Helicopter Noise Footprints Prediction Environment

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The aim of this work is to describe an integrated simulation procedure based on the coupling of aeroelasticity, aerodynamics and aeroacoustics analysis, developed within AGUSTA in order to predict helicopter noise footprints in wind tunnel testing as in real flight conditions, under the assumption of stabilised manoeuvring conditions. Application of the simulation methodology can be helpful not only during analysis, in order to determine noise contour levels emitted in various flight manoeuvres (particularly those requested by certification needs), but also a priori as a design tool to orient design choices towards containing environmental impact of the helicopter. As a matter of fact most of recent works involving industries and research establishments extensively refer to interpolated data from experimental database, surely in order to maintain affordable calculation times free from those, usually heavy, of CFD methodologies, but primarily due to the fact that the various aeroacoustic tools developed lack exhaustive validation if extended to the whole flight envelope. Far less usual for these reasons are applications that determine noise contour levels as result of a complete loop that only makes use of simulation tools. This paper is intended to be a description of the simulation system general architecture and to describe the preliminary validation activity conducted on a wind tunnel model rotor.

Introduction

As far as the problem of noise radiated by helicopters has been growing in importance, not only in relation to the more and more restrictive rules that govern acoustic pollution, but also as crucial item in increasing rotorcraft public acceptance, it becomes necessary for helicopter manufacturers to be equipped with a reliable methodology for aeroacoustic predictions as an essential tool of strategic importance.

Even recent NATO directives (see ref. [1] and [2]) show growing interest towards reducing acoustic pollution and recommend that industries and research establishments acquire enhanced capabilities of modelling noise sources and propagation mechanisms of acoustic perturbations, in order to develop sufficiently reliable prediction methodologies.

Such a task turns out to be particularly complex as it requires the exercise of most of the disciplines involved in helicopter analysis, being influenced also by their reciprocal actions, so that the prediction of noise footprints on the ground comes to be only the last step of a simulation procedure with strong multidisciplinary connotations. The problem becomes even more demanding if the heavy directivity characteristics of noise radiated by helicopters are considered, as well as strong dependence of the perceived acoustic perturbation on the atmospheric propagation mechanisms (influenced in turn by meteorological conditions that, due to their instantaneous variability, clearly need to be treated by means of statistical methodologies).

As a matter of fact most of recent works involving industries and research establishments extensively refer to interpolated data from experimental database, surely in order to maintain affordable calculation times free from those, usually heavy, of CFD methodologies, but primarily due to the fact that the various aeroacoustic tools developed lack exhaustive validation if extended to the whole flight envelope. Far less usual for these reasons are applications that determine noise contour levels as result of a complete loop that only makes use of simulation tools.

It was such a scenario that gave birth within AGUSTA to the “Operational Aeroacoustic Simulator” project (ref. [3] and [4]) that aims to develop an integrated calculation system capable of predicting noise footprints emitted by helicopters in wind tunnel testing as in real flight conditions, under the assumption of stabilised manoeuvring conditions.

This paper deals with the simulation system general architecture, focusing in particular on the integration and interfacing activity between the various prediction tools involved. It turns out to be a description of the full methodology and, even if it doesn’t exhaust the complex validation matter, it does demonstrate the acquisition of a thorough methodology.

Results from preliminary validation activity conducted on a wind tunnel model rotor are finally presented.

Logical scheme of the process

The heart of the whole process is the aeroacoustic prediction tool that requires time history data of aerodynamic pressure (from whose propagation essentially the noise disturbance comes out) over the surfaces involved in generation of aeroacoustic sound. Accurate description of the noise sources kinematic behavior also plays a significant role in that it helps apply appropriate boundary conditions to the analyzed flowfield and drives the accuracy of calculated propagation distances between sources and observers.

A strong integration activity between the various disciplines involved is therefore required in order to connect the different steps of the whole process logical flux (see Figure 1).

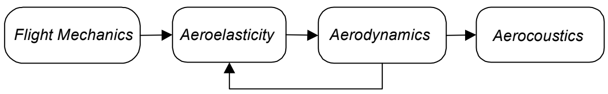


Figure 1: Logical flux of the Aeroacoustic Simulator

- **Flight Mechanics:** First of all rotorcraft trim parameters are to be calculated for the specified operating condition. Given the aircraft geometric and inertial characteristics together with the flight condition in terms of velocity components, the trim parameters and input controls to be imposed to each rotor are determined.
- **Aeroelasticity:** Output parameters from the previous step are exploited for determining rotor kinematic, dynamic and aeroelastic behavior. Blade elastic deformability herein plays a relevant role, being responsible for angle of attack modifications at the various blade sections. Most of the existing aeroelastic codes rely however on very simplified aerodynamic models, that while dramatically reducing calculation times, don't meet on the other hand the constraint of having the flowfield around blades reproduced with a high degree of precision and resolution, as needed for aeroacoustic simulations. For these reasons it becomes necessary to make use of a dedicated tool for unsteady 3D aerodynamic analysis.
- **Aerodynamics:** Aerodynamics codes perform flowfield calculation around blades with a precision that is strictly dependent on the implemented equations complexity. They usually require as input data the blade rigid motion and elastic deformations that in turn come out from aeroelastic simulations often based, as above mentioned, on simplified aerodynamic models. The strong interactions of blades aerodynamics with their kinematic and aeroelastic behavior calls for the implementation of a simulation loop linking aeroelastic and aerodynamic codes. This allows blade motion and deformations coming from the former to be used by the latter to calculate aerodynamic pressures, that in turn become the new loading forces in determining blade aeroelastic response, the iterative procedure continuing until convergence is reached. Also far wake inflow effects are likely to be introduced in the simulation loop, which may require using dedicated codes.
- **Aeroacoustics:** Blade motion and pressure distributions coming out of the iterative loop described above constitute the starting point for the aeroacoustic calculation. Noise signal reaching a generic observer is determined by propagating pressure perturbations coming from the blades. Finally the helicopter noise footprints are drawn for a generic observer grid of given coordinates in space. The acoustic simulation is made up of two distinct phases: the first one performs calculation in free space, simulating a wind tunnel test in an anechoic chamber, while the second one accounts for atmospheric absorption effects, together with ground reflection, aircraft engine disturbance and "broad band" component of noise. This can therefore be used to reproduce real noise footprints emitted by helicopters during flight maneuvers; it also helps in determining rotorcraft noise indices to be examined during certification procedures.

General architecture of the Simulator

In this section a detailed description of the simulation framework will be provided. A general flowchart of the whole system can be found in Figure 2.

The process may follow two different strategies, depending on whether noise footprints are reconstructed from experimental database (e.g. coming from a wind tunnel test campaign) or the user wants to perform the full simulation procedure, starting from helicopter operational conditions, and subsequently generating the acoustic database through exploitation of the rotor kinematic-dynamic-aeroelastic behavior. Both strategies lead to generation of the aeroacoustic tool input files.

❑ **AEROACOUSTIC PATTERN RECONSTRUCTION FROM EXPERIMENT :**

- **Experimental database:** This usually includes space coordinates of rotor pressure transducers as well as airloads time histories over a whole rotor revolution, and kinematic parameters describing the blade motion.
- **BNPUTIL module:** This aims at setting up the acoustic tool input files (i.e. BENP code files) from the experimental database, as usually provided from wind tunnel campaign. Sound sources

geometry is reconstructed from spatial displacement of the pressure probes, together with aerodynamic loads on the blades. Some visualization options are included allowing for the following graphical representations:

- ➢ visualization of wind tunnel data, in terms of time and frequency behavior of blade pressures and acoustic signal on the microphones, as well as noise contour levels on the observer grid;
- ➢ visualization of sound sources pressure distribution together with their rigid motions along a whole rotor revolution;
- ➢ visualization of the acoustic simulation results, in terms of time and frequency behavior of microphones sound signals, as well as noise contour levels on the observer grid.

❑ **AEROACOUSTIC PATTERN RECONSTRUCTION FROM SIMULATED DATABASE:**

- **CATIA module:** CATIA is becoming the standard reference within aeronautical industries as a CAD tool for 3D modeling, considered its extensive capabilities with complex surfaces representation; herein it provides the blade geometric model needed for further simulation steps.

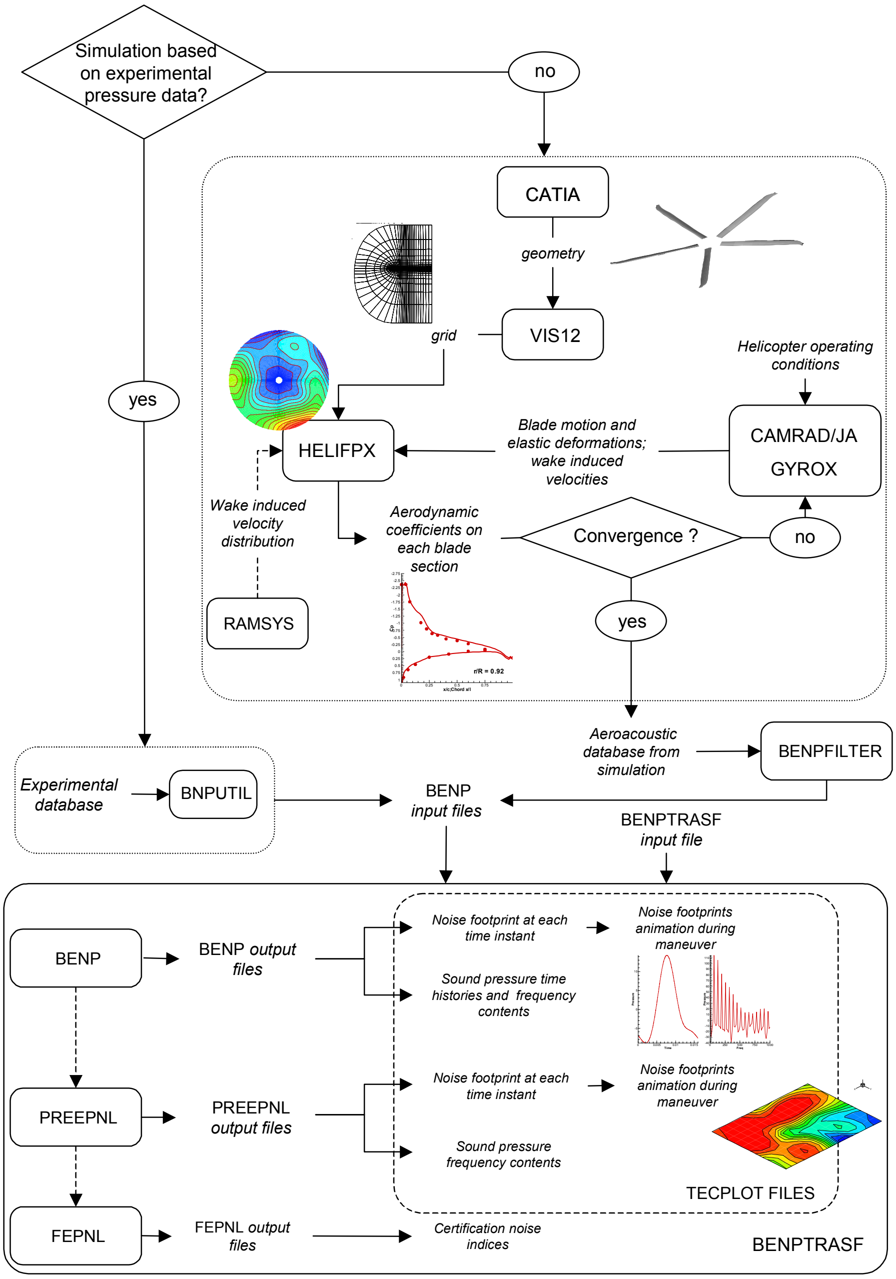


Figure 2:Simulation System General Chart

- **VIS12 module:** This is a grid generation tool basically developed by ONERA and improved later on within the EU funded programme ROSAA (ref.[5]). Given the model geometry it automatically generates C-H topology structured 3D grids around the blade. This is done by means of a series of 2D sectional meshes subsequently wrapped around cylindrical surfaces, by exploitation of a hybrid mesh generation algorithm of the algebraic-numeric type. Grid refinement is allowed over characteristic curves outside the blade tip region (these are among the most difficult to simulate because of the strongly non-linear effects occurring at high speed, and therefore crucial in aeroacoustic noise generation). Shock delocalisation can therefore be captured with deeper precision which helps in improving aeroacoustic results.
- **Aerodynamic-Aeroelastic loop:** The helicopter performance prediction, together with loads and aeroelastic behavior simulation is a very complex task usually addressed by means of comprehensive codes combining dynamic and aeroelastic models with simplified 2D-based aerodynamic representations. This can lead to some drawbacks when trying to apply such methods to blades of complex shapes, which typically show strong 3D effects, as is the case for innovative tip shapes. The need for reliable aerodynamic simulations of such blades would ask for CFD 3D unsteady tools that are fed with rigid motion and elastic distortions coming from aeroelastic tools. Within the Operational Simulator, the strategy of merging the two codes after a whole rotor revolution has been presently adopted; a fully coupled approach (which is nevertheless on going as a next step) would be actually not allowed while adopting aeroelastic codes based on harmonic approach. Data exchange between the two modules includes the following steps:
  - ⇒ the comprehensive code determines trim conditions, rotor motion and wake induced velocities, providing the blade displacement to the CFD tool;
  - ⇒ CFD calculated aerodynamic coefficients are given back to the comprehensive code and used to determine the new rotor response and wake behavior.

  The coupling procedure structure is shown in Figure 3: CFD simulated aerodynamic coefficients are updated taking into account induced modifications by the blade kinematic solution and rotor wake configuration arising between two consecutive iteration steps of the comprehensive code, that in turn adapts rotor aeroelastic behavior to the newly calculated CFD solution.

  Convergence is achieved when corrections on blade displacement as well as aerodynamic coefficients distributions become negligible, meaning that CFD flowfield is coherent with rotor motion and inflow coming from the aeroelastic simulation.

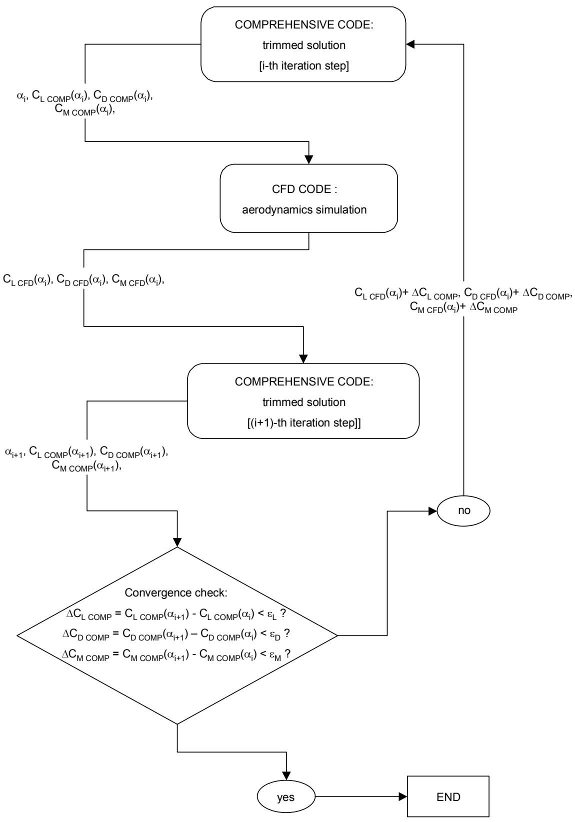


Figure 3: Aeroelasticity-Aerodynamics coupling technique

- **HELIFPX module:** HELIFPX (ref.[6]) is a CFD code based on a full potential approach aimed at prediction of 3D unsteady blade aerodynamics over a range of different flight conditions, from hover to high speed forward flight. Developed within the EU ROSAA project as an enhancement of the previous HELIFP code (ref. [7]), it has been improved by reducing numerical errors, incrementing efficiency, and refining the involved physical phenomena representation. This was achieved by implementation of acceleration techniques, viscid-inviscid coupling and free wake modeling.

  The code is based on a zonal approach that makes use of three different models, linked to each other through transpiration velocity distribution corrections applied over calculation domains boundaries as described below:
  - ➢ the flowfield external to the blade as well as near wake system are modeled based on potential equations, by means of a finite volume formulation. An entropy correction model is included capable of capturing compressibility effects, and transpiration velocity distributions can be imposed in order to model non uniform inflows, as coming

from rotor wake, boundary layer effects as well as elastic deformations;

- flow adjacent to the blade is calculated by means of a viscous interaction model exploiting a hybrid "field-integral boundary layer" approach (reliable until incipient separation conditions) and based upon unsteady boundary layer equations of the first order. Coupling strategy is of the strong type and time consistent, in that convergence is achieved at each time step for both viscous and inviscid model;
- overall flowfield balance makes use of a BEM strategy for both free and prescribed wake calculation, allowing to capture BVI effects and improving therefore induced velocities prediction; the methodology seems to be reliable provided that transonic non linear effects remain negligible, as is the case for subsonic flows free from shock wave events.

As already mentioned, great relevance has been given to the introduction of solution acceleration techniques (GMRES and MULTIGRID) that also improve code robustness, by making it less sensitive to computational grid characteristics.

The HELIFPX code however can only perform rigid motions, elastic deformability effects being taken into account in a fictious way by applying on the blade surface transpiration velocity distributions that act by locally modifying flow incidence at the various blade sections.

- **Aeroelastic module:** Two different codes can be exploited:

  - **CAMRAD/JA** (ref. [11] and [12]) is a commercial comprehensive code for rotorcraft analysis that provides aerodynamic and structural loads calculations, as well as kinematic, dynamic and elastic behavior of rotors, together with helicopter performances and maneuverability. The blade structural model is based on beam theory applied to rotary wings, under the assumption of rectilinear elastic axis and high aspect ratio blades. Dynamic and elastic calculation exploits a modal approach based on variables separation techniques to separately solve in time and space domains. Both blade rigid motions and elastic deformations are included. As far as calculation of aerodynamic loads is concerned, the code makes use of a second order lifting line approach, utilizing aerodynamic coefficients at the various blade sections coming from 2D static airfoil characterization corrected for 3D and unsteady effects based on thin airfoil theory. A dynamic stall empirical model is also included and corrections are provided for transversal velocity components as well as blade sweep curvature. Finally, a wake calculation module is given (both for free and prescribed wake) estimating non uniform inflow on rotor disk and providing corrections based on lifting surface theory.

  - **GYROX** is an in-house developed code performing dynamic and aeroelastic calculation of helicopter rotors with the intent of predicting static and vibratory loads transmitted to the mast in typical operative conditions.

    This code is actually built to investigate any general isolated rotor behaviour as typically a wind tunnel campaign does, so the helicopter trim has to be supplied by an external code: it could be for instance FLIGTHLAB (ref. [13]), which is another comprehensive code available within AGUSTA.

    Different from CAMRAD, GYROX basic formulation is entirely based on a FEM approach providing modal and frequency response to aerodynamic and inertial loads acting on the blades. The blade structural model is built on the basis of monodimensional (beam) elements discretisation, characterized by negligible axial and shear stresses, rigid cross section and infinitesimal elastic displacements, under the assumption of a linear piecewise elastic axis.

    The displacement field of a generic point inside each finite element is given through the so called "shape functions", after determination of corresponding nodal displacements, that are the main unknowns of the discrete problem, by means of Lagrange's equations. As far as the numerical solution algorithm is concerned, the code can make use of both a "Harmonic Balance" method, that solves the problem in frequency domain by determining harmonic coefficients of the Lagrangian variables, and a "Newton-Raphson" algorithm that still works in the frequency domain, but helps overcome problems that arise from introduction of non linear terms, even if it requires heavier calculation times.

    Aerodynamic modeling is very similar to CAMRAD's, in that it makes use of experimental 2D airfoil characterization, provided that suitable corrections are given for compressibility and unsteadiness phenomena (referring to Glauert's theory). 3D effects in the tip region are also represented (by introducing proper tip loss factors) and radial flow is taken into account.

- **Wake calculation module:** Accurate representation of far wake-induced velocity field seems to have a strong influence on blade loads computation, especially for those flight conditions, like descending flight and low advance ratio forward flight, that are more sensitive to wake interactional effects.

  As already mentioned HELIFPX includes a BEM module for wake calculation but several drawbacks have been arising when attempting to apply it. This has driven wake calculations within Aeroacoustic Simulator towards exploitation of CAMRAD simplified formulation.

  However, attempts have been made to setting up a more sophisticated calculation by introducing in the simulation framework the BEM code RAMSYS (see ref. [9] and [10]). This code has been explicitly developed as an analysis tool devoted to the whole helicopter interactional aerodynamics, with particular emphasis on BVI effects, it can also be utilized also on isolated rotors. After modeling the wake by means of quadrilateral panels, the Neumann problem is solved for Laplace's equation in the velocity potential, considered constant over each panel (as follows from a zero order formulation).

Calculated induced inflow is then exploited by HELIFPX through application of appropriate velocity distributions.

Considering the heavy computational effort requested even for a isolated rotor calculation, the RAMSYS simulation has been run herein only once at the beginning of the aerodynamic-aeroelastic loop, while remainder of the simulation has been performed exploiting CAMRAD simplified wake calculation. Such a simplified strategy, while allowing considerable CPU saving, prevents on the other hand from capturing BVI effects with sufficient precision, thus leading to considerable drawbacks from the acoustic simulation point of view.

- **AEROACOUSTIC SIMULATION:**

An integrated framework, named BENPTRASF (ref.[14]), has been implemented with the aim of interfacing all the available tools dedicated to acoustic calculations.

The user can choose between various acoustic formulations and subsequently required input data, such as:

- physical properties to be included within the database, could be pressure, velocity, spatial pressure gradient, pressure time derivative, density, velocity potential;
- physical surface to be assumed as sound source, could be the blade surface rather than a fixed or rotating Kirchhoff surface surrounding the whole rotor;
- time discretization requested for aerodynamic data, i.e. interval duration and sampling frequency.

A TECPLOT format visualization module has also been included providing graphical outputs suitable for direct comparison of simulated results with experimental ones.

BENPTRASF structure is articulated based on the following modules:

- **BENPFILTER module:** Starting from the aerodynamic solution extracted acoustic database, it directly writes acoustic solver input files, automatically checking that data contained in the acoustic database are consistent with the formulation chosen for acoustic calculation.
- **BENP module:** This is the AGUSTA proprietary main acoustic code (ref. [15], [16], [17], [18] and [19]) simulating the aeroacoustic component of noise emitted both by an isolated rotor or a complete helicopter in free space, as for reproduction of emitted sound signatures in wind tunnel anechoic chamber.

It exploits a BEM methodology for writing the flowfield governing equations in such a way that the solution as a whole can be written as a superposition of elementary solutions. This automatically takes into account propagation effects and therefore overcoming typical field methodologies drawbacks due to unsteadiness of acoustic disturbance.

Within BENP code various formulations have been included suitable for different flight regimes:

1. linear Ffowcs Williams-Hawkings formulation determines thickness and loading components of noise; this is a reliable approach while trying to simulate low speed flight regimes;
2. Ffowcs Williams-Hawkings formulation with the addition of quadrupole non linear terms, whose effects become important in case of transonic flight;
3. Kirchhoff formulation that performs noise evaluation exploiting aerodynamic data on a fictitious surface, either fixed or rotating with subsonic or supersonic speed, and surrounding real noise sources; such an approach seems to be reliable in case of high speed regimes;
4. Kirchhoff/ Ffowcs Williams-Hawkings formulation, that, differently from the previous one, helps overcoming difficulties in calculating pressure gradients normal to the Kirchhoff surface and allows also surfaces permeability to the fluid.

Concerning adopted numerical algorithms, for each acoustic formulation the user can choose between:

i. integration of aerodynamic data over acoustical surface;
ii. integration of aerodynamic data over physical surface by means of numerical evaluation of time derivatives (so called "Farassat formulation 1");
iii. integration on the physical surface with analytical evaluation of time derivatives of the involved quantities (known as "Farassat formulation 1A").

Scattering effects induced modifications (i.e. by helicopter fuselage) in noise footprints can also be considered. Finally the user is given the possibility of introducing corrections for non uniform inflows impinging the fuselage (see ref.[20], [21], [22]).

BENP calculations determine the acoustic signal for a generic observer of given coordinates in space in terms of time and frequency behavior. From this, the noise contour levels on a microphone grid can be reproduced.

- **PREEPNL module:** The PREEPNL code (ref. [23]) has been developed with the aim of modifying the acoustic signal as a consequence of the real physical conditions in which emission occurs. This is done in order to estimate the effectively released

noise levels ("Effective Perceived Noise Level"), starting from free space simulation.
The adopted approach is known as "ray acoustics" because of approximating spherical waves through which pressure disturbance propagation occurs by means of a series of direct rays drawn from the noise source to the observer. Such an approximation makes sense provided that spherical waves acoustic energy decay laws (basically depending on frequency) are properly reproduced along the covered distance. For each spectrum frequency an acoustic ray is constructed to which the corresponding amount of acoustic energy is assigned. Analysis of energy content alterations can therefore be led separately for the various frequencies and the superposition of results gives the final spectrum at the microphones.
PREEPNL also accounts for the presence of reflecting terrain: an acoustic impedance can be assigned to the ground in order to estimate direct ray energy absorption, together with time delay in propagation of the reflected one. Possible interference effects can therefore be calculated between direct and reflected signals that simultaneously reach the same observer .
As far as the aircraft engine is concerned, it doesn't address any of the classical rotor aeroacoustic noise generation mechanisms, which necessarily forces relying on empirical or statistical methods. Herein engine acoustic models have been introduced based on noise measurements on isolated engines over terrains of known characteristics. The mathematical model is therefore reliable to a certain limited extent, when strong effects of engine installation on directionality of emitted noise are considered.
Starting from time behaviors of pressure at microphones, corrected values are provided due to emission in real space, both in terms of spectral contents (calculated in third octave bands) and intensity of sound levels.

- **FEPNL module:** FEPNL (ref.[24]) allows calculation of helicopter noise indices as specified by certification rules, by means of sound pressure levels obtained both from experimental measures and calculated through numerical simulation. Calculation is limited to the three certification microphones at certification flight conditions.
  Sound pressure data are modified in order to take into account the following effects:
  - non linearities in frequency response of the microphones mounted caps;
  - non linearities in frequency response of the measurement instrumentation;
  - corrections for background noise (referring to ICAO or FAA rules).

  Further corrections are applied to account for possible deviations of the followed trajectories from those prescribed by certification guidelines.
- **Visualization module:** The commercial code TECPLOT (ref. [25]) has been chosen in the framework of the Simulator because of its extensive capabilities in graphical representation of an extended class of data, from X-Y plotting to both 2D and 3D surface and volume visualization, by means of a user-friendly interface. Starting from BENP and PREEPNL output the following TECPLOT files are created:
  - time evolution (from BENP output) and frequency content (from BENP or PREEPNL output) of sound pressure over each of the observers;
  - noise footprint over the observer grid at each simulated time step with simultaneous visualization of noise sources and their motion;
  - animation of noise footprint over the observer grid along the whole maneuver together with sound sources motions. This is run by means of the program Framer within TECPLOT package.

Preliminary validation activity

Herein a description will be given to the preliminary validation activity performed in order to check effectiveness of the developed tool. A choice has been made to refer to the collected database within the European project HELISHAPE (ref. [7]), which is an exhaustive DNW wind tunnel test campaign devoted to aerodynamics and acoustics assessment of a 4-bladed articulated rotor equipped with two sets of blades (denoted respectively as 7A and 7AD) with different tip configurations. The 7A blade has been chosen for validation activity because of its very simple geometric configuration, characterized by rectangular planform and piecewise rectilinear twist distribution (see Figure 4).

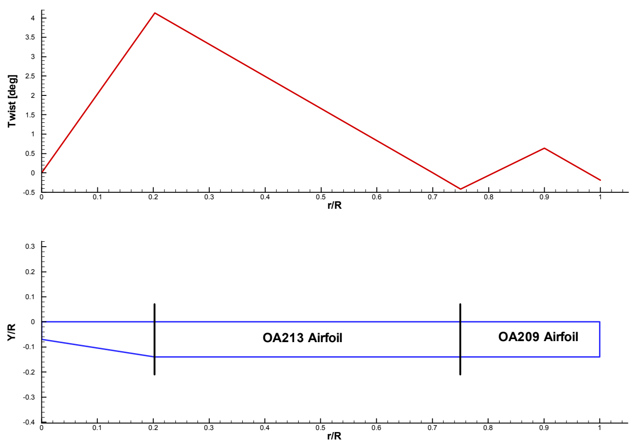


Figure 4: 7A blade layout

Description of the experimental database

Two test conditions have been selected among all HELISHAPE cases, of medium and high speed forward flight respectively, denoted as TC067 and TC152 (see Table 1 for characteristic features and kinematic parameters of the two test cases). Due to the relatively low advance ratio, test case TC067 was expected to exhibit the stronger wake effects and associated noise signature to be considerably affected by BVI phenomena as well.

			TC067	TC152
air speed [m/s]			35.73	70.89
ω [rad/s]			101.7	109.3
μ			0.16737	0.33114
tip Mach number			0.61649	0.61658
air temperature [K]			297.34	298.88
air density [kg/m^3]			1.18262	1.17475
pitch motion	stat [deg]		4.78	7.9
	1/rev	amplitude [deg]	3.78	7.46
		phase [deg]	325	295
lead-lag motion	stat [deg]		-1.81	-1.88
	1/rev	amplitude [deg]	0.14	0.17
		phase [deg]	1	353
flap motion	stat [deg]		2.93	2.43
	1 /rev	amplitude [deg]	0.20	0.23
		phase [deg]	211	201

Table 1: Test cases characteristic features

The 7A rotor was instrumented with 117 pressure transducers mainly distributed in five spanwise sections onto three blades.

A traversing array of 11 movable microphones, mounted below the rotor at a distance from it equal to $Z_{micr} = -2.3$ [m] $\approx$ 0,5 D (being D the rotor diameter), was used for acoustic measurements. The rake was traversed during the tests along streamwise direction covering a whole of 15 positions separated by a distance $\Delta X_{micr} = 0.5$ [m]. Microphones coordinates in X and Y directions can be found in Table 2 (origin of the reference system is located at the rotor hub).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
X_{micr} [m]	-4.0	-3.5	-3.0	-2.5	-2.0	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0

	1	2	3	4	5	6	7	8	9	10	11
Y_{micr} [m]	-2.687	-2.154	-1.613	-1.070	-0.527	0.014	0.553	1.095	1.638	2.181	2.725

Table 2: Experimental microphone distributions

In order to characterize discrete frequency noise, acquired time signatures at the microphones were acquired synchronously with the rotor revolution. Experimental results used for comparisons are obtained as an average of elementary signals and noise footprints also are drawn based on the spectrum of the averaged signatures.

Coherently with the Simulator general architecture, both the available procedures for calculation have been tested, exploiting first experimental blade pressures and then the complete aerodynamic-aeroelastic-aeroacoustic simulation loop. Obtained results will be discussed in the following section.

Aerodynamic data from experimental acquisition

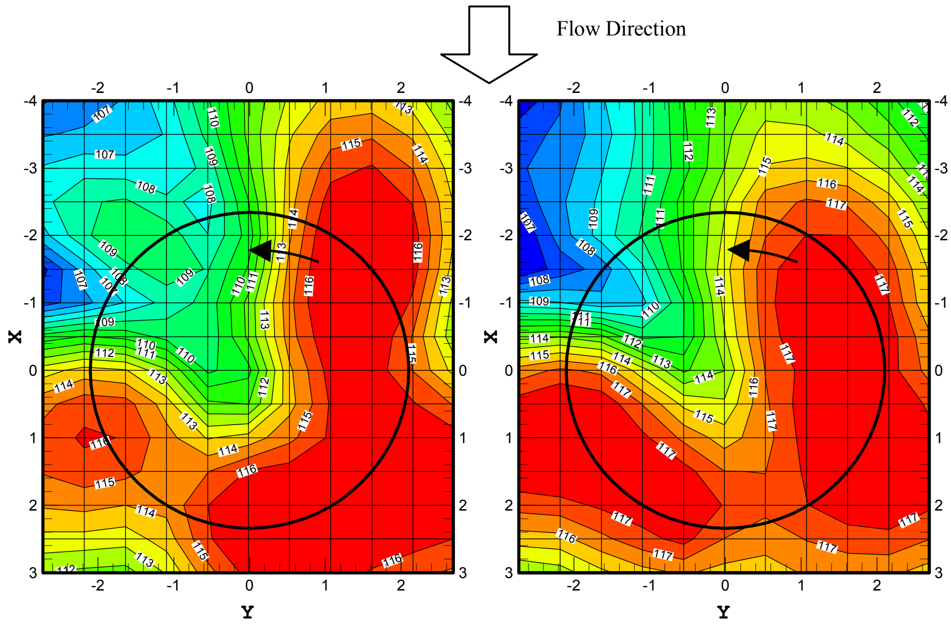
Good agreement is shown in comparing experimental and simulated noise footprints (see Figure 5 and Figure 6) for both considered test cases. Even if some deviations appear in terms of sound pressure level absolute values, good prediction capability is demonstrated at least for noise footprint configuration shape, and differences less than 2 dB are shown almost throughout the entire measurement region.

Concerning sound signal reconstruction, two microphones (whose coordinates are given in the following) have been selected in the maximum noise regions (one in the advancing side and the other in the retreating side of the blade) and associated signatures have been studied. Satisfactory correlation has been achieved, both in terms of time history and frequency content (particularly as regards peak to peak SPL values) along a whole rotor revolution (see Figure 7 and Figure 8):

Microphone 1: x=-2,5 [m]; y=1,638 [m]; adv. side
Microphone 2: x= 0 [m]; y=;-2,154 [m]; retr. side.

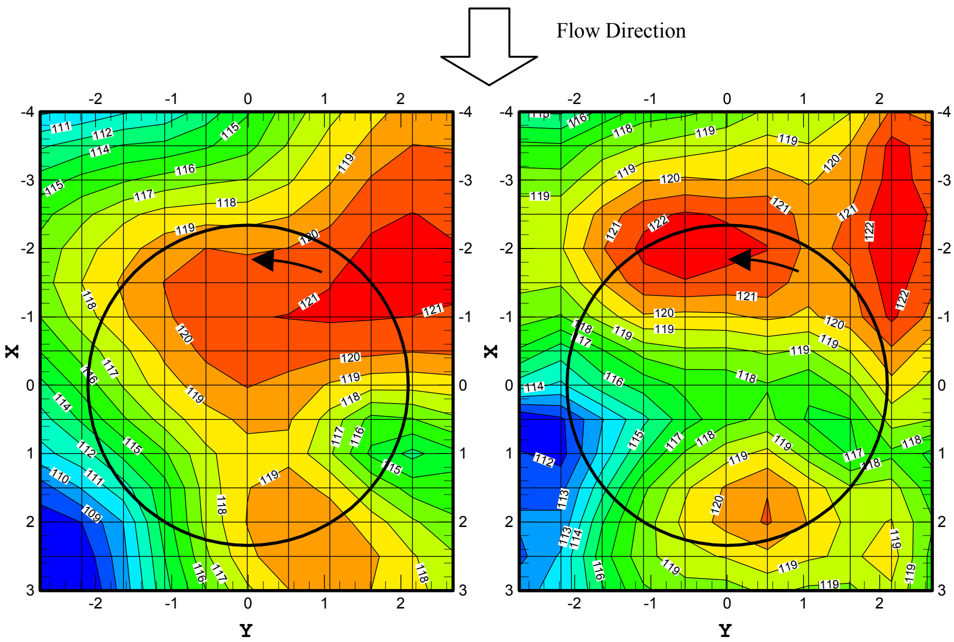
Further deviations from experimental noise footprints could be explained as follows:

- necessarily poor spatial resolution of the pressure probes on the blades has led to definition losses of acoustic sources;
- rotor has been implicitly assumed to be periodic (thus allowing to virtually cluster all the probes over a unique blade); however different behaviours have been evidenced on experimental acquisitions for each of the blades, particularly concerning kinematic parameters, thus suggesting the hypothesis of a slightly unbalanced rotor;
- due to bad functioning of some of the probes during experiments, pressure data interpolation has become necessary in order to obtain a connected panelling, which has driven on the other hand towards not fully reliable load reconstruction, especially nearby tip leading edge, which, as already mentioned, is the most critical region for generation of aeroacoustic sound.



(a) **(b)**

Figure 5: TC067: comparison between simulated (a) and experimental (b) noise footprint



(a) **(b)**

Figure 6:TC152: comparison between simulated (a) and experimental (b) noise footprint

Complete simulation loop

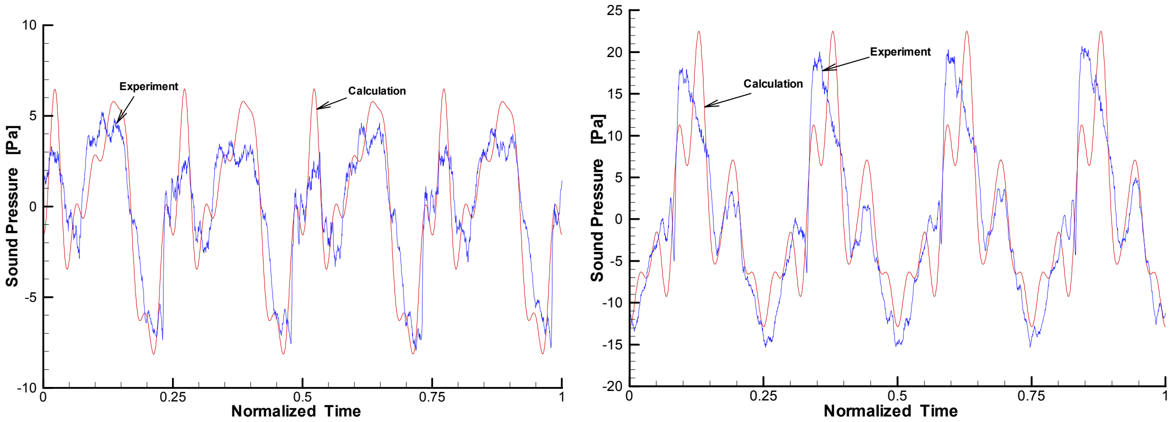
Given the 7A blade CATIA model, a group of points has been extracted describing the blade surface, over which the computational grid has been set up (Figure 9).

A preliminary study on grid sensitivity has also been performed, particularly refining blade tip and leading edge regions, which show major aeroacoustic impact.

The following grid dimensions have finally been chosen:

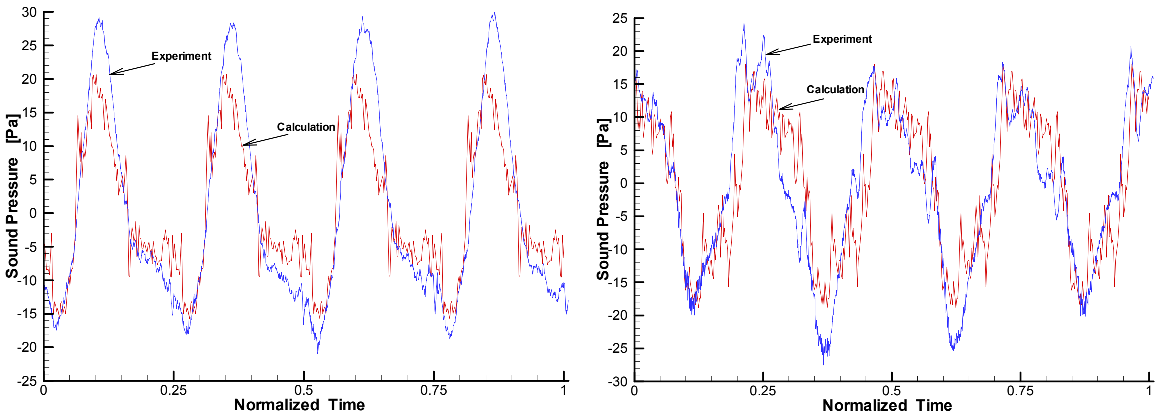
- 112 points in chordwise direction including the slit, equally distributed over upper and lower airfoil surface;
- 24 points in vertical direction both above and below the blade;
- 24 points in spanwise direction, 16 of them over the blade surface.

The trim procedure has been conducted providing that



(a) (b)

Figure 7: TC067: comparison of acoustic experimental and simulated signature at microphone 1 (a) and 2 (b)



(a) (b)

Figure 8: TC152: comparison of acoustic experimental and simulated signature at microphone 1 (a) and 2 (b)

convergence was reached on the whole rotor thrust, together with roll and yaw moments.

After discretization of the blade through 20 aerodynamic and 48 inertial spanwise stations, aeroelastic simulation has been performed by means of a rigid blade formulation. Aerodynamic load harmonics have been included in order to capture with sufficient reliability unsteady effects. Finally the wake calculation relied upon a uniform inflow formulation: however, due to the poor maximum azimuthal resolution (10 degrees) allowed, wake interactional effects and particularly BVI events are not expected to be satisfactorily captured.

In executing the aerodynamic simulation only the outboard part of the blade has been taken into account, being the HELIFPX calculation not sufficiently reliable in the inboard region. This is due to the "reverse flow" phenomena which are not easily reproducible and strongly influenced by interference effects of the hub. It has however to be noted that, being the inner part of the blade characterized by low velocities, the adopted approximation is supposed to be reasonably acceptable. Acceleration techniques (GMRES and Multigrid) have

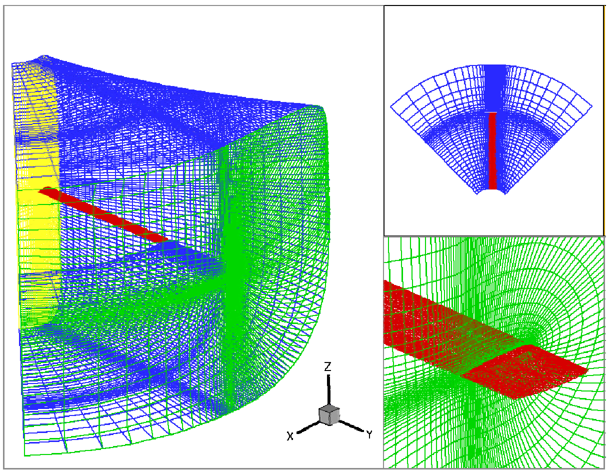


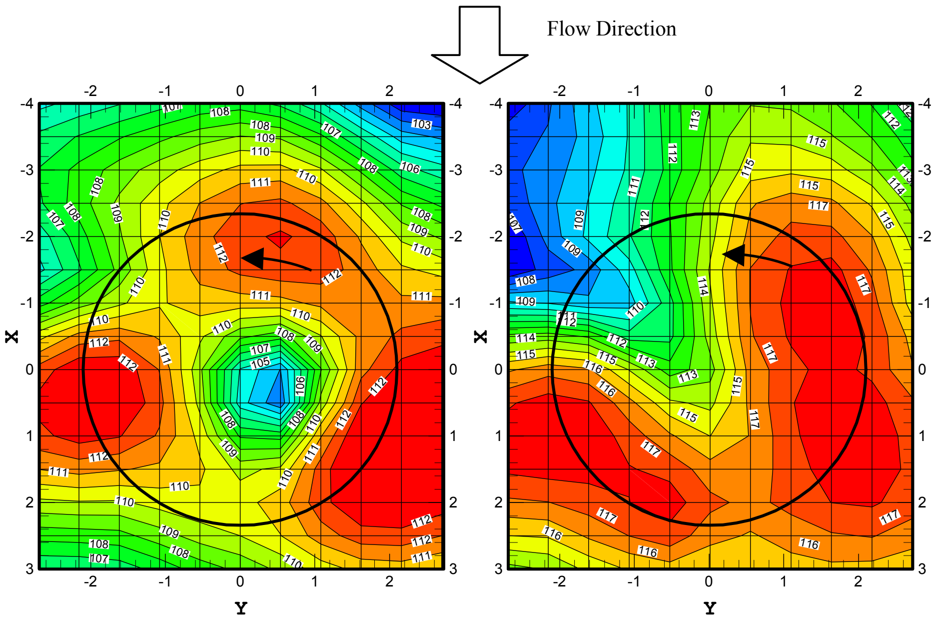
Figure 9: Computational grid over 7A blade for aerodynamic calculation

been exploited in performing aerodynamic calculations and an azimuthal discretization of 0.5 degree has been imposed. As already mentioned, the wake induced velocity distribution has been derived from

CAMRAD/JA as a consequence of the limited functioning of the BEM module within HELIFPX.

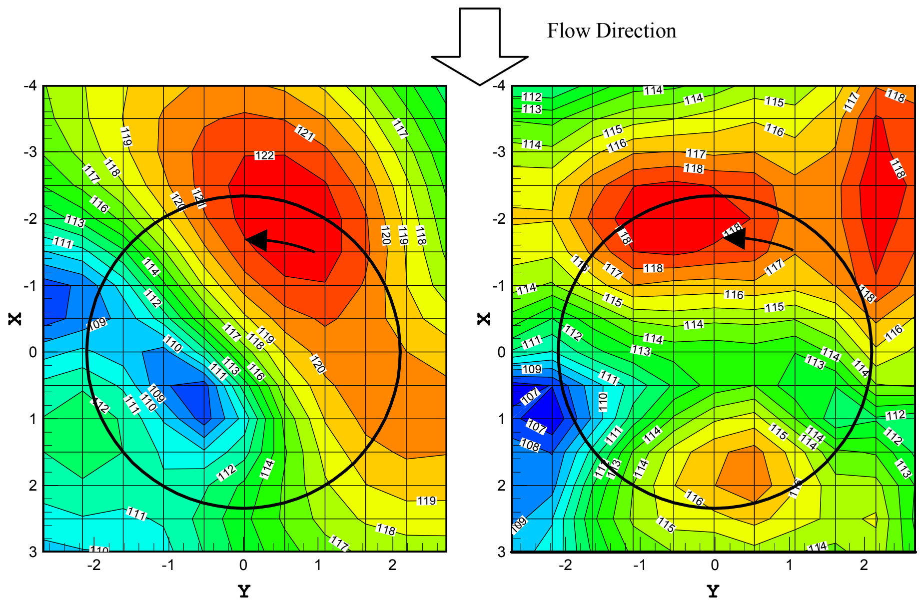
A certain number of iterations has been performed in aerodynamic-aeroelastic coupling loop, while monitoring effects on aerodynamic coefficients distributions over the blade together with parameters describing rotor aeroelastic behavior; convergence was reached after a few iterations. As already mentioned, data exchange between the two codes involved all the aerodynamic coefficients and the loop convergence was tested consequently. Nevertheless, different convergence criteria should also be investigated.

As far as the acoustic calculation is concerned, a linear Fofwcs Williams-Hawkings formulation has been chosen for free space simulation and Farassat formulation 1A has been exploited as the solution algorithm with integration of aerodynamic loads on the physical surfaces at the panel centroids. Fuselage scattering effects have also been introduced to some extent in calculations, thus leading to minor modifications in noise footprints predictions.



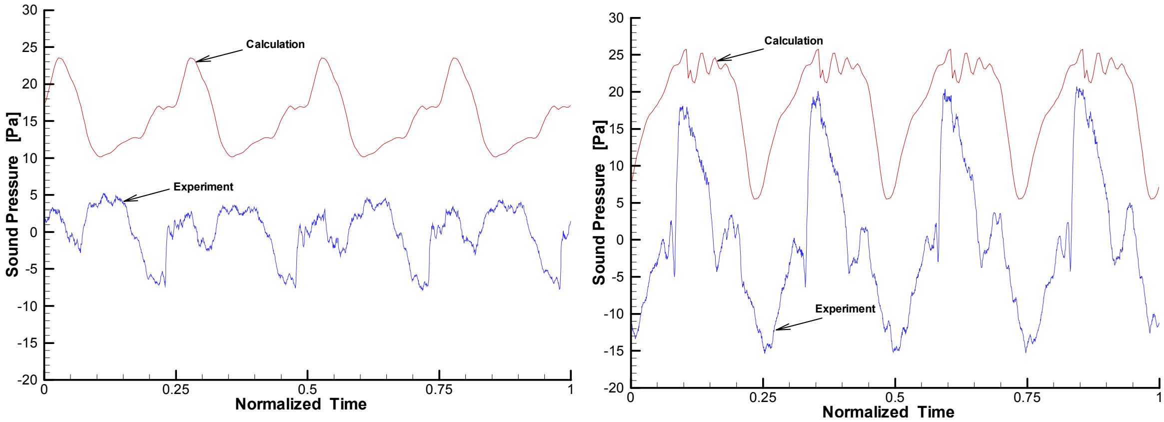
(a) (b)

Figure 10:TC067: comparison between simulated (a) and experimental (b) noise footprint



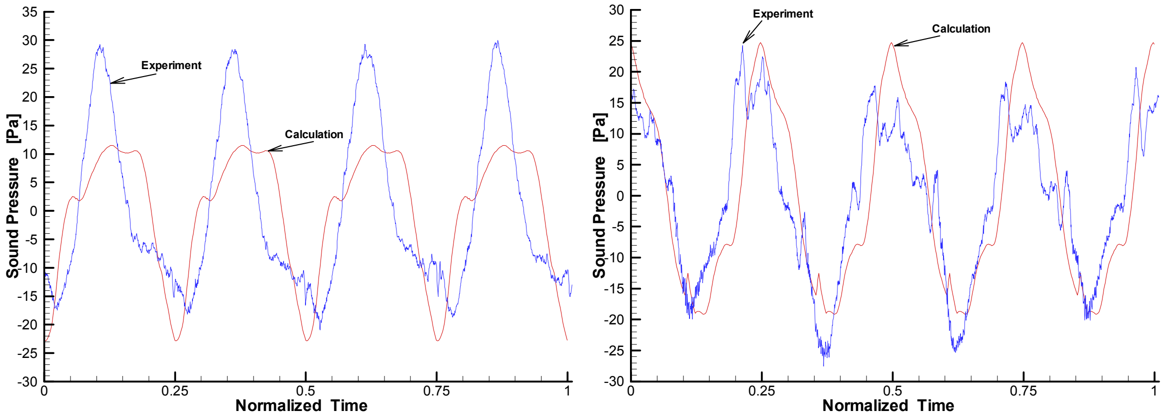
(a) (b)

Figure 11:TC152: comparison between simulated(a) and experimental (b) noise footprint



(a) (b)

Figure 12: TC067: comparison of acoustic experimental and simulated signature at microphone 1 (a) and 2 (b)



(a) (b)

Figure 13: TC152: comparison of acoustic experimental and simulated signature at microphone 1 (a) and 2 (b)

Achieved correlation (see Figure 10 and Figure 11) is far from being completely satisfactory, as also shown by acoustic pressure signatures over the microphones (see Figure 12 and Figure 13). It's worth observing that the simulated acoustic perturbations, while exhibiting time domain general behaviors comparable to the experimental ones, show on the other hand strong offsets in sound pressure levels (and in some cases in peak to peak values also). Finally, as expected, BVI events are very difficult to be captured primarily because of the limited accuracy in wake calculation.

The key point in the simulation procedure is indeed pressure reconstruction on the blade: even if aerodynamic coefficient distributions at fixed span stations and azimuthal steps are accurately reproduced, time evolution of pressure loads (and of their frequency contents as a consequence) is the most important thing with the aim of reliable acoustic calculations. As far as aerodynamic pressure reconstruction is concerned, compared to good correlation obtained for points not interested by impulsive phenomena (Figure 14 a), bad results are achieved for pressure probes located near the leading edge of the blade (Figure 14 b) that, as already mentioned, plays a major role in the acoustic simulation because of the strong BVI pressure peaks it experiences.

By means of the visualization module the simulated maneuver in the wind tunnel can also be reproduced, by fixing microphone positions and fictitiously assigning to the rotor a translational velocity equal to the wind's one.

Conclusions and future developments

In this paper a perspective has been drawn onto the state of the art of helicopter aeroacoustic predictions tools within AGUSTA.

An integrated simulation environment has been developed including codes that address aeroelastic, aerodynamic and aeroacoustic rotor behavior determination. Tool effectiveness has been assessed on a wind tunnel model rotor. Compared to the very promising results from application of the simulation procedure to experimental pressure distributions, correlation achieved exploiting the entire simulation

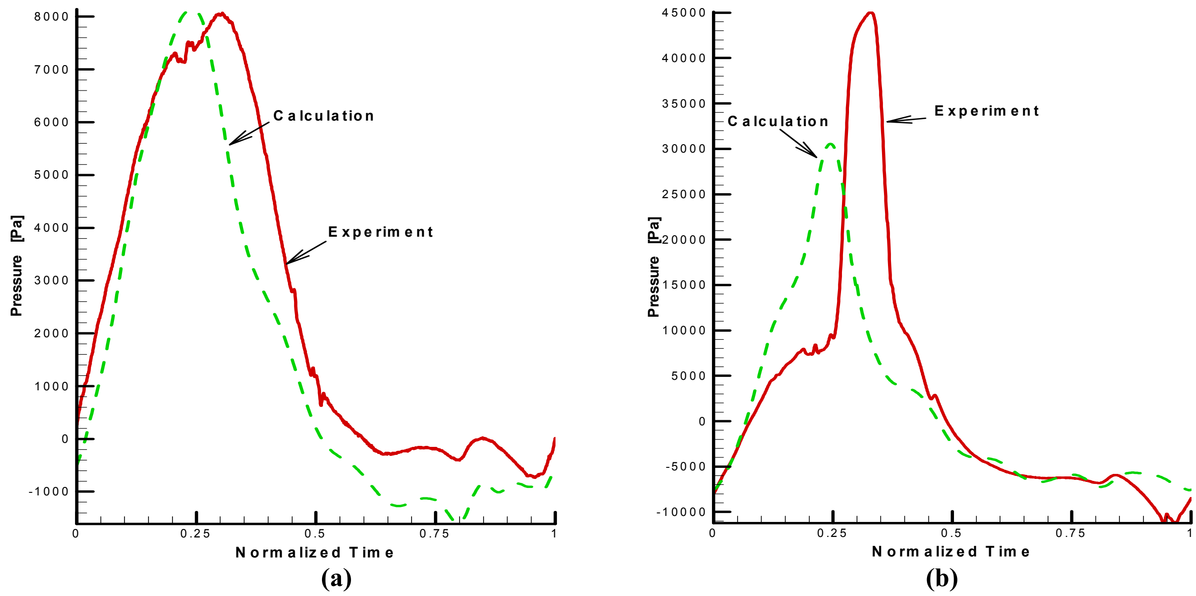


Figure 14: Comparison of experimental and simulated blade pressure time histories on probes located near trailing edge at middle spanwise (a) and near leading edge in the tip region (b)

tool to extract acoustic database wasn't so satisfactory, due essentially to lacks in aerodynamic calculation.

Enhancement of the project is now on going in collaboration with Politecnico di Milano and is focused in improving the aerodynamic simulation through exploitation of an Euler calculation of the flowfield around blades rather than a potential one. Great importance is given also to the introduction of an efficient and accurate wake prediction system inside the loop. Calculations are in progress (ref.[8]) and preliminary results will be soon available, not limited to wind tunnel models, but extended also to real helicopter rotors.

According to preliminary validation activity results a series of further possible interventions has been recognized aimed at improving tool efficiency:

- introduction of new more reliable codes, particularly:
  - ➢ exploitation of GYROX code as an alternative aeroelastic tool, as it is supposed to better reproduce variations of aerodynamic loads due to blade elastic deformations;
  - ➢ implementation of a dedicated tool for prediction of the BVI phenomena;
  - ➢ exploitation of other codes for predicting steady flow over non rotating surfaces that contribute to the scattering phenomena;
- exploitation of different aeroacoustic formulations instead of the linear FWH;
- final validation activity by exploitation of in flight collected database during acoustic certification campaign.

Once the complete loop accuracy will be gathered, the outlined procedure will provide a reliable tool to optimize the rotor blade design and a useful guidance to determine optimum operational flight envelopes from the noise emission point of view.

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