Design, Development and Flight Test of Vertical Take-Off and Landing UAV, Cyclocopter

Professor Emeritus Seung Jo KIM
Seoul National University
Cyclocopter Team from 2000 to 2015

- Chul Yong YUN
- Dae Sung KIM
- Young Ha YOON
- Ill Kyung PARK
- Jai Sang JUNG

Prof. Seung Jo KIM
with
4 Doctors
& 16 Masters

Phase II (2004~2008)
- In Seong HWANG
- Ho Yong LEE
- Chang Sup HWANG
- In Oh JEONG
- Yun Han LEE
- Dong Jun SHIN

Phase III (2009~2015)
- Seung Yong MIN
- Choong Hee LEE
- Seung Kyu YOON
- Seoung Eun CHUN
- Sung Hwan CHO
- Chun Jin PARK
- Yun Seong KIM
- Myeong Hun SEUNG
- Chang Moo HUR
# Unique Features of Cyclocopter Related Research

1. No government funding at all!!

2. Generous funding on supercomputing related research from Microsoft

- MOU between SNU and MS, Intel and Samsung
- Cyclocopter and Pegasus Cluster Supercomputer
- STAR-CD license by cooperation with CD-Adapco
- 56th Rank among Top500 Supercomputers
<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>3</td>
<td>Dedicated and self motivated graduate students for the creation of Cyclocopter</td>
</tr>
<tr>
<td>4</td>
<td>Positive Inflow of able students who are already confident on design, manufacturing and flying of model aircrafts when they enter our laboratory</td>
</tr>
</tbody>
</table>
Almost every design, analysis, manufacturing and flight tests were done in our Laboratory.

“Materials in, Cyclocopters out”

as what SpaceX of Elon Musk is doing “Materials in, Rockets out”
Almost every design, analysis, manufacturing and flight tests were done in the Laboratory.

Step III : Experimental Room
Thrust & Power Measurement
Ground Test

Step IV : Outdoor Test
Ground & Flight Test

“Materials in, Cyclocopters out”
As what SpaceX of Elon Musk is doing “Materials in, Rockets out”
Unique Features of Cyclocopter Related Research

6 Difficult to publish many papers due to the time-consuming technical hard works (Dedication and Sacrifice)

7 Taking longer time to finish Ph.D while doing the Cyclocopter research (No publish, No graduation Policy!)
Contents

1. Introduction to Cyclocopter
2. Cyclocopter Design Studies
3. Flight Vehicle Developments
4. Tests and Flight Demonstrations
5. Concluding Remarks
What is Cyclocopter?

- A Vertical Take-Off and Landing Aircraft
- Utilization of the Cycloidal Blade System (CBS) to make propulsion force
- Multiple Blades are used as a Cycloidal Rotor
- Multiple Rotors produce motion and maneuvering capabilities such as pitching, yawing and rolling motions
Introduction - Cycloidal Blade System

Cycloidal Blade System

- Horizontal rotary wing (Rotation about horizontal axis)
- Cyclic pitch variation
- Easy to change the direction of thrust (Any direction; perpendicular to the rotating axis)
- Vertical Take-off and Landing
- Hovering and forward flight
- High maneuverability
- Low noise
- Used in ship maneuvering under the name of Voith-Schneider Propeller
Introduction - Cycloidal Blade System

- **Dual Rotor Conceptual Configuration**

- **Low-Pitch System**
  - Low speed forward flight & hovering
  - Small pitch variation
Applications of Cycloidal Blade System

- **Cyclocopter**
  - Vertical Take-off and Landing Aircraft

- **Wind / Water turbine**
  - Vertical axis turbine with active variable pitch control mechanism
  - Rotor efficiency enhancement by cycloidal blade system or individual blade control method
Introduction – History

- **In the 1920’s and 1930’s**
  - University of Washington: Kirsten, Eastman
    - Research for cycloidal blade motion
    - Apply to Airship ‘Shenandoah’ → broke up
  - NACA: Wheatley
    - Low pitch motion, Cyclogiro
  - Marine applications
    - Voith-Schneider propeller
    - High performance and maneuverability

- **Other Research in the 1990’s and 2000’s**
  - Bosch Aerospace
    - Ground test for six-bladed cycloidal rotor
  - University of Maryland after us
    - Development of Cycloidal rotor for Micro-Air Vehicle Applications
Introduction – History

- **D-DALUS in Austria**
  - IAT21 company in Austria is studying a D-DALUS cyclocopter for commercialization
  - Recently, D-DALUS demonstrated a indoor hovering flight performance.

- **Similar projects are being studied in USA, Israel, Singapore, Japan, etc.**
Contents

1. Introduction of Cyclocopter
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4. Tests and Flight Demonstrations
5. Concluding Remarks
A. Aerodynamic Analysis of Cycloidal Blade System
**Aerodynamic theory of cycloidal blade system**

- **Momentum theory**
  - upstream half of the rotor
    - Mass conservation
    - Momentum conservation
      \[ F = \dot{m}(V_2 - V_1) \quad \Rightarrow \quad T_u \cos \psi = \dot{m}w \]
    - Energy conservation
      \[ T_u \nu_u = \iint_S \frac{1}{2} (\rho V \cdot dS)|V|^2 + \iint_S pV \cdot dS \quad \Rightarrow \quad T_u \nu_u = \dot{m}w^2 / 2 \]
    - Inflow
      \[ \nu_u = \dot{w} \sin \psi / 2 \]
    - Element thrust
      \[ dT_u = 2\rho R \left( \frac{\nu_u}{\sin \psi} \right)^2 d\psi \]
  - Downstream half of the rotor
    - Mass flow rate:
      \[ \dot{m} = \rho UA \]
      \[ U = \sqrt{(\dot{w} \cos \psi)^2 + (\dot{w} \sin \psi + \nu_d)^2} \]
    - Momentum conservation
      \[ dT_d = \dot{m}(w_\infty + \nu_d \sin \psi) - \dot{m}w \sin \psi = \dot{m}w_\infty \]
    - Energy conservation
      \[ dT_d (\nu_d + w \sin \psi) = \dot{m}(2w w_\infty \sin \psi + w^2_\infty) / 2 \]
    - Element thrust
      \[ dT_d = 2\rho R \nu_d \sqrt{w^2 + 2w \dot{v}_d \sin \psi + \dot{v}_d^2} d\psi \]

**Assumptions**
- Multiple streamtube model
  - Upstream half of the rotor
  - Downstream half of the rotor
- Infinitesimal thin actuator cylinder
- Flow: perpendicular to actuator cylinder
Aerodynamic theory of cycloidal blade system

- **Blade element theory**
  
  Perpendicular component: \( U_p = v_u = \lambda R \Omega \)
  Tangential component: \( U_T = R \Omega \)
  Inflow angle: \( \phi = \tan^{-1}\left(\frac{U_p}{U_T}\right) \)

- **Upstream part of the rotor**
  - Resultant velocity \( U_R = \sqrt{U_T^2 + U_p^2} \)
  - Effective angle of attack \( \alpha = \theta - \phi \)
  - Element lift and drag
    \[ dL = \frac{1}{2} \rho U_R^2 \left( \frac{N_b d \psi}{2\pi} \right) c C_l = \frac{\rho N_b c}{4\pi} U_R^2 \alpha(\theta - \phi) d \psi \]
    \[ dD = \frac{\rho N_b c}{4\pi} U_R^2 C_d d \psi \]
  - Element thrust \( dT_U = dL \cos \phi - dD \sin \phi \)
  - Inflow equation
    \[ 4k_{emp} \lambda^2 = \sigma a(1 + \lambda^2) \left\{ (\theta - \phi) \cos \phi - \frac{C_d}{a} \sin \phi \right\} \sin^2 \psi \]

- **Downstream part of the rotor**
  - Element thrust
    \[ dT_D = \frac{\rho N_b c}{4\pi} U_R^2 \left\{ a(\theta - \phi) \cos \phi - C_d \sin \phi \right\} \]
  - Inflow equation
    \[ 4v_d \sqrt{w^2 + 2wv_d \sin \psi + v_d^2} = \sigma U_R^2 \left\{ a(\theta - \phi) \cos \phi - C_d \sin \phi \right\} \]
Study of the Cycloidal Blade System

- **Flow tilting**
  - There is three causes of the flow tilting
  - 1\(^{st}\), different induced velocity between advancing and retreating side
  - 2\(^{nd}\), virtual camber effect
  - 3\(^{rd}\), Magnus effect

1. **different induced velocity**
   - The cause of difference is the blade drag force of the upstream half
   - The flow is tilted in rotating direction of the rotor
Study of the Cycloidal Blade System

2. Virtual Camber Effect

- Compared to the rotor radius, the chord length of blade is too long to ignore.
- The radius of the rotation varies along the chord. This causes the varied rotation velocity.
- Like cambered airfoil blades, the angle of attack at each point along the chord is different.
- The angle of attack by camber effect is

$$\alpha_{\text{camber}} = \frac{2}{C_{L_0}} \pi \int_0^\pi \left( \theta - \theta_x \right) \left( \cos \theta_0 - 1 \right) d\theta_0$$
3. Flow tilting (Magnus effect)

- Another cause of the flow tilting is Magnus effect
- Analyzing CFD simulation, roughly to 5 deg effective angle of attack modulation (geometric modulation less the induced one) Refer from Iosilevskii, Gil, and Yuval Levy. (Israel) "Experimental and numerical study of cyclogiro aerodynamics." *AIAA journal* 44.12 (2006): 2866-2870.
- “Although the magnitude of the actual Magnus effect on the shaft cannot be accurately estimated, an approximate calculation disclosed that it would be at least a third of the observed lateral force.” Refer from Wheatley, John B., and Ray Windler. "Wind-tunnel tests of a cyclogiro rotor." (1935).
Study of the Cycloidal Blade System

- **Gyroscopic forces**
  - Two gyroscopic effects which influence the motion of an aircraft: the *precession and the nutation*
  - The torque-induced precession is explained using the principle of conservation of angular momentum

\[
\frac{\partial L}{\partial t} = M
\]

\[
\partial L / \partial t : \text{time rate of change in the angular momentum } L
\]
\[
M : \text{torque of the external forces applied to the body}
\]

- The precession translated to the flight dynamics of a cyclocopter with rotating cylinders (ex. it leads to a rolling motion, if a yawing moment is applied.)

\[
p = -\frac{M}{I_{zz} \omega_z}
\]

\[
p : \text{induced roll rate}
\]
\[
M : \text{aerodynamic yawing moment}
\]
\[
I_{zz} \omega_z : \text{angular momentum of the rotating rotor}
\]

- Nutation is a slightly irregular motion of the rotation axis.
- It can be observed if a gyroscope shows precession and, in addition, is disturbed by an external force.
- The effect of nutation might be observed as tumbling, as *yaw and roll angles are expected to oscillate at the same time.*
B. CFD Analysis of Cycloidal Blade System
CFD Analysis

- **Star-CD is attempted**
- **Set up the condition of simulation**
  - Sliding mesh
    - Rotor domain rotates
    - Pitch angle of each blade is changed
    - ASI (Arbitrary Sliding Interface) method
  - k-ε/Low Reynolds turbulence model
  - Mesh type
    - Structured and unstructured
  - Number of mesh
    - Blade domain: 9,020
    - Rotor domain: 98,400
    - Total mesh: 134,200
  - Boundary condition
    - Pressure and no slip wall
  - Parallel computing
    - 4 CPUs
CFD Analysis

- **Airflow around the rotating cycloidal rotor**
  - Induced flow
    : normal direction to the blade path
  - Downward flow
    : inclined direction by the inner airflow of the CBS rotor.
    : the inner airflow increases the resultant velocity at the right and lower position (270° < $\Psi$ < 360°), and it decreases the resultant velocity at the left and lower position (180° < $\Psi$ < 270°). Therefore, the non-symmetry downstream is occurred.
  - The area of induced flow is about 2 times as large as the area of downward flow
  - The speed of downward flow is about 2 times as large as the speed of induced flow
CFD Analysis

- Airflow

Stream line

Velocity field
CFD Analysis

- Individual blade force
- Individual blade torque
- Total rotor force

Lower part is larger than upper part in force and torque by camber effect
Not symmetric pressure distribution!

Lift coefficient vs. azimuth angle

Vertical force

Horizontal force

Lift coefficient, \( C_l \)
Azimuth angle, \( \phi \)
With camber effect
Without camber effect

Vertical force coefficient, \( C_y \)
Azimuth angle, \( \phi \)
With camber effect
Without camber effect

Horizontal force coefficient, \( C_x \)
Azimuth angle, \( \phi \)
With camber effect
Without camber effect

Upper rotor
Lower rotor

\( c/R = 0.375 \)
Flow Visualization of CFD results

- Cambered Airfoil

- If a cambered airfoil is used along the circumference of the rotor, the virtual camber angle will be zero.
- The cambered airfoil produce a much smaller wake and blade vortex interaction than symmetric one.

Study of the Cycloidal Blade System

- **Initial pitch angle (Preset angle)**

- Initial pitch angle can compensate the virtual camber effect
- The proper initial pitch angle could maximize the thrust per required power
- The thrust was maximized at about zero initial pitch angles as shown in CFD analysis
- Hence, in case of **cyclocopter**, the initial pitch angle **improves efficiency** but decreased the thrust
- In case of **wind turbine**, the initial pitch angle **should be applied** because its aim is maximizing efficiency
C. Experimental Studies of Cycloidal Blade System
A cycloidal blade system for fundamental experiments is designed to investigate its fundamental characteristics in hover.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blade</td>
<td>2, 3, 6</td>
</tr>
<tr>
<td>Rotating speed</td>
<td>0 ~ 600 RPM</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>0° ~ 35°</td>
</tr>
<tr>
<td>Rotor radius</td>
<td>0.4m, 0.45m, 0.5m</td>
</tr>
<tr>
<td>Phase angle</td>
<td>-70 ~ +110°</td>
</tr>
<tr>
<td>Chord</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Span</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Airfoil section</td>
<td>NACA 0012</td>
</tr>
</tbody>
</table>
Pitch Control System

Hub arm
Center of rotation
Pitch link
Eccentricity point

\[ \theta = \frac{\pi}{2} \cos^{-1}\left(\frac{a^2 - \hat{L}^2 + \hat{p}^2}{2a\hat{p}}\right) - \sin^{-1}\left(\frac{\varepsilon}{a} \cos\Psi + \varepsilon\right) \]

\[ \theta = \theta_n \sin(\Psi + \varepsilon) \]

Rotating disk
Non-rotating control block

Magnitude of thrust
Direction of thrust

Neutral state
Translation
Translation and rotation

Sinusoidal low pitch motion
Test setup and Instrumentation

- Six load cell ➔ Thrust
- Torque balance ➔ Torque and Power
- RPM checker ➔ Rotating speed
- Strain gauge ➔ Blade motion

Torque balance

\[ \text{Micro strain} \]

\[ \text{Applied torque, Nm} \]

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Experimental Result

Baseline Configuration ($N_b = 6, c = 0.15, R = 0.4, s = 0.8$)

- Forces increase in the quadratic fashion
- Maximum thrust = 4.5 kgf at 30 deg.
- Agreement between the analytical predictions and the experimental results is excellent

- Powers increase in the cubic fashion
- Comparing to the analytical predictions
  - Good up to 20 deg
  - Fair-to poor from 25 deg
Experimental Result

Baseline Configuration \((N_b = 6, c = 0.15, R = 0.4, s = 0.8)\)

- **Thrust vs. Amplitude of pitch angle**
  - Pitch angles are tested up to 30°
  - Magnitude of thrust can be adjusted by varying amplitude of pitch angles
  - Thrust increases almost linearly

- **Vertical force vs. Phase angle of eccentricity**
  - 450 RPM and 25° of pitch angle
  - Phase angle of eccentricity:
    - \(-70° \sim 110°\)
    - Max. vertical force between 10° and 20°
    - Not Max. vertical force in phase angle of 0°
  - Vertical forces disappear at -60° and 110°
Experimental Result

Effect of the rotor radius

- Thrust of six-bladed rotor at 400 RPM & 20° phase angle
  - $R = 0.4 \text{m} : 1.7 \text{kgf}$
  - $R = 0.45 \text{m} : 2.5 \text{kgf}$
  - $R = 0.5 \text{m} : 3.3 \text{kgf}$

- Power loading
  - Fixed tip speed : 15.7 m/s
    - $R=0.5 \Rightarrow 7 \text{kgf/HP}$
    - $R=0.4 \Rightarrow 6 \text{kgf/HP}$
    - Helicopter $\Rightarrow 3\sim4 \text{kgf/HP}$

- The larger rotor, the better efficiency
  (The lower solidity, the better efficiency)

The aircraft with cycloidal rotor can be efficient in hover compared with helicopter and other VTOL aircraft.
Experimental Result

Effect of number of blade

- 2 bladed, 3 bladed, 6 bladed
- Thrust increase with $N_b$
  - $2N_b : 2.9$ kgf
  - $3N_b : 3.5$ kgf
  - $6N_b : 4.1$ kgf
- 2 bladed rotor
  - Vibration is severe
- Efficiency
  - $(N_b = 3) > (N_b = 2) > (N_b = 6)$
  - $N_b = 6 \rightarrow$ Profile drag increase
  - Thrust($N_b=3$) > Thrust ($N_b=2$)
- Thrust vs. rotor radius
  - Thrust does not increase linearly as the number of blade increases
Comparison : Power Loading

Comparison of cycloidal blade system with various helicopters for the power loading

<table>
<thead>
<tr>
<th>Rotorcraft</th>
<th>Ideal PL</th>
<th>Actual PL</th>
<th>Estimated PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS 350</td>
<td>8.15</td>
<td>3.87</td>
<td>5.70</td>
</tr>
<tr>
<td>MD-500</td>
<td>7.33</td>
<td>3.89</td>
<td>5.13</td>
</tr>
<tr>
<td>Agusta A109</td>
<td>7.25</td>
<td>3.52</td>
<td>5.07</td>
</tr>
<tr>
<td>CH-47</td>
<td>7.12</td>
<td>3.25</td>
<td>4.98</td>
</tr>
<tr>
<td>AH-1</td>
<td>6.70</td>
<td>3.52</td>
<td>4.69</td>
</tr>
<tr>
<td>AS 365</td>
<td>6.35</td>
<td>3.70</td>
<td>4.44</td>
</tr>
<tr>
<td>Lynx</td>
<td>6.23</td>
<td>2.59</td>
<td>4.36</td>
</tr>
<tr>
<td>AS 332</td>
<td>5.66</td>
<td>3.17</td>
<td>3.96</td>
</tr>
<tr>
<td>UH-60</td>
<td>5.51</td>
<td>3.13</td>
<td>3.85</td>
</tr>
<tr>
<td>CH-53</td>
<td>4.45</td>
<td>2.34</td>
<td>3.11</td>
</tr>
</tbody>
</table>

Cycloidal rotor | 6.0 kg/HP

$PL_e = PL_i \times FM$

The Power Loading of Cycloidal Rotor is the highest according to this table.
Comparison: Analyses and Experiments

- Comparison of CFD and analytical data with experimental data

The comparison of results shows that the CFD analysis of the CBS offers the very accurate results when compared with the experimental results.

CFD analyses would be essential tool for the design of the cycloidal rotor system.
Introduction – Research progress in SNU

• Development of UAV Cyclocopter, 1st version (2003.03 ~ 2004.12)
  – Development of unmanned VTOL vehicle
  – Optimal rotor design by parametric study
  – Two rotors with same rotating direction

Blade design and manufacturing
Control mechanism
Thrust variation
Introduction – Research progress in SNU

• Development of UAV Cyclocopter, 2nd version (2005.01 ~ 2005.12)
  – Rotor design by simulation based optimization
  – Anti-torque and maneuvering by tandem rotor configuration
  – Powered by brushless motors and Li-Po batteries
Introduction – Research progress in SNU

- Development of Mini Cyclocopter, 1st version (2005.07 ~ 2005.10)
  - Two rotors rotating in opposite direction for the rotor torque compensation
  - Powered by brushless motors
  - Success in maintaining hovering state
Introduction – Research progress in SNU

- Development of Mini Cyclocopter, 2nd version (2006.01 ~ 2006.07)
  - Two main rotors rotating in the same direction and tail rotor is added for the torque compensation of the main rotors
  - Up & down / left & right motion to change thrust direction and thrust magnitude
  - Using gyro for attitude control
Cyclocopter mini 3

- Development of new Cyclocopter with 4 rotors

- The aircraft consists of four rotors, and two pairs of rotors rotate in opposite direction to compensate anti-torque
- Each rotor has four elliptic blades
- The blade is supported at center position to be connected with the hub arm
- The rotors are operated by their own motor systems and control devices

- Rotor design by CFD and FE structural analysis
- Control mechanism design using swash plate
- Power transmission by brushless motors and timing belts
- Experimental measurement of thrust and required power
Cyclocopter mini 3

- **Movement of thrust center**

![Diagram of CG of cyclocopter and maneuvering for pitching and rolling motion.](image-url)
Cyclocopter mini 3

• **Experiment of the Cyclocopter with 4 rotors**

  – Total weight of cyclocopter: 12kg (including 4 Li-Po batteries & landing gear)
  – 4 brushless motors (Plettenberg Orbit30 model)
  – 2 gyros (Futaba GYA352 model)

  – Experimental result
    • Thrust: 16 kgf
    • Power: 3.5 hp
    • Rotating conditions
      : 1100rpm and pitch angle 25°
Cyclocopter mini 4

**Mini Cyclocopter, 4th version (2009)**

- The aircraft consists of **four rotors**, and two pairs of rotors rotate in opposite direction to compensate anti-torque.
- The rotors are operated by their own motor systems and control devices.
- **Swash plate** and several connecting devices are newly designed to reduce instrumental errors.
- Power transmission by **brushless motors (4EA)** and timing belts (2EA).

<table>
<thead>
<tr>
<th>Cyclocopter design variables</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Rotating speed</td>
<td>1200 rpm</td>
</tr>
<tr>
<td>Radius of rotor</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Span of blade</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Airfoil</td>
<td>NACA 0018</td>
</tr>
<tr>
<td>Weight</td>
<td>12 kg</td>
</tr>
<tr>
<td>Total thrust</td>
<td>16.4 kgf</td>
</tr>
</tbody>
</table>
Cyclocopter mini 4

- **Power plant**
  - Model: Orbit 30-12
  - DC brushless motors (4EA)
  - Experimental performance: output power is 1067 W with 22.4V and 57.4A (efficiency: 0.83) at 12070 rpm
  - Weight: 305 g
  - Model: PQ-B5000N-CP
  - Lithium-polymer battery
  - Rated voltage: 22.2 V (6 unit cells of 3.7 V)
  - Capacity: 5000 mAh
  - Discharge rate: continuous 22C (110A)
    - sustain (<30sec) 30C (150A)
    - burst (<5sec) 50C (250A)
Cyclocopter mini 4

- **Pitch angle control**

  - Servo No.1: control of blade pitch angles at up/down positions (azimuth angles 90° and 270°)
    up/down direction thrust
  - Servo No.2: control of blade pitch angles at left/right positions (azimuth angles 0° and 180°)
    back/forth direction thrust
• **Improvement of control parts**

Diagram of control mechanism: mini3 & mini4

- The location of control point is moved from T.E. to L.E.
  - The blade C.G. location is also moved close to the quarter-chord point
- The linkage connecting to the servo motor is changed to dual bridge
  - The blade pitch angle change could be more accurate
- More simplified control mechanism
Cyclocopter mini 4

- **Power transmission**

  - Reduction ratio: 9 : 1
  - Timing belt – pulley
  - Main shaft;
    - Carbon composite pipe
    - Diameter of 25.0mm & thickness of 1.0mm
  - Modification;
    - Main shaft of left and right rotor is almost connected
    - Remove sub shaft (located inside the main shaft in mini3)
    - Belt-pulley structure is modified from individual rotor operation to dual running
      (number of pulleys: 4 → 2EA)
Cyclocopter mini 4 - Manufacturing

- Manufacturing process of blade

1. Blade Master & Mold Modeling using CATIA
2. Mold & Rib Manufacturing by CNC
3. Mold Waxing & Painting
4. Skin laminating with Glass/Epoxy composite
5. Assembling Skin & Roving & Rib & Spar
6. Rectangular Composite Blade
Cyclocopter mini 4 - Manufacturing

- **Fuselage**

  - In mini3, central part of the fuselage structure is relatively weak to twist motion
  - To modify the structure, the design is changed as follows;
    - Belt-pulleys are installed inside the fuselage which is shown as “V” shape.
    - In addition, the connecting parts of fuselage plates are changed from rods (aluminum 6061) to plates (aluminum 2024)
Cyclocopter mini 4 - Experiment

- **Single rotor test**

  - Install one-rotor system on measuring units: Lift force and rotating speed are measured
  - Loadcells and a rpm gage are used and experimental data are visualized by LABVIEW
A. Development of Cyclocopter Mini 5
Cyclocopter Mini 5

Mini Cyclocopter, 5th version

- New mechanical pitching system and semi-monocoque hub for flow efficiency
- Power transmission by single brushless motor and timing belts (2EA)

<table>
<thead>
<tr>
<th>Cyclocopter design variables</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating speed</td>
<td>1100 rpm</td>
</tr>
<tr>
<td>Radius of rotor</td>
<td>0.27 m</td>
</tr>
<tr>
<td>Span of blade</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Airfoil</td>
<td>NACA 0018</td>
</tr>
<tr>
<td>Weight</td>
<td>12.8 kg</td>
</tr>
<tr>
<td>Total thrust</td>
<td>16.32 kgf</td>
</tr>
</tbody>
</table>

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Quadrotor Cyclocopter

- Development of Quadrotor Cyclocopter

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rotors</td>
<td>4</td>
</tr>
<tr>
<td>Number of blades</td>
<td>4</td>
</tr>
<tr>
<td>(per one rotor)</td>
<td></td>
</tr>
<tr>
<td>Airfoil</td>
<td>NACA0018</td>
</tr>
<tr>
<td>Rotor radius</td>
<td>0.27 m</td>
</tr>
<tr>
<td>Blade span length</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Blade Chord length</td>
<td>0.105m</td>
</tr>
<tr>
<td>(at center position of the blade)</td>
<td></td>
</tr>
<tr>
<td>Max. pitch angle</td>
<td>25°</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>1100 RPM</td>
</tr>
<tr>
<td>Thrust</td>
<td>16 kgf</td>
</tr>
<tr>
<td>(Total thrust of four rotors)</td>
<td></td>
</tr>
<tr>
<td>Weight of vehicle</td>
<td>12.8 kg</td>
</tr>
</tbody>
</table>
Quadrotor Cyclocopter

- **Hub-spoke shape and rotor control mechanism**
  - Hub-spoke: two plates connected with cross members → semi-monocoque structure
  - Control mechanism: swash plate type → pitch-phase control type
Quadrotor Cyclocopter

- Composite rotor manufacturing

- Mold
- Upper & lower skin
- De-molding
- Assembly & balancing
- Composite blade
Quadrotor Cyclocopter

- **Attitude control of the vehicle**

(Side view)

(Front view)

(Top view)
Quadrotor Cyclocopter

- **Flight control system**
Quadrotor Cyclocopter

- **Motor and FCS**
  - Electric motor and its controller

- **FCS and AHRS**
Experimental Setup

- **Ground test bed**
  - Four load cells measuring vertical forces and thrust center
  - A load cell measuring horizontal force
  - A tachometer and a digital power meter measuring rotational speed and consumed power
Single Rotor Test

- **Performance**

Battery-to-rotor efficiency = 0.75 (assumed)

(5.24 kgf, 3.13 kgf/HP)

(5.24 kgf, 4.17 kgf/HP)
Single Rotor Test

- **Direction of thrust**
  - Inclined angle ≈ 20°

- **Ground effect**
  - In this research, it is assumed that ground effect on the rotor is negligibly small
Dual Rotor Test

- Reduced efficiency of 3 kgf/HP
- Phase angle of the control device
  - Horizontal forces between two rotors are cancelled out because horizontal forces from the two rotors have almost same magnitude but acts in opposite directions
  - The direction of the resultant force is upward
  - When the phase angle of the control device is set to 20°, dual rotor has the ability to generate more powerful and efficient thrust than the case of 0°

CASE : RPM : 1100, Max. pitch angle : 15°
Quad Rotor Test

- **Determined operating condition**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. pitch angle</td>
<td>22°</td>
</tr>
<tr>
<td>Phase angle of the control device</td>
<td>+ 20°</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>1100 RPM</td>
</tr>
<tr>
<td>Measured Thrust (on the test bed)</td>
<td>16.32 kgf</td>
</tr>
<tr>
<td>Weight of vehicle</td>
<td>12.8 kg</td>
</tr>
<tr>
<td>Consumed electric power (for thrust of 16.32 kgf)</td>
<td>4300 W</td>
</tr>
<tr>
<td>Efficiency (kgf/HP)</td>
<td>2.83 kgf/HP</td>
</tr>
<tr>
<td>Power loading (estimated)</td>
<td>3.77 kgf/HP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. pitch angle (for hovering)</td>
<td>&lt; 20°</td>
</tr>
<tr>
<td>Consumed electric power (for hovering)</td>
<td>&lt; 3000 W</td>
</tr>
<tr>
<td>Efficiency (kgf/HP)</td>
<td>3.18 kgf/HP</td>
</tr>
<tr>
<td>Power loading (estimated)</td>
<td>4.24 kgf/HP</td>
</tr>
</tbody>
</table>
Experimental Setup

- Recirculation effect was observed during the tethered tests in the indoor environment
- Tethered tests were performed in the outdoor environment by using a high tower crane
- PID gains of the FCS were adjusted to appropriate values
Movie Clips of Experiments

VTOL UAV Cyclocopter Flight Test

SNU ASL
Outdoor Flight Demonstration

VTOL UAV
Cyclocopter
Outdoor Flight

SNU ASL
B. Development of Twin Rotor Cyclocopter
# Twin Rotor Cyclocopter

- **The 110kg class two-rotor UAV cyclocopter**

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length with rotors</td>
<td>3,152mm</td>
</tr>
<tr>
<td>Height</td>
<td>2,310mm</td>
</tr>
<tr>
<td>Width</td>
<td>4,200mm</td>
</tr>
<tr>
<td>Weight</td>
<td>110kg</td>
</tr>
<tr>
<td>Diameter</td>
<td>2,000mm</td>
</tr>
<tr>
<td>Span length</td>
<td>1,500mm</td>
</tr>
<tr>
<td>Airfoil</td>
<td>NACA0018</td>
</tr>
<tr>
<td>Chord length</td>
<td>247mm</td>
</tr>
<tr>
<td>RPM</td>
<td>420RPM</td>
</tr>
<tr>
<td>Pitch angle</td>
<td>0~35º</td>
</tr>
<tr>
<td>Type</td>
<td>4-stroke single rotor rotary engine</td>
</tr>
<tr>
<td>Power</td>
<td>44 HP at 8750rpm(MAX)</td>
</tr>
<tr>
<td></td>
<td>29 HP at 5900rpm (continuous)</td>
</tr>
<tr>
<td>Chamber Vol.</td>
<td>294cc</td>
</tr>
</tbody>
</table>
## Twin Rotor Cyclocopter

### Various cycloidal rotor configurations

<table>
<thead>
<tr>
<th></th>
<th>Quad-rotor</th>
<th>Twin-rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control Algorithm</strong></td>
<td>Similar to the quad-rotor propeller type</td>
<td>A little complex for decoupling roll-yaw motion</td>
</tr>
<tr>
<td><strong>Flow pattern</strong></td>
<td>Flow interference in back and forth rotor</td>
<td>Simpler than quad-rotor</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>Complex</td>
<td>Simple</td>
</tr>
<tr>
<td><strong>Power transmission</strong></td>
<td>Dividing power into two main axis</td>
<td>Locating engine near the main axis, the gearbox can be compact</td>
</tr>
<tr>
<td><strong>Forward flight</strong></td>
<td>Disadvantage (lift difference between back and forth rotor)</td>
<td>Advantage (Main rotor operate like main wing of airplane)</td>
</tr>
</tbody>
</table>

- **Two rotors rotating in same direction and a tail rotor**
- **Four rotors of tandem configuration**
Twin Rotor Cyclocopter

- **Specifications**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length with rotors</strong></td>
<td>3,152mm</td>
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<tr>
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<td>2,310mm</td>
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<tr>
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<td>4,200mm</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>110kg</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
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</tr>
<tr>
<td><strong>Span length</strong></td>
<td>1,500mm</td>
</tr>
<tr>
<td><strong>Airfoil</strong></td>
<td>NACA0018</td>
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<tr>
<td><strong>Chord length</strong></td>
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</tr>
<tr>
<td><strong>RPM</strong></td>
<td>420RPM</td>
</tr>
<tr>
<td><strong>Pitch angle</strong></td>
<td>0~35º</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>4-stroke single rotor rotary engine</td>
</tr>
<tr>
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<td>44 HP at 8750rpm (MAX)</td>
</tr>
<tr>
<td></td>
<td>29 HP at 5900rpm (continuous)</td>
</tr>
<tr>
<td><strong>Chamber Vol.</strong></td>
<td>294cc</td>
</tr>
</tbody>
</table>
Twin Rotor Cyclocopter

- Attitude Control scheme
Twin Rotor Cyclocopter

- The base frame, FCS and engine of REMO-H were used

  ** REMO-H is commercial UAV helicopter for spraying agriculture chemicals. REMO-H is made and sold by SUNGWOO Engineering in KOREA.**
Twin Rotor Cyclocopter

- **FCC (Flight Control Computer)**

  - Processor: 150MHz Embedded Processor
  - Channel: 8ch control signal
  - Sensor: position, velocity and attitude sensor
  - Weight: 2kg
  - Size: 170 x 200mm

* Provided by Flight dynamics & control Lab. in Chungnam Nat’l Univ.
Twin Rotor Cyclocopter

- Power transmission
  - Water cooling system was equipped
  - The 12V alternator changes the battery for electronic control system (Servo, Receiver, FCS, etc.)
Twin Rotor Cyclocopter

- **Power transmission**

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>type</strong></td>
<td>4-stroke single rotor rotary engine</td>
</tr>
<tr>
<td><strong>power</strong></td>
<td>33 kW at 8750 rpm</td>
</tr>
<tr>
<td><strong>weight</strong></td>
<td>ca. 17 kg</td>
</tr>
<tr>
<td><strong>torque</strong></td>
<td>39 Nm at 7500 rpm</td>
</tr>
<tr>
<td><strong>chamber volume</strong></td>
<td>294 cc</td>
</tr>
<tr>
<td><strong>max. rpm</strong></td>
<td>11,000 rpm</td>
</tr>
<tr>
<td><strong>ignition</strong></td>
<td>PVL Fire 650</td>
</tr>
<tr>
<td><strong>clutch</strong></td>
<td>2-disc dry centrifugal clutch</td>
</tr>
</tbody>
</table>

- Lack of vibration due to balanced rotating masses
- The extreme performance with a very flat torque curve
Twin Rotor Cyclocopter

- **Main rotor**
  
  - Extended Blade length (1m => 1.5m)
  - To reduce bending stress, the blade length is increased to inboard and outboard for 150mm and 250mm, respectively.
Twin Rotor Cyclocopter

- **Shaft whirling**
  - Critical speed of shaft whirling is calculated
  - Whirling speed by concentrated mass at tip of cantilever shaft;

\[
\Omega^2 = \Omega_0^2 \left(1 - \frac{4Ap l^2}{\pi^2 EI}\right) \quad \Omega_0 = \frac{3.67}{l^2} \sqrt{\frac{EI}{\rho A}}
\]

\[
\begin{align*}
E & : \text{elastic modulus (68.9 GPa)} \\
I & : \text{area moment of inertia (6.275e-7 m}^4) \\
p & : \text{concentrated mass + thrust (50 kgf)} \\
\rho & : \text{density of shaft (2700 kg/m}^3) \\
A & : \text{cross sectional area of shaft (8.47e-4 m}^2) \\
\end{align*}
\]

Shaft material : AL6063

- Critical speed of shaft whirling is **3,633 rpm**
Twin Rotor Cyclocopter

- **Applications for the drag reduction**
  - Using the equation of “Drag of Wings with End Plates” Naca report 267

\[
\Delta C_D = \frac{C_L^2 S}{\pi b^2} \frac{1.66 \left( \frac{2h}{b} \right)}{1 + 1.66 \left( \frac{2h}{b} \right)} - 2C_F \left( \frac{2h}{b} \right)
\]

\[
\begin{align*}
2h & : \text{height of end plate (0.125m)} \\
b & : \text{span of wing (1.5m)} \\
C_L & : \text{lift coefficient (2\pi\alpha)} \\
S & : \text{area of wing (0.3705m^2)} \\
C_F & : \text{frictional drag coefficient} \\
\alpha & : \text{blade pitch angle}
\end{align*}
\]

- If the frictional drag of the end plates is neglected,

\[
\Delta C_D = 0.25146\alpha^2
\]

1.54HP saving power

Calculating drag of two main rotors
Twin Rotor Cyclocopter

- **Tail rotor configuration**
  - Tail rotor configuration and CG position
    
    \[
    \begin{align*}
    F_M & = \text{Main rotor thrust} \\
    F_T & = \text{Tail rotor thrust} \\
    T_M & = \text{Main rotor position from CG} \\
    \end{align*}
    \]

- It is determined that the tail rotor produces approximately 14.85kgf
- The size of tail rotor is designed for compensating anti-torque and plus sufficient force of pitching motion

<table>
<thead>
<tr>
<th>Main rotor consume power (HP)</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main rotor rotation speed (RPM)</td>
<td>420</td>
</tr>
<tr>
<td>Main rotor position from CG (mm)</td>
<td>50</td>
</tr>
<tr>
<td>Tail rotor position from CG (mm)</td>
<td>2,250</td>
</tr>
</tbody>
</table>
Twin Rotor Cyclocopter

- Cam-path control mechanism

- Control mechanism: Fixed & Pinned type → Cam-path type
- The control link bearings are passed along the cam-path
- Advantage: Axisymmetric control mechanism
  All pitch angle paths are same
Twin Rotor Cyclocopter

- Cam-path control mechanism

Upward & Downward thrust control
Backward & Forward thrust control
Twin Rotor Cyclocopter

- Test bed

- Five tension-compression load cells are installed
- Three load cells are placed in a triangular arrangement and measure the magnitude of the lift force, rolling moment and pitching moment
- The other two load cells measure the forward-backward force and yawing moment
Twin Rotor Cyclocopter

- Ground test
Twin Rotor Cyclocopter

- **Result of the ground test**

  - The test result shows similar tendency to CFD and analytical data
  - The test result values a little bigger than the expected ones (Ground effect)
Twin Rotor Cyclocopter

- Tethered test
Twin Rotor Cyclocopter in tethered test
Twin Rotor Cyclocopter in tethered test
Twin Rotor Cyclocopter

- **Result of the tethered test**

  - Left side graph shows coupled rolling and yawing motions because of gyroscopic precession and nutation.
  - The graph of rolling and yawing rate shows similar tendency.
  - Right side graph shows stable hover flight motion under the tethered condition.
Contents

1. Introduction of Cyclocopter

2. Cyclocopter Design Studies

3. Flight Vehicle Developments

4. Tests and Flight Demonstrations

5. Concluding Remarks
Concluding Remarks

- **The continued research efforts of Cyclocopter since 2000 were introduced**
  - The analytic, the computational and the experimental approaches for the parametric design practice were done to understand the fundamental characteristics of Cycloidal Blade System
  - The causes of flow tilting were identified as the drag of rotating blades, virtual camber effect and Magnus effect
  - To compensate the virtual camber effect, cambered airfoil or initial pitch angle could be used
  - Setting the initial pitch angle could reduce the tangential drag on the blade

- **The series of UAV Cyclocopter were developed and tested extensively**
- **More elaborate research may need for more efficient design of Cyclocopter**
- **Technologies obtained by the Cyclocopter research would be easily applied to the Vertical Axis Wind Turbine and the Water Turbine with efficiency for the Electricity Generation**
Concluding Remarks

- CBS concept appeared 100 years ago, but it becomes a real aircraft at the Aerospace Structures Laboratory in SNU in the 21st century
- Cyclocopter has many advantages as an rotary wing aircraft

**Good Power Loading**
- Higher thrust output at the same power input

**Good Hovering Performance**
- Cyclocopter rotor could be designed for efficient hovering performance

**Low Aerodynamic Noise**
- Much lower rotor blade vortex interaction noise

**Same Vehicle Attitude at Forward Flight**
- Do not need to tilt the rotor or vehicle during forward flight
Thank you.

Q&A