Range and Endurance Tradeoffs on Personal Rotorcraft Design

Christopher A Snyder
Propulsion Systems Analysis Branch
NASA John H. Glenn Research Center

AHS 72nd Annual Forum & Technology Display
West Palm Beach, Florida
May 17-19, 2016
Motivation

There is increasing interest in vertical-lift vehicles, improving mobility and overall utility / flexibility. Baseline a nominal, one hour mission, assess performance for alternative missions.

Portions of or entire vertical-lift missions tend to be closer to the populace (and more flights expected), so environmental considerations (noise, emissions, etc.) are especially important.

Electric systems and new designs enabled by these systems offer the potential for reduced noise and point of use emissions, enhanced vehicle and mission capability, etc.

Compare and contrast previous and new vehicles; traditional versus all-electric architectures. Improve understanding for their strengths / weaknesses; identify future analysis and R&D areas.
Outline

• Introduce baseline vehicles
• Review propulsion and energy systems
  – Electric motors / system parameters (Dever)
  – Compare and contrast traditional versus battery / electric motor systems
• Discuss analysis methodology and assumptions
• Present Results
  – Power required for various mission segments
  – Mission radius versus hover and loiter duration
• Summary
• Future work
Baseline vehicles
Single Main (SMR) Helicopter, Tilt Rotor and Vertical Take Off and Landing (VTOL) Aircraft

payload (450 lbs. passengers / luggage + 200 lbs. pilot) ≈ 1 hour mission

Images not to scale
Baseline vehicles (cont.)

Single Main Rotor (SMR) Helicopter

Larger area translates to improved hover efficiency

Pilot, cargo, passengers

Rotor area
Baseline vehicles (cont.)

Tilt Rotor

VTOL aircraft

Designs allow better cruise aerodynamics, fly on wing
Baseline vehicles (cont.)

Roughly similar scale, highlights rotor area variation → hover efficiency
Impressive weight and loss reductions for Electric Motor / Electronics are occurring

<table>
<thead>
<tr>
<th>Technology year</th>
<th>Power/weight, hp/lb. (kW/kg)</th>
<th>Electric motor $\eta$, %</th>
<th>Controller $\eta$, %</th>
<th>Net $\eta$, %</th>
<th>Net Loss, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>State of the art</td>
<td>1.9 (3.1)</td>
<td>90</td>
<td>94</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>15 year</td>
<td>3.4 (5.6)</td>
<td>95</td>
<td>98</td>
<td>93</td>
<td>7</td>
</tr>
<tr>
<td>30 year</td>
<td>4.9 (8.0)</td>
<td>98</td>
<td>99</td>
<td>97</td>
<td>3</td>
</tr>
</tbody>
</table>

**Non-cryogenic**

*Power-to-weight includes electric motor (3,8,16 hp/lb.) + controller (5,6,7 hp/lb.)*

“15 year” power-to-weight goals are being demonstrated today
Efficiency goals are taking a little longer (power/weight first)
Reduced losses = less thermal management (less weight)

* Dever, T.P.; Duffy, K.P.; Provenza, A.J.; Loyselle, P.L.; Choi, B.B.; Morrison, C.R.; and Lowe, A.M.
Electric motor’s power-to-weight and efficiency are competitive or better than current systems;

BUT efficiency doesn’t overcome deficiencies in energy storage (critical for range / endurance)

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Power / weight, hp/lb. (kW/kg)</th>
<th>Efficiency</th>
<th>Fuel, energy density, MJ/kg</th>
<th>Net energy density, MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery all-electric, SOA</td>
<td>1.9 (3.1)</td>
<td>85</td>
<td>0.70</td>
<td>0.60</td>
</tr>
<tr>
<td>15 year</td>
<td>3.4 (5.6)</td>
<td>93</td>
<td>1.75</td>
<td>1.63</td>
</tr>
<tr>
<td>30 year</td>
<td>4.9 (8.0)</td>
<td>97</td>
<td>3.15</td>
<td>3.06</td>
</tr>
<tr>
<td>Diesel cycle, SOA Advanced</td>
<td>0.53 (0.9)</td>
<td>37</td>
<td>Diesel, 43.0</td>
<td>15.9</td>
</tr>
<tr>
<td>Diesel, Advanced</td>
<td>1.06 (1.8)</td>
<td></td>
<td>43.0</td>
<td></td>
</tr>
<tr>
<td>Reciprocating (IC) gasoline / Otto Cycle</td>
<td>0.71 (1.2)</td>
<td>27</td>
<td>Gasoline, 43.5</td>
<td>11.7</td>
</tr>
<tr>
<td>Advanced Gas turbine</td>
<td>5.0 (8.2)</td>
<td>24</td>
<td>Jet-A, 42.8</td>
<td>10.3</td>
</tr>
<tr>
<td>(500hp / 373kW class)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*For electric systems, “Fuel” is lithium battery, assuming average of lithium ion and sulfur, cell only* (also from Dever)
Analysis Tool: NASA Design and Analysis of Rotorcraft (NDARC)

Overall Program Layout

Propulsion / energy models
Mission Profiles

Vehicle sizing profile

(1) 5 min. idle
(2) Takeoff + 5 min. hover (OGE)
(3) Climb to cruise altitude at MCP, range credit
(4) Cruise at $V_{br}$ to mission range
(5) Hover or loiter ($V_{be}$) at altitude
(6) Return

Vehicle hover / loiter profile

Idle, Takeoff, and hover at sea level, ISA
Cruise altitude at 2,000 or 5000 ft, ISA

At sea level, ISA:
(1) 5 min. idle
(2) Takeoff + 5 min. hover (OGE)
(3) Climb to cruise altitude at MCP, Range credit
(4) Cruise at $V_{br}$ out or (6) Return
(5) Hover or loiter ($V_{be}$) at altitude
(7) 5 min. hover (OGE) + Landing
Additional study assumptions

• For conversion of SMR helicopter and Tilt rotor to all-electric, maintain empty weight + fuel (retrofit).
  
  Electric motor + battery = former propulsion + nominal fuel load

• Electric motors sized for mission requirements (no power lapse with high / hot).

• For Advanced VTOL: sized to meet 200 nmi. range. Electric motor sized to meet hover power requirements.

• Takeoff, determine range and endurance with:
  
  Full payload (450 lbs. passengers / luggage)
  
  200 lbs. pilot

  For all-electric, additional battery up to design gross weight

  (SMR helicopter & Tilt rotor)
Results
## Baseline vehicles

<table>
<thead>
<tr>
<th>Parameter ↓</th>
<th>Vehicle →</th>
<th>Single Main Rotor (SMR) Helicopter</th>
<th>Tilt Rotor</th>
<th>All-Electric VTOL Aircraft, 15 year technology</th>
<th>All-Electric VTOL Aircraft, 30 year technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design gross weight (DGW), lb. (kg)</td>
<td>2,050 (932)</td>
<td>2,545 (1,157)</td>
<td>2,785 (1,266)</td>
<td>2,200 (1,000)</td>
<td></td>
</tr>
<tr>
<td>Disk loading / wing loading, lb/ft^2</td>
<td>3.6 / N.A.</td>
<td>14 / 50</td>
<td>16 / 50</td>
<td>16 / 50</td>
<td></td>
</tr>
<tr>
<td>Nominal fuel weight, lb. (kg), % DGW *</td>
<td>160 (73), 8%</td>
<td>200 (91), 8%</td>
<td>630 (286), 23% (590 MJ battery)</td>
<td>270 (123), 12% (456 MJ battery)</td>
<td></td>
</tr>
<tr>
<td>Sea level maximum rated power (MRP), hp (kW)</td>
<td>190 (142)</td>
<td>470 (350)</td>
<td>456 (340)</td>
<td>350 (262)</td>
<td></td>
</tr>
<tr>
<td>Engine type</td>
<td>Reciprocating (Otto cycle)</td>
<td>Advanced turboshaft</td>
<td>All-electric, 15 year technology</td>
<td>All-electric, 30 year technology</td>
<td></td>
</tr>
<tr>
<td>Engine weight, lb. (kg), % DGW</td>
<td>270 (123), 13%</td>
<td>310 (141), 12%</td>
<td>105 (48), 4%</td>
<td>60 (27), 3%</td>
<td></td>
</tr>
<tr>
<td>Power / DGW, hp/lb. (kW/kg)</td>
<td>0.09 (0.15)</td>
<td>0.18 (0.30)</td>
<td>0.16 (0.27)</td>
<td>0.16 (0.27)</td>
<td></td>
</tr>
<tr>
<td>Cruise velocity (V_{br}), knots (km/h) *</td>
<td>95 (176)</td>
<td>185 (343)</td>
<td>200 (370)</td>
<td>200 (370)</td>
<td></td>
</tr>
<tr>
<td>Range, nmi (km) *</td>
<td>195 (360)</td>
<td>200 (370)</td>
<td>150 (280)</td>
<td>150 (280)</td>
<td></td>
</tr>
</tbody>
</table>
Power requirements vary greatly with vehicle design

- Engines sized by hover, loiter power much less
- Significantly lower hover power for SMR Helicopter than other vehicles, cruise / loiter power also less, but at ½ their speed
- Tilt rotor and VTOL loiter effectively on their wings (large area coverage)
High hover power requirements significantly reduce range
- Improved hover efficiency mitigates range penalty for hover endurance
- 30 year battery retains significant fraction of baseline capability
- 15 year battery (equal DGW) achieves minimal range
- Advanced VTOL (vehicle resized) shows similar characteristics

Base = hydrocarbon baseline
E15y = Electric, 15 year technology
E30y = Electric, 30 year technology
Lower loiter power requirements roughly 2x time at range
- Most trends very similar to hover range / duration results
- Reduced gas turbine efficiency at part power results in less loiter capability than 30 year battery electric

Base = hydrocarbon baseline
E15y = Electric, 15 year technology
E30y = Electric, 30 year technology
Summary

• High hover power requirements can dominate vehicle design, constrains other segment characteristics.

• Loiter power levels are much lower; vehicles optimized for cruise mission retains significant loiter capability.

• Electric motors seem to be already competitive (or better) than traditional HC-fueled engines (weight & \( \eta \)).

• However, energy storage (battery) technology is limiting factor. 30 year technology projections are getting close to parity for some vehicles / missions. Suggests a hybrid solution. (Paper discusses HC range extenders.)
Future Work

- Just scratched the surface, new vehicles and missions are being developed and analyzed to better understand and exploit the potential for these systems.
- Tools / various performance models are being upgraded. Capture inter-dependencies among systems and components (such as hydrocarbon range extenders).
- Push / pull of research and technology:
  - What is the potential for various, future technologies?
  - Which future technology (or suite of technologies) have the best promise?
Acknowledgments

This work was supported by the Aeronautics Research Mission Directorate (ARMD)

Advanced Air Vehicle Program (AAVP) / Revolutionary Vertical Lift Technology (RVLT) Project

Questions?
Backup Slides
## Baseline vehicles

<table>
<thead>
<tr>
<th>Vehicle →</th>
<th>Parameter ↓</th>
<th>Single Main Rotor (SMR) Helicopter</th>
<th>Tilt Rotor</th>
<th>All-Electric VTOL Aircraft, 15 year technology</th>
<th>All-Electric VTOL Aircraft, 30 year technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design gross weight (DGW), lb. (kg)</td>
<td>2,050 (932)</td>
<td>2,545 (1,157)</td>
<td>2,785 (1,266)</td>
<td>2,199 (1,000)</td>
<td></td>
</tr>
<tr>
<td>Empty weight, lb. (kg)</td>
<td>1,100 (500)</td>
<td>1,690 (768)</td>
<td>2,135 (970)</td>
<td>1,549 (704)</td>
<td></td>
</tr>
<tr>
<td>Disk loading / wing loading, lb/ft^2</td>
<td>3.6 / N.A.</td>
<td>14 / 50</td>
<td>16 / 50</td>
<td>16 / 50</td>
<td></td>
</tr>
<tr>
<td>Nominal fuel weight, lb. (kg), % DGW *</td>
<td>160 (73), 8%</td>
<td>200 (91), 8%</td>
<td>628 (285), 23% (589 MJ battery)</td>
<td>270 (123), 12% (456 MJ battery)</td>
<td></td>
</tr>
<tr>
<td>Sea level maximum rated power (MRP), hp (kW)</td>
<td>190 (142)</td>
<td>469 (350)</td>
<td>456 (340)</td>
<td>351 (262)</td>
<td></td>
</tr>
<tr>
<td>Engine type</td>
<td>Reciprocating (Otto cycle)</td>
<td>Advanced turboshaft</td>
<td>All-electric, 15 year technology</td>
<td>All-electric, 30 year technology</td>
<td></td>
</tr>
<tr>
<td>Engine weight, lb. (kg), % DGW</td>
<td>267 (121), 13%</td>
<td>312 (142), 12%</td>
<td>105 (48), 4%</td>
<td>60 (27), 3%</td>
<td></td>
</tr>
<tr>
<td>Engine power / weight, hp/lb. (kW/kg)</td>
<td>0.71 (1.2)</td>
<td>1.50 (2.46)</td>
<td>4.34 (7.1)</td>
<td>5.6 (9.2)</td>
<td></td>
</tr>
<tr>
<td>Sea level power specific fuel consumption, lb./hp-h (kg/kw-h)</td>
<td>0.500 (0.305)</td>
<td>0.574 (0.350)</td>
<td>N.A.</td>
<td>N.A.</td>
<td></td>
</tr>
<tr>
<td>Power / DGW, hp/lb. (kW/kg)</td>
<td>0.09 (0.15)</td>
<td>0.18 (0.30)</td>
<td>0.16 (0.27)</td>
<td>0.16 (0.26)</td>
<td></td>
</tr>
<tr>
<td>Cruise velocity (V_{br}), knots (km/h) *</td>
<td>95 (176)</td>
<td>185 (343)</td>
<td>200 (370)</td>
<td>200 (370)</td>
<td></td>
</tr>
<tr>
<td>Range, nmi (km) *</td>
<td>195 (360)</td>
<td>200 (370)</td>
<td>150 (280)</td>
<td>150 (280)</td>
<td></td>
</tr>
</tbody>
</table>
Hydrocarbon Range Extenders significantly lighter than 15 year batteries or for extended endurance (> 1 hour)

Advanced diesel hardware weight is slightly higher than the gas turbine, but its fuel efficiency results in the lightest system

<table>
<thead>
<tr>
<th>Engine type</th>
<th>Hardware weight, lb. (kg)</th>
<th>Fuel weight, lb. (kg)</th>
<th>Total weight, lb. (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced diesel - 15 year - 30 year</td>
<td>127 (58) 114 (52)</td>
<td>41 (18) 39 (18)</td>
<td>167 (76) 153 (70)</td>
</tr>
<tr>
<td>Gas turbine - 15 year - 30 year</td>
<td>101 (46) 89 (41)</td>
<td>81 (37) 77 (35)</td>
<td>181 (82) 167 (76)</td>
</tr>
<tr>
<td>Lithium Battery - 15 year - 30 year</td>
<td>-</td>
<td>337 (153) 188 (85)</td>
<td>337 (153) 188 (85)</td>
</tr>
</tbody>
</table>

100 hp (74.6 kW) output electrical power for 1 hour  (for scaling purposes)
Assume advanced hydrocarbon-fueled engine:
  Diesel 1.1 hp/lb. (1.8 kW/kg), 0.377 lb./hp-h (0.23 kg/kw-h)
  Gas Turbine 1.5 hp/lb. (2.46 kW/kg), 0.75 lb./hp-h (0.457 kg/kw-h)
Mission power versus segment and cruise / loiter speed

<table>
<thead>
<tr>
<th>Segment</th>
<th>HP</th>
<th>HP</th>
<th>HP</th>
<th>HP</th>
<th>HP</th>
<th>knots</th>
<th>knots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>idle</td>
<td>TO/</td>
<td>Climb</td>
<td>Cruise (Vbr)</td>
<td>hover</td>
<td>loiter (Vbe)</td>
<td>Vbr</td>
</tr>
<tr>
<td>SMR Helicopter</td>
<td>61</td>
<td>181</td>
<td>170</td>
<td>130</td>
<td>172</td>
<td>92</td>
<td>95</td>
</tr>
<tr>
<td>Tilt rotor</td>
<td>68</td>
<td>374</td>
<td>345</td>
<td>208</td>
<td>387</td>
<td>119</td>
<td>185</td>
</tr>
<tr>
<td>VTOL (15 year)</td>
<td>39</td>
<td>407</td>
<td>366</td>
<td>145</td>
<td>456</td>
<td>118</td>
<td>199</td>
</tr>
<tr>
<td>VTOL (30 year)</td>
<td>34</td>
<td>317</td>
<td>281</td>
<td>114</td>
<td>351</td>
<td>92</td>
<td>194</td>
</tr>
</tbody>
</table>

Idle and Take Off / hover OGE 5 minute duration each
Climb segment generally about 2 minutes duration
END