Study on Synchronous Effects of Free Surface and Propeller Rotation on Vessel Rudder Force

Pham Ky Quang¹*, Vu Van Duy², Trinh Xuan Tung¹, Dang Dinh Chien³ and Co Tan Anh Vu⁴

1 School of Excellent Education, Vietnam Maritime University, No. 484 Lach Tray Street, Haiphong, Vietnam
2 School of Mechanical Engineering, Vietnam Maritime University, No. 484 Lach Tray Street, Haiphong, Vietnam
3 Faculty of Navigation, Vietnam Maritime University, No. 484 Lach Tray Street, Haiphong, Vietnam
4 Maritime Insitute, Ho Chi Minh City University of Transport, No. 2 Vo Oanh Street, Hochiminh City, Vietnam
*E-mail: phamkyquang@vimaru.edu.vn

Abstract. The paper presents a theoretical foundation of the effects of free surface and propeller rotation on the flow surrounding the rudder of a vessel. This is the scientific ground to evaluate the instability of the rudder force, thence building a research model and applying CFD in simulated to calculate the phenomenon. On the other hand, this paper also issues the idea of designing and creating a test system for carrying out practical experiments on related problems by using ship models similar to M/V TAN CANG FOUNDATION. The input data merely including ship’s lines, ship’s speed, rudder angle… are observed in the period of maneuvering the vessel in the Haiphong fairway, Vietnam. The results are shown in this article distinctly figure out pulsating air bubbles caused by the synchronous effects of the free surface, the propeller rotation and indicate that the oscillating period of the rudder force at the time cavitation at the leading edge of the rudder which has not been formed is compatible with the revolutions of the propeller.

1. Introduction
The rudder always keeps a vessel sailing on track of the intended course or steering the vessel to a new course. Therefore, it is termed a controlling object for creating the rudder force to alter the vessel’s course.

The propeller is the last part converting the engine power into the thrust that helps the vessel go astern or ahead and forwards. The propeller rotation also imposes a direct influence on the maneuverable characteristics of the vessel.

The rudder force is produced by converting the energy of the behind propeller flow. That is why the characteristic of the behind propeller flow is the major factor impacting the effectiveness of the procedure of converting this energy.

Figure 1 illustrates the propeller rotation, depth of propeller in comparison with the surface and operational data in practice consisting of rpm \( n_i \), angle rudder \( \phi_i \). The energy of the behind propeller flow shall be converted into the rudder’s force. Value R depends on the rudder area, angle rudder and the velocity of flow surrounding rudder. This proves that the quality of the behind propeller stream has crucial effects on the rudder force (in magnitude as well as direction).
The paper figures out the theoretical foundation present an idea of designing a test system then compares, analyzes, evaluates $R$-value according to different solutions that are suitable to given mathematics problems. Results of the study including practical experiment shall prove the synchronous effects caused by free surface and the propeller rotation on the flow around the propeller. In detail, it mentions the pulsating air bubbles phenomenon surrounding the rudder (mostly appears on the rudder’s surface that is on the same side as the propeller rotation) created by the synchronous effects of free surface and propeller rotation. It also indicates the phenomenon of oscillating rudder force which has a compatible period with the propeller revolutions.

2. Study model and mathematics foundation

2.1. Study model

The objectives of the mathematical problem are determining hydrodynamics data of flow at the transitional zone between rudder and propeller (Figure 2) [1-3]. This means all values of the behind rudder flow (equivalent to output data of problem No.1) shall be input data interacting with rudder (equivalent to input one for problem No.2). In this model, all vertical components of velocity playing a crucial role in converting the energy of flow into rudder force effectively $R$ are evaluated.

A question is raised here that “how the propeller rotation and free surface influence the vertical components of velocity at the transitional zone between rudder and propeller?”

2.2. Method of simulated calculation

In simulated calculating, using an arithmetic method, only the propeller rotation effect is taken into account. The effect of the free surface is not due to the assumption of applying a cylinder cover surrounding the propeller (Figure 3).
Figure 3. The study model using an arithmetic method

Foundation of the hydrodynamics of flow passing through the propeller and the interaction between flow and propeller have been introduced by many authors [4-8]. The Finite volume method with the (k-ω) model is the main way to solve the issue of this study. All the equations in this paper represent the theoretical basis of the research issue, only the Navier-Stokes equation was used directly to determine the velocity field in the calculation space as shown below:

- For non-compressed liquid, the continuity equation always exists and the Navier-Stokes equation:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

\[
\frac{d\vec{V}}{dt} = \vec{F} - \frac{1}{\rho} \triangledown p + \nu \Delta \vec{V}
\]

Where: \(\vec{V}(u, v, w)\) : absolute velocity vector of the surveyed liquid elements; \(\vec{F}\) : advance number of propeller; \(\rho\) - specified gravity of liquid (kg m\(^{-3}\)); \(\nu\) : hydrodynamic viscosity coefficient (m\(^2\)s\(^{-1}\)); \(P\): pressure (N m\(^{-2}\)); \(\Delta\) - Laplace operator.

- For mathematical problem relating to the kinetic propeller, mathematics foundation is presented in the following formulas:

According to Jonh and Poul [7] and other studies [9-12], the equation of determining the propeller thrust:

\[
T = \rho \cdot n^2 \cdot D^4 \left( \frac{V_p}{nD} \right)^c \left( \frac{\eta}{\rho n D^2} \right)^f \left( \frac{P_0 - e}{\rho n^2 D^2} \right)^g
\]

Where: \(D\) - diameter of the propeller (m); \(V_p\) : ahead speed of vessel (knot); \(N\) : propeller revolutions (rpm); \(\rho\) specified gravity of liquid (kg m\(^{-3}\)); \(p_0\) - \(e\) : stationary pressure at the propeller shaft (N m\(^{-2}\)).

Thrust coefficient: \(K_T = \frac{T}{\rho n^2 D^4}\)  

Advance number of propeller: \(J = \frac{V_p}{nD}\)

Reynolds number: \(Rn = \frac{\rho n D^2}{\eta}\)
Cavitation factor: $\sigma = \frac{p - e}{\frac{1}{2} \rho n^2 D^2}$

(7)

Turning moment coefficient: $K_T = \frac{Q}{\rho n^2 D^5}$

(8)

Calculating thrust formula: $T = K_T \rho n^2 D^4$

(9)

Turning moment: $Q = K_T \rho n^2 D^5$

(10)

Propeller rotating power: $P = \frac{Q \omega}{75} = \frac{2\pi}{75} K_T \rho n^3 D^5$

(11)

Working efficiency of propeller: $\eta_p = \frac{K_T}{K_Q} \frac{J}{2\pi}$

(12)

2.3. The method of practical experiment

The practical experiment model is built up by the idea of designing and manufacturing a system that is in accordance with the technical standard. The followings are the main modules of this system:

- Flow leading module (Figure 4): consists of a tank containing liquid with a dimension of 5.0 m in length, 2.0 m in width and 1.5 m in height and a controlling flow part ensuring the stream is pushed by the propeller and turns back at suction gate as a steady flow.

![Figure 4. Leading current system](image)

- Driving propeller module: is formed of a 3 phase electrical engine (power capacity 15 KW), a belt, a gear, and a propeller shaft system. Dynamic balancing, sealing, lubricating is calculated according to the technical standard. The entire driving part putting on the frame of the carriage carrying a circulation tank creates a continuous and mobile system, facilitating works of operation and maintenance.

![Figure 5. Overview of the test system and driving propeller combination](image)

The propeller-rudder combination shown in Figure 5 [13] and Figure 6 is made up of a propeller and a rudder. Data of rudder and propeller, as well as other operational data, is obtained as per Froude
similar standard applying to M/V TAN CANG FOUNDATION, with DWT 7040 MT, the ratio of similarity $k = 10$.

The observation chamber and measuring equipment: the observation chamber made of the tempered glass has a dimension of $1.5 \text{ m} \times 1.0 \text{ m}$, a rudder angle indicator and combination equipment including a hydraulic rudder force gauge and a vertical velocity at transitional zone gauge.

The hydraulic driving system used for determining the rudder force is illustrated in Figure 7, including two-piston cylinders, two pressure gauges (combine with two sensors of liquid pressure in cylinders) and a liquid-locking valve. When the rudder angle is changed, the liquid-locking valve is opened to adjust the position of these pistons before being locked to fix the rudder angle during the operating process. The rudder force is calculated based on liquid pressure indicated at the pressure gauges and on the piston area. The observation window is on the side of the tank, therefore, it is convenient to observe physical phenomena occurring on the lower pressure side of the rudder when the rudder rotates at different angles.

![Figure 6. Combination of rudder-propeller](image)

![Figure 7. Observation chamber and measuring equipment](image)

### 3. Analyzing the results of study

#### 3.1. Input data

- Geometrical dimensions: According to the booklet of M/V TAN CANG FOUNDATION specifications of propeller are shown as the following:

  - Diameter: $D = 3.65 \text{ m}$
  - Pitch: $P = 2.459 \text{ m}$
  - Pitch Ratio: $\frac{P}{D} = 0.6737$
  - No. of blade: $Z = 4$
  - Expanded area: $A_e = 6.6962 \text{ m}^2$
  - Expanded area ratio: $\frac{A_e}{A_0} = 0.64$
  - Boss ratio: $\frac{D_b \hat{D}}{D} = 0.173$
  - Section: $NACA 66; a = 0.8$
  - Propeller weight: 4400 kg

- Revolutions of propeller in the 7 following cases: $n_i = (90; 100; 110; 120; 130; 140; 150)$ rpm;

- The value of rudder angle in the 8 following cases $\phi_i = (0^\circ; 5^\circ; 10^\circ; 15^\circ; 20^\circ; 25^\circ; 30^\circ; 35^\circ)$

Thus, there are 56 combinations of propeller revolutions – rudder angle $(n_i, \phi_i)$.

#### 3.2. Analyzing the results of simulated calculation
The Fluent - Ansys program is applied to carry out the simulated calculation for cases with different values of \((n_e, \phi_i)\) [13-14]. Thus, particular values at the transitional zone are obtained, such as vertical velocity, turbulent viscosity, the pressure at the surface of the propeller… however, the authors just focus on studying the vertical velocity value only.

The following images described in Figure 8 are the results of the simulated calculation in detail for 4 cases with different revolution.

![Contour of Axial Velocity](image1.png)

a) \(n_1 = 120\) rpm

![Contour of Axial Velocity](image2.png)

b) \(n_2 = 130\) rpm
When carrying out the practical experiment, it is apparently observed that many air bubbles are under the surface and surround the rudder, especially most air bubbles are distributed on the surface of the rudder which is on the same side with the propeller rotation. This phenomenon is one of the primary reasons causing the cavitation on the rudder that results in instability of the rudder force although propeller revolutions and the rudder angle is unchanged. Figure 9 shows the comparison of the output data between the simulated calculation method and the practical experiment.
Figure 9. Pulsating air bubbles phenomenon caused by free surface and the propeller rotation: (a) The result obtained by the simulated calculation method; (b) Result obtained by practical experiment.

Summarizing the results of calculating the rudder force \( R \) in Table 1 which each row shows the rudder force in different solutions as following:

- **Solution 1:** According to Rawson and Tupper [8], the practical calculation formula is applied:

\[
R = 577A_R V^3 \sin \phi
\]  

(13)

Where: \( A_R \): contact area of the rudder (for M/V TAN CANG FOUNDATION, \( A_R = 12 \text{ m}^2 \)); \( V = 1.3V_p \) (speed of vessel in respect of the revolutions of propeller),

- **Solution 2:** The method of simulated calculation based on the arithmetic method.

- **Solution 3:** The practical experiment method.

Based on the results shown in Table 1, the chart of the relation between the rudder force \( R \) and different \( (n_i, \phi_i) \) values, illustrating in Figure 10. From the results shown in specific cases, with 3 different methods mentioned above, revolutions of the rudder of 140 rpm in Table 1 corresponding to Figure 10c, it is clearly seen that the rudder force that is obtained by the practical experiment and by the arithmetic method is respectively 12.5% and 13.3% lower (on average) than that by the experimental formula. Furthermore, the authors focus on evaluating the instability of the rudder force due to the effects of the free surface and the propeller rotation.

**Table 1.** Summarizing the results of calculating the rudder force in cases of different combinations

| Revolutions of the rudder \( (n_i) \), rpm | 0° | 5° | 10° | 15° | 20° | 25° | 30° | 35° |
|----------------------------------------|----|----|-----|-----|-----|-----|-----|-----|
| 120                                    | 0  | 36696.33 | 73113.66 | 108975.10 | 144008.10 | 177946.10 | 210531.30 | 241515.80 |
| 130                                    | 0  | 37166.79 | 74051.01 | 110372.22 | 145854.36 | 180227.46 | 213230.42 | 244612.20 |
| 140                                    | 0  | 32752.35 | 65164.88 | 94919.92 | 126892.98 | 154995.22 | 189765.80 | 215258.56 |
| 150                                    | 0  | 43067.22 | 85807.00 | 127894.40 | 169009.40 | 208839.50 | 247081.80 | 283445.50 |
| **The rudder angle \( (\phi_i) \) according to 3 solutions** | 0° | 36696.33 | 73113.66 | 108975.10 | 144008.10 | 177946.10 | 210531.30 | 241515.80 |
| 0°                                    | 37166.79 | 74051.01 | 110372.22 | 145854.36 | 180227.46 | 213230.42 | 244612.20 |
| 15°                                   | 32752.35 | 65164.88 | 94919.92 | 126892.98 | 154995.22 | 189765.80 | 215258.56 |
| 20°                                   | 43067.22 | 85807.00 | 127894.40 | 169009.40 | 208839.50 | 247081.80 | 283445.50 |
| 25°                                   | 43831.72 | 87330.20 | 130164.70 | 172009.56 | 212546.70 | 251467.86 | 288477.10 |
| 30°                                   | 38132.97 | 75103.80 | 110639.40 | 151367.92 | 189165.94 | 216261.62 | 250974.99 |
| 35°                                   | 49947.78 | 99515.80 | 148327.20 | 196010.90 | 242204.40 | 286556.40 | 328729.70 |
| 40°                                   | 52253.06 | 104108.8 | 155173.07 | 205057.56 | 253383.06 | 299782.08 | 343901.80 |
| 45°                                   | 45982.64 | 92656.12 | 131897.05 | 180450.16 | 220443.21 | 257889.92 | 292315.85 |
| 50°                                   | 57338.02 | 114240.10 | 170273.60 | 225012.60 | 278040.80 | 328955.10 | 377368.40 |
| 55°                                   | 58925.84 | 117403.67 | 174988.87 | 231243.72 | 285740.39 | 338064.60 | 387818.60 |
| 60°                                   | 51264.75 | 103314.64 | 148739.80 | 201181.41 | 245736.40 | 290735.04 | 341279.84 |
Figure 10. The evaluating and comparing the value of the rudder force at different rudder angles

Figure 11 illustrates the value $R$ of the rudder force at different periods and combinations ($n_i, \phi_i$). The results shown in Figure 11 determine the oscillating period of the rudder force which is compatible with the revolution of 150 rpm is $f \approx 2.5$ Hz. In a similar pattern, other combinations ($n_i, \phi_i$) also show the result of compatibility between the oscillating period of the rudder force and the propeller revolutions.

Figure 11. The rudder force at different periods when $n = 150$ rpm and $\phi = 5^\circ$

4. Conclusion
The results of a simulated calculation using the arithmetic method and the practical experiment prove the synchronous effect of free surface and the propeller rotation on the distribution of vapor phase
(pulsating air bubbles phenomenon) in the room around rudder (mostly appears on the surface of the rudder that is the same side as the propeller rotation).
Calculating the rudder force affecting rudder with 3 methods (particular data of M/V TAN CANG FOUNDATION is used for this calculation).
Figuring out the impact of free surface and the propeller rotation on the value of the rudder force, as mentioned below:

(1). Amplitude is 12.5% lower (on average) in comparison with the published experimental formula and 13.3% lower (on average) in comparison to the simulated calculation using the arithmetic method;
(2). Proving the oscillating period of the rudder force when the local cavitation at the leading edge of the rudder has not yet appeared is compatible with the propeller revolutions.

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