Conceptual Design Approach of Agricultural Aircrafts

Nidhi Sharma[1], Dr. K Tamil Manna[2]
Corresponding author email: nid.sharma83@gmail.com
[1] Research Scholar, Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi
[2] Associate Professor,School of Engineering and Technology,IGNOU,New Delhi

Abstract- The paper summarises the conceptual designing approach of an agricultural aircraft intended to use for agricultural industry needs. The agricultural aircraft flies at a very low altitude for most of the part of their flight time. Their designing is critically important to maintain a very little room for errors. The proposed design is efficiently workable in highly variable loading conditions also.

Keywords- Agriculture; Altitude; Aviation;Drag;Lift

1. Introduction

The transportation of people, equipment, cargo or different article through aviation mode is a most prominent method. The latest designing approaches to creating aircrafts of various size, shape and operational capabilities are making them suitable to be used in different sectors, i.e., agricultural, other than transportation. Aircrafts are becoming an important element of the burgeoning agricultural industry. The use of agricultural aircrafts is generally for crop dusting, fertilizer spraying, spreading insecticides, topdressing and hydro-seeding. There is a need to increase efficiency, cost-effectiveness, environmental compatibility and safety of such aircrafts. To inculcate the prerequisite, the designing and operational capabilities needed to modify of an existing aircraft. The inherent capabilities of an original design are a hurdle to modify the existing aircraft as per requirement and also it is not cost effective. Under these circumstances, it is necessary to consider invitations of the design of the new aircraft. In this paper, a conceptual designing for an agricultural aircraft is proposed.

Literature Survey

The agricultural industry is using helicopters and fixed-wing aircrafts, i.e., Air tractors for its various uses [1]. The most commonly used of aircraft is crop and insecticides dusting. It first started in the 1920s, when in the United States a war-surplus biplane named Stearman and De Havilland Tiger Moth was converted in agricultural aircraft to be used for crop dusting. In the 1940s, in New Zealand fixed-wing, purpose-built agricultural aircraft was developed which were effective insecticides and fungicides and aerial top-dresser [2]. Now the US and Europe have developed the small, rugged and useful aircrafts. These have many operational capabilities such as wings with spraying system and wind turbine operated pumps. The agricultural aircrafts have been designed for larger farms also, typically to be used in New Zealand, Australia. Such aircrafts are turboprop powered, i.e., PAC Cresco or consisting twin-engine, i.e., Lockheed [3]. The helicopters have also been modified for hydro-seeding through its tanks and drop system similar to aerial firefighting. For using a helicopter for agricultural use, tanks are attached on or outside its body, and a spray rig is attached sufficiently below the main rotor blade which extends outward to the sides[3].

Some major examples of agricultural aircraft

India has also developed some agricultural aircrafts mainly designedHindustan Aeronautics. In 1968 HAL-31 Mk I was designed, in which cockpit was directly attached to the wing leading edge. It was modified to Hindustan HA-31 Basant in the 1970s. Its further development led to HA-31 Mk II Basant, and it first flew on the 30 March 1972. Basant generates 400 hp (298 kW) through its Avco Lycoming IO-720 piston engine, and it consists fixed tail-wheel landing gear. Basant is low-wing monoplane which is a conventionally braced, with a raised cockpit enable to give the pilot a good view from all sides during the spraying operations. In the 1980s the production of Basant stopped after building 39 aircrafts [4].

The Hongdu N-5 is a Chinese agricultural aircraft first flown in 1982. It consists only one engine, and it is low wing monoplane. It is available in versions powered by a piston engine or a turboprop [5]. The AT-401B is a rugged, durable air tractor aircraft. It is designed for clean aerodynamics, install with major safety features, ease of operational performance and an economical piston engine plane. It is capable for a 400-gallon workhorse powered by the Pratt and Whitney R-1340 radial engine [6].

The AT-502 A/AT-502 B has a big 500-gallon payload, so fewer trips out and back, fewer landing and takeoffs needed. It posses wider swaths of 52 ft wingspan [7].

The AT-602 is designed for operators needing more than 500 gallons, but less than the 800 gallon AT-802. It is faster aircraft which takes just one load to spray a 125-acre circle at 5 gallons per acre. The inbuilt powerful PT-60AG engine shortened the ferry times [8].

The fire fighters are also finding their place in the agricultural industry and providing another dimension to their capabilities such as AT-802F "Fire Boss." It is capable of scooping 820 gallons of water in 30 seconds and comes back to its position in just a minute. It is a land-based aircraft or a scooper. It can drop an initial load of retardant then remain close to the fire by scooping water from a nearby lake [9].

2. Design requirements

The requirement explored that the aircraft must be capable of flying at very low altitude such as 10 m from the ground. It is to be designed for a maximum speed of 250 km/hr, a range of 500 km, and payload of 600 kg. The gross weight of aircraft is to be considered as 2267 kg. The specific fuel consumption may be considered 0.12 kg/kW-hr. For wing layout design the span, wing area and taper ratio 12.67 m, 24.67 m2 and 0.45 may be considered. For the horizontal and vertical tail layout the area, taper ratio, span and volume coefficient should be considered as 4 m2, 0.45, 4.266 m and 0.50 and 0.95 m2, 0.8, 1.46 m and 0.04 respectively. The diameter of the fuselage may be considered 4.1 m. The typical power loading for an agricultural aircraft is 11. All such data is assumed through a historical approach.

3. Design Methodology

Agricultural flying differs in many aspects from other commercial flights. First of all, it is generally executed at a very low altitude for the greater part of the flight, allowing very little room for error. In case of a manned aircraft, the pilot has to fly with constant and intense attention during operational flight. Another influence of this low altitude flight is the effect of wind and turbulence. The change of wind speed with height is much more noticeable near to the ground. This gradient of wind affects airplane performance directly. The second aspect of agricultural aviation is the highly variable loading conditions. The weight of aircraft and its center of gravity can vary considerably in short time span. This brings a need for frequent re-trimming to keep control forces constant. The technique for take-off and landing on a short field is also different than it is on commercial flights. Both the ambient temperature and the elevation of the field have effects on performance. [10]

The conceptual designing of agricultural aircrafts may be done in five steps

- Identification of aircraft's designing parameters
- Establishment of aircraft's design requirement
- Determination of geometrical parameters
- Determination of performance parameters
- Aircrafts layout design

4. Designing parameters

The various geometrical aspects of sizing from a conceptual design are as follows:

(i) Takeoff-Weight buildup
(ii) Empty-Weight Estimation
(iii) Fuel Fraction Estimation
(iv) Mission Segment Weight Fractions
(v) Specific Fuel Consumption
(vi) Lift to drag ratio estimation

The aspects of performance from a conceptual design are as follows:

(i) Power

(ii) Wing loading

(iii) Stall speed

(iv) Take off distance

(v) Landing distance

For designing layout of the aircraft following parameters need to be estimated:

(i) Wing layout

(ii) Tail volume coefficient

(iii) Tail layout

(iv) Fuselage layout

5. Geometric parameter estimation

Total weight of aircraft is named "Design takeoff gross weight." It is a sum of crew weight, passenger weight (payload), fuel weight and the empty weight (all other remaining weight). Empty weight consist the weight of the structure, engine, landing gear, fixed equipment, avionics, and all other weight which are not considered in the crew, payload or fuel.

The equation below summarizes the takeoff weight buildup.

$W_o = W_{crew} + W_{payload} + W_{fuel} + W_{empty}$

The empty weight fraction (We/Wo) can be estimated statistically from historical trends [11], as shown in Fig.1.

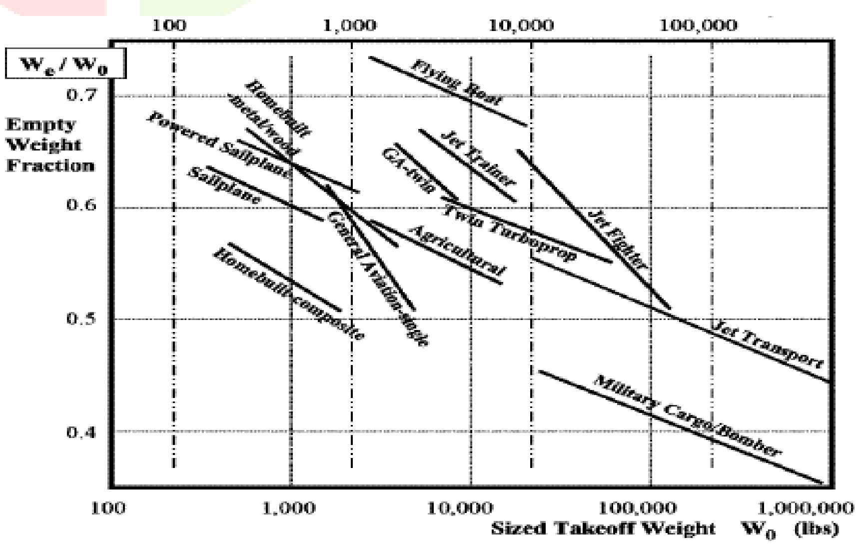

Fig.1 Empty weight fractions

Only a part of aircraft's fuel is available for performing the mission. The other fuel is reserved or "trapped fuel" which cannot be pumped out of the tanks. The total fuel fraction assuming a 6% allowance for reserved and trapped fuel can be estimated as:

$W_f / W_o = 1.06 (1 - W_x / W_o)$

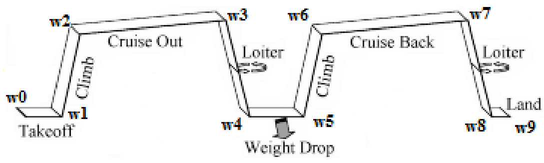

Fig.2 Agricutural aircraft's mission profile

The typical mission profile for agricultural aircrafts is shown in figure 2 above:

The warm-up, take off, landing weight fraction can be estimated historically. Table 1 gives typical historical values for initial sizing [11].

Conditions	W_i/W_{i-1}
Warm up and take off	0.970
Climb	0.985
Landing	0.995

Table 1 Historical mission segment weight fraction

The cruise segment mission weight fractions can be found using Breguet range equation:

$R = (V/C)*(L/D)max * \ln (W_{i-1}/W_i)$

The loiter weight fraction can be found using equation:

$E = (L/D)*(l/C)*\ln (W_{i-1}/W_i)$

Specific fuel consumption (SFC) is the rate of fuel consumption divided by the resulting thrust. Propeller engine SFC is normally given C_{bhp} (BHP = 550 ft-Ib/s). The engine produces thrust via propeller which has an efficiency η_p [11].

$\eta_p = TV/550 \text{ hp}$

Lift to drag ratio is the measure of the design's overall aerodynamic efficiency. This ratio majorly gets affected by the configuration arrangement. L/D majorly varies by two aspects of the design: wing-span and wetted area at subsonic speeds. In level flight lift is known, it must equal the aircraft weight. Thus, L/D is solely dependent upon drag. The aspect ratio of the wing has historically been used as the primary indicator of wing efficiency. Aspect ratio is calculated by dividing the wing reference area from the square of the wingspan. For initial design purposes, the aspect ratio can be selected from historical data. Drag varies with altitude and velocity. L/D ratio is a significant factor in determining of maintaining the efficient cruise efficiency. It is reported that the maximum cruise or loiter efficiency occurs for the highest value of the L/D ratio. For any altitude, there is a particular velocity which maximises the L/D ratio, and the cruise should operate at that velocity. The most efficient loiter speed for a propeller aircraft occurs at a slower velocity that yields an L/D of 86% of L/Dmax [11].

Type of engine	Cruise	Loiter
Jet	0.866 $(L/D)_{max}$	$(L/D)_{max}$
Propeller	$(L/D)_{max}$	0.866 $(L/D)_{max}$

Table 2 Lift to drag ratio

The tires are sized to carry a maximum weight of the aircraft. Typically the main tire carries about 95 of the total weight. Nose/aft tires carry about 10% of the static load but experience more dynamic loads during landings.

Using statistical tire sizing data

Diameter of main tire = 5.1 $(\text{wheel weight})^{0.349}$

Width of main tire = 2.3 $(\text{wheel weight})^{0.312}$

Tail tires are about a third the size of main tires.

6. Performance parameter estimation

The thrust to weight ratio (T/W) and wing loading (W/S) are two most important parameters affecting aircraft performance. T/W directly affects the performance of the aircraft. It is not a constant. The weight of aircraft varies during flight as fuel is burnt. The term "thrust to weight" is associated with jet engine aircraft. For propeller powered aircraft the equivalent term has classically been the "power loading," expressed as the weight of the aircraft divided by its horse power (W/hp).

For aircraft design primarily for efficiency during the cruise, a better initial estimate of the required T/W can be obtained by "thrust matching." Assuming thrust is aligned with the flight path, T/W must be equal to the inverse of L/D.

(T/W) cruise = 1/ (L/D) cruise

$P/W_o = aV_{max}^C$

The wing loading is the ratio of aircraft weight to the reference wing area. Wing loading significantly affects the climb rate, stall speed, landing and take off distances, therefore, the performance of aircraft also gets influenced by wing loading. The wing loading determines the design lift coefficient, and impacts drag through its effect upon its wetted area and wing span. The stall speed of an aircraft is directly determined by wing loading and maximum lift coefficient. The equation below states that lift equals weight in level flight and that at stall speed the aircraft is at maximum lift coefficient.

$W=L=q_{stall}SC_{Lmax}=½\rho V^2_{stall}SC_{Lmax}$

$W/S = 1/2\ \rho V^2_{stall}C_{Lamx}$

$V_{To}= 1.2\ V_{Stall}$

$V_{Approach}= 1.3\ V_{Stall}$

The take off parameter (TOP) is the take off wing loading divided by the product of density ratio, take off lift coefficient and take off thrust to weight ratio.

$$\text{Take off parameter} = \frac{W/S}{\sigma C_L T/W}$$

$C_L\ \alpha\ 1/V^2$

$C_L/C_{Lmax} = V^2_{Stall}/V^2_{To}$

"Landing ground roll" is the actual distance the aircraft travels from the wheels first touch to the time the aircraft comes to a complete stop. Landing distance is largely determined by wing loading. Landing distance can be calculated using the below equation.

Landing Distance $=80(W/S)\ (1/C_{Lmax}) + Sa$ (ft)

7. Layout design

Wing layout: - The geometric dimensions necessary for the layout of the reference (trapezoidal) wing or tail can be obtained by the following equations:

$b = \sqrt[2]{AS}$

$C_{Root} = 2S/b\ (1+\lambda)$

$C_{Tip} = \lambda C_{Root}$

Tail volume coefficient: - For the initial layout, historical approach is used for estimation of tail size. The primary purpose tail is to counter the moments produced by the wing. Thus tail size would be in one way related to wing size. Referring to the historical data we get

$C_{HT} = 0.50$

$C_{VT} = 0.40$

For a T-Tail configuration, five percent decrement is needed to be done in the coefficients. Tail arm for an aircraft with a front mounted propeller engine is 60 percent of the length of aircraft. The following expression may be considered to calculate vertical and horizontal tail volume area.

$$C_{VT} = \frac{L_{VT} S_{VT}}{b_W S_W}$$

$$C_{HT} = \frac{L_{HT} S_{HT}}{C_W S_W}$$

Fuselage Layout: - Fuselage length can be estimated using the following expression

Fuselage length = $a w_o^c$

Here a =4.04 and c=0.23.

8. Results

To estimate loads at different stages of mission profile, the empty weight is considered 58% of the gross weight by considering the figure 1.

(i) Load estimated

W_e	1314 kg
W_1	2199 kg
W_2	2142.4 kg
W_3	2142.4 kg

W_4	2140.15 kg
W_5	1540 kg
W_6	1517.15 kg
W_7	1500.5 kg
W_8	1497.44 kg
W_9	1489.96 kg

(ii) Fuel tank size estimated

Burnt fuel weight	177.04 kg
Trapped fuel weight	
Total fuel weight	187.6 kg
Fuel tank capacity	190 kg
Permissible crew weight	153 kg

(iii)Tires size estimated

	Main tire	Nose tire
Diameter	0.572 m	
Width	19.97 m	

Estimated performances parameters

T/W	0.09
Power	322.5 KW
W/S	91.89
V_{Stall}	29.72 Km/hr
V_{To}	1.2 V_{Stall}
$V_{Approach}$	1.3 V_{Stall}
Take of distance	136.63 ft
Landing distance	1284.65 ft

Estimated layout parameters

For wing layout	
C_{Root}	2.686 m
C_{Tip}	1.2 m
C	2.04 m
λ	2.767 m
For horizontal tail layout	
C_{Root}	1.47 m
C_{Tip}	0.6615 m
C	1.117 m
Y	0.93 m
For vertical tail layout	
C_{Root}	1.72 m
C_{Tip}	1.37 m
C	1.55 m
λ	0.35 m
For fuselage layout	
Fuselage length	8.75

9. Conclusion

Since 30 years, there hasn't been a significant advancement in the design of an agriculture aircraft in any Asian countries. Hence, there is a lot of scope for advancement in this sector. It is a tried to exploit this opportunity by designing an agriculture aircraft. The aircraft is supposed to suit the requirements of the agricultural field as variable load and low altitude flight.

10. Scope of future study

Aircraft design studies in this research are limited to conventional fuels and tube wing configurations. Applying climate impact reduction technologies to blended wing body aircraft could enable further emissions and climate impact savings. Some research opportunities exist to continue this work. One area with potential for research advancement involves linear climate model development. Further studies of aircraft climate impacts, most notably aviation-induced cloudiness are needed to improve the accuracy of conceptual design climate models.

References

1. Akesson, N. B., & Yates, W. E. (1974). *The use of aircraft in agriculture* (No. 94). Food & Agriculture Org..
2. McRee, G. J. (1977). *The Role of Aerospace Technology in Agriculture: 1977 Summer Faculty Fellowship Program in Engineering Systems Design, NASA-Langley Research Center, American Society for Engineering Education, Old Dominion Research Foundation*. National Aeronautics and Space Administration.http://en.wikipedia.org/wiki/Agricultural_aircraft
3. Moser, R., Heiko, A., & Gnatzy, T. (2010). The Indian aerospace industry 2019.
4. Eriksson, S. (2015). 8 Newly industrialising economies and the aircraft industry. *The Global Commercial Aviation Industry*, 231.http://www.airtractor.com/aircraft/401b
5. Gormley, D. M., Erickson, A. S., & Yuan, J. (2014). *A low-visibility force multiplier: assessing china's cruise missile ambitions*. NATIONAL DEFENSE UNIV FORT MCNAIR DC INST FOR NATIONAL STRATEGIC STUDIES. http://www.airtractor.com/aircraft/602
6. Thrush, A., & AgCat, G. General characteristics.
7. Özdemir, S. E. G. A. H. (2005). *Multi Objective Conceptual Design Optimization of an Agricultural Aerial Robot (AAR)*(Doctoral dissertation, MS Thesis, Aerospace Engineering Department, METU, Ankara).
8. Raymer, D. (2002). *Enhancing aircraft conceptual design using multidisciplinary optimization* (Doctoral dissertation, Institutionen för flygteknik).
9. McLeod, I. M., Lucarotti, C. J., Hennigar, C. R., MacLean, D. A., Holloway, A. G. L., Cormier, G. A., & Davies, D. C. (2012). Advances in aerial application technologies and decision support for integrated pest management. In *Integrated Pest Management and Pest Control-Current and Future Tactics*. InTech.
10. SERIES, A. E. (1988). Aircraft landing gear design: principles and practices. Raymer, D. P. (1999). Aircraft design: A conceptual approach, american institute of aeronautics and astronautics. *Inc.*, *Reston, VA*, 21. *Symbol used*

Where

W_f/W_o – Mission fuel fraction

W_x/W_o – Mission weight fraction

L/D - Lift-to-Drag ratio

W_o - Gross weight

P - Power

R- Range

C - Specific fuel consumption

V - Velocity

b - Span

S - Reference Wing Area

C_{HT} - Horizontal tail coefficient

C_{VT} - Vertical tail coefficient

C_{root} - Wing root chord

C_{tip} - Wing tip chord

A (b^2/S) - Aspect ratio

λ (C_{tip}/C_{root}) - taper ratio

t/c (t_{max}/c) – Airfoil Thickness ratio

c (bar) – mean aerodynamic chord

y (bar) – Distance of mean aerodynamic chord from the centreline