Hybrid Power in Light Aircraft: Design Considerations and Experiences of First Flight

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Talk outline

- Principles of flight – propulsion power & energy requirements
- Electric & hybrid-electric aircraft
- Simulation environment, system design & modelling
- Experimental characterization of engine, motor / generator, batteries, propeller
- Cambridge University hybrid-electric demonstrator aircraft, ground & flight tests
- Summary & Conclusions
What about electric aircraft?

- Environmental issues – noise, pollution
- Low fuel costs
- ‘Zero’ maintenance
- Low vibration
- Instant, reliable start-up
- No altitude effects
- Aerobatics
- Torque-speed characteristics
- Distributed propulsion
Why NOT?

- Power
- Endurance
- Cost
- Availability
- Maturity
Principles of flight

- Lift and Drag

- Total drag
  - Form drag
  - Induced drag

\[ \text{For slow speeds} \]
\[
\text{Lift, } L \quad \text{thrust} \quad \text{drag, } D \quad \text{weight}
\]

\[ \text{For fast speeds} \]
\[
\text{Lift, } L \quad \text{thrust} \quad \text{drag, } D \quad \text{weight}
\]

\[ \Rightarrow \text{L/D is figure of merit} \]
Principles of flight

- Lift over Drag → glide angle

- L/D max for various aircraft:
  - Space shuttle: 2:1
  - Parachute: 4:1
  - Light aircraft: 10:1
  - Airliner: 15:1
  - Glider: 60:1
Propulsion power requirements

Propeller power (level flight) = \( m_{\text{total}} \times v_{\text{airspeed}} \times g \) = \( P_L \) (min.) (S.I. units)

\[
\ell_{\text{prop}} \times \frac{L/D}{e_{\text{prop}}}
\]

Propeller power (climbing) = \( P_L + \left( v_{\text{vertical}} \times m_{\text{total}} \times g \right) / e_{\text{prop}} \) = \( P_C \) (max.)

The ratio between max. power, \( P_C \) and min. power, \( P_L \) determines the operating band for the propulsion system.

(note: in the equations above, the only constant value is g !)
Propulsion power - example

- L/D = 9:1 @ 58 mph = 570 ft/min, @ 27 m/s → 3 m/s sink rate at 450 kg

- Min. power for level flight = 26 HP (19 kW)
- 80 mph cruise takes around 40 HP (30 kW)
- Max. power climb at: 80 HP → 1200 ft/min (60 kW → 6 m/s)
Propulsion power requirements

- Effect of L/D on max./min. power ratio

1200 ft/min
58 mph
450 kg
\(e_{\text{prop.}} = 70\%\)
Electric vs. internal combustion

- Energy content of petrol = 45 MJ/kg = 12.5 kWhr/kg of which ~30% can be turned into power = 3.7 kWhr/kg
- 4-stroke petrol engine power rating ~ 1 HP/kg = 0.75 kW/kg
- Modern electric motors have an efficiency of ~90% and a power rating of ~ 5 kW/kg
- Battery storage capacity is ~200 Whr/kg ie. only 5% of petrol !!
- An 80 HP (60 kW) electric motor would save 68 kg in weight = 13.5 kWhr of batteries; this only corresponds to 3.5 kg of petrol
- Hence, an electric aircraft must be efficient ie. high L/D and/or lightweight and/or slow flying .....
Batteries & endurance

Range = \frac{m_{\text{batts}} \times \text{batt. energy} \times e_{\text{prop}} \times e_{\text{motor}} \times L/D \times \frac{1}{g}}{m_{\text{total}} \times \text{density}}

Endurance = \frac{\text{Range}}{\text{airspeed}}

**SSDR microlight example:**

\(m_{\text{total}} = 220 \text{ kg} \), \(e_{\text{prop}} = 70 \% \), \(e_{\text{motor}} = 90 \% \), \(L/D = 10 \),
\(g = 9.81 \text{ m s}^{-2} \), \text{batt. energy density} = 720 \text{ kJ/kg} \ (200 \text{ Whr/kg})

With 20 kg of LiPo cells eg. 24 \times Kokam 40 Ahr = 4 kWhr
this gives:

\(~ 30 \text{ mins. flight} \implies 25 \text{ mile range @ 50 mph}\)
• Maiden flight 1\textsuperscript{st} March 2009 at Sywell Aerodrome by test pilot Paul Dewhurst of Flylight Airsports Ltd

Photos: David Bremner
Hybrid-electric aircraft: performance & efficiency?

- Potential advantages over conventional propulsion, where *peak and cruise powers are significantly different*:
  - Increased fuel efficiency
  - Reduced noise
  - Higher peak power
  - Parallel redundancy

- Use electric propulsion enhancements to address some of the drawbacks in fuel-burning engines
Hybrid-electric aircraft

- Thermodynamic efficiency of internal combustion engines e.g. piston engine

- Engine sized for peak power is less efficient at (low) partial power settings
Hybrid – electric concept

- Electric motor: very high power-to-weight ratio (5kW/kg), rapid and precise control – combined with a combustion engine running at peak efficiency
Hybrid-electric prototype

- 75cc, 4-st petrol engine  2.8 kW
- 15 kW brushless electric motor
- Parallel hybrid, 2.4 kWhr LiPo
- Custom BLDC controller
- Engine + motor = 8 kg

- Modified Alatus motor-glider
- Sleek airframe
- Fitted <115kg microlight category
Hybrid-electric prototype

• First test flight: September 2010 at Sywell

• Climb rate was modest and system rather under-powered, but parallel hybrid operation successfully demonstrated
A multi-disciplinary project to investigate the theory and practise of hybrid-electric aircraft propulsion over a range of aircraft scale:

- Airframe aerodynamic simulation
- Propulsion system component characterisation & modelling
- Demonstrator build
- Ground & flight testing
- Comparison of practical flight test results with those from simulations
## Simulation environment

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>UAV</th>
<th>Single Seater</th>
<th>Airliner</th>
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### Component Analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>X-Plane</th>
<th>X-Plane + Exp. Data</th>
<th>X-Plane</th>
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<tr>
<td>Airfoil</td>
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<tr>
<td>Propeller</td>
<td>JavaProp &amp; PropSelect</td>
<td>JavaProp, PropSelect + Exp. Data</td>
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<tr>
<td>IC Engine</td>
<td>Simulink</td>
<td>Simulink + Exp. Data</td>
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<tr>
<td>Turbofan Engine</td>
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<td>/</td>
<td>GasTurb</td>
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<tr>
<td>Motor</td>
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<td>Simulink + Exp. Data</td>
<td>Simulink</td>
</tr>
<tr>
<td>Battery</td>
<td>Simulink</td>
<td>Simulink + Exp. Data</td>
<td>Simulink</td>
</tr>
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</table>

### Mission Profile

| Typical | ISR | Cross Country, Circuits | Medium Range (≈ 900 miles) |

### Goal of the Analysis:
- Determine fuel saving potential and/or performance enhancements
- Determine trade-off between engine and motor configuration
Simulation environment – SONG aircraft in X-Plane

- X-Plane + Matlab / Simulink model of SONG aircraft has been developed to include navigation & autopilot (PID) modules such that it can ‘fly’ a defined 3-d mission in real-time.
Simulation environment – SONG aircraft in X-Plane
Simulation environment – SONG aircraft

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<tr>
<td>B</td>
<td>B</td>
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</table>

\[ C_D = C_{DP} + B \times C_L^2 \]

\[ m \times g = \frac{1}{2} \rho \times v^2 \times A \times C_L \]

\[ T_R = \frac{1}{2} \rho \times v^2 \times A \times C_D \]
Cruise (level flight) power requirement $\approx 6.2$ HP (4.3 kW)

Climb power requirement for 600 ft/min $\approx 20$ HP (15 kW)

Hence, a 10 HP (7.4 kW) engine at $\sim 2/3$ throttle should be close to it’s most efficient operating point in cruise

With a 14+ HP (10+ kW) electric boost motor for climb

Electric motor also operates as generator in cruise to recharge the batteries

Battery capacity for 10 mins. @ full power = 2.4 kWhr
Parallel Hybrid power unit design

- Parallel combination of a *modified* Honda GX160 and Joby JM1
- Total power: 7 kW engine + 13 kW motor = 20 kW (27 HP)
- Common shaft, up to 7000 RPM
Power unit design & modeling – electric motor

- Measured motor performance to determine model parameters for JM1 over wide operating range
Power unit design & modeling – electric motor

\[ T_{\text{out}} = \left( \frac{I}{k_Q} \right) - T_{\text{Loss}} \]

\[ \omega = (V - I \cdot R) k_v \]

\[ P_{\text{shaft}} = T_{\text{out}} \cdot \omega \]

\[ P_{\text{electric}} = I \cdot V \]

\[ \eta = \frac{P_{\text{shaft}}}{P_{\text{electric}}} \]
Power unit design & modeling – petrol engine
• Torque-Speed Characteristics of the Honda GX160: Matching of the data derived from ADVISOR and the experimental data obtained.
High power tests were conducted in an open field to measure the motor / propeller combined performance.
Power unit design & modeling – propeller

- Experimental results were compared against JavaProp and PropSelector models to verify the characteristics

Advance ratio, \( J = \frac{v}{n d} \)
• Electrical energy storage uses Kokam Lithium Polymer pouch cells with a capacity of 40 Ahr: 16 x SLPB 100216216H
LiPo cells must be carefully monitored for voltage & current limits

Cell characterization is a key factor for capacity gauging and safe operation including, ageing effects

Characteristics vs. C-rate: 1C = 40 A
Hybrid-electric power system schematic

Fuel tank

Fuel pump & throttle servo

Honda GX160 (7 kW)

Joby JM1 (10 kW)

Reduction drive 2.6:1

Power Controller

Throttles

Battery pack 1 8 x 40 Ahr cells

Battery pack 2 8 x 40 Ahr cells

BMS 1

BMS 2

Twin throttle arrangement:

• Independent setting of powers
• Pilot manages fuel / power flow
• Bi-directional electrical power modes for motor / generator
Hybrid-electric power controller - hardware

- motor connectors
- smoothing capacitors
- MOSFET drive boards
- fan
- battery power connectors
- logic / control PCB
- MOSFETs
- heatsink
Hybrid-electric power unit - hardware
Hybrid-electric demonstrator aircraft
Hybrid-electric demonstrator – mass budget

- Maximum take-off mass = 235 kg (airframe structural limits +6/-4 G)
- Pilot & fuel: 97.5 kg

SONG Empty Operating Weight: 137.5 kg
Hybrid-electric demonstrator – avionics & data logger

- Electrically isolated custom avionics unit (total mass ~ 500g)
- Records flight & power system data to SD card every 2 seconds

- Displays & logs:
  - Airspeed, altitude, vertical speed
  - Voltage, current, RPM, motor temp., engine temp., time
Hybrid-electric demonstrator – first test flights

- First ‘hops’ along the 1 km runway at Sywell Aerodrome took place on the 10th Sept. 2014
- BMAA Test pilot: Paul Dewhurst, Flylight Airsports
Hybrid-electric demonstrator – flight test data

- Example data from test flight to 1500 ft:
Hybrid-electric demonstrator performance

• Power from petrol engine and electric motor blend smoothly – pilot has twin throttles to select desired balance

• Fuel flow rate at 50 mph cruise is < 3 litres/hr with a 20% reduction for every 1 kW of electric power applied:
  - No electric boost: 2.9 litres/hr
  - 1 kW boost: 2.4 litres/hr
  - 2 kW boost: 2.0 litres/hr

• Further work is ongoing to optimize system performance
Summary & Conclusions

- We have successfully demonstrated a parallel hybrid-electric aircraft which can operate in various modes, including electric assist and battery recharging.

- Electric & hybrid-electric technology can offer improved performance and economy in aircraft – under the right conditions…

- In future, as battery energy density improves, the benefits of greater ‘electrification’ will also increase.

…With thanks to The Boeing Company for sponsorship
Thank you for your attention

• Questions / discussion?