SearchWing - Flight physics for dummies

How does weight impact range?

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I do not have a clue about the physics of flight. So I collect some basic principles from literature to answer questions like: What does a ten percent increase in weight mean in terms of range?

1 Weight and Range

What is the influence of additional or less weight on range?

1.1 Level Flight

Level flight means the plane does not increase or decrease altitude and it does not change its speed. The searchwing plane will be in this mode of operation for over eighty percent of the time. As the plane does not change the altitude it means that it is not accelerated in vertical direction. Therefore there is no net vertical force acting on the fuselage. The gravitational force due to the mass of the drone F_g is exactly compensated by the lift L which is produced by the wings [1, p. 147].

The plane does not change the speed. Therefore there is no acceleration in horizontal direction. The plane experiences a drag force D due to the movement through air which results in friction between the body of the plane and the air. This drag force is compensated by the thrust T which is produced by the propeller.

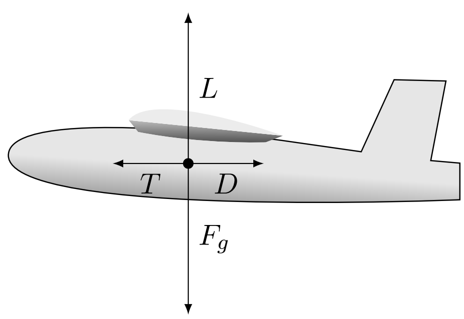

Figure 1: Condition for level flight - weight force equals lift and drag is equal thrust

Equation 1 and 2 describe the conditions of level flight. The gravitational force F_g is related to the mass m and the gravitational acceleration $g = 9.81 m/s^2$. With a mass of 2kg of our plane we must produce a lift of $L = F_g = 2kg \cdot 9.81m/s^2 \approx 20N$ for level flight. If the thrust is increased the plane will accelerate in horizontal direction.

$$L = F_g = mg \tag{1}$$
$$T = D \tag{2}$$

1.2 Lift

The lift of a wing depends on speed of the wing through air, the angle of attack α, the area of the wing and the shape of the wing. Figure 2 shows a wing with an angle of attack of ten degrees with respect to air flow.

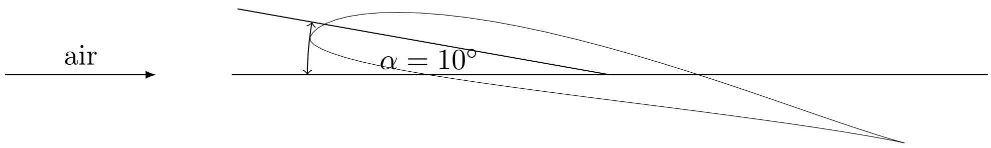

Figure 2: Wing and angle of attack

Equation 3 states the lift force of a wing which depends on wing area A, the speed through air V, the density of air ρ and the lift coefficient C_L [1, p. 78].

$$L = C_L \frac{1}{2} \rho V^2 \cdot A \tag{3}$$
$$D = C_D \frac{1}{2} \rho V^2 \cdot A \tag{4}$$

Equation 3 shows a quadratic dependency of the lift on speed through air V. There is a linear dependency on the wing area A. The lift coefficient C_l depends on the angle of attack - that is discussed in the following two sections.

1.2.1 Lift coefficient - 2D / Infinite Wing

Figure 3 shows the lift and drag coefficients C_l and C_d for a wing with infinite span from an XFOIL simulation of the S3010 profile [2]. That infinite length assumption is similar to a wing section in a wind tunnel which is attached to perpendicular planes at both ends of the wing. It neglects effects at the wing tips. Important points regarding the lift coefficient are

- The lift coefficient depends on the angle of attack α of wing vs air.
- The dependency is nearly linear up to an angle of approx. 10 degrees.
- There is an angle of attack where the lift is maximum. Here maybe 12 degrees.
- Increasing the angle of attack even further reduces the lift coefficient - this loss of lift is called stall.

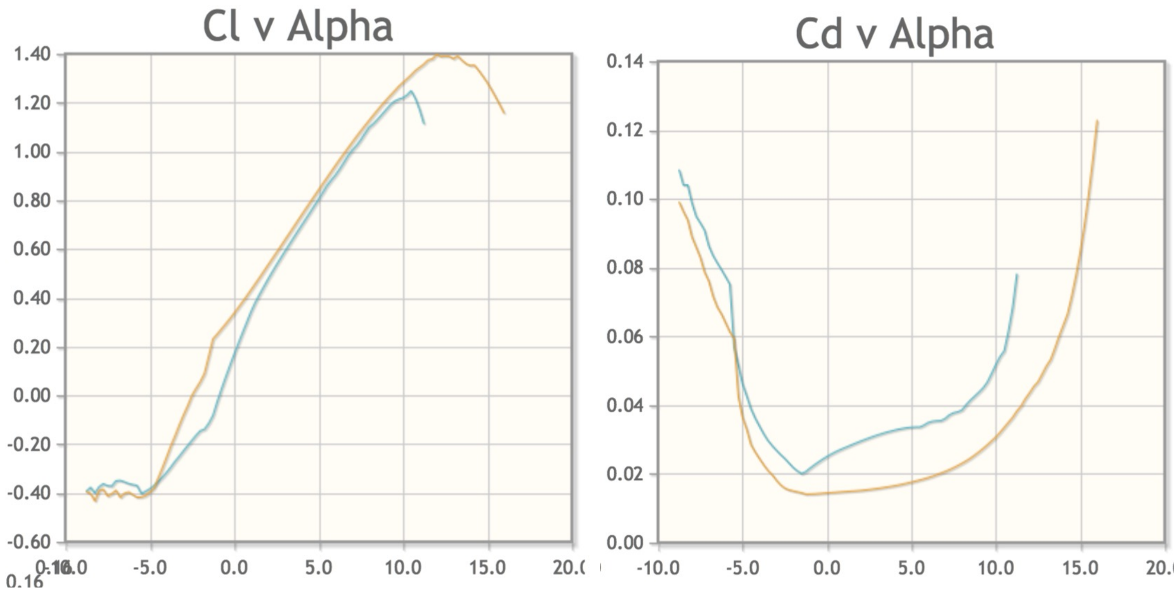

Figure 3: Left: C_l vs. angle of attack, Right: C_d vs. angle of attack

The X-UAV Mini Talon has an airfoil shape which is at least similar to the S3010. The green line is for a Reynolds number of 50000 and the orange curve is for a Reynolds number of 100000. Plots for other Reynolds numbers can be found in [2]. The Reynolds number is described in chapter 2.

1.2.2 Real wing with limited wing span

A real wing has a finite span with a wing aspect ratio $AR = w/l$ where w is the wing span and l ist the wing chord. The aspect ration AR is often estimated as shown in equation 5.

$$AR = \frac{w}{l} = \frac{w^2}{A} \tag{5}$$

Figure 4 shows the measurement results of lift coefficients for different wing aspect ratios from Ludwig Prandtl from 1920. The wing depth was 20cm and the span varied between 20cm and 140cm. The wing profile of the wing used for the measurements is depicted in figure 5.

The lift coefficient for a given angle is reduced when the aspect ratio reduces. An increased aspect ratio will give a higher lift at a given angle, i.e. the slope of the lift curve is reduced. The wing with the aspect ratio 1:3 in figure 4 also shows that the maximum achievable lift is reduced. The basic behaviour is however very similar to the 2D wing, i.e. there is a more or less linear relation between lift coefficient and angle. The aspect ratio of a Boing 747-400 is 6.96 while for a motor glider Stemmer S10 it is 28.2 [4, p. 203]. The slope of the lift curve for an ideal infinite thin wing is 2π when the angle is given in radians. Ludwig Prandtl estimates the reduced slope for a finite wing in equation 7 [5, p. 263] [3].

$$\frac{\partial C_l}{\partial \alpha} = \frac{1}{1 + 2/AR} \tag{6}$$

$$\tag{7}$$

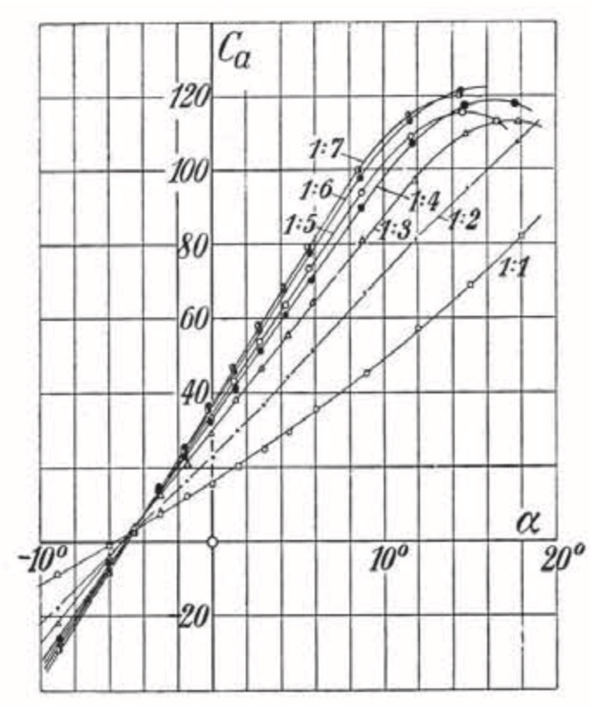

Figure 4: C_a ($= C_l$) vs. angle of attack for different wing aspect ratios from [3, p.51]

Figure 5: Wing profile of the wing used in the measurements in figure 4

An equivalent view of this behaviour is that the finite wing experiences an airflow which is bend by an additional induced angle α_i. So the equivalent angle of attack is reduced compared to the angle of attack for an infinite 2D wing. To achieve the lift of the 2D infinite wing one has to add an additional induced angle α_i to the angle of attack α_{2D} of the infinite wing [3][p. 37]. Figure 6 shows the bend airflow with the induced drag W_i. The angle of attack for the infinite wing α_{2D} is related to the finite wing α_{3D} according to equation 8 [3][p. 37].

$$\alpha_{2D} = \alpha_{3D} - \frac{c_l}{\pi \cdot AR} \tag{8}$$

Note that the angles are computed in radians.

1.2.3 Lift for the XUAV-Minitalon

The X-UAV Minitalon has a wing area of approximately $30dm^2$. The density of air depends on altitude and temperature. A typical value for the density of air is $\rho = 1.2kg/m^3$ [1, p. 32, fig. 2.2] [6]. At 1200m altitude it reduces to $1.1kg/m^3$. The Minitalon has a wing span w of 1.3m.

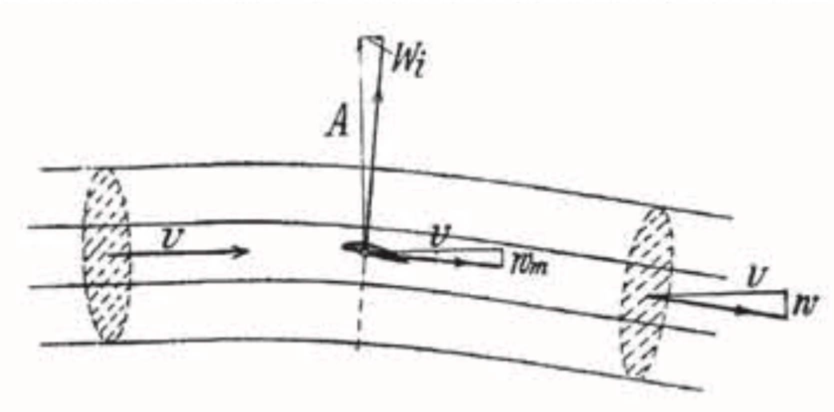

Figure 6: Airflow showing the induced angle α_i due to induced drag W_i (from [3][p. 37])

The wing area is $30dm^2$ which translates to an average chord length $l = A/w = 0.3m^2/1.3m$ of 0.23m which results in an aspect ratio AR of 5.63.

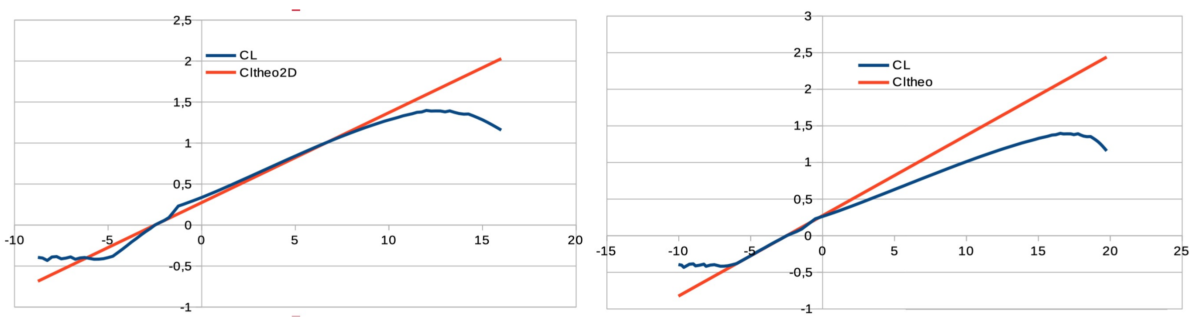

Figure 7: Lift of the infinite wing (left) vs. lift of the finite wing with aspect ration of 5.63 (right)

Figure 7 shows the lift coefficient of the infinite wing on the left and lift coefficient of the finite wing with an aspect ratio of 5.63. Both show the lift coefficient versus the angle of attack. A lift coefficient of 1 is achieved approximately at an angle of 7 degrees for infinite wing but at 10 degrees for the finite real wing with an aspect ratio of 5.63. The induced angle is accordingly 3 degrees.

A rough estimation for the X-UAV Mini Talon is shown in equation 9 for a speed of 50 km/h. At an angle of 7 degrees of the real finite wing the lift coefficient is approximately 0.74. So this is the situation for the wing at an angle of 7 degrees.

$$L = C_l \frac{1}{2} \rho V^2 \cdot A = 0.74 \cdot \frac{1}{2} \cdot 1.2 \frac{kg}{m^3} \cdot (50 \frac{km}{h})^2 \cdot 0.3m^2 = 25.7N \tag{9}$$

Note that at 100 km/h the lift force L will be a factor 4 higher due to the quadratic impact of the air speed. So flying at 100 km/h with an angle of attack of seven degrees will produce a lift of 102.8 N. The lift of 25.7 N is higher than the weight, so this lift will not result in level flight. For level flight the lift must be equal to the weight of 20 N, i.e. the speed must be reduced or the angle of attack must be reduced.

1.3 Drag

The total drag D_{tot} is composed of the profile drag D_p of the wing, the induced drag D_{ind} and the drag of the fuselage and other components D_{fuse}.

$$D_{tot} = D_p + D_{ind} + D_{fuse} \tag{10}$$
$$= \frac{1}{2}\rho V^2 \cdot A_{wing}(C_d + C_{d,ind} + C_{d,fuse}) \tag{11}$$

The drag also increases quadratic with the velocity through air V and is linear with the wing area A as shown in equation 4. For the X-UAV Mini Talon at a speed of 50 km/h and a wing area $A = 30dm^2$ the resulting drag force D is given in equation 11.

1.3.1 Profile Drag

The profile drag D_p is the drag which is more or less independent of the aspect ratio of the wing. For the angles which are used during flight, the profile drag is also more or less constant. Figure 3 shows the lift and drag coefficients for the S3010 profile which is similar to the wing of the X-UAV Mini Talon. The drag coefficient C_d is estimated with 0.02 from figure 3 for an angle of attack of 7 degrees. For a speed of 50 km/h, the resulting profile drag D_p is estimated in equation 12.

$$D_p = \frac{1}{2}\rho V^2 \cdot A_{wing}C_{d,wing} = \frac{1}{2} \cdot 1.2kg/m^3 \cdot (50km/h)^2 \cdot 30dm^2 \cdot 0.02 = 0.6N \tag{12}$$

1.3.2 Induced Drag

The induced drag D_{ind} is the drag which is a direct consequence of the produced lift. The induced drag results from the air which is accelerated in downward direction producing the lift of the plane [3, p.35]. The induced drag depends on the aspect ratio of the wing. With higher wing aspect ratio, the induced drag is reduced. The induced drag coefficient $C_{D,ind}$ is given in equation 13 with the aspect ratio of the wing AR.

$$C_{D,ind} = \frac{C_L^2}{\pi \cdot AR \cdot e} \tag{13}$$

The factor e is called the Oswald efficiency factor. e is in the range between 0 and 1 and depends on the shape of the wing. Typically e is in the range between 0.7 and 0.95. For an angle of attack of seven degrees the lift coefficient C_L is approximately 0.74 as shown in figure 7. At a speed of 50 km/h for the mini talon this results in equation 16.

$$D_{ind} = \frac{1}{2}\rho V^2 \cdot A_{wing}C_{D,ind} \tag{14}$$
$$= \frac{1}{2}\rho V^2 \cdot A_{wing}\frac{C_L^2}{\pi \cdot AR \cdot e} \tag{15}$$
$$= \frac{1}{2} \cdot 1.2kg/m^3 \cdot (50km/h)^2 \cdot 30dm^2 \cdot \frac{0.74^2}{\pi \cdot 5.63 \cdot 0.8} \tag{16}$$
$$= 1.34N \tag{17}$$

The induced drag increases when the plane flies at a high angle of attack with a slow speed compared to a high speed flight with a low angle of attack.

1.3.3 Fuselage drag

The fuselage is assumed to look like a typical fuselage with a with diameter d and a length l where length is at least 3 times larger than the diameter. The zero lift drag calculation is based on the drag of a flat plate with skin friction coefficient C_f [7][p. 302].

$$C_f = \frac{0.074}{Re^{0.2}} \tag{18}$$
$$= \frac{0.074}{840000^{0.2}} \tag{19}$$
$$= 0.0049 \tag{20}$$

The Reynolds number Re is referred to the length of the fuselage for this calculation. Chapter 2 describes the calculation of Re with respect to the wing. With a length of 80cm and a speed of 15 m/s, the resulting Reynolds number is 840000. The skin friction coefficient C_f is therefore 0.0049. The drag of the fuselage the depends on the surface area of the fuselage. I estimate the surface area from the area of a cylinder with a diameter of 12cm with $A_{fuselage} = 2\pi rl = 6.28 \cdot 0.06 \cdot 0.8m^2 = 0.3m^2$.

$$D_{fuse} = C_f \frac{1}{2}\rho V^2 \cdot A_{fuselage} \tag{21}$$
$$= 0.0049 \frac{1.2kg/m^3}{2} \cdot (50km/h)^2 \cdot 0.3m^2 \tag{22}$$
$$= 0.17N \tag{23}$$

Raymer states equivalent skin friction coefficients for different plane configurations in [8][p. 280]. For a clean supersonic aircraft he states 0.0025 and for a prop seaplane 0.0065. The drag coefficient of the fuselage can be referenced to the wing area as shown in equation 25.

$$C_{D,fuse} = C_f \frac{A_{fuselage}}{A_{wing}} \tag{24}$$
$$D_{fuse} = C_{D,fuse} \cdot \frac{1}{2}\rho V^2 \cdot A_{wing} \tag{25}$$

To account for the drag of the elevator, wing fuselage interaction and other unknowns I use a drag coefficient for the fuselage $C_{D,fuse}$ which is 3 times higher than calculated, i.e. $C_{D,fuse} = 0.0147$.

1.3.4 Total drag for the X-UAV Mini Talon

The total drag is the sum of the drag of the wing ($= D_p + D_{ind}$) and the drag of the fuselage as stated in equation 27.

$$D_{total} = D_p + D_{ind} + D_{fuse} \tag{26}$$
$$= 0.6N + 1.34N + 3 \cdot 0.17N = 2.45N \tag{27}$$

For a non accelerated flight, this drag force is equal to the thrust. Energy is force times distance and power is energy per time. This translates to a power for the thrust as given in equation 28.

$$P = \frac{W}{t} = \frac{D_{total} \cdot s}{t} = D_{total} \cdot V = (2.45N \cdot 50km/h) = 34W \tag{28}$$

This power is the mechanical power that needs to be provided by the propeller. The required electrical power depends on the overall efficiency of the propulsion system. A typical efficiency estimate is 50 percent. That results in an electrical power of 68W. Note that this is just an example calculation for an assumed angle of attack of seven degrees and a speed of 50 km/h.

1.4 Level Flight reloaded

The previous section showed that lift depends on the speed through air, the angle of attack of the wing and the mechanical design of the plane. Level flight means that the weight has to be compensated by the lift. The speed and the angle of attack define the lift force. For level flight for each speed there is a corresponding wing angle. Increasing the angle of attack increases the lift coefficient. We saw that at 7 degrees at 50 km/h, the lift force was 25.7N while the 2kg mass required a lift force of 20N. Flying with 7 degrees at 50 km/h is not a level flight situation but the plane would accelerate. For level flight the weight F_w of the plane must be compensated by the lift L as shown in equation 1 and the thrust compensates the drag D as given in equation 2. The lift equation 3 then results in equation 30.

$$F_w = L \tag{29}$$

$$mg = C_L \frac{1}{2} \rho V^2 \cdot A \tag{30}$$

The lift coefficient C_L is a function of the angle of attack as shown in figure 7. For a given weight you can choose a certain angle of attack together with a speed that will exactly compensate the weight force F_w. If you fly very slow, then you need a high angle of attack to generate enough lift to keep the plane in the air. At a very high speed you need a very low lift coefficient C_L. The drag then results from your chosen combination of angle of attack and speed. In steady flight with no acceleration the drag must be compensated by the thrust of the propeller. The work that will be consumed is this drag force multiplied by the distance s as shown in equation 31.

$$W = D \cdot s \tag{31}$$

If you want to maximize the distance s that you can travel with given energy E, then you need to minimize the drag. The maximum range is achieved at that point where the drag is minimal. As both lift and drag are proportional to the square of the speed V^2, changing speed will impact the drag and lift forces by the same factor. What you want to achieve is the minimum possible drag for a given lift. For that you have to choose the angle of attack where the C_L/C_D relation is maximum. Figure 3 shows C_L/C_D versus the angle of attack. C_D is the total drag including profile drag, induced drag and fuselage drag. The angle is the angle of attack including induced angle due to the finite wing.

The maximum for C_L/C_D is at 5 degrees angle of attack. The lift coefficient C_L at 5 degrees is 0.6 while the total drag coefficient C_D is 0.057. The lift to drag ratio C_L/C_D is 10.75.

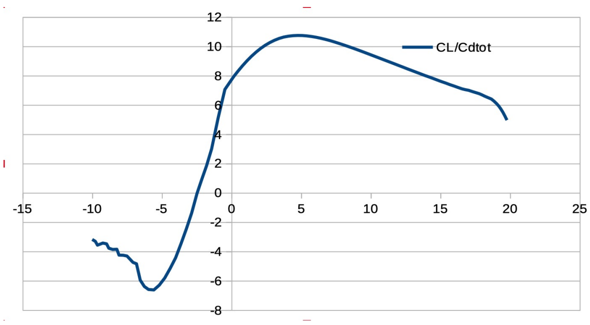

Figure 8: C_L/C_D vs. angle of attack

Now lets do some example calculation for the X-UAV Mini Talon with a total weight of 2kg. The angle of attack must be 5 degrees for maximum range. For a given lift coefficient and a given weight the resulting speed is given in equation 35

$$F_w = L \tag{32}$$

$$mg = C_L \frac{1}{2} \rho V^2 \cdot A \tag{33}$$

$$\Leftrightarrow V^2 = \frac{2mg}{C_L \rho A} \tag{34}$$

$$\Leftrightarrow V = \sqrt{\frac{2mg}{C_L \rho A}} \tag{35}$$

The lift coefficient C_L is related to the angle of attack of the wing. Figure 9 shows the required velocity of the plane for a weight of 2kg versus the angle of attack of the plane.

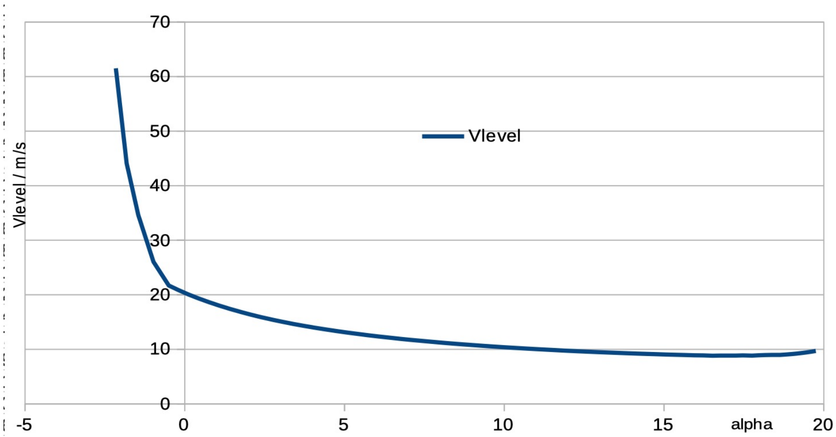

Figure 9: Velocity V for level flight vs. angle of attack

For a low speed a high angle of attack is required. Figure 10 shows the required power not including the loss of the propulsion system for different speeds. With increasing speed, the power increases dramatically. At 100 km/h the required power is approximately 100 W. So with 50 percent efficiency this means 200W electrical power from the battery. The minimum

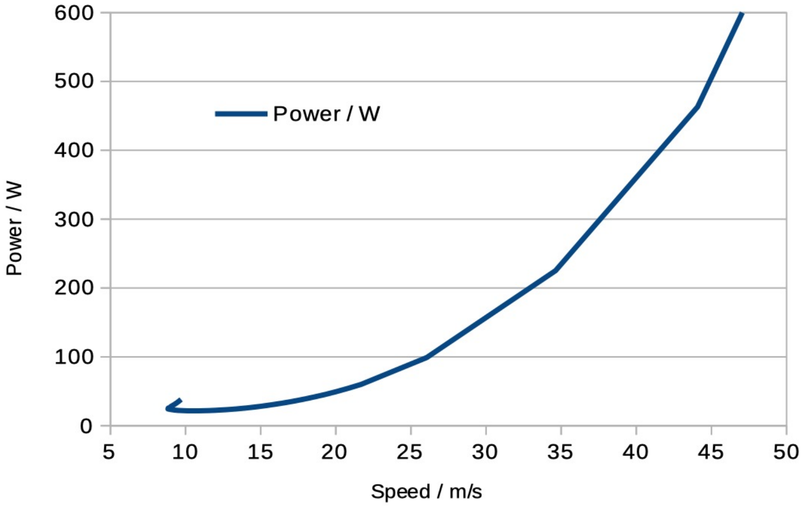

Figure 10: Power vs. speed

speed of 8,9 m/s is at an angle of attack of 17 degrees which yields the maximum lift coefficient of 1.39. The maximum range is at the angle of attack of 5 degrees where the lift to drag ratio is maximum at 10.75 with a lift coefficient of 0.6.

$$V = \sqrt{\frac{2mg}{C_L \rho A}} \tag{36}$$

$$V = \sqrt{\frac{2 \cdot 2kg \cdot 9.81m/s^2}{0.6 \cdot 1.2kg/m^3 \cdot 0.3m^2}} \tag{37}$$

$$V = 13.4m/s = 48km/h. \tag{38}$$

The optimum speed for level flight is given in equation 38 at 48 km/h at an angle of attack of 5 degrees. The resulting drag derived from equation 27 is given in equation 40. The drag coefficient for the wing is 0.0156 from figure 3 for the angle of attack of five degrees. The drag coefficient of the fuselage is again estimated with 0.0147.

$$D_{total} = \frac{1}{2}\rho V^2 A_w (C_{D,p} + C_{D,ind} + C_{D,fuse}) \tag{39}$$

$$= \frac{1}{2}\rho V^2 A_w (0.0156 + \frac{C_L^2}{\pi \cdot AR \cdot e} + 0,0147) \tag{40}$$

$$= \frac{1}{2} 1.2kg/m3 \cdot (48km/h)^2 \cdot 0.3m^2 \cdot (0.0156 + \frac{0.6^2}{\pi \cdot 5.63 \cdot 0.8} + 0.0147) \tag{41}$$

$$= 1.8N \tag{42}$$

The resulting distance derived from equation 31 is then shown in equation 44 for a given battery capacitance of 148 Wh.

$$
\begin{aligned}
s &= \frac{W}{D} && (43)\\
&= \frac{148Wh}{1.8N} && (44)\\
&= \frac{148W3600s}{1.8N} && (45)\\
&= 296km && (46)
\end{aligned}
$$

The mechanical power after the propeller to compensate the drag for flying in maximum range mode is given in equation 49.

$$
\begin{aligned}
P &= D \cdot V && (47)\\
&= 1.8N \cdot 48km/h && (48)\\
&= 24W && (49)
\end{aligned}
$$

With an efficiency of the propulsion system of 50 percent, the estimated range reduces to 148 km and the power for level flight increases to 48 Watt.

1.5 Weight

If everything remains the same but the weight of the plane changes, then parameters like required power, range and speed for maximum range are affected.

$$
\begin{aligned}
L_{new} &= L_{old}\frac{m_{new}}{m_{old}} && (50)\\
D_{new} &= D_{old}\frac{m_{new}}{m_{old}} && (51)\\
V_{new} &= V_{old}\sqrt{\frac{m_{new}}{m_{old}}} && (52)\\
Range_{new} &= Range_{old}\frac{m_{old}}{m_{new}} && (53)\\
P_{new} &= P_{old}(\frac{m_{new}}{m_{old}})^{\frac{3}{2}} && (54)
\end{aligned}
$$

Table 1 shows the optimum speed for maximum range, the range and the required power for level flight for the optimum speed for different weights of the plane. Increasing the weight of

Table 1: Impact of changed weight of the plane

Parameter/Weight	1.5 kg	2 kg	2.5 kg
V / m/s	11.6	13.4	15
Range / km	185	148	110
Power / W	31	48	67

the plane from 2 kg to 2.5 kg will reduce the range from 148 km to 110 km. The required power during level flight will increase from 48 W to 67 W because the drag increased from 1.8 N to 2.3 N while the speed increased from 13.4 m/s to 15 m/s.

1.6 Speed

The previous sections showed that the optimum speed is given by the angle of attack that will yield the maximum lift to drag ratio. For this plane the optimum speed is 13.4 m/s. If the speed is changed, the range will be reduced. Figure 11 shows the range of the plane versus

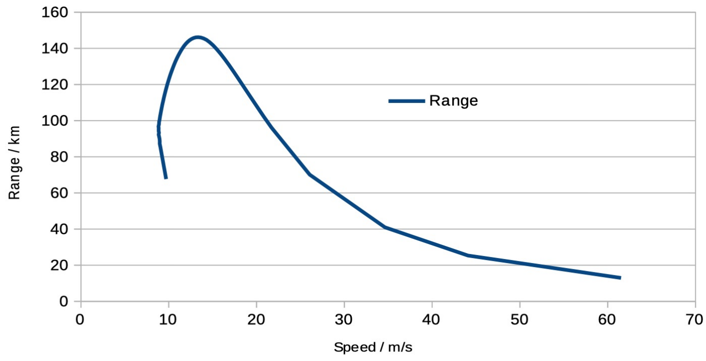

Figure 11: Range vs. speed

speed of the plane. The maximum range of 148 km is possible with an airspeed of 13.4 m/s (= 48 km/h). At 100 km/h the range reduces to 70 km. For minimum speed of 9 m/s with the angle of attack giving the maximum lift coefficient the range reduces to 90 km.

Equation 35 with the condition for level flight can also give the required lift coefficient for a given speed as shown in equation 58.

$$F_w = L \tag{55}$$

$$mg = C_L \frac{1}{2} \rho V^2 \cdot A \tag{56}$$

$$\Leftrightarrow C_L = \frac{2mg}{\rho V^2 A} \tag{57}$$

$$\tag{58}$$

If this expression for the lift is used in equation 40 to replace the lift coefficient in the expression for the induced drag, then the total drag can be expressed as a function of speed.

$$D_{total} = \frac{1}{2} \rho V^2 A_w (C_{D,p} + C_{D,ind} + C_{D,fuse}) \tag{59}$$

$$= \frac{1}{2} \rho V^2 A_w (C_{D0} + (\frac{2mg}{\rho V^2 A_w})^2 \frac{1}{\pi \cdot AR \cdot e}) \tag{60}$$

$$= \frac{1}{2} \rho V^2 A_w C_{D0} + (\frac{2}{\rho V^2 A_w} \frac{(mg)^2}{\pi \cdot AR \cdot e}) \tag{61}$$

$$= D_0 + D_{ind} \tag{62}$$

This calculation assumes that drag coefficients for the wing and the fuselage are not a function of the angle of attack. The fuselage drag is already modelled as constant. The drag coefficient of the wing was previously taken from the xfoil simulation. I take the drag coefficient from the previous optimum angle of attack. Then $C_{D0} = C_{D,p} + C_{D,fuse} = 0.0156 + 0.0147 = 0.03$

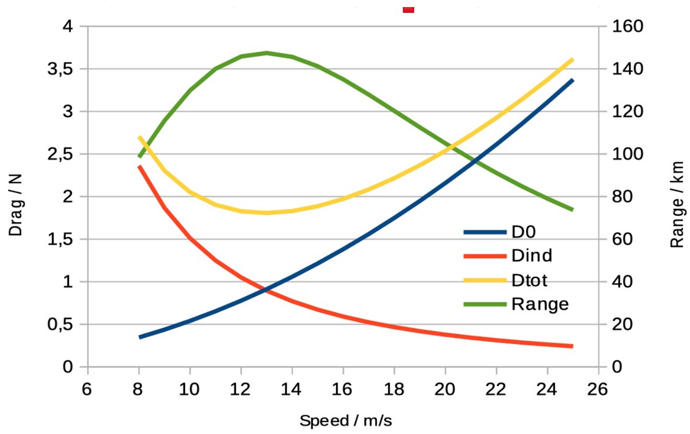

Figure 12: Drag and Range vs. speed

is not a function of angle of attack. The induced drag is proportional to $\frac{1}{V^2}$ and the profile drag D_0 is proportional to V^2.The range of the plane is calculated with equation 44. Figure 12 shows this relation of induced drag, profile drag, total drag and range as a function of speed. The minimum drag with the maximum range is at the point where induced drag and profile drag is equal. Looking at the drag plot for the wing from xfoil simulation in figure 3 then the assumption of constant drag coefficient is especially wrong for the high angle of attack range, i.e. for the low speed situation. This is also visible when figure 12 is compared with figure 11 where the profile drag as a function of angle of attack is included in the analysis.

1.7 Profile drag

In the previous chapter a constant profile drag $C_{D0} = C_{D,p} + C_{D,fuse}$ with an value of 0.03 was introduced. This parameter combines the skin friction drag for the fuselage and the wing plus the pressure drag for the wing. The skin friction and pressure drag was taken from the xfoil simulation results. The fuselage skin friction was estimated. Figure 13 shows the drag and

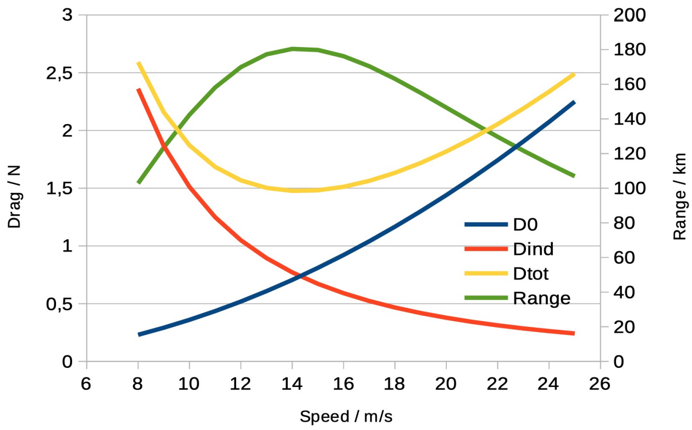

Figure 13: Drag and Range vs. speed for $C_{D0} = 0.02$

range versus speed for a changed profile drag of 0.02. The optimum speed increases to 14 m/s.

The range increases to 180km due to the reduced drag. Figure 14 shows the drag and range

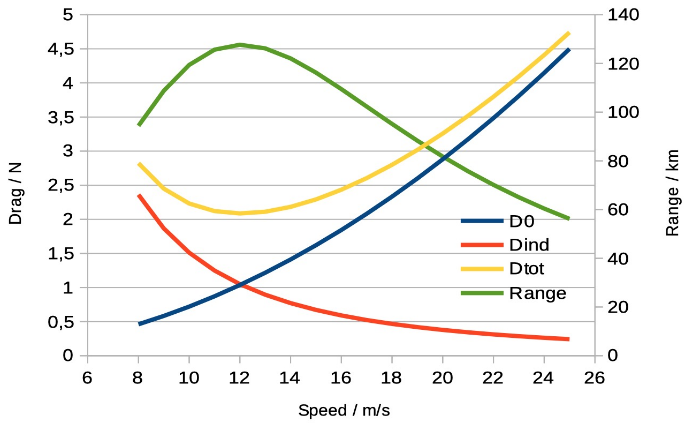

Figure 14: Drag and Range vs. speed for $C_{D0} = 0.04$

versus speed for a changed profile drag of 0.04. The optimum speed reduces to 12 m/s. The range reduces to 127 km due to the increased drag. Table 2 shows the impact of changed drag.

Table 2: Impact of changed drag of the plane

Parameter/C_{D0}	0.02	0.03	0.04
V / m/s	14	13.4	12
Range / km	180	148	127
Power / W	42	48	50

When the drag is reduced, the speed for optimum range increases together with the range. The power requirement for level flight at optimum speed with an assumed propulsion efficiency of 50 percent decreases.

2 Reynolds number

The Reynolds number is a number that relates the size of a physical object, i.e. here the wing chord, to the properties of (here) air [1, p. 431, Appendix 2]. Equation 63 shows how the Reynolds number Re relates to the air speed and the properties of air.

$$Re = \frac{\rho \cdot V \cdot l}{\mu} \tag{63}$$

In equation 63 ρ is the density of air and μ is the viscosity of air (typ: $1.7 \cdot 10^{-5}$ kg/ms) [5, p. 1]. l is the chordlength of the wing. With these numbers the Reynolds number for the X-UAV Mini Talon at a speed of 7 m/s with a chord lengh of 20 cm is shown in equation 64.

$$Re = \frac{\rho \cdot V \cdot l}{\mu} = \frac{1.2kg/m^3 \cdot 7m/s \cdot 0.2m}{1.7 \cdot 10^{-5} kg/ms} = 98800 \tag{64}$$

So the mini talon is operating in a Reynolds number regime of approx. 100000 already at low speeds of about 25 km/h. With increasing speed, the Reynolds number increases linearly. At 100 km/h the Reynolds number for the Talon is approx. 400000.

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