Reanalysis of experimental data on towing resistance of a barge in a two-layer fluid

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1 INTRODUCTION

In a stratified ocean, the waves generated by a moving obstacle include surface waves and internal waves. The wave-generated resistance due to internal waves dominates the total drag resistance of the obstacle cruising slowly. This is the dead-water phenomenon which refers to the feeling of an added resistance when the ship sailing on a stratified ocean whereas the free surface is still. Gou et al. [1] carried a series experiments of a three-dimensional barge towing in a two-layer fluid with varying barge drafts. The towing resistance was measured in both homogeneous and a two-layer fluid. The trends of added resistance coefficient C_{add} versus Froude number Fr and $C_{\mathrm{add}}/(d/h_1)^2$ versus Fr are shown respectively. From the results, the conclusion can be drawn that the trends for draft d/h_1=0.5, 0.6 and 0.7 had a good agreement with the conclusion drawn by Grue [2]. That is $C_{\mathrm{add}}/(d/h_1)^2$ depending on the Froude number only in the range close to critical speed (Fr>0.85 in the present), irrespective of the draught. Obviously, $C_{\mathrm{add}}/(d/h_1)^2$ depends on Froude number and the barge drafts when Froude number is small.

In this work, motivated with the study of the drag force on an orographical obstacle in the homogeneous flow in Esler et al. [3], a new dimensionless scaling method is used to investigate the relation between the resistance coefficient and the barge draught. Additionally, the raw experimental data are processed more precisely. On the one hand, the convergence of the towing resistance raw data over time are checked and the data from relatively stable segments are selected; on the other hand, because each round of experiments will cause disturbance to the density stratification, the towing resistances for each round experiments are listed respectively replaced the direct averaging. After the reanalysis, the effect of the barge draft is relatively small over the whole scope of the towing speed.

2 EXPERIMENTAL SETUP AND DATA PROCESSING

2.1 Experimental Setup

The experimental setup will be briefly reviewed before the reanalysis of the experimental data. The tank is 12m long, 1.2m wide, and water depth during the tests remains to 0.6m. In this experiment the towing length is about 7m. The tank is equipped with a low speed towing system. The dimension of the barge model is 0.6m long (L), 0.45m wide (B), and 0.35m height. Two force sensors with the total maximum capacity of 3000gf were used to measure drag force, connected the barge to the towing system with an aluminum alloy column. The photo of the experimental setup is in Figure 1.

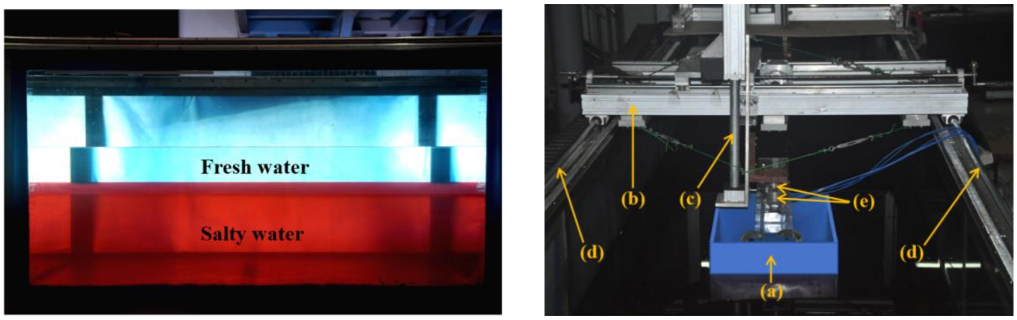

Figure 1: The photo of the two-layer fluid and the towing system: (a) the tested box model; (b) the towing carriage; (c) the positioning device; (d) the slideway; (e) the force sensors.

The depth in each layer is h_1=0.2m and h_2=0.4m. The initial density of two fluids is of ρ_1=997 kg/m^3 and ρ_2=1024 kg/m^3. The towing speed U is varied from 0.06m/s to 0.24m/s corresponding to Reynolds number UL/υ from 5000 to 20000. The barge drafts d are varied from 0.10 to 0.20m, and the draft to upper layer depth ration d/h_1 ranges from 0.5 to 1.0.

2.2 Data Processing

The data of force sensors were recorded during the towing process. A total towing process (shown in Figure 2) is composed of the impulsive accelerating part, the steady moving part and the impulsive decelerating part. In the previous analysis, the resistance values were obtained by averaging the data over the steady moving part. In this work, the steady part is divided into five equal sub-periods as shown in Figure 2. The mean value of the resistance in every sub-period is obtained. By comparing the results of the five segments, we find that results of the five segments are basically similar at low speeds, but not yet at relatively high speeds. The reason is the limitation of the length of the tank. Since the variation of towing resistance in the last two segments has been smaller than the initial segments, the average value of the last two segments is taken as the result of the towing resistance.

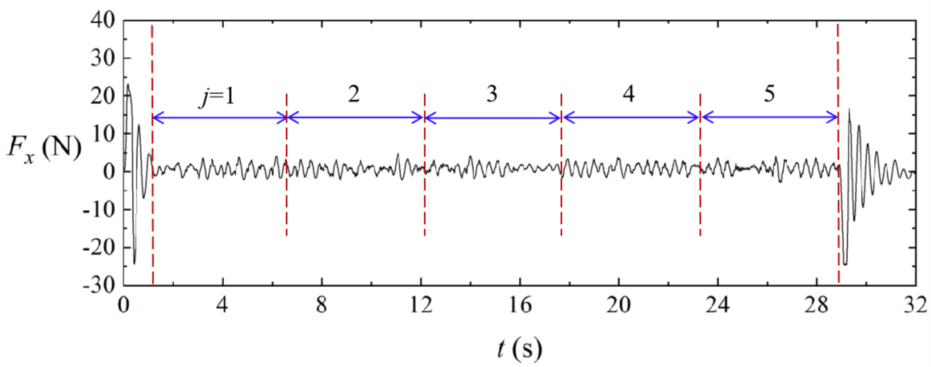

Figure 2: Time-series of resistance and five equal sub-periods (j=1~5) in the two-layer fluid of d=0.10 m, U=0.12 m/s.

For every barge draft, two rounds were performed in turn for the repetitive measurements. A ‘round’ here includes the experiments conducted for all the towing speeds. In the previous analysis, the resistance was obtained by the averaging of the two rounds results. However, the stratified conditions should be different between the two rounds because of the disturbance of the barge. With this consideration, the density data were recorded at rest before every round, and the result of each round will be analyzed individually.

3 RESULTS AND DISCUSSION

3.1 Dimensional Results

Figure 3 shows the measurements of the density $\rho(z)$ and the buoyancy frequency profiles $N(z)$ of two rounds of d=0.12m. A comparison of the two rounds shows that the thicker pycnocline corresponds to a lower peak value of buoyancy frequency profile. The buoyancy frequency profile $N(z)$ is:

$$N(z) = \sqrt{\frac{g}{\rho(z)}\frac{\partial\rho(z)}{\partial z}} \tag{1}$$

Figure 4 shows the dimensional resistance results versus the towing speed of d=0.12m in both the homogeneous (F_d) and two-layer fluid (F_s). Two rounds of the results in the two-layer fluid are plotted individually due to their different pycnocline thicknesses. The resistance in round 2 generally behaves smaller, and more visibly for the towing speed U=0.14m/s and 0.16m/s, where there is a local maximum of resistance F_s. This illustrates that the resistance due to internal wave-generated acting on the obstacle always decreases with the stronger mixture at the interface.

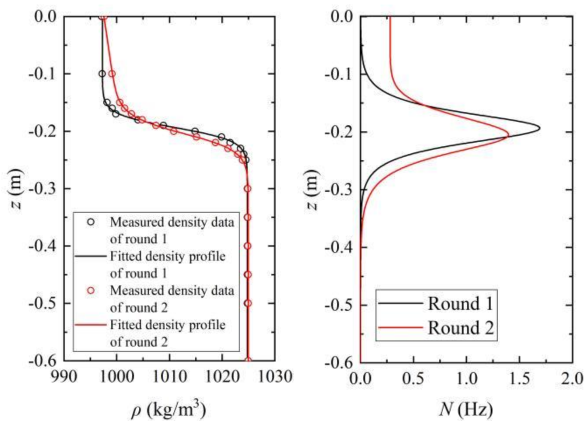

Figure 3: The density and the buoyancy frequency profile of two rounds of d=0.12 m

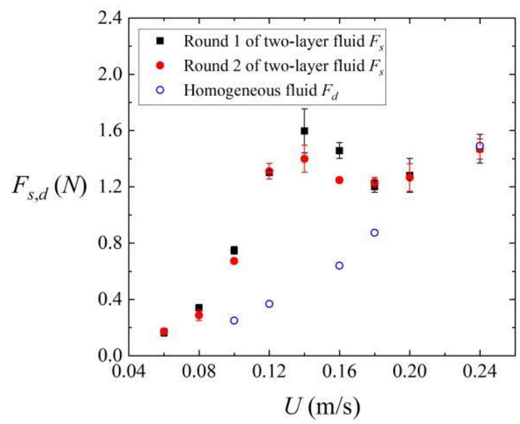

Figure 4: Resistance in the homogeneous fluid F_d and the two-layer fluid F_s versus the towing speed U of d=0.12 m

3.2 Dimensionless Results and Discussion

The trends of the internal wave-generated resistance coefficient ΔC_{sd} versus Froude number Fr are shown in Figure 5. $\Delta C_{sd} = C_s - C_d$, $C_{s,d} = F_{s,d}/0.5\rho SU^2$ are the resistance coefficient in a two-layer stratified fluid and homogeneous fluid, respectively. $Fr=U/c_0$ denotes the Froude number regarding the internal waves, with c_0 the phase velocity of linear long internal waves, defined as:

$$c_0^2 = \frac{g(\rho_2-\rho_1)h_1h_2}{\rho_2h_1+\rho_1h_2} \tag{1}$$

A new dimensionless scaling method was introduced in Esler *et al*. (2007), by studying the drag force on a topographical obstacle in the homogeneous flow. In their study, the drag force was expressed as $F_d=D\cdot\rho gh^2L$. In this expression, ρ is the fluid density; h is the fluid depth; L is the radial scale of the obstacle, and D is a dimensionless drag coefficient. The coefficient $D/(d/h)^{5/3}$ was found to only depend on a transcritical similarity parameter $\Gamma=(Fr-1)/(d/h)^{2/3}$, for the specific conditions, irrespective of the obstacle height d. This led to a new scaling method $D/(d/h)^{5/3}$ versus Γ, which showed a regular relationship between the drag force and its influencing parameters of the flow speed and the obstacle height. It should be noted, this relationship only applies under the relatively small obstacle height d. Motivated with the research of Esler *et al*. (2007), in our study, the internal wave-generated resistance has been scaled by the similar dimensionless method $D/(d/h_1)^{5/3}$ versus Γ, where $D=(F_s\text{-}F_d)/(\rho_1 g h_1^2 L)$ and $\Gamma=(Fr\text{-}1)/(d/h_1)^{2/3}$ with d the barge draught and L the barge length.

Figure 6 shows the new scaling results of the three shallow drafts in round 1 measurements. Compared with Figure 5, under this new scaling method, the results show that the discrepancy among the different draft is small, especially for low-speed situations. With the increase of towing speed, the results of different drafts have some differences. The scaling method derived in open areas with a homogeneous fluid is not rigorous when applied directly to flume tests with two-layer fluid, and the derivation is needed to obtain a more suitable scaling method, which will be the subject of future work.

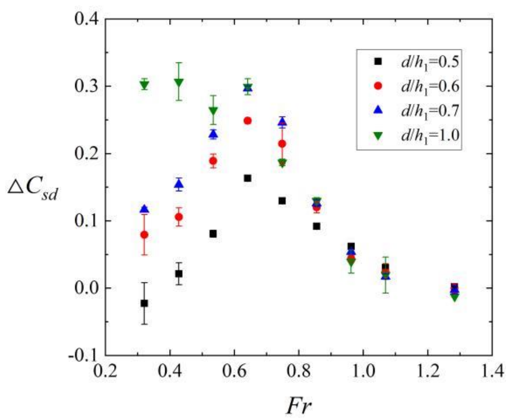

Figure 5: Coefficient of the internal wave-generated resistance ΔC_{sd} versus Fr (of the round 1 measurements).

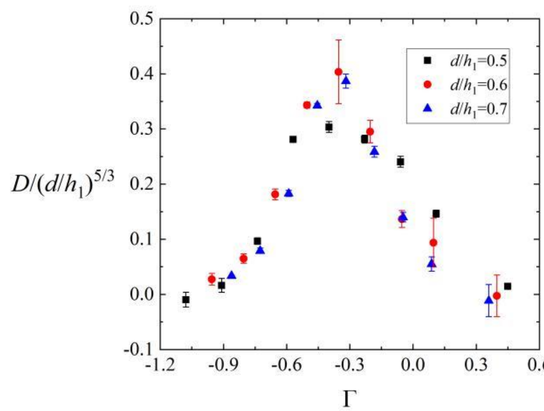

Figure 6: A new scaling method $D/(d/h_1)^{5/3}$ versus Γ (of the round 1 measurements), where $D=(F_s\text{-}F_d)/(\rho_1 g h_1^2 L)$ and $\Gamma=(Fr\text{-}1)/(d/h_1)^{2/3}$.

4 CONCLUSION

A new scaling method $D/(d/h_1)^{5/3}$ versus Γ is extended from the drag force in the homogeneous flow into that in the two-layer fluid. By the reanalysis of the experimental data on towing resistance of a barge in a two-layer fluid, the scaling results is independent on the barge draft especially for low-speed situations. That means the scaling method is also suitable for the internal wave-generated resistance. In the future, the scaling method will be derived rigorously to investigate the relationships between the internal wave-generated resistance and the parameters.

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