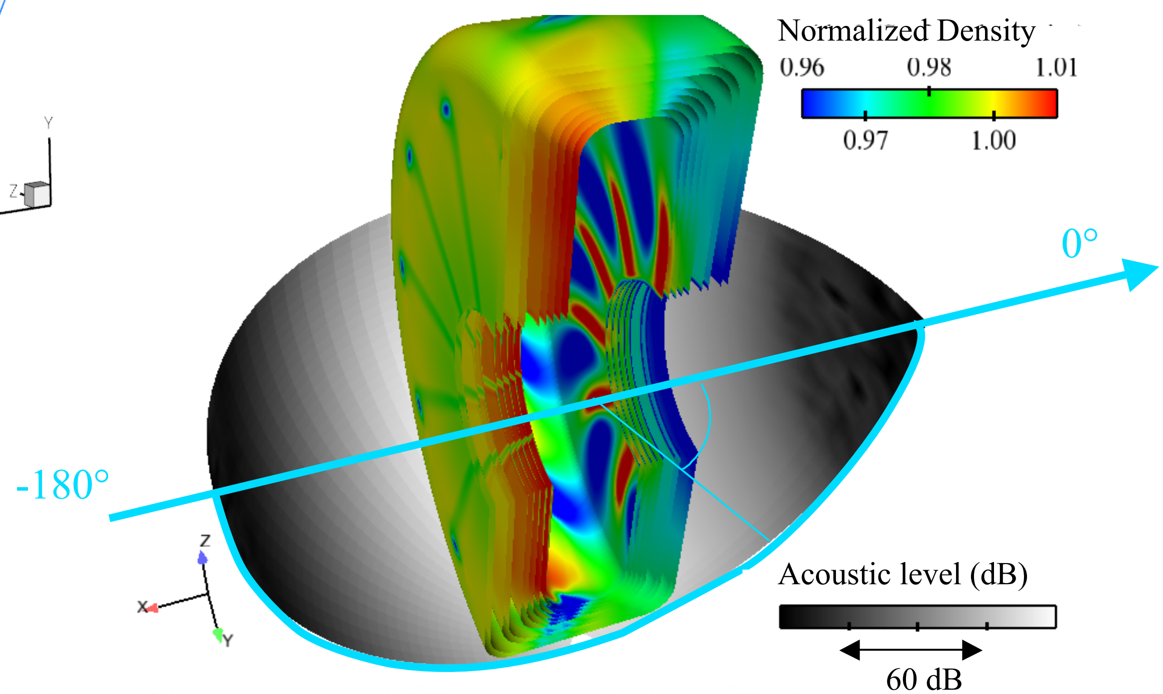


A different approach to accuracy assessment: example of application



A single propeller is enclosed in a growing set of closed surfaces. A steady state CFD (1 canal, 3M cells) simulation provides the input fields on the surface.

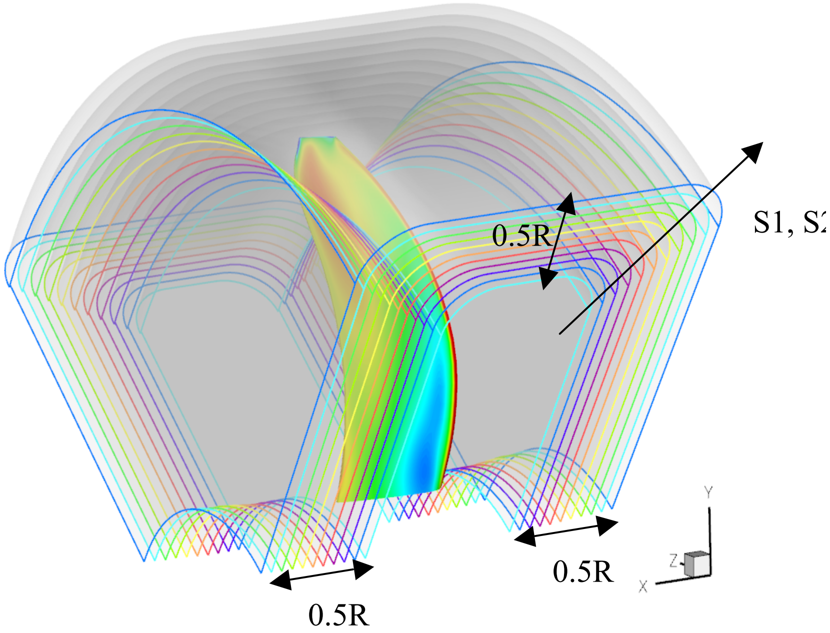
Trailing edge vortices cross the surfaces, a weak shock is located on the extrados of the blade.

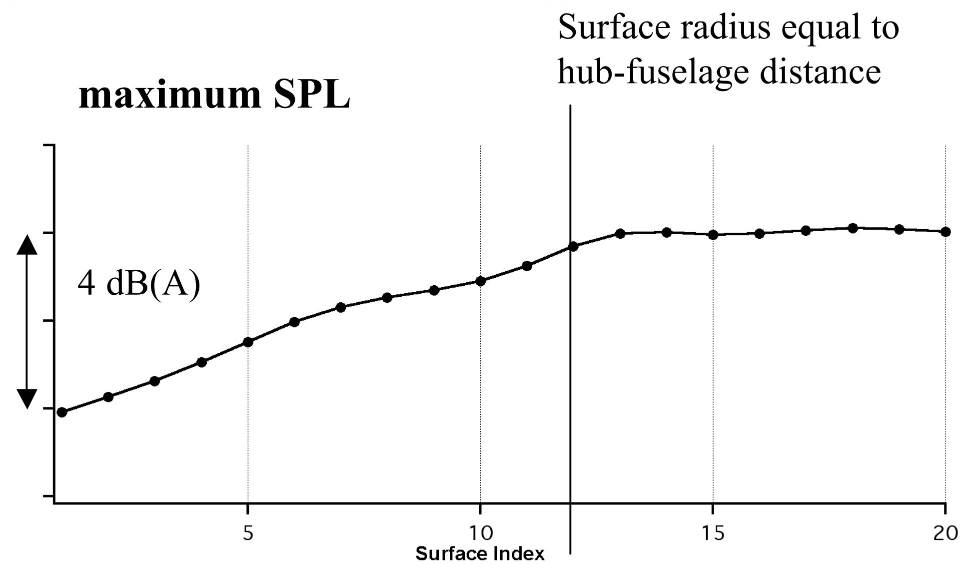


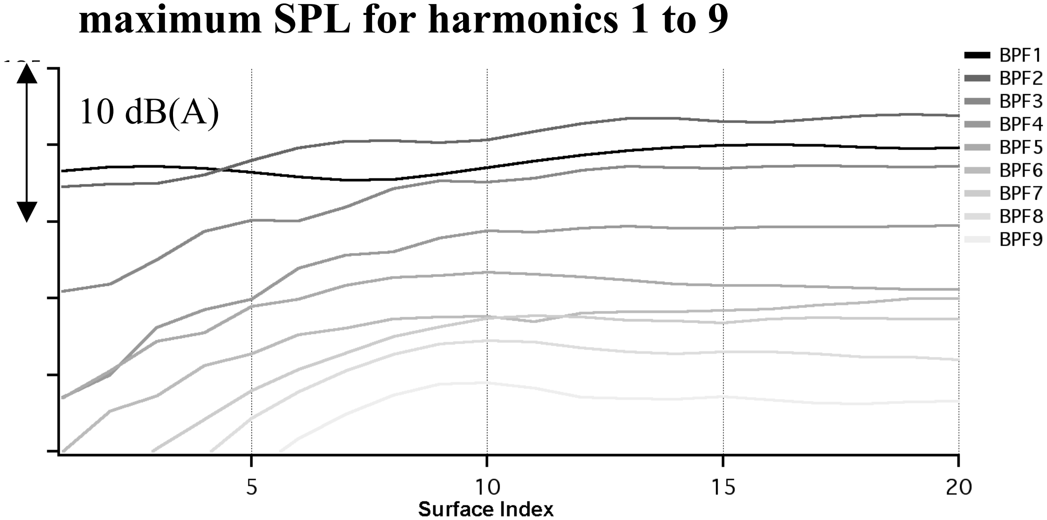
For each surface, acoustic levels are computed

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

A different approach to accuracy assessment: example of application



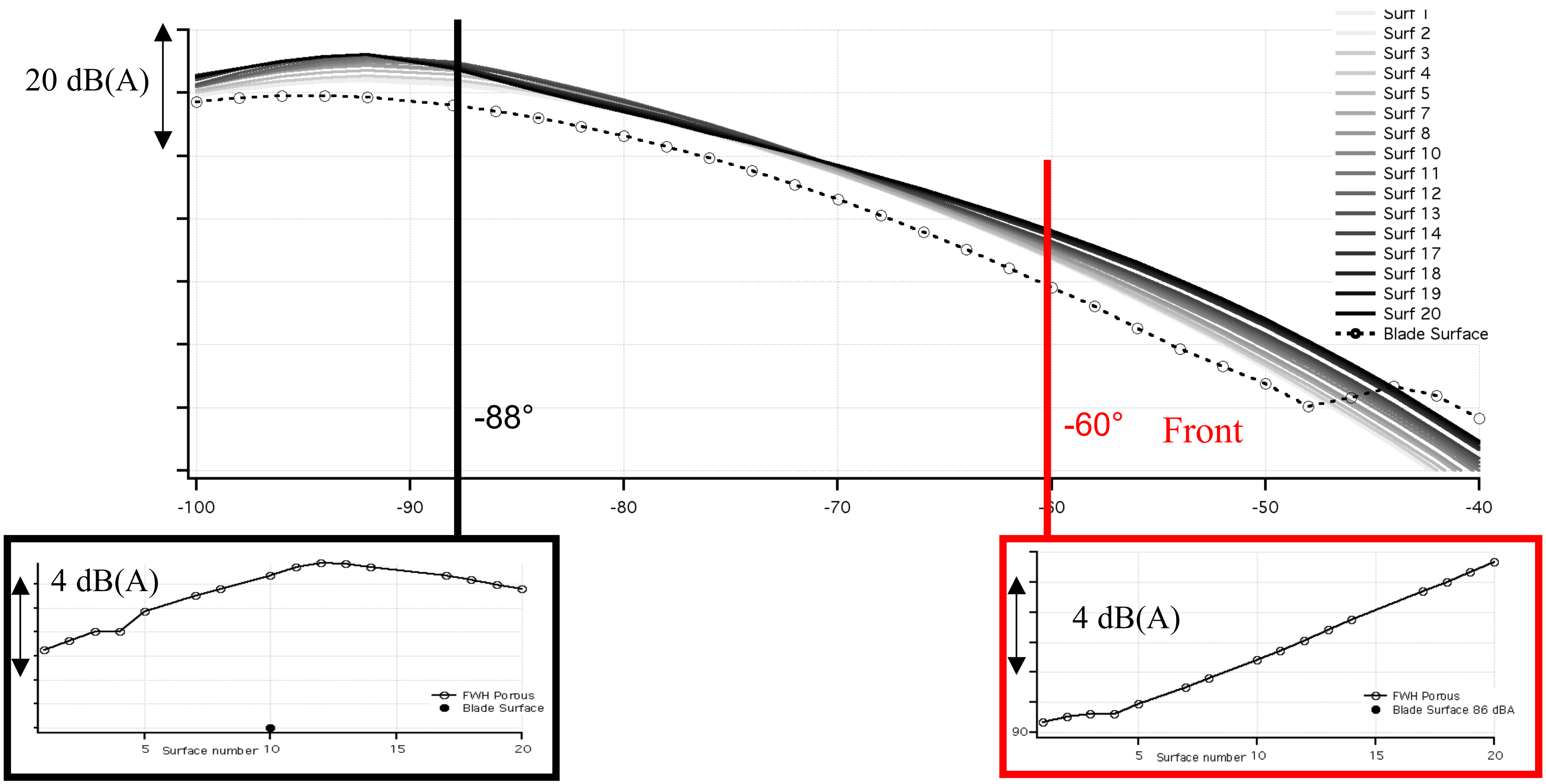




As expected, maximum acoustic levels converge toward a given value as the surface grows.

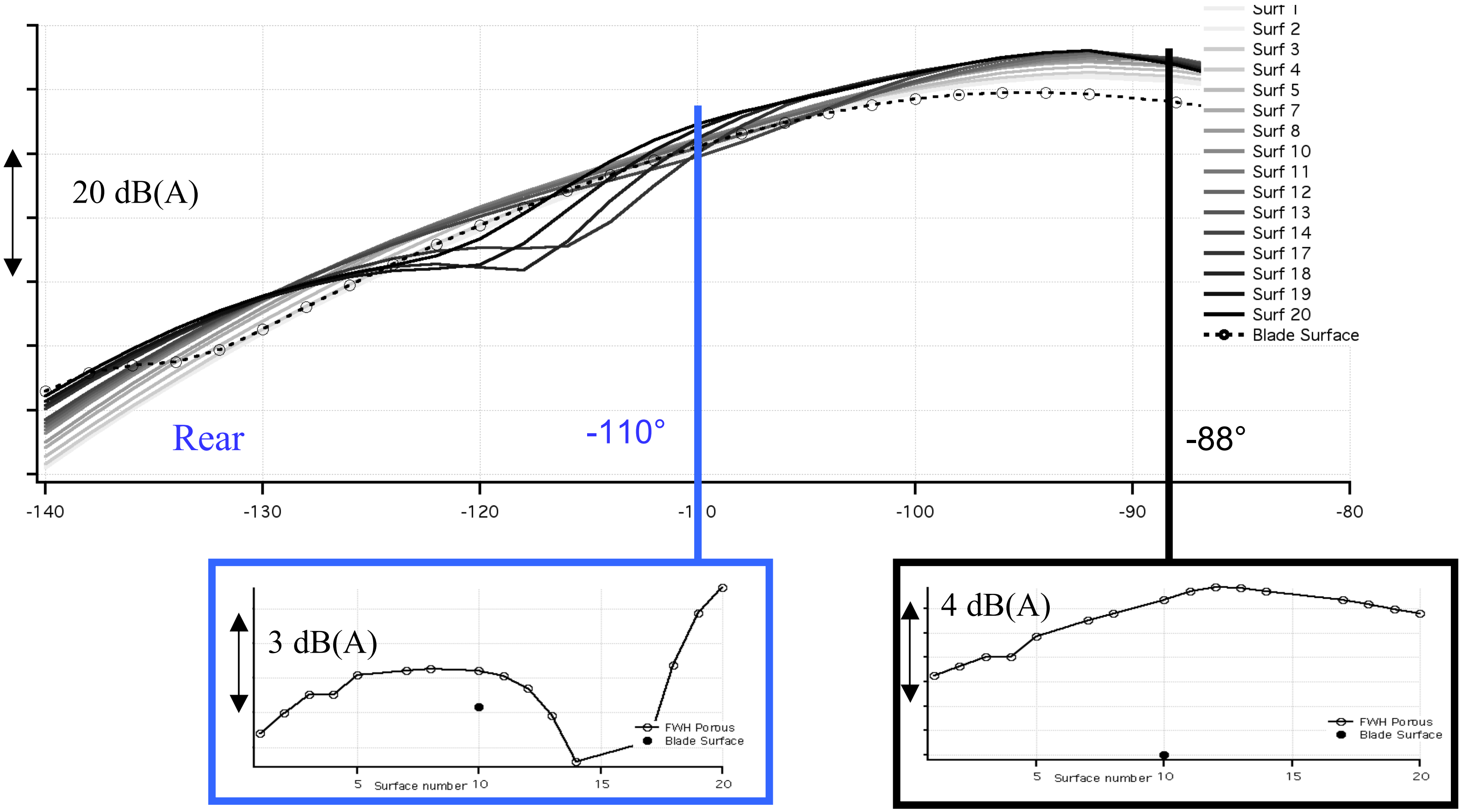
Is it the same for any given directivity angle?

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



A different approach to accuracy assessment: example of application

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



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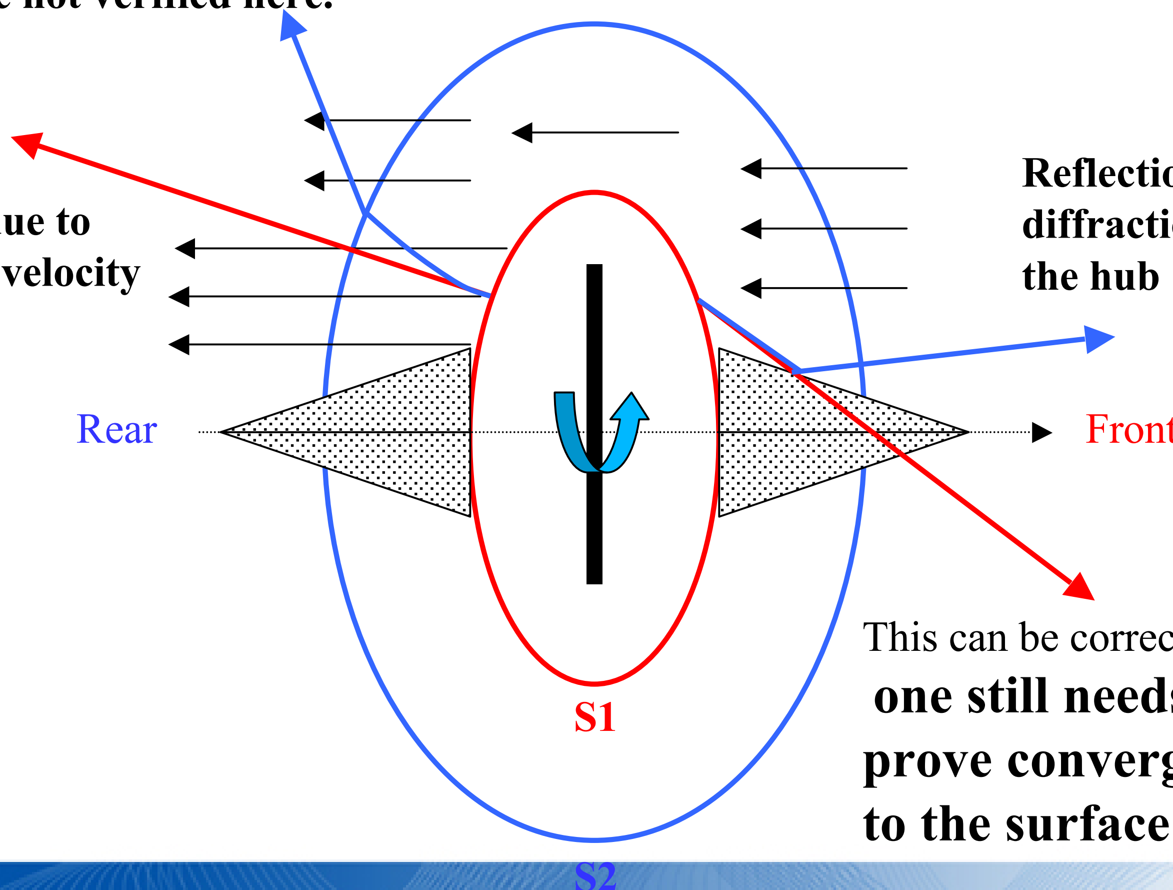
For some angles, the SPL continues to change although most probably all acoustic sources are long enclosed by the surface.
The explanation for the evolution of the SPL at a given directivity angle between large integration surface **lies in the fact that the assumptions used to derive the free space Green's function are not verified here.**



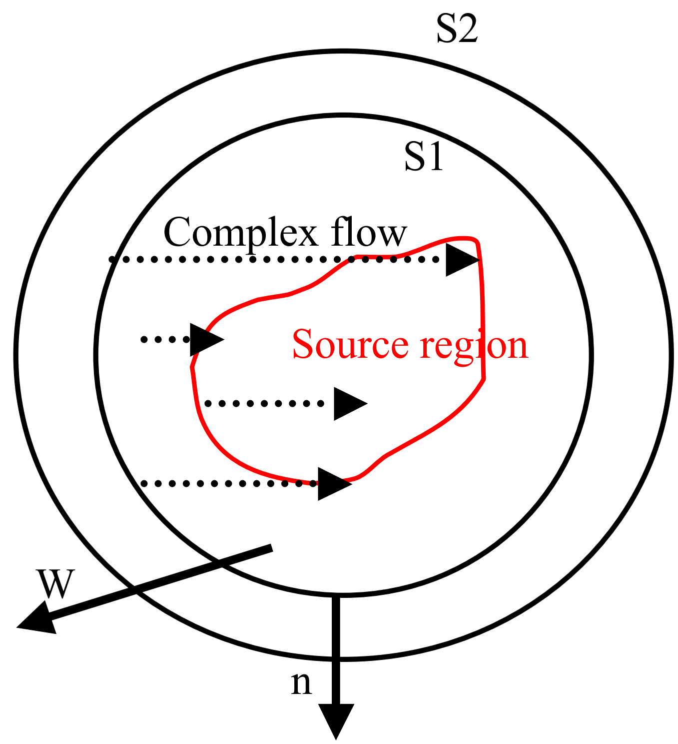
This can be corrected, but…
one still needs a simple tool to prove convergence with respect to the surface location

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

In our 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 can be neglected in the vicinity of the integration surface.

Of course, Myers fluctuating energy does not represent the acoustic energy…
but how does this energy flux correlates with the acoustic flux in the far field?

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



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 improved.

Yet, in order to meet the next milestones mentioned earlier, assessing the quality of these methods is critical. Different approaches have been developed to deal with this issue. The methods followed in our studies all rely on conservation principles.

It is only by maintaining uncertainty below the smallest possible threshold that future shape optimization methods or real-time monitoring techniques will provide realistic and forward-thinking results.