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AN UPDATE TO A SEMI-PHYSICAL METHOD FOR THE MASS ESTIMATION OF FUSELAGES CARRYING LIQUID HYDROGEN FUEL TANKS IN CONCEPTUAL AIRCRAFT DESIGN

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Abstract

Hydrogen-powered aircraft can contribute to the effort of reducing aviation´s climate impact. A better understanding of the liquid hydrogen storage with respect to airframe integration is required to improve the predictive qualities of overall aircraft design studies. This paper presents the synthesis of loads and mass estimation models in hydrogen aircraft design. A case study is performed on the assessment of non-integral liquid hydrogen tanks and their impact on the fuselage structure. The introduction of loads analysis and analytical design of primary fuselage structures is able to capture more design sensitivities compared to a design process that fully relies on empirical methods. Technical challenges of the fuel tank integration in the rear of the fuselage are reviewed and critical design parameters discussed. The update includes a revision of how one of the applied mass estimation methods is adapted and a method for estimating the fuselage center of gravity.

Keywords

Hydrogen Aircraft, Conceptual Aircraft Design, Fuselage Mass Estimation, Hydrogen Fuel Tank Integration

1. INTRODUCTION

The adoption of hydrogen as a primary energy carrier for an aircraft requires the consideration of various components. Furthermore, a hydrogen tank system has to be designed and its properties with respect to mass and volume need to be estimated. Concurrently, the tank system has to be allocated within the airframe, which generally lowers the overall performance of the aircraft due to increased structural mass and wetted area. Most of the published studies so far have focused on structural or thermodynamic aspects of the tank design itself or on the question where to generally integrate the tanks on the airframe. Integrating the tank system in the fuselage tends to be the favored option in research and industry concepts. However, the consequences to the structure holding the tank i.e. the fuselage need to be considered as well to determine the impact of the hydrogen tank on overall aircraft design. The efforts within the DLR project *Exploration of Electric Aircraft Concepts and Technologies* (EXACT) have led to a more detailed assessment of how such a fuel tank integration will impact the fuselage structure and its mass. The present paper addresses one of many aspects when modelling liquid hydrogen storage in overall aircraft design. The method is applied to a short-range low-wing turbofan airliner.

2. METHODOLOGY

A holistic process is necessary to investigate the performance of hydrogen aircraft. All the technical parameters driving the design of an aircraft need to be considered. The design process in this study comprises a multifidelity analysis. Figure 1 shows the schema of the iterative process that converges the results of several sub modules in the loop. In the subsequent paragraphs the purpose and fidelity level of every tool within the process is discussed.

2.1. Overall Aircraft Design Process

The conceptual design tool *openAD* is the first component of the tool chain and is used to generate a consistent overall aircraft design. WOEHLER et. al. introduced the tool methodology and knowledge base in [1].

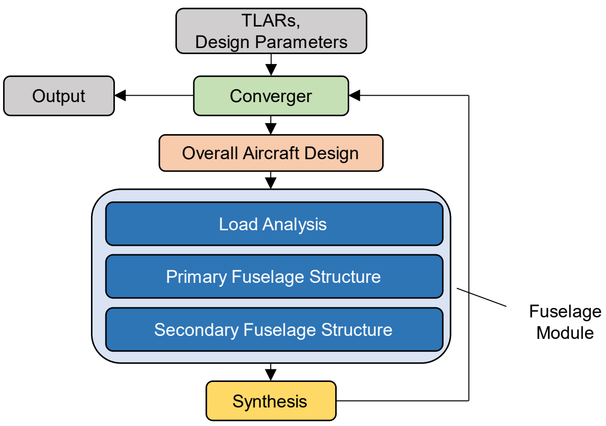

FIG 1 Overall aircraft design workflow including the fuselage module to estimate the fuselage primary and secondary structure mass.

The tool generates an aircraft model written in the Common Parametric Aircraft Configuration Schema (CPACS). CPACS is a data format for aircraft design that has been presented by ALDER et.al. [2]. The aircraft model is then passed on to disciplinary tools which populate it with higher fidelity analysis. The fuselage module comprised of loads analysis, primary and secondary structure mass estimation calculates the total fuselage mass. The liquid hydrogen fuel tank properties are modelled in the synthesis module. The tanks are sized by the required fuel volume and simplified input parameters such as a fixed gravimetric index. The fuel volume is a result of the required design range at a specified standard passenger payload. The fuselage tail length is updated every workflow run in order to fit to the dimensions of the hydrogen tanks. The updates on geometry and masses are given as fixed inputs to *openAD* in the next iteration, which generates a new and consistent aircraft model again. The loop is reiterated until the convergence criteria are satisfied.

2.2. Fuselage Assessment

The fuselage mass is usually assessed on a low fidelity level in conceptual aircraft design studies. Empirical methods from literature typically require basic geometrical inputs e.g. fuselage length, diameter and type of wing and propulsion integration which are sufficiently accurate to calculate the total structural mass of a conventional fuselage based on statistics. The standard mass method for the total fuselage structural mass which is applied in the conceptual aircraft design tool openAD is published in Luftfahrttechnisches Handbuch [3]. It is herein referred to as the LTH-method. However, the approach of this study is to consider the fuselage as an assembly of primary and secondary structure and to incorporate physics-based analysis to capture effects of the concentrated mass of the fuel tanks in the rear of the fuselage. Hereafter, the various assembly components of the fuselage are described and mass estimation methods introduced.

2.2.1. Primary Fuselage Structure

In the scope of this study, the primary structure is comprised of

- Skin panels
- Frames
- Stringers
- Pressure bulkheads.

Mixed Analytical-Empirical Approach

The skin panels, frames and stringers are partially analytically sized and their mass estimated via the tool PANDORA, which was presented by PETSCH in [4]. The tool was adapted by PETSCH to function in an automated design workflow [5]. This analytical assessment requires a load estimation which is provided through the conceptual design loads estimation tool LOADzero and conceptual landing gear loads estimation tool LGLOADzero which were presented by HECKEN [6]. The loads estimation considers the actual mass and positioning of the liquid hydrogen tanks on the aircraft. The liquid hydrogen tanks are integrated in the non-pressurized part of the fuselage. The critical load cases in each region on the fuselage skin are identified in the tool PANDORA. The pressurized region of the hull is considered in the stress flow calculation. The skin is discretized into a mesh and the critical skin thickness is calculated for each point based on the CPACS structure definition by using local frame and stringer pitch, stress flows as well as material parameters. The stringer and frame distributions along the fuselage hull are predefined based on typical fuselage structures of similar aircraft.

The total mass of the pressure bulkheads is derived trough an empirical method based on first principles published by TORENBEEK [7]:

$$(1)\quad m_{\text{Bulkhead}_{\text{Nominal}}} = C_{\text{Shell}} \cdot d_{\text{Fus}}^2 \cdot l_{\text{Ref}} \cdot \frac{1}{g}.$$

The method requires the diameter of the fuselage d_{Fus}, a reference length l_{Ref}, a calibration factor C_{Shell} and the acceleration g. It is based on typical sizes of pressure bulkheads in the fuselage tail of conventional aircraft. For this study the method was adapted in a way to account for the diameter increase due to the scaling of the rear pressure bulkhead to the size of the fuselage constant cross-section. It was assumed that the rear pressure bulkhead typically makes up two thirds of the total bulkhead mass. It was also assumed that the rear pressure bulkhead´s diameter is typically equivalent of 2/3 of a fuselage constant cross-section diameter. As eq. (1) indicates, the mass scales with the area i.e. the square of the diameter, thus an exponent of 2 is added. These assumptions combined give the mass for 'rear full size' pressure bulkheads

$$(2)\quad m_{\text{Bulkhead}_{\text{Rear}}} = m_{\text{Bulkhead}_{\text{Nominal}}} \cdot \frac{2}{3} \cdot \left(\frac{1}{2/3}\right)^2$$

and for the remaining bulkhead mass

$$(3)\quad m_{\text{Bulkhead}_{\text{Rest}}} = m_{\text{Bulkhead}_{\text{Nominal}}} \cdot \frac{1}{3}.$$

The sum of skin, stringer, frames and total bulkhead masses is then calibrated to the total primary shell structure mass of a known reference aircraft

$$(4)\quad m_{\text{Primary}} = (m_{\text{SkinPanels}} + m_{\text{Frames}} + m_{\text{Stringers}} + m_{\text{Bulkhead}_{\text{Rest}}} + m_{\text{Bulkhead}_{\text{Rear}}}) \cdot f_{\text{Shell}}$$

via the calibration factor f_{Shell}. The calibration factor is then used for the analysis of fuselages with integrated hydrogen tanks.

Empirical Approach

Alternatively to the introduced mixed analytical-empirical approach the primary fuselage structure can also be estimated via a purely empirical method by TORENBEEK [7]. Similar to the method for the estimation of the pressure bulkhead mass, the method for the skin, stringer and frames is based on first order principles and is calibrated on real data. The combined mass of the three components plus an additional mass for unideal shapes and cutouts is given by TORENBEEK to be

$$(5)\quad m_{\text{PrimaryTorenbeek}} = C_{\text{Shell}} \cdot d_{\text{Fus}}^2 \cdot l_{\text{Fus}} \cdot \frac{1}{g}.$$

The primary structure mass is driven by the fuselage volume and assumptions on ideal aluminium alloy structures.

The calibration factor C_{Shell} is of the same value as the one used for the calculation of the pressure bulkhead masses and represents a stack-up of assumptions for the skin panels, stringers and frames. For more details on this stack-up refer to the respective chapter in [7]. This method enables a lower runtime compared to the mixed analytical-empirical approach and is still able to capture the major impacts of the hydrogen tank installation on the overall fuselage structure. It is referred herein as the Torenbeek method and its influence on the results is discussed on the basis of case studies in chapter 3.

2.2.2. Secondary Fuselage Structure

The secondary fuselage structure is comprised of

- Cabin floor
- Floor support structures
- Wheel bays
- Doors
- Windows
- Wing carry-trough structure etc.

The combined mass of these components is estimated via another empirical method provided by TORENBEEK [7]. According to the method, the total mass of the secondary structures

$$(6)\quad m_{\text{Secondary}} = \Omega_{\text{fl}} \cdot \sqrt{n_{\text{ult}}} \cdot d_{\text{Fus}} \cdot l_{\text{Fus}} \cdot \frac{1}{g},$$

scales linearly with the length and diameter of the fuselage and a calibration factor Ω_{fl}. Furthermore, it is dependent on the square root of the ultimate load factor n_{ult}. TORENBEEK states that most components of the secondary structure are related to the cabin floor area. Thus, for this study, the dependency on the fuselage length is replaced by a dependency on the cabin length. The cabin floor structures, doors and windows make up a large majority of the secondary structures and are not affected by an integration of liquid hydrogen tanks in the back of the fuselage. It is assumed that the tank integration affects only the primary structure. The method for the estimation of the secondary structure was therefore adjusted to account for the cabin length

$$(7)\quad m_{\text{Secondary}} = \Omega_{\text{fl}} \cdot \sqrt{n_{\text{ult}}} \cdot d_{\text{Fus}} \cdot l_{\text{Cabin}} \cdot \frac{1}{g} \cdot f_{\text{Secondary}},$$

and was recalibrated via $f_{\text{Secondary}}$ on data for existing aircraft.

2.2.3. Modified LTH Method

The LTH method was modified and prepared as a fourth option in order to present an even simpler alternative to the fully empirical Torenbeek method. The result of the LTH mass estimation is multiplied by a factor

$$(8)\quad f_{\text{LTH}} = 1 - \phi_{\text{S,Ref}} + \phi_{\text{S,Ref}} \cdot \frac{l_{\text{Fuselage,Ref}}}{l_{\text{Cabin,Ref}}} \cdot \frac{l_{\text{Cabin}}}{l_{\text{Fuselage}}}$$

where $\phi_{\text{S,Ref}}$ is the ratio of secondary to total structure mass of the reference aircraft

$$(9)\quad \phi_{\text{S,Ref}} = \frac{m_{\text{SecondaryStructure,Ref}}}{m_{\text{TotalStructure,Ref}}}.$$

This way, the theoretical secondary share of the structure mass is controlled to not grow with the fuselage length. The ratio of fuselage and cabin length of the reference aircraft is included so the factor becomes 1 when no changes to the fuselage are applied. The center of gravity of the fuselage changes with the implementation of the fuel tanks too. Therefore, a calibration based on simple assumptions was devised. The total cog position of the reference fuselage is assumed to be

$$(10)\ cog_{\text{Ref}} = \begin{pmatrix} \phi_{\text{S,Ref}} \cdot cog_{\text{S,Ref}} \\ +(1-\phi_{\text{S,Ref}}) \cdot cog_{\text{P,Ref}} \end{pmatrix} \cdot f_{\text{CoG}}$$

where cog_{Ref} is a known or set value and f_{CoG} is the overall cog calibration factor. Furthermore, $cog_{\text{S,Ref}}$ is the assumed cog position of the secondary structure and $cog_{\text{P,Ref}}$ is the assumed cog position of the primary structure of the reference aircraft. The overall calibration factor needs to be computed via

$$(11)\ f_{\text{CoG}} = \frac{cog_{\text{Ref}}}{(\phi_{\text{S,Ref}} \cdot cog_{\text{S,Ref}} + (1-\phi_{\text{S,Ref}}) \cdot cog_{\text{P,Ref}})}.$$

In the case study below the cog position of the secondary structure was assumed to be at the middle of the cabin length. The cog of the primary structure was assumed to be at the middle of the fuselage length. To estimate the new cog position of the fuselage with LH2 tank, the updated theoretical ratio of secondary to total structure mass is defined to be

$$(12)\ \phi_{\text{S}} = \phi_{\text{S,Ref}} \cdot \frac{l_{\text{Fuselage,Ref}}}{l_{\text{Cabin,Ref}}} \cdot \frac{l_{\text{Cabin}}}{l_{\text{Fuselage}}}.$$

Then, the new cog position is computed according to

$$(13)\ cog = (\phi_{\text{S}} \cdot cog_{\text{S}} + (1-\phi_{\text{S}}) \cdot cog_{\text{P}}) \cdot f_{\text{CoG}}$$

with the earlier computed factor f_{CoG}. This approach gives the quickest results and doesn´t require new tools for the mass estimation. The case studies below reveal that its results are close to the more advanced Pandora method.

The Pandora and the Torenbeek method include their own assumptions with respect to the center of gravity (cog) of the primary and secondary fuselage structures which were calibrated with a global calibration factor to meet the target cog of the reference aircraft.

2.3. Post-Processing

The unconventional fuel tank integration in the rear of a fuselage requires attention to the more pronounced shift in center of gravity during flight and ground operations. This behavior is analyzed in a weight and balance evaluation.

3. CASE STUDIES

The workflow was applied to a single-aisle short-range aircraft. Its design is based on a state-of-the-art turbofan airliner with a design range of 2900nm. The selected fuel tank integration in the rear of the fuselage causes a large shift in center of gravity when payload and fuel are loaded and unloaded i.e. consumed. To ensure a reasonable aircraft design for a constant fuselage cross-section the design range was reduced compared to the reference aircraft. For this study, three design ranges were analyzed: 1500nm, 1750nm and 2000nm. Figure 2 shows how the fuel tank geometries were adapted to fit inside the volume of the fuselage tail.

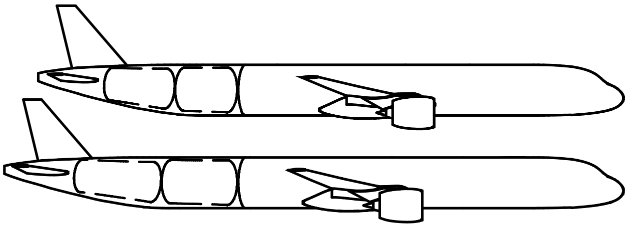

FIG 2 Side-view on the 1500nm design range variant on top and 2000nm design range variant at the bottom.

The spacings of the tanks to each other and to the fuselage hull may require to be larger to be technically feasible but this is not the focus of this study. Each aircraft variant is designed and all lifting surfaces are resized accordingly. The resulting wing positions may require an adapted door layout compared to the reference aircraft. However, this is not considered in the mass estimation method.

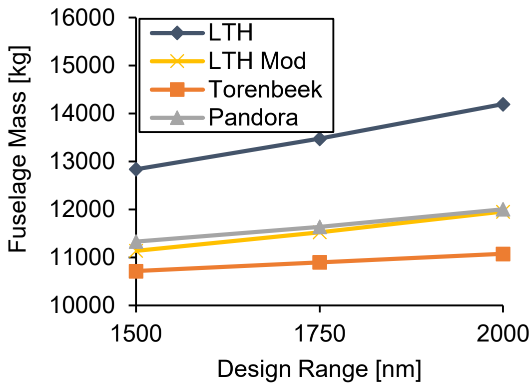

FIG 3 Parametric study on fuselage mass over design range for the different mass estimation methods.

The fuselage furnishing mass as part of the fixed equipment is kept constant for each design since the cabin is considered constant in its dimensions. Its cog position is assumed at half the cabin length. Figure 3 shows the results of the fuselage masses for the different design ranges and mass estimation methods.

The Pandora method gives results that are on average 14% lower compared to the standard LTH method. A double-digit decrease is expected as the LTH method treats the fuselage length as a standard fuselage without distinguishing between primary and secondary structure. The empirical, but adapted Torenbeek method gives a higher average reduction of -19% of fuselage mass compared to the LTH method. The modified LTH method predicts very similar reductions in mass to those of the Pandora method. Obviously, the gap against the standard LTH method increases with design range i.e. tank size due to the increasing fuselage length and the corresponding effects on fuselage mass. A smaller slope for the change in fuselage mass in case of the Torenbeek method with increasing fuselage length is recognized. Contributing to this behavior may be the fact that the primary fuselage mass in the Torenbeek method scales linearly with the fuselage length while the LTH method predicts mass growth with an exponent greater than one. The partially analytical Pandora method also predicts a slope similar to the LTH method. In this case the Pandora method gives more conservative results compared to the fully analytical Torenbeek method. However, this may change if other aircraft categories or design ranges with different cabin cross-sections are investigated.

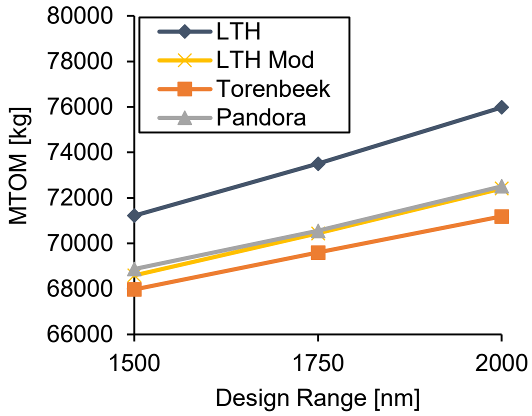

FIG 4 Parametric study on MTOM estimation over design range for the different mass estimation methods.

Figure 4 shows the resulting maximum take-off masses for each configuration and fuselage mass estimation method. The lighter fuselage mass estimated by the alternative methods results in a lower take-off mass. With the Pandora method an average reduction of -4% maximum take-off mass is predicted. The Torenbeek and the modified LTH method predict a reduction of -5.4% and -4.2%, respectively. To the first order these changes in take-off mass mean an equivalent reduction in fuel burn. Considering the order of magnitude, this impact on aircraft performance should not be neglected in conceptual aircraft design studies. The proximity of the modified LTH method to the other alternative methods shows that simple assumptions can serve as an initial best guess to improve fuselage mass estimation in the absence of more accurate methods.

In Figure 5 is the split among primary and secondary structure mass estimation shown. Since the modified LTH method does not reflect that level of detail the respective total mass is shown. The chart shows the case for the 2000nm design range. The secondary structure mass is equal for the Pandora and for the Torenbeek method as they both are linked to the cabin area which is constant.

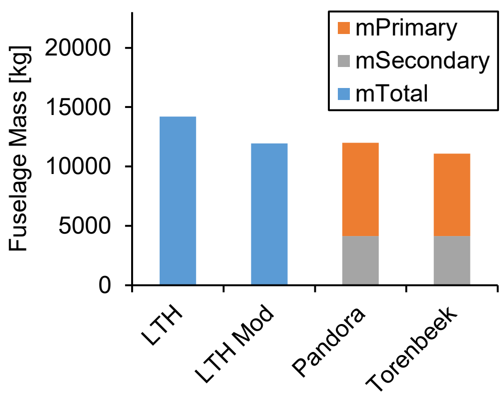

FIG 5 Parametric study on fuselage mass over design range for the different mass estimation methods.

The Pandora method predicts a 13% larger primary structure compared to the empirical Torenbeek method. The validity of this, however, cannot be confirmed in the absence of a more detailed analysis. Both methods imply simplifications or are based on first principles. In conclusion, the methods both increase the accuracy of the aircraft design process by respecting the individual aspects of primary and secondary fuselage structure but do not give a full picture of how a primary fuselage structure mass may change due to the integration of large hydrogen tanks.

4. WEIGHT AND BALANCE ISSUES OF WING-MOUNTED MAIN LANDING GEARS

The fuel tank integration in the rear of the fuselage is challenging in terms of balancing the aircraft with respect to flight and ground operation. Furthermore, the sizing of the horizontal stabilizer is affected by the relatively larger shift in center-of-gravity due to the long fuselage with the payload in the front and the fuel in the rear. Two methods from Torenbeek have been included in openAD to align the stabilizer size with physical requirements [8]. One is the landing stall condition and the other is the take-off rotation condition. In this study, the more demanding condition for the stabilizer was found to be the required download during take-off rotation. The most forward cog position that drives this requirement lies further ahead than for conventional kerosene aircraft, increasing the nose down moment of the total mass around the landing gear. Although the stabilizer together with the elevator on the hydrogen aircraft has a larger lever arm to lift the nose up, this shift in cog is too significant to maintain the volume coefficient for the horizontal stabilizer in place on the reference aircraft. This could be mitigated by an increase in tailplane authority e.g. by means of a droop-nose to increase the lift coefficient of the tailplane. However, this was not considered in this study and therefore the sizing method indicates a volume coefficient increase of at least 40% and up to 70% higher compared to the reference aircraft. The volume coefficient rises with increasing design range i.e. fuel tank size.

The figure 6 shows how the longitudinal position of the main landing gear is related to the most aft cog position, a tip-back angle margin δ and the required landing gear height. The landing gear strut of a wing-mounted landing gear is attached in the space between rear spar and trailing-edge high-lift device and is inclined by the angle γ.

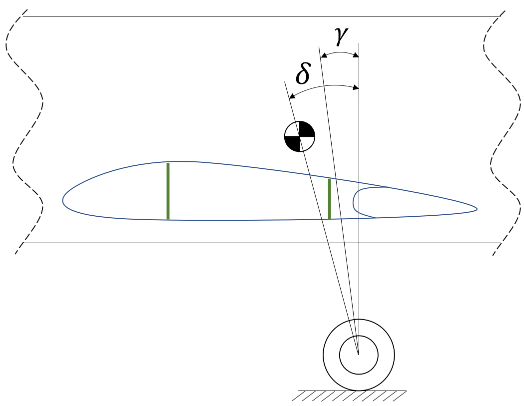

FIG 6 Positioning of the wing-mounted main landing gear respecting tip-back angle margin and structural integration.

The wing position is also determined by the most aft cog position and a required minimum static margin. Thus, for the wing-mounted landing gear, the strut inclination γ is a result of wing and landing gear positioning. The most aft cog position is defined by zero payload and fully loaded fuel tanks. With the same input for minimum static margin as for the reference aircraft, the main strut inclination would become too extreme. The wheel would even sit behind the wing trailing edge. This is deemed unacceptable for structural integration.

One way to tackle this problem and thus, to move the position of the tires forward with respect to the wing chord is to increase the minimum static margin. This shifts the wing to the rear. However, this increases the horizontal tail plane size and adds more trim drag in flight due to higher overall static margins in flight. Figure 7 shows the weight and balance analysis of the case with a filling level allowance of 100%, design payload and increased static margin.

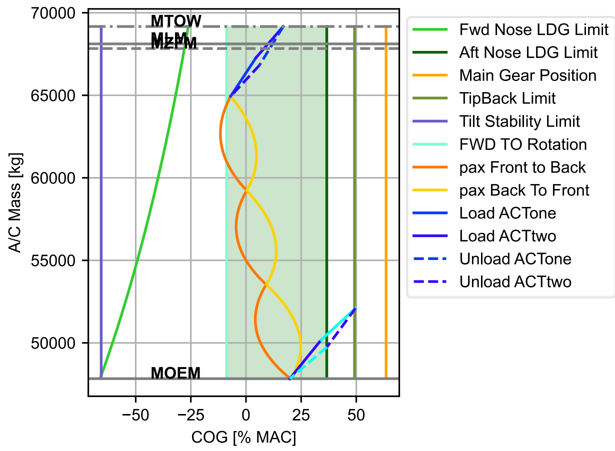

FIG 7 Weight-and-balance analysis for full fuel tank filling allowance and higher minimum static margin.

The graph indicates that with moderate payloads no ground operation limits are violated. The tip-back margin is respected. However, it is obvious that filling the tanks up to 100% volume would violate the minimum load on the nose landing gear for safe steering on ground. This limit type is evaluated after the design process is finished. Around half of the fuel is allowed to be tanked to keep the 6% minimum share in total load on the nose wheels. The operational limitation of this is considered acceptable as this type of flight is rarely operated.

Another opportunity to integrate the main landing gear in the wing is to limit the filling level of the fuel tanks. This moves the maximum cog position towards the nose and with it the wing and the landing gear, enabling a reasonable strut inclination. The positive side effect is that due to the forward shift of the tires the tail download requirement during take-off rotation decreases and thus, the tail size decreases too, improving the efficiency of the aircraft. Figure 8 shows the weight and balance analysis of the case with a filling level allowance of 50% and design payload. The graph indicates that the allowed fuel volume further decreases in order to safely steer the aircraft on ground. Additionally, the tip-back limitation cog has moved forward due to the restriction on the filling level of the tanks. The graph also shows that if the fuel tanks are filled 100% without payload the aircraft may tip back if no safety measures like a stabilizer stick or other vehicles are used. These operational aspects need to be managed but are not considered a major disadvantage of the configuration. The aircraft can still safely take off with a small amount of fuel and zero payload. The classical wing-mounted landing gear that is enabled by the cog restriction is a valid reason to accept some operational limitations. An alternative to the wing-mounted landing gear would be a fuselage-mounted integration.

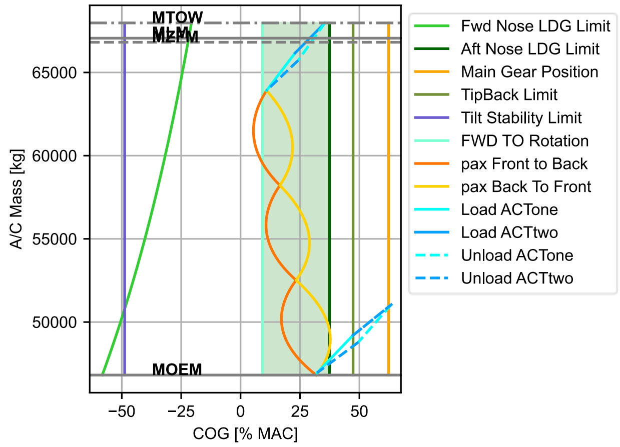

FIG 8 Weight-and-balance analysis for 50% fuel volume allowance and lower minimum static margin.

The latter allows less restrictions on tank filling levels but requires a larger fairing and heavier landing gear due to the integration issues of fuselage-mounted main landing gears and the overall higher cog position of hydrogen aircraft. However, a detailed comparison of wing-mounted versus fuselage-mounted landing gears is out of the scope of this study. Nevertheless, two design parameters, i.e. the tank volume allowance at zero payload and the minimum static margin were discussed as enablers for a wing-mounted main landing gear.

5. CONCLUSION

This paper presents a semi-physical mass estimation method for aircraft fuselages carrying liquid hydrogen tanks in the context of conceptual aircraft design. The aircraft design process with the new semi-physical method was compared to a process that employs a fully empirical method from literature for the estimation of the fuselage mass. The semi-physical method requires more tools, but is able to cover effects of hydrogen fuel tank installations that the empirical method is insensitive to e.g. the actual share of the pressurized fuselage. In the case of this study, the semi-physical method estimated slightly higher fuselage masses compared to the empirical method. The validity of either method could not be assessed in the absence of higher fidelity tools. However, the methods both improve the aircraft design process and understanding for hydrogen aircraft with fuel tanks in the fuselage by respecting the individual aspects of primary and secondary fuselage structure. Applying the methods gives better results than to use top-level fuselage mass estimation methods that do not make that distinction. Integration challenges of a wing-mounted landing gear for the hydrogen aircraft configuration were identified and possible solutions discussed.

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