

Structural Analysis of a Rotorcraft Fuselage in a Multidisciplinary Environment

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Abstract

The helicopter constitutes a very important branch of the aeronautical industry despite being expensive, tricky to operate and requiring a high maintenance effort. Its ability to hover and operate under low airspeed, combined with the ability to land in almost every spot makes helicopters superior to fixed wing aircraft in certain missions. Moreover, helicopters also compete with earth bound vehicles when it comes to operations in sparsely populated areas or when the infrastructure impedes the use of automobiles. Therefore, the field of application for helicopters is wide ranging from aerial observation over general transport of passengers and cargo up to medical transport of severely injured patients.

Recently, interest has grown to improve typical limitations of rotorcraft, such as to reduce noise and to extend the flight envelope by increasing cruise velocity. Novel and more effective helicopter designs might work in a wider operating range and/or could transport more payload in terms of mass and volume, for instance enhanced medical equipment allowing a better and faster treatment of the patient. These objectives lead to unconventional design concepts, e.g. compound helicopters that feature additional lifting surfaces and propellers. To date the statistical knowledge of such configurations that could be beneficial during early design phases is limited.

However, the rotorcraft design process is very challenging since it is mainly driven by the desired functionality. Accordingly, helicopter fuselages often feature cut-outs that influence the load path and hence the structure and mass. In turn, a sufficiently precise estimation of the helicopter total mass is required for a feasible performance analysis, thus calling for an iterative design process.

With the aim to create and evaluate traditional but also new unconventional rotorcraft concepts, an integrated, automated multidisciplinary process chain covering the conceptual and preliminary design stages has been established within the German Aerospace Center (DLR). It allows the design of virtual rotorcraft configurations starting from scratch, based on few minimum input parameters, e.g. mission range, cruise velocity, payload, blade number and rotor configuration. This process chain features a modular approach to allow for high flexibility concerning the redefinition of certain parameters that become available during the design process.

The presented paper describes the process chain and the common data format used to combine the different tools. Particular attention is turned on the analysis of the fuselage structure. Exemplary, the generation of a generic rotorcraft is shown gradually from the very beginning by evaluating the required input parameters up to the structural analysis of the fuselage.

1. Introduction

The design of a new rotorcraft is generally considered as a highly challenging task. Contrary to fixed-wing aircraft there is a wider and more heterogeneous design space. For example, rotorcraft consist of engines, rotors, drive shafts, gears, electronics, flight controls and landing gear which all have to work independently and together for safe usage. While majority of aircraft is operated in a controlled environment of paved runways, set flight paths and traffic controllers, rotorcraft are very often used to reach areas that cannot be accessed by airplanes. Helicopters land and take off almost anywhere which makes them useful but also vulnerable. Moreover, rotorcraft feature a lot more moving parts than aircraft do. These circumstances lead to an increased demand on the operating and maintenance crew but also for the engineers during the design process.

The design process of fixed and rotary wing aircraft is commonly divided into three phases which are the conceptual, preliminary and detailed design phases. At the very beginning there are just the requirements specified by the customer, for instance specific missions, payload, range, etc. Based on these top level aircraft requirements (TLAR) several possible designs and configurations are evaluated and assessed in highly multidisciplinary analyses. The result of the conceptual design phase is the external configuration of the rotorcraft with its dimensions.

At this time the outer mold line of the rotorcraft is defined as well as the main load paths. In the following preliminary design phase more detailed calculations are performed in order to determine the internal configuration of the rotorcraft. This includes the positioning and first sizing of the load-carrying parts as well as the integration of the components. The degrees of freedom to

change the external configuration during the preliminary design are limited to parameters like blade twist, airfoil shape, etc.

In the concluding detailed design phase, all details of the aircraft are defined for the final design drawing. Ideally the design is frozen after every design phase. Changes in a previous phase require a comprehensive repetition of the subsequent design steps. The deeper the change occurs the more of the process has to be repeated. For instance, a change in the TLARs requires a complete repetition of the design process.

Since the conceptual design phase requires a high number of calculations (at reduced level of detail) this stage calls for fast and automated analysis tools and efficient engineering. Each advance in the design phases demands an increase in computational fidelity.

A suitable arrangement of the computational methods is required. The tools are classified into four levels starting with the Level 0 (L0) design tools. These tools work mostly with empirical methods and very simple physical assumptions providing much output with only limited input. Level 1 (L1) design tools have a better physical modelling but are still fast enough to perform iterative procedures in terms of conceptual sizing and optimization loops. Level 2 (L2) design tools have a very good physical modelling; however, their computational time exceeds the limits of the primary sizing loop. They are used afterwards and give sophisticated feedback. Thus, conceptual and preliminary design tools depend on detailed knowledge of existing configurations using empirical, lower and medium physical models. On the one hand this approach is just logical and eligible since it is very efficient based on a wide and stable fundament. On the other hand, the support on the exploration of new, unconventional configurations is only very limited due to a lack of existing data.

Level 3 (L3) design tools are the most complex programs. They have the greatest time demand and their pre- and post-processing procedures cannot be performed automatically. L3 tools are not integrated in the presented design process at this time.

The majority of helicopters feature a main rotor that delivers the lift and thrust while the tail rotor generates a lateral force to compensate for the torque caused by the main rotor. This rotor arrangement is regarded as the conventional rotorcraft configuration. Other types compensate the main rotor torque by using two main rotors that are located above each other on the same axis (Coaxial), behind each other (Tandem), separated in lateral direction (Side-by-Side) or feature intermeshing rotor discs (Flettner). A reasonable trim requires a suitable share of thrust for the two main rotors.

Another type of unconventional rotorcraft is the compound helicopter. In general, this type of helicopter is an extension of the previous mentioned configurations and features auxiliary lifting surfaces to produce lift and propellers to generate thrust. The idea is a reduction of the rotational speed of the main rotor without a global loss of lift. By this means, the blade tip speed is kept constant at approximately $M=0.9$ while the cruise speed is increased. The reduction of main rotor thrust requires a new trim with an advanced share of lift and thrust forces between the main rotor and compound components (wing and propeller). Figure 1 shows a classification of different rotorcraft.

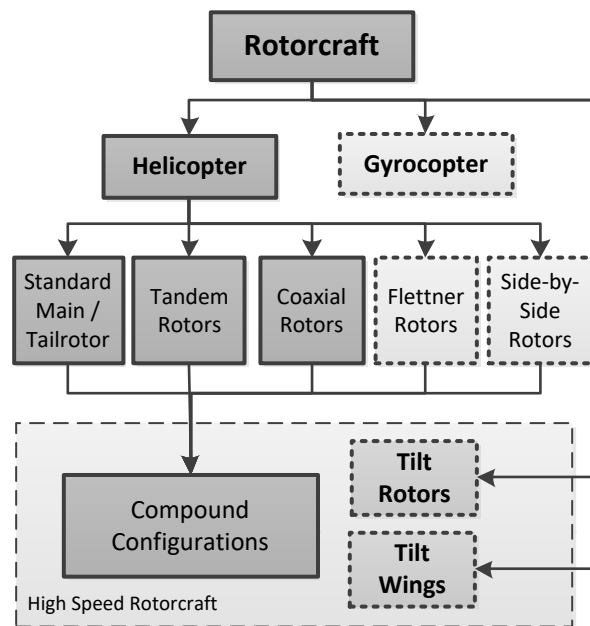


Figure 1: Hierarchical overview of rotorcraft configurations

Compound configuration and tilting disc rotorcraft are alternative approaches to enter the flight realm of high speed rotorcraft. Tilt rotor and wing configurations are not covered by the presented project.

Two unconventional rotorcraft configurations are schematically shown in Fig. 2. Both helicopters do not require a tail rotor. The coaxial rotorcraft uses the compensating effect of two contra-rotating main rotors while the compound helicopter runs its two propellers at different blade pitch, thus generating a stabilizing force like a conventional tail rotor does.

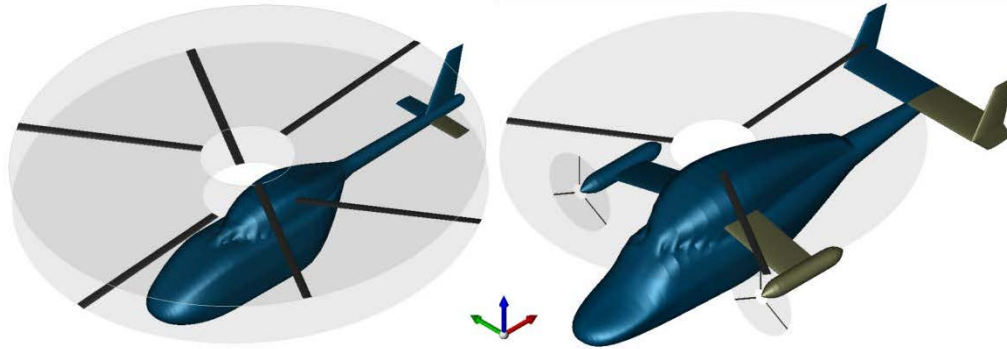


Figure 2: Unconventional configurations: coaxial (left) and compound (right)

To evaluate rotorcraft configurations in the conceptual and preliminary design stage an automated, integrated process chain has been set up at DLR. The objective of this multidisciplinary toolbox is the generation and analysis of appropriate rotorcraft models according to user-specified TLARs to assess selected configurations.

In this paper the aforementioned process chain is introduced with particular attention on the structural analysis and design of the fuselage. This procedure is considered as an L2 preliminary design routine. The software framework and the common data format will be presented. The main focus of the presented paper is the introduction of the applied methodology. However, as example, a generic coaxial rotorcraft is generated by this tool chain and the evaluated configuration will be statically sized according to generic representative load cases. Concluding this paper an outlook on future work and demands will be given.

2. Data management

Multidisciplinary design involves different disciplines that all require different input, i.e. the corresponding analysis tools need to communicate with each other. For the sake of efficiency, the tools should be automated and parametric to allow good communication between each other and to avoid manual processing of input and output. Therefore, one common data format should be used to unify the input and output data, thus eliminating the unnecessary need of unit conversions or adopting input- and output of the various tools to each other. Hence, the presented tool chain uses the common data format CPACS (Common Parametric Aircraft Configuration Schema; Nagel et al. 2012). It is the key component for the communication and data exchange between the user and the analysis tools but also between all integrated software modules.

Each rotorcraft configuration is stored in its own CPACS file. Every individual tool in the design process takes the dataset stored in the corresponding CPACS file as input, conducts its calculations and stores the results in the CPACS file, thus stepwise expanding the original file.

As the analysis tools steadily evolve due to the integration of new technologies or methods, the maintenance of the chain respectively the tool interfaces is a major task. A schematic overview of the maintenance cost considering the tool interfaces is shown in Fig. 3 with only five exemplary tools. It can be seen that the number of tool interfaces without a common data format follows a quadratic increase

$$n_i = n_t(n_t - 1) \quad (\text{Eq. 1}),$$

with n_i denoting the number of interfaces and n_t the number of analysis tools involved in the design process. In this scenario, maintenance can rapidly become confusing and unclear since all tools respectively their interfaces need constantly be adapted to each other. The demand to keep the latest versions running may then easily lead to programming errors. Contrary, the approach with a common data format leads to a linear increase of tool interfaces

$$n_i = 2n_t \quad (\text{Eq. 2}),$$

thus significantly reducing the amount of interface maintenance. Additionally, the complexity of interface maintenance is reduced since one side of each interface always follows the unified data format.

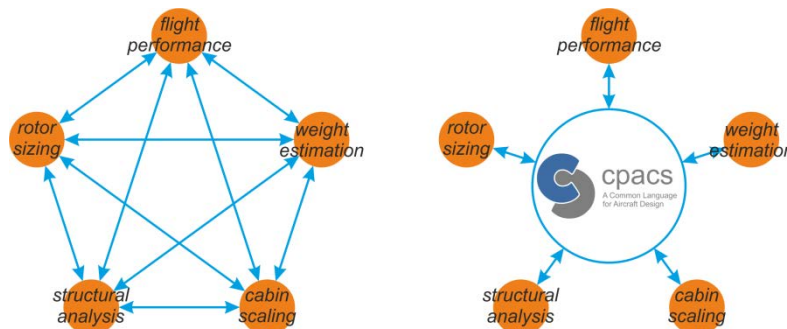


Figure 3: Tool interfaces without (left) and with (right) CPACS

Besides the common data format a framework is required to connect the different software modules. In general, the integrated design tools are developed at different facilities; in the context of the presented paper this means three institutes in two cities. For the purpose of connecting the design tools, the presented process chain is controlled by the DLR developed software framework RCE (Remote Component Environment; Seider et al. 2012). With RCE it is possible to set up a process chain with different modules that are located at different sites. RCE connects different servers via internet by executing the corresponding design software merely on the server where it has been installed. This means that the source code of the respective design tool does not leave the facility where it has been developed, thus keeping the disciplinary knowledge at the corresponding facility. Hence, each tool can be

maintained and enhanced by the developing specialist allowing fast resolving of potential problems. Furthermore, this approach allows fast and easy integration of new partners adding their know-how to the project. By now four servers from three institutes in two cities are connected in one graphical user interface.

To efficiently work with the CPACS data format the two libraries TIXI and TIGL are used by the design tools since they provide standardized routines. TIXI is a library for the handling of input and output data while TIGL is a graphic library to process geometric information.

All tools and libraries that were introduced in this section are available for download at their homepages (CPACS homepage; TIXI homepage; TIGL homepage; RCE homepage). However, it needs to be mentioned that the CPACS scheme used in the presented work has been edited to fit current rotorcraft definitions.

3. Design process

At the very beginning of the design process the TLARs consisting of the desired cruise velocity, payload mass, range, and helicopter configuration are specified by the user. The helicopter configuration consists of the number of blades per main rotor and the arrangement of the rotors. The three base configurations examined in the project are the standard main/tail rotor configuration, the tandem rotor configuration and the coaxial rotor configuration. Additional requirements for the fuselage, such as cabin volume can be entered but are not required. If not specified the cabin volume will be averaged by the payload mass. In a first step the TLARs are evaluated and the initial mass fractions are estimated with statistical methods based on a database of about 140 existing rotorcraft. The initial maximum take-off mass is determined as well as the initial dimensions of the rotorcraft. The maximum take-off mass m_{tom} consists of the operating empty mass m_{oem} , the payload and fuel masses:

$$m_{tom} = m_{oem} + m_{payload} + m_{fuel} \quad (\text{Eq. 3}).$$

The operating empty mass m_{oem} consists of the rotorcraft empty mass m_{em} and the operator masses m_{om}

$$m_{oem} = m_{om} + m_{em} \quad (\text{Eq. 4}).$$

An initial fuselage is estimated based on the required cabin volume or the payload mass. The rotors are arranged in a virtual design environment according to the TLARs and general design requirements for rotors. The fuselage is placed under the rotors with respect to the required configuration.

The calculations applied in this step are considered as L0 procedures. The initial configuration is stored in the CPACS file and sent to the scaling loop.

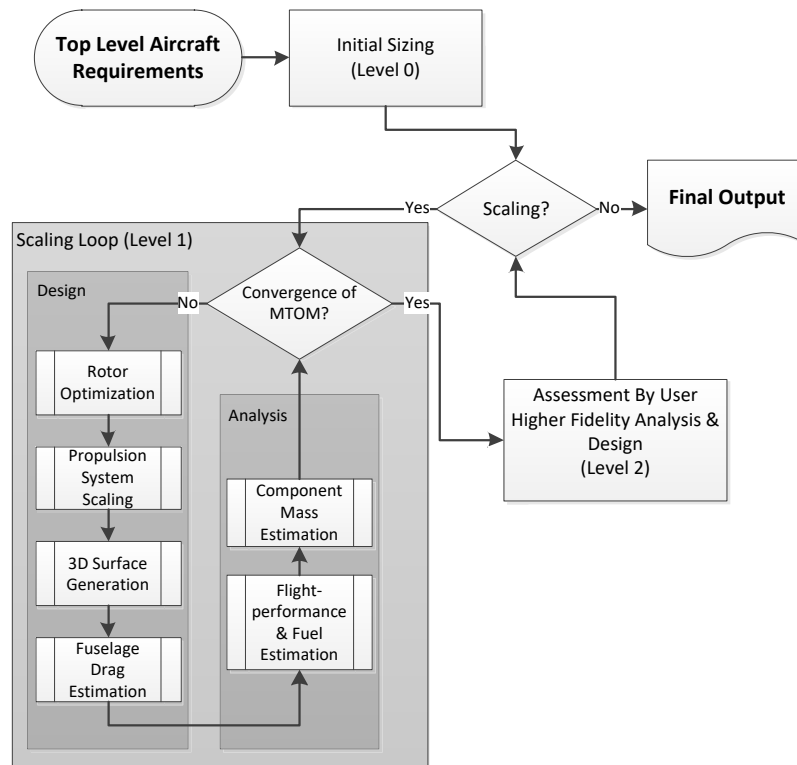


Figure 4: Principle structure of the design process (Weiand and Krenik 2016)

This loop consists of a design branch and an analysis branch. The design branch performs the sizing and optimization task. The analysis branch performs the calculation of the operating empty mass and the required fuel mass in order to meet with the design mission. The loop iterates the maximum take-off mass. The tools applied in this stage are considered as L1 design tools and constitute the boundaries of the conceptual design phase. The design branch first optimizes the blade planform by adapting the radius, the chord and the rotational speed. The adaption of the rotor disc results in an adaption of the tail boom with the stabilizers and the tail rotor if applied. In case of a tandem rotor configuration a maximum overlapping ratio must be taken into account, which often leads to a longer cabin by keeping the payload mass constant. In the next step a linear blade twist is optimized for minimum power in cruise flight. After the optimization of the basic main rotor geometry a 3D model of the rotorcraft is developed by sizing a generic fuselage with respect to the determined component scales. It automatically instantiates fuselage components from a catalogue and scales them to match the required overall dimensions. A three dimensional geometry model is automatically generated in CATIA by the tool GEOGEN (geometry generation module) and subsequently transformed into the CPACS denoted description of profiles and sections for

further geometric processing, e.g. structural or aerodynamic analyses. It shall be noted at this point that GEOGEN also features the generation of rotor blade and wing components. A detailed description of GEOGEN is provided by Kunze (2013). A generic assembly of the fuselage divided into its components is shown in Fig. 5.

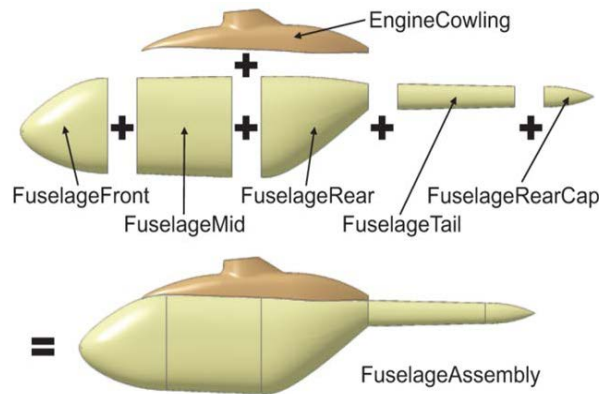


Figure 5: Assembly of fuselage components (Kunze 2013)

The 3D model serves as input for the calculation of the aerodynamic properties of the fuselage according to different angles of attack and sideslip (Kunze 2013). Due to the highly functionality driven design of helicopter fuselages, there is often a region of separated flow at the rear of the fuselage below the tail boom which has to be taken into account. The applied tool is based on the commercial flow solver VSAERO (Maskew 1987). The computational basis is the usage of a linearized 3D panel method which is coupled to a viscous solver. The line of separation can be calculated. The direct calculation of the flow behind the separation line is difficult, but the influence of the geometry on the area of separation is quite good predictable.

In the next step the propulsion system is scaled based on the statistics of 69 turboshaft engines which are installed in existing rotorcraft. Different parameters like specific fuel consumption and engine mass can be estimated in relation to the take-off mass of the rotorcraft (Krenik and Weiland 2016).

At this point the design branch of the sizing loop ends and the analysis branch starts. The analysis begins with the higher order estimation of the fuel fraction with respect to the required mission profile. A flight performance calculation is conducted including the calculation of trimmed flight conditions.

The minimum mission profiles consist of one flight segment which covers the complete range. Trim calculations are performed at the beginning and the end of every flight segment (Krenik and Weiland 2016). For this purpose the tool HOST (Helicopter Overall Simulation Tool; Benoit et al. 2000) is used. The fuel mass is adapted iteratively for each flight segment.

In the next step the operating empty mass is calculated by estimating and summing up the individual component masses. The mass estimation of the component groups is conducted using the tool MASERATI (mass estimation of rotorcraft based on statistics) which is based on statistical methods. Implemented methods are the equations as proposed by Beltramo and Morris (1980), Layton (1992), Palasis (1992) and Johnson (2009) as well as a so-called best-of variant which allows user specified composition of the different methods. Essential parameters that determine many mass groups are the fuselage surface area s_{body} and the design gross weight m_{dg} . For example the methods provided by Beltramo, Layton and Palasis require s_{body} and m_{dg} for the estimation of five mass groups each respectively six times for m_{dg} by Palasis. Contrary the methods specified by Johnson use s_{body} only once and m_{dg} only three times, thus allowing a wider base for weight estimation. Masses are estimated for complete groups (e.g. body group, landing gear, drive system, etc.) according to the format proposed in report RP No. 08 by the Society of Allied Weight Engineers (SAWE, 1997). Taking into account the positions of the component masses as specified by GEOGEN, MASERATI can calculate the global inertia tensor as well as the centre of gravity. The updated mass fractions compute a new maximum take-off mass. This step closes the primary loop. If convergence of m_{tom} has been achieved, the conceptual design phase might be considered as terminated and the design process shifts to the preliminary design phase. As a result from the conceptual part of the presented process chain the external configuration of the rotorcraft is determined. In other words, a 3-side-view of the outer shape of the fuselage and the rotors is available.

The preliminary design deals mainly with the determination of the internal configuration. In theory the positions of load carrying elements are already determined in the conceptual design phase. In the preliminary design phase these elements have to be sized according to the required manoeuvre loads.

Because of the strong dependence of the structural analysis on the fuselage geometry and the weight and balance characteristics, the fuselage geometry generation and mass estimation tools shall be explained in more detail subsequently.

The structure is statically sized and finally investigated regarding its energy absorption abilities when exposed to survivable crash landings. The crashworthiness tool is currently under development. It is based on the parametric aircraft crash tool AC-CRASH (Schwinn 2014; Schwinn 2015a) and will feature rotorcraft specific modelling approaches to conduct crash analyses with the explicit finite element (FE) code VPS (Virtual Performance Solution), formerly known as PAM-CRASH.

In CPACS the rotorcraft fuselage is described as an outer aerodynamic fuselage which represents the outer hull and a structural fuselage that serves as

mounting for the reinforcements that carry global torsion and bending. Figure 6 shows both definitions.

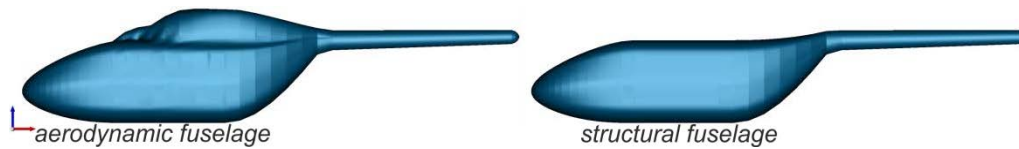


Figure 6: Aerodynamic and structural fuselage definitions

It can be seen that for the presented rotorcraft the difference between both fuselages is the engine cowling which has primarily aerodynamic reasons. Therefore, it does not contribute to any bearing of external load which is introduced into the fuselage. However, it shall be mentioned at this point that for detailed design analysis the aerodynamic drag caused by the cowling should be taken into account.

As an example for the described process chain, a generic rotorcraft featuring a coaxial rotor configuration with the TLARs

- payload: 860 [kg],
- range: 555 [km],
- cruise velocity: 190 [km/h],

was generated using the aforementioned design modules. The masses that were determined by MASERATI respectively by the rotor sizing and engine estimation tools are listed below in Tab. 1. Note that the given values are in [kg] and rounded when summed up to m_{oem} which is the maximum operating empty weight consisting of the structural masses, the systems masses, the propulsion masses, and the operators ($m_{operators} = 180$ kg) as defined in Eq. (4).

The mass items in green denote the structural group, the mass items in blue describe the propulsion group while the system masses are depicted in red. The main rotor weight and the engine weight were not estimated using MASERATI but by the rotor sizing and engine estimation tools and are therefore independent from the applied method in MASERATI.

Table 1: Overview of the mass estimation methods

Mass item	Johnson	Beltramo	Layton	Palasis
Fuselage	461	613	515	521
Empennage	22	24	18	24
Lighting Gear	156	75	32	179
Nacelle	63	45	43	46
<i>Main Rotors</i>	<i>102</i>			
<i>Engine</i>	<i>188</i>			
Transmission	117	348	67	354
Air Conditioning	33	36	31	36
Auxiliary Power	66	72	86	71
Avionics	228	91	113	92
Electrics	207	134	158	160
Flight Controls	139	148	143	151
Fuel system	75	64	93	93
Furnishings	289	70	70	70
Hydraulics	56	23	17	24
Instruments	73	30	19	19
Load Handling	74	5	38	5
Structure	702	757	608	770
Propulsion	407	638	357	644
Systems	1240	673	768	721
m_{oem}	2529	2248	1913	2315

It can be seen from Tab. 1 that the masses computed by using the methods proposed by Johnson lead to the heaviest results due to the systems mass group. Components of this group, for instance the furnishings, are often mission dependent and therefore difficult to estimate when using statistical approaches. However, these methods provide technology factors to scale the results based on the availability of reference data and new technologies.

For the structural analysis in this paper the mass estimation method applied was the one proposed by Johnson since it is considered to feature the highest coupling grade of geometric and performance characteristics. Within the presented work the technology factors have all been set to $\chi_i = 1$.

The convergence of the sizing loop leads to the preliminary design phase. The simulation of the required manoeuvre cases is performed by HOST. The selected flight and ground manoeuvres are evaluated and the resulting loads are stored in the CPACS file as forces and moments acting on dedicated points on the rotorcraft. However, it must be noted that the integration of the load case generation by HOST is not yet fully integrated into the process chain. In the presented work, therefore, some chosen representative air- and ground load cases were integrated into the process chain to conduct static sizing. Based on

the obtained information during the design process the structural analysis with FE tools may be initiated consecutively. The results of the L2 calculations have to be directed back to the sizing loop. Here the L1 results need to be corrected by the results of the higher order computation and the sizing has to be repeated with updated technology parameters. Detailed information on the overall design process at the conceptual design stage is presented by Weiland and Krenik (2016).

4. Structural analysis

As mentioned earlier one of the results from the conceptual design phase is the outer aerodynamic mould of the rotorcraft. However, since the frames and stringers of a fuselage serve as a reinforcing structure carrying global bending and torsion the fuselage needs to be provided with the primary structure. For this purpose the tool F-DESIGN (fuselage design) was developed. According to user specified input the frames and stringers are calculated based on knowledge based design criteria as well as geometric requirements and subsequently stored in the CPACS file. The user input required for the distribution of primary structure is defined in so-called design sets which comprise the definition of master frames, master stringers and various regions in longitudinal and circumferential direction with arbitrary spacing. A generic distribution of frames and stringers for the given coaxial helicopter as depicted in Fig. 2 and Fig. 6 is shown in Fig. 7.

Additionally, the material parameters and (initial) geometric properties (profile dimensions, thicknesses) are assigned to the airframe and stored in the CPACS file. F-DESIGN also features the possibility of distributing the reinforcing structure according to desired non-loadbearing cut-outs. By this means, cut-outs for doors, cargo ramps, etc. can be integrated into the model. Detailed information on the cut-out modelling and on the available distribution methods of the reinforcing structures on the structural fuselage is given by Lier et al. (2015) and Schwinn (2015b, 2015c).

The fuselage in the presented work was provided with two pilot doors and two passenger doors, located symmetrically on each side. Since the fuselage cut-outs are supposed to bear no load, the load path will alter around the cut-outs, thus redistributing the loads. In the region where the load from the main rotors is introduced into the fuselage, the pitch of the frames was reduced.

After F-DESIGN the tool ROFUMA (rotorcraft fuselage mass assessment) is called which generates an FE model of the helicopter. Depending on the so-called analysis type node in CPACS either merely an FE model is generated, statically analysed or, if specified by the user, statically sized using the S-BOT+ module (Scherer et al. 2013).

ROFUMA generates the mesh in GFEM (global finite element) quality. Static analyses are conducted using the ANSYS solver. Modelling is conducted using the APDL (ANSYS parametric design language) code. Engineering constants (e.g., cross section area, moments of inertia, centre of gravity) of the structural elements (which are profiles with material properties assigned) are automatically computed and applied to the corresponding elements. Stringers are discretized using elastic beam elements (ANSYS Beam 188) that feature arbitrary cross sections. Frames and fuselage skin is discretized using elastic shell elements (ANSYS shell 181).

Structural and system masses as estimated by MASERATI in the preceding step are modelled as single nodal masses constrained to the structure with RBE3 elements distributing the load over a user-specified region. The rotors are also modelled as single mass points. The external forces and moments are applied as nodal loads on the corresponding nodes. The nodal masses that were included in the model are the ones presented in Tab. 1. The lift generated by the two main rotors is distributed equally. Since the investigated rotorcraft configuration is of coaxial type, the moments about the yaw-axis are equal in size so that the anti-torque moments compensate each other.

The FE model of the fuselage airframe without the covering panels and nodal constraints is shown in Fig. 7 on the left while the complete FE model including the constrained nodal masses and nodal loads is depicted on the right.

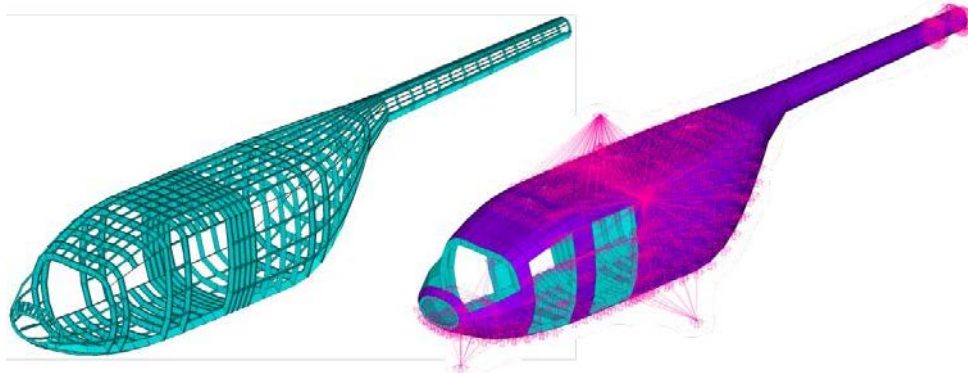


Figure 7: Airframe model showing the stringer and frame distribution (left) and with constrained nodal masses (right)

Figure 8 shows a static analysis of the coaxial helicopter during a banked turn with a bank angle of $\phi=70^\circ$. The left side shows the rotorcraft fuselage with panels while the picture on the right side shows the fuselage with removed panels for better visibility of the frames.

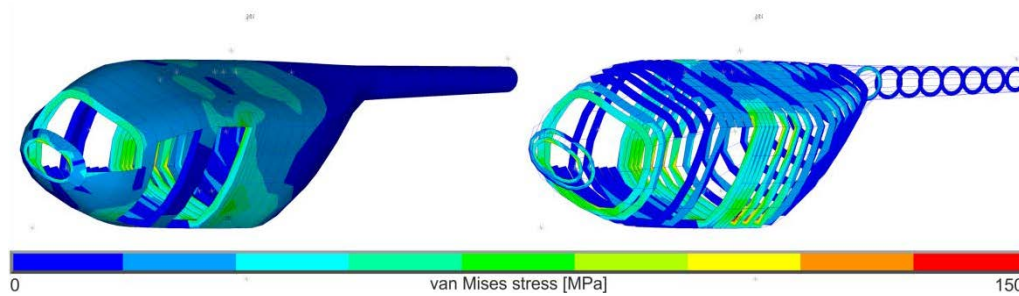


Figure 8: Van Mises stress distribution during banked turn manoeuvre

The structural sizing module S-BOT+ is based on the tool S_BOT that was originally developed for sizing of aircraft wings (Nagel et al. 2008) and enhanced for the use of aircraft fuselages (Scherer et al. 2013). Recently it was extended for the use with rotorcraft fuselages. It uses the fully stressed design (FSD) principle which is seen as the most common structural sizing method in the preliminary design stage. It follows the objective to choose the element thickness in a way that the maximum stress level of all considered load cases equals the maximum allowed stress. For statically determined structures where all components can be sized independently, this method leads to a design featuring minimum mass. For structures with multiple load paths like air- and rotorcraft fuselages this design approach is not necessarily leading to optimum mass design. However, the FSD solution is usually very close to optimum mass design leading to good estimations of the fuselage mass during the preliminary design stage.

As the structural load in a fuselage changes depending on the thickness values of the structure, the FSD is implemented in an iterative loop. Comparing the actual elemental stress and the material limits as defined in the CPACS file, a scaling factor is calculated for each element for all considered load cases. The element is then sized with respect to the largest value of all applied load cases. All elements are sized separately and thus independent from each other. The workflow of the S-BOT+ module is depicted in Fig. 9.

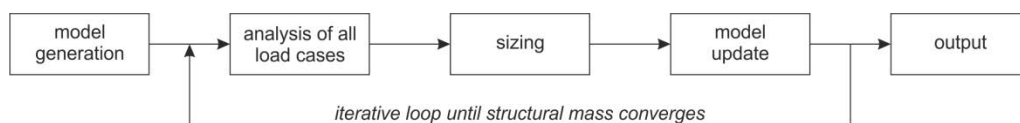


Figure 9: S-BOT+ workflow

For the purpose of structural sizing, a set of ten generic load cases covering the hovering state, pull up manoeuvres, banked turns and vertical jump take-off have been manually evaluated and integrated into the design chain respectively CPACS file for the presented coaxial helicopter.

Figure 10 gives an overview which load case was the critical one for the sizing of the shell elements. It can be observed that the front cockpit area and the

region around the pilot doors is loaded most critically according to load case no. 4 which corresponds to a 2.5g pull up manoeuvre. The rear part of the fuselage after the cabin door cut-out is dominated by load cases no. 9 and 10 which correspond to a banked turn at an angle of $\phi=70^\circ$. The interior upper part of the fuselage is sized according to load cases no. 5 and 6 which represent the same manoeuvre but at an angle of $\phi=30^\circ$ which is comprehensible since the increase of the bank angle evokes wider load attack vectors into the airframe.

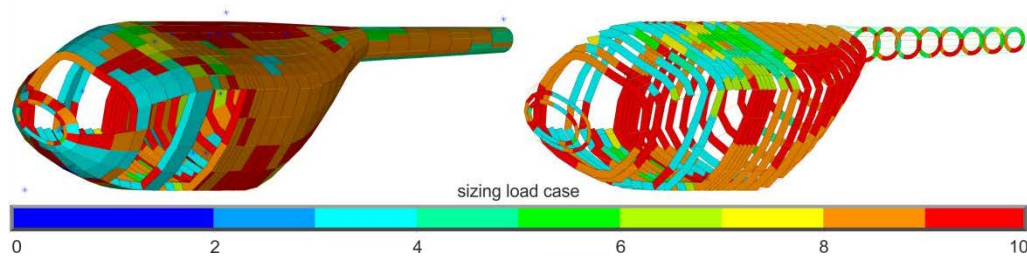


Figure 10: Sizing load cases

The thickness distribution of the sized fuselage is shown in Fig. 11. Most of the shell elements feature a thickness of about $t = 1.1$ mm while some centred frames feature thicknesses around $t = 2.5$ mm. However, fuselage skin panels are thicker around the door cut-outs due to the altered load path. The area of the thicker fuselage skin panels shows symmetrical behaviour with respect to the roll-yaw axis.

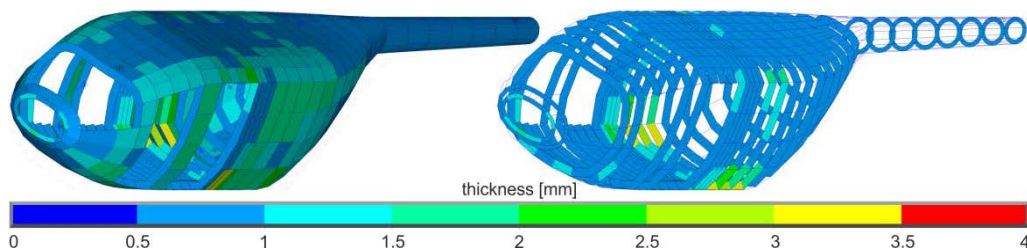


Figure 11: Fuselage thickness distribution

The convergence behaviour of the fuselage mass is illustrated in Fig. 12. The initial panel thickness for the fuselage skin was set to $t = 10$ mm for demonstration purposes in the presented paper. Therefore, the initial mass resulting from the frames and skin is very high. However, already at the second iteration the thicknesses are significantly reduced due to the resulting low stresses in the first iteration. Convergence of the fuselage mass is reached after five iterations resulting in a total mass of $m_{\text{total}} = 288.1$ kg summed up by the mass of $m_{\text{beams}} = 150.1$ kg for the beam elements and $m_{\text{shells}} = 138$ kg for the shell elements.

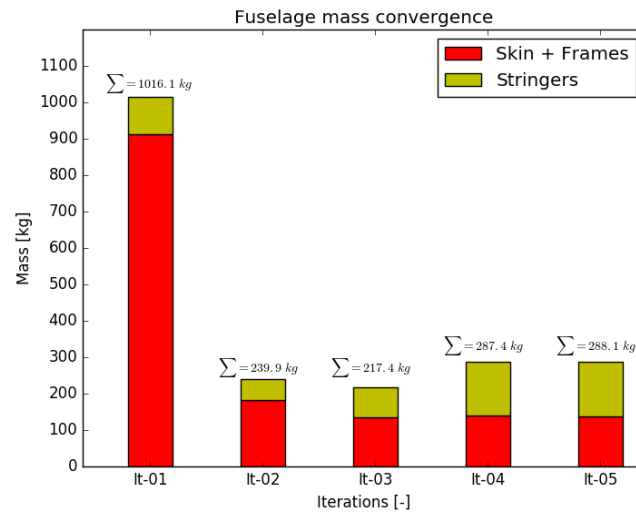


Figure 12: Convergence of fuselage mass

The mass of the sized fuselage $m_{f,sized} = 288.1$ kg compared to an estimated value of $m_{f,estimated} = 461$ kg using the methods proposed by Johnson corresponds to only about 62%. This discrepancy in sized and statistically estimated fuselage weight can be explained by the following reasons:

- The limited availability of critical load cases for the sizing process. The flight load cases integrated were of symmetrical nature. Asymmetric flight manoeuvres, e.g. combinations of pull ups and banked turns, lead to a combination of load factor increase and spatial load introduction into the structure increasing structural demand.
- The absence of joints in the numerical model which significantly contribute to the structural weight.
- The crash load case has not been integrated into the process chain and thus, not been considered yet. However, the application of the severe impact on rigid ground requires thicker and therefore heavier structures to avoid a critical load transfer to the crew and passengers, thus having a substantial influence on the fuselage mass.

5. Conclusion and Outlook

In this paper the DLR tool chain for conceptual and preliminary evaluation of rotorcraft models was presented. Basic tools have been introduced and the functionality of the process chain has been explained. The need for a common data format and a connecting software framework has been highlighted and the solutions that were applied in the described process chain have been presented.

Mass estimation methods that are applied to the introduced process chain have been shown and compared to each other on the example of a generic coaxial

helicopter. The process of an initial stiffness distribution on the structural fuselage hull was explained and exemplary shown.

The setup of the structural analysis was announced. Results from a static sizing run according to generic user-specified air- and ground load cases were presented and compared to initial weight estimations based on statistics.

Future work requires the integration of the automated calculation of loads with the tool HOST to fully benefit from a closed, self-contained design loop.

Moreover, it is desired to use semi-automated workflows, for instance to break the chain after the conceptual design phase: At the end of the conceptual phase the outer dimensions are fixed and subsequently the reinforcing primary structure is distributed. However, there are designs where the automated distribution of reinforcing stringers and frames may become difficult since the expected spatial design differs from the generated one.

As helicopters are difficult to fly and often operate under complicated circumstances, a crash evaluation tool needs to be integrated after the static sizing of the fuselage. Even when the detail level is only on preliminary design, crash analyses may reveal potential vulnerability of the design. The integration of the crash analysis into the sizing process finally leads to a more exact thickness distribution, thus leading to a more precise mass prediction. However, due to the fact that FE crash analyses do not fit within the scope of very fast calculations in the pre-design, an approach to reduce the calculation time is considered necessary.

6. Acknowledgements

The work presented in this paper was achieved within the DLR internal research project EDEN (Evaluation and Design of Novel Rotorcraft Concepts). The authors would like to gratefully acknowledge and appreciate the financial support as well as to thank Alex Krenik for his valuable contribution to the project EDEN.

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