The dynamic research and position estimation of the towed array during the U-turn process

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Abstract. A dynamic model for estimating position of ship towed array during U-turn manoeuvre is introduced and developed. Based on this model, the influences of the parameters such as time step and segment length on the numerical simulation are analysed. The results indicate that decreasing the time step has little effect on the simulation accuracy but will increase the computational time. The selection of segment length has a great influence on the estimation of ship towed array position during U-turn manoeuvre. Reducing the segment length somewhat increases the computational complexity and significantly improves simulation precision.

1. Introduction

Measuring ship radiated noise by using its own towed array is more flexible, more convenient, and at lower cost, if compared with the traditional methods based on a fixed array or an auxiliary measurement ship. Ship's towed array normally dragged after the stern is usually applied to measure the radiated noise of other vessels. It is very difficult to measure its own radiated noise due to the existing measurement blind zones near the bow. Theoretically the deficiency can be overcome when ship makes a special manoeuvre such as U-turn during measurement. In this case, it is significant to accurately predict the position of ship towed array composed of unequally distributed hydrophones during U-turn manoeuvre, because the spatial location and spacing of hydrophones will greatly affect the beam formation and matched field inversion during measurement and analysis of ship own radiated noise.

Many theoretical and experimental researches on the localization of ship towed array system have been done by some researchers such as Srivastaava [1] and Duncan [2,3]. In 1998, Srivastaava conducted an experiment to verify the developed model of the underwater towed cable-array system during loop manoeuvre, in which the X, Y, Z coordinates of the cable-array system and tow-point tension for different radii and speeds during the circular manoeuvre could be recorded. The results showed that the experimental results of tails, lateral shift, depth of array, and tow-point tension were in good agreement with the theoretical values. Based on this, in 2002, Duncan carried out a hydrodynamic simulation and experiment to estimate the location of hydrophones in the towed array during U-turn manoeuver of the tow-vessel. The results showed that the path of towed array was far more sensitive to the tangential and normal drag coefficients than it was to any of other parameters. Meanwhile, the vessel speed had little effect on the array path.

In this paper, a simplified dynamic model for calculating the localization of towed array system during U-turn manoeuvre is established. And the influences of different time steps and nodes' number on simulation results are discussed.

2. Dynamic model

Generally, as shown in Figure 1, the towed array system is composed of a tow cable, forward vibration isolating mass (VIM), instrument module, acoustic module and aft module [4]. The forward VIM is used as a buffer and vibration isolator. The instrument module including temperature sensor, depth sensor, and so on can acquire the environmental parameters for acoustic calculation. The acoustic module composed of tens or hundreds of hydrophones distributed at different intervals along the towed cable is the main part of towed array system. The aft module, in addition to isolating vibration, can increase the resistance and keep the state of towed array. Normally, a small towed array only consists of two parts: towed cable and acoustic module.
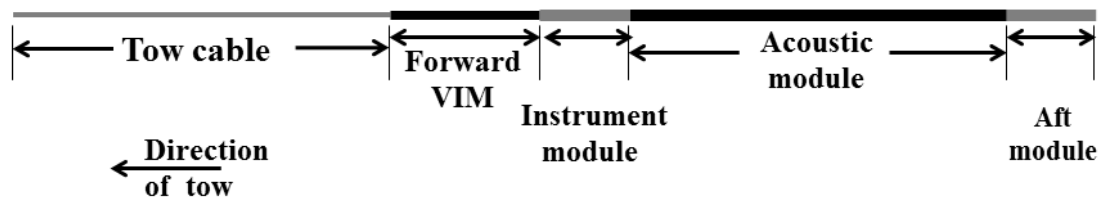
Figure 1. The typical layout of a towed array.

The towed array system is approximately assumed as a uniform towed cable neglecting the difference of modules' material and diameter. And starting with the stern, the towed cable can be equally divided into n sections, each of which is modelled as a mass-spring. The force analysis of the ith section is shown in Figure 2, where M_i(kg) is the mass of the ith segment, T_i and T_{i+1} are the tensions acting on the ith segment, and Fd_{ni} and Fd_{ti} are the normal and tangential hydrodynamic drag forces respectively. The cable end at the stern can be considered as hinge joint and the other end is free [5].
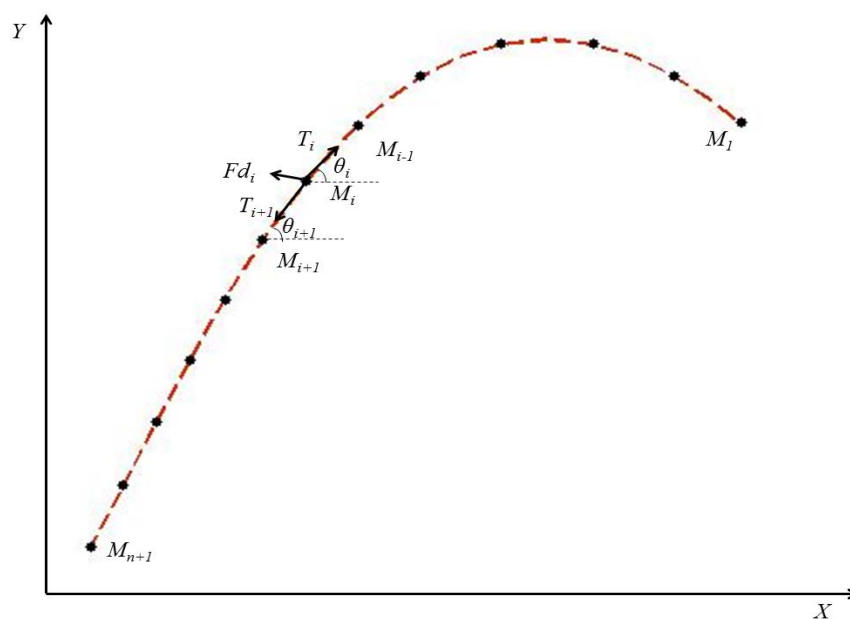
Figure 2. The towed cable model and force analysis of the ith section.

The equilibrium equations of forces for the ith segment can be expressed as

$$\begin{cases} T_i - T_{i+1} - Fd_i = M_i a_i & (1 < i \le n) \\ T_i - Fd_i = M_i a_i & (i = n+1) \end{cases} \tag{1}$$

The tension acting on the ith segment of cable related to its coordinates and velocities on either end of the segment can be represented as

$$T_i = A_i E_i \left(\frac{l_i}{l_{i0}} - 1 \right) + \alpha_i A_i \frac{\dot{l}_i}{l_{i0}} \tag{2}$$

Where, A_i is the cross-sectional area of towed cable (m^2), E_i is the Young's modulus of cable material (Pa), α_i is the damping coefficient, l_{0i} is the initial length of the ith segment (m). l_i, the real length of the ith segment (m) can be written as.

$$l_i = (\delta x_i^2 + \delta y_i^2)^{1/2} \tag{3}$$

$$\dot{l}_i = \frac{\delta x}{l_i} \delta \dot{x} + \frac{\delta y}{l_i} \delta \dot{y} = (v_{x,i} - v_{x,i+1}) \cos \theta_i + (v_{y,i} - v_{y,i+1}) \sin \theta_i \tag{4}$$

In which, $\delta x_i = x_i - x_{i+1}$ and $\delta y_i = y_i - y_{i+1}$.

Bedendender [6,7] presented a model to calculate the normal and tangential hydrodynamic drag forces in which the fluid is assumed to be stationary. The equations are given as follows

$$Fd_n = 0.5 C_{dn} \rho_0 D v^2 (a \sin \varphi |\sin \varphi| + b \sin \varphi) \tag{5}$$

$$Fd_t = 0.5 C_{dt} \rho_0 D v^2 (d \cos \varphi |\cos \varphi| + e \sin \varphi + g |\cos \varphi| / \cos \varphi + h \sin \varphi |\sin \varphi|) \tag{6}$$

Where C_{dn} is the normal drag coefficient, C_{dt} is the tangential drag coefficient, ρ_0 is the density of the fluid (kg·m^{-3}), D is the diameter of cable (m), v is the velocity of flow, φ is the angle between cable and flow. When $a=1$, $d = \pi C_{dt} / C_{dn}$, and b, e, g, $h=0$, the equation (5) and (6) can be simplified as Wilson model [8], as shown below

$$\begin{cases} Fd_{ni} = -0.5 C_{dn} \rho_0 D_i l_i v_{n,i} |v_{n,i}| \\ Fd_{ti} = -0.5 C_{dt} \rho_0 \pi D_i l_i v_{t,i} |v_{t,i}| \end{cases} \tag{7}$$

In which D_i is the diameter of the ith segment (m), $v_{n,i}$ is the mean normal velocity of the ith segment (m/s) and $v_{t,i}$ is the mean tangential velocity of the ith segment (m/s).

The mass of the ith segment is given by

$$M_i = M_{i0} + M_a \tag{8}$$

Where, M_a is additional mass causing by the drag force of the fluid, and can be expressed as [9,10]

$$M_a = \rho_0 \pi r^2 \tag{9}$$

In which, r is radius of the towed cable.

3. Simulation and analysis
The parameters of ship U-turn manoeuvre and its own towed array are shown in Table 1.

Table 1. Parameters of simulation

Parameters	Value
Overall section length	800 m
Segment length	20 m
Number of segments	40
Section diameter	0.05m
Young's modulus	7.8×10^{10} Pa
Tension damping coefficient	1×10^{9} Pa.s
Normal drag coefficient	1.2
Tangential drag coefficient	2.5×10^{-3}
Tow vessel length	120 m
Turning radius	200m
Vessel speed	5 m/s

According to the developed model, the simulated motion paths and relative positions of vessel and towed array are shown in Figure 3(a) and Figure 3(b) respectively in which the black bold line denotes the position of vessel, the blue dotted line refers to the towed array, and red dashed line is the motion trail of vessel U-turn. Next, it is very important and practical for high-accurate and real-time simulation to analyse and optimize the parameters such as time step and segment length on the numerical simulation.
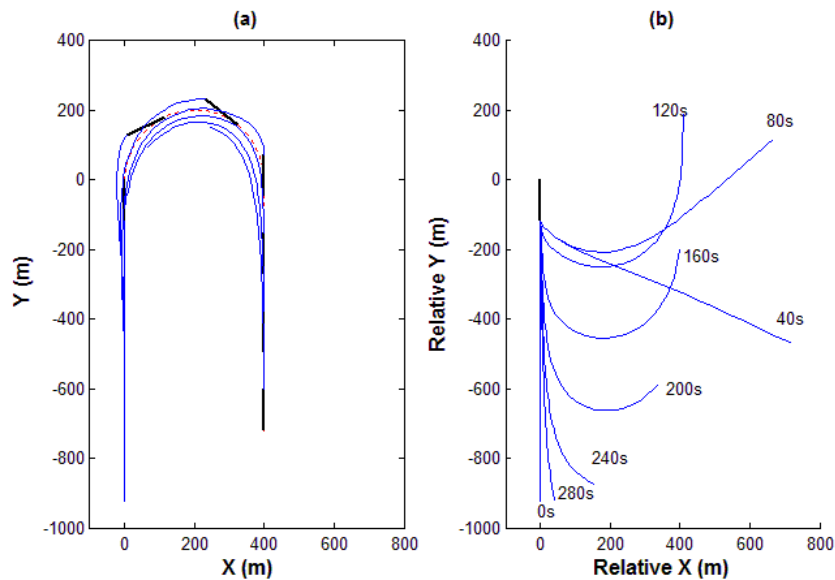

Figure 3. Simulation results of U-turn manoeuvre.
(a) Path of vessel and towed array, (b) Relative Position of vessel and towed array.

3.1 Different time step
Figure 4 shows the influences of different time steps(dt=5.0×10^{-4}, 2.0×10^{-4}, 1.0×10^{-4}, 5.0×10^{-5}, 2.0×10^{-5}, 1.0×10^{-5}, 5.0×10^{-6}, 2.0×10^{-6}, and 1.0×10^{-6}s) on the simulation results, in which the bottom axis is time step (s), the left axis is computing time (s), and the right axis is maximum node position

change (m) in reference to the simulation result of minimum time step ($dt=1.0\times10^{-6}$s). It can be found that the selection of time step has a certain influence on the simulation result. If the time step is too large, the simulation will overflow. As the time step is reduced, the computing time will increase but its simulation accuracy rises slowly. Therefore, it is very important to select an optimum time step in simulation.
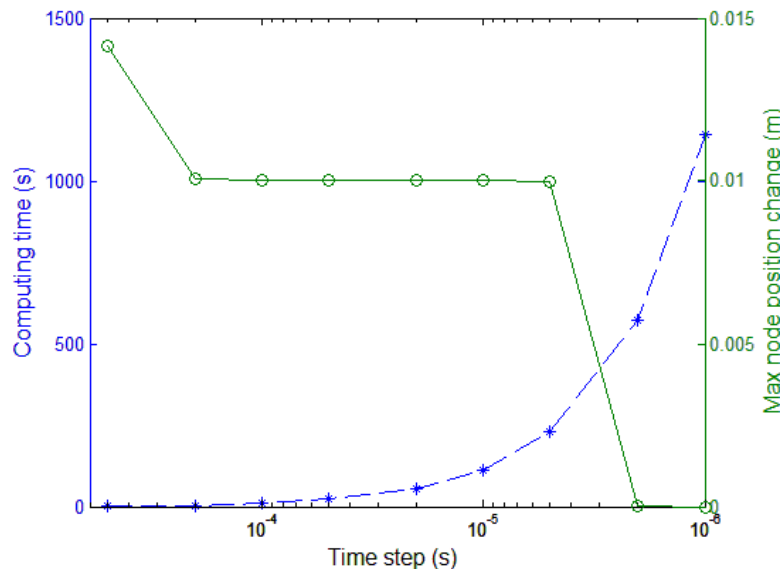

Figure 4. Influences of different time steps on simulation results.

3.2 Various meshing

Figure 5 show six meshing cases of the towed array which is divided into 4, 8, 16, 32, 64 and 128 sections respectively. In these cases, there are five invariant nodes in which node 1 is at the junction between ship and its towed array and not for analysis, and node 5 is farthest from the ship. Supposing $dt=2.0\times10^{-5}$s, the simulation paths of the corresponding node 2 to node 5 for six meshing cases during ship U-turn manoeuvre are demonstrated in Figure 6. It can be known that the meshing way of towed array have a great effect on the position estimation accuracy of its nodes.
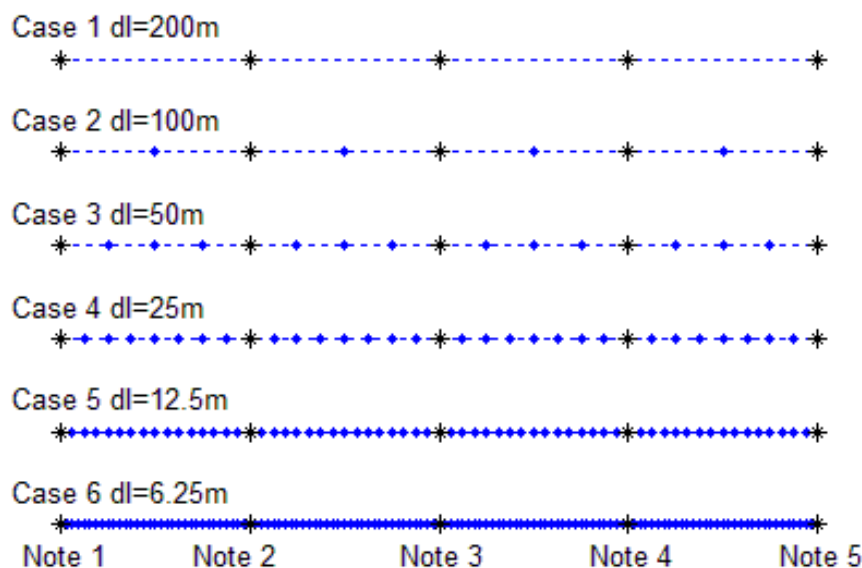
Figure 5. Different segmentation methods.
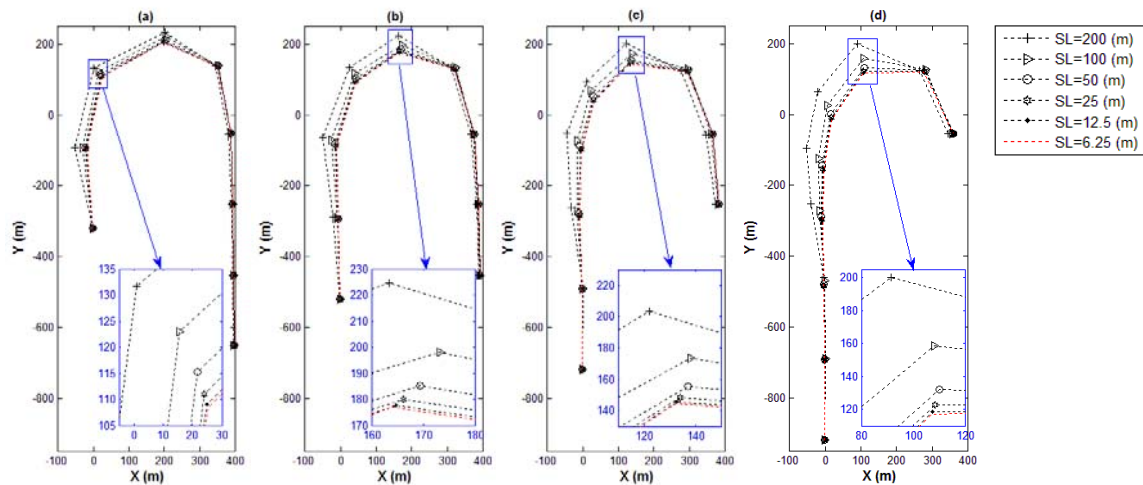
Figure 6. Instantaneous positions of node 2 to node 5 for 6 different cases.
(a) Path of Note 2, (b) Path of Note 3, (c) Path of Note 4, (d) Path of Note 5.

Table 2 lists much more information about the position differences of each node. It illustrates that there is an upward trend in computing time for the reason that the decline of segment length leads to the number of sections increases. Besides, the max node position changes of 4 common nodes are given by using the results of min segment length as a reference value. It can be known that the farther away from the towed ship, the larger the max position change. On the other hand, with the segment length decreases, the max position change diminishes. The max value in the table reaches 88m. In addition, compared with the calculation of different time step, simulation results are more sensitive to the change of different segment length.

Table 2. Simulation results for different meshes

Segment length (m)	Computing time (s)	Max node position change (m)			
		Note 2	Note 3	Note 4	Note 5
200	10.375	33.435	47.744	64.284	88.118
100	17.469	17.459	26.647	34.211	41.857
50	30.516	8.043	12.170	14.967	17.510
25	56.047	3.040	4.514	5.464	6.197
12.5	108.109	0.835	1.216	1.464	1.636
6.25	213.086	0.000	0.000	0.000	0.000

4. Conclusions

In this paper, a dynamic model for estimating position of towed array is put forward basing on former research. The model is simple and intuitive, and has a strong flexibility and universality. According to the theoretical model, a series of numerical simulation are carried out by altering the parameters of time step and segment length. The results indicate that the selection of time step has a certain influence on the simulation result. When the time step is too large, the calculation overflows. When the time step decreases, the computing time increases, but the upward trend of calculation accuracy is not obvious. On the other hand, the selection of segment length has a great influence on the simulation result. Both calculation quantity and calculation precision rises with the segment length reduces.

Acknowledgments

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