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Vidyarthi, Kushagra; Beuker, Mathijs; Yin, Feijia; Voskuijl, Mark; Pavel, Marilena

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HOPLITE - A CONCEPTUAL DESIGN ENVIRONMENT FOR HELICOPTERS INCORPORATING MORPHING ROTOR TECHNOLOGY

Kushagra Vidyarthi, k.vidyarthi@tudelft.nl
Mathijs Beuker, beuker.m.j@gmail.com
Feijia Yin, f.yin@tudelft.nl
Mark Voskuijl, m.voskuijl@tudelft.nl
Marilena Pavel, m.d.pavel@tudelft.nl
Faculty of Aerospace Engineering, Delft University of Technology (The Netherlands)

Abstract
The SABRE project has been initiated under the EU's Horizon 2020 programme for development of blade morphing technologies for helicopter rotors. The project targets reductions in fuel burn and NOx emissions of upto 5-10% through the use of morphing rotor blades. A new design tool for rotorcraft, HOPLITE, is being developed to investigate the effects of rotor morphing on engine emissions and fuel burn. HOPLITE uses low-fidelity models for quick and reasonably accurate force and power calculations for major components of the vehicle. The main rotor is modelled using the Blade Element Method, and accounts for changes in blade shape due to rotor morphing and other geometrical modifications. Additionally, a robust fuselage parameterization method, and an equation based engine model have been incorporated in HOPLITE to include the impact of rotor morphing on the design of the helicopter as a whole. The main argument behind the development of HOPLITE is to combine various low-fidelity methods, such that quick design assessments can be performed for various purposes, and, simultaneously, have sufficient fidelity to capture changes in blade shape due to rotor morphing. Actuator disk models can perform a quick analysis, but are unable to match the required level of fidelity. In comparison, traditional CFD simulations or experimental campaigns will be cost and time intensive. Hence, there is a need for a new tool. Due to a multidisciplinary and modular approach used by HOPLITE, it can be used for a wide range of tasks, such as design space exploration and optimization. Furthermore, it can be used in conjuction with high fidelity methods. This paper describes the current work done towards the development of various modules of the tool, theoretical aspects of engine, fuselage and rotor modelling, and initial results obtained during development and testing of individual modules. Theoretical aspects of conceptual design capabilities of the tool have also been briefly described in this paper. Future work will involve development and integration of conceptual design functions in HOPLITE for conventional helicopters, and expansion of these algorithms to non-conventional rotorcraft designs.

1. INTRODUCTION

The current state-of-the-art in helicopters indicates that the main rotor system of the vehicle is a multi-point design. This results in the rotor being sub-optimal in all flight regimes. To address this issue, the Shape Adaptive Blades for Rotorcraft Efficiency (SABRE)[1] project has been initiated under the EU's Horizon 2020 programme. The main goal of the project is the development of blade morphing technologies for helicopter rotors. SABRE envisions rotor blades whose shape can be changed at a frequency of 1/rev or 2/rev depending on the concept. The goal of the project is to optimize rotor performance in all flight conditions and achieve reductions of 5-10% in fuel consumption, noise and NOx emissions[1].

Through the use of morphing blades, the need for a compromise in the geometry of helicopter rotors is eliminated as the blades can change shape to suit operating conditions. The project envisions a multi-functional morphing rotor that combines different morphing concepts to allow for a broad range of shape changes. In this way, a number of physical mechanisms for reducing power consumption and emissions can be addressed simultaneously.

One of the requirements arising out of SABRE is the need for a tool which can assess the impact of rotor morphing on engine emissions and fuel consumption, and on the overall design of the helicopter. The analysis of the rotor needs to be fast enough to quickly assess the impact of rotor morphing, but also needs to have sufficient fidelity level, so that it is able to capture the effect of changes in rotor blade shape. These two requirements dictate the choice of software code which can be used for rotor analysis. For this purpose, various software codes available for rotorcraft design and analysis have been looked at. Two codes frequently utilized for conceptual design of rotorcraft are NDARC, developed by NASA[2], and the toolbox developed during the course of RIDE project[3]. Specifically these two tools have been compared, since their algorithms and capabilities are placed on the opposite ends of the performance and fidelity spectrum.

NDARC is capable of conceptual design of a wide range of rotorcraft configurations. The tool can perform a range of calculations, enabling the user to create a new rotorcraft design for a given input mission and performance requirements. It has been validated consistently[4] over the course of its development. NDARC utilizes the actuator disk model and energy balance methods for computation of rotor power requirements. This implementation, despite being fast, is unable to account for local changes in blade shape. As a result, NDARC's utility for the SABRE project is limited and a higher fidelity modelling method for the rotor is necessary to properly analyse local changes in blade shape, which may arise due to rotor morphing.

The toolbox developed under the RIDE project is as versatile as NDARC. It features high-fidelity methods for fuselage modelling, and is capable of wide range of analysis methods such as full scale numerical analysis of the fuselage, including boundary layer calculations and pressure drag estimation using VSAERO[3]. It also possesses high-fidelity optimization algorithms for the fuselage size. A library of different helicopter components allows for better control over the outer fuselage shape. The use of high-fidelity methods results in a large computational power and time penalty. Therefore, this toolbox also has limited utility for the requirements of the SABRE project.

After looking at already available codes for rotorcraft design and analysis, it was decided that a new tool will be required, such that it is tailor-made to fulfil the analysis requirements of the SABRE project. This tool will be used for a variety of purposes, such as the comparison of different morphing techniques based on aerodynamic efficiency, or power consumption and component weight. The tool should be able to predict changes to critical performance parameters, such as maximum fuel load, payload capacity, top speed and rate-of-climb. Therefore, it must be able to utilize concepts of aerodynamics, structures and flight mechanics for a high-level analysis of the complete helicopter, and should combine speed with a reasonable level of fidelity. The multidisciplinary analysis capability of the tool will enable a broader usage in various research settings as well. HOPLITE (Helicopter Conceptual Design and Performance Analysis tool) is the outcome of these requirements.

HOPLITE models the helicopter at a sub-system level, and implements design and analysis algorithms in a modular architecture for four primary subsystems of the helicopter, i.e. the main rotor, fuselage, tail rotor and engine. These modules are used for single-point analyses, and operate at varying levels of fidelity. They form the core of the tool, and are appropriately named Analysis Modules. A description of these modules in given in Sec. 2. These modules are controlled by higher level modules, which are appropriately named Control modules. They form the interface between the tool and the user, and are responsible for the implementation of the two main operation modes of the tool: the Design mode and the Analysis mode. The Control modules are described in Sec. 3. A description of the operation modes is given in Sec. 4. Additional support modules have also been created, which are utilized by all Analysis modules for their operation. These support modules implement algorithms for standard atmosphere and trim calculations. A pyramidal scheme for architecture of HOPLITE is shown in Fig. 1.

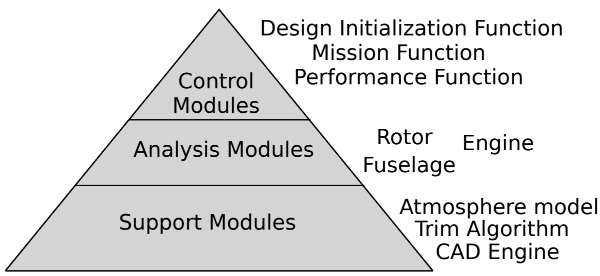

Figure 1: Architecture levels of HOPLITE

During the course of development of HOPLITE, various components have been tested individually and in combination with other modules. Key results are discussed in Sec. 5. For validation purposes, the MBB Bo105 has been selected as the reference vehicle by the SABRE consortium, due to the abundance of data in the public domain. In order to maintain uniformity and promote future interoperability between project members, the Bo105 has also been used for validation of HOPLITE. Initial work focussed on development and testing of the Analysis modules of the tool, since they form the core of the basic working of HOPLITE. Once these modules have been properly implemented, it would be rather straightforward to develop the tool further. Full scale development and testing of the conceptual design capabilities of the tool and further development goals are discussed in Sec. 6.

2. ANALYSIS MODULES

The Analysis modules form the core of HOPLITE's design and analysis capabilities, as mentioned before. These modules form the second layer of the architecture of the tool, and are used by the Control modules as single-point analysis tools. This means that these modules simulate their respective helicopter components for one flight state at a time. There is no direct interaction between the user and the Analysis modules. Based on the input flight condition (velocity, rate-of-climb, altitude), the modules calculate force and power requirements of their respective components. These outputs are then combined to obtain the total power required by the helicopter for the input flight condition. This implementation is beneficial because the Analysis modules can be run in parallel, thereby reducing computation time. In addition, these modules can be used independently to simulate isolated components when provided with the necessary inputs for their operation. A brief description of individual modules is given below.

2.1. Rotor Modelling

Rotor Modelling is the first of the two most important aspects of the tool from the point-of-view of the SABRE project. The model for the main rotor is required to be detailed enough to capture local changes in the shape of the blade and calculate forces generated as a result. This requirement has made the Blade Element Model (BEM) a viable candidate for rotor modelling. Additionally, it is computationally less expensive, in comparison to a full numerical simulation. During the course of development of morphing concepts by various project partners, extensive high-fidelity analysis will be performed on rotor blades with morphed shapes in order to assess the changes in local blade aerodynamics. This data can be coupled with the Blade Element model to improve prediction capabilities of the model. Necessary provisions have also been made in the rotor module, so that rotor performance data, or corrections to aerodynamic data, resulting from experimental methods (whirl tower and wind tunnel tests) and numerical methods (coupled CFD-CSD methods, CAMRAD II analysis etc.) can be used for analysis of the rotor, such that the Blade Element model can be bypassed altogether.

The blade element implementation facilitates the division of the rotor blade into a number of sections at incremental radial stations along the span. Fifteen blade elements have been used in preliminary testing of the model. These blade elements have varying geometric properties (incidence angle, chord, airfoil shape, twist), which can change linearly or non-linearly along the blade span. Forces calculated for blade elements along the span are then integrated numerically along the span and azimuth to obtain the total forces of the rotor for one complete rotation. The rotor model uses the Glauert inflow model[5] with corrections for calculation of variation in induced velocity along the blade span and azimuth (in forward flight). The model also features the Prandtl tip loss function[5] in order to ensure that the physical effect of a finite number of blades, in comparison to an infinite disk, is modelled with a reasonable level of fidelity. Blade flapping is accounted for by use of flapping equations in the form of a first order Fourier series, as described by Pavel[6].

Once the flow conditions for a particular blade element are known, airfoil lookup tables are employed for calculation of lift and drag coefficients. Lookup tables increase the calculation speed for rotor forces, and remove the unreliability of panel codes like XFoil, due to flow separation or compressibility effects. Airfoil tables also allow for incorporation of morphing of the main rotor, since aerodynamic tables will be obtained from experimental testing of different morphing concepts during later stages of SABRE. These tables can be used as input to the rotor module. Airfoil data is corrected for compressibility effects (Karman-Tsien corrections[7]), and high angle of attack and post-stall corrections (Viterna corrections[8]) are also applied to improve accuracy of rotor analysis.

The rotor module requires the current flight condition and rotor control angles (collective and cyclic pitches, disk tilt angle) generated by the trim algorithm as input parameters to the Blade element model. These parameters are important as they influence the forces on the rotor blades. The total thrust and power requirements of the rotor are then fed back to the trim algorithm, which iterates to obtain convergence. Fig. 2 shows the workflow of the rotor module.

The most effective way to validate the functioning of the rotor model is by comparing the power curves generated by the tool against those of the reference helicopter. This requires other modules of the tool to function in conjunction with the rotor module. As a result, preliminary results and validation of the rotor model and the tool as a whole is discussed in Sec. 5.

2.2. Engine Modelling

The Engine model is the second most important aspect of HOPLITE, as dictated by SABRE requirements. The main function of the engine model is prediction of the real-time fuel burn and NOx emission index in response to changes in power required due to blade morphing. In keeping with the already established standard of operation of individual Analysis modules, the engine module has also been designed for single-point analysis. This enables the module to function with morphed as well as unmorphed rotors, thereby increasing the versatility of the model. The model has been developed by considering the Rolls Royce M250-C20B Turboshaft engine as the baseline engine, since this engine is used in the reference helicopter.

The engine has been modelled using Gas Turbine Simulation Program (GSP)[9]. GSP is a component based generic modelling tool, which allows steady state and transient simulation of various gas turbine engine configurations. A 0-D thermodynamic model of the engine has been created using GSP, and is shown in Fig. 3. This model does not depend on detailed dimensions of the engine, and relies more upon the internal thermodynamic processes of the engine for a design point calculation. To facilitate this, the design point needs to selected and defined carefully in terms of power required, fuel flow rate and mass flow rate. Off-design calculations rely upon the design point to a very large extent.

For the input shaft power requirement, the GSP model calculates critical engine parameters, such as inlet and outlet temperatures of components, mass flow rate through the engine, and fuel burn and engine emissions. The design point for the 0-D model has been selected as Sea-Level ISA take-off conditions with 100% shaft power required. Using this reference point, off-design conditions can be analysed using GSP.

Fuel flow rate, CO_2 and NO_X emissions are the desired output parameters of the engine model. CO_2 emissions are directly dependent on fuel flow rate. Therefore, emphasis has been given to the calculation of NO_X emissions. The NO_X emission index ($EINO_X$) is influenced by a large number of factors. The combustion chamber geometry for the reference engine is not available and therefore, a simplified semi-empirical method has been employed for emission index estimation. This method requires combustor inlet temperature, pressure, fuel consumption and $EINO_X$ as input data at the reference point of the engine in order to compute off-design emissions. $EINO_X$ at the reference point has been predicted by use of a validated empirical correlation recommended by FOCA[10].

The emission model has been validated using measured emission data[10] for a typical Landing Take-off (LTO) cycle. A typical LTO cycle contains ground idle (GI), take-off (TO) and climb to 3000 feet (914 meters), and approach (AP) to land. For a helicopter, the TO process includes hover and climb (TO) to 3000 feet (914 meters), with the rest remaining identical. Additionally, the emission model has been verified based on a one-hour flight mission scenario. A comparison of Fuel flow rate and $EINO_x$ predicted by the model for the LTO cycle has been compared with data available from FOCA[10], and is shown in Figs. 4 - 5.

The validated model has been used for regression analysis, and simplified equations have been developed for quick and easy prediction of engine emissions and fuel flow rates. The first task in development of regression models is the selection of input parameters which influence fuel burn and $EINO_X$ the most. Several parameters, which may directly or indirectly influence fuel burn and emissions, have been considered. In order to identify the relevance of parameters under consideration, a sensitivity analysis has been performed.

The first main parameter which influences fuel flow and emissions is shaft power required from the engine. Fig. 6 shows the variation of $EINO_X$ and fuel flow rate with respect to the shaft power and flight speed. ISA sea-level conditions have been considered. The figure shows that both the $EINO_X$ and fuel flow rate are strongly dependent on the shaft power requirement, but are less sensitive to the flight speed. Increasing flight altitude has no direct influence on $EINO_X$ and fuel flow rate for constant shaft power required. It should be noted that shaft power required from turboshaft engines employed in helicopters is

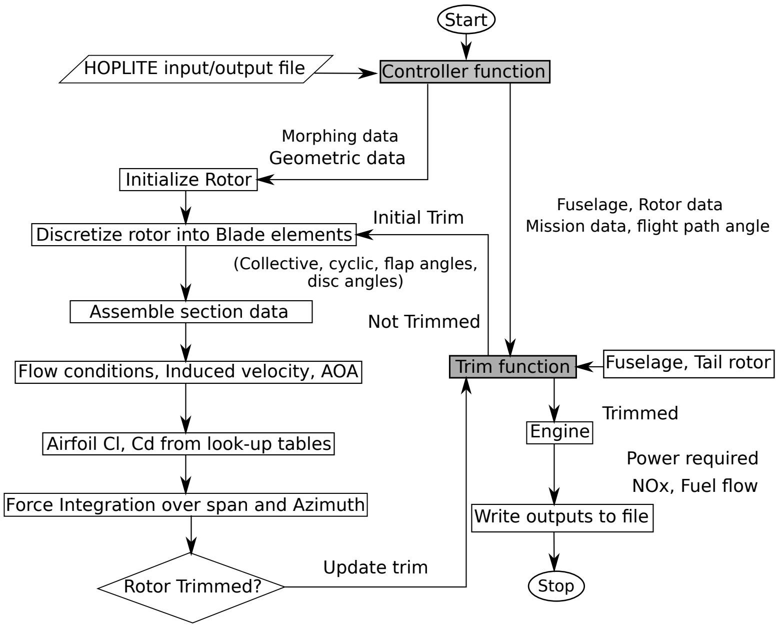

Figure 2: Workflow diagram of rotor module

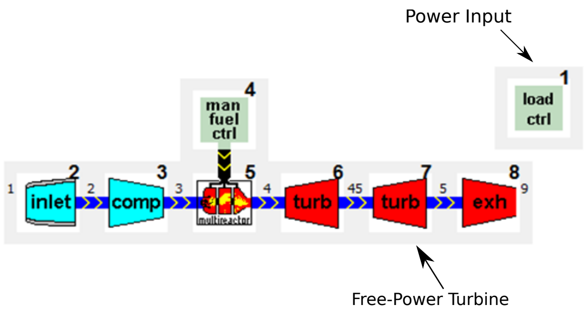

Figure 3: 0-D Thermodynamic model of M250 turboshaft engine modelled in GSP

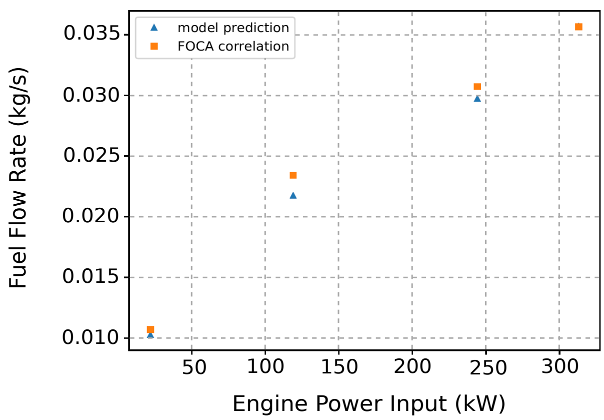

Figure 4: Fuel flow rate validation for LTO cycle

usually influenced by altitude and flight speed. Hence, these parameters would indirectly influence fuel burn and emissions.

The second major parameter to influence emissions and fuel flow of the engine is ambient temperature. Fig. 7 shows the variation of $EINO_X$ and fuel flow rate versus the shaft power and flight speed when the ambient temperature increases from ISA condition to ISA+30K. From the figure, it can be clearly seen that in addition to shaft power required, engine parameters are also influenced by ambient temperature conditions. The variation in ambient temperature conditions translates to the departure of temperature from standard atmosphere conditions, e.g. due to hot day operations or hot and high take-off conditions. It should be noted that fuel flow rate is not influenced by temperature variations. On the other hand, NO_X formation is affected by ambient temperature. This can be observed in the figure.

The results of sensitivity analyses have reduced the number of input parameters for regression models for engine fuel flow and emissions to two, i.e. shaft power required and ambient temperature deviation from standard atmospheric conditions. Final regression models for emissions and fuel flow rate predictions are represented by Eq. 1, where $\beta_o, \beta_1, \beta_2$ and ϵ are constants.

$$EINOx = \beta_o + \beta_1.SHP + \beta_2.\Delta T_{sa} + \epsilon \quad (1)$$
$$\dot{m}_f = \beta_o + \beta_1.SHP + \epsilon$$

Regression equations for fuel flow and engine emissions are linear, with shaft power required being the dominant input parameter. This makes the equations easy to implement in HOPLITE's engine module, and allow for quick and accurate

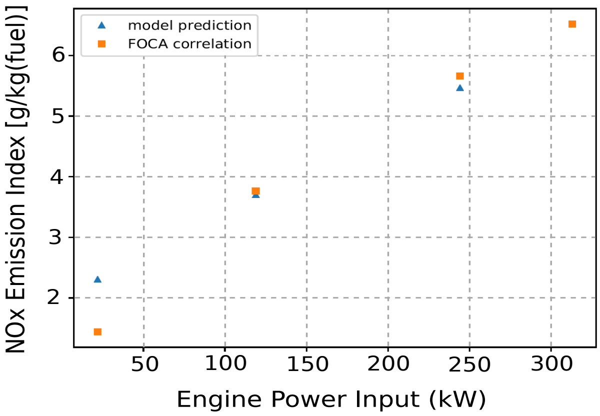

Figure 5: EI NOx validation for LTO cycle

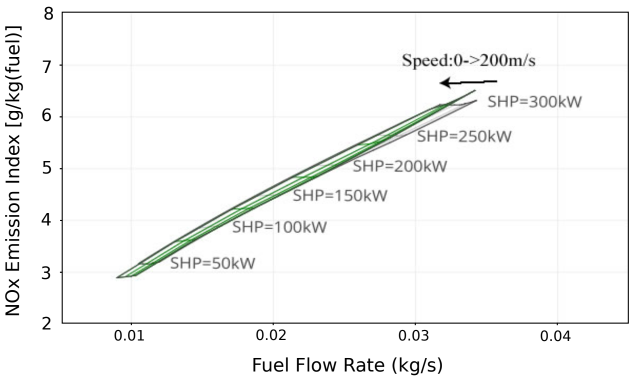

Figure 6: Sensitivity of fuel flow rate and EINOx to flight altitude for ISA condition for a given shaft power (SHP) and speed range

calculations of the desired parameters. A validation of the engine model is discussed in Sec. 5, alongside the validation for rest of the modules.

2.3. Fuselage Modelling

The Fuselage model implemented in HOPLITE is important in assessing specific modifications to the fuselage and its layout, which will result from rotor morphing. Aspects such as overall layout, fuel tank volume, payload volume, cargo hold dimensions, number of passengers and external dimensions of the fuselage, will be affected directly or indirectly by rotor morphing. Therefore, it is necessary for the model to be robust and fast, and respond adequately to different modifications which may happen to the fuselage during analysis of rotor morphing. In this direction, a unique parameterization method for the fuselage has been developed.

The helicopter fuselage is modelled by a series of super-elliptic cross sections, which are placed along the longitudinal axis of the fuselage. These

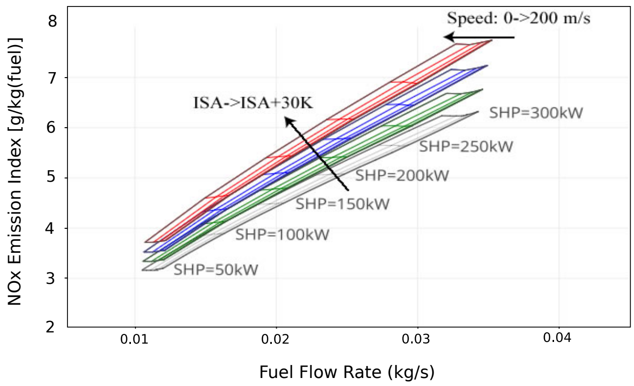

Figure 7: Sensitivity of fuel flow rate and EINOx to ambient temperature at sea level for a given shaft power (SHP) and speed range

cross-sections can be lofted together to form a solid. The cross-section shapes are created using a method first described by Freeman and Mineck[11]. These super-ellipses are defined by Eq. 2.

$$\begin{aligned} y(\theta) + y_0 &= |\cos\theta|^{\frac{2}{n}} \cdot a \cdot \mathrm{sgn}(\cos\theta) \\ z(\theta) + z_0 &= |\sin\theta|^{\frac{2}{m}} \cdot b \cdot \mathrm{sgn}(\sin\theta) \end{aligned} \quad (2)$$

for $0 < \theta < 2\pi$, where a and b are the semi-diameters of the curve, n and m are power factors describing the curve's curvature, x_0 and y_0 indicate the offset from the origin and the sgn function returns the sign of the term. A tube-like shape can be created by positioning a series of super-ellipses along their common out-of-plane axis. Local control of fuselage shape is maintained through a distribution of super-ellipse parameters a, b, n, m, $y0$, $z0$ along the fuselage's longitudinal axis. Distributions of most relevant parameters along the longitudinal axis have been created to globally control the shape of the fuselage. These parameters are height (H(x)), width (W(x)), power factors n (N(x)) and m (M(x)), and a reference height from the longitudinal axis (Zo(x)).

In most cases, the outer shape of a helicopter fuselage is symmetric about the longitudinal plane. Thus, for each x-location of the cross-section distribution, $y_0 = 0$ is a valid assumption. Locally, at any longitudinal x-location i, $H(x_i) = 2b$, $W(x_i) = 2a$ and $Z0(x_i) = z_0$.

Example parameter distributions that define the fuselage cross sections are shown in Figs. 8-9. Fig. 8 shows the side view of a fuselage and includes the H-curve for height and Zo-curve for longitudinal axis of the fuselage. These curves are related to the outer contour through,

$$\begin{aligned} H(x) &= z_{up}(x) - z_{low}(x) \\ Z0(x) &= \frac{1}{2}\left(z_{up}(x) + z_{low}(x)\right) \end{aligned} \quad (3)$$

where z_{up} and z_{low} represent the z-coordinates of the upper and lower contours respectively. Fig. 9 shows the W-curve, which equals the outer width contour. Finally, the power factor distributions N and M control the super-ellipse shape on the top/bottom and sides respectively. Fig. 10 shows the resulting series of cross sections due to the parameter distributions. These cross sections are subsequently lofted together to form a solid 3D shape.

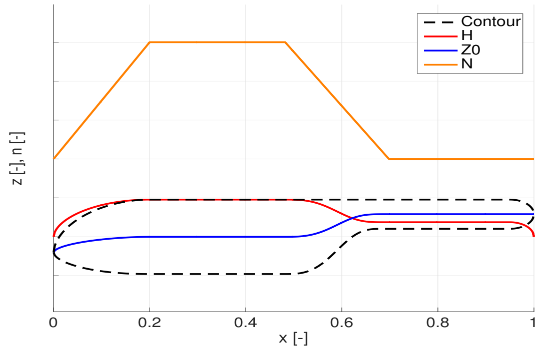

Figure 8: Longitudinal super-ellipse parameter distribution - Side view

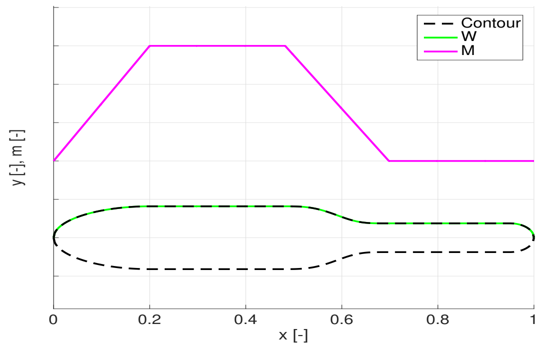

Figure 9: Longitudinal super-ellipse parameter distribution - Top view

The true strength of the fuselage parameterization method lies in the number of parameters required to define a fuselage shape. A low number of parameters is desired for user-friendliness. Fig. 11 shows the side view of a typical fuselage model created using the parameterization method described above. The figure also shows some of the parameters required to define the fuselage. Variables in red are mandatory inputs for the parameterization algorithm, yellow are optional inputs, and blue can be calculated from other variables. Approximately 30 parameters are required to define the overall size and shape of the fuselage. This makes the parameterization method robust and capable of handling any changes required to be made to the fuselage.

Parasite power calculation of the fuselage is based on an empirical flat-plate drag area, which is used to compute the drag coefficient of the fuselage based on the maximum take-off weight of the helicopter. The fuselage modelling algorithm has been currently applied to create a CAD model of a conventional helicopter configuration, which has been discussed in Sec. 5. Future applications of the algorithm also involve coupling to a commercial CFD solver for better aerodynamic analysis of the fuselage shape. The CAD model can also be used as a starting point for development of the internal layout or detailed structural analysis of the fuselage.

2.4. Support Modules

A number of support modules are required for proper functioning of the primary Analysis modules. These modules are available for all other components. They form the third layer of HOPLITE's architecture, and are briefly described below:

1. **Standard Atmosphere module** - This module implements the International Standard Atmosphere model as described by ICAO[12]. The module requires flight altitude and an ambient conditions parameter, which sets conditions such as hot day operations, as inputs. The outputs are air pressure, temperature, density and viscosity. These parameters are used by rotor, fuselage and engine modules for calculation of power required, and engine emissions etc. The rotor module relies heavily on atmosphere data for force and power calculations, and Mach and Reynolds' number calculations for various corrections applied to airfoil data.

2. **Trim Algorithm** - This module forms the interface between major analysis modules of HOPLITE, and is responsible for trimming the vehicle in any flight state. The trim algorithm implemented in HOPLITE is a 3-DOF, multi-rigid body model, which trims the vehicle using a Jacobian inversion method. Equations of motions for the helicopter have been obtained from the work of Pavel[6]. The model presented by Pavel is a 6-DOF model, but it has been simplified by assuming translations and rotations are allowed only in the longitudinal plane. For future implementation, the full 6-DOF model will be used, in order to improve stability at high

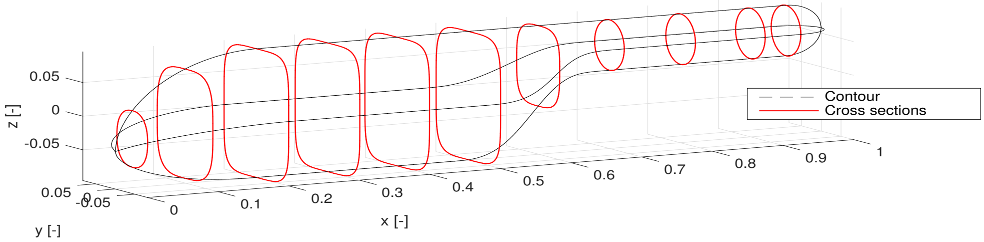

Figure 10: Isometric view of fuselage showing distribution of super-ellipses along longitudinal axis

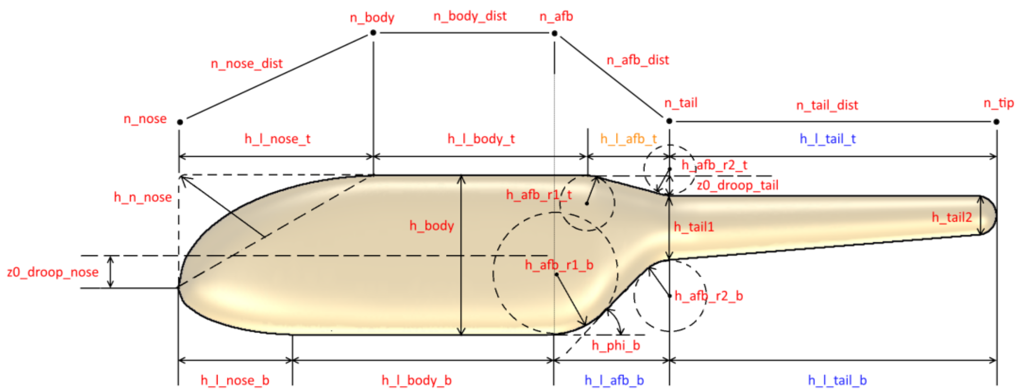

Figure 11: Side view of fuselage showing variables necessary for fuselage modelling

speeds, and also to facilitate trim for configurations with multiple rotors.

The trim algorithm performs an initial trim calculation based on the required flight conditions. The results are used as an input to fuselage and rotor modules; the two main analysis modules of HOPLITE. The analysis modules compute the forces of their respective components based on control angles provided as input by the trim module. The forces are fed back to the trim algorithm, which calculates the accelerations in horizontal ($\dot{u}$) and vertical ($\dot{w}$) directions, along with a pitch rate ($\dot{q}$). The algorithm iterates until the accelerations are below a preset minimum value. The algorithm incorporates stick limits on collective and longitudinal cyclic controls, and rate limits on control angles to reduce the time taken to trim the vehicle. Once trim has been achieved, the total power required by the helicopter is used as an input to the engine module for calculation of real-time emissions and fuel burn values. Therefore, the trim algorithm essentially interacts with all major modules of HOPLITE, and forms the backbone for any operation mode.

3. **CAD Engine** - The CAD engine has been implemented keeping in mind internal and external volume constraints. The parameterization method developed for the fuselage has been implemented in the CAD engine, and allows for quick changes to the fuselage geometry and internal design. It will also be useful to detect any inconsistencies in design parameters or sizing parameters of the helicopter. Additionally, the CAD model created by HOPLITE can form the basis for further structural or aerodynamic analysis, as desired by the user.

Since support modules assist Analysis modules in their analysis, their individual validation results are of little value. Nevertheless, preliminary results generated by the trim algorithm and the CAD engine in particular have been discussed in Sec. 5.

3. CONTROL MODULES

These modules form the main interface between the Analysis modules and the user, and control the execution of the Analysis modules. Control modules accept design requirements from the user in the form of an input file. Based on the amount of data available from the user as input, they decide which analysis modules need to be executed, and which functions of HOPLITE should be brought into use for the task specified in user inputs. As a result, these modules are placed in the top layer of the tool's architecture, as seen in Fig. 1. The Control modules are responsible for two main functions of the tool, i.e. Conceptual Design and Performance Analysis functions. These functions are briefly described below.

3.1. Conceptual Design Functions

Conceptual design capabilities of HOPLITE indirectly arise from one of the main SABRE requirements, i.e. the tool should be able to predict what rotor morphing does to the helicopter as a whole. The tool goes a step further and tries to apply the predicted modifications to the helicopter, so that a more direct visual comparison can be made between configurations with the baseline rotor and the morphed rotor. The goal is to reduce the workload of the user, by transferring redesign tasks of the helicopter from the user to the tool. Conceptual design functions are also capable of performing the design of a helicopter for specific user requirements from the ground up. This makes the tool more versatile, and allows the user to perform a wide variety of tasks from one single piece of code. These functions incorporate two sub-routines for generating an initial design based on specific requirements, and for creation of a design space for any optimization algorithms to work in. The design space is also based on top-level user requirements. The two sub-routines are described below.

1. **Design Space generation** - This is one of the most important algorithms of the tool, and undertakes the tasks of initial weight estimation, and calculation of minimum engine power and rotor diameter. The algorithm uses top-level requirements, such as payload weight, number of passengers, maximum range and cruise speed, to calculate the maximum take-off weight (MTOW) of the helicopter for the given mission profile. The calculated MTOW is used for sizing and weight estimation of individual components in the next stages. Other top-level requirements such as hover ceiling, service ceiling and maximum forward speed are used to create a design space, which is essentially a plot of disk loading vs power loading for the helicopter, and is inspired by the work of Kamal[13]. Such a diagram is shown in Fig. 12 for the reference Bo105 helicopter. The figure shows various top-level performance requirements used for determining the feasible region of the design space (unshaded), and also shows the disk loading and power loading for the Bo105 ("Reference Value" in Fig. 12). The design space can be used for estimation of engine power (from a fixed power loading) and rotor disk diameter (from a fixed disk loading) from MTOW calculated during previous steps of the algorithm. This allows for a fast estimation of important dimensions of the helicopter. The algorithm can also be used for any optimization or redesign tasks as well, since a design space with various additional performance requirements enforced on the configuration can be created. Looking at Fig.

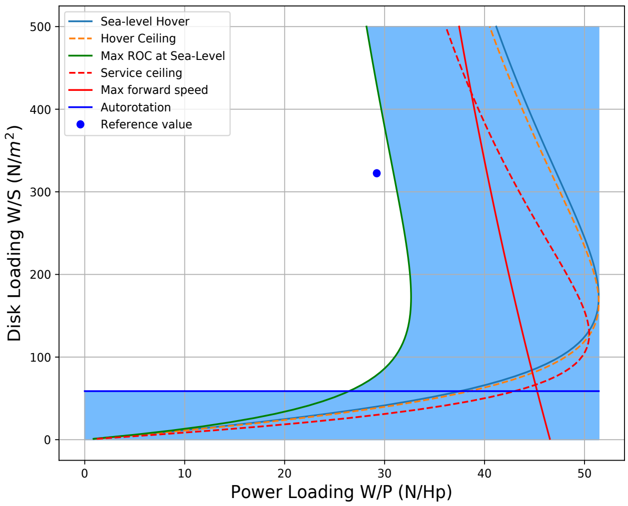

Figure 12: Design space algorithm applied to Bo105

12, the most optimal design would be in the bottom right of the feasible region. This signifies the smallest possible engine and rotor capable of fulfilling operational requirements. It can be observed that the reference helicopter is away from the most optimal point. This is due to the fact that the equations used to develop the design space are based on the actuator disk model for the rotor. The associated simplifications made in this model influence the shape and position of the curves of the design space. More detailed models will result in shifting of the curves, and will lead to the reference values for the helicopter coming closer to the optimal point. Also, additional constraints may arise due to additional performance requirements, which would result in a further shifting of various curves and feasible region of the design space. It is important to mention that this algorithm is used only for an initial calculation of helicopter size. This size is used as a starting point for more detailed calculations, which would modify dimensions of different components of the vehicle. This initial calculation will lead to a reduction in computational time. A flow chart for the design initialization algorithm is shown in Fig. 13.

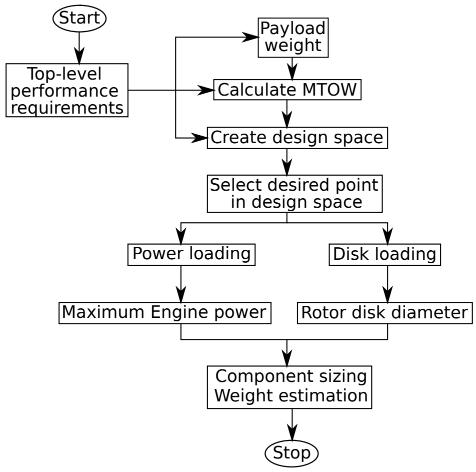

Figure 13: Design initialization task flow diagram

2. **Design Initialization, Sizing and Weight Estimation** - Once the Design space function has been executed, the MTOW of the vehicle and size of the rotor disk are available for a predefined mission definition. These parameters influence the sizes of almost all other components of the helicopter. A database of 27 light-utility helicopters has been compiled, and dimensions of important components of the fuselage, landing gear and tail rotor have been analysed. Regression models for sizes of different components have been developed from this data for use in detailed sizing of the helicopter. These models have been developed with an intention of keeping the number of input parameters to a minimum. As a result, the MTOW and rotor disk diameter are featured in almost all sizing equations of the helicopter. The regression models will be validated during further development of HOPLITE, and will be expanded to heavier helicopters in the future.

   Weight estimation is based on statistical models developed by Beltramo and Morris[14] in the 1980s. The overall accuracy of these models is acceptable, since significant changes have not been seen in manufacturing processes of different structural components. Thus, these models can still be used, until updated models are available in the future.

The two main conceptual design sub-routines can work together with optimization algorithms in order to achieve redesign of the baseline helicopter in response to rotor morphing, or perform conceptual design of the helicopter for user defined top-level requirements.

3.2. Performance Analysis functions

When an optimizer will be incorporated in HOPLITE, it will require feedback from the tool's Analysis modules for a predefined mission. Performance Analysis functions come into picture at this point. These functions interact directly with the Analysis modules, and gather performance data for each component of the helicopter in response to a predefined mission profile. In essence, these functions decompose a mission profile into discrete analysis points, which are then passed as input to the Analysis modules. The output is in the form of performance metrics, such as power required for each component. These are then stitched back together to generate performance metrics for the entire helicopter for the given input mission profile. This allows the Analysis modules to work in any operation mode desired by the user without modifications. The Performance Analysis functions are composed of two main modules, which are the Mission module and the Performance module. These are briefly described below.

1. **Mission Module** - The mission module is responsible for decomposing the mission profile into discrete analysis points as described above. Individual analysis points are defined as a data set that comprises of forward velocity, altitude, rate-of-climb or flight path angle, and ambient operating conditions (e.g. hot day conditions). HOPLITE has a set of predefined missions, termed as Design missions, for performing sizing of various components such as fuel tanks, engine, fuselage, and for judging the performance of various components in different flight states. These missions have been inspired by similar missions for fixed wing aircraft used during the conceptual design process. The mission module can also accept user defined missions, for analysing

the performance of a particular configuration for a desired application. The mission definition has been standardized to allow the tool to use any mission profile.

2. **Performance Module** - This module performs the task of gathering data from individual Analysis modules, and consolidating parameters such as forces, moments, power required, engine emissions and fuel burn. These parameters can be then used by Conceptual design functions for design modifications, or for optimization tasks as required. The Performance module also contains algorithms for creation of performance plots and output files, which can be analysed by the user independently, or used as further inputs to external tools of higher fidelity.

A schematic of the interaction between Performance Analysis modules and various Analysis modules is shown in Fig. 14. Analysis modules are executed in parallel for a given Analysis point. The Mission module loops over the entire mission profile sequentially, allowing the Performance module to generate the required performance metrics of the helicopter for the complete mission profile.

Control modules can perform a number different tasks. These are grouped into two operation modes, which are described in the subsequent sections.

4. OPERATION MODES

HOPLITE's modules define the components it can analyse and basic tasks it is capable of performing. The tool's Operation modes define the sequence in which these tasks are performed, and which modules are executed at what point. Operation modes also dictate what kind of outputs will be available after completion of all tasks. The choice of operation mode is dependent on specific user inputs, and the amount of data available to the tool as input. The two main operation modes of the tool, the Design mode and the Analysis mode, are described below.

4.1. Analysis Mode

This mode is a collection of the most basic tasks performed by HOPLITE, and in essence, is an implementation of the Performance Analysis functions of the tool. It requires a large number of user inputs, specifically all data generated by Conceptual Design functions of the tool. This mode is useful when a fixed helicopter configuration is required to be analysed for different missions or flight regimes, or to modify very specific parameters in the helicopter, and assess their impact on performance. This mode has been developed keeping in mind the requirements of the SABRE project. The Analysis mode does not utilize all modules available in HOPLITE, and relies only upon the modules present under Performance Analysis function and individual Analysis modules for the helicopter. A schematic workflow of this mode is shown in Fig.14.

During the initial development and testing of the tool, the Analysis mode has been heavily tested. For fulfilling SABRE requirements, this mode is found to be sufficient for comparison of different morphing concepts.

4.2. Design Mode

This operation mode utilizes maximum modules and capabilities of HOPLITE. It makes use of Conceptual design functions, in addition to all modules used in the Analysis mode. As a result, many additional tasks, such as design space exploration, configuration optimization, conceptual design from scratch, can be performed by the tool. In addition, this mode is capable of incorporating and interfacing external optimization algorithms or higher fidelity analysis tool. This mode, and its component modules, are under active development at the time of writing this paper, and will be described in more detail in future.

5. INITIAL RESULTS

During the course of development of HOPLITE, different modules and algorithms have undergone extensive testing so that their accuracy can be improved and operational ranges established. In its current state, the Analysis modules of the tool have been successfully developed and tested. Initial testing has been performed for a simple mission. Mission parameters are described in table below.

Parameter	Description
Flight Regime	Straight and Level flight
Climb angle	0 degree
Velocity Range	0 - 50 m/s
Altitude Range	Sea-level to 3000 m
Operating weight	2500 kg

Table 1: Mission profile description for testing of HOPLITE's modules

Important results of extensive testing have been

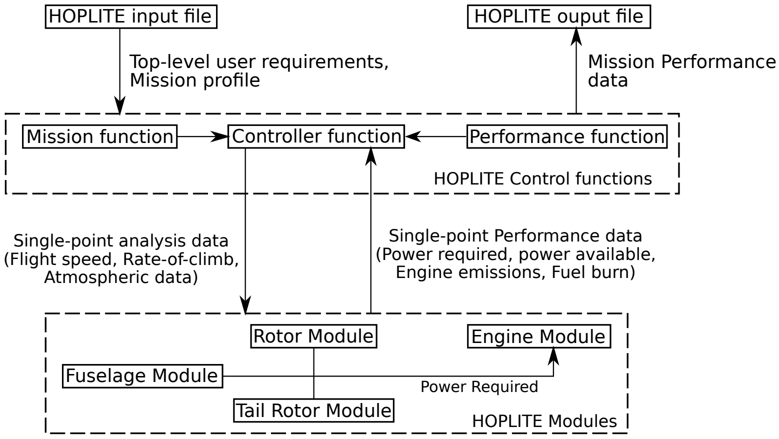

Figure 14: Workflow of HOPLITE in Analysis mode

discussed in the following sections. It should be noted that the Control modules are still under development at the time of writing this paper. As a result, the fuselage parameterization algorithm has been tested by means of the CAD engine, which is a component of the Support modules of the tool. The validation of performance metrics generated by HOPLITE has been done using flight test data for sea-level flight of the Bo105 helicopter. Unfortunately, flight test data for higher altitudes is either unavailable or unreliable at this stage. Therefore, validation of performance metrics for higher altitudes has not been possible, and a more theoretical approach for judging the results has been utilized.

5.1. Fuselage parameterization

For testing of the Fuselage parameterization algorithm, external dimensions of Bo105 have been used as input to the CAD engine. The output is shown in Fig. 15. In the figure, the exact shape of the fuselage differs slightly from the real helicopter due to the distribution of power factors m and n. Outer dimensions in terms of maximum length, width and height are approximately equal to those of the reference helicopter.

Additionally, the CAD engine has been able to implement a parametric method for creation of the rotors and tail surfaces. The rotors have the same dimensions as those of the Bo105 and also feature a linear twist and chord distribution. The CAD engine will be a useful asset in the future development of the tool, where internal and external volume constraints will be enforced on the fuselage for conceptual design and optimization purposes.

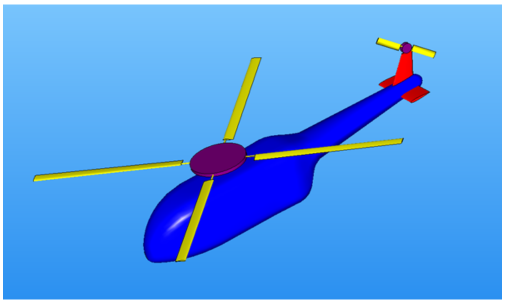

Figure 15: CAD model of a conventional helicopter configuration

5.2. Power Prediction

Analysis modules of HOPLITE have been connected together and tested for the mission profile described above. Initial results, in the form of curves for power required vs true airspeed, are shown in Fig. 16 for various flight altitudes. The curves obtained follow the familiar inverted bell-shaped profile for a helicopter in straight and level flight.

Various observations can be made from Fig. 16. At low speed, rotor power dominates, and fuselage parasite power becomes dominant for higher speeds. As forward speed increases, power curves at different altitudes tend to converge due to fuselage drag being the dominant component of power requirement. It can also be seen that as the altitude is increased, power required for hovering increases for a constant vehicle weight. Minimum power speeds on the power curves are very close to the actual minimum power speed of the reference helicopter. Unfortunately, it is hard to validate these curves for higher altitudes due to unavailability of flight test data. Nevertheless, power prediction by HOPLITE can be explained properly by means of theoretical calculations

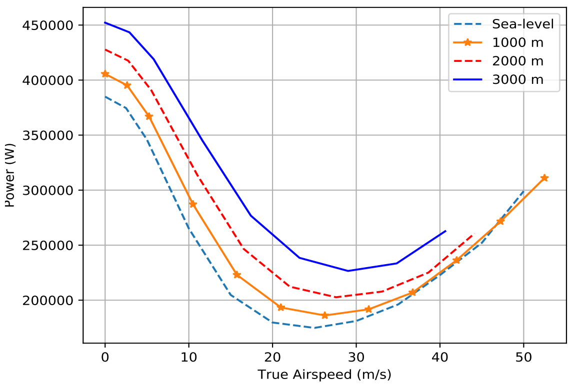

Figure 16: Power required vs Airspeed for Bo105 at various flight altitudes

found in standard texts on helicopter aerodynamics. Therefore, power prediction by the tool is found to be satisfactory at the current levels of fidelity of rotor and fuselage models.

5.3. Engine Modelling

The engine model has already been validated for an LTO cycle. The dominant input parameter of the model is shaft power required. Therefore, the model's performance has been tested for the mission profile described above. Power required calculated for the reference helicopter by the Analysis modules has been used as input to the engine model. The resultant fuel flow rate and NOx emission index curves are shown in Figs. 17 - 18.

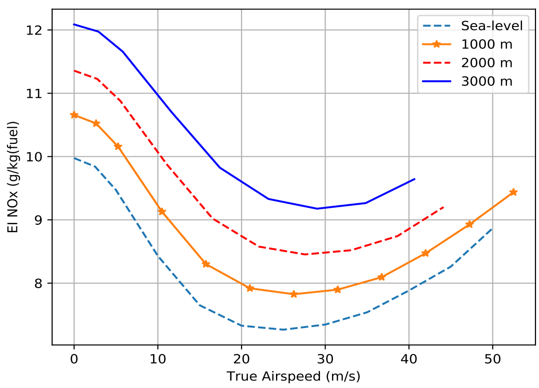

Figure 17: Engine Emission vs Airspeed for Bo105 at various flight altitudes

The curves tend to follow trends similar to those seen in Fig. 16, since the main input parameter of the regression models for the engine model is engine shaft power requirement. It is interesting to note that as the altitude is increased, unlike fuel flow rate and power required curves, lines for NOx emission index do not converge at higher speeds. This can be attributed to the additional parameter of ambient temperature variation in the regression equation for NOx emission (Eq. 1).

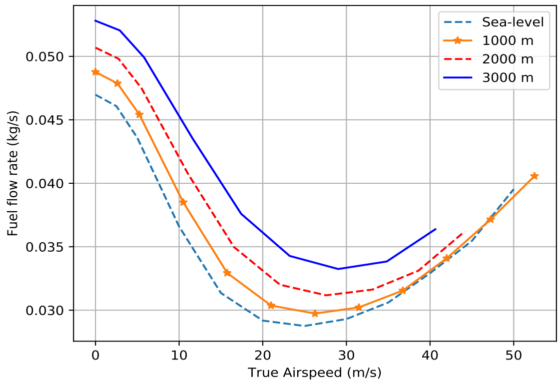

Figure 18: Fuel flow rate vs Airspeed for Bo105 at various flight altitudes

5.4. Trim Algorithm

Trim data for the Bo105 at altitudes other than sea-level is scarce or unreliable. The support module for Trim has been used in the mission analysis and power calculations. Due to the various approximations made to simplify rotor and fuselage models, the control angles are underestimated by the trim algorithm when compared to flight test data at sea-level. Nevertheless, an intuitive validation of the algorithm is possible by analysing the collective pitch angle calculated by the algorithm. The collective pitch is plotted against forward speed for different altitudes in Fig. 19.

The curve for a fixed altitude follows the inverted bell-curve profile also seen in power curves (Fig. 16). As the flight altitude is increased, collective pitch is found to increase. This is intuitively correct, since there is not much difference in the thrust required for trim at low speed due to a constant vehicle weight used during the analysis. However, due to a reduction in density, the rotor blades must now operate at a higher angle of attack to generate the same amount of force. Therefore, a higher collective is required for trim, which is seen in the plot. At higher speeds, specifically above 90 knots, the trim algorithm has difficulty in computing control angles due to control cross-coupling, and deficiencies in the rotor model. This will be

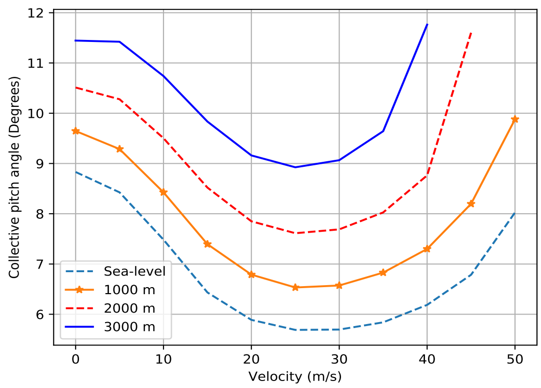

Figure 19: Collective pitch vs Airspeed for Bo105 at various flight altitudes

addressed in future developmental work of the tool.

6. FUTURE WORK

Future work towards improvement of Analysis modules of HOPLITE would involve incorporation of higher order flap dynamics models, and improvement of inflow models for targeted improvements in rotor modelling. The fuselage model will include weight estimation and sizing models for its components. The current 3-DOF trim algorithm has problems at high speeds. This will be remedied by exploring a 6-DOF force model for the helicopter.

Conceptual design capabilities of the tool will be implemented, and expanded to include heavier weight class helicopters, and different rotorcraft configurations like co-axial rotors and tandem rotors. Emphasis will also be laid on validation of performance improvements due to rotor morphing, and possible scaling of the morphing concepts to rotors of different sizes and applications.

7. CONCLUSIONS

The current status of development process of HOPLITE and its components has been presented in this paper. Active development of the tool is still in progress, and many components of the tool require improvements. The rotor module has been designed with the intention of coupling speed with acceptable levels of fidelity for a quick analysis of different morphing concepts being developed under the SABRE project. The preliminary results obtained during development and initial testing of HOPLITE are promising. Trends seen in power curves, engine emissions and fuel burn predictions are intuitively correct, and can be explained reasonably well using simple calculations. The theoretical aspects for algorithms for design space development and design initialization have been described in this paper as well. These algorithms will be incorporated and tested in the future.

The final objective of the development program of HOPLITE is the creation of a software package which is capable of accomplishing conceptual and preliminary design of conventional and unconventional rotorcraft, using a combination of medium and low fidelity methods, and at the same time demonstrating the feasibility of various morphing concepts applied to rotors. The tool can serve as a base for applications like design space exploration, as a base for higher order analysis methods, or for more advanced purposes such as development of a new vehicle configuration from the ground up.

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