

FLIGHT PERFORMANCE CALCULATION OF ROTORCRAFT IN THE CONCEPTUAL DESIGN PHASE

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Abstract

Rotorcraft design involves different disciplines within the aeronautical sciences and due to that it is a highly challenging and complex process. During the last years the German Aerospace Center (DLR) developed an integrated design framework within internal projects. The simulation environment RCE (Remote Component Environment) is used which allows coupling of tools developed by various institutes and distributed calculation on different servers. Therefore, it is possible to place the tools on the hosting institutes for administration and maintenance purposes but still being able to use the tools during the design process. The flight performance calculation is one of the main parts within a sizing loop. To analyze the flight mechanic properties the simulation tool HOST (Helicopter Overall Simulation Tool) developed by Airbus Helicopters was implemented into the process. This paper presents the implementation of HOST into the distributed design environment and the execution of flight performance calculations. The results of the iteration of the required range with the adaption of fuel mass are also shown. Finally, a comparison of a simulation model generated during the presented design process with a validated HOST model is shown.

Keywords

Rotorcraft design; flight performance; conceptual and preliminary design; fuel estimation; high velocity configurations

NOTATIONS

Symbols

A_{MR}	Main rotor disc area, m ²
a	Additional fuel mass factor, kg/km
C_T	Thrust coefficient, -
c_{MR}	Main rotor chord, m
G_{MTOM}	Weight force at maximum take-off mass, N
m_{BEM}	Basic empty mass, kg
m_{blade}	Blade mass, kg
m_{EQU}	Equipment mass, kg
m_F	Fuel mass, kg
m_{fe}	Furnishing and equipment mass, kg
m_{MTOM}	Maximum take-off mass, kg
m_{Fnew}	New fuel mass, kg
m_{OM}	Operator's mass, kg
m_p	Payload mass, kg
m_{propu}	Propulsion mass, kg
m_{SMM}	Specific mission mass, kg
m_{struc}	Structure mass, kg
m_{syst}	System mass, kg
R_{dif}	Range difference, m
R_{actual}	Actual range, km
$R_{required}$	Required range, km
R_{MR}	Main rotor radius, m
V_h	Horizontal velocity, m/s
V_{hnew}	Reduced horizontal velocity, m/s
σ	Rotor density, -
Ω_{MR}	rotor speed, rad/s
θ	Pitch angle, deg
ϕ	Roll angle, deg

Abbreviations

ACT/FHS	Advanced Control Technology / Flying Helicopter Simulator
AFDD	U.S. Army Aeroflightdynamics Directorate
CAMRAD II	Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics
CPACS	Common Parametric Aircraft Configuration Schema
CREATION	Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrttechnik)
EDEN	Evaluation and Design of Novel Rotorcraft Concepts
HOST	Helicopter Overall Simulation Tool
IRIS	Integrated Rotorcraft Initial Sizing
MDO	Multidisciplinary Design and Optimization
NDARC	NASA Design and Analysis of Rotorcraft
RCE	Remote Component Environment
RIDE	Rotorcraft Integrated Design and Evaluation
TLAR	Top Level Aircraft Requirements
TRIAD	Technologies for Rotorcraft in Integrated and Advanced Design

1 INTRODUCTION

The design of rotorcraft configurations is a highly multidisciplinary challenge like aircraft design. Major disciplines like aerodynamics, structural design or flight performance calculations are involved to develop new configurations.

The German Aerospace Center (DLR) developed a sizing workflow for rotorcraft design [1]. After a revision of some modules the current design workflow is called IRIS (Integrated Rotorcraft Initial Sizing). The development of this design environment is a collaboration between the DLR Institutes of Flight Systems, Aerodynamics and Flow Technology, and Structures and Design. In 2010 DLR started the first internal project RIDE (Rotorcraft Integrated Design and Evaluation) and afterwards (2014) the project EDEN (Evaluation and Design of Novel Rotorcraft Concepts) to create a tool chain for rotorcraft design. After developing new calculation tools, adapting some tools from the aircraft design and validating the developed tool chain with reference calculations, the third internal project TRIAD (Technologies for Rotorcraft in Integrated and Advanced Design) started in 2018. The goal of this project is to predict the impact of new technologies on a virtual rotorcraft and new high speed configurations. As higher airspeeds are a big challenge for new rotorcraft configurations, new technologies are investigated, e.g. wing combinations, additional thrust generators (props) and composite materials. In this new project two additional DLR Institutes have been involved. The Institute of System Architectures in Aeronautics supports the structure and process of the tool chain. To further investigate the exchange of information between design and application the Institute of Aerospace Medicine develops a Medical and Rescue Compartment for a new rescue helicopter.

Other research institutions like ONERA or NASA developed similar design tools. ONERA developed C.R.E.A.T.I.O.N. which is a multidisciplinary computation platform for the evaluation of rotorcraft concepts with respect to flight performance and environmental impact [2], [3]. NASA developed the rotorcraft system analysis tool NDARC (NASA Design and Analysis of Rotorcraft). It is a design and analysis code for rapidly sizing and conducting performance analysis of rotorcraft concepts [4]. To calculate the flight performance NDARC uses CAMRAD II (Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics) [5].

The whole design process of a new rotorcraft configuration can be divided into three main phases according to Raymer [6]: the conceptual, the preliminary and the detailed design phase (see FIG 1). The design process starts with the conceptual design phase. Therefore it is necessary to define mission requirements and specific configuration restrictions. The accuracy of these Top Level Aircraft Requirements (TLARs) improves during the sizing loop. Result of this first phase is the external configuration, a mass and balance estimation, and a flight performance calculation. At the end of this first phase already 80 – 90% of the new configuration is defined even though the detailed construction has not yet begun. The second phase is the preliminary design phase.

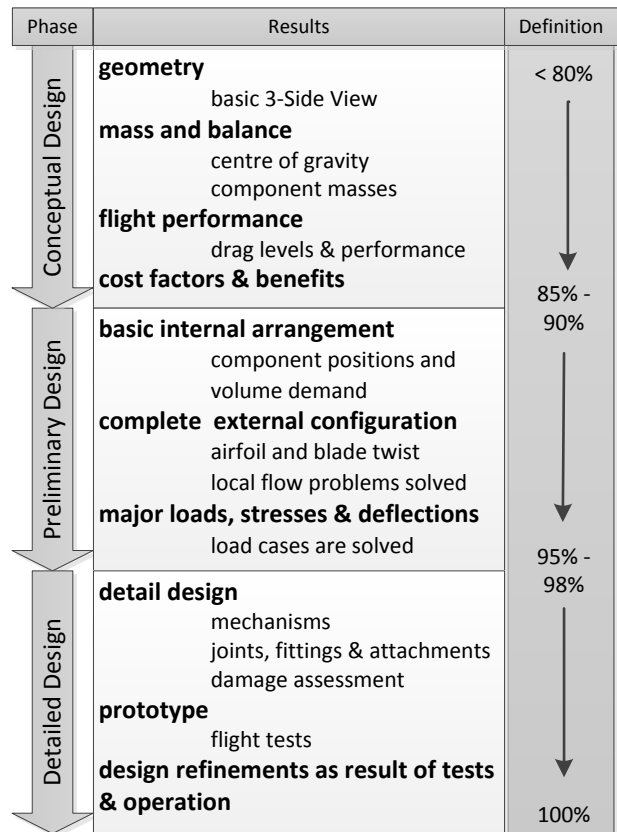


FIG 1 Rotorcraft design process in three phases

The goals are to define the basic internal arrangement, to complete the exact shape of the external configuration, and to solve the major load cases.

The last phase is the detailed design phase to finish the design process. In the last phase the focus is on the detailed design of mechanisms and components, damage assessment, and in the end, the production of a prototype for flight tests. IRIS includes the conceptual and parts of the preliminary design phase. The detailed design phase is not part of the presented framework.

Due to the fact that the flight performance calculation is one of the main parts of rotorcraft design the Airbus developed simulation tool HOST (Helicopter Overall Simulation Tool) was implemented into IRIS. During one run of the design process, HOST is executed in the primary sizing. So the results of the flight performance calculation influence each sizing loop. This paper presents the implementation of HOST into the distributed design workflow IRIS and the execution of flight performance calculations inside a sizing process.

2 DESIGN WORKFLOW

2.1 Design environment and data model

IRIS is build up with the collaboration framework RCE (Remote Component Environment) [7]. This software, developed by DLR, allows the coupling of tools and a distributed calculation on different servers. Hence it is

used to develop and set up the workflows for the iterative computational procedures which are needed to perform the sizing task. All tools used in the workflow remain on the server of the responsible institutes for maintenance and administration. For users on different locations it is possible to start the framework and get the results of all implemented tools but cannot edit the program code. To save all the important results calculated for a configuration it is reasonable to use a universal data format where all information of the designed configuration can be stored. Therefore, DLR developed the data model CPACS (Common Parametric Aircraft Configuration Schema) which is used within IRIS. This XML data format was originally developed for fixed-wing aircraft to have all information of an airplane in one file. To use it within the rotorcraft design projects a path is included to describe parametric rotorcraft. Currently, the extensions of the path necessary during the projects are not part of the official CPACS version but there are efforts to synchronize the included rotorcraft path extensions with the official CPACS version. During the design process the CPACS file is sent from one tool to the next one and all tools store their results in a specific path. Within every sizing loop the new calculated values can be updated in the CPACS file.

2.2 Tool classification

The tools in this design workflow have different physical modeling levels. Also the set of results and the computation time differ. To compare the different tools according to their physical modeling levels a classification in four levels ranging from 0 to 3 is made. FIG 2 shows the four tool levels with their uncertainties and robustness versus computation time and amount of required input data. The tools classified as level 0 start with the TLARs defined by the user.

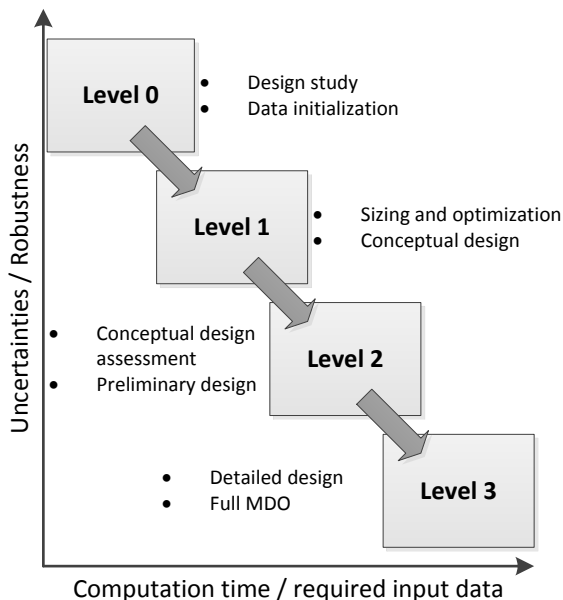


FIG 2 Tool classification in 4 different level

From the TLARs level 0 tools a data initialization is starting and generates a first setup of data based on statistics and simple mathematical equations. As shown in FIG 2 the uncertainties are the highest but the computation time is the fastest at level 0. Tools classified as level 1 are used for higher iterative procedures like sizing and optimization. Therefore, these tools start the conceptual design like described in the previous chapter. The uncertainties and robustness are lower but computation time and amount of required input data are higher. For example tools which are using the blade element theory can be classified as level 1 tools.

For the assessment of conceptual design the preliminary design level 2 tools are used. The physical modeling order is higher but the computation time is too high for an implementation in an iterative sizing loop. These tools (e.g. the unsteady panel method free-wake code) are arranged in a queue without performing recursive loops. The lowest uncertainties and robustness show level 3 tools. The detailed design is covered by them. Numerical methods including complex discretization like CFD calculations or full MDO (Multidisciplinary Design and Optimization) are common methods for this level. The computation time and the required input data are the highest. Tools of this level calculations or are not implemented into this design environment at this time.

Design approaches in [8] show a comparable classification of the tool levels from 1 to 3. In such a classification the previously described tool level 0 and 1 are combined to one level. Due to this reason the physical modeling levels between an initialization tool and a conceptual design tool can show clear differences within the works of DLR and also ONERA [9] show a level 0 classification.

2.3 IRIS

The primary sizing workflow of IRIS uses a traditional approach by iterating the maximum take-off mass, see [10]. The design process starts with a definition of at least the minimum TLARs which are listed in TAB 1. The minimum TLARs consists of the required payload mass the rotorcraft has to transport. Payload is part of the specific mission mass. The iterating take-off mass consists of the basic empty mass, fuel mass and specific mission mass, see equation (1).

$$m_{MTOM} = m_{BEM} + m_F + m_{SMM} \quad (1)$$

$$m_{SMM} = m_P + m_{OM} + m_{EQU} \quad (2)$$

Besides the payload mass the specific mission mass consists of the operator mass and the equipment mass, see equation (2). The required range and cruise speed are values to define at the beginning. The number of blades on each main rotor has shown to be sensible and needs also to be defined at the beginning, too.

TAB 1 Minimum top level aircraft requirements to execute the design process

Parameter	Unit
payload mass	kg
cruise speed	m/s
range	km
number of main rotor blades	-
main rotor arrangement	-

The last requirement is the main rotor arrangement. It is important because of the many different configurations of rotorcrafts. The choice between standard main/tail rotor configuration, coaxial or tandem is currently possible within the workflow of DLR [1]. Besides the described minimum TLARs it is possible to define optional requirements, as shown in TAB 2. The user can define inner dimensions of the middle fuselage section with height/width/length for certain cabin requirements if needed. Another important factor is the cargo hold payload fraction. From experience, up to 20% of the payload mass can be stored in the rear fuselage part depending on its design. The integration of a stern ramp will forbid storing payload in the rear part.

For the scaling of the rotor it is also possible to define a blade or disk loading, or a reference rotor radius to set boundaries. To take air density for hot and high requirements into account a reference altitude and temperature are optional specifies.

TAB 2 Optional top level aircraft requirements

Parameter	Unit
inner dimensions of the middle fuselage section (height/width/length)	m
cargo hold payload fraction	-
design blade loading	-
design disk loading	N/m ²
reference rotor radius	m
reference altitude	m
reference air temperature	°C

The primary sizing consists of two parts, the design and the analysis part. After input of the TLARs the process starts and the initial sizing using level 0 tools begins. With simple physical modeling and calculations based on statistics the initial sizing produces a first data set. If the user does not define an inner volume, the fuselage is scaled based on statistics. A first rotor sizing during the level 0 initialization is also performed. Lock number, rotor radius, rotor density and the moment of inertia are estimated (see [1] for a detailed description). All calculated values during the initialization are updated in the CPACS data model.

The iteration of the maximum take-off mass delivers a converged external configuration. The design part and the analyses part take turns in every loop (as displayed in FIG 3). In this figure it can be seen how the CPACS data model is used as an input. This data set can either be the result of an initialization or the result of a previous calculation with the intention to perform a resizing. All tools in the sizing loop are classified as level 1 tools. With this part the preliminary design starts (as described in chapter 2.2).

The design part starts with the rotor sizing. Different sizing approaches are available.

- Empirical sizing with regression curves.
- Sizing with a specified disc loading
- Sizing with a specified blade loading in connection with different combinations of flight altitude and ambient temperature.
- Setting a boundary for a maximum allowed rotor radius.
- Setting a constant rotor radius and sizing the rotor solidity (constant blade loading, variable disc loading)

These options allow a sensible input of design parameters for sizing and positioning of the rotors as the main part of the external configuration. The geometry generation is the next step resulting in a three dimensional surface of the fuselage. Basis for this is a complex approach, see Kunze [11].

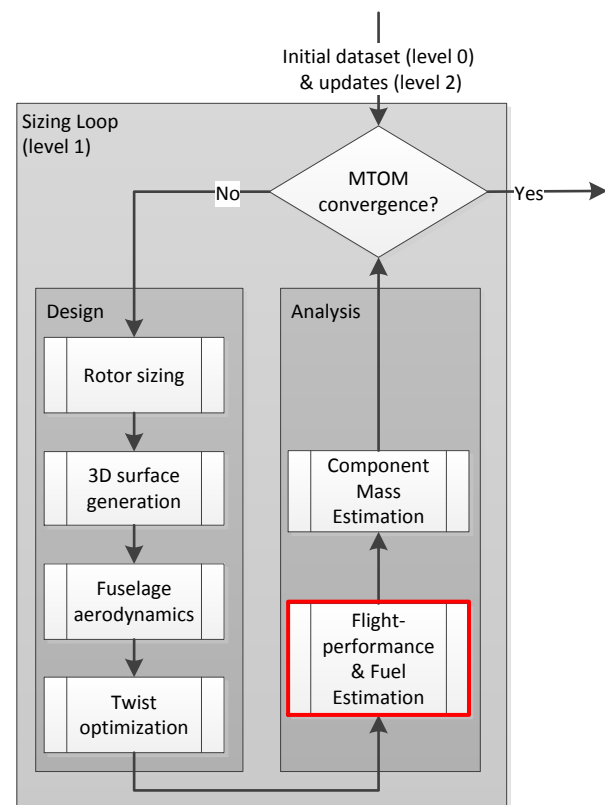


FIG 3 The primary sizing loop [1]

A CAD model of the helicopter surface is generated by coupling the commercial software CATIA V5 with the data model. For the surface generation the fuselage of the rotorcraft is divided into different segments. The fuselage assembly consists of the front, mid, rear tail and rear cap fuselage parts plus an engine cowling on top [1]. The multiple templates for every segment are assembled to build the fuselage surface.

Based on the generation of the fuselage surface, the calculation of the fuselage aerodynamics follows. The first option is the computation of the aerodynamic properties by a module (see [11]) using the commercial software VSAERO [12]. The aerodynamic module generates a structured surface mesh on the surface created in the previous step. For a clean fuselage (e.g. no rotor hub, empennage or landing gear) the module calculates the fuselage polar for every direction for different flight conditions e.g. angle of attack and sideslip angle. Second option is to scale an existing polar by similarity laws. The new forces and moments are calculated with the existing polars and cabin volume with respect to the new cabin volume.

In order to take the influence of additional sources of drag into account a correction of the polars by handbook methods is conducted. Here irregularities of the fuselage like rotor hub, empennage and landing gear are taken into account. The calculated polars of the clean fuselage will be corrected by different methods. For rotor hub and landing gear Keys [13] generates different regression curves by using the maximum take-off mass to estimate drag areas. In [14] Stepniewski divided e.g. the rotor hub into simple individual components for which drag areas are determined individually. For a rotor hub it is divided into blade shank, blade connection, bearing and middle section. The results are stored in the CPACS file.

With the calculation of the fuselage aerodynamics the design part of the sizing loop finishes and the analysis part starts. At the end of the design part it is possible to reduce the required power for a desired flight condition by optimizing the rotor blade twist, see [15]. First part of the analysis is the fuel estimation and flight performance calculation conducted by HOST. At first, based on 69 helicopter turboshaft engines summed in a statistic with respect to the maximum take-off mass, a statistic engine module defines a value of the specific fuel consumption (see [15]). With this value and the data stored in the CPACS file a flight mechanical model is generated. Different flight conditions are calculated to get the necessary power at these and allow an estimation of the necessary fuel (see more in next chapter).

Last module in the sizing loop of FIG 3 is the component mass estimation. Based on statistical methods, component masses are estimated allowing a mass breakdown for the virtual configuration. Summing up the mass breakdown results in the basic empty mass (see equation (3)), with the subcomponents are structure mass, propulsion mass, system mass, and the mass of furnishings and equipment.

$$m_{BEM} = m_{struc} + m_{propu} + m_{syst} + m_{fe} \quad (3)$$

Different methods have been implemented, where it is optional for the user which one to use. By now the methods proposed by Palasis [16], Beltramo [17], Layton [10] and the AFDD (U.S. Army Aeroflightdynamics Directorate) models by Johnson [4] are implemented. The AFDD mass models feature the highest coupling grade of geometric and performance characteristics with the resulting component mass.

To take new technologies into account and to scale component masses so-called technology factors can be used [1].

After completing the analysis part the convergence check of the maximum take-off mass is conducted. A change of the maximum take-off mass of less than 1% is considered as a converged loop. After the finished sizing loop higher fidelity computations and resizing can be used to further develop the results. These tools (level 2) show a significant higher computation time and required data and therefore cannot be integrated into the primary sizing loop. For aerodynamic analyses, unsteady panel and free-wake codes can be used. To position frames and stringers, to distribute the masses and external loads, or to statically analyse and size the fuselage with finite element methods, a more detailed structural design analysis is possible on basis of a converged external configuration (for more details see [18]).

3 FLIGHT PERFORMANCE CALCULATION

3.1 HOST

The used tool for the flight performance calculation HOST was developed by Airbus Helicopters in the 1990s [19]. The tool consists of a combination of the rotor code R85 capable of rigid and elastic blade simulation and the helicopter simulation code S80. Main functions of HOST are the trim calculations, time domain simulation and equivalent linear systems but currently IRIS only uses the trim calculation function. During the analysis arm of the sizing loop, HOST is executed in batch mode to estimate the fuel mass.

3.2 Input data and Dataset

Using all data calculated in the preceding modules and stored in the CPACS data model the required informations are extracted to generate a simulation model. For example necessary values are component positions, rotor dimensions, mass fractions, corrected fuselage polars with rotor hub, empennage and landing gear. These values are taken, for instance, from the initialization and rotor optimization.

A simulation model consists of different components. FIG 4 shows the subdivision of a conventional main/tail rotor helicopter configuration into the different model files. With several different python scripts the values needed are read from the XML-paths of the CPACS data model. In the next step the different components for the entire HOST model are written. The cell file describes the mass of the fuselage calculated during the sizing process, the position of the center of gravity (C.G.) and the inertia matrix.

The aero files of fuselage, horizontal and vertical stabilizer contain the translation and rotation positioning and the calculated and corrected fuselage polar from the sizing process. Different combinations of sideslip angle and angle of attack in a look up table displayed the fuselage polars. The rotor files of main and tail rotor contain the general informations, e.g. the positioning, number of blades of the rotor, mean chord, rotating speed.

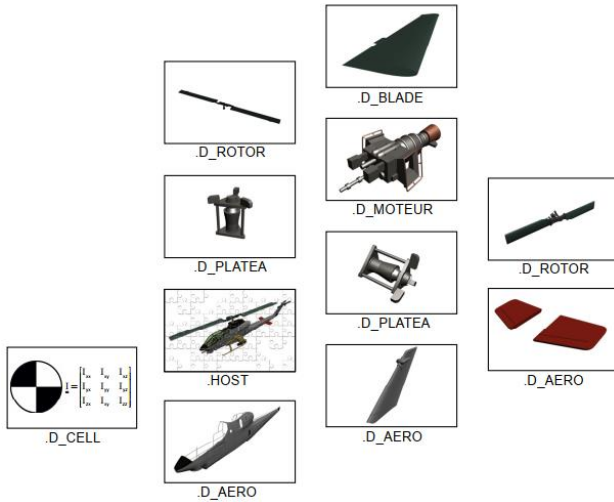


FIG 4 Simulation model components for a conventional main/tail rotor helicopter configuration

The blade files describe the hub geometry with positions of prelead/lag, precone, lead/lag, flapping pitch and parameters for flapping stiffness and damping. Changes of these parameters are small from design study to design study and that is why empirical values are used. If necessary they can be changed manually.

Also the blade geometry is defined in detail with chord and twist for every section and mass and inertia in the blade files. The swashplate files (platea in FIG 4) describe the dependencies of the commands (pedals, collective and cyclic control) to the pitch angles of the rotor blades. To synchronize the rotating directions and speeds of main/tail rotor the motor file (moteur in FIG 4) is used. It does not represent a dynamic behaviour of an engine. All models are merged in the general HOST file where the different movements, observations and interactions of the components are defined. For coaxial or tandem configurations the simulation model contain different components like, for example, two main rotors instead of one plus tail rotor. All described model files are generated automatically during the sizing loop without the monitoring of the user. The execution of the HOST calculation is conducted in batch mode. At the end of the HOST module execution the results are post-processed and stored in the CPACS file. Python scripts are again used for this task. Typical outputs from HOST which have to be processed later are amongst other required power, orientation of the rotorcraft, and command controls for the actual flight condition.

3.2.1 Fuel mass estimation

The trim and performance calculation are the basis for the computation of the fuel mass. This computation is done iteratively for every flight segment. The fuel estimation loop consists of the HOST calculation tool and a small script to adapt the fuel mass. At first the HOST calculation tool generates a simulation model as described before. HOST covers the trim and flight performance calculation at different flight conditions. Because all HOST calculations are executed in batch mode during the process, the generation of the trim condition file before every calculation is

important. The parameters needed for the trim condition file are horizontal velocity (corresponds to the cruise velocity from the TLARs), first adopted orientation and control commands of the rotorcraft, and the current maximum take-off mass. The equilibrium law for the trim calculations is always six degrees of freedom calculation. The fixed parameters are all accelerations and rotating accelerations along the three axes. Free parameters are four control commands and two fuselage orientations. The four control commands are collective control (DDZ), lateral control (DDL), longitudinal control (DDM) and yaw control (DDN). The free orientations of the fuselage are pitch (θ) and roll (Φ) angle. At least two flight conditions have to be used to calculate the actual range. These two conditions are at the beginning and at the end of a flight segment. In the first flight condition the trim is calculated with the initial fuel mass at the beginning of the flight segment. Using the required power at the minimum of two breakpoints and an estimated specific fuel consumption based on the maximum take-off mass and a mean value of the mass flow, the actual range is calculated.

With the actual range possible for the flight segment a small script adapts the initial fuel mass. First the difference between actual and required range (segment range or at least overall range from the TLARs) is calculated (see equation (4)). Afterwards with equation (5) and (6) a new fuel mass to minimize the difference is determined.

$$R_{dif} = R_{actual} - R_{required} \quad (4)$$

$$a = \frac{m_F}{R_{actual}} \quad (5)$$

$$m_{F_{new}} = m_F - a \times R_{dif} \quad (6)$$

Convergence of the fuel mass is reached as soon as the difference between actual and required range is minimized with a change of the fuel mass less than 1%.

3.2.2 High velocity HOST calculation

For the design of contemporary rotorcraft flight conditions at the limits of the conventional rotor envelope have to be taken into account. At high flight speeds the aerodynamics of the rotor disc show increasing areas of nonlinear flow. These high speed effects result in a worse convergence of the trim algorithms. Because no control commands or fuselage orientations are available as initial values before the first start of HOST, an immediate calculation of higher velocities can cause problems. There are different ways to solve such problems.

One way is to execute a trim sweep starting with hover up to the desired flight speed. Another way is to reduce the required velocity until the trim calculation obtains the equilibrium conditions and then gradually raising the velocity until the required flight speed is reached. The results from every previous flight condition serve as the initial value for the next calculation.

This latter approach was chosen because many unnecessary calculations can be eliminated. FIG 5 shows the programmed process for the stepwise approach to a high

velocity trim. The programmed process is a combination of python and shell scripts. Main part of the process is a *while-loop* which is executed until the velocity reaches the required end velocity (V_h). It starts with a first reduction of the velocity to $V_{h_{new}}$. The amount of velocity that is reduced at this point is adjustable. At the moment 1 % steps of the end velocity are used to have very small steps. This reduced velocity is the initial value for the *while-loop*.

First the trim condition file is written. The intermediate trim results for the six degrees of freedom are stored in CPACS file. The initial setup for these values is zero. Every time a calculation with reduced velocity was successful these values are updated and used as start values for the next calculation with an increased velocity. After an unsuccessful calculation with reduced velocity it is reduced further. As soon as the velocities inside the *while-loop* approach the target velocity after gradually increasing the velocity the abort criteria is reached. A final HOST trim calculation with the last calculated start values and final velocity is now executed.

This approach can be applied for every HOST calculation in the design environment to deal with flight conditions at higher velocities.

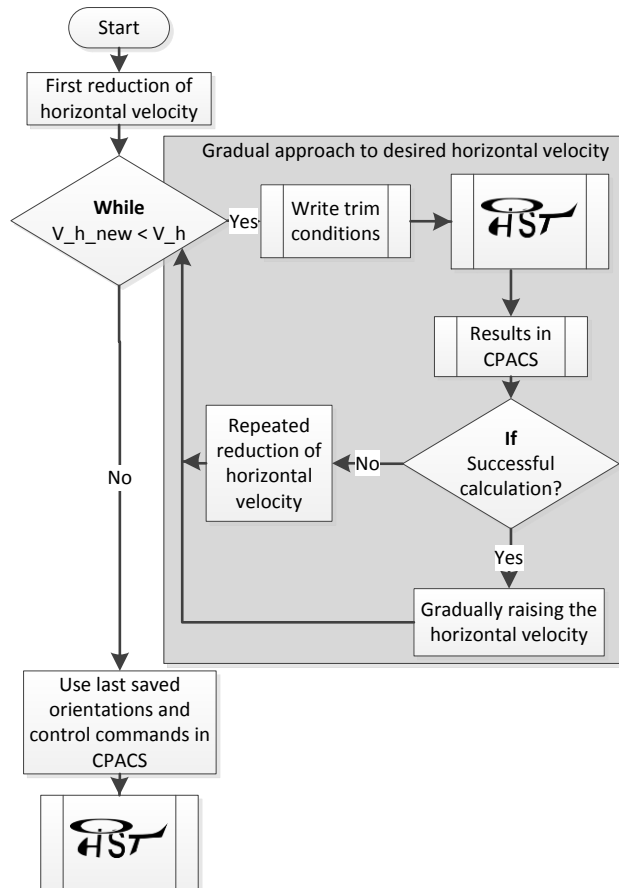


FIG 5 Process for high velocity trim calculations with HOST

4 RESULTS

4.1 Analyze of the fuel estimation loop

This chapter shows results of the iterative fuel mass computation and the simulation model generated for the flight performance calculation as it is used during the process. At first calculations with a variation of the required range were conducted.

TAB 3 TLARs for the reference helicopter

Parameter	Value
payload mass	809 kg
cruise speed	65 m/s
range	615 km
number of main rotor blades	4
main rotor arrangement	standard
cargo hold payload fraction	0.2
cabin height	1.25 m
cabin width	1.5 m
cabin length	1.7 m

The TLARs listed in TAB 3 have been identified for the ACT/FHS (Advanced Control Technology / Flying Helicopter Simulator) research helicopter operated by DLR [20]. This helicopter is a highly modified variant of an originally EC135.

The process was executed with three different required ranges. The range for the first calculation was set to 615km as specified in TAB 3. For the second and third calculation, ranges of 700km and 800km were chosen, while all the other TLARs remain fixed. The resulting fuel masses corresponding to the three ranges are shown in FIG 6.

The results show the actual range (black) and fuel mass (red) versus the iteration steps during the fuel estimation loop. For every iteration shown the HOST module executes a flight performance calculation including a gradually approach of the velocity as described in chapter 3.2.2. Only the last result points of the diagrams shows the fuel mass after the last change of the range. There is no HOST calculation executed anymore because the fuel mass has converged at this point. Generally it is seen that the actual range quickly approaches the required range. The characteristics of the curves are clearly convergent. After the first calculation most of the required range is reached. To cover up the range difference the fuel mass has to be increased. After the fuel calculation has ended the whole sizing loop continues and iterates until the maximum take-off mass converges. To finish the whole iterative process the fuel mass and maximum take-off mass have to converge. When the required range becomes larger more calculations are necessary to approach the range and finally converge the fuel mass.

The result of the calculation with a required range of 615km shows a fast approach to the range and, after a first jump, a smooth increase of the fuel mass to convergence after four calculations. For a required range of 615km the process ends with a fuel mass of 534 kg.

For a required range of 700km the fuel mass converges after six calculations. The required range is reached after four calculations. The fuel mass changes afterwards are small and only wait to finish until the maximum take-off mass of the whole sizing loop converges. For every loop inside the sizing loop the fuel estimation calculation is executed at least one time.

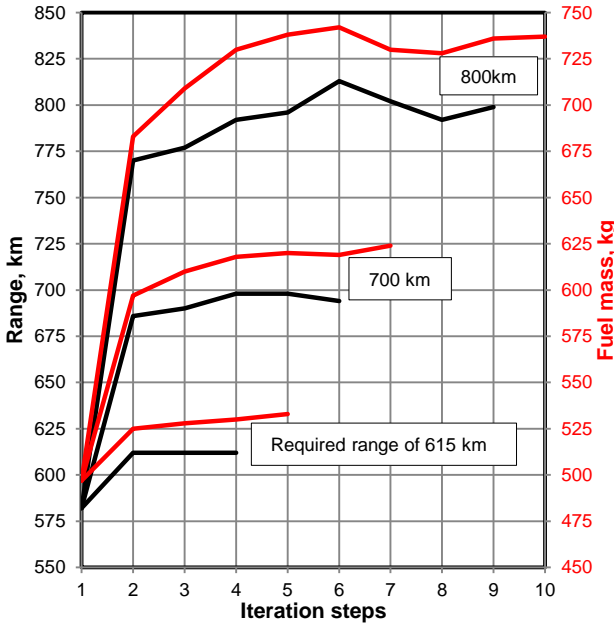


FIG 6 Fuel estimation loop results for different ranges

That is why six calculations are carried out although the required range is reached after four calculations. At the end the calculation finishes with 624 kg fuel mass.

The results of the last calculation with a required range of 800 km in FIG 6 show a similar behavior. After five calculations the required range is reached but the fuel estimation loop has to wait until the maximum take-off mass has converged. Therefore, the fuel loop needs nine calculations and finishes the small loop with a fuel mass of 737 kg. Because the design framework is an iterative process, change of the fuel mass and actual range affect most of the other calculations like rotor sizing and mass estimation. The general results, including the disk and blade loading, of the three different calculations are listed in TAB 4, together with the parameters of the reference helicopter.

It is seen that not only the fuel mass changes because of a variation of the required range. The higher fuel mass leads to an increased basic empty mass and a higher blade mass calculated by the mass estimation module, which results in a bigger maximum take-off mass at the end of the sizing loop. Also, the rotor sizing responds because of the higher disk loading for a higher required range, which results from a higher maximum take-off mass. The radius and mean chord increase to compensate the higher mass, too.

TAB 4 General results for three different required ranges

	ACT/ FHS	615 km	700 km	800 km
m_{MTOM} , kg	2,910	2,932	3,069	3,240
m_{BEM} , kg	1,544	1,590	1,635	1,694
m_F , kg	557	534	624	737
R_{MR} , m	5.10	5.16	5.25	5.35
c_{MR} , m	0.289	0.284	0.291	0.300
m_{blade} , kg	27.1	25.5	26.8	28.5
R_{actual} , km	615	612	694	799
Ω_{MR} , rad/s	41.35	40.71	40.03	39.23
G_{MTOM}/A_{MR} , N/m ²	349	344	348	353
C_T/σ	0.089	0.090	0.091	0.092

4.2 General characteristics of the virtual configuration

The characteristics of the HOST simulation model for the virtual configuration are now examined in more detail. After a converged result this model is ready to use. Furthermore a HOST model can easily be generated from an output CPACS file. The output from the computation with the TLARs listed in TAB 3 is compared with the validated HOST model with rigid rotor blades of the ACT/FHS. To compare the two different simulation models a parameter scanning of the horizontal velocity from hover (0 km/h) to a velocity of 260 km/h in 5 km/h steps was done.

FIG 7 compares the total power of the virtual and reference configuration with two different flight masses for each. It must be noted that in the two simulation models no system power or transmission losses are taken into account. To simulate different take-off masses two filling grades of fuel are used. Generally the simulations show similar results the faster the speed becomes. The power curves of the virtual and reference configuration with 100% to 80% fuel mass show a good agreement over the whole velocity range. During hovering the highest deviation between the simulation models is seen. For the virtual configuration the required power in hover is 500 kW. The value of the reference is 480 kW.

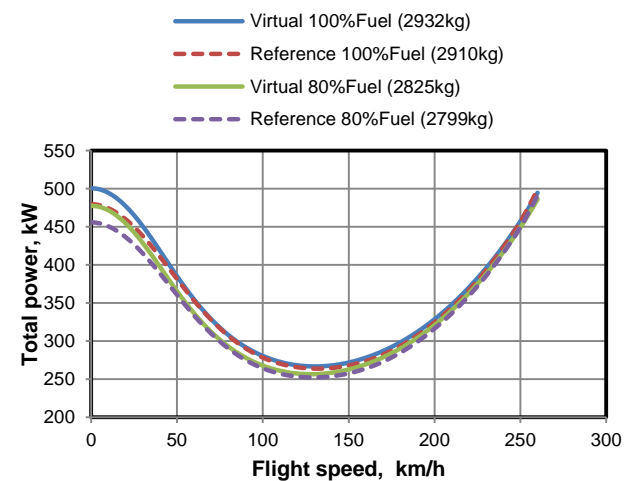


FIG 7 Total power vs. flight speed

To analyze the highest difference in power during hovering of 4% in more detail FIG 8 shows the curves for induced power, airfoil power and fuselage power (parasite) of the two models at maximum take-off mass. The influence of the tail rotor on the required total power is comparably small and it is not considered in FIG 8 where only the main rotor power curves are compared. The induced power has its maximum at hover. Due to the decreasing induced velocities with increasing advance ratio the required induced power decreases. On the other hand the fuselage and airfoil power generally show the most influence at the higher velocities.

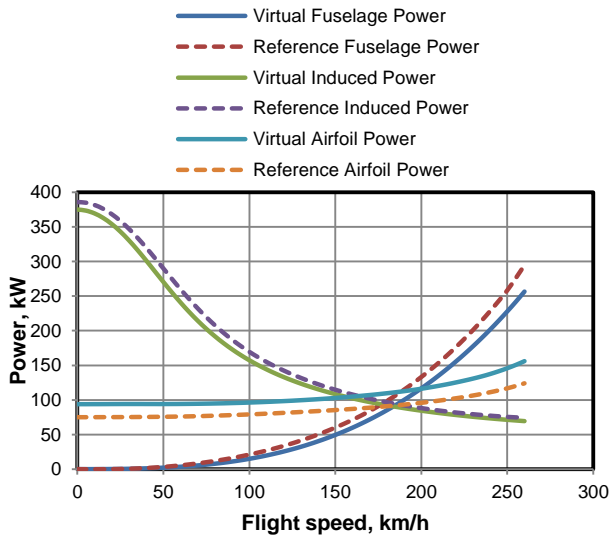


FIG 8 Comparison of main rotor and fuselage power curves

During hover the virtual configuration needs less induced power compared to the reference model. Different reasons affect the lower induced velocity for the virtual configuration e.g. the interaction between main rotor and fuselage and the lower disk loading because of the different take-off mass and main rotor radius. Because the aerodynamic polars differ, despite the assumed fuselage dimensions of the reference helicopter (TAB 3), the fuselages of the virtual and reference simulation model are not identical and the fuselage power shows differences when the velocity increases. To justify the different polars, especially the correction of the polars with handbook methods does not cover up all irregularities of a fuselage.

The constant offset of the airfoil power is justifiable with the blade geometries. Whereas the simulation model of the virtual configuration actually uses a rectangular blade tip and a NACA 23012 airfoil. In contrast the ACT/FHS model uses a more advanced blade geometry with a rounded blade tip. That is why the virtual configuration needs more airfoil power and the offset is constant for all velocities. Currently it is not possible to choose different blade geometries during IRIS but in future more advanced blade geometries, like the ERATO blade [21], will be available.

As described, the different induced power and airfoil power needed in hover of the virtual configuration affect the offset for the required total power during hovering. The differences between the two models at higher velocities for airfoil and fuselage power are similar and that is why they almost balance each other in the figure of the summed required power (FIG 7).

5 SUMMARY

5.1 Conclusions

This paper presented the implementation of HOST into the new DLR developed rotorcraft sizing process IRIS with focus on the following points:

- It has shown the automatically generation of simulation models, executed HOST calculation in batch mode during the sizing process and afterwards update of results in the CPACS data model is functional,
- for future high velocity configurations the extension of the performance calculation allows stepwise approach to a required velocity,
- the comparison between the virtual simulation model generated during the sizing process and the ACT/FHS reference configuration show similar results.

5.2 Outlook

Including the possibility to choose different blade geometries for performance calculations like advanced blade geometry with a rounded blade tip or geometries like the new ERATO blade have to be elaborated in future. Another point is the implementation of a thermodynamic engine model for more sophisticated estimations of specific fuel consumption considering the dependence on altitude, temperature and rotational speed of the output-shaft. During the internal project TRIAD it will be possible to perform load case computations on a virtual configuration using HOST for subsequent structural analysis with higher fidelity tools.

REFERENCES

- [1] P. Weiand, D. Schwinn, M. Schmid and M. Buchwald, "A multidisciplinary process for integrated rotorcraft design," in *43th European Rotorcraft Forum*, Milan, Italy, 2017.
- [2] P.-M. Basset, A. Tremolet, F. Cuzieux, C. Schulte, D. Tristrant, T. Lefebvre, G. Reboul, M. Costes, F. Richez, S. Burguburu, D. Petot and B. Paluch, "The C.R.E.A.T.I.O.N. project for rotorcraft concepts evaluation: The first steps," in *37th European Rotorcraft Forum*, Vergiate and Gallarate, Italy, 2011.
- [3] P.-M. Basset, A. Tremolet, F. Cuzieux, G. Reboul, M. Costes, D. Tristrant and D. Petot, "C.R.E.A.T.I.O.N. the ONERA Multi-Level Rotorcraft Concepts Evaluation Tool: The Foundations," in *Future Vertical Lift Aircraft Design Conference*, San Francisco, CA, 2012.
- [4] W. Johnson, "NDARC: NASA Design and Analysis of Rotorcraft," NASA/TP-2009-215402, 2009.
- [5] W. Johnson, "CAMRAD II Software Description," [Online]. Available: <http://www.johnson-aeronautics.com/documents/CAMRADIIoutline.pdf>. [Accessed 29 06 2018].
- [6] D. Raymer, "Aircraft Design: A Conceptual Approach," American Institute of Aeronautics and Astronautics, Reston, VA, 2006.
- [7] D. Seider, P. Fischer, M. Litz, A. Schreiber and A. Gerndt, "Open Source Software Framework for Applications in Aeronautics and Space," in *IEEE Aerospace Conference*, Big Sky, MT, 2012.
- [8] J. D. Sinsay, "Re-imagining Rotorcraft Advanced Design," in *Rotorcraft Virtual Engineering Conference*, Liverpool, UK, 2016.
- [9] P. M. Basset, P. Beaumier and T. Rakotomamonjy, "C.R.E.A.T.I.O.N.: A numerical workshop for rotorcraft concepts generation and evaluation," in *Rotorcraft Virtual Engineering Conference*, Liverpool, UK, 2016.
- [10] D. M. Layton, "Introduction to Helicopter Conceptual Design," American Institute of Aeronautics and Astronautics Professional Studies Series Correspondence Course, Salinas, CA, Sep.1991-Mar.1992.
- [11] P. Kunze, "Parametric Fuselage Geometry Generation and Aerodynamic Performance Prediction in Preliminary Rotorcraft Design," in *39th European Rotorcraft Forum*, Moscow, Russia, 2013.
- [12] J. Nathman, "VSAero - A Computer Program for Calculating the Nonlinear Aerodynamic Characteristics of Arbitrary Configurations. User's Manual, Version 7.2," Analytical Methods Inc., Redmond, WA, 2007.
- [13] C. N. Keys and R. Wiesner, "Guidelines for Reducing Helicopter Parasite Drag," *Journal of the American Helicopter Society*, vol. 20, no. 1, pp. 31-40, 1975.
- [14] W. Z. Stepniewski and C. N. Keys, "Rotary-Wing Aerodynamics - Volume II: Performance Prediction of Helicopters," Dover Publications, Inc., Mineola, NY, 1984.
- [15] A. Krenik and P. Weiand, "Aspects on Conceptual and Preliminary Helicopter Design," in *Deutscher Luft- und Raumfahrtkongress*, Braunschweig, Germany, 2016.
- [16] D. Palasis, "Erstellung eines Vorentwurfsverfahrens für Hubschrauber mit einer Erweiterung für das Kipprotorflugzeug," VDI-Verlag, Reihe 7, Nr. 201, Düsseldorf, Germany, 1992.
- [17] M. N. Beltramo and M. A. Morris, "Parametric study of helicopter aircraft systems costs and weights," NASA-CR-152315, 1980.
- [18] D. Schwinn, P. Weiand and M. Schmid, "Structural Analysis of a Rotorcraft Fuselage in a Multidisciplinary Environment," in *NAFEMS World Congress*, Stockholm, Sweden, 2017.
- [19] B. Benoit, A.-M. Dequin, K. Kampa, W. von Grünhagen, P.-M. Basset, B. Gimonet, "HOST, a General Helicopter Simulation Tool for Germany and France," in *American Helicopter Society 56th Annual Forum*, Virginia Beach, VA, 2000.
- [20] J. Kaletka, H. Kurscheid and U. Butter, "FHS: the New Research Helicopter: Ready for Service," *Aerospace Science and Technology*, vol. 9, no. 5, pp. 456-467, 2005.
- [21] B. G. van der Wall, C. Kessler, Y. Delrieux, P. Beaumier, M. Gervais, J.-F. Hirsch, K. Pengel, P. Crozier, "From Aeroacoustics Basic Research to a Modern Low-Noise Rotor Blade," *Journal of the American Helicopter Society*, vol. 62, no. 4, pp. 1-16, 2017.