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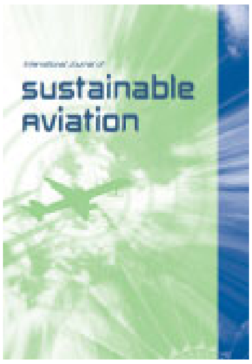

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Comparative study of piston vs. electric single-seat tandem helicopter

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Abstract: The paper presents a starting, but necessary comparative study between two diverse designs of single-seat tandem helicopter configuration, piston-propelled vs. electrically-driven. Both possibilities have their pros and cons, and need to be considered in detail, with respect to the initial requirements. In this investigation, the primary design objectives include 100 kg of payload as well as satisfactory performances in both hover and progressive flight. The comparison is conducted through the initial sizing procedures that enabled the estimation of takeoff mass (along with its main contributors), but also characteristic speeds, flight limits and basic helicopter performances. Used models and assumptions are explained in the paper. In the beginning, some essential advantages of tandem configuration helicopters are mentioned and accentuated. Also, future trends in electric aviation are considered. After that, total mass is decomposed into several main components and rotor dimensioning is performed. By assuming sufficient available power, it is possible to estimate the basic helicopter performances in both axisymmetric and progressive flight. Obtained results are presented graphically and numerically. In the end, some conclusions and recommendations for further research are given. For the time being, piston-propelled single-seat tandem helicopter can achieve better numerical results.

Keywords: tandem helicopter; performances; power curve; hover; progressive flight; empty-to-takeoff mass ratio.

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1 Introduction

The advantages of vertical flight in both urban and rural environments, as well as off-shore platforms, are really abundant. In addition to being able to take off and land almost anywhere as well as provide great assistance in avoiding crowds or delays, such air vehicles can also be used for observation, deliveries or rescue missions. As nicely formulated by Leishman (2006), Raymer (2018) and Yeo (2019), the first vertical-takeoff-and-landing (VTOL) air vehicle that comes to mind is most definitely a helicopter. On one hand, rotors of great diameter are suitable for producing thrust since induced velocities through the rotor disk can remain small which helps in keeping a satisfactory (as low as possible) value of power-to-weight ratio. On the other hand, some accompanying downsides include large rotor area and required space, dynamic issues, noise and forward speed limitations.

As stated by Raymer (2018), the simplest, most usually employed, conventional helicopter concept implies a single main rotor located near the centre of gravity (CG) accompanied by a much smaller, tail rotor that is mainly used to counteract the strong torque generated by the main rotor. Although this solution has proven well over the decades, it requires the most space due to the main rotor size as well as the prolonged tail boom that has to be placed sufficiently aft of the main rotor. Therefore, this concept is the least convenient for urban environments or places with limited accessibility. Other possibilities, such as tandem, coaxial, side-by-side, or multi-rotor, also exist (Yeo, 2019). Tandem configuration, comprising two smaller counter-rotating rotors, is still abundantly investigated as demonstrated by Mehrabi and Davari (2020), Pena et al. (2021), Sal (2020), Tan et al. (2019), Weishaupl and Prior (2019) and Zhang et al. (2020). Apart from the decreased rotor size, it is better suited for transportation since it allows a wider range of possible CG locations between the fore and the aft rotor. Rotor interference, and consequent efficiency loss on the aft or lower rotor, is their greatest disadvantage. Coaxial configurations, consisting of two rotors rotating in opposite directions around the same axis, and requiring very complex and multi-component rotor hubs, are expensive for both production and maintenance. It may be observed that the mentioned full-scale rotorcrafts are traditionally powered by either piston or turbine engines (Russell et al., 2015). On the other hand, technologically less demanding multi-rotor arrangements, that do not allow blade pitching motion, are continuously gaining popularity.

Stricter and stricter regulations on air pollution and noise favour small-size rotors in combination with electric motors and relatively cheap electronics. There is much talk about using such air vehicles, even in urban environments (some examples are AIRBUS Vahana and Trek Aerospace FlyKart 2). However, when their performances are inspected in detail, it immediately becomes obvious that energy storage is their main limiting factor. The current levels of battery technology, as listed by Zubi et al. (2018), greatly inhibit the desired performances, i.e., range and endurance.

For these reasons, this paper presents a comparative study between two diverse designs of a single-seat tandem helicopter configuration, piston-propelled vs. electrically-driven. Both possibilities have their advantages and disadvantages. Piston-propelled solution generally achieves better aerodynamic performances while the electric variant promotes further technological development, aviation sustainability, emission reduction and is generally more environmentally acceptable. For a more comprehensible insight, it is necessary to perform the initial dimensioning, as well as estimate and contrast the aerodynamic performances of the both solutions.

2 Conceptual design of a tandem helicopter

This chapter presents some of the fundamental steps in the conceptual design phase of tandem helicopters.

2.1 Initial requirements

As declared by Raymer (2018), every conceptual design of air vehicles begins with a well balanced definition of initial requirements that are not supposed to be altered in the subsequent phases of development. In this study, it is most important to ensure a useful mass of m_u = 100 kg that roughly corresponds to either a pilot or a single (wounded) passenger. Secondly, the range should preferably be above $R > 150$ km at the cruising speed of $V_{cr} > 100$ km/h. These requirements coincide with rescue, delivery or sight-seeing missions in a metropolis area.

Although scarce, some examples of relatively similar flying systems exist, for example AVIDRONE 210TL, LAFLAMME AERO LX300, DP-14 MULTI MISSION UAS, DP-12 RHINO, etc. Their basic properties can be found on-line. They are all unmanned, of simple geometric design, composite or metal structure, while significant differences in rotor size and overall configuration can be observed.

And that is why an important note must be made here. Rotor blade aerodynamics (i.e., the geometric features of rotors and blades such as rotor diameter D, blade chord c, number of blades N_b, rotor solidity σ, etc.) must be considered from the beginning of the design process, usually by some computational method such as momentum theory (MT), blade element theory (BET), their combination – blade element momentum theory (BEMT), vortex theory, computational fluid dynamics (CFD) approach, etc. Also, some starting presumptions should be made.

Here, it is assumed that:

- the helicopter operates at sea-level and density can be estimated by standard atmosphere model
- the blade number is $N_b = 3$
- the rotor tip speed is limited to $V_{tip} = 170$ m/s to avoid compressibility effects.

Also, any downsides of rotor overlapping on aerodynamic performances are neglected.

2.2 Helicopter propulsion systems

As stated by Russell et al. (2015), large-size rotorcrafts are most often powered by either turbine or piston engines. The choice between the two is usually made in accordance with the aircraft size/mass, desired structural complexity/simplicity, specific fuel consumption and maintenance costs. Here, where required, the assumed specific fuel consumption of a piston engine is $SFC = 285$ g/kW/h.

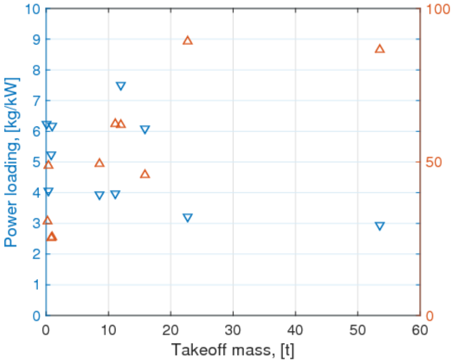
On the other hand, constant efforts are being made to redesign the helicopter powerplant and make it greener – less polluting, electric (powered by batteries or fuel cells), quieter, with ideally zero emissions. The development of highly efficient electric motors with increased power-to-weight ratios, in combination with improved battery technology, pave the path to future electric rotorcrafts (Russell et al., 2015). For this reason, in this comparative study, the purely electric variant is also considered. Another possibility of ‘hybrid electric powerplant’, that includes a gas turbine that powers a generator that in turn powers electric motors (allowing the operation at optimal efficiency), is also quite interesting, but was not considered here in more detail.

Although not of vital importance in this research study, rotor noise presents quite the issue for sustainable and green aviation, particularly in densely populated areas. It may be reduced by profiling the blade tips (thus reducing the strength of tip vortices) or by special operational procedures that enable reducing the interaction between the blades and shed wakes. Either way, a strong relation between the blade rotation and powerplant exists, and should be taken into account in subsequent design phases.

2.3 Starting design parameters

Two crucial design parameters that enable the initial helicopter dimensioning, i.e., an appropriate estimation of the required rotor diameter D and engine power P for a given takeoff mass m_o are power loading m/P [kg/kW] (ratio of helicopter mass to power) and disk loading m/A [kg/m^2] (ratio of helicopter mass to rotor disk reference area). Although available data are somewhat scattered and depend on both the helicopter size and category (transport or civil/utility) as well as its powerplant type, it is possible to arrange them and extract some useful relations, as illustrated in Figure 1, with respect to the takeoff mass.

Figure 1 Tandem helicopter power and disk loading (see online version for colours)



On the other hand, for small tandem helicopters, Raymer (2018) recommends the following mean values of power and disk loading, respectively: m/P = 3.6 kg/kW and m/A = 40 kg/m^2. These recommendations fit well with the data collected by the authors.

2.4 Mass estimation

It therefore seems that the only thing that remains to be done, in order to perform the initial helicopter dimensioning, is to estimate the takeoff mass as accurately as possible. The procedure differs a bit for the piston and electric options, as presented in continuation.

2.4.1 Piston propelled variant

Initially, it can be assumed that the takeoff mass m_o of a piston-propelled tandem helicopter comprises useful payload m_u, fuel mass m_f and empty mass m_e, as presented by equation (1):

$$m_o = m_u + m_f + m_e \tag{1}$$

While useful payload m_u is fixed to 100 kg, fuel mass m_f mainly depends on aircraft aerodynamic quality (e.g., lift-to-drag ratio L/D and rotor efficiency FM) along with the desired performances (e.g., range R or endurance E) as well as engine specific fuel consumption SFC. Here, the assumed lift-to-drag ratio is relatively low, L/D = 2.5, since helicopters are 'aerodynamically unclean' constructions, while the assumed rotor efficiency of FM = 0.7 corresponds to medium-quality helicopter rotors. In the end, the empty mass m_e is probably the hardest to accurately evaluate. From the realised air vehicles (both manned and unmanned) and freely available data, it is possible to extract the following fitting function, equation (2), that is also illustrated in Figure 2. Due to the limited accessible information, the same relation is used for the electric version of the tandem helicopter.

$$m_e = 0.5914 m_o^{0.9602} \tag{2}$$

After the mass equation is iteratively solved, it is possible to estimate the individual mass components. Although many input variables were considered (rotor diameter D, cruising speed V_{cr}, aerodynamic quality, specific fuel consumption SFC, etc), it was concluded that useful payload m_u and range R principally dictate the mass distribution. Figure 3 illustrates the obtained relations.

Figure 2 Approximation of the relation between empty and takeoff mass (see online version for colours)

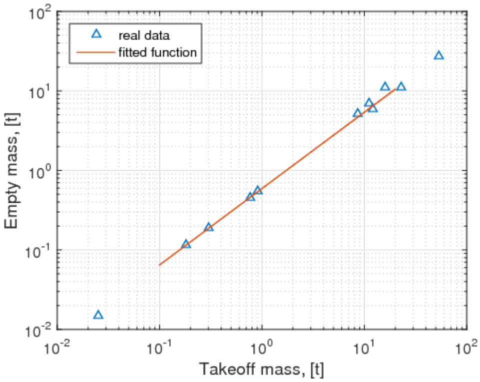
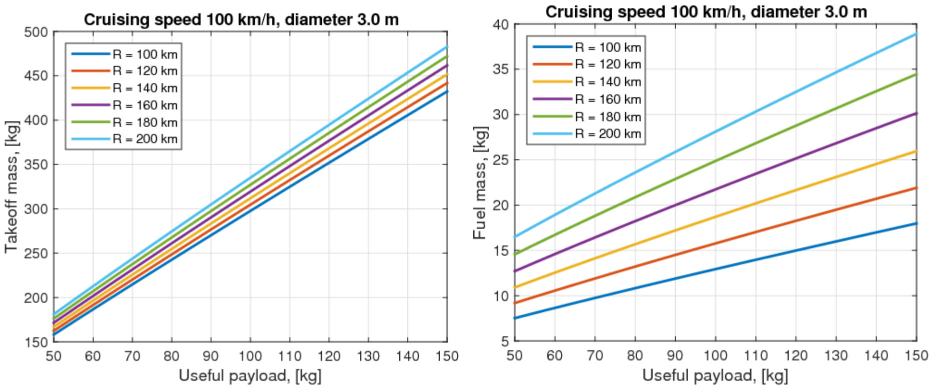


Figure 3 Relation between the, (a) takeoff (b) fuel mass and useful payload mass for different ranges and fixed cruising speed (V_{cr} = 100 km/h) and rotor diameter (D = 3 m) (see online version for colours)



(a) (b)

In the end, the combination (m_o, m_e) = (320 kg, 198 kg) seemed the most appropriate. It allows different combinations of useful payload m_u and range R spanning from

(m_u, R) = (94 kg, 210 km) to (m_u, R) = (109 kg, 90 km), as the two quantities are inversely proportional. Also, the chosen values are in good correspondence with the values recommended by Raymer (2018) or presented by Weishaupl and Prior (2019) and Yeo (2019).

The estimated reservoir volume is then approximately V_f = 30 dm^3 for the fuel density ρ_f = 770 kg/m^3.

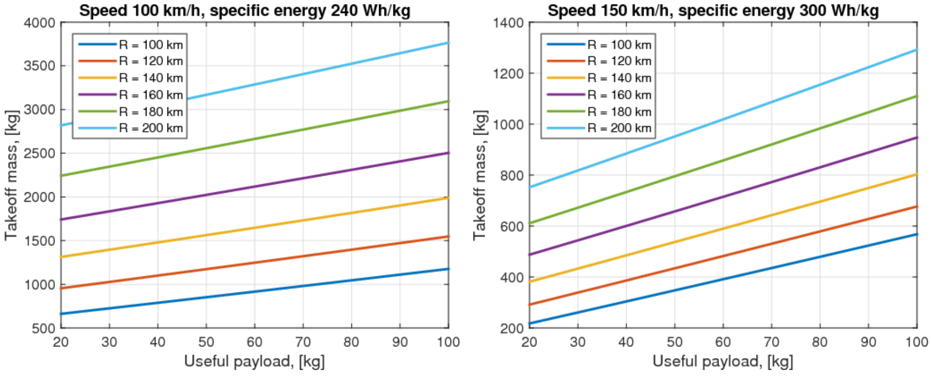
2.4.2 Electric variant

A similar computation can be conducted for the electric helicopter, with an important difference in the main contributors to the takeoff mass, as given by equation (3). Here, instead of the fuel mass, we talk about the mass of batteries m_b, that is expected to be significant and directly proportional to the required power and flight endurance.

$$m_o = m_u + m_b + m_e \tag{3}$$

Again, after iteratively solving equation (3), it is possible to obtain various interesting relations between the considered quantities. In this case, each of the investigated four variables (useful payload, range, cruising speed and specific energy of batteries) significantly affects the mass distribution, as illustrated in Figure 4. As before, rotor diameter is set to 3 m.

Figure 4 Relation between the takeoff and useful payload mass for different ranges, cruising speeds and battery specific energy, (a) 240 Wh/kg (b) 300 Wh/kg (see online version for colours)



(a) (b)

Following the inspection of Figure 4, it immediately becomes obvious that the mass of batteries drastically increases the takeoff mass of the small tandem helicopter, which leads to a serious questioning of the viability of this concept. As expected, takeoff mass escalates with useful payload and range, but also decreased cruising speeds since they imply longer flight endurances. Augmented values of battery capacity (i.e., battery specific energy) somewhat reduce the helicopter mass, but insufficiently. In order to design a feasible electric tandem helicopter, further advances in battery technology are required.

The only combination that seems acceptable is (m_o, m_e, m_b) = (605 kg, 367 kg, 138 kg). It can be obtained for useful payload m_u = 100 kg, range R = 100 km, cruising speed V_{cr} = 150 km/h and battery specific energy of 280 Wh/kg. It may be observed that the initially desired range had to be reduced in order to keep the aircraft in the ultra-light category. Also, in this case, the volume required to store the estimated mass of batteries is approximately V_b = 100 dm^3.

2.5 Rotor dimensioning

Once the takeoff mass is determined, and by using the recommended value of disk loading, the rotor diameter can be attained. Again, we talk about a nominal, mean value, that can be slightly increased or decreases, in order to satisfy a particular purpose or desired mission. Here, we opted for the rotor diameter of D = 3 m (as could be observed in the previous section) mostly because of the space limitations. Three blades are chosen for obtaining a more acceptable dynamic behaviour of the rotor, while the necessary blade chord is estimated in accordance with the standard airfoil performances and rotor thrust coefficient. It somewhat differs for the piston-propelled and electric variant, due to the differences in takeoff mass:

- blade chord c_b = 0.15 m for the piston-propelled
- blade chord c_b = 0.24 m for the electric tandem helicopter.

3 Performance analysis

Following the computation of the takeoff mass m_o that directly determines the required thrust T per rotor (that differs for the two considered concepts), it is necessary to determine just how much power P_{req} must be consumed in order to satisfy the initial requirements and perform the basic missions of hovering and progressive flight. The recommended value of power loading suggests that an engine of 90 kW available power should be an adequate solution for present tandem helicopter. However, this should be checked in more detail by more advanced computational methods such as the expanded MT (that includes tip losses and viscous effects) (Leishman, 2006).

The analysis presented in continuation does not depend on the engine type, but solely on the computed masses and adopted geometric characteristics of the two rotors.

3.1 Hover

Hover is the primary flight condition that requires more power than progressive flight at medium speeds and is the first phase to be analysed. The required power can initially be estimated by equation (4):

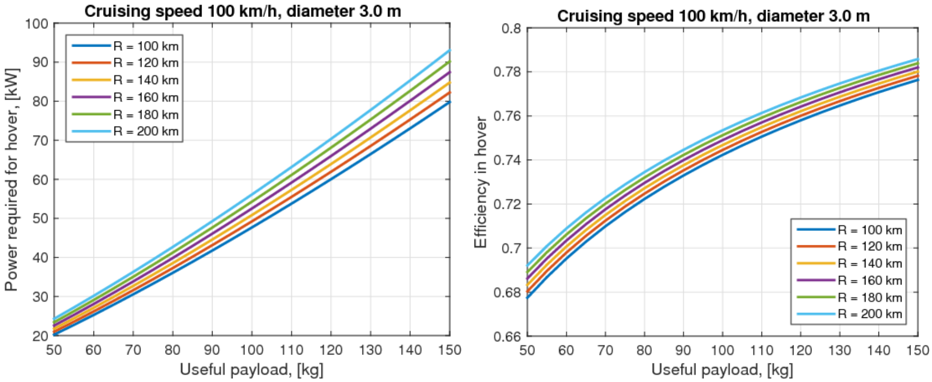
$$P_{h,req} = 1.1 \left[2 \left(\frac{\kappa C_T^{3/2}}{\sqrt{2}} + \frac{\sigma C_{do}}{8} \right) \rho A V_{tip}^3 \right] \tag{4}$$

where ρ is the air density, A is the disk area, V_{tip} is the blade tip speed, κ = 1.2 is the correction factor that takes into account the irregular distribution of induced velocities along the rotor disk, $C_T = T/(\rho A V_{tip}^2)$ is the thrust coefficient, $\sigma = 2N_b c/(D\pi)$ is the rotor solidity and C_{do} is the airfoil drag coefficient. The increase of 10% is made to include the transmission losses.

Figure 5 illustrates the estimated power required for hover $P_{h,req}$ as well as rotor efficiency FM for the piston-propelled variant. It can be seen that hovering with the useful payload of 100 kg requires approximately 52 kW. Also, satisfactory values of rotor efficiency, close to 0.75, can be achieved.

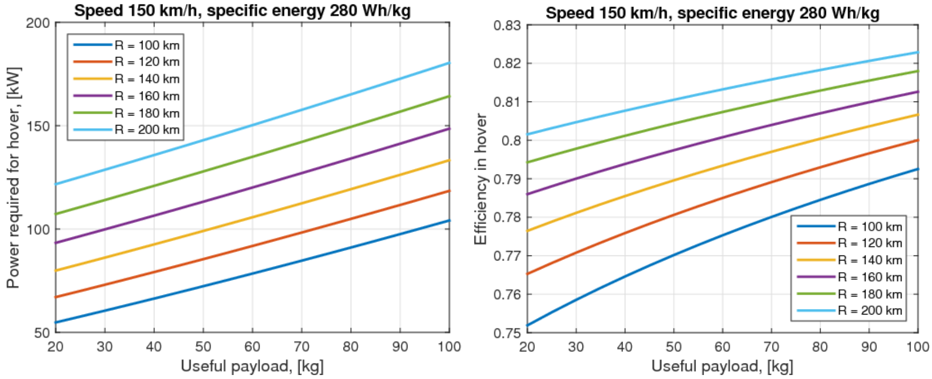
Similarly, it is possible to depict the required power and rotor efficiency for the electric tandem helicopter which is depicted in Figure 6. In this case, hovering with the useful payload of 100 kg requires significantly more power, over 100 kW. On the other hand, since the greatest part of the total required power is induced power, the obtained rotor efficiency is quite high, approximately 0.8.

Figure 5 (a) Required power (b) Rotor efficiency in hover for piston-propelled tandem helicopter (see online version for colours)



(a) (b)

Figure 6 (a) Required power (b) Rotor efficiency in hover for electric tandem helicopter (see online version for colours)



(a) (b)

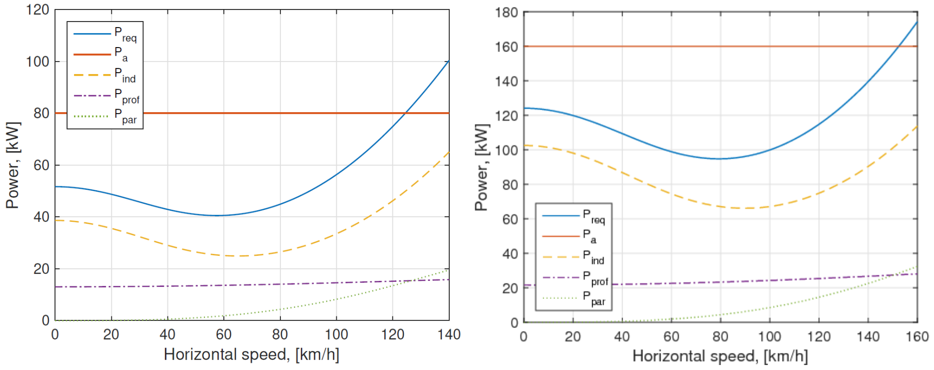
3.2 Progressive flight

As can be expected, the power required for progressive flight $P_{p,req}$ of a tandem helicopter includes more components (induced, profile and parasitic) that account for the somewhat changed fluid flow around the aircraft as well as the additional drag that stems from both the blades and the fuselage (Leishman, 2006). The used expression is provided by equation (5):

$$P_{p,req} = 1.1\left\{2\left[\kappa C_T\lambda + \frac{\sigma C_{do}}{8}\left(1+4.65\mu^2\right)\right] + \frac{1}{2}\frac{f}{A}\mu^3\right\}\rho A V_{tip}^3 \tag{5}$$

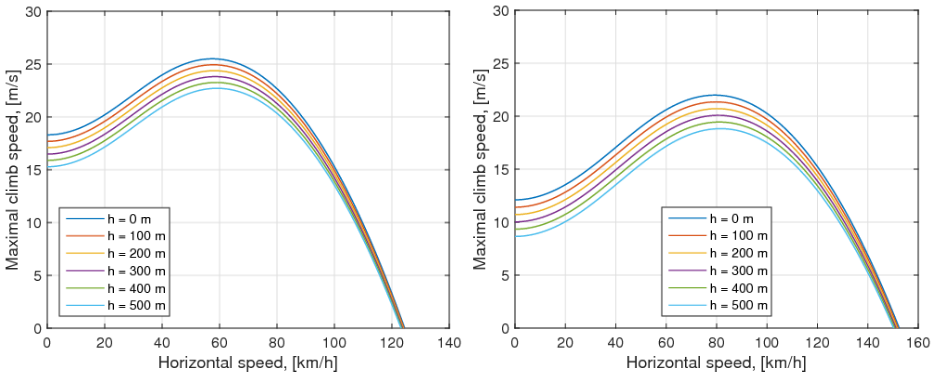
where λ is the inflow ratio, μ is the forward speed ratio and f is the equivalent wetted area of the fuselage, landing gear, rotor hubs, etc. Additional losses induced by compressibility effects and zones of reversed flow are neglected at this point.

Figure 7 Power required for horizontal flight of, (a) piston-propelled (b) electric tandem helicopter (see online version for colours)



(a) (b)

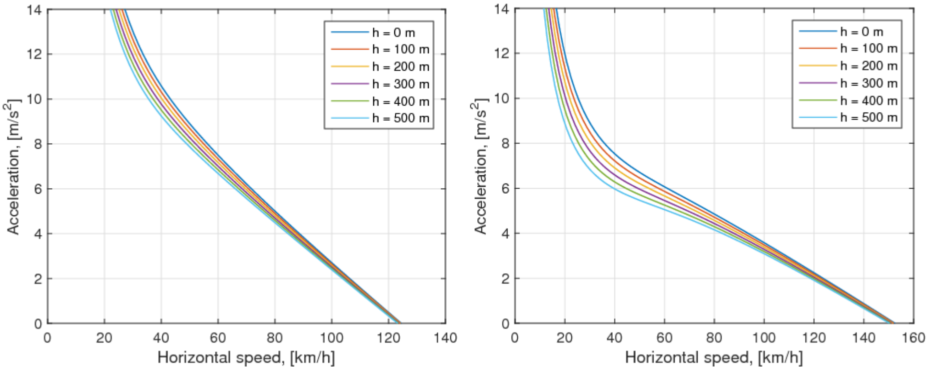
Figure 8 Maximal climbing speeds in horizontal flight of, (a) piston-propelled (b) electric tandem helicopter (see online version for colours)



(a) (b)

Figure 7 presents the estimated required P_{req} and assumed available P_a power for progressive flight of a single-seat tandem helicopter (both piston-propelled and electric) together with the contributing components of induced P_{ind}, profile P_{prof} and parasitic power P_{par} at sea-level flight conditions. Due to considerable differences in takeoff masses, much higher available power had to be assumed for the electric variant in order to ensure satisfactory values of horizontal speeds. However, this value is arbitrary and dictated by the characteristics of the actual engine that is to be installed.

Figure 9 Maximal acceleration in horizontal flight of, (a) piston-propelled (b) electric tandem helicopter (see online version for colours)



(a) (b)

The excess power $\Delta P = P_a - P_{req}$ can be used for either climbing or accelerating of the aircraft as depicted in Figures 8 and 9. Although partially dependent on assumed available power, the differences in obtained performances of the two concepts are obvious. Despite being equipped with a weaker motor (i.e., of less available power), piston-propelled tandem helicopter seems able to achieve both higher climbing speeds as well as acceleration levels. Both performances are illustrated for several different altitudes h.

Furthermore, for the piston-propelled variant, it can be concluded that the optimal speed (for the least required power and the longest endurance) is $V_{E_{\max}}$ = 58 km/h, while the speed of the longest range is somewhat higher $V_{R_{\max}}$ = 90 km/h which is sufficiently close to the initially requested cruising speed V_{cr} = 100 km/h. These values imply that the maximal range and endurance of $R_{\max}$ = 129 km and $E_{\max}$ = 105 min, respectively, can be achieved with the proposed piston-propelled, single-seat tandem helicopter configuration.

On the other hand, for the electric variant, the obtained performances are less satisfactory. The computed optimal speed (of the longest endurance) of $V_{E_{\max}}$ = 80 km/h ensures just $E_{\max}$ = 22 min of flight. Also, even when flying at the speed of the longest range $V_{R_{\max}}$ = 118 km/h, a mere maximal range of $R_{\max}$ = 36 km can be achieved. The degraded values of range and endurance obtained here, in comparison to the values used in the mass estimation section, are a consequence of a more detailed and accurate power computation.

Of course, in subsequent design phases, these preliminary results should be validated further by more advanced numerical methods.

3.3 Endurance fixed to E = 1 h

It is probably most interesting to compare the two configurations with respect to the fixed endurance since that is where they really diverge due to the significant mass of batteries. Here, a one hour endurance was chosen, E = 1 h, while the payload remains m_u = 100 kg. This, relatively low endurance is selected in order to obtain an acceptable takeoff mass of the electric variant. In both cases, it is assumed the helicopter cruises for E = 1 h at the cruising speed V_{cr} = 80 km/h, thus crossing the distance R = 80 km.

In order to satisfy the imposed requirements, the piston-propelled helicopter should have the takeoff mass m_o = 290 kg, would require approximately P_r = 40 kW of power, resulting in the required energy E_r = 40 kWh.

On the other hand, for the same starting assumptions, the electric helicopter should have the takeoff mass m_o = 650 kg (since more than 350 kg would be batteries, the air-frame would have to be extremely light and durable while not taking up more than 30% of the takeoff mass), would require approximately P_r = 100 kW of power, resulting in the required energy E_r = 100 kWh.

To conclude, in order to carry the same payload, for the same amount of time and to the same distance, an electric helicopter would have to be heavier more then twice (more precisely 2.24 times), and would require more than doubled amount of power in comparison to the piston-propelled version. These differences would only grow with longer endurance or range.

4 Conclusions

In the end, it can definitely be concluded that piston-propelled single-seat tandem helicopter still significantly outperforms its electrically-driven counterpart. This is mostly caused by the substantial mass of batteries (but also the increased mass of empty structure that is supposed to carry both the useful and energy storage payloads) as well as technological limitations of contemporary batteries. Since it can be expected that these aspects will be improved in near future, the concept of electric tandem helicopter should not be completely discarded, but should certainly be investigated with great care.

For the intended piston-propelled single-seat tandem helicopter that carries 100 kg of useful payload the following characteristics can be recommended:

- takeoff mass m_o = 320 kg
- empty mass m_e = 198 kg
- rotor diameter D = 3 m (where the tip speed is V_{tip} = 170 m/s and rotor angular velocity Ω = 1,082 rpm)
- rotor contains N_b = 3 rectangular blades whose chord is approximately c = 15 cm
- continuous available power equal or greater than 80 kW.

On the other hand, for the intended electric single-seat tandem helicopter also capable of carrying 100 kg of useful payload, the following combination of design variables seems viable:

- takeoff mass m_o = 605 kg
- empty mass m_e = 367 kg
- battery mass m_b = 138 kg
- rotor diameter D = 3 m (where the tip speed is V_{tip} = 170 m/s and rotor angular velocity Ω = 1,082 rpm)
- rotor contains N_b = 3 rectangular blades whose chord is approximately c = 24 cm
- continuous available power equal or greater than 160 kW.

Further investigations should include: more comprehensive studies of mass distribution (particularly in cases of electric air vehicles that are not numerous), aerodynamic effects of rotor overlapping [according to Leishman (2006), the expected power increase generally amounts to 15%], the existence of fuselage and landing skids as well as thorougher flow investigations resembling Mehrabi and Davari (2020), Tan et al. (2019) and Weishaupl and Prior (2019) or flight dynamics and control analyses similar to Pena et al. (2021), Sal (2020) and Zhang et al. (2020).

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