Turboelectric Distributed Propulsion Test Bed Aircraft

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Outline

• Introduction
• Turboelectric Distributed Propulsion (TeDP)
• Subscale Test Bed
• Scaling From Test Bed Aircraft to Full Scale
• Phase I Technical Approach
• Results to Date
• Next steps
Introduction

• NASA Subsonic Fixed Wing (SFW) Project N+3 Goals
  – 2025 Timeframe, Based on B777-200LR Baseline
  – Noise: -52dB Reduction
  – Emissions: -80% Reduction
  – Fuel Burn: -60% Reduction

• In Order To Meet Goals ⇒ New Configurations, Materials, and Propulsion Technologies
  – Hybrid Blended Wing Body (HBWB) Config.
  – HBWB Provides High Cruise L/D, Noise Shielding With Upper Surface Mounted Engines
    • With Pylon Mounted UHB Engines, HBWB Provides -52% Fuel Burn Reduction\(^1\)
    • Still Requires Additional 8% Fuel Burn Reduction to Meet N+3 Goals

1) Felder et al. ISABE-2011-1340
TeDP

- HBWB Fuel Burn Can Be Further Reduced 18%-20%** Using TeDP Propulsion Concept¹
- **Total Fuel Burn Reduction HBWB+TeDP = 70%-72%**
- TeDP Uses Electric Motor Driven Fans Coupled To Gas Turbine Generators Via Transmission Lines

** Assumes Superconducting Motors and Generators

¹ Felder et al. ISABE-2011-1340
TeDP Advantages

• Boundary Layer Ingestion (BLI)
  – Reduces Average Inlet Velocity and Drag of Inlet
  – Reduces Fuel Burn Compared to Pylon Mounted Design

• Reduces Wake Drag of Vehicle
  – Re-energizes Wake of Airframe With Fan Thrust Stream

• Decouples Propulsion From Power
  – Power and Propulsion Can be Placed at Optimum Locations
  – RPM of Power Generating Turbine Independent of Fan RPM

• Very High Effective Bypass Ratio
• Safety: Redundancy For Both Propulsion and Power
• Differential Thrust For Trim and Possible Yaw Control

1) Felder et al. ISABE-2011-1340
TeDP Challenges

- Inlet Distortion Due to BLI and Inlet Geometry
  - Reduced Fan Performance, Increased Blade Fatigue Due to BLI and Inlet Secondary Flows
- Aerodynamics and Propulsion Closely Coupled
  - Possible Nonlinear Interaction Between Sectional Aero Performance and Thrust Level (Mass Flow and Spillage Vary With Thrust Level)
- Effect of Individual Fan Thrust Level/Mass Flow on Adjacent Fan Performance and Distortion
- Reliance on Superconducting Motors/Generators to Reduce Propulsion System Weight Fraction
- Increased System Complexity and New Technologies
TeDP Challenges

- Airfoil/Fan System is Closely Coupled
- Changes in Thrust Level Affect:
  - Circulation
  - Spillage Induced Blockage
  - Stagnation Point Movement
- Thrust Level Can Have Significant Effects on Sectional $C_l$ and $C_m$
Subscale Test Bed

- **LEARN Project:** Design Distributed Propulsion System For Small Test Bed Aircraft
- Successful TeDP Implementation Poses Significant Challenges, Even For N+3 2025 Time Frame
- Develop a Flying Demonstrator For TeDP Concepts, Systems, and Technologies
  - Allows Early Investigation of Complex Aerodynamics, Propulsion, and Systems Vital to Success of a TeDP Configuration
  - Reduce Development Risk of Larger, Dedicated TeDP Configuration by Converting Small, Single Engine Aircraft Already in NASA’s Inventory
Subscale Test Bed

• Test Bed Aircraft Allows Early Assessment of Multiple TeDP Technologies and Challenges
  – BLI
    • Distortion Challenges
  – Aerodynamic/Thrust Coupling
    • Effect of Thrust Level and Mass Flow on Sectional Aerodynamic Characteristics ($C_l$, $C_m$, Trim and Trim Drag)
    • Approach and Landing Configurations
    • High Angle-of-Attack Behavior, Stall, Separation and Effect on Thrust Level
  – Spanwise Differential Thrust
    • For Trim and Possible Yaw Control
    • Effect of Changing Spanwise Thrust Levels, Mass Flow and Spillage on Neighboring Fans Thrust and Performance
  – Inlet Area Design
    • Changes in Mass Flow With Thrust Effect Spillage and Blockage
    • Is Moveable Inlet Lip Required to Adjust For Various Flight Conditions?
Scaling

- Technologies Developed On Test Bed Need To Scale To Full Scale Transport Configuration

- **Scalable Technologies**
  - BLI Effects: Match BL Height to Inlet Height Ratio, Shape Factor
  - Aerodynamic/Propulsive Coupling
    - Effect of Fan Thrust/Mass Flow on Circulation, $C_l$, $C_m$, Stagnation Point
      - Approach/Landing Configurations, Climb, High Lift/Angle-of-Attack
    - Adjacent Fan’s Thrust/Spillage Level on Neighboring Fan Performance Distortion Characteristics
  - Movable Inlet Lip Geometry to Adjust For Flight Conditions
  - Power Distribution Topology

- **Scaling Challenges**
  - Low Speed Converging vs. High Speed Diverging Inlet
    - Distortion Levels
  - Electric Power Levels
  - Shock Upstream of Inlet at Transonic Speeds
Phase I Technical Approach

• Phase I Goal: Test Multi-Fan Model Based On Conceptual Test Bed Aircraft Installation
  – Measure Installed Thrust, Inlet Distortion, Surface Pressures, Boundary Layer Profiles, and Required Fan Power
  – Examine Effect of Adjacent Fan Thrust Level on Neighboring Fan Distortion and Performance
    • Increased Scope of Program to Examine Multiple Fans

• Phase I Major Tasks
  – Select Proposed Test Bed Aircraft
  – Evaluate Required Performance of TeDP System to Replace Baseline IC/Propeller Based Propulsion
  – Select COTS Electric Ducted Fan/Motor
  – Design BLI Inlet/S-Duct, and Exhaust
  – Design Wind Tunnel Test Model of Propulsion System
  – Generate 3D CFD Model of Wind Tunnel Test Article
  – Perform Wind Tunnel Test of Model Propulsion System
Test Bed Aircraft

• TG-14A Motor Glider
  – Previously Selected as an Excellent Candidate For Conversion to an Electric Aircraft Test Bed Under Previous Program
  – Chosen For a Combination of Aerodynamic Performance, Available Space, and High MTOGW/Useful Load

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<th>Aircraft</th>
<th>Manufacturer</th>
<th>Type</th>
<th># of Seats</th>
<th>Motor</th>
<th>Propeller</th>
<th>Endurance</th>
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<td>Grupo Aeromot</td>
<td>Motor Glider</td>
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<td>Rotax 912</td>
<td>Hoffmann HO-V62R-1/170FA</td>
<td>5 hrs</td>
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<td>Length</td>
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<td>Airfoil</td>
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<td>1874 lbs</td>
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Test Bed Aircraft

• Baseline Power plant
  – 100 Hp (74 kW) Rotax 912
  – Take-Off Thrust ~ 550 lbs
  – Cruise Speed 97 kts
    • $T_a=270$ lbs
    • $T_r=120$ lbs

• Airfoil and Design Conditions
  – NACA 643-618, 18% Thick
  – TG-14A Root Chord ~ 57.25 Inches
  – $Re_c=4.96 \times 10^6$ at Cruise, STP
  – To Maximize BLI Benefit, Want Fan Inlet at $C_p \geq 0 \implies x/c \geq 0.90$

![TG-14A Thrust Available vs. Thrust Required](chart1)

![XFOIL Predicted Pressure Distribution](chart2)
Notional Test Bed TeDP System

- Based on COTS Electric Ducted Fans
- Compromise Between Available Fan Thrust, # of Fans, Fan Efficiency and Required Power

Flying Wind Tunnel Allows Early Assessment Of Multiple TeDP Technologies/Challenges

Investigate:
- BLI
- Aero/Thrust Coupling
  - Effect of Thrust Level on $C_L$, $C_M$, $C_D$
  - $\alpha$ Effects, Approach/LandingConfigs.
- Spanwise Differential Thrust
  - Spillage Effects on Adjacent Fan Perf.
- Inlet Design
EDF Fan Choice

• Investigated COTS EDF Fans
  – Produced For R/C Hobby Enthusiasts
  – Come In Several “Standard Sizes” From 30mm to 140mm With Thrust Levels From Less Than 1 lbs to 46 lbs

• Chose Schuebeler DS-94-DIA HST DSM6745-700
  – Best Combination of Thrust, Efficiency, Power Required, and Number of Required Fan Units
  – 5.04 inch ID, 14.57 in² FSA
  – Thrust = 29 lbs Static @ 9.8 kW
  – Efficiency 70%, FPR ~ 1.1
  – 18 Individual Fans Required to Replace TG-14A 100 HP Rotax
Model Design and Duct Sizing

- Model Designed For 3ft x 4ft Low Speed Wind Tunnel
- Test 3 Fan, Multi-Inlet Geometry
- Three Configurations Considered
  - 2D Airfoil Vertical Mount
    - Determine Effect of Thrust on $C_l$, $C_m$, $C_d$
    - Reduced Chord, Reynolds #, Subscale Fan
  - Floor Mounted Hump Geometry
    - Full Scale Chord/Fan, Reynolds Number
    - No Lift, Drag, Moment
  - Floor Mounted Flap Plate Geometry
    - Simple, Inexpensive
    - No Pressure Gradient Effects
- Chose Hump Geometry
  - Allows Full Scale Fans, Flight Reynolds #
  - Correct BL and Pressure Gradient
Model Design and Duct Sizing

• Initial Estimate of Boundary Layer From XFOIL
  – $Re_c=4.96 \times 10^6$ at TG-14A Cruise of 97 kts
  – Assumed Turbulent Boundary Layer
  – TG-14A Root Chord = 57.25 inches
  – At $x/c=0.90$, $\delta \sim 1.4$ inches

• Duct Design
  – TG-14A is Low Subsonic $\rightarrow$ Converging Duct
  – Duct Capture Area Based on Required Mass Flow Estimate For TG-14A
    Thrust Available at Cruise $T_a=15$ lbs/fan, $\dot{m} = 0.0828$ slugs/s
  – For Required Mass Flow, Inlet Area Estimated to be 32.8 in$^2$
  – Duct Width 6.0 inches (Minimum $\Delta$ Between Fans), Height 5.47 Inches
  – 25% of Inlet Height Occupied by Boundary Layer
  – Inlet to Fan Face L/D $\sim 1$ Used
CFD Model

- CFD Model of Wind Tunnel Experiment Developed To Provide Insight Into EDF Duct Flowfield
  - Model Includes Tunnel Walls, Inlets, Duct System, and Motor/Fan Plug
  - Provide Guidance in Inlet/Duct Design, Inlet Distortion Estimates

- Simulations Run Using OVERFLOW CFD Code
  - To Match Free Air Pressure Distribution, Model t/c Reduced From 18% to 15.8% Due to Model Blockage
  - Cases Investigated
    - Full Cruise Thrust Available $T_a=270\text{ lbs} \rightarrow 15\text{ lbs/fan}, \dot{m} = 0.0828\text{ slugs/s}$
    - Cruise Thrust Required $T_r=120\text{ lbs} \rightarrow 6.6\text{ lbs/fan}, \dot{m} = 0.0642\text{ slugs/s}$
    - Windmill
    - Differential Thrust: Full/Cruise on Center and Left Duct, Right Duct Idle
  - EDF Modeled as an Actuator Disk in Fan Annulus
    - Actuator Disk $\Delta p$ Specified as BC, $\Delta p$ Adjusted to Obtain Desired Mass Flow
CFD Model Results

Comparison of XFOIL Free-air and OVERFLOW Tunnel Hump Geom. Pressure Distributions
\( \alpha=0^\circ, \text{Re}_c=4.96\times10^6 \)

Design Mass Flow

Below Design Mass Flow Creates Blockage

- XFOIL Free-air, \( t/c=0.180 \)
- OVERFLOW Tunnel \( t/c=0.158 \)
- OVERFLOW: EDF Config., Windmilling, \( T=3.1 \text{ lbs, } m_{\text{ax}}=0.040 \text{ slugs/s} \)
- OVERFLOW: EDF Config., Cruise Thrust, \( T=9.4 \text{ lbs, } m_{\text{dof}}=0.0627 \text{ slugs/s} \)
- OVERFLOW: EDF Config., Full Thrust, \( T=15.7 \text{ lbs, } m_{\text{dof}}=0.0808 \text{ slugs/s} \)
CFD Model Results

OVERFLOW Predicted Wind Tunnel Hump Model Duct Mach Contours
Vertical Cut Through Duct Centers, Cruise Speed, V_c = 97 kts

Full Thrust:
\( m_{\text{full}} = 0.0808 \text{ slugs/s} \)
\( T = 15.7 \text{ lbs} \)

Cruise Thrust:
\( m_{\text{cruise}} = 0.0627 \text{ slugs/s} \)
\( T = 9.4 \text{ lbs} \)

Windmilling:
\( m_{\text{wind}} = 0.040 \text{ slugs/s} \)
\( T = 3.1 \text{ lbs} \)
CFD Model Results

OVERFLOW Predicted Wind Tunnel Hump Model AIP Total Pressure Recovery
Cruise Speed, \( V = 97 \text{ kts} \)

- **Full Thrust:**
  - \( m_a = 0.0808 \text{ slugs/s} \)
  - \( T = 15.7 \text{ lbs} \)

- **Cruise Thrust:**
  - \( m_a = 0.0627 \text{ slugs/s} \)
  - \( T = 9.4 \text{ lbs} \)

- **Windmilling:**
  - \( m_a = 0.040 \text{ slugs/s} \)
  - \( T = 5.1 \text{ lbs} \)
CFD Model Results

TeDP OVERFLOW Predicted Wind Tunnel Hump Model Surface Streamlines

V_{in} = 97 kts

Full Thrust
m_{in} = 0.0808 slugs/s
T = 15.7 lbs

Cruise Thrust
m_{in} = 0.0827 slugs/s
T = 9.4 lbs

Windmilling
m_{in} = 0.040 slugs/s
T = 3.1 lbs

Pressure Coefficient
1.00
0.86
0.73
0.59
0.45
0.32
0.18
0.06
0.00
-0.09
-0.23
-0.36
-0.50
-0.64
-0.77
-0.91
-1.05
-1.18
-1.32
-1.45
-1.59
-1.73
-1.86
-2.00
-2.14
-2.27
-2.41
-2.55
-2.68
-2.82
-2.95
-3.09
-3.23
-3.36
-3.50
CFD Model Results

TeDP OVERFLOW Predicted Wind Tunnel Hump Model Surface Streamlines

V_∞ = 97 kts

Full Thrust
T = 15.7 lbs

Cruise Full Full
T_R=9.4, T_a=15.6, T_i=15.7

Windmill Full Full
T_R=2.7, T_a=15.3, T_i=15.7

Pressure Coefficient
1.00
0.86
0.73
0.69
0.45
0.32
0.18
0.06
-0.09
-0.23
-0.36
-0.50
-0.64
-0.77
-0.91
-1.05
-1.18
-1.32
-1.45
-1.59
-1.73
-1.86
-2.00
-2.14
-2.27
-2.41
-2.55
-2.68
-2.82
-2.95
-3.09
-3.23
-3.36
-3.50
CFD Model Results
CFD Model Results

• Overall CFD Results Positive
  – At Design Point ($T_a$) and Cruise ($T_r$) Inlet, Distortion Low For Aggressive L/D
  – No Separation In Duct For $T_a$ and $T_r$ Cases, Only Separation at Windmilling
  – Large Pressure Distribution Effect For Increased Blockage Below Design $\dot{m}$
  – Predicted Thrust Levels Higher Than Estimated Based On Mass Flow
    • Increased Blockage Below Design Mass Flow
    • Positive BLI Effect

• Differential Thrust Results Show Adjacent Fan Impacted
  – Increased Distortion Observed For Large Differential, But Still Small
  – CFD Predicts Increased Lip Separation on Adjacent Fan and Small Thrust Reduction

• Based On CFD Results Some Minor Mods Made
  – S-Duct Inlet and Exit Transition Smoothed, Outer Lip Geometry Adjusted
Wind Tunnel Model/Test

• Model Tested In UIUC 3’x4’ Low Speed Tunnel
  – Airfoil Manufactured Using CNC Sculpting From High Density Urethane
  – Duct System Manufactured Using Stereo Lithography

• Power Required For Full Rated Fan Thrust is 52 Volts at 190 Amps
  – Preliminary Runs Made Using 4 Deep Cycle Marine Batteries in Series
    • Not Enough Power, Only Able To Obtain 44 Volts at 130 amps at Full Load (5.7 kW)
  – Investigated DC Power Supply – Too Costly
  – Used Lithium Polymer Battery Packs Obtained From Fan Manufacturer (14s 7800 mAh)
    • Produced 49 volts at 136 amps (6.7 kW)
    • Available Power 30% Below 9.75 kW Required To Achieve Full Rated Power
    • Run Times Limited to Approximately Two Minutes at Full Power
Wind Tunnel Model/Test

• Instrumentation
  – Center Duct Fan Mounted on a Thrust Balance
  – Center Duct Equipped With 40 Port Miniature Inlet Distortion Rake
  – Surface Static Pressure Taps Along Model Centerline
  – Traversing Pitot Probe to Measure BL Thickness Upstream of Centerline Duct Entrance
  – Left and Right Ducts Have Static Pressure Ports to Measure Flow Rates
  – Suction Used Upstream of Model to Remove Tunnel Floor BL

• Two Week Entry Completed Sept. 27th
  – Tunnel Speed Set to Match TG-14A Cruise Reynolds No. (~ 164 ft/s)
  – Conditions Included
    • All Fans Running: Static Thrust, 100% - 75% - 50% Power and Windmill
    • Differential Thrust Combinations Using 100%, 50% Power and Windmill Settings
  – Smoke Flow Visualization
Wind Tunnel Set-Up

Center Fan Distortion Rake

Flow

Rear Cover Removed

Center Fan Thrust Stand
Test Results

Comparison of XFOIL Free-air, OVERFLOW, and Experimental Pressure Distributions

\[ \alpha = 0^\circ, \text{Re} \approx 5 \times 10^6 \]

- \( C_p \) vs. \( x/c \)

**Graph Details**
- **Graph Title**: Comparison of XFOIL Free-air, OVERFLOW, and Experimental Pressure Distributions
- **Axes**:
  - Y-axis: \( C_p \)
  - X-axis: \( x/c \)
- **Legend**:
  - XFOIL Free-air, \( t/c = 0.180 \)
  - OVERFLOW, Clean, \( t/c = 0.158 \)
  - OVERFLOW: Cruise Thrust
  - OVERFLOW: Full thrust
  - Exp.: Clean Hump Model
  - Exp.: 100% Throttle
  - Exp.: 50% Throttle
- **Input Power (kW)**
  - Range: 0 to 9 kW
  - \% Throttle
- **Test Results**
  - All Fans Operating
Test Results

Center Fan Inlet Distortion Rake Total Pressure Contours
$U_{\infty}=172$ ft/s, $Re_{\infty}=5 \times 10^6$

$P_o/P_{o,\infty}$

$p_{1p}/p_{1o}$

$DPCP_{avg}$

$DPRP_{max}$
Test Results

Comparison of OVERFLOW and Experimental Pressure Distributions and Thrust Levels

\( \alpha = 0^\circ, \text{Re}_{\infty} \approx 5 \times 10^6 \)

- **Cp**
- **x/c**

Legend:
- OVERFLOW: 100% 100% 100%
- OVERFLOW: 100% 100% 50%
- OVERFLOW: 100% 100% 0%
- Exp.: 100% 100% 100%
- Exp.: 100% 100% 50%
- Exp.: 100% 100% 0%
- Exp.: 50% 100% 50%
- Exp.: 0% 100% 0%

Thrust (lbs):
- Baseline: 100% 100% 100%
- Case: 100% 100% 50%
- Case: 100% 100% 0%
- Case: 100% 50% 50%
- Case: 50% 100% 0%
- Case: 0% 100% 0%

Changes:
- +2.6%
- +3.5%
- +6.1%
- +7.9%
Test Results

Center Fan Inlet Distortion Rake Total Pressure Contours

$U_{\text{in}} = 172 \text{ ft/s}, R_e = 5 \times 10^6$

Test Results

NASA Aeronautics Research Institute
Summary and Lessons Learned

• Test Results Positive
  – Experimental Results Generally Compared Well to CFD Predictions
  – Thrust Level at Design Point ~ 8% Below Predicted
    • Lower Thrust a Result of Inadequate Battery Power
  – Significant Blockage Effect on Surface Pressures at $\dot{m}$ Below Design $\dot{m}$
  – Distortion Levels Low
    • Effect of Converging Duct and Low Mach Number
  – Moveable Inlet Lip Would Minimize Off Design Mass Flow Effects

• Differential Thrust Has Significant Effect On Adjacent Fan
  – Although Levels Still Low, Adjacent Fan Distortion Does Increase
  – Spillage From Decreased Mass Flow Affects Adjacent Fan Incoming Pressure Distribution, Reducing Effective Inlet Velocity $\Rightarrow$ Increases Thrust
  – Should Increase Inlet Lip Radius to Better Account for Changes in Effective Lip Angle-of-attack Due to Neighboring Fan Spillage
Next Steps

**Overall Phase II Investigation Goals**

- 2D Airfoil, Five Fan/Prop Configuration (~3D Effects)
  - Investigate Multiple Fan/Prop, Differential Thrust Effect on 2D Airfoil
  - Aero/Thrust Coupling Effect on Lift, Drag, and Moment (Overall and Sectional)
  - Multi-Fan Circulation Effect ... Linear?
  - Neighboring Fan/Prop Spillage Effect on Thrust, Distortion and Unsteady (Overall and Sectional)
  - Moveable Inlet Lip To Adjust For Off Design Conditions?

**Approach**

- CFD Investigation: OVERFLOW Model and Inlet Design
  - Effects of Movable Inlet Lip
  - Spillage Tolerant Lip Design

- Subscale Wind Tunnel Test: 5 Fan 2D Airfoil Model
  - Measure Overall and Sectional Lift, Drag, Moment, and BL Profiles Upstream of Inlets
  - Measure Individual Fan Thrust
  - Test Differential Thrust Effects: Steady and Unsteady Effects
  - Test Angle-of-Attack Effects, Including Approach to Stall and Stall

- Phase II Option: Full Scale Transport to Subscale Test Bed CFD Based Scaling Study

**Phase III: Flying Test Bed Implementation**