Design Space for Efficient Aircraft

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Outline

• Introduction
• Design Space for Efficient Aircraft
• Ride Comfort Improvement System
• Wind Turbine Technology
• Concluding Remarks
Early Proposal for Electric Propulsion

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SYSTEM FEATURES:
- TWO POWER CELLS, ONE MOTOR
- EITHER CELL STACK WILL SUSTAIN LEVEL FLIGHT
- EQUAL INSTALLED POWER AND WEIGHT AND DURATION TO GASOLINE SYSTEM
- REFUEL BY ANODE EXCHANGE
- RECYCLE LITHIUM FROM LiOH

CELL STACK
37.5 KW CELL STACK (METO)
75.0 KW TAKEOFF AND CLIMB
AC MOTOR;
~150 KW TAKEOFF AND CLIMB
~75 KW METO
H₂O₂ STORAGE IN EXISTING TANKS
DC/AC INVERTER
COOLING TUBES BONDED TO WING SKIN

79-1265
Electric Propulsion for High Performance Light Aircraft
Historical Jet Fuel Prices

Price information as of 22 April 2008:

- NY Harbor $3.5424
- US Gulf Coast $3.5124
- LA $3.5058
- Rotterdam $3.5843
- Singapore $3.4224
Impact of Fuel Efficiency

• Impact of fuel on aircraft operating cost is significant and is main component of operating cost at current fuel prices

• Reduction of fuel usage also has beneficial on air pollution with X% reduction of fuel burn for a given mission resulting in a similar reduction in emissions
  – European Aeronautics Vision 2020 includes:
    • 50% reduction in fuel consumption (i.e., 50% reduction in CO$_2$)
    • 80% reduction in NO$_x$
    • 50% reduction in perceived noise
Breguet Range Equation for Prop Airplane

Range, R, of a propeller-driven airplane at constant lift coefficient is governed by:

\[
R = \frac{\eta_p}{\text{BSFC}} \frac{L}{D} \ln \frac{W_0}{W_1}
\]

\[
\frac{W_F}{W_P} = \left( e^{\frac{R \text{ BSFC}}{\eta_p L/D}} - 1 \right) \left( \frac{W_E}{W_P} + 1 \right)
\]

where:
- \( \eta_p \) = propeller efficiency
- BSFC = brake specific fuel consumption
- L/D = airplane lift-to-drag ratio
- \( W_0 = W_E + W_P + W_F \)
- \( W_1 = W_0 - W_F \)
- \( W_F = \) fuel, \( W_E = \) empty weight, \( W_P = \) payload
Performance Characteristics of Prop Airplane in Cruise

\[ \eta_p \text{BHP} = C_D \frac{1}{2} \rho_\infty V^3 S \]

\[ W = L = C_L \frac{1}{2} \rho_\infty V^2 S \]

Simple parabolic drag polar:

\[ C_D = C_{D_0} + \frac{C_L^2}{\pi \cdot AR \cdot e} \]

Minimum required thrust condition:

\[ C_L (C_{D_{\text{min}}}) = \sqrt{C_{D_0} \cdot \pi \cdot AR \cdot e} \]

\[ C_{D_{\text{min}}} = 2C_{D_0} \]

\[ \left( \frac{L}{D} \right)_{\text{max}} = \frac{1}{2} \sqrt{\frac{\pi \cdot AR \cdot e}{C_{D_0}}} \]

Note:

- Increase in aspect ratio, AR, or Oswald’s efficiency factor, e, increases \((L/D)_{\text{max}}\) but also increases \(C_L(C_{D_{\text{min}}})\)
- Application of laminar flow reduces \(C_{D_0}\) and, increases \((L/D)_{\text{max}}\) but decreases \(C_L(C_{D_{\text{min}}})\)
Design Space for Personal Air Vehicles

Initial cruise conditions: \( h = 8,000 \) ft at 100 KTAS (SA)

- High \((L/D)_{max}\) requires high effective aspect ratio and low zero-lift drag coefficient

- High \((L/D)_{max}\) operation at low speed (100 KTAS) and low altitude (< 10,000 ft) does not require high wing loading \((W/S < 15 \text{ lb/ft}^2)\)
Sample Highly Efficient Low-Speed PAV
Stemme S8

- Retractable tricycle gear
- $W_{TO} = 1,874$ lb
- BHP = 115
- AR = 18.6
- $(W/S)_{TO} = 10.0$ lb/ft$^2$
- $(L/D)_{max} = 38 \@ 66$ KTAS
- Cruise@MCP, MSL = 151 KTAS
- Fuel consumption @ MCP = 6.5 U.S. gallon/hr
- Cruise@ 55% MCP, MSL = 130 KTAS
- Fuel consumption @55% MCP = 3.77 U.S. gallon/hr
Design Space for Personal Air Vehicles

Initial cruise conditions: \( h = 8,000 \text{ ft at 200 KTAS (SA)} \)

- High \((L/D)_{\text{max}}\) requires high effective aspect ratio and low zero-lift drag coefficient

- High \((L/D)_{\text{max}}\) operation at relatively high speed (200 KTAS) and low altitude (< 10,000 ft) requires high wing loading.

- Speed does come at a price if wing loading is not raised to match higher speed
Factors Inhibiting PAV Efficiency

• Stall speed limit:
  – LSA Category: 45 knots
  – FAR Part 23 Category: 61 knots

• Low stall speed requirement combined with ineffective high-lift system results in low wing loading vehicle

• Laminar flow technology is required to reduce wing loading for optimum cruise

• High aspect ratio wing technology increases wing loading for optimum cruise
Stall Speed and Maximum Lift for GA Aircraft

Holmes (1982)

61-knot rule
Design Options for Improved Efficiency

• Operation at higher wing loading through application of more effective high-lift systems
  – Higher $(L/D)_{\text{max}}$
  – Improved ride quality

• Continue operation at relatively low wing loading
  – Incorporate gust alleviation system for improved ride quality
Modern PAV Design
Lancair Legacy, Source: http://www.cafefoundation.org/

\[(W/S)_{TO} = 26.66 \text{ lb/ft}^2\]

MTOW = 2,200 lb

\[S = 82.5 \text{ ft}^2\]

\[C_{L_{\text{max, clean}}} = 1.51\]

\[C_{L_{\text{max, flaps}}} = 2.35\]

\[V_s = 56.9 \text{ kts}\]
Effect of Circulation Control on Lift

$t/c = 0.17$ supercritical airfoil, Englar et al (1993)
Active Gust Control

- Aerodynamic loading on blade can be modified through:
  - Wing incidence angle
  - Airspeed
  - Wing size
  - Wing aerodynamic characteristics

- Focus is on small fast-acting systems to alleviate load spikes due to gusts
  - Reduced fatigue and extreme loading
  - Improved ride quality

- Gust alleviation goal to drive lift change due to vertical gust to zero:

\[
\Delta L' = \Delta L - \Delta L_{\text{Gust-Alleviation}}
\]

\[
\Delta L' = \left(C_{L_{\alpha}} \Delta \alpha - C_{L_{df}} \Delta \delta_f \right) \frac{1}{2} \rho_{\infty} V_{\infty}^2 S
\]

\[
\Delta \alpha = U_{de} / V_{\infty}
\]

\[
C_{L_{\alpha}'} = C_{L_{\alpha}} - C_{L_{df}} \frac{\Delta \delta_f}{\Delta \alpha} \rightarrow \approx 0
\]
**Microtab Concept**

- Deploy (near-)normal to flow direction
- Forward of the trailing edge
  - Upper or lower surface
- Hinge-less device
  - Small actuation forces
- $h_{tab} \sim$ boundary layer thickness
- Trailing-edge flow condition is altered
Tab Deployment Study

\[ \text{Time} = 0.005 \]
\[ T_{\text{deploy}} = 1 \text{ Ut/c} \]
Trailing-Edge Mesh Detail - Microflap
Body-fitted O-grid

Rectracted  Fully deployed
Baseline Parameters

- **S809 or NACA 0012 airfoil**
  - Tab located at 0.95c on the lower surface
  - Tab deploys normal to the chord line
  - Flap located at trailing edge
  - Flap rotates

- **Flow Conditions**
  - $Ma = 0.25$
  - $Re = 1.0 \times 10^6$

- $h_{\text{tab}} = h_{\text{flap}} = 1.00\%c$

- $T_{\text{deploy}} = T_1 - T_o = T_{\text{deploy}} \frac{U_\infty}{c} = 1.00$

- Sinusoidal deployment velocity profile:

$$V_{\text{tab}} = \frac{\pi}{2} \left( \frac{h_{\text{tab}}}{T_{\text{deploy}}} \right) \sin \left( \frac{\pi (T - T_o)}{T_{\text{deploy}}} \right)$$

$$\omega_{\text{flap}} = \frac{\pi}{2} \left( \frac{\theta_{\text{deploy}}}{T_{\text{deploy}}} \right) \sin \left( \frac{\pi (T - T_o)}{T_{\text{deploy}}} \right)$$
Microflap Deployment
T = 0 - 0.2, T_{deploy} = 1.00, NACA 0012, \alpha = 0^\circ, \; \text{Re} = 1.0 \times 10^6, \; \text{Ma} = 0.25
Microflap Deployment

$T = 0.4 - 0.6$, $T_{\text{deploy}} = 1.00$, NACA 0012, $\alpha = 0^\circ$, $Re = 1.0 \times 10^6$, $Ma = 0.25$
Microflap Deployment

$T = 0.8 - 1.0$, $T_{\text{deploy}} = 1.00$, NACA 0012, $\alpha = 0^\circ$, $Re = 1.0 \times 10^6$, $Ma = 0.25$
Microflap Deployment

\( T = 1.0 - 1.2, \ T_{\text{deploy}} = 1.00, \ NACA\ 0012, \ \alpha = 0^\circ, \ Re = 1.0 \times 10^6, \ Ma = 0.25 \)
Microflap Deployment Time Effect

NACA 0012, $\alpha = 0^\circ$, $Re = 1.0 \times 10^6$, $Ma = 0.25$
Wind Turbine Technology

• Wind-based electric energy has become cost effective
• Cost effectiveness has spurred large companies (FPL, GE, Siemens, etc.) to enter the market
• Push to drive cost of energy down has resulted in much larger wind turbines
• Push to beat “square-cube law” (rotor power goes by diameter-squared, rotor mass goes by diameter-cubed) has resulted in significantly lighter composite rotor structures
• Modern rotors have efficiency of approx. 52% vs. theoretical maximum of 59.7%
• Modern rotors use variable speed to maximize efficiency and variable pitch to control torque/power
• Technology developments are focused on lighter structures for given energy capture or increased energy capture through longer blades for unchanged rotor mass
• Technology is bifurcating:
  – Land-based utility-scale wind turbines (blade length ≤ 45 m, P ≤ 3 MW)
  – Off-shore wind turbines (P ≥ 5 MW)
  – Wind turbines for residences and small businesses (P = 0.5 - 50 kW)
Conclusions

• It is timely to (re-)consider electric aircraft
• In order for these vehicles to achieve acceptable range performance, they may have low wing loading to operate at high L/D
• Gust alleviation system may be required to provide satisfactory ride quality and to mitigate impact of gust loading on structure
• As we move forward and reduce our oil dependency and emissions, wind power may be able to provide a large percentage (>20%?) of electric energy needs in USA including power for electric vehicles and/or hydrogen production for fuel cells