LANDING GEAR DESIGN AND ASSESSMENT METHODOLOGY IN THE AVACON PROJECT

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Abstract

In the scope of the AdVanced Aircraft CONfiguration (AVACON) research project the potential of unconventional landing gear configurations is one of the research questions. The AVACON research baseline aircraft has been defined by the German Aerospace Center (DLR) and implements a selection of technologies for an entry into service in the year 2028. From the research baseline, innovative configurations will be derived and analyzed. Especially by further increasing the bypass ratio of the engines to reduce emissions and fuel burn. Therefore, a central aspect of AVACON is the integration of high bypass ratio engines with large nacelle diameters. It is planned to analyze configurations with over wing positioned nacelles. This offers the potential to integrate unconventional landing gear designs, for example a body landing gear. AVACON contains a dedicated work package in which Bauhaus Luftfahrt e.V. and the Hamburg University of Technology are cooperating with industry support to assess possible landing gear configurations. Several landing gear requirements are taken into account in the AVACON landing gear work package. Configurational requirements comprise the take-off rotation, tipping, turnover angle, ground mobility, nacelle clearance and wing tip clearance. Furthermore, the landing and taxiing shocks have to be absorbed by the landing gear. The structure of the landing gear has to be dimensioned accordingly. The Certification Specification (CS25) specifies load cases, which the landing gear structure has to withstand. These load cases are used as to estimate the forces, which are applied on the landing gear. A preliminary sizing loop using structural simulation is established to size the main structural component of the landing gear according to these load cases. After the design of the landing gear structure, a preliminary kinematics analysis is carried out with special regards on the actuation of the landing gear. This paper presents the application of this process on the research baseline. The preliminary sizing of the main structural components and conceptualizing of the kinematics is demonstrated. The system off-takes necessary for the actuation, which are an input for the sizing of the system architecture, are estimated using the dimensions and weights of the landing gear design.

Nomenclature

Symbol	Description	Unit			
AC	Aircraft	-	MRW	Maximum Ramp Weight	kg
act	Actuation	-	NLG	Nose Landing Gear	-
ARB	AVACON Research Baseline	-	*P*	Power	W
AVACON	Advanced Aircraft Concepts		*p*	Pressure	Pa
c	Specific Heat Capacity	J/K	*Q*	Volume Flow	m³/s
CoG	Center Of Gravity	-	*Ref*	Reference	-
d	Diameter	m	sys	System	-
g	Gravity Constant	m/s²	T	Landing Gear Track	m
k	Adaption factor	-	*t*	Time	s
KE	Kinetic Energy	J	UHBR	Ultra High Bypass Ratio	-
L	Length	m	*V*	Volume	m³
leg	Landing gear strut		*v*	Speed	m/s
m	Mass	kg	*W*	Wheel	-
max	Maximum	-	*w*	Width	m
MLG	Main Landing Gear	-	*Θ*	Temperature Rise	°C

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1. INTRODUCTION

The ambitious goals defined in the Strategic Research and Innovation Agenda [1] call for changes in the aircraft that can affect its overall configuration. A large contribution is expected to be achieved by changes in propulsion technologies. If the trend of the last decades of increasing bypass ratio is extended, this will have an impact on the aircraft configuration [2]. The AdVanced Aircraft CONfiguration (AVACON) research project was started in 2018, with its main purpose to analyze, amongst other aspects, the impact of engines with large bypass ratios on the aircraft configuration and to further improve the multidisciplinary cooperation of the German research entities applying conceptual aircraft design. The integration of Ultra High Bypass Ratio (UHBR) engines impacts the aircraft configuration in several ways. The task of the AVACON work package for landing gears is to analyze the impact on conventional landing gear arrangements and to test the performance of unconventional arrangements. One of the possible configuration changes affecting the landing gear is an over-wing engine position. In later project stages this opens the landing gear design space for body landing gear and other arrangements. Figure 1 explains this approach. Figure 1 a) shows a conventional aircraft configuration. Figure 1 b) displays a possible future aircraft configuration with UHBR engines and increased nacelle diameter d_2, which is larger than the nacelle diameter d_1 of the conventional aircraft configuration. Therefore, the landing gear length has to be enlarged as well to fulfil the required nacelle clearances to the ground, see the difference in length compared to the conventional configuration represented by L_1. As a result the weight of the landing gears increases, and hence, the weight of the aircraft. Furthermore, the storage space of the retracted landing gears is enlarged and the track T_2, the distance between the two Main Landing Gears (MLG), has to be widened to be still able to retract the MLG sideward. This increases the loads on the wing during landing as the lever arm between the MLG and the wing root is increased. Figure 1 c) shows again a possible future aircraft configuration with UBHR engines. This time the engines are mounted above the wings. The two MLG are designed as fuselage integrated body landing gears. Therefore, the landing gear length is smaller, illustrated by L2 in Figure 1 c). This results in a lower landing gear and aircraft weight. Additionally, a lighter landing gear helps to reduced the required power for retraction, which could result in a lower actuation system weight. Moreover, the wing weight could be reduced as no additional structure is needed for attaching the MLG. However, it has to be investigated how such a landing gear configuration is retracted into the fuselage. Therefore, one of the objectives of the landing gear work package of the AVACON project is to analyze the impact of such a body landing gear configuration and to determine the possible benefits and synergy effects of the structural integration and the impact on the subsystem architecture.
In the first stage of the project, the landing gear assessment will be performed for the AVACON Research Baseline (ARB) and a conventional arrangement. This paper presents the applied methods in the AVACON landing gear work package and the results for the conceptual landing gear design of the ARB.

2. APPLIED METHODOLOGIES

This Section introduces the applied methodologies, which will be used for designing the different landing gears for the corresponding aircraft configurations in the AVACON project.

2.1. Landing gear Positioning

The common landing gear type for large transport aircraft is the tricycle landing gear [3]. This type consists of one Nose Landing Gear (NLG) and two MLG. The position of these three landing gears has to fulfill several requirements in relation to the aircraft. The considered requirements are:

- Take-off rotation
- Tipping
- Nacelle clearance
- Wing tip clearance

This limits the possibilities for the positioning of the landing gears. The attachment to the aircraft structure is another important point for the configuration of the nose and MLG. The MLG are normally fixed to the wing structure. This ensures the fulfillment of the mentioned requirements and leads to relatively simple kinematics and storage of the landing gear.

2.2. PRELIMINARY STRUCTURAL AND COMPONENT SIZING METHOD

The structure of each landing gear has to withstand high loads. The Certification Specification for Large Transport Aircraft (CS-25) [4] defines several load cases, to which the considered landing gear has to comply. The following load cases are used to design the landing gear structure in the AVACON project:

- Level landing condition
- Tail down condition landing
- Side load condition inboard
- Side load condition outboard

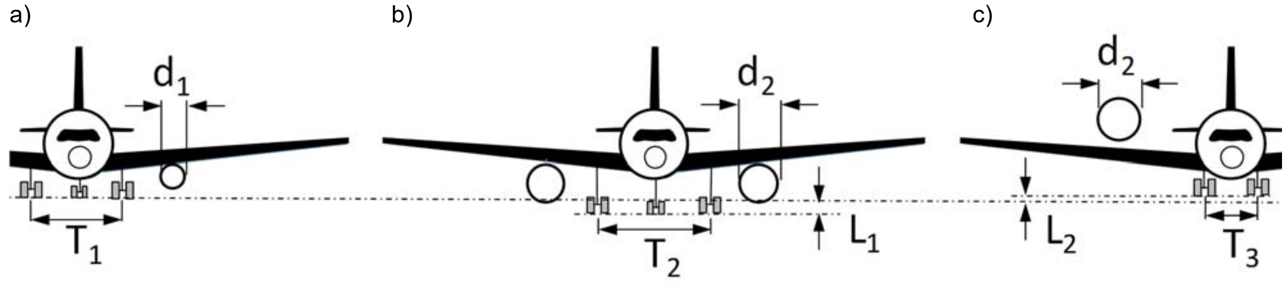

Figure 1: a) Conventional aircraft configuration; b) Aircraft configuration with UHBR engines with increased nacelle diameter and enlarged landing gears; c) Aircraft configuration with UHBR engines mounted over the wings and shortened landing gears (nose landing gear not displayed)

An additional spring back load case is defined, which represents the spring back of the landing gear after touching the ground at landing. The landing impact results in a vertical force. This vertical load is derived from the aircraft weight and the shock absorber [5]. It is applied in the above mentioned load cases. Furthermore, it serves as base for the additional occurring forces of each load case. With the different load cases and the calculated forces, a structural optimization loop is started to size the landing gear structure. The entire sizing process of one landing gear is displayed in Figure 2.

At the beginning a landing gear configuration of, for example, one main landing gear is defined. The gas spring of the shock absorber is calculated using the Maximum Ramp Weight (MRW) of the aircraft. This defines the diameter of the telescopic shock strut. The subsequent weight optimization uses a beam model of the defined landing gear configuration in the finite element structural simulation with CALCULIX [6] to minimize the weight of the landing gear according to the applied loads.

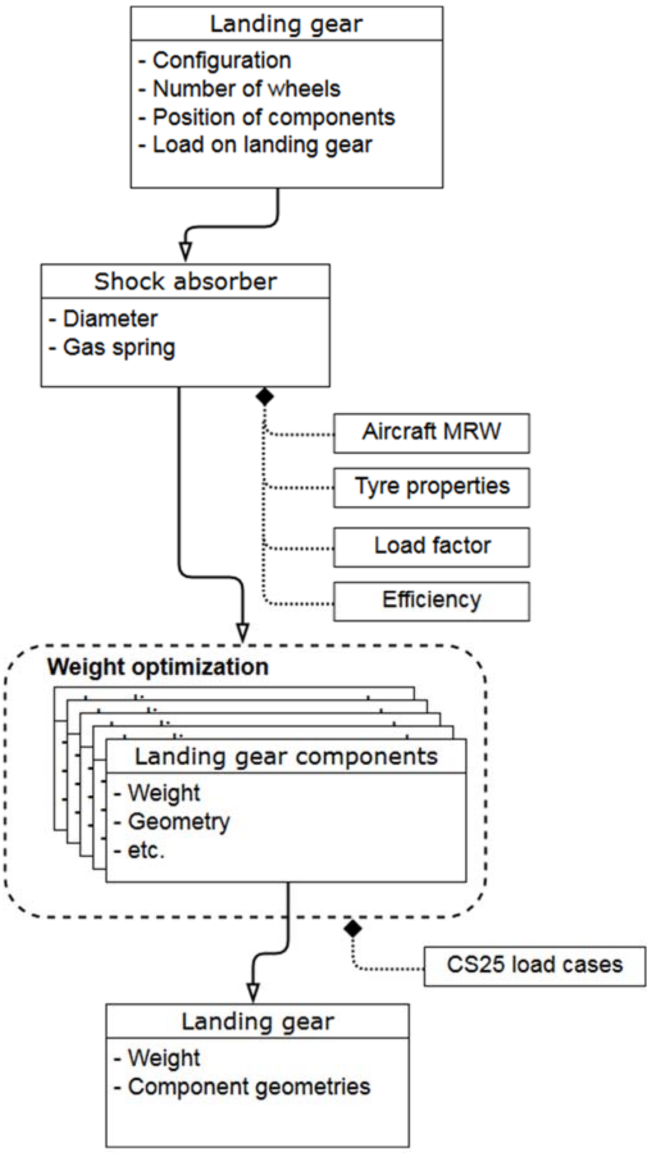

Figure 2: Sizing method for landing gear [5]

2.3. TYRE SIZING

The statistical sizing method from Raymer [3] is used for the tyre selection. With this method the tyre diameter and width can be calculated. The method consists of the following two formulas:

$$d = 5.3\ (m_W g)^{0.315}$$

$$w = 0.39\ (m_W g)^{0.480}$$

where, d is the tyre diameter, w is the tyre width, m_W is the mass on the corresponding wheel and g is the gravity constant. The different factors and superscripts in the formulas are values used for transport aircraft.

Furthermore, a maximum tyre pressure is used, based on data for existing aircraft with similar landing gear arrangement and maximum take-off weight.

With the calculated dimensions of the tyre and the maximum pressure a tyre from available data [7] is selected.

$$\begin{gathered} selected\ tyre = \min\left|V_{Raymer} - V_{tyre\ data}\right| \\ and\ p_{tyre\ data} < p_{max} \end{gathered}$$

where, V_{Raymer} is the volume calculated from the diameter and width of the tyre sizing from Raymer. V_{tyre} data is the volume calculated using the diameter and width of existing aircraft tyres. p_{tyre} is the rated tyre pressure from the tyre data and p_{max} is the assumed allowed tyre pressure.

2.4. BRAKE SIZING

Another important component of the undercarriage of an aircraft are the brakes to decelerate the aircraft on the ground, especially after touch down of the tyres. The brakes are very safety critical and mounted on the MLG for a common tricycle landing gears arrangement. For the mass estimation of the tyres, an approach utilizing the kinetic energy of the aircraft at landing is used. This kinetic energy has to be dissipated by the brakes (and spoilers). The brakes transform the energy into heat and therefore, have to be very heat resistant. The kinetic energy, which has to be dissipated during braking can be calculated with the following formula [8]:

$$KE = \ 0.00443\ \mathrm{m}_{AC} g \mathrm{v}^2\ /\ \mathrm{N}\ \text{with}\ \mathrm{v} = \mathrm{v}_{Ref}/1.3$$

where, KE is the kinetic energy, m_{AC} is the mass of the aircraft, g is the acceleration due to gravity, v_{Ref} is the approach speed and N is the total number of brakes, which normally equals the number of MLG tyres.

The mass of one brake can then be calculated using the formula suggested by Currey [9]:

$$m_{brake} = \frac{KE}{1400\ \theta\ c} f_{mat}$$

where, Θ is the temperature rise of the brake, which is set to 500°C [9]. c is the specific heat capacity of the used material. The calculation is based on steel as material of the brakes. For steel, the brake material factor, f_{mat}, is 1.0. By applying different values of f_{mat}, a brake weight estimation for other materials can be obtained. For the ARB carbon brakes are assumed. Therefore, a brake material factor of 0.86 is assumed [9].

2.5. ANTI-SKID SYSTEM, BRAKE ACTUATION AND SHIMMY DAMPER

Statistical methods [10] are used for the mass estimation of the anti-skid system, the brake actuation, the shimmy dampers and other miscellaneous components, which are so far not included in the more detailed methods described above. These statistical methods are based on known landing gear and aircraft data. For the mentioned components, the mass estimation depends only on aircraft data, for example maximum landing weight and approach speed for the shimmy damper. Other components are only calculated as a percentage of other components they depend on. For example, the anti-skid system mass is calculated as 3 % of the entire brake mass.

2.6. PRELIMINARY SIZING METHOD ACTUATION

The process for the design of the kinematics is based on the industrial development process described in VDI 2221 [11] and the down pointing part of the V-process [12]. It is adjusted to the typical steps needed for the development of a kinematic system and split into six steps [13]. For the feasibility analysis of the actuation system the first three steps are relevant, which are shown in Figure 3. During the definition step the design requirements for the following process are evaluated. Therefore, a number of inputs are required. One input for the kinematic analysis are the weights and the positons of the centres of gravity (CoG) of the different structural components of the MLG. During the standard process at the *Institute of Aircraft Systems Engineering* of *Hamburg University of Technology*, these are calculated by a method based on analytical mechanics.

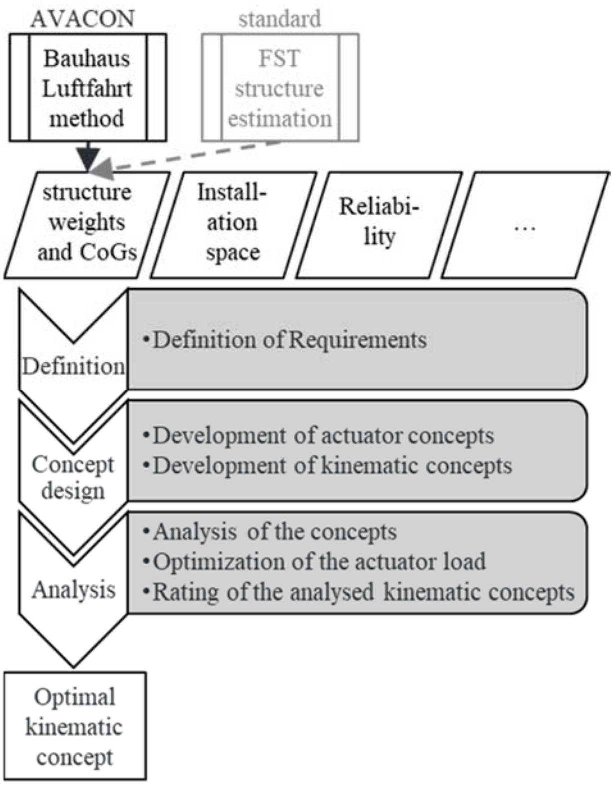

Figure 3: Development process for kinematic and actuation [13]

This basic method was developed by Schulz [14]. To improve the applicability of its results in the process of requirement definition for kinematic analysis, it has been enhanced in the area of side strut load estimation. The flexibility has been improved by implementing a parametric strut direction. This allows the analysis of conventional MLGs, which retract sidewards, as well as unconventional MLGs (e.g. forward retracting body landing gear). The load estimation and sizing is extended by a moment equilibrium and respects multiple load cases to improve the accuracy. Due to the organization of the AVACON project this standard method is replaced by the sizing method of *Bauhaus Luftfahrt e.V.* which is described within this paper. In the early preliminary design phase a first estimation of the required actuator power can be calculated based only on the weights and the CoGs of the different components of the MLG [14]:

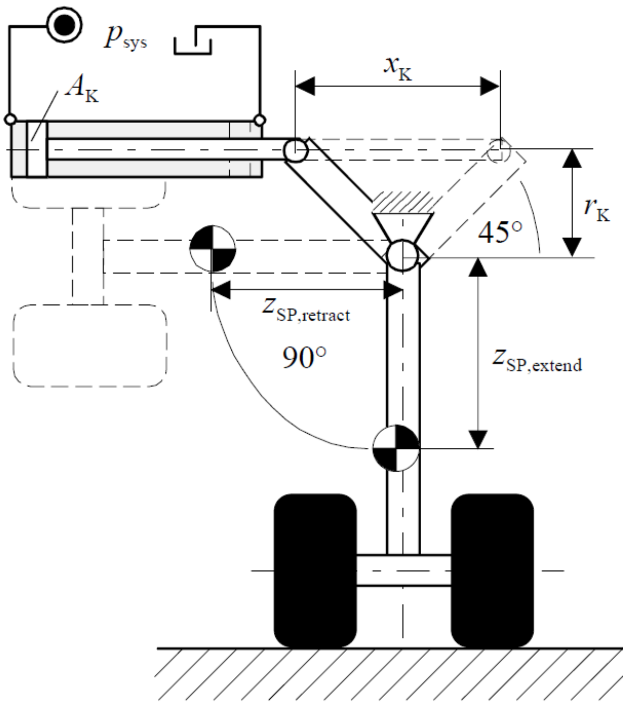

Figure 4: Basic actuation for estimation in early development phase [14]

$$
\begin{aligned}
&P = k_{act} \cdot Q \cdot p_{sys}\\
&with{:}\ Q_{Act} = \frac{m_{leg}\, g}{p_{sys}} \cdot \frac{2\, z_{CoG}}{t}\\
&\rightarrow P = k_{act} \cdot \frac{2\, m\, g\, z_{CoG}}{t}
\end{aligned}
$$

where, Q is the actuator volume flow, p_{sys} the hydraulic system pressure m_{MLG} the total weight of the leg of the MLG, z_{CoG} the distance of the CoG of the leg from the rotation axis, t the retraction/extension time and k_{act} an adaptation factor to respect the complexity of the real actuation.
In the detailed preliminary design phase an increasing number of boundaries of the actuation design space are fixed. Using the inputs shown in Figure 3, the detailed preliminary development of specific actuator concepts becomes possible.

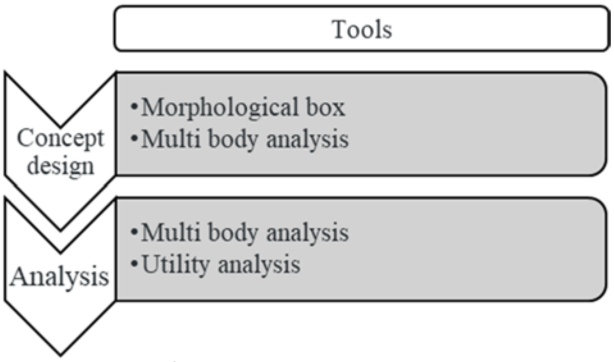

Figure 5: Tools for concept design and analysis steps

For the detailed preliminary development, a multi body analysis is used to identify promising concepts of actuation according to their required actuation power and energy. The preselected concepts are then rated by a utility analysis [11] with respect to the criteria defined by Doberstein [13]. This method allows to identify the pros and cons of the body landing gear vs. the MLG in detail and thus enables the engineer to make a sound decision for the optimal concept.

3. APPLICATION ON AVACON RESEARCH BASELINE

The ARB was derived from the top-level aircraft requirements of a Boeing 767 and enhanced with technologies representative for an entry into service of 2028. It serves as realistic and competitive reference for all studied technologies. Details about the ARB are published by Woehler et al [15]. The main characteristics are listed below in Table 1:

Table 1: Main characteristics of the ARB [15]

Parameter	Unit	Value
Design Range	nm	4600
Maximum Payload	t	30
Maximum Take-Off Weight	t	140
Max. Landing Weight	t	115.4
Wing Span	m	52
Fan Diameter	m	2.4
Cruise Mach Number	-	0.83
$V_{Approach}$	kts	134

The MLG is conventionally mounted at the rear spar of the wing. The length of the landing gear is a result of the requirements introduced in Section 2.1.
With the rear spar position and the position on the ground a first configuration of one MLG of the ARB is set up. The positioning of the MLG in relation to the aircraft is displayed in Figure 6. Table 2 shows resulting clearances, which are achieved with the designed MLG configuration.

Table 2: Clearances for designed main landing gear with requirements

Requirement	Value [deg] (Requirement)
Nacelle clearance including 15cm additional clearance	7 (5)
Wing tip clearance	40 (8)
Take-off rotation	11 (10)
Tipping requirement	15 (15)

Each MLG has a telescopic shock strut consisting of the main fitting and the sliding tube, which both together form the shock absorber. Furthermore, two side stays were selected comparable to the MLG of an Airbus A350 [16]. A bogey arrangement with four wheels is chosen due to the size of the aircraft and comparable aircraft in size such as the Boeing B767 [17]. The developed landing gear sizing method is used for the sizing of the dimensions of the structural components the MLG. Figure 7 displays the results of the sizing process.
Table 3 shows the weight of the different components, which are sized in the structural optimization.

Table 3: Calculated masses for the structural components

Component	Weight [kg]
Main fitting	372
Sliding tube	276
Bogey	96
Wheel axle forward	85
Wheel axle aft	85
Side stay forward	68
Side stay aft	60
Total	1042

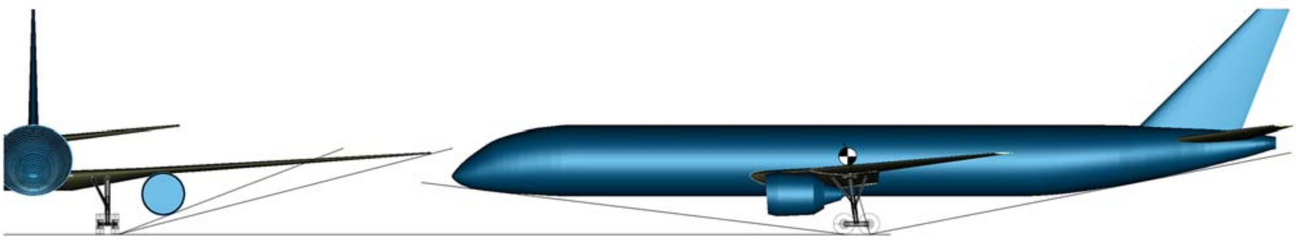

Figure 6: Positioning of the main landing gear at the wing of the AVACON research baseline

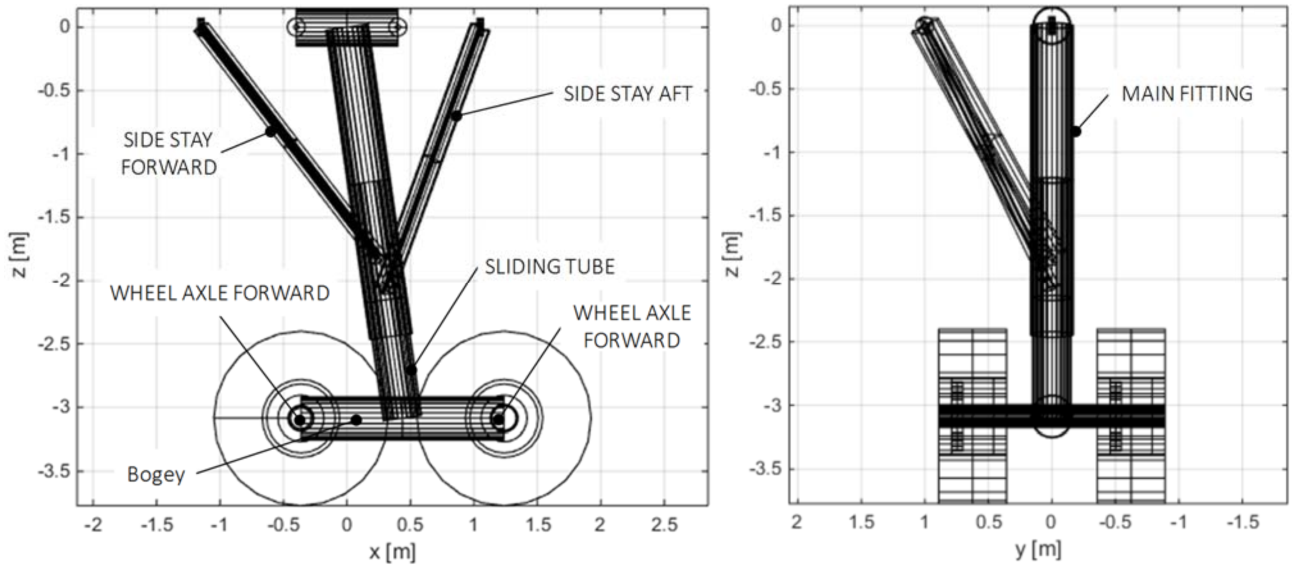

Figure 7: Designed main landing gear configuration for the AVACON research baseline

The results of the structural sizing are compared to the outcomes of the weight estimation of a statistical approach from the "Luftfahrttechnisches Handbuch" (LTH) [10]. The results of the comparison are displayed in Figure 8. The displayed weight estimations for brake, tyre, brake actuation and anti-skid system refers to one entity in each case. The last entry of the total weight refers to the weight of one MLG consisting of the weight of the structural components, four wheels/tyres, fours brakes plus actuation and the anti-skid system. Figure 9 shows the comparison with the components weight normalized to the results of the methods from [10]. It can be seen that the calculated weights of the developed methods are lower than the results based on the statistical data. This is for several reasons. The mass estimation of the statistical method does not take into account geometrical dimensions of the landing gear except the length of the main strut. Other dimensions, for example length of the side stays are not considered, as it is not the intention of these methods to be able to investigate different landing gear configurations, but to give a first mass estimation. Furthermore, the developed method depends strongly on the selected material properties. The brake weight differs relatively strongly. The reason may be that carbon is assumed as material for the calculated brake weight. In contrast, the data used for the statistical methods of the LTH is historical data and carbon brakes only became available to commercial aircraft in the late 1980s [18]. Therefore, this data mirrors the weight of steel brakes. The total landing gear weight estimates differs less than 10% between both methods.

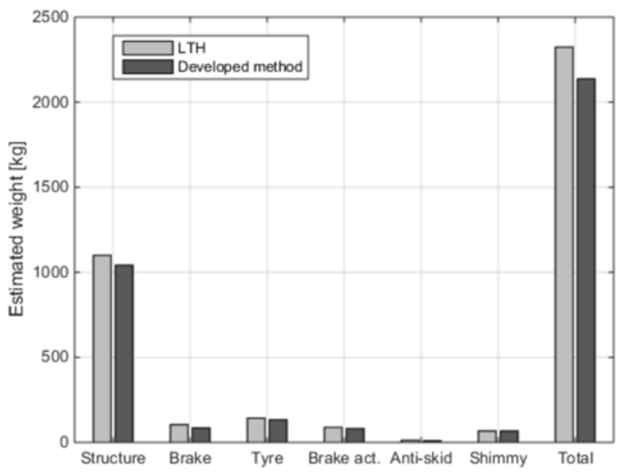

Figure 8: Comparison of the mass estimation results with masses calculated using statistical methods [10]

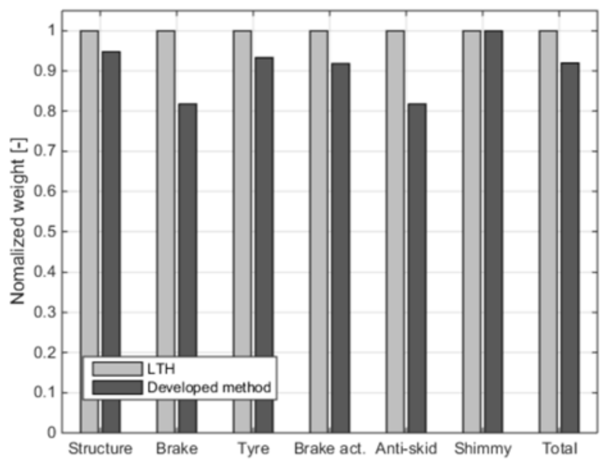

Figure 9: Mass comparison with normalized weights

The results for early preliminary design estimation of the required actuation power for the ARB is shown in Table 4. As actuation time a typical value of t = 10 s is chosen.

Table 4: Early design phase estimation for required power of MLG actuators

Concept	Req. power [kW]	
	Landing gear	Door
Wing mounted	60,3	39,4

This estimation does only take into account the structural masses of the MLG. But for the forward retracting body landing gear, the aerodynamic forces might not be negligible. During movement the aerodynamic moment is developing the opposite way than the weight moment (extendend: high aerodyn. moment, low weight moment; retracted: low aerodyn. moment, high weight moment). This effect can be observed for example at nose landing gears (NLGs). Doberstein [13] found that the maximum combined load moment remains rather constant over the retraction process and does not differ significantly from the maximum weight load moment for the configuration analysed in his thesis. Nevertheless, this cannot be taken as a general rule.

4. PLANNED STUDIES

One of the main focuses of the AVACON Project is the investigation of over wing mounted engines. With this configuration new landing gear configurations are possible. A fuselage integrated landing gear could be a solution, which helps to increase the aircraft performance by saving weight as a shorter landing gear could be incorporated. However, such a landing gear configuration has to fulfil the same requirements as a conventional wing mounted landing gear. The structural integration of the MLG into the fuselage is another important point, which has to be considered. Therefore, planned studies comprise the investigation of landing gear integration possibilities and their structural impact on the fuselage. A simplified structural fuselage model is under development, which offers the possibilities for the integration of the here presented structural landing gear model. To complete the structural comparison of the wing mounted landing gear of ARB and the fuselage integrated landing gear, a structural wing model is required as well. The objective of this wing model is to assess the weight impact of the MLG loads on the entire wing weight. In the end the comparison of the total weights on aircraft level between the two landing gear configurations can be drawn.
Upcoming studies regarding the MLG actuation are focused on the application of the method for the detailed preliminary design phase (see chapter 2.1, [7]). For these studies it is planned to identify the optimal actuation concepts for both landing gear configurations: landing gear on wing and body landing gear. Finally, these two configurations are compared to analyse whether, and under which circumstances, the body landing gear configuration offers advantages in terms of the actuation. With this knowledge the aim is to give a recommendation if the body landing gear configuration is feasible for the application in aircraft with over wing engine configurations.

5. CONCLUSION

In this paper an overview of the planned landing gear activities in the research project AVACON is given. The project aims to assess the impact of UHBR engines for future aircraft configuration, which could be mounted over the wing. This leads to new alternative landing gear designs, such as a body landing gear. The first step of the project was to define an AVACON research baseline aircraft (ARB) to be able to evaluate the upcoming design changes. For the ARB a preliminary main landing configuration was designed and a first structural sizing was conducted with a developed method. The developed method defines the landing gear as a simplified beam model and dimensions the structural components according to defined load cases. The weight of other parts of the landing gear, such as tyres and brakes, where estimated using literature methods. A first comparison with methods based on statistical data showed good consistency.
The actuation of the landing gear is also part of the project. Here, a simple analytical method was applied to estimate the required power to retract the landing gear.
The next steps are to further develop and extend the introduced methods. One focus lies here on the structural integration of an alternative body landing gear into the fuselage. Therefore, a structural model of the fuselage, which offers the possibility to attach the MLG, is under development.

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