

A New Method for Accurate Prediction of Ship's Inertial Stopping Distance

^{1,2}Langxiong Gan, ²Liangming Li, ^{2,3}Yuangzhou Zheng and ⁴Baogang Zhang

¹School of Naval Architecture, Ocean and Civil Engineering,
Shanghai Jiao Tong University, Shanghai 200240, China

²School of Navigation,

³School of Transportation, Wuhan University of Technology, Wuhan 430063, China

⁴Shanghai Maritime Safety Administration, Shanghai 200086, China

Abstract: This study aims to research the prediction of ship's inertial stopping distance. Accurate prediction of a ship's inertial stopping distance helps the duty officers to make the collision avoidance decisions effectively. In this study ship's inertial stopping distance is calculated using the ALE (Arbitrary Lagrangian Eulerian) algorithm implemented in the FLUENT code. Firstly, a method for predicting the inertial stopping distance of a floating body based on the FLUENT code is established. Then, the results calculated by the method are compared with those obtained from the empirical formulae and the physical model tests. The comparison result indicates that the proposed method is robust and can be used effectively to predict the ship's inertial stopping distance.

Keywords: ALE algorithm, fluent implementation, inertial stopping distance, topley model

INTRODUCTION

The quantitative calculation of a ship's inertial stopping distance plays a very important role in the ship engineering field. Especially for the restricted areas such as bridge water area, the reversing stopping distance of a ship needs to be predicted accurately by quantitative calculation of the motions of a ship. The stopping and reversing stopping distance can be calculated by many different methods currently. Empirical equations are adopted by Ship's Handling. However, these theory equations do not consider the practice deeply in the calculation. Hence, the calculation result to some degree is inaccurate. More sophisticated methods is needed to handle this issue (Hirt *et al.*, 1974; Jing, 1984; Wu, 1988; Chen, 2008; Liang *et al.*, 2011; Barrasa *et al.*, 2012).

In order to provide precise prediction performance of ship's inertial stopping distance, this study introduces an ALE (Arbitrary Lagrangian Eulerian) algorithm to improve the prediction accuracy. The prediction result is compared with the physical model tests and related empirical equations to show high effectiveness of the proposed method in the prediction the ship's inertial stopping distance.

EMPIRICAL FORMULA METHOD

The empirical formula presented by Captain Topley is as follows Wu (1988):

Table 1: Time halved constant of ship's speed

Tonnage	C (min)	Tonnage	C (min)	Tonnage	C (min)
1000	1	36000	8	120000	15
3000	3	45000	9	136000	16
6000	3	55000	10	152000	17
10000	4	66000	11	171000	18
15000	5	78000	12	190000	19
21000	6	91000	13	210000	20
28000	7	10500	14		

$$S_j = \left[v_1 t + \frac{C(v_0 - v_1)}{0.693} (1 - 2^{-t/C}) \right] \quad (1)$$

where,

S_j = The inertial stopping distance

v_1 = The ship's speed of stopping engine or dropping anchor

v_0 = The ship's initial speed of stopping

t = The elapsed time used for ship's stopping

C = The time halved constant of ship's speed and can be calculated according to Table 1: The elapsed time refers to the time from the start of braking to the vanishing of inertia, which can be calculated by:

$$v_1 = v_0 \cdot e^{-t/T_s} \quad (2)$$

where,

v_1 = The ship's speed at any time during the stopping period

T_{st} = The time halved constant of ship's speed $T_{st} = C/\ln 2$

A BRIEF INTRODUCTION OF ALE ALGORITHM

The ALE (Arbitrary Lagrangian Eulerian) method was first presented by Hirt *et al.* (1974). As for the calculation of fluid mechanics, it was used to study the problem of numerical simulation of incompressible viscous fluid and flow of free surface. The ALE method has advantage in dealing with the changeable computational domain, like the deformation and movement of the computational domain caused by the movement of walls, as well as the problem of free surface and the solidification in the casting process, etc.

The governing equation of ALE method:

The mass conservation equation: As for the volume element, the law of conservation of mass can be described as that the increasing rate of fluid mass contained in the element equals to the fluid mass inflowing through the surface of the element per unit of time. The mathematical expression of this law is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \quad (3)$$

where,
 v = The velocity vector
 ρ = The fluid density

If the discretized grids of the computational domain move at the speed of $v'_b = v_b$ (x, y, z, t), the corresponding mass conservation equations is:

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot v_b + \nabla \cdot [\rho(v - v_b)] = 0 \quad (4)$$

where, $\nabla \cdot (\rho v_b)$ is caused by the movement of grids. If $v_b = 0$, the equation becomes equation of continuity described by the Eulerian method. If the grids move at the same speed as the fluid, namely v , the equation becomes equation of continuity described by the Lagrangian method.

The momentum conservation equation: As for the fluid element, the momentum conservation equation can be described as that the force a fluid element subjected to equals to the element's mass multiplied by its acceleration. The corresponding non-conservative form of the momentum conservation equation is:

$$\rho \frac{Dv}{Dt} = \nabla \times \sigma'' + \rho f \quad (5)$$

Combined with Eq. (3), Eq. (5) becomes:

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho v) = \nabla \cdot \sigma'' + \rho f \quad (6)$$

where,
 σ'' : Stress tensor (surface force)
 f : Body force

If the discretized grids of the computational domain move at the speed of $v'_b = v_b$ (x, y, z, t), the corresponding momentum conservation equations is:

$$\frac{\partial (\rho v)}{\partial t} + \rho v \nabla \cdot v_b + \nabla \cdot [\rho(v - v_b)v] = \nabla \cdot \sigma'' + \rho f \quad (7)$$

After moving the items concerning v_b in Eq. (4) and (7) to the right side of the equations and describing the equations under the Cartesian coordinate system, the continuity equation becomes:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho, v) = S_c \quad (8)$$

where, S_c is the source item when taking the movement of the grids into account, $S_c = \rho \nabla \cdot v_b - \nabla \cdot (\rho v_b)$. For the incompressible fluid, $S_c = 0$.

The momentum is:

$$\frac{\partial (\rho v_i)}{\partial t} + \nabla \cdot (\rho v_i v) = (\nabla \cdot \sigma'')_i + \rho f_i + S_i \quad (9)$$

where, S_i is the source item of the i^{th} direction concerning the movement of grids under the Cartesian coordinate system, where:

$$S_i = -\rho v_i \nabla \cdot v_b + \nabla \cdot (\rho v_i v_b) = \nabla \cdot (\rho v_i) v_b \quad (10)$$

In the Fluent code, it's allowed to define source item and the UDF function defined by macro DEFINE_SOURCE is called by activating the three source items of the momentum equation. The gradient $\nabla (\rho, v_i)$ in the function can be obtained by the macro C_U_G (c, t).

Algorithm based on FLUENT: Due to the movement of floating body, the size of the computational Euler domain is larger in the direction of the velocity, which is 10 to 20 times the length of ships with large block coefficient. Concerning that only a small part of the computational domain around the hull moves with the ship, it is advisable to predict the inertial stopping

distance by using a small computational domain. The algorithm can be described as follows:

- Calculate the ambient flow field of the floating body until it converges to a stable state.
- Get the resistance of floating body by integral of surface pressure.
- Add up the resistance of floating body and the braking force.
- Calculate the acceleration of the floating body.
- Get the movement speed of the grids v_b by calculating the speed of floating body.
- Calculate the source item S_i and iterate at the current moment to get the solution.
- Calculate the speed of next moment and judge if v_b is equal to the initial towing speed. If it is, the calculation is over; if it isn't, turn to (2) for another circulation.

EXPERIMENT TESTS AND RESULTS

Constrained by the engineering conditions, it is difficult to get the accurate prediction of the inertial stopping distance for different types of ships. When conducting the laboratory investigations, confined to the hardware environment, we can only use models with certain reduced scale based on the similarity to conduct the experiment of inertial stopping distance prediction. Here we use the experimental data from the towing experiment of a subsea tunnel's joint to verify the accuracy of different algorithms for computing the inertial stopping distance. The sub-tunnel is regarded as the equivalent to ships with large block coefficient. The inertial stopping distances of different ships under lose speed and drifting condition are simulated by adjusting the rotational inertia of the model in a towing ship pool. The CFD is used to calculate the stopping time and distance from braking until the sub-tunnel's stopping moving.

The results of model experiment: Figure 1 and 2 show the physical model of the floating sub-tunnel in the towing experiment.

To investigate the application of the ALE algorithm implemented in FLUENT to calculate the ship's inertial stopping distance, we conduct a series of towing experiment with the initial velocity varying from 7 to 3 kts and the end speed fixed at 2 kts, under an overall of 15 specific working conditions. Then we get the data of a real ship with tonnage of 72000 by model calculation and conversion. The results are shown in Table 2.

The results of ALE algorithm: In order to verify the accuracy of the ALE algorithm used to calculate the

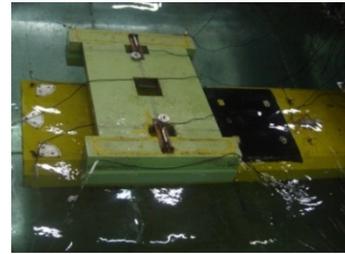


Fig. 1: The physical model of floating sub-tunnel



Fig. 2: Sub-tunnel under integrated towing load case

Table 2: The conversion value of the stopping distance of the experiment

	6 kts	5 kts	4 kts	3 kts	2 kts
7 kts	315.4	584.2	1009.3	1605.3	2317.2
6 kts	-	317.6	641.3	1154.5	1889.9
5 kts	-	-	320.1	731.5	1395.3
4 kts	-	-	-	348.0	878.2
3 kts	-	-	-	-	411.2

Table 3: The inertial stopping distance of the sub-tunnel calculated by ALE algorithm

	6 kts	5 kts	4 kts	3 kts	2 kts
7 kts	318.2	591.8	1024.3	1635.2	2369.9
6 kts	-	320.6	650.1	1175.3	1928.5
5 kts	-	-	326.0	750.8	1430.7
4 kts	-	-	-	355.4	900.2
3 kts	-	-	-	-	426.6

ship's inertial stopping distance, the numerical computations with respect to 15 working conditions are carried out. The results are shown in Table 3.

The results of the topley model: The Topley model is used for simplified calculation of ship's inertial stopping distance. To compare the effectiveness of different algorithms, the ship's parameters are set as follows: 180 m in length, 38 m in breadth, 11 m in draft, 72000 ton of full load displacement, initial speed of 7 kts, end speed of 2 kts. The unit of the velocity v is kts and the unit of S is translated into m. By combining Eq. (2) and (1) we obtain:

$$S_J = \left[v_1 \cdot -C \log_2 \frac{v_1}{v_0} + \frac{C(v_0 - v_1)}{0.693} \left(1 - 2^{\log_2 \frac{v_1}{v_0}} \right) \right] / 60 \quad (11)$$

Table 4: The inertial stopping distance of the 72000-ton ship

	6 kts	5 kts	4 kts	3 kts	2 kts
7 kts	343.9	639.6	1109.7	1767.1	2640.1
6 kts	-	340.8	696.5	1264.7	2074.1
5 kts	-	-	349.6	793.2	1513.5
4 kts	-	-	-	380.0	966.6
3 kts	-	-	-	-	456.6

Table 5: The comparison between experiment data and ALE results

Experimental results	ALE	Residual error	Relative error (%)
315.4	318.2	2.8	0.90
584.2	591.8	7.6	1.30
1009.3	1024.3	15.0	1.50
1605.3	1635.2	29.9	1.90
2317.2	2369.9	52.7	2.30
317.6	320.6	3.0	0.90
641.3	650.1	8.8	1.40
1154.5	1175.3	20.8	1.80
1889.9	1928.5	38.6	2.00
320.1	326.0	5.9	1.80
731.5	750.8	19.3	2.60
1395.3	1430.7	35.4	2.50
348.0	355.4	7.4	2.10
878.2	900.2	22.0	2.50
411.2	426.6	15.4	3.70

Table 6: The comparison between experiment data and results of empirical formula

Experimental results	ALE	Residual error	Relative error (%)
315.4	343.9	28.5	9.00
584.2	639.6	55.4	9.50
1009.3	1109.7	100.4	9.90
1605.3	1767.1	161.8	10.10
2317.2	2640.1	322.9	13.90
317.6	340.8	23.2	7.30
641.3	696.5	55.2	8.60
1154.5	1264.7	110.2	9.50
1889.9	2074.1	184.2	9.70
320.1	349.6	29.5	9.20
731.5	793.2	61.7	8.40
1395.3	1513.5	118.2	8.50
348.0	380.0	32.0	9.20
878.2	966.6	88.4	10.10
411.2	456.6	45.4	11.00

The results are shown in Table 4. Table 5 and 6 show the comparison of the experiment data with the results calculated by the ALE algorithm and empirical formula, respectively. The relative error rate is computed.

From Table 5 and 6 it can be found that when compared with the experiment data, the results calculated by the ALE algorithm reach relative precision of 98% while the results calculated by the

empirical formula reach relative precision of 90.4%. It is apparent that the precision of the former method is notably higher than the latter one.

CONCLUSION

The ALE method has advantage in dealing with the problems of changeable computational domain like the fluid-solid coupling problem, especially for the deformation or movement of the computational domain caused by the movement of walls. And it can be effectively applied to predict the ship's inertial stopping distance.

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