A Study on the Safe Maneuvering of a G/T 100,000 Ton LNG Vessel by Using Her Control Surface through a Narrow Channel

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Abstract

Nowadays LNG has been beginning to take the place of petroleum as fuel all over the world and VLCC tankers of LNG will take the same sea routes that had been used by VLCC tankers of petroleum in the last part of the 20th century.

The transportation of LNG by a VLCC include more dangerous nature of sea peril than that of petroleum. We already know the dimensions of a disaster a LNG tanker could bring about in the case of the LNG tanker, Yuyo-Maru No. 10 in the Tokyo Bay of Japan in 1974. From the point of safety when we construct a LNG base or LNG pier in the base, the appropriate government authority and constructing company had better take sea pilots or some ships handling experts to participate in a prior consultation of the design of the project.

A G/T 100,000 ton LNG base and pier were completed in November of 1996 in Inchon harbour in Korea and LNG VLCC tankers of G/T 100,000 ton class have been entering into the base ever since.

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This study was started and completed to comply with the requisition of the Sea Pilot Association of Inchon harbour in advance of the opening of the LNG base.

As the entrance and exit channels leading to Inchon harbour were constructed in the years of 1930s, it was one of the most pressing works for Inchon sea pilots in 1996 to certify the method of safe passing maneuvering of a G/T 100,000 ton LNG tanker through the Pudo narrow channel prior to commencing actual piloting of the LNG VLCC tanker.

The author made some mathematical models computing maneuvering of a vessel changing her course with her control surface through a narrow channel and computed maneuvering of a G/T 100,000 ton LNG tanker and also made maneuvering simulations of the vessel by a desk-top simulator.

The results of computations and simulations are well coincided with each other in qualitative aspects to assure safe passing of the LNG VLCC.

Abbreviation

B: breadth of a vessel or coefficient of homogeneous equation

d: draft

L: length of a vessel

k': non-dimensionalized turning moment coefficient

m': non-dimensionalized mass

n'_z: non-dimensionalized moment of inertia about Z axis

r': non-dimensionalized angular velocity

r_s: steady turning angular velocity

$\dot{r}'$: non-dimensionalized angular acceleration

t': non-dimensionalized time

T': non-dimensionalized yaw inertia coefficient

u: forward velocity

v': non dimensionalized transverse velocity

$\dot{v}'$: non-dimensionalized transverse acceleration

X: Force exerting forward

Y: Force exerting athwartship

α: wind force angle

δ: rudder angle

$\dot{\delta}'$: non-dimensionalized rudder angle velocity

ϕ: angular quantity

ϕ_d: quantity of the changed heading

κ: 2d/L

σ: root of characteristic equation

σ': non-dimensionalized root of the above

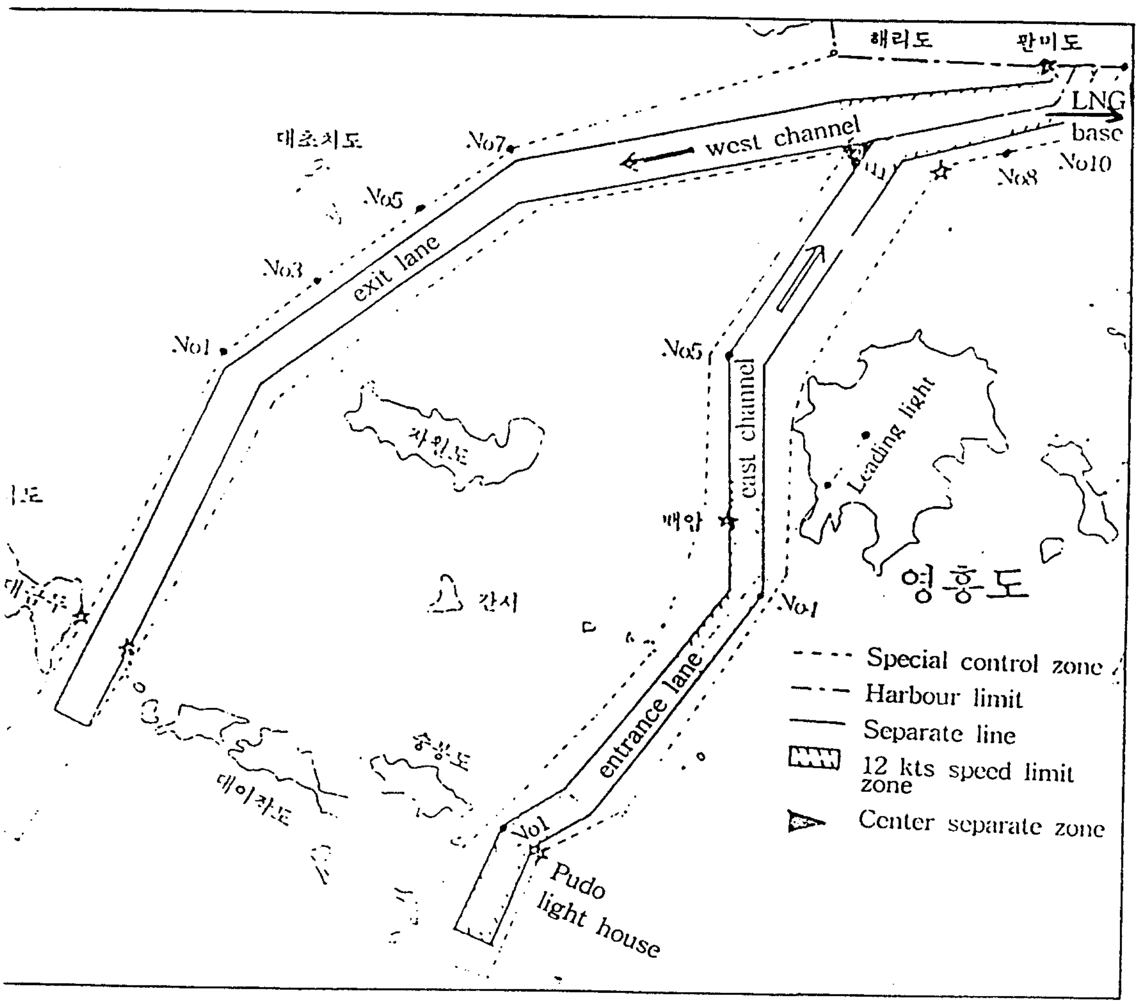

Fig. 1 Entrance and exit lane to Inchon harbour

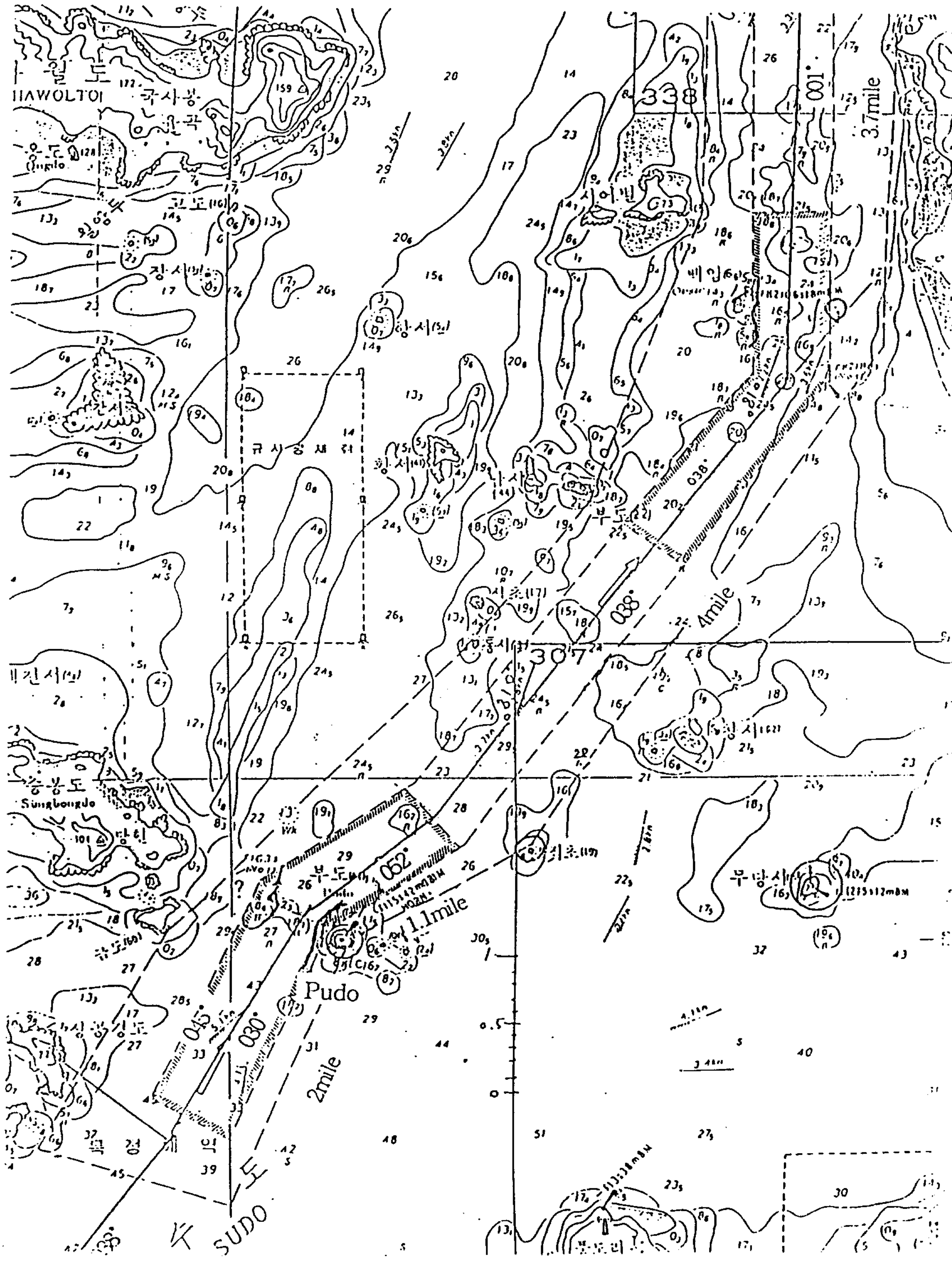

Fig. 2 The Pudo channel

1. Theory and developing theoretical methods to solve problems

1.1 Coordinate system and mathematic models of motions

When we use coordinate system fixed on the center of gravity of a moving vessel(see Fig. 1.1) surge, sway and yaw motions of the vessel can be demonstrated as follows:

$$\left.\begin{aligned} & m(\dot{u}-vr) = \\ & X(\dot{u}, \dot{v}, \dot{r}, u, v, r, n, \delta) \cdots ① \\ & m(\dot{v}+ur) = \\ & Y(\dot{u}, \dot{v}, \dot{r}, u, v, r, n, \delta) \cdots ② \\ & I_z \dot{r} = \\ & N(\dot{u}, \dot{v}, \dot{r}, u, v, r, n, \delta) \cdots ③ \end{aligned}\right\} \cdots (1.1)$$

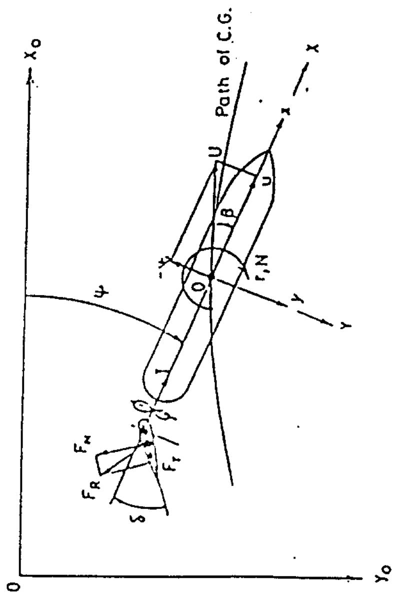

Fig. 1.1 Coordinate system

When we control the maneuvering motions with only rudder angle keeping the output of main engine as constant, the surge equation can be neglected and also when we want to get approximation of maneuvering motions we can get good result of solution even if we neglect non-linear terms of equation (1.1).

The linearized equations of yaw and sway motions can be written as follows:

$$\left.\begin{aligned} & n'_z \dot{r}' - N'_r r' - N'_v v' \\ & \quad = N'_\delta \delta \cdots\cdots ① \\ & m'_y \dot{v}' - (Y'_r - m') r' \\ & - Y'_v v' = Y'_\delta \delta \cdots ② \end{aligned}\right\} \cdots (1.2)$$

$$\left.\begin{aligned} & v' = \frac{1}{N'_v} \times \\ & (n'_z \dot{r}' - N'_r r' - N'_\delta \delta') \\ & \dot{v}' = \frac{1}{N'_v} \times \\ & (n'_z \ddot{r}' - N'_r \dot{r}' - N'_\delta \dot{\delta}') \end{aligned}\right\} \cdots (1.3)$$

Substituting equation (1.3) into equation (1.2), we get equation (1.4).

$$T'_1 T'_2 \ddot{r}' + (T'_1 + T'_2)\dot{r}' + r' = k'\delta + k' T'_3 \dot{\delta}' \cdots\cdots (1.4)$$

where,

$$T'_1 + T'_2 = -\frac{m'_y N'_r + n'_z Y'_v}{Y'_v N'_r + N'_v (m' - Y'_r)}$$

$$T'_1 T'_2 = \frac{m'_y n'_z}{Y'_v N'_r + N'_v (m' - Y'_r)}$$

$$T'_3 = \frac{m'_y N'_\delta}{Y'_v N'_r + N'_v (m' - Y'_r)}$$

$$k' = \frac{N'_v Y'_\delta - Y'_v N'_\delta}{Y'_v N'_r + N'_v (m' - Y'_r)}$$

$$= \frac{r'_s}{\delta}$$

With fixed rudder to mid-ship we get characteristic equation as follows:

$$(m'_y \; n'_z) \ddot{r}' - (m'_y N'_r + n'_z Y'_v) \dot{r}'$$
$$+ [Y'_v N'_r + N'_v (m' - Y'_r)] r' = 0$$

$$\{(m'_y \; n'_z) \sigma^2$$
$$- (m'_y N'_r + n'_z Y'_v) \sigma$$

$$+ [Y'_v N'_r + N'_v (m' - Y'_r)]\} r' = 0$$

$$\sigma_1, \sigma_2 =$$

$$\frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \cdots (1.5)$$

· · · · characteristic equation.

Course stable : $\sigma < 0$.

That is : A > 0, B > 0, C > 0.

$A = m'_y \; n'_z > 0$:under all conditions.

$B = m'_y(-N'_r) + N'_z(-Y'_v) > 0$

: under all conditions.

$$C = Y'_v N'_r + (m' - Y'_r) N'_v \gtreqless 0$$

(magnitude of N'_v decide the sign (+) or (−).

A constant rudder angle gives

$\ddot{r}' \simeq 0$ and $k' T'_3 \dot{\delta}' \simeq 0$

and equation (1.4) can be written as:

$$(T'_1 + T'_2) \dot{r}' + r' = k' \delta$$

$$T'_1 + T'_2 \simeq T'_1 = T'$$

$$T \dot{r}' + r' = k' \delta \quad \cdots\cdots (1.6)$$

The solution of equation (1.6) is as follow:

$$r'(t') = k' \delta \; (1 - e^{-\frac{t'}{T'}}) \cdot \cdot (1.7)$$

1.2 Mathematic models for computing rudder executing time and etc. when a vessel alters her course

When a vessel alters her course by a angular quantity of ϕ_d with rudder angle $\delta = \delta_1$, the optimum rudder action can be demonstrated as shown in Fig. 1.2.

But as the time interval to make a rudder angle is very short, we can neglect the time interval and the optimum rudder action can be shown as in Fig. 1.3.

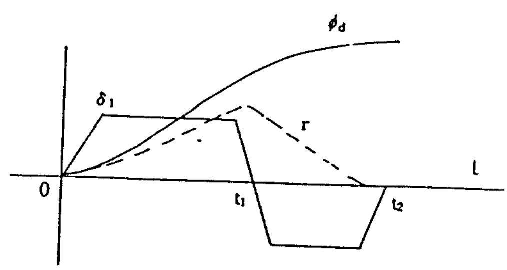

Fig. 1.2

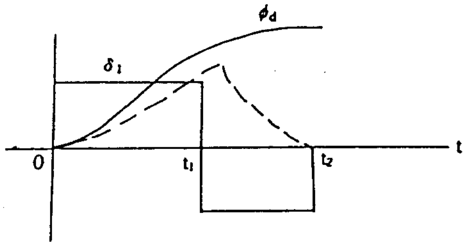

Fig. 1.3

To keep consistency of rudder executing time from t' to t'_1 and t'_2 ($t' = 0 \sim t'_2$) in the calculating equations, we assume the optimum rudder actions as being shown in Fig. 1.4.

$$= -k'\delta_1[1 + e^{-\frac{t'_2}{T'}} - 2e^{-\frac{(t'_2 - t'_1)}{T'}}] = 0$$

$$\therefore 1 + e^{-\frac{t'_2}{T'}} - 2e^{-\frac{(t'_2 - t'_1)}{T'}} = 0$$

Condition (2):

At the instant $t' = t'_2$, $\phi(t'_2) = \phi_d$

$$\phi(t'_2) = k'\delta_1 \int_0^{t'_2} (1 - e^{-\frac{t'}{T'}})dt'$$

$$- 2k'\delta_1 \int_{t'_1}^{t'_2} (1 - e^{-\frac{t' - t'_1}{T'}})\, dt'$$

$$\phi(t) = \int r'(t')dt' + c$$

($\phi = 0$ at initial condition).

$$\phi_d = k'\delta_1 \, [t' + T'e^{-\frac{t'}{T'}}]_0^{t'_2}$$

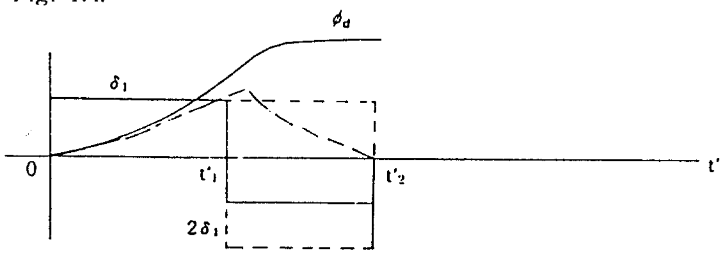

Fig. 1.4 Assumed rudder action for time consistency($-2k'\delta_1 + k'\delta_1 = -k'\delta_1$)

So we can demonstrate angular velocity as follow:

$$r'(t') = k'\delta_1 (1 - e^{-\frac{t'}{T'}})$$

$$-2k'\delta_1 (1 - e^{-\frac{t' - t'_1}{T'}}) \cdot \cdot \cdot (1.8)$$

At the instant when a vessel has completed her course altering, there exist two clear conditions;

Condition (1):

At the instant $t' = t'_2$, $r'(t'_2) = 0$,

$$r'(t'_2) = k'\delta_1 (1 - e^{-\frac{t'_2}{T'}})$$

$$-2k'\delta_1 (1 - e^{-\frac{(t'_2 - t'_1)}{T'}})$$

$$-2k'\delta_1[t' + T'e^{-\frac{(t' - t'_1)}{T'}}]_{t'_1}^{t'_2}$$

$$= k'\delta_1(t'_2 - T' + T'e^{-\frac{t'_2}{T'}})$$

$$-2k'\delta_1 \, [t'_2 - T'$$

$$+ T'e^{-\frac{(t'_2 - t'_1)}{T'}} - t'_1]$$

$$\phi_d = k'\delta_1[(2t'_1 - t'_2) +$$

$$T'(e^{-\frac{t'_2}{T'}} - 2e^{-\frac{(t'_2 - t'_1)}{T'}} + 1)] = 0$$

$$e^{-\frac{t'_2}{T'}} - 2e^{-\frac{(t'_2 - t'_1)}{T'}} + 1 = 0$$

· · · from condition (1)

$$\phi_d = k'\delta_1(2t'_1 - t'_2) \quad \cdots (1.8)$$

· · · from condition (2)

Rudder executing time t_1 and t_2 can be calculated from equation (1.9) and the problems of maneuvering with the control surface can be solved.

1.3 Calculations of maneuvering motions of a G/T 100,000 ton LNG vessel

To get trust worthy approximation of maneuvering motions of a real vessel, we had better compute hydro-dynamic coefficients of her hull and then compute her maneuvering indices (K and T) using the hydro-dynamic coefficients and lastly compute maneuvering motions by the indices.

(1) Particulars of the LNG VLCC

Disp. : 120,194 ton

$L_{PP} \times B \times T$: $290 \times 46.8 \times 12$ (m³)

B/d : 3.9

L/B : 6.2

C_b : 0.72, rudder area = 1/60·

$$= \frac{290 \times 12}{60} = 58 \text{ m}^2$$

Speed : 20 kt (Speed limit 12 kt in the channel leading to Inchon harbour)

(2) Non-dimensionalized mass and moment of inertia

$$m' = 120{,}194 / \frac{1}{2} \rho \, l^2 d$$

$$= 0.232 \text{ (d : draft)}$$

$$m'_y = 1.75 \times 0.232 = 0.407$$

$$n'_z = 0.029$$

(3) Hydro-dynamic coefficients computations (in deep sea)

$$Y'_v = -\frac{1}{2} \pi \kappa - 1.4 \, C_b B/L$$

$$= -0.293$$

$$Y'_r = \frac{\pi}{4} \kappa = 0.065$$

$$N'_v = -\kappa = -0.083$$

$$N'_r = -0.54\kappa + \kappa^2 = -0.038$$

where, κ : 2d/L.

Above hydro-dynamic coefficients must be corrected to a hull attatched with rudder and screw propeller. To make the corrections we had better compare the coefficients of a hull with those of the same hull attached with her rudder and propeller both of which are already well known and then we can find out correction data to apply to a real vessel.

	Model No. 8,1,1	Model No. 8,0,0	The ratio of coefficients
Y'_v	-0.035	(-0.309)	1.1
Y'_r	0.089	(0.064)	1.4
N'_v	-0.095	(-0.121)	0.8
N'_r	-0.077	(-0.064)	1.2

where, the ratio of coefficients = Coefficients of completed vessel ÷ Coefficients of bare hull.

(4) Coefficients of a completed LNG vessel (in deep sea)

$m' = 0.232$, $m'_y = 0.407$, $n'_z = 0.029$

Y'_v = -0.293 × 1.1 = -0.322

Y'_r = 0.065 × 1.4 = 0.091

N'_v = -0.083 × 0.8 = -0.066

N'_r = -0.038 × 1.2 = -0.046

Aboves are the coefficients of the LNG vessel in deep sea and must be corrected to those of the same vessel moving in a shallow water for computing maneuvering motions in the water of a narrow channel.

(5) The coefficients in shallow water (h=1.25d)

$m'_{xh} = m' \times 1.3 = 0.232 \times 1.3 = 0.302$

$m'_{yh} = m' \times 4 = 0.232 \times 4 = 0.928$

$n'_{zh} = n_z \times 1.66 = 0.029 \times 1.66 = 0.048$

$Y'_{vh} = Y'_v \times 4.54 = 0.232 \times 4.54 = 1.462$

$Y'_{rh} = Y'_r \times 1.5 = 0.091 \times 1.5 = 0.137$

$N'_{vh} = N'_v \times 5 = -0.066 \times 5 = -0.330$

$N'_{rh} = N'_r \times 3.2 = -0.046 \times 3.2 = -0.147$

A = 0.045, B = 0.207, C = 0.160

σ_1 = -0.98, σ_2 = -3.62, T' = 1.02

(6) Computations of Y'_δ and N'_δ (in deep sea)

Rudder force

$$= 2.2 \times \frac{1}{2} \rho A u^2 \sin\delta\cos\delta$$

$$= 1.1 \rho 58 \times 36 \times \frac{1}{2} \sin 2\delta$$

$$= 1.1 \rho 58 \times 36 \times \delta \ (\sin 2\delta \simeq 2\delta)$$

where,

ρ = 0.105, A= 58 m², u = 6 m/s

$$Y_\delta \delta = 2297 \rho \delta$$

$$Y'_\delta = \frac{2297\rho}{\frac{1}{2}\rho L d u^2}$$

$$= +0.037 \text{ (in deep sea)}$$

Rudder moment

$N_\delta \delta$ =

$$-2.2 \times \frac{1}{2} \rho A u^2 \sin\delta\cos\delta \times \frac{L}{2}$$

$$\simeq -2297 \rho \delta \times \frac{L}{2}$$

$$N'\delta = \frac{-2297\rho\delta \times \frac{L}{2}}{\frac{1}{2}\rho L^2 d u^2}$$

= -0.018 (in deep sea)

$Y'_{\delta h} = Y'_\delta \times 2$(h=1.25d) = 0.074

$Y'_{\delta h}$ = 0.074

$N'_{\delta h} = -0.036 = N'_\delta \times 2 = -0.036$

Computation of k' value

k' (in deep sea)

$$= \frac{N'_v Y'_\delta - Y'_v N'_\delta}{Y'_v N'_r + N'_v (m' - Y'_r)} = 1.50$$

k = -0.030, kδ = 0.03 × 15°

= 0.46 deg/sec

k' (h=1.25d) = 0.83

k = -0.017, kδ = 0.26 deg/sec.

2. Computations of maneuvering motions of the LNG vessel through the Pudo narrow channel

2.1 In the case of altering course with no wind and current

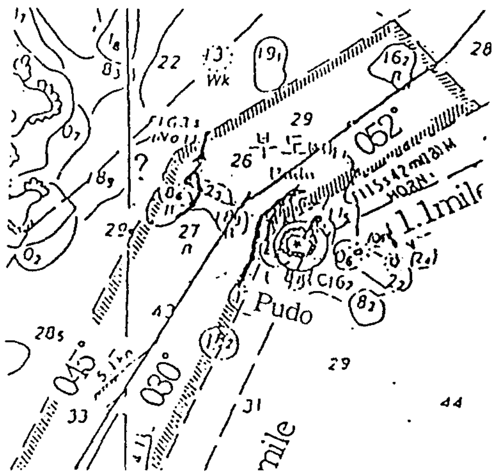

Fig. 2.1 Pudo narrow channel and courses

(1) Analysis of motions of altering course from 030° to 052°

$$\left.\begin{aligned} \phi_d &= k'\delta_1 (2t'_1 - t'_2) \\ e^{-\frac{t'_2}{T'}} - 2e^{-\frac{t'_2 - t'_1}{T'}} &+ 1 = 0 \end{aligned}\right\}\cdots(2.1)$$

$22^\circ / 57.3 =$

$-0.8(-15^\circ / 57.3)(2t'_1 - t'_2)$

$2t'_1 - t'_2 = 1.83$

$t'_2 = 2t'_1 - 1.83$

$$\exp. -\frac{2t'_1 - 1.83}{1.02}$$

$$-2\exp. -\frac{t'_1 - 1.83}{1.02} + 1 = 0$$

$$6.01\exp. -\frac{2t'_1}{1.02} - 2$$

$$\times 6.01\exp. -\frac{t'_1}{1.02} + 1 = 0$$

$$\exp. -\frac{t'_1}{1.02} = 1.91 \text{ or } 0.09$$

$$-\frac{t'_1}{1.02} = 0.65 \text{ or } -2.41$$

$t'_1 > 0 \quad \therefore\ t'_1 = 2.45$

$2.45 \times 290 = 711$ m

$t'_2 = 2 \times 2.45 - 1.83 = 3.07$

$3.07 \times 290 = 890$ m

$T' = 1.02$

$S_{T'} = 1.02 \times 290 = 296$ m

$T = 296 \div 6 = 49$ secs

As we can see in the above analyses, when we use the rudder angle of 15 degrees, after 49 seconds by time, advancing 296m forward by distance, the vessel will commence turning to stb'd with the angular velocity of 0.26° / sec and altering course from 030° to 052° will be completed at the instant when she proceeds 890 m forward after the rudder angle ordered.

From the above analyses there will be no problem of maneuvering with no wind and current.

2.2 Computations of maneuvering motions of altering course with strong current

(1) Problems arising before arriving the point at which the rudder order is to be delivered

Approaching course toward the Pudo light house is 030° and the current direction of flood tide is 045°. Therefore entering vessels will receive the current from 15° on the port quarter (see Fig. 2.1). The maximum velocity of the current is 5.1 kt which is equivalent to 2.62 m/sec. As we see in Fig. 2.1, this current will turn the vessel to port and the vessel must keep her course 030° using stb'd rudder.

Computations of the stb'd rudder angle to cope with the strong current are as follows:

① Case 1

Ship speed 12 kt = 6.17 m/sec (limit speed due to regulations)

Current speed 5.1 kt = 2.62 m/sec

Rudder moment = Moment due to current

$$2 \times 2.2 \times \frac{1}{2} \rho_w A u^2 \sin\delta \cos\delta \times \frac{L}{2}$$

$$= 0.1 \times \frac{1}{2} \rho_w \times 2.62^2 L^2 \times d$$

where, d : draft

$$2 \times 2.2 \times 58(6.17 - 2.62\cos 15^\circ)^2 \times 0.25$$
$$= 845 \times 0.1 \times 2.62^2 \times 290 \times 12 = 2389$$
$$845 \sin 2\delta = 2389$$
$$\sin 2\delta \doteqdot 2.83$$

As we do not find any coping rudder angle, maneuvering is impossible.

② Case 2

Ship speed 12 kt = 6.17 m/sec

Current speed 4 kt = 2.06 m/sec

$$2 \times 2.2 \times \frac{1}{2} \rho_w A u^2 \sin\delta \cos\delta \times \frac{L}{4}$$

$$= 0.1 \times \frac{1}{2} \rho_w \times 2.62^2 \times L^2 d$$

$$2 \times 2.2 \times 58(6.17 - 2.06\cos 15)^2$$
$$\times 0.25 \sin 2\delta$$
$$= 1114 \sin 2\delta \ \text{ton} \cdot \text{m}$$

$$0.1 \times 2.06^2 \times 290 \times 12 = 1477 \ \text{ton} \cdot \text{m}$$
$$\sin 2\delta \doteqdot 1.33$$

Same as in the case 1.

The reason that the vessel is uncontrollable with her control surface is coming from greater shallow water effect of her hull compared with that of a small vessel.

For example, if a small vessel of 100 m length with the draft of 4 m receives current of 4 kt in the same channel, rudder angle to be used to cope with the current is only 5° or 6°.

(2) Computations of appropriate rudder angle for coping with the current and allowable speed limits of the current for safe maneuvering

When we maneuver a large vessel in a narrow channel, in a harbour or some congested waters near it, the coping rudder angle to keep a ship's course had better be limited to about

15° , because the rudder angle of more than that would make it difficult to make appropriate maneuvering action in the next case of a critical situation coming up step by step and soon a dangerous situation is liable to develop.

Appropriate current speed computation;

$$2\times2.2\times\frac{1}{2}\rho_w A(6.17-\chi)^2$$

$$\sin15^\circ\ \cos15^\circ\ \times\frac{L}{2}$$

$$=0.1\times\frac{1}{2}\rho_w x^2 L^2\times d$$

(= Y Force × lever)

$$31.9\ (6.17-\chi)^2=348\chi^2$$

$$316\chi^2+392\chi-1215=0$$

$$\chi\quad 1.4\ \text{or}\ \ 2.7$$

Current speed = 1.4 m/sec

1.4 m/sec = 2.8 kt

Allowable current speed = 2.8 kt

Therefore the allowable maximum current speed to be able to be coped with using rudder angle of 15° is 2.8 kt.

(3) Some problem as might be expected during altering course in front of the Pudo light house

When a G/T 100,000 ton LNG vessel alters her course from 030° to 052° using 15° rudder angle, she will proceed 296 m straight forward on the course (1.02 × 290 = 296 m) and the lapse of time is 48 seconds (296 ÷ 6.17 = 48) before commencing to turn to stb'd with angular velocity of 0.26 deg/sec. But considering the time lapse to make 15° rudder angle and the current speed, actual proceed distance would be 409 m [(6 + 48) × (6.17 + 1.4) = 409 m] before commencing of turning. After then the time lapse for completing the course altering will be 85 seconds (22 ÷ 0.26 = 85).

Therefore the lapse of time and distance proceeded from the instant of rudder order to completion of altering course is as follows;

$$\text{Time}\ t=\frac{1}{2}(\text{time lapse to get }15^\circ\ \text{rudder angle})+T+\phi_d/0.26$$

$$=6+48+85=139\ \text{seconds}$$

= 2 minutes 19 seconds

Distance S = 139 × (6.17 + 1.4)

= 1052 m

As the vessel keeps 15° coping rudder angle to stb'd to keep straight on the course, she must use 30° rudder angle stb'd to alter her course keeping almost the hard stb'd rudder until the direction of current is right abaft her stern and then she must use coping rudder angle to port to cope with current now coming from her stb'd quarter.

The navigable width of the Pudo channel for a G/T 100,000 ton LNG tanker of 12 m draft is of almost 2~3 cables, that is, 370~555 m only.

In such a narrow channel it is

dangerous that a VLCC tanker uses 30° rudder angle and keeps the hard stb'd rudder for some long lapse of time and then uses contrary rudder angle suddenly for safe maneuvering.

Therefore the allowable speed of current had better be limited to 2 kts for the G/T 100,000 ton LNG tanker for safe maneuvering.

When the vessel receives 2 kts current from her port quarter by 15°, the rudder angle to cope with the current for keeping straight course is as follows;

$$2\times 2.2\times \frac{1}{2}\rho A u^2 \sin\delta\cos\delta \times \frac{L}{2}$$

$$0.1\times \frac{1}{2}\rho\times 1^2\times 290\times 12\times L$$

$$1595\ \sin 2\delta = 348$$

$$\sin 2\delta = 0.2182$$

$$2\delta = 12.6^\circ,\ \delta = 6.3^\circ$$

(4) Computations of tracks of the vessel passing through the Pudo channel altering her course from 030° to 052°

$$r(t) = k\delta\,(1-e^{-\frac{t}{T}})$$

$$= 0.0173\times 15\,(1-e^{-\frac{t}{48}})$$

where,

$T' = 1.02$, L = 290,

$u_0 = 6.2$ m/sec, $r_s = 0.26$ deg/sec.

① In the case of no current:

$$\left.\begin{aligned} \phi(t) &= k\delta\int(1-e^{-\frac{t}{T}})dt \\ &= k\delta\,(t-T+T_e^{-\frac{t}{T}}) \\ x_i &= \sum_{i=0}^{130} u_0\cos\phi_i \\ y_i &= \sum_{i=0}^{130} u_0\sin\phi_i \end{aligned}\right\}\cdots(2.2)$$

where,

k : turning moment coefficient

T : yaw inertia coefficient.

② In the case of 2.8 kts current

$$\left.\begin{aligned} x_i &= \sum_{i=0}^{130}[u_0\cos\phi_i \\ &\quad + u_c\cos(15^\circ-\phi_i)] \\ y_i &= \sum_{i=0}^{130}[u_0\sin\phi_i \\ &\quad + u_c\sin(15^\circ-\phi_i)] \end{aligned}\right\}\cdots(2.3)$$

3. Simulation data and results

3.1 Conditions of the vessel and external forces

(1) Conditions of the vessel

L_{PP} : 290 m, Propeller diameter : 7.5 m

B : 46.8 m, Propeller pitch : 5.3 m

d_m : 12.0 m, Rudder area ratio : 1/60

C_B : 0.72, Rudder area : 58 m²

Disp. : 120,194 K/T, Aspect ratio : 1.5

Speed : 12 kts

Main eng. : SHP 45,000(Diesel)

(2) External conditions

The depth of the Pudo channel : h/d=1.25

Table 2.1 Tracks of the vessel

t time(sec)	r angular velocity (deg/sec)	ϕ heading change (deg)	x forward proceeded dist. from rudder ordered point(m)	y transverse dist. from the original course(m)	x_c dist. with current of 2.8 kts(m)	y_c dist. with current of 2.8 kts(m)
10	0.05	0.25	62	0.3	76	4.0
20	0.09	0.95	124	1.3	152	8.7
30	0.12	2.00	186	3.5	228	14.0
40	0.15	3.34	248	6.1	304	20.5
50	0.17	4.91	310	11.4	380	28.2
60	0.19	6.68	372	18.6	455	37.4
70	0.20	8.61	433	27.9	530	48.4
80	0.21	10.66	494	39.3	604	60.8
90	0.22	12.81	554	53.0	678	75.2
100	0.23	15.04	614	69.1	751	91.2
110	0.23	17.35	673	87.6	823	109.1
120	0.24	19.71	731	108.5	894	128.8
130	0.24	22.11	788	131.8	964	150.3

Wind direction :

From stb'd bows 25° (True 055°)

Current direction :

From port quarter 15° (True 225°)

Wind receiving area of the hull :

$A=1,733m^3$

$B=8,873m^3$

Coefficient of wind force : 1.2

Angle of wind force : $\alpha=70°$

Moment due to wind :

$$Ra \times \sin\alpha \times (0.5-a) \times L$$

$$I_z + i_z = 4I_z$$

3.2 Results of simulation

The figures of simulations conducted under various conditions are attached as Appendix 1. But the summarized results is shown in table 3.0.

Table 3.0 Results of simulations

current (kt)	used rudder angle(deg.)	wind speed(m/sec) 6	8	10	12
4	15	×	×	×	×
4	20	△	△	△	△
3	15	×	×	×	×
3	20	○	○	○	○
2	15	○	○	○	○
2	20	○	○	○	○
1	15	○	○	○	○
1	20	○	○	○	○

○ :maneuvering easy △ :difficult
× :impossible

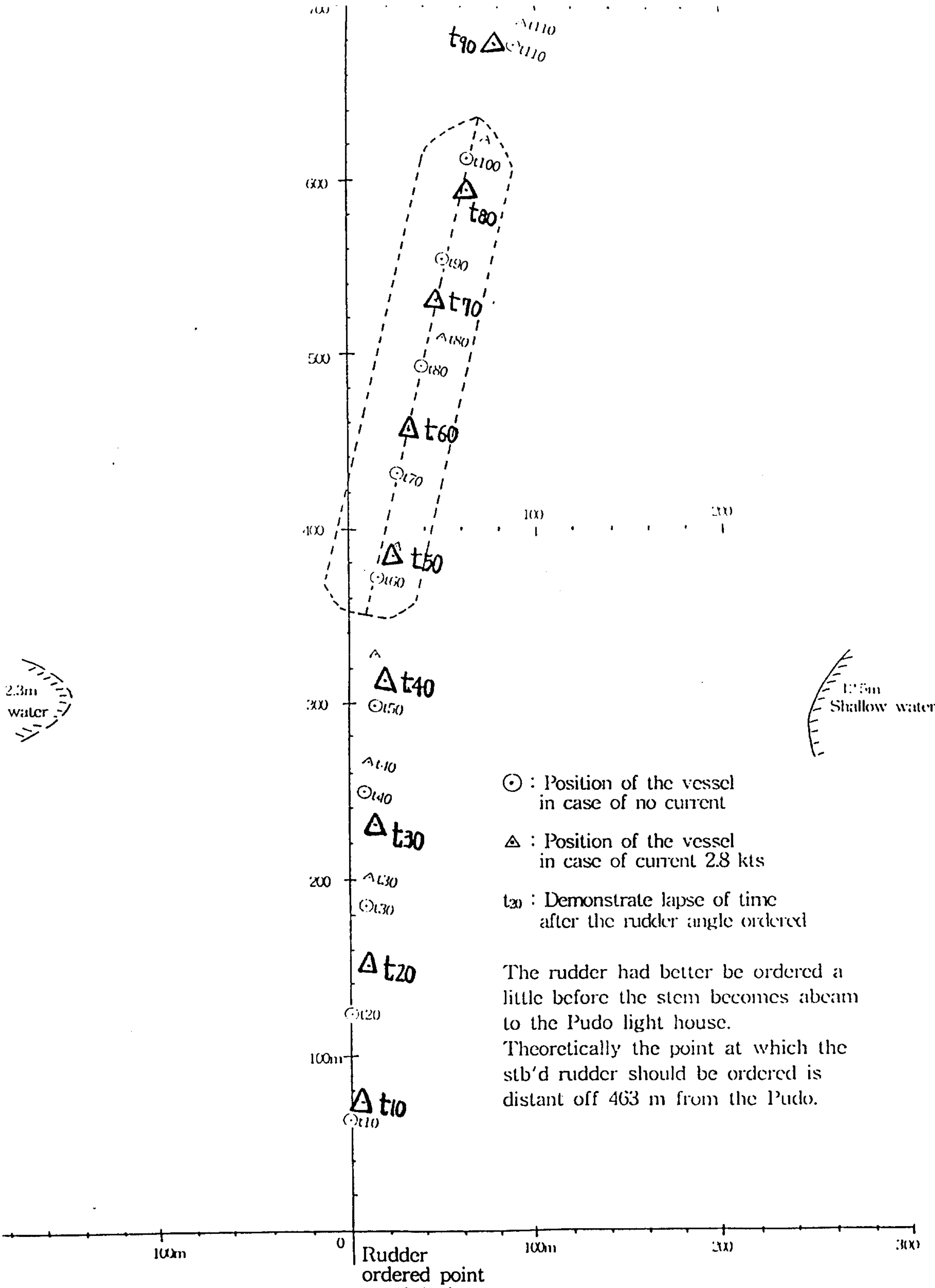

Fig. 2.2 The tracks of the vessel in the Pudo channel

4. Conclusion

(1) The computed results of maneuvering, the results of simulation and maneuverings of real vessels in the Pudo channel are well coincided with each others in qualitative aspects.

(2) The entering vessel of G/T 100,000 ton LNG had better pass through the Pudo channel at the last stage of flood tide to get sufficient under-water clearance near the pier of the LNG base.

(3) The limit speed of current allowable is 2.8 kts but the speed had better be limited to 2 kts for safe maneuvering.

(4) The maneuvering of the VLCC of LNG should be conducted with emergency precautions and the most strict alertness (see Appendix 2).

References

1. 尹点東, "巨大型船操船論", 亞成出版社, 1983.
2. 尹点東, "船舶操縱의 理論과 實務", 1993.
3. 尹点東, "Tanker 運用의 理論과 實務", 第一文化社, 1982.
4. 日本關西造船協會, "造船設計便覧", 海文堂, 1983.
5. 杉原喜義, "理論運用學(船體運動編)", 海文堂, 1967.
6. 岩井聰, "操船論", 海文堂, 1972.
7. 橋本進, "操船の基礎", 海文堂, 1988.
8. 本田啓之輔, "操船通論", 成山堂, 1986.
9. 日本造船學會, "第2回操縱性シンポジウム", 1970.
10. 日本造船學會, "第3回操縱性シンポジウム", 1981.
11. 日本造船學會(運動性能研究委員會), "操船の航行安全と操縱性能", 1987.
12. 三光汽船海務部, "巨大船の操船上の問題點", 1970.
13. 美國造船學會, "Principles of Naval Architecture", 1989.
14. 大韓民國水路局, "1996 潮汐表 第1卷", 1995.

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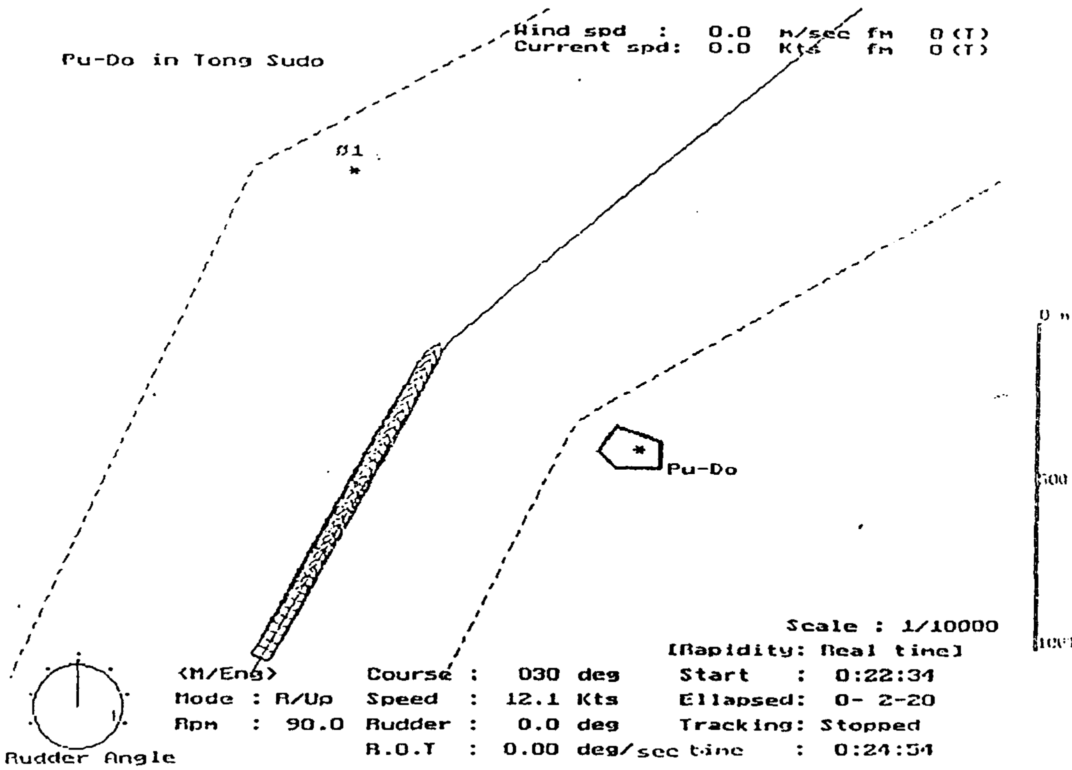
1999-Present : Professor of Korea Maritime University

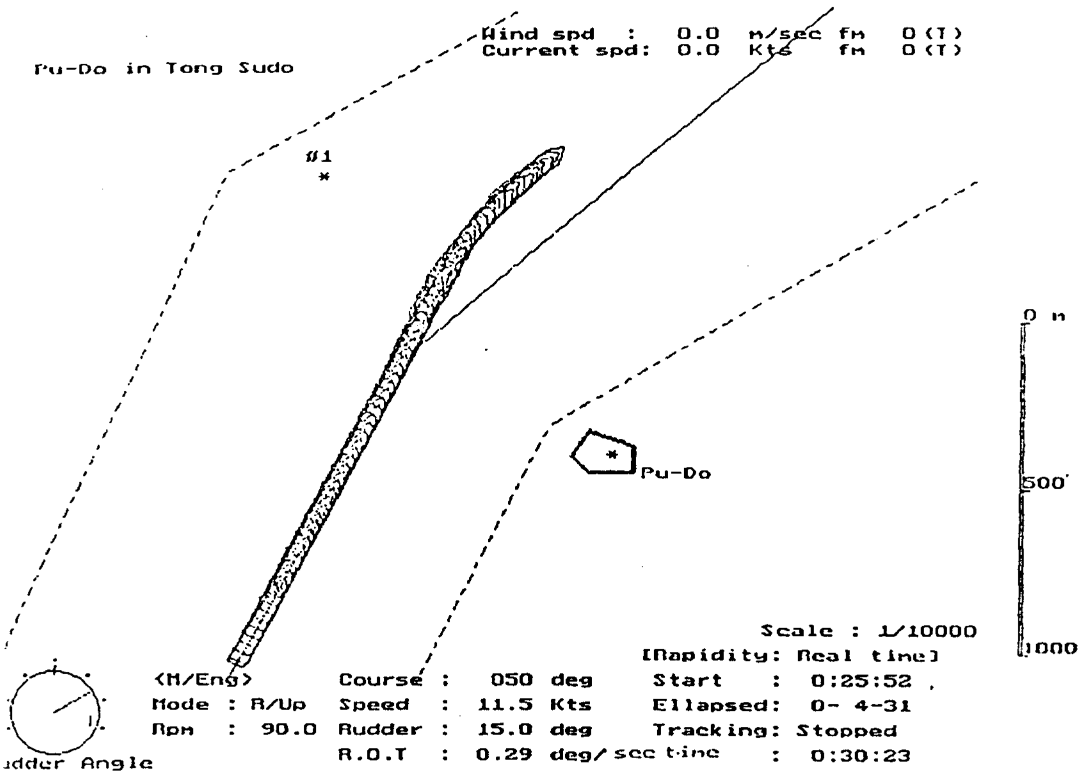
(Maritime Meteorology)

Appendix 1. Figures of simulations



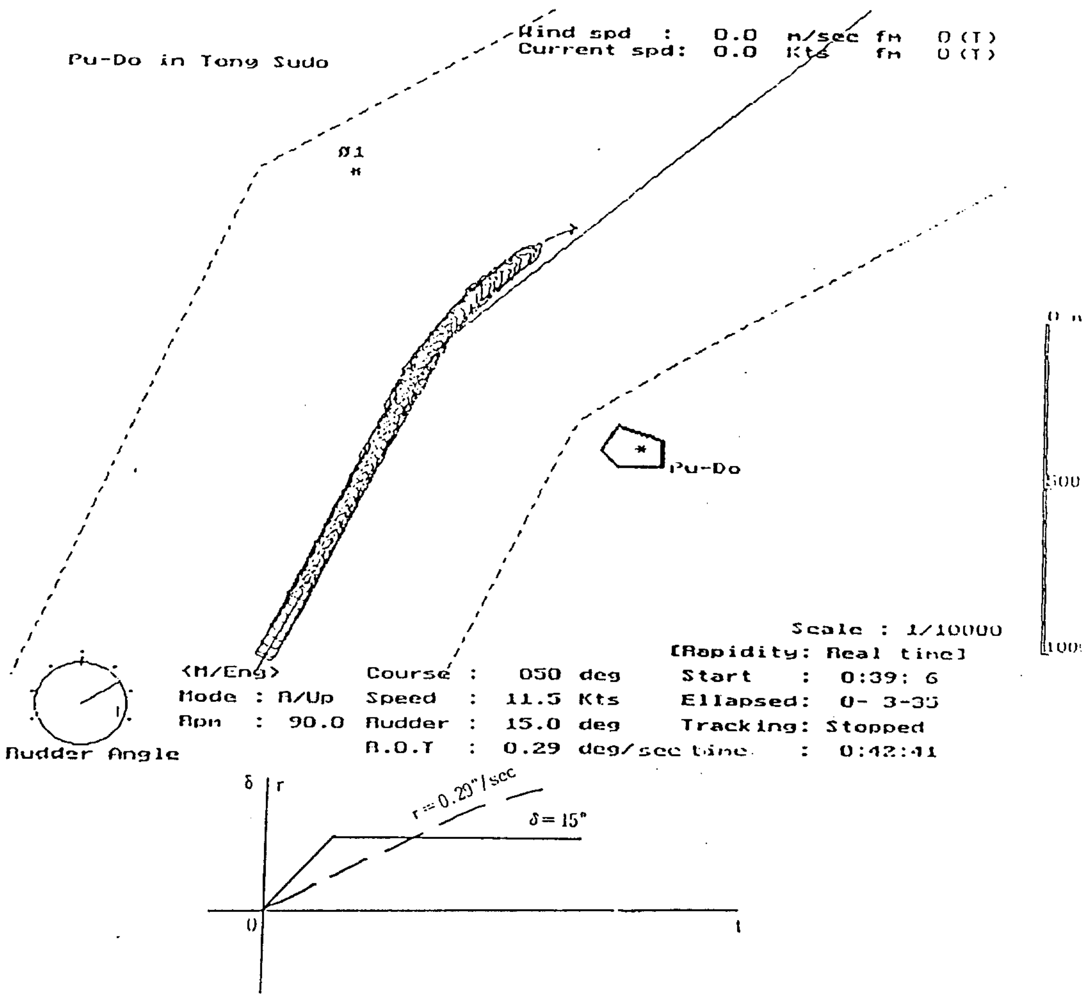
App. Fig. 1.1

The G/T 100,000 ton LNG vessel proceeds into the Pudo channel straightly with rudder mid-ships with no wind and current.



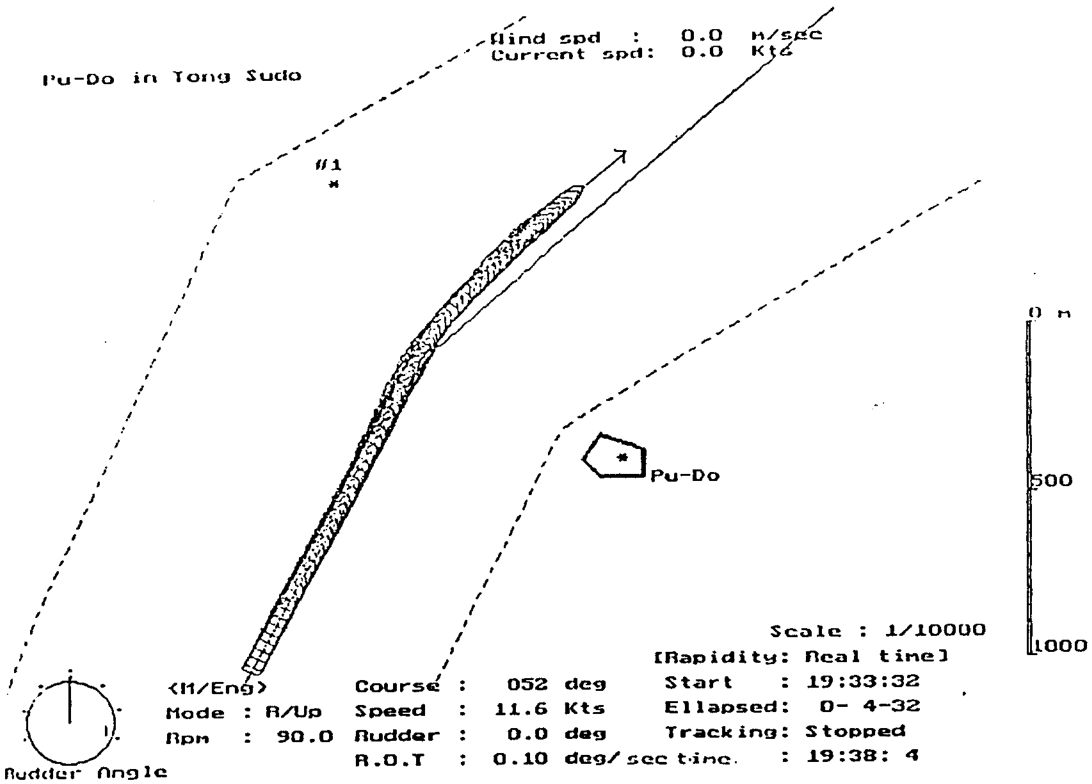
App. Fig. 1.2

Ordered stb'd 15° of rudder when the stem was abeam with the Pudo. Computation manifested rudder order of stb'd 15° at the point 1.7L off from the Pudo.



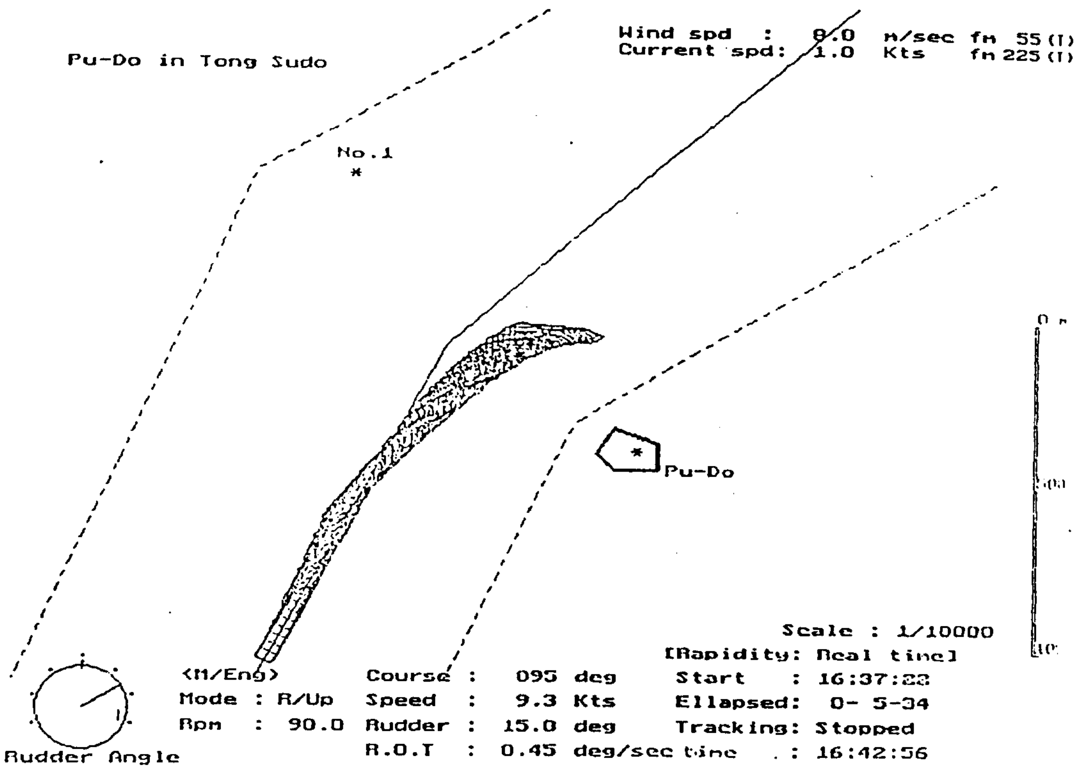
App. Fig. 1.3

Ordered stb'd 15° before the stem was abeam with the Pudo but she had to use contrary rudder angle due to the angular velocity of 0.29 deg/sec.



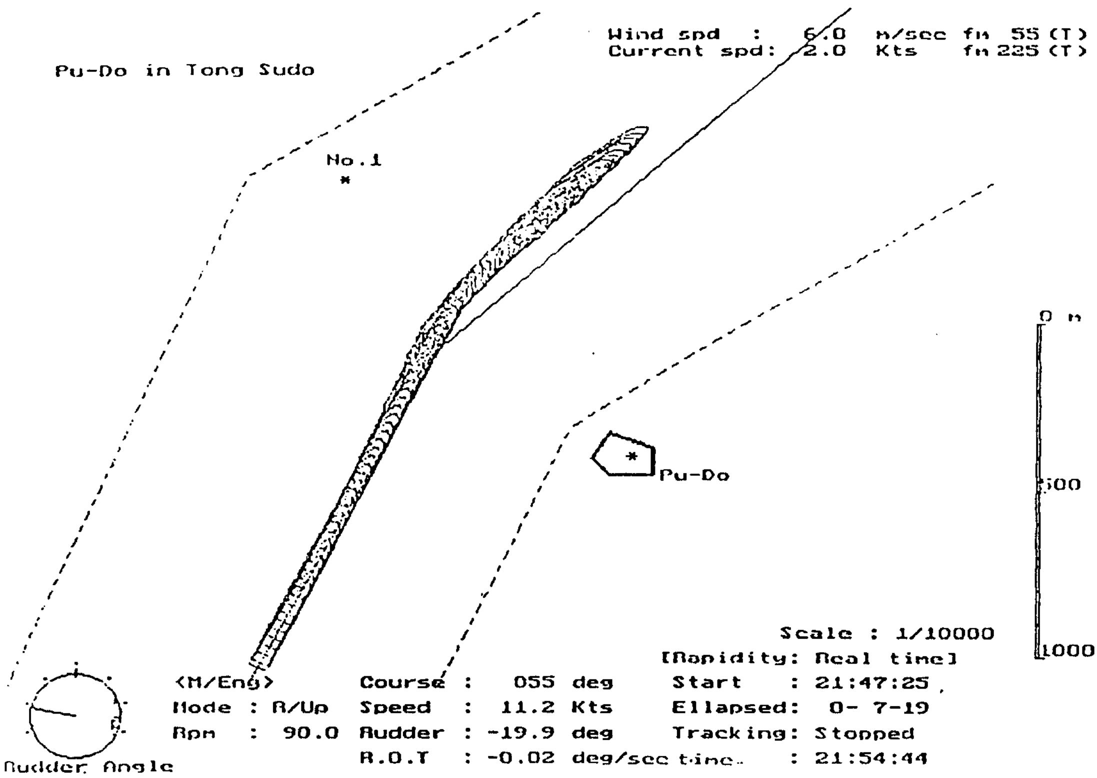
App. Fig 1.4

Before stb'd stem was abeam, ordered stb'd 15° and when the heading was of 043° (3 minutes and 18 seconds after rudder order), ordered port 20° and when the heading was of 049° (4 minutes after initial rudder order), ordered mid-ships and now she is steady on her course.



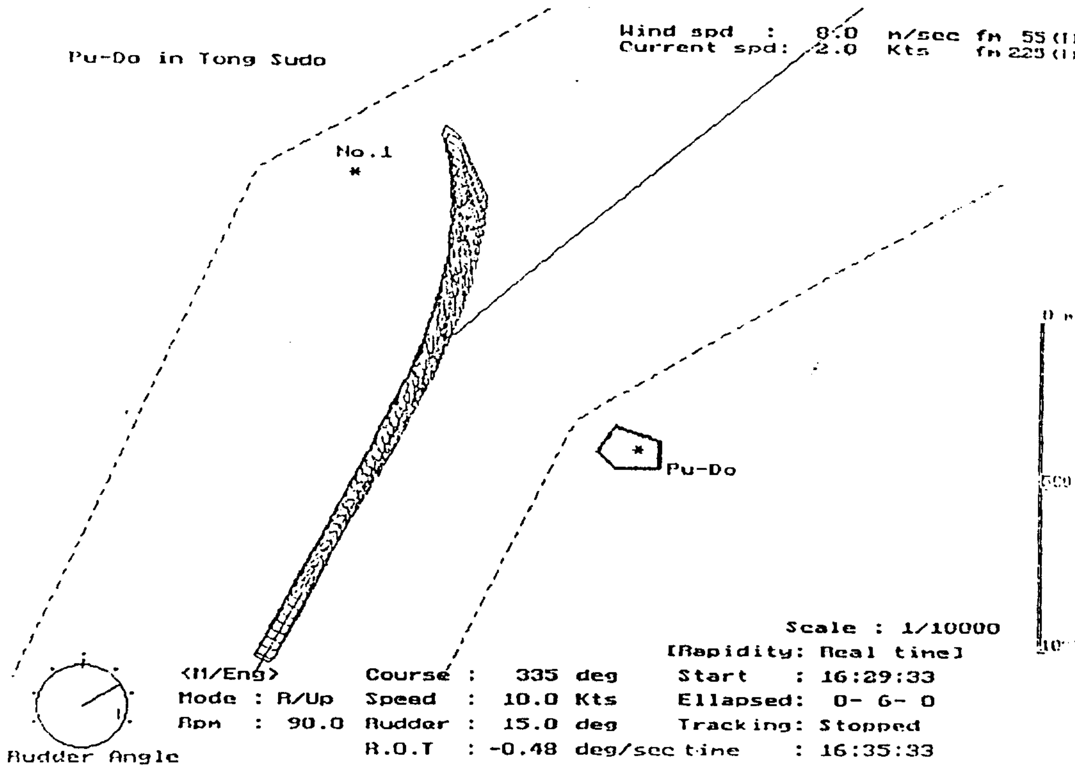
App. Fig. 1.5

Used stb'd 15° to keep steady on course but she turned to stb'd. So with smaller rudder angle than 15° she can keep her course. With 20° of rudder angle she can maneuver very easily. Current of 1 kt makes no problem.



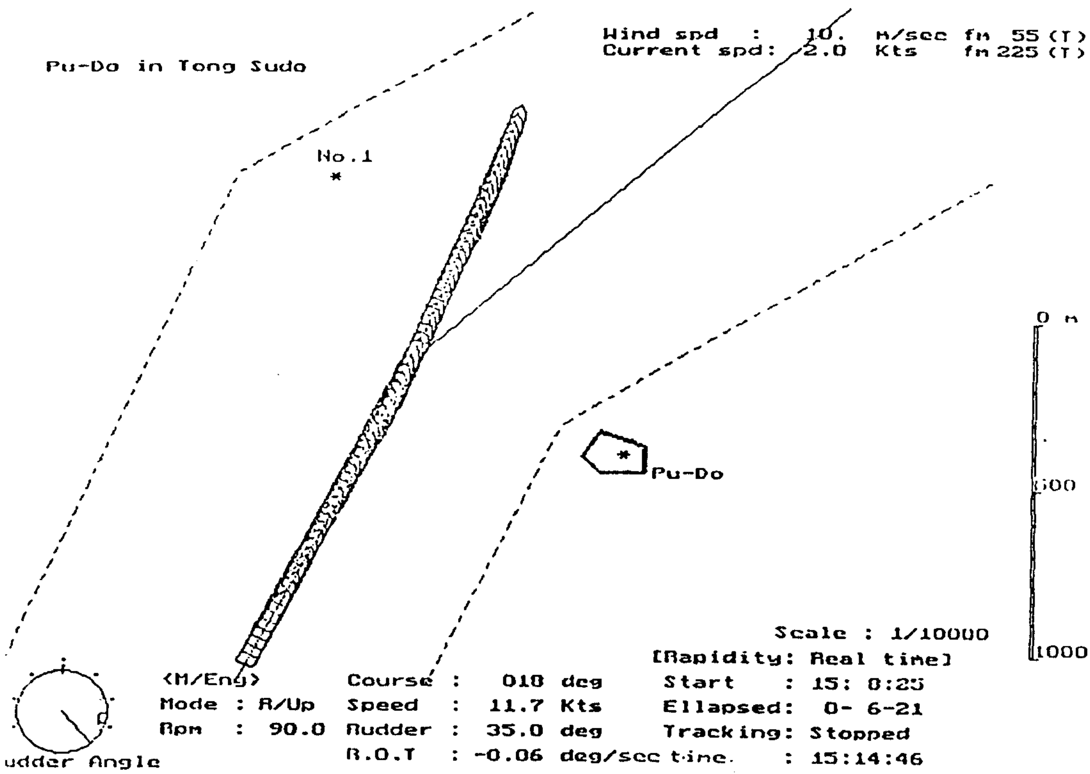
App. Fig. 1.6

It was impossible to keep course with stb'd 15° . So ordered hard stb'd a little before the stem was off 2L dist. from the course changing point and with hard rudder she was able to maneuver but she had to keep the hard rudder for some long time. Current of 2 kts commences to make problems.



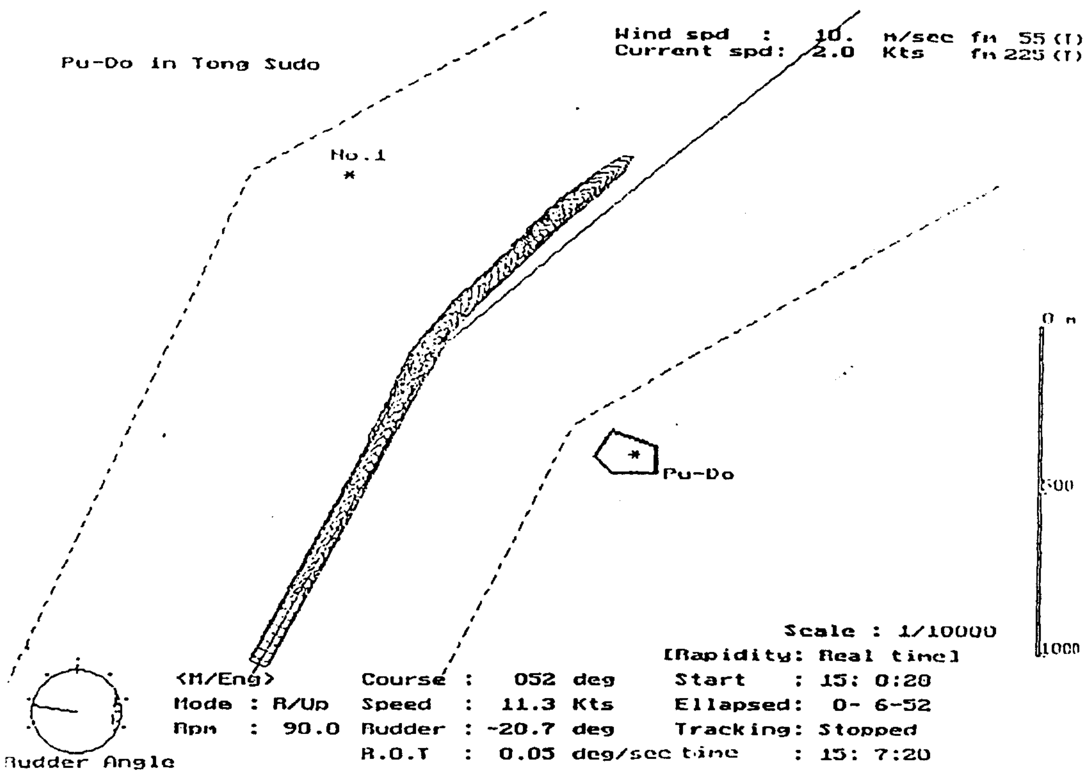
App. Fig. 1.7

Once she start to turn to port she could not return to her original course with stb'd 15° rudder.



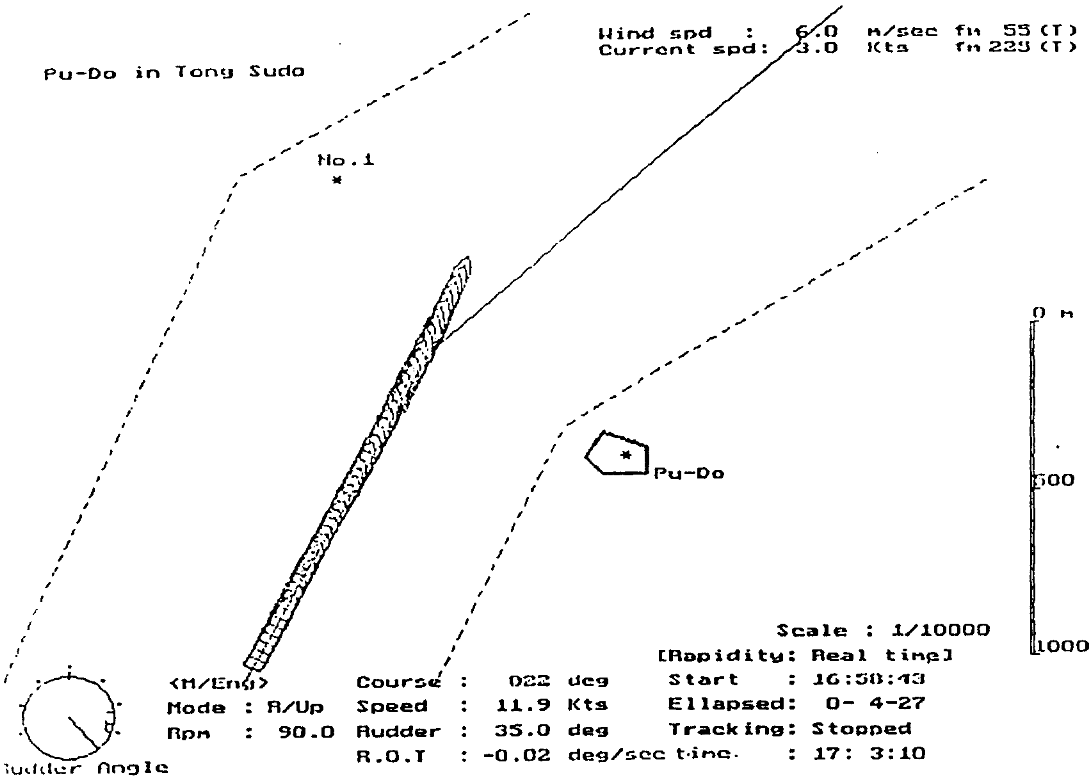
App. Fig. 1.8

As she turned gradually to port with stb'd 15°, ordered hard stb'd when the stem was off 2L dist. from the course changing point. Nevertheless, she turned gradually to port so it was impossible to keep course with stb'd 15°.



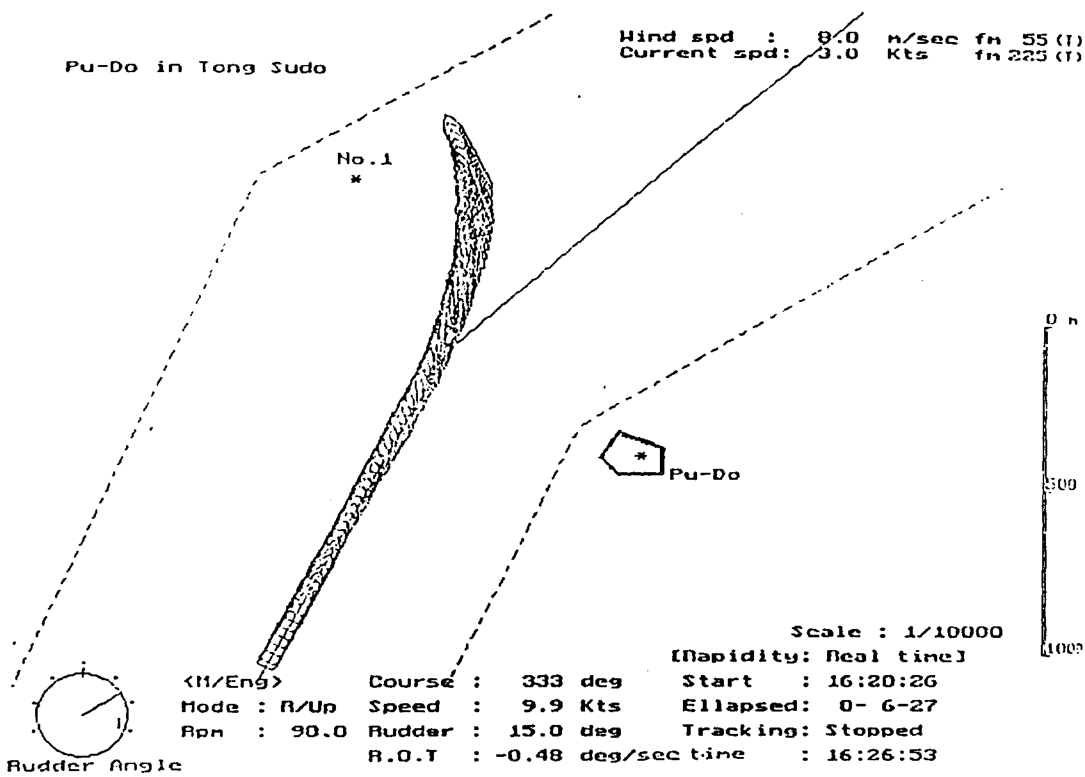
App. Fig. 1.9

She kept on course with stb'd 20° and when her stem was at 1.5L dist. from the course changing point, ordered hard stb'd rudder and then hard port rudder keeping her on the course.

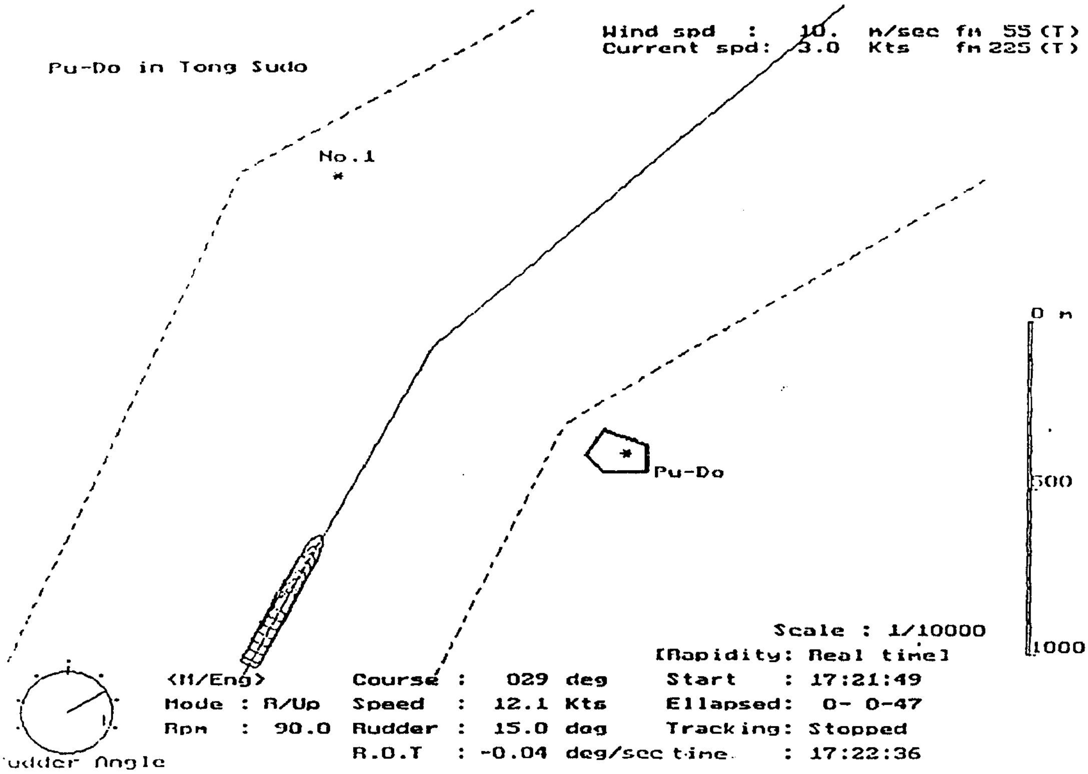


App. Fig. 1.10

Notwithstanding unable to keep course with stb'd 15°, proceeding with the same rudder angle, ordered hard stb'd when she was dist. 1.5L off from the course changing point and she did not returned to new curse with angular velocity of 0.02 deg/sec to port.

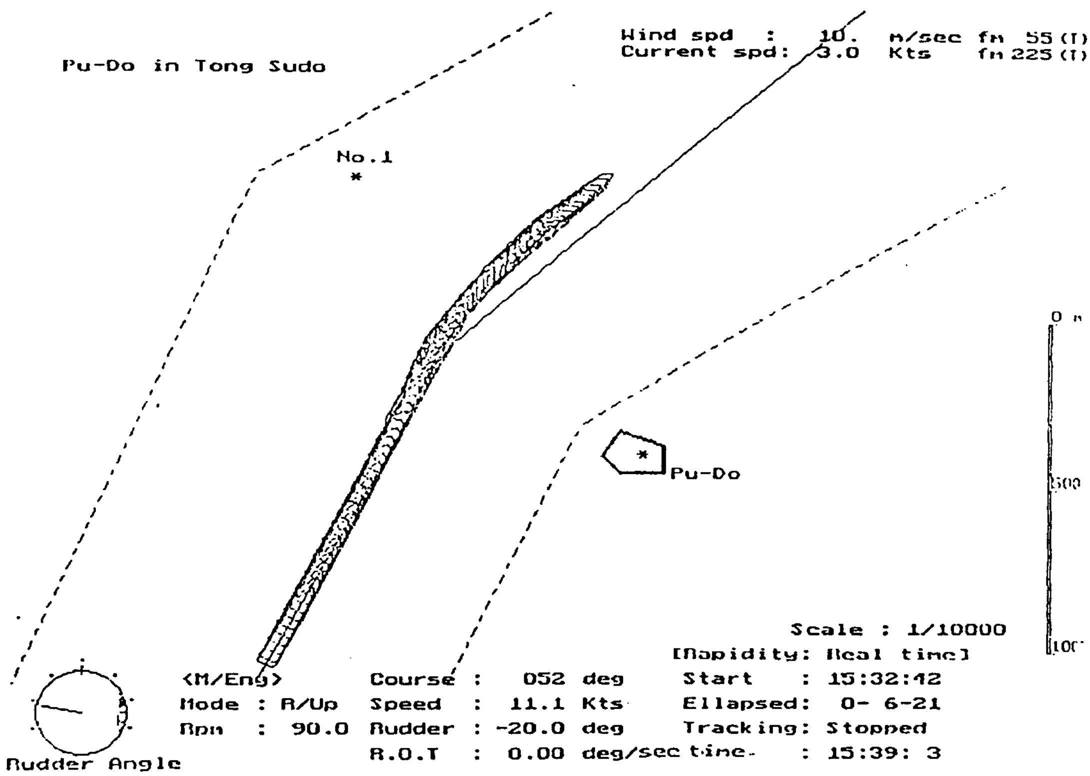


App. Fig. 1.11
Impossible to keep on her course with stb'd 15° .



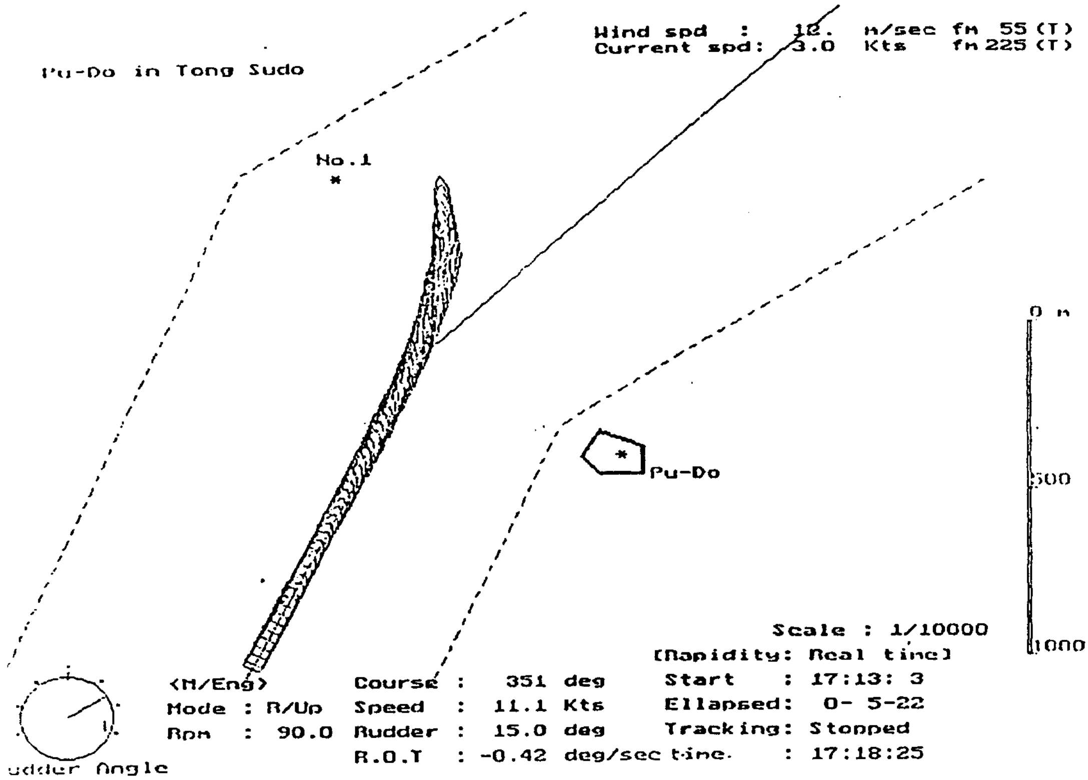
App. Fig. 1.12

Proceeded forward about 45 seconds with stb'd 15° turning gradually to port.



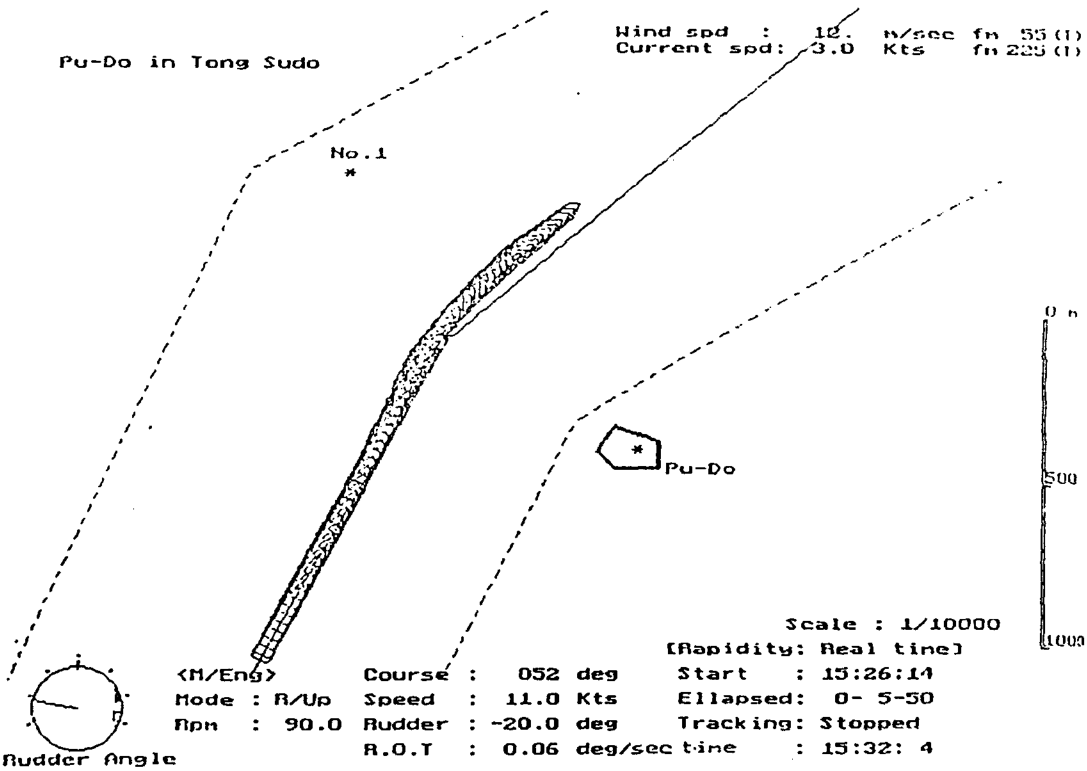
App. Fig. 1.13

Used stb'd 20° to keep on course and used hard stb'd to turn to stb'd but it was difficult to maneuver.

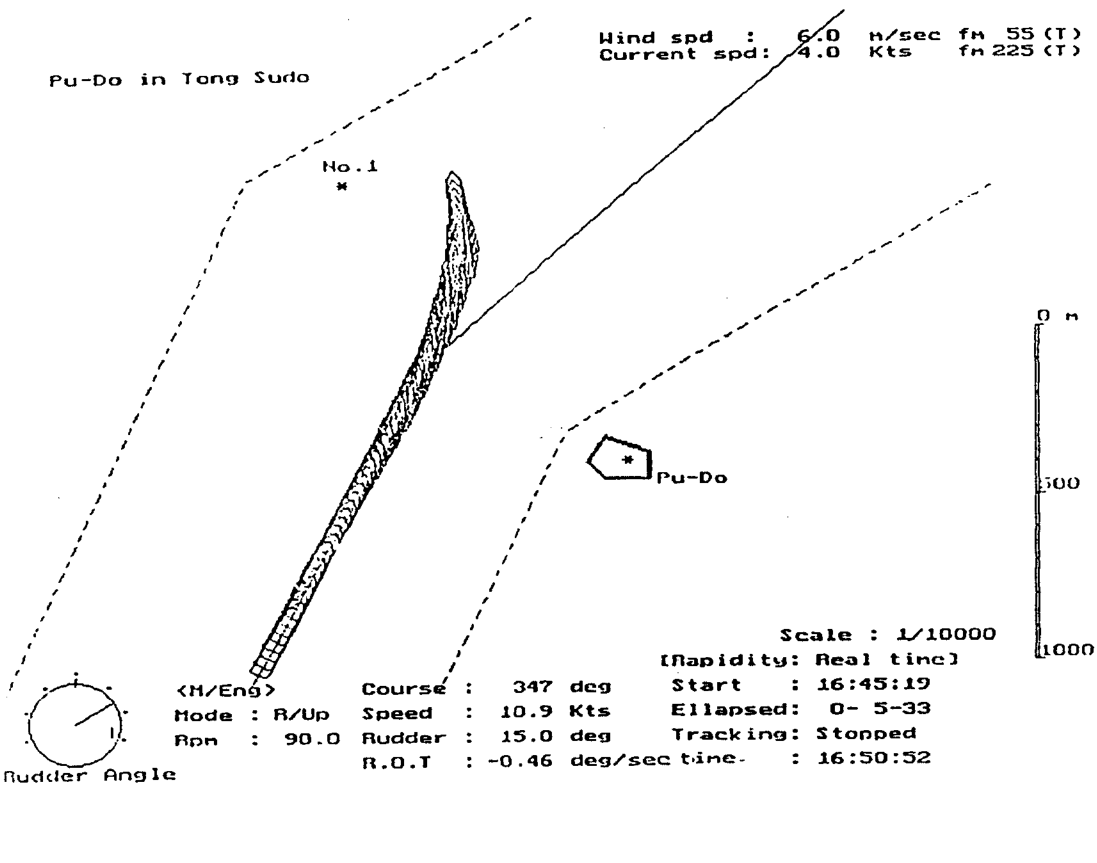


App. Fig. 1.14

Kept stb'd 15° to be steady on her course. It was not possible to keep on course.

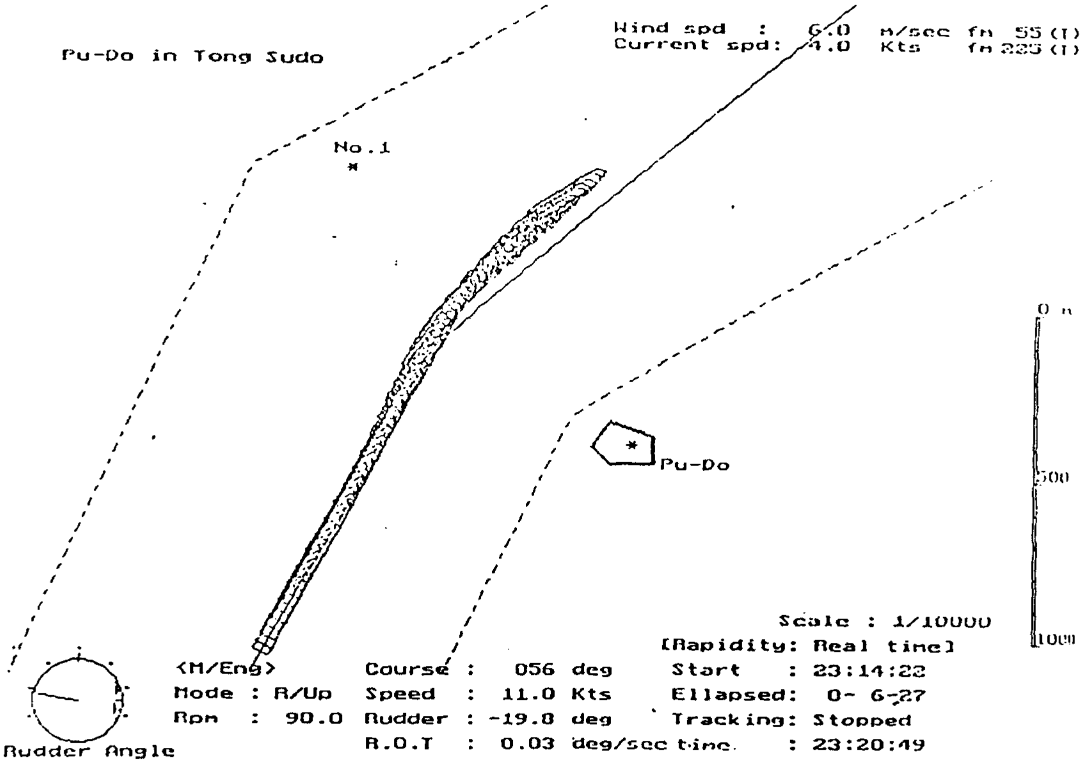


App. Fig. 1.15
Using 20° stb'd to keep on her course, used hard stb'd to change course.



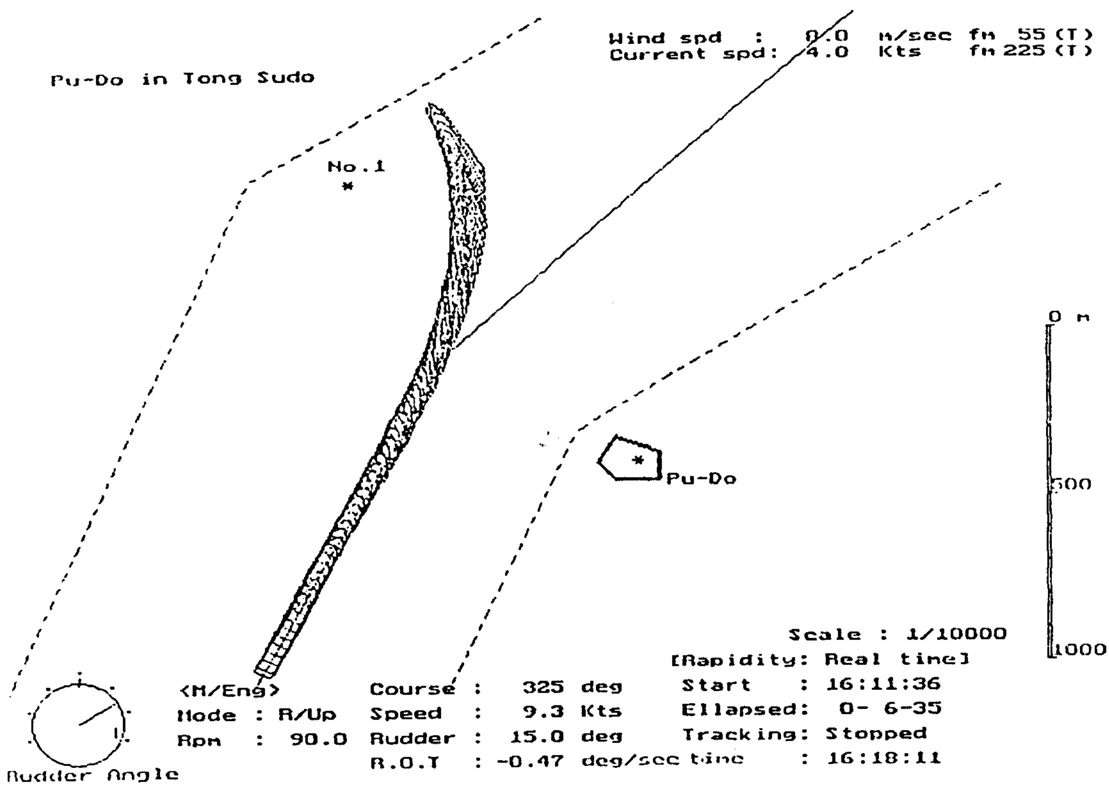
App. Fig. 1.16

Impossible to keep on her course with stb'd 15° .



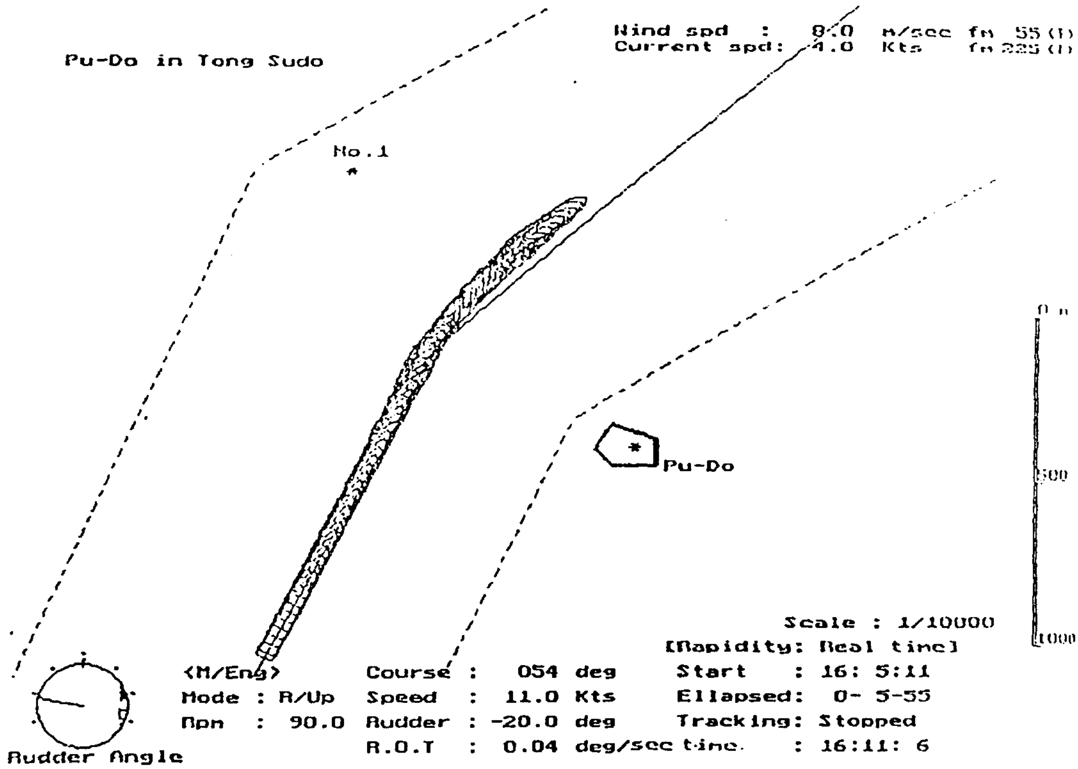
App. Fig. 1.17

Using 20° of coping rudder, maneuvered with hard rudders but actually it was impossible to make safe maneuvering.



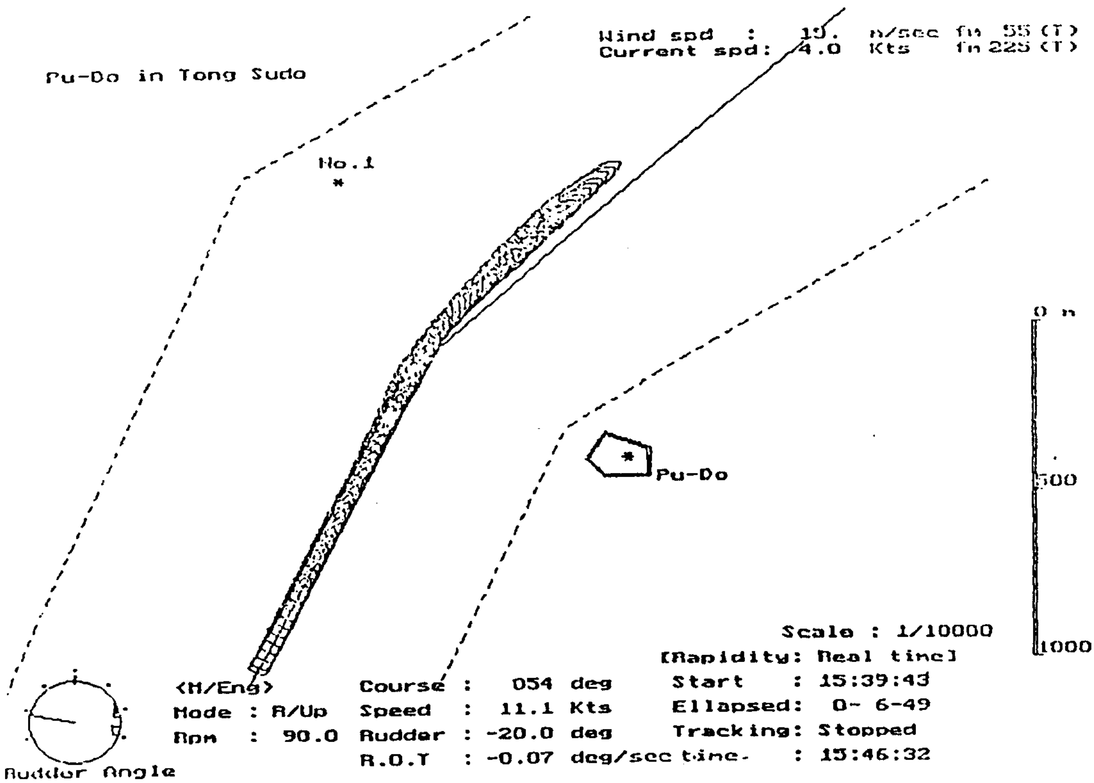
App. Fig. 1.18

Impossible to keep course with stb'd 15° .



App. Fig. 1.19

With coping rudder of stb'd 20° , maneuvered with hard rudders and it was far off from safe maneuvering.



App. Fig. 1.20

Using 20° of coping rudder, ordered hard stb'd to change course when she was dist. 2.5L off from the course changing point but it was very hard to be steady on her new course.

Appendix 2. Safety precautions for a LNG VLCC approaching to a narrow channel and LNG base

App. Table 2.0 Counter measure plan for safety

<table>
<tr><th colspan="2">Item</th><th>The outline of measures for safe conducting of the LNG VLCC</th></tr>
<tr><td rowspan="13">Entering and exiting to or from port</td><td>Pilots</td><td>2 pilots (main and co.)</td></tr>
<tr><td>Warning and guiding boat</td><td>Pilot station → berth (1 boat)</td></tr>
<tr><td>Fire fighting boat</td><td>1 boat equipped with foam distribution and 1 ordinary fire fighting boat</td></tr>
<tr><td>Emergency tow line</td><td>Fire wire with other necessary ropes each on the bow and stem</td></tr>
<tr><td>Tug boat</td><td>3,000HP×5(arriving) and 3,000HP×4(leaving)</td></tr>
<tr><td>Entering and exiting time</td><td>From sunrise to sunset</td></tr>
<tr><td>Rudder control</td><td>Not permissible to be controlled by the auto system</td></tr>
<tr><td>Overtaking</td><td>Not permissible to VLCC each other</td></tr>
<tr><td>Visibility</td><td>At least more than 1,000m</td></tr>
<tr><td>Wind force</td><td>Under only 12m/sec of max.</td></tr>
<tr><td>Swell</td><td>Under the height of 1.5m</td></tr>
<tr><td>Speed</td><td>Under 12 kts</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td rowspan="5">Getting or leaving a pier</td><td>Getting and leaving</td><td>From sunrise to sunset</td></tr>
<tr><td>Wind force</td><td>Under only 12m/sec of max.</td></tr>
<tr><td>Swell</td><td>Under 1.0~1.2m</td></tr>
<tr><td>Tug boat</td><td>3,000HP×5(alongside) and 3,000HP×4(leaving)</td></tr>
<tr><td>Approaching speed to pier</td><td>15m/sec, 10cm/sec and 5cm/sec</td></tr>
</table>

Appendix 3. Explanation of solving linearized equations of maneuvering motions

$$\left.\begin{aligned} & n_z' \dot{r}' - N_r' r' - N_v' v' = N_\delta' \delta \quad \cdots\cdots \text{①} \\ & m_y' \dot{v}' - (Y_r' - m')r' - Y_v' v' = Y_\delta' \delta \cdots\cdots \text{②} \end{aligned}\right\} \cdots\cdots (1.1)$$

$$\left.\begin{aligned} & v' = \frac{1}{N_v'}(n_z' \dot{r}' - N_r' r' - N_\delta' \delta) \\ & \dot{v}' = \frac{1}{N_v'}(n_z' \ddot{r}' - N_r' \dot{r}' - N_\delta' \dot{\delta}') \end{aligned}\right\} \cdots\cdots (1.2)$$

Inserting equation (1.2) into the equation ② of equation (1.1) we get equation(1.3).

$$\frac{m_y'}{N_v'}(n_z' \ddot{r}' - N_r' \dot{r}' - N_\delta' \dot{\delta}') - (Y_r' - m')r' - \frac{Y_v'}{N_v'}(N_z' \dot{r}' - N_r' r' - N_\delta' \delta) = Y_\delta' \delta$$

$$m_y' n_z' \ddot{r}' - m_y' N_r' \dot{r}' - m_y' N_\delta' \dot{\delta}' - N_v'(Y_r' - m')r' - Y_v' n_z' \dot{r}' + Y_v' N_r' r' + Y_v' N_\delta' \delta = N_v' Y_\delta' \delta$$

$$m_y' n_z' \ddot{r}' - (m_y' N_r' + Y_v' n_z')\dot{r}' + \{Y_v' N_r' + N_v'(m' - Y_r')\} r' = (N_v' Y_\delta' - Y_v' N_\delta')\delta + m_y' N_\delta' \dot{\delta}'$$

$$\frac{m_y' n_z'}{Y_v' N_r' + N_v'(m' - Y_r')}\ddot{r}' - \frac{m_y' N_r' + Y_v' n_z'}{Y_v' N_r' + N_v'(m' - Y_v')}\dot{r}' + r'$$

$$= \frac{N_v' Y_\delta' - Y_v' N_\delta'}{Y_v' N_r' + N_v'(m' - Y_r')}\delta + \frac{m_y' N_\delta'}{Y_v' N_r' + N_v'(m' - Y_r')}\dot{\delta}' \cdots\cdots (1.3)$$

The reason disposing the equations as (1.3) is as follows:
The equations (1.1) are two simultaneous differential equations of the first order in two unknowns, the horizantal-velocity component v' and the yaw angular velocity r'. The solutions for v' and r' correspond to the standard solutions of second order differential equations are as follows:

$$\left.\begin{aligned} & \text{yaw}: \quad a_{11}\dot{r}' + a_{12} r' + a_{13}\dot{v}' + a_{14} v' = a_{15}\delta \\ & \text{sway}: \quad a_{21}\dot{r}' + a_{22} r' + a_{23}\dot{v}' + a_{24} v' = a_{25} \end{aligned}\right\} \cdots\cdots (1)$$

where, $a_{11}= n_z' = I_z' - N_{\dot{r}}' \simeq 2I_z'$

$a_{12}=- N_r'$ $\quad a_{21}=- Y_{\dot{r}}' \simeq 0$

$a_{13}=- N_{\dot{v}}' \simeq 0$ $\quad a_{22}=-(Y_r' -m')$

$a_{14}=- N_v'$ $\quad a_{23}= m_y' =m' - Y_{\dot{v}}'\simeq 2m'$

$a_{15}= N_\delta'$ $\quad a_{24}=- Y_v'$

$a_{25}= Y_\delta'$

With rudder fixed ($\delta=0$) the differential eguations of (1) becomes homogenous. The general solutions of the homogenous eguations can written as:

$$\left.\begin{aligned} r' &= R_1' e^{\sigma_1' t'} + R_2' e^{\sigma_2' t'} = R' e^{\sigma' t'} \\ v' &= V_1' e^{\sigma_1' t'} + V_2' e^{\sigma_2' t'} = V' e^{\sigma' t'} \\ \text{and } \dot{r}' &= R'\sigma' e^{\sigma' t'}, \quad \dot{v}' = V'\sigma' e^{\sigma' t'} \end{aligned}\right\} \qquad \text{......(2)}$$

Substituting equation (2) into (1) which is a set of homogeneous equations when rudder angle is zero ($\delta=0$)

$$(a_{11}\sigma' + a_{12})R' +(a_{13}\sigma' + a_{14})V' =0$$

$$(a_{21}\sigma' + a_{22})R' +(a_{23}\sigma' + a_{24})V' =0$$

In order to have a non-trivial solution, the characteristic determinant must be zero ($\Delta=0$), which gives the dynamic course stability of the vessel.

$$\Delta=\begin{vmatrix} (a_{11}\sigma' + a_{12})(a_{13}\sigma' + a_{14}) \\ (a_{21}\sigma' + a_{22})(a_{23}\sigma' + a_{24}) \end{vmatrix} = A\sigma'^2+B\sigma+C=0 \qquad \text{......(3)}$$

where $A= a_{11} a_{23}- a_{21} a_{13}= n_z' m_y'$

$$B=\begin{vmatrix} a_{11} & a_{14} \\ a_{21} & a_{24} \end{vmatrix}+\begin{vmatrix} a_{12} & a_{13} \\ a_{22} & a_{23} \end{vmatrix} = a_{11} a_{24}+ a_{12} a_{23}=- n_z' Y_v' - m_y' N_r'$$

$$C= a_{12} a_{24}- a_{22} a_{14}= N_r' Y_v' - N_v'(Y_r' -m')$$

$$= N_r' Y_v' + N_v'(m' - Y_r')$$

Therefore the stability roots(or eigen values of the equations) are;

$$\sigma' =\frac{-B\pm\sqrt{B^2-4AC}}{2A} \quad (A>0,\ B>0,\ C>0 \text{ stable } \ C>0 \text{ unstable})$$

The angular velocity r' and transverse velocity v' are functions of t'.

So it can be written as follows:

$$(A\sigma^2+B\sigma+C)Re^{\sigma t}=0,\quad \frac{A}{C}\sigma^2+\frac{B}{C}\sigma+1=0,\quad (T_1+1)(T_2+1)=0$$

where, $T_1 T_2=\frac{A}{C}$, $T_1+ T_2=\frac{B}{C}$

For example:

$$\chi^2+\frac{3}{2}\chi+\frac{1}{2}=0 \rightarrow 2\chi^2+3\chi+1=0$$

$$\chi=\frac{-B\pm\sqrt{B^2-4AC}}{2A}=\frac{-3\pm\sqrt{9-4\times2\times1}}{2\times2}=\frac{-3\pm1}{4}$$

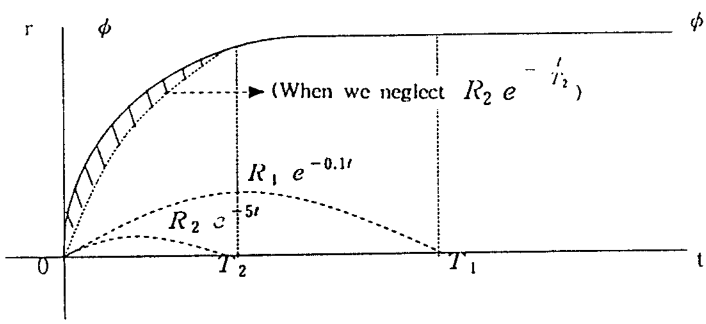
$$\chi=-\frac{1}{2} \quad \text{or} \quad -1$$

$$(2\chi+1)(\chi+1)=0 \rightarrow T_1\ T_2=2,\ T_1+T_2=3$$

$$(T_1\sigma+1)(T_2\sigma+1)=0$$

$$T_1=-\frac{1}{\sigma_1},\ T_2=-\frac{1}{\sigma_2}$$

From $r(t)=R_1 e^{\sigma_1 t}+R_2 e^{\sigma_2 t}=R_1 e^{-\frac{t}{T_1}}+R_2 e^{-\frac{t}{T_2}}$, if we assume $\sigma_1=-0.1$, $\sigma_2=-5$, then $r(t)=R_1 e^{-0.1t}+R_2 e^{-5t}$



App. Fig. 3.1 Head angle change due to σ_1 and σ_2