The Dynamic Performance of a Rotating Frustum of a cone*

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ABSTRACT
Flettner rotor is a wind-assisted ship propulsion device and it could be used to decrease the fuel consumption. The lift coefficient of the traditional Flettner rotor increases with the increasing spinning ratio. So it is better to hire a high spinning ratio to obtain high lift force. However, the corresponding spinning ratio to the maximum lift-drag ratio is around 2 and the lift-drag ratio decreases when the spinning ratio exceeds 2. So hiring high rotation rate is not economical.

In this paper, we propose a new type of rotors composed of rotating frustum of a cone and Thom disc. The numerical investigation reveals that at high spinning ratio, the new rotor could not only maintain high lift coefficient, but also get high lift-drag ratio and the practicability is highly enhanced. And the performance of the rotating frustum is then investigated thoroughly.

Keywords
Flettner rotor, wind-assisted ship propulsion, lift-drag ratio

1 INTRODUCTION
In 1926, a vessel, named the Baden-Baden, sailed across the Atlantic, with its sails replaced by twin rotatable cylinders, as shown in Figure 1. This is a demonstration of the conclusion that the Magnus effect could be exploited to provide an efficient and effective way of ship propulsion, conducted by Anton Flettner. The rotatable cylinders became immediately known as Flettner rotors. It was reported that the rotor vessels reached the expected speed and shown some advantages over a reference vessel equipped with sails. Further commercial development did not take place, however, due to the grave financial depression of the late 1920's and to the emergence of diesel-powered craft.

Nowadays, because of the need to reduce the rate of release of CO₂ to the atmosphere, the potential role of the Flettner rotor is being reexamined. Enercon brought into service in late 2010 the vessel E-Ship 1, with four Flettner rotors. Deltamarin launched their new showcase ro-pax vessel "DeltaChallenger" during the Nor-Shipping 2015 exhibition. To reduce fuel consumption the vessel has six rotor six rotor sails, giving 10% of the total propulsion power. Norsepower, founded in 2012, aimed to reduce the environmental impact of shipping by providing its Rotor Sail Solution technology, had installed the rotors on the Ro-Ro, Cruise ferry and Tanker.

Flow around a non-rotating cylinder has been subjected to decades of research due to its complicated wake flow, vortex generation and shedding phenomena. Rotation of cylinder adds another level of complexity caused by the moving wall boundary layer. The study of rotating cylinders is not as extensive as for the stationary cylinders. Yet some fundamental studies of rotating cylinders were carried out in the past, as wind tunnel tests by Reid (1924), Thom (1934) and Swanson (1961), and the computational work by Elmiligui et al. (2004), Mittal and Kumar (2003), Stojkovic et al. (2003). However, the majority of studies were carried out at low Reynolds numbers (Re = V_D / v) in a range of 10² < Re < 10⁴. This range is far below the operational values for a real Flettner rotor. Lack of studies at high Re leaves the performance of Flettner rotor at full scale largely unknown.

Badalamenti and Prince (2008) had experimentally

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investigated the effects of endplates on the aerodynamic behavior of a rotating circular cylinder for $1.6 \times 10^4 < \text{Re} < 9.5 \times 10^4$ and peripheral velocity to freestream velocity ratios of $\alpha \leq 8$. They found that, for equi-sized plates, increasing the plate size caused the lift at high velocity ratios to be significantly augmented by an amount that was directly proportional to the endplate size ratio $D_e/D$. The lift results also suggest that the combined effects of very large endplate size and high aspect ratio could be used to produce exceptionally high lift. However, measurements of the power indicated it would be very inefficient to do so. Because although endplates can significantly enhance lift and improve the lift-to-drag ratio, a limiting lift coefficient was always reached.

Thouault et. al. (2010) investigated the aerodynamic characteristics of a rotating cylinder by means of Unsteady Reynolds Averaged Navier-Stokes simulations. The predictive capability of URANS simulations have been assessed by comparison with the experiment of Badalamenti and Prince (2008). They also found that cylinders of smaller aspect ratio show higher drag and lower lift.

Li et. al. (2012) numerically studied the aerodynamic performance of Flettner rotors at a full scale Reynolds number, $\text{Re} = 1.6 \times 10^6$, in relation to the change of spin ratio $\alpha$ and aspect ratio $AR$. The results show that lift coefficient increases almost linearly with increase of $\alpha$ in the range $0 < \alpha < 3$ and the increase slows down for $\alpha > 4$. The drag coefficient is higher than for 2D rotating cylinders and about the same order of magnitude as lift coefficient, due to strong 3D effects.

As mentioned above, the lift and drag force of the Flettner rotor both increase with the increasing spinning ratio, and the relative increased amount of the drag is bigger than that of the lift with increasing spinning ratio, so there is a peak for lift-to-drag ratio. The peak lift-to-drag ratio occurring at fairly low $\alpha$ (close to $\alpha = 2$). This hampers the use of higher spinning ratio for high lift force. We propose a new type of rotors, which could obtain both high lift force and lift-to-drag ratio. The performance of the new type of rotor is then investigated numerically.

2 ASSESSMENT OF CFD PREDICTIONS

2.1 Numerical method

The flow field is solved by an incompressible Reynolds Averaged Navier-Stokes (RANS) method. In the present study, Menter’s Shear Stress Transport (SST) $k$-$\omega$ two equation models are employed. The Navier-Stokes equations are solved by the segregated scheme. A second order discretization of the convective term is used for both Navier-Stokes equations and turbulent model throughout all simulations.

The numerical method is then used to compute the experimental cases, conducted in a wind tunnel by Badalamenti and Prince (2008), for verification and validation. The relevant parameters of the rotors are described in Figure 2, and the spinning ratio is defined as $\alpha = V_s/V_\infty = \Omega D/(2V_\infty)$, the cylinder aspect ratio $AR = b/D$ and the endplate (or disc) diameter ratio $D_e/D$. The computational domain is a cuboid, as shown in Figure 3. The flow flows along positive x axis, and the rotor rotates around z axis. The dimensions of the rotor and the computational domain are detailed in Table 1.

To reduce the computational effort, only half of the cylinder is modeled and a symmetry plane is used at the mid-span. The rotor and disc are both defined as no-slip rotating wall. An inlet boundary condition is set on the front part of the domain with a prescribed velocity. On the rear part of the domain, an pressure outlet boundary condition is imposed. The symmetry boundary is applied to the other three boundaries of the domain.

![Figure 2 Sketch of the relevant parameters](image)

![Figure 3 Computational domain for validation](image)

### Table 1 Dimension of rotor and computation domain

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor diameter, D</td>
<td>0.0889</td>
</tr>
<tr>
<td>Rotor height, H</td>
<td>0.45</td>
</tr>
<tr>
<td>End disc diameter, De</td>
<td>0.1778</td>
</tr>
<tr>
<td>Distance: inlet plane to rotor axis</td>
<td>5 H</td>
</tr>
<tr>
<td>Distance: side boundaries to rotor</td>
<td>4-6 H</td>
</tr>
<tr>
<td>Distance: outlet plane to rotor axis</td>
<td>10 H</td>
</tr>
</tbody>
</table>

2.2 Grid-dependence verification

For spinning ratios $\alpha = 2$, Reynolds number $\text{Re} = 7.1 \times 10^4$, a grid dependence study has firstly been carried out. A cut-cell grid with prism layer mesh on the wall was generated. The rotor and disc were meshed separately to give a much finer grid. Refined meshes were generated in the area around the rotor and disc, as well as in the wake region , in order to accurately capture the flow properties...
for the validation study. A special near-wall mesh resolution was applied to all surfaces with the no-slip boundary condition. Details of the near-wall mesh generation are given in Figure 4. Three mesh densities are investigated: a coarse grid of $1.37 \times 10^6$ nodes, a medium grid of $2.28 \times 10^6$ nodes and a fine grid of $6.03 \times 10^6$ nodes. For all variations, the maximum dimensionless wall distance is $y^+ (\text{max}) = 1$ on the cylinder and $y^+ (\text{max}) = 1.5$ on the disc. It has been kept constant for all grids to benefit from the low-Re near wall formulation of the k-ω SST turbulence model. Small differences are observed on the lift and drag coefficients compared to the fine grid, and the lift and drag coefficients are both converged to the measured values, as shown in Table. 2. The Strouhal numbers predicted present is comparable with the maximum predicted value, 0.43, by Thouault et. al. (2010). In the next sections, calculations are performed with the medium grid.

![Surface mesh of the computational domain](image)

(a) Surface mesh of the computational domain

![Surface mesh on Flettner rotor](image)

(b) Surface mesh on Flettner rotor

Figure 4 Computational domain and surface mesh

<table>
<thead>
<tr>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_L$</td>
<td>5.101</td>
<td>5.022</td>
<td>5.02</td>
</tr>
<tr>
<td>$C_D$</td>
<td>1.406</td>
<td>1.335</td>
<td>1.311</td>
</tr>
<tr>
<td>St</td>
<td>0.380</td>
<td>0.438</td>
<td>0.478</td>
</tr>
</tbody>
</table>

Table 2 Comparison of $C_L$ and $C_D$ with experimental results for grid dependence study

For $\alpha=2$, the wake is deflected and features an alternate vortex shedding, as shown in Figure 5. Between the endplates, an alternate vortex shedding is detected due to flow separation occurring on the cylinder surface. The shed vortices rapidly disappear downstream. The alternate vortex shedding induces force oscillations of small amplitude on the cylinder, so the predicted values in Table 1 are averaged. In the cylinder near field, two tip vortices are therefore generated.

![Wake topology at $\alpha=2$ and Re= $7.1 \times 10^4$](image)

Figure 5 Wake topology at $\alpha=2$ and Re= $7.1 \times 10^4$ (iso-surface of $Q=5 \times 10^7$ s$^{-2}$ colored by turbulent viscosity, $\mu_t$)

2.3 Comparison to experimental data for validation

The predicted lift coefficient $C_L$, drag coefficient $C_D$ and lift-to-drag ratio $C_L/C_D$ are then compared with those measured by Badalamenti and Prince (2008), as shown in Figure 6, with a range of varied spinning ratios. The red solid lines represent the experimental results and the green dash lines the predicted results.

![Comparison with data by Badalamenti and Prince (2008)](image)

Figure 6 Comparison with data by Badalamenti and Prince (2008b). (a) $C_L$; (b) $C_D$; (c) $C_L/C_D$

Both lift coefficient and the drag coefficients show a
satisfactory agreement with measured data around \( \alpha = 2 \). For lower spinning ratios (\( \alpha < 2 \)), the predicted lift coefficient is a little higher than the measured values and the predicted drag coefficient is a little lower than the measured values. The predicted lift-to-drag ratio is obviously higher than the measured values. For higher spinning ratios (\( \alpha > 2 \)), the predicted lift coefficient turns to be a little lower than the measured values and the predicted drag coefficient becomes a little higher than the measured values.

Overall, the RANS predicted \( C_L \) and \( C_D \) compares well to the measured \( C_L \) and \( C_D \). And the predicted lift-to-drag ratio compares well to the measured value, especially when \( \alpha > 2 \). It manifests that the selected RANS method can reasonably well predict the general behavior of rotating cylinders.

3 THE PRESENT ROTORS

The Figure 6 also shows that the maximum lift-to-drag ratio is obtained at around \( \alpha = 2 \). At this spinning ratio, the lift force reaches far higher than the maximum value. To obtain higher lift force, higher spinning ratio is preferred. But higher spinning ratio results in higher drag force, so hiring higher spinning ratio will not economical. To deal with this dilemma, we proposed a new type of rotors.

The present rotor is a little different from the classic Flettner rotors, with the rotating cylinder replaced by a rotating frustum of a cone, as shown in Figure 7. A cone was cut by a plane which is parallel to its base, leaving a frustum of a cone, with the height named \( b \), the base diameter \( D \) and the top diameter \( d \). Because the rotors are all installed in the deck, so at the base there is no need for the existence of the end disc.

The dimensions of the new rotor and the computational domain are detailed in Table 2, where the numbers in bold indicate the case extensively studied. The \( d=0.1 \)m case represents the classical Flettner rotors, using as reference case. Because the new rotors are imagined to be installed in the ship, the no-slip wall boundary is applied on the bottom of the computation domain. Other boundary conditions are the same as described in Part 2.

<table>
<thead>
<tr>
<th>Table 2 Dimension of new rotor and computation domain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimension</strong></td>
</tr>
<tr>
<td>Rotor base diameter, ( D ) [m]</td>
</tr>
<tr>
<td>Rotor top diameter, ( d ) [m]</td>
</tr>
<tr>
<td>Rotor height, ( H ) [m]</td>
</tr>
<tr>
<td>End disc diameter, ( D_e ) [m]</td>
</tr>
<tr>
<td>Distance: inlet boundaries to rotor axis</td>
</tr>
<tr>
<td>Distance: side boundaries to rotor axis</td>
</tr>
<tr>
<td>Distance: top boundaries to rotor axis</td>
</tr>
<tr>
<td>Distance: outlet boundaries to rotor axis</td>
</tr>
</tbody>
</table>

The spinning ratio for the new rotor is also defined as \( \alpha = V_c/V_\infty = D/2V_\infty \), where \( D \) is the base diameter of the new rotor. Using the same \( D \), Reynolds numbers is also defined as \( Re = V_cD/\nu \). All the cases calculated below are at \( Re = 7.1 \times 10^4 \). In the following the aerodynamic performance of new rotor is presented in terms of averaged lift and drag coefficients. Also studied is the influence of top diameter, end disc and aspect ratio.

4 PERFORMANCE OF THE NEW ROTOR

The averaged lift and drag coefficients of the new rotor with top diameter \( d=50 \) mm (solid lines) as functions of \( \alpha \) are shown in Figure 8, together with the results of \( d=100 \)mm (dash lines) a for comparison to the classical Flettner rotors. For all the spinning ratios studied here, the lift and drag coefficients of new rotor are both almost lower than those of Flettner rotor, except for the lift coefficient at high spinning ratios.

![Figure 8 Comparisons of lift and drag coefficients between the new rotor (d=50mm) and Flettner rotor (d=100mm)](image)

Figure 9-11 shows the vortical structures of the two types of rotors for \( \alpha = 2 \), 4 and 6, using an iso-surface of \( Q=5 \times 10^3 \) s\(^{-2}\), colored by x component of vorticity vector.
It can be seen that because of the flow in z direction around the rotors induced by vertical gradient of frustum of a cone, the vortices are prohibited, especially for the vortex shedding from the disc, compared to those of the Flettner rotors. So the lift and drag coefficients of the new rotors are lower than those of Flettner rotors.

Figure 9 Vortical structures represented by an iso-surface of $Q=5\times10^3 \text{s}^{-2}$ at $\alpha=2$ (colored by x component of vorticity vector)

Figure 10 Vortical structures represented by an iso-surface of $Q=5\times10^3 \text{s}^{-2}$ at $\alpha=4$ (colored by x component of vorticity vector)

Figure 11 Vortical structures represented by an iso-surface of $Q=5\times10^3 \text{s}^{-2}$ at $\alpha=6$ (colored by x component of vorticity vector)

Though both of the lift and drag coefficients of the new rotors are lower than those of Flettner rotors, the lift-to-drag ratio shows different behaviors, as shown in Figure 12. Different from the rapid drop after rapid rise around $\alpha=2$ for the lift-to-drag ratio of Flettner rotor, the lift-to-drag ratio of the new rotor keeps increasing until $\alpha=4$, then the curve goes down slowly with increasing spinning ratio. This property of the new rotor allows application of higher spinning ratio for higher lift, with little increase of the drag. The application scenarios for the rotors are broadened.

Figure 12 Comparison of lift-to-drag ratios between the new rotor (d=50mm) and Flettner rotor (d=100mm)

In the following, the influences of top diameter, end disc and aspect ratio on the lift-to-drag ratio are studied.

4.1 Influence of top diameter (d)

Figure 13 shows the lift-to-drag ratio as functions of spinning ratio, with respect to different top diameter. For small top diameter, the lift coefficient is too lower, so as the lift-to-drag ratio; for large top diameter, the lift-to-drag ratio shows a rapid drop after rapid rise. It seems that the best choice here is to use medium top diameter. For top diameter $d=50\text{mm}$, the lift coefficient increases more than the drag coefficient, as the spinning ratio increases, compared with other values of top diameter.

Figure 13 Influence of the top diameter on the lift-to-drag ratio

4.2 Influence of the existence of end disc

Figure 14 shows the lift coefficient, the drag coefficient and the lift-to-drag ratio with and without the end disc. The existence of the end disc could effectively decrease the drag coefficient and increase the lift coefficient, thus the end disc has positive influence on the lift-to-drag ratio. And the positive influence increases with increasing spinning ratio.

Figure 14 Influence of the existence of end disc on the lift-to-drag ratio

4.3 Influence of aspect ratio (AR)

Figure 15 shows the lift coefficient, the drag coefficient and the lift-to-drag ratio as functions of spinning ratio, with respect to different aspect ratio. Generally, the drag coefficient decreases with increasing aspect ratio, the lift coefficient increases with increasing aspect ratio, so the lift-to-drag ratio increases with increasing aspect ratio, and the maximum lift-to-drag ratio, corresponding to the same spinning ratio ($\alpha=4$) for all aspect ratio, also increases with increasing aspect ratio.
5 DISCUSSIONS AND CONCLUSIONS

In this paper, we presented a new type of rotors to resolve the pain point of the Flettner rotor: the lift-to-drag ratio increases rapidly with increasing spinning ratio before $\alpha=2$, and then drops rapidly with further increasing spinning ratio, such that the efficiency and the high lift force cannot obtained together. The proposed rotor allows application of higher spinning ratio for higher lift, with little increase of the drag, so as to obtain high efficiency.

Then the influences of top diameter, end disc and aspect ratio on the lift-to-drag ratio of the new rotor are studied. To the parameters studied here, the medium top diameter is preferred; the taller the rotor, the higher the maximum lift-to-drag ratio could be obtained. We only ascertain the positive influence of the end disc on the lift-to-drag ratio, the parameter study is still required for the best end disc size. It is worth noting that all of the above conclusions are based on the Reynolds number, $\text{Re}=7.1 \times 10^4$. As mentioned before, this is still below the operational values for a real rotor. Lack of studies at high Re leaves the performance of the new rotor at full scale and the Re dependence largely unknown. Also the power required to rotate the rotors has to be evaluated, this is what have to be done before the rotor could be installed to propel the ship.

There is one more thing need to be considered is that the dynamic performance of the rotors is evaluated under an ideal condition that the rotors considered solely. For the reality, the wind induce the wavy sea and the rotor will move with the ship in response to the wavy sea.

REFERENCES


