BADA Family H – A Simple Helicopter Performance Model for ATM Applications

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Abstract— **While several aircraft performance models (APM) for fixed-wing aircraft are commonly used by the Air Traffic Management (ATM) community, no such model is available for rotorcraft. In an attempt to fill this gap, the authors have developed Base of Aircraft Data (BADA) Family H, an extension to the BADA model dedicated to helicopter aircraft. The objective of this new APM is to provide, using a simple theoretical model and for various helicopter types, realistic estimates of helicopter performance to support trajectory prediction and fuel burn estimation in ATM applications such as Air Traffic Control simulations or environmental assessment tools. This paper describes the design and structure of the new APM, and the methodology used to develop a model instance for a specific helicopter type. The initial validation results presented for three helicopter models demonstrate a good fit between helicopter performances computed with the new APM and both theoretical expectations and reference performance data. Future work will address known limitations of the model, in terms of supported helicopter types and operations, and further validation of its suitability to ATM applications.**

Keywords—aircraft performance model, helicopter, rotorcraft, air traffic management

I. INTRODUCTION

The aircraft is one of the key actors in the Air Traffic Management (ATM) system. ATM research and development activities and Air Traffic Control (ATC) systems that require information on aircraft performances rely on a substitute of the real aircraft, in the form of an aircraft performance model (APM). While several APM for fixed-wing aircraft are commonly used by the ATM community, no such model is available for rotorcraft. The flight dynamics of rotorcraft have been extensively studied [1,2,3,4], resulting in very detailed six degrees of freedom (DoF) models. The computing requirements associated with these models may however be too high for typical ATM applications, and the datasets available to complement these theoretical models cover only a limited number of helicopter types. A simplified theoretical model was proposed in [7], but it still requires iterative computations and was validated only on scale helicopter models. A recent research effort [8] does propose a rotorcraft performance model that has been designed for environmental assessments and could meet other ATM requirements, but the corresponding datasets have not been made available to the ATM community.

In an attempt to fill this gap, the authors have developed Base of Aircraft Data (BADA) Family H [10], an extension to the BADA APM [9] dedicated to helicopter aircraft. The objective of this new APM is to provide, using a simple theoretical model and for various helicopter types, realistic estimates of helicopter performance to support trajectory prediction and fuel burn estimation in ATM applications such as Air Traffic Control simulations or environmental assessment tools.

This paper first describes the design and structure of the new APM, and the methodology used to develop a model for a specific helicopter type. Validation results are then presented for three helicopter models: examples of helicopter performances computed with BADA H are compared with theoretical expectations and reference performance data. The final part of the paper addresses known limitations in the initial release of BADA H, as well as the future work that is planned on this model.

II. DESIGN AND STRUCTURE OF THE MODEL

BADA H follows a design similar to the other BADA families (3 and 4) [9]. Each aircraft model (representing a specific aircraft type) is described via a set of coefficients that are used by the APM mathematical formulas. The physical model is based on a mass-varying kinetic approach, which considers the aircraft as a point and requires the modelling of underlying forces that cause aircraft motion. The APM is structured into four models: action, motion, operations and limitations.

A. Action model

The action model allows the computation of the forces acting on the aircraft via their associated powers. It includes three categories of actions: aerodynamic (power required), propulsive (engine power and fuel consumption) and gravitational (weight).

1) Power required

The power required is defined as the amount of power to be provided to the helicopter aircraft for steady flight (constant speed and altitude). It is the sum of the main rotor power, the tail rotor power, the power required to run the auxiliary systems, and a number of power losses [4]. The power required model of BADA H is based on the previous research on helicopter aerodynamics, but simplified to capture the key performance aspects required by ATM applications without iterative computations.

Since BADA H is a 3-DoF point-mass model, it does not require a specific modelling of the tail rotor. The first simplification applied to this model consists in integrating implicitly the power requirements of the tail rotor and auxiliary systems, as well as the power losses, into the power requirements of the main rotor. The power required by the main rotor can be defined as the sum of the profile power, the induced power, and the parasite power [1,4,5]. This power and its component powers can be represented by a nondimensional power coefficient C_P:

$$C_P = \frac{P}{\rho\pi R^2 \left(\Omega R\right)^3} \tag{1}$$

where P is the power [W], ρ is the air density [kg/m^3], R is the main rotor diameter [m] and Ω is the main rotor rotation speed [rad/s].

The profile power P_o is the power required to overcome the profile drag that results from the friction of air on the rotor blades. Several models of the profile power coefficient have been proposed, such as [1,6]:

$$C_{P_o} = k_1\left(1 + 4.6\mu^2\right) \tag{2}$$

or [2]:

$$C_{P_o} = k_2\left(1 + 3\mu^2 + \frac{3}{8}\mu^4\right) \tag{3}$$

where k_1 and k_2 are constant values (specific to each helicopter) and μ is the advance ratio, which is a nondimensional representation of the helicopter true airspeed V_{TAS} [kt]:

$$\mu = \frac{V_{TAS}}{\Omega R} \tag{4}$$

The profile power model selected in BADA H is based on the model from [1,6], generalized to provide a better fit to the reference performance data (cf section IV):

$$C_{P_o} = c_1 + c_2\mu^2 \tag{5}$$

where c_1 and c_2 are constant nondimensional values (specific to each helicopter).

The induced power P_i is the power required to overcome the induced drag generated by the airflow circulation around the rotor blades as they create lift. This component of the power required is the most complex to model, and proposed models [1,4] require an iterative resolution of equilibrium equations that were deemed too complex for typical ATM applications. One way to simplify those equations is to assume a constant rotor tilt angle equal to zero. Considering that this assumption is compatible with the hover conditions and that the induced power component becomes negligible compared to the other components at typical forward flight speeds [5], the induced power model selected in BADA H implements this simplification, which results in the following induced power coefficient:

$$C_{P_i} = c_3 C_T \sqrt{\sqrt{\mu^4 + C_T{}^2} - \mu^2} \tag{6}$$

where c_3 is a constant nondimensional value (specific to each helicopter) and C_T is the nondimensional thrust coefficient:

$$C_T = \frac{T}{\rho\pi R^2 \left(\Omega R\right)^2} \tag{7}$$

where T is the thrust [N], ρ is the air density [kg/m^3], R is the main rotor diameter [m] and Ω is the main rotor rotation speed [rad/s]. It is further assumed that weight accounts for the highest component in thrust, so that for all conditions of speed, pressure and temperature ratio, we have:

$$T = mg_0 \tag{8}$$

where m is the aircraft mass [kg] and g_0 is the gravitational acceleration [m/s^2]. This assumption implies that the thrust coefficient no longer represents the amount of force created by the main rotor to lift or accelerate the helicopter, but only the force required to sustain the weight.

The parasite power P_p is the power required to overcome the parasite drag that results from the friction of air on the helicopter body. Previous research efforts [1,4,6] agree on the same simple model for the parasite power coefficient, which has been selected in BADA H:

$$C_{P_p} = c_4\mu^3 \tag{9}$$

where c_4 is a constant nondimensional value (specific to each helicopter).

The final form of the power required model in BADA H includes an additional empirical term that improves the fit between the model and the reference performance data (cf section IV), resulting in the following expression of the nondimensional power required coefficient:

$$C_{Preq} = c_1 + c_2\mu^2 + c_3 C_T \sqrt{\sqrt{\mu^4 + C_T{}^2} - \mu^2} + c_4\mu^3 + c_5 C_T{}^2\mu^3 \tag{10}$$

where C_T is the thrust coefficient [-], μ is the advance ratio [-], and c_1 to c_5 are constant nondimensional values (specific to each helicopter).

The power required model of BADA H does not take ground effect [4,5] into account: this simplification was considered acceptable for ATM applications since helicopters fly in ground effect only for a very short time during typical operations.

2) *Engine power and fuel consumption*

The engine power and fuel consumption models of BADA H are based on previous internal research on piston and turbine engines [11]. Since most helicopter types handled by ATM/ATC applications are equipped with turbine engines [12], this research has focused on turbine engine modelling: a separate model for piston engines is planned as a future work.

The engine power model includes the contribution from all engines and provides the power available from the engines as a function of throttle setting and atmospheric conditions. A turbine engine may be operated either by direct control of the throttle, or through the use of predefined power settings, called ratings. A rating model is provided in BADA H to determine those values, and this rating model is made available for several different ratings, namely maximum take-off (MTKF) and maximum continuous (MCNT). The idle (minimum power) rating model has not been defined yet in BADA H, because of a lack of reference data: this rating does not seem to be used in typical helicopter operations. The different ratings have their own respective set of coefficients but share the same formula, which provides the nondimensional power available coefficient C_{Pav} as a function of the atmospheric conditions:

$$C_{Pav} = a_1 + a_2\sqrt{\delta} + a_3\delta + a_4\sqrt{\theta} + a_5\theta \tag{11}$$

where δ is the pressure ratio [-], θ is the temperature ratio [-], σ is the density ratio [-], and a_1 to a_5 are constant nondimensional values (specific to each helicopter).

The power that the engines can produce at a given rating is limited to a specific value, determined by the main gearbox limitations and (when applicable) the engine flat-rate. For each rating, this maximum power P_{max} [W] is provided in the rating model. The final form of the power available model in BADA H is:

$$P_{av} = min\left(P_{max}, \rho_0\pi R^2\left(\Omega R\right)^3 C_{Pav}\right) \tag{12}$$

where P_{av} is the power available [W], P_{max} is the maximum all-engine power [W], ρ_0 is the air density in standard atmosphere at mean sea level [kg/m^3], Ω is the main rotor rotation speed [rad/s], R is the main rotor radius [m], and C_{Pav} is the power available coefficient [-].

At any engine power setting, the all-engine power P_{eng} can be represented by a nondimensional engine power coefficient C_{Peng}:

$$C_{Peng} = \frac{P_{eng}}{\rho_0\pi R^2\left(\Omega R\right)^3} \tag{13}$$

The fuel consumption model for the turbine engine model provides the fuel consumption F [kg/h] as a function of the engine power coefficient and the atmospheric conditions:

$$F = f_1 + f_2\delta + f_3C_{Peng} + f_4\delta C_{Peng} \tag{14}$$

where δ is the pressure ratio [-], C_{Peng} is engine power coefficient [-], and f_1 to f_4 are constant nondimensional values (specific to each helicopter).

B. Motion model

The motion model relates the geometric, kinematic and kinetic aspects of the aircraft motion, allowing the aircraft performances and trajectory to be calculated. The total-energy model selected for BADA H equates the rate of work (i.e. power) done by forces acting on the aircraft to the rate of increase in potential and kinetic energy:

$$P_{eng} - P_{req} = mg_0\frac{dh}{dt} + mV_{TAS}\frac{dV_{TAS}}{dt} \tag{15}$$

where P_{eng} is the all-engine power [W], P_{req} is the power required [W], m is the aircraft mass [kg], g_0 is the gravitational acceleration [m/s^2], h is the altitude [m], and V_{TAS} is the true airspeed [m/s].

The variation of mass is accounted for through the fuel consumption model:

$$-F = \frac{dm}{dt} \tag{16}$$

where F is the fuel flow [kg/s] and m is the aircraft mass [kg].

C. Operations model

The operations model captures aspects of aircraft operation that are not directly related to actions or motion laws, but are still necessary to compute aircraft motion [9,10]. Operating airspeeds can be defined as constant true airspeeds (TAS), constant calibrated airspeeds (CAS), or several optimum speeds: maximum endurance (also known as minimum power), maximum range and long range. Various types of flight segments are taken into account, such as climb at constant engine rating or constant rate of climb, descent at constant rate of descent, cruise, or hover. While climb and descent operations are often performed by airplanes at predefined engine ratings (e.g. climb at maximum climb rating or descent at idle rating), flight recordings of helicopter operations [13] indicate that climbs and descents are usually performed by helicopters at constant vertical rates, typically 800 to 1000ft/min for climb and 400 to 700ft/min for descents. The constant rate mode has been selected accordingly as the default operating mode for climb and descent operations in BADA H.

D. Limitations model

The limitations model provides the boundaries within which the APM is valid. These boundaries limit the flight envelope in terms of weight (from operating empty weight OEW to maximum take-off weight MTOW), altitude (up to maximum operating altitude h_{MO}) and speed (up to never exceed speed V_{NE}).

III. IDENTIFICATION OF THE MODEL COEFFICIENTS

Each aircraft model (representing a specific helicopter aircraft type) in BADA H is described via a set of coefficients that are used by the APM mathematical formulas. The generation of a specific aircraft model instance aims at identifying the values of the coefficients that achieve the best fit between calculated and reference aircraft performance parameters. The identification process of BADA H follows a design similar to the identification process of other BADA families (3 and 4) [9].

A. Reference data requirements

To enable the identification of all the coefficients that describe the aircraft model instance, a number of aircraft reference data items are required. These data can be divided into two categories: technical specification data and performance data. Technical specification data consist of general aircraft characteristics such as model name, engine type, limitations and dimensions. Performance data consist of aircraft flight data that provide the performance values (e.g. rate of climb/descent, fuel flow, or maximum cruise speed) associated to specific flight conditions (e.g. aircraft weight, operating speed and altitude, atmospheric conditions, or engine ratings).

The BADA H APM requires modelling of power required and power available, while fuel flow is modelled as a function of engine power. As the original aircraft data for power required, power available and power-specific fuel consumption are not easily available, the BADA H model identification process has been designed to work with reference data that are typically available from helicopter flight manuals, such as hover ceiling charts, maximum cruise speed charts, or fuel consumption charts (cf Section IV).

The precision and granularity of data values, together with data coverage of the aircraft flight envelope, have a high impact on the quality of the corresponding BADA H model. To ensure that the obtained coefficients robustly represent the aircraft behaviour over normal operating conditions, various reference data points that cover operations of aircraft at different airspeeds, aircraft masses and atmospheric conditions shall be used. The available aircraft performance reference data, however, do not always cater for this requirement of aircraft flight envelope coverage. In this case, an aircraft model can be identified, but its fidelity can only be assessed and guaranteed for the range of available reference data conditions.

B. *Coefficients identification*

The system of ordinary differential equations (ODE) formed by (15) and (16) provides the way to compute aircraft performances based on BADA H, once the model coefficients for power required, power available and fuel consumption are known. The objective of the model identification process is to obtain the BADA H APM coefficients from a set of known flight data points. To that aim, the same ODE system can be used for coefficient identification purposes if we consider that right-side values of (15) and (16) are the observed values, while left-side values are estimated by means of the BADA H model. The adopted optimization solution is the least squares solution that minimizes the sums of square errors (SSE) defined as:

$$SSE_1 = \sum_{i=1}^{n} \left[P_{av} - P_{req} - \left(m g_0 \frac{dh}{dt} + m V_{TAS} \frac{dV_{TAS}}{dt} \right) \right]^2 \qquad (17)$$

$$SSE_2 = \sum_{i=1}^{n} \left[F + \frac{dm}{dt} \right]^2 \qquad (18)$$

where n is the total number of data samples through all the reference performance data considered for the given aircraft type.

IV. VALIDATION OF THE MODEL

In order to validate the physical model and identification process described in the previous sections, examples of helicopter performances computed with BADA H will be qualitatively compared with both theoretical expectations (set out by previous research) and reference performance data (obtained from helicopter flight manuals).

Twenty helicopter types have been modelled so far in BADA H, whose maximum take-off weight (MTOW) varies from 1,500 to 30,000kg. Three of these models, the main characteristics of which are summarized in Table I, will be used as examples in this section. The specific name of each model cannot be disclosed to respect the confidentiality of the reference performance data.

TABLE I. MAIN CHARACTERISTICS OF THE HELICOPTER MODELS USED AS EXAMPLES

Model number	**Engine type**	**Number of engines**	**Weight class [kg]**
H1	Turbine	1	2,000 to 4,000
H2	Turbine	2	4,000 to 6,000
H3	Turbine	2	10,000 to 12,000

A. *Power required*

The behaviour of the power required model of BADA H can be compared with the theoretical behaviour described in previous research [1,4]. Fig. 1 illustrates the effect of airspeed and aircraft mass on the power required for level flight at sea level and ISA conditions, for the H2 model. The shape of the plot is consistent with similar plots from [1,4] for both the airspeed and mass effects. The power required decreases from hover to low airspeed, because of the reduction in induced power, and increases from low to high airspeed, because of the increase in parasite power. An increase in aircraft mass results in an increase in power required, and this effect is more pronounced at low airspeeds. Fig. 2 illustrates the effect of airspeed and pressure altitude on the power required for level flight at medium mass and ISA conditions, for the same H2 model. The shape of the plot is again consistent with similar plots from [1,4]: the power required increases with altitude from hover to low airspeed, but decreases with altitude at higher airspeeds.

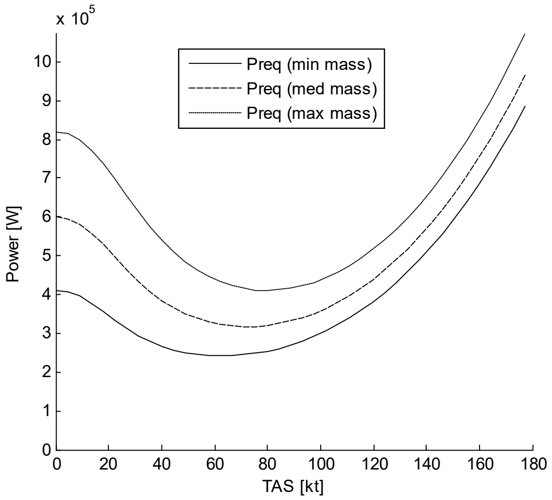

Fig. 1. Effect of airspeed and mass on power required (model H2, sea level, ISA)

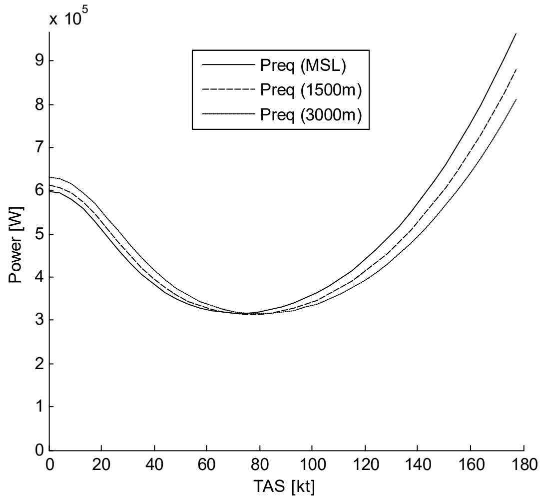

Fig. 2. Effect of airspeed and altitude on power required (model H2, medium mass, ISA)

B. *Hover ceiling*

The hover ceiling represents the maximum altitude at which a helicopter can hover at given engine power rating, aircraft mass and air temperature: at this altitude and zero airspeed, the power required equals the power available (unless hover ceiling is limited by the maximum operating altitude, but such flight conditions have been discarded from the following comparisons). Typical performance charts from helicopter flight manuals provide hover ceiling data for a wide range of aircraft masses and outside air temperatures (OAT), usually at the highest engine power rating (MTKF). While hover ceiling data are usually provided for flight conditions both in and out of ground effect, only the second case will be considered here since BADA H does not take ground effect into account. Fig. 3, 4 and 5 provide comparisons between hover ceiling reference data (full lines) and BADA H estimates (dashed lines) for the three example models, in order to assess the consistency between the power required and the power available (MTKF) models of BADA H in the typical flight conditions where the MTKF rating is employed. All three models demonstrate a similar goodness of fit, where the effects of temperature, altitude and aircraft mass are correctly reproduced, including the sharp decrease in hover ceiling at high weights once the maximum available power (engine flat-rate or transmission limit) has been reached.

C. *Maximum cruise speed*

The maximum cruise speed represents the maximum speed at which a helicopter can cruise at given engine power rating, aircraft mass, altitude and air temperature: at this speed, the power required equals the power available (unless maximum cruise speed is limited by the maximum operating speed, but such flight conditions have been discarded from the following comparisons). Typical performance charts from helicopter flight manuals provide maximum cruise speed data for a wide range of aircraft masses and pressure altitudes (H_p), usually at the maximum continuous engine power rating (MCNT). Fig. 6, 7 and 8 provide comparisons between maximum cruise speed reference data (full lines) and BADA H estimates (dashed

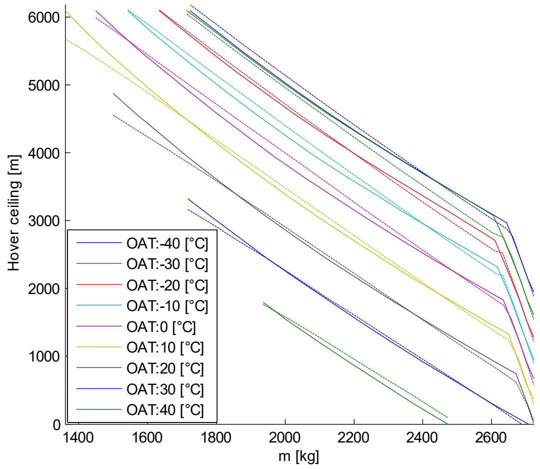

Fig. 3. Hover ceiling comparison (model H1, MTKF power)

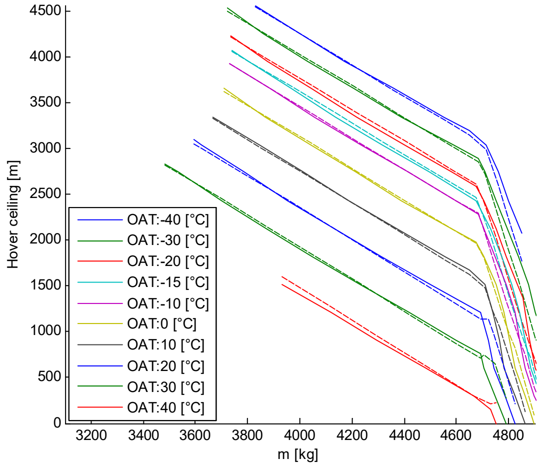

Fig. 4. Hover ceiling comparison (model H2, MTKF power)

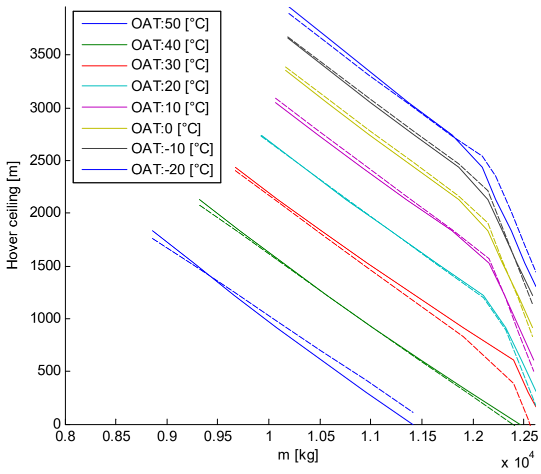

Fig. 5. Hover ceiling comparison (model H3, MTKF power)

lines) for the three example models, in order to assess the consistency between the power required and the power available (MCNT) models of BADA H in the typical flight conditions where the MCNT rating is employed. The H1 and H2 models demonstrate a similar goodness of fit, where the effects of altitude and aircraft mass are correctly reproduced. The H3 model, however, cannot reproduce the large reduction in maximum cruise speed that occurs at high altitude and mass for this helicopter type: as a result of the least-square criterion used in the identification process, the model minimizes the error over all flight conditions, to the detriment of the accuracy at low altitudes and masses.

D. Fuel consumption

Typical performance charts from helicopter flight manuals provide cruise fuel consumption data for a wide range of aircraft masses, airspeeds and pressure altitudes. Fig. 9, 10 and 11 provide comparisons between fuel flow reference data (full lines) and BADA H estimates (dashed lines) for the three example models, in order to assess the accuracy of the power required and fuel flow models of BADA H in typical cruise flight conditions. While reference data were available down to zero airspeed for the H3 model, they were only available down to 50kt for the H1 model and 20kt for the H2 model. All three models demonstrate a similar goodness of fit, where the effects of airspeed and aircraft mass are correctly reproduced.

V. KNOWN LIMITATIONS AND FUTURE WORK

The initial release of BADA H presented in this paper has focused on the key features required to model the performances of the most common helicopter types in ATM applications. This section discusses areas for improvement and further work that could be conducted to validate the model behaviour.

The power required model of BADA H currently assumes that the helicopter is equipped with a single main rotor. This is the most common configuration, but some helicopter types are equipped with two main rotors, which can be arranged in different configurations (e.g. tandem, coaxial or intermeshing). In addition, the engine power model of BADA H can only manage turbine engines at the moment, while some very common helicopter types are equipped with piston engines. Such limitations will need to be addressed if a wider coverage of helicopter types is requested by the ATM community.

Several performance aspects have been disregarded in the initial release of BADA H, because they were deemed unimportant for ATM applications. The impact of ground effect on the power required, for instance, or the impact of altitude and temperature on the never exceed speed, have not been modelled but could be included if they prove useful to some applications.

For the sake of consistency with the other BADA families, the formulation of the total-energy model in BADA H makes a small-angle approximation regarding the flight path angle. Helicopters, however, can climb and descend at high flight path angles (up to 90°) that exceed the domain of acceptability of this approximation. While high-angle operations, including

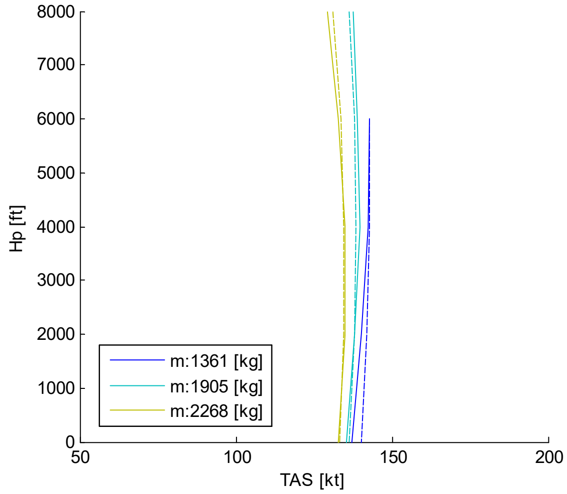

Fig. 6. Maximum cruise speed comparison (model H1, ISA)

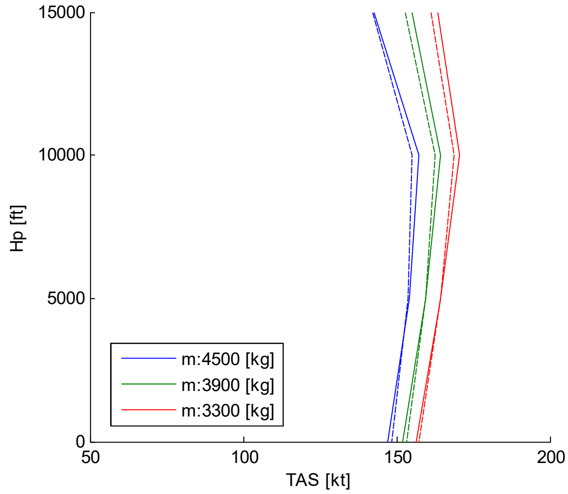

Fig. 7. Maximum cruise speed comparison (model H2, ISA)

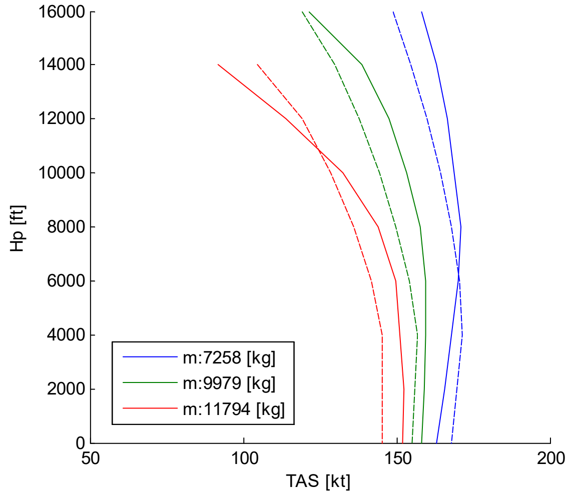

Fig. 8. Maximum cruise speed comparison (model H3, ISA)

vertical climb and descent, can be simulated with the current model, the accuracy of the performances computed in such cases could not been assessed because of a lack of reference data corresponding to these operations.

As mentioned in section II.C, climbs and descents seem to be usually performed by helicopters at constant vertical rates, instead of constant engine power rating. The value of the constant rate selected for each climb and descent operation can be defined by local procedures or pilot preference, and is therefore difficult to model at the aircraft level: a specific analysis will be required to evaluate the goodness of fit between the vertical profiles computed using the BADA H operations model and the vertical profiles observed in helicopter flight recordings.

VI. CONCLUSIONS

An extension to the BADA APM dedicated to helicopter aircraft has been presented in this paper. The objective of this new APM is to provide, using a simple theoretical model and for various helicopter types, realistic estimates of helicopter performance to support trajectory prediction and fuel burn estimation in ATM applications. The initial validation results presented for three helicopter models have demonstrated a good fit between helicopter performances computed with the new APM and both theoretical expectations and reference performance data. Future work will address known limitations of the model, in terms of supported helicopter types and operations, and further validation of its suitability to ATM applications.

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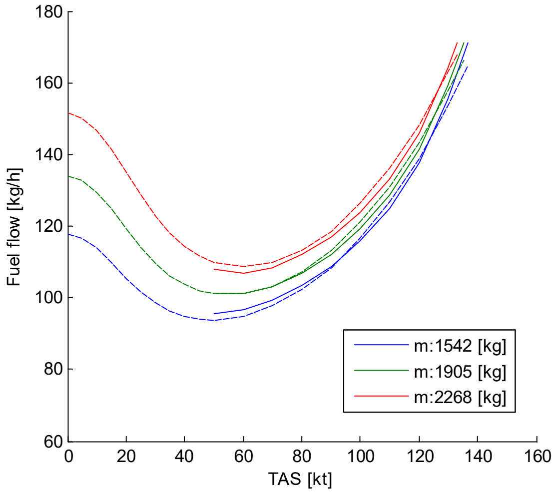

Fig. 9. Fuel flow comparison (model H1, ISA, sea level)

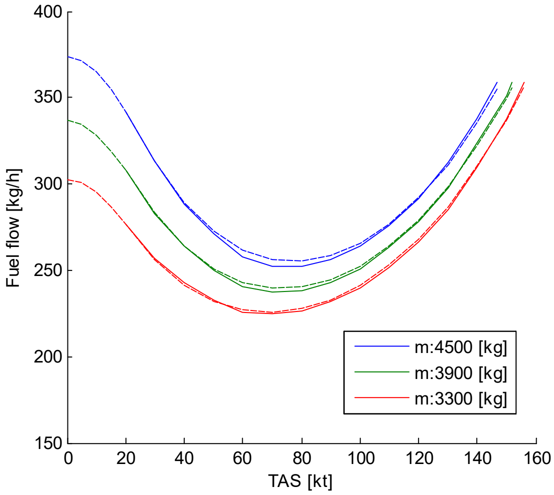

Fig. 10. Fuel flow comparison (model H2, ISA, sea level)

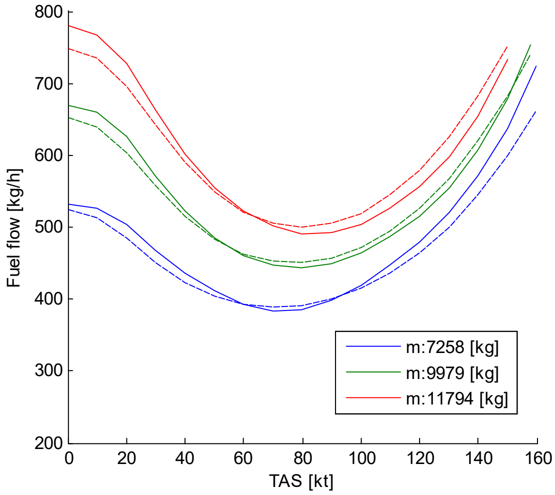

Fig. 11. Fuel flow comparison (model H3, ISA, sea level)

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David Phu is currently a Safety Nets expert in the SESAR R&D department at EUROCONTROL and has previously worked on aircraft performance modelling with the BADA team as part of the EUROCONTROL Graduate Program. He holds a master's degree from Cranfield University in Aerospace Vehicle Design and an engineering degree in ATC computer systems from the ENAC in Toulouse.