PRELIMINARY WEIGHT ESTIMATION FOR DIFFERENT ACTUATOR TYPES FOR LANDING GEAR RETRACTION

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Abstract

The electrification of aircraft subsystems is one focus of aerospace research to increase the efficiency of aircraft. Especially the replacement of the conventional centralized hydraulic system with its dedicated actuators for flight controls and landing gear retraction are considered in this context. Two alternative actuator types are investigated as possible replacement. The first alternative actuator type is the Electro Mechanical Actuator (EMA) and the second one is the Electro Hydrostatic Actuator (EHA). In this work, simplified weight estimation methods from literature as well as developed methods are used to estimate the weight of the different components an EMA or EHA consists of. These methods are used to estimate the weight of the different actuator types for landing gear retraction. The influence of different landing gear parameters on the actuator weight is presented. These landing gear parameters are the weight of the landing gear, the distance of the center of gravity of the landing gear to the revolution axis around which it is retracted and the available lever arm of the actuator, which corresponds to the required force. A case study is performed comparing the two different actuators for a conventional wing mounted landing gear with a shorter fuselage integrated body landing gear. For both actuator types the shorter body landing gear led to a lighter actuator compared to the longer conventional landing gear. In the comparison of the actuator types itself, the EMA resulted to be lighter than the EHA for the body landing gear.

Nomenclature

Symbol	Description	Unit			
C	Constraint	-	*Ref*	Reference	-
COG	Center of gravity	-	*retract*	Landing gear retraction	-
D	Housing diameter		*P*	Power	kW
d	Rod diameter	m	*p*	Pressure	Pa
dead	Refering to dead length	-	*PE*	Power electronics	-
EHA	Electro hydrostatic actuator	-	*s*	Wall thickness	m
EMA	Electro mechanical actuator	-	*T*	Torque	Nm
F	Force	N	*t*	Time	s
g	Acceleration due to gravity	m/s²	*U*	Displacement	m³/rev
l	Length	m	*x*	Actuator lever arm	m
LG	Landing gear	-	*ρ*	Density	kg/m³
M	Mass	kg	*φ*	Retraction angle	°
MEA	More Electric Aircraft	-	*ω*	Angular velocity	Rad/s
n	Number of revolutions	1/min			

1. INTRODUCTION

The European Commission stipulated ambitious long-term emission reduction targets for the aviation sector [1]. The fulfilment of these targets require a substantial increase of the overall aircraft efficiency including the propulsion system. One strategy to increase the aircraft efficiency is the "More Electric Aircraft" (MEA) [2], with the Boeing B787 being one of the first representatives for a large commercial transport aircraft [3]. With the MEA approach the subsystems, such as flight controls for example, shall be electrified by removal of hydraulic actuators or at least hydraulic pipes.

Electro Mechanical Actuators (EMA) and Electro Hydrostatic Actuators (EHA) are the two actuator types which are discussed in this context. The Boeing B787 introduced EMA for spoiler actuation [4]. EHA are as well already in use as back up solution for the actuation of the spoilers of the Airbus A380 as so-called Electrical Back-up Actuator (EBHA) [5].

A set of simplified mass estimation methods for the different components of EMA and EHA already exist [6], [7]. In the presented work these methods are used and extended to estimate the actuator weight for landing gear retraction.

The presented methods are utilised to evaluate different case studies of landing gears with special regard of the aircraft configuration. The first considered aircraft configuration is a conventional aircraft with engines mounted under the wings with focus on the diameter of the nacelle. Increasing the fan diameter of the engines for improved efficiency and to reduce fuel consumption [8] could require enlarged landing gear main struts. This increases the overall landing gear weight and hence, the required actuation power. A further case study presents a possible future aircraft equipped with engines incorporating an increased fan diameter and mounted over the wing to avoid unnecessarily long landing gear main struts. With this over wing configuration the landing gear could be shortened and integrated as a fuselage mounted body landing gear. Subsequently the landing gear weight and required retraction power can be reduced. The developed actuator mass estimation methods are applied on the different landing gear layouts to estimate the actuator weight and to identify possible weight benefits of a fuselage mounted body landing gear compared to a conventional landing gear configuration.

2. LANDING GEAR PARAMETERS

The weight of the actuators depends significantly on different landing gear parameters. The considered parameters for this work are:

- Parameter 1: The weight of the landing gear
- Parameter 2: The distance from the centre of gravity (CoG) of the landing gear to its revolution axis for retraction
- Parameter 3: The lever arm of the attack point of the actuator to the revolution axis

The three parameters are described in Figure 1. Parameter 3 defines the required length of the actuator. A longer lever arm results in a longer stroke of the actuator and hence, a longer total length.

The geometric assumptions and relations are displayed in Figure 2. In fully retracted position the assumption is made that the actuator is in a horizontally position. Then the length of the actuator can be calculated depending on the retraction angle and x (Parameter 3) as follows:

$$l_{Actuator} = \frac{1}{3}\left(x\sin(\varphi) - l_{dead} + \left(l_{dead}^2 - 2l_{dead}\,x\sin(\varphi) + x^2\,(\sin(\varphi))^2 + 6xl_{dead}\sin(\varphi) + 6x^2(1-\cos(\varphi))\right)^{\frac{1}{2}}\right) \quad (1)$$

The additional parameter l_{dead} accounts for a dead length which both, the housing of the actuator and the actuator rod, need for the interference of internal components, for example.

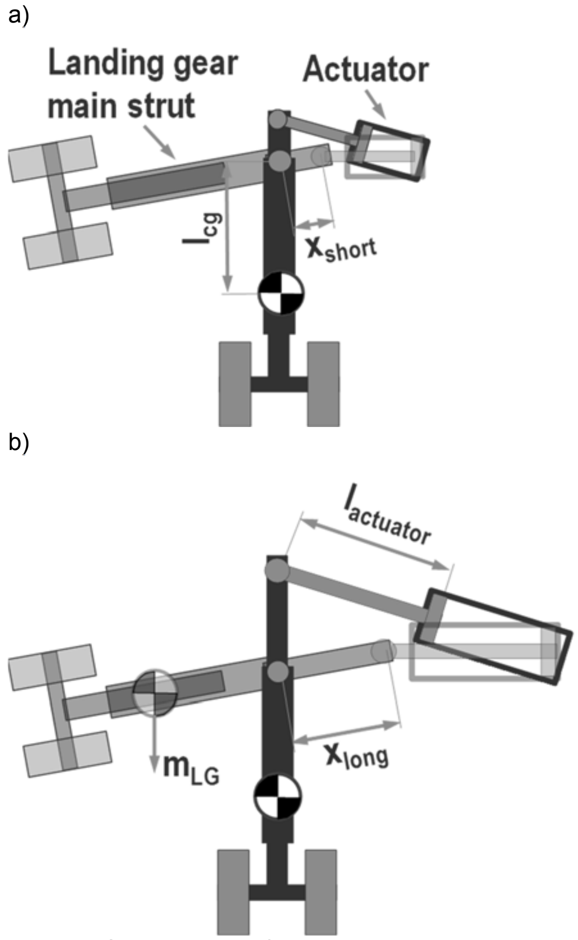

Figure 1: Comparison of a short (a) and long (b) actuator stroke

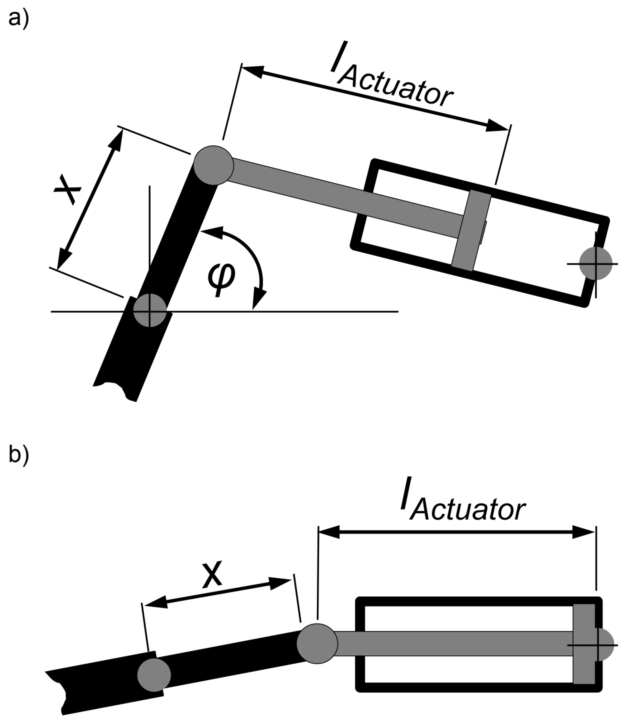

Figure 2: Geometric relations for the modelling of the actuator.

Three different lever arm lengths are used for the different studies. The lever arms are called x_{short}, x_{middle} and x_{long}. Table 1 shows the applied values of the three lever arms.

Table 1: Applied lever arm lengths

Lever arm	Length [m]
x_{short}	0.15
x_{middle}	0.25
x_{long}	0.35

3. ACTUATOR TYPES

Two actuator types are discussed as possible solutions to achieve a MEA. These two types are:

- Electro Mechanical Actuators (EMA)
- Electro Hydrostatic Actuators (EHA)

Schematic descriptions of the two actuator types are displayed in **Fehler! Verweisquelle konnte nicht gefunden werden.** and Figure 4 [9]. The main components of the EMA are:

- Electric motor
- Ballscrew
- Gearbox
- Bearing
- Ram

The main components of the EHA are:

- Electric motor
- Pump
- Hydrostatic actuator (Piston, cylinder, ram)

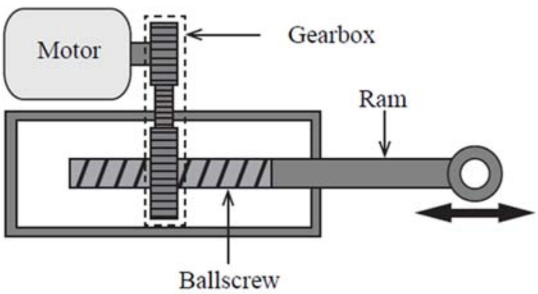

Figure 3: Schematic sketch of an EMA [9]

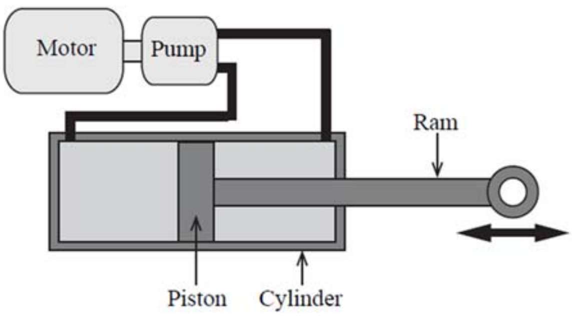

Figure 4: Schematic sketch of an EHA [9]

4. POWER ESTIMATION

As first step, the required power for landing gear retraction is estimated. As first approach, the following formula is used to estimated the retraction force:

$$F_{Actuator} = 1/x(2l_{COG}M_{LG}g\,tan(\varphi) + l_{COG}^2 M_{LG}\dot{\omega}) \quad (2)$$

Where $F_{Actuator}$ is the force, l_{COG} is the distance from the revolution point of the landing gear to its center of gravity, M_{LG} is the weight of the landing gear, g is gravitational acceleration, φ is the retraction angle and $\dot{\omega}$ is the angular velocity.
The required power can then be calculated as follows:

$$P = \frac{F_{Actuator} l_{Actuator}}{t_{retract}} \; with \; t_{retract} = 10s \quad (3)$$

Where P is the retraction power, $l_{actuator}$ is the stroke of the actuator and $t_{retract}$ is the retraction time, which is set to 10s. Since the calculation of $F_{actuator}$ is based on the above introduced landing gear parameters, the required power can be estimated in relation to these parameters. Figure 5 shows the estimated power. The x-axis shows the landing gear weight, the y-axis the distance from the revolution point of the landing gear to its center of gravity and the different line types represent the different length of actuator strokes as introduced above, see Table 1. The marked square is used as validation point. In [10] the retraction power for a landing gear with a weight of M_{ref}=2137kg of a medium range widebody aircraft is estimated. The distance from the revolution point of the landing gear to its center of gravity is $l_{COG,\,ref}$ = 2.5m. The estimated retraction power is stated to be P_{ref} = 60.3kW. The estimated value for the retraction power using the simplyfied approach from above results in a required retraction power of 64-68kW depending on the assumed actuator stroke. Therefore, the introduced simple approach shows good relative agreement with the result from literature.

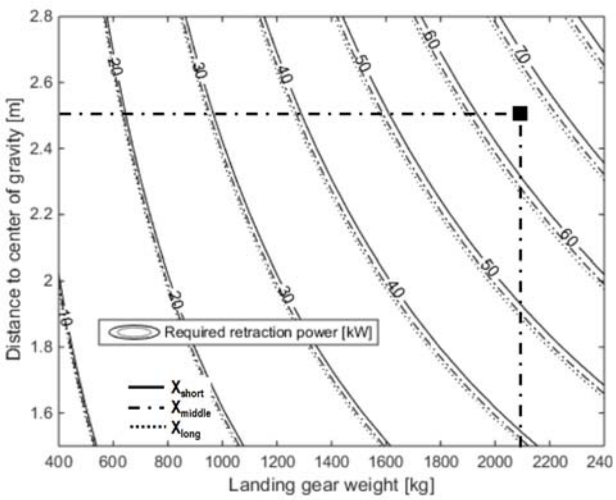

Figure 5: Retraction power estimation for the considered landing gear parameters

5. COMPONENT WEIGHT ESTIMATION

In this section, the weight estimation methods for the different components are presented. First the method for estimating the weight of the electric motor is presented, as both actuator types have this component in common. Afterwards the methods specific for each actuator type are introduced.

5.1. Electric motor weight estimation and power electronics

The weight of the electric motor is estimated using the following relation [11]:

$$M_{Motor} = 0.628T^{\frac{3}{3.5}} + 0.783 \qquad (4)$$

Here M_{Motor} is the mass of the electric motor and T is the required torque, which the motor has to deliver. Replacing the torque T in the formula above by

$$\mathrm{T} = \frac{P}{2\pi n\,/(60min^{-1})} \qquad (5)$$

with n being the revolutions per minute of the electric motor. Figure 6 displays the weight estimation of the electric motor regarding the first two above described landing gear parameters (Parameter 1 and Parameter 2) for different revolutions per minute. With increasing number of revolutions per minute, the weight of the electric motor decreases. The rotational speed is important also for the selection of the gearbox, which has to provide the reasonable gear ratio.

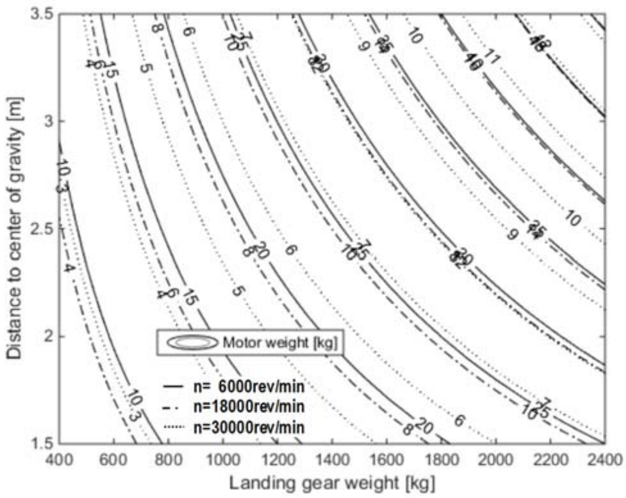

Figure 6: Weight estimation of the electric motor

For the weight estimation of the power electronics a simple assumption is used. Their weight is calculated by applying a power density factor of 2.3kW/kg, see [6]. In this way, the weight of the power electronics is coupled directly to the required power.

5.2. Electro mechanical actuators components

The gearbox of the EMA is used to reduce the rotational speed of the electric motor. In this work data of existing gearboxes is used to estimated the weight. This serves as basic estimation as the design of a gearbox and its components is fairly complicated and a relatively high number of input parameters and assumptions is required. The data is taken from [12]. To select the gearbox from the existing data, three steps are performed:

1. Calculate required torque with gearbox max revolutions
2. Check if selected gearbox is designed for required torque
3. Check if resulting pitch of roller screw is lower than 5mm per revolution

Figure 7 shows the result of the gearbox weight estimation for the three landing gear parameters.

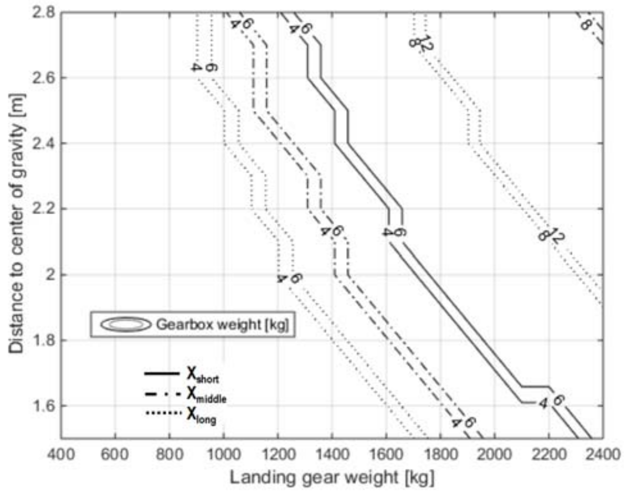

Figure 7: Gearbox weight estimation for the considered landing gear parameters

The ballscrew or roller screw and the ram are the next components for the weight estimation. As for the gearbox existing data was used to estimate the weight of the roller screws [13]. The result of the weight estimation is displayed in Figure 8. The weight is estimated using the calculated actuator force. The selected roller screw has to withstand this actuator force. Reducing the force, and hence, increasing the lever arm leads to a reduced roller screw weight.

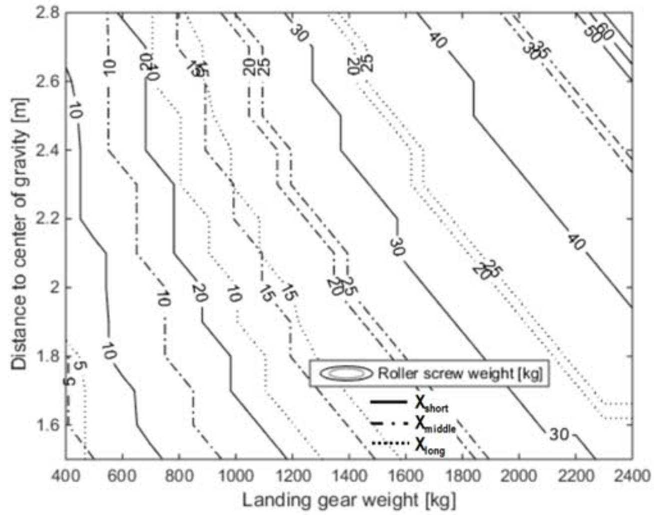

Figure 8: Roller screw weight estimation fort he considered landing gear parameters

To absorb the applied loads, the roller screw has to be supported. Therefore, bearings are required. The weight of the bearings is estimated by the following relation [7]:

$$M_{Bearing} = \left(\frac{F_{Actuator}}{C_{0,ref}}\right)^{\frac{3}{2}} M_{ref} \qquad (6)$$

Here, $M_{Bearing}$ is the weight of the used bearing, $F_{Actuator}$ is the actuator force, $C_{0,ref}$ is the design force of a selected reference bearing with a reference mass M_{ref}. In this case a reference bearing is selected from literature with $C_{0,ref}$ = 212kN and $M_{0,ref}$ = 9.94kg [14].

Finally, the weight of the entire EMA can be calculated by summing up the weight of the different components:

$$M_{EMA} = M_{Motor} + M_{Gearbox} + M_{Roller\ screw} + 2M_{Bearing} + M_{PE} \qquad (7)$$

5.3. Electro hydrostatic actuator components

This section introduces the weight estimation methods used for the different components of the EHA. The first component is the hydrostatic actuator itself, which is comparable to a conventional hydrostatic actuator actuated by a central hydraulic system. Figure 9 shows a schematic representation of a hydrostatic actuator. In the sketch, D refers to the diameter of the housing, d to the diameter of the rod, s is the wall thickness of the actuator housing, A is the annular area of the piston, l is the length of the housing (and the rod) and p is the pressure inside the actuator.

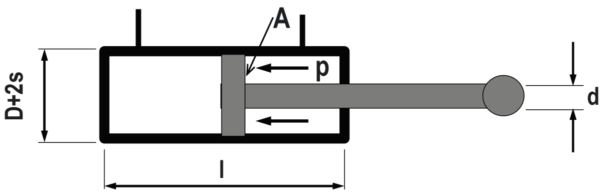

Figure 9: Schematic representation of a hydrostatic actuator

There are different pressure levels, with which today's aircraft operate. The Boeing B787 as one of the most recently aircraft put into service has a pressure level of 5000psi in its hydraulic system [3]. Therefore, for the design of the EHA in the presented study the pressure is also assumed to be p=5000psi. This pressure is used to calculate the diameter of the piston:

$$A = \frac{F_{Actuator}}{p} \qquad (8)$$

To come up with a reasonable preliminary design and weight estimation of the actuator other constraints are considered as well. For the required wall thicknesses of the actuator two simplified load cases are assumed. The first load cases is sizing of the actuator due to the inner pressure and the second load case is buckling of the (extended) actuator. Furthermore, a minimal wall thickness of 5mm is assumed for the actuator. For the calculation of the weight of the actuator an optimization is performed:

$$\min\{M_{Actuator}(D, d, s, l, \rho) \mid c(D, d, s) \geq 0\} \qquad (9)$$

Where, $M_{Actuator}$ is the weight of the hydrostatic actuator depending on its dimensions and material density ρ. The constraints are represented by c.

Figure 10 shows the results of the weight estimation. Interestingly, the middle length (x_{middle}) of the investigated lever arms results in the lowest actuator weight for relative light landing gears. Increasing the landing gear weight leads to the same actuator weight for x_{middle} and x_{long}.

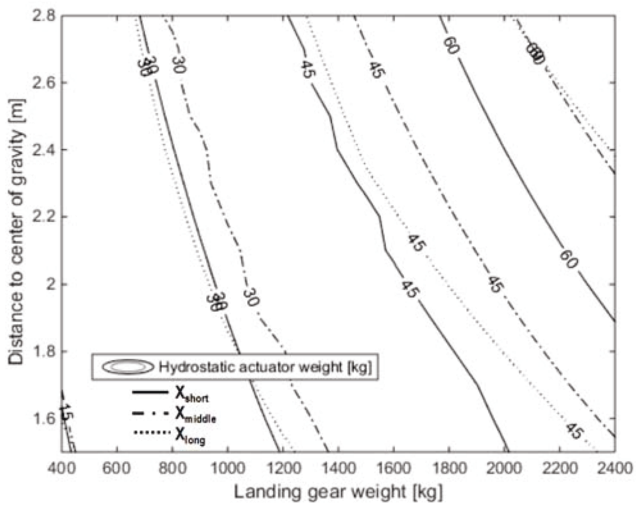

Figure 10: Weight of the hydrostatic actuator for the three landing gear parameters

For the weight estimation of the pump a simplified relation from literature is taken [11], which relates the weight of the pump with its displacement:

$$M_{Pump} = 0.339U + 2.038 \qquad (10)$$

where M_{Pump} is the weight of the pump and U is the displacement.

For the integration block, which shall contain the necessary components such as checking valve, filter and accumulator, the weight estimation model of [11] is used as well:

$$M_{Block} = 0.105P + 2 \qquad (11)$$

In this equation the mass of the integration block M_{Block} is related to the power requirement P of the EHA. P is inserted here in kW.

The total weight of one EHA can now be calculated by adding the up the single component weights introduced before:

$$M_{EHA} = M_{Motor} + M_{PE} + M_{Pump} + M_{Actuator} + M_{Block} \qquad (12)$$

6. COMPARISON OF EMA AND EHA

Now the two total weights of the two different actuator types can be compared for the three landing gear parameters. Figure 11 shows the total weight for the EMA and Figure 12 for the EHA. In each figure points are marked (▲, ♦, ●, ■). ▲ and ● denote the landing gear weight and length of a narrow-body aircraft comparable to an Airbus A320. ♦ and ■ can be considered as an example for a landing gear of a wide-body aircraft comparable to a Boeing B767. Comparing ▲ and ♦ in Figure 11, it can be seen for both points that a short lever arm leads to an increased weight of the actuator and it is favorable to increase the lever arm

of the actuator. In Figure 12 the two points, ● and ■, show that for a small landing gear weight the lever arm of the actuator does not make a big difference. However, for heavier landing gears a smaller actuator lever arm seems to be advantageous.
Linking both figures and comparing ▲ with ● and ♦ with ■, the results show that the EMA is lighter for the lighter landing gear and certain lever arm lengths, but isheavier for the shortest lever arm. With increasing landing gear weight and distance from its CoG to the revolution axis the EHA is lighter. The weight difference depends strongly on the different lever arms of the actuator. For the two points ▲ and ●, the two actuator types can be almost of the same weight or the EHA is ~15% lighter as the EMA for unfavorable lever arms of the EMA. For the two points ♦ and ■, the weight difference can be even bigger and the EHA can be up to ~55% lighter than the EMA.
In general, for lighter landing gears the EMA and the EHA have more or less the same weight, with the EMA being slightly lighter depending on the lever arm of the actuator. Going to higher landing gear weights, the EHA is the actuator type with less weight. The reason for this is that for heavier landing gears the components of the EMA, such as gearbox and roller screw, have a disproportionately increased weight.
The landing gear weight itself has a larger influence on the weight of the actuator than the distance of the *CoG* of the landing gear to the revolution axis.

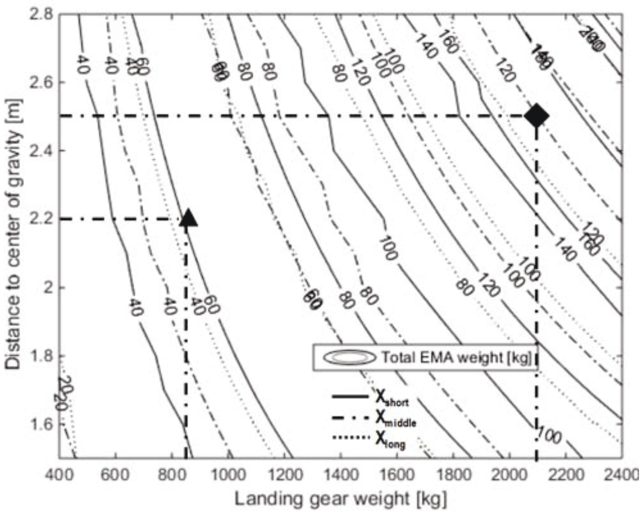

Figure 11: Total EMA weight for the three different landing gear parameters

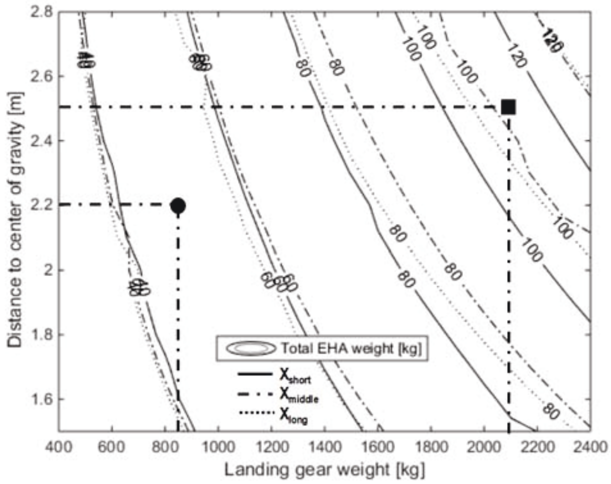

Figure 12: Total EHA weight for the three landing gear parameters

7. CASE STUDY

A possible future aircraft could be equipped with ultra high bypass ratio engines to reduce fuel consumption [8]. Mounting these engines above the wing could reduce the length of the landing gear and save weight, see Figure 13. A first comparison of a conventional wing mounted landing gear and a fuselage integrated body landing gear is presented in [15]. Figure 14 shows the dimensions of the two landing gears. The length of the landing gear struts is determined by the requirements of the “Certification specifications and acceptable means of compliance for large aeroplanes” (CS 25) [16]. As can be seen, the fuselage integrated landing gear is significantly shorter and its structural weight is ~30% lighter. For these two introduced landing gears it is now possible to estimate the weight of the different actuator types and compare them.

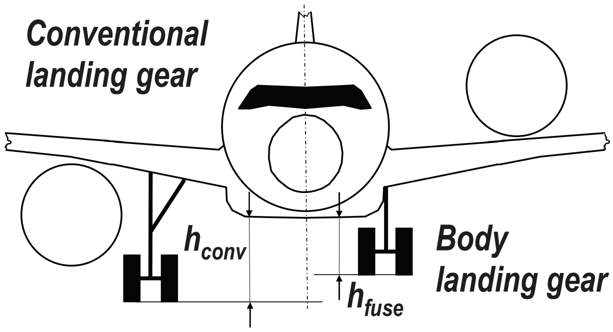

Figure 13: Comparison of conventional wing mounted landing gear with fuselage integrated body landing gear [15]

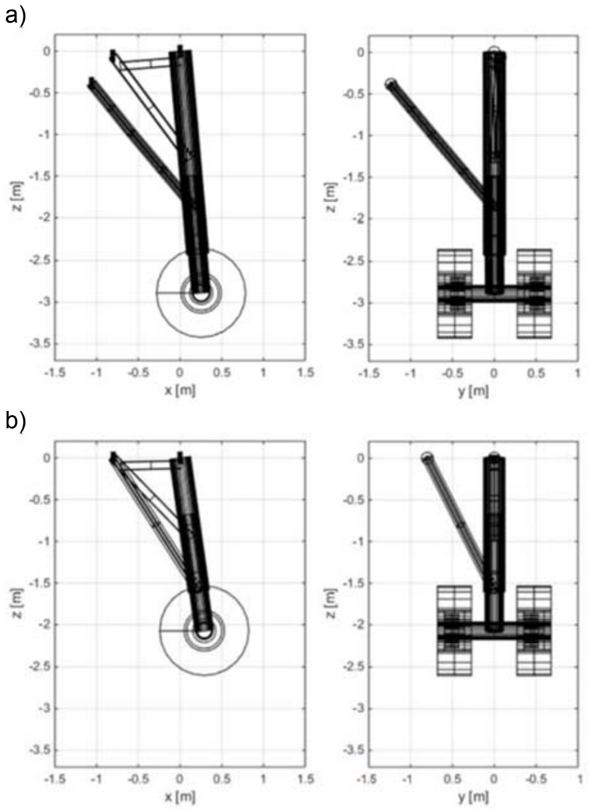

Figure 14: Dimensions of the conventional landing gear (a) and the fuselage integrated body landing gear (b) [15]

Figure 15 and Figure 16 show again the results of the weight estimation for the two different actuator types. This time the points ♦ and ■ denote the conventional wing mounted landing gear and the points ▲ and ● mark the fuselage integrated body landing gear. When using an EMA a weight saving of ~20kg can be achieved for a fuselage integrated body landing gear compared to the conventional landing gear. For the EHA , the weight saving is of the same order of magnitude with ~15-20kg.
For both aircraft configurations the EMA offers the lightest actuator if the lever arm is relatively long, the weight difference is ~2-5kg.

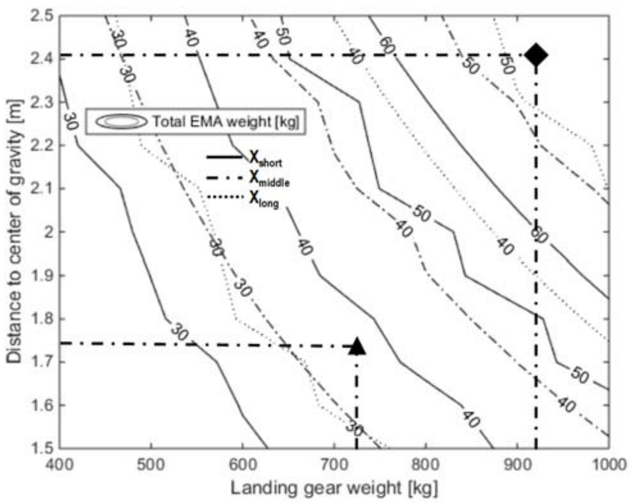

Figure 15: EMA weight for the wing mounted landing gear (♦) and the fuselage mounted landing gear (▲)

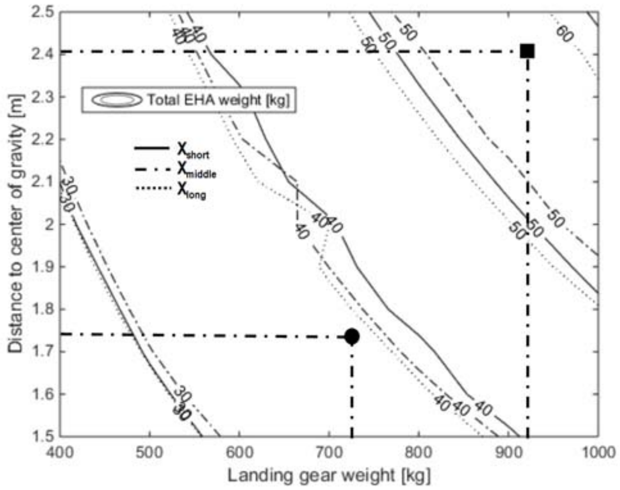

Figure 16: EHA weight for the wing mounted landing gear (■) and the fuselage mounted landing gear (●)

8. CONCLUSION AND OUTLOOK

Electro Mechanical Actuators (EMA) and Electro Hydrostatic Actuators (EHA) are discussed as alternatives for conventional hydraulically actuated subsystems in today's aircraft. The presented work offers a conclusion of different methods for weight estimation for the different components of these actuator types. Based on various landing gear parameters, namely the weight of the landing gear, the distance of the center of gravity of the landing gear to the revolution axis for retraction and the lever arm of the actuator, serve as design parameters for the weight estimation of the actuator types. The results show that for the EMA the lever arm of the actuator is of crucial importance since its influence on the actuator weight is dominant. For lighter landing gears a shorter lever arm of the actuator seems to be advantageous, but with increasing landing gear weight a longer actuator stroke results in a lighter actuator.
For the EHA, the impact of the lever arm on the actuator weight is very small for lighter landing gears. This means that the resulting actuator weight does not vary in that extend as for the EMA. The impact increases slightly for heavier landing gears. For the investigated lever arm lengths the middle length led to the actuators with the lowest weight.
A performed case study shows that for a fuselage integrated body landing gear a weight saving of ~20kg is possible for both actuator types compared to a conventional wing mounted landing gear. The EMA was the lighter actuator type for both landing gear configurations. However, the weight difference between both actuator types is relatively small.
Future work could include the refinement of the applied estimation models. For example, the weight estimation methods of the gearbox and the roller screw is based on actual data. Therefore, a wide range of the investigated landing gear parameters resulted in the same gearbox and roller screw weight because the calculated different loads led to the same gearbox.
The presented methods may serve for preliminary design and first weight estimation. They show weight tendencies of the different actuator types. For more a detailed design some additional aspects should be taken into account. For example, due to safety reasons an alternative mode of

extending the landing gear could be required especially for EMA as this actuator type may jam [17]. This could lead to additional weight of the actuator.
Furthermore, a comparison of the presented results with a conventionally actuated landing gear could be of interest. A conventionally retracted landing gear is equipped with a hydrostatic actuator pressurized by the pump of the central hydraulic system of the entire aircraft. Therefore, this comparison would have to include not only the actuators, but also the power generation. This would lead to an assessment of the entire subsystem architecture.

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