Project no. 5
Airplane Propulsion System Characteristics

5.1 Piston (reciprocating) engines

The propulsion system with piston engine must use a propeller (airscrew) or a fan as an aerodynamic "tool" for generation of power (thrust) usable for propulsion of the airplane.

It can be shown that the available power of the single engine-propeller unit is equal

$$P_{avail} = P_{deliv} \cdot \eta_{\text{prop}} \tag{5.1}$$

where:

P_{deliv} - the power delivered by the engine (engine's output power),
η_{prop} - aerodynamic efficiency of the propeller.

The delivered power P_{deliv} should be calculated base on altitude characteristics of the piston engine. Flight tests show that for simple, non-supercharged piston engine the power goes down with increasing of the flight altitude according to formula:

$$P_{deliv} = P_0 \cdot \frac{\sigma - k}{1 - k} \quad , \tag{5.2}$$

where:

P_0 - the take-off power of engine (on ground)
$\sigma = \frac{\rho}{\rho_0}$ - relative air density
k - experimental constant factor range 0.08 up to 0.15; common value: 0.12

Fig. 1 presents an example characteristic of an engine with P_0=300 kW and k=0.12.

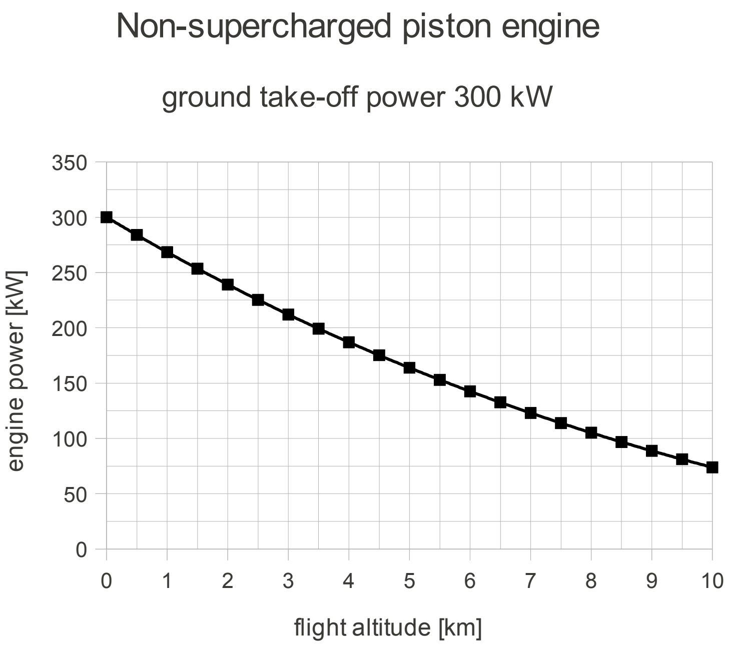

Figure 1

If the piston engine is equipped with single-stage compressor, the altitude characteristic is quiet different:

- maximal power of the engine N_{max} is performed on an altitude h_{nom} called as *engine nominal altitude;* this altitude generally depends on design solution of engine and supercharging system;
- between the ground and nominal altitude the output power increase linear

$$P_I(h)=P_0+\frac{P_{max}-P_0}{h_{nom}}\cdot h \quad ; \tag{5.3}$$

- above the nominal altitude power decrees according to equation

$$P_{deliv}=P_{max}\cdot\frac{\sigma_{nom}-k}{1-k} \quad , \tag{5.4}$$

where

P_{max} - maximum power of engine for nominal altitude

$\sigma=\frac{\rho}{\rho_{nom}}$ - relative air density based on air density for nominal altitude

k - experimental constant factor range 0.08 up to 0.15; common value: 0.12

An example of the characteristic of single-stage supercharged engine is presented on fig. 2 (N_0=300 kW, h_{nom}=3 km, N_{max}=330 kW).

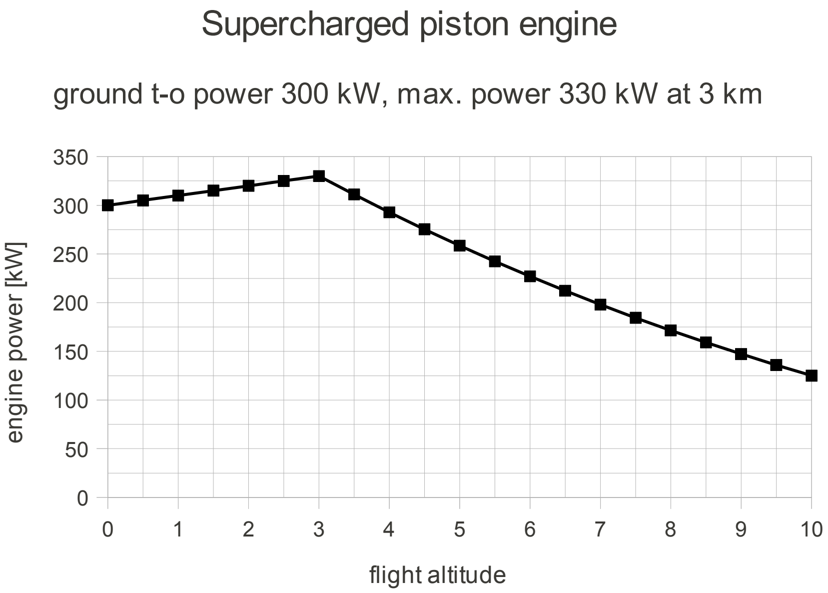

Figure 2

5.2 The turboprop engine

Some bigger and faster airplanes are powered by turboprop engine with a variable pitch multi-blade propeller. Wind tunnel and flight tests show that output power of the turbine engine for constant rotational speed of the turbine and compressor unit depends on the flight altitude according to the formula:

$$P_{deliv}=P_0\cdot\left(\frac{\rho}{\rho_0}\right)^{0.7} \quad . \tag{5.5}$$

It is easy to check that the altitude characteristic of the turboprop engine is similar to the characteristic of non-supercharged piston engine (see fig. 1), but for this type of engine the power drops down slower than the power of piston engine.

5.3 The propeller efficiency characteristic

The aerodynamic efficiency of the propeller η_{prop} depends on it's geometric parameters (ie. type of blades sections, blades thickness, shape, chord and number of blades) as well as depend on flight conditions (flight altitude and speed) and power of the engine. For purpose of project no. 5 we assume that the efficiency η_{prop} is a function of the non-dimensional flight speed only $\bar{V}=\frac{V}{V_{ref}}$ and does not depend on flight altitude. The characteristic $\eta_{prop} = f(\bar{V})$ is given on fig. 3. The propeller design reference flight speed V_{ref} should be estimated as $V_{ref}=0.8\cdot V_{end}$ (V_{end} - see equation (5.6)).

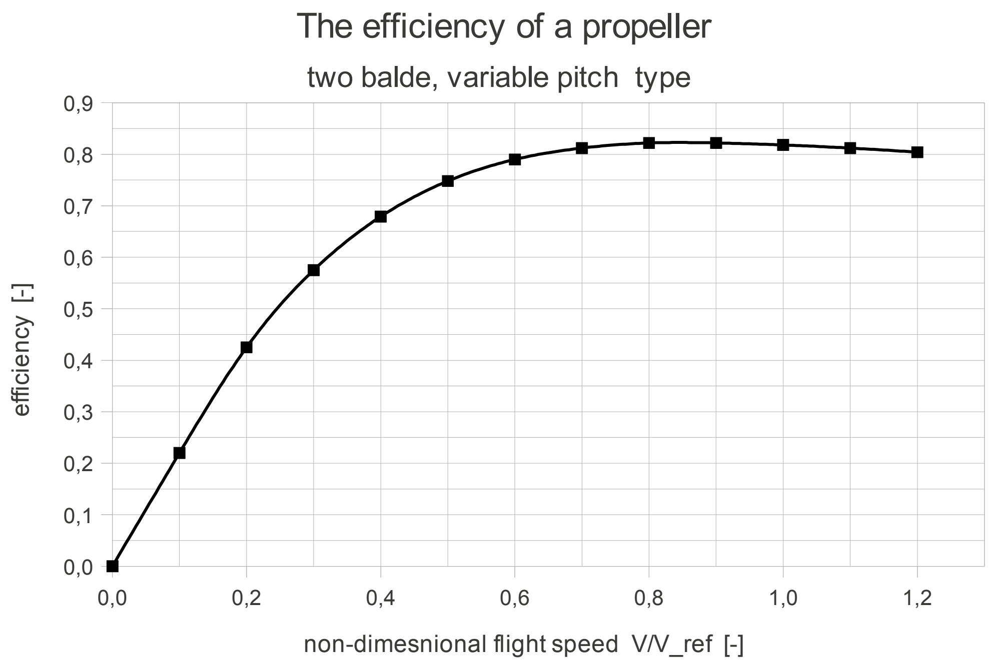

Figure 3

The calculation of available power for piston or turboprop engine should be performed using a table (see Table 5.1).

Table 5.1	Power characteristics of the piston or turboprop engine with a propeller					
$V=\bar{V}\cdot V_{ref}$ [m/s]	Flight altitude h [km]					
	0.0	2.0	4.0	6.0	.....	12.0
0.0	0	0	0	0	0	0
10.0						
20.0						
.....	......					
120.0						

Remark: largest value of the flight speed V_{end} (an example value of 120 m/s in table 5.1) can be estimated using following (obvious!) formula

$$V_{end}=\left(\frac{2\cdot n_{eng}\cdot P_{max}\cdot\eta_{\text{prop max}}}{\rho_0\cdot S_w\cdot C_{\text{D min}}}\right)^{\frac{1}{3}}, \qquad (5.6)$$

where n_{eng} denotes number of airplane's engines and $\eta_{prop\ max}$ is the maximum value of the propeller efficiency.

An example of available power of the single engine and variable pitch propeller system presents fig. 4.

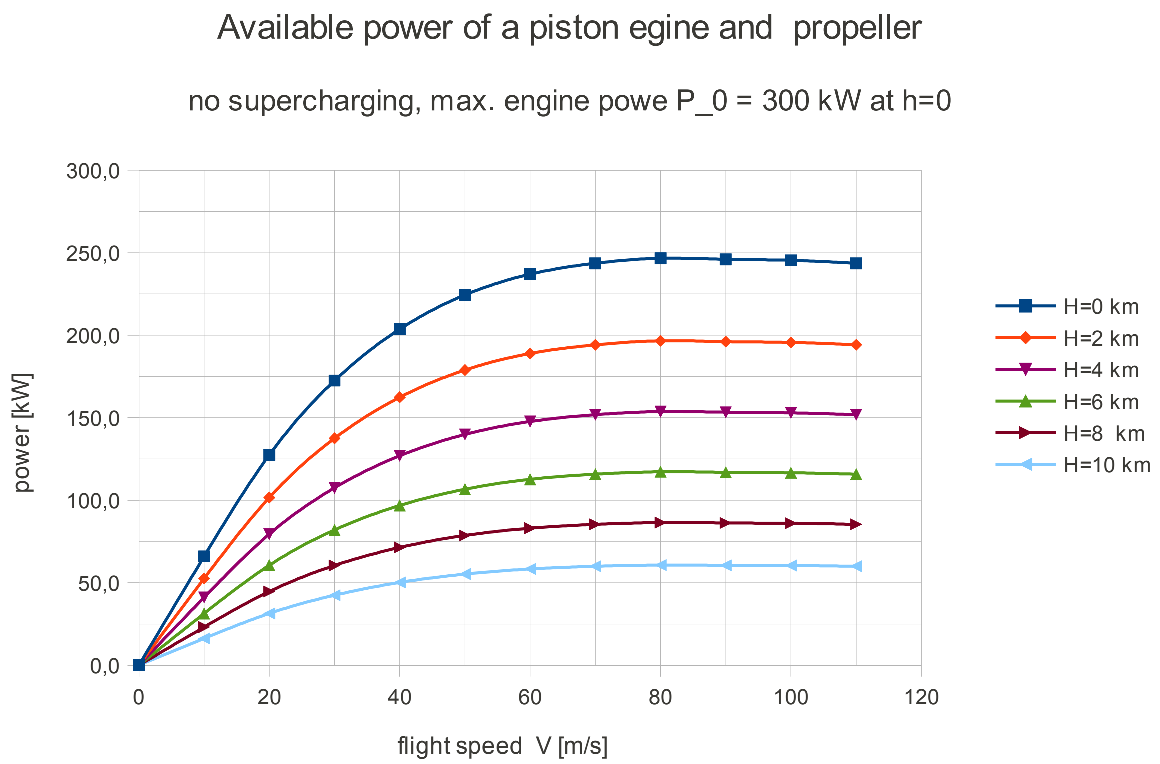

Figure 4

5.4 Turbojet Powerplant

Characteristics of the turbojet engines – thrust and specific fuel consumption - are usually given by manufactures as a function of flight Mach number and flight altitude. The data can be easy directly used for calculation of powered flight performance of the aircraft without any additional work. The turbojet engines data sometime can be found on famous engines manufacturers web home page (Turbomeca, Rolls-Royce).
If the data are unavailable, following raw approximations for the thrust can be apply:

- old-fashion single-spool turbojets:

$$T(Ma,H)=T_{0\_H}\cdot\left(1-0.605\cdot Ma+0.725\cdot Ma^2\right), \qquad T_{0\_H}=T_{0\_0}\cdot\left(\frac{\rho}{\rho_0}\right)^{0.86} \qquad (5.7)$$

where

T_{0_0} - so-called *ground level static thrust* usually given as one of the airplane engine data;

- newest twin-spool engines:

$$T(Ma, H) = T_{0\_0} \cdot (c_0 + c_1 \cdot Ma + c_2 \cdot Ma^2) \ . \qquad (5.8)$$

Values of the approximation coefficients c_0, c_1 and c_2 are given in table 5.2.

Remarks:

1. *Note that all coefficients c_0, c_1, c_2 depends on flight altitude.*
2. *For intermediate altitudes (ie. 2, 4, 8, 10 km) use linear interpolation for calculation of these coefficients.*
3. *For engines with by-pass ratio greater than 2:1 use same approximation as for 2:1.*

Table 5.2 Thrust characteristics approximation coefficients

Flight altitude [km]	By-pass ratio 2:1			By-pass ratio 1:1		
	c_0	c_1	c_2	c_0	c_1	c_2
0	1.000	-0.600	0.360	1.000	-0.790	0.380
6	0.650	-0.325	0.250	0.630	-0.515	0.310
11	0.400	-0.230	0.220	0.380	-0.410	0.300

The calculation of thrust of the engine should be made using table 5.3.

Table 5.3 Thrust characteristics of the turbojet engine

Ma	Flight altitude h [km]					
	0.0	2.0	4.0	6.0	.....	12.0
0.0						
0.2						
0.4						
.....	......					
1.4						

Remark: similarly as for reciprocating or turboprop engines, largest value of the Mach number Ma_{end} (an example value of Ma=1.4 in table 5.3) can be estimated using following formula similar to (5.1):

$$Ma_{end} = \frac{1}{a_d} \cdot \sqrt{\frac{2 \cdot n_{eng} \cdot T_{max}}{\rho_0 \cdot S_w \cdot C_{D\,min}}} \ , \qquad (5.9)$$

where n_{eng} denotes number of airplane's engines, T_{max} is the maximum value of the thrust of single engine and a_s denotes speed of sound for the altitude of T_{max} (usually for h=0!).

Fig. 5 and 6 presents example characteristics of the single-spool and double-spool turbojet engines with same static thrust T_{0_0} of 10 kN (10 000 N).

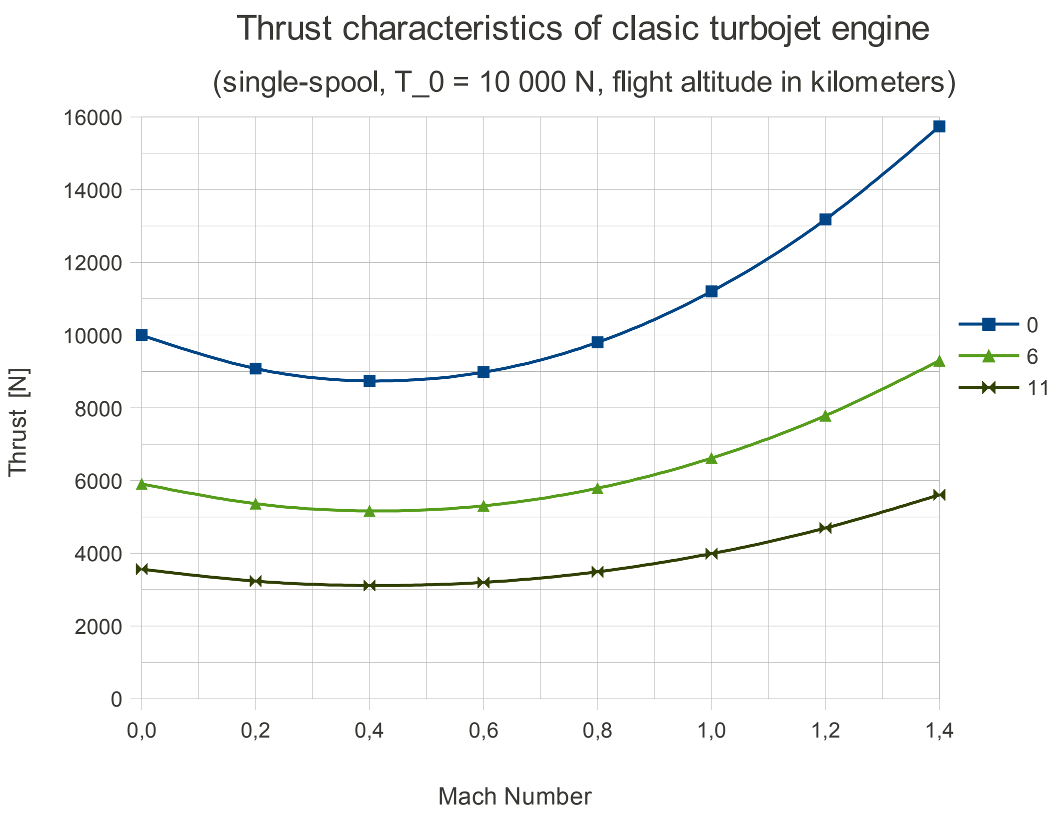

Figure 5

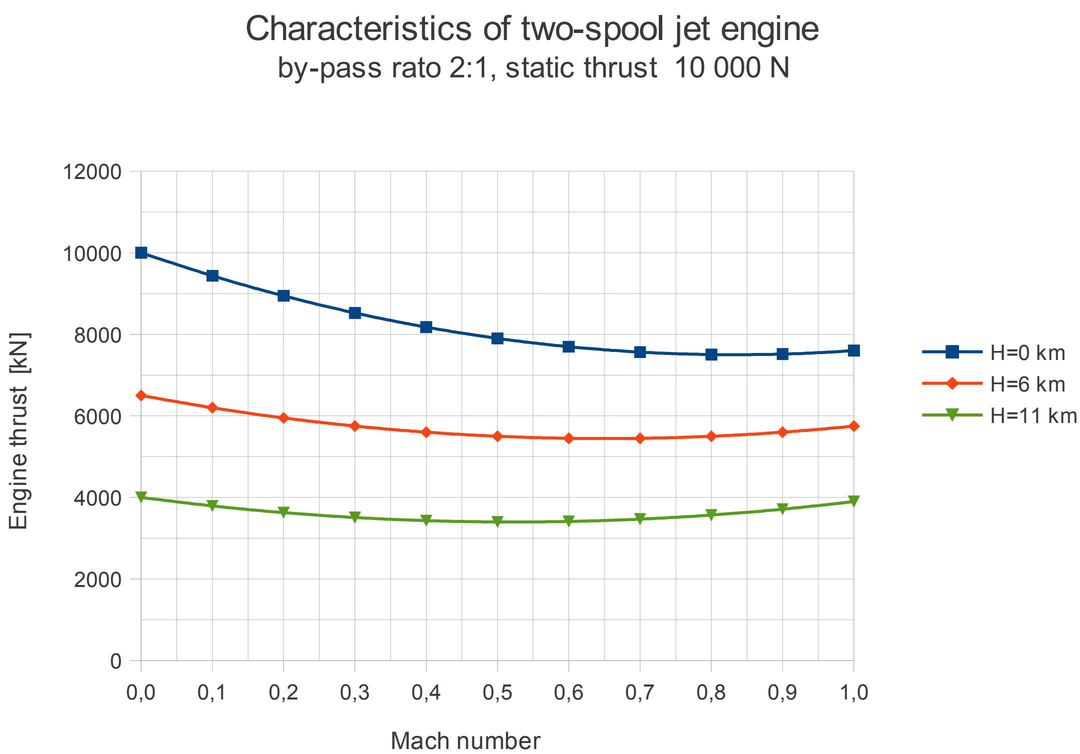

Figure 6