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Stopping manoeuvre of high speed vessels fitted with screw and waterjet propulsion

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Concern about the increase in high-speed vessel traffic necessitates steps to bring out safety guidelines in order to regulate and improve their manoeuvrability. The stopping abilities of vessels ranging from medium speed containerships to high-speed vessels have been estimated. Assuming a straight contour track, the stopping distances have been checked against the known stopping criteria of IMO

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INTRODUCTION

Conventional passenger vessels are being increasingly replaced by high-speed vessels (HSVs), which are becoming more popular due to their speed. The continued growth in the size and speed of fast vessels has made their design, construction and operation a challenge. There is considerable research interest in the development of high-speed transport vessels. Researchers are being pushed to design hybrid hull forms that are both fast and safe. These fast vessels should have good stability, seaworthiness and provide an easy ride. The manoeuvring behaviour of a high-speed vessel is important for its safety and operational efficiency. However, the prediction of vessels behaviour experimentally is a complex process. Reducing the risk of collision falls with good design (assuming the handling of the vessel is safe). The concern about safety of the rapidly growing high-speed vessels necessitates steps to bring out guidelines to regulate and improve their manoeuvrability.

Marine diesel engines are often not run at full power in order to ensure that adequate power is available to drive a conventional fixed-pitch propeller throughout its speed range. Sung and Rhee[1] presented a numerical study to estimate the stopping ability of diesel vessels with fixed pitch propeller and comparisons were made with the sea trial measurements. Yabuki *et al*,[2] based on their experimental and simulation studies, reported that vessels fitted with controllable pitch propellers are less stable during stopping manoeuvre, particularly in windy condition. The use of waterjet propulsion for large, high-speed ferries allows the designer to maximise the performance at high power output without having to compromise for lower speeds and emission control. High-speed vessels show hump in the resistance curve, particularly when they operate in planing or semi-planing modes. The conventional screw propulsion system may not respond adequately to such a situation where the vessel has to accelerate from the displacement mode to the planing/semi-planing mode. This problem is not present in vessels with waterjet propulsion systems (Hunt[3]).

Manoeuvring, stopping, reversing and docking are achieved much more efficiently in vessels fitted with waterjet propulsion than those with screw propulsion. The use of waterjets in high-speed vessels is becoming popular due to their better applicability in shallow waters. Other advantages include safety (absence of an open rotating blade), minimal damage susceptibility to floating debris, a good pickup, less turbulent wake, minimal appendage drag, less cavitation and low internal noise, etc.

Self-propelled, free-running model tests are an efficient way of determining the manoeuvring characteristics of a vessel. But the high speed of HSVs and their light displacement combined with waterjet propulsion makes conventional manoeuvring tank facilities inadequate for performing free-running model tests. Manoeuvring characteristics may depend highly on speed for vessels with a Froude number greater than 0.25~0.3. The extrapolation of manoeuvring characteristics obtained through model tests at low vessel speeds to the high-speed range is not reliable (Perdon[4]). The classical approach of predicting the manoeuvring performance of a vessel is to generate a database of hydrodynamic coefficients of a particular vessel to be included in a manoeuvring simulation. This approach is time-consuming and expensive.

STOPPING MANOEUVRE OF VESSELS WITH SCREW PROPULSION

In a stopping manoeuvre, the vessel trajectory is generally curved (Fig 1), with the curved track length termed as *track reach*. The terms *lateral deviation* and *head reach* respectively represents the lateral and longitudinal displacements of the vessel from the original approach phase. The track is curved due to the additional drag and other extraneous effects on the vessel during the stop manoeuvre. The behaviour of a vessel is complex in a stopping manoeuvre. Some simplifications make the mathematical formulation easier without loss of the stopping manoeuvre generalities. A simpler option to the track contour is a straight one, which makes the mathematical modelling simple, and such a track offers less drag resulting in a longest possible track reach in a stop manoeuvre. This is a safer predicted estimate of the stopping distance.

The equation of motion of a vessel with a displacement Δ moving with a speed U in stopping manoeuvre can be represented as below (Clarke and Hearn[5]):

$$\frac{\Delta(1+k_1)}{g}\frac{dU}{dt} = -T(n, U, t) - R(U) \qquad (1a)$$

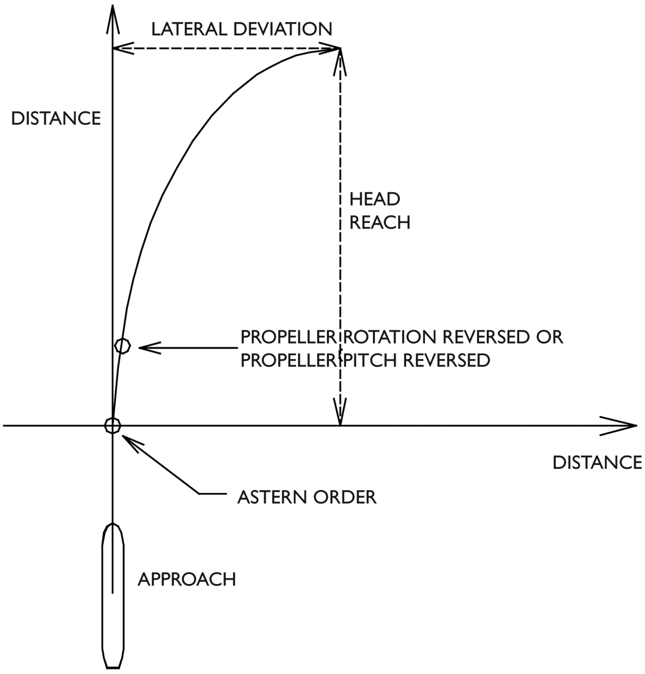


Fig 1: Stopping manoeuvre

Where k_1 is the longitudinal added mass coefficient, T is the propeller thrust (which depends on the propeller revolution n, the vessel speed U and time t), R is the vessel resistance depending on vessel speed U. The displacement of the vessel is given in terms of the acceleration due to gravity (g), water density (ρ), length between perpendiculars (L), breadth (B), draughts (T) and block coefficient of the vessel as follows:

$$\Delta = g\rho\nabla = g\rho LBTC_B \qquad (1b)$$

The thrust changes from T_F (thrust at forward approach speed) to T_A (aft-ward thrust) linearly with time until T_A reaches the maximum constant reverse thrust value, as shown in Fig 1, which continues until the vessel is stopped. Equation (1a) can be split as follows, up to the time at which the reverse thrust is achieved (t_r) and the other beyond this.

$$\frac{\Delta(1+k_1)}{g}U\frac{dU}{ds} = -(T_A+T_F)\frac{t}{t_r} - R\left(\frac{U}{U_0}\right)^2 \qquad (2a)$$

$$\text{for } O < t > tr$$

$$\frac{\Delta(1+k_1)}{g}U\frac{dU}{ds} = -T_A - R\left(\frac{U}{U_0}\right)^2 \text{ for } t > tr \qquad (2b)$$

Here s is the distance travelled by the vessel along the track, R_0 is the ahead resistance in the approach speed U_0. D'Archangelo[6] presented the track reach S_T of the vessel by solving the equations (2a) and (2b) as follows:

$$S_T = \left[\frac{\Delta(1+k_1)U_0^2}{2gR_0}\log_e\left(1+\frac{R_0}{T_A}\right)\right] + 0.5U_0t_r \qquad (3)$$

Equation (3) is rewritten below by non-dimensionalising the track reach by L, ($S=S_T/L$), as IMO[7]

$$S = A\log_e(1+B) + C \qquad (4a)$$

where

$$A = \frac{\Delta(1+k_1)U_0^2}{2gR_0L} \tag{4b}$$

$$B = \frac{R_0}{T_A} \tag{4c}$$

$$C = \frac{0.5U_0t_r}{L} \tag{4d}$$

The displacement is given by equation (1b) and the resistance R_0 at the approach speed U_0 is given by

$$R_0 = 0.5\rho C_T U_0^2 A_{WS} \tag{5}$$

where C_T is the total resistance coefficient of the vessel at the approach phase and A_{WS} is the wetted surface area of the vessel.

Alternatively,

$$R_0 = -0.5\rho U_0^2 L^2 X'_{uu} \tag{6a}$$

where

$$X'_{uu} = -SC_T/L^2 \tag{6b}$$

Equations (1b) and (6) in equation (4b) results in the following equations:

$$A = -\frac{2B'T'C_B(1+k_1)U_0^2}{2X'_{uu}} = -\frac{m' - X'_{\dot{u}}}{2X'_{uu}} \tag{7}$$

where

$$B' = B/L \quad T' = T/L$$

$$m' = 2LBTC_B/L^3 \quad X'_{\dot{u}} = -k_1 m'$$

The thrust of a propeller in astern condition is given by

$$T_A = \rho n^2 D^4 K_T \tag{8}$$

where n is the propeller revolutions, D its diameter and K_T is the thrust coefficient for zero advance velocity.

The propeller torque in astern condition, with the torque coefficient at zero advance velocity (K_Q), is

$$Q_A = \rho n^2 D^5 K_Q \tag{9}$$

The astern power available per shaft for the vessel is (N = total number of shafts)

$$\frac{P_A}{N} = 2\pi n Q_A \tag{10}$$

From equations (9) and (10), it follows that

$$\frac{P_A}{N} = 2\pi\rho n^3 D^5 K_Q \tag{11}$$

Equation (11) can be rearranged as

$$n^2 = \left(\frac{P_A}{2\pi\rho D^5 K_Q N}\right)^{2/3} \tag{12}$$

Equation (12) in place of n^2 in equation (8) gives the total thrust astern as

$$T_A = (\rho N)^{1/3}\left(\frac{P_A D}{2\pi}\right)^{2/3}\left(\frac{K_T}{K_Q^{2/3}}\right) \tag{13}$$

Substituting equation (4c) in equation (13) and $R_0 = P_E/U_0$, where P_E is the effective power in the approach phase, the coefficient B can be represented as

$$B = \frac{P_E/U_0}{(\rho N)^{1/3}\left(\frac{P_A D}{2\pi}\right)^{2/3}\left(\frac{K_T}{K_Q^{2/3}}\right)} \tag{14a}$$

Equation (14) takes the following form with the use of equation (6a) and the relation $P_E = \eta_D P_S$, where η_D is the quasi propulsive coefficient and P_S is the shaft power.

$$B = \frac{(-0.5\rho X'_{uu})^{1/3}(\eta_D L P_S)}{(\rho N)^{1/3}\left(\frac{P_A D}{2\pi}\right)^{2/3}\left(\frac{K_T}{K_Q^{2/3}}\right)} \tag{14b}$$

This can be rearranged as

$$B = \left[-\frac{-2\pi^2 X'_{uu}}{N}\right]^{1/3}\left[\frac{\eta_D}{(D/L)(P_A/P_S)}\right]^{2/3}\left[\frac{1}{K_T/K_Q^{2/3}}\right] \tag{14c}$$

The coefficient B can be estimated by knowing the vessel resistance coefficient X'_{uu}, propeller diameter, ratio of the astern-power to ahead-power, quasi-propulsive coefficient of the propeller and the factor $K_T/K_Q^{2/3}$.

Rearranging equation (4d), the coefficient C can be written as

$$C = \frac{t_r}{2L/U_0} \tag{15}$$

which shows that the coefficient C depends on the vessel size, speed and time taken to get the reverse thrust.

STOPPING MANOEUVRE OF VESSELS WITH WATERJET PROPULSION

The steering of a vessel propelled by waterjets is generally by the deflection of the jets. For large waterjets, the deflection is usually accomplished by rotating a steering sleeve. A steering sleeve consists of a duct of somewhat larger width than the jet and about two to three jet diameters in length, depending on the type. The sleeve may have a bell-mouth entry to ensure that the entire jet enters the sleeve when it is fully deflected. Steering angles for the sleeve are usually about ±30 deg. Some waterjets use a type of nozzle rather than a sleeve. Regardless of the details of the method used to deflect the jet, the steering effect is a function of the gross thrust of the jet and the angle through which the jet is deflected.

Waterjets provide very good manoeuvring at low speed, because the reversing buckets may be set at intermediate positions where only part of the jet flow is intercepted and reversed. There is a wide range of forward and reverse thrust including a neutral position, which is obtainable at a fixed engine speed merely by adjusting the reversing bucket position. In addition, the steering gear allows thrust vectoring for both ahead and astern operation. A vessel operating with waterjets can be moved sideways for docking or undocking by manipulation of the waterjet operations, which needs an experienced operator.

For a vessel with waterjet propulsion, the effects of rudder and propulsion in the excitation force part of the equations of motion are replaced by the action of the waterjet in the deflected position. The theoretical formulation presented by Perdon[4] for the waterjet thrust variation and manoeuvring forces have been adopted here to account for the propeller and rudder contributed components of the excitation.

The waterjet overall thrust variation is expressed as

$$T(v, r, \delta) = T_a(1 - |v' - 0.33r'|)^{0.6}\sqrt{1 - 0.4\sin|\delta|\sqrt{\delta}} \qquad (16)$$

T_a is the thrust for approach speed during straight course. The term $\sqrt{1 - 0.4\sin|\delta|\sqrt{\delta}}$ in the above equation takes care of the loss of thrust due to the bucket deviation and the term $(1 - |v' - 0.33r'|)^{0.6}$ account for the effects of the drift velocity in the vicinity of the inlet on the inflow water to the waterjet.

Control forces due to bucket deflection δ are expressed through projection of thrust as below:

$$X_\delta = T\cos 2\delta \qquad (17a)$$

$$Y_\delta = T\sin 2\delta \qquad (17b)$$

$$N_\delta = x_J Y_\delta \qquad (17c)$$

where x_J is the distance of the jet bucket from the vessel centre of gravity.

The angle considered is twice the bucket deflection because the bucket does not act as a perfect deflector and the maximum lateral force is obtained for 45 deg rather than for 90 deg.

Waterjets fitted with reversing gear are capable of exerting enormous stopping power when the vessel in which they are fitted is at a speed. This is because the net reverse thrust applied is the sum of the gross thrust (less losses) and the momentum drag. It is not practical to turn the jet through a full 180 deg reversal, so the jet is deflected downwards and forward as much as possible with respect to the vessel. In some designs the jet is divided into two parts and deflected downwards and sideways as well as forward. For maximum effect, it is desirable that the reversed jet flow should clear the hull of the vessel as much as possible. Flow impinging on the stern will apply a forward thrust, which is not required during braking, stopping or going astern. The downward deflection of the jet will produce a large vertical force creating a bow-down moment on the vessel, which may increase the danger of plough-in in some types of hull.

The braking force achieved, with the jet having a forward velocity component V_f, is given by

$$F_B = mV_f + D_m \qquad (18)$$

where D_m is the momentum drag given by the water mass flow rate (m) and vessel speed (V_S). That is,

$$D_m = mV_S \qquad (19)$$

The braking force given by equation (18) is much more than the net forward thrust of the propulsor if full reverse thrust is applied, and resistance of the hull adds to it. But, full reverse thrust is usually not applied unless an emergency crash-back situation becomes necessary.

From a propulsion machinery point of view, there is no problem in generating full reverse thrust at high forward speed by applying full engine power. It makes no difference to the engine or pump what happens to the jet after it leaves the nozzle or at what speed the vessel is moving forward, provided it is high enough to avoid pump and inlet cavitation. In a crash-back situation, engine power must be reduced sufficiently after the initial deceleration, as the chance of formation of cavitation is high while the vessel approaches towards a stop (Allison and Dai[8]).

STOPPING MANOEUVRE CRITERIA

The International Maritime Organization is responsible for setting up standards for safety in marine operations and for the prevention and control of marine pollution. The manoeuvring characteristics put forward by IMO interim standards for vessel manoeuvrability are the measure of a vessel's performance, quality and handling ability. These can be predicted at the design stage and can also be measured easily for model tests or for vessel trials.

The criteria for the assessment of vessel manoeuvring characteristics proposed by IMO's Marine Safety Committee, which is a sub-committee on Ship Design and Equipment, (Daidola *et al*[9]), places the following assessment for a vessel's stopping ability:

> 'Stopping ability: Stopping ability is measured by the "track reach" and "time to dead in water" realised in a stop engine/full astern manoeuvre performed after a steady approach at full test speed. Lateral deviations are also of interest, but these are very sensitive to the initial conditions and wind disturbance.'

The above abilities and qualities of a vessel are assessed in its initial design stage using theoretical/numerical methods or by using pre-determined empirical expressions. Better understanding is reached by performing model tests, which are only possible towards the final stages of the design. The real values of the above characteristics in a practical environment are obtained by conducting full-scale sea trials, which is mandatory for newly built vessels prior to the operation of the vessel.

IMO Interim Standards

The IMO Interim Standards specify several manoeuvring qualities and the vessel should be consistent with their specific criteria. They are to be evaluated with manoeuvring tests performed in deep unrestricted water, a calm environment, and with steady approach at test speed. The specified standards of manoeuvring are for the vessel at full load and even-keel conditions. Values obtained from tests performed at any other condition should be corrected to the specified conditions. The specified criteria are explained below (Palomares[10]).

> Stopping ability is the measure of the vessel's capacity to stop within a certain distance (track reach) when full engine astern is applied to a vessel sailing at full test speed. The track reach should not exceed 15 vessel lengths except for very large vessels, where the Administration/Authority may decide on the criteria to be applied.

Trial conditions

The above tests/trials are to be conducted at the specified conditions, such that:

- *Deep unrestricted waters*: Sheltered unconfined waters, with the depth more than four times the vessel draught
- *Calm environment*: Wind not to exceed Beaufort scale 5, waves not to exceed sea state 4 and only uniform current, if any
- *Full load & even keel*: Fully loaded condition with zero trim is the required test condition, but up to a variation of 5% is allowed. Alternatively, the trial may be conducted in a ballast condition with a minimum of trim and sufficient propeller immersion
- *Test speed*: The approach speed is at least 90% of the vessel speed, corresponding to 85% of the maximum engine output.

If the above test conditions cannot be satisfied, then corrections need be applied to the test results.

Korean and Japanese proposals

The IMO specifies that the track reach should not be more than 15 times the vessel length. Korean guidelines suggest that the track reach be increased to 20 times the vessel length, as many large vessels are unable to meet the IMO standard on stopping. Japanese guidelines suggest that the track reach be determined as:

- 15 vessel lengths if $(\Delta MCR V_{MCR} F_n^2) < 1.0$
- $5 + 10(\Delta/MCR) V_{MCR} F_n^2$, if $\Delta MCR V_{MCR} F_n^2 \geqslant 1.0$

where Δ the vessel displacement in tonnes, MCR is the Maximum Continuous Rating of the Engine in hp and V_{MCR} is the vessel speed at MCR.

NUMERICAL EXAMPLES

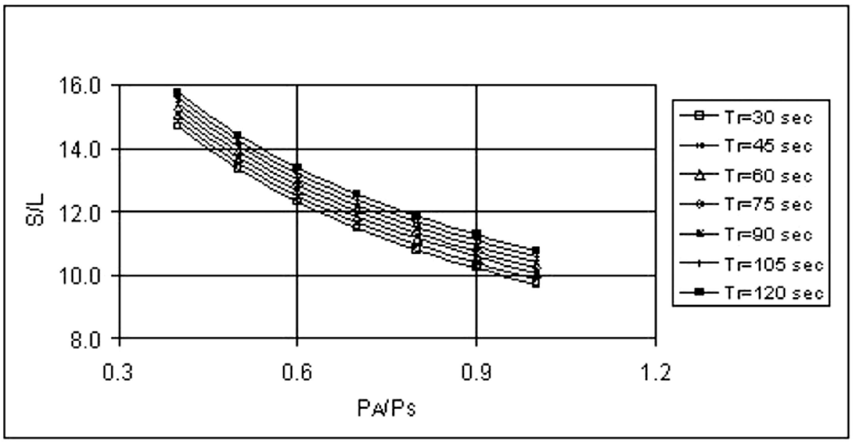
The above formulation is valid for vessels operated by screw propellers. Different types of vessel are considered here for the estimation of stopping distances for which the required input data are available from Clarke and Hearn[5]. The stopping distances of these vessels under different operating conditions with varying reversing time and astern-ahead power ratio have been estimated. Table 1 gives the particulars of the vessels and their propulsion characteristics used for analysis. These vessels include a tanker, a gas carrier, a general cargo vessel, a passenger ferry and two high-speed vessels.

The stopping distances estimated for the tanker are presented in Figs 2a and 2b. The gas carrier, general cargo and passenger ferry vessels shown in Table 1 operate at a higher speed compared to the tankers, the stopping distances of which are shown in Figs 3, 4 and 5 respectively, for a range of reverse timings and astern-ahead power ratios. The stopping distance becomes shorter with faster reversing of the propeller thrust and also with higher astern power. It is also evident from these results that the stopping distance (S/L) increases with the size of the vessel. This may be read in line with the suggestions put forward by the Korean and Japanese representatives of the Working Group (WG) on the Manoeuvrability of Ships and Manoeuvring Standards under the Ship Design and Equipment (DE) Committee, a sub-committee of the Marine Safety Committee (MSC) of IMO, for increasing the S/L values from 15.0 for large vessels (Daidola *et al*[9]).

The braking force given to a waterjet propelled vessel is much more than the net forward thrust of the propulsor if full reverse thrust is applied, and resistance of the hull adds to it. Thus the total aft-ward thrust can even be greater than three times the forward thrust. The thrust reversing time for

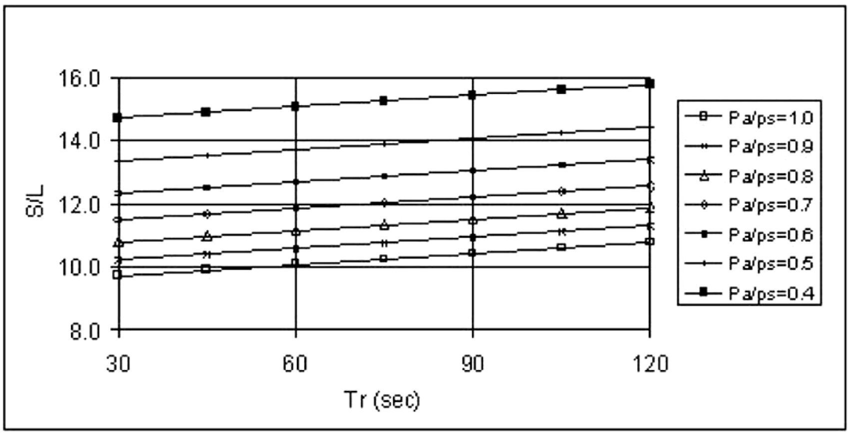
Vessels	Tanker	Gas Carrier	General Cargo	Passenger Ferry	HSV Monohull	HSV Catamaran
Particulars						
Length (m)	332.2	276.1	160.9	175.0	120.5	96.0
Breadth (m)	54.25	41.141	23.161	28.50	15.40	24.80
Draught (m)	20.48	10.97	7.466	6.75	3.350	3.90
C_B	0.833	0.767	0.597	0.589	0.527	0.194
Propulsion						
Propulsion	Screw	Screw	Screw	Screw	Waterjet	Waterjet
Diameter (m)	8.98	7.62	6.71	4.56		
Pitch (m)	6.151	6.172	6.468	4.834		
Blade AR	0.571	0.780	0.565	0.601		
$K_T/K_Q^{2/3}$	2.23	2.26	2.19	2.12		
QPC	0.651	0.717	0.741	0.660		
Propellers Nos	1	1	1	2	4	4
Speed (knots)	15.3	20.0	15.0	20.0	42.0	37.3

Table 1: Vessel and propulsion particulars



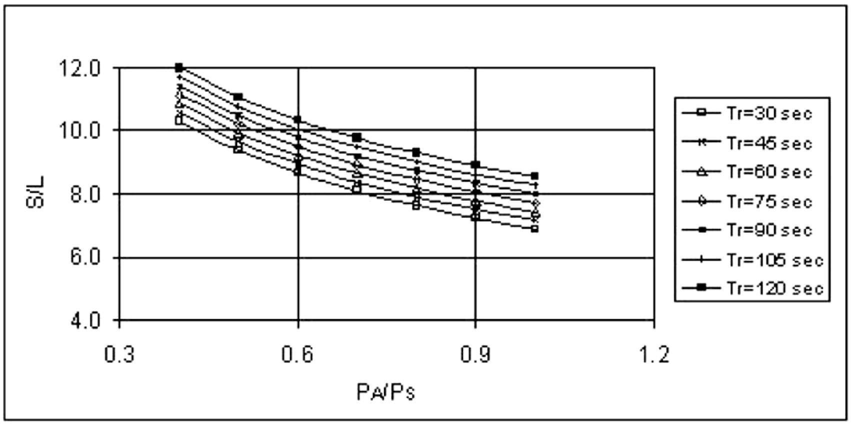
(a)

Fig 2a: Stopping distance of tanker for different astern to ahead power ratios



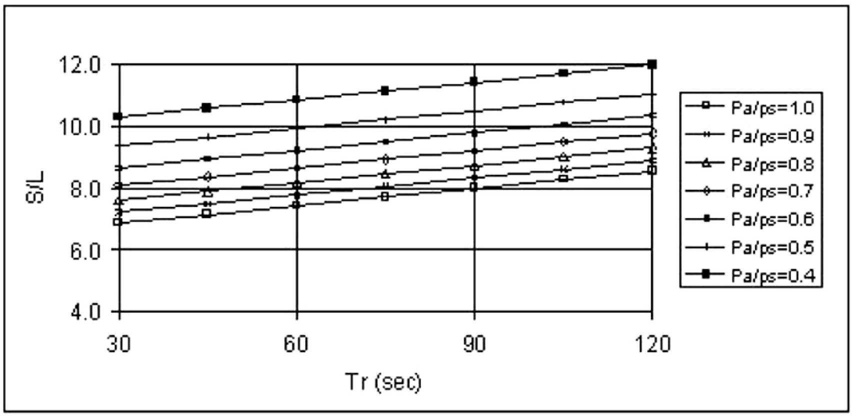
(b)

Fig 2b: Stopping distance of tanker for different reverse thrust timings



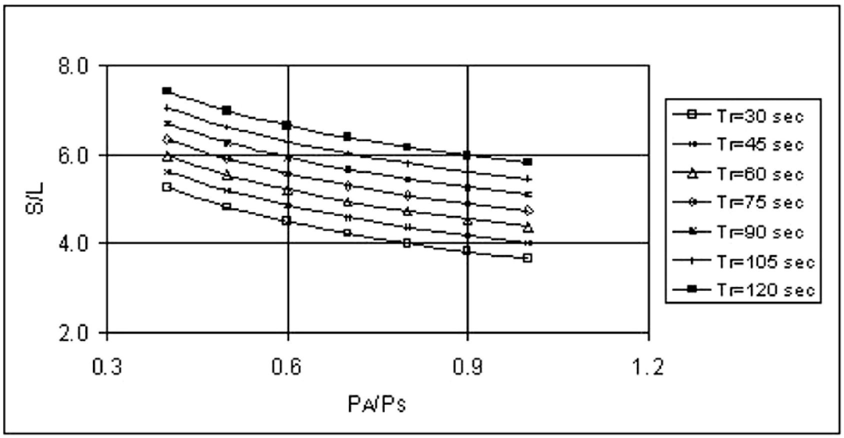
(a)

Fig 3a: Stopping distance of gas carrier for different astern to ahead power ratios



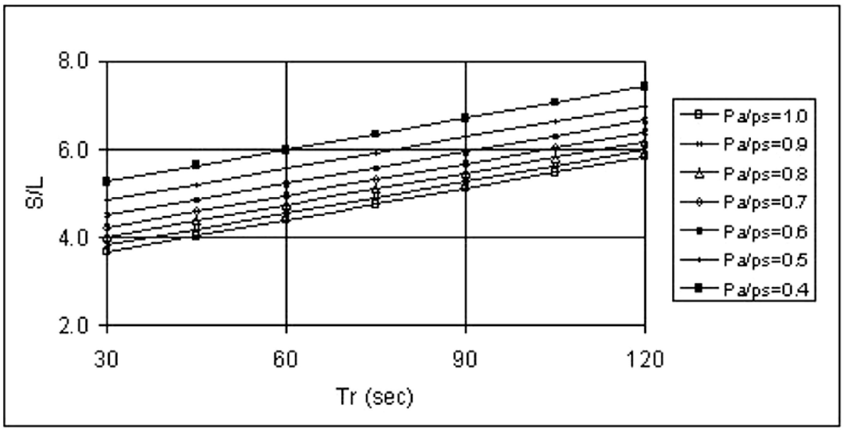
(b)

Fig 3b: Stopping distance of gas carrier for different reverse thrust timings



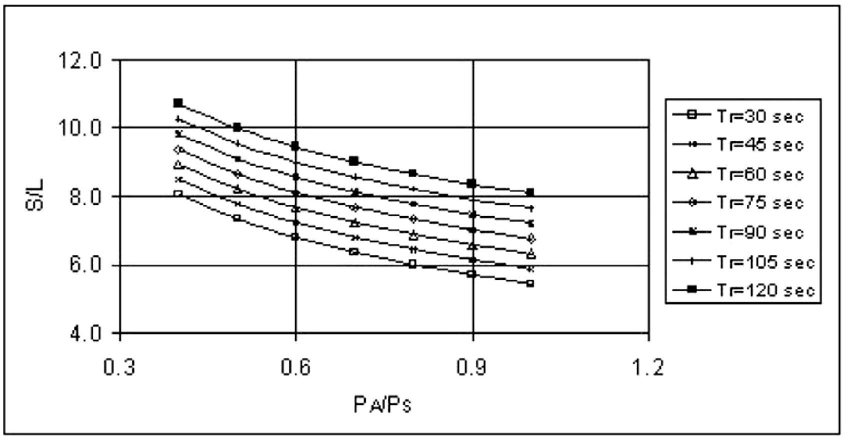
(a)

Fig 4a: Stopping distance of general cargo vessel for different astern to ahead power ratios



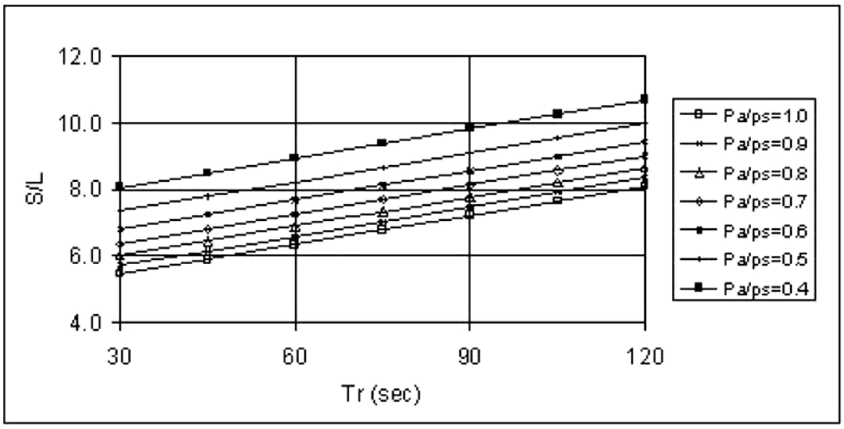
(b)

Fig 4b: Stopping distance of general cargo vessel for different reverse thrust timings



(a)

Fig 5a: Stopping distance of passenger ferry for different astern to ahead power ratios



(b)

Fig 5b: Stopping distance of passenger ferry for different reverse thrust timings waterjet propulsion is quite low compared to a screw propelled vessel. For a waterjet propelled vessel the time required for reversing thrust from full ahead to full astern is usually 10s or less (Way[11]). Considering these aspects, the stopping distances of the mono-hull HSV and the catamaran HSV are estimated using the present method for the reversing time varying from 10 to 60s and the ratio of astern to ahead thrust varying from 0.5 to 3.5. The results are presented in Fig 6 for the mono-hull HSV and in Fig 7 for the catamaran HSV. The stopping distances for both these vessels are less than 8.0 times the vessel length even in the worst case considered here. It is far less than the stopping distances of conventional vessels operating with screw propellers.

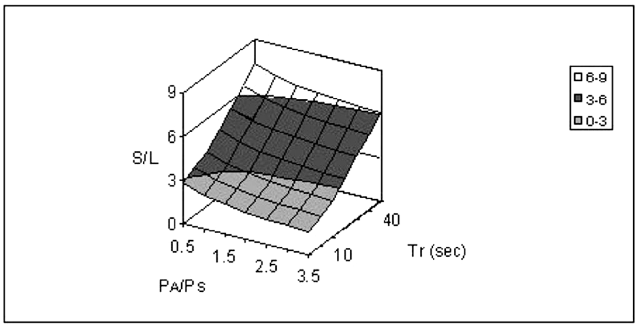


Fig 6: Stopping distance of mono-hull HSV based on power ratios and reverse timings

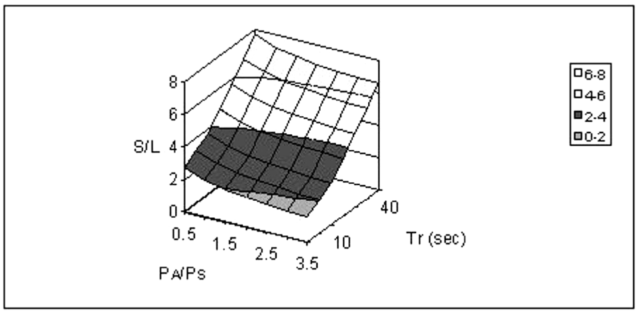


Fig 7: Stopping distance of catamaran HSV based on power ratios and reverse timings

The stopping manoeuvre formulation and analysis for different vessels have been carried out in the present study by estimating the track reach in full astern operation. These values are plotted against the IMO and the Korean proposed limits (and subsequently approved by IMO), in Fig 8. All these vessels satisfy both these criteria in all the operating conditions considered here. The track reach of the high-speed vessels studied, mono-hull and catamaran, takes less than twice the vessel length to come to a stop in water after the order for full astern is given. A sudden stop of these vessels become possible because they use waterjet propulsion, where the astern force including the momentum drag may be a few times of the net forward thrust. Also, the time required for the reversal of thrust with a waterjet propulsion system is normally about 10s, whereas for the screw propulsion system it may take 30s to 60s (Way[11]). The track reach distance increases with size for vessels having similar type of propulsion and thrust reversing time.

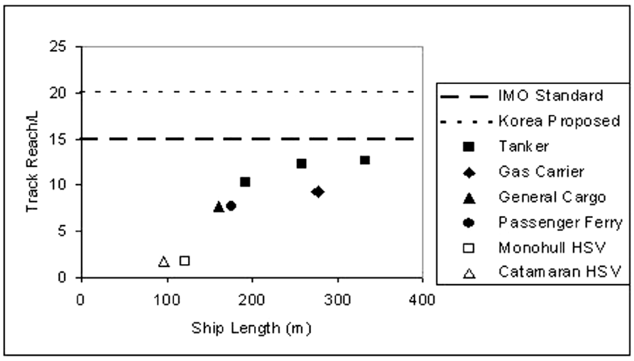


Fig 8: Track reach in full astern stopping test

CONCLUSION

The stopping ability of a vessel at its maximum operating speed is a major aspect of vessel controllability. This capability of a vessel is determined by the characteristics of its propulsion system, control device and hull form. The design considerations with respect to stopping ability can be summarised as follows:

- All vessels have to be brought to a rest position with ease, at any operating speed, within a reasonable distance after the necessity is anticipated or the order is executed. This is achieved by reversing the thrust and the time required for it depends on the type of propulsion and efficiency of the transmission system.

Free running model tests are considered to be the most reliable method nowadays for predicting a vessel's stopping manoeuvre. But model tests are not feasible for various design options of a vessel, as they are expensive and time-consuming. The model test facilities are also scant, particularly for the testing of high-speed vessel models.

The stopping abilities of vessels ranging from medium speed containership to high-speed vessel have been estimated, verified with known results and checked for the set stopping criteria. Based on the numerical studies carried out the stopping ability of high-speed vessels with waterjet propulsion has been found to be far above the IMO manoeuvring criteria, which is based on stopping tests performed on conventional vessels. For practical purposes a pilot also stops a vessel by high frequency cycling (if there is traffic around), low frequency cycling (if there is not much traffic around) and stopping such that the vessel comes abeam (normally using the vessel's beam with velocity to stop a vessel and this manoeuvre is generally performed outside the entrance of the port).

The HSVs considered here are those with waterjet propulsion. A more extensive study on HSVs, including model tests, needs to be carried out to develop more concrete criteria for high-speed vessel manoeuvring. HSVs with waterjet propulsion, where the astern power available is two to four times the shaft power and the thrust reversal time is usually less than 10s, can be brought to a stop within one to two vessel lengths, which make it safer compared to vessels with screw propulsion. Stopping criteria checks carried out here show that a more stringent condition could be applied to the high-speed vessels. But general criteria to this effect could be ascertained only after the conduct of more detailed study on many other high-speed vessels, with improved formulations and extensive model test results. The sudden deceleration of the vessel leads to higher wave generation. Thus the subsequent effects also need to be addressed while drastic improvements in the vessel stopping ability are achieved.

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