Research and Development on Cycloidal Propellers for Airships

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Cycloidal propellers are known to be high thrust propulsors. They generate thrusts by controlling cyclically attack angles of rotating blades. In addition, they have characteristics of omni-directional and instantaneous control capabilities to yield high thrusts from small input power. We have been working to analyze their performances for several years. Experimental tests on thrust and power consumption measurements were performed with a three bladed propulsor, and indoor flight tests were carried out on an airship of 20 meters in length with a pair of these thrusters, and its flight performances were evaluated.

Nomenclature

\[ h = \text{wing span of rotational blade} \]
\[ c = \text{chord length of rotational blade} \]
\[ n = \text{rotational speed of driving arm} \]
\[ V_0 = \text{vehicle flight speed} \]
\[ Q = \text{volume of hull} \]
\[ C_D = \text{total volume drag coefficient} \]
\[ \eta = \text{thrust/power consumption} \]

I. Introduction

Airships are environmentally friendly, safe vehicles. In particular, non-rigid airships are attractive since they have gentle and soft structures. However, their kinetic capacities are low in case of conventional types, and for this reason they need quite a few ground crew for their take-offs and landings. If this bottleneck can be circumvented, then many people can enjoy comfortable and safe flights without unbearable costs. Therefore, developments of new type of high performance propulsors are necessary to enable airships to acquire larger markets throughout the world. For embodiments of transporter airships for forestry products, or airships for communication and broadcast relay, or for rescue purpose at times of larger-scale disasters, we have been developing cycloidal propellers with high thrust.

Cycloidal propellers are known to be an omni-direction high-lift thruster. The basic concept of cycloidal propellers were presented in 1828, and commercialized in 1931 under a name of Voith Schneider Propeller for naval vessels. In Japan, the first tug boat with these propellers was constructed in 1936. Cycloidal propellers are more efficient than conventional helicopter rotors in terms of thrust by power ratios. Control mechanisms of cycloidal propellers are generally sophisticated since attack angles of all blades have to be varied cyclically during rotations.

Nevertheless, these propellers have been successfully applied to tug boats, high-speed warships, and other navel ships, and have realized high-speed response control of large-scale ships with large inertia. The basic mechanisms of cycloidal propellers are shown in Fig. 1. High thrust forces can be yielded in an arbitrary direction by changing

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quickly attack angles of the symmetrical wings positioned diagonally. The propellers obviously generate counter reaction forces in the opposite rotational direction. This can be cancelled by placing the vehicle’s center of gravity appropriately or by introducing a counter rotating propeller to work like a helicopter tail rotor. As is shown in Fig. 1, Point O is the rotation center of all the blade driving arms’ concentration ends. Point N is the connection point of all the control rod ends. When Point N coincides with Point O as in Fig. 1 (a), each rotating blade travels in the air with a zero attack angle, by yielding no thrusts. On the other hand, as is shown in Fig. 1 (b), Point N deviates from Point O, then the blades rotate along the positions: B → C → D, and D → A → B, resulting in the generation of thrusts along these paths, even though no thrusts are yielded at positions B and D, since their attack angles are zero.

II. Airship-type Aerial Base Robot

Figure 2 shows a design concept of a 20 metered Airship-type Aerial Base Robot. The maximum diameter of the hull is 7 meters and the length is 20 meters. The envelope is made of pressurized double layered skin. A pair of cycloidal propellers is located at the fore hull. Counter balances are installed at the aft hull so that the hull kept level balance. This counter balances can be electric batteries for electrically driven cycloidal propellers. Two pairs of engine driven cycloidal propellers can be equipped at appropriate location of the fore and aft hull. In addition, a small quantity of batteries for control of the wing attack angles is installed under the hull for precise adjustment of pitch balance by replacing the batteries along the hull axis. In this way, adjustment of the center of gravity position of the vehicle can be done. Tail fins of this airship are simple stabilizers. A pressurized fabric structure is adapted to the tail fin stabilizers to contribute to lightness and increase safety in case of contacts to the ground. And the tail fins are X-letter shaped type. Table 1 shows design specifications of the propellers and the airship robot.

<table>
<thead>
<tr>
<th>Table 1. Propeller and hull design data</th>
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</thead>
<tbody>
<tr>
<td>Span ( h )</td>
</tr>
<tr>
<td>Number of Blades ( z )</td>
</tr>
<tr>
<td>Chord Length ( c )</td>
</tr>
<tr>
<td>Blade Orbit Radius of Thruster ( r )</td>
</tr>
<tr>
<td>Driving Arm Rotational Speed ( n )</td>
</tr>
<tr>
<td>Expected Maximum Vehicle Flight Speed ( V_0 )</td>
</tr>
<tr>
<td>Volume of Hull ( Q )</td>
</tr>
<tr>
<td>Total Volume Drag Coefficient of Hull ( C_D )</td>
</tr>
<tr>
<td>Number of Thruster Units/Vehicle ( M_s )</td>
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</tbody>
</table>

Figure 2. Airship-type Aerial Base Robot

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III. Thrust Measurement Test of Cycloidal Propeller

A. Measurement method

Figure 3 shows an experimental setting for thrust measurement tests. In these tests, one of electrically driven propellers made for 20 metered airship was utilized. This propeller was mounted to a test bed anchored on the ground. Four sets of load cells were installed between the test bed structures and the propeller to measure thrusts in the independent horizontal directions. Thrusts in the directions of two horizontal axes were estimated by sampling load cells’ output through a personal computer. In this way, thrust mean values were acquired as well as directions of the estimated maximum thrusts. The data sampling sequences were as follows; wing pitch angles were controlled by radio commands, and these were set by every 5 degrees from 0 to 27 degrees at the maximum. Rotational speeds of the propeller blades were controlled from 1rps to 8rps at the maximum.

B. Experimental results

Figure 4 shows results of estimated two dimensional thrusts in each controlled axis. At first, wing pitch angles were so controlled that the maximum thrust might occur along X-axis toward the negative direction. However, the maximum thrust actually occurred in the direction deviated by about 10 degrees from X-axis toward the plus direction of Y-axis. The maximum thrust achieved 500 Newton.

Next, wing pitch angles were so controlled that the maximum thrust might occur in the minus direction of Y-axis during rotation of the blades. As a result, the maximum thrust occurred in the direction deviated by about 10 degrees from Y-axis toward the minus direction of X-axis. In this case, the maximum thrust attained 460 Newton. Figure 5 shows a measured air flow field around the propulsor when the wing pitch angles were so controlled as to yield the maximum thrust in the negative direction of X-axis. It was seen that the air flow directions have negative components of Y-axis. This would be caused by unsteady effects due to vortex generations and their sheddings. These characteristics would be regarded as a nature of cycloidal propellers, and Fig.4 data would also indicate identical phenomena.

Figure 3. Thrust measurement test setting

Figure 4. Thrust directions and estimated thrusts

Figure 5. Measured air flow directions and velocities

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IV. Efficiency Improvement

Various drags are imposed to rotating blades of cycloidal propellers. Among these drags, there are profile drags of the driving arms and drags induced by blade tip vortices. Major purpose of examinations here is reductions of these two kinds of drags.

A. Fairing effects

Driving arms are shaped as a tapered arm. Thrust/power consumption rate denoted as $\eta$ is chosen as an indicator of power-efficiency, which is a ratio of a thrust versus the corresponding power consumption. Improvement of thrust/power ratio was experimentally examined by installing a fairing with a sectional shape of airfoil NACA0024 to each driving arm. Figure 6 shows the propulsor after installing fairings. The measurement method was similar to the method mentioned in the previous section. Performance assessment was conducted by comparing thrust/power consumption with fairings and without them. Figure 7 shows results of improvement rates $(\eta_2-\eta_1)/\eta_1$, for various pitch angles and averaged value over all the rotational speeds and pitch angles. Subscript 1 for thrust/power consumption rate means cases without fairings and Subscript 2 means with fairings. Slight improvements were shown in low rotational speed of 1rps to 3rps, except for a case of 1rps at 5deg. On the other hand, the maximum improvement rates achieved nearly 30% in higher rotational speeds. Improvement rate curves fluctuate, which may be caused by the drag characteristics of fairings. The optimum airfoil thickness ratio of fairings must be determined corresponding to rotational speeds in actual operation.

![Figure 6. Cycloidal propeller with fairing](image6.png)

![Figure 7. Rotational speed vs. improvement rates $(\eta_2-\eta_1)/\eta_1$.](image7.png)

B. Winglet effects

Wings are often equipped with winglets in order to suppress wing-tip vortices. It is known that the lift coefficient of three-dimensional wings can be augmented by winglet effects. As a result, increase of thrust and thrust/power consumption rates can be attained. There are a quite few reports on winglet effects in the steady flow. However, there are few reports of winglet effects in the unsteady flows. Authors have not yet found reports about winglet effects on cycloidal propellers. In our tests, geometrically different five winglets were examined. In this paper, results of one type winglet are presented. Figure 8 shows a sample shape of winglet. This winglet is made of carbon fiber reinforced plastic. The measurement method was identical to the afore-mentioned method in Section III. Figure 9 shows results of thrust measurement test. At rotational speeds over 3rps, augmentation of thrusts were shown more evidently with winglets than without them. More specifically, average increased rates of thrusts were 12% in case of 3rps, 22% in case of 4rps and 24% in case of 5rps. By these results, it can be said that winglets are effective in practical rotational speed of the propulsor. Figure 10 shows results of improvement rates. In low rotational speed area, improvement rates were not high. Meanwhile, improvement rates were remarkably higher in high rotational speed area.

![Figure 8. A winglet sample](image8.png)
Figure 11 shows the maiden flight of 20 metered Airship-type Aerial Base Robot with a pair of electrically driven cycloidal propellers. Flight tests were carried out in March 2008 in Taiki, Hokkaido, Japan. The purpose of the flight tests was to verify the robot’s fundamental movements. Rotational speeds of the propellers were kept under 5rps. Controls of rotational speeds and wing pitch angles were made by radio commands. The airship could successfully make a vertical take off and a forward level flight. Successively, the vehicle hovered and made reverse flight. Kinetic performances of the cycloidal propeller equipped airship were shown to be much maneuverable than vehicles equipped with conventional fan-type thrusters.

V. Flight Test of Airship-type Aerial Base Robot

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Figure 11. A flight test

VI. Conclusion

Thrust characteristics of a cycloidal propeller were investigated experimentally. Usefulness of cycloidal propellers for airships was shown by these results. It was found that installments of fairings and winglets were effective in improving thrust/power consumption rates. However, it is necessary that adaptation of winglets to a cycloidal propeller should be examined in more detailed experimental investigations.

References


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