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Time differences in operation states of "Stena Baltica" ferry during the open water areas passages

Keywords

navigation, reliability, large system, asymptotic approach, limit reliability function, navigation

Abstract

The paper deals with analysis of ships operation states in open water areas effected by environmental constraints influencing on ship sea keeping parameters in application to "Stena Baltica" ferry operated at the Baltic Sea between Gdynia and Karlskrona harbors.

1. Introduction

Sea effects the ship during open water passage induces ship responses as motion, slamming, rolling etc. as the main constraints the whole system. To describe the ship system as a simply model in a seaway, it is necessary to introduce dynamic responses of a ship during passage (see *Figure 1*).

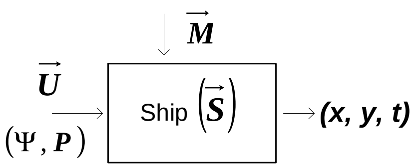


Figure 1. Model of a ships in a seaway

The state of a ship is describe by control vector $\vec{U}$ expressed by heading (Ψ) and power output (P). The ship motion is depicted by sea keeping constraints vector ($\vec{M}$). The ship position is expressed by x (lat) y (long) and time (t) determines the actual ship's position in a seaway.

Vector ($\vec{S}$) specifying the ship's geometrical parameters [3]. Based on the type of ship and her operation criteria of the vessel and a set of operating criteria is recommended for each trip. The main available sea keeping criteria recommended for passenger ferry operation should be her lack of casual contents to ship, less fatigue to passenger (crew injure) and to cargo damages.

Judgment of degree of danger to the ship is dependent on control vector: speed and course. Control of the ship movement in open sea is based on recommendation for reducing speed and or course changes in proper time.

There are the main factors that should be taken into account to establish state of ship control vector:

- Observation of waves;
- Encounter degrees of waves;
- Observation of wind;
- Main engine revolution;
- Propeller slip;
- Shipping seas on deck the bow;
- Degree of rolling;
- Degree of yawing;
- Degree of slamming;
- Other general observation of the ship behavior.

Additionally it is recommended to reduce fuel consumption, expected time to arrival (ETA) and in conclusion to care of ship safety.

The analysis of environmental effects on ship movements during sea passage must be considered taking into account the following aspects [1]:

- Ship category (type of cargo, age, geometrical parameters etc);

- Ship systems or functions (layout, type of propulsion);
- Ship operation (voyage duration, areas);
- External influences (weather, season, navigational infrastructure, shore based systems);
- Risk associated with consequences (damage to ship or fatalities to passengers or crew);
- Accident category.

Every master of a ship is obliged to receive an accurate description of the sea environmental condition before departure and during sea passage.
There are emergency states in which the ship can be found during her operation as damage by waves, taking water, collision, fire, grounding, oil spill, the crew or passenger sickness, or total loss.
The main forecast environmental data is given in *Table 1.*

Table 1. Forecast environmental data

Kind of data	Units	Remarks
Wind	[m/s, [^{o}]]	Speed, direction
Sea	[m], [^{o}],	Height, direction,
Swell	[s]	period
Currents	[m], [^{o}],	Height, direction,
Dangers	[s]	period
	[m/s], [o]	Speed, direction
	-	Ice, Fog etc.

It is important to every master the knowledge of the ship's responses as waves and winds components that may met the ship during her sea passage.
Information on surface currents are important specially during navigation in restricted water areas.
Ships sailing in rough seas are subject to motions and in consequences are loosing their speed.
In *Figure 2* there has been shown the environmental effects on speed loss by ship in rough seas.

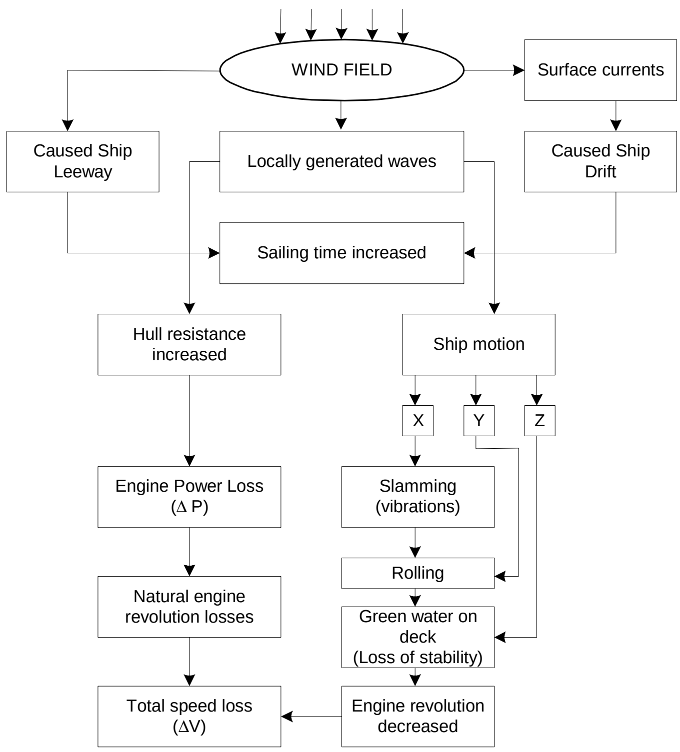
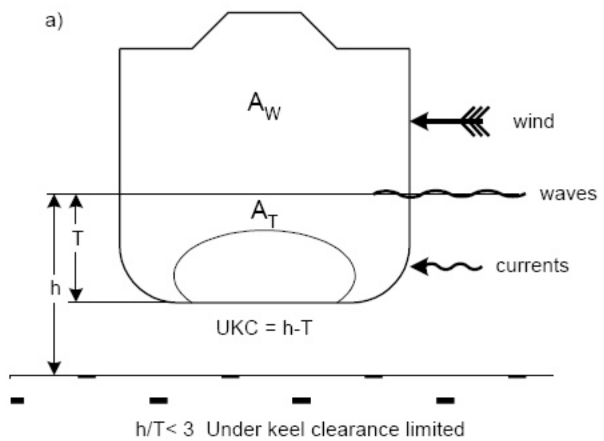


Figure 2. Environmental effects on speed loss during sea passage in rough seas [5]

The speed depends on the hull form, draft of the ship, depth of water, environmental condition and state of the engine power, or propeller setting. In *Figure 3* there have been shown two different ship's hull reaction on environmental condition in different phase of navigation.



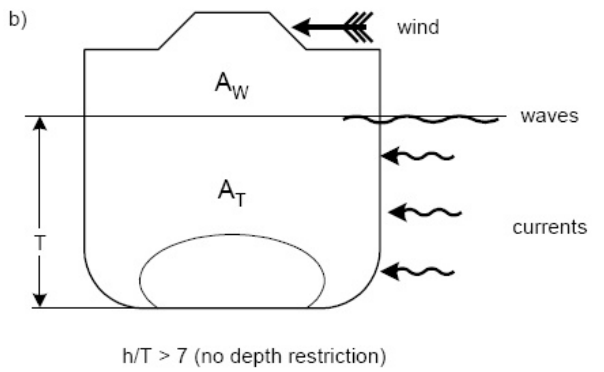


Figure 3. Different ship's curves reaction on environmental conditions: a. navigation in restricted water areas (Ferry); b. navigation in open water areas (Bulk Carriers) [12]

For practical application the ship speed loss curves are used. Environmental parameters such as waves, swell, wind and current are used in calculation. A ship being influence by many factors which interact in a complex manner. Relation between the ship speed and total hull resistant will clarify the action of particular forces on hull during ship movement in different environmental condition.

2. Environmental conditions and the ship speed loss

The thrust that is gain by the propeller effects is equal to the sum of calm water resistance, environmental effects as wave, wind, currents and shallow water resistances. (See *Figure 4*.)

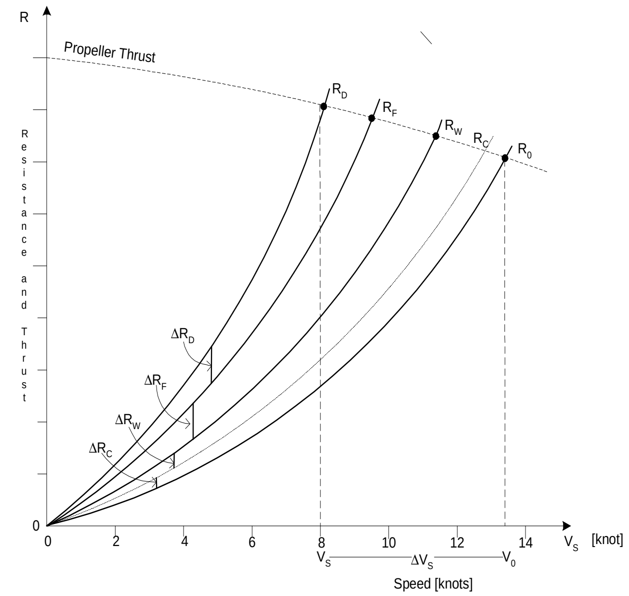


Figure 4. The ship speed changes due to environmental conditions

Total resistance of the ship during her movements is given by:

$$R_T = R_O + R_C + R_W + R_F + R_D \text{ [kN]} \quad (1)$$

where:
R_T – total hull resistance in difficult environmental conditions;
R_O – resistance in calm water;
R_W – additional resistance in waves;
R_F– additional resistance in wind;
R_D –additional resistance in shallow waters;
R_C –additional resistance in currents.

In the same way is determined the speed loss of the ship during her moving:

$$V_S = V_0 - \Delta V_S,$$

$$\Delta V_S = \Delta V_C + \Delta V_W + \Delta V_F + \Delta V_D \quad \text{[knot]} \quad (2)$$

where
V_0 – speed in calm water;
V_S – speed in different environmental constraints;
ΔV_S – total speed loss due to environmental conditions;
ΔV_C – speed loss in currents;
ΔV_W – speed loss in waves;
ΔV_F – speed loss in wind;
ΔV_D – speed loss in shallow water.

Ferry make vessel especially susceptible to wind due to her large windage of super structure A_W but the external forces of waves seems to be small (see *Figure 3*).
Dynamic characteristic of ship motion is important to predict ship responses in term of wave spectra and ship geometry during her sea passage.
Speed is the main ship performance characteristic. The actual ship speed can be expressed in functional form as:

$$V_S = V_O - \Delta V_W \quad \text{[knot]} \quad (3)$$

$$V_0 = F(n) \quad \text{[knot]} \quad (4)$$

where:
$a_1 b_1$ – coefficients obtained by experimental method;
F{n} - propeller revolution function [r p m];

Loss of speed in waves during passage in open waters conditions is given by formula:[5]

$$\Delta V_W = aH + bH^2 + cH\cos q_w \quad \text{[knot]} \quad (5)$$

where:
a,b, c – coefficients obtained by experimental method;
H - significant wave heights [m];
q_w – wave to ship track angle [^{0}].

Prediction of engine power in the open sea phase of navigation is given by formula:[11]

$$P = P_O - \Delta P \quad [kW] \quad (6)$$

$$P_O = a_1 n^3 \quad [kW] \quad (7)$$

$$\Delta P = b_1 \Delta V_W + c_1 \Delta V_{W2} \quad [kW] \quad (8)$$

where:
a_1, b_1, c_1 – coefficient;
n – propeller revolutions [rpm];
ΔV_w – speed loss due to waves [knot].

Speed loss presented in graphical form is given in *Figure 5*.

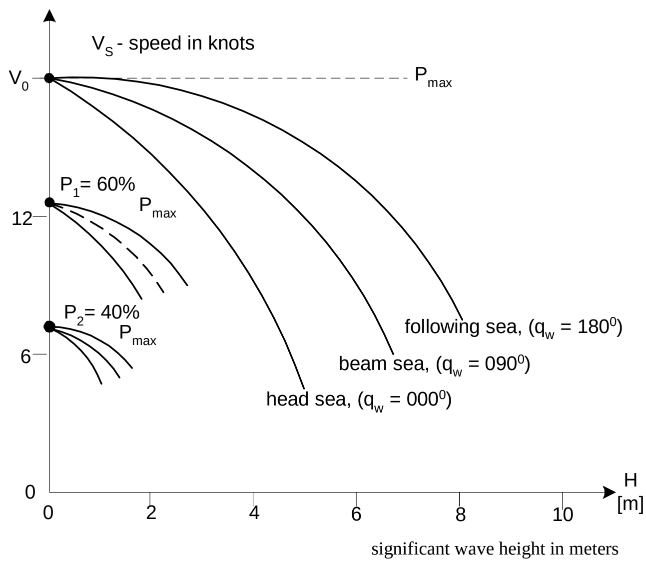


Figure 5. Speed curves for various engine power setting. It is possible to establish the functional relation between ship, wave period and wave to ship track in relation to available power output

Such function is given as [3]:

$$V_S = f(P, H^2, q_w, T_w) \quad [knots] \quad (9)$$

where:
P – power output [kW];
H – significant wave height [m];
T_W – predominant wave period [s];
q_w– wave to ship track [^{0}].

For safety reason an approach to model of the ship speed function on a seaway should be prepared for every ship. Information recorded from ship's logbook as speed against wave height or wind speed will make possible construct speed curves. The speed function to established is effective and useful in navigation passage planning.

3. Ship speed in shallow waters

The shallow water influence the ship speed. There have been given information in reference [4] on depth influence the ship speed. The formula is as fallow:

$$h = k \cdot T \quad [m] \quad (10)$$

where:
h – depth of water influencing on ship speed[m];
k – coefficient equals to: $\frac{4.44}{C_B^{1.3}}$;
C_B – ship block coefficient;
T – ship draft [m].

The amounts that the ship is reducing her speed will depend on the following elements [4]:

- Type of ship;
- Proportion of water depth (h) to static mean draft of the ship (T), (i.e. the h/T value);
- Ship block coefficient (C_B).

Loss in speed in shallow water is given in *Figure 6*.

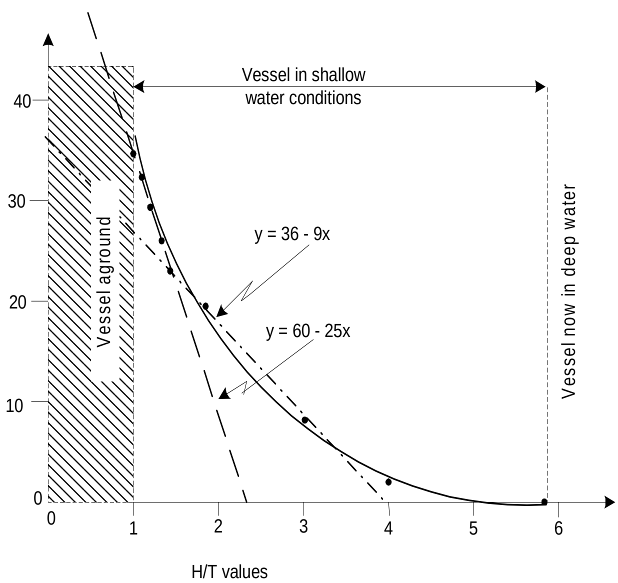


Figure 6. Loss in speed in shallow water [4]

The loss of speed in % equals to:

$$\Delta V_D = 60 - (25 \cdot h/T), \quad [\%] \quad (11)$$

for an h/T of 1.10 – 1.40

$$\Delta V_D = 36 - (9 \cdot h/T), \quad [\%] \quad (12)$$

for an h/T of 1.5 – 3.0
The formula (11) and (12) shows the percentage of loss speed relative to full service speed in deep water (h/T > 7).
In conclusion the ship speed can decrease by about 30% when h/T is 1.10 – 1.40.
Propeller rpm can decrease by about 15% when h/T is 1.10 – 1.40 [4].
According to above the times of each ships operation stage during sea passage is different in each trip. Ship liner as ferry is covering in calm water the same distances from A to B ports. Weather the times of the time of sea passage during each voyage is changing due to degree of environmental constraints. Distances to cover may change in order to alternatives for course diversion. This make increasing in fuel consumption.
The fuel consumption during sea passage depends on the following factors:

- Ship parameters such as from of hull, weight type of main engines, propellers, etc.;
- Number of engaged main engines;
- Ship speed relative to ground;
- Water depth;
- Weather, current, wind, waves;
- Ship draft.

A set of collected statistic on time difference in which the ship is operated in different states there will developed the realistically ship operation criteria to establish save speed during passages in open sea phase.

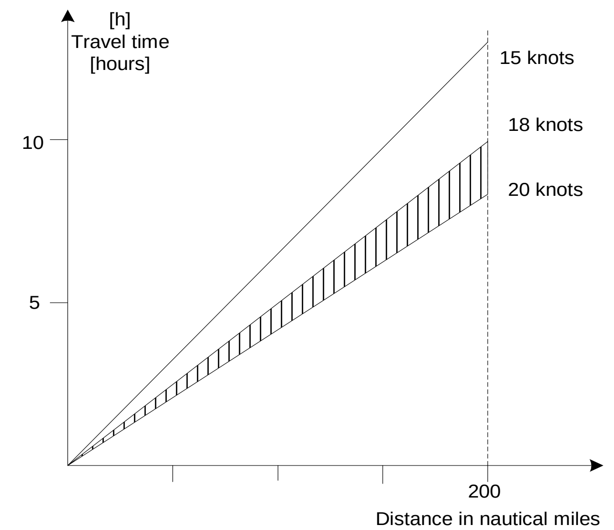


Figure 7. Heuristically defined feasible state space as a function of voyage distance and max/min ship speed in open sea phase [3].

4. The ship speed loss of ferry "Stena Baltica"

The speed characteristics of ferry were estimated in empirical way. Number of observations collected in 2008 (winter time) was limited to 319.
This has given us a rough estimation the speed loss mainly in bad weather condition. (See *Figure 8*).The ship speed over the ground was measured against wind speed in Beaufort scale using GPS navigator and ECDiS systems.
The ferry has large superstructure in the transverse projection area above waterline so the ship is very susceptible to wind, less to waves.
The ratio of superstructure area to transverse projected area below waterline (draft of the ship) AT/Aw equals to 7.8. She moves at sea as a sailing vessel. The high speed loss in the head winds is suspected to be cause by the fact that the forward ship superstructure amounts to 573 m^2. The side superstructure area equals to 4200 m^2. In this case the speed loss characteristics have been constructed against wind speed.

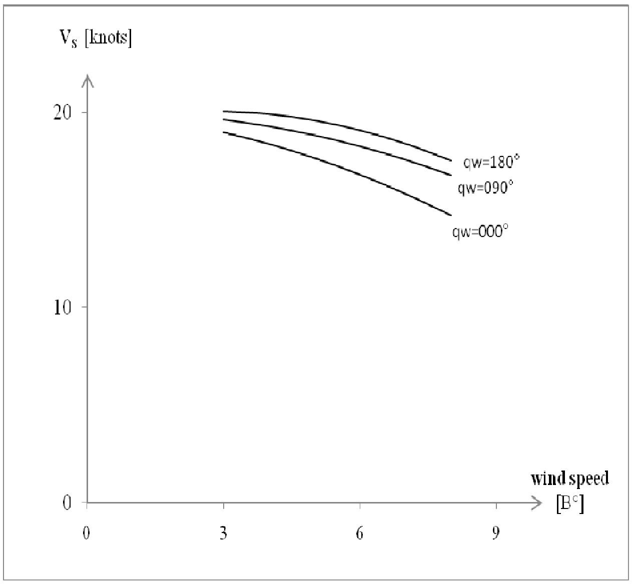


Figure 8. The ship speed in knot against the wind speed in Beaufort scale.

To establish the ferry speed characteristic the polynomial regression function have been used. The output shows the results a second order polynomial model to describe the relationship between ΔV_s and B. (See equations 13-16). The equations to fitted model is:

$$\Delta V_{Si} = a_1 B + b_1 B^2 + r_1, \quad (13)$$

for an $q_w = 000^0$,

$$\Delta V_{Si} = a_2 B + b_2 B^2 + r_2, \quad (14)$$

for an $q_w = 090^0$,

$$\Delta V_{Si} = a_3 B + b_3 B^2 + r_3, \quad (15)$$

for an $q_w = 180^0$,

then

$$V_{Si} = V_o - \Delta V_{Si}, \quad (16)$$

where
$a_1 = +0.14958$, $b_1 = +0.63520$, $r_1 = -0.00121$,

$a_2 = -0.04758$, $b_2 = +0.056061$, $r_2 = -0.00667$,

$a_3 = -0.50050$, $b_3 = +0.91883$, $r_3 = -0.59286$.

The actual speed curves for different q_w have been shown in *Figure 8*.

5. The statistics of time differences in open sea operation states of "Stena Baltica"

Taking into account the operation process of the considered ferry we distinguish the following as its eighteen operation states [13]:

- an operation state z_1 – loading at Gdynia Port,
- an operation state z_2 – unmooring operations at Gdynia Port,
- an operation state z_3 – leaving Gdynia Port and navigation to "GD" buoy,
- an operation state z_4 – navigation at restricted waters from "GD" buoy to the end of Traffic Separation Scheme,
- an operation state z_5 – navigation at open waters from the end of Traffic Separation Scheme to "Angoring" buoy,
- an operation state z_6 – navigation at restricted waters from "Angoring" buoy to "Verko" Berth at Karlskrona,
- an operation state z_7 – mooring operations at Karlskrona Port,
- an operation state z_8 – unloading at Karlskrona Port,
- an operation state z_9 – loading at Karlskrona Port,
- an operation state z_{10} – unmooring operations at Karlskrona Port,
- an operation state z_{11} – ship turning at Karlskrona Port,
- an operation state z_{12} – leaving Karlskrona Port and navigation at restricted waters to "Angoring" buoy,
- an operation state z_{13} - navigation at open waters from "Angoring" buoy to the entering Traffic Separation Scheme,
- an operation state z_{14} – navigation at restricted waters from the entering Traffic Separation Scheme to "GD" buoy,
- an operation state z_{15} – navigation from "GD" buoy to turning area,
- an operation state z_{16} – ship turning at Gdynia Port,
- an operation state z_{17} – mooring operations at Gdynia Port,
- an operation state z_{18} – unloading at Gdynia Port.

To identify all parameters of "Stena Baltica" ferry operation process the statistical data about this process, have been collected during 42 round trip. [14]

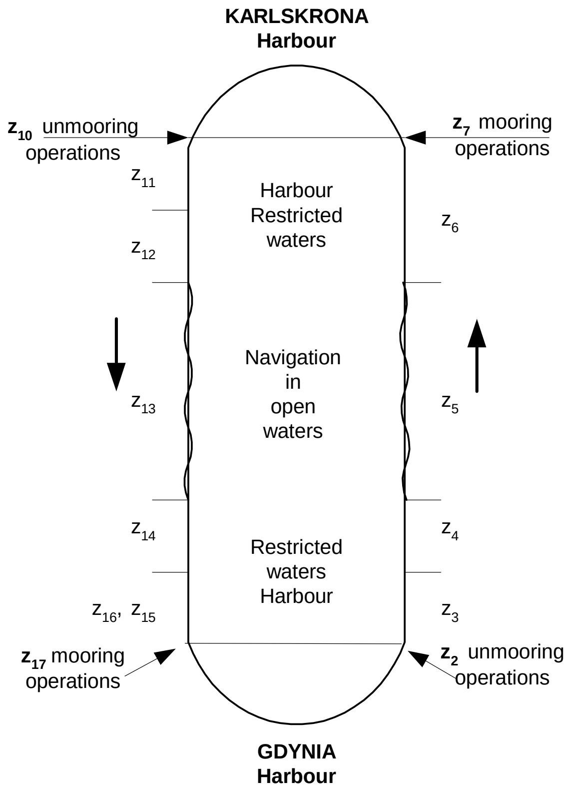


Figure 9. The "Stena Baltica" round trip operation process at sea

In *Figure 9* there have been distinguished only the states of the ferry in her round trip when she was in the navigation process.

In *Table 2* there have been collected the statistical data time differences in sea navigation states.

Table 2. The time difference of states during navigation passage

State	**Phase of navigation**	**Time of operation**		**Remarks**
		t_{min} **[h]**	t_{max} **[h]**	
z_3	Harbour. Restricted waters	0.50	0.75	Harbour, regulation speed limitation
z_4	Restricted waters	0.75	1.50	Weather restrictions
z_5	Open waters	7.75	12.00	Environmental constraints
z_6	Restricted waters. Harbour	0.50	0.67	Different weather condition
z_{11}	Harbour. Restricted waters	0.05	0.10	Ships turning abilities
z_{12}	Restricted waters	0.35	0.67	Weather and ships traffic condition
z_{13}	Open waters	7.75	12.00	Environmental constraints
z_{14}	Restricted waters	0.70	1.15	VTS operation and harbour regulations
z_{15} z_{16}	Harbour	0.77	0.77	Due to dense traffic in harbour, speed limitation

These experimental data have shown that the main constrains in ferry operation states in open sea is the speed loss due to bad weather condition.

6. Conclusion

1. The ferry operation states z_5 and z_{13} are the longest time differences occurred in open water navigation due to speed loss during unexpected environmental constraints.
2. The major uncertainties involved in the present analysis of the speed loss characteristic are introduced by calculation using small amount of information (319 observations).
3. The required ship speed loss appeared not to exceed 25 percent of full speed in calm water in forward direction of the wind speed below 8-9 Beaufort scale.
4. To say more about the ferry sea keeping characteristic that the route optimization especially in winter season is expected to improve the economics.
5. In commercial applications the most important objective function for ship operation problem is the minimize the voyage cost.
In modern ship operation the following criteria are commonly used;
   a. Ship safety;
   b. Prevention of ship damage;
   c. Maintenance of time schedule;
   d. Passenger / crew comfort;
   e. Economy of navigation;
   f. Minimize the voyage costs (mainly fuel costs).

6. The recorded date from the ship's logbook the wave height, speed and power output, from the past voyages, will help to further development in establish the ship sea keeping characteristic.
7. Information on the actual speed of the ship in different phase of navigation and in different environmental constraints will help the navigator to establish ETA (Estimated Time of Arrival) with good approximation to every position of the ship destination.

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