THE PILOT ACOUSTIC INDICATOR: A NOVEL COCKPIT INSTRUMENT FOR THE GREENER HELICOPTER PILOT

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Abstract

This paper presents the Pilot Acoustic Indicator (PAI), one the outcomes of the Clean Sky GRC5 project MANOEUVRES. The PAI is an instrument designed to present information on the current and expected noise emission levels to the rotorcraft pilot, to allow him/her to adequately react to incipient high noise conditions and effectively fly low acoustic impact procedures, such as in terminal manoeuvres. In-flight noise estimation is based on the interpolation within a pre-calculated database of acoustic hemispheres interrogated through the retrieval of a limited set of current rotorcraft state parameters. Noise information is subsequently synthesized in an index for cockpit display, through a dedicated graphical interface. The paper details the PAI design, development and prototypal implementation, aimed to be integrated in an industrial research flight simulator for functional demonstration and assessment.

1. INTRODUCTION

Among the various aspects of the environmental emissions of aircraft, noise can be considered to be the most directly annoying for overflown communities, and thus can be deemed as one of the key factors to work on for broadening the public acceptance of flying machines. The situation is particularly delicate when it comes to rotorcrafts, since they are more prone to fly their missions at limited altitudes due to air traffic control constraints and also because their unique vertical take-off and landing capabilities permit operations from helipads located in densely populated urban areas.

Having an on-board instrument conveying information on the emitted noise footprint would be advantageous for the pilot for different reasons. For a start, he/she could monitor in real time the intensity and evolution of produced noise and apply, when possible, the suitable corrective actions to maintain it within acceptable limits. Additionally, such an instrument would allow the assessment of the noise impact of different manoeuvring strategies in training/verification/evaluation activities, without the need to fly at low altitudes over an ad-hoc prepared, ground-deployed acoustic acquisition infrastructure.

In this regard, the Clean Sky - Green Rotorcraft 5 (GRC5) project MANOEUVRES[1,2] concerns an innovative approach geared towards quieter rotorcraft manoeuvres, especially during terminal flight phases. A major topic in the project concerns the design, development and testing of a novel in-flight measurement system for rotor blade flapping that will be able to provide reliable rotor state information to feed an algorithm that, together with other data retrieved from the helicopter avionics, will enable the run-time estimation of the emitted noise. The present paper illustrates how MANOEUVRES Work Package 4 has succeeded in producing a set of noise indexes in real-time and displaying it to the pilot on a dedicated instrument: the Pilot Acoustic Indicator (PAI). The next section illustrates the adopted noise monitoring methodology, and is followed by the one dedicated do the presentation of the implemented noise estimation computational procedure. Finally the PAI itself is described.

2. NOISE ESTIMATION METHODOLOGY

The starting point of the noise estimation algorithm is the database of Sound Pressure Level Hemispheres (SPLHs), which are briefly described in paragraph 2.2., that has been produced by Work Package 1 of the MANOEUVRES project.[3] This database has been populated with all the SPLHs calculated for a reasonable range of the three mapping variables: thrust coefficient C_T, advance ratio μ and Tip Path Plane Angle Of Attack (TPP-AOA) α_{TPP}. From such database, an interpolated SPLH can be calculated for the actual values, i.e. the values of the three mapping parameters estimated from the current flight condition.

The requirements for the PAI call for two different operating modes: *Ground Noise* and *Emitted Noise*. The former refers to the noise index evaluated by radiating the Helicopter (H/C) noise to the Ideal Flat Ground (IFG) situated at the distance provided by the current height above ground. The latter refers to a noise index evaluated locally, on the surface of the H/C-centred SPLH, regardless of current height above ground.

In the case of the *Emitted Noise* PAI operating mode, the subsequent and final step is to evaluate the maximum values of sound intensity on the obtained SPLH, and to produce the noise indexes accordingly. On the other hand, for the *Ground Noise* PAI operating mode, it is first necessary to propagate the Sound Pressure Level (SPL) values from the obtained SPLH surface to the IFG below the helicopter. This is achieved by a two-step process. First the interpolated SPLH, which is fixed to the helicopter body-axes, is positioned in space taking into account the current helicopter pitch, roll and yaw attitude angles. Subsequently the SPL values are radiated to the ground. Finally, noise indexes relevant to the radiated SPL values are calculated.

2.1. Assumptions on wind and atmospheric phenomena

Wind and atmospheric phenomena, such as fog, rain, mist, hail, wind-shear, etcetera, in general have a deep influence at various level of the presented procedure, but it has been soon realised that it would be impossible to take them into account in the presented algorithm, since most of the necessary values couldn't possibly be available in a real-time operating environment. It has therefore been decided to assume ideal conditions with no wind, and to neglect the effects of all atmospheric phenomena.

2.2. Sound Pressure Level Hemispheres

Acoustic noise data is provided in form of SPL values defined on a suitable number of points distributed on a hemispherical surface centred in the intersection between the main rotor axis and Tip Path Plane (TPP), considered fixed to the helicopter body axes. The points, referred to as *microphones*, are equally spaced by $15°$ in latitude and longitude, and in order to permit the compensation of the helicopter attitude (see paragraph 3.3.1.) are provided from the South pole ($90°$ of latitude) up to $-30°$ (i.e. $30°$ above the equator). Such distribution yields:

- a total number of 24 microphones per parallel $(360/15)$
- a total number of 8 considered parallels (from $+75°$ through $-30°$)

that, with the addition of the single microphone located at the hemisphere south pole, produces a total of 193 microphones per hemisphere. For every microphone the spectrum of SPL data is supplied for the first 20 multiples of the fundamental Blade Passage Frequency (BPF) at $28\,\mathrm{Hz}$ interval, in the range $28\,\mathrm{Hz} - 560\,\mathrm{Hz}$. Since all PAI-related calculations are frequency independent, the A-weighted noise intensity has been precalculated for every single microphone in every single SPLH starting from its spectral components. The radius R_H of the SPLH has been chosen to be large enough so that for any distance $R > R_H$ dipole effects can be assumed to be negligible, and the helicopter can be considered as a anisotropic monopole source. The resulting SPLH radius is $150\,\mathrm{m}$.

2.3. Choice of the noise measure

When it comes to producing a single noise index to be used for a synthetic description of the intensity of sound, and to compare it with suitable threshold values, multiple options are possible. As the high-level goal of the Clean Sky-GRC5 efforts is to reduce the environmental impact of rotorcraft operations, it has been decided to adopt as a measure of noise index the value obtained applying to the SPL the A[4] weighting curve, thus producing values in dBA. Since such weighting curve is representative of the response of the human ear, it is generally adopted when dealing with the subjective perception of sounds (and in particular of noise) by humans. In particular, the dBA levels thus obtained are directly comparable against the noise limits imposed by the various regulations.

2.4. Sound radiation model

Sound propagation is a very complex phenomenon and, in order to be accurately modelled, the knowledge a wide variety of parameters and quantities is essential. For PAI implementation it has been decided to adopt a simplified sound radiation model for two reasons. On one hand, the necessity to produce an indication to the pilot, and therefore to process all data, in real-time sets a limit on the quantity and on the complexity of the calculations that can be performed with the expected on-board available number-crunching power. On the other hand, during normal operations of the helicopter most of the quantities necessary for applying a detailed sound propagation algorithm are simply unknown, since no sensors are provided on-board for measuring them. It has therefore been decided to adopt a simplified sound radiation model that takes in consideration only the conservation of the total acoustic power, and that will be presented in the next paragraphs. Such simplified model produces a slight overestimation of the noise in most of the cases, thus yielding conservative indexes.

The formula for calculating the acoustic power L_W at the generic distance d from an ideal point source where a pressure $P(d)$ is measured is:

(1) $$L_W = 10\log_{10}\left(\frac{\frac{P\left(R\right)^2}{\rho c}S\left(d\right)}{W_0}\right)$$

where

- W_0 is the reference acoustic power $= 10^{-12}\,\mathrm{W}$
- S is the area of the surface of radiated sound
- ρ is the density of air
- c is the velocity of propagation of sound in air

It is important to note that in our simplified propagation model the total acoustic power is invariant with the distance d from the source. The sound decay is therefore proportional to the spherical spreading:[5]

(2) $$L_P = L_W + 10\log_{10}\left(\frac{1}{4\pi d^2}\right)$$

Indeed, from 1

(3) $$L_W = 10\left(\log_{10}\left(\frac{P\left(d\right)^2}{\rho c W_0}\right) + \log_{10} S\left(d\right)\right)$$

Rearranging, we get

(4) $$L_W = 10\left(\log_{10}\left(\frac{P^2}{{P_0}^2}\right) + \log_{10}\left(4\pi d^2\right)\right)$$

where ${P_0}^2$ is the reference effective pressure,

(5) $${P_0}^2 = \rho c W_0 = 4\times 10^{-10}\,\mathrm{Pa}^2$$

Finally

(6) $$L_W = L_P\left(d\right) + 10\log_{10}\left(4\pi d^2\right)$$

Therefore, since $L_P\left(R_H\right)$ is known, with R_H as radius of the hemisphere, L_W can be computed from:

(7) $$L_W = L_P\left(R_H\right) + 10\log_{10}\left(4\pi {R_H}^2\right)$$

and compute $L_P\left(d\right)$ for d being the length of an arbitrary ray connecting the helicopter to the observer:

(8) $$L_P\left(d\right) = L_P\left(R_H\right) + 10\log_{10}\left(\frac{{R_H}^2}{d^2}\right)$$

It is worth to be noted that the adopted simplified radiation model is frequency independent, and for this reason it has been possible to neglect frequency dependent attenuation and to directly radiate to the ground the noise A-weighted intensity that has been precalculated at every microphone location starting from the spectral components of the SPL.

2.5. Sound Pressure Level Hemispheres mapping parameters

As it has been pointed out, at the time of the present writing, in compliance with the approved MANOEUVRES Description Of Work (DOW) the set of parameters chosen to map the SPLH database are:

- thrust coefficient C_T
- advance ratio μ,
- TPP-AOA α_{TPP}

In order to allow the maximum flexibility the noise estimation computational procedure has been designed and implemented in such a way to make it invariant to the change of coordinates used to map the SPLHs.

3. NOISE ESTIMATION COMPUTATIONAL PROCEDURE

Figure 1 shows the high-level flow chart of the developed noise estimation computational procedure, where the following colour scheme has been adopted:

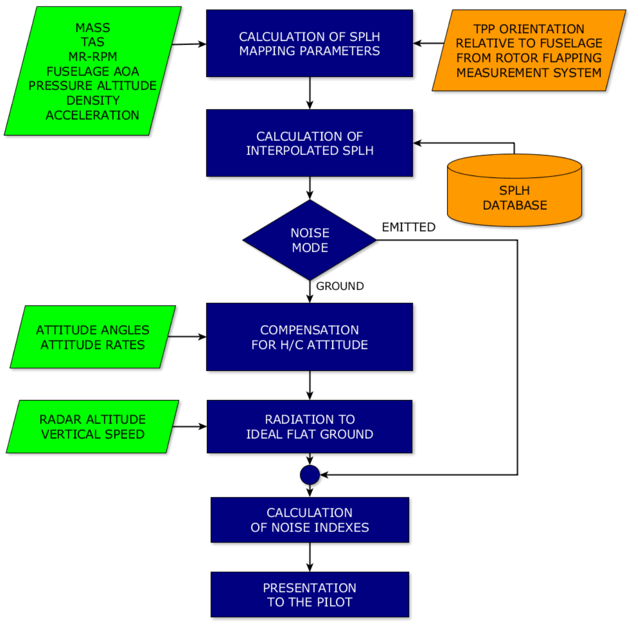

Figure 1: Flow chart of the noise estimation computational procedure.

- boxes with a white text on a blue background are used to indicate procedure steps;
- boxes with a black text on a green background are used to indicate data acquired from the on board helicopter avionic data bus;
- boxes with a black text on an orange background are used to indicate data obtained from the outcomes of different MANOEUVRES Work Packages, namely the Rotor Flapping Measurement System from WP2/WP3 and the SPLH database from WP1.

It is worth to be noted here that since the PAI requirements ask for an indication to the pilot both of the current and the predicted (over a 5 seconds timespan) value of noise indexes, the presented procedure is executed twice. On the first run it is fed with the actual values of the input quantities and it produces the current noise indexes. A second pass is then performed using a predicted set of the input parameters that best estimates their value at the end of the 5 seconds interval, and yielding the predicted noise indexes. For the sake of clarity, in the following discussion all considerations will be referred to the current values case, while a dedicated paragraph (3.6.) will be used to point out the differences implied in running the procedure for evaluating the predicted values.

3.1. Calculation of SPLH mapping parameters

This step of the procedure deals with the calculation of the current values of the set of parameters (C_T, μ and α_{TPP}) used to map the SPLHs.

3.1.1. Evaluation of thrust coefficient

The thrust coefficient C_T is defined as

(9) $$C_T = \frac{T}{\rho A\left(\Omega R\right)^2}$$

where

- T is the main rotor thrust magnitude,
- ρ is the air density,
- A is the area of the main rotor disc,
- Ω is the main rotor rotation speed,
- R is the main rotor radius.

Figure 2 shows a balance of the forces acting on the helicopter in a generic flight condition,

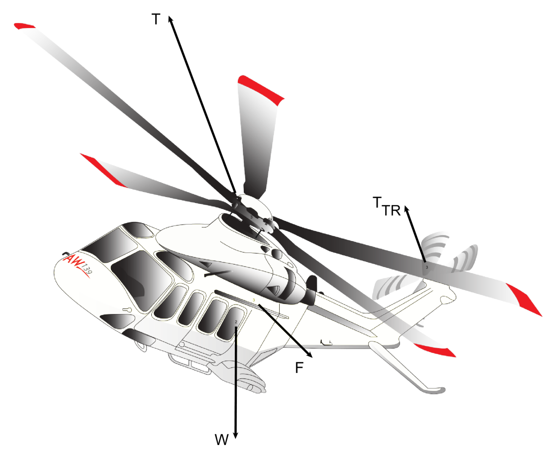

Figure 2: Balance of forces acting on the helicopter CG.

corresponding to the balance equation

(10) $$m\mathbf{a} = \mathbf{T} + \mathbf{T}_{TR} + \mathbf{F} + \mathbf{W}$$

where

- $\mathbf{T}$ is the main rotor thrust vector $(T = |\mathbf{T}|)$,

- $\mathbf{W}$ is the helicopter weight vector ($W = mg = |\mathbf{W}|$),
- $-m\mathbf{a}$ is the inertia force, $\mathbf{a}$ being the helicopter acceleration,
- $W\mathbf{n} = \mathbf{W} - m\mathbf{a}$ is the total mass force, or apparent weight ($\mathbf{n}$ is the load factor vector),
- $\mathbf{T}_{TR}$ is the tail rotor thrust vector,
- $\mathbf{F}$ is the helicopter fuselage aerodynamic resultant force.

The latter is given by the sum of fuselage drag, sideforce, and lift, resulting in

(11) $$\mathbf{F} = X\mathbf{e}_x^b + Y\mathbf{e}_y^b + Z\mathbf{e}_z^b$$

where $\left(\mathbf{e}_x^b, \mathbf{e}_y^b, \mathbf{e}_z^b\right)$ are the unit vectors of the (x, y, z) axes of the fuselage body frame. Helicopter fuselage force components can be written as

(12) $$X = \frac{1}{2}\rho V^2 S C_X, Y = \frac{1}{2}\rho V^2 S C_Y, Z = \frac{1}{2}\rho V^2 S C_Z$$

where

- ρ is the outside air density,
- V is the remote velocity,
- S is the fuselage reference surface,
- $(C_X, C_Y, C_Z)$are the fuselage force coefficients.

The force balance equation (10) can be rewritten in the following form

(13) $$\mathbf{T} = -\left(\mathbf{T}_{TR} + +\mathbf{F} + W\mathbf{n}\right)$$

Therefore, the final expression of the thrust coefficient is:

(14)
$$C_T = \frac{\left|W\mathbf{n} + \frac{1}{2}\rho V^2 S\left(C_X\mathbf{e}_x^b + C_Y\mathbf{e}_y^b + C_Z\mathbf{e}_z^b\right) + \mathbf{T}_{TR}\right|}{\rho A\left(\Omega R\right)^2}$$

Among the above quantities A, S, R are constants, and depend on the specific helicopter type. The coefficients (C_X, C_Y, C_Z) can be related to the coefficients of drag, sideforce and lift (C_D, C_Q, C_L), and also depend on the specific helicopter type[1]. The tail rotor thrust can be related to a tail rotor performance model, given its current values of RPM and collective pitch.

The rest of data can be taken from the avionic data bus:

- W is the current value of the helicopter weight, retrieved from the Flight Management System (FMS);
- $\mathbf{n} = -\frac{1}{g}\mathbf{a}_t$ where $\mathbf{a}_t$ is the total acceleration sensed at the helicopter center of gravity and measured by the on-board Inertial reference System (IRS);
- ρ is the air density, evaluated by the Air Data Computer (ADC);
- V is the TAS, evaluated by the ADC;
- Ω is the main rotor rotation speed and is provided by the FMS.

A first approximation of the thrust coefficient C_T can be obtained by neglecting force components normal to the trajectory, and approximating the residual force with fuselage drag:

(15) $$C_T = \frac{\left|W\mathbf{n} + \frac{1}{2}\rho V^2 S C_D\mathbf{e}_x^b\right|}{\rho A\left(\Omega R\right)^2}$$

3.1.2. Evaluation of advance ratio

Advance ratio μ is defined as:

(16) $$\mu = \frac{V\cos\alpha_{TPP}}{\Omega R}$$

For calculating the current value of μ the procedure is fed with the following data, taken from the helicopter avionic bus:

- TAS is calculated by the on-board ADC;
- Ω is provided by the FMS.

3.1.3. Evaluation of tip-path-plane angle of attack

The TPP-AOA is defined as the angle from the main rotor tip path plane to the helicopter airspeed vector. As

[1] At low values of the helicopter fuselage angles of attack and sideslip, the coefficients (C_X, C_Y, C_Z) may be approximated as coincident with (C_D, C_Q, C_L).

such, it can be expressed combining the orientation of the airspeed vector with respect to the helicopter fuselage body axes and the orientation of the main rotor tip path plane with respect to the fuselage. Therefore, this involves two separate problems:

1. Evaluate the orientation of the airspeed vector with respect to the helicopter fuselage; this amounts to evaluating the fuselage angle of attack and angle of sideslip;
2. Evaluate the orientation of the main rotor tip path plane with respect to the fuselage; this, within the hypothesis of a definite tip path plane, amounts to evaluating the cyclic flapping angle components of the main rotor blades.

In order to solve the first problem with a direct measurement, one possibility relies in the adoption of a swivelling air data boom, adequately placed outside the region interested by the main rotor wake. Today, this solution is sometimes adopted in experimental and military helicopters, while it is not considered in typical production helicopters. In absence of a direct measurement of the fuselage angles of attack and sideslip, an estimation procedure can be considered. A recent attempt to such evaluation, in connection with the MANOEUVRES project, is scheduled for presentation at the 41st European Rotorcraft Forum 2015.[6]

In the MANOEUVRES project, the second problem is approached through a direct measurement of the main rotor blade angles, and specifically the flapping angle. In fact, assuming that the blade tip trajectories lie in a plane, the relative orientation of such plane (the tip path plane) with respect to the shaft, and therefore the fuselage, depends only on the longitudinal and lateral cyclic flap components. The rotor state measurement system developed in the WP2 and WP3 of the MANOEUVRES project provides thus the necessary input to the estimation algorithm, which merges the measurement or estimation of the fuselage angles of attack and sideslip with the measurement of the flapping angle of the blades.

In steady symmetric flight, the relation between TPP-AOA, relative airspeed/fuselage orientation and relative rotor disk/fuselage orientation simplifies to the following relation:

$$\alpha_{TPP} = \alpha_f + i_m + a_{1s} \tag{17}$$

where

- α_f is the fuselage angle of attack,
- $-i_m$ is the mast tilt angle with respect to the fuselage z axis.
- a_{1s} is the longitudinal cyclic flap component.

Consequently, given the constant i_m, by retrieving the fuselage angle of attack α_f (from a direct measurement or a model-based estimation) and the longitudinal cyclic flap a_{1s} (from the rotor state measurement system), the TPP-AOA can be estimated.

3.2. Calculation of interpolated SPLH

This step is dedicated to the calculation of the SPLH associated with the current flight condition of the helicopter starting from the SPLHs calculated in WP1 and available in the database. The values of C_T, μ and α_{TPP} calculated in the previous step are used to search the SPLH database and locate the 8 hemispheres adjacent to the point identified by the current triplet of parameters that will be used as input for the interpolation process. The SPL value for every microphone on the current SPLH is then obtained by means of a tri-linear interpolation from the SPL value of the corresponding microphones located at the same latitude and longitude on the 8 adjacent hemispheres. The resulting interpolated current SPLH will be used for all the subsequent steps of the procedure.

3.3. Effects of helicopter attitude

When dealing with *Emitted Noise* calculation, after the previous step the procedure jumps directly to the final noise index calculation.

When performing *Ground Noise* calculation, however, it must be noted that the helicopter in flight will generally experience different orientations of its body axes with respect to the local vertical, as it is measured by the onboard IRS and quantified by the pitch, roll and yaw attitude angles. Since the calculated SPLH is fixed with the helicopter fuselage axes, its orientation in space rigidly follows that of the helicopter fuselage. Therefore, before radiating to the ground, it is necessary to perform the corresponding 3D rotation, placing the SPLH with the correct pitch, roll and yaw attitudes (in general, this means that the SPLH z axis will not be perpendicular to the ground). Figure 3 shows a perspective rendering of this operation where for the sake of clarity only the microphones placed on a single parallel (75° of latitude) have been radiated to ground.

Two different scenarios have then been evaluated to proceed to the radiation to the ground step.

The first considered solution was to leave the SPLH ro-

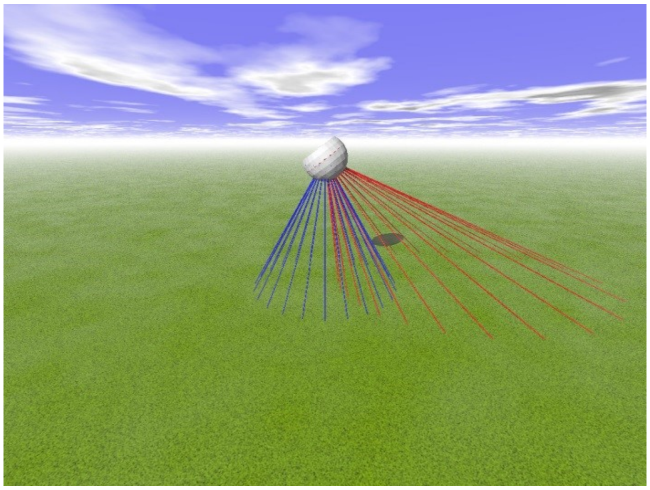

Figure 3: Radiation to the ideal flat ground: the nominal hemisphere radiation (blue) is rotated to account for helicopter actual attitude (red).

tated and radiate (red lines in Figure 3) from the SPLH centre to the ground all the microphones intensities. However, this approach has a number of drawbacks.

First of all the resultant distribution of intensities on the ground is unevenly spread, making it difficult to calculate the noise indexes in case of the directional representation, and therefore asking for a post-radiation interpolation on the ground.

Additionally, the radiating algorithm itself has proven to be less efficient in terms of math intensity, since with this approach all the calculations must to be done at run-tine without the possibility to use pre-evaluated constant, as in the case that will be explained in the following sections.

For this reason it has been decided to add to the procedure an intermediate step that given the rotated SPLH yields, by means of an interpolation on the hemisphere surface, a normally orientated SPLH, that will subsequently be radiated to the Ideal Flat Ground (blue lines in Figure 3).

3.3.1. Compensation for helicopter attitude

In the previous step it has been shown how, starting from the current values of C_T, μ and α_{TPP} it is possible to obtain from the SPLH database the current SPLH. Since SPLHs are fixed with the helicopter body frame, the just obtained current SPLH will be rotated with respect to the ground. The purpose of this step of the procedure is to re-obtain a SPL distribution at the microphones on a normally orientated SPLH. Supported by the observation that spatial gradients of the SPL on the hemisphere surface are moderated, this steps calculates the SPL at the position of the microphones on an equivalent, normally orientated SPLH by means of an interpolation on the SPLH surface. Figure 4 shows the flowchart of the procedure.

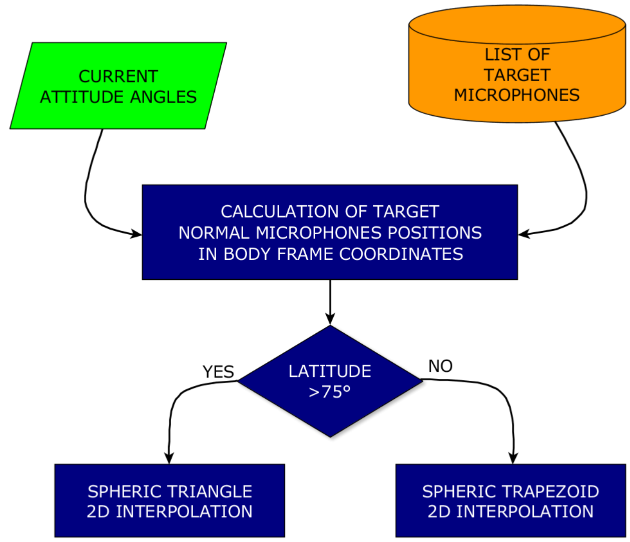

Figure 4: Compensation for h/c attitude flowchart.

As for the interpolation on the SPLH surface, taking a look at the hemisphere surface it can be immediately realised that a simple bilinear interpolation scheme would include sensible errors deriving from the uneven grid pattern. With the aim of finding a spherical shape that best approximates the single surface element of the hemisphere, many figure have been analysed, and eventually two different solutions have been adopted (Figure 5):

- a spherical trapezoid, for latitudes above the last ($75°$) parallel;
- a spherical triangle, for the final hemisphere portion close to the pole.

The two different cases will now be detailed separately.

3.3.2. Interpolation on the spherical trapezoid

The SPL Intensity I_P at the microphone located in the generic point P, *MIC*(Θ_P, ϕ_P), on the spherical trapezoid surface (Figure 5) will be calculated by interpolation starting from the values of SPL intensities $I_0 ... I_3$ at the four known microphones *MIC*(Θ_i, ϕ_j),

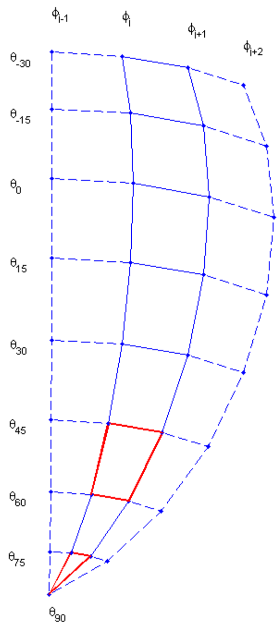

Figure 5: Surface of the SPLH.

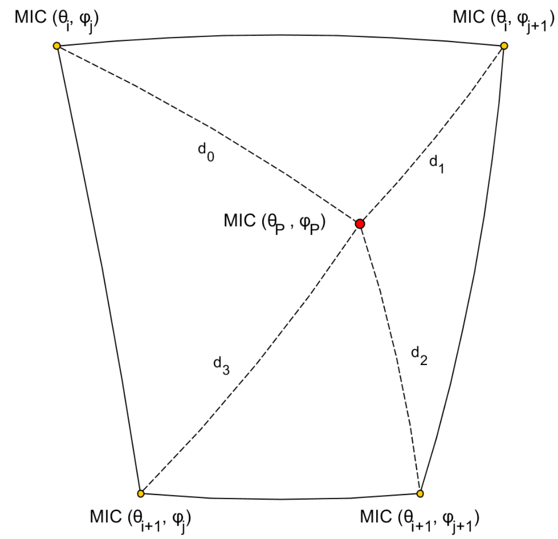

Figure 6: Interpolation on spherical trapezoid.

MIC (Θ_i, ϕ_{j+1}), *MIC* $(\Theta_{i+1}, \phi_{j+1})$ located at the four vertexes of the spherical trapezoid surrounding P (Figure 6):

(18) $I_P = \alpha_0 I_0 + \alpha_1 I_1 + \alpha_2 I_2 + \alpha_3 I_3$

For evaluating the four weights $\alpha_0 ... \alpha_3$ the following procedure has been adopted. First of all, the distances d_i are computed along the great circle using the haversine formulation.[7]

(19)

$$k_i = \sin\left(\frac{\Theta_i - \Theta_P}{2}\right)^2 + \cos\Theta_i \cos\Theta_P \sin\left(\frac{\phi_i - \phi_P}{2}\right)^2$$

(20) $d_i = 2r\tan^{-1}\left(\sqrt{\frac{k_i}{1-k_i}}\right)$

It is now possible to calculate the four weights $\alpha_0 ... \alpha_3$

(21) $\beta_i = \left(\frac{d_i}{\sum_{j=0}^{3} d_j}\right)^2$

(22) $\alpha_i = \frac{\beta_i}{\sum_{j=0}^{3} \beta_j}$

3.3.3. Interpolation on the spherical triangle

The procedure is quite similar for the case of the last portion of the hemisphere, the one limited by the parallel at $75°$ and the pole, the only difference being that the number of reference points goes from four to three (Figure 7).

(23) $I_P = \alpha_0 I_0 + \alpha_1 I_1 + \alpha_2 I_2$

Again, distances d_i are computed along the great circle using the haversine formulation 19 and the three weights $\alpha_0 ... \alpha_2$

(24) $\beta_i = \left(\frac{d_i}{\sum_{j=0}^{2} d_j}\right)^2$

(25) $\alpha_i = \frac{\beta_i}{\sum_{j=0}^{2} \beta_j}$

3.4. Radiation to Ideal Flat Ground

Once SPL intensities are known on the normal orientated SPLH, they can be radiated to the IFG.

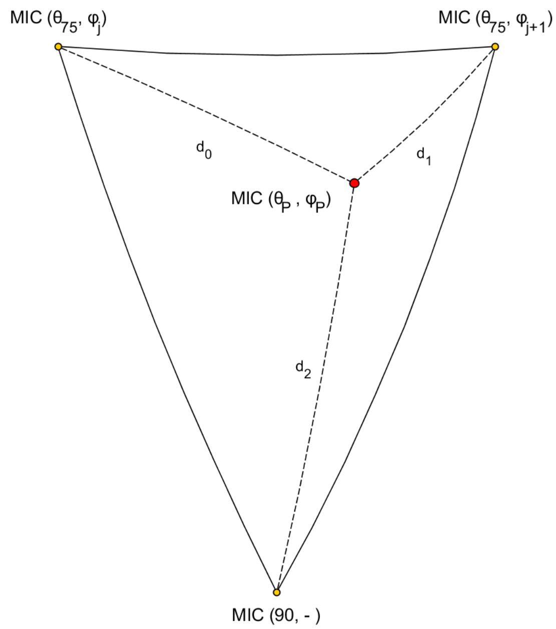

Figure 7: Interpolation on spherical triangle.

Figure 8 outlines the situation.

SLP intensity on the ground $I(\theta)_g$ of the generic microphone at latitude θ can be computed starting from the value of its intensity $I(\theta)_H$ on the surface of the SPLH of radius R_H

(26) $I(\theta)_g = I(\theta)_H + A_\theta$

where the altitude above ground and latitude-dependent attenuation A_θ is given by

(27) $A_\theta = 20\log_{10}\dfrac{R_H}{\rho_\theta} = 20\log_{10} R_H - 20\log_{10}\rho_\theta$

Noting that

(28) $\rho_\theta = \dfrac{\rho_{90}}{\sin\theta}$

where ρ_{90} is the distance between the centre of the SPLH and the ground, i.e. the flight altitude, (27) can be rewritten as:

(29) $A_\theta = [20\log_{10}(R_H\sin\theta)] - 20\log_{10}\rho_{90}$

and defining

(30) $A_{\theta_0} = 20\log_{10}(R_H\sin\theta)$

the final expression of attenuation results

(31) $A_\theta = A_{\theta_0} - 20\log_{10}\rho_{90}$

substituting in (26)

(32) $I(\theta)_g = I(\theta)_H + A_{\theta_0} - 20\log_{10}\rho_{90}$

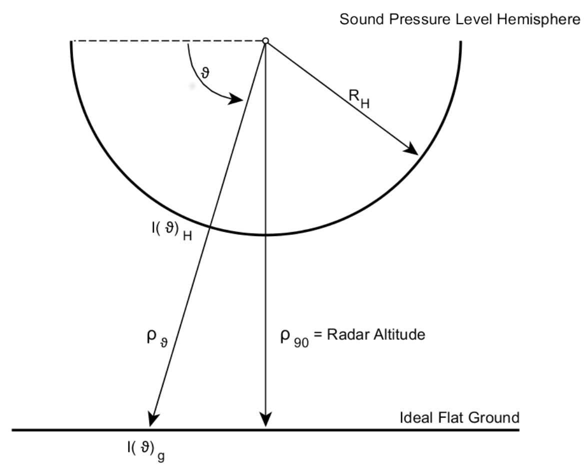

Figure 8: SPL Intensity radiation from SPLH to Ideal Flat Ground.

Expression (32) is particularly efficient for a real time calculation. In fact, A_{θ_0} is only dependent on the radius R_H of the SPLH and on the latitude θ of the particular microphone, and since both are known constants it can be pre-calculated at software launch time. The other component $20\log_{10}\rho_{90}$ is only dependent on the current flight altitude above ground ρ_{90}, or Radar Altitude (RA) as it is often called, minus the distance between the origin of the SPLH and the RA sensor, also a known constant, and is the same for every single microphone on the SPLH, so it needs to be calculated only once per iteration. RA is measured by the on board Radar Altimeter, and is therefore retrieved from the helicopter avionic data bus. After the presented radiation step of the procedure every microphone is associated with the SPL intensity that it produces on the ideal flat ground.

3.4.1. A note on flight altitudes below the radius of the SPLH

As it has been shown, the radius R_H of the SPLH has been chosen in such a way that for distances $R > R_H$ dipole effects vanish and the helicopter can be considered as an isotropic source.

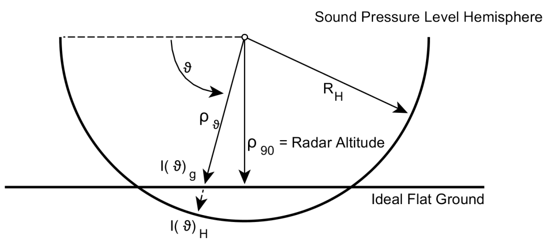

Figure 9: Radiation for flight altitudes below the radius of the SPLH.

When the flight altitude above terrain is lower than the radius of the SPLH the assumption above is no longer valid, and a precise calculation of SPL would require the careful evaluation of all the complex dipole effects, an option which has not been considered to be feasible for the purpose of PAI. Even in this case, therefore, the noise intensity on the ground will be calculated using equation (32), where ρ_{90} will be smaller than R_H, de facto *back radiating* inside the SPLH from its surface (Figure 9).

3.5. Noise indexes calculation

Once the values of intensities have been calculated, it is straightforward to produce noise indexes simply taking the maximum value in dBA of the obtained intensities within the applicable domain.

Since radiation to the IFG occurs from a normally orientated SPLH, and therefore produces an homogeneous distribution on the ground, it is possible to make considerations on the SPLH surface both for the *Emitted Noise* and for the *Ground Noise* mode, since, as it has been shown, in the latter case SPL intensities at every microphone have been calculated to take in account the attenuation due to radiation to the IFG.

The entire SPLH surface is the domain for the Global Indicator, while for the Directional Indicator five different domains are defined, as it can be seen in Figure 10.

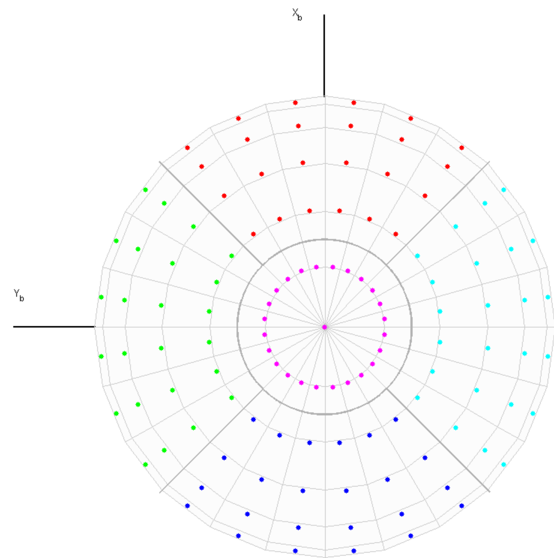

Figure 10: South pole (bottom) view of SPLH microphones used for Directional Indicator.

3.6. Differences when calculating trend indexes

As it has been pointed out, the procedure has been presented above for the case of the calculation of the current noise indexes, i.e. the noise indexes associated with the current state of the helicopter. The requirements for the PAI, however, ask to provide the pilot with an additional trend value of the noise indexes, that is to say the predicted value of the indexes over a few (5) seconds timespan.

The procedure adopted for calculating the predicted values is exactly the same, the only difference being the input data it is fed with. The next paragraph will point out such differences.

3.6.1. Calculation of predicted SPLH mapping parameters

Precise prediction of thrust coefficient, advance ratio and TPP-AOA is quite a complicated task since, among the rest, in order to carry it out rigorously the future action of the pilot on flight controls should be known at prediction time. For the purpose of producing a trend value of the noise indexes and experimenting the usefulness of their presentation to the pilot it has been decided to adopt a leaner yet still effective prediction algorithm for C_T, μ and α_{TPP}: their value is simply extrapolated forward in time, with the polynomial coefficients calculated using the last available samples.

3.6.2. Calculation of interpolated SPLH

As it can be easily imagined, no change in the procedure is requested when evaluating the interpolated SPLH from the mapping parameters

3.6.3. Compensation for helicopter attitude

The input for the compensation of helicopter attitude are the pitch and roll attitude angles. In order to estimate their value in the prediction window, it is necessary to know the angular rates (p, q, r), which are measured by the on board IRS and therefore read from the avionic bus. Once the angular rates are known, a simple forward integration yields the predicted values of pitch and roll that will be used for feeding this step of the procedure

3.6.4. Radiation to ideal flat ground

RA is the only input value to this step of the procedure. Its value at the prediction window can be estimated starting from the current value and forward integrating the GPS vertical speed, which is available on the avionic data bus.

4. THE PILOT ACOUSTIC INDICATOR

The PAI has been conceived as secondary flight navigation instrument of practical and straightforward use. It provides the pilot with the estimated noise emission index and additional information. This may allow him/her to react adequately in order to fly low-noise procedures effectively, with minimum impact on his/her workload. Given that the PAI is a secondary flight navigation instrument, it has been designed to be integrated into Multi-Function Display (MFD), with the possibility for the pilot to turn it on or off according to the situation, and to switch between the two operating modes of *Emitted Noise* estimation and *Ground Noise* estimation.

4.1. General requirements

PAI requirements concerning Human Machine Interface (HMI) aspects [8] [9] [10] [11] [12] have been defined by analysing the characteristics of the helicopter cockpits and reviewing regulations, standards and design guidelines relevant to the data presentation on aeronautical cockpit displays.

4.1.1. Presentation configurations

The PAI has two configurations: *Default presentation* and *Full presentation*. The Default presentation provides the noise emission index by the Global Indicator, whilst the Full presentation completes the information to the pilot by showing the Directional Indicator alongside the Global Indicator, as shown in the following figure.

4.1.2. Operating modes

The PAI provides two operating modes: *Ground Noise* and *Emitted Noise*. When the *Ground Noise* mode is selected, the noise index is evaluated by radiating the H/C noise to the IFG situated at the distance provided by the current height above ground retrieved from the relevant avionic data bus. When the *Emitted Noise* mode is selected, the noise index is evaluated locally, on the surface of the H/C centred SPLH, regardless of current height above ground.

4.2. Global Indicator

The Global Indicator (Figure 11) is based on a linear scale composed by two segments. The first represents admissible noise values, while the second one represents noise values exceeding a given threshold. At the side of the linear scale, a triangle-shaped pointer shows the current noise index value.

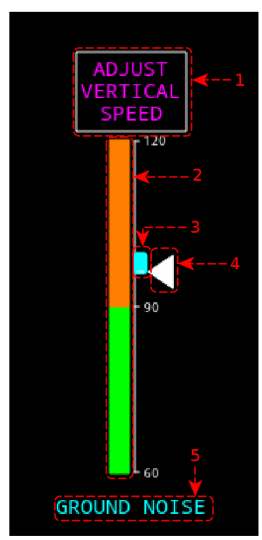

Figure 11: PAI Global Indicator.

Additionally, this indicator provides noise trend information in terms of a cyan bar that, starting from the current index value, shows the expected noise index value at the end of the prediction window if no corrective action is taken by the pilot.

Figure 11 shows the Global Indicator elements:

1. *Corrective Action Advice Box*. It is the box where the suggested corrective manoeuvre (intended to reduce noise) appears. It is displayed in magenta on black background, with white perimeter only if a corrective action is applicable.
2. *Linear Scale*. The linear scale, which is permanently displayed, is composed by two segments; the green one represent the allowed noise values set, while the amber one is the not allowed noise values set. On the right side of the linear scale a numeric scale is shown.
3. *Trend Bar*. The trend bar shows the 5-seconds-ahead prediction of the noise index value.It is permanently displayed in cyan on black background.
4. *Current Noise Index*. The white arrow points to the current value of the noise index
5. *Operational Mode Label*. The cyan label indicates the currently active operating mode (*Ground Noise* or *Emitted Noise*).

4.3. Directional Indicator

The Directional Indicator (Figure 12) is based on a radial scale composed by five areas: four sectors of an annulus plus a central circle. The thickness of each area is directly proportional to the current noise emission index relevant to that region. Information is shown only when the noise emission index is above the currently selected threshold. In *Emitted Noise* mode the indicated regions correspond to four lateral sectors and the lower spherical segment of the SPLH.

In *Ground Noise* mode the circular sectors display the noise index in each of the $90°$ sectors drawn around the ground-projected helicopter current position, while the central circle shows the noise emission index evaluated at the ground-projected helicopter current position. The Directional Indicator does not provide any trend information.

Figure 12 shows the Directional Indicator elements:

1. *Front Sector*. This shows the Current Noise Index value in the zone ahead of the helicopter (from $315°$ to $45°$).

Figure 12: PAI Directional Indicator.

2. *Right Sector*. This shows the Current Noise Index value on the right side of the helicopter (from $45°$ to $135°$).
3. *Back Sector* .This shows the Current Noise Index value in the rear zone of the helicopter (from $135°$ to $225°$).
4. *Left Sector*. This shows the Current Noise Index value on the left side of the helicopter (from $225°$ to $315°$).
5. *Lower Sector*. This shows the Current Noise Index below the helicopter (Nadir).
6. *Helicopter Symbol*.
7. *Outer Circle*. This identifies the Noise Index full scale value for all sectors except the Lower Sector.
8. *Inner Circle*. This identifies the Noise Index full scale value for the Lower sector.
9. *Operational Mode Label*. The cyan label indicates the currently active operating mode (*Ground Noise* or *Emitted Noise*).

5. TESTS ON FLIGHT SIMULATOR

The MANOEUVRES DOW includes a functional demonstration of the PAI on a flight simulator. A fully-featured PAI demonstrator has therefore been developed and integrated in a research flight simulator available at the Helicopter System Design department of AgustaWestland in order to carry out the required simulated flight test campaign.

PAI demonstrator hardware included a dedicated PC that has been integrated in the simulator environment. Input for the PAI algorithm were retrieved from the simulator real-time network, while the output was directly fed to the pilot MFD.

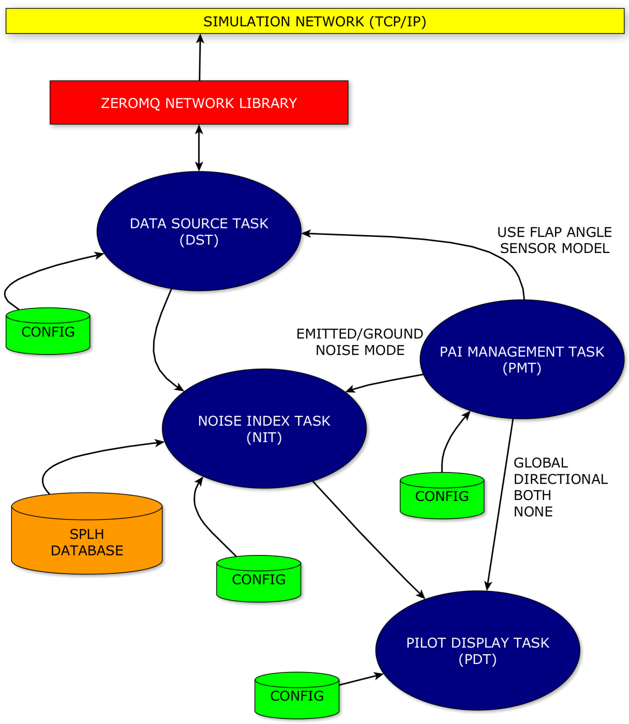

Figure 13: PAI Demonstrator software architecture.

Figure 13 shows the software architecture adopted for the PAI demonstrator. The whole functionality has been split among four co-operating tasks, communicating via TCP/IP sockets. Data Source Task takes care to retrieve from the Flight Simulator network all necessary data (boxes in green background in Figure 1), to calculate values of C_T, μ and α_{TPP} and to feed all information, including the predicted values, to Noise Index Task. The latter is in charge to generate the current and predicted interpolated SPLHs, starting from data available in the aeroacoustic database, compensate for helicopter attitude and radiate to IFG - according to the selected operating mode - and pass the set of current and predicted Noise Indexes to the Pilot Display Task, dedicated to symbols generation and display management. PAI Management Task, as the name implies, is in charge of managing the whole operations.

Final PAI demonstration is planned for Autumn 2015, and will be performed involving AgustaWestland professional test pilots that will test PAI in a number of simulated terminal trajectories.

6. CONCLUSIONS

This paper detailed the design and development of the Pilot Acoustic Indicator, an innovative instrument for the helicopter pilot capable of displaying real-time information on the current noise impact around the helicopter and on the ground, together with a prediction within a few seconds time span. Within the MANOEUVRES project WP4, currently in its final deployment, a fully functional PAI prototype has been implemented, including relevant hardware, software and pilot graphical interface, and interfaced with a research flight simulator made available by AgustaWestland.

The PAI capitalises most of the outcomes of the other MANOEUVRES WPs; it employs the aeroacoustic database produced by WP1, and uses data from the rotor state measurement system developed by WP2 and WP3. This device, capable of evaluating blade attitude angles in real time, can be considered, together with the PAI, the key enabling technology for the MANOEUVRES in-flight noise estimation system.

The availability of such a system is expected to foster the public acceptance of helicopters, since it will allow pilots to adjust, when possible, their manoeuvres in order to minimise noise emissions. Consequently, exploiting PAI indications, it will be possible to fly quieter trajectories, providing sensible benefits to the overflown communities especially when approaching or departing from helipads in densely populated areas.

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LIST OF ACRONYMS

ADC Air Data Computer

BPF Blade Passage Frequency

DOW Description Of Work

FMS Flight Management System

GRC5 Green Rotorcraft 5

H/C Helicopter

HMI Human Machine Interface

IFG Ideal Flat Ground

IRS Inertial reference System

MFD Multi-Function Display

PAI Pilot Acoustic Indicator

RA Radar Altitude

SPL Sound Pressure Level

SPLH Sound Pressure Level Hemisphere

TPP Tip Path Plane

TPP-AOA Tip Path Plane Angle Of Attack

REFERENCES

[1] L. Trainelli, A. Rolando, E. Zappa, S. Manzoni, M. Lovera, M. Gennaretti, G. Bernardini, P. Cordisco, M. Terraneo, E. Vigoni, R. Grassetti, MANOEUVRES An Effort Towards Quieter, Reliable Rotorcraft Terminal Procedures, *Proceedings of Greener Aviation: Clean Sky breakthroughs and worldwide status*, Brussels, Belgium, 2014.

[2] L. Trainelli, M. Lovera, A. Rolando, E. Zappa, M. Gennaretti, P. Cordisco, R. Grassetti, M. Redaelli, Project MANOEUVRES Towards Real-Time Noise Monitoring and Enhanced Rotorcraft Handling Based on Rotor State Measurements, *41st European Rotorcraft Forum*, Munich, Germany, 2015 (to be presented).

[3] Gennaretti M., Bernardini G., Anobile A., Serafini J., Trainelli L., Rolando A., Scandroglio A., Riviello L., Acoustic prediction of helicopter unsteady manoeuvres, *41st European Rotorcraft Forum ERF 2015*, Munich, Germany, 2015 (to be presented).

[4] ANSI S1 rev4 - Specification for sound level meters, American National Standards Institute, 1983.

[5] S. Marburg, B. Nolte, Computational Acoustics of Noise Propagation in Fluids - Finite and Boundary Element Methods, Springer, 2009.

[6] Trainelli L., Riboldi C. E. D., Bucari M., Observing the Angle of Attack of the Tip Path Plane from Rotor Blade Measurements, *41st European Rotorcraft Forum ERF 2015*, Munich, Germany, 2015 (to be presented).

[7] R. W. Sinnott, Virtues of the haversine, Sky and Telescope, vol. 68, no. 2, p 158, 1984.

[8] Advisory Circular 25-11B: Electronic Flight Displays, Federal Aviation Administration, 2014.

[9] Advisory Circular 25.1302-1: Installed Systems and Equipment for Use by the Flightcrew, Federal Aviation Administration, 2013.

[10] Certification of Transport Category Rotorcraft, Federal Aviation Administration, 2013.

[11] Standard ARP4032B: Human Engineering Considerations in the Application of Color to Electronic Aircraft Displays, SAE, 2013.

[12] Standard ARP5364: Human Factor Considerations in the Design of Multifunction Display Systems for Civil Aircraft, SAE, 2003.