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A Performance Review of a High Altitude Long Endurance Drone

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Abstract – In this study, a performance review on a high altitude long endurance (HALE) drone which can operate at high-altitude as high as 19.81 km (65000 ft) and can fly typically more than 24 hours was done. General methodology for calculating aircraft performance was presented with an example on an unmanned aerial vehicle (UAV) which is in service today. Maximum endurance and range of UAV were calculated in an interval of 9-16 km flight altitude and 0.35-0.75 flight Mach number. A basic mission profile was chosen for the UAV which is one of the most important design inputs in aircraft design. While the aircraft is designed according to the requirements (payload, range, cost, etc.), mission profile parameters such as altitude and cruising speed of the aircraft are the keys for the selection of engine type. A turbofan engine performance model was used to predict the endurance and range of UAV. The engine performance model gives the output for fuel consumption and thrust which are necessary for endurance and range and also for checking if there is enough thrust to overcome the aerodynamic drag at a given flight speed and altitude. The results were presented as a guide for engineering students, performance engineers and UAV designers in a step by step approach.

Keywords – Unmanned Aerial Vehicle, Aircraft Performance, Engine Performance, Endurance, Range

I. INTRODUCTION

UAVs have increased their use, versatility and variety in many areas of civil and military applications. UAV can be defined as "An aircraft which is designed or modified, not to carry a human pilot and is operated through electronic input initiated by the flight controller or by an onboard autonomous flight management control system that does not require flight controller intervention." Therefore, UAV is an aircraft which can autonomously fly or can be remotely controlled to perform a specific mission without flying crew inside. Missiles or one time use air vehicles are not considered as UAVs. Unmanned air vehicles have a lot of varieties including micro, tactical, strategical and combat types [1]. UAV types cover a wide range in terms of size, weight, altitude, speed, endurance and range, the general classification of UAVs are given in Table I.

The suitability of UAVs in "dull, dirty and dangerous" missions increases the success of UAVs in service and demonstration. Examples of these missions include: border & costal patrol and monitoring, homeland security, combat, law enforcement & disaster operations, digital mapping & planning/land management, search & rescue, fire detection and firefighting management, communications and broadcast services, precision agriculture and fisheries, ground transportation monitoring and control, satellite augmentation systems, air traffic control support, power transmission line monitoring, environmental research & air quality, management/control [2]

In the 1990s NASA led a program, with industry partners, to develop technologies to assist a fledgling UAV market. This effort brought the potential of a commercial UAV market into focus. Continuing work developed from that effort seeks resolution of major technological and policy impediments that restrain the development of these aircraft to their full potential. The nine-year long NASA program, called Environmental Research Aircraft and Sensor Technology (ERAST), helped to redefine UAV technology with research on engines, sensors and integrated vehicles that would conquer the barriers to high altitude, long-endurance (HALE) aircraft. In parallel, US Department of Defense has issued several roadmaps for developing and employing UAVs in the next 20-30 years ahead of time [3][4][5]. In literature there is a lot of studies for further reading on UAVs [6][7][8].

Engines of various types and sizes (power) are used to propel aircraft and make them fly. In general, propulsion systems provide propulsion by pushing atmospheric air or gases in the opposite direction of motion after a combustion process.

TABLE I. GENERAL CLASSIFICATION OF UNMANNED AIR VEHICLES [1]

No	Class	Mass (lb)	Size (m)	Operating Altitude (ft)	Range (km)	Endurance (h)
1	Micro	< 0.2	< 0.10	< 50	0.1-0.5	< 1
2	Mini	0.2-1	0.10-0.30	< 100	0.5-1	< 1
3	Very Small	2-5	0.30-0.50	< 1000	1-5	1-3
4	Small	5-20	0.5-2	1000-5000	10-100	0.5-2
5	Medium	100-1000	5-10	10000-15.000	500-200	3-10
6	Large	10000-30000	20-50	20000-40000	1000-5000	10-20
7	Tactical/combat	1000-20000	10-30	10000-30000	500-2000	5-12
8	MALE	1000-10000	15-40	15000-30000	20000-40000	20-40
9	HALE	> 5000	20-50	50000-70000	20000- 40000	30-50

Engine type and power level is done according to the mission or the aircraft flight profile. Engine selection process is similar for unmanned and unmanned aerial vehicles and it is based on mission profile. Essentially, engines must provide enough power or thrust at a given flight speed and altitude with the least amount of fuel consumption and engine weight. For a given distance to fly or endurance on the air, total amount of required fuel depends also on engine type due to different fuel consumption levels. Fuel weight eventually affects the gross weight and also overall dimensions of the aircraft. Certain types of engines are favorable and common in a power range and are impractical or inefficient outside this range. The general engine types include electric, piston, wankel, gas turbines (turbojet, turbofan, turboprop and turboshaft), ramjet, pulsejet, scramjet, rocket etc. Each engine type cannot be used efficiently in all flight speed and altitude range. In other words, there is an efficient speed and altitude interval for each engine type for best performance.

II. Aircraft Performance

Calculations are needed to estimate if an aircraft to accomplish the requirements set forth in the mission profile. For instance, ability to take off and land, carry payloads, fly at required altitudes at speeds, maneuvers, endurance and range, aerodynamic lift and drag etc. are estimated as a part of flight performance calculations. Flight duration, endurance and range can be estimated using equations below [9][10][11]:

$$R_F = R_{CL} + R_{CR} + R_D \quad (1)$$

$$t_F = t_{CL} + t_{CR} + t_D \quad (2)$$

$$t_B = t_F + t_{GR} \quad (3)$$

$$R = \frac{V}{C}\frac{L}{D} ln \frac{W_{i-1}}{W_i} \quad (4)$$

$$E = \frac{L/D}{C} ln \frac{W_{i-1}}{W_i} \quad (5)$$

Eq(4) is the modified Breguet range formula for constant velocity and altitude for a jet aircraft. In the above equations, definitions are as follows: R, range; R_{CL}, climb distance (horizontal); R_{CR}, cruising distance or range; R_D,

the descent distance (horizontal); t_F , total flight time; t_{CL}, climbing time; t_{CR}, cruise time; t_D, duration of descent; t_B , block flight time; t_{GR} , ground maneuvers time (taxi, takeoff and landing); V, the speed of the plane, C, specific fuel consumption; L, lift force; D, drag force; W, aircraft weight and η_p is propeller efficiency. It can be noted from Figure 1 that, the velocities required for maximum endurance and maximum range are different. Typically, velocity for maximum range is higher than the velocity for maximum endurance.

For the aerodynamic lift and drag force calculation, the below generic formulas are used:

$$L = \frac{1}{2}\rho V^2 c_l S \quad (6)$$

$$D = \frac{1}{2}\rho V^2 c_d S \quad (7)$$

Lift force formula consists of air density (ρ), flight speed (V), lift coefficient (c_l) and wing area (S). It is normally assumed that lift force equals to the instantaneous weight of UAV, during cruise and loiter. At a given speed and altitude of UAV, lift coefficient can be calculated with the below formula:

$$c_l = \frac{2W}{\rho V^2 S} \quad (8)$$

Drag force calculation is similar to lift formula, except that it has drag coefficient. Drag coefficient (c_d) has two parts, namely parasite (zero lift) drag (c_{d_0}) and lift-induced drag:

$$c_d = c_{d_0} + \frac{c_l^2}{\pi ARe} \quad (9)$$

$$c_{d_0} = c_{f_e}\frac{S_{wet}}{S} \quad (10)$$

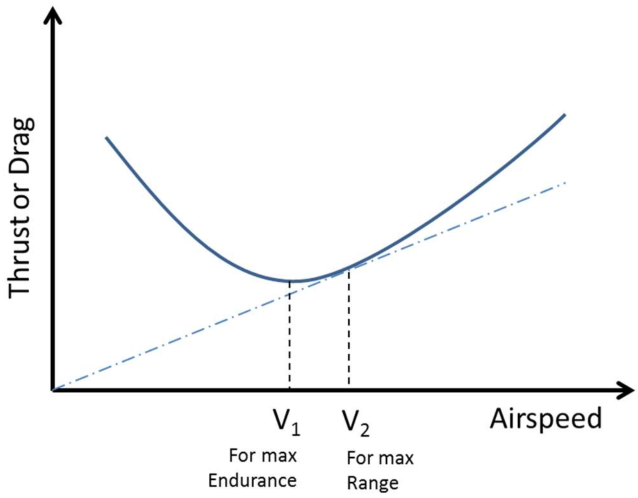

Fig. 1. General range conditions for jet aircraft [12]

In above equations, c_{d_0}, parasite (zero lift) drag coefficient; c_{f_e}, equivalent skin friction coefficient; Swet, total wet area of UAV; S, wing area; c_d, drag coefficient; AR, aspect ratio; e, Oswald efficiency.

After calculating lift and drag forces, it is important to estimate the maximum lift-to-drag ratio (L/D) to achieve maximum endurance per Eq(5).

$$c_{d_0} = c_{f_e}\frac{S_{wet}}{S} \quad (10)$$

$$\left(\frac{L}{D}\right)_{max} = \frac{1}{2\sqrt{\frac{c_{d_0}}{\pi ARe}}} = \frac{1}{2\sqrt{c_{d_0}k}} \quad (11)$$

$$c_{l_{(L/D)max}} = \sqrt{\pi ARec_{d_0}} = \sqrt{\frac{c_{d_0}}{k}} \quad (12)$$

$$k = \frac{1}{\pi ARe} \quad (13)$$

III. Case Study

In this study, `Global Hawk` UAV was selected as a model. `Global Hawk` UAV is the world's first fully autonomous HALE unmanned aerial system providing persistent intelligence, surveillance and reconnaissance to warfighters, the Global Hawk is designed to fly up to 19.81 km (65,000 feet) for more than 35 hours and see through any inclement weather at any time [13].

In this study, two main performance parameters were investigated which are maximum endurance and maximum range. The calculations were done using a genuine computer code. The computer code calculates not only aircraft performance, but also turbofan engine performance parameters such as thrust specific fuel consumption and thrust force [14]. The `Global Hawk` UAV uses Rolls-Royce AE 3007 turbofan engine [15] and therefore this engine was modeled in the computer code as well.

Fig. 2. Global Hawk unmanned air vehicle [16]

For maximum endurance, the computer code was run for different airspeed and altitude. Results were plotted in Figure 3 in the interval of airspeed 0.35-0.75 Mach and altitude 9-16 km. It was found that maximum endurance is 35.25 at an altitude 11 km and 0.35 Mach.

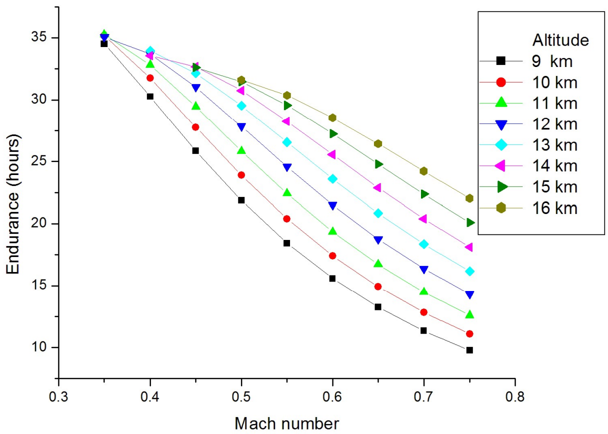

Fig. 3. Calculated endurance for UAV

Alternatively, maximum endurance can be calculated using Eq (5) and the input data set is given in Table II. The maximum endurance value found (35.25 h) was compared with literature value of 35 h in Table IV and it is a close value a deviation of 0.5%.

$$E = 28.3257 \frac{L/D}{C} ln \frac{W_{i-1}}{W_i} \qquad (5)$$

$$= 28.3257 * \frac{31.85}{18.61} * ln \frac{11794}{5698} = 35.25 \text{ h}$$

Additionally calculated lift to drag ratio and thrust specific fuel consumption (installed) were plotted in Figure 4-5.

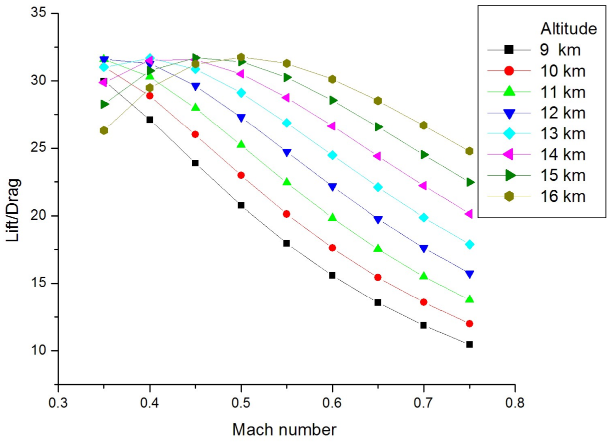

Fig. 4. Calculated lift to drag ratio for UAV

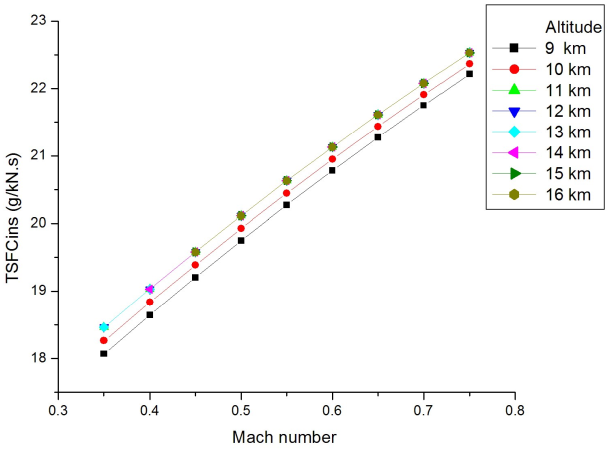

Fig. 5. Calculated thrust specific fuel consumption (installed)

TABLE II. INPUT DATA SET FOR MAX ENDURANCE

Parameter	Value*	Unit
AR, aspect ratio	25	
e, Oswald efficiency	0.75	
S_{wet}, total surface wet area	185.93	m^2
S, wing area	50.29	m^2
c_{fe}, equivalent skin friction coefficient	0.0035	
W_{i-1}, UAV weight at cruise start	11794	kg
W_i, UAV weight at cruise end	5698	kg
C, installed specific fuel consumption	18.61	gr/(kN.s)
h, cruise altitude	11	km
V, cruise flight speed	371.8	km/h
L/D, lift to drag ratio	31.85	

*source [17]

As a second step, the computer code was run in order to find the maximum range for the UAV. The results are shown in Figure 6. Maximum range was calculated to be 18618 km which is within a 0.5% deviation from literature value of 18520 km as shown in Table IV.

Alternatively, maximum range can be calculated using Eq (13) and the input data set is given in Table III. For an aircraft which has a jet engine (not propeller), maximum range occurs at a speed which is not at L/D_{MAX}, it will be at a higher speed.

$$R = 28.3257 \frac{V}{C}\frac{L}{D} ln \frac{W_{i-1}}{W_i} \quad (13)$$

$$= 28.3257 * \frac{690.5}{21.19} * 28.53 * ln \frac{11555}{5698} = 18618 \text{ km}$$

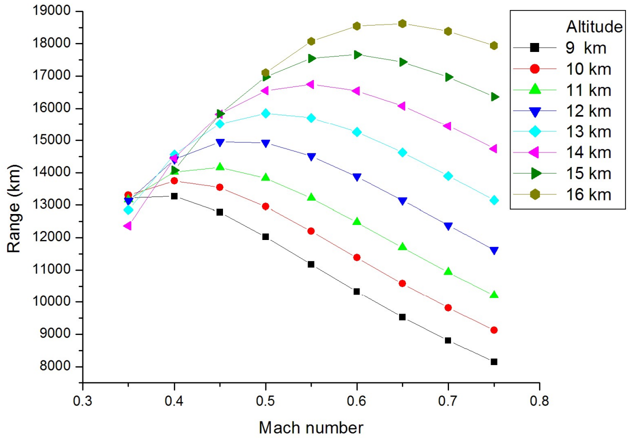

Fig. 6. Calculated range for UAV

TABLE III. INPUT DATA SET FOR MAX RANGE

Parameter	Value*	Unit
AR, aspect ratio	25	
e, Oswald efficiency	0.75	
S_{wet}, total surface wet area	185.93	m^2
S, wing area	50.29	m^2
c_{fe}, equivalent skin friction coefficient	0.0035	
W_{i-1}, UAV weight at cruise start	11555	kg
W_i, UAV weight at cruise end	5698	kg
C, installed specific fuel consumption	21.19	gr/(kN.s)
h, cruise altitude	16	km
V, cruise flight speed	690.5	km/h
L/D, lift to drag ratio	28.53	

*source [17]

TABLE IV. COMPARISON OF RESULTS

Specifications	Literature value*	Calculated value	Deviation (%)
Ferry Range (km)	18520	18618	0.5
Maximum Endurance (hour)	35	35.25	0.7

*source [16]

IV. CONCLUSION

In this study, a performance review on a high altitude long endurance (HALE) `Global Hawk` UAV was done. Steps and general equation were given for calculating aircraft performance. Main aircraft performance parameters were calculated in an interval of 9-16 km flight altitude and 0.35-0.75 flight Mach number. Additionally, lift to drag ratio and thrust specific fuel consumption (installed) were plotted for the same range. The results and methodology can be used by engineering students, performance engineers and UAV designers as a guide.

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