Study on high performance of a ship propulsion device by using the Weis-Fogh mechanism

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Abstract
The purpose of this study is to develop a high performance propulsive mechanism with high efficiency at high sailing speed by using a mechanism of rotary reciprocating wing motion based on the two-dimensional Weis-Fogh model. The sailing tests by both towing the model ship and its self-propulsion were carried out. In the towing test, the thrust of the model ship, the drag acting on the wing, and the wing opening angle in motion were measured for various parameters such as the wing moving speed and the sailing speed of the model ship. On the other hand, in the self-propulsion test the sailing speed of the model ship was measured for various frequency of wing reciprocating motion. The following results were obtained. The change of the wing opening angle in the mechanism of rotary reciprocating wing motion is obviously different from that of the wing opening angle in the mechanism of linear reciprocating wing motion. It was confirmed that the former is effective for the speeding up of the wing motion in comparison with the latter.

Keywords: Ship propulsion system, Weis-Fogh mechanism, Hydraulic machine, Unsteady flow, Wing

1. Introduction
The Weis-Fogh mechanism (Weis-Fogh, 1973, Lighthill, 1973) has been known as a novel mechanism of lift generation (Kolomenskiy, 2011, Maxworthy, 1979, Furber and Ffowcs Williams, 1979). One of the authors proposed a two-dimensional model of ship’s propulsion mechanism using the Weis-Fogh mechanism (Tsutahara and Kimura, 1984). In the theoretical studies (Tsutahara and Kimura, 1985a) the dynamic characteristics of the force acting on the wing were investigated by the analysis based on the two-dimensional potential flow. On the other hand, in the experimental studies (Tsutahara and Kimura, 1986a, 1986b, 1987, Tsutahara et al., 1988a, 1988b, 1990, Ro et al., 1990) it was clarified that the proposed model can operate sufficiently as the ship’s propulsion mechanism. Then the performance can be fully improved by controlling the physical quantity for the wing motion such as the speed, the acceleration, and the opening angle. The maximum propulsive efficiency reaches at more than 70% when the speed ratio $V/U$ that is the ratio of the wing moving speed $V$ to the sailing speed $U$ is less than 0.5. For the case of the speed ratio less than 0.5 cavitation must not occur until fairly higher sailing speed. Moreover, the potential flow can be realized by controlling the wing motion (Sakamoto and Tsutahara, 2017), so that higher efficiency may be expected. That is, the present model is a superior ship’s propulsion mechanism which can be applicable not only to lower sailing speed but also to higher sailing speed.

In the two-dimensional model ship’s propulsion mechanism (Tsutahara, 1993, Tsutahara et al., 1994b) and the various types of pump (Tsutahara and Kimura, 1988c) the wing reciprocates on the orbit in the straight line perpendicularly with the flow direction (propulsive direction). It shall be called the mechanism of linear reciprocating wing motion, but it includes several problems that should be improved for higher sailing speed of the ship. On the other hand, for the case of application to a fan the new type of mechanism was developed (Tsutahara and Kimura, 1994a), in which the wing reciprocates along the arc-formed orbit in the channel as shown in Fig.1. In this model the ship moves
upward in Fig.1, and the fluid flows downward. The point P in the wing, which is the 1/4 chord length point, moves with the moving speed of \( V \) along the arc-formed orbit in the channel, and the wing opens as in (a) and (d) in Fig.1. The inclining angle of the chord line in the wing to the uniform flow is defined as the wing opening angle \( \alpha \). Then the wing translates in the channel as in (b) and (e) in Fig.1 keeping the opening angle or changing it. Finally it closes with touching its leading edge to the other wall as in (c) and (d) in Fig.1. The structure of the mechanism is simple, and it is easy to speed up of the wing motion. This mechanism is also based on the Weis-Fogh mechanism, and it should be called the mechanism of rotary reciprocating wing motion.

The purpose of this study is to develop the high performance propulsive mechanism with high efficiency at high sailing speed by using the mechanism of rotary reciprocating wing motion in a channel as the two-dimensional Weis-Fogh model. The characteristics of this improved model ship are investigated.
2. Experimental apparatus and procedure

Figure 2(a) shows the overview of the model ship which was improved concerning high sailing speed. The ship is a type of catamaran, and the mechanism of rotary reciprocating wing motion is centered in the ship. The wing axis of 5 mm in diameter is maintained at the position of 12.5 mm from the leading edge in the wing, and the position is 1/4 chord length point as shown in Fig.2(b). Both ends of the wing axis are supported by two arms, and the wing reciprocates along the arc-formed orbit in the channel because the arms turns in the rotating axis circumference and reciprocate. So that 1/4 chord length point in the wing moves along the arc-formed orbit of a sector of 350 mm in radius and 41.3 degree in central angle. The rotational vibration of the rotating axis was performed by the crank mechanism. The frequency of wing reciprocating motion \( N \) (rps) agrees with the rotational frequency of a flywheel, and so that the time-averaged wing moving speed \( V \) (m/s) in the channel is given by

\[
V = 0.494 \cdot N \tag{1}
\]

because the channel width is 247 mm.

The wing of NACA0020 is used, and it is made of aluminum. The upper part at the trailing edge in the wing is connected to the stick which is fixed at the wing axis using a string as shown in Figure 2(b). The propulsive mechanism in which the wing is connected with an extension spring (0.6 mm in wire diameter) or a chain as shown in Fig.2(c) or Fig.2(d) as the string is called Type A or B, respectively. The wing opening angle in Type B is fixed whereas its angle in Type A can be adjusted automatically.

Both the thrust coefficient \( C_T \) of the model ship and the drag coefficient \( C_D \) of the wing are defined as follows, respectively.

\[
C_T = T / \left( \rho U^2 / 2 \cdot S \right) \quad C_D = D / \left( \rho U^2 / 2 \cdot S \right) \tag{2}
\]

where \( T \) denotes the thrust of the model ship; \( D \) the drag acting on the wing; \( U \) the sailing speed of the model ship; \( S \) the area of the wing; \( \rho \) the fluid density, respectively. In the towing test the thrust \( T \) under a certain constant sailing speed is measured as shown in Fig.3. When the sailing speed by towing the ship is larger than the self-propulsion speed of the ship corresponding to the wing moving speed, the towing force \( F_r \) from the stem is measured by using the spring scale under the pulling force \( F_r \) from the stern. On the other hand, when the sailing speed by towing the ship is less than the self-propulsion speed, the pulling force \( F_r \) from the stern is measured by using the spring scale under the towing force \( F_r \) from the stern. As the result the thrust by towing is given by the following equation as the time-averaged value.

\[
T = D_u - F_r + F_r \tag{3}
\]
where $D_U$ is the ship resistance corresponding to the sailing speed $U$ without operating wing, and it is measured using the spring scale. The ship resistance $D_U$ is approximately proportional to the second power of the sailing speed $U$ as shown in Fig.4. On the other hand, in the self-propulsion test the thrust $T$ of the ship is equal to the ship resistance $D_U$ corresponding to the sailing speed $U$ because the thrust is balanced with the ship resistance during the sailing. The sailing speed $U$ in self-propulsion is given by measuring the sailing time of the ship at a certain constant section. The drag $D$ acting on the wing is measured with two strain gages which were stuck on the middle section of the arm. The experimental data is measured for several seconds at the sampling frequency of 2 kHz, and the low-path filter of 100Hz is processed for the data. Then the time averaged drag acting on the wing is given as the average of the result.

The propulsive efficiency is defined as follows:

$$\eta = \frac{C_T \cdot U}{C_D \cdot V}$$

3. Experimental results and discussions

3.1 Sailing test by towing

The relationships between the thrust $T$ and the sailing speed $U$ for Type A and B are shown in Fig.5 for frequency of wing reciprocating motion $N$, respectively. The maximum wing opening angle in Type B is fixed to 10 degrees whereas its angle in Type A can be adjusted automatically.

![Fig. 5](image_url)

(a) Type A (b) Type B

Fig. 5 The relationships between the thrust $T$ and the sailing speed $U$ for Type A and B are shown for the frequency of wing reciprocating motion $N$, respectively. The maximum wing opening angle in Type B is fixed to 10 degrees whereas its angle in Type A can be adjusted automatically.

The sailing test is performed by the fire proof water tank in National Institute of Technology, Nara College because it is difficult for the experimental facility to reach 1.0m/s in the sailing speed. In the towing test the thrust $T$ of the model ship, the drag $D$ acting on the wing, and the wing opening angle $\alpha$ in motion are measured for various parameters such as the wing moving speed $V$ and the sailing speed $U$ of the model ship. On the other hand, in the self-propulsion test the sailing speed $U$ is measured for various frequency of wing reciprocating motion $N$. The wing opening angle $\alpha$ in motion also is observed with a video camera which is arranged in the upper part of the channel in the model ship.
frequency of wing reciprocating motion even for the same \( V/U \), so that the similarity is not possible. Figure 7 shows the relationships between the drag coefficient \( C_D \) and the speed ratio \( V/U \) for Type A and B, and these results also have the same tendency as mentioned above. The reason is that the wing opening angle in Type A varies with the absolute value of the wing moving speed not the non-dimensional value \( V/U \).

An example of the change of the wing opening angle \( \alpha \) in the channel is shown in Fig.8 (a). In both Type A and B the wing widely opens on the opening stage, and the tendency is the same as that of the mechanism of linear reciprocating wing motion. The wing opening angle in Type B is almost constant on the translation stage because the angle is fixed with the chain. On the other hand, its angle in Type A decreases gradually. Then the wing in Type A becomes approximately parallel to the other wall when it approaches the other wall, and the wing is closed smoothly as shown in Fig.8 (b). This prevents the generation of jet that decreases the performance, and its characteristic is obviously different from that of the mechanism of linear reciprocating wing motion. Both the wing behavior and the force acting on the wing in the channel must be clarified to estimate the performance of the mechanism.
Figure 9 shows the relationship between the propulsive efficiency $\eta$ and the speed ratio $V/U$ for Type A and B. The maximum propulsive efficiency reaches at almost 30% in the scope of this experiment. The propulsive efficiency has the highest value when the speed ratio is less than 1.0 as mentioned before (Tsutahara et al., 1985a). The propulsive efficiency of Type A is much larger than that of Type B in the range of the speed ratios less than 3.0.

3.2 Sailing test by self-propulsion

The relationship between the sailing speed $U$ and the frequency of wing reciprocating motion $N$ is shown in Fig. 10 (a). The sailing speed increases with increasing $N$. The sailing speed of Type A is much larger than that of Type B under the constant $N$. The maximum sailing speed reaches at 0.8m/s when $N$ is 5rps (wing moving speed = 2.47m/s). The maximum sailing speed of the model ship using two wings in the mechanism of linear reciprocating wing motion reached at 0.59m/s under the wing moving speed of 0.19m/s (Tsutahara and Kimura, 1985b). 2.47m/s in wing moving speed is highest-speed so far, and the present mechanism is effective for the speeding up of the wing motion. The reason why the sailing speed of the
model ship corresponding to the increase of the wing moving speed did not rise, one wing was used and the ship resistance became large relative to that of the conventional model ship. In order to speed up the wing motion an engine instead of DC motor may be used in the mechanism.

When the sailing speed of the ship is high, the pressure on the upstream side of the wing falls and the air from the upper side of the wing was sucked into the water. So that the performance decreases because of the bubble contamination into the channel, but it can be prevented by lowering the position of the wing. Then the stem of the model ship also was lowered and it sailed as shown in Fig.10 (b). So that the sailing speed corresponding to the frequency of wing reciprocating motion was not completely obtained because the ship resistance is different from the towing test because of the different of the ship inclination. It is important for the performance improvement to keep the appropriate ship geometry corresponding to the sailing speed.

4. Conclusions

The purpose of this study is to develop the high performance propulsive mechanism with high efficiency at high sailing speed by using the mechanism of rotary reciprocating wing motion in the channel as the two-dimensional Weis-Fogh model. The characteristics of this improved model ship were investigated. The following conclusions were obtained.

(1) The change of the wing opening angle in the mechanism of rotary reciprocating wing motion is obviously different from that of the wing opening angle in the mechanism of linear reciprocating wing motion.

(2) It was confirmed that the mechanism of rotary reciprocating wing motion is effective for the speeding up of the wing motion in comparison with that of linear reciprocating wing motion.

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Fig. 10 Experimental results for sailing test by self-propulsion of model ship

(a) Relationship between sailing speed $U$ and frequency of wing reciprocating motion $N$ for Type A and B. The maximum wing opening angle in Type B is fixed to 10 degrees whereas it angle in Type A can be adjusted automatically.

(b) Sailing State of Type A when the frequency of wing reciprocating motion $N$ is 5rps.
References


