FEATHER project in JAXA and toward future electric aircraft

Akira Nishizawa
Section leader of emission free aircraft section
Innovative Aircraft Systems Research Aircraft Systems Research Team
Next Generation Aeronautical Innovation Hub Center
Japan Aerospace Exploration Agency (JAXA)

Hiroshi Kobayashi (JAXA) and Hiroshi Fujimoto (The Univ. of Tokyo)

2nd On-Demand Mobility and Emerging Aviation Technology Roadmapping Workshop, 8-9 March 2016 Lockheed Martin Global Vision Center Arlington VA
Outline

1. Future Vision and Issues
2. FEATHER project
3. Toward future electric aircraft
1. Future Vision and Issues

1. 1 Future vision

A 19th-Century Vision of the Year 2000

1. 2 Problems of Small Aircraft

**Higher Cost**

- Unit ticket fees for domestic flights (in JAPAN, 2014)

**Lower Safety**

- Number of fatal accidents per 1 million flight time (average during 1982-1999 in USA)

Source: NTSB Aviation Accident Database

The fatal accident rate of small aircraft is about **10X higher** than that of large aircraft.
1.3 Major issues and solution

Goal: Popularization of General Aviation

Issues:
- Reduction of operating cost
  Current: 3~5X higher than airliner
- Reduction of fatal accidents
  Current: 10X higher than airliner

Solution:
- Electric aircraft technologies
  - Potential strength of Japanese industries
    (electric motor, battery, power device, ...)

Utilization:
- PAV, AirTaxi, ODM

JAXA
Outline

1. Future Vision and Issues
2. FEATHER project
3. Toward future electric aircraft
2. FEATHER Project

2.1 Outline of FEATHER project

Mission
- Development of JAXA’s unique electric propulsion systems

<table>
<thead>
<tr>
<th>FY2012</th>
<th>FY2013</th>
<th>FY2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Fabrication</td>
<td>Integration and flight test</td>
</tr>
</tbody>
</table>

1. Multiplexed motor
2. Regenerative air brake

![Diagram of power, altitude, and time relationship with fault and safe altitude markers.]

![Diagram of aerodynamic drag, wind energy, and power lever with RGN and CHG components.]

Descent → Wind energy → Power lever → CHG → RGN → Aerodynamic drag

Power lever

Fault

Safe altitude
2.2 Overview of the demonstrator

Original aircraft: Diamond aircraft type HK36TTC-ECO

- Multiplexed motor
- Pilot interface
- Li-ion battery
- Reduction gear
- Electric motor
- Monitoring unit
- Power lever
- Display
- Under wing container
- Battery pack
2.3 Electric propulsion system
## 2.4 Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing span</td>
<td>16.33m</td>
</tr>
<tr>
<td>Take-off weight at the flight test</td>
<td>800kg</td>
</tr>
<tr>
<td>Crew member</td>
<td>1 person</td>
</tr>
<tr>
<td>Types of electric motor and inverter</td>
<td>Permanent magnet type synchronous motor (three-phase) and IGBT inverter</td>
</tr>
<tr>
<td>Motor control method</td>
<td>FOC (Field-oriented control)</td>
</tr>
<tr>
<td>Maximum total shaft power (at RPM)</td>
<td>60kW (2.5min. at 6586RPM), 63kW(proven at flight)</td>
</tr>
<tr>
<td>Type of power source</td>
<td>Lithium-ion battery (32 cells in series)</td>
</tr>
<tr>
<td>System voltage (open circuit at 100%SOC) and Current</td>
<td>128V, 750A</td>
</tr>
</tbody>
</table>
2. FEATHER Project

2.5 Multiplexed electric motor system

- Characteristics
  - Compact
  - Light weight (2.17 kW/kg)
  - High efficiency (95%)
  - High strength of structure
### 2.6 Regenerative air brake system (1/4)

| Characteristic features | 1. Augmentation of descent rate **by only pulling the power lever w/o** conventional air brake  
|                         | 2. **No weight penalty** based on the field-oriented control method  
|                         | 3. **Maximization** of the regenerative electricity for variable air speeds |

#### Diagram

- **Power lever**
  - Motor
  - Inverter
  - Generator
  - Rectifier
  - Capacitor
  - DC/DC
  - Battery

- **Conventional**
- **Field-oriented control**
  - Motor/Generator
  - Inverter
  - Battery
2.6 Regenerative air brake system (2/4)

Motor torque is used as a command value in field-oriented control method.

Torque command value

\[ T = \begin{cases} \frac{C_{PWR}}{\text{PWR}} \delta_{PL}, & \text{Constant} \\ \delta_{PL} \leq 100\% \\ \text{Variable} \end{cases} \]

(\(0\% \leq \delta_{PL} \leq 100\%\))

Power lever displacement

2. FEATHER Project
2. FEATHER Project

2.6 Regenerative air brake system (3/4)

- Torque command value (corresponding to power lever max)
- Counter torque of Prop.
- Free rotation (NTL)
- Rotational speed
- Airspeed
- Torque

- ✓ Pitch angle of a blade = constant

The torque command value has to intersect with counter torque curve of propeller, otherwise the rotational number becomes zero or negative.

Maximization of the regenerative electricity
2.6 Regenerative air brake system (4/4)

Specially designed power lever to facilitate the control of descent rate and regeneration.

\[ V_{\text{air}} \] is not necessary as the feedback parameter to maximize the regenerative power in this system.

Block diagram of the regenerative air brake system.
航空機用電動推進システム技術の飛行実証

FEATHER
Flight-demonstration of Electric Aircraft Technology for Harmonized Ecological Revolution
2. FEATHER Project

2.7 Flight demonstration

An example of flight test data
2. FEATHER Project

2.7 Flight demonstration

Descent by using the conventional airbrake

Descent by using the “regenerative airbrake system”

Correlation of the power lever displacement, regenerative power and consequent descent rate, dH/dt during descent by using regenerative airbrake system
Outline

1. Future Vision and Issues
2. FEATHER project
3. Toward future electric aircraft
3. Toward future electric aircraft

**Range Extension**

- **High AR wing**
- **Simple conversion** of petrol to battery (4PAX, L/D<10)
- **Drag reduction** (L/D>25)

**Energy density/Whkg**

- **High energy density** Li-ion battery
- **Fuel cell & H₂**
- **TOYOTA’s MIRAI** with 2.0kW/kg FC stack.

Hitachi demonstrated 335Wh/kg and 30Ah on Nov. 2014 and they have developed by 2020.

3. Toward future electric aircraft

Automatization

1. Electric propulsion system have a high affinity for automatization.
2. Electric motor have a high response performance.
3. Electric motor can be flexibly arranged on a wing or a fuselage.

Power by wire

Key technology

Collaborative work

Motor
Inverter

Sensors

Computer

Sensing Actuator

Control Algorithm

Alternative S&C

Torque
Thrust
Airspeed

△N_p → △V_s → △L
Thank you

http://www.aero.jaxa.jp/eng/research/frontier/feather/
http://hflab.k.u-tokyo.ac.jp/index.html
1. Backgrounds & Objectives

Long-term research toward zero-emission aircraft

Electric and hybrid propulsion system for aircraft

1. FEATHER project
2. Concept study of fuel cell–gas turbine hybrid aircraft

collaborative work
1. Backgrounds & Objectives

Target and mission of FEATHER

Mission of FEATHER project
➢ To get flight permission from JCAB as the first case of electric manned flight in Japan
➢ Development of JAXA’s unique electric propulsion system
➢ Flight validation of the new functions and system performance

## Milestones

<table>
<thead>
<tr>
<th>2012-2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>March</td>
<td>July</td>
</tr>
<tr>
<td>Start</td>
<td>Complete of electric propulsion system</td>
<td>Integration</td>
</tr>
<tr>
<td>FY2012</td>
<td>FY2013 Design</td>
<td>FY2014 Integration and flight test</td>
</tr>
<tr>
<td>FY2013</td>
<td>Fabrication</td>
<td></td>
</tr>
</tbody>
</table>

- **2012-2013**: Design
- **2013**: Fabrication
- **2014**: Integration and flight test
- **2015**: Approval for flight test

### Flight Tests

- **600m Runway Jump test**: ~0.5min, ~10m
- **2000m Runway Jump test**: ~5min, ~80m
- **2700m Runway Short traffic pattern flight test**: ~120~150km/h, ~20min, ~600m

1. **Backgrounds & Objectives**
2. Systems

A) Electric motor-glider system
   A1) Electric propulsion system
      A1-1) Driving system
         Multiplexed motor
         Inverter
         Radiator & Pump
         Reduction gear
         Propeller
      A1-2) Power source
         Li-ion battery
      A1-3) Pilot interface
         Power lever
         Display
      A1-4) Management system
         System control unit
   A2) Measurement system
   A3) Airframe system
   A4) Charging system

System configuration
3. Concepts

1. Multiplexed motor
2. Regenerative air brake

![Diagram showing concepts with axes for power, altitude, and time, along with visual representations of fault, safe altitude, and aerodynamic drag.](image-url)
### 3.1 Multiplexed electric motor system (1/3)

| Our motivations | 1. Avoidance of “loss of engine power” for single piston engine aircraft.  
2. Redundancy of electric motors. |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Other researches | 1. Distributed motors and fans for VTOL (Alex M. Stoll et al. of Joby Aviation, 14th AIAA Aviation Technology, Integration and Operations Conference 2014, AIAA2014-2407)  
| Our selection of approach | Putting **multiplexed motor on a propeller shaft** |
### Technical issues for us

1. Reduction of the size and weight

2. Optimization of the number of motors

3. Isolation of failures

### Our solutions

1. Directly coupling with each motor (additional joint parts are unnecessary)

2. Quadruplex motor based on the trade-off analysis

3. Individual contactors

---

**Graph:**
- X-axis: Number of motors
- Y-axis: $W_{th}/W_{th, min}$
- Data points:
  - $W_{th}$: Blue diamonds
  - $W_{th, min}$: Red squares

---

**Diagram:**
- Motor axis
- Motor housing
- #1, #2, #3, #4

---

**Table:**

<table>
<thead>
<tr>
<th>Technical issues for us</th>
<th>Our solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reduction of the size and weight</td>
<td>1. Directly coupling with each motor (additional joint parts are unnecessary)</td>
</tr>
<tr>
<td>2. Optimization of the number of motors</td>
<td>2. Quadruplex motor based on the trade-off analysis</td>
</tr>
<tr>
<td>3. Isolation of failures</td>
<td>3. Individual contactors</td>
</tr>
</tbody>
</table>
3.2 Regenerative air brake system (1/5)

### Our motivations
1. **Elimination** of conventional systems by multifunctionality of electric motor.
2. **Regeneration of electricity** by electric motor.

![Airbrake](image1)

![Regenerative air brake system](image2)

### Other researches
2. WATTsUP can recuperate 13% of energy on every approach and reduce the field length of landing (Pipistrel, Aircraft News, 31 Mar 2015)

### Our selection of approach
1. Utilization of aerodynamic drag on the prop. due to regeneration
2. Simultaneously **harvesting** a certain amount of energy
### 2.6 Regenerative air brake system (1/4)

**Technical issues for us**
1. Simplify the control of descent rate
2. Avoidance of weight penalty and hardware complexity
3. **Maximization** of the regenerative electricity

**Our solutions**
1. Augmentation of descent rate **by pulling the power lever**
2. The simplest system configuration based on the field-oriented control method
3. Formulation of control algorithm based on the aerodynamic features

![Power lever diagram](image)

![Conventional vs. Field-oriented control](image)
3. Concepts

3.2 Regenerative air brake system (3/5)

Motor torque is used as a command value in field-oriented control method.
3. Concepts

3.2 Regenerative air brake system (3/5)

- Motor torque
- Rotational speed

Airspeed = constant
Pitch angle of a blade = constant

Aerodynamic feature of Prop.

Reverse Rotation

Significant Drag!!

Disadvantage of FOC

Torque command value (RGN maximum)
3. Concepts

3.2 Regenerative air brake system (3/5)

Motor torque

Airspeed = constant
Pitch angle of a blade = constant

Aerodynamic feature of Prop.

Rotational speed

Free rotation (NTL)

Torque command value (RGN maximum)

Opportunity loss
3. Concepts

3.2 Regenerative air brake system (3/5)

Airspeed = constant
Pitch angle of a blade = constant

Maximization of the regenerative electricity

Aerodynamic feature of Prop.

Free rotation (NTL)

Torque command value (RGN maximum)
3. Concepts

3.2 Regenerative air brake system (4/5)

Wind tunnel tests results for the actual propeller in RGN mode

(The flight demonstration was mainly conducted at angle of propeller pitch, $\beta=14$deg)
4. Flight demonstration

Typical example of the short traffic path
An example of flight test data
5. Summary

We have succeeded in flight demonstration as follows:

1. **Avoidance of complete power loss** in engine failure during climb by using the multiplexed electric motor
2. **Regeneration of electricity** about 8% of maximum motor output during descent
3. Control of descent rate by the proposed **regenerative airbrake system** without conventional airbrake
4. Continuous “**regenerative soaring**” free from descent in thermal condition

Acknowledgement: The wind tunnel test in this research was partly supported by the Ministry of Education, Culture, Sports, Science, and Technology grant (Basic Research A, number: 26249061).
\[ \Delta N_p \rightarrow \Delta V_s \rightarrow \Delta L \]

- Torque
- Thrust
- Airspeed