Aeronautical Engineering Design I

Electric Aircraft

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Introduction

- Electric propulsion could be a turning point in aviation history.
- Recent advances in electric propulsion and battery technologies have allowed serious and useful missions to be accomplished by electric aircraft.
- The design process of electrical aircraft is similar to gasoline-powered airplanes but the details are very different.
- The electrical aircraft match the performances of gasoline-powered airplanes in terms of speed and climb rate but they are significantly inferior in terms of range and endurance.
- The limitation on electric aircraft performance is battery technology not the motors.

Introduction

A good reference to start with:

Traub, L., “Range and Endurance Estimates for Battery-Powered Aircraft”, *J. Aircraft* 48(2), 2011.

Introduction

Yuneec E430 (first electric aircraft to receive FAA Airworthiness Certificate, 2009)

Introduction

Pipistrel Taurus G4

Introduction

Pipistrel Alpha Electro

Introduction

Cessna 208 Caravan (MagniX eCaravan)

(largest electric aircraft to fly)

Physics and Units

Quantity	Definition	Unit (SI)	Unit (British)
Work	= force*distance	N.m (joules)	lb.ft
Power	= work/time	joules/s (watts)	lb.ft/s or hp 1 hp = 550 lb.ft/s
Electrical Power	= electric current * Δ voltage (= I*ΔV)	amperes*volts (watts)	
Energy	power*time	watt*h (Wh) 1 Wh = 3600 joules	hp.h
Specific Energy	energy /mass	W.h/kg	-
Energy Density	energy/volume	W.h/liter	-

Historically, electric motors, power supplies and system components are always defined in **metric units**. 1 kW = 1.341 hp.

Electric propulsion advantages, disadvantages

Advantages	Disadvantages
“Green technology”, no hydrocarbon emissions	“Remote emissions”
>90% energy efficiency compared to ~20% in gasoline	Best batteries have ~20 times less energy density then gasoline
Better reliability than gasoline engines	
Safer, no fuel or oil for fires	Batteries can catch fire
Can be overpowered for a short time (lower rated engine)	
Engines don’t loose power with altitude	Fuels cells loose power with altitude due to cold
Engines are smaller and lighter than equivalent gasoline engines	Overall weight is heavier when batteries are included

Electric propulsion advantages, disadvantages

Advantages	Disadvantages
	Takes longer to “refuel”, charge time higher than refuelling time
Fuel cost per flight hour is less	Overall cost is more
	There is no weight, range and drag benefit due to fuel burn
	Batteries have limited lifetimes
	Batteries loose power as their charge ends
	Chemicals used for batteries are toxic and carcinogenic
	Inferior in performance in terms of speed, range, endurance and payload compared to similar gasoline-powered airplane

Electric propulsion basics

- Brushless DC permanent magnet motors (BLDC-PM) are currently the best choice for aircraft applications due their high efficiency, low weight, lack of sparking and good torque.
- "Li-ion" batteries are currently the only batteries that are really practical for aircraft. They have good energy density, hold their charge for a long time but have a fire hazard if they are short-circuited or charged too rapidly.
- Consider how many recharge cycles the battery can endure, the recharge rate, temperature sensitivity, insulation and cooling requirements, fire hazard, system cost, handling issues and environmental issues when selecting a battery.

Electric propulsion basics

	Chemistry	Typical Values (Wh/kg)	Typical Values (Wh/L)	Name	Notes
old	Lead-acid	45	100	Lead acid	automotive
	Alkaline	100	300	Alkaline	flashlights
Nickel	NiFe	25	30	Nickel Iron	locomotives, mining
	NiCd	60	150	Nickel Cadmium	classic "NiCad"
	NiH	75	60	Nickel Hydrogen	space probes
	NiMH	90	300	Nickel Metal Hydride	replaced NiCad
	NiZn	100	280	Nickel Zinc	automobile, electronics
Li-ion[1]	Li-ion	100–265	250–700	Lithium ion	generic term
	Li-ion Polymer	100–265	250–730	Lithium Polymer	polymer electrolyte
	LiCoO2	200	—	Lithium Cobalt Oxide	handheld electronics
	LiFePO4	120	170	Lithium Iron Phosphate	tools, vehicles
	LiMn2O4	150	—	Lithium Manganese Oxide	laptops, medical equip
	LiNiMnCoO2	260	500	Lithium Nickel Manganese Cobalt Oxide (NMC)	aircraft, road vehicles
	LiS	400	250	Lithium Sulfur	aircraft, road vehicles
	LiS (2020)	500	1000	Licerion[2] (LiS)	aircraft, road vehicles
	Li titanate	90	170	Lithium Titanate	high power/low energy
	Li-air	600	200	Lithium-Air	experimental
misc	Na-ion	150	50	Sodium Ion	laptops, bikes
	Molten salt	220	290	Molten salt	
	Silver Zinc	200	700	Silver Zinc	laptops, hearing aids
Comparisons	Wood	4500	3600	Wood	it floats
	Coal	8000	10000	Coal	it smells
	Jet Fuel	11000	10000	Jet Fuel	love that smell
	Gasoline	12000	9000	Gasoline	too expensive
	LH2	39406	2790	Liquid Hydrogen	too cold
	Uranium	2.2E + 10	4.3E + 11	Uranium	too scary
	Antimatter (c^2)	9.0E + 10		Antimatter	beam me up

Electric aircraft run-time, range, loiter, climb

- Battery energy content = battery specific energy * battery mass

$$battery\ energy = Wh/kg.kg = Wh$$

- Run-time endurance (hours) (independent of flight condition):

$$E = \frac{m_b E_{sb} \eta_{b2s}}{1000 P_{used}}$$

m_b: mass of batteries (kg),

E_{sb}: battery specific energy (Wh/kg),

η_{b2s}: total system efficiency from battery to motor output shaft,

P_{used}: average power used during that period of time (kW).

Electric propulsion system efficiency

- Total system efficiency from battery to motor output shaft (η_{b2s}):

  Motor controller: -2%,

  Motor: -5%,

  Gearbox: -2%

  $\eta_{b2s} = 1 - 0.02 - 0.05 - 0.02 \approx 0.90$

  This does not include propeller losses.

- In straight and level flight $(L = W, T = D)$:

  $P_{used}\eta_p = TV_\infty = DV_\infty = \frac{W}{L/D}V_\infty = \frac{mg}{L/D}V_\infty$, total power used for flight

  must be increased by $1/\eta_p$.

Electric aircraft flight endurance (loiter time)

- Level flight endurance or loiter time (hours):

$$E = 3.6\frac{L}{D}\frac{E_{sb}\eta_{b2s}\eta_p}{gV_\infty}\frac{m_b}{m}$$

V_∞: velocity (km/h),

E_{sb}: battery specific energy (Wh/kg),

η_p: propeller efficiency.

- Endurance is maximized by flying at $L/D = 0.866(L/D)_{max}$ (slower than velocity yielding $(L/D)_{max}$).

Electric aircraft flight range

- Level flight range (km):

$$R = 3.6\frac{L}{D}\frac{E_{sb}\eta_{b2s}\eta_p}{g}\frac{m_b}{m}$$

- Range is maximized by flying at $(L/D)_{max}$.

Electric aircraft rate of climb

- Rate of climb (m/s):

$$V_v = \frac{1000\eta_p}{g}\frac{P_{used}}{m} - \frac{V_\infty}{3.6\,L/D}$$

V_∞: velocity (km/h),

P_{used}/m: power to weight ratio (kW/kg),

η_p: propeller efficiency.

Battery mass fraction, known run-time

- Battery mass fraction is defined as:

$$BMF = \frac{m_b}{m}$$

- Battery mass fraction, known run-time (independent of flight condition):

$$BMF = \frac{m_b}{m} = \frac{W_b}{W} = \frac{1000E}{E_{sb}\eta_{b2s}}\frac{P_{used}}{m}$$

E: known run-time (hours),

E_{sb}: battery specific energy (Wh/kg),

η_{b2s}: total system efficiency from battery to motor output shaft,

P_{used}: average power used during that period of time (kW).

Battery mass fraction, loiter

- Battery mass fraction for loiter:

$$BMF = \frac{m_b}{m} = \frac{W_b}{W} = \frac{E V_\infty g}{3.6 E_{sb} \eta_{b2s} \eta_p \, L/D}$$

E: loiter time (endurance) (hours),

V_∞: velocity (km/h),

η_p: propeller efficiency.

Battery mass fraction, range

- Battery mass fraction for range:

$$BMF = \frac{m_b}{m} = \frac{W_b}{W} = \frac{Rg}{3.6E_{sb}\eta_{b2s}\eta_p\, L/D}$$

R: range (km),

V_∞: velocity (km/h),

η_p: propeller efficiency.

Battery mass fraction, climb

- Battery mass fraction for climb:

$$BMF = \frac{m_b}{m} = \frac{W_b}{W} = \frac{h}{3.6 V_v E_{sb} \eta_{b2s}} \frac{P_{used}}{m}$$

h: required climb altitude (km).

- Climb rate is maximized by flying at $L/D = 0.866(L/D)_{max}$ (slower than velocity yielding $(L/D)_{max}$, i.e. 76% of the speed for $(L/D)_{max}$, 60-80 knots for most general aviation aircraft).

Total required battery mass fraction and sizing equation

- Total required Battery Mass Fraction is found as the **sum** of the various mission segment Battery Mass Fractions.
- Mass available for batteries:

$$BMF_{available} = \frac{m_o - m_e - m_{payload} - m_{crew}}{m_o}$$

$$BMF_{avalable} = \frac{W_o - W_e - W_{payload} - W_{crew}}{W_o}$$

- Electric aircraft sizing equation:

$$W_o = \frac{W_{payload} + W_{crew}}{1 - BMF - \frac{W_e}{W_o}}$$

Electric aircraft sizing

- BMF is equivalent to fuel weight fraction (W_f/W_o) in gasoline-engine aircraft.
- Empty weight fraction (W_e/W_o) for initial sizing can be estimated based on statistical relationships for gasoline-engine aircraft based on gross weight (W_o). However, the constant terms should be adjusted using data for recent electric-powered aircraft.
- Empty weight is everything else that is not payload, crew or batteries → batteries take the place of fuel.
- **Be careful!** Most manufacturer data gives payload + crew weight as one, labeled as payload.