Setting up methods and tools for flight performance evaluation of rotorcraft concepts

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July 2009

Abstract

On the one hand Rotary Wings aircraft (manned or Uninhabited Aerial Vehicle, UAV) have a high potential of civil and military applications, thanks to their Vertical Take-Off and Landing (VTOL), hover and low speed capabilities. On the other hand, the variety of the rotorcraft concepts is particularly rich. There is a revival of interest for revisiting alternate concepts with respect to the helicopter by using new technologies especially in the field of UAVs. Hence, for a type of missions, it is important to be able to assess and to compare these concepts or to innovate the most suited concept. ONERA ("Office National d'Etudes et de Recherches Aérospatiales" : the French Aerospace Lab) has a role of expertise and innovation in this field. In this paper the works to capitalize, organize and develop the methods and tools for the evaluation of rotorcraft concepts from the flight performances point of view will be presented as well as the perspective in this area at ONERA.

INTRODUCTION

Rotorcraft (including RW Uninhabited Aircraft Systems, UAS) have the Vertical Take-Off and Landing (VTOL) capability and they are the best suited for hover and low speed flights (including lateral and rearward flights). Thanks to this specificity, they have a wide field of civil and military applications such as the transports of persons and/or load in areas which can not be reached by fixed-wings airplanes and many other tasks like observation, Emergency Medical Services, Search and Rescue, fire fighting, …

On the other hand, the variety of Rotary-Wings (RW) aircraft is very rich (much more than in the case of fixed-wings).

For examples, many concepts exist with multiple lifting rotors such as tandem configuration, coaxial counter-rotating rotors, tilt-rotors, quad-rotors (tilting or not), intermeshing rotors, … Many configurations use also ducted fan or shrouded rotors/propellers, protecting the blades, they could be good candidates for applications with flights close to obstacles. Some concepts look not very far from the classical single main rotor and single tail rotor helicopter. For example the concept of reduced rotor revolution speed is interesting for long endurance or high speed capabilities. Many concepts of compound or hybrid helicopters have been explored in the past [1] and are now revisited with new technologies. They consist not only in adding to the helicopter auxiliary lift and/or propulsion devices, but also to redefining the role of the main rotor, the controls and power management/distribution. Some concepts are further from the helicopter like the stoppable rotor concept (e.g. Canard Rotor Wing concept) or the tail-sitters which have the VTOL capability and after a transition manoeuvre can fly horizontally more or less like fixed-wings.

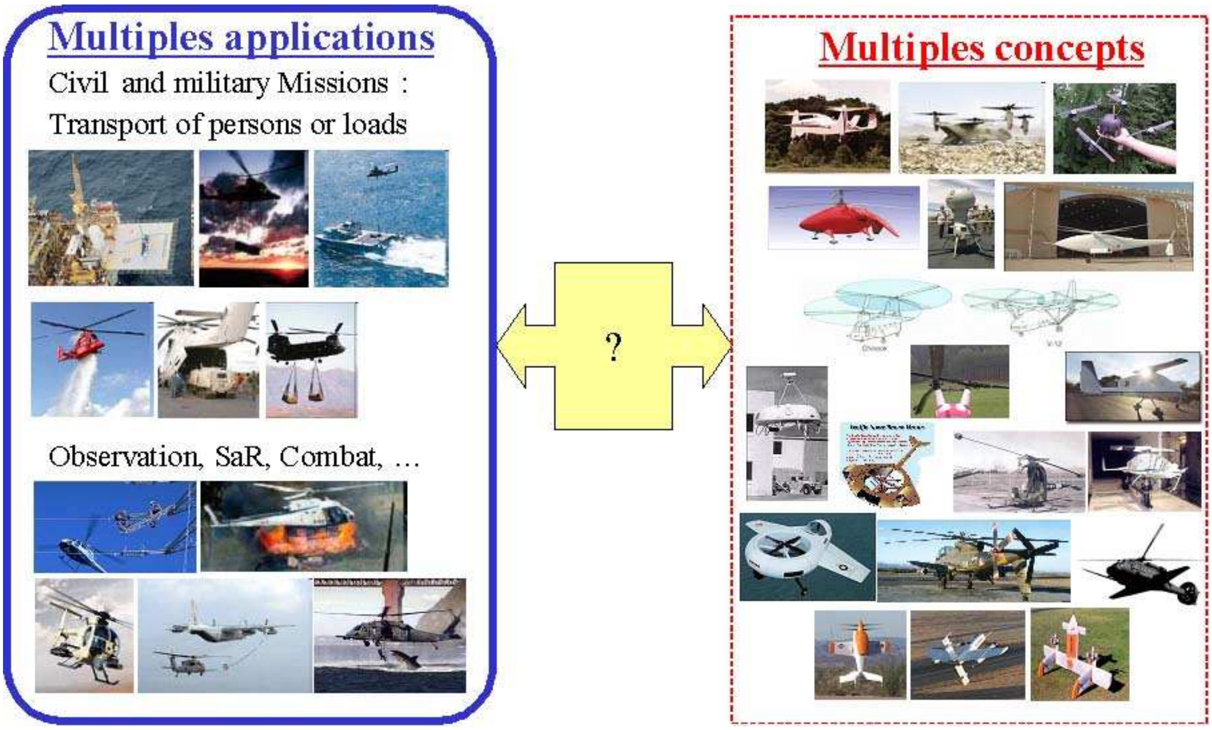

Figure 1 : Which concept is the most suited for a kind of missions ?

An important point to notice is that the growing interest for UAVs increases the variety of rotorcraft concepts to be assessed. Indeed some concepts were abandoned due to technological or piloting difficulties. For example the tail-sitters can hardly be piloted without a high performance Flight Control System especially for the manoeuvre from the horizontal flight back to the vertical one and landing. But more importantly, the rise of the UAVs makes appear many projects with rotorcraft concept vehicles because the risk and cost associated with their development is lower than with manned aircraft.

The main goal of ONERA in this area is the evaluation of concepts first from the flight performances point of view and then according to other criteria depending on the application (acoustics, vibrations, etc.). This goal aims at fulfilling the role of expertise for the French Ministry of Defence, the industry, European projects, … A corollary is that the methods and tools developed for expertise can also be used for innovation of new concept or proposing new missions. That is useful and necessary for contributing to a long term vision of the future of rotorcraft.

The evaluation of concept may require preliminary conceptual design steps depending on the level of detail available in the description of the rotorcraft to be assessed. That is the case especially if the starting point of the study is only the expression of the needs in terms of application, typical mission profile and main flight performances.

Furthermore, the evaluation of concept is also connected to the Multidisciplinary Design Optimization (MDO). Indeed before evaluating the performances of a concept, its characteristics (number of blades, radius, chord, rotation speed of the rotors, etc.) must be optimized with criteria and constraints depending on the application and on the kind of concept. In the case of rotorcraft, the multidisciplinary character of the problem is very strong due to the high level coupling between aerodynamics, blade dynamics, flight mechanics, power-engine system, … Moreover, one of the “trump card” of ONERA is that all the fields of expertise require to achieve that kind of technical MDO are present in different departments organized by disciplines : applied aerodynamics, flight dynamics, structures, acoustics, …

The paper will first present a brief state-of-the-art in the field of methods for the pre-sizing of rotorcraft as well as about Multidisciplinary Design Optimization (MDO) applied to rotorcraft.

Then it will address more deeply the key problems of :

- comparing the performances of different rotorcraft configurations (e.g. : the single main rotor helicopter, the coaxial rotorcraft and the tilt-rotor) ;
- optimizing some sizing parameters with respect to a flight performance criterion (such as the endurance).

Two kinds of methods and tools for assessing the performances will be presented. The first one is based on the energy method which makes use of analytical expressions for estimating the different power consumptions. The second one make use of flight mechanic simulation models which have been implemented in a more general program for computing the performances on the different parts of a complete mission profile including : hover, climb and descent, cruise, loitering flight, …

Some interesting concrete results will be given (e.g. regarding the endurance optimization) as well as more general perspectives of development of such evaluation tools.

STATE-OF-THE-ART

For the sake of brevity here will be evoked two kind of complementary methods : the pre-sizing by applying statistics on databases w.r.t. existing rotorcraft and MDO techniques.

All the helicopter builders use their own databases based on their previous developments and flight tests. They conserve jealously these databases which allow them to interpolate or extrapolate in a certain extent a new helicopter depending mainly on its gross weight. In [2], an interesting presentation of that kind of typical approach shows the application of correlation techniques based on multiple regression analysis on a database including about 180 conventional single lifting rotor helicopters. A limit of this pre-sizing approach by statistics is of course that it can not be applied for the pre-sizing of concept which are completely different from the ones of the database.

An attempt to go beyond this limit is presented in [3]. This paper gives results which are of a precious help for the very first steps of the pre-sizing process. The database used in [3] includes conventional full-scale helicopters as well as very different kinds of RW-UAVs : coaxial, tilt-rotor, ducted fan, slowed rotor, … The design trends analysis provides analytical laws for assessing the gross weight from the payload or useful load (including payload and fuel) which is often the first input drawn from the application needs. Then from the gross weight many important parameters can be deduced by using the simple analytical laws deduced from the trends analysis. For example, once the gross weight is known the total take-off power can be estimated, from which can be selected an engine and hence the fuel weight, the engine weight and thus the empty weight. From the gross weight different laws are also given depending on the rotorcraft concept for a first assessment of the rotor diameter (and tail rotor in case of classical helicopters). From the main rotor diameter can then be estimated the fuselage length and the total length (rotors turning) as well as other rotor characteristics such as the mean chord, …

Both papers [2-3] indicate that this approach based on existing flying configurations allows to take into account and to incorporate in the early stages of the pre-sizing, some design constraints that emerge only during more advanced stages of the design process. This point depends of course on the technological generation of the rotorcraft included in the database and that may prevent from finding optimized parameters in ranges which were not explored before.

Therefore the use of MDO techniques is interesting to surpass this limitation. But both approaches are useful and complementary in the conceptual and preliminary design. If the MDO techniques are more applied at advanced stages of the design, there is a tendency to use them as soon as possible in the pre-design process. Indeed, MDO can be defined as a formal methodology for the design of complex coupled systems in which the synergistic efforts of coupling between various interacting disciplines or phenomena are explored and exploited at every stage of the design process.

MDO allows designers to incorporate all relevant disciplines simultaneously. The optimum of the simultaneous problem is superior to the design found by optimizing each discipline sequentially, since it can exploit the interactions between the disciplines. However, including all disciplines simultaneously significantly increases the complexity of the problem.

MDO is an engineering design approach for large-scale system design that copes with the design problem through a decomposition of the system into its constituent subsystems. These subsystems are intrinsically linked through design, function, and performance. MDO methods employ individual analysis for each subsystem, which are then aggregated by a system-level coordination procedure that ensures compatibility of the subsystems. There are many MDO formulations which will not be presented there (see for example [4]).

In [5], two MDO formulations are implemented on preliminary helicopter design: All At Once (AAO) and Collaborative Optimization (CO). In both formulations, the design is made parallel, that is to say the various disciplines taken into account (vehicle engineering, economic analysis, propulsion design, performance analysis, stability and control analysis, transmission design, weight and balance, aerodynamic design, structural analysis, rotor dynamics and noise analysis) operate in parallel and “independently” (exchanges only through the system-level coordination) : they can therefore use more complex tools in their analysis which provides an even better evaluation of the aircraft performances. Disciplines are integrated using a common platform ModelCentre. Results yielded by AAO and CO are very similar but their implementation differs. AAO is quick, simple, and optimization is only performed at the system level whereas CO is longer, more complex and optimized at two levels : disciplines and system.

STATUS OF THE EVALUATION TOOL

The starting point of the evaluation depends on the level of details available in the description of the rotorcraft. If the rotorcraft is known and well-defined, the evaluation can use directly the “expert model” like the flight dynamics code EUROPA (« EUropean ROtorcraft Performance Analysis ») or H.O.S.T. (“Helicopter Overall Simulation Tool” created by Eurocopter and developed for years with contributions of ONERA). If the rotorcraft is defined only by its main characteristics, the evaluation may start from the power balance assessment. But if only the specification in terms of needs by the potential users is given, the evaluation process must start from the very beginning as a conceptual and preliminary design study i.e. from the analysis of the expression of needs.

All these cases occurred during different studies performed by ONERA for the European Community, the Industry and the French Ministry of Defence. Therefore the general scope of the evaluation spreads from the initial analysis of the needs (step 0) until the MDO and final comparisons as presented on the Figure 2 hereafter.

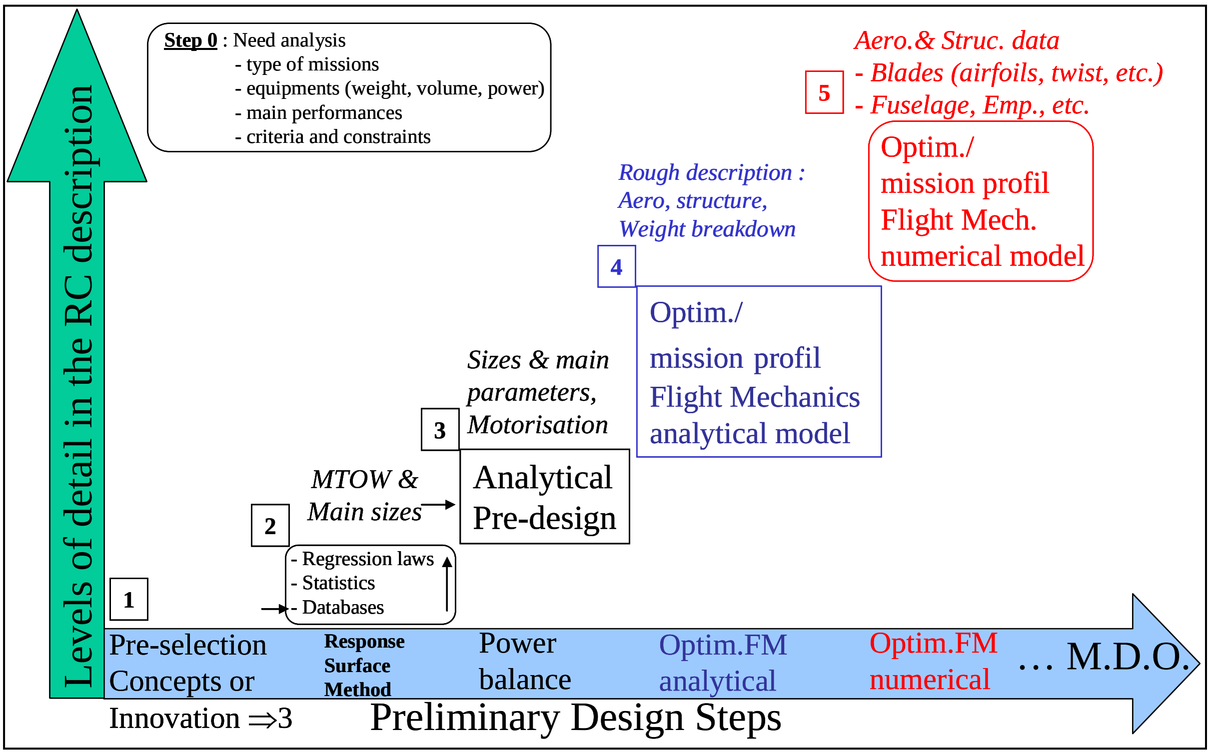

Figure 2 : main steps of the conceptual study.

After the “step 0” which is very important as it conditions the definition of the rotorcraft as well as the criteria and constraints for the evaluation, a pre-selection of the concepts which are potential candidates for the intended application is made (“step 1”). An extensive review has been performed in 2008 of the different rotary-wing concepts describing their advantages and drawbacks. This review will be enriched and updated regularly as soon as new rotorcraft concepts are invented.

Then a first estimate of the main characteristics (gross weight, main sizes, etc.) of each concept is determined more or less based on statistics as evoked before from databases or Response Surface Models (“step 2”). This step must provide all the data required for applying the “analytical pre-design” (“step 3”) based on the power balance method.

The following steps (4 and 5) make use of flight mechanics models which can be “analytical or numerical” depending on the kind of rotor model : a blade element model decomposes the blade in radial sections distributed along its span and is therefore a “numerical model” by opposition to a direct explicit formulation of the forces and moments developed by a rotor (“analytical model” or rotor disk model).

MDO iterations appear later on Figure 2 although as mentioned before MDO is already used in the first steps for example through the Response Surface Models.

The present work is a continuation and development of the methods and tools set up by ONERA for the evaluation of RW-UAVs during the CAPECON project (***C****ivil UAV* ***AP****plications &* ***E****conomic Effectivity of Potential* ***CON****figuration Solutions).* This European project of the fifth framework was devoted to the study of civil UAVs from the survey of potential applications until the pre-design of UAS including seven

UAVs : five fixed-wings UAVs (High Altitude Long Endurance or Medium Altitude Long Endurance) and two RW-UAVs. A general presentation of the work achieved by the group dedicated to RW-UAVs is presented in [6].

A first view of the basis of models and tools built by ONERA for assessing the performances of different RW-UAV configurations has been presented in [7]. These simulation tools have been created or adapted to this purpose partly during the European project CAPECON. A significant work has been done by ONERA for modelling the aerodynamic interferences, especially for the coaxial rotors. The first level of these tools is the analytical assessment of the required power by the energy method. The second level is the non-linear comprehensive flight mechanic simulation of these rotorcrafts. The third level is the iterative computation of the required power and the fuel consumption during an entire mission including hover, climb, cruise, …

Modelling :
The modelling (i.e. capturing by equations) of the specificities of each concept is a key task. For example in [7], the assessment of the coaxial configuration requires first to model the aerodynamic interaction between the two coaxial contra-rotating rotors with a level of detail and assumption adapted to the step of evaluation. Of course all the validation efforts with respect to available database and/or more advanced simulation tool must be performed. Yet about the validation aspect, it must also be kept in mind that the evaluation are done in relative value through comparisons of different concepts. Therefore the models must be coherent i.e. settled on the same level of assumption and kind of approach.

Example of this modelling effort were presented in [7], where the flight performances of four rotorcraft concepts were compared : classical helicopter, coaxial, tilt-rotor and tandem rotorcraft.

Power balance method :
The power balance method, also called energy method, is based on the decomposition of the necessary power (P_N) to make fly a rotorcraft in different terms :

- the induced power (P_i) : corresponding to the work of the rotor to accelerate the air through its disk in order to develop a thrust mainly dedicated to the lift ;
- the airfoil profile drag power (P_p) : the blades generating not only lifting forces but also drag, the rotor spends a part of the power due to the drag of its blades ;
- the anti-torque power (P_a) : in the case of rotorcraft concept with anti-torque device as for the classical helicopter, a tail rotor spends a part of the power to develop a lateral force in order to compensate the main rotor torque due to the drag forces on its blades ;
- The power for overcoming the drag of all the other elements except the blade airfoils (i.e. fuselage, empennage, etc.) (P_F) : that is required in translation flight in order to overcome all the drag forces occurring with the translation speed.

Hence in hover :
For the concepts with an anti-torque device like the conventional helicopter (or the NOTAR, etc.) :

$$P_{N\_hover} = P_i + P_p + P_a$$

For the concepts which are « naturally equilibrate » in torque (all concepts using two contra-rotating rotors, the blade tip-jet) :

$$P_{N\_hover} = P_i + P_p$$

In translation flight :

$$P_N = P_{N\_hover} + P_F$$

For illustration, the power required (P_N) is compared on Figure 3 for four concepts from hover to forward level flights up to 270km/h. The general trends are well caught : the tilt-rotor needs lower power at high speeds but more at low speeds, the tandem concept requires the lowest power in hover but the highest at the higher speed, the coaxial and the helicopter are good compromise with the coaxial being less demanding in terms of power at the lower speeds (see [7] for more details).

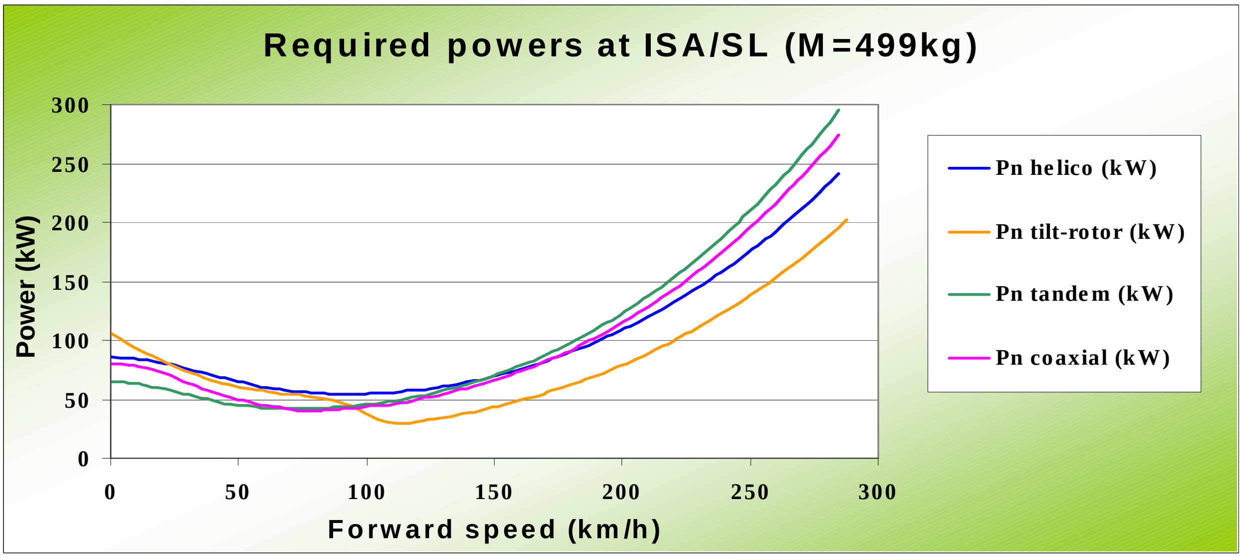

Figure 3 : example of comparisons of the necessary power for the main rotorcraft concepts.

This method allows a good first assessment of the total required power to make fly the rotorcraft in different flight conditions. The best endurance speed and the best range speed can be deduced from the curve of the required power with respect to the forward speed. The comparisons with the available power (provided by the engine) allows determining the ceilings and maximum speeds, leading to a flight envelope curve in terms of reachable altitude and speed.

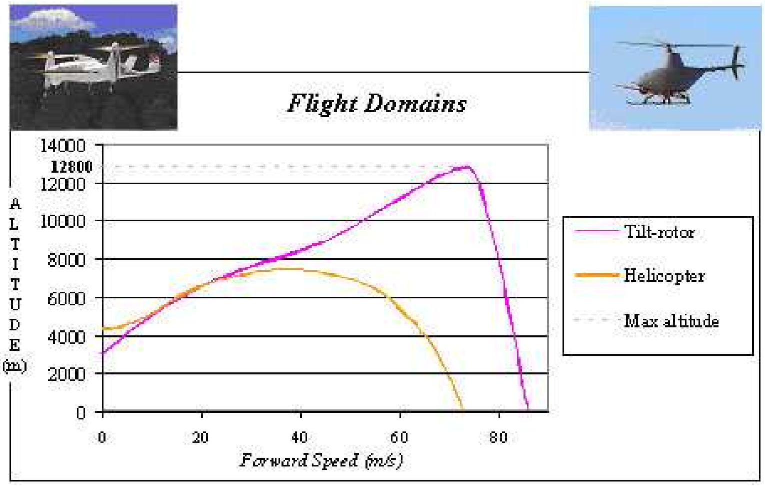

Figure 4 : Flight domain comparisons between a tilt-rotor and an equivalent helicopter UAV.

The power balance method can also be used to perform trends analysis before optimization with more complex models. Indeed the advantage of having analytical formula makes easier the interpretation allowing to get interesting first insights in the influences of the parameters.

For example, let’s consider the effect of the main rotor rotation speed on the required power in the case of a helicopter. The conventional helicopters have a constant RPM (Revolution Per Minutes) and are piloted by the pitch angle variation of the blades. But some concepts explore the interest of slowed rotor (like the Hummingbird A160 for increasing the endurance).

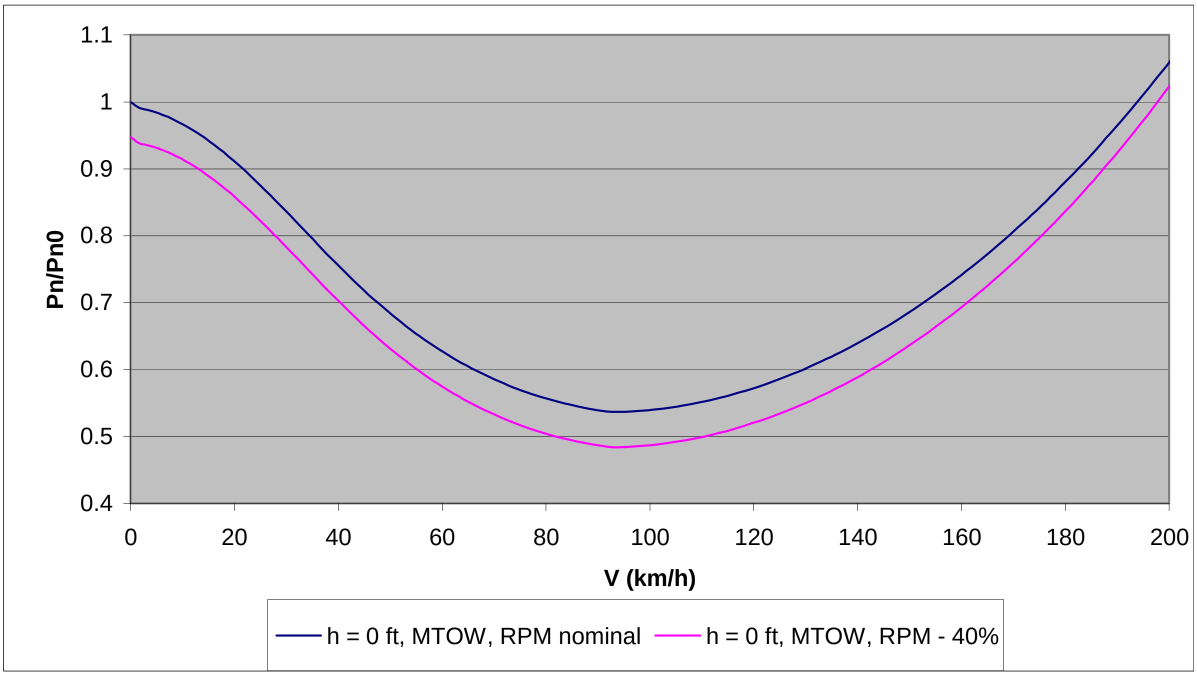

Figure 5 : Variation of the needed power with the rotor rotation speed.

On Figure 5, it can be seen that a RPM (Ω) reduction of 40% reduces the required power (w.r.t. the nominal one Pn0) for all the speeds from hover up to 200km/h. That is due to the decrease in the profile power when the RPM decreases (U being the blade tip speed : U=Ω.R) :

$$Pp = \frac{\rho \cdot R \cdot b \cdot c}{8} \cdot U^3 \cdot Cx = \frac{\rho \cdot R^4 \cdot \Omega^3 \cdot b \cdot c}{8} \cdot Cx$$

$$Cx = 0.028 \cdot Czm^6 - 0.013 \cdot Czm^2 + 0.0075 \cdot Czm + 0.008$$

$$Czm = \frac{1{,}04 \cdot 6 \cdot M \cdot g}{\rho \cdot R \cdot b \cdot c \cdot \Omega^2 \cdot R^2}$$

Yet, when the altitude increases this positive effect decreases and it can even disappear for high altitude (Figure 6).

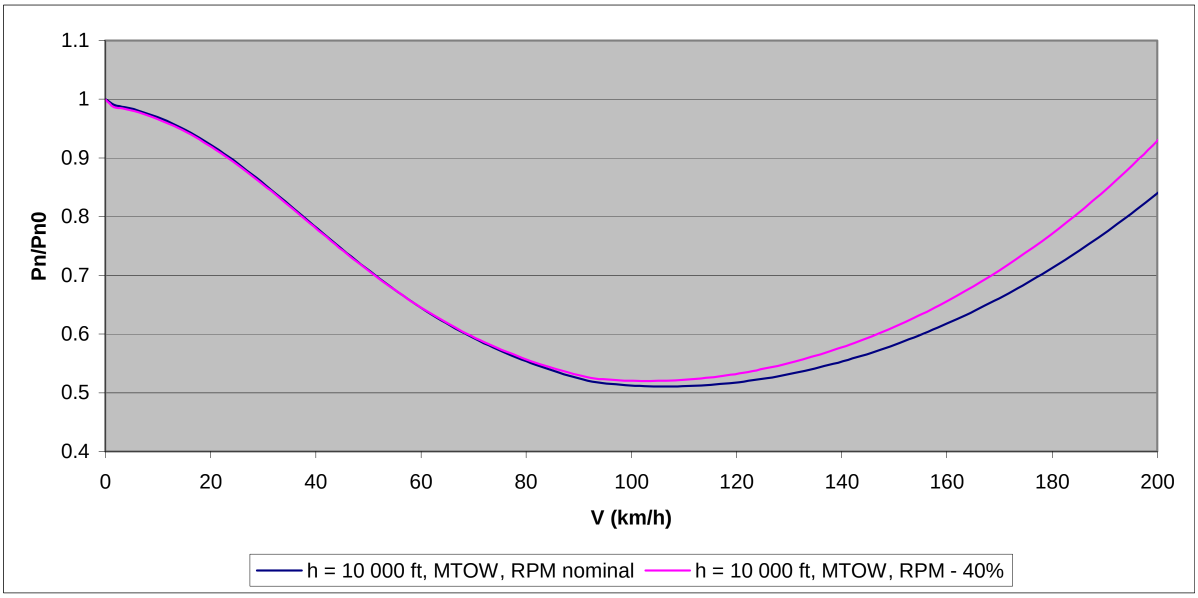

Figure 6 : Effect of the reduction of the RPM at high altitude.

This impact of the altitude comes from the air density (ρ) which decreases when the altitude increases. It turns out that the mean lift coefficient of the blade (Czm) increases strongly when the decrease in (ρ) is combined with a RPM decrease (Czm is inversely proportional to ρ and Ω^2). The drag coefficient which is more or less constant until 0.65 increases strongly for higher values of Czm due to its dependency on Czm^2 and Czm^6. Hence the effect of the (ρ) and (Ω^3) terms which are at the numerator of (Pp) is surpassed by the effect of these terms on (Czm) and (Cx).

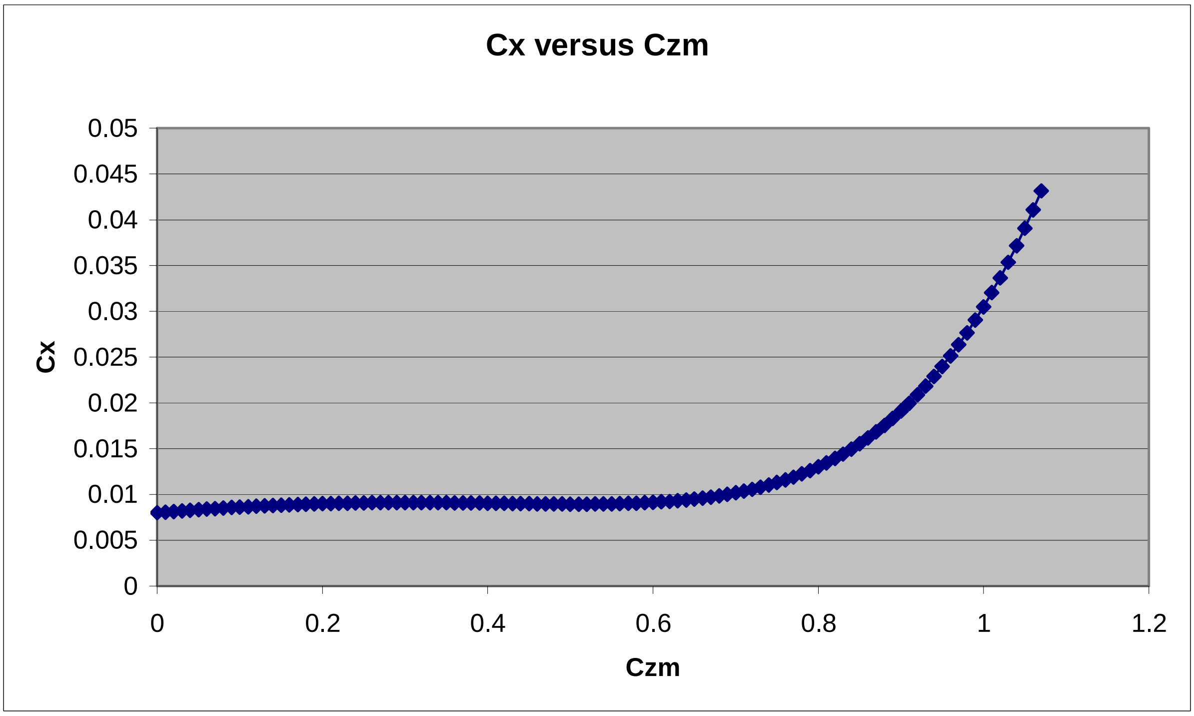

Figure 7 : variation of the blade drag coefficient Cx with the blade mean lift coefficient Czm.

Therefore in order to still get the interest of the reduction of the RPM on the decrease in the needed power, the gross weight must be reduced. The previous calculations have been done at the Maximum Take-Off Weight (MTOW). The following results (Figure 8) are obtained at 95% of the MTOW.

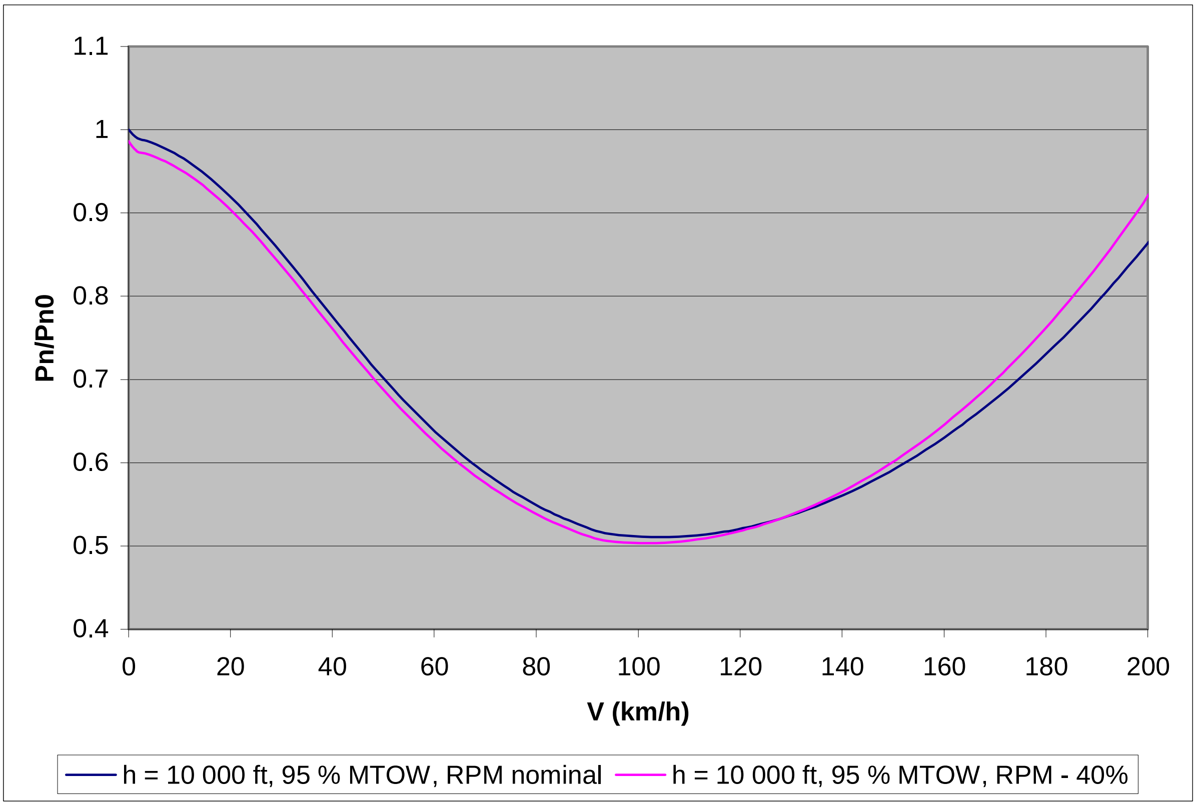

Figure 8 : effect of the reduction of the RPM at high altitude and lower gross weight.

In that last case, the RPM reduction is still interesting but with a lower gross weight and at lower speeds (below 130 km/h in the present study case).

OPTIMIZATION TOOLS WITH FLIGHT MECHANIC MODELS

Beyond these analytical tools built for each kind of rotorcraft configuration, more sophisticated flight mechanic simulation tools have been adapted. The equilibrium of the forces and moments resulting at the rotorcraft centre of gravity is computed iteratively by making vary the controls and rotorcraft attitudes. This method allows in principle a better estimation of the powers required by the rotors because of the use of more complex models. But also in the power balance method, the variation of the rotorcraft attitude (pitch and bank angles) can hardly be taken into account. Thus the variation of the drag of the rotorcraft with the attitude angles is usually not captured by this first approach (whereas it is caught by the flight mechanic models).

However it should be underlined here that the realism of a model depends not only on its level of sophistication but also on the inputs values of the parameters describing the aircraft.

Moreover, as introduced in [7] the flight mechanic simulation models have been implemented in a more general program for computing the performances on the different parts of a complete mission profile including : hover, climb, cruise, loitering flight, … This tool has been extended for the optimization of some rotorcraft parameters (rotor radius, RPM, mean chord, etc.).

This optimization tool has three iterative loops : one on the steps of the mission profile, which included another internal loop in order to perform enough computation points on each mission step for taking into account the variations of gross weight, altitude and temperature on the duration of each section of the mission, and a third one which aims at optimizing one or several rotorcraft parameters with different optimization algorithms (of gradient or evolutionary type).

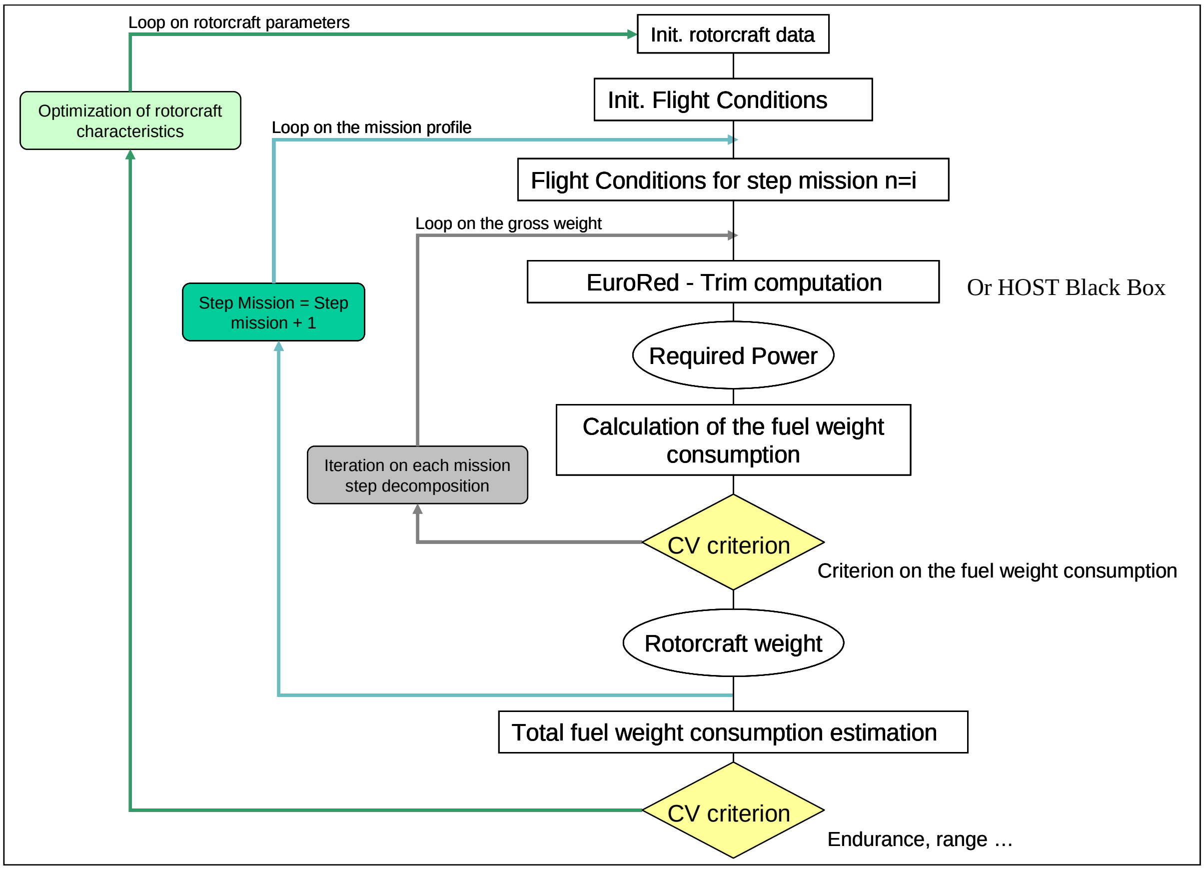

Figure 9 : first prototype of the optimization tool using flight mechanic models.

The flight mechanic module (derived from EUROPA in the following example) is called iteratively for assessing the required power at each calculation point depending on the flight condition (weight, altitude, temperature, speed) and on the rotorcraft parameters.

This tool has been first applied to a helicopter with an optimization goal of reducing the fuel consumption (thus increasing the endurance). The following graph shows some results when optimizing the number of blades, the main rotor chord, radius or rotation speed. The profile mission has five main steps : take-off and hover, cruise at Vbr (Velocity of best range), loitering flight at Vbe (Velocity of best endurance), cruise back at Vbr, hover, with the constraint of keeping at least a reserve of fuel for 20 minutes of flight at Vbe.

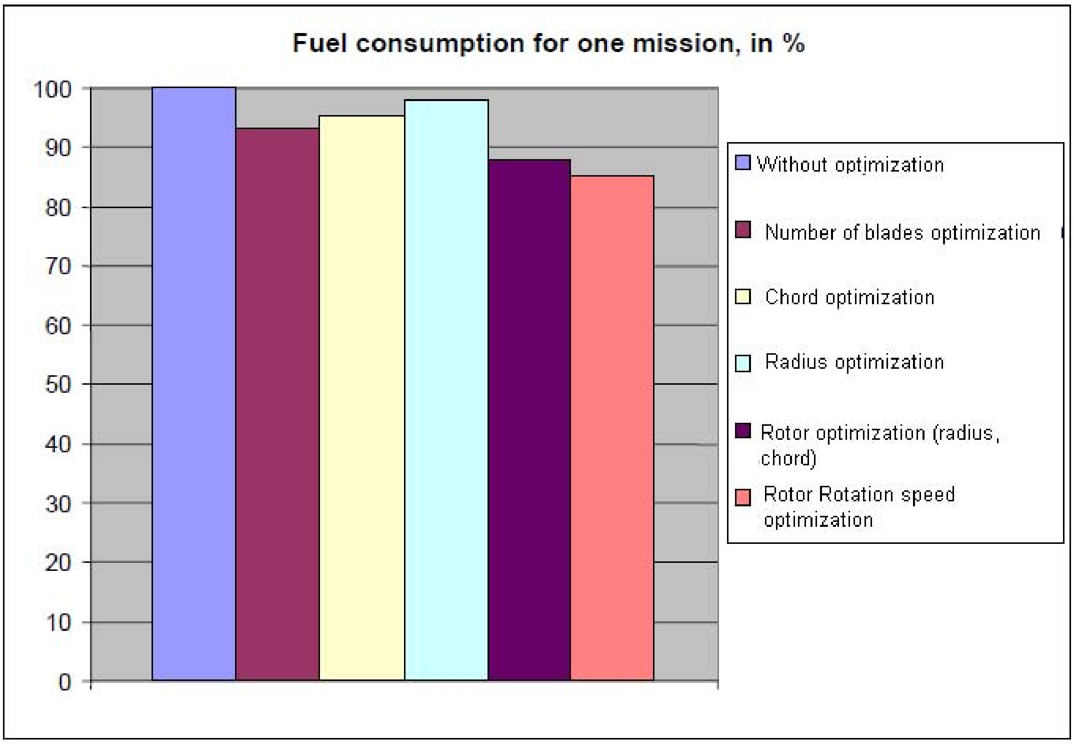

Figure 10 : example of results of optimization on a profile mission for a helicopter.

For example, the case of the optimization of the rotor rotation speed confirms the first insights obtained with the analytical power balance method. A reduction of about 39.4% in the main rotor RPM tends to reduced the fuel consumption of about 15.4%.

Yet, the results have been obtained with an analytical rotor model (not a blade element model). The effect of reducing the RPM on the blade dynamics is therefore not entirely captured as well as some aerodynamic aspects. A next step will be to go on that kind of investigation with a blade element model.

CONCLUSION

A general overview of the methods and tools developed by ONERA for the evaluation of rotorcraft concepts is presented here. In the paper the main focus is on flight mechanic performances.

A general approach is exposed for the evaluation of rotorcraft concept by comparisons of their flight performances. The starting point of the evaluation depends on the available data for describing the rotorcraft or its typical missions. The different steps of the conceptual study have been described from the initial analysis of mission needs, the pre-selection of rotorcraft concepts as potential candidates, the statistics approach and trends analysis, the power balance method, the flight mechanic simulation and the MDO techniques have been evoked.

Then for the optimization of some sizing parameters, a method has been presented from the first assessment and insights obtained with the analytical power balance approach until the optimization on an entire mission profile by using the flight mechanic model and two kinds of optimization algorithms.

In order to better address the multidisciplinary character of rotorcraft evaluation studies, a proposal of federative project between five ONERA departments has been prepared. This project called

C.R.E.A.T.I.O.N. for "**C**oncepts of **R**otorcraft **E**nhanced **A**ssessment **T**hrough **I**ntegrated **O**ptimization **N**etwork" aims at building a generic calculation platform for the comparisons of any kind of rotorcraft concepts by really including MDO techniques and the expertises of the different departments (aerodynamics, flight dynamics, structures, etc.). A collaboration with our German partner the DLR is also foreseen in a parallel project on their side.

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