

Chapter 4

Estimation of wing loading and thrust loading - 8

Lecture 16

Topics

4.14.9 Selection of propeller diameter for a chosen application

Example 4.19

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4.14.9 Selection of propeller diameter for a chosen application

A propeller is selected to give the best efficiency during a chosen flight condition which is generally the cruising flight for transport airplanes. Some companies may use their own propellers. However, design fabrication and testing of propeller are complicated technical tasks. Hence, the general practice is to use the standard propellers and the charts corresponding to them. As a first step, the number of blades of the propeller is decided depending on the amount of power to be absorbed by the propeller.

The power absorbed by a propeller depends mainly on three geometric features of the propeller viz. diameter, solidity ratio ($\sigma_p(r)$) and activity factor (AF). The last two quantities are defined as follows.

$$\text{Solidity ratio at a radius 'r'} = \sigma_p(r) = \frac{N_b c}{2\pi R} \quad (4.130)$$

$$\text{Activity factor} = AF = N_b \times \frac{1,00,000}{16} \int_{0.2}^{1.0} (r/R)^3 (c/d) d(r/R) \quad (4.131)$$

where,

N_b = Number of blades in the propeller.

C = Chord of the blade section at radius 'r'.

R = radius of the propeller (d/2).

d = diameter of the propeller.

The multiplying factor (100,000/16) is inserted so that the AF per blade has a convenient magnitude (80 to 200).

The two bladed propellers are used on the general aviation aircraft and for engines with power rating upto 200 kW. They are simpler, lighter and cheaper than propellers with 3 or more blades. However, the two bladed propellers would become too large for higher power ratings. The Mach number, corresponding to the resultant velocity at propeller tip, may exceed critical Mach number of the blade resulting in lowering of propeller efficiency.

According to Ref.1.19, chapter 10 and Ref.1.15, chapter 3, the three bladed propellers are preferred for engines with rating between 200 to 500 kW. Four bladed propellers are used for engines with higher ratings. Early version of ATR – 72 airplanes had 4 bladed propellers. The present versions have 6 bladed advanced propellers. (see subsection 4.14.12)

At the present stage of preliminary design process, the number of blades can be chosen from trends indicated by the data collection.

The designer of a new airplane generally chooses the diameter of the propeller using the design chart (e.g. Fig.4.15c) appropriate to the propeller. Consider a four bladed propeller. Following steps are used to select the diameter of a propeller.

(a) Choose a level flight condition i.e. altitude (h_c) and speed (V_c).

(b) Obtain lift coefficient (C_L) in this flight using :

$C_L = W / (0.5\rho V_c^2 S)$. Obtain the corresponding C_D from the drag polar of the airplane.

(c) Obtain THP required during the flight using : $THP = (0.5\rho V_c^3 S C_D) / 1000$

(d) Assume η_p between 0.8 to 0.85 depending on likely maximum value of η_p .

(e) Obtain BHP = THP/η_p . Then RPM (N) which will give this power output at the chosen h_c with low BSFC is known from the engine curves e.g. Fig.4.12.

Calculate $n = N/60$.

(f) Calculate $C_s = V(\rho/Pn^2)^{1/5}$.

(g) From the design chart like Fig.4.15c, obtain the value of J on the dotted line, corresponding to the value of C_S in step (f). Also obtain the value of β from the same curve. Obtain the value of η_p from the upper part of the design chart.

(h) Since V , n and J are known, obtain propeller diameter using : $d = V/n J$

(i) If the value of η_p obtained in step (g) is significantly different from the value of η_p assumed in step (d), then iterate by using the value of η_p obtained in step (g).

Finally round-off the propeller diameter to nearby standard value.

Remark :

The choice of the parameters of the propeller like, diameter, pitch, blade size are also influenced by factors like noise level of the propeller, ground clearance, and natural frequency of the blade. Refer chapter 6 of Ref.3.4.

Example 4.19

For the sixty seater turboprop airplane considered in example 4.16, obtain the diameter of the propeller from the consideration of cruise at $V_{cr} = 500$ kmph and $h_{cr} = 4.5$ km. Assume that the propeller has RPM of 1200 and is a constant speed propeller.

Solution :

From example 4.16 we note the following.

$$W/S = 3570 \text{ N/m}^2, C_D = 0.02224 + 0.036 C_L^2, W = 208757 \text{ N},$$

$$S = 58.48 \text{ m}^2$$

Further, $V_{cr} = 500$ kmph = 138.9 m/s at h_{cr} of 4.5 km, $\rho = 0.7768 \text{ kg/m}^3$

$$C_L = \frac{q(W/S)}{\rho V^2}$$

Hence,

$$C_L = \frac{2 \times 3570}{0.7768 \times 138.9^2} = 0.4764$$

$$C_D = 0.02224 + 0.036 \times 0.4764^2 = 0.03041$$

$$\begin{aligned}\text{THP required} &= \frac{1}{2000} \rho V^3 S C_D \\ &= \frac{1}{2000} \times 0.7768 \times 138.9^3 \times 58.48 \times 0.03071 = 1851 \text{ kW}\end{aligned}$$

Since, the airplane has two engines, THP per engine = 1851/2 = 925.5 kW

Note : As regards the propeller, the actual airplane may have an advanced six bladed propeller. Such propellers are currently manufactured by M/S Ratier Figeac, Avenue Ratier, 46100 Figeac, France. The propeller charts for this propeller do not seem to be available in open literature. For the sake of this example, the steps to obtain the diameter of the propeller are illustrated using propeller charts given in Figs.4.15a to d. From Fig.4.15a, the maximum efficiency can be taken as 0.85.

Consequently, BHP per engine is 925.5/0.85 = 1088.8 kW = 1088800 W

N = 1200 or n = 1200/60 = 20 rps

$$\text{Hence, } C_s = V(\rho/Pn^2)^{1/5} = 138.9(0.7768/1088800 \times 20^2)^{1/5} = 2.472$$

From design chart in Fig.4.15c, corresponding to $C_s = 2.472$, the values of $\beta = 39.5^\circ$ and $J = 1.76$ from lower part of the figure and $\eta_p = 0.84$ from the upper part of figure are obtained.

$$\text{Hence, propeller diameter} = d = \frac{V}{Jn} = \frac{138.9}{1.76 \times 20} = 3.95 \text{ m}$$

The value of η_p is obtained as 0.84 instead of the assumed value of 0.85

$$\text{Hence, BHP required per engine} = \frac{925.5}{0.84} = 1101.8 \text{ kW}$$

Consequently,

$$C_s = 138.9(0.7768/1101800 \times 20^2)^{1/5} = 2.466.$$

Within the accuracy of graphs, $J = 1.76$ is obtained.

Hence, propeller diameter = d = 3.95 m.

Remarks :

(i) It is interesting to note that ATR – 72 – 200 has a propeller of diameter 3.93 m.

(ii) Example 4.4 of Ref.3.3 illustrates the procedure to obtain diameter of propeller for a general aviation aircraft.

4.14.10 Procedure for obtaining THP for given h, V, BHP and N

For calculating the performance of the airplane, the thrust horse power (THP) is needed at different values of engine RPM(N), break horse power (BHP), flight speed (V) and flight altitude (h). In this context the following may be noted.

(a) The engine output (BHP) depends on the altitude, the flight speed and the throttle setting.

(b) The propeller absorbs the engine power and delivers THP; $THP = \eta_p \times BHP$

(c) The propeller efficiency depends, in general, on BHP, V, N and β .

(d) The three quantities viz. d, V and n can be combined as advance ratio ($J = V/nd$).

(e) Once η_p is known :

$$THP = \eta_p \times BHP \text{ and } T = THP \times 1000 / V .$$

The steps required to obtain η_p depend on the type of propeller viz. variable pitch propeller, constant speed propeller and fixed pitch propeller. The steps in the three cases are presented below.

I) Variable pitch propeller

In this type of propeller the pitch of the propeller is changed during the flight so that the maximum value of η_p is obtained in various phases of flight. The steps are as follows.

(a) Obtain the ambient density (ρ) for the chosen altitude. Also obtain the engine BHP at chosen V and N.

(b) Obtain $C_p = P / (\rho n^3 d^5)$; P is BHP in watts

(c) Obtain $J = V/nd$

(d) Calculate $C_s = J/C_p^{1/5}$

(e) From the design chart for the chosen propeller (e.g. Fig.4.15c for a four bladed propeller), obtain β which will give maximum efficiency. Obtain corresponding η_p .

Consequently,

$$\text{THP} = \eta_p \times \text{BHP} \text{ and } T = \text{THP} \times 1000 / V ; \text{ note } V \neq 0$$

(f) To get the thrust (T) at $V = 0$, obtain BHP of engine at $V = 0$ at the chosen altitude and RPM. Calculate C_p . From Fig.4.15b obtain C_T and β at this value of C_p and $J = 0$. Having known C_T , the thrust (T) is given by :

$$T = \rho n^2 d^4 C_T$$

II) Constant speed propeller

The variable pitch propellers were introduced in 1930's. However, it was noticed that as the pilot changed the pitch of the propeller, the engine torque changed and consequently the engine RPM deviated from its optimum value. This rendered, the performance of the engine-propeller combination, somewhat sub-optimal. To overcome this problem, the constant speed propeller was introduced. In this case, a governor mechanism alters the fuel flow rate so that the required THP is obtained even as rpm remains same. The value of β is adjusted to give maximum possible η_p .

The steps to obtain η_p are the same as mentioned in the previous case.

III) Fixed pitch propeller

From Fig.4.15b it is observed that a fixed pitch propeller has a definite value of C_p for a chosen value of advance ratio (J). Consequently, the propeller can absorb only a certain amount of power for a given value of J. Thus, when the flight speed changes, the power absorbed by the propeller also changes.

However, for the engine-propeller combination to be in equilibrium i.e. run at a constant r.p.m, the power absorbed by the propeller and that produced by the engine must be the same. This would render the problem of determining power output as a trial and error procedure. However, it is observed that the fixed pitch propellers are used in general aviation aircraft which use piston engines. The torque of a piston engine remains nearly constant over a wide range of r.p.m's. Using this fact, the torque coefficient (C_Q) and torque speed coefficient (Q_s) are

deduced in Ref.1.5, chapter 16, from the data on C_P & C_T . Further a procedure is suggested therein to obtain η_p at different flight speeds.

Herein, the procedure suggested in the Appendix of Ref.4.8 is presented.

It is assumed that the propeller is designed for a certain speed, altitude, rpm and power absorbed.

Let,

V_0 = design speed (m/s)

N_0 = design rpm ; $n_0 = N_0 / 60$

BHP_0 = BHP of the engine under design condition (kW)

d = diameter of propeller (m)

J_0 = Advance ratios under design condition = $V_0 / n_0 d$

β_0 = design blade angle; this angle is fixed

η_0 = efficiency of propeller under design condition

The steps, to obtain the THP at different flight speeds, are as follows.

1. Obtain from the propeller charts, C_T and C_P corresponding to J_0 and β_0 . These values are denoted by C_{T0} and C_{P0} .

2. Choose values of J from 0 to a suitable value at regular intervals. Obtain from the relevant propeller charts, the values of C_T and C_P at these values of J 's and the constant value of β_0 .

3. Calculate J/J_0 , C_T/C_P and C_{P0}/C_P from values obtained in step 2.

4. Calculate:

$$T_0 = \eta_0 BHP_0 \times 1000 / V_0 \quad \text{and} \quad (4.130)$$

$$K_0 = T_0 C_{P0} / C_{T0} \quad (4.131)$$

5. The assumption of constant torque (Q_0) gives that N and P are related. Note:

$$Q_0 = P_0 / 2\pi n_0$$

This yields:

$$\frac{N}{N_0} = \sqrt{\frac{C_{P0}}{C_P}} \quad (4.132)$$

$$V = V_0 \times \frac{J}{J_0} \times \frac{N}{N_0} \quad (4.133)$$

$$\text{and } T = T_0 \frac{C_{P0}}{C_{T0}} \frac{C_T}{C_P} = K_0 \frac{C_T}{C_P} \quad (4.134)$$

Consequently, $\text{THP} = TV/1000$ and $\text{BHP} = \text{THP}/\eta_p$

Remarks:

- (i) Example 4.5 in Ref.3.3 can be referred to for an illustration of the procedure.
- (ii) Sometimes the manufacturer of the propeller may give an estimated variation of η_p vs J which can be used at various flight speeds and altitudes. Such a variation is used in Appendix 'A' of Ref.3.3 for estimation of the performance of a general aviation aircraft (Piper Cherokee PA 28-180).