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Rotorcraft Performance and Environmental Impact Evaluation by Multidisciplinary Modelling

Pierre-Marie Basset, Gabriel Reboul, Binh DangVu, Sébastien Mercier

Abstract**—**Rotorcraft provides invaluable services thanks to their Vertical Take-Off and Landing (VTOL), hover and low speed capabilities. Yet their use is still often limited by their cost and environmental impact, especially noise and energy consumption. One of the main brakes to the expansion of the use of rotorcraft for urban missions is the environmental impact. The first main concern for the population is the noise. In order to develop the transversal competency to assess the rotorcraft environmental footprint, a collaboration has been launched between six research departments within ONERA. The progress in terms of models and methods are capitalized into the numerical workshop C.R.E.A.T.I.O.N. "Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network". A typical mission for which the environmental impact issue is of great relevance has been defined. The first milestone is to perform the pre-sizing of a reference helicopter for this mission. In a second milestone, an alternate rotorcraft concept has been defined: a tandem rotorcraft with optional propulsion. The key design trends are given for the pre-sizing of this rotorcraft aiming at a significant reduction of the global environmental impact while still giving equivalent flight performance and safety with respect to the reference helicopter. The models and methods have been improved for catching sooner and more globally, the relative variations on the environmental impact when changing the rotorcraft architecture, the pre-design variables and the operation parameters.

Keywords**—**Environmental impact, flight performance, helicopter, rotorcraft pre-sizing.

I. Introduction

The rotorcraft are irreplaceable for many civil and military missions requiring VTOL, hover and low speed capabilities, for example: Emergency Medical Service (EMS), Search and Rescue (SAR), offshore missions. However, wider uses and new kind of missions still require reducing their environmental footprint and cost. On the other side, there are many rotary wing aircraft concepts, although the most well-known is the helicopter. This rich variety is nowadays extending due to the worldwide interest for Rotary Wing Uninhabited Aerial Vehicles.

Improving the tradeoff between flight performance and environmental impact is of growing interest.

Most nations are nowadays convinced that sustainable development requires limiting both Green House Gas (GHG) emissions and non-renewable natural resources consumption (fossil energy, rare minerals etc.). Reducing the noise emitted by aircraft is also of first importance. The Advisory Council for Aviation Research and innovation in Europe (ACARE) gives some targets to stimulate the research and development in these areas. The goals to be reached in 2020 with respect to 2000 are: 50% reduction of CO_2 emissions, 80% reduction of NOx and -50% of perceived external noise with -10 EPNdB per operation. The Clean Sky Joint Technology Initiative is one example of European collaborative research. Many other initiatives towards these goals exist also in other international collaborations as well as in national, companies and research institutes own programs.

At ONERA, the French Aerospace Lab, CREATION was a federative research project (2011-2014) setting up the foundations of a numerical workshop for the generation and evaluation of rotorcraft concepts [1]-[4]. Beyond the flight performance calculation, it includes the noise ground footprint and the air pollutants assessments. In order to further develop the capability to assess the rotorcraft environmental impact, a federative research axis, called RIO for "Rotorcraft Innovation Orientation", has been funded in 2015-2016. This paper summaries this collaborative work.

Before presenting it, it is worthwhile, as background, to mention other comparable initiatives like NDARC (NASA Design and Analysis of RotorCraft, [5], [6]) and EDEN (Evaluation and DEsign of Novel rotorcraft, [7]). An example of collaboration in this field between ONERA and NASA is described in [8]. Considering that in the future the rotorcraft could contribute to reduce the airport congestion thanks to their VTOL capability, more numerous and heavier rotorcraft, able to transport 90 to 120 passengers over about 1000 km, has been studied. In this assumption, the GHG emissions of rotorcraft become a significant contribution to the climate warming within the air transport impact.

The common point between these numerical tools is the use of simplified models able to provide quick and realistic answers with few inputs as required for conceptual studies. They can be qualified as "high performance models" as opposed to the "high fidelity models" in the tradeoff accuracy-fidelity/complexity-computational cost. Examples of more comprehensive models for rotorcraft simulations are the HOST [9], CAMRAD [10] or FlightLab [11] codes. They cannot directly be used in the early pre-design phase, not only because of their computational time but mainly because they require a complete set of data inputs describing the rotorcraft, which is of course not available at the stage of preliminary conception starting from scratch.

Among the differences between CREATION and the other mentioned tools, at least three can be briefly cited here. Besides the differences between the models, in CREATION special attention has been paid to the use of Multidisciplinary

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Design Optimization methods. They are applied for deriving surrogate models from databases or from the simulations by models or a chain of models with a too high computational cost. They have been also studied for solving the multi-objectives optimization problem of a rotorcraft pre-sizing, [3], [4]. A second difference is the fact that in CREATION, beyond the capability to study prescribed rotorcraft configurations (helicopters, compounds, tilt-rotors, etc.) as predefined by the engineer who wants to evaluate them, a “creation capability” has been developed in the sense that the numerical workshop is able to generate rotorcraft configurations which are not imposed by the a priori ideas of the user. For this purpose a pseudo-random rotorcraft architecture generator has been developed combining fuselage, rotor(s), propeller(s) and wing(s) with rules as safeguards for avoiding “unflyable” rotorcraft [12]. The third difference underlined here is the development and use of acoustics models for the relative comparisons of rotorcraft configurations at the early stage of preliminary conception.

Noise and air quality pollution have direct impacts on the surrounding population. Noise is surely the first main concern. Indeed, it is the most specific pollution generated by rotorcraft, especially during the landing approach, the noisy “flap-flap-flap” due to Blade Vortex Interaction (BVI), is a high acoustic signature of rotorcraft. That is why it is crucial for a better acceptance of rotorcraft to take into account and to reduce their emitted noise as early as possible in the preliminary conception.

After presenting the models and methods, the practical case of study, an urban transport mission, is described. Then the results are given for the pre-sizing of a reference helicopter and for an alternate rotorcraft reducing significantly the environmental impact, while still providing the same levels of flight performance and safety. Design trends are discussed as well as their relative comparisons.

II. Models and Methods

A. The CREATION Workshop

The clear issue addressed here is: how can be found the best suited rotorcraft concept for a kind of missions by using both flight performance and environmental impact criteria? The conservative and pragmatic approach usually applied consists in starting from the helicopter configuration and adapting its pre-design with respect to the mission requirements. The original approach proposed here is placed much more upstream in the conceptual study. It consists in exploring more widely the design space in terms of rotorcraft configurations combining rotary wings, fixed wings and propellers.

A numerical workshop has been built by ONERA for this purpose; it is named CREATION for “Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network”.

The models are organized by disciplinary modules and complexity levels. Seven disciplinary modules are the core pillars of this computational workshop. The two central modules are “Flight performance” and “Environmental impact” (Fig. 1). Around them, five “means modules” provide the required data:

- Missions & Specifications,
- Architecture & Geometry,
- Weights & Structures,
- Aerodynamics,
- Power Generation.

This “horizontal organization” in disciplines is developed in a “vertical structuration” in modeling levels in order to adapt the computation to the available data and to the requested fineness of the analysis. Four main levels of modeling have been implemented in most of the modules:

- Level 0: Response Surface Models based on databases or simulations,
- Level 1: simple analytical models based on physics,
- Level 2: more comprehensive analytical models,
- Level 3: numerical models.

The higher level models are often called “high fidelity” models. But that does not mean that the low level models are of poor fidelity. A low level model can provide more realistic results than a higher one if it is the most adapted to the available data. Indeed, the sources of uncertainties come not only from the model assumption and formulation, but also from the data inputs. Therefore, the use a complex “high fidelity” model with a lot of lacking data may give wrong results. In summary, with low level models, the goal is to obtain quickly a good assessment with the available data, whereas with the high level models, the emphasis is put on the capability to represent the physics, i.e. it is more a fidelity in capturing the underlying causes rather than a fidelity in providing the correct resulting effects.

For instance, in the module “Flight Performance”, the level 1 model is based on the power balance also called energy method. The required power (Preq) to make fly a rotorcraft at a certain flight point (depending on the gross weight, altitude, temperature, airspeed) is calculated by analytical formula for each of its components:

– Pi: the induced power for generating the main rotor thrust for compensating the weight,
– Pb: the blade airfoil mean drag power spent for overcoming their aerodynamic drag opposing to their rotation,
– Paf: the power spent for overcoming the global airframe drag in translation flight,
– Pat: the power which is spent by an anti-torque device like a tail rotor in helicopter single main rotor – single tail rotor configuration.

The level 3 of the “Flight Performance” module is based on a blade element model, i.e. a numerical discretization of the rotor blades represented by lifting line theory (as in HOST, CAMRAD or FlightLab).

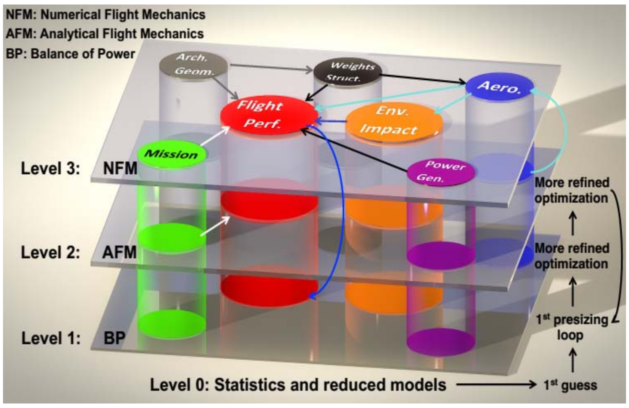

Fig. 1 Organization of the CREATION workshop in disciplinary modules and modeling levels

Examples of models have been described in previous papers [1], [2]. In recent developments some specific aircraft components are modeled like ducted fan and on-going work is focused on the aerodynamic interaction between components (rotor/rotor, rotor/propeller, propeller/wing, etc.).

Hereafter, more details are given on the models, methods and metrics for the “Environmental Impact” assessments.

B. Acoustics Models and Metrics

The acoustic model is based on the ONERA *Flap* code [13]. The *Flap* code has been developed to predict helicopter rotors noise (main rotor with emphasis on Blade-Vortex Interaction, tail rotor or Fenestron®) at early stage of development. That means that the code is fast in order to test a lot of configurations and also that the code can be run with a relative small number of input data. Those capabilities are made at the cost of simple empirical and analytical models.

Hereafter, are presented the five main subroutines of the code predictions methodology:

- **Trim** subroutine: The low frequency airloads are computed using quasi-steady linear aerodynamics including compressibility and three-dimensional corrections. The loads and the moments are adjusted with those of the flight dynamics code. In the case of a Fenestron®, the duct effect is taken into account as described in [14].
- **Wake geometry** subroutine: The whole vorticity sheet geometry is computed using a semi-empirical model based on Beddoes’ model [15].
- **BVI airloads** subroutine: The blade pressure fluctuations created by the BVI are computed using an analytical blade response function [16]. The geometry of the interactions (angles and strength) is determined by the wake geometry subroutine. These pressure fluctuations are added to the low frequency contribution computed in the trim subroutine.
- **Noise radiation** subroutine: A Ffowcs-Williams and Hawkings solver based on the PARIS code [17] is used with a compact chord approach to determine the noise radiation from the blade pressure fluctuations.
- **Empirical models** subroutine**:** Empirical models are used to compute additional complex sources such as broadband noise or compressibility effect at high speed [18].

The *Flap* code can also be chained with an acoustic propagation code (the ONERA CARMEN code [19]) based on a ray tracing approach. This chaining is done using hemispheres source corresponding to specific flight conditions. Consequently, one hemisphere can be used for several flight points allowing computing more efficiently time integrated acoustic metrics, like SEL or EPNdB, along a given trajectory.

For optimization purpose in the pre-sizing phase, the code computes the noise ground footprint on a large area for each configuration (or time step) from which an averaging of the noise level is performed to obtain a single value to be used as a criterion. In term of metrics, dB(A) are used to take into account human ear sensitivity.

The number of inputs necessary to run the code can be adjusted using additional hypothesis. When this number is low as in the framework of the CREATION workshop, it is advice to use the obtain noise levels for relative comparison. Fig. 2 shows as an example a relative comparison between 14 different rotorcrafts for the main rotor noise in a 6° approach flight. It compares the ranking obtained with the code and with certification measurements. The maximum discrepancy between measurements and prediction is equal to 3 ranks. It proves the ability of the code to distinct noisy from quiet configurations.

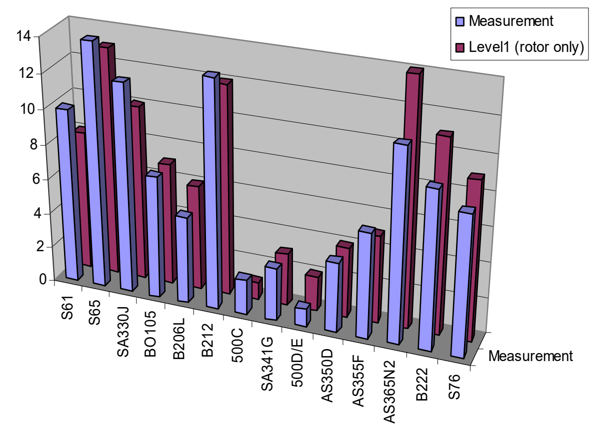

Fig. 2 Relative comparison between 14 different rotorcrafts for main rotor noise in a 6° approach flight

C. Air Pollution Models and Metrics

The air pollution has different negative impacts. The two most prominent ones are the climate warming due to the GHG and air quality degradation.

As discussed for example in [20], the contribution of the helicopters to the emission of GHG is nowadays rather small: air transportation represents 3% to 5% of the total anthropogenic GHG emissions and helicopters about 1% of that, hence about 0.04% of the total. Yet, the alarming situation has been internationally recognized (see COP-21 etc.) and any contributing sector cannot ignore this strong societal concern. The future extension of the use of rotorcraft must go hand in hand with a careful attention to the limitation of their pollution. The metric proposed in [20] is expressed in terms of: kilogram of fuel burned / hour / kilogram of useful load (on a typical mission profile at Sea-Level in standard atmosphere condition). The interesting point of this metric is that it takes into account the specificities of helicopter missions. In order to capture the uniqueness of rotorcraft operations for hover and low speed typical missions, it is proposed to adopt a time-based metric (typically hourly fuel consumption) rather than a distance-based metric more adapted for airliners. A drawback of this metric is that it reduces the air pollution assessment to the quantity of fuel burnt and in a certain extent to the Direct Operating Cost. The CO_2 emissions are directly proportional to the quantity of fuel burnt. Indeed, if the combustion is considered as complete, these two quantities are connected by a stoichiometric relationship giving a direct proportionality dependency:

$$\text{Quantity of } CO_2 \text{ emitted} \cong 3.15 \text{ x quantity of consumed fuel}$$

Therefore, all efforts for reducing the CO2 emissions will be directly beneficial to the reduction of fuel consumption and reciprocally. But the assumption of complete combustion by turboshaft engines should be examined more closely taking into account the flight conditions (altitude and temperature) as well as the engine regime. Other pollutants contributing climate warming must be considered, like NOx.

In the previously evoked assumption of using more and more heavy rotorcraft as a complementary means for passengers transportation [8], another example metric is considered, the Average Temperature Response (ATR). This metric uses an altitude sensitive climate model and take into account the life duration of each of the pollutants.

A more direct impact of the emitted pollutants is the effect on the quality of the air that we breathe. Helicopters have many missions with long phases in hover and low speed, at low altitude or low height above the population. The will to extend the produced services by the rotorcraft to the community and especially the missions closed to the population, requires a careful attention to air pollution. In Europe, 93% of people are exposed to air pollution levels above the recommended thresholds by the World Health Organization (WHO, [21]). It is now recognized that it causes many diseases and not only to the human respiratory system. For example, fine Particulate Matters (PM2.5 have a size below 2.5 μm) can go across our different physiological barriers and reach the brain contributing to some neuro-degenerative diseases (e.g. Alzheimer, Parkinson). The WHO air quality guidelines (AQGs) are given in terms of concentration for a certain pollutant over a period. For example for PM2.5: 10 $\mu g/m^3$ annual mean, 25 $\mu g/m^3$ 24-hour mean. A proposed metric would be to assess the percentage of contribution of a certain source of pollution (say a kind of helicopter operation) on the concentration of a pollutant over a period corresponding to the considered threshold.

Whatever the considered environmental impact, the quantities of emitted pollutants must be first assessed. In CREATION, these quantities of air pollutants are calculated by the "Power Generation" module from the fuel burnt based on the experimental results and statistical expressions given in [22].

D. Life Cycle Analysis

The objective of this part of the project is to evaluate more widely the environmental impact of the rotorcraft than was previously done in CREATION. The aim is to evaluate the global environmental impact of the rotorcraft including all steps of its life, from its manufacturing to its end of life, and considering different all aspects of environmental impacts like Global Warming, toxic emissions, or mineral resources depletion. To do so, the Life Cycle Assessment (LCA) methodology has been carried out with output data coming from the CREATION model. This methodology is used to convert design data (mass, constitutive materials etc.) and fuel consumption into environmental impacts with the help of environmental data bases available in the literature. Based on the well-recognized ReCePi method [23], seven different environmental impacts categories are considered here: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Abiotic Depletion of non-fossil resources (ADP-non fossil) and Abiotic Depletion of fossil resources (ADP-fossil).

Each impact category is evaluated on each step of the rotorcraft life cycle, considering four main phases: the extraction of the needed materials, the manufacturing of the rotorcraft, the use of the rotorcraft and finally, its end of life.

The life duration of the rotorcraft is assumed to be 40 years with an exploitation hypothesis of five missions per day with 200 days per year of exploitation. The results are presented in equivalent emissions per passenger and per mission. This methodology is therefore useful to evaluate the influence of the design options on the different environmental impacts including all the steps of the rotorcraft life cycle, from its manufacturing to its end of life, pointing out the most dominant polluting phases and revealing the possible transfer of impacts from one phase to another. Hence, the LCA is required for finding the best compromise in order to optimize the design of the new rotorcraft with a global environmental footprint decrease objective.

III. Practical Case of Study

A typical case of missions for which the environmental impact has strongly limited the use of rotorcraft is the case of urban missions. Moreover it has a great potential of applications both for inhabited or unmanned aircraft systems. Therefore it is interesting to develop our numerical means of investigation (models and methods) for the practical case of an urban transport mission.

In order to deal with a concrete case, an example of transport mission has been defined: transport 15 passengers from the Charles de Gaulle airport (CDG) until the Paris/Issy-les-Moulineaux heliport and return to the same airport with the same number of passengers. Accounting for 100 kg per passenger, the payload is 1,500 kg. The rotorcraft must be of category A for being able to go on a take-off or landing with an engine failure. A rotorcraft with two engines is therefore considered.

The commercial flights over Paris "intramurals" are not allowed (restricted to EMS, governmental or exceptional cases). Therefore, the way points of the mission have been defined such that the rotorcraft flies over the roads at the urban periphery of Paris (Fig. 3). The advantage of this constraint is that the ground noise footprint emitted by the rotorcraft is immerged in this already noisy environment due to the high traffic of ground vehicles on these peripheral roads.

The mission profile has two different cruise phases due to different flying rules in terms of altitude over Roissy (1600 m) and Paris (450 m), as shown on Figs. 4 and 5. Knowing that the average ground altitude of Issy is about 100 m, the height above the ground for the cruise phase over the Paris peripheral ("cruise 2") is 350 m. This is a rather short mission in terms of distance around 80 km (two times about 39 km). The cruise speed has been first fixed to Vh= 60 m/s. After the pre-sizing for this nominal mission, further comparisons have been done for higher cruise distances and speeds.

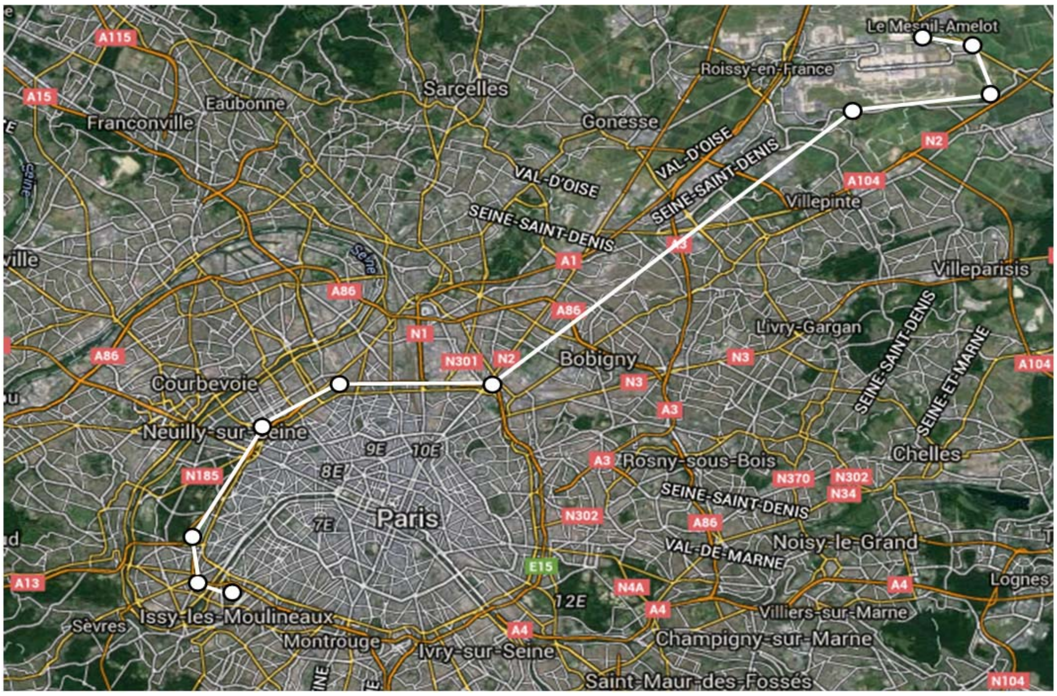

Fig. 3 Overview of the waypoints of the example urban transport mission between Roissy – Charles de Gaulle airport and the Paris heliport near Issy les Moulineaux

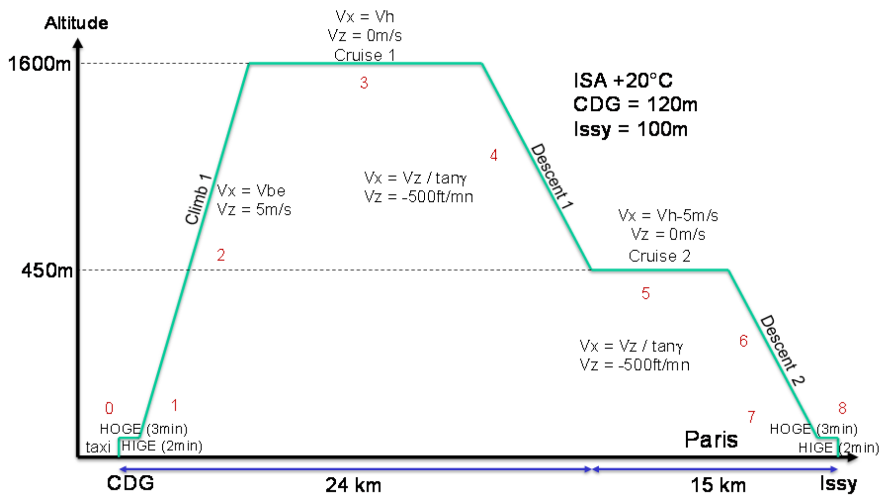

Fig. 4 Mission profile from CDG airport to Issy heliport

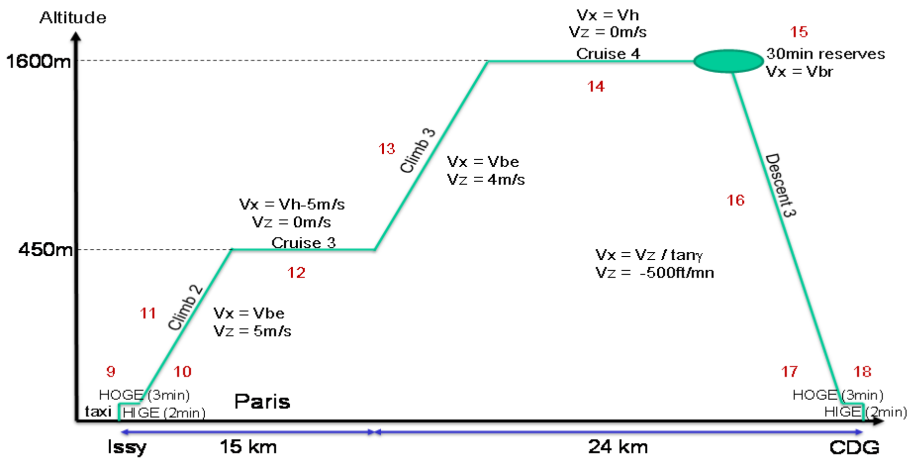

Fig. 5 Mission profile from Issy to CDG (including the reserves for the calculation of the required fuel)

Two options have been studied for the slope of descent: a classical one at 6° and a steeper one at 9° for reducing the noise ground footprint level. An example of 3-D mission profile for the case at 9°of descent slope is presented on Figs. 6, 7. The 34 numbers correspond to the discretization points, i.e. the flight points where the computations have been performed for describing the mission. For example on Fig. 6, the point 13 is at the middle of the landing approach on Issy heliport. The point 28 on Fig. 7 is the one for taking into account the reserve of fuel. Notice that due to this mandatory fuel reserve (30 minutes of flight), the fuel weight onboard for the mission is higher than the effective fuel burnt which is the one to account for the emitted air pollutants.

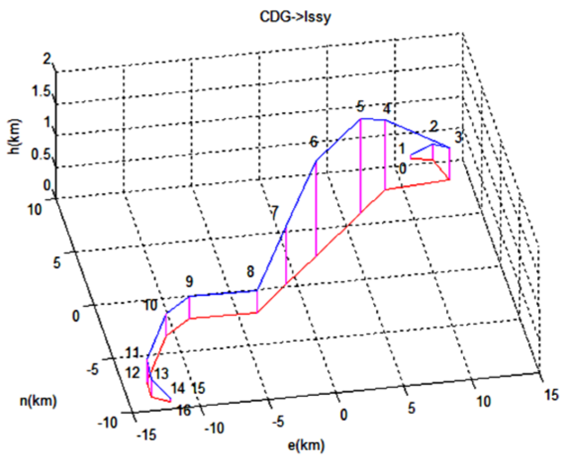

Fig. 6 3D mission profile from CDG to Issy

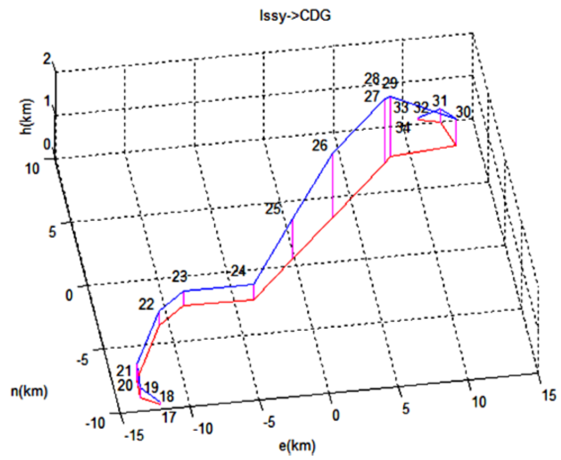

Fig. 7 3D mission profile from Issy to CDG

IV. Pre-Sizing of a Reference Helicopter

The pre-sizing has been performed with the CREATION numerical workshop. It includes three main loops:

- One on the design variables: main rotor disk loading (MS in kg/m²), blade tip speed due rotor rotation (Umr in m/s), two different blade geometries, two different slopes of descent;
- For each set of these design parameters, a loop is performed until the convergence on the gross weight;
- The most internal loop is the one on the whole mission profile (i.e. the computation for each of the 34 flight points) in order to assess the required fuel weight besides performance and environmental criteria.

Two different helicopters have been pre-sized for this mission:

- A *"basic helicopter"* in the sense that it corresponds to current technologies and pre-sizing method. It uses standard rectangular blades (represented by a rotor analytical polar derived from HOST computations of the EC225 helicopter), a classical blade tip speed (Umr = 210 m/s) and a standard slope of descent of 6 deg. Its pre-sizing has been done by minimizing its weight, leading to a gross weight of 3394 kg for a main rotor disk loading of 30 kg/m².

- A *"reference helicopter"* meaning that it represents the best achievable, with up to date best technologies for minimizing the environmental impact and especially the noise. It uses Blue-Edge© blades [24], [25] which have advanced blade geometry with a double sweep shape at the tip for reducing the noise caused the Blade Vortex Interaction (BVI). The slope of descent has been set at 9°, as the example of typical noise abatement landing procedure (except for the comparisons in Table I where the design slope is 6° for both helicopters). Its pre-sizing has been performed by optimizing the disk loading (MS) and the blade tip speed due to rotation (Umr) such that a global criterion, including both the gross weight and the acoustic nuisance, is minimized.

Hereafter, this pre-sizing process and results are summarized.

TABLE I
BASIC HELICOPTER AND REFERENCE HELICOPTER PRE-SIZED WITH 6°OF SLOPE OF DESCENT

	Basic Helicopter	Ref. Helicopter
Main rotor blades b	5	5
Main rotor radius R	6 m	6 m
Blade mean chord c	0.33 m	0.33 m
Blade tip speed Umr	210 m/s	170 m/s
Wmto	3394 kg	3380 kg
Wempty	1661 kg	1661 kg
Wfuel	233 kg	219 kg
dBA13 (slope 6°)	62.4 dBA	57.6 dBA

For the sake of simplicity, the number of blades *(b)* of the main rotor is fixed to five, the tail rotor is a Fenestron® (i.e. a ducted fan both for safety and acoustic reasons), the helicopter is equipped with two turbine engines pre-sized within the pre-sizing loops, the main rotor blade aspect ratio (radius/chord, R/c) is fixed to 18 for respecting structural constraints.

For "pre-sizing quickly" the two helicopters (basic and reference ones), the main rotor solidity σ, i.e. the ratio of the surface of the blades over the rotor disk surface, is thus fixed:

$$\left.\begin{matrix} b = 5 \\ \frac{R}{c} = 18 \end{matrix}\right\} \Rightarrow \sigma = \frac{b.c.R}{\pi.R^2} \cong 0.08842$$

Sweeps are performed both on the main rotor blade tip speed due to rotation (Umr= Ω.R) and on the main rotor disk loading (MS= gross weight/disk Surface = Wmto/(π.R²)).

For each set of the design variables (MS, Umr), a convergence loop on the gross weight is performed. From a first estimate of the weight, the engine sizing requirements in terms of maximum power demand are calculated in Hover Out of Ground Effect (HOGE), in forward flight and in the most demanding One Engine Inoperative (OEI) case. Internal pre-sizing loops within the turbine engine model are performed giving its sizing characteristics (e.g. sizes and weight) and performance (e.g. specific fuel consumption). Once the engine system is sized, the loop over the entire mission profile (including reserve) is done for calculating at each of the 34 flight points: the fuel consumption, the emitted air pollutants, the mean noise level on the ground footprint. After this loop on the mission profile, the weight breakdown model computes the weights of the different helicopter components and provides a new estimation of the total gross weight consistent with the previous sizing results. This sizing loop is performed until the convergence on the gross weight giving a helicopter sizing *weight consistent* for a certain set of the design parameters.

For the *basic helicopter*, the blade tip speed Umr being fixed at a classical value of 210 m/s, the optimum value of the disk loading minimizing the weight is about: MS=30 kg/m². The gross weight is then 3394 kg.

For the *reference helicopter*, double sweeps have been performed on (MS, Umr). The objective criteria are to minimize both the gross weight (Wmto) and the emitted noise during the landing approach (dBA13). This noise criterion is calculated at the middle of the landing approach (flight point 13 with a height above the ground about 273 m) as being the average noise level in dBA over the noise ground footprint. A global criterion or *performance index J* is defined by normalizing each criterion and taking the following sum:

$$J = \frac{1}{2}\left[\left(\frac{Wmto}{Wmto_{Max}}\right)^2 + \left(\frac{dBA13}{dBA13_{Max}}\right)^2\right]$$

An example of illustration of the results is presented in Fig. 8.

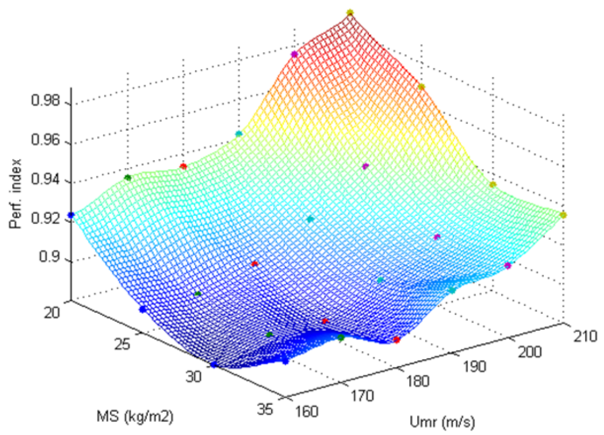

Fig. 8 Global criterion J (Perf. index) resulting from pre-sizing results for a double sweep on (MS, Umr) for the reference helicopter case

The minimum of J is obtained for (MS=29.46 kg/m², Umr=160 m/s). However, for this design point the blade mean lift coefficient *Czm* is 0.7 in HOGE which is too high for warranting enough maneuverability in hover and low speed flights. Therefore, a higher blade tip speed of 170 m/s is preferred giving a *Czm* closer to 0.6 in HOGE at maximum take-off weight. Hence a good compromise between flight performance, low environmental impact and safety margin is chosen for the reference helicopter HO15 at (MS=30kg/m², Umr=170m/s).

An example of results in terms of emitted noise over the flight points of the mission profile is presented on Fig. 9. The noise levels (in dBA) are compared for the basic helicopter (in blue) and for the reference helicopter HO15 operating with two different slopes of descent 6° or 9°. The reference helicopter is about -4.8dBA less noisy than the basic helicopter thanks both to a lower rotation speed and to advanced blade geometry reducing the BVI. Of course the differences due to the slope of descent appear only for the flight points on descents. The further reduction of noise due to the steeper approach is about -1.5dBA in the reference helicopter case HO15. Notice that the steeper approach reduces also the noise exposure level and that more complex noise abatement procedure such as decelerated flight can go beyond in terms of the reduction of the noise resulting on the ground.

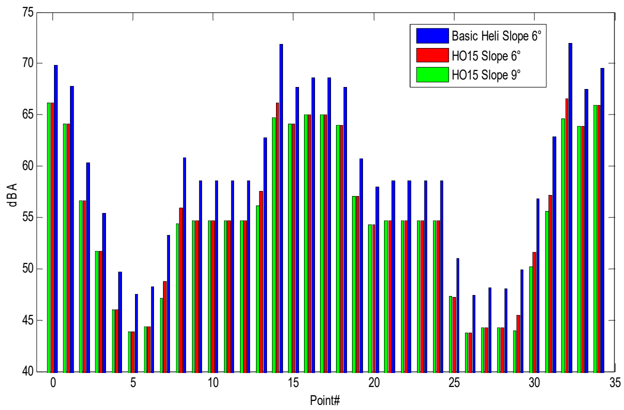

Fig. 9 Average noise level on the ground for the basic helicopter and the reference helicopter (HO15) with a slope of descent of 6 or 9 deg

V. Pre-Sizing of an Alternate Rotorcraft

The goal is to propose an alternate rotorcraft concept for this urban transport mission with a significant reduction of the environmental impact and with the same level of flight performance and safety.

The field of possible solutions depends on the time horizon considered in terms of future technologies. Very futuristic innovating concepts promising high gains can be imagined. Yet, a safeguard constraint is here to be able to compare the results by using calculation models of same degree of maturity as the ones used for the helicopter case. The exercise is thus to study if significant environmental impact reduction can be reached without a strong gap between the technologies used for this alternate concept and for the reference helicopter HO15 case. By this way, the same pre-sizing and evaluation models can be applied, thus allowing a good consistency and reliable relative comparisons.

One example of alternate concept is presented hereafter (Fig. 10). It is a tandem twin rotor configuration with optional auxiliary propulsion which can be a rim driven electric ducted fan. The first intended idea behind this configuration is that lift and propulsion are independent in order to dissociate the aircraft pitch attitude, the rotor angle of attack and the slope. The airframe pitch attitude should be closed to zero for the comfort of the passengers, whereas the slope of descent must be steep and adjustable for reducing the BVI and the ground noise footprint.

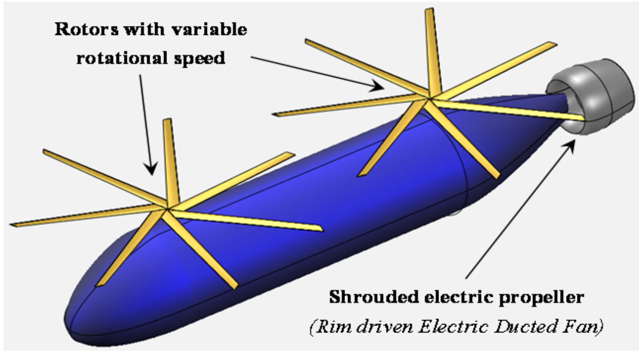

Fig. 10 Draft scheme of alternate concept

Examining the longitudinal equilibrium of this configuration, the forces are drawn on Fig. 11 with the simplifying assumption that the total drag force is applied at the center of gravity G. The forces are this global drag $\vec{D}$, the weight $\vec{W}$ and the rotor thrusts: $\vec{T_f}$ for the front rotor and $\vec{T_r}$ for the rear rotor. The pitch attitude is noted θ, the angle of attack is α, the slope γ, θ_f and θ_r are respectively the longitudinal tilt angles of the front and rear rotors.

Writing the longitudinal equilibrium of the forces ("propulsion – drag" and "lift – weight" equations) and of the pitching moments (see on Fig. 11) provide three equations under which are shown the sign (positive or negative) of the different terms. Assuming that the propulsive force $\vec{F}$ produced by the rear ducted fan is aligned with the aircraft longitudinal axis and the total drag $\vec{D}$ is applied at the center of Gravity, the only remaining positive moment (pitch-up) is produced by the front rotor as can be seen on the pitching moment equilibrium equation. The tandem configuration is thus able to fly at zero pitch attitude in hover or in forward flight, whereas a helicopter having only four controls (three for the main rotor and one for the tail rotor) for 6° of freedom, the helicopter pitch and roll angles cannot be set at zero, whatever the airspeed.

The interest of the rear auxiliary propulsion is of course mainly to unload the rotors of all or part of their propulsive contribution (see "propulsion – drag" equation on Fig. 11). A simple analytical solution can be obtained by adding two equations to this problem. By definition: $\theta = \alpha + \gamma$. So, let us consider the case at zero pitch attitude (preferred case for the comfort of passengers): $\alpha = -\gamma\ (\theta = 0)$ and assuming that both rotors have the same tilt angle:

$$\theta_f = \theta_r = \theta_{rot}$$

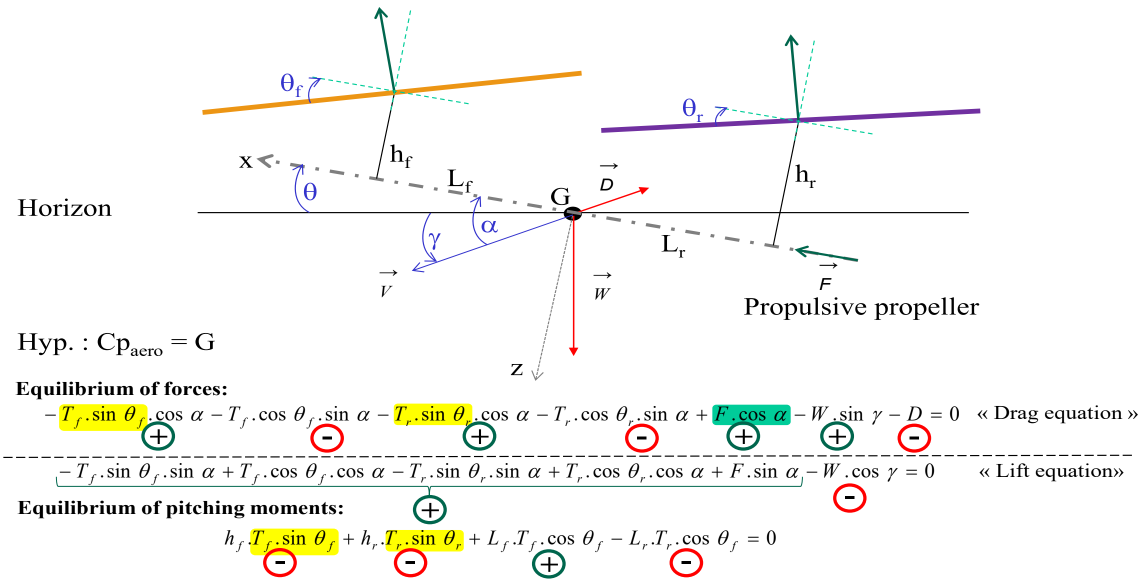

Fig. 11 Scheme of the longitudinal equilibrium

Dividing the drag equation by the lift equation provides the relationship:

$$\tan(\alpha+\theta_{rot}) = \frac{F.\cos\alpha - W.\sin\gamma - D}{-F.\sin\alpha + W.\cos\gamma}$$

Assuming that α and γ are small angles, it can be simplified into:

$$\theta_{rot} \cong \frac{F-D}{W}$$

Showing that the propulsive force F could decrease or even make null the rotors longitudinal tilt angles (F=D => θ_{rot}=0).

Yet the acoustic model used here does not take into account for the aero-acoustic interaction between the rotors. Therefore, the interest of keeping θ_{rot} close to zero for avoiding the BVI between the rotors is not captured. On the contrary, the present acoustic model version predicts a resulting noise on the ground stronger because the rotors wake skew angles are reduced when θ_{rot} is null. Moreover, the auxiliary propulsion induces different penalties, i.e. additional weight, drag and cost (both for the conception and maintenance). Therefore, the following study has been done with *a tandem twin rotor configuration without auxiliary propulsion* (*F=0*). In that case, the propulsion is insured by tilting forward the rotor thrusts. The rotors being identical counter-rotating rotors, the yaw equilibrium (torque compensation) means that the thrusts are nearly the same. Thus, the pitching moment equilibrium (see Fig. 11) is obtained by reducing the front rotor tilt closed to zero ($\theta_f \cong 0$) which is in practice positive for reducing the front rotor wake interference on the rear rotor. As sketched in Fig. 12, the drag of the rotors pylons, masts and hubs generate significant drag above the center of gravity contributing to the pitching up moments and hence reducing the difference between the rotors tilt angles.

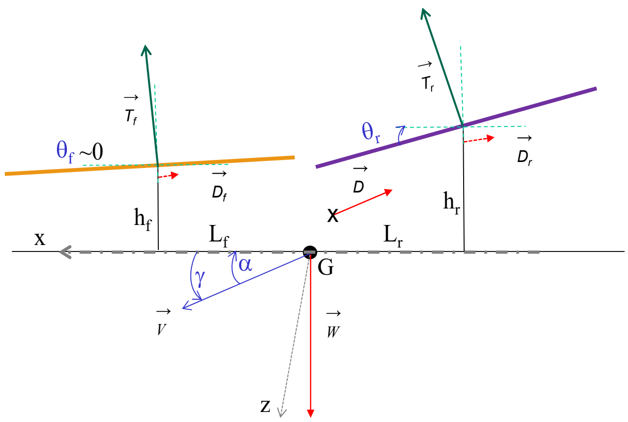

Fig. 12 Scheme of the longitudinal equilibrium for the tandem

The tandem rotor configuration is less demanding than a helicopter one in terms of required power mainly in hover and low speeds for three reasons. First, because there is no need of an anti-torque system, therefore all the useful power is available for lift and propulsion (the tail rotor in hover required about 12% of the total power). Second, because the induced power is reduced when the lift demand is shared between several lifting rotors instead of one. The theoretical induced power in the momentum theory for one rotor of surface S (S= π.R²) developing a thrust T is:

$$Pi_{1rotor} = \frac{T^{3/2}}{\sqrt{2.\rho.S}}$$

For two isolated rotors of the same surface S developing half of the thrust demand, the induced power is smaller:

$$Pi_{2rotors} = 2 \times \frac{(T/2)^{3/2}}{\sqrt{2.\rho.S}} = \frac{T^{3/2}}{2.\sqrt{\rho.S}}$$

Thus:

$$Pi_{1rotor} = \sqrt{2} \times Pi_{2rotors} \cong 1.414 \times Pi_{2rotors}$$

Of course, when the two rotors are one above the other, as in the coaxial case, they induce velocities on each over increasing the induced power. Fig. 13 derived from [26], shows the overlap interference factor *Kov* variation with the horizontal hub spacing d/D (D is the rotor diameter) and for different vertical separations. *Kov* is the ratio between the induced power for the two rotors and double of the induced power of one isolated rotor for the same thrust in hover. A positive effect of the interference appears when d/D is closed to one because of the upwash induced by a rotor near its external periphery, thus reducing the induced downwash through the other rotor. So, a third positive effect in the power reduction is obtained by choosing a d/D just above 1, a few percentages more for the blade tip clearance between the two rotors. A reduction of about 4% compared to the case of two isolated rotors is thus obtained: Kov=0.96.

A drawback of the tandem configuration concerning the power required is the higher aerodynamic drag due to the two rotor pylons, masts, heads and hubs and sometimes to a longer fuselage. The drag penalty has been taken into account by considering that the tandem has 50% more drag than the HO15 helicopter.

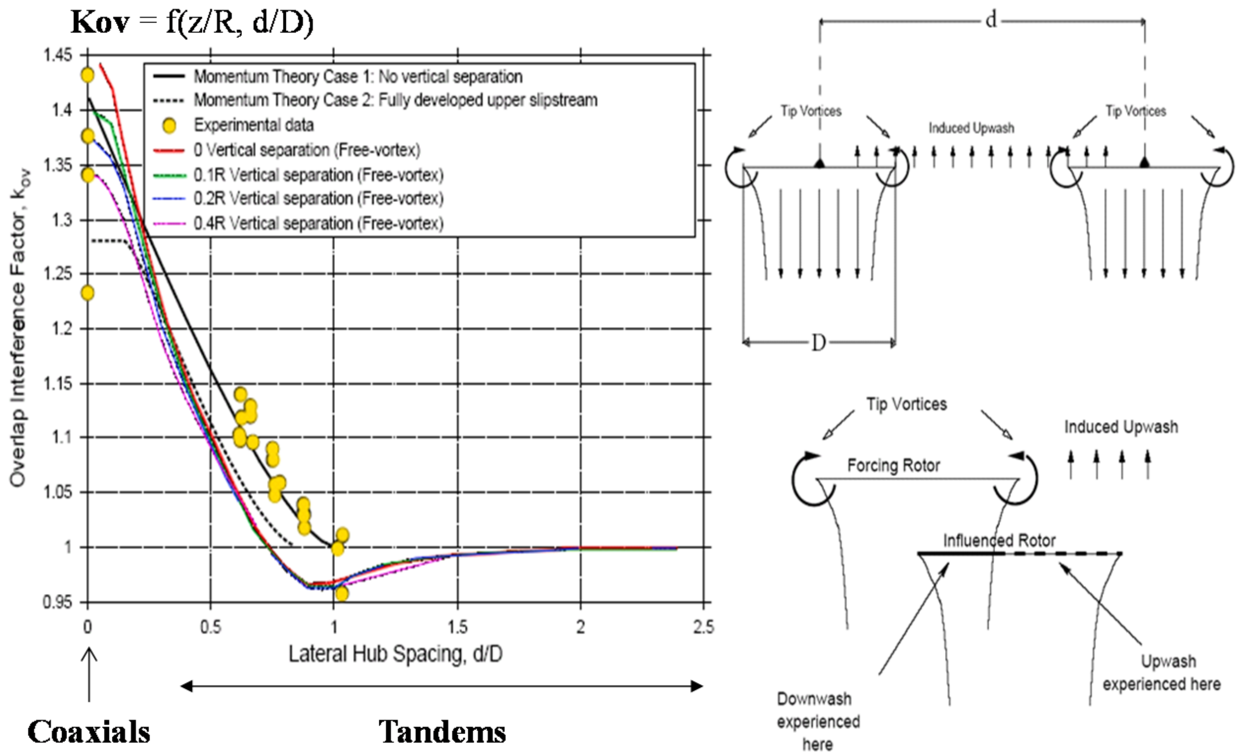

Fig. 13 Overlap interference factor Kov for dual rotor configuration [26]

A. Fixed Number of Blades and Rotor Solidity

First, for each of the rotor of the tandem, the same number of blades as for the helicopter HO15, i.e. 5, is considered, and thus, each of the rotors has the same rotor solidity as the helicopter main rotor (σ = 0.08842) since the blade aspect ratio stays fixed (R/c=18).

Applying the same pre-sizing method as for the helicopter, a double sweep on the two main design parameters, i.e. rotor disk loading (MS) and blade tip speed due to rotation (Vtip=Umr), is performed. As before, the three main criteria are: the mean noise level on the ground during the landing approach (dBA13), the required fuel weight for the all mission (including reserve) Wfuel and the margin of blade mean lift coefficient Czm with respect to the maximum acceptable values in hover and in forward flight. A good compromise is obtained for: MS=20 kg/m² and Umr=140 m/s.

The resulting tandem (XO15-5) has two smaller rotors than the helicopter: R=5.47m, c=0.30m. The fuselage length can be kept to 15 m as for the HO15. The rotors being unloaded (MS=20 kg/m² instead of 30 kg/m² for the HO15), the blade rotational speed can be reduced (Umr=140m/s instead of 170m/s). Thus, the noise level decreases (dBA13 = 53.2 dBA), and despite that the rotorcraft is heavier (Wmto=3751 kg), the required fuel weight decreases (Wfuel=203kg) and with it, also the air pollution. That is due to the reduction of the power demand. Indeed the chosen tandem configuration provides a decrease in the induced power, as explained previously, and the significant reduction of the rotors rotational speed decreases the blade mean drag power.

B. Results with Unfixed Number of Blades and Solidity

Another pre-sizing has been performed considering as extra free design parameter the number of blades (b, the same for each rotor). Using the same pre-sizing method and criteria, the best compromise has been found for the case of seven blades. The results are given in Table II.

TABLE II
PRE-SIZING RESULTS

	HO15	XO15-5	XO15-7
Number of rotor blades b	5	5	7
Main rotor radius R(m)	6	5.47	7
Blade mean chord c(m)	0.33	0.30	0.39
Blade tip speed Umr(m/s)	170	140	110
Disk loading MS (kg/m²)	30	20	15
Fuselage length (m)	15	15	18
Wmto (kg)	3411	3751	4639
Wempty (kg)	1677	2048	2913
Wfuel (kg)	233	203	226
dBA13 (dBA)	56.1	53.2	48.7
Noise difference (dBA)	-2.9		-4.5

VI. RELATIVE COMPARISONS

A. For the Fixed Nominal Mission

Once again, the philosophy here is to draw the design trends more from the relative comparisons than from the absolute values. From Table II, it can be seen that the XO15 with five bladed rotors (XO15-5) is about 3 dBA less noisy (half as noisy) than the reference helicopter and needs 30kg less of fuel. XO15-7 (7 bladed rotors) is even less noisy (-4.5 dBA) than the XO15-5.

With the XO15-7, the reduction of noise is pushed further thanks to a stronger decrease of the rotors disk loading: MS is divided by two with respect to the HO15 by using not only two lifting rotors, but also more blades and bigger blade surface while keeping a reasonable fuselage length for 15 passengers. By this significant unloading, the rotors rotational speed can be even further reduced and thus the noise. The counterpart is that the rotors being bigger, and hence, also the fuselage (+3 m), the empty weight is heavier resulting in a required fuel weight closer to the HO15 case although lower. Therefore, the XO15-7 is the least noisy configuration (see Fig. 14), whereas the XO15-5 is the best compromise considering not only the noise, but also fuel consumption, and hence, air pollution (see the comparisons on the required power in Fig. 15).

B. For Different Ranges and Cruise Speeds

Considering that the alternate concept XO15-5 is less demanding in terms of fuel, the question addressed here is to determine if it is only the case for a mission like the nominal one with more hover and low speed than cruise flight phases.

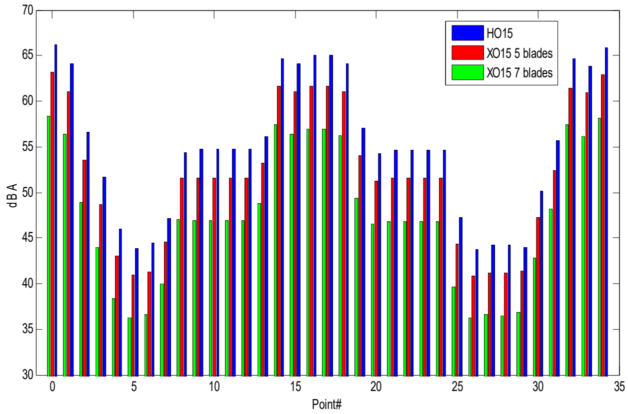

Fig. 14 Comparisons of the noise emitted on the ground by HO15, XO15-5, XO15-7 for each flight point

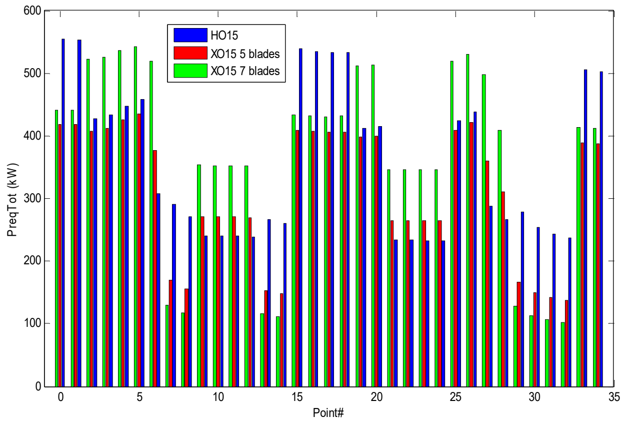

Fig. 15 Comparisons of the required power by HO15, XO15-5, XO15-7 for each flight point

Here, the interest of a variable rotor rotational speed is underlined. Indeed, in hover and low speed flights (as for the landing approach), the reduced rotation speed for decreasing the noise is considered (Umr=140 m/s), whereas in cruise flight, the blade tip speed is here kept at the value of the reference helicopter (Umr=170 m/s), otherwise the advance ratio (μ=Vcruise/Umr) will be too high preventing exploring the same range of cruising speeds.

Double sweeps have been done both on the cruise distance (the double of the range) and on the cruise speed:

$$\text{Dcruise (km)} \in [80 \text{ to } 1600], \text{Vcruise(km/h)} \in [220 \text{ to } 320]$$

The results show that even for such missions with a longer range and a higher cruising speed, the tandem configuration XO15-5 is still requiring less fuel than the reference helicopter. At least for the cruising speeds tested (Vcruise ≤ 90 m/s = 320 km/h), the configuration is more efficient. Its lifting efficiency compensates its higher aerodynamic drag.

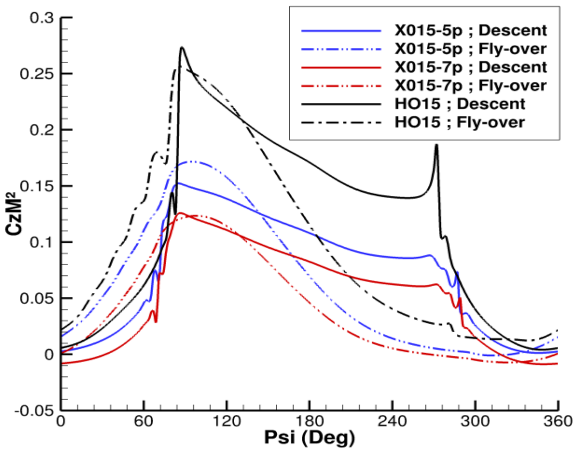

Fig. 16 Lift force coefficient at r/R =0.86 (Cz is the local lift coefficient, M is the local Mach number, Psi the blade azimuth angle)

C. Focus on Acoustics

Fig. 16 presents the normal force coefficient on the blade at a radial station of r/R =0.86 in descent and fly-over for the three considered configurations. All flight cases are free from strong BVI interactions. Consequently, the main contributions come from broadband and loading noise. Yet, HO15 shows the strongest interactions, including some small interactions in advancing side (between 0° and 180°) during fly-over. It also has the strongest loading justifying the highest noise level. On the other hand, XO15-7 has the smallest loading and interactions. This absence of strong blade-vortex interaction is mainly due to the use of a steep approach angle (9° instead of the more conventional 6° angle). Consequently, the wake is quickly convected above the rotor reducing the numbera of possible interactions with the following rotating blades.

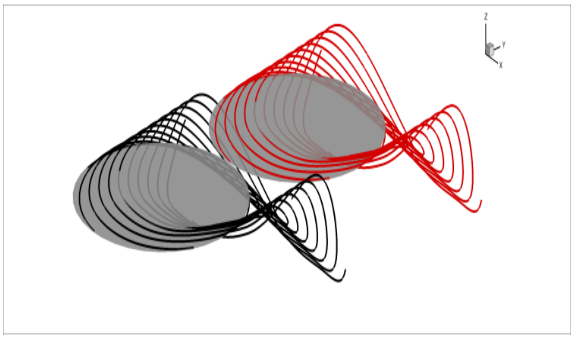

Fig. 17 Tip vortex geometry predicted by the noise module for the XO15-5 tandem in approach

The present acoustic model is not able to take into account possible interactions between rotors. However, it has been checked that there is no such noisy interaction in the case of the tandem rotorcraft. The tip vortex trajectories for the XO15-5 are presented in Figs. 17 and 18, respectively, for the descent and the fly-over flights. In both cases, both rotors seem independent, i.e. their blades do not cut the wake of the other rotor.

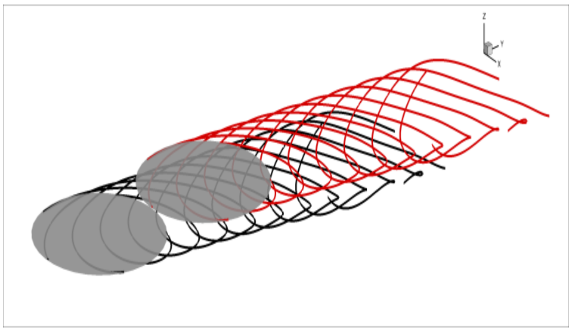

Fig. 18 Tip vortex geometry predicted by the noise module for the XO15-5 tandem in fly-over

D. Focus on Life Cycle Analysis

A first Life Cycle Assessment (LCA) is carried out on the reference HO15 rotorcraft. The aim is to identify the main environmental impacts and the main impacting phases of the rotorcraft life cycle. The results of the seven different environmental impacts considered here (GWP, ODP, AP, EP, POCP, ADP non-fossil and ADP fossil) on the four phases of the life cycle of the HO15 helicopter (production of materials, manufacturing of the rotorcraft, use and end of life) have been evaluated. The typical results obtained on the global environmental footprint of the HO15 are presented in Table III. Notice that the results are normalized per passenger and per mission, and that the impacts of the entire life cycle are the sum of the impacts of all the phases of the life cycle.

It can be noticed (Table III) that the *use phase* represents by far the main impacting phase of the life cycle. Indeed, the *use phase represents more than 99% of the total impacts* for six of the seven studied environmental impacts (GWP, ODP, AP, EP, POCP and ADP fossil). This confirms the results generally obtained for transportation products which consume fuel and produce the main pollutions during the use phase because of combustion emissions. However, it can be noticed that the material production phase represents a significant part of ADP non-fossil impact because of mineral resources consumed for the rotorcraft production. Indeed, the material phase represents more than 20% of the ADP non-fossil impact of the HO15. From these first results, it clearly appears that the fuel consumption reduction represents the main key point for the rotorcraft global environmental impact reduction, and thus, the main driving force for the XO15 design combined with noise reduction. The use of light materials and the reduction of power demand were therefore the main objectives of the XO15 new rotorcraft design.

In order to quantify the environmental benefit of the new design, a comparative LCA has been performed between the HO15 and the optimized XO15-5. The comparative LCA consists in carrying out the LCA of the XO15 and then calculating the relative differences of each environmental impact for each phase of the life cycle in order to quantify the relative variation of the environmental impacts induced by the new design. The relative variations of the impacts are calculated with the formulas:

$$\%RV(impact\ \ i, phase\ \ j) = \frac{(impact\ \_XO15(i,j) - impact\ \_HO15(i,j))}{impact\ \_HO15(i,j)}$$

$$\%RV\ \_total\ impact(i) = \frac{(total\_impact\_XO15(i) - total\_impact\_HO15(i))}{total\_impact\_HO15(i)}$$

with "*%RV*", the Percentage Relative Variation.

The comparative LCA results are presented in Table IV. Notice that the last line of Table IV represents here the relative variation of the environmental impacts on the entire life cycle and is consequently not the sum of the values of all the phases (see above "*%RV_total impact(i)*" expression).

From a general point of view, it can be seen that the new design enables a reduction of about 18% of the total environmental impacts, whatever the considered impact category. This result is directly linked to the 18.4% reduction of fuel consumption induced by the new design. Indeed, the use of two slowed rotors highly reduces the needed power, reducing the fuel consumption despite the 10% mass increase of the rotorcraft induced by this twin-rotor configuration.

TABLE III
EQUIVALENT EMISSIONS OBTAINED FOR GLOBAL WARMING POTENTIAL, OZONE DEPLETION POTENTIAL, ACIDIFICATION POTENTIAL, EUTROPHICATION POTENTIAL, PHOTOCHEMICAL OZONE CREATION POTENTIAL, ABIOTIC DEPLETION FOR NON-FOSSIL AND FOSSIL RESOURCES FOR THE HO15 HELICOPTER

Metrics	GWP	ODP	AP	EP	POCP	ADP (non-fossil)	ADP (fossil)
Phases	kg CO_2 eq.	kg CFC-11 eq.	kg SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ
Material	5,72E-01	7,08E-07	5,74E-03	5,02E-04	2,18E-04	1,02E-05	1,18E-02
Manufacture	3,23E-02	3,66E-09	1,37E-04	1,59E-05	6,00E-06	6,37E-09	4,84E-04
Use	5,21E+02	9,67E-05	8,10E-01	7,48E-02	4,84E-02	4,15E-05	7,39E+00
End Of Life	-2,20E-01	-2,06E-08	-4,47E-03	-1,29E-04	-1,89E-04	-1,95E-06	-3,22E-03
Entire Life Cycle	5,22E+02	9,74E-05	8,12E-01	7,52E-02	4,84E-02	4,97E-05	7,40E+00

Results are shown in units per passenger and per mission.

TABLE IV
COMPARATIVE LCA RESULTS OF THE XO15-5 ROTORCRAFT IN RELATIVE VARIATION OF IMPACTS COMPARED TO THE REFERENCE HO15 HELICOPTER

Metrics	GWP	ODP	AP	EP	POCP	ADP (non-fossil)	ADP (fossil)
Phases	kg CO_2 eq.	kg CFC-11 eq.	kg SO_2 eq.	kg PO_4 eq.	kg C_2H_4 eq.	kg Sb eq.	MJ
Material	14,7%	5,6%	-1,1%	5,5%	-0,3%	-12,5%	28,9%
Manufacture	20,7%	20,7%	20,7%	20,7%	20,7%	20,7%	20,7%
Use	-18,4%	-18,4%	-18,4%	-18,4%	-18,4%	-18,4%	-18,4%
End Of Life	18,5%	17,3%	-7,6%	12,4%	-4,2%	-12,4%	19,9%
Entire Life Cycle	-18,4%	-18,2%	-18,3%	-18,3%	-18,4%	-17,4%	-18,4%

Going into details on each phase of the life cycle, complementary observations can be drawn.

Concerning the material phase, GWP, ODP, EP and ADP impacts increase between 5% and 30% because of the production of the supplementary parts induced by the twin-rotor configuration. These parts are mainly composed with composite materials which are particularly detrimental to these environmental impacts. However, AP and POCP decrease up to 1% because of the low impact of composite materials on these impact categories combined with the decrease of the engines weight, mainly composed of highly impacting metallic alloys on AP and POCP impacts.

Concerning the manufacturing phase, all the environmental impacts increase about 20% because of the mass increase of the rotorcraft and because of the massive use of composite materials (for the fuselage and blades) which are highly energy consuming during the manufacturing phase.

Concerning the end of life phase, it can be seen on Table III that the end of life phase values are all negative. These negative values indicate that the environmental impact for the end of life phase are in the opposite sign of the other impacts, and thus, represent a positive effect on the environment. The end of life phase is by this way often considered as a credit that can be subtracted to the other environmental impacts and therefore contribute to the decrease of the total impacts given in Table III. The results obtained in the XO15 LCA are also negative for the end of life phase, but the calculation of the relative variation of impacts given in Table IV can be either positive or negative without indicating that the end of life phase has a detrimental effect when this relative value is positive. Actually, positive values on the end of life line of Table IV indicate that there is a better recycling performance of XO15 than HO15, while the negative values of Table IV indicate the opposite. Thus, positive effects are observed on GWP, ODP, EP and ADP fossil. This is due to the increase of metallic material use due to the increase of landing gear, mechanical transmission and gearbox masses. These parts, mainly made of metallic alloys have a great benefit in end of life because of their ability to be efficiently recycled. In the opposite AP, POCP and ADP non-fossil impacts decrease because of the decrease of the engines mass which contain a large quantity of nickel or cobalt alloys, highly impacting these environmental impact categories. The decrease of the use of these alloys consequently decreases the recycling performance. But in any case, the absolute value of the end of life phase is still negative, indicating a beneficial effect on the total environmental impacts.

It should also be noticed that only metallic alloys participate to the recycling benefit of this phase. Indeed, composite materials, which are composed of carbon or glass fibers combined with thermoset plastics are not yet recyclable and do not participate to the beneficial impact of the recycling phase of the rotorcraft. This is the main disadvantage of aeronautical composite materials despite their low weight capability.

To summarize the comparative LCA between HO15 and XO15, the use of a twin-rotor configuration induces a 10% mass increase because of the increase of the mass of rotors, transmission, and gear boxes, but this additional mass is counterbalanced by a 18% decrease of the fuel consumption thanks to a more efficient rotorcraft well suited for this mission and thus requiring less power. As the use phase is by far the main contributor to the global environmental impact, the benefit of this large consumption reduction is more beneficial than the detrimental effects caused by the increase of the rotorcraft weight, so that the total impacts of the XO15 are reduced for all the considered environmental impact categories.

VII. Conclusion

The helicopter configuration (single main rotor – single tail rotor) has been imposed as the most simple one for missions requiring VTOL capabilities. Still nowadays it is the most widely spread VTOL configuration. However, this paper demonstrates that very significant reductions of the environmental impacts (mainly noise and fuel consumption) can be reached by adapting the rotorcraft concept to the missions and by decreasing the rotor rotational speed at least for the hover and low speed flights.

Even if the models are simple enough to be used in the pre-sizing phase, they have been validated with respect to experimental data and more complex models ("high fidelity"), and thus, they give the correct design trends at least in relative values. An interesting conclusion which may be drawn from the presented work is that significant reduction of the environmental impact can be obtained without degrading the flight performance and safety. For example, one important result which can be underlined is the strong noise reduction obtained by decreasing the rotor revolution speed. Decrease the disk loading by increasing the lifting surfaces (e.g. by increasing the number of rotors and/or blades and/or blade surface) is not a standalone solution, but a condition for allowing a significant decrease of the rotor speed. Indeed increasing the lifting surfaces means an increase of the gross weight and therefore a compromise is required on the disk loading.

With the benefit of hindsight, it is noticeable that a lot of researches and developments are devoted to high speed rotorcraft, whereas significant progress can still be performed in the predilection and predominant field of application of rotorcraft, i.e. in hover and low speed flights. Tiltrotors and compounds fast rotorcraft absorb nowadays a great amount of research funding even for example in Clean-Sky II European project. But the extension of the uses and applications of rotorcraft should also come from important improvement of the ratio performance/environmental impact in their low speed flights domain of excellence. It is worth noting that the strong decrease of rotor rotation speed proposed here is not incompatible with high speed flights if a variable, i.e. adjustable rotor speed system can be implemented.

Instead of considering a new concept with a technology rupture with too few experimental feedbacks for developing a model with the same level of validity, as in the models used for the reference helicopter, it has been first preferred to study what can be done with the same technologies, hence the same models. A next step would be to explore further concepts with stronger technological gaps. For example, a power generation with hybrid or all electric system would surely reduce the environmental impact on the use phase. But such a study would require developing reliable models to provide enough validated power and weight assessments as well as a careful attention to the transfers of impacts (from the use phase to the other life cycle phases).

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References

[1] P.-M. Basset, A. Tremolet, F. Cuzieux, C. Schulte, D. Tristrant, T. Lefebvre, G. Reboul, M. Costes, F. Richez, S. Burguburu, D. Petot, B. Paluch, "The C.R.E.A.T.I.O.N. project for rotorcraft concepts evaluation: the first steps", 37th European Rotorcraft Forum, Gallarate, Italy, 13-15 September, 2011.

[2] P.-M. Basset, A. Tremolet, F. Cuzieux, G. Reboul, M. Costes, D. Tristrant, D. Petot, "C.R.E.A.T.I.O.N. the Onera multi-level rotorcraft concepts evaluation tool: the foundations", Future Vertical Lift Aircraft Design Conference, American Helicopter Society Specialists meeting, San Francisco, CA, USA, 18-20 January 2012.

[3] A. Tremolet, P.-M. Basset, "Some meta-modeling and optimization techniques for helicopter pre-sizing", 38th European Rotorcraft Forum, Amsterdam, The Netherlands, 4-6 September, 2012.

[4] P.-M. Basset, A. Tremolet, N. Bartoli, T. Lefebvre, « Helicopter pre-sizing by multidisciplinary – multi objective optimization », OPT-i 2014, International Conference on Engineering and Applied Sciences Optimization, M. Papadrakakis, M.G. Karlaftis, N.D. Lagaros (eds.), Kos Island, Greece, 4-6 June 2014.

[5] W. Johnson: "NDARC « NASA Design and Analysis of Rotorcraft: Theoretical Basis and Architecture », American Helicopter Society Aeromechanics Specialists' Conference, San Francisco, CA, January 20-22, 2010.

[6] C. Russel and W. Johnson, "Conceptual design and performance analysis for a large civil compound helicopter", Future Vertical Lift Aircraft Design Conference, American Helicopter Society Specialists meeting, San Francisco, CA, USA, 18-20 January 2012.

[7] P. Weiand, A. Krenik, "A Multidisciplinary Toolbox for Rotorcraft Design", Rotorcraft Virtual Engineering Conference, Royal Aeronautical Society Conference, Liverpool, November 2016.

[8] C. Russell, P.-M. Basset, "Conceptual Design of Environmentally Friendly Rotorcraft – A Comparison of NASA and ONERA Approaches", American Helicopter Society 71st International Annual Forum, Virginia Beach, VA, USA, May 5-7, 2015.

[9] B. Benoit, A.-M. Dequin, K. Kampa, W. Grunhagen, P.-M. Basset, B. Gimonet, "HOST: A general helicopter simulation tool for Germany and France", American Helicopter Society, 56th Annual Forum, Virginia Beach, May 2000.

[10] W. Johnson, "Technology Drivers in the Development of CAMRAD II," American Helicopter Society Aeromechanics Specialist Meeting, San Francisco, California, January 1994.

[11] R. Du Val, "FLIGHTLAB: A Suite of Rotorcraft Virtual Engineering Tools," Rotorcraft Virtual Engineering Conference, Royal Aeronautical Society Conference, Liverpool, November 2016.

[12] P.-M. Basset, A. Tremolet, P. Beaumier, T. Rakotomamonjy, "CREATION: a numerical workshop for rotorcraft concepts generation and evaluation," Rotorcraft Virtual Engineering Conference, Royal Aeronautical Society Conference, Liverpool, November 2016.

[13] G. Reboul, A. Taghizad, "Semi-analytical modeling of helicopter main rotor noise", Proceedings of the 38th European Rotorcraft Forum, Amsterdam, Netherland, 2012.
[14] R. Huot, "Improving the modeling of the Fenestron in the Eurocopter Simulation Tool", Master Thesis, Kungliga Tekniska Hogskolan, Stockholm, Sweden, 2013.
[15] T. S. Beddoes. "A wake model for high resolution airloads", Proceedings of the 2nd International Conference on Basic Rotorcraft Research, Triangle Park, USA, 1985.
[16] L. Filotas, "Vortex Induced Helicopter Blade Loads and Noise", Journal of Sound and Vibration, 27(3):387-398, 1973.
[17] P. Spiegel and G. Rahier. "Theoretical study and prediction of BVI noise including close interactions", Proceedings of the AHS Technical Specialists Meeting on Rotorcraft Acoustics and Fluid Dynamics, Philadelphia, USA, 1991.
[18] R. Pegg, "A Summary and Evaluation of Semi-Empirical Methods for the Prediction of Helicopter Rotor Noise", NASA TM 80200, NASA, 1979.
[19] P. Malbéqui, Y. Rozenberg and J. Bulté, "Aircraft noise modeling and assessment in the IESTA program", Proceedings of Inter-noise congress, Osaka, Japon, 2011.
[20] F. Verlut, N. Dyrla, "Definition by Eurocopter of a Green Metric to Assess gas Emitted by Helicopters in Operation," 36th European Rotorcraft Forum, Paris, France, September 6-9, 2010.
[21] World Health Organization: "Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, Global update 2005, Summary of risk assessment", WHO/SDE/PHE/OEH/06.02.
[22] T. Rindlisbacher, "Guidance on the Determination of Helicopter Emissions," Swiss Confederation Federal Office of Civil Aviation (FOCA), Ref. 0 / 3/33/33-05-20, Bern, Switzerland, March, 2009.
[23] M.J. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, R. Van Zelm, "ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level," First edition "Report I: Characterisation", 6 January 2009.
[24] P. Rauch, M. Gervais, P. Cranga, A. Baud, J.-F. Hirsch, A. Walter, P. Beaumier, "Blue Edge™: "The Design, Development and Testing of a New Blade Concept," 67th Annual Forum of the American Helicopter Society Proceedings, Virginia Beach, VA, May 3-5, 2011.
[25] B. G. van der Wall, C. Kessler, Y. Delrieux, P. Beaumier, M. Gervais, J.-F. Hirsch, K. Pengel, P. Crozier, "From ERATO Basic Research to the Blue EdgeTM Rotor Blade," American Helicopter Society 72nd Annual Forum, West Palm Beach, Florida, May 17–19, 2016.
[26] J. G. Leishman, "Principles of Helicopter Aerodynamics", 2nd Edition, March 2006 publication by Cambridge University Press (North America) in hardback. SBN-13: 9780521858601 | ISBN-10: 0521858607.