Detection of Near-propeller Bubbles and Thrust Power in a Constant Torque Control Motor Propulsion System*


The AC motor drive system is widely used in electric propulsion systems. This motor drive system has a far faster response time (by up to several milliseconds) than a conventional system. It is also possible to monitor the state (current, voltage, torque, rotational speed) of the motor accurately in real time. If bubbling in the vicinity of the propeller is detected by monitoring the motor state, an additional special device such as a torque meter can be omitted from the propulsion system. Furthermore, a faster response time allows advanced propeller control, enabling the suppression of bubble formation and the resulting effects in real time. This paper demonstrates the detection of bubbles and fluctuating thrust due to bubble entrainment by monitoring signals from the motor, as it is driven in constant torque control mode. A fluctuating thrust force can be detected and well correlated with any bubble interactions using the monitoring signal.

1. Introduction

Fluctuations of waves and the relative hull orientation of a ship can cause air bubble entrainment or even cavitation on propeller surfaces. The propeller slip and racing caused by bubble entrainment and cavitation greatly reduce the thrust of the propeller and the efficiency of ship propulsion [1]. A conventional ship with a direct drive engine system employs a governor or a speed limiter. These devices control the fuel injection and regulate the engine speed, suppressing propeller slip and racing. Detection of varying rotational torque requires an additional torque meter, the output of which is fed back to the control device. However, the accuracy of a torque meter is somewhat limited. For example, the shaft horsepower meter used in internal combustion engines requires temperature correction and centrifugal force correction, and an update time of 5 seconds is usually used [2]. In contrast, the electric motor drive system used in diesel electric (electric propulsion) ships can respond in a much shorter time due to the rapid progress of power electronics in recent years. Control reaction time could be on the order of several milliseconds, which is much faster than is possible with a conventional engine system. In addition, the internal signal that is used to control the motor can provide monitoring data such as current, voltage, torque, and rotational speed in real time.

This suggests the possibility of real-time monitoring of the propeller state using an electric motor system. The advantages of such a system compared with a conventional propulsion system are twofold. First, an additional torque meter can be omitted, thus decreasing the number of maintenance-requiring components. Second, the rapid detection of anomalous behavior in the propulsion system enables faster action and recovery with appropriate control schemes. This makes it possible to suppress the reduction of the thrust force and the loss of propulsion efficiency caused by bubble entrainment and cavitation near the propeller. However, knowledge of the transient behavior of the propeller after bubble entrainment is limited [3].

To help deal with this situation, we have demonstrated the detection of near-propeller bubbles and thrust power variations by observing the monitoring data of an electric motor system.
The motor propulsion system was installed in a circulating water channel. Bubble behavior near the propeller was observed using the monitoring data of the control circuitry and optical images obtained by a high-speed camera. The variations in the monitoring data after bubble entrainment were recorded, analyzed and characterized in the experiment.

2. Experimental equipment and experimental methods

2.1. Experimental equipment

The experiment was carried out in the horizontal circulation water channel located at the Tokyo University of Marine Science and Technology [2]. Water is circulated by a single impeller with a diameter of 1.6 m, and a rated output of 90 kW. The experimental section measures L: 9.0 m × B: 2.2 m × D: 1.6 m. Flow velocity is regulated by remote control, and velocity distribution through the test section is ± 2.0%. Fig. 1 is a block diagram of the experiment. The propulsion mechanism was installed in the test section of the water channel.

The motor was driven by a Yaskawa Electric Co. SGD7S-330A100A motor drive, with an AC servomotor output rated at 5 kW (SGM7A-50AFA61: Yaskawa Electric Co.). The control cycle period of this drive is 126 μs. In this study, the motor was operated in constant-torque control mode. For the propulsion mechanism, a 321 type made by the Yamato Motor Co., Ltd. was used, with a propeller diameter of 187 mm.

The motor drive receives the torque command generated by the electronic control unit (FA-M3: Yokogawa Electric Corporation) and operates the motor accordingly, while at the same time sending the torque monitor signal and the rotational speed monitor signal to a data logger (NR-600: Keyence Corporation). In order to measure the effective current, voltage and power of the motor, a current probe (model 3274: Hioki Electric) and a voltage probe (model L9438-50: Hioki Electric) are installed in the main power cable of the motor drive. These probes are connected to a watt meter (model 13183: Hioki Electric). The output of the watt meter is collected by the data logger to monitor the effective motor voltage, current, and power. Thrust force was measured by a load cell (LC 1122-K500: A&D) installed between the propulsion mechanism and the frame of the water channel. These data were recorded at a sampling rate of 1 kHz. Recorded items were the rotational speed command, the torque command, the rotational speed monitor output, the torque monitor output, the effective motor voltage, the effective motor current, the effective motor power, and the load cell output.

In parallel to the electric monitoring of the propeller state, bubble behavior near the propeller was optically observed with a high-speed camera (Fastcam SA4: Photron Co., Ltd.) that was installed on the side observation port of the circulating water channel. The lens used in this experiment was an AF-S Micro NIKKOR 60mm f/2.8G ED manufactured by Nikon Corporation. The shutter speed and frame rate were 125 Hz. The aperture size was set to F2.8. Bubbles and propeller parts were illuminated by a halogen light source installed at the bottom wall of the channel. The propulsion motor was synchronized with the high-speed camera by a trigger signal from the electronic control unit.

The motor drive system has two operating regions under constant-torque control mode. Below the base speed, the motor is operated in the constant-torque region. The output torque of the motor is expressed by $T_m (\text{Nm}) \propto \Phi \text{ (Wb)} \cdot I \text{ (A)}$, which is proportional to the product of the magnitude of the magnetic flux $\Phi$ and the drive current $I$. In the constant-torque region, the magnetic flux $\Phi$ is constant. The motor power can thus be represented by $P(W) = T_m (\text{Nm}) \cdot \omega \text{ (rad/s)} = T_m (\text{Nm}) \cdot 2\pi n \text{ (s$^{-1}$$)$}$ and is proportional to the rotational speed $n$. The
induced electromotive force generated in the motor winding is expressed as \( V(V) \propto \Phi(Wb) \cdot 2\pi n(s^{-1}) \). The induced electromotive force is proportional to the product of the magnetic flux \( \Phi \) and the rotational speed \( n \). Above the base speed, the motor is operated in the constant-power region, in which field weakening is used to keep the motor voltage \( V \) constant regardless of the rotational speed \( n \). In this region, the available torque \( Tm \) decreases in inverse proportion to the rotational speed \( n \) to keep the motor power \( P \) constant [5]. In this experiment, motor torque was set to less than 15 Nm and the rotational speed was set to less than 40 s\(^{-1} \) so that measurement was performed in a constant-torque region.

2.2. Experimental methods

Fig. 2 illustrates in detail the propulsion mechanism installed in the water circulation channel.

The depth of the anti-cavitation plate \( Ds \) was 70 mm from the water surface. The depth of the propeller axis \( Dp \) was 185 mm. Flow velocity was set to \( Vf = 0.5 \) m/s. Those values were chosen so that bubble entrainment would occur frequently in this setup. The motor torque was set at three values: 100%, 95%, and 90% of the rated torque of 15 Nm. The motor was accelerated linearly from 0 (Nm) to the set torque (Nm) in 10 seconds. After the torque reached a set point, it was maintained for 20 seconds. The rotational speed \( n \) and motor output power \( P \) changed according to the set torque as described in the preceding section. Therefore, a higher torque set value increased both the rotational speed and the motor power. A load fluctuation on the propeller will cause a variation of its rotation speed in the constant-torque control mode. For example, when the propeller load decreases and the torque falls due to air entrainment, the motor increases its rotational speed until it restores the torque of the propeller. The thrust force was obtained by subtracting the self-weight moment load, which was measured before the experiment.

2.3. Noise reduction

A noise component is superimposed on the signal data acquired by the data logger.

The main sources of noise are electrical and mechanical fluctuations linked to the rotation of the propeller and the servomotor.

These are due to the control feedback period and rotational vibration of the propeller. Therefore, the noise component can be treated as a high-frequency component, and the signal component of the phenomenon of interest can be extracted using a low-pass filter. The low-pass filter is implemented as a finite impulse response (FIR) filter [6] in order to prevent any phase delay among different frequencies. The filter was designed with the window function method. The time constant was 101 ms (number of taps: 101). The cutoff frequency was set to match half of the propeller's rotational speed. Since propeller rotation changes during the measurement, the cutoff frequency was also changed over time.

2.4. Image signal processing method

An area around the propeller was clipped from the optical image, and the brightness in the picture was calculated for each image frame. The processed frame region was 78 mm wide and 190 mm high. The processing region in the captured image is shown by a white line in Fig. 3. Image processing was performed in the frame region so that bubbles following after the propeller do not affect the brightness value. Each original picture was recorded with 12-bit brightness depth. This was converted into a percentage, and the average brightness of all the pixels in the region was calculated. The average brightness value in the frame area changed with the reflection intensity.
from the propeller itself, since the propeller was rotating. Therefore, as in the previous section, only entrained bubble components were extracted by the low-pass filter. The time constant of the filter was set to 1 s (number of taps: 125).

### 3. Experimental Results and Discussion

An example of a measurement is shown in Fig. 4. Line legends are indicated in the figure. The horizontal axis indicates the elapsed time after the acceleration, in seconds.

As the motor torque increases linearly, the motor rotational speed rises in proportion to the square root of the torque, which follows the characteristics of the propeller torque/rotational speed [7]. The torque reaches set point in 10 seconds and the motor rotates at a constant speed. Since the thrust is proportional to the square of the rotational speed, it rises linearly and then becomes constant.

The motor current does not have a peak that perfectly matches the motor torque, as described in section 2.1. Several peaks can be observed in the measurements, in 2) rotational speed, 3) motor voltage, 5) thrust, 6) brightness and 7) motor power. The motor voltage and the motor power, however, have a certain delay relative to other curves. This is because of the processing delay of the wattmeter used to measure current and voltage and to calculate power. For this reason, motor current, voltage and power data were not evaluated in this study.

Fig. 5 is an enlarged view of the constant torque region of Fig. 4. In this data, 13 peak points are evaluated, as indicated by numerals. As the brightness rises, indicating bubble entrainment, the thrust decreases. At the very same time, the rotational speed increases to keep the torque constant.

Fig. 6 shows the transition images, every 80 ms from the occurrence of peak 1. Cavitation is seen before the occurrence of entrainment. Due to propeller motion, bubbles are entrained from the water surface. This suction continues, depending on local flow conditions.

The difference of the peak times for brightness and rotational speed is evaluated in Fig. 7. The horizontal axis indicates the peak time of the rotational speed. The brightness peak time deviates by 19 ms from the rotational speed peak time. This variation is thought to be due to the 8 ms frame rate of the high-speed camera and the behavior of bubbles, but it is synchronized as a whole and there is no qualitative tendency. Therefore, it can be seen that the rotational speed increases simultaneously...
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This is because the motor drive (control cycle period of 126 μs) detects the load fluctuation caused by bubble entrainment and rapidly controls the rotational speed. Thus, in the constant-torque control mode, it is shown that the entrainment phenomenon can be detected by monitoring the rotational speed output signal from the motor drive.

The difference between the thrust peak time and the rotational speed peak time is shown in Fig. 8.

Overall, the thrust peak lags behind the rotational speed peak time by about 50 ms. The reason for this can be ascribed to a mechanical delay. The load cell is installed between the frame of the water channel and the propulsion mechanism, so it measures the propulsion force of the mechanism, not the thrust force directly, as shown in Fig. 2.

3.1. Comparison of rotational speed peak and brightness peak

Fig. 9 shows the peak correlation of rotational speed and brightness for 100%, 95%, and 90% torque set points. The horizontal axis indicates the rotational speed in rpm, the vertical axis indicates the brightness. At 90% torque, only four bubble entrainments were observed.

Points in the red frame are the data obtained when there was no entrainment. The brightness is almost the same among different torque set points when no bubble entrainment occurs. The rotational speed increases as the torque set point increases. As the amount of bubble entrainment increases, the brightness and the rotational speed increase and the data point moves to the upper right. At each torque setting value, the brightness and the
rotational speed rise similarly. Therefore, bubble entrainment can be detected from the rotational speed under the constant-torque control mode.

3.2. Correlation between rotational speed and thrust force

Peak data for rotational speed and thrust are shown in Fig. 10. The red-framing of some data points indicates the absence of entrainment.

It can be seen that a higher torque set point results in a higher rotational speed and larger thrust. The variation of the thrust peak at 100% torque is larger than that at other set points, which may be due to a lack of stiffness in the propulsion mechanism installation. As confirmed previously, bubble entrainment decreases the thrust force and increases the rotational speed. Therefore, when the motor is operated in constant-torque control mode, bubble entrainment induces a drop in thrust force, which varies inversely with rotational speed due to the influence of bubbles. These data clearly show that bubble entrainment causes a reduction in thrust force [3]. In addition to that fact, our experimental results suggest the possibility of detecting bubble entrainment solely by monitoring the rotational speed.

![Fig. 10 Correlation between thrust and rotational speed](image)

4. Conclusion

Near-propeller bubbles and fluctuation of thrust force were detected by observing the monitor signal of the AC servomotor in constant-torque control mode. Rotational speed, thrust force and brightness in the vicinity of the propeller were measured simultaneously to evaluate the bubble entrainment, yielding the following results:

1. Peak time and magnitude at the occurrence of bubbles were well correlated with the rotational speed of the motor, which was monitored at the motor drive in real time. Thus, it was confirmed that bubble occurrence around the propeller can be determined solely by monitoring the motor state.

2. Thrust force variation due to near-propeller bubbles is well correlated with the rotational speed of the motor. This implies that thrust force can be estimated by signal processing of the motor's rotational speed signal. While a delay of approximately 50 ms was observed in the thrust peak due to lack of stiffness in the installation mechanism of the strain gauge, the time of appearance of the thrust peak could be successfully detected by the motor rotational speed signal.

References