# Safe Dynamics and Control of a Rotor Vehicle on a Track

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*Abstract* - **This paper presents the concepts and tests of a Flettner rotor vehicle model on a track that can travel safely in a straight line under constant wind force conditions using rotor power. It also discusses emergency operational procedures, primarily a main rotor trip (MRT) function that immediately disengages the rotor from the power train, and a runback (rapidly reducing system loading) feature that can be implemented when the rotor stalls or when other dangerous operating conditions suddenly appear. While such procedures are necessary for the safe operation of this type of vehicle, there are also economic considerations that may make it necessary to halt or rapidly curtail rotor rotation. In our simulations and experiments, we use a stall detector to show the utility of our novel MRT and runback procedures using the moving average method, and compare it to methods that govern low vessel velocities using threshold speed data. The results of our experiments showed that symptom-based control is more appropriate than timing based control. We then analyzed the merits, demerits, risk and countermeasure (MDRC) aspects of both policies. While a concrete guiding principle for risk counter-measures has yet to be determined, the eventual result is expected to be a fusion of the two policies.**

***Keywords - Flettner rotor vehicle; Rotor speed control; MRT and runback; MDRC***

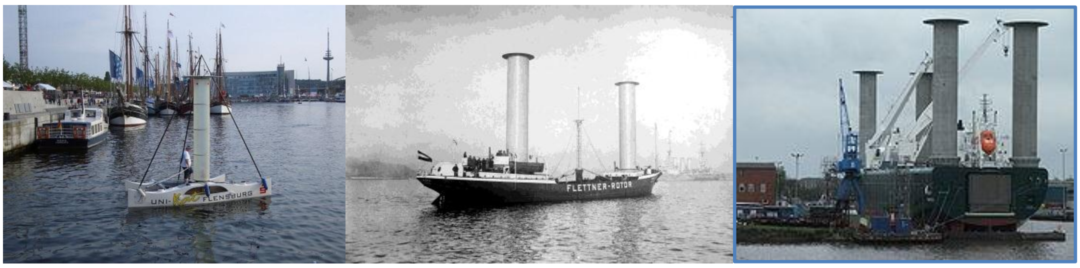
## I. INTRODUCTION

### A. Background

The importance of energy conservation and reduced oil consumption as factors for preventing global warming, in response to both rising fuel oil prices, and in response to the “peak oil” crisis identified by the Club of Rome have become increasingly apparent in recent years amidst the growing scarcity of carbon-based energy sources, despite the development of new high-cost technologies for obtaining such energy.

As a method for stimulating discussion and promoting development of energy conservation technologies on land, numerous solar- and wind-power car contests have been held. At sea, significant interest has been paid to Flettner rotor ships, which are designed to take advantage of the Mugnus effect. Such vessels include the “Baden Baden” (600 t) that was launched in 1920, as shown in Fig. 1 (b) [1], the single rotor vessel Uni-cat Flensberg (Fig. 1 (a)) that was launched in 2007 [1], and the 10,500 ton E-ship 1 produced by Enercon (Fig. 1 (c)). The E-Ship 1 has been in commercial operation since 2011 and boasts a 30% reduction in fuel consumption compared to similar-sized vessels [2].

While numerous types of wind-assisted (windmill, wing-sail, rotor, etc.) vessels have been proposed for commercial use [3-4], there was little incentive to construct them in previous years because fuel oil prices were low. Currently, however, aiming at even further decreases in carbon dioxide ($CO_2$) production, a number of wind-assisted propulsion methods have been promoted. These include a study conducted by a Japanese maritime institute that promotes crane ships with hard and soft sails as next generation wind-assisted ships [5]. In that study, specific attention was paid to the evaluation of a new weather routing system that actively searches for favorable winds at times when overall weather conditions are calm [6].




(a) Single rotor [1] (b) Double rotors (Barden Barden) [1] (c) Four rotors (E-ship1) [2]

Fig. 1 Flettner rotor ships in Germany

In other areas, numerous vehicles on a track and robots have been studied due to their attractive characteristics, which include controlled movement, operational simplicity and overall safety [7-8]. The potential utility of air-cushioned vehicles, especially their characteristics for stable operation during forward travel over various terrains has also been noted [9], and a study has been conducted on an air-cushioned train. [9]

### B. *Conventional Studies*

The approximate relative performance of several wind-assisted ships (windmill, wing-sail, rotor, etc.) in the 21,000-ton range was measured in 1975. In the Motor Ship 1979 tradeshow, it was demonstrated that the Flettner rotor ship entry was capable of the fastest speeds at true wind angles over 70 °against the wind direction of headwinds [3]. It was also shown that the Flettner rotor ship had a large stall angle from -50 °to 50 °, as well as the steepest stall property, while windmill ships do not have a stall angle. This suggests that Flettner rotor ships have a "safety brake mode" that allows them to travel against strong winds, and thus avoid obstacles in dangerous situations. The "jairo mode" of rotor has also been presented in a literature, though it may be simply a sensor function. A "generation mode" operation of rotor has also been suggested, even though it may be only applicable to crane ships with sails and a vertical rotation axis.

Furthermore, while studies on aerial and aquatic Flettner rotor vessels [10~12] have been identified, we have been unable to locate any studies concerning land based rotor vehicles on a track. However, Ref. 9 was considered to be particularly relevant to our current study in consideration of the fact that the controlling the trajectories of rotor vehicles would be difficult if they were not on a track. Another study discussed underwater vessel dynamics using a Hamiltonian model and aquatic locomotion using a submerged robotic Flettner rotor concept, with variable circulation used effective mass containing around fluid mass to actual rotor mass [12].

While the abovementioned studies have provided a number of useful suggestions for future studies, this study aims at clarifying the basic mechanics of the Flettner rotor system and, in order to avoid complications, will not address unrelated issues.

### C. *Purpose*

This paper presents the concept of a Flettner rotor vehicle model on a track, including safety tests that offer particular ease of analysis. The reason for selecting the Flettner rotor system for analysis was its characteristics, which are as follows:

- Flettner rotor vessels are the fastest class of wind-assisted ships when travelling at true wind angles over 70 °against the wind direction property because the rotors exert a stronger lift force than wings or windmills.

- Flettner rotor vessels have a "safety brake mode" that can be utilized to move the ship against the wind in hazardous weather situations, if necessary, to avoid obstacles.

Previously, we presented the static characteristics of an experimental device with a small aspect ratio, that is, a low gravity center and a high lift/drag ratio during testing of a constant rotor speed land-based rotor vehicle.

- Other various functions can be expected from Flettner rotors, which may be safer than rotating blades.

Here, from the viewpoints of safety, we will discuss our novel main rotor trip (MRT) and runback (which means the rotor is rapidly run back to low load) operations. These are operations that can be executed when the vehicle stalls or when a dangerous condition suddenly occurs. While both operations are expected to be necessary for safe rotor control systems in the future, there are also economic operations that will require the rotor to be stopped or slowed drastically when its operation is unnecessary.

## II. CONCEPT OF FLETTNER ROTOR VESSEL ON A TRACK

Figure 2 shows a diagram of a Flettner rotor vehicle model on a track performing a switchback operation test between stations under conditions where the headwind is 45 ° and the fair wind is 135 °. Here, a switchback operation means a train operation as repeated forward and reverse run for climbing a mountain

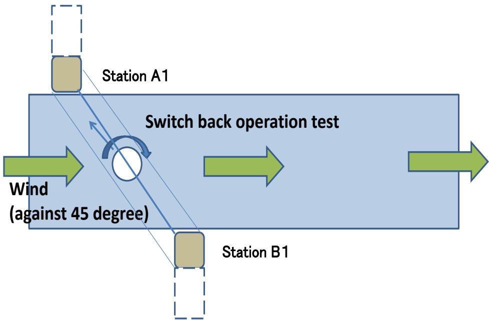



Fig. 2 A rotor vehicle switchback operation test on tracks

In this paper, we presented the concept of a rotor vehicle system on a track along with a model rotor vehicle (shown in Fig. 2) that can run safely in a straight-line direction without swinging under constant wind conditions from a 45 °headwind through fair winds to 45 °degree tailwinds if the rotor direction is reversed as required by wind direction.

## *A. Static characteristics*

A photograph of our experimental vehicle test setup is shown in Fig. 3.

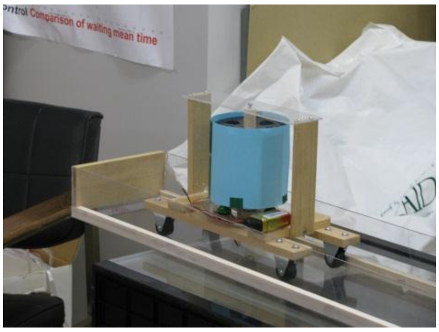



Fig. 3 Experimental rotor car model on a track

### *1) Simulation Conditions:*

Simulation conditions for the rotor and body, air, and for interaction between vehicle and wind are shown in Tables 1-3 below. The lift force correction coefficients in Table 3 were obtained via experiments using a weight on a balance under various wind velocities [13]. The vortex model was omitted for simplicity as it is contained in a correction coefficient. A small aspect ratio and a light rotor were adopted to decrease the danger of the vehicle overturning during strong wind conditions.

TABLE 1 ROTOR & BODY

| | Rotor | | Body | |
|---|---|---|---|---|
| | Mass | Hight | Radius | Mass |
| Values | 0.086kg | 0.1m | 0.05m | 0.6kg |

TABLE 2 AIR

| | Viscous degree [20C] | Density |
|---|---|---|
| Values | $1.822 \times 10^{-5}$Pa s | 1.205kg/m$^3$ |

TABLE 3 INTERACTION BETWEEN VESSEL & WIND

| | Cd | Correction Coefficients of Lift Force | Direction |
|---|---|---|---|
| Values | 0.21 | 0.676 | Against 45 ° |

The reason for a 33% (55% in another measurement method) loss may be noted as follows [13]:

- Errors may exist in the measuring force method.
- There is a fluid loss flow due to flakes splitting from the fluid vortex and flow behind the rotor.
- A large degree of liquid resistance is assumed in the ship model, despite the fact that frictional loss is small in this land vehicle examination model.

## *B. Basic Theory*

The well known textbook on fluid mechanics [14] states that a circulation

$$\Gamma = 2\pi r^2 \omega \tag{1}$$

exists around a rotating rotor with radius *r* and angular speed $\omega$.

Thus, the complex velocity potential around the rotating rotor with circulation $\Gamma$ under a fluid field with velocity *u* theoretically becomes

$$f(z) = u(z + \frac{r^2}{z}) - j\frac{\Gamma}{2\pi}\log z. \tag{2}$$

Then, the following lift force *L* acts on the rotor in the vertical direction against the flow direction from the speed decrease side to the speed increase side:

$$L = -\rho u \Gamma l \tag{3}$$

where $\rho$ is the density of the fluid, and *l* is the tentative length of rotor.

In actuality, the flaking occurs behind the flow and thus does not become part of any future potential flow. Furthermore, the following drag force *D* acts on the rotor in the flow direction.

$$D = C_d \frac{1}{2} \rho S u^2 \tag{4}$$

where *Cd* is the 3D coefficient of the drag-considered Reynolds number. Note that form drag and the induced drag force are omitted here. It is also important to note that S is a section area for wind direction change since it is a rotor, not a wing. This makes the analysis easier. Here, we neglected the dependence of rotation speed on drag force. Consequently, synthetic lift and drag force act on the rotor, and the rotor vehicle advances in the direction of the synthetic force to the extent it is unrestrained.

### *C. Results*

This static characteristic has a multi-valued vehicle speed function for the rotation speed during headwind conditions, as shown at the triangle area in Fig. 4. There is also a non-linearity aspect that is highly sensitive to wind velocity changes in the low load area. In such situations, use of MRT or runback may be required. It should also be noted that it may be necessary to convert the wind velocity using the Reynolds similarity rule to scale-up using the rotor diameter as the tentative length while keeping the aspect ratio the same.

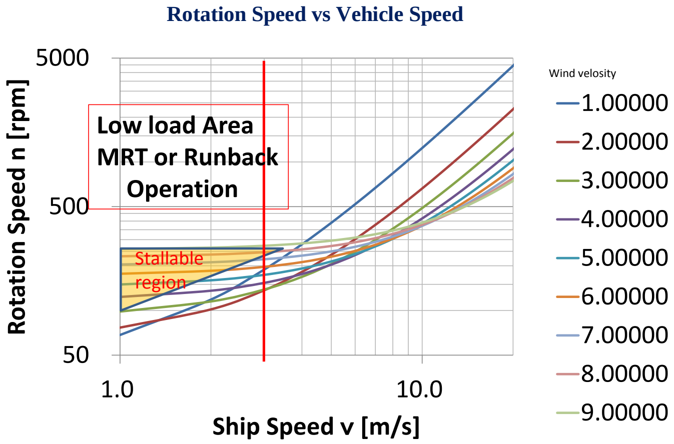



Fig. 4 Static characteristics for vehicle speed (45 °against the headwind)

## III. DYNAMICS AND CONTROL

In this section, we present the dynamic characteristics of the experimental vehicle shown in Fig. 3. Here, we used a simple dynamic model derived from a basic force balance without a vortex and an effective air mass [12]. All mechanical losses were derived in a correction coefficient obtained by the static experiments listed in Table 3. However, a motor model was considered into the rotation of the rotor model instead of circulation [12].

### *A. Specification of virtual geared motor*

Using this simulation, we show the specifications of a virtual geared motor at the various no-load and load conditions shown in Tables 4 and 5. This virtual motor and simulation are not available on the market.

The model equations use the functional torque and counter electromotive force constants to obtain the required property as follows:

$$\begin{aligned} I(t) &= \frac{1}{L_{coil} s + R} (V_r(t) - \kappa_i(\omega(t))\omega(t)) \\ \tau_r(t) &= \kappa_\tau(\omega(t)) I(t) - \tau_l(t) \\ \omega(t) &= \frac{1}{Js} \tau_r(t) \end{aligned} \tag{5}$$

where J is the polar moment of inertia and varies in the case of no load and load operations. Vr(t) is the motor input voltage, I(t) is motor current, $\omega(t)$ is motor rotation angular speed, $\tau_l(t)$ is load torque, and $\tau_r(t)$ is the rotation torque. $L_{coil}$ refers to inductance and R refers to the resistance of the coil in the magnetic levitation equipment. $\kappa_\tau$ refers to the function name on the torque constant. $\kappa_\tau$ refers to the function name on the inverse power generation constant.

TABLE 4 NO LOAD OPERATION

| Term | Voltage | Rotation | torque | Current |
|---|---|---|---|---|
| Values | 12V | 1900rpm | 0Nm | maxA |

TABLE 5 LOAD OPERATION

| Term | Voltage | Rotation | torque | Current |
|---|---|---|---|---|
| Values | 2.4V | 360rpm | 0.0301Nm | 0.0521A |
| Values | 4.8V | 701rpm | 0.157Nm | 3.49A |

### *B. Static and dynamic characteristics for wind velocity*

In the original non-linear model, the following functions are used to obtain the rotor vehicle speed.

$$\dot{v}(t) = f_1(u(t), v(t), \theta(t)) + f_2(v(t)) \tag{6}$$

Where v(t) is vessel speed, and $\theta(t)$ is the wind direction. $f_1$ is the effect of wind (lift and drag) and $f_2$ is an air resistance effect during no wind situations based on the assumption that there will be no interaction between effects. In the linearized model, the derivative functions are used to obtain the rotor vehicle speed.

### *C. Step response and frequency property*

The step response and frequency response for vehicle speed at a wind velocity marked by a 0.5 m/s raising and lowering step change are shown in Figs. 5 and 6, respectively. The step response shown in Fig. 5 indicates that these non-linearity changes are larger than the linear model at the lowering step change of wind velocity.

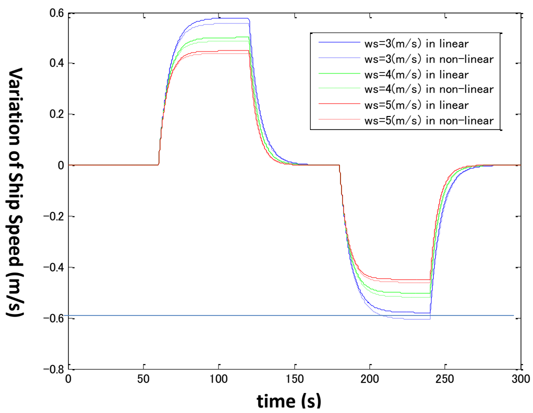



Fig. 5 Step response of vehicle speed for wind velocity with a 0.5 m/s raising and lowering step change

These figures suggest that, due to the step response discussed in the literature [15], this non-linearity will make the stability margin worse than the step response of the linear model, even though the non-linearity in the level control of the tank model shows improvements over that of the linear model.

The frequency response in Fig. 6 shows that the sensitivity for the change of wind velocity will be small at high frequency. Thus, a specific low-pass filter with the cut-off frequency defined by Fig. 6 will be effective for sensing data in the case of feed-forward control for a wind velocity disturbance.

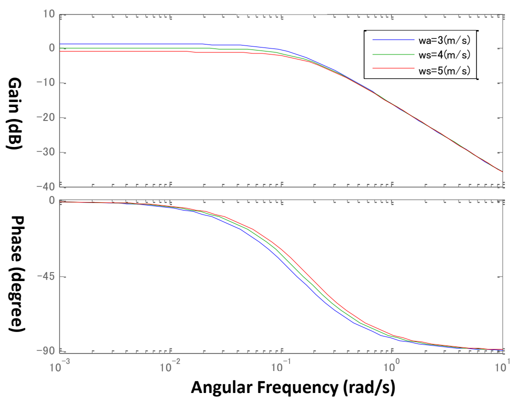



Fig. 6 Frequency response of vessel speed for a wind velocity of 0.5 m/s

### *D. MRT and runback*

To prioritize safety, timing or symptom based MRT or runback operations were proposed for the low load area using a threshold speed or stall detector. These operations take effect when the vehicle stalls or when a dangerous driving state occurs, as shown in Fig. 7.

Grounds may be scarce for changing state of MRT or runback in threshold speed type conditioned sequence not but stall detector type one because threshold speed changes which it belongs in high speed area or low speed area. We call such change to timing or symptom base change.

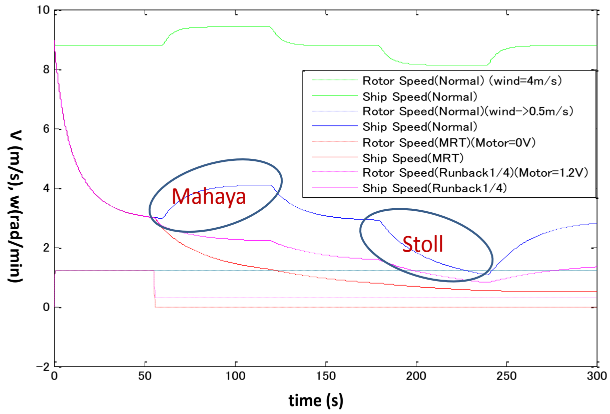



Fig. 7 MRT and runback (1/4) operation in the low speed area using a threshold speed

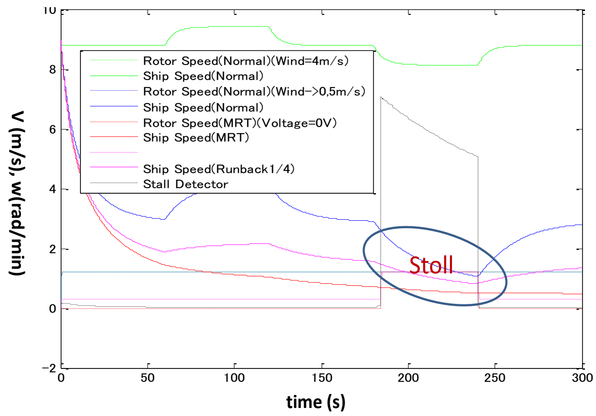



Fig. 8 MRT and runback (1/4) operation at low speed using a stall detector

Therefore, the stall detection type conditioned sequence may be more robust during the state change, as shown in Fig. 8. This can be likened to an administrative policy that is symptom-based, not timing- or load-based.

### *E. Merits, demerits, and risk analysis*

The merits, demerits, risks, and countermeasures of the two MRT and runback policies are listed in Table 6. As can be seen in the table, use of the adaptive timing base by monitoring the symptoms would be a decision of the timing by the predictive symptom base.

Other MRT and runback conditions, with the exception of dangerous vehicle speed, which is highly sensitive to wind speed changes, must be considered by operational experts. These operation modes are designed to prevent total vehicle loss, not for economic considerations. In other words, they are direct measurements of stall or dangerous driving wind velocity, as well as vibration measurements that include yawing, rolling, pitching, heaving, etc.

TABLE 6 MERITS, DEMERITS, RISK AND COUNTERMEASURES OF TWO MRT & RUNBACK POLICIES TYPES

| Item | Timing base | Symptom base |
|---|---|---|
| Merits | It might be useful to caring for prevention and prognosis. Simple and low cost | It does not waste. It has adaptability to the situation change and robustness to the property change. |
| Demerits | The operation might become useless. | The effect is not necessarily achieved. complex and high cost |
| Risk | Appropriate timing differs as and shifts by situation. | It is likely to become too late. |
| Counter-measurement | Adaptive timing base by monitoring symptom | Predictive symptom base |

### *F. Results*

This non-linearity will make the stability margin worse than the stability margin in the case of linear property. It is contrasted with the example that the non-linearity in the level control of a tank model make better it than the one of the linear model. It can be said that the linearization is a risky in this example.

Using simulations, we show the utility of our new MRT and runback operations with a stall detector using the moving average method at lower vessel speeds and compare it to those using threshold speeds. Then, we determined that the detector type conditioned sequence (such as the one shown here) may be more robust for state changes, and that the most appropriate policy is symptom based rather than timing based. Moreover, we analysed the merits, demerits, risk and the countermeasures for both policies. The optimum approach for risk countermeasures remains unclear, but it is anticipated that they will require a fusion of the two policies.

## IV. CONCLUSIONS

### A. Solid Results

The second version, with an aspect ratio of 4, was produced, and the rotation speed was controlled by a microcomputer system equipped with a rotary encoder and a liquid crystal display (LCD).

### B. Important Estimated Results

Because it was important to clarify the multifaceted static characteristics and dynamics of the system in order to determine problems related to non-linearity, safety related timing and symptom based MRT and runback operations were proposed for the low load area using threshold speeds or a stall detector when the vehicle was in danger of stalling or when dangerous operating conditions occur. However, it should also be noted that future rotor control systems are likely to encounter economic situations that will require the rotor to be stopped when it is unneeded.

We then conducted simulation studies using a stall detector to demonstrate the utility of our MRT and runback operations using the moving average method and compared the results to methods for handling low vessel speeds using the threshold speed. The results indicated the most appropriate policy was timing based rather than symptom based. Additionally, we analyzed the merits, demerits, risk and the countermeasure for both policies. The optimum approach for risk countermeasures remains unclear, but it is anticipated that they will require a fusion of the two policies.

### C. Position of This Paper

Except for the definitive results mentioned above, most of the conclusions from this paper are the results of simulations that have yet to be verified. Nevertheless, it was decided to proceed with publication as the results may concern the safe operation of Flettner rotor ships currently in operation. Once those conjectured results have been verified or modified by actual shipboard observations, a new Flettner rotor traffic system on a track will be our future study theme.

### D. Future Theme

The future themes related to this study are based on the first author’s student curriculum. The comparison to the submerged robotic Flettner rotor system is omitted here even though it is considered important.

*1) MRT for Strong Wind:*

Conditions and dynamics of a rail-based rotor vessel model for economic operation against a 45 °wind could not been shown here as was first planned. In future studies, the necessity and methodology of MRT and rotor speed control related to economic borderline wind speed and rotor speed plane conditions, as well as their relation to various vehicle speeds, will be discussed.

*2) Weather-routing by untracked rotor vehicles:*

Since we have also developed a micro-computer controlled model roboat (robot boat) with double water propellers and dual distance sensors that is designed to use a subsumption architecture with a perceiving and action cycle to avoid obstacles, we may be able to remove the track for the rotor and water-screw vessel model in a pool-sized environment if the power-width modulation (PWM) control of propellers is sufficient to allow use of the “safety brake mode” based on wind conditions. This, in turn, would allow corrections to the routing of the untracked rotor and water-screw vessel model based on changing wind conditions.

*3) Using Wind Turbines. Together:*

It may be possible to compensate for the stall wind angle of rotor vessels using wind turbines or wing sails as emergency power supply and/or to provide auxiliary power for fuel conservation, even though loss of energy will become larger.

## ACKNOWLEDGMENT

We would like to extend our gratitude to the 2010 and 2011 laboratory members that participated in the development of various model vehicles. We would especially like to acknowledge the contributions of Mr. Hirao for his roboat model, Mr. Asada who produced a wing-sail model and Mr. Umegaki who help our study. Moreover, we also would like to thank Prof. Shun Takashima of Hosei University who proposed a lecture on a Process Control.

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## APPENDIX

Here, let add an experimental result in the second version rotor, with an aspect ratio of 4, for improving the results in this paper by you.

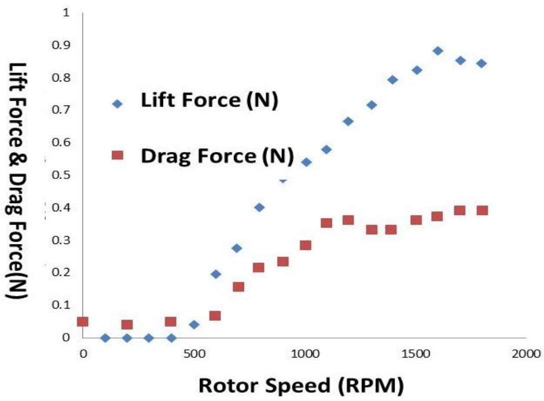


Fig. A1 Lift Force & Drag Force (Aspect ratio 4, Wind Speed = 3.5 m/s)

The inclination of theoretical lift force for rotor speed can be computed as follows.

$$y = 1.21 * 3.5 * 6.28^2 * 0.05^2 * 0.4 / 60 * x = 2.78 * 10^{-3} x$$

Assuming that the inclination of lift force is 0.9N/1000rpm from the data of Fig.A1, it is 32.4% of the one of theoretical lift force. That is, the loss is about 67.6%. We guess that the reason of dead zone in low rotation speed area and saturation in high rotation speed area may be both slip loss between rotor and around air. Vortex loss can not be shown in this wind speed.

The reason is not known that L/D (Lift Force/Drag Force) change from 1.25 to 2 at about 1100rpm.