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FUEL WEIGHT DETERMINATION OF ULTRALIGHT AND VERY LIGHT HELICOPTERS AT THE PRELIMINARY DESIGN STAGE

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Abstract

In recent years, a large number of one- to two-seat-type helicopters have appeared, raising the possibility to determine the dependencies inherent in these classes. Such dependencies are extremely necessary at the preliminary design stage, in particular, for determining the fuel mass. The relative mass of fuel depends on the required range and flight time of the helicopter, as well as on the characteristics of the engine and the required power of the helicopter. Based on statistical data, the article presents an approximate relation of the hourly fuel consumption of engines that small helicopters are equipped with. The additional amount of fuel required to complete missions has also been determined. General dependency of the fuel weight that can be used at the preliminary design stage is presented according to the analysis results.

Keywords: ultralight helicopter, very light helicopter, fuel consumption, preliminary design.
Type of the work: original article

1. INTRODUCTION

Helicopters of small-weight categories that have appeared and are actively developing in recent years are usually referred to as ultralight and very light helicopters (ULH and VLH, respectively). As a rule, these are one- to two-seated rotary-wing aircraft with the maximum takeoff weight in the range of 250–750 kg. They are distinguished by their simplicity of design, low cost and simplified requirements for flight approval in many countries. The main uses of such vehicles are in training flights and entertainment. Sometimes, they are used for crop dusting, transportation of small cargo onboard or external sling, monitoring and observation. Piston two-stroke or four-stroke engines are used usually in the power plants of such rotorcraft. There are also helicopters equipped with gas turbine engines (GTEs). A large number of small helicopters have been designed in recent years, which has raised the possibility to determine the dependencies inherent in these classes, which is an extremely necessary step at the preliminary design stage, in particular, the parameters of the fuel weight.

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2. MAIN PARAMETERS OF THE HELICOPTER WEIGHT

The existing methods that are used to determine the parameters of helicopters at the preliminary design stage are mainly focused on the parameters of helicopters with much heavier takeoff weight due to the widely known and well-estimated statistics of those (see, e.g., [1–4]). ULH and VLH have their own features. The authors have analysed 36 types of aircraft developed over the past 25 years; the parameters of the main rotor of such helicopters have been presented earlier [5]. Determination of the takeoff weight is the most important task at the preliminary design stage.

The takeoff weight of the rotorcraft m_0 is defined as the sum of the masses of an empty helicopter me, target load or payload m_t, service load m_s (it can be included into the operating empty weight) and fuel m_f, according to the classical approach [1,6]:

$$m_0 = m_e + m_t + m_s + m_f \tag{1}$$

Typically, the service load includes the mass of the crew and special equipment. The specificity of small helicopters is that special additional equipment is not used, and the crew and the passenger refer to the same category and can be often counted as one [7]. This is especially evident for single-seat helicopters.

The masses of the crew and the target load should be combined and taken into account as the mass of the payload m_p based on the specifics of ULH and VLH. So in this case, Eq. (1) will be introduced in the following form:

$$m_0 = m_e + m_p + m_f \tag{2}$$

The relative mass of the fuel depends on several parameters, the main being the range and the flight time of the designed vehicle. Both of these indicators, as a rule, are established in the technical requirements for helicopters. This is specific to ULH and VLH. It is most important for helicopters of transport categories to carry cargo over a certain range, but the time during which the helicopters can be in the air performing, e.g., a training flight, is often more important when applied to the small aircraft.

It is advisable to consider two mission options to satisfy these two aforementioned conditions: flights to the required range and the flight duration. An altitude of 200 m is considered for both mission options – this is the most frequently used echelon by general aviation users of ULH and VLH.

The mass of fuel for flying at a given flight range should include fuel consumption for engine warm-up, acceleration and climb, cruise flight, and descent and deceleration. Unused and 5% navigation fuel reserves should be taken into account in this case.

“The unusable supply for each tank must be established as not less than the quantity at which the first evidence of malfunction occurs under the most adverse fuel feed condition occurring under any intended operations and flight manoeuvres involving that tank” is according to existing requirements for ULH and VLH [8,9]. Certainly, small helicopters do not have special service tanks; however, as a rule, the main tank has special volumes at the fuel intake points, which ensure uninterrupted fuel flow during helicopter maneuvers. Existence of such design elements allows to reduce the volume of the unused fuel to almost zero. Generally, flight modes’ fuel consumption is determined by the flight time of the specified mode and the required power. The fuel that is needed to warm up the engine does not depend on the required power of the helicopter. Thus, the fuel mass for the maximum-range flight mode can be determined using the following equation:

$$m_f = 1.05\cdot\left(Q_h\cdot t_h + c_{e_{cl}}\cdot P_c\cdot t_c + c_{e_{cr}}\cdot P_{cr}\cdot\frac{L}{V_{cr}} + Q_d\cdot t_d\right), \qquad (3)$$

where
1.05 – the coefficient that takes into account 5% navigation fuel reserve,
Q_h – fuel consumption at engine warm-up mode (kg/h),
t_h – duration of engine warm-up (h),
$c_{e_{cl}}$ – specific fuel consumption at climb mode (kg/kW h),
P_c – required power at climb mode (kW),
t_c – climb duration (h),
$c_{e_{cr}}$ – specific fuel consumption at cruising mode (kg/kW h),
P_{cr} – required power at cruise mode (kW),
L – range (km),
V_{cr} – cruising speed (km/h),
Q_d – fuel consumption in descent mode (kg/h) and
t_d – descent duration (h).

The distance that the helicopter travels during the climbing stage is small; so, it is not considered in this calculation.

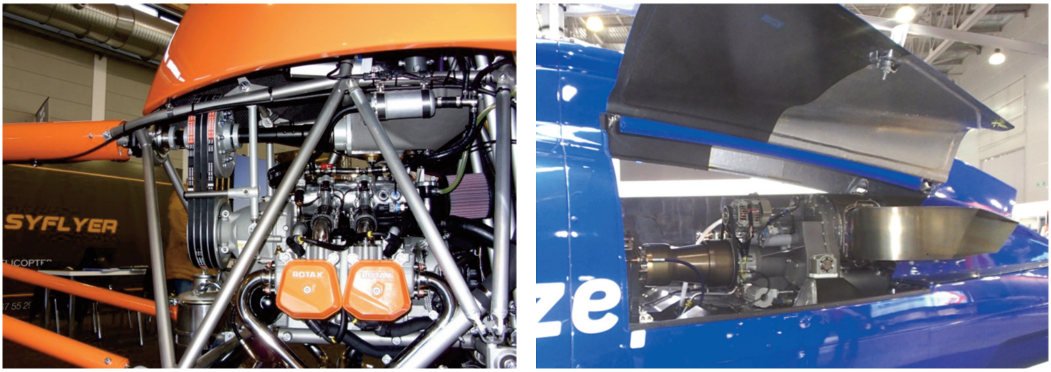
Fuel for a flight for the specified flight duration can be determined in the same way:

$$m_f = 1.05\cdot\left(Q_h\cdot t_h + c_{el}\cdot P_c\cdot t_c + c_{e_{ec}}\cdot P_{ec}\cdot\left(t_f - t_c - t_d\right) + Q_d\cdot t_d\right), \qquad (4)$$

where
t_f – specified flight duration (h),
P_{ec} – the required power at the economic flight speed (kW) and
$c_{e_{ec}}$ – specific fuel consumption at economic flight speed (kg/kW h).

The maximum fuel mass determined for the two possible missions must be considered because the helicopter must satisfy both specified conditions.

Specific fuel consumption data on the flight modes at the preliminary design stage might be correlated with the maximal engine mode, based on the statistical data of the energy parameters of the helicopters. The hourly fuel consumption at the maximal engine mode of the power plants of small weight helicopters (Fig. 1) depends on their power. Statistical data and approximation of the obtained values that are typical for the main models of piston and GTEs that are used for ULH and VLH are shown in Fig. 2. Unfortunately, there are only three types of GTEs in the world that are used for ULH and VLH. The analysis was performed by using the data on these engines. It can be seen that the specific fuel consumption of existing GTEs is almost twice the value for piston engines; however, the weight of these engines as themselves is significantly less. It becomes more noticeable, especially, when the power of the engines increases to values >120 kW. Comparison of GTE consumption data with the relations presented in previous papers {(curve 2 in Fig. 2) [10]; (curve 3 in Fig. 2) [2]}, as well as with similar data from several outdated sources {(curve 4 in Fig. 2) [11]; (curve 5 in Fig. 2) [12]}, shows that the data for the smallest manned helicopters are significantly understated and cannot be used. This is due to a large-scale factor that is not sufficiently taken into account in these dependencies. At the same time, the parameters of the piston engines determined for light helicopters give a very close convergence with those for the ULH [10] (curve 2, Fig. 2).



(a) (b)

Figure 1. Installation of Rotax 912 engine on a Dynali H-3 helicopter (a) and TS-100 engine on a Zefir helicopter (b).

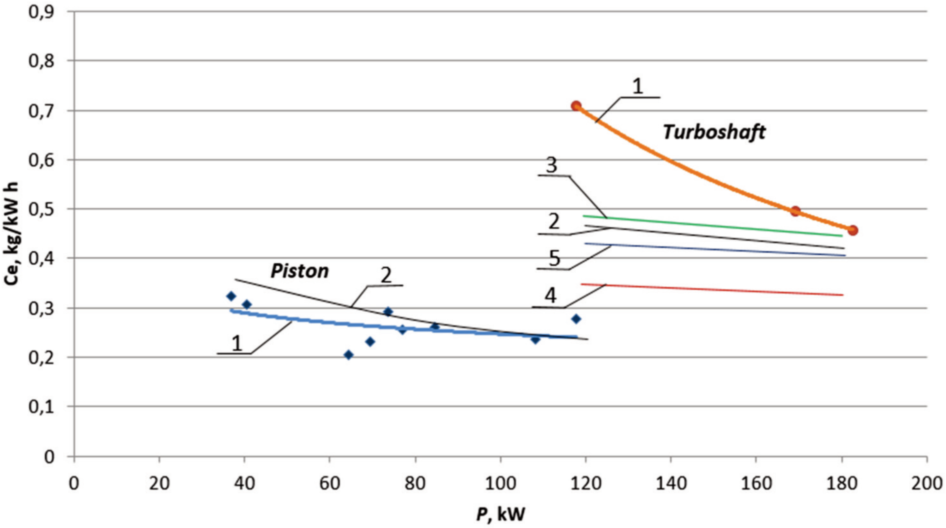


Figure 2. Dependence of specific hourly fuel consumption on engine power of ULH and VLH. Curve 1 – approximated statistical analysis data, curves 2–5 are the dependencies recommended by various authors, P – maximal engine power, Ce – specific fuel consumption.

Functions that shows the dependence of the specific fuel consumption on the maximal engine power can be expressed as follows.

For piston engines:

$$c_e = \frac{0.5799}{P^{0.174}}, \tag{5}$$

where P – the maximal engine power (kW).

For GTEs:

$$c_e = \frac{79.90}{P^{0.991}}. \tag{6}$$

The maximum power of the engines can be used during consideration of the climb mode. Certainly, small helicopters do not always use the maximum power mode during climbing, but for performing preliminary fuel calculations, such a conservative approach can be used. The power required to drive the rotors is significantly reduced in cruising and economic modes, but there are still losses that are necessary to ensure the engine operation, for example, the losses of friction between pistons and cylinders, changing of the piston movement direction, and so on. These values become relatively larger in the total power rate in the case of maintaining a constant engine revolutions per minute (RPM) value even with less shaft torque. Accordingly, the specific consumption increases [10]:

$$c_{e_{cl}} = 1.0 \cdot c_e \tag{7}$$

$$c_{e_{cr}} = 1.14 \cdot c_e \tag{8}$$

$$c_{e_{ec}} = 1.16 \cdot c_e \tag{9}$$

Fuel consumption during the engine warming up can be determined from experimental data. It can be seen on the record of the ULH engine throttle position, for instance (Fig. 3). It does not exceed 40% of the full opening position. Thus,

$$Q_h = 0.4 \cdot c_e \cdot P. \tag{10}$$

The total fuel consumption during the descent will be very insignificant and does not exceed the consumption in the economic speed mode.

$$Q_d = 0.6 \cdot c_e \cdot P \tag{11}$$

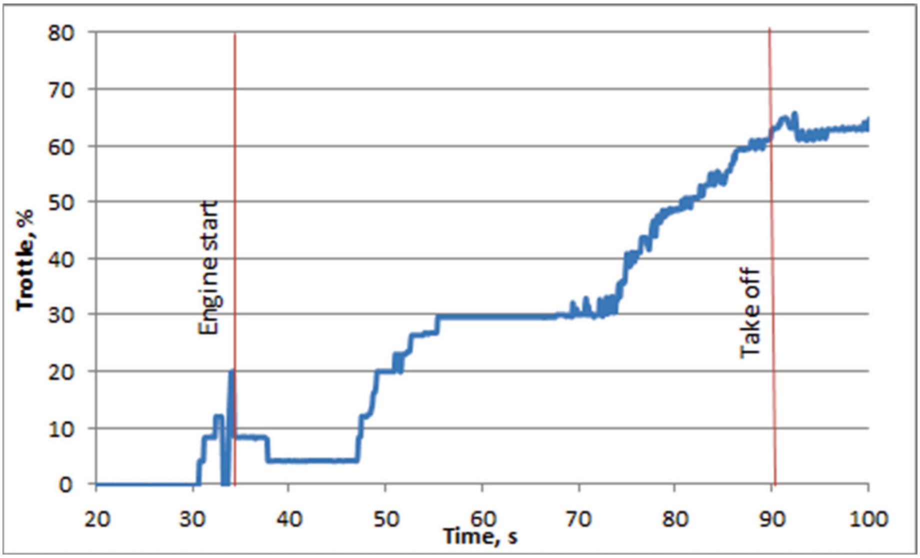


Figure 3. The dependence of the position of the engine throttle of the ultralight helicopter on the time needed for warming up.

If the time of cruise mode can be determined by a given flight range, the time for different modes should be determined by other methods. The time required for the engine's warming up before takeoff was determined based on the results of the statistical data analysis of the video recordings of different aircraft. The authors' video files contained the ambient temperature data, but the Web videos that have no indication of the weather conditions were also considered. In this case, the temperature was determined approximately, being estimated from the people's clothes. The obtained data are summarised in Table 1. It can be seen that the warm-up time practically does not depend on the ambient temperature and rather depends on the time that the pilot is preparing for the flight. Most of the records were made during warm weather, which is a typical feature of small-sized helicopters, which are rarely used during the cold season.

Table 1. The time from the moment the engine starts to lift off from the ground.

Manufacturer	**Helicopter type**	**Ambient temperature**	**Warm-up duration**
Robinson	R-22	+25°C	2 min 45 s
Robinson	R-22	+15°C	1 min 50 s
RS Helikopter	VA-115	+15°C	1 min 40 s
RS Helikopter	VA-115	+3°C	1 min 10 s
RS Helikopter	VA-250	+15°C	1 min 45 s
Heli-sport	CH-7 Kompress	+15°C	1 min 50 s
Heli-sport	CH-77 Ranabot	+20°C	2 min 20 s
Guimbal	Cabri G2	+25°C	1 min 20 s
Dynali	H-3	+18°C	1 min 20 s
EDM Aerotech	CoAX 2D	+20°C	2 min 30 s
OKB Rotor	R-30	–10°C	2 min 10 s
OKB Rotor	R-30	+25°C	1 min 40 s

According to the presented data, the time required to warm up the engine before takeoff was fixed at the upper limit of the observed values and amounted to 3 min. The obtained result in terms of hourly parameters is as follows:

$$t_h = 0.05. \tag{12}$$

The time required for a helicopter to climb during takeoff is determined following the average rate of climb inherent in vehicles of small-weight categories. The rate of climb varies depending on the weight of the vehicle and the flight mode. The typical rates of climb of ULHs and VLHs were analysed to derive the averaged value. On average, the vertical speed of such rotorcraft is 4 m/s.

The helicopter flight altitude is 200 m according to the flight scenarios indicated above. Accordingly, the time required to climb to the designated altitude will be 50 s, which in hourly terms will be

$$t_c = 0.014. \tag{13}$$

The vertical speed of the helicopter descent can be taken equal to the rate of climb. In this case, the time that is spent on the descent will be equal to

$$t_d = t_c = 0.014. \tag{14}$$

The value of the power required by the helicopter for flight at cruising and economic speeds at the preliminary design stage can be determined in a few ways. For example, the following relationship [2] can be used in the preliminary design stage:

$$P_v = \left(16.4\cdot 10^{-3}\Omega R\left(1+3.3\cdot 10^{-6}\cdot v^3\right)+\frac{0.372\cdot DL\cdot I}{v}+0.615\cdot \bar{D}_e\cdot v^3\right)\cdot m_0\cdot g, \tag{15}$$

where

ΩR – rotor tip speed (m/s),
v – speed of horizontal flight (m/s),
DL – disc loading (Pa),
I – induction coefficient,
$\bar{D}_e$ – relative drag of the designed helicopter.

This dependence presupposes the setting of several parameters, in particular, the maximum takeoff mass of the helicopter, which can be solved by an iterative choice during the parameter optimising stage. The calculation by multicriteria relations gives a significant error, considering that the parameters change during the preliminary design process. The required power for cruising and economic modes of flight can be taken as a function of the maximum required power of the helicopter for approximate calculations. Typically, this value for ULH and VLH is in the following ranges:

$$P_{cr} = 0.7\ldots 0.8\cdot P, \tag{16}$$

$$P_{ec} = 0.6\ldots 0.7\cdot P. \tag{17}$$

Such dependencies correspond to the design parameters of several analysed small-weight helicopters. The relation of the fuel weight can be determined in the following form for a flight at a specified range using the average value of the indicated power:

$$m_f = 1.05\cdot c_e\cdot P\left(0.0424+0.855\cdot\frac{L}{V_{cr}}\right). \tag{18}$$

Determination of the fuel mass during a flight for a given duration can be performed in the same way:

$$m_f = 1.05 \cdot c_e \cdot P\left(0.0213 + 0.754 \cdot t_f\right). \tag{19}$$

The maximum fuel consumption for auxiliary operations is equivalent to working for 0.0445 h or 2.7 min at maximum engine power mode, as can be seen from the obtained relations. This value is significantly less than the suggested auxiliary time of 20 min [1,7,8]. A 5% navigation fuel reserve is a separate value in these relations and can be changed depending on the local requirements for rotarcrafts.

The values of the range and flight time, as well as the cruising speed, in these relations are specified, as a rule, but the value of the maximum engine power should be determined before this stage. In this case, the type of engine should also be selected, since the number of types of produced engines is very small.

3. CONCLUSION

Thus, the mass of fuel for helicopters of small-weight categories at the stage of preliminary design can be determined according to two criteria – a specified flight duration or a specified flight range. The largest value obtained should be taken following a conservative design approach. The maximum fuel consumption for auxiliary operations is equivalent to working of 2.7 min at maximum engine power mode.

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