Experiment study on the towing resistance of a barge in a two-layer fluid

Ying Gou*, Wenbiao Xu, Xinwei Zhang, Bin Teng

State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China
gouying@dlut.edu.cn

HIGHLIGHTS

- Three-dimensional towing experiments of a barge in still two-layer fluid are carried out.
- Added resistance in a two-layer fluid is obtained by subtracting the resistance in homogeneous fluid. The effects of towing speed, barge draft and interface position on added resistance are investigated.

1 INTRODUCTION

The drag resistance is generally attributed to three parts: skin friction resistance, form drag and wave-making resistance. If the towing speed is low the wave-making resistance is very small and can be ignored in uniform fluid. However, in a stratified ocean, the wave-making resistance is not only due to the surface wave but also the generation of internal waves. This is the dead-water phenomenon which refers to the feeling of an added resistance when the ship sailing on a two-layer fluid whereas the free surface is still.

The earlier study of dead-water phenomenon in detail was made by Ekman (1904). Then the internal wave-making resistance and corresponding boat dynamics were concerned by many researchers. Mercier et al. (2011) carried out a two-dimension experiments, in which the boat model was driven by a constant force and the acceleration can be obtained. In their studies the Ekam's experiments were revisited first and more general situations of stratified fluid were considered. Grue (2015) investigated the dead water resistance of a ship by nonlinear numerical model. The ship dimensions were corresponding to those of Polar ship Fram. In his study, the effect of draught and Froude number on resistance coefficient were investigated. Besides the drag force, the interfacial wave field was also shown. The results had a good agreement with laboratory measurements made by Lacaze et al. (2013). Besides the dead-water phenomenon on ship, the resistance on ice floe in stratified fluid is also a main research point. Ptte et al. (1995) carried a series of experiments of two-dimensional ice keel models with varying degrees of slenderness to measure the drag force. Waters and Bruno (1995) also investigated the drag force on four ice floes. In their study, instead of ice keel, each ice floe had square-shaped plan form but with different under-ice topographies.

The purpose of the paper is to investigate the drag force on a barge in a two-layer fluid by three-dimensional experiments. Series of experiments are carried out to examine the dependence of the additional drag on parameters such as towing speed, barge draft and interface position. Unlike the referred researches in which the lower layer depths is much higher than the upper layer depths, the upper and lower layer depths ration is 1:2 and 1:1 in this study. These parameters are therefore varied to achieve information on the corresponding trends. Both non-stratified and stratified tests were performed.

2 EXPERIMENT SET UP

The tests were conducted in PLA University of Science and Technology's tank facility in both non-stratified and stratified fluid. 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 highest velocity of towing carriage is up to 0.1m/s with a 0.001m/s resolution. The dimension of the barge model is 0.6m long (L), 0.45m wide (B), and 0.35m height. It was constructed of polystyrene. 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 experiment set up is in Figure 1. The data of force sensors were recorded during the towing process. The resistance values were obtained by averaging the data over the steady stage with stable towing speed.

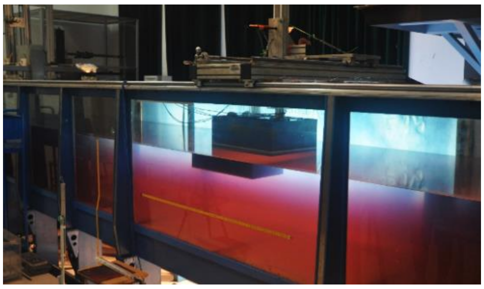

Fig. 1 Experiment set up

Table 1 Experiment parameters

Interfacial position	Barge draft (m)	Towing speed (m/s)
h_1=0.2m h_2=0.4m	0.10	0.06; 0.08; 0.10; 0.12; 0.14; 0.16; 0.18; 0.20; 0.24
	0.12	
	0.14	
	0.20	
	0.24	
h_1=0.3m h_2=0.3m	0.20	
	0.22	
	0.24	

For the two-layer stratified experiments, the fresh water with depth h_1 and density ρ_1=0.997g/cm^3 is layered above the colored saline water with depth h_2 and density ρ_2=1.024g/cm^3. Nineteen electrical conductivity probes with 0.1mV resolution are mounted to measure the electrical conductivity of the stratified water and thus salinity through the water column. The vertical distance between two probes is 5cm and down to 1cm in the vicinity of interface.

The towing speed U is varied from 0.06m/s to 0.24m/s corresponding to Reynolds number UL/υ from 5000 to 20000. Two interface positions are considered, h_1:h_2=1:2 and h_1:h_2=1:1 with a constant total water depth h=0.6m. For the former interface position case the barge drafts d are varied from 0.10 to 0.20m, and the draft to upper layer depth ration d/h_1 ranged from 0.5 to 1.0. In addition, the draft 0.24 are also performed. For the case h_1:h_2=1:1, the barge drafts are 0.20, 0.22 and 0.24, d/h_1 ranged from 0.67 to 0.80. The experiment parameters in two-layer fluid are listed in Tab.1

3 RESULTS AND DISCUSSION

The tests were performed in non-stratified fluid first in order to compare with the resistance in two-layer fluid. Fig. 2 shows the resistance F_d in homogeneous fluid with draft d=0.1m. The observation of the results is that the resistance is directly proportional to the square of the towing speed. That means the drag resistance coefficient $C_d=F_d/0.5\rho S u^2$ is a constant and little dependence on Reynolds number. The other cases with different drafts have the same trends. The similar conclusion was also obtained by Waters et al. (1993). In their report, residual resistance coefficient versus Reynolds number was shown. The residual resistance coefficient obtained by subtracting the friction resistance coefficient from the total resistance coefficient. The friction resistance coefficient obtained by flat plat test is very small, so the residual resistance is the main part of the total resistance.

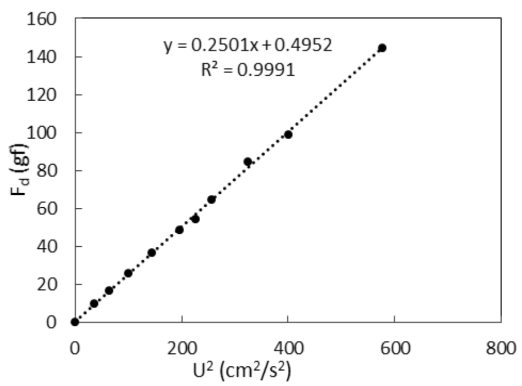

Fig. 2 Towing resistance in homogeneous fluid with draft *d*=0.1m

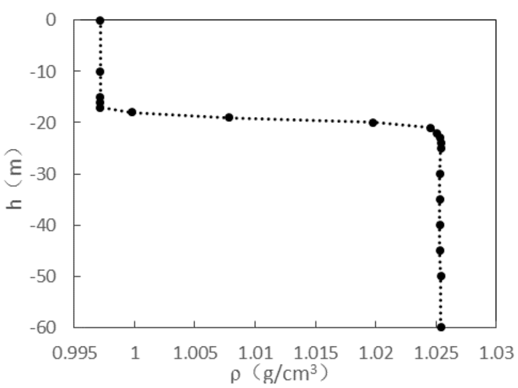

Fig. 3 Density profile before towing tests for two-layer fluid with h_1=0.2m and h_2=0.4m

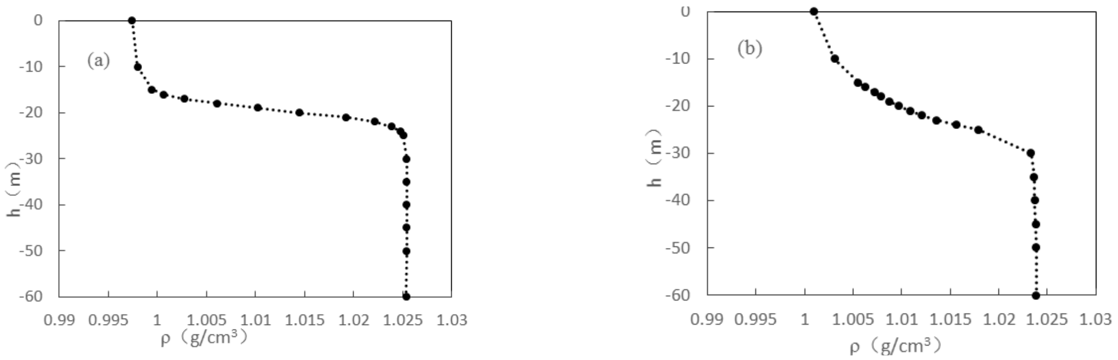

Fig. 4 Density profile after a series of experiments with barge drfat d=0.1m (a) and d=0.2m (b)

Fig. 3 shows the density profile before the tests with about a few centimeters of pycnocline. Through the process of experiments, diffusion and mixing are unavoidable. Fig. 4 shows the density profile after a series of tests with barge draft d=0.1m and 0.2m, respectively with the thicker of pycnocline. It is easy to understand that the light disturbance (a) led to smaller mixing than that in (b).

Fig. 5 plots drag resistance as function of towing speed both in homogeneous and stratified fluid with draft d=0.1m (a) and d=0.2m (b). The drag resistance increases approximate linearly with the towing speed in stratified fluid. The trend is different with the typical evolution of the drag versus speed obtained by Ekman (1904). In his figure, there is a local maximum of the drag resistance for the stratified case. Besides the difference of stratified conditions, the most important reason should be the discrepancy of model geometry, which led to the discrepancy of form drag and the internal wave making. Obviously, the added resistance F_{add}, obtained by subtracting the non-stratified results F_s from the stratified test results F_d, attains its maximum. That means the internal wave effect diminished at both low and high speed. It is in agreement with that from other studies. From the comparison between Fig. 5(a) and (b), it can be seen that the larger of the barge draft is, the stronger the drag gets.

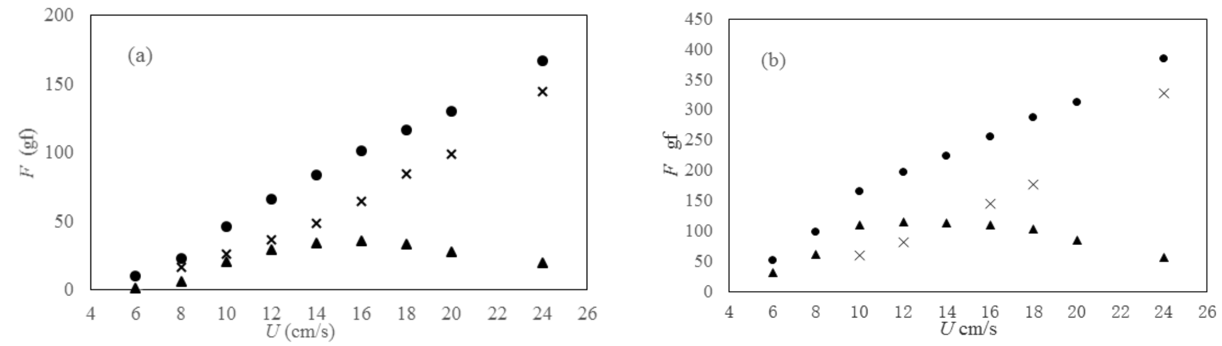

Fig. 5 Drag resistance with draft d=0.1m (a) and d=0.2m (b) vs. towing speed. F_s in two-layer fluid with h_1=0.2m and h_2=0.4m (•), F_d in non-stratified fluid (×) and the added resistance F_{add}=F_d-F_s (▲).

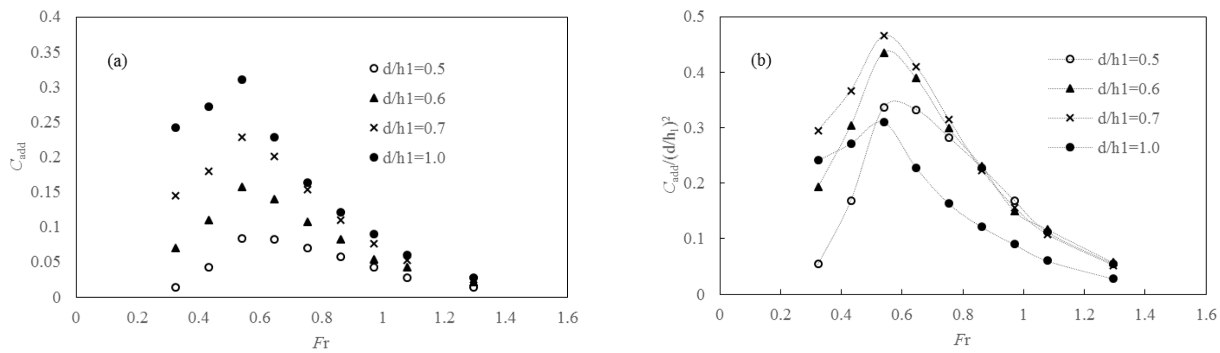

Fig. 6 Added resistance coefficient C_{add} vs. Fr (a) and $C_{add}/(d/h_1)^2$ vs. Fr (b), with h_1=0.2m and h_2=0.4m

In order to present the data for further interpretation, the trends of added resistance coefficient C_{add} versus Froude number Fr are shown in Fig. 6(a). The drag resistance coefficient in a two-layer stratified fluid is also can be defined by $C_s=F_s/0.5\rho SU^2$, as well as that defined in non-stratified fluid. So the added resistance coefficient can be obtained by $C_{add}= C_s-C_d$. The non-dimensional velocity Fr is defined by U/c, where c is the maximum wave speed (Gill, 1982), defined as

$$c^2 = \frac{g(\rho_2-\rho_1)}{\rho_2}\frac{h_1 h_2}{h_1+h_2}$$

$C_{add}/(d/\mathrm{h}_1)^2$ versus Fr is also plotted in Fig.6(b) based on the numerical conclusion drawn by Grue (2015). In his study, $C_{add}/(d/\mathrm{h}_1)^2$ depends on the Fr only in the range close to critical speed, irrespective of the ship draught. Fig. 6 gathers four drafts with h_1=0.2m and h_2=0.4m. In addition, the draft d=0.24m are also performed, but because of the heavy disturbance the result is not shown here. According to the results from other studies on dead-water phenomenon of boat, the added resistance coefficient value should reach the maximum when the Fr is slightly smaller than the critical Froude number. But the corresponding Froude number in the present shown in Fig. 6(a) is only 0.5~0.6, much smaller than the critical Froude number. Moreover, we can find that the added resistance coefficient reached its maximum at almost identical Froude number, irrespective of the barge draught. In Fig. 6(b), the trends for draft d/h_1=0.5, 0.6 and 0.7 had a good agreement with the conclusion drawn by Grue (2015). That is $C_{add}/(d/\mathrm{h}_1)^2$ depends on the Froude number only in the range close to critical speed (Fr>0.85 in the present), irrespective of the draught. But the conclusion is not apply for draft d/h_1=1.0. There are should be many reasons led to the difference, for example the discrepancy of the model configuration we had mentioned above. In addition, the numerical study is under strictly two-layer stratified conditions in the open sea. But in the experiment, the pycnocline and the mixing are unavoidable, especially for the heavy disturbance case draught d/h_1=1.0, seen in Fig. 4(b). Especially, the generated wave seemed to attach to the barge with the deeper draft cases. In order to investigated the effect of interface position, the tests are also performed for $h_1= h_2$=0.3m with draft d=0.20m, 0.22m and 0.24m. Because of the limitation of space, the results are not shown here. The trends of C_{add} versus Fr are similar with that in h_1=0.2m condition. Especially, the trend of $C_{add}/(d/h_1)^2$ for the three draughts has a good agreement with the conclusion drawn by Gure (2015) mentioned above.

4 CONCLUSIONS

Three-dimensional experiments are carried out to investigate the drag resistance on a barge model in a two-layer fluid. Comparing with the dead-water phenomenon of boat, some different characteristics of the drag resistance on barge configuration are obtained. The added resistance coefficient reaches its maximum when the Fr in the range 0.5~0.6, much smaller than the critical Froude number. For relative small draughts, $C_{add}/(d/h_1)^2$ depends on the Froude number only in the range close to critical speed (Fr>0.85), irrespective of the draught. But this conclusion is not applied for the case d/h_1=1.0. An extended study should be continued for deeper draught cases.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation of China with Grant No. 51490672 and 51479026.

REFERENCES

Ekman, V. W., 1904. On dead water, Norw.N. Polar Exped. 1893-1896: Sci. Results, XV, Christiana, Ph.D. thesis.

Gill, A. E., 1982. Atmosphere-ocean dynamics: Academic Press (London), pp. 128.

Grue J, 2015. Nonlinear dead water resistance at subcritical speed. Physics of Fluids, 27, 337-355

Lacaze L. et al., 2013. Wave patterns generated by an axisymmetric obstacle in a two-layer flow. Experiments in Fluids, 54, 1-10

Mercier M. J., Vasseur R., and Dauxois T., 2011. Resurrecting dead-water phenomenon. Nonlinear Processes in Geophysics, 18, 193-208.

Pite H. D., Topham D. R. and Hardenberg B. J., 1995. Laboratory measurements of the drag force on a family of two-dimensional ice keel models in a two-layer flow. Journal of Physical Oceanography, 25, 3008-3031

Waters J. K., Bruno M.S., 1995. Internal wave generation by ice floes moving in stratified water: Results from a laboratory study. Journal of Geophysical Research, 100, 13635-13639.

Waters J. K. et al., 1993. A laboratory investigation of sea ice dynamics in a stratified waterbody. Technical report. SIT-DL-93-9-2695