AN EXPERIMENTAL STUDY ON THE HOVER PERFORMANCE CHARACTERISTICS OF THE COAXIAL PROPELLERS CONFIGURATION FOR THE DRONE

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Abstract

Drone (or Passenger Drone) is one of hot issues in eVTOL industry present. So many companies such as E-hang, Airbus, Volocopter, Uber, Workhorse, etc. release their new concept taxi drone. In near future (within 2030), this taxi drone will enter commercial market and taxi service company (ex: Uber) will start to enter service only if these drones are commercialized. One of this taxi drone is required at the urban air mobility environment. This request compact sized vehicle operated between urban buildings with heavy payload which need to cover passengers. So, several candidate concept of taxi drone such as E-hang 184, Workhorse Surefly introduce the coaxial propellers design. Also, the more heavier payload with given sized vehicle drive these coaxial propellers drone described in figure1 [1] The purpose of this study is to present reliable performance data by experimental studying coaxial propellers configuration and to identify the characteristics of coaxial propellers to be used at the design, production, and verification and performance evaluation. To do this, experimental device was developed that can test at low Reynolds number($Re \approx 3\times10^5$) of coaxial propellers. The experimental device basically constructed the DAQ which can measure torque, rpm, power so that the performance characteristics of the upper and lower propellers can be known. The experiments which composed of the different H/D ratio (0.1~0.8) defined as the ratio of distance of upper / lower propellers divided by its diameter and the different propeller's diameter's ratio were conducted. Experiments were carried out on the coaxial propeller after verifying the calibration. As a result of comparing the values with F.M.(Figure of Merit), it was found that the coaxial propeller of the same diameter showed a constant FM at the H/D ratio(0.2~0.3) and the highest value of all conditions tested was achieved when the diameter of the upper part of the propeller was smaller than the diameter of the lower part confirmed.

1. INTRODUCTION

1.1. Background

Taxi Drone (or Passenger Drone) is one of hot issues in eVTOL industry present. So many companies such as E-hang, Airbus, Volocopter, Uber, Workhorse, etc. release their new concept taxi drone. In near future (within 2030), this taxi drone will enter commercial market and taxi service company (ex: Uber) will start to enter service only if these drones are commercialized. One of this taxi drone is required at the urban air mobility environment. This request compact sized vehicle operated between urban buildings with heavy payload which need to cover passengers. So, several candidate concept of taxi drone such as E-hang 184, Workhorse Surefly introduce the coaxial propellers design. Also, the more heavier payload with given sized vehicle drive these coaxial propellers drone described in figure1 [1]. From this trend, several studies on coaxial rotor's performance has been conducted. Taylor[2] had studied the wake visualization of coaxial rotor in addition to single and tandem rotor by experiment. Coleman [4] reviewed several studies on coaxial rotor performance. Leshiman [5-6] had studied the aerodynamic performance and hover efficiency (figure of merit) for the coaxial rotor based on momentum theory. Stephen [7] had studied the impact on the power, thrust and current due to the ratio of distance (H/D) between the propeller diameter (D) and height of upper and lower propeller (H). To do this study, he built the test rig which could control the height of upper and lower propeller. Ramasamy [8] studied the aerodynamic performance of the coaxial rotor and tandem rotor. Most of these studies had focused on the vehicle of the small drone or conventional manned helicopter which had more than 1 meter radius.It has been requested to improve payload of present drone to supply public service which are water spray drone for agricultural purpose, parcel

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delivery drone for big size, reconaisance, etc. Specially, the taxi drone or passenger drone has started to research and develop to supply public transportation service to reduce time and money in city. To do this study, the vehicle which has the the payload more than 30kg was selected. For passenger drone which are operated in high buildings in city, the compact size is required. That the reason why the coaxial type drones are attractive and entering into the demonstration. The representatives of these coaxial drone types are E-hang 184 and Workhorse Surefly. These introduce the coaxial propeller design similar to normal drones. For public service or national infra observation such as electric line, oil pipe, big bridge, traffic control, etc., more compact drone are required to access near the infra and to get exact information. To satisfy the heavier payload and compact size, the coaxial type drone is extremely attractive. In addition to these attractions, BLDC motor are easy to compose coaxial type drone not like the helicopter. For these reasons, this study has focused on coaxial drone with high payload (more than 30kg). To this study, 26~29inches propellers have been adopted. These propellers are generally operated in the range of low Reynolds No. (Re~3x10^5). These aerodynamic environment are not easy to predict the exact aerodynamic performance by analysis tool. So, the experimental study was required to estimate exact aerodynamic performance. Figure 1 show the several type of drone and the representatives of passenger drone

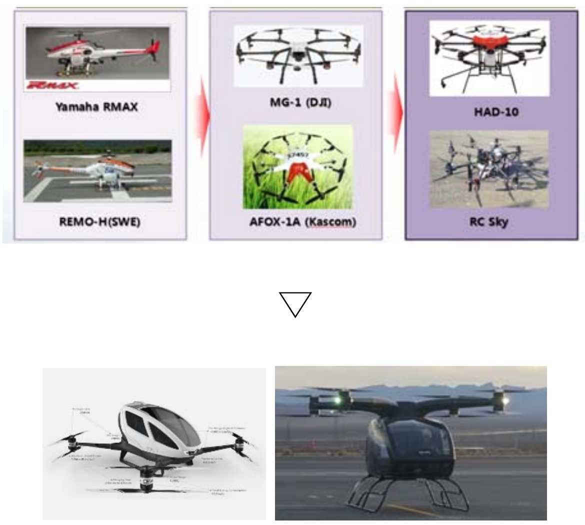

Figure 1 Several Types of Taxi Drone and Multicopters

1.2. Purpose

This study focused on experimental study on the hover performance characteristics of the coaxial propellers configuration of drone which has the payload more than 30kg useful to civil and military area. This study was conducted to various configuration of rotor diameter change of upper and lower propeller. And also the various ratio of distance (H/D) between the propeller diameter (D) and height of upper and lower propeller (H) can affect aerodynamic performance. To find out the optimal design point, the design guideline is required to adopt the coaxial type. To suggest and propose the design guideline for coaxial drone such as passenger drone more than 30kg payload, The representative diameter of propellers as 26” and 29” were chosen and ratio of distance(H/D) between the propeller diameter(D) and height of upper and lower propeller(H) were change to find out the optimal value.

2. DEVEOPMENT OF TEST RIG

2.1. Test Rig Design

Test rig design was conducted according to the following procedures. For the test of 30kg payload drone, 26” and 29” propeller were selected. To test these propellers, the requirements of test rig were established. And the test rig design was conducted satisfying these requirements.

2.1.1. Requirements

Test rig was designed to do some ranges of performance tests which cover several propeller size and height of upper and lower propeller. The items to be measured are thrust, torque and electric power. To control operational propeller rpm, it can be measured. The range of propeller’s size is 15~30”. Table 1 shows the summary of initial requirements of test rig.

Table 1. Initial Requirements

Propeller’s Diameter	Measured Items	Maximum Height of Upper and Lower Prop.
15~30”	Thrust (N) Torque(Nm) RPM(1/rev) Electric Power(W)	85~850(mm)

To check the interface and interference between test rig and propeller, 3D design tool (CATIA) was applied to initial design. Based on initial

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requirement, all items such as propeller diameter, sensors and height of upper and lower prop. Figure 2 shows the 3D design and representative size of test rig for coaxial propellers.

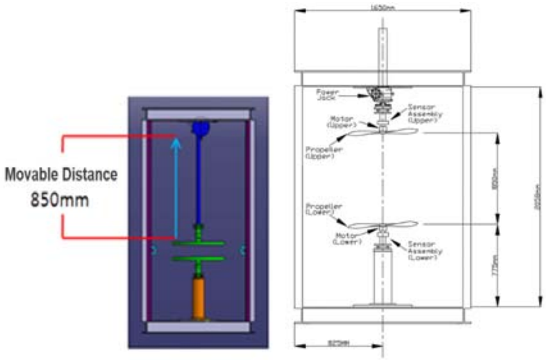

Figure 2 Initial Design of Test Rig for coaxial propellers

2.1.2. Test Rig Setup

Test rig was composed of measuring sensors, power supply, DAQ module, monitoring and data; processing which made by LabVIEW software. To do rotate the propeller on test rig, PWM signal in control program transferred to DAQ module and ESC can control electric current to match rotational speed. Figure 3 shows the architecture of DAQ system. Figure 4 shows Overview of Test Rig and Typical section of Measurement of Test Rig. The linear guide has a role of isolation of thrust to measure pure whole thrust of propeller. The measurement system of the upper and lower propeller are exactly identical system. The electric motor can be easily exchanged with another electric motor of different size of propeller. Optic sensor for measuring rpm was installed on the base of drive motor. Reflective tape was attached on the propeller to give a pulse signal.

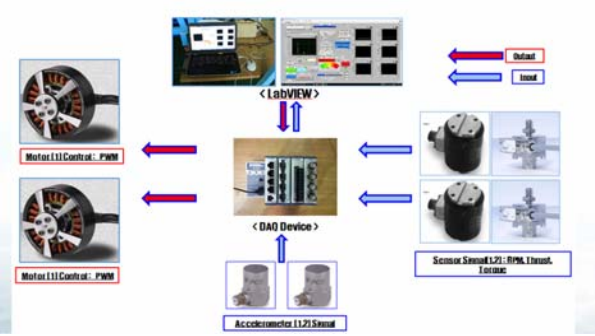

Figure 3 Data Acquisition System Architecture

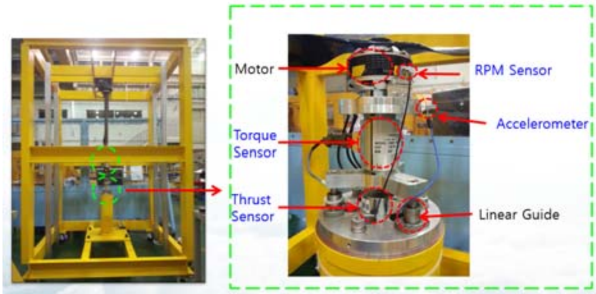

Figure 4 Overview of Test Rig and Typical section of Measurement

2.1.3. Sensors

As described in sec 2.1.1 requirement, the 4 major sensors were installed. They are Thrust, Torque, RPM and Electric Power. Additionally, Vibration was monitored to verify data quality and safety.

Loadcell for thrust measurement is U2b-0.5kN (HBM) which can measure tensile and compressive load both. On the test rig, upper propeller generate compressive load and lower propeller generate tensile load. The max capacity of loadcell was 0.5kN which predicted based on 29"x9.5 propeller capacity (0.1kN) with margin (5 times). The signal of Loadcell is transferred to DAQ module by 10 kHz rate. The data was measured for 5 seconds after stabilization and achieved as mean value. Figure 5 shows the loadcell geometry for thrust measurement. Table 2 shows the specification of Loadcell for thrust measurement.

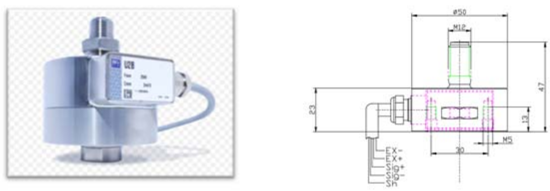

Figure 5 Loadcell Geometry for Thrust Measurement

Table 2. Loadcell for Thrust Measurement

Model	U2b(HBM)	
Position	Upper (Compression)	Lower (tension)
Max Capacity	0.5kN	0.5kN
Sensitivity	2.0006mV/V	- 1.9997mV/V
Linearity	0.001%	0.003%
Hysteresis	0.021%	0.025%
Supply Voltage	5V	5V

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Loadcell for torque measurement is 2508-02A (PCB) which can measure torque of propeller. The max capacity of loadcell was 11.3Nm which predicted based on 29”x9.5 propeller capacity (2.3Nm) with margin (5 times). The signal of Loadcell is transferred to DAQ module by 10 kHz rate. The data was measured for 5 seconds after stabilization and achieved as mean value. Figure 6 shows the loadcell geometry for torque measurement. Table 3 shows the specification of Loadcell for torque measurement.

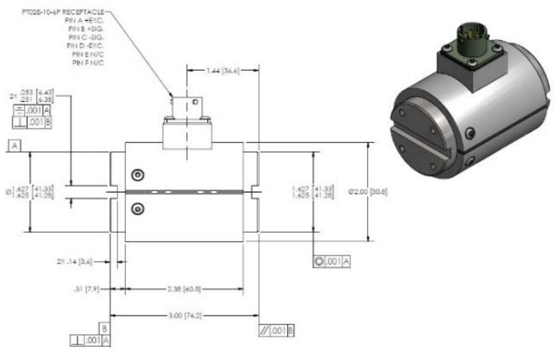

Figure 6 Loadcell Geometry for Torque Measurement

Table 3. Loadcell for Torque Measurement

Model	2508-02A(PCB)	
Position	Upper	Lower
Max Capacity	11.3Nm	11.3kN
Sensitivity	2mV/V	2mV/V
Linearity	0.1%	0.1%
Hysteresis	0.1%	0.1%
Supply Voltage	10V	10V

Accelerometer for vibration measurement is 352C03 (PCB) which can measure acceleration of test rig which can be generated by unbalance of propeller assembly with sensors. This sensor is very valuable to monitor the test rig status and health during test. From this sensor, the resonance of test rig and excessive vibration can be monitored to be operated safely. The max capacity of loadcell was ±4900m/s2 peak. The signal of Loadcell is transferred to DAQ module by 10 kHz rate. The data was monitored in real time for monitoring. Figure 7 shows the Accelerometer Geometry for Vibration Monitoring. Table 4 shows the specification of accelerometer

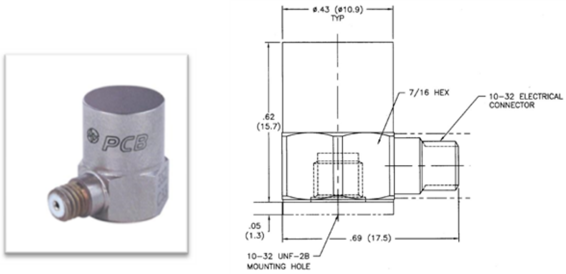

Figure 7 Accelerometer Geometry for Vibration Monitoring

Table 4. Specification of accelerometer

Model	352C03 (PCB)
Position	Upper=Lower
Max Capacity	±4900 m/s^2 pk
Sensitivity	2mV/V
Linearity	0.1%
Hysteresis	0.1%
Supply Voltage	10V

Optical sensor for rotational speed measurement is BF4R(Autonics) which can measure rotational speed of propeller. The reflective tape was attached on the one of propeller. This sensor generate pulse when the tape pass over this sensor. To improve the accuracy, the distance of sensor and tape was chosen as 4mm. Figure 8 shows overview of optical sensor. Table 5 shows the specification of optical sensor

Figure 8 Overview of Optical Sensors

Table 5. . Specification of optical sensor

Model	Autonics (BF4R)
Type	Fiber optic
Distance	2~10MM
Object	Reflective Tape (Non-Transparent)

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Response Time	0.5ms
Supply Voltage	18~24V DC

To measure electric voltage and current, the eLogger V4 module was adopted. This module was generally used in flight test of drone to get electric information and to monitor battery's remain capacity. To monitor and get electric information, same module was used. Figure 9 shows the general overview of ELogger V4.

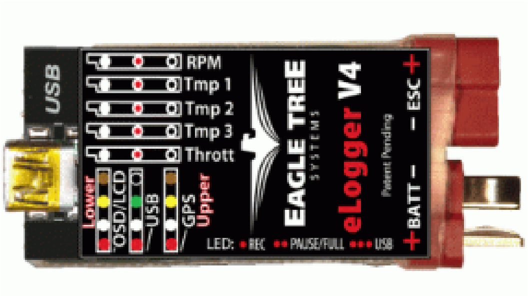


Figure 9 Overview of ELogger V4

2.1.4. DAQ Module

DAQ module was composed of sensors, signal conditioning, data acquisition, data processing, display and saving. For major sensors, total 4 modules were adapted to get data. All DAQ modules adopted the NI 92xx series. LabVIEW was used to build up DAQ system. This DAQ module can adjust gain and offset of sensors for calibration. It also control drive motor by PWM control. It shows the monitoring parameters like vibration or resonance, propeller rpm, thrust and torque. Figure 10 shows the GUI of this DAQ module

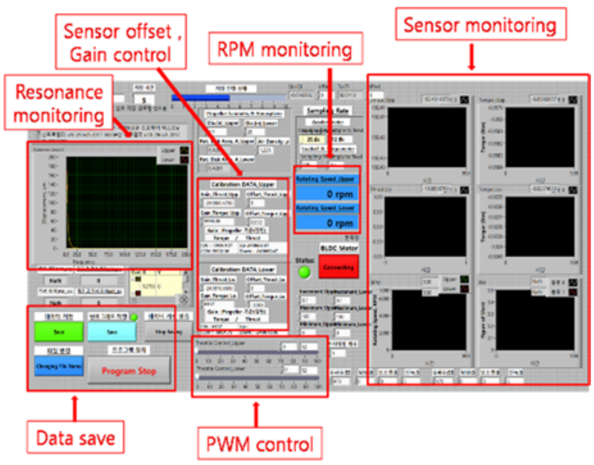


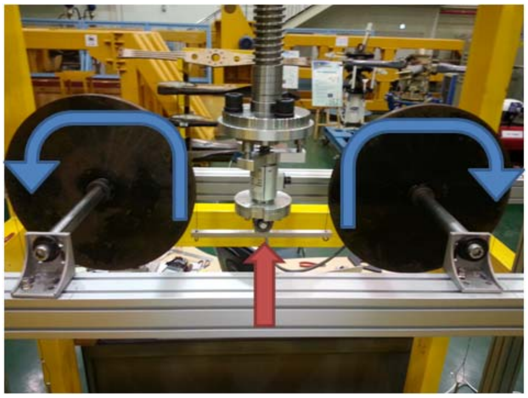
Figure 10 GUI of DAQ Module

2.2. Test Rig Calibration

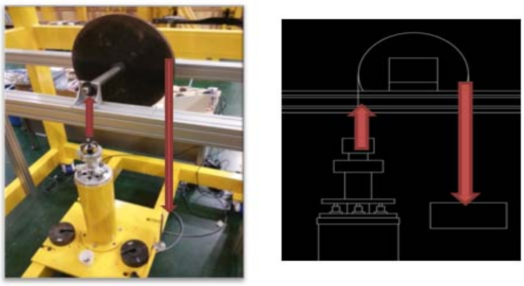
The calibration of major sensors on test rig was conducted. Thrust and torque sensors were major sensors. So, the calibration on these sensors were done using simple device using pulley mechanism.

2.2.1. Thrust Sensors

To evaluate accurate propeller thrust, Loadcell for thrust measurement was calibrated by applying known load. The known load was applied by pulley system. The load was applied from 2kg to 10kg by each 2kg step. Figure 11 shows the basic concept of thrust sensor calibration. Upper figure shows upper thrust sensor calibration and lower figure shows lower thrust sensor of coaxial propeller test rig. Figure 12 shows the calibration results of both thrust sensors. The linearity of measured data is very good as R^2=0.9999. The thrust gain of calibration was calculated by averaging of 3 times repeated test data.



(a) Upper sensor calibration rig



(b) Lower sensor calibration rig

Figure 11 Thrust Sensors Calibration

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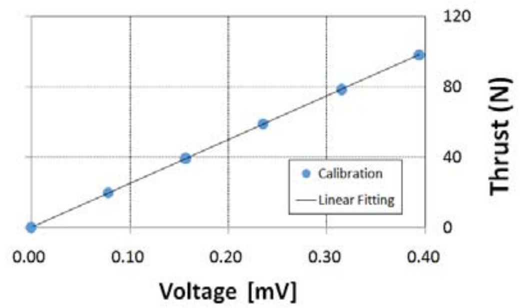
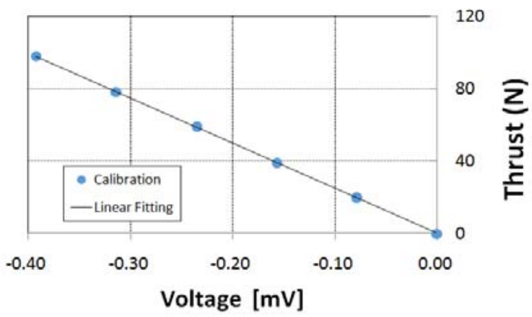


(a) Upper sensor calibration result



(b) Lower sensor calibration result

Figure 12 Calibration Result of Thrust Sensor

2.2.2. Torque Sensors

To evaluate accurate propeller torque, Loadcell for torque measurement was calibrated by applying the known load. The known load was applied by pulley system. The load was applied from 2Nm to 10Nm by each 2Nm step. Figure 13 shows the basic concept of torque sensor calibration. The figure shows lower torque sensor of coaxial propeller test rig. Figure 14 shows the calibration results of both torque sensors. The linearity of measured data is very good as R^2=0.9999. The thrust gain of calibration was calculated by averaging of 3 times repeated test data.

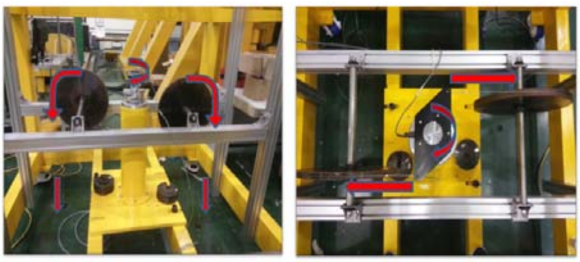
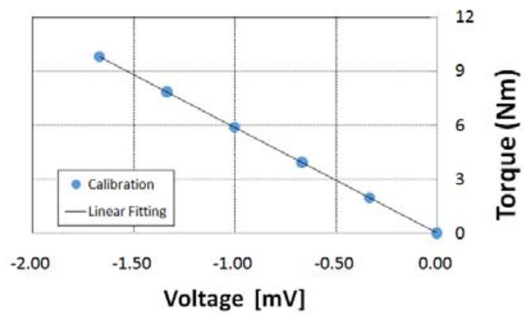
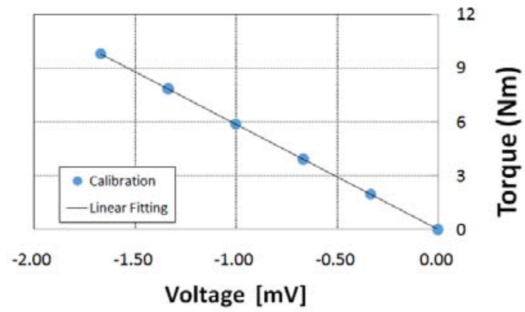


Figure 13 Torque Sensors Calibration



(a) Upper sensor calibration result



(b) Lower sensor calibration result

Figure 14 Calibration Result of Torque Sensor

3. TEST RESULTS

3.1. Test Propellers

3.1.1. Static Balancing

All propellers are required to conduct static balancing to reduce vibration even though these are commercial. To get accurate measured data, simple device for static balancing was made. As a weight for static balancing to meet small spanwise moment, thin tape was used by attaching on root to minimize the performance influence. Figure 15 shows the test propellers. Figure 16 shows the static balancing device.

<Test Propellers (26 & 29 inch)>

Parameter	Unit	Specification			
Rotation direction	N/A	CW	CCW	CW	CCW
Diameter	**mm**	660.4 (26inch)	660.4 (26inch)	736.6 (29inch)	736.6 (29inch)
Weight	g	81.7	82	108	107.7
Root-cut	mm	35 (0.59R)	35 (0.59R)	35 (0.47R)	35 (0.47R)
Propeller pitch	inch	8.5	8.5	9.5	9.5
Solidity	N/A	0.1149	01149	0.094	0.094
Motor	Kv	T-MOTOR U13 (100Kv)			
ESC	A	T-MOTOR FLAME (100A)			

Figure 15. Specification of the Test Propellers

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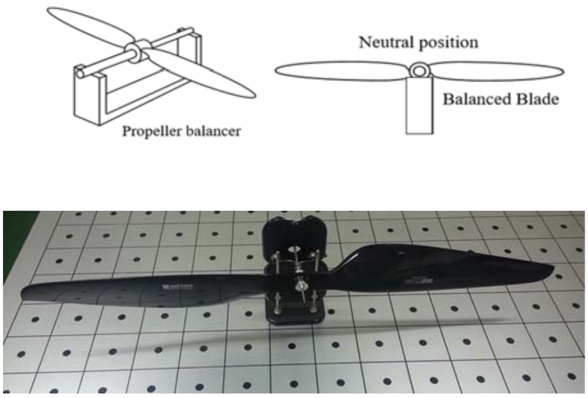

Figure 16. Static balancing for Test Propellers

3.1.2. BLDC Motor

BLDC Motor for performance test was selected as a T-motor products since T-motor propeller were used to do performance test. The details on this BLDC motor was described on Table 6.

Table 6. . Specification of BLDC Motor

Model	 U13 (T-Motor)
KV	100
Battery Voltage	6~12s (22.2~44.4V)
Weight	1280g
Dimension	Φ118.4x58.8mm
Max. Power	3210W
Max. Current	65A

3.2. Single Propeller Test

The single propeller test was conducted to verifying each propeller performance before doing coaxial test. This test can give benefit the confidence on test rig and also accurate performance data of test propeller. This test was conducted following procedures. The initial test rpm was 1,000rpm and increased up to 4,200rpm at each 200rpm step. Each test was repeated by 3 times. Final data was processed by averaging. Final data was shown as non-dimensional index, Figure of Merit (F.M.). The lower part of coaxial test rig was used to do this test. Figure 17 shows the single propeller test rig.

Figure 17. Single Propeller Test

Test data shows there is negligible difference between clockwise (CW) direction the counter-clockwise (CCW) direction. Figure 18 shows the test results shown by power vs. thrust. Figure 19 shows the test results shown by power vs. thrust considering solidity.

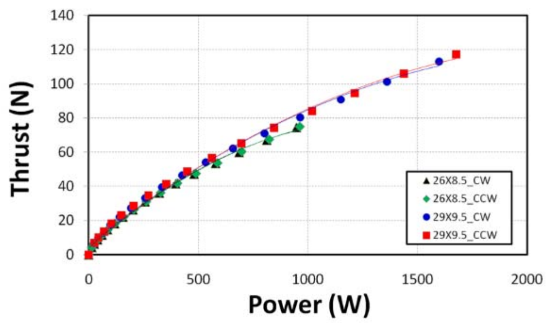

Figure 18. Test result of Single Propeller

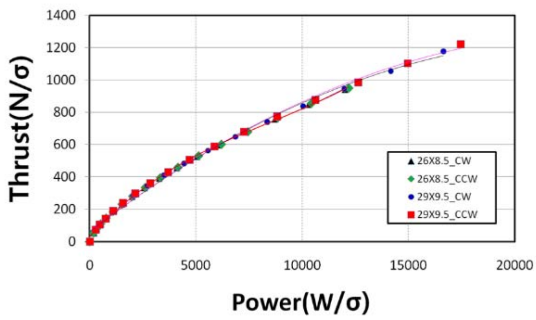

Figure 19. Test result of Single Propeller with

solidity

To do compare in detail, figure of merit was calculated according to rotor rpm. At lower rpm, there is small difference between CW and CCW direction. But at nominal speed, figure of merit difference was negligible. Figure 20 shows the figure of merit comparison

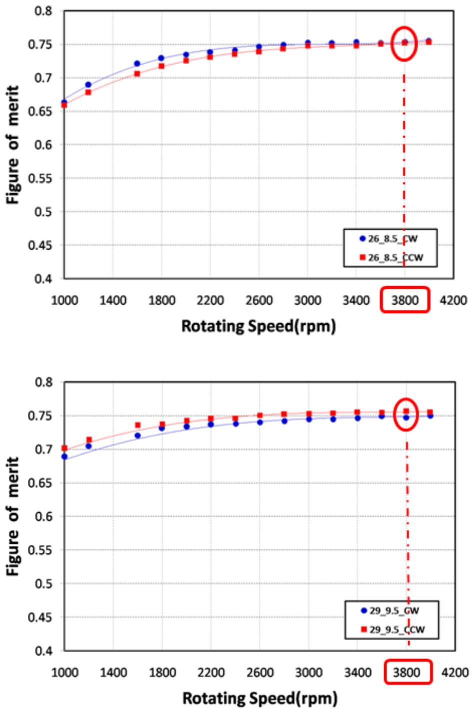

Figure 20. Test result of Single Propeller as Figure of Merit

3.3. Coaxial Propeller Test

After verifying single propeller performance, the coaxial propeller test was conducted for 26in, 29in and combination. The nominal rpm was fixed with 3,800rpm and H/D ration was changed from 0.1 to 0.8. Figure of merit was calculated. Each test was repeated by 3 times. Final data was processed by averaging. Final data was shown as non-dimensional index, Figure of Merit (F.M.). Figure 21 shows the coaxial propeller test. Figure 22 shows 26” coaxial propeller test. Figure 23 shows 29” coaxial propeller test result.

Figure 22 figure of merit has high value at 0.2~0.3 H/D ratio. Figure 23 show figure of merit has high value at 0.2~0.3 H/D ratio. So, the high performance of coaxial propeller at various H/D ratio may located at 0.2~0.3 H/D ratio.

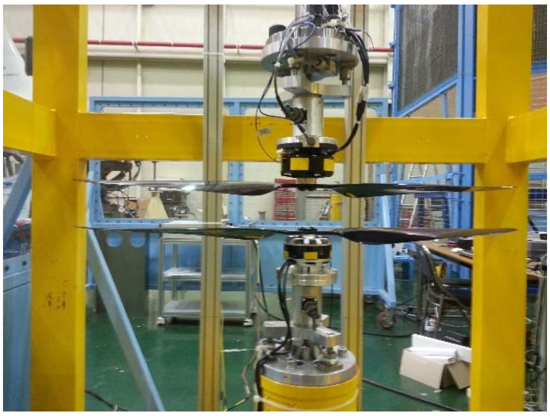

Figure 21. Coaxial Propeller Test

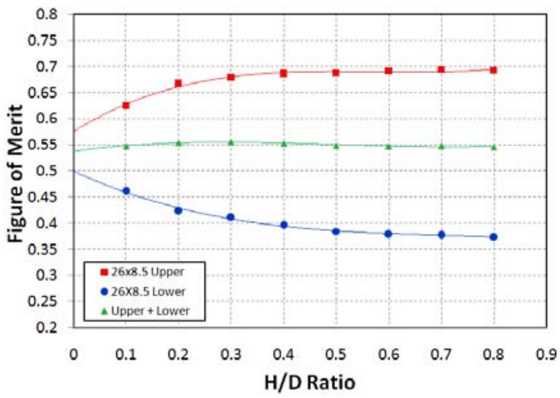

Figure 22. 26” Coaxial Propeller Test

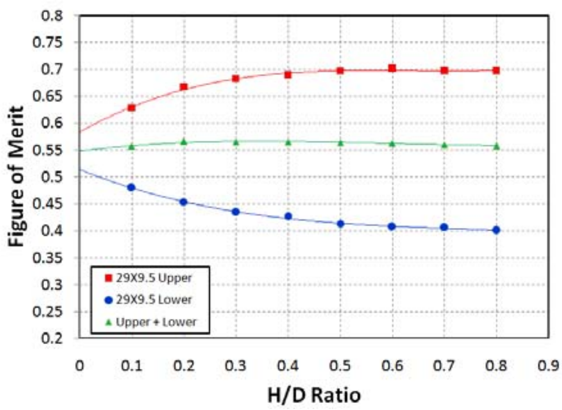

Figure 23. 29” Coaxial Propeller Test

Figure 24 shows that shorter diameter at upper propeller was more effective than longer diameter at lower propeller. H/D ratio effect is similar to the one.

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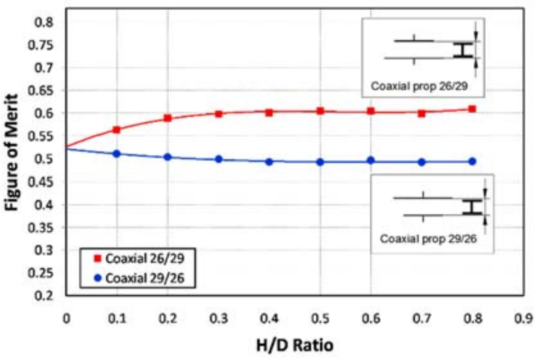

Figure 24. 26"/29" vs. 29"/26" Coaxial Propeller Test

4. CONCLUSIONS

The purpose of this study is to present reliable performance data by experimental studying coaxial propellers configuration and to identify the characteristics of coaxial propellers to be used at the design, production, and verification and performance evaluation. To do this, experimental device was developed that can test at low Reynolds number(Re≈3×10^5) of coaxial propellers. The experimental device basically constructed the DAQ which can measure torque, rpm, power so that the performance characteristics of the upper and lower propellers can be known.

The experiments which composed of the different H/D ratio (0.1~0.8) defined as the ratio of distance of upper / lower propellers divided by its diameter and the different propeller's diameter's ratio were conducted. Experiments were carried out on the coaxial propeller after verifying the calibration. As a result of comparing the values with F.M.(Figure of Merit), it was found that the coaxial propeller of the same diameter showed a constant FM at the H/D ratio(0.2~0.3)

The highest value of all conditions tested was achieved when the diameter of the upper part of the propeller was smaller than the diameter of the lower part confirmed.

From this study, KARI can use this result to design future taxi drone or heavy drone in operated in urban air mobility environment.

Acknowledgement

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