WORKBOOK

AIRCRAFT PROPULSION SYSTEMS

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1. CHARACTERISTICS OF THE PROPULSION SYSTEM

Characteristic of the aircraft propulsion system is a dependency of the power supplied to the aircraft propulsion, through piston engine or turbine engine and propeller (available power N_r), or of the jet engine thrust (available thrust P_r) from flight velocity (or Mach number) and flight altitude.

In the case of propeller propulsion, regardless whether it's a piston engine or turbine engine, determination of propulsion system characteristics has two stages:

- selection of the propeller,
- calculation of the available power as a function of flight speed and altitude.

Described methodology is based on a set of propeller characteristics presented in [2] and it can be used for the piston propulsion, as well as the turbine propulsion.

Characteristics of the jet engines are usually directly provided in the information materials from the engine manufacturer, in the form of algebraic formulas, tables and graphs of engine thrust as a function of flight speed (Mach number) and altitude.

2. PROPELLER PROPULSION

2.1. Selection of the propeller

Our Selection of the propeller for the airplane is based on the choice of this characteristic (among the available propeller characteristics) for which the propeller, in the assumed conditions, has the greatest aerodynamic efficiency η_s and on the calculation of the propeller diameter.

Calculations must be conducted in the following stages:

a) Choose – using the performance data of the airplane – conditions of propeller selection:

V_d – flight speed [m/s],

h_d – flight altitude [m],

N_d – engine power [W],

n_{sd} – engine revolutions (revs) corresponding to the selected power [r/s].

As flight speed and flight altitude, we need to assume maximum speed of the horizontal flight and altitude on which it is achieved (from the airplane data). We can also (in the case of passenger, transport or touristic airplane) assume the cruise speed. Engine power and revs that correspond to it, must be assumed as equal to nominal or permanent maximum power. We just need to remember that this power should be given at altitude h_d .

In the case of some types of engines (high-revving low-power engines, turbine engines), it must be assumed that the engine is equipped with a reducer, which reduces the angular speed of the propeller to the range of 1500-2500 r/min. Usually, the degree of reduction (shift between revolutions of the propeller and revolutions of the engine shaft) can be found in the airplane description among the data concerning propulsion system.

b) Calculate diameterless feature of the propeller using the following formula:

$$C_d = V_d \sqrt[5]{\frac{\rho_d}{N_d * (n_{sd})^2}} \qquad (1)$$

where: ρ_d is the air density (in kg/m^3) at the altitude of h_d

c) Using the propeller characteristics (e.g. figures Z.24-Z.30 in [2]) select the propeller, which for the calculated value C_D has the highest efficiency η_s (graphs $J=f(C_D)$).

d) Calculate the propeller diameter using the following formula:

$$D = \frac{V_d}{J * n_{sd}} \qquad (2)$$

e) Check whether the Mach number at the end of the propeller blade, during the flight at high speed and expressed with the following formula:

$$Ma_{kl} = \sqrt{V_{max}^2 + (\pi * n_{sd} * D)^2} / a_{dd} \qquad (3)$$

where:

V_{max} – maximum allowable flight speed, assumed as 1.2 of the maximum speed in the airplane data,

a_{dd} – speed of sound at the altitude of h_d

does not exceeds the limit values, which are equal to 0.8 for wooden or composite propellers, and 0.9 for propellers made out of metal.

f) Check whether the propeller diameter is not too small in regard to the transverse dimensions of the fuselage or engine nacelle. Average diameter values of the propellers selected for typical piston engines, with power from 100 kW to 1000 kW, range from 2 m to 4 m.

For high-revving low-power engines (below 100 kW) propeller diameters can be even below 1m. In the case when propeller diameter is too big or too small, you need to (in consultation with the project lecturer) slightly change the conditions for selection: flight speed, power or engine revolutions.

2.2. Determination of available power

Available power of the propulsion system comprising of the engine and propeller is determined by the following formula:

$$N_r = N * \eta_s \tag{4}$$

Calculation method of dependency of available power from flight speed and flight altitude, depends on whether the propeller is fixed or adjustable.

2.2.1. Adjustable propeller

Adjustable propellers, and more precisely – blade shifting control systems, are designed in such manner that during the flight by changing the angle of blades arrangement in regard to changing flight conditions (flight speed, engine power), they maintain angle of attack on the blades close to the optimal. System of automatic regulation maintains constant engine revolutions (and propeller revolutions) chosen by the pilot and therefore it maintains constant engine power. Thus, for the adjustable propellers:

$$C_N = \frac{N}{\rho * n_s^3 * D^5} = const \tag{5}$$

This significantly simplifies the calculation of dependency of available power from flight speed, because the propeller operating point on the characteristic $C_N(J)$ and $J(C_D)$ is known for the given flight speed (we know C_N and J). The most convenient way to perform the calculations is to use a table (Table 1).

A. For a number of flight altitudes from h=0 to h_{max}, higher 2000-3000 meters from the theoretical upper limit of the airplane, provided in its performance data, we select from the engine data, the power corresponding to this flight altitude. In the absence of further information about the engine, a decrease in the power of piston engine without a compressor (altitude characteristic of the engine) can be determine using the following formula (Fig. 1a):

$$N(h) = N(0) * \frac{\sigma - k}{1 - k} \qquad (6)$$

where:

N(0) – engine power on the ground (h=0),

$N=N_0$ – relation of air density at the altitude of h to air density on the ground,

k – dimensionless empirical coefficient with values from 0.08 to 0.25;

Average values of the typical piston engines range from 0.12 to 0.16.

Altitude characteristic of the piston engine with a compressor is more complex (fig. 1b, engine with two-stage compressor).

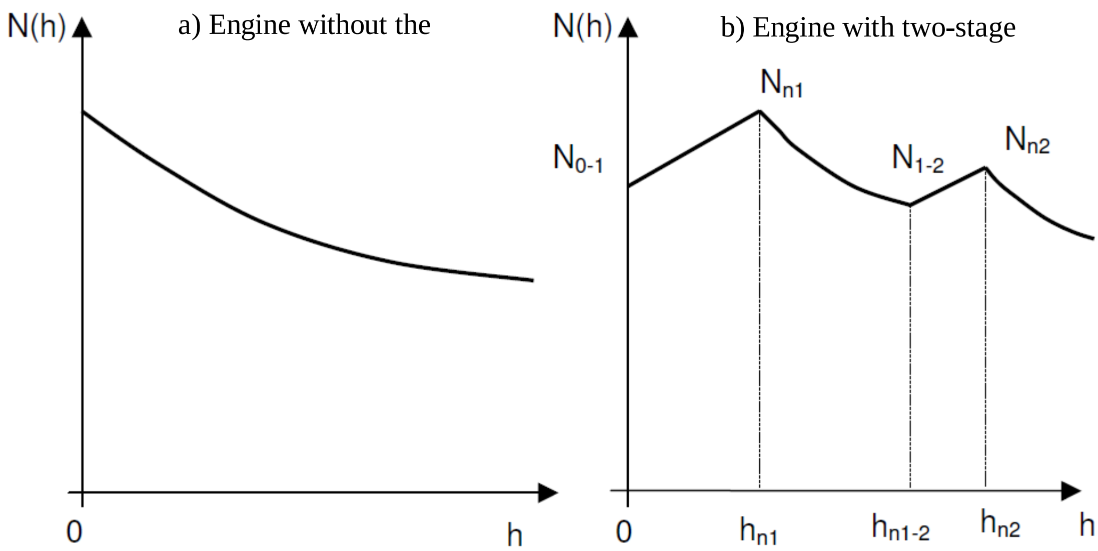

Fig. 1.

Fig 1. Altitude characteristics of the piston engine

In the altitude range 0-h_{n1-2}, the compressor operates in the first gear, whereas above the altitude h_{n1-2}, it operates in the second gear. In the altitude range 0-h_{n1} and h_{n1-2}-h_{n2} , in which the compressor efficiency is sufficient to maintain a constant pressure of charging, dependence of engine power from the altitude is linear (formula for the altitude range 0-1):

$$N(h) = N_{0-1} + \frac{N_{n1} - N_{0-1}}{h_{n1} - h_{0-1}} * (h - h_{0-1}) \quad (7)$$

In the remaining range of altitudes, you need to use formula (6), while in place of N(0), you must use $N(h_{n1})$ or $N(h_{n2})$ and in place of ,you must use h/h_{n1} or h/h_{n2} .

Engines, in which the compressor is driven by a turbine that uses exhaust gases, have approximately constant power independent of altitude, up to the flight altitudes of 6-8 km. Above this flight altitude, the power is decreasing in accordance with the formula analogous to (5.6).

Power of the turbine engine driving the adjustable propeller (turbo-propeller propulsion) depends on the altitude, in accordance with the following formula:

$$N(h) = N_0 * \left(\frac{\rho}{\rho_0}\right)^{0,6} \quad (8)$$

B. With known engine power, we determine power coefficient according to (5).

C. Assume number of flight speed values V, from 0 to speed about ±50% higher than maximum flight speed given in the airplane technical data and calculate feed of the propeller J.

D. Using propeller characteristics $C_N(J)$ for the calculated values C_N and J, read value of the propeller angle □s, and from the characteristics □s(J) for the calculated J, read value $_s$ – value of propeller efficiency, and calculate N_r according to (4).

E. The calculations must be repeated for several flight altitudes from h_1=0 to h_k. The results are presented in the graph (fig. 2).

Table 1. Speed-altitude characteristics of the propulsion system with the adjustable propeller

Flight altitude h= h_1 [m], engine power for this altitude N = N_1 [kW] $C_N=C_{N1}$					
No.	V [m/s]	J=V/(n_s* D)	□s [degrees]	□s	N_r=N*□s
1					
2					

…					
n					
Flight altitude h= h_2 [m], engine power for this altitude N = N_2 [kW] $C_N=C_{N2}$					
No.	V [m/s]	J=V/(n_s* D)	$\square_s$ [degrees]	$\square_s$	$N_r=N*\square_s$
1					
2					
…					
n					
Flight altitude h= h_k [m], engine power for this altitude N = N_k [kW] $C_N=C_{Nk}$					
No.	V [m/s]	J=V/(n_s* D)	$\square_s$ [degrees]	$\square_s$	$N_r=N*\square_s$
1					
2					
n					

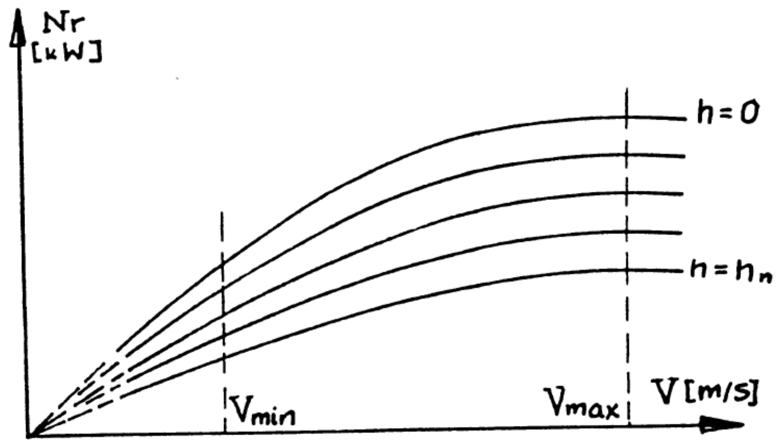

Fig 2. Speed-altitude characteristics of the propulsion system

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2.2.2. Fixed propeller

Fixed propeller is currently used only for low-power piston engines, which drive light aircrafts with maximum speed of horizontal flight not exceeding 200 km/h. It's easy to check that for this type of propulsion system any change in flight speed or altitude leads to a change in rotational speed of the engine. This is due to the fact that for the determined operating conditions of the entire propulsion system, power generated in the engine $N(n_s)$ must balance the power absorbed by the propeller:

$$N(n_s) = C_N * \left(\frac{V}{n_s * D}\right) * \rho * n_s^3 * D^5 \qquad (9)$$

In the formula (9), $N(n_s)$ means the revolution characteristic of the engine for the given flight altitude. Therefore, for the given flight altitude, each flight speed should correspond to exactly one value of the rotational speed of the engine, ensuring balance of the system. However, it's not hard to notice that the relation (5.9) is nonlinear algebraic equation with unknown n_s (n_s occurs here in third power and in the form of nonlinear functions $N(n_s)$ and $C_N(V/(n_s*D))$). This equation can be solved only in approximate manner using numerical methods. This problem can be omitted by assuming approximate dependence of the engine power from rotational speed. For the piston engines in the operational range of work, torque on the motor shaft:

$$M_s = \frac{N}{2 * \pi * n_s} \qquad (10)$$

changes only in a slightly manner, which means that the value N/n_s (which can be determined from the rotational characteristic of the engine) is constant for the given flight altitudes. Therefore:

$$C_N = \frac{N}{\rho * D^5 * {n_s}^3} = \frac{1}{\rho * D^5} * \frac{N}{n_s} * \frac{1}{n_s^2} = \frac{const(h)}{n_s^2} \qquad (11)$$

This allows us to determine a point of balance for interaction of engine and propeller based on the characteristic $C_N(J)$ and formula (11) in the following manner:

A. We assume a number of values for feed J from zero to a value for which $C_N = 0$.

B. From propeller characteristic we read values of power coefficient C_N and propeller efficiency n_s .

C. For the read values C_N, engine revolutions n_s can be calculated using the transformed equation (11):

$$n_s = \sqrt{\frac{const(h)}{C_N}} \qquad (12)$$

D. Flight speed corresponding to the balance conditions is

$$V = J * n_s * D \tag{13}$$

E. Available power of the propulsion system is therefore equal to the constant value N/n_s multiplied by the revolutions determined from (12) and the propeller efficiency:

$$N_r = N * \eta_s = \frac{N}{n_s} * n_s * \eta_s \tag{14}$$

With the increase of the feed (and thus the flight speed), the engine revs increase, because the angles of attack in the propeller blades decrease and coefficient of the aerodynamic resistance C_x, which is responsible for the propeller anti-torque also decreases. Usually, for certain flight speed, significantly lower than maximum speed of the horizontal flight, the revolutions n_s calculated according to (11) are greater, than maximum revolutions allowable by the manufacturer for the given engine. This requires the correction of the above-mentioned calculation procedure in the following manner:

A. Calculate limit value of the power coefficient $C_{N\text{-}gran}$:

$$C_{N-gran} = \frac{N_{max}}{n_{s-max}^3 * n_s} \tag{15}$$

where N_{max} and $n_{s\text{-}max}$ mean maximum power and maximum allowable revolutions of the engine.

B. From the propeller characteristic for the calculated value $C_{N\text{-}gran}$, read J_{gran}.

C. Assume a number of feed values J, from the value J_{gran} to the value corresponding to C_N=0 and from the propeller characteristic read C_N and n_s .

D. Available power and flight speed can be determined from the following formula:

$$N_r = C_N * \rho * n_{s-max}^3 * D^5 * \eta_s \tag{16}$$

$$V = J * n_{s-max} * D \tag{17}$$

Obviously the above-described calculations must be carried out for a range of flight altitudes, while taking into account change in the engine power, along with the flight altitude, in accordance with the recommendations described in paragraph 2.2.1. The most convenient way to carry out these calculations is by using a table (Table 2).

Figure 3 shows the speed characteristic of the engine with maximum power of 115 kW, with revolutions (of the propeller) 1800 r/min and with fixed propeller with a diameter of 2315 mm selected for the maximum power, flight altitude h=0 and flight speed 250 km/h. You can see that the limit speed of this propeller was 247.5 km/h and is nearly equal to the selection speed, which means that the propeller has been correctly adapted to higher flight speeds.

Table 2. Speed-altitude characteristics of the propulsion system with fixed propeller

Flight altitude h= h_1 [m], engine power for this altitude N = N_1 [kW]							
No.	J	C_N	s	n_s [r/s]	V [m/s]	N [kW]	N_r [kW]
1							
2							
.. ..							
n							
Flight altitude h= h_2 [m], engine power for this altitude N = N_2 [kW]							
No.	J	C_N	s	n_s [r/s]	V [m/s]	N [kW]	N_r [kW]
1							
2							
.. ..							
n							
Flight altitude h= h_k [m], engine power for this altitude N = N_k [kW]							
No.	J	C_N	s	n_s [r/s]	V [m/s]	N [kW]	N_r [kW]
1							
2							
.. ..							
n							

Available power as a function of flight speed

Nr_0 – available power corresponding to full charging pressure

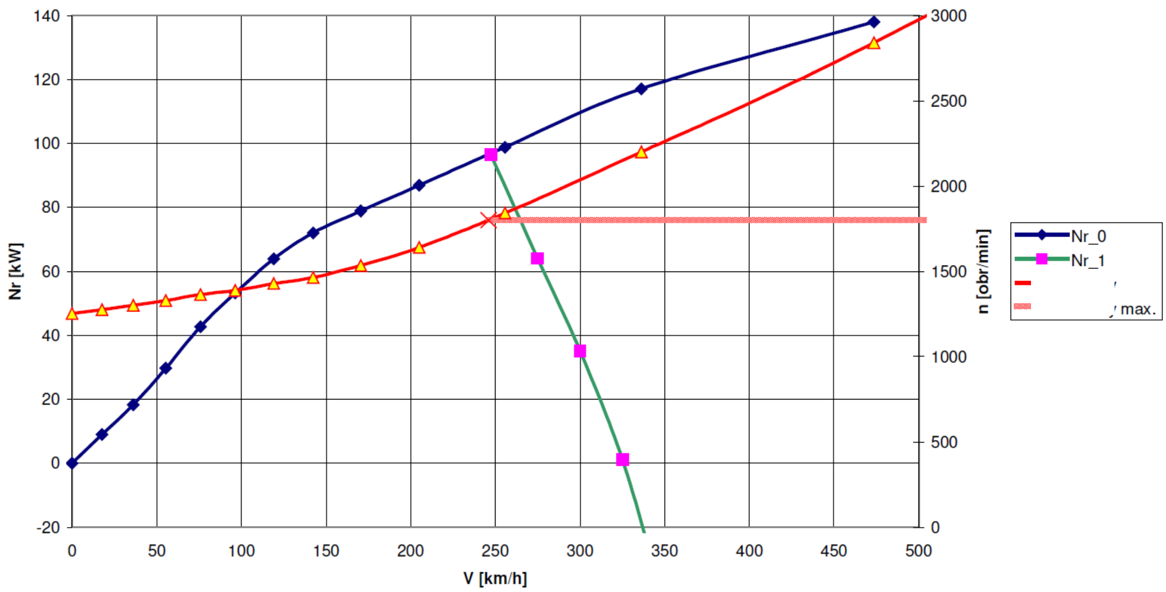

Fig 3. Speed characteristic of the engine with maximum power of 115kW

2.3. Turbo-jet propulsion

Characteristics of the turbo-jet engine are usually provided by the manufacturers, in the form of dependency of engine available thrust from the Mach number and flight altitude (speed-altitude characteristics). They can be directly used for the calculations of the airplane performance without any additional conversions.

In the absence of original engine characteristics, dependency of thrust form the Mach number and flight altitude for the single flow engine can be estimated using the following approximated formulas:

$$P_r(Ma,h) = P_r^* * \left(1 - 0{,}605 * Ma + 0.725 * Ma^2\right) \tag{18}$$

$$P_r^* = P_{r-0} * \left(\frac{\rho}{\rho_0}\right)^{0{,}85} \tag{19}$$

where $P_{r\text{-}0}$ is so called static thrust of the engine obtained on the ground with the flight speed equal to zero.

For dual flow engines, you can assume linear decrease of thrust along with the increase of Mach number:

$$P_r(Ma, h) = P_r^* * (1 - K_p * Ma) \quad (20)$$

where K_P is a dimensionless coefficient, ranging from 0.3 for engines with dual flow degree of 1:1 to 0.65 for engines with dual flow degree of 1:8 and more.

The most convenient way to perform the calculations of jet engines characteristics is to use a table (Table 3) and their results (available thrust as a function of flight speed and altitude) should be presented in the graph (Fig. 4, example of the single flow engine with static thrust 10 000 N).

Table 3. Characteristic of the turbo-jet engine

Ma	Flight altitude h [km]					
	0.0	2.0	4.0	6.0	.. ..	12.0
0.0	Pr_0					
0.2	Pr_1					
0.4	Pr_2					
.. ..	.. ..					
1.6	Pr_n					

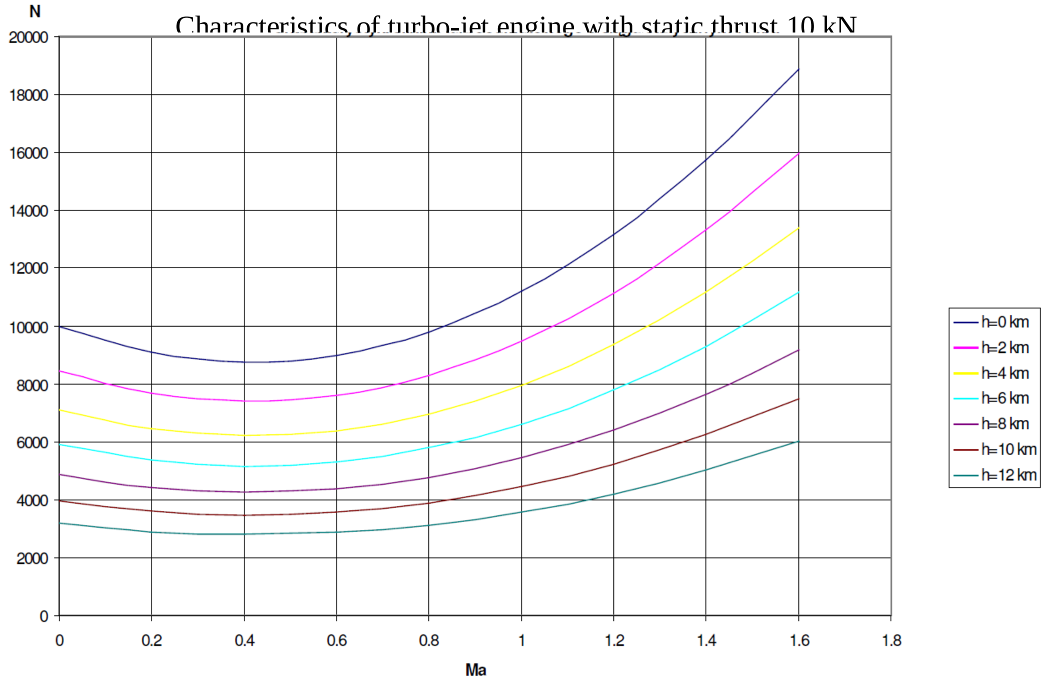

Fig 4. Single flow engine with static thrust