Analysis of Estimation Methods for Submarine Towing Resistance

Shancheng Li, Guanghui Zeng*, Guangda Wang
Naval Submarine Academy, Qingdao, Shandong, 266000, China

***Abstract*—In order to estimate the drag of submarine towing effectively, based on the analysis of the drag components of submarine towing, the friction resistance and residual resistance of submarine towing are estimated according to the empirical formula of towing surface ship resistance. Subsequently, CFD is used to simulate the towing resistance of submarine on water surface. The CFD simulation results are compared with those estimated by empirical formula. It is shown that the friction resistance of submarine Towing on the surface can be calculated by "Towing Guide at Sea" and "Towing" empirical formula, and the residual resistance can be estimated by the "Towing" formula or Shen Pugen's formula. However, a head shape coefficient of approximately 1.5 is found to be more suitable for the residual resistance estimation formula of a towed submarine.**

Keywords*—Submarine; towing resistance; CFD simulation; empirical formulas; maritime rescue

I. Introduction

When a submarine loses power at sea, maritime rescue forces must tow it back to port using tugboats to maintain operational readiness. Accurately estimating towing resistance is crucial for optimizing towing efficiency and managing risks. Determining the resistance caused by submarine towing provides a reference for formulating towing operation plans and rapidly estimating towing resistance.

Currently, there is extensive research on the towing resistance of ships. To assess the accuracy, some scholars use towing tanks, wind tunnel test methods [1-4], fluid mechanics (CFD) software [4-7] to calculate towing resistance. Although these methods yield high calculation accuracy, they are complex in terms of modeling and require significant manpower and material resources, making them economically unfeasible. Consequently, to reduce towing costs and simplify the calculation process, researchers often use empirical formulas for conservative estimation [8-9] to calculate the towing resistance. Overall, estimating drag resistance through empirical formulas can be time-efficient; however, the accuracy may be limited.

The estimation method of towing resistance put forward in the guidance document "Guide to Towing at Sea" of China Classification Society has played a positive role in ensuring the safety of towing at sea [10]. However, Shen Pugen of Shanghai Salvage Bureau estimated and verified the towing resistance of different kinds of towed objects under various sea conditions in long-term practice, and found that the "estimation method of towing resistance at sea" proposed in the Guide to Towing at Sea has certain limitations. This method does not take into account the influence of different factors on the resistance of towed objects. For example, when the towed object has been suspended in the port for a long time, the marine organisms will growing on the underwater hull, and the pollution bottom is serious, the friction resistance of the towed object will obviously increase; The bow shape of the square barge of an engineering ship is different from that of a normal streamlined ship, and the eddy current resistance and wave-making resistance (which collectively called residual resistance) generated by it will increase exponentially, which need to be considered in the estimation of towing resistance [11-12].TOWING of the UK also pointed out that towing offshore platforms needs to consider the influence of dirty bottom [13], which can increase towing resistance. Therefore, when selecting empirical formulas, it is essential to adjust the coefficients of these formulas based on the varying conditions of the object.

To verify the accuracy of empirical formulas, many scholars use CFD or experimental methods to verify the empirical formulas. Chen et al. [14] demonstrated that the CCS formula is effective in estimating towing resistance by comparing it with STAR-CCM for the towing resistance of semi-submersible floating offshore wind turbine force in still water. An et al. [15] calculated the towing resistance of an offshore platform using CFD/AQWA, and found that the CCS formula closely aligned with the hydrodynamic algorithm. Based on a numerical model developed by MOSES, Ding et al. [16-17] accurately calculated the dynamic response and towing resistance of the offshore anemometer tower during wet towing. The calculated results were then compared with those obtained from the "Guidelines for Drag Resistance at Sea" (CCS, 2012), revealing a close correlation between the two sets of results. This indicates that numerical simulation can effectively validate the empirical formula and assess its rationality.

However, despite numerous studies, there is limited research on estimating the drag resistance of submarines. It remains to be discussed whether the formulas used for towing ships on the water's surface can be applied to submarines operating in similar conditions. Unlike existing research, this article applies empirical formulas for the towing resistance of surface vessels (such as the "Guidelines for Sea Towing" and the Shen Pugen formula) to submarine towing scenarios for the first time, verifying their applicability through CFD simulations. Additionally, a recommendation is made to optimize the bow shape coefficient (0.15-0.2) for the streamlined bow characteristics of submarines has been proposed, filling the research gap in current submarine drag resistance estimation methods. The structure of this article is as follows: Section II (Methods and Models) elaborates in detail for the estimation methods of frictional resistance and residual resistance of submarine towing resistance, and introduces the CFD simulation model settings. Section III (Results and Analysis) compares various empirical formulas with CFD simulation results, discusses sources of error, and offers optimization suggestions. Section IV (Conclusion) summarizes the key findings and proposes correction coefficients applicable to the estimation of submarine drag resistance.

II. Methods and Model

Submarines typically float on the water surface while being towed, and their towing resistance primarily consists of tugboat resistance, submarine resistance, and streamer resistance. Since the towing occurs at the surface, the drag experienced by the tugboat and towing cable is similar to that of surface ships. Therefore, this paper will not address these aspects.

This paper mainly studies submarine resistance. When a submarine is towed on the water surface, its resistance consists mainly of water resistance and air resistance. Water resistance can be further categorized into rough-sea resistance and still water resistance [18]. Due to the low speed during towing and the limited portion of the submarine exposed to the water, hydrostatic resistance is the predominant factor, which is also the focus of this paper. Hydrostatic resistance can be subdivided into friction resistance and residual resistance, both of which are closely related to the type of submarine and the towing speed, and they represent the main components of submarine resistance. This paper specifically investigates the estimation of friction resistance and residual resistance. Air resistance and rough-sea resistance for submarines can be estimated by referencing the towing resistance of surface ships. The empirical formula used is commonly utilized to calculate the towing resistance of surface vessels.

A. Estimate Methods

1) Friction resistance estimation: The formula for calculating the friction resistance of submarine towing on the water surface can be derived from the guidance document provided by the China Classification Society, "Guidelines for Towage at Sea".

$$F_f = 1.67 A_1 v^{1.83} \times 10^{-3} \tag{1}$$

Among them: F_f is the frictional resistance, KN; A_1 is the wet surface area under water, m^2; v is the towing speed, m/s.

The formula considers the influence of wet surface area and speed on towing resistance, but does not consider the influence of wet surface area roughness of towed objects.

By comparison, the book "Towing" published by OPL Press in the UK provides an estimation formula for towing resistance of offshore platforms, which includes a fouling coefficient [13].

$$F_f = 3.522 F_1 A_1 v^2 \times 10^{-3} \tag{2}$$

Among them: F_f is the frictional resistance, KN; F_1 is the fouling coefficient of the towed object, as shown in Table I; A_1 is the wet surface area of the towed object, m^2; v is the towing speed, m/s.

The formula introduces the fouling coefficient of the towed object, which can well reflect the influence of wet surface roughness on friction resistance.

Shen Pugen noted that "Guidelines for Towage at Sea" is suitable for estimating towing friction resistance when the surface area is clean and the speed lower than 6kn. If there is a fouling, the Towing formula is more applicable. Shen Pugen also made modifications to formula in the "Guidelines for Towage at Sea", adding a fouling coefficient to consider the impact of surface roughness of objects.

$$F_f = 1.3566 \times A_1 \times F_1 \times V^2 \times 10^{-4} \tag{3}$$

Among them: F_f is the frictional resistance, KN; A_1 is the wet surface area under water, m^2; F_1 is the growth coefficient of marine organisms on the wet surface of the towed object, and the value of F_1 is the same as that in Table I.

TABLE I VALUE OF THE FOULING COEFFICIENT

Marine life on wet surface of towed objects	F_1
The surface is clean and free of attachments	0.3
The surface is clean , with adhesive material	0.4
There are slight marine organisms on the surface	0.5
Minor marine organisms /small shellfish attachments	0.6
Minor marine/shellfish attachments	0.7
Moderate amount of marine life/shellfish attachments	0.8
A large number of marine life/shellfish attachments/obvious convex surface	0.9

2) Residual resistance estimation: The "Guidelines for Towage at Sea" of China Classification Society provides the fundamental formula for calculating residual resistance when towing an object on the water surface. This formula accounts for the weight of the towed object; however, it does not consider the impact of varying bow shapes on residual resistance.

$$F_B = 0.147 \delta A_2 V^{1.74+0.15V} \tag{4}$$

Among them: F_B is the residual resistance, KN; δ is the Square coefficient; A_2 is the Cross-sectional area of immersed part of towed object in ship, m^2; V is the towing speed, m/s.

The book "Towing" published by OPL Press in Britain provides a formula estimating the remaining drag of offshore platforms during towing, taking into account the influence of the bow shape of the towed object [5].

$$F_B = 0.62 \times F_2 \times A_2 \times V^2 \qquad (5)$$

Among them: F_B is the residual resistance, KN; F_2 is the Bow shape coefficient of towed object. The coefficient can be selected according to the different bow shape of the towed object. The value of F_2 is shown in Fig. 1. A_2 is the Cross-sectional area of immersed part of towed object in ship, m^2. V is the towing speed, m/s.

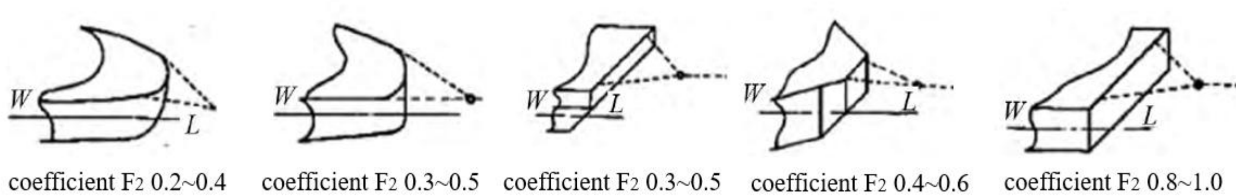

Fig. 1. The bow shape coefficient F2 of towed object.

Shen Pugen summarized the estimation of towing residual resistance and proposed a method for assessing towed residual resistance.

$$F_B = 1.3919 \times A_2 \times F_3 \times V^2 \times 1.2 \times 10^{-2} \qquad (6)$$

Among them: F_B is the residual resistance, KN; F_3 is the Bow shape coefficient of towed object. The value of F_2 is shown in Fig. 1. A_2 is the maximum cross-sectional area below waterline of towed object, m^2. V is the towing speed, m/s.

Compared to surface ships, submarines have a more streamlined design, and their bows are smoother. Therefore, the minimum bow coefficient selected is 0.2 in this case.

B. Calculation Models

The research object of this paper is the suboff model, which is a standard hull type of submarine provided by the American Defense Advanced Technology Research Agency for the related research of submarine. The main hull length L=4. 356 m, in which the forebody (inlet section) length L1=1. 016 m, the parallel middle hull length L2=2. 229 m, the postbody (outlet section) length L3=1. 111 m, and the maximum diameter 2R=0. 508 m. Fig. 2 is a schematic longitudinal section of the main hull of SUBOFF submarine.

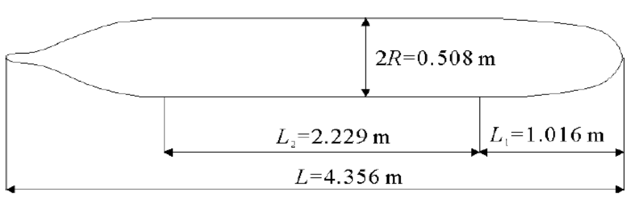

Fig. 2. Sectional view of the main hull of suboff submarine.

The square coefficient of the submarine is 0.4, and a draft of 5/6D is selected for estimation. At this time, the wet surface area below the waterline is 11 m^2, and the cross-sectional area of submarine immersed in water is 0.18 m^2.

In order to further analyze the rationality of various resistance formulas, the CFD is used to simulate the submarine resistance. The surface resistance of submarine will be simulated by Star-ccm in CFD software.

The calculation domain is set as illustrated in Fig. 3. The entrance is 3 times the length of the bow, while the exit is five times the length of the bow. The distance from the left and right sides of the pool wall is 2 times the length of the boat, the distance from the top to the hull is 1 time the length of the boat, and the distance from the bottom to the hull is 3 times the length of boat l.

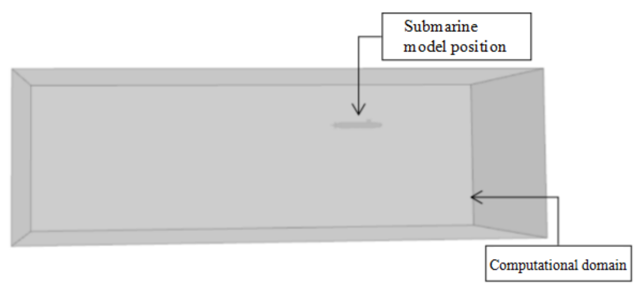

Fig. 3. Compute domain settings.

The VOF model of starccm software is utilized for calculations, with the grid generated by starccm. The mesh surrounding the submarine, the free liquid surface, the waves produced by the submarine, and the wake are encrypted [19]. The computational domain grid is illustrated in Fig. 4, with a total of 5.43 million grid cells.

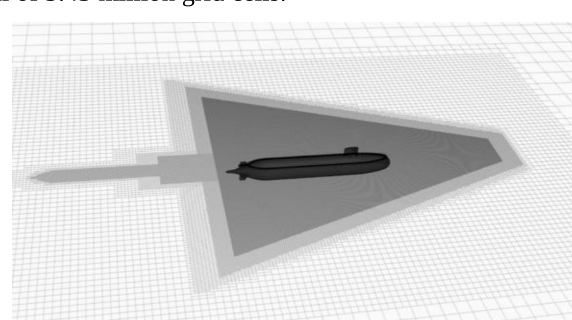

Fig. 4. Grid division.

The draft is 5/6 D of the submarine's diameter, and the SST k-ω model has been selected as the turbulence model. The inlet features a uniform inflow, while the outlet adopts pressure outlet. The two side walls of the basin and the upper surface of the basin are symmetrical boundary, and the bottom surface of the basin can be set as non-slip wall boundary.

III. Results and Analysis

A. Frictional Resistance

According to the "Guidelines for Towage at Sea", "Towing" and Shen Pugen estimation formula, three different calculation methods were used to estimate the friction resistance at different Towing speeds, and the results are shown in Table II.

TABLE II ESTIMATION RESULTS OF FRICTION RESISTANCE

Towing speed		Frictional resistance($\times 10^{-3}$)(KN)		
kn	m/s	Guidelines for Towage at Sea	Towing	Shen Pugen's estimation method
1	0.51	5.44	3.07	4.39
2	1.03	19.34	12.30	17.54
3	1.54	40.63	27.67	39.47
4	2.06	68.78	49.19	70.18
5	2.57	103.46	76.86	109.65
6	3.09	144.44	110.69	157.90
7	3.60	191.51	150.65	214.92
8	4.12	244.53	196.77	280.71
9	4.63	303.34	249.04	355.27
10	5.14	367.85	307.46	438.60

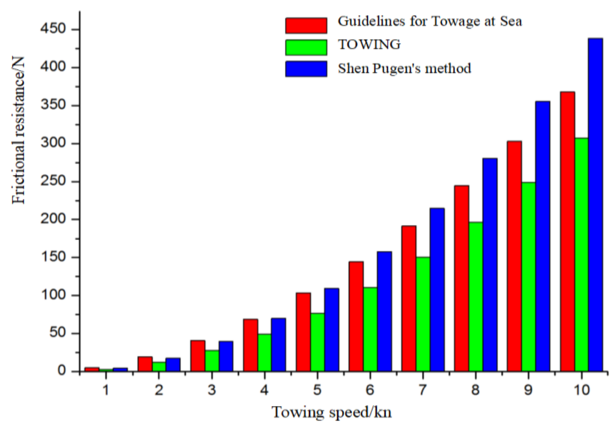

Fig. 5. Comparison of friction resistance estimation.

Based on the resistance estimation results presented above and in Fig. 5, it is evident that friction resistance increases with towing speed. The results obtained using Shen Pugen's method are comparable to those estimated by the Guidelines for Towage at Sea at low speeds. However, as speed increases, the estimated resistance values exceed those provided by the Guidelines for Towage at Sea. In contrast, the estimation results from the Towing formula consistently yield lower values.

B. Residual Resistance

The residual resistance estimated by different formulas is shown in Table III.

TABLE III ESTIMATION RESULTS OF RESIDUAL RESISTANCE

Towing speed		Residual resistance($\times 10^{-3}$)(KN)		
kn	m/s	Guidelines for Towage at Sea	Towing	Shen Pugen's estimation method
1.00	0.51	3.19	8.82	8.80
2.00	1.03	11.11	35.28	35.20
3.00	1.54	24.57	79.38	79.20
4.00	2.06	45.54	141.11	140.80
5.00	2.57	77.03	220.49	220.00
6.00	3.09	123.36	317.51	316.79
7.00	3.60	190.65	432.16	431.19
8.00	4.12	287.55	564.46	563.19
9.00	4.63	426.22	714.39	712.79
10.00	5.14	623.72	881.97	879.98

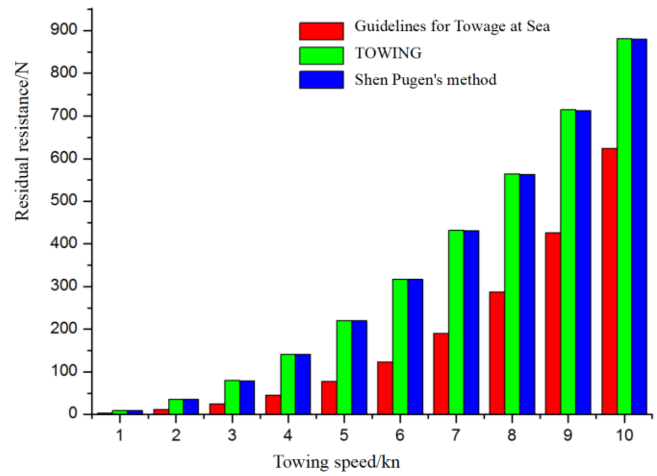

Fig. 6. Comparison of residual resistance estimation.

According to the resistance estimation data presented above and in Fig. 6, it is evident that the results from the "Towing" and Shen Pugen's estimation method are similar at different Towing speeds. This similarity arises because both formulas incorporate distinct coefficients to account for the influence of different factors on Towing resistance. While the primary distinction between the two formulas is the differing coefficients, the meanings and value ranges of the other parameters are quite similar, resulting in comparable estimates from both methods.

There is a big difference between the estimation results of "Guidelines for Towage at Sea" and the other two methods, especially at high speed. The reasons are that the bow shape of towed object is not considered in "Towing Guide at Sea", and the residual resistance will increase sharply with the increase of speed. However, differences in speed parameterization cause significant discrepancies between "Towing Guide at Sea" and the other two formulas. When the speed is high, this difference will be enlarged, resulting in an increase in the difference between the estimated values.

C. CFD Calculation Results

The results of friction resistance and residual resistance obtained by CFD simulation calculation are as follows in Table IV:

TABLE IV CFD SIMULATION RESULTS

Towing speed		Frictional resistance($\times10^{-3}$)(KN)	Residual resistance($\times10^{-3}$)(KN)
kn	kn		
2	1.03	19.00	15.40
4	2.06	64.41	88.40
6	3.09	154.41	213.40
8	4.12	255.00	272.19
10	5.14	416.19	596.71

The CFD simulation results are compared with the results of various formulas. The error calculation formula is set as: Error = (resistance value estimated by empirical formula-resistance value calculated by simulation)/resistance value estimated by empirical formula.

Table V presents a comparison of friction resistance. It can be seen that the calculation error of the estimation formula in the Guidelines for Towage at Sea is the smallest among the other three methods during the low speed stage. However, the error value of Shen Pugen's estimation method is smaller than the other three estimation methods. Additionally, the speed exceeds 4kn. The resistance value calculated by "Towing" formula is smaller than that obtained from the Shen Pugen formula, which is 1.3 times different from that calculated by Shen Pugen formula. In comparison, it is observed that the calculation error of this formula is greater than that of the Shen Pugen formula.

TABLE V CALCULATION ERROR OF FRICTION RESISTANCE

Towing speed		Guidelines for Towage at Sea	Towing	Shen Pugen's estimation method
kn	m/s			
2	1.03	1.78%	-54.49%	-8.30%
4	2.06	6.36%	-30.91%	8.23%
6	3.09	-6.90%	-39.49%	2.22%
8	4.12	-4.28%	-29.59%	9.16%
10	5.14	-13.14%	-35.37%	5.11%

Table VI presents a comparison of residual resistance. The results obtained using Shen Pugen's estimation method are very similar to those estimated by "Towing" formula, and the estimated results of the two empirical formulas are more than 30% larger than the simulation calculation results. Analysis reveals that both formulas introduce a shape coefficient for the bow of the towed object; as the bow shape of the towed object becomes more pronounced, the coefficient increases. In this study, the coefficient F2 = 0.2, which is the recommended minimum; however, the formula result is still too large. Therefore, for submarines, which have better bow streamline, its coefficient should be smaller. For the estimation results from the Guidelines for Towage at Sea, the estimation error is large at low speeds, but it gradually decreases as speed increases. This trend occurs because residual resistance is minimal at low speeds, while it sharply increases with higher speeds.

TABLE VI CALCULATION ERROR OF RESIDUAL RESISTANCE

Towing speed		Guidelines for Towage at Sea	Towing	Shen Pugen's estimation method
kn	m/s			
2	1.03	-38.58%	56.35%	56.25%
4	2.06	-94.11%	37.36%	37.21%
6	3.09	-72.99%	32.79%	32.64%
8	4.12	5.34%	51.78%	51.67%
10	5.14	4.33%	32.34%	32.19%

In order to analyze the influence of the shape coefficient of the towed object bow on the estimation of residual resistance, the estimation is conducted again using two coefficient values: 0.1 and 0.15. The errors between the estimated results and the CFD simulation results are presented in Table VII.

TABLE VII RESIDUAL DRAG ERROR OF DIFFERENT BOW SHAPE COEFFICIENTS

Towing speed		F2=0.1		F2=0.15	
kn	m/s	Towing	Shen Pugen's estimation method	Towing	Shen Pugen's estimation method
2	1.03	-30.96%	-31.25%	12.70%	12.50%
4	2.06	-87.93%	-88.36%	-15.29%	-15.57%
6	3.09	-101.63%	-102.09%	-24.42%	-24.72%
8	4.12	-44.66%	-44.99%	3.56%	3.34%
10	5.14	-102.97%	-103.42%	-25.31%	-25.62%

It can be seen that when the shape coefficient of the towed bow is 0.1, the estimated value is significantly too small, which does not conform to the actual situation. When 0.15 is taken, the estimated values can be within an acceptable error range, and the error is smaller compared to 0.2. Therefore, it is suggested that the bow shape coefficient should be between 0.15 and 0.2. Of course, the proposed range for the bow shape factor (0.15-0.2) is derived from the Suboff standard model, which represents a typical streamlined submarine and is applicable to the majority of submarines. For non-standard designs, such as submarines with spherical bows or irregular geometric shapes, the coefficients should be adjusted based on CFD simulations or experimental tests.

IV. CONCLUSION

Based on the analysis of towing resistance in submarines, this paper estimates towing resistance using various empirical formulas and then uses CFD to carry out numerical simulations. After comparison, the following conclusions can be drawn:

1) When estimating the friction resistance of submarine towing, we can use the Guide to Towing at Sea or Shen Pugen's method to estimate it.

2) It is necessary to consider the influence of bow shape coefficient when estimating the residual drag of submarine Towing, so it is suggested to use "Towing" or Shen Pugen method.

3) The bow shape of submarine is more streamlined, so it is suggested that the bow shape coefficient should be between 0.15 and 0.2.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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