ICAS Daniel & Florence GUGGENHEIM MEMORIAL LECTURE

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

Prof. Seung Jo KIM
with
4 Doctors
& 16 Masters

Phase I (2000~2003)


Chul Yong YUN


Dae Sung KIM


Young Ha YOON


Ill Kyung PARK


Jai Sang JUNG

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

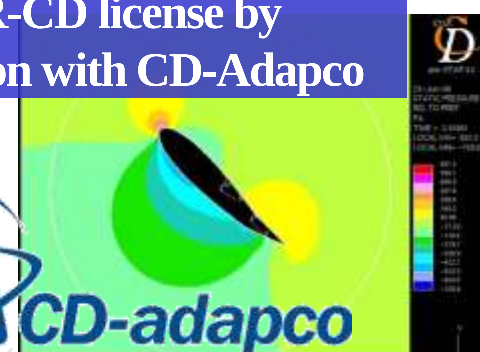
1	No government funding at all !!
2	Generous funding on supercomputing related research from Microsoft

Microsoft

MOU between SNU and MS, Intel and Samsung

Cyclocopter and Pegasus Cluster Supercomputer

STAR-CD license by cooperation with CD-Adapco



CD-adapco


TOP500 CERTIFICATE

Manufactured by Self-made at

Seoul National University, Korea

is ranked

No. 56

among the world's TOP500 Supercomputers with

Congratulations from The TOP500 Editors

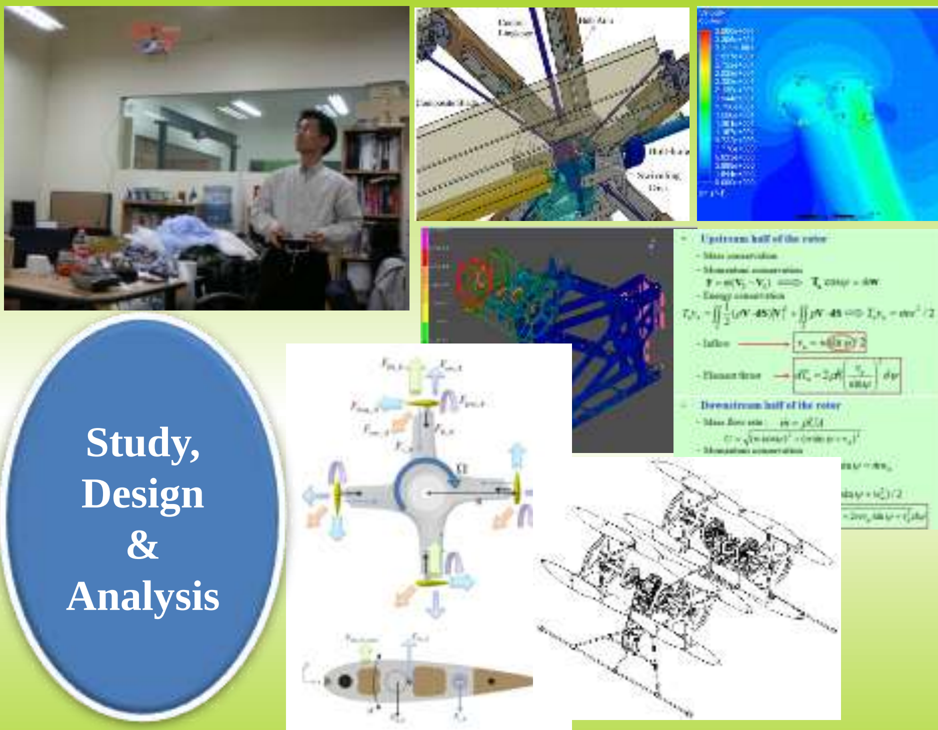
56th Rank among Top500 Supercomputers

Unique Features of Cyclocopter Related Research

3	**Dedicated and self motivated graduate students for the creation of Cyclocopter**
4	**Positive Inflow of able students who are already confident on design, manufacturing and flying of model aircrafts when they enter our laboratory**

Unique Features of Cyclocopter Related Research

5 Almost every design, analysis, manufacturing and flight tests were done in our Laboratory



Study, Design & Analysis

Step I : Student Room

Metal Composite Parts & Assembly

Step II : Manufacturing Facilities

"Materials in, Cyclocopters out"

as what SpaceX of Elon Musk is doing "Materials in, Rockets out"

Unique Features of Cyclocopter Related Research

5 Almost every design, analysis, manufacturing and flight tests were done in the Laboratory

Thrust & Power Measurement Ground Test

Step III : Experimental Room

Ground & Flight Test

Step IV : Outdoor 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**)

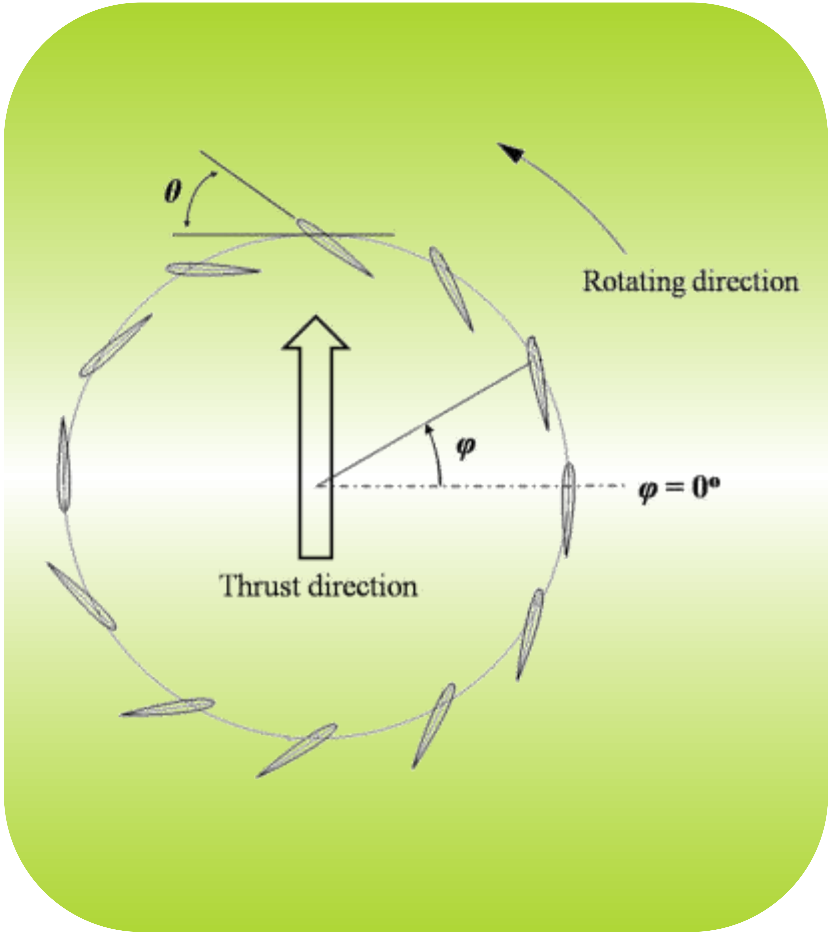
7 Taking longer time to finish Ph.D while doing the Cyclocopter research (**No publish, No graduation Policy!**)

Contents

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

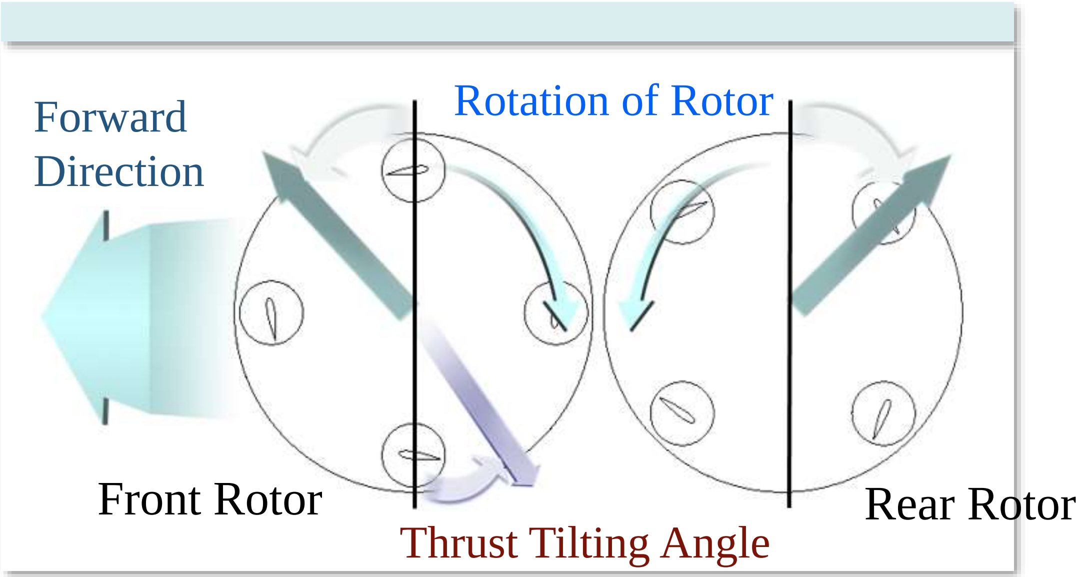


Cycloidal Blade System

- 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

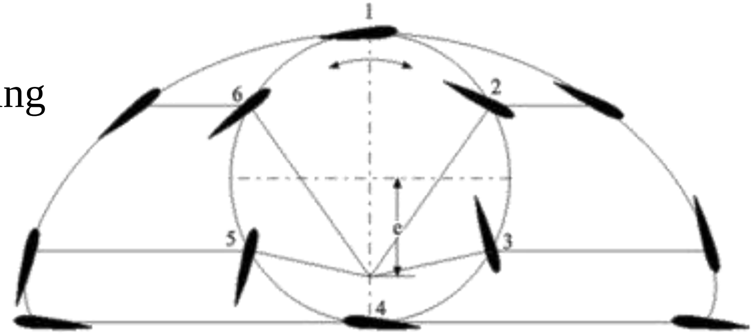
Introduction - Cycloidal Blade System

- **Dual Rotor Conceptual Configuration**



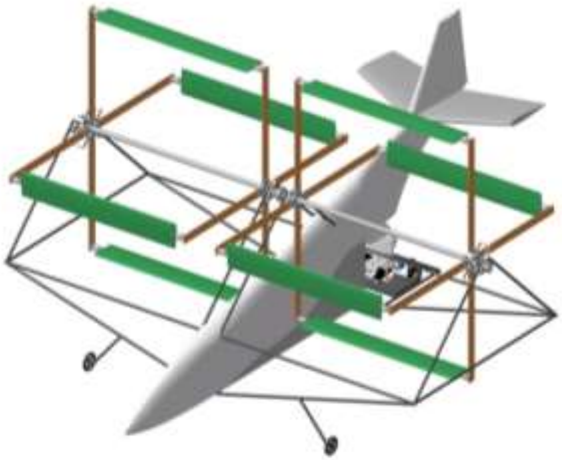
Blade pitch angle variation of cycloidal blade system

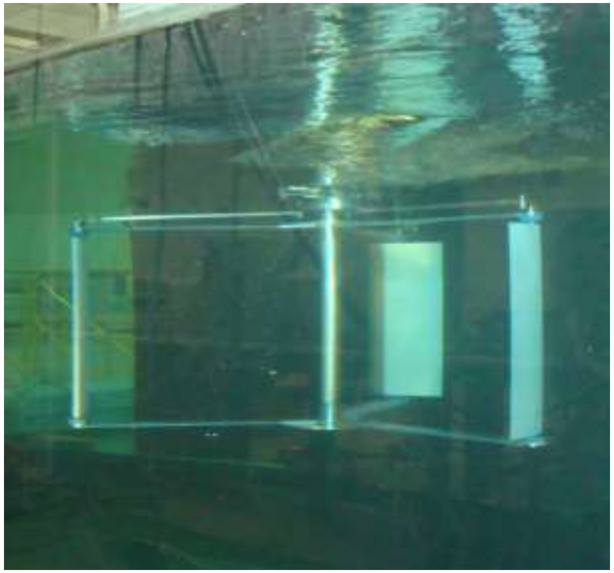
- **Low-Pitch System**
  - Low speed forward flight & hovering
  - Small pitch variation



Applications of Cycloidal Blade System

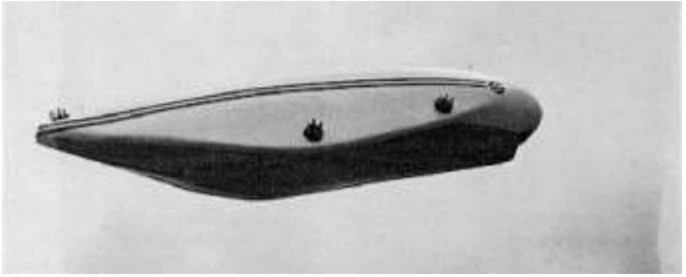
- **Cyclocopter**
  - Vertical Take-off and Landing Aircraft
- **Wind / Water turbine**
  - Vertical axis turbine with active variable pitch control mechanism
  - Rotor efficiency enhancement by cycloidal blade system or individual blade control method

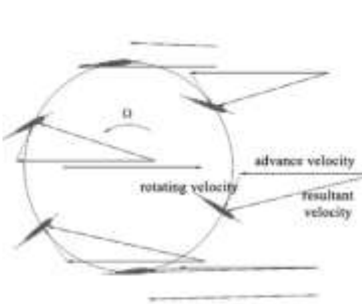




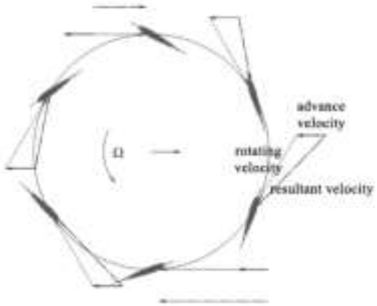
Introduction – History

- **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





High pitch system

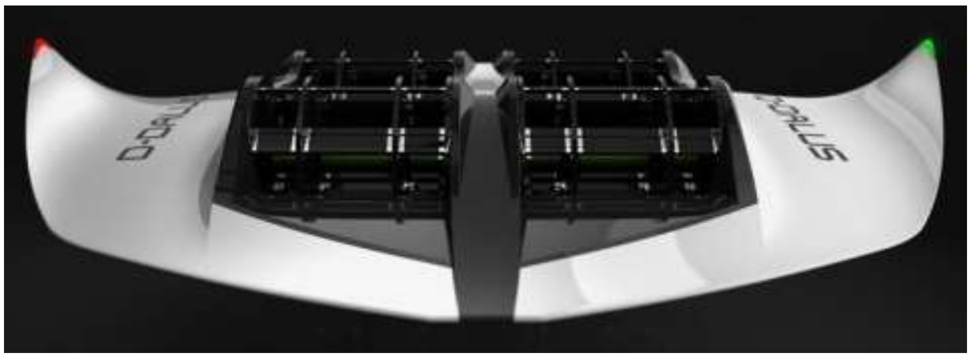


Low pitch system

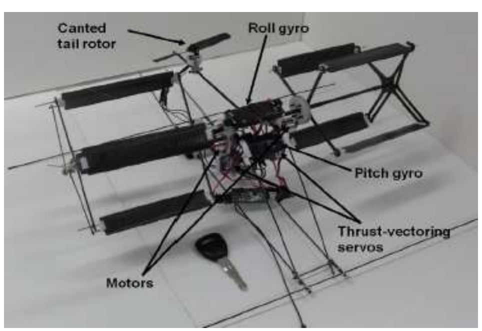
- **Other Research in the 1990's and 2000's**
  - Bosch Aerospace
    - Ground test for six-bladed cycloidal rotor
  - University of Maryland after us
    - Development of Cycloidal rotor for Micro-Air Vehicle Applications

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.

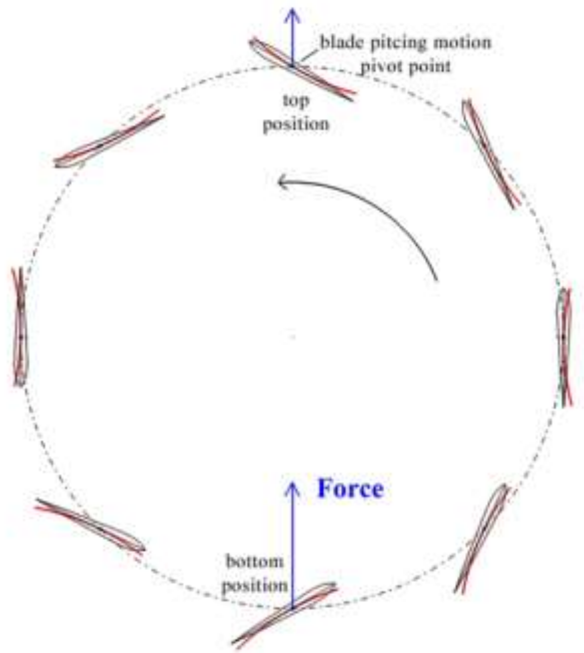


- **Similar projects are being studied in USA, Israel, Singapore, Japan, etc.**



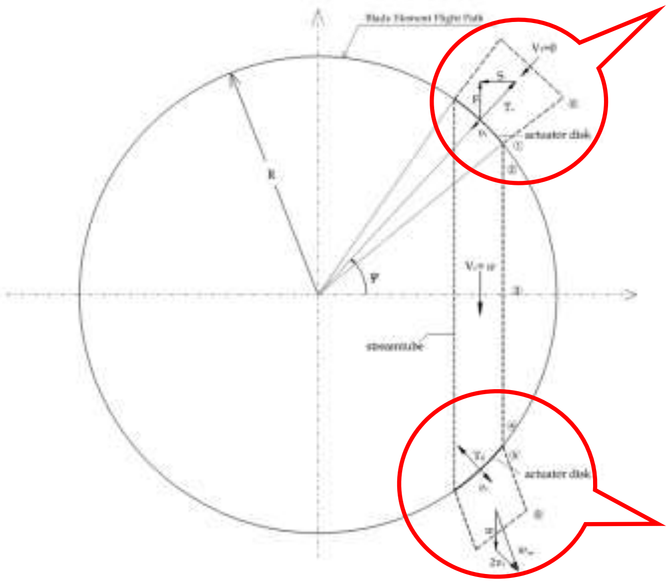
Contents

A. Aerodynamic Analysis of Cycloidal Blade System



Aerodynamic theory of cycloidal blade system

- **Momentum theory**



Assumptions

- **Multiple streamtube model**
  - Upstream half of the rotor
  - Downstream half of the rotor
- **Infinitesimal thin actuator cylinder**
- **Flow : perpendicular to actuator cylinder**

- **Upstream half of the rotor**
  - Mass conservation
  - Momentum conservation

$$\mathbf{F} = \dot{m}(\mathbf{V_2} - \mathbf{V_1}) \Longrightarrow \mathbf{T_u} \cos\psi = \dot{m}\mathbf{w}$$

  - Energy conservation

$$T_u v_u = \iint_S \frac{1}{2}(\rho \mathbf{V}\cdot\mathbf{dS})|\mathbf{V}|^2 + \iint_S p\mathbf{V}\cdot\mathbf{dS} \Longrightarrow T_u v_u = \dot{m}w^2/2$$

  - Inflow → $v_u = w\sin\psi/2$
  - Element thrust → $dT_u = 2\rho R\left(\frac{v_u}{\sin\psi}\right)^2 d\psi$

- **Downstream half of the rotor**
  - Mass flow rate : $\dot{m} = \rho U A$

$$U = \sqrt{(w\cos\psi)^2 + (w\sin\psi + v_d)^2}$$

  - Momentum conservation

$$dT_d = \dot{m}(w_\infty + w\sin\psi) - \dot{m}w\sin\psi = \dot{m}w_\infty$$

  - Energy conservation

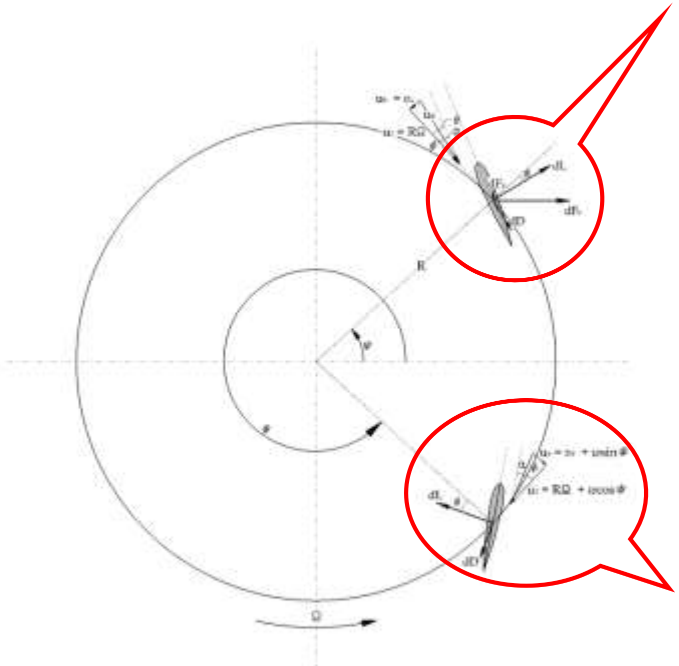
$$dT_d(v_d + w\sin\psi) = \dot{m}(2ww_\infty \sin\psi + w_\infty^2)/2$$

  - Element thrust $dT_d = 2\rho R v_d \sqrt{w^2 + 2wv_d\sin\psi + v_d^2}\, d\psi$

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 : $\phi = \tan^{-1}(U_P / U_T)$



Perpendicular component : $U_P = w\sin\psi + v_d$
Tangential component : $U_T = R\Omega + w\cos\psi$

- **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

$$dL = \frac{1}{2}\rho U_R^2 \left(\frac{N_b d\psi}{2\pi}\right) cC_l = \frac{\rho N_b c}{4\pi} U_R^2 a(\theta - \phi) d\psi$$

$$dD = \frac{\rho N_b c}{4\pi} U_R^2 C_d d\psi$$

  - Element thrust $dT_U = dL\cos\phi - dD\sin\phi$
  - Inflow equation

$$4\kappa_{emp}\lambda^2 = \sigma a(1+\lambda^2)\left\{(\theta-\phi)\cos\phi - \frac{C_d}{a}\sin\phi\right\}\sin^2\psi$$

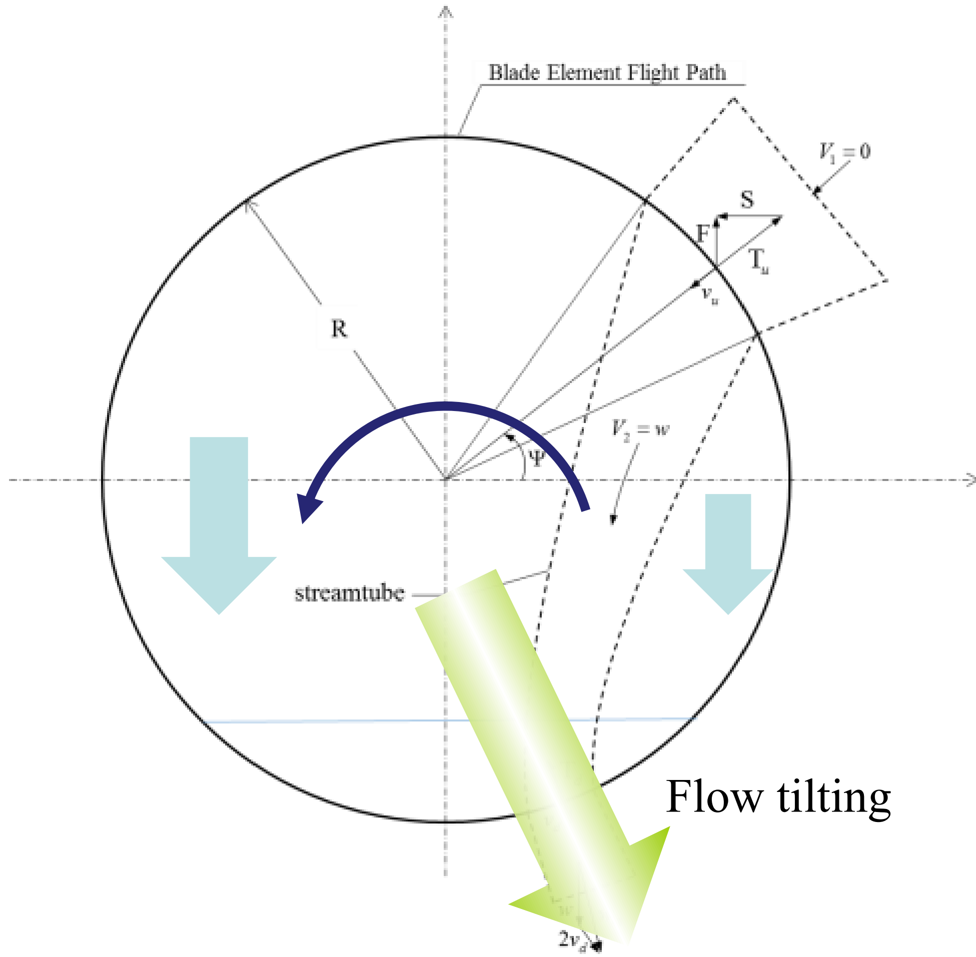
- **Downstream part of the rotor**
  - Element thrust
  - Inflow equation

$$dT_D = \frac{\rho N_b c}{4\pi} U_R^2 \{a(\theta-\phi)\cos\phi - C_d \sin\phi\}$$

$$4v_d\sqrt{w^2 + 2wv_d\sin\psi + v_d^2} = \sigma U_R^2\{a(\theta-\phi)\cos\phi - C_d\sin\phi\}$$

Study of the Cycloidal Blade System

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

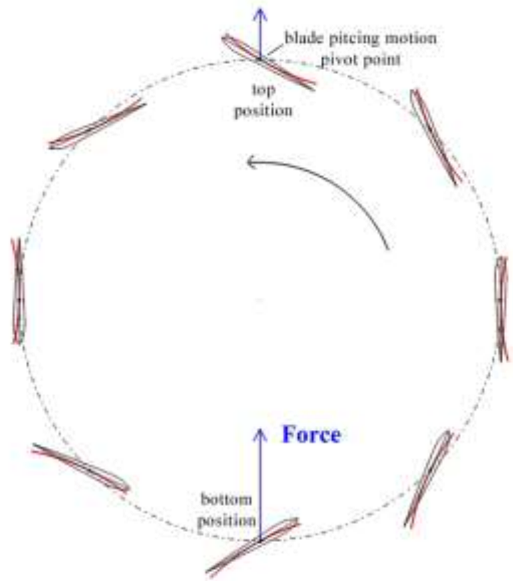


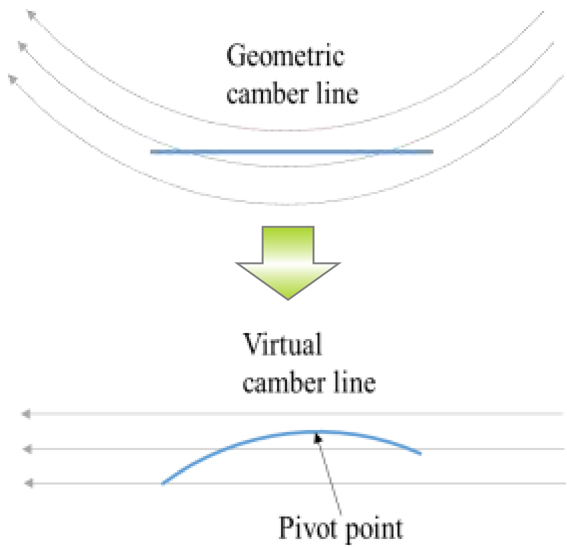
1. different induced velocity

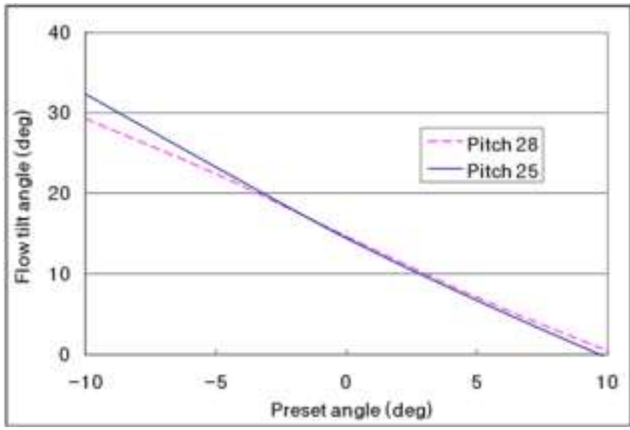
- The cause of difference is the blade drag force of the upstream half
- The flow is tilted in rotating direction of the rotor

Study of the Cycloidal Blade System

2. Virtual Camber Effect







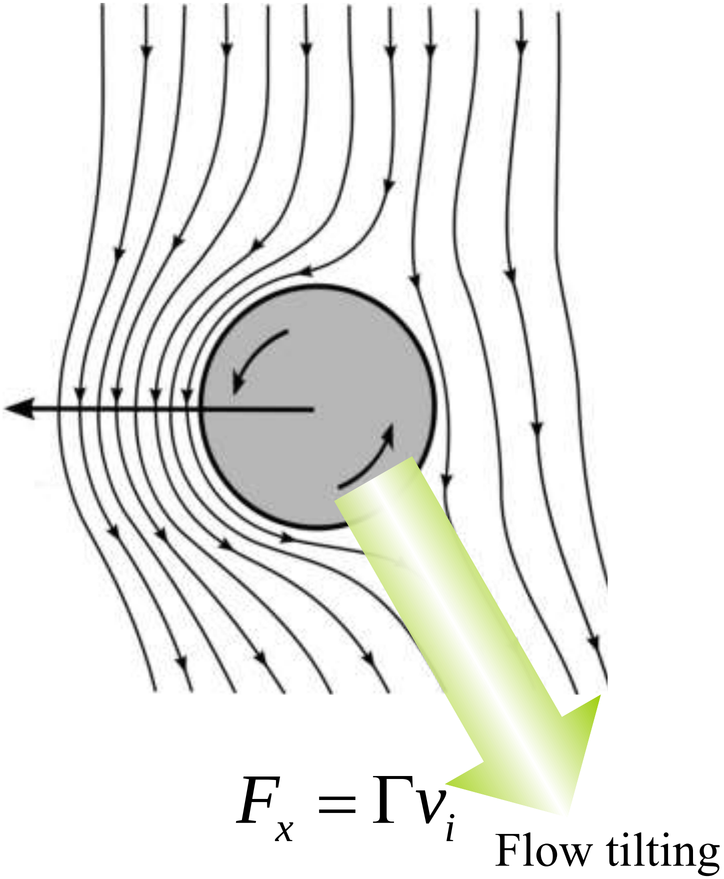
- Compared to the rotor radius, the chord length of blade is too long to ignore.
- The radius of the rotation varies along the chord. This causes the varied rotation velocity.
- Like **cambered airfoil blades**, the angle of attack at each point along the chord is **different.**
- The angle of attack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

$$\alpha_{camber} = \frac{2}{C_{L_\alpha}} \int_0^\pi (\theta - \theta_x)(\cos\theta_0 - 1) d\theta_0$$

Study of the Cycloidal Blade System

3. Flow tilting (Magnus effect)

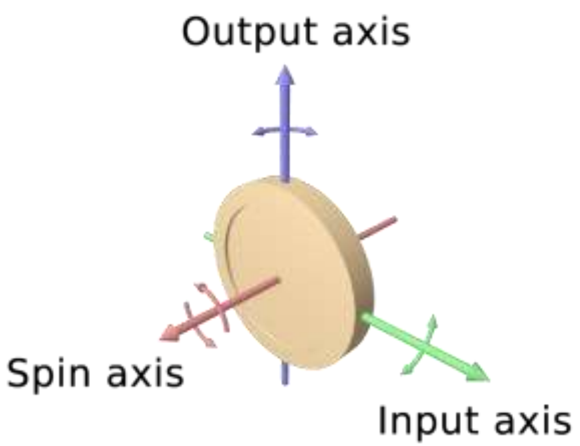
- Another cause of the flow tilting is Magnus effect
- Analyzing CFD simulation, roughly to **5 deg effective angle of attack modulation** (geometric modulation less the induced one) Refer from Iosilevskii, Gil, and Yuval Levy.(Israel) "Experimental and numerical study of cyclogiro aerodynamics." *AIAA 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).



$$F_x = \Gamma v_i$$

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



$$\frac{\partial L}{\partial t} = M$$

$\partial L / \partial t$: time rate of change in the angular momentum L

M : 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.)

$$p = -\frac{M}{I_{zz}\omega_z}$$

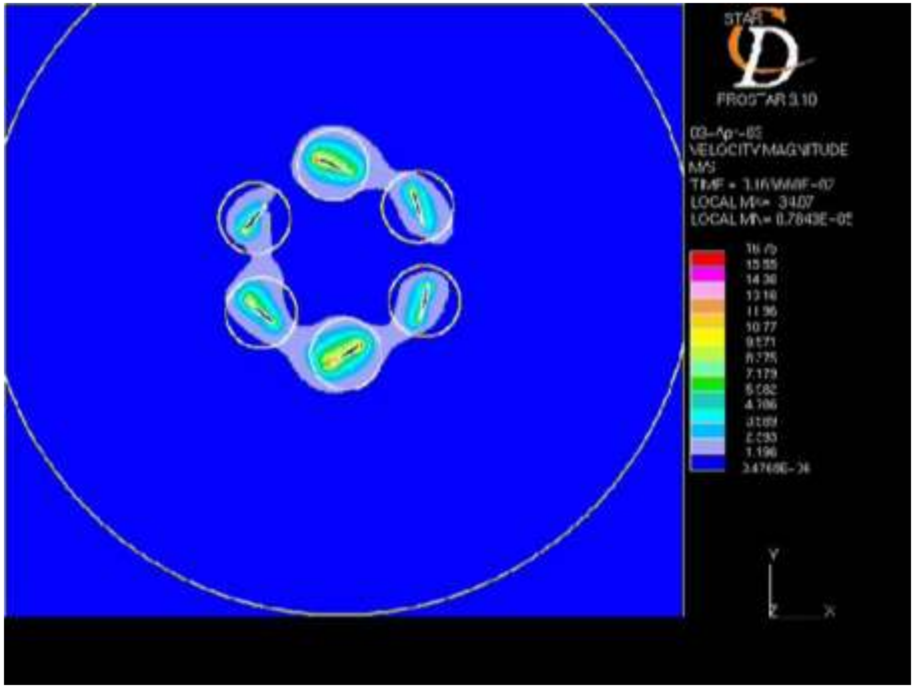
p : induced roll rate

M : aerodynamic yawing moment

$I_{zz}\omega_z$: 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**.

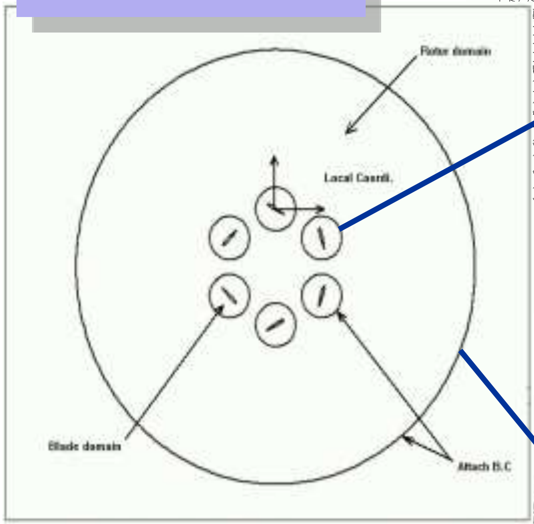
B. CFD Analysis of Cycloidal Blade System

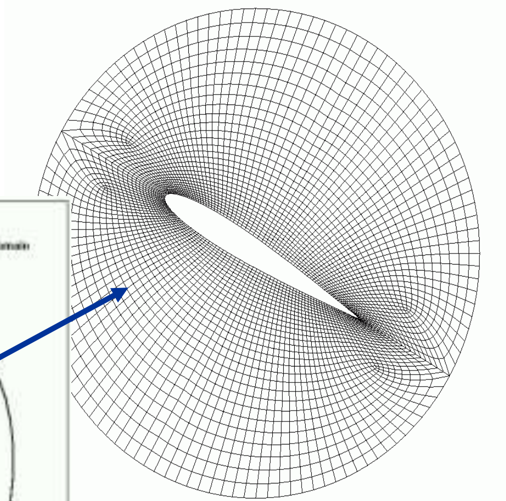


CFD Analysis

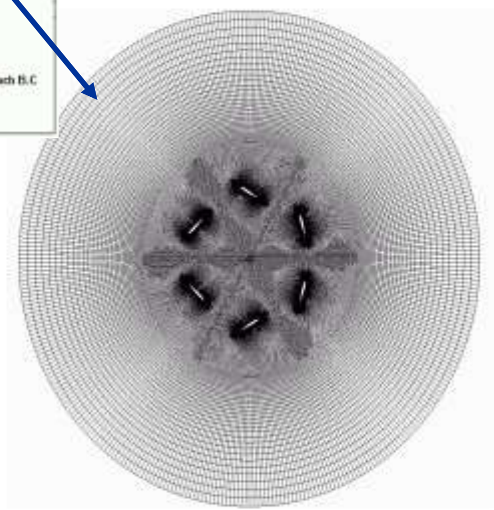
- ***Star-CD* is attempted**
- **Set up the condition of simulation**
  - Sliding mesh
    - ✓ Rotor domain rotates
    - ✓ Pitch angle of each blade is changed
    - ✓ ASI (Arbitrary Sliding Interface) method
  - k-ε/Low Reynolds turbulence model
  - Mesh type
    - ✓ Structured and unstructured
  - 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

Rotating domain & transient B.C.

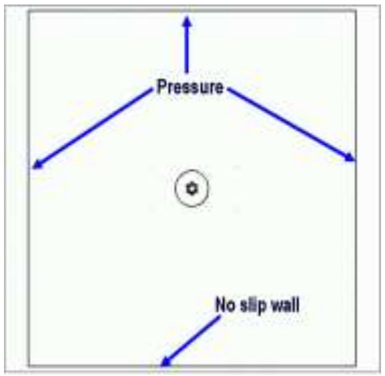




Blade domain



Rotor domain



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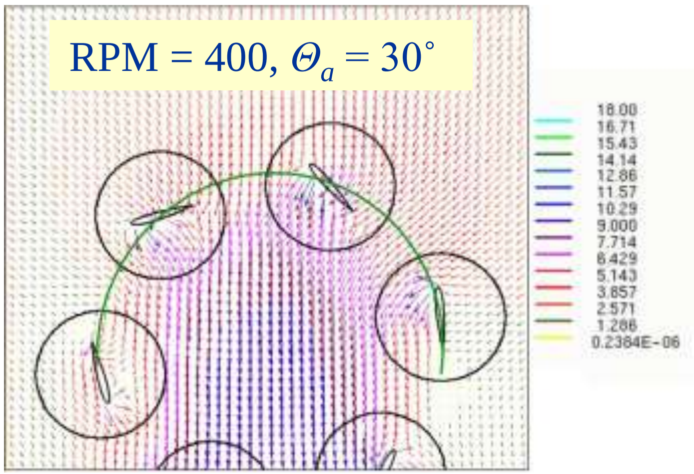
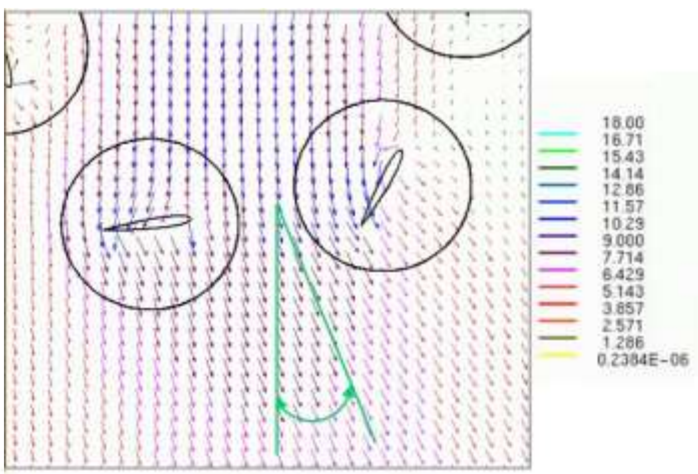
CFD Analysis

- **Airflow around the rotating cycloidal rotor**





– Induced flow

: normal direction to the blade path

– Downward flow

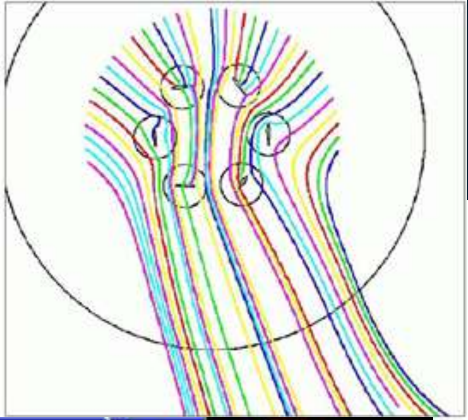
: inclined direction by the inner airflow of the CBS rotor.

: the inner airflow increases the resultant velocity at the right and lower position (270° < Ψ <360°), and it decreases the resultant velocity at the left and lower position (180°<Ψ<270°). Therefore, the non-symmetry downstream is occurred.

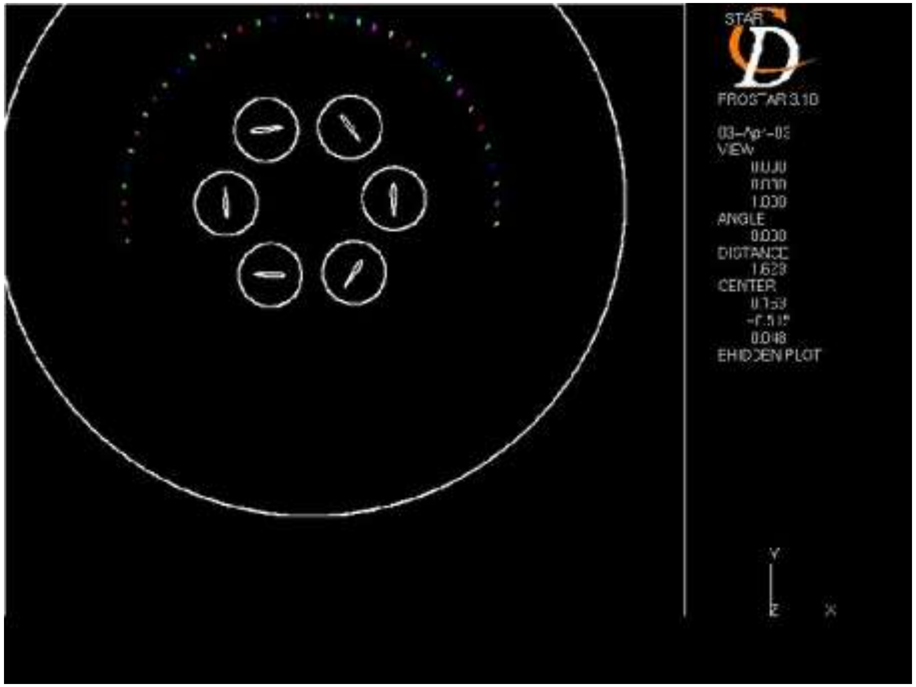
– The area of induced flow is about 2 times as large as the area of downward flow

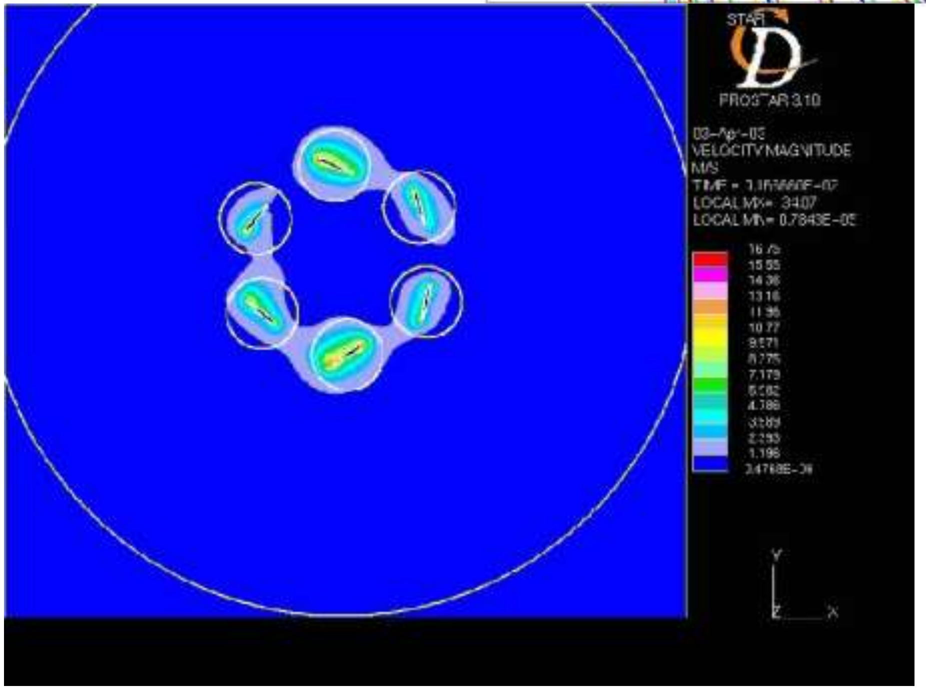
– The speed of downward flow is about 2 times as large as the speed of induced flow

CFD Analysis



- **Airflow**





Stream line	Velocity field

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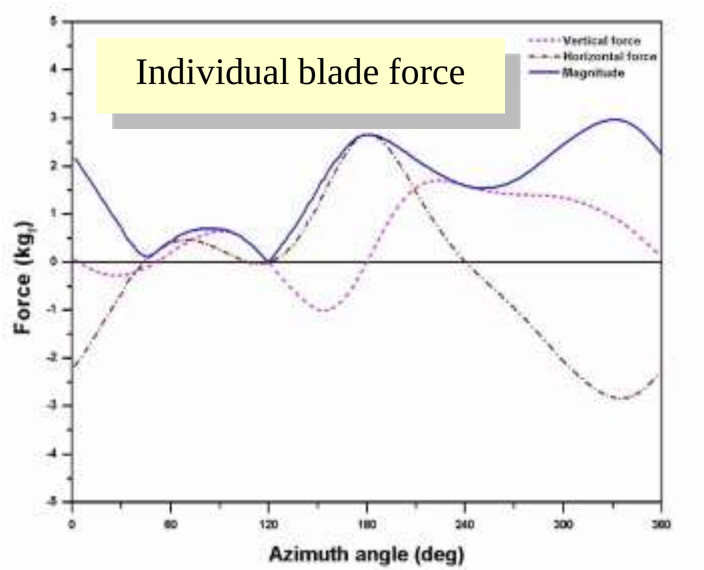
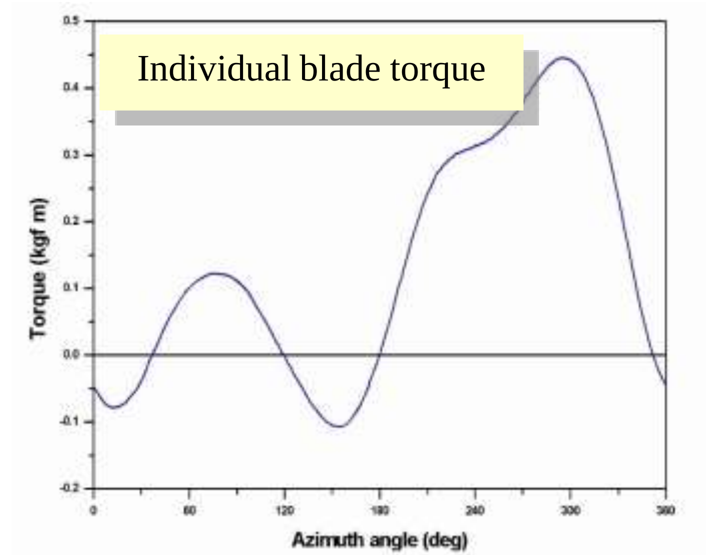
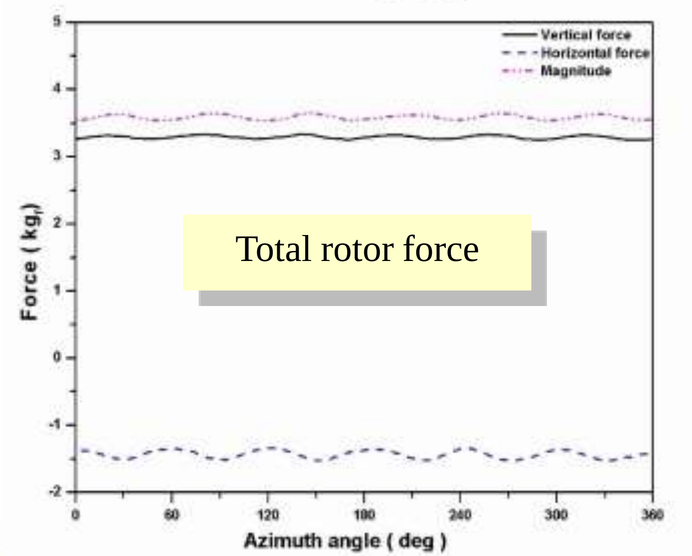
CFD Analysis

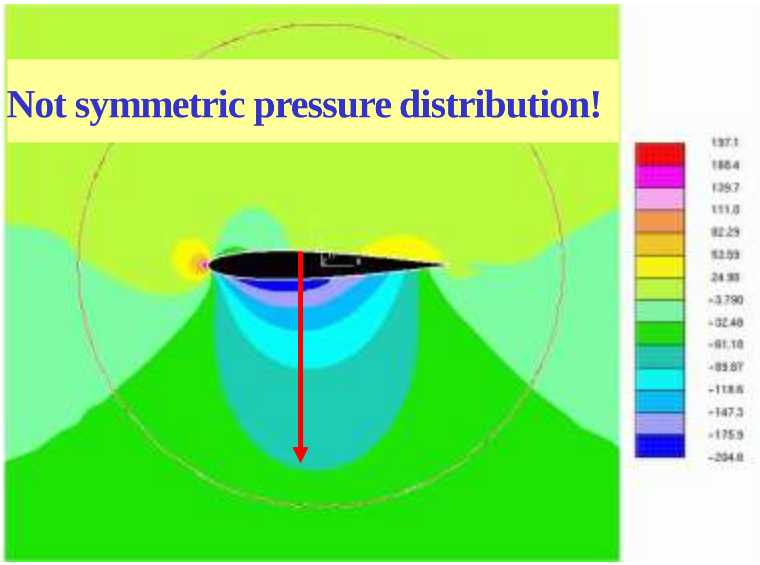


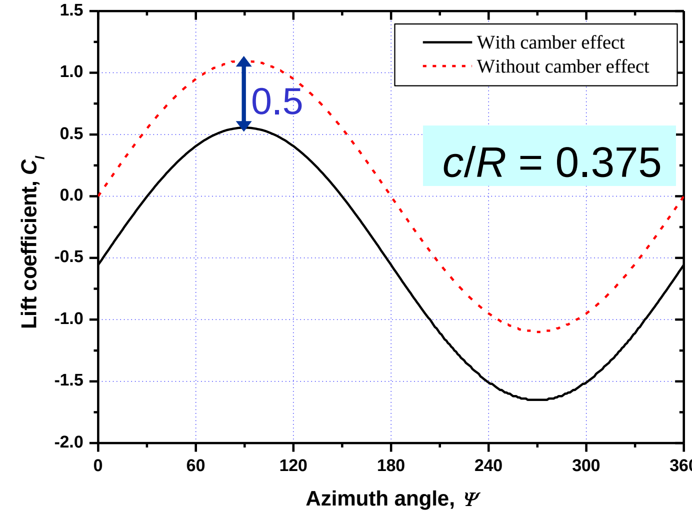




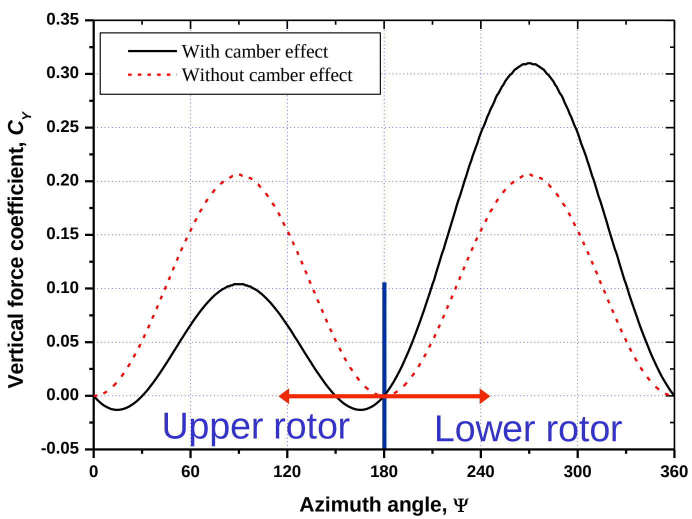
Lower part is larger than upper part in force and torque by camber effect

CFD Results on Pressure Distribution

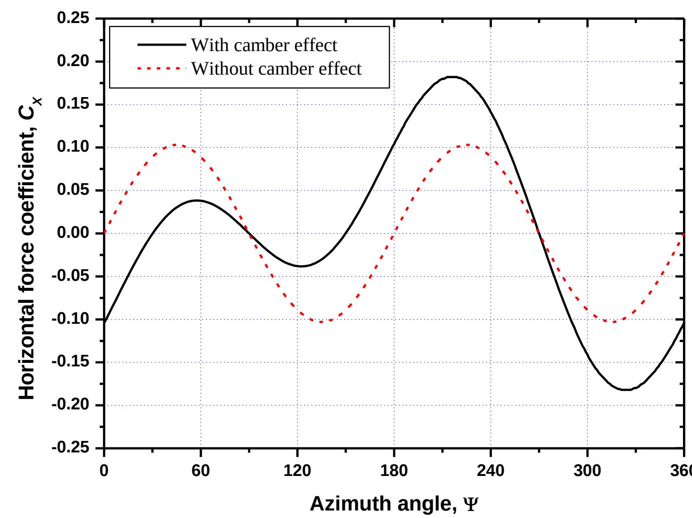




Lift coefficient v.s. azimuth angle



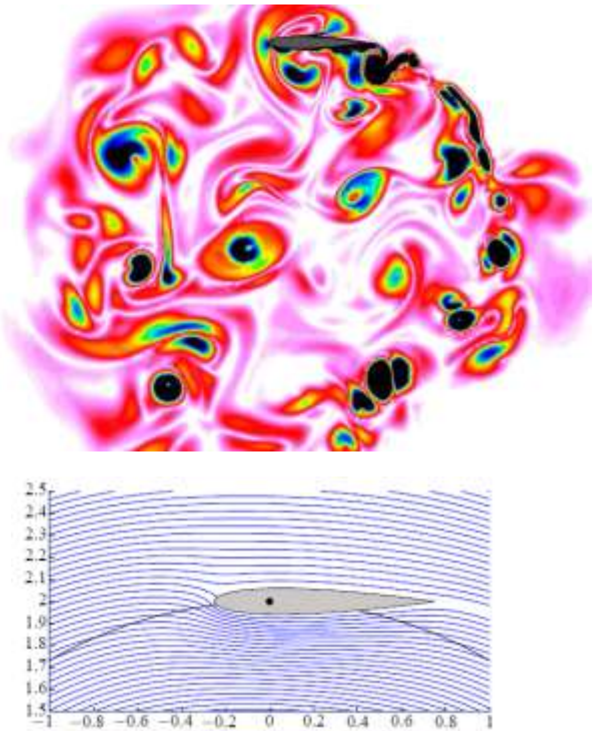
Vertical force



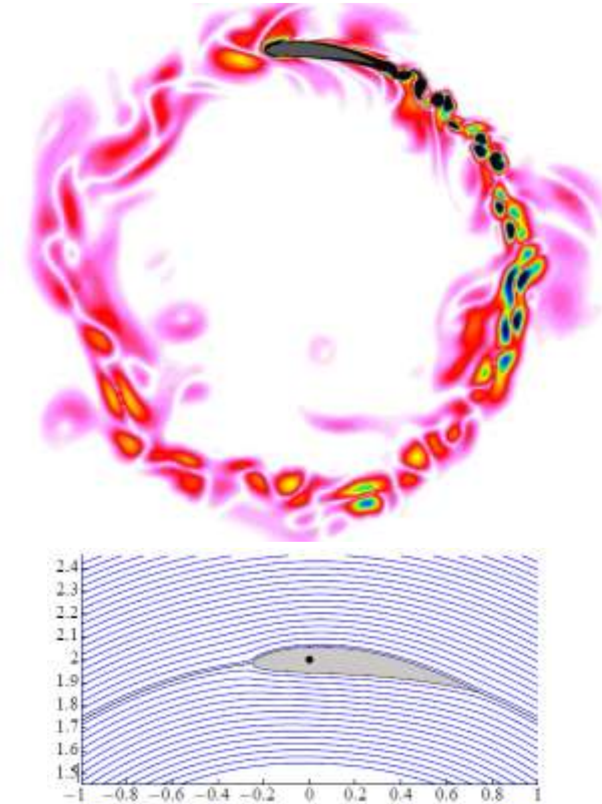
Horizontal force

Flow Visualization of CFD results

- **Cambered Airfoil**



CFD simulation of the NACA0012



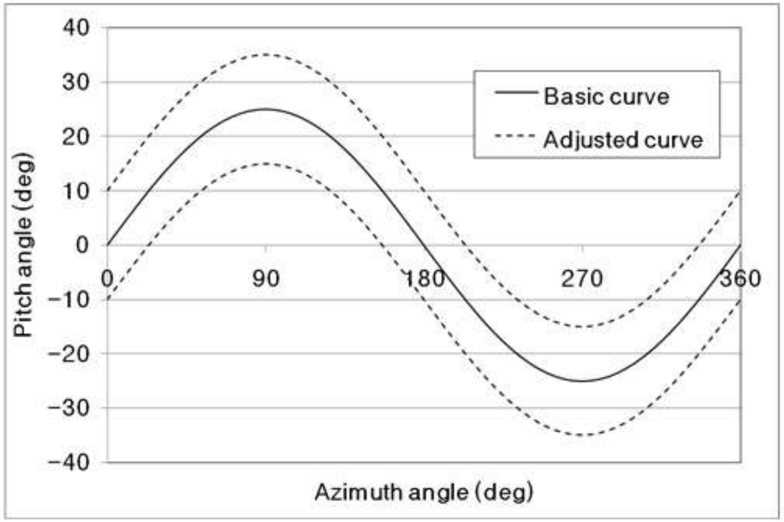
CFD simulation of the NACA6512

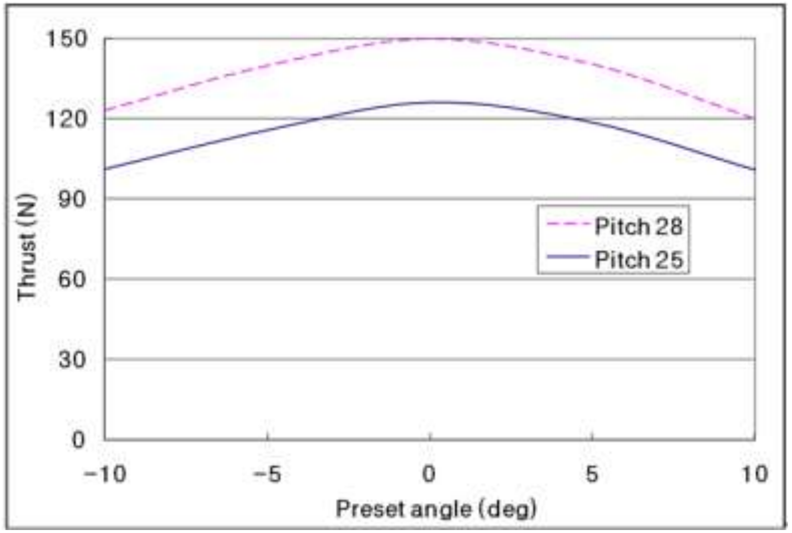
- If a cambered airfoil is used along the circumference of the rotor, the virtual camber angle will be zero.
- The cambered airfoil produce a much smaller wake and blade vortex interaction than symmetric one.

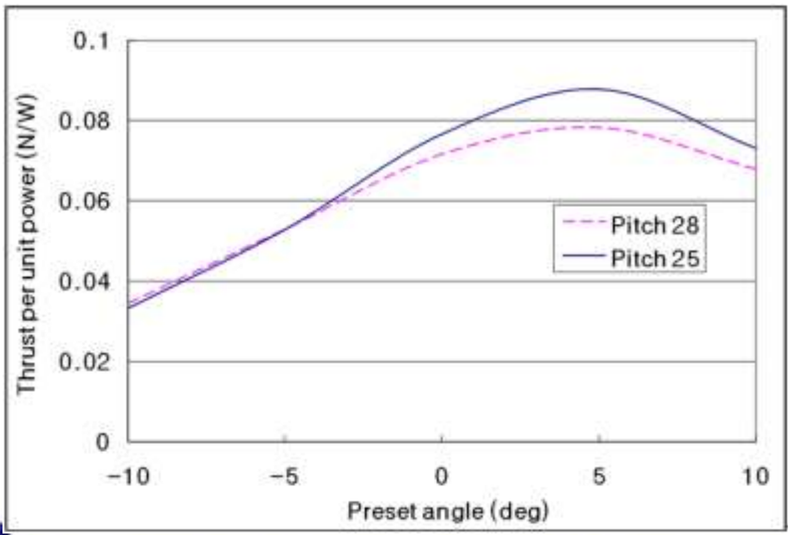
Simulation result is referred from Fagley, Casey, Chris Porter, and Thomas McLaughlin. *Curvature effects of a cycloidally rotating airfoil*. AIAA-2014-0255Reston: AIAA, 2014.

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

Experimental Test Model

A cycloidal blade system for fundamental experiments is designed to investigate its fundamental characteristics in hover.

Parameter	Range
Number of blade	2, 3, 6
Rotating speed	0 ~ 600 RPM
Pitch angle	0° ~ 35°
Rotor radius	0.4m, 0.45m, 0.5m
Phase angle	-70 ~ +110°
Chord	0.15 m
Span	0.8 m
Airfoil section	NACA 0012

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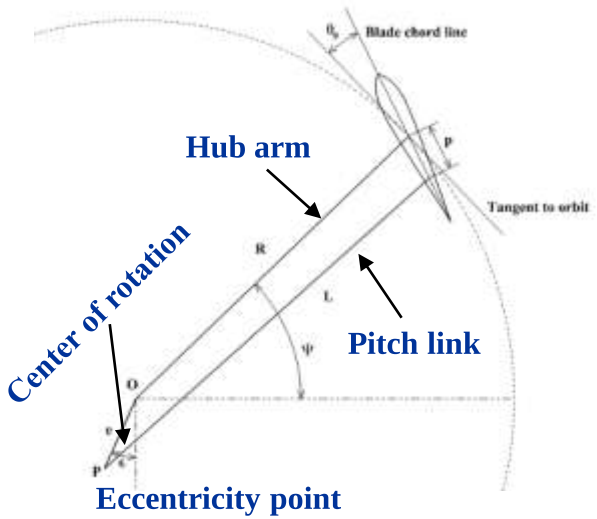
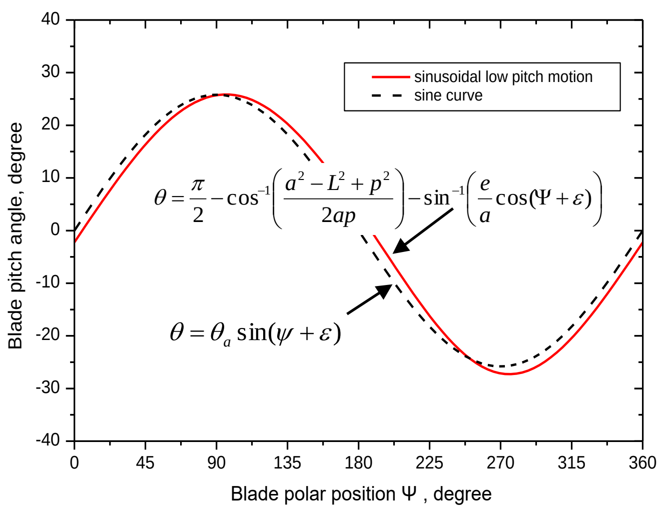
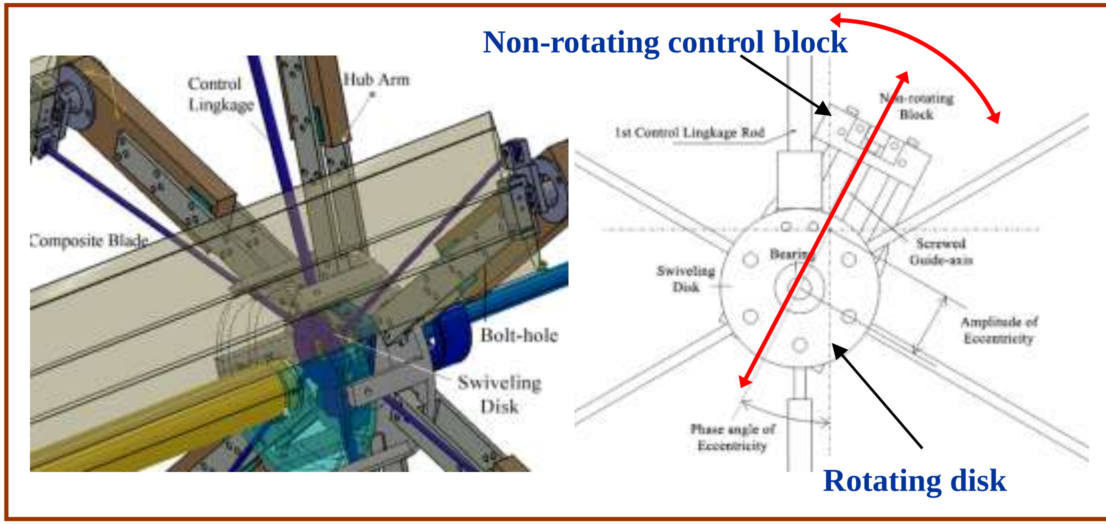
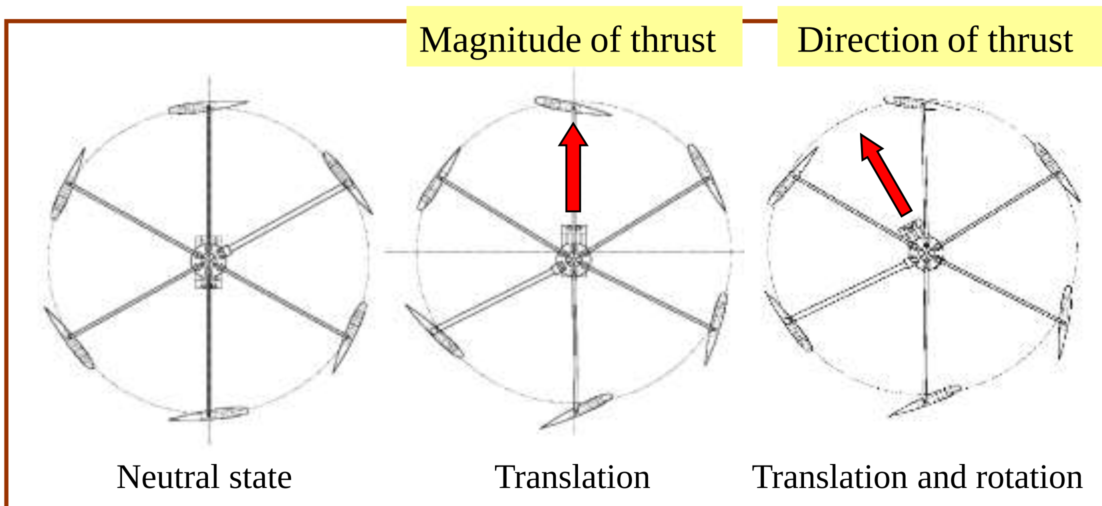
Pitch Control System





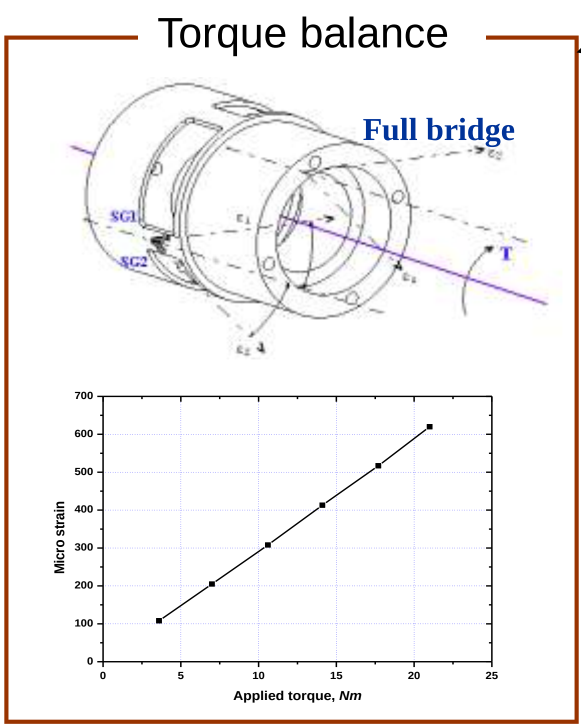
Sinusoidal low pitch motion

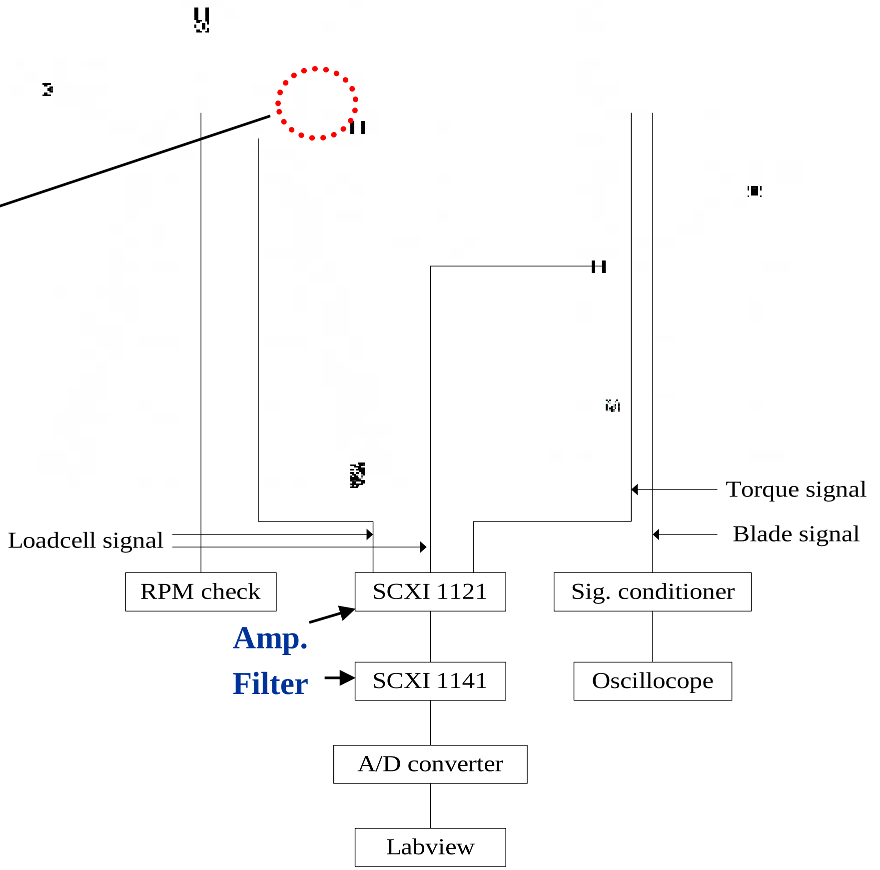




Test setup and Instrumentation

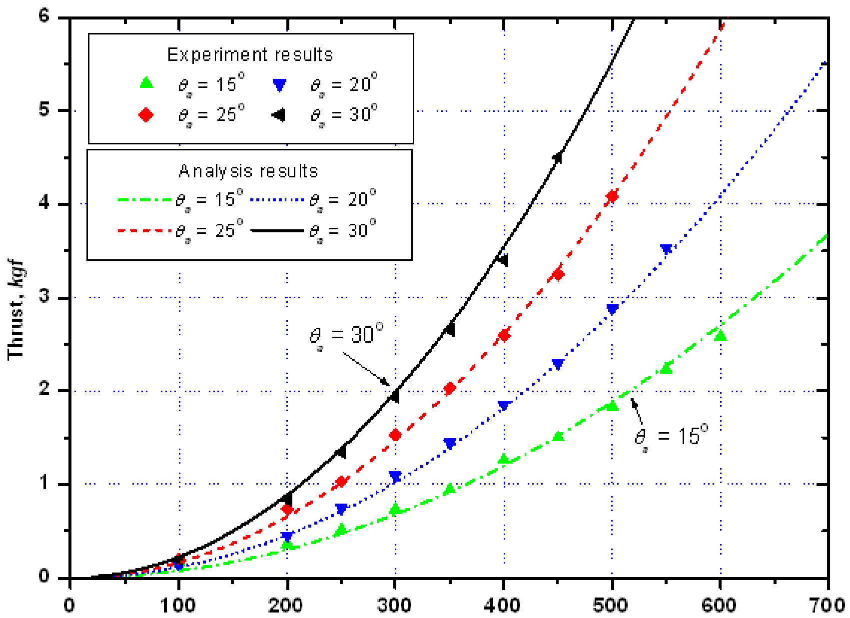
- Six load cell ➔ Thrust
- Torque balance ➔ Torque and Power
- RPM checker ➔ Rotating speed
- Strain gauge ➔ Blade motion

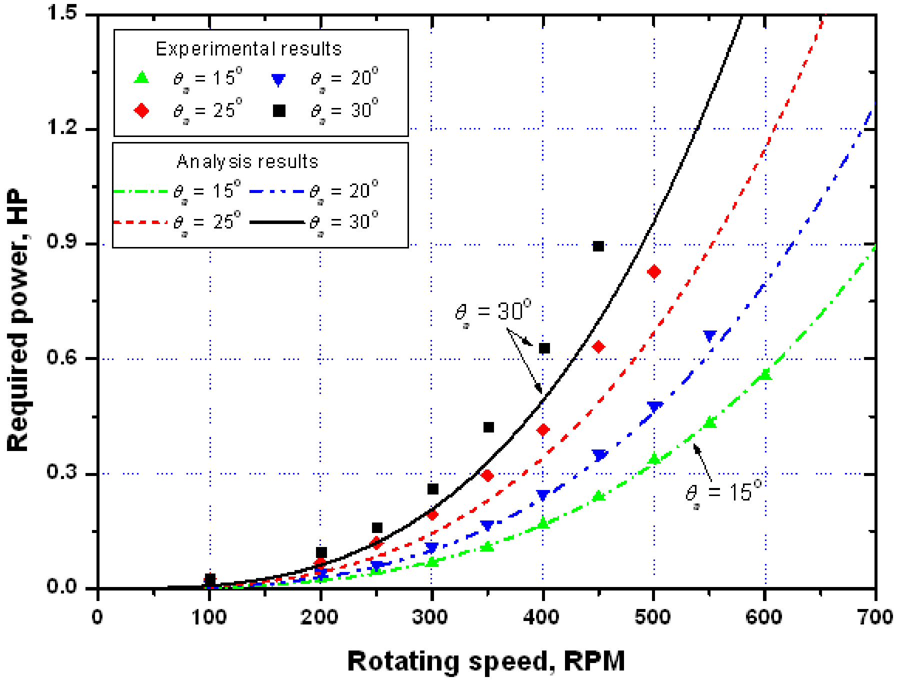




Experimental Result

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

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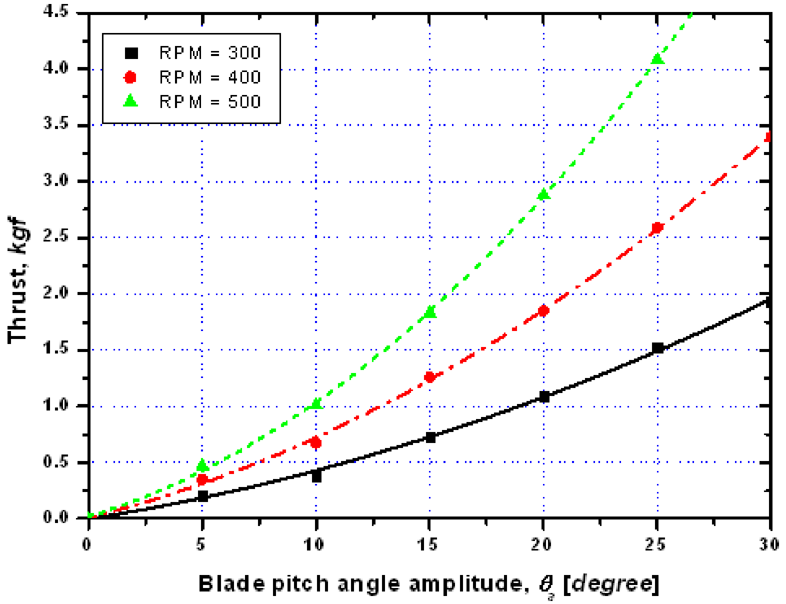
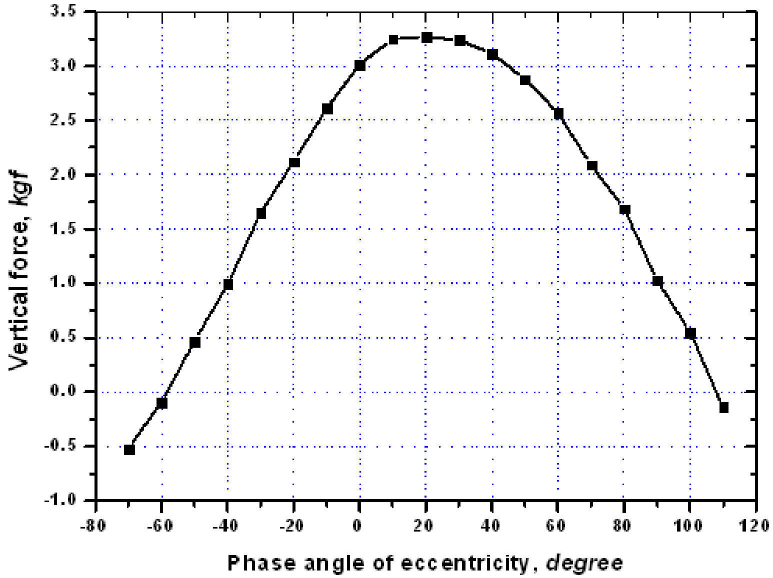
Experimental Result

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˚ ~ 110˚
    : Max. vertical force between 10˚ and 20˚
    : Not Max. vertical force in phase angle of 0˚
  - Vertical forces disappear at -60˚ and 110˚

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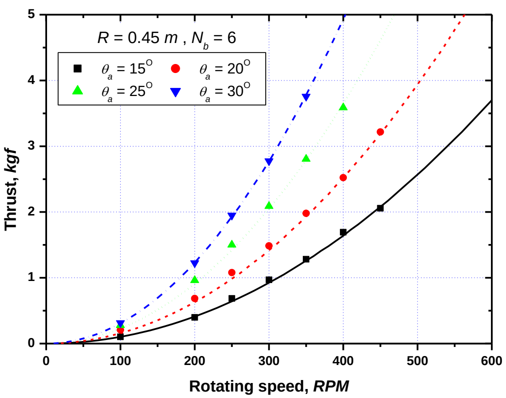
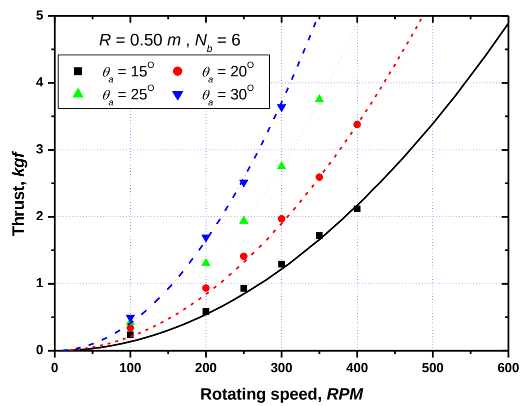
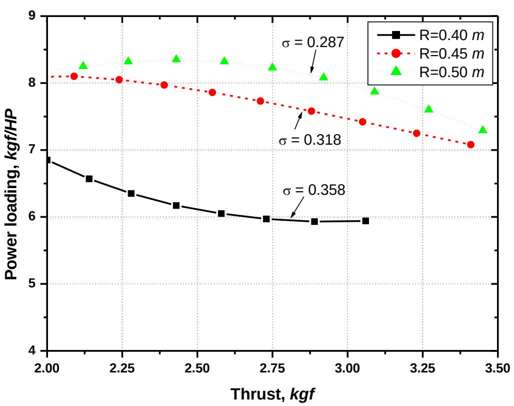
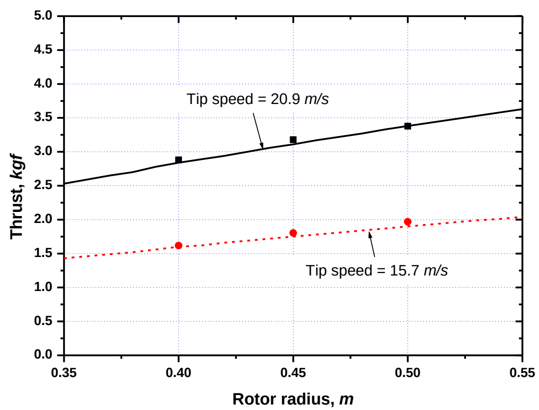
Experimental Result

Effect of the rotor radius









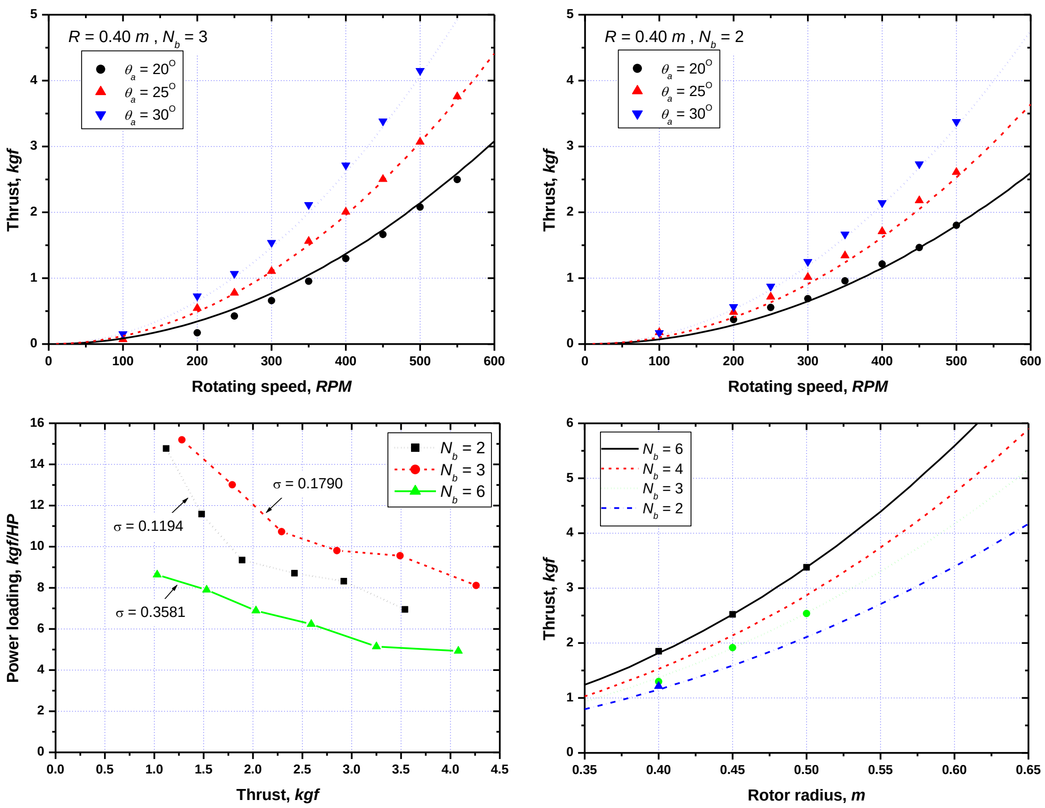
- Thrust of six-bladed rotor at 400 RPM & 20° phase angle
  - R = 0.4m : 1.7 kgf
  - R = 0.45m : 2.5 kgf
  - R = 0.5 m : 3.3 kgf
- Power loading
  - Fixed tip speed : 15.7 m/s
  - R=0.5 ➔ 7 kgf/HP
  - R=0.4 ➔ 6 kgf/HP
  - Helicopter ➔ 3~4 kgf/HP
- The larger rotor, the better efficiency

(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
  - 2 N_b : 2.9 *kgf*
  - 3 N_b : 3.5 *kgf*
  - 6 N_b : 4.1 *kgf*
- 2 bladed rotor
  - Vibration is severe
- Efficiency
  - (N_b = 3) > (N_b = 2) > (N_b = 6)
  - N_b = 6 ➔ 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

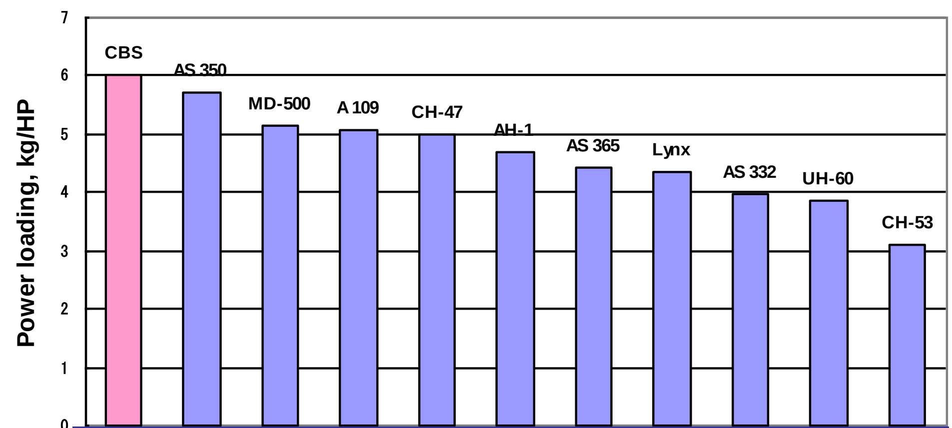
Comparison : Power Loading

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

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

Cycloidal rotor	**6.0 kg/HP**

$$PL_e = PL_i \times FM$$



Hovering efficiency (Power Loading)

The Power Loading of Cycloidal Rotor is the highest according to this table

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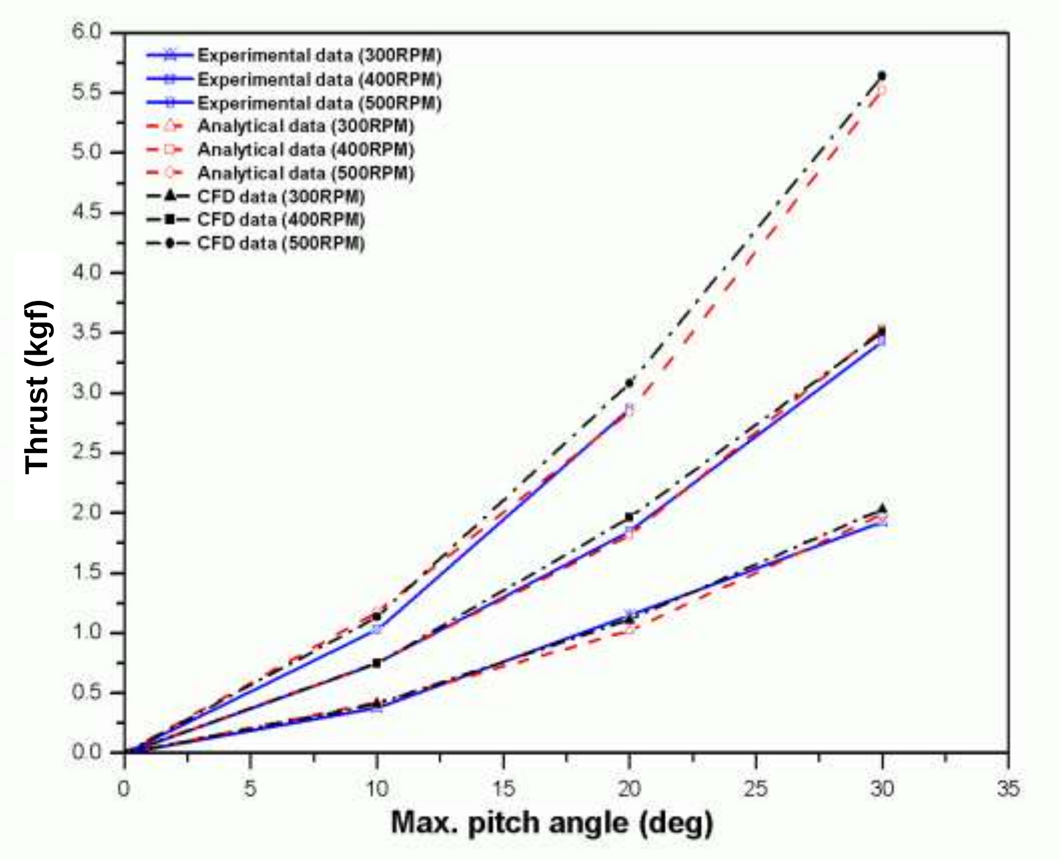
Comparison : Analyses and Experiments

- **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

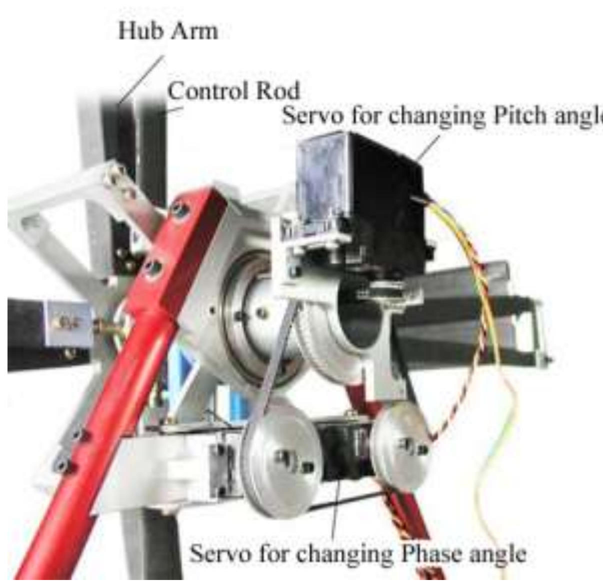
Contents

Introduction – Research progress in SNU

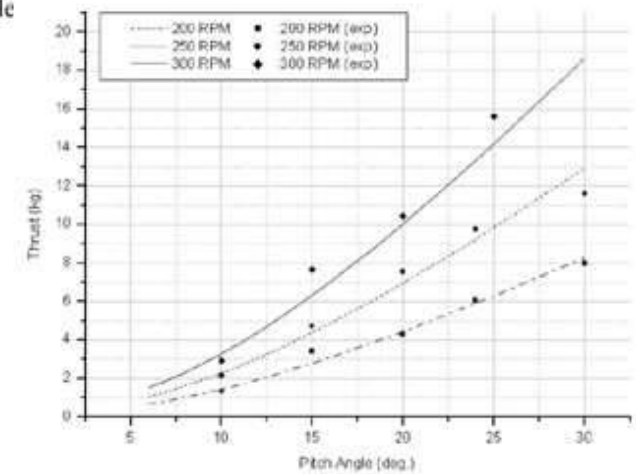
- **Development of UAV Cyclocopter, 1st version (2003.03 ~ 2004.12)**

- Development of unmanned VTOL vehicle
- Optimal rotor design by parametric study
- Two rotors with same rotating direction

Blade design and manufacturing



Control mechanism

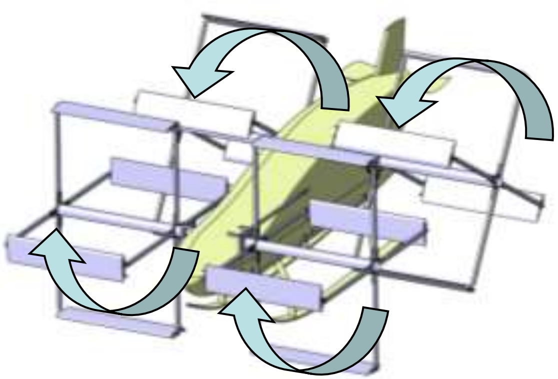


Thrust variation

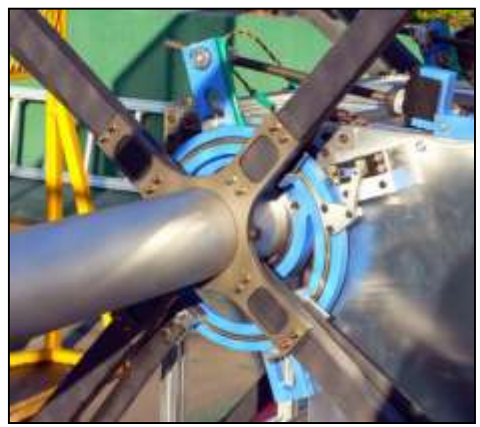
Introduction – Research progress in SNU

- **Development of UAV Cyclocopter, 2nd version (2005.01 ~ 2005.12)**

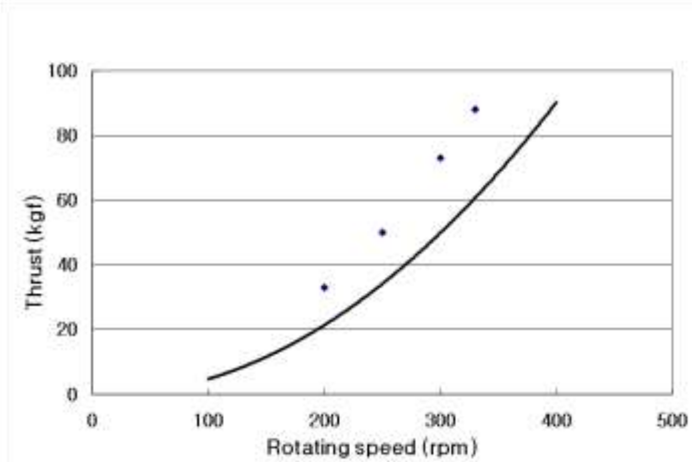
  - Rotor design by simulation based optimization
  - Anti-torque and maneuvering by tandem rotor configuration
  - Powered by brushless motors and Li-Po batteries



Tandem rotor configuration



Control device and rotor hub

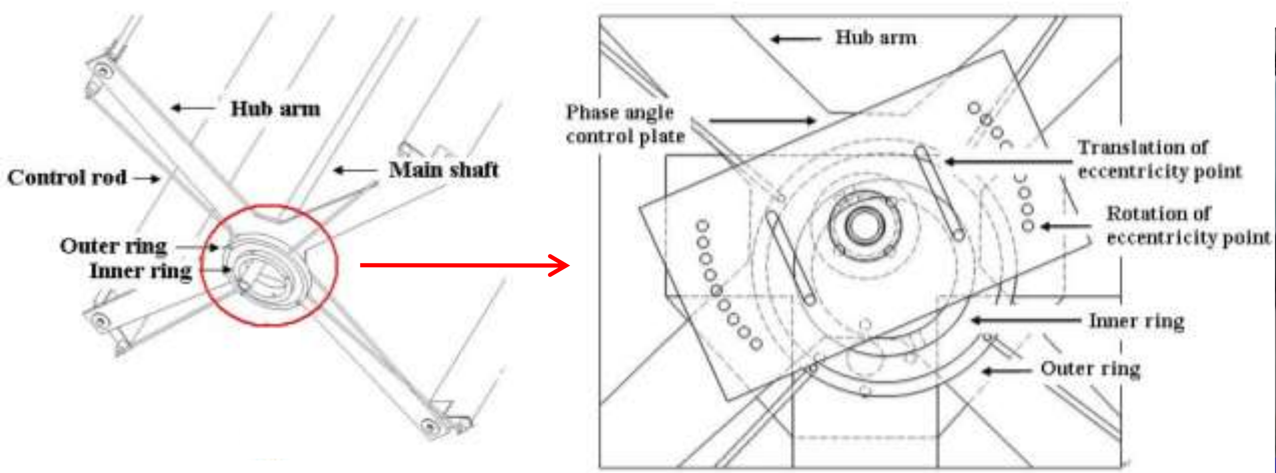


Experimental result

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



Control mechanism

Operating picture

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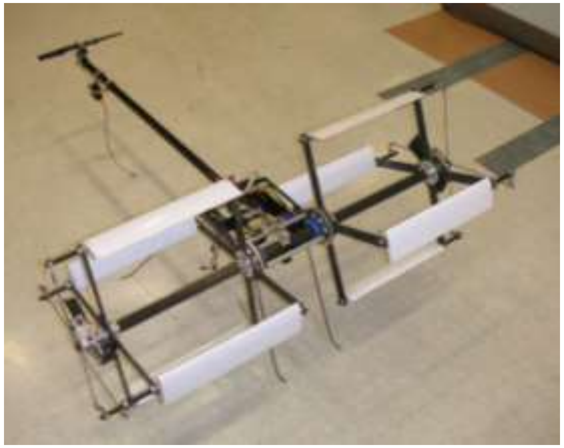
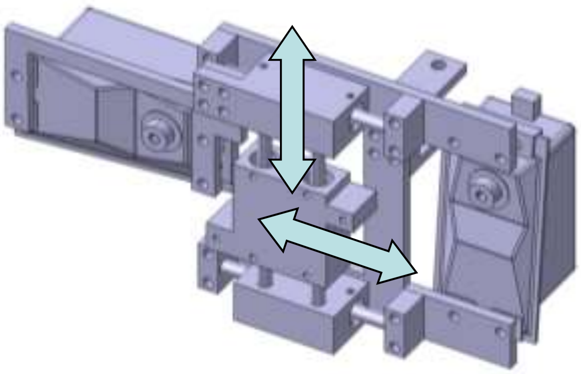
Introduction – Research progress in SNU

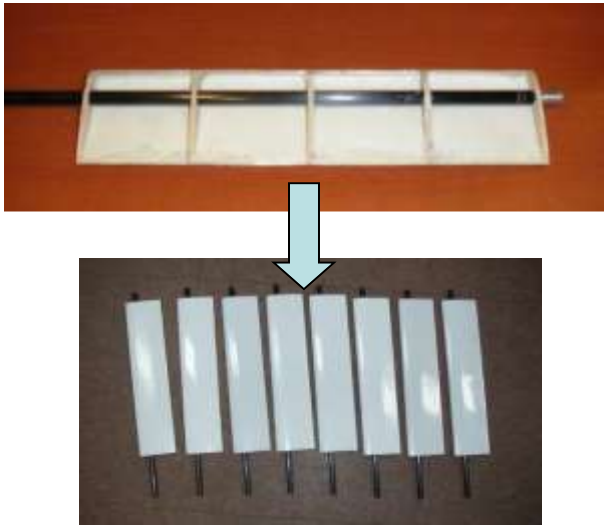
- **Development of Mini Cyclocopter, 2nd version (2006.01 ~ 2006.07)**



- 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



Control mechanism

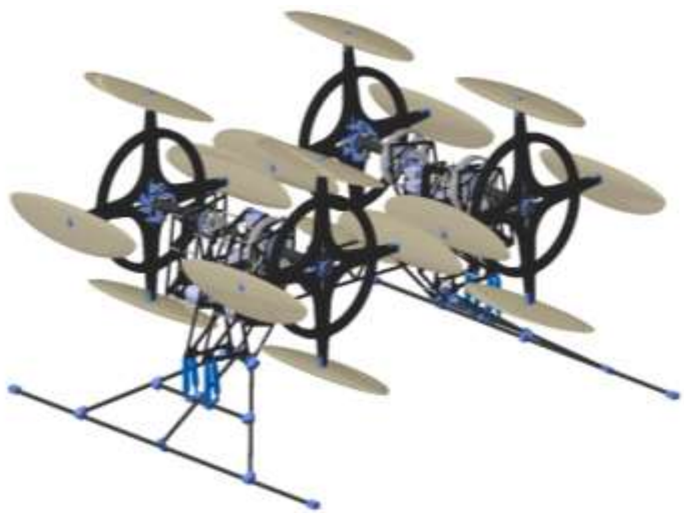


Composite blades

Operating picture

Cyclocopter mini 3

- **Development of new Cyclocopter with 4 rotors**

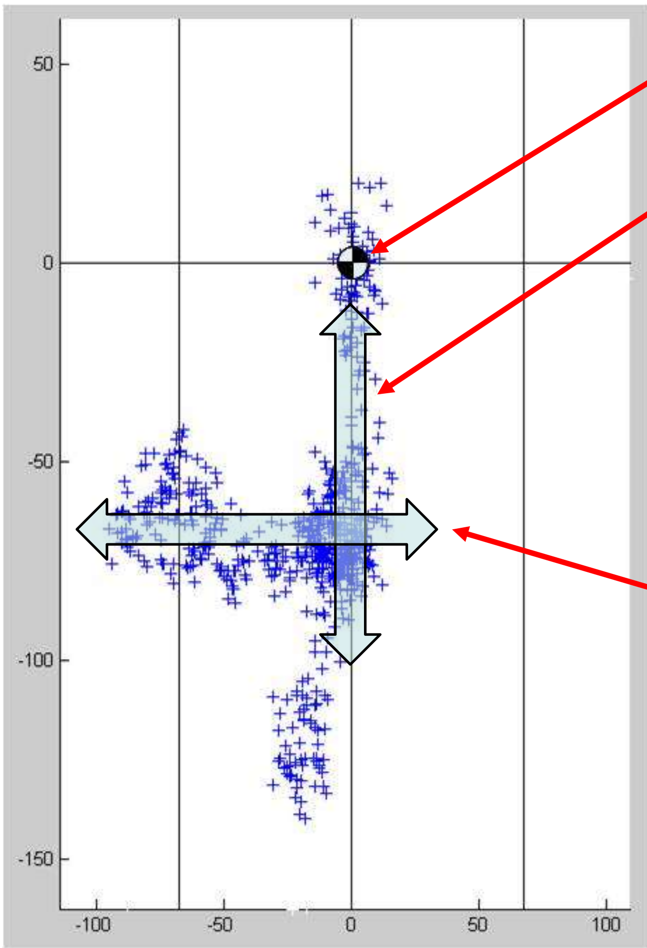


  - The aircraft consists of four rotors, and two pairs of rotors rotate in opposite direction to compensate anti-torque
  - Each rotor has four elliptic blades
  - The blade is supported at center position to be connected with the hub arm
  - The rotors are operated by their own motor systems and control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

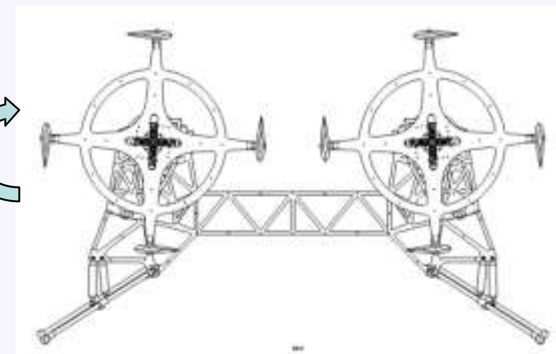
Cyclocopter mini 3

- **Movement of thrust center**

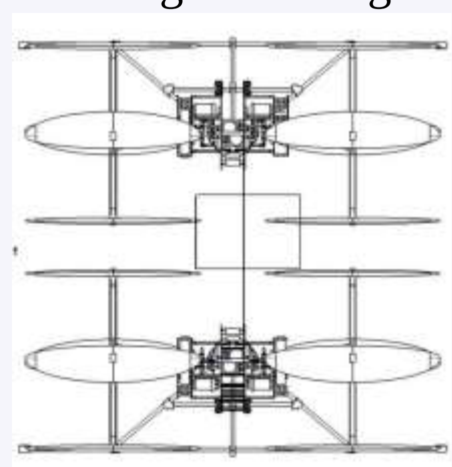


CG of cyclocopter

Maneuvering for pitching motion



Maneuvering for rolling motion



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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^{o}

Cyclocopter mini 4

Cyclocopter design variables	
Rotating speed	1200 rpm
Radius of rotor	0.25 m
Span of blade	0.5 m
Airfoil	NACA 0018
Weight	12 kg
Total thrust	16.4 kgf

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)

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

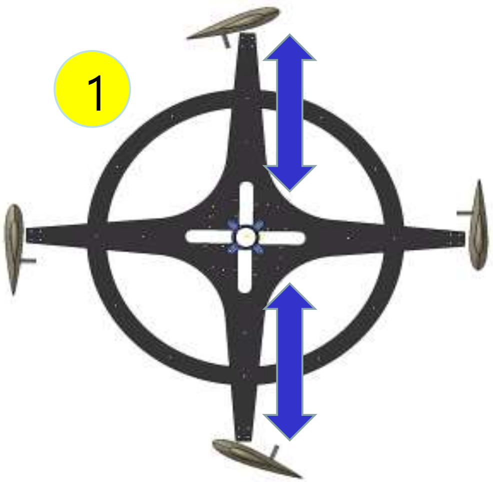
– Discharge rate: continuous 22C (110A)

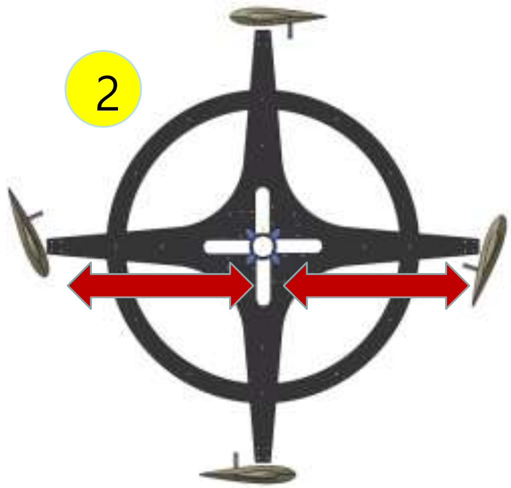
sustain (<30sec) 30C (150A)

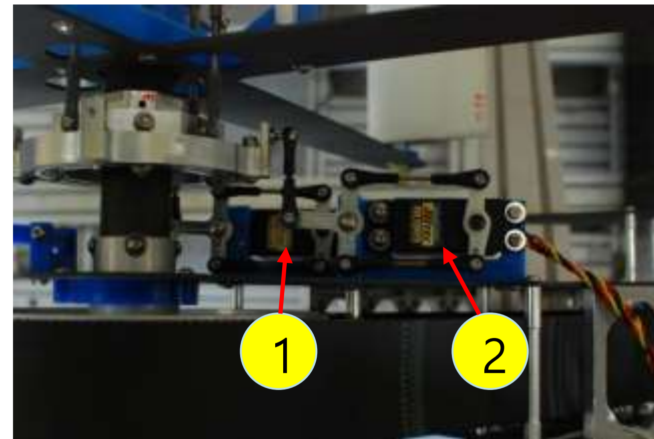
burst (<5sec) 50C (250A)

Cyclocopter mini 4

- **Pitch angle control**







Pitch angle control servos

- Servo No.1: control of blade pitch angles at up/down positions

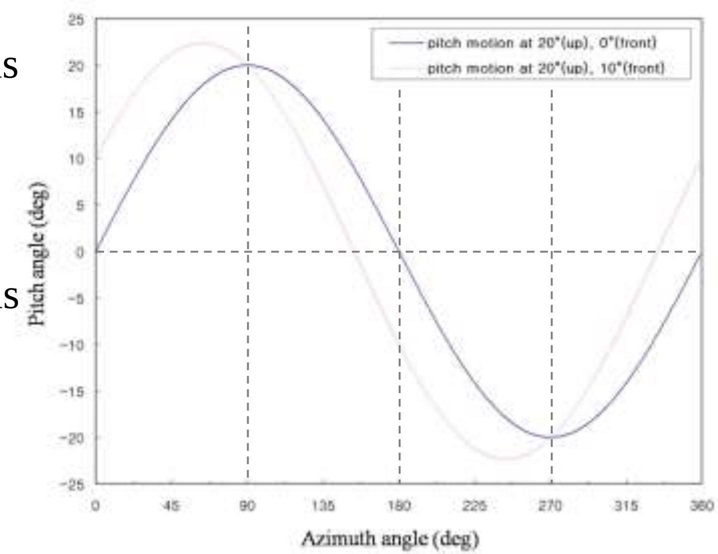
  (azimuth angles 90° and 270°)

  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



Cyclocopter mini 4

- **Improvement of control parts**

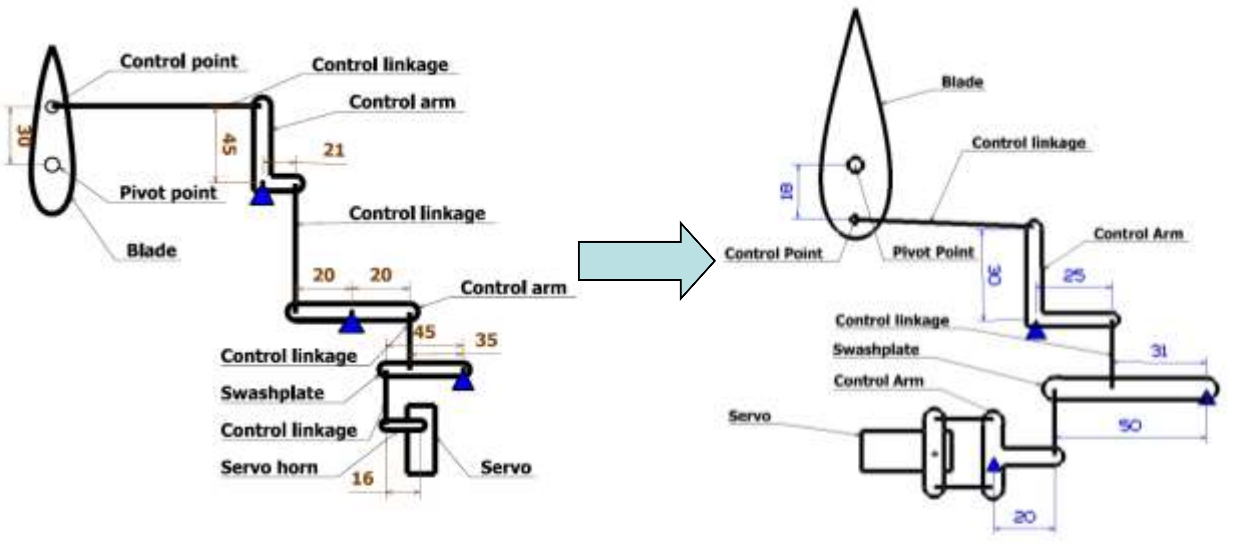


Diagram of control mechanism : mini3 & mini4

mini3

mini4

Control parts modification

- 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

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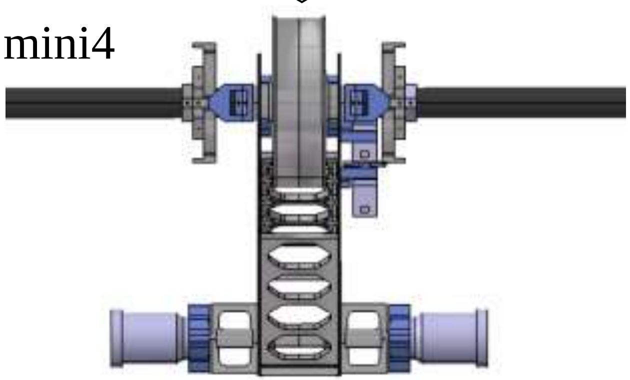
Cyclocopter mini 4

- **Power transmission**

mini3

mini4

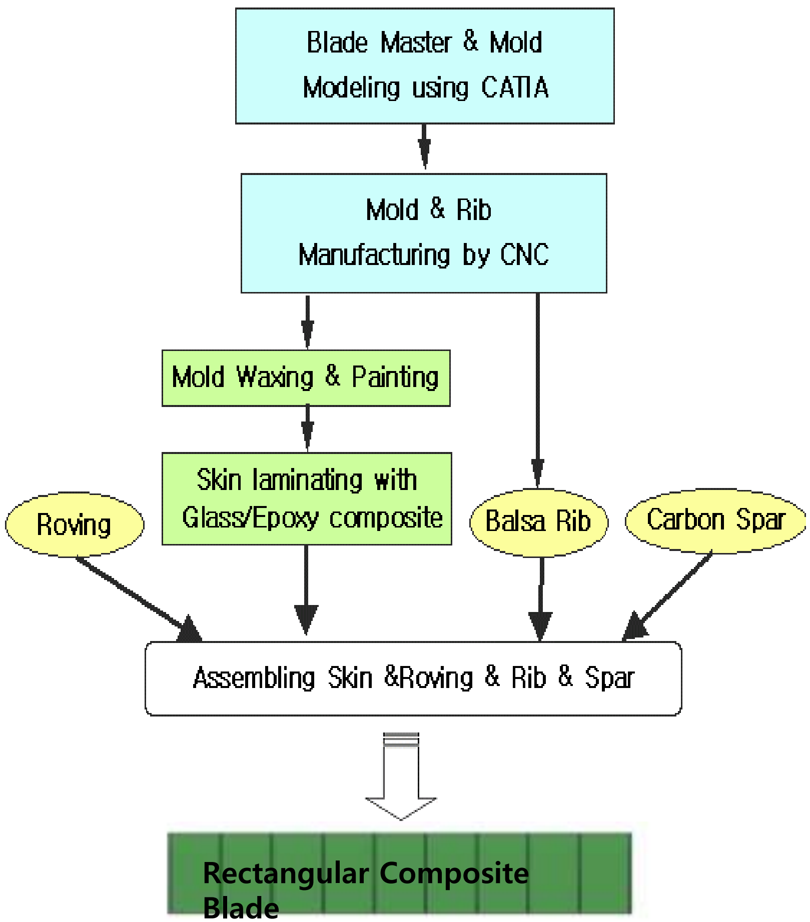


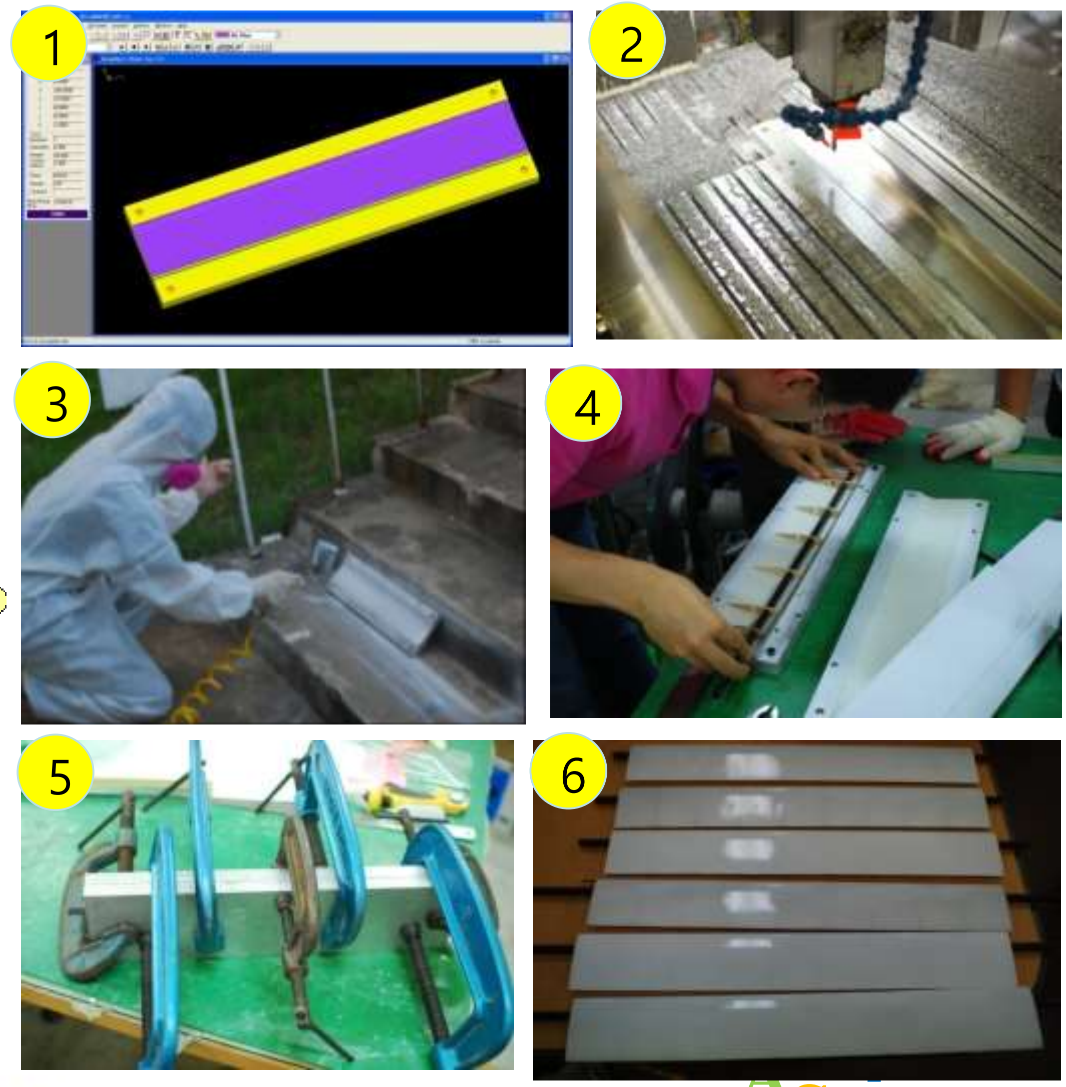
Transmission parts modification

- 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

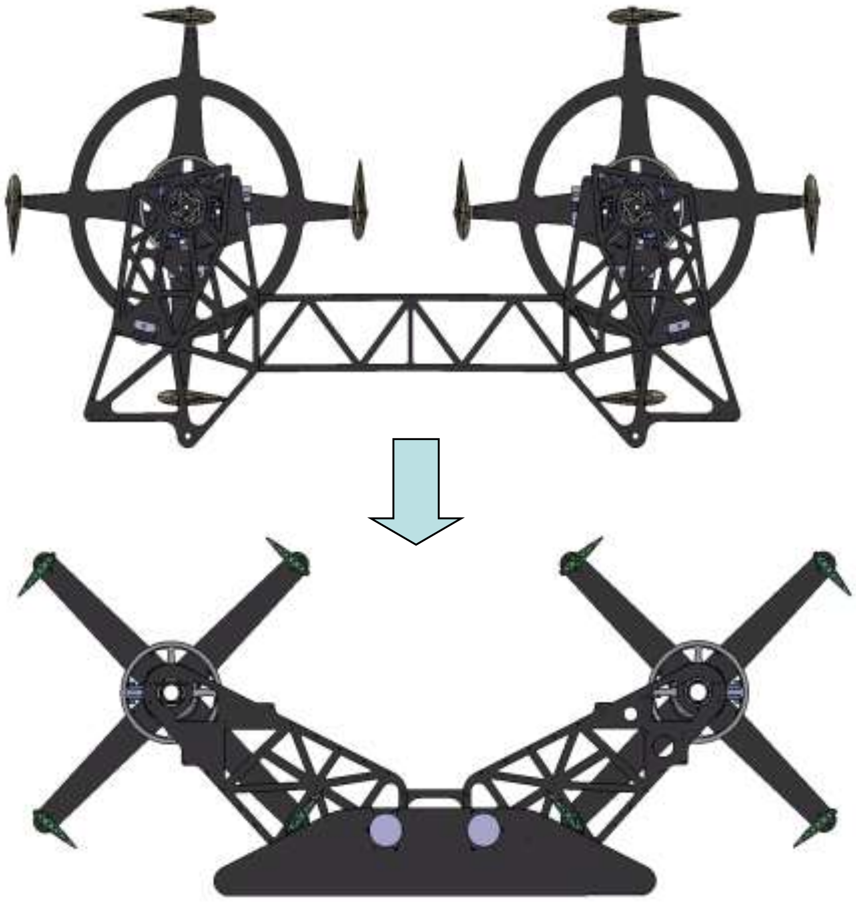
- **Manufacturing process of blade**





Cyclocopter mini 4 - Manufacturing

- **Fuselage**



– In mini3, central part of the fuselage structure is relatively weak to twist motion

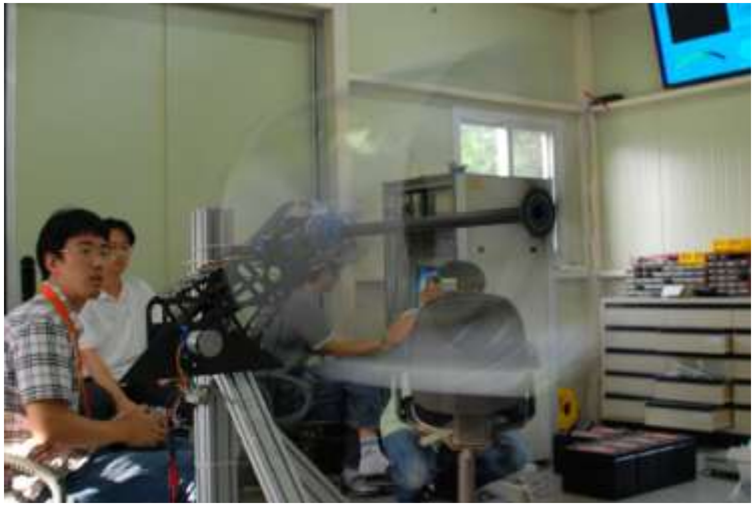
– To modify the structure, the design is changed as follows;

- 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

Contents

A. Development of Cyclocopter Mini 5

Cyclocopter Mini 5

Cyclocopter design variables	
Rotating speed	1100 rpm
Radius of rotor	0.27 m
Span of blade	0.5 m
Airfoil	NACA 0018
Weight	12.8 kg
Total thrust	16.32 kgf

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)

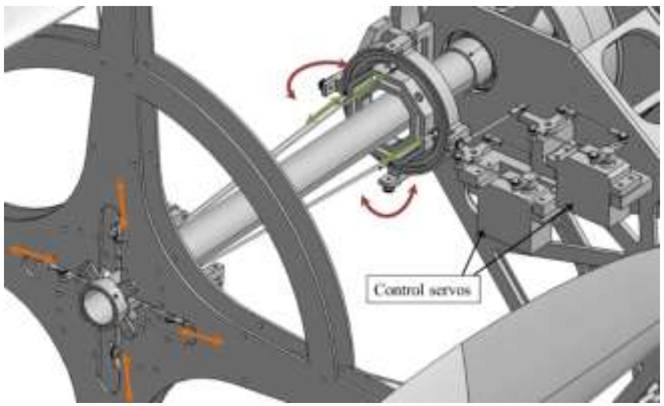
Quadrotor Cyclocopter

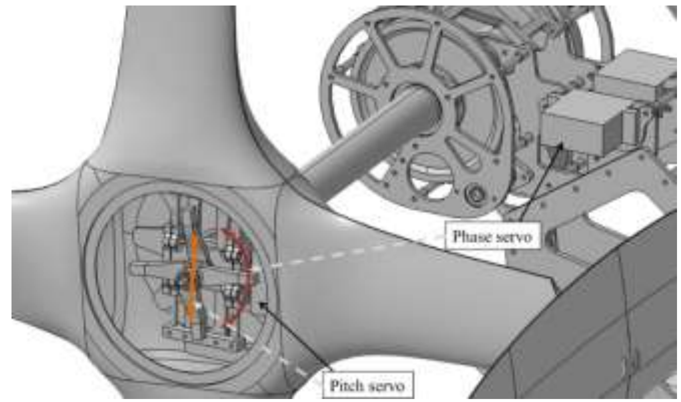
- **Development of Quadrotor Cyclocopter**

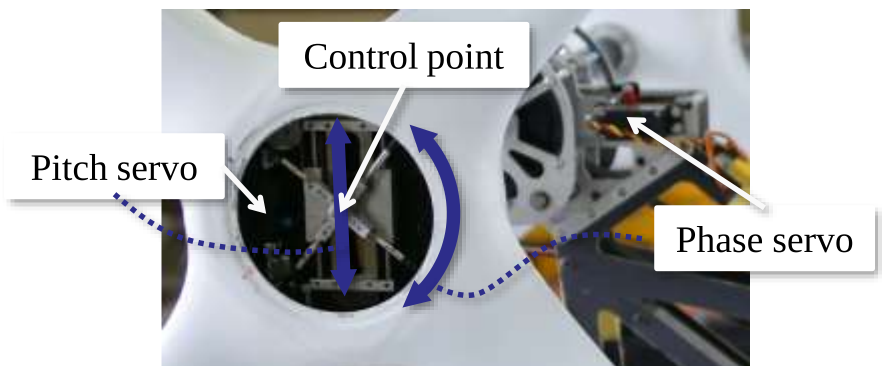
Specifications	
Number of rotors	4
Number of blades (per one rotor)	4
Airfoil	NACA0018
Rotor radius	0.27 m
Blade span length	0.5 m
Blade Chord length (at center position of the blade)	0.105m
Max. pitch angle	25°
Rotational speed	1100 RPM
Thrust (Total thrust of four rotors)	16 kgf
Weight of vehicle	12.8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

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



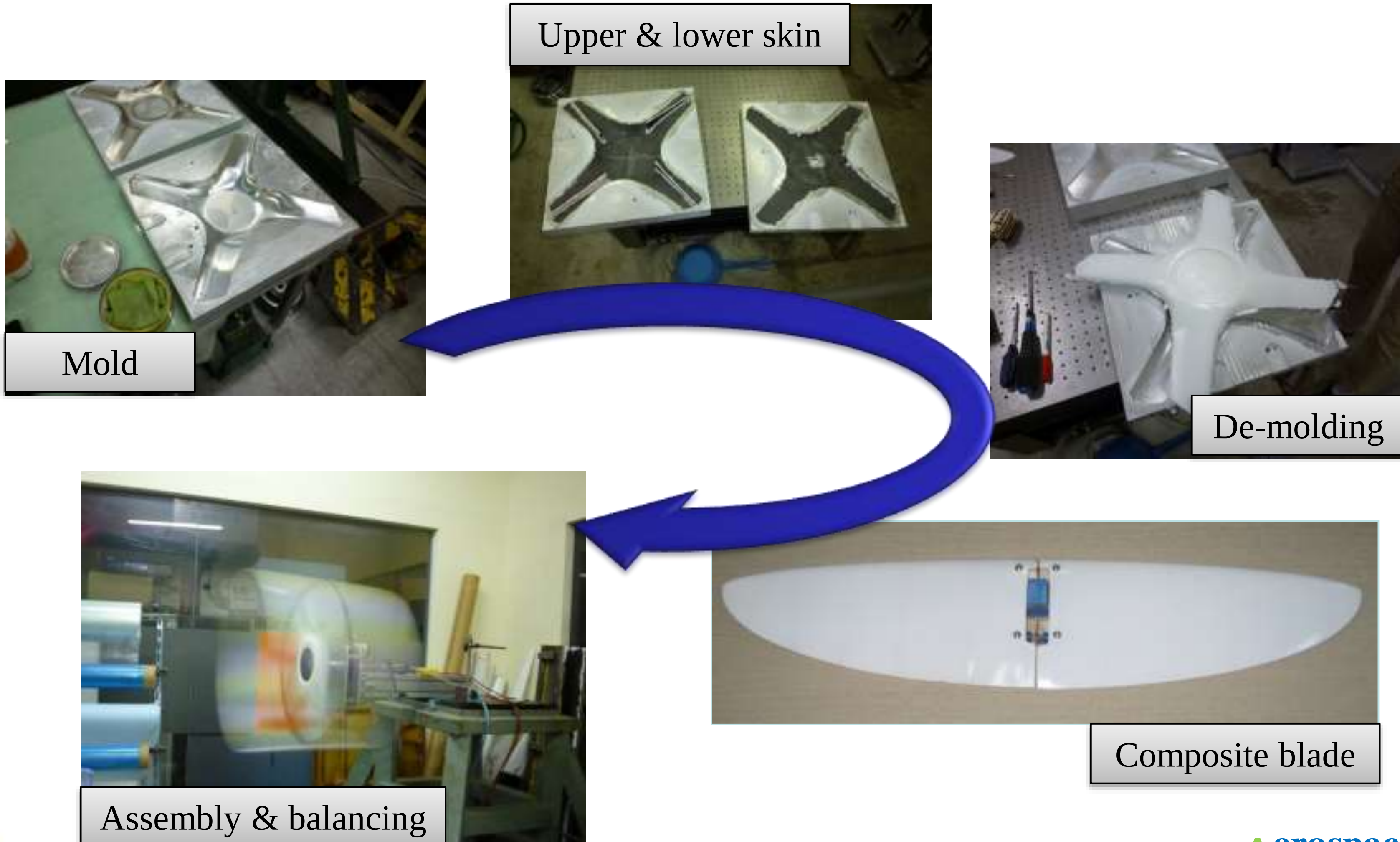




Control mechanism

Quadrotor Cyclocopter

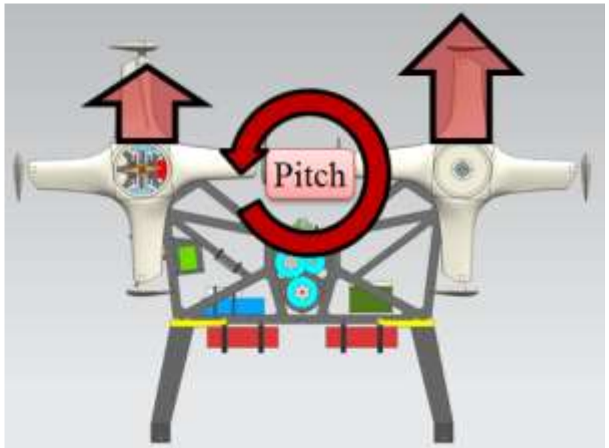
- **Composite rotor manufacturing**



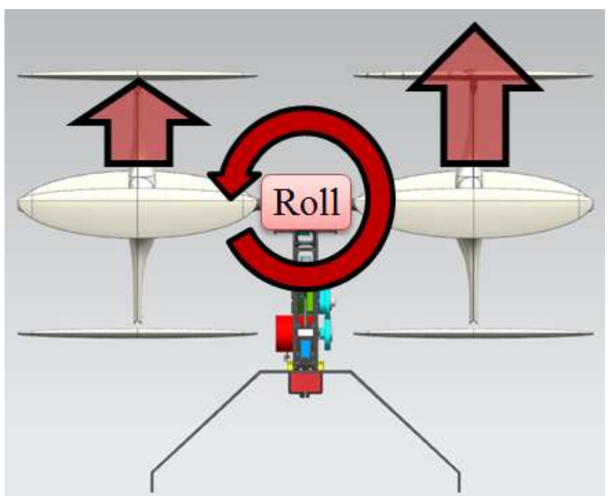
Quadrotor Cyclocopter

- **Attitude control of the vehicle**

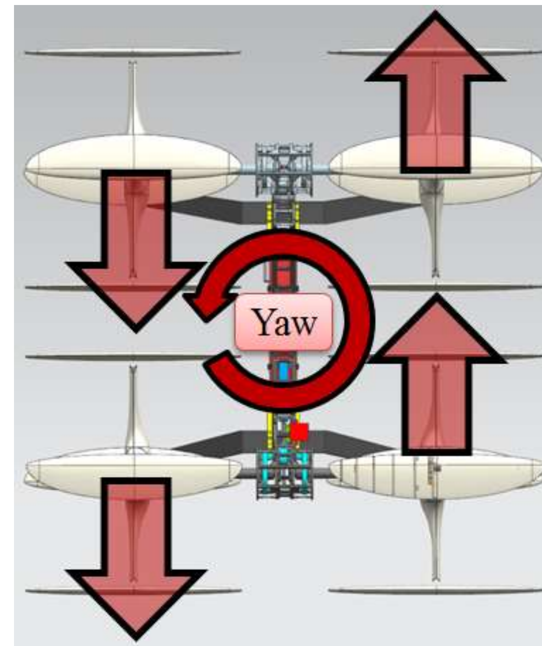
(Side view)



(Front view)

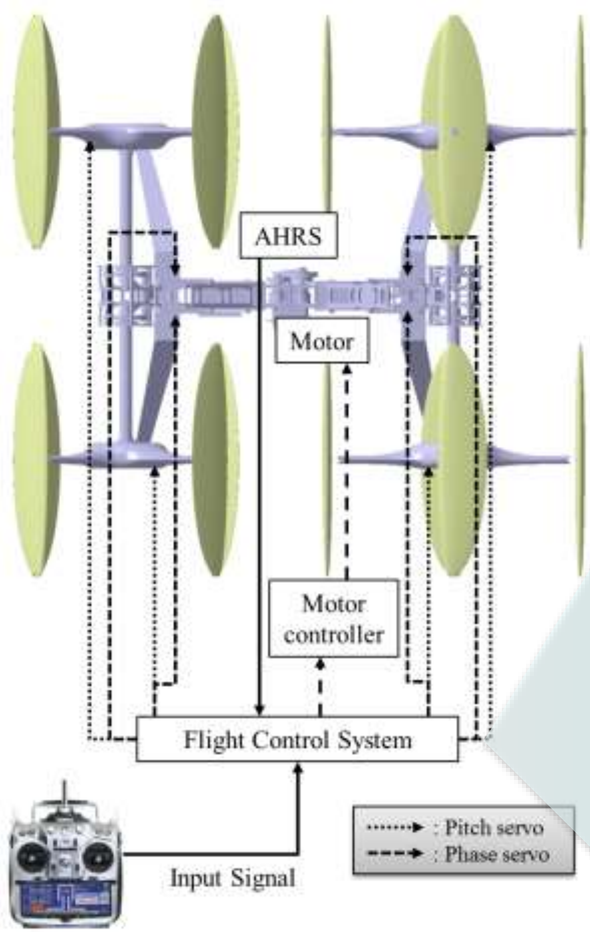


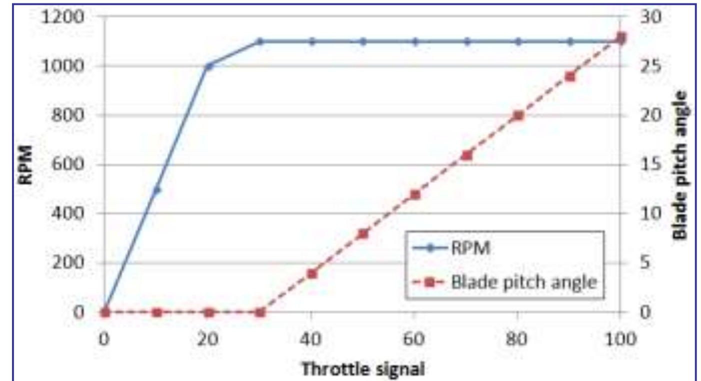
(Top view)

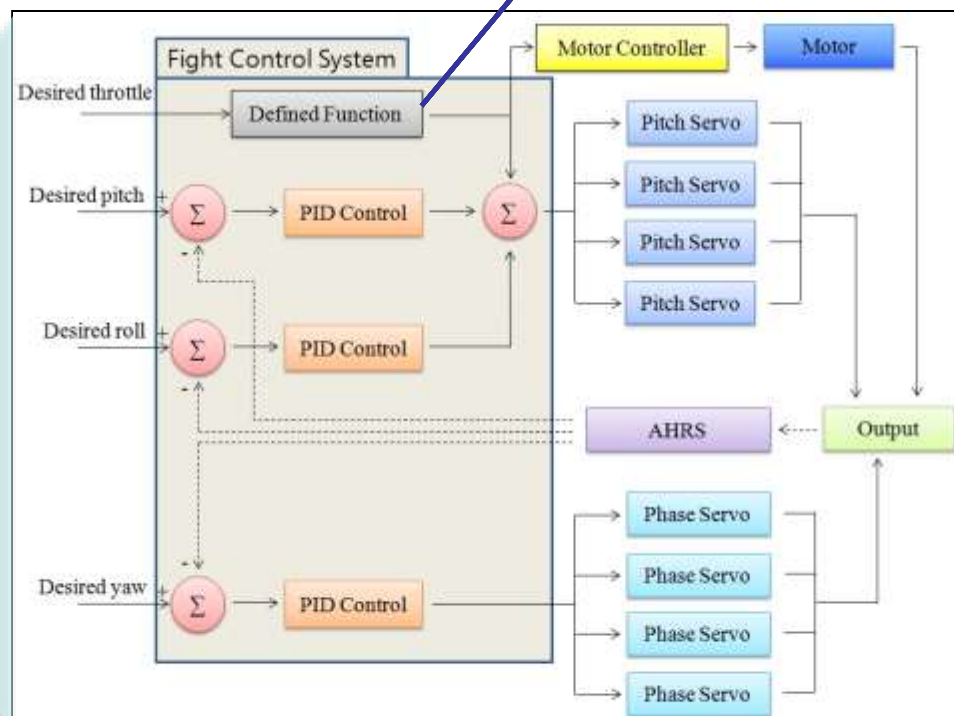


Quadrotor Cyclocopter

- **Flight control system**



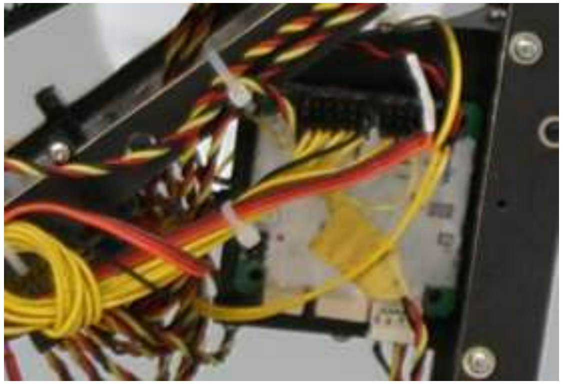




Quadrotor Cyclocopter

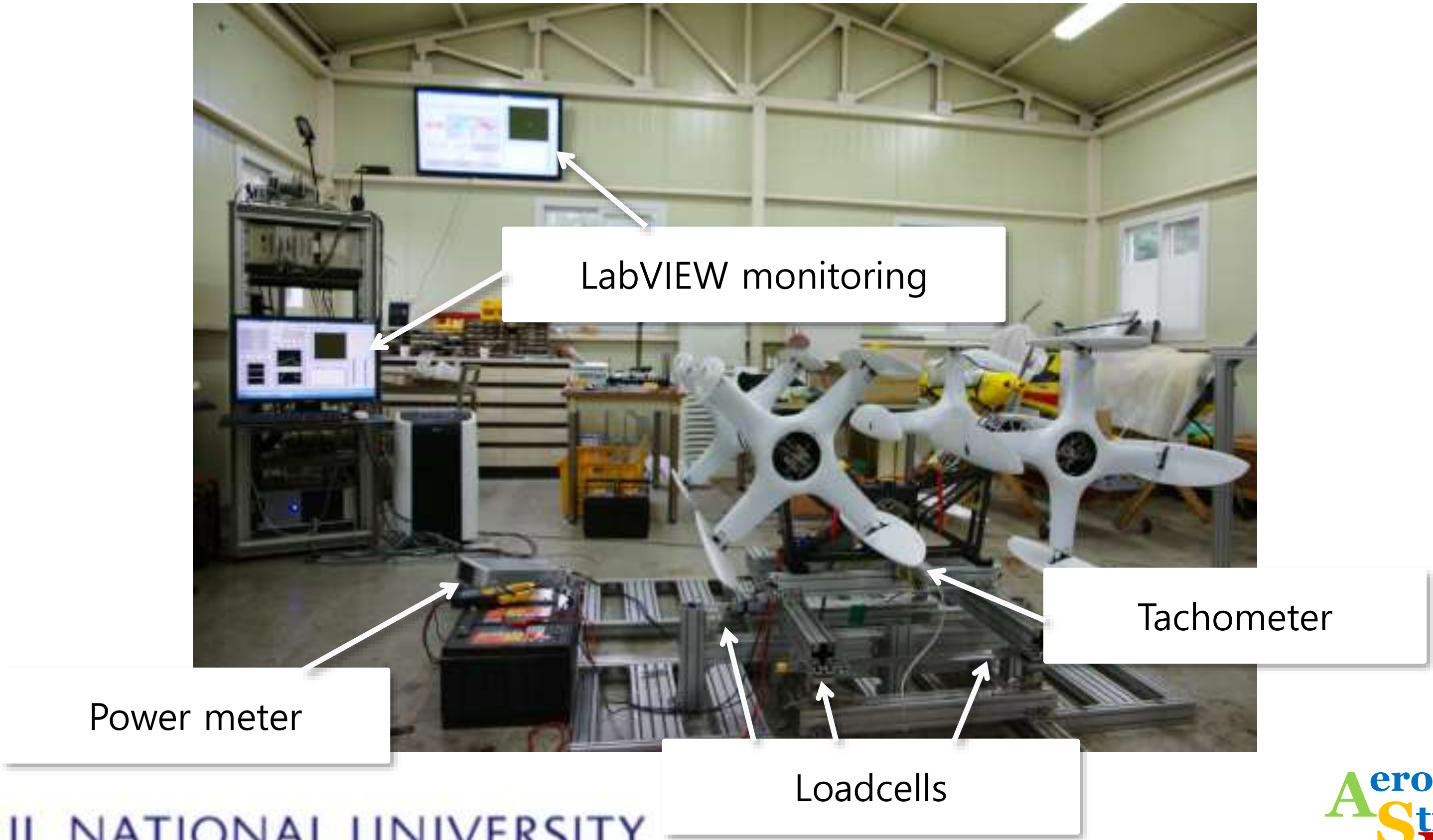
- **Motor and FCS**
  - Electric motor and its controller

  - FCS and AHRS



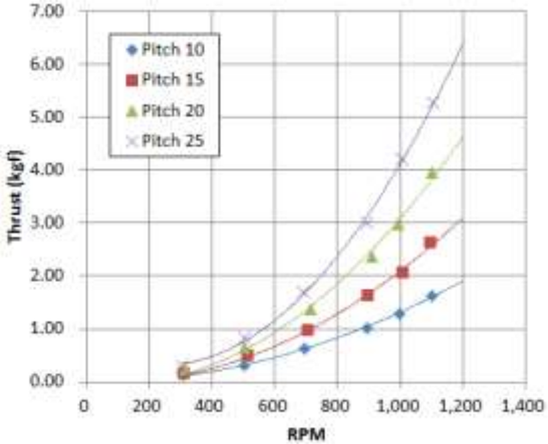
Experimental Setup

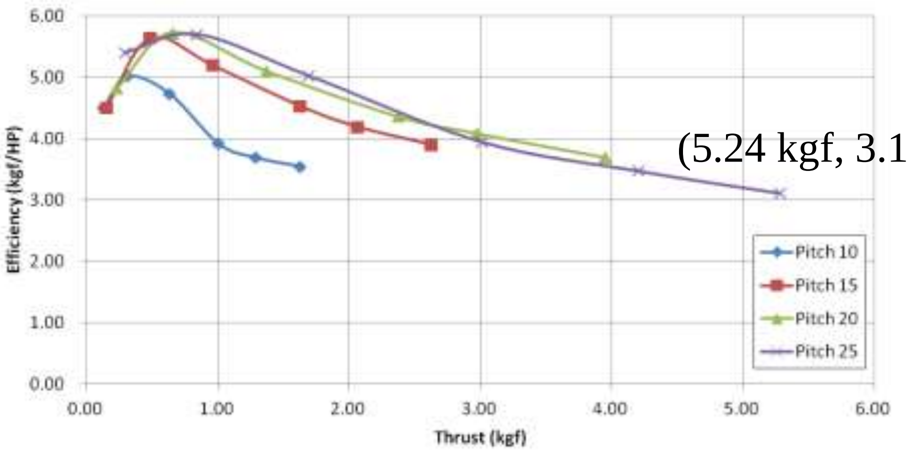
- **Ground test bed**
  - Four load cells measuring vertical forces and thrust center
  - A load cell measuring horizontal force
  - A tachometer and a digital power meter measuring rotational speed and consumed power



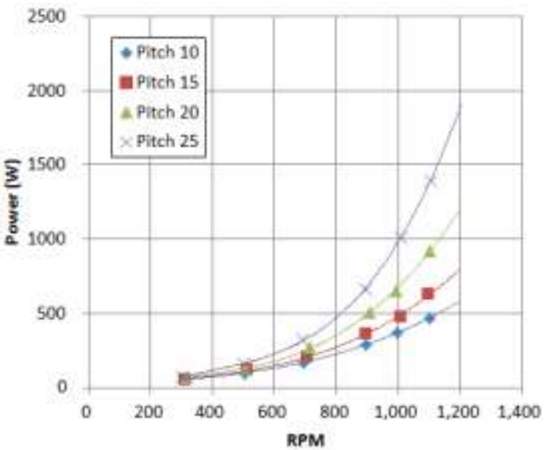
Single Rotor Test

- **Performance**

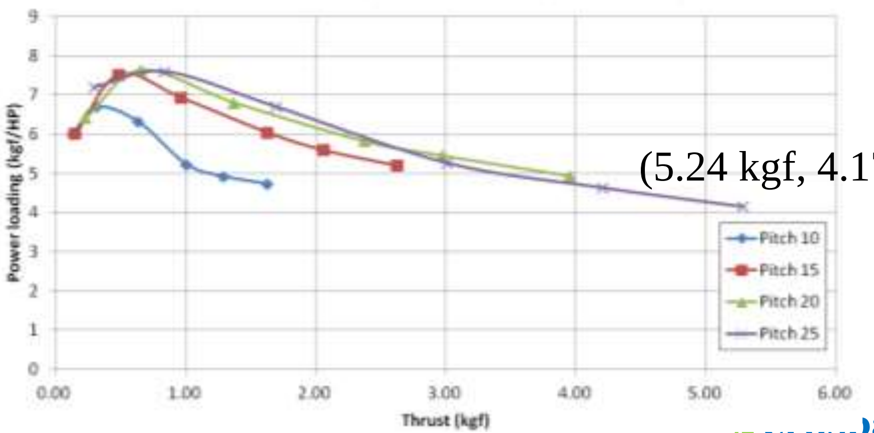




(5.24 kgf, 3.13 kgf/HP)



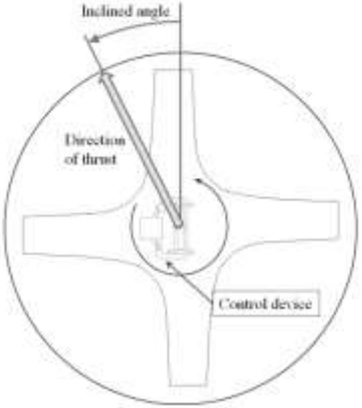
Battery-to-rotor efficiency
= 0.75 (assumed)

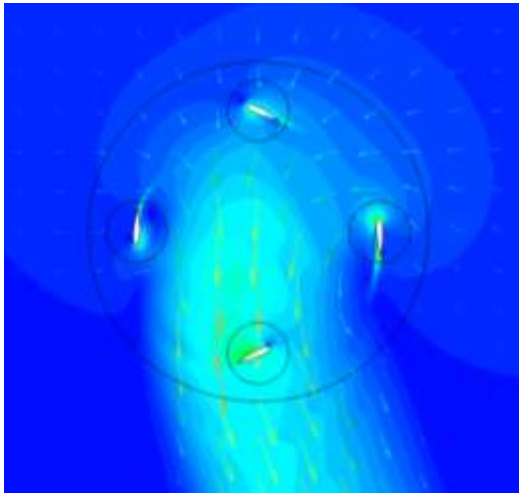


(5.24 kgf, 4.17 kgf/HP)

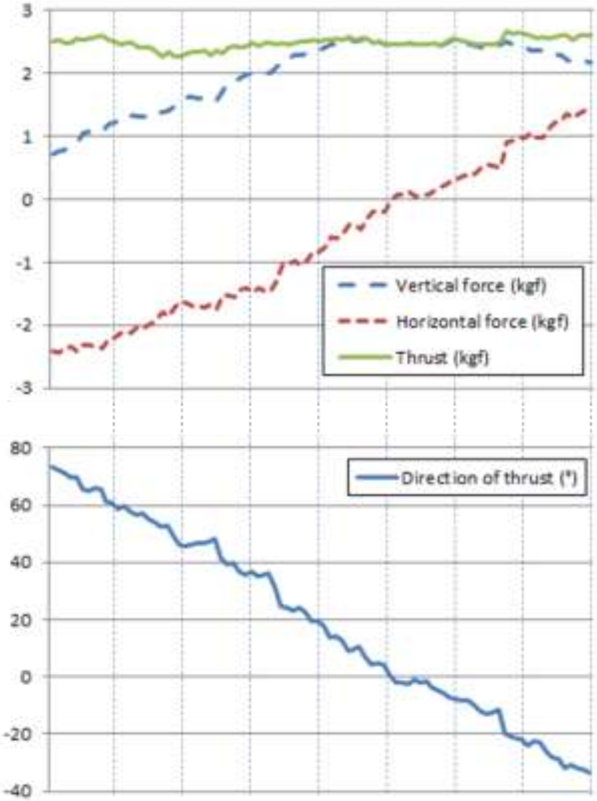
Single Rotor Test

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





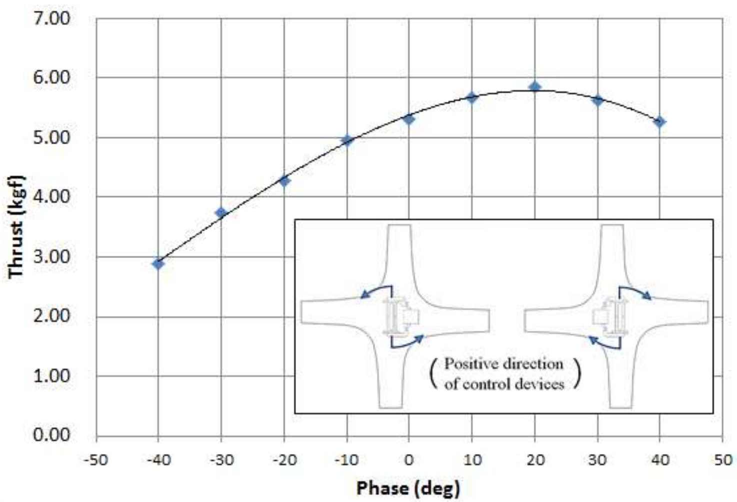
- **Ground effect**
  - In this research, it is assumed that ground effect on the rotor is negligibly small

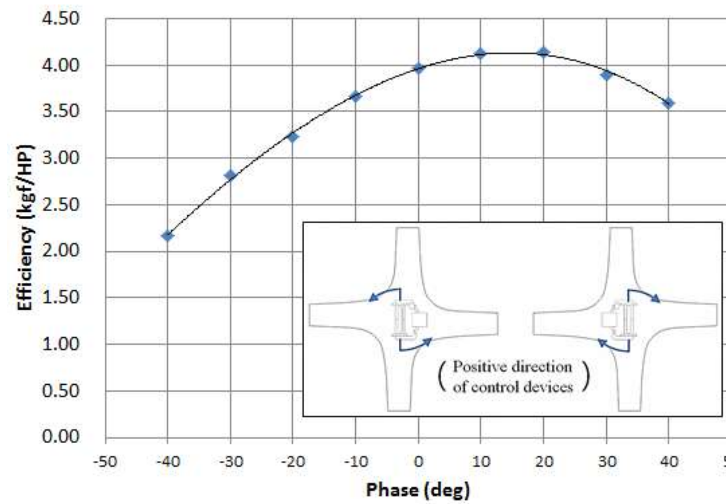


Dual Rotor Test

- **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**

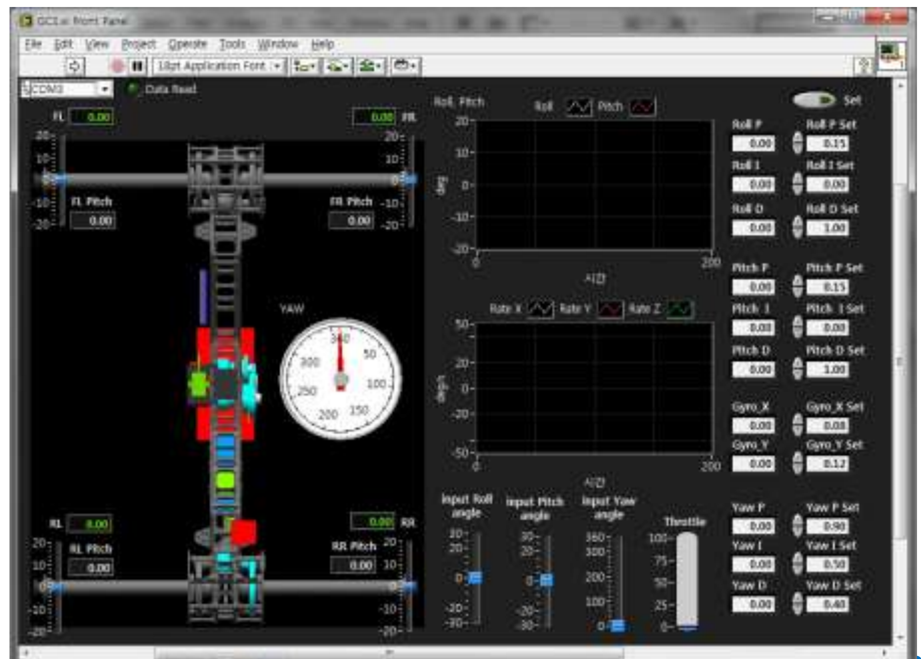
Maximum thrust	
Parameter	**Value**
Max. pitch angle	22°
Phase angle of the control device	+ 20°
Rotational speed	1100 RPM
Measured Thrust (on the test bed)	16.32 kgf
Weight of vehicle	12.8 kg
Consumed electric power (for thrust of 16.32 kgf)	4300 W
Efficiency (kgf/HP)	2.83 kgf/HP
Power loading (estimated)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

Hovering	
Parameter	**Value**
Max. pitch angle (for hovering)	< 20°
Consumed electric power (for hovering)	< 3000 W
Efficiency (kgf/HP)	3.18 kgf/HP
Power loading (estimated)	4.24 kgf/HP

Experimental Setup

- **Tethered flight test configuration**

- 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

Outdoor Flight Demonstration

VTOL UAV

Cyclocopter

Outdoor Flight

SNU ASL

B. Development of Twin Rotor Cyclocopter

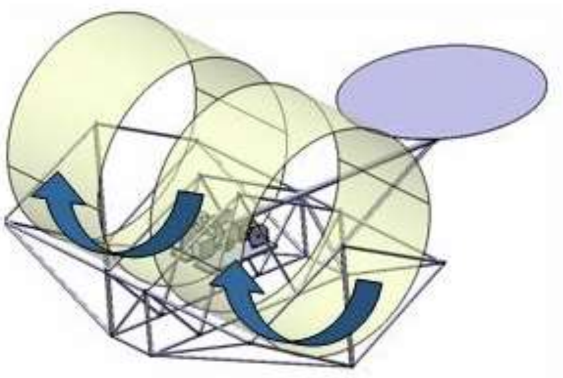
Twin Rotor Cyclocopter

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

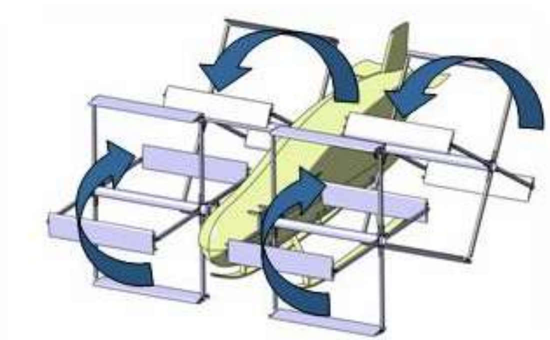
Specifications		
Length with rotors		3,152mm
Height		2,310mm
Width		4,200mm
Weight		110kg
Rotor	**Diameter**	2,000mm
	Span length	1,500mm
	Airfoil	NACA0018
	Chord length	247mm
	RPM	420RPM
	Pitch angle	0~35º
Engine	**Type**	4-stroke single rotor rotary engine
	Power	44 HP at 8750rpm(MAX)
		29 HP at 5900rpm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

Twin Rotor Cyclocopter

- **Various cycloidal rotor configurations**



Two rotors rotating in same direction and a tail rotor

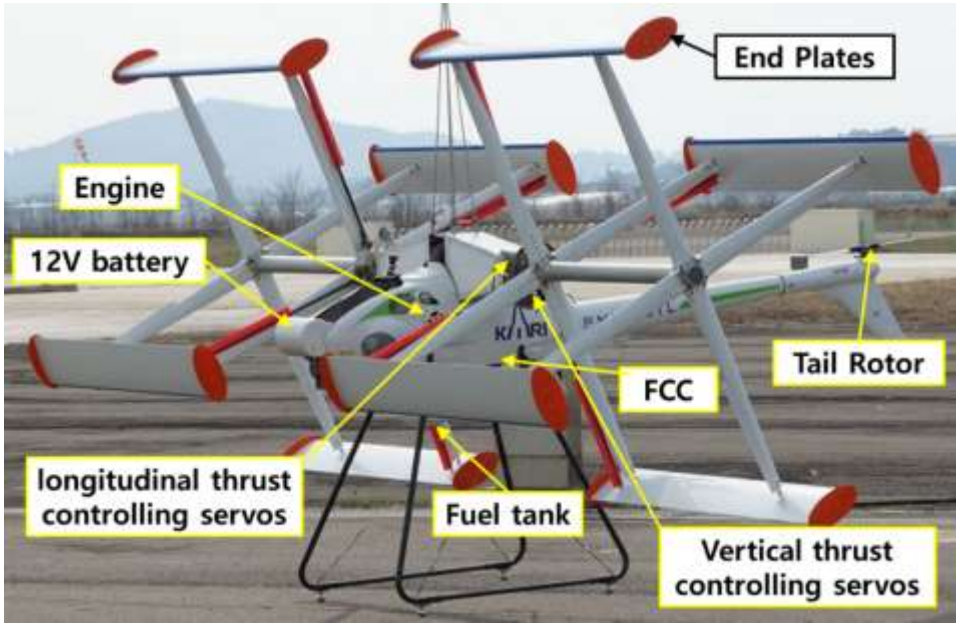


Four rotors of tandem configuration

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

Twin Rotor Cyclocopter

- **Specifications**



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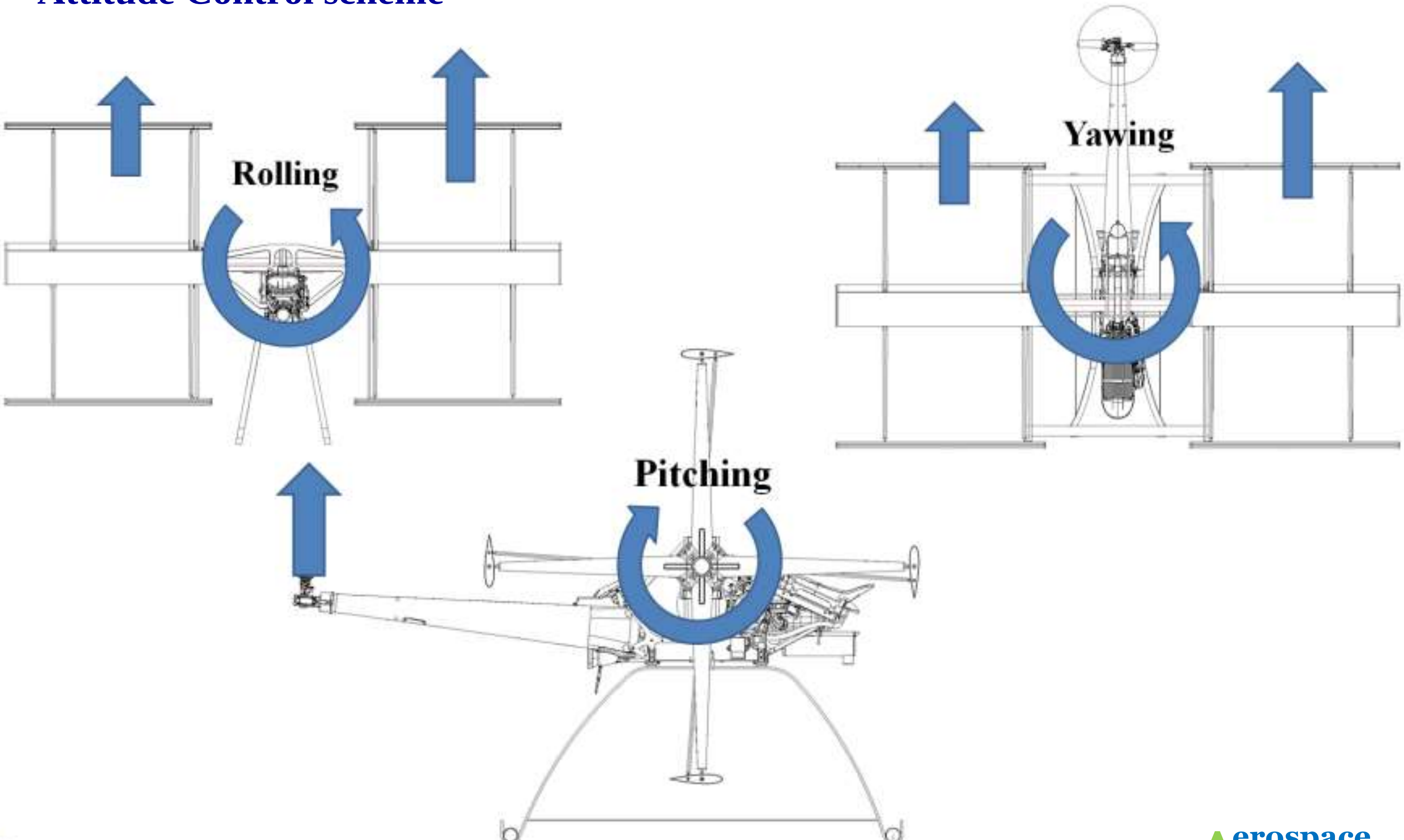
	RPM	420RPM
	Pitch angle	0~35º
Engine	Type	4-stroke single rotor rotary engine
	Power	44 HP at 8750rpm(MAX)
		29 HP at 5900rpm (continuous)
	Chamber Vol.	294cc

Twin Rotor Cyclocopter

- **Attitude Control scheme**



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Twin Rotor Cyclocopter

- **The base frame**

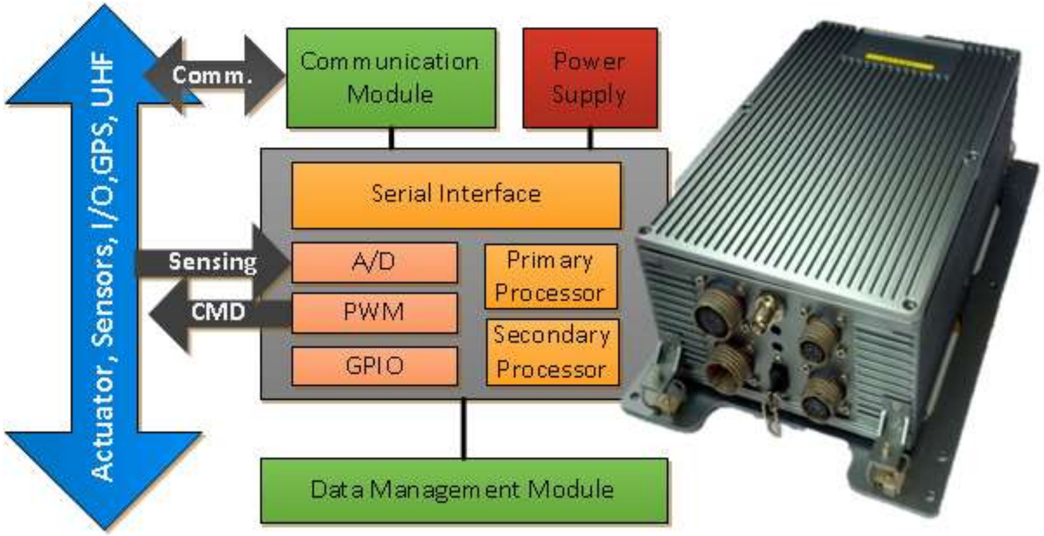
  – The base frame, FCS and engine of REMO-H were used

  ** 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)**

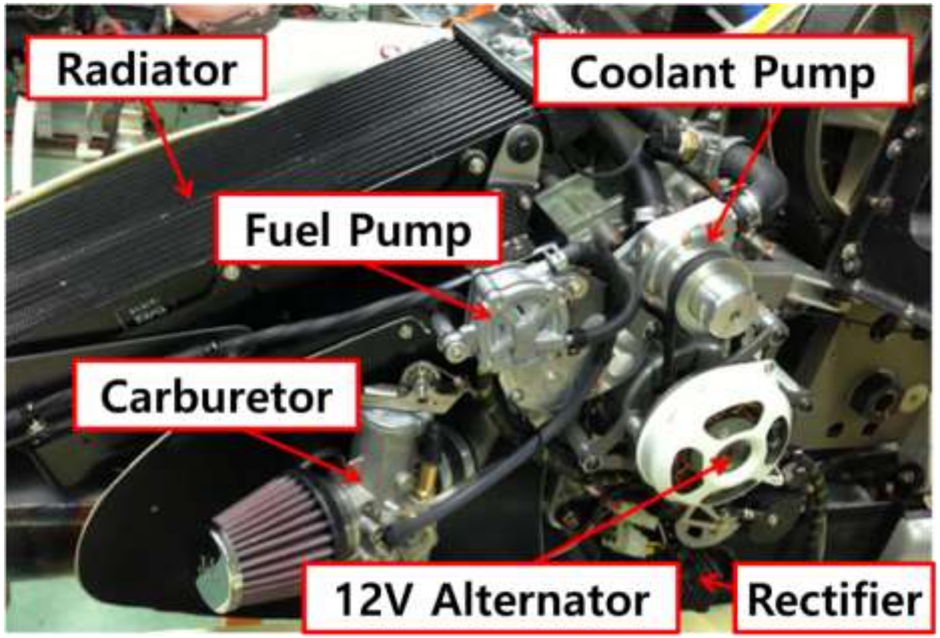


  - Processor : 150MHz Embedded Processor
  - Channel : 8ch control signal
  - Sensor : position, velocity and attitude sensor
  - Weight : 2kg
  - Size : 170 x 200mm

* 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

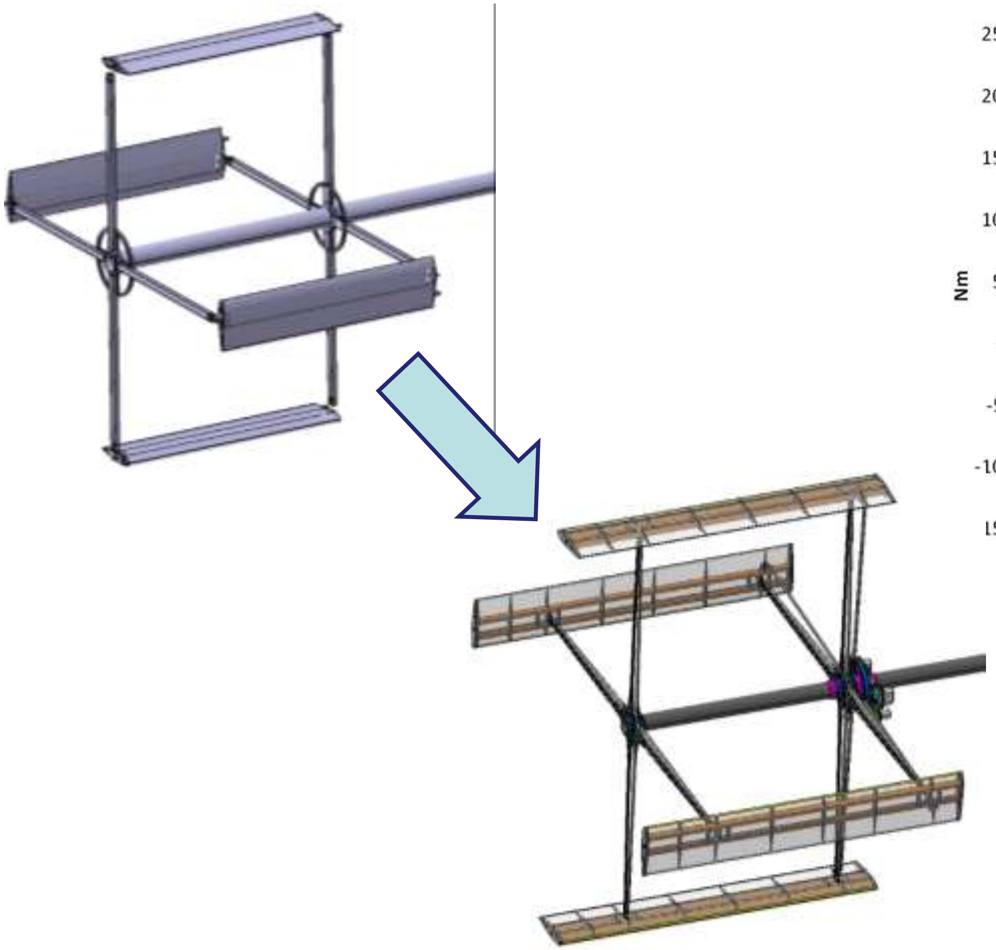
- **Power transmission**

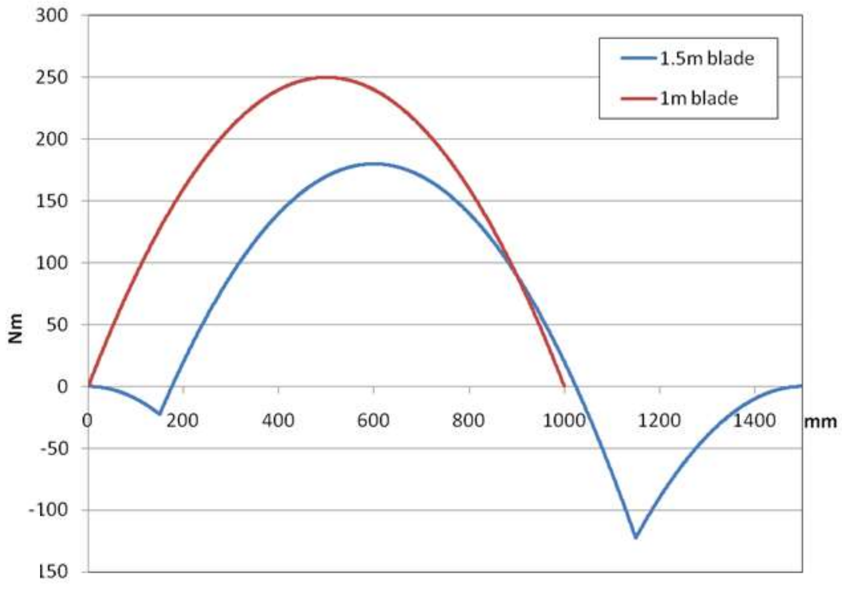
Specifications	
type	4-stroke single rotor rotary engine
power	33 kW at 8750 rpm
weight	ca. 17 kg
torque	39 Nm at 7500 rpm
chamber volume	294 cc
max. rpm	11,000 rpm
ignition	PVL Fire 650
clutch	2-disc dry centrifugal clutch

- 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;

$$\Omega^2 = \Omega_0^2 \left(1 - \frac{4Apl^2}{\pi^2 EI}\right) \qquad \Omega_0 = \frac{3.67}{l^2}\sqrt{\frac{EI}{\rho A}}$$

E : elastic modulus (68.9 GPa)

I : area moment of inertia (6.275e-7 m^4)

p : concentrated mass + thrust (50 kgf)

l : shaft length (1.15 m)

ρ : density of shaft (2700 kg/m^3)

A : cross sectional area of shaft (8.47e-4 m^2)

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

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

2h : height of end plate (0.125m)

b : span of wing (1.5m)

C_L : lift coefficient (2πα)

S : area of wing (0.3705m^2)

C_F : frictional drag coefficient

α : blade pitch angle

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

$$\Delta C_D = 0.25146\alpha^2$$

calculating drag of two main rotors → **1.54HP saving power**

Twin Rotor Cyclocopter

- **Tail rotor configuration**
  - Tail rotor configuration and CG position

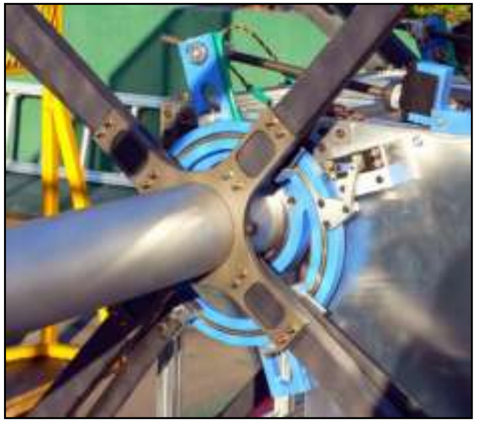
Main rotor consume power (HP)	22
Main rotor rotation speed (RPM)	420
Main rotor position from CG (mm)	50
Tail rotor position from CG (mm)	2,250

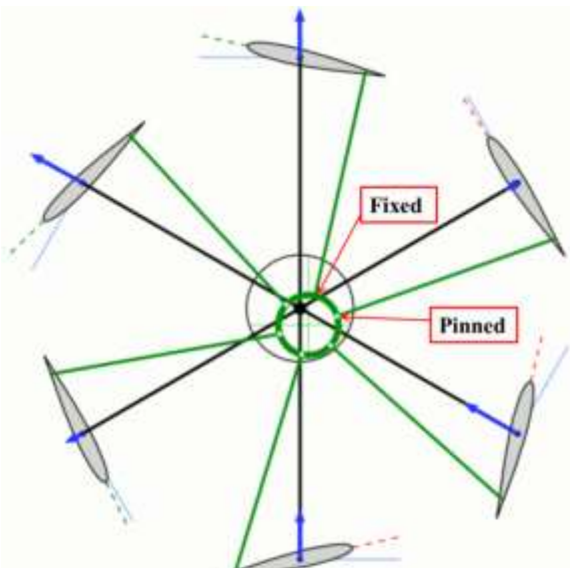
$$\frac{\text{Main rotor consume power}}{\text{Main rotor rotating speed}} = \text{Main rotor thrust} \times \text{Main rotor position} + \text{Tail rotor thrust} \times \text{Tail rotor position}$$

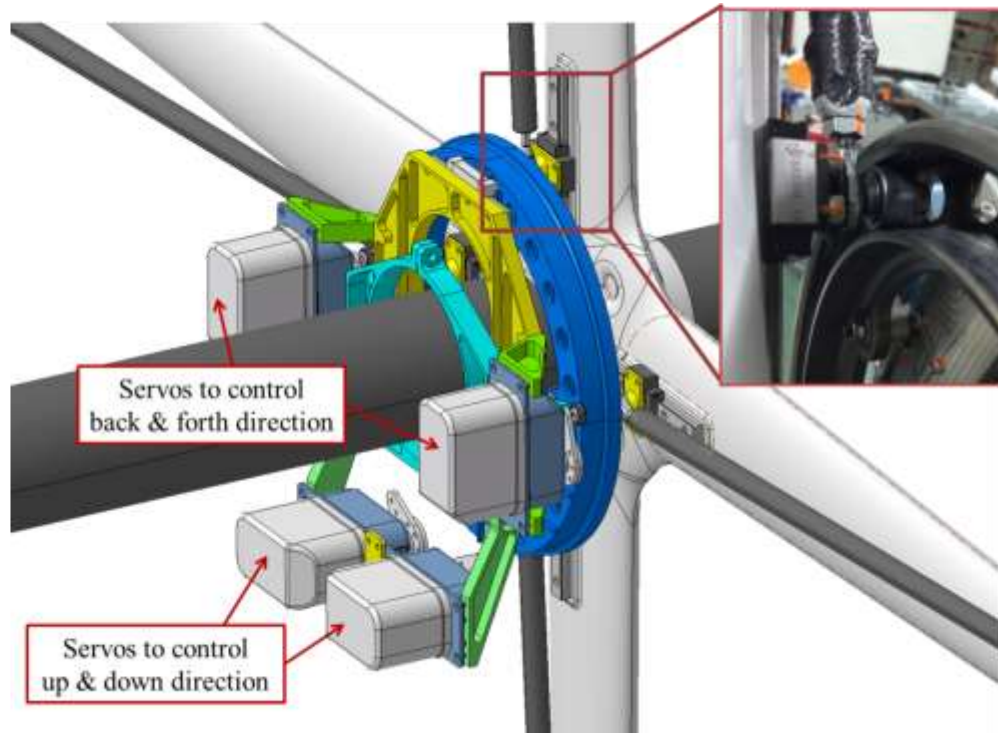
  - It is determined that the tail rotor produces approximately 14.85kgf
  - The size of tail rotor is designed for compensating anti-torque and plus sufficient force of pitching motion

Twin Rotor Cyclocopter

- **Cam-path control mechanism**





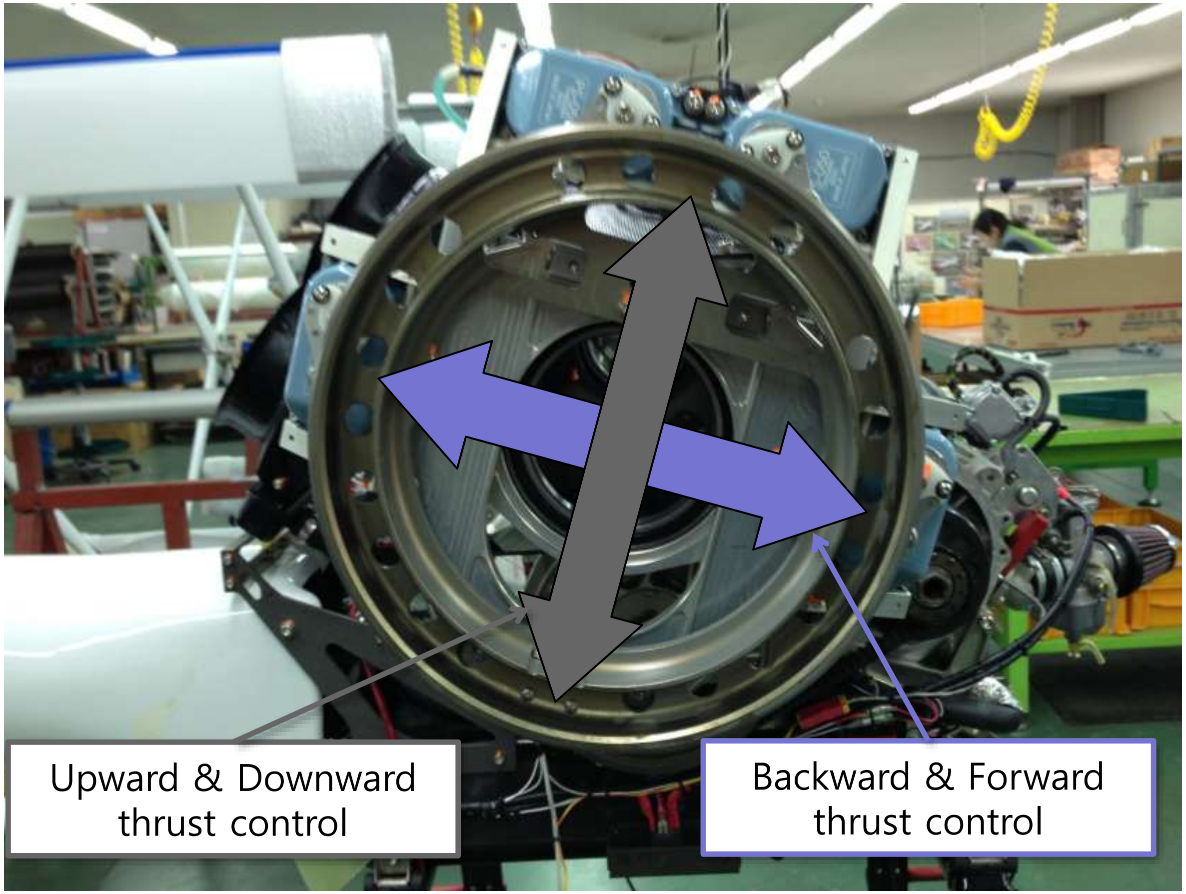


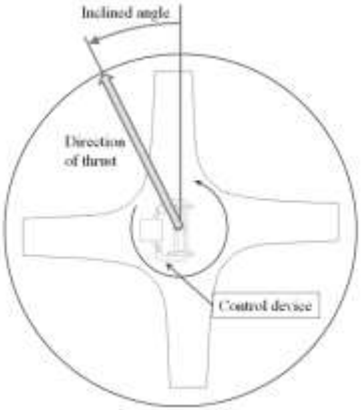
– Control mechanism : Fixed & Pinned type → Cam-path type
– The control link bearings are passed along the cam-path
– Advantage : Axisymmetric control mechanism

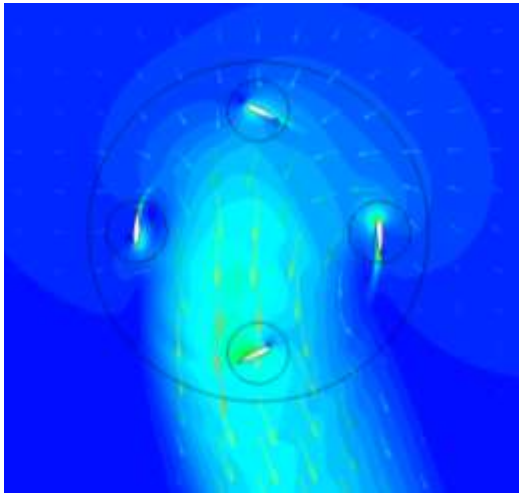
All pitch angle paths are same

Twin Rotor Cyclocopter

- **Cam-path control mechanism**

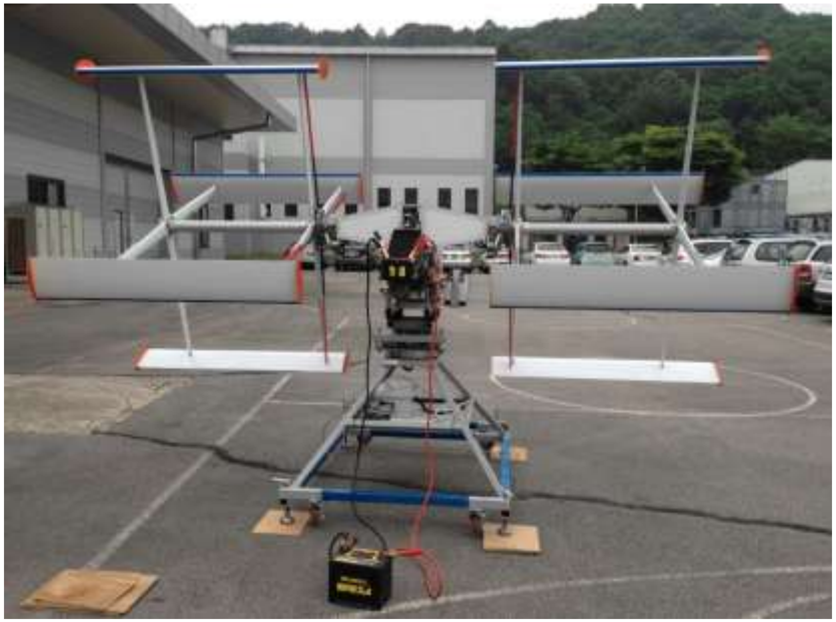


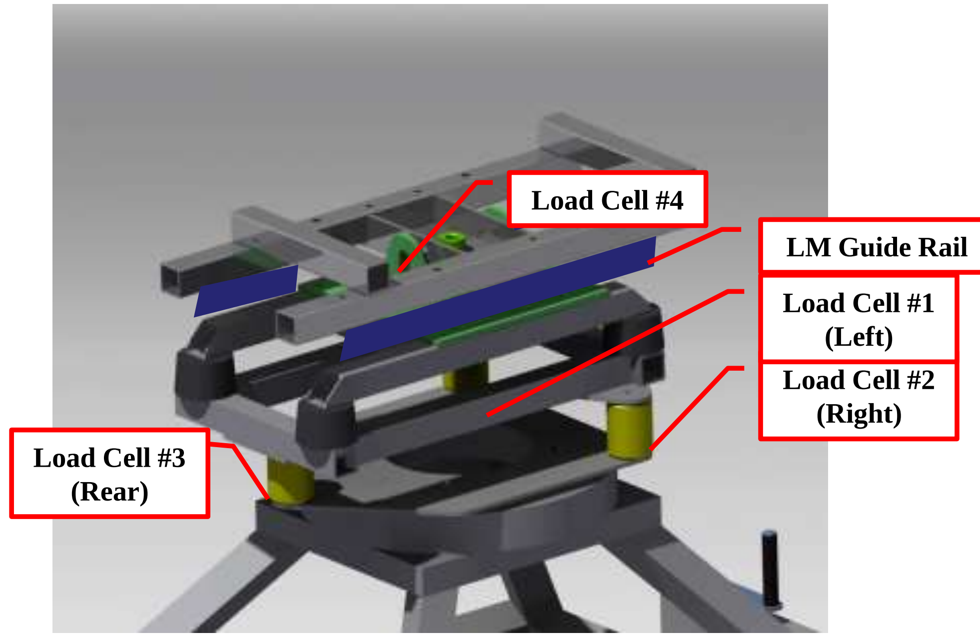




Twin Rotor Cyclocopter

- **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**

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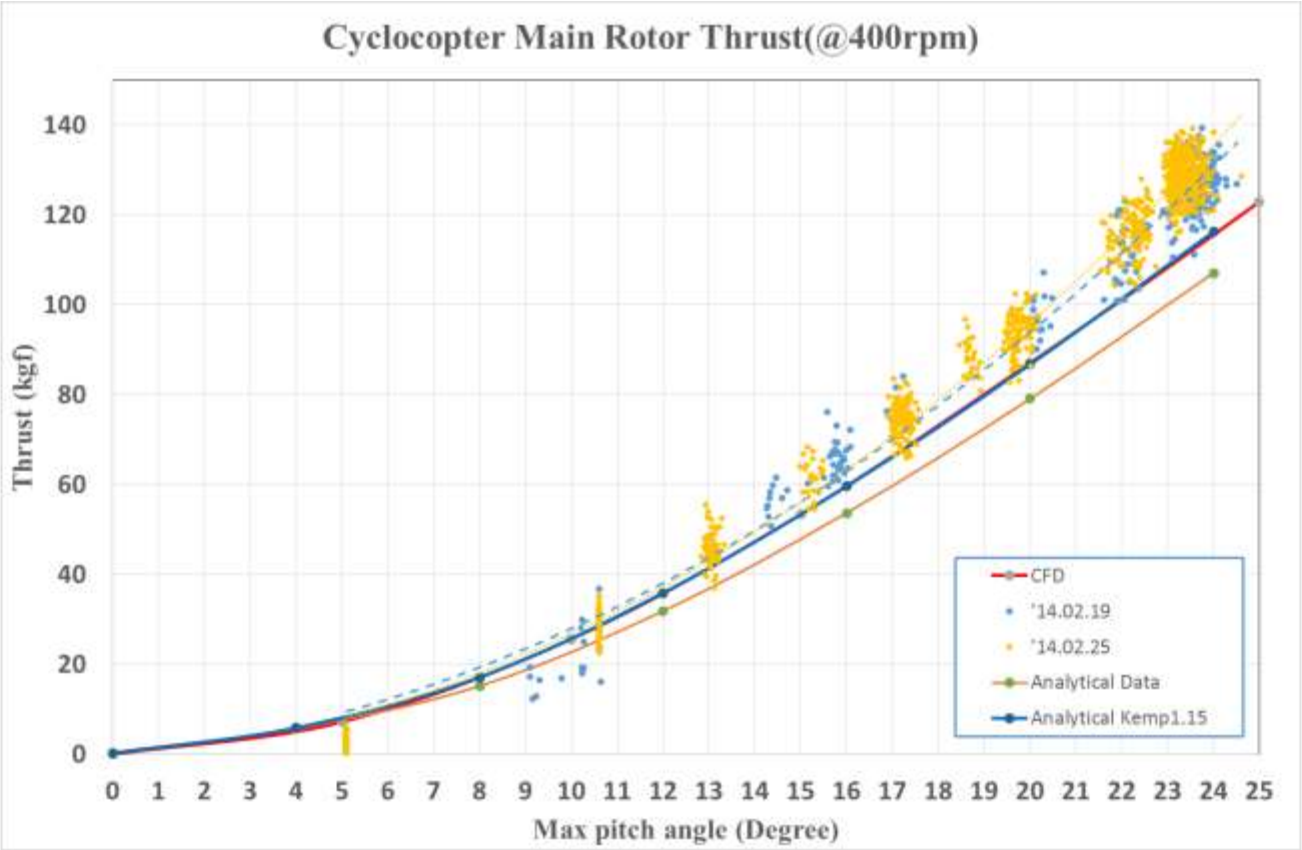
Twin Rotor Cyclocopter

- **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

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Laboratory

Twin Rotor Cyclocopter in tethered test

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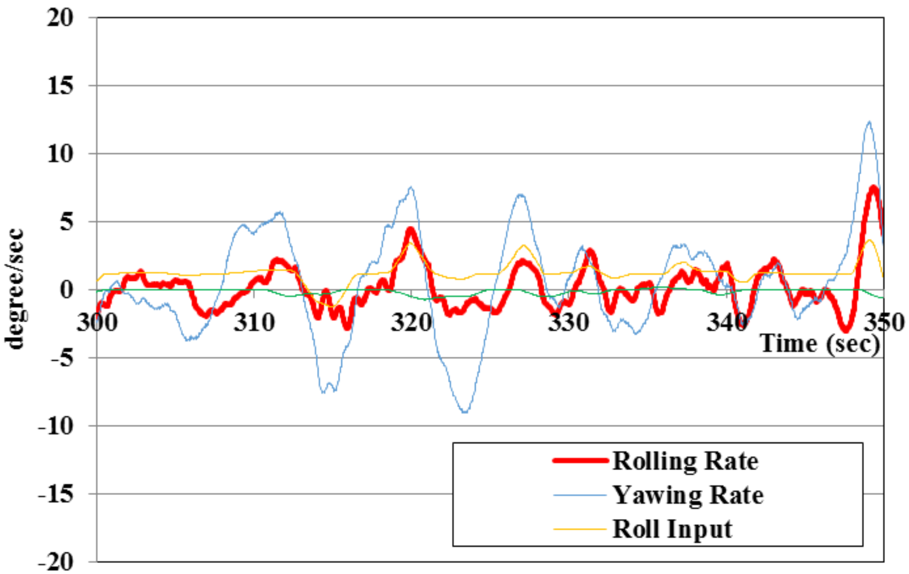
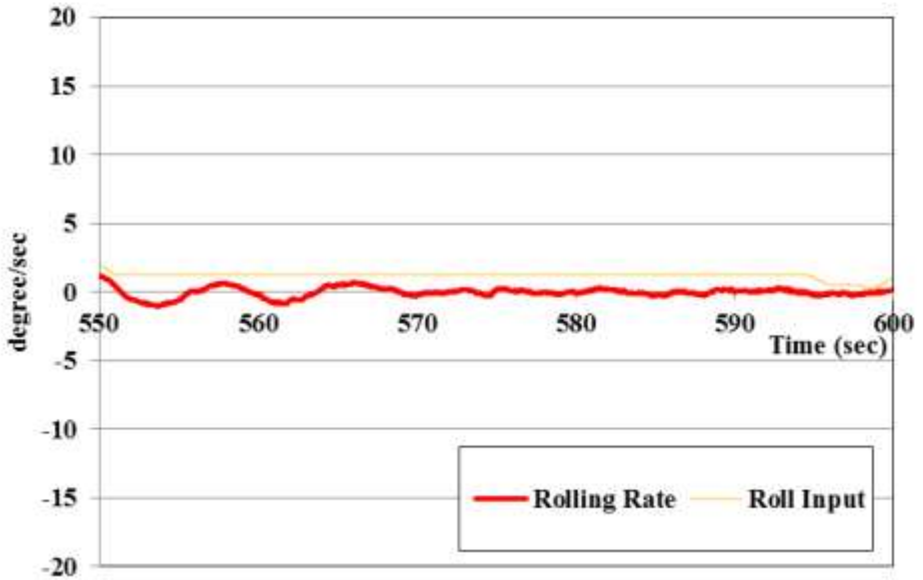
Aerospace Structures Laboratory

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

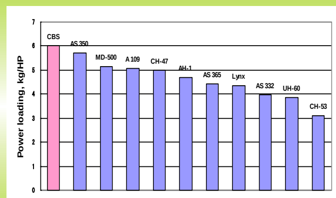
Concluding Remarks

- **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**

Higher thrust output at the same power input

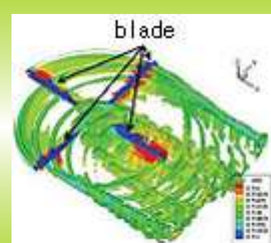


Good Power Loading

Cyclocopter rotor could be designed for efficient hovering performance

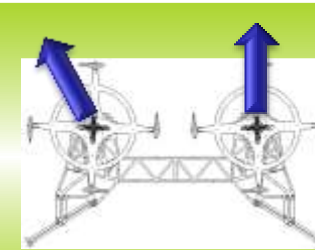
Good Hovering Performance

Much lower rotor blade vortex interaction noise



Low Aerodynamic Noise

Do not need to tilt the rotor or vehicle during forward flight



Same Vehicle Attitude at Forward Flight

END