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Directional stability of ships and safe handling

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Abstract

Present manoeuvrability standards as set up by IMO do not include criteria for directional stability of ships. However, most ships with high block coefficient are inherently dynamically unstable. Ships having moderate or small amount of directional instability could be handled quite safely, but ships having large amount of directional instability are difficult to handle and may pose danger to sea traffic. The paper presents results of the study of the possibility of safe handling of directionally unstable ships. A number of pilots were asked to manoeuvre directionally unstable models with different amount of instability and an attempt was made to establish allowable limit of directional instability of ships on the basis of the analysis of these tests. The results were compared with the similar study performed in Japan.

1 Introduction

In early eighties International Maritime Organisation (IMO) started to develop standards of manoeuvring qualities of ships taking into account the fact, that the percentage of accidents caused by insufficient manoeuvrability appeared to be quite high. This task has been accomplished in 1993 when IMO adopted by Resolution A.751(18) Interim Standards for Ship Manoeuvrability. Those standards comprise standards of turning ability, initial turning ability, yaw checking ability and stopping ability. They do not include, however, criteria for dynamic course stability.

At the time the criteria of Resolution A.751(18) were considered there were proposals advanced also for standards related to dynamic stability on straight course, but due to widely spread opinions in that respect the final agreement could not be reached. It is well known that many ships currently in operation reveal certain amount of dynamic instability and in particular all full-bodied ships are, as a rule, dynamically unstable. This in the majority of cases does not prevent safe handling of such ships. In some cases, however, where the amount of dynamic instability is to large, handling of such ships is difficult and their operation may pose danger to the traffic. Such ships should not be allowed to be constructed any more.

There were several attempts to establish a link between characteristics of dynamic stability on straight course and safe handling. In particular work of the Panel RR 742 of the Shipbuilding Research Association of Japan [1,2,3] followed by the work of Yoshimura and others [4] which are referred to below, has to be mentioned. Also, bearing in mind that the present stability standards are of the interim nature, IMO is currently making an attempt to establish new standards where criteria for dynamic stability might be included.

2 Measures of the dynamic course stability

Reaction of a ship to the application of rudder may be described by the equation proposed by Nomoto [5,6]:

$$T_1 T_2 \dddot{\psi} + (T_1 + T_2)\ddot{\psi} + \dot{\psi} = K(\delta + T_3 \dot{\delta})$$

in which all the coefficients: $T_1 T_2$, $(T_1 + T_2)$, T_3, $and\, K$ are proportional to the following measure (criterion) of stability:

$$D = Y_\beta(-N_r) - (m + m_x - Y_r)\, N_\beta$$

where: $Y_\beta, N_\beta, Y_r, N_r$ - are linear coefficients of hydrodynamic forces and moments acting on ship hull.

When value of D is positive and large, dynamic directional stability is good, when this value is negative the ship is directionally unstable. Criterion D can not be evaluated on the basis of conventional sea trials, because behaviour of the ship depends on rudder force and damping forces of the hull.

The amount of dynamic directional instability is usually assessed on the basis of relation between rudder angle and angular velocity (rate of change of heading) as, for example, established on the basis of spiral (or reverse spiral) test. The results of these tests are presented in the form of angular velocity versus rudder angle (fig 1). For dynamically stable ships this relation is strictly defined whether for dynamically unstable ships there appears a histeresis loop and the relation between these two quantities is in the form of „S" curve as shown in the fig 1. At zero ruder angle there are two stable equilibrium points and one point of unstable equilibrium. Points of stable equilibrium on the Y-axis fix the histeresis loop height and histeresis loop width is fixed by vertical tangents to curve S. Slope of the tangent to the curve S at zero point is equal to the coefficient K' (Nomoto coefficient) which is negative for dynamically stable ships and positive for dynamically unstable ships. Criteria for dynamic course instability could be then the following quantities:

histeresis loop height (r')
histeresis loop width , total (δ_{lw})

The loop height is a direct measure of the inherent characteristics of the hull+propeller+fixed rudder where the effect of rudder is comparatively small. The loop width is more sensitive to the efficiency of the rudder.

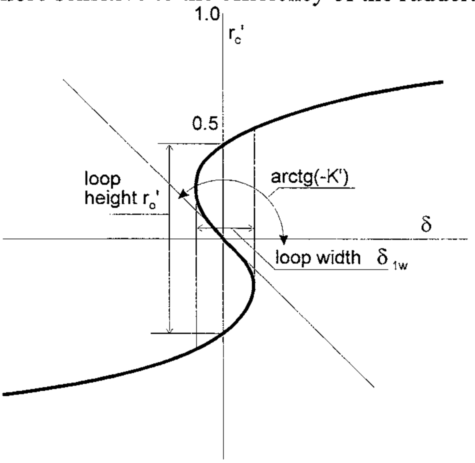

Fig.1. Angular velocity versus rudder angle

3 Proposed criteria for directional instability

Various proposals in relation to the standard of dynamic course instability were *inter allia* summarised by Norrbin [7], others were submitted to IMO or published in quoted references:

Gertler & Gover [8]:
Height of histeresis loop: $r_0' \leq 0.2^0/s$ (for 500' ship)
Loop width $\delta_{1w} \leq 4^0$
Voitkunsky et al [9]:
Histeresis loop height (stipulated): $r_S' \leq 0.333\, r_{30}'$ (fig.2)
USSR/IMO [10]
Histeresis loop height (stipulated): $r_S' \leq 0.15\, r_{30}'$, or $r_0' \leq 0.075$
(original of the document submitted to IMO does not contain the above criteria)
Clarke et al [11]:
Positive dynamic stability (no loop)
Chinese national requirements [12]:
Passenger ships: Histeresis loop height $r_0' = 0$ (dynamically stable or marginally unstable),
Cargo ships ($C_B < 0.8$): Histeresis loop height $r_0' < 0.10$,
Cargo ships ($C_B > 0.8$): Histeresis loop height $r_0' < 0.20$
IMO, Working Group [13]:
No more than 30^0 phase advance should be required by the helmsman to ensure adequate course keeping.

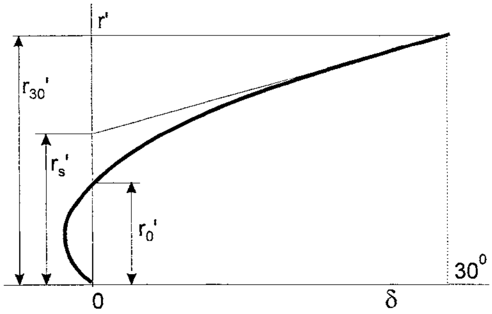

Fig.2. Estimation of stipulated loop height

4 Japanese investigations of the relation between directional stability and the difficulty of manoeuvring

In late eighties Panel RR 742 of the Shipbuilding Research Association of Japan was created. The panel conducted a series of tests of the relation between the directional instability and the degree of difficulty of ship handling. [1,2,3]. It was discovered that between those characteristics there is remarkable correlation which is seen from fig.3. Difficulty of steering depends on angular velocity of the directionally unstable ship with rudder fixed. On this basis diagram shown in fig.4 was prepared where ranges of easy and difficult handling from the pilot's point of view were marked. The demarcation line between those ranges constitutes the proposal of the instability standard in the form of histeresis loop width.

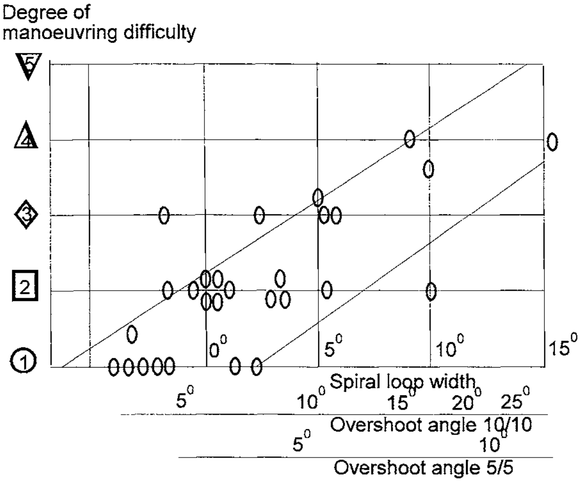

Fig.3. Relation between the actual directional stability and the degree of manoeuvring difficulty

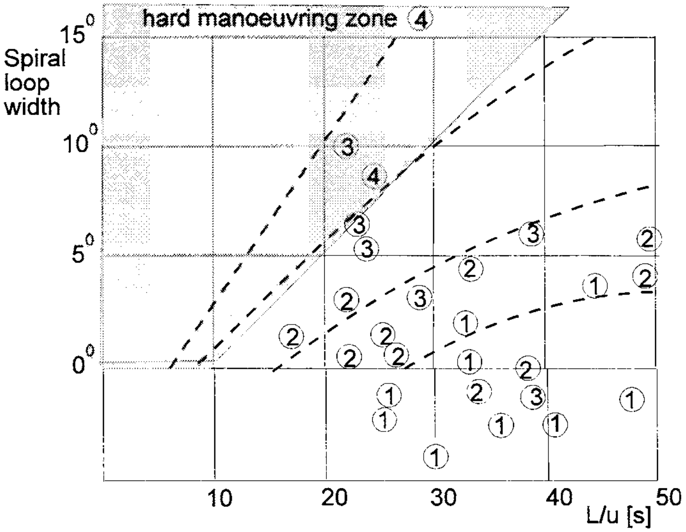

Fig.4. Ease of manoeuvring from the viewpoint of a pilot
1 - easy steering, 5- most difficult steering

5 Tests performed in the Ilawa ship handling research and training centre

The Ilawa Ship Handling Research and Training Centre (SHRTC) located at the lake Silm near Ilawa was described in several papers [14,15,16]. SHRTC is fully equipped to perform training of ship masters and pilots in handling of ships using large manned models. Some of the models used in the Centre are models of ships which are directionally unstable. One of these models, the model of VLCC of 280 000 tdw- "BLUE LADY"- executed in model scale 1:24 was used for a series of tests aimed at checking the possibility of control of directionally unstable ships.

Model BLUE LADY is directionally moderately unstable at full load and in ballast condition revealing, however, large degree of instability when trimmed to the bow. Series of standard zig-zag and spiral tests were performed in all three loading conditions and the results of these tests are given in the table 1. As it is seen the total width of the histeresis loop established on the basis of spiral test is:

for full load condition = 5.9^0
for ballast condition = 3.3^0
for the model trimmed to the bow = 23.6^0

In particular because of large degree of instability in the condition trimmed to the bow it was impossible to perform zig-zag tests $10/10^0$, $10/5^0$ and $5/5^0$ because model did not change the deviation from the original course when applying counter rudder. The results of these tests are shown in fig.5.

A number of pilots were asked to steer the model on a loop comprising two straight sections (about 2 Nm in full scale each) on which pilots had to keep the model in leading lines or keeping the compass course as close as possible. They were asked also to assess the possibility to control the model during various manoeuvres.

Table 1. Results of spiral and zig-zag tests of the model BLUE LADY

Model BLUE LADY		full load	balast	trimmed
Spiral test	Width of histeresis loop [^{0}]			
	starboard	3.4	2.6	8.0
	port	2.5	0.7	15.6
	Height of histeresis loop [^{0}/s]			
	starboard	0.86	0.66	1.25
	port	0.96	0.86	1.10
Zig-zag tests	Overshoot angles first/second [^{0}]			
	10/5 starboard	7/28	3/9	36/∞
	port	6/22	4/7	∞/-
	10/10 starboard	12/37	6/13	∞/-
	port	16/32	8/10	∞/-
	20/20 starboard	17/19	8.12	21/23
	port	16/16	11/8	56/23

The track of the model was monitored and deviations from the straight course as well as rudder angles were recorded.

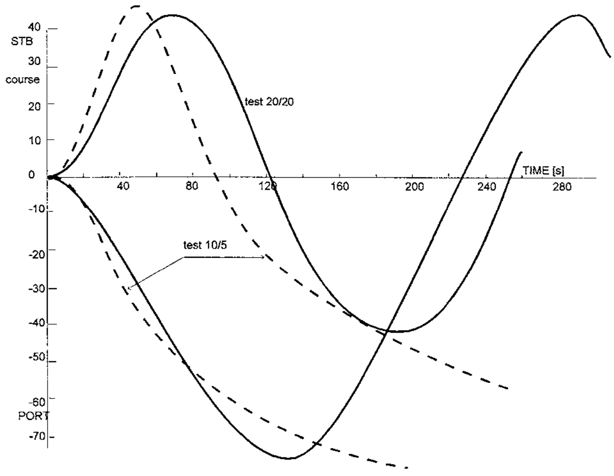

Fig.5. Results of zig-zag tests of the model BLUE LADY in trimmed condition

The analysis of the recorded exercises showed that in spite of directional instability the model could be controlled fairly easily in both full load and in ballast condition although there were wide differences in the ability of various pilots in keeping the model on straight course. For example, one of the pilots reacted nervously applying rudder angles up to 37^0 and steering the ship with large deviations from the predetermined course whether another one applied rudder angles up to 10^0 and controlled the ship within 1^0 deviation from the course.

In the Table 2 there are shown example results achieved in steering the model in trimmed condition by two pilots out of 14, one best and another average, in the form of rudder angles used. The model in this condition showed high degree of dynamic instability and great skill was necessary to maintain the model on straight course without excessive deviations from it. However, when such deviation happened it was necessary to use maximum rudder angles to counter deviation and sometimes long time passed until the model was returned to the original course.

Table 2. Parameters of the distribution of rudder angles. Model BLUE LADY trimmed to the bow.

parameter	pilot 2b	pilot 1
$\bar{\delta}$	$-.0.26^0$	-3.61^0
$\bar{\delta}_{1/3}$	9.65^0	4.20^0
$\bar{\delta}_{1/10}$	8.83^0	2.52^0
$\bar{\sigma}$	6.76^0	29.3^0

The distributions of rudder angles used in this condition are show also in fig.6.

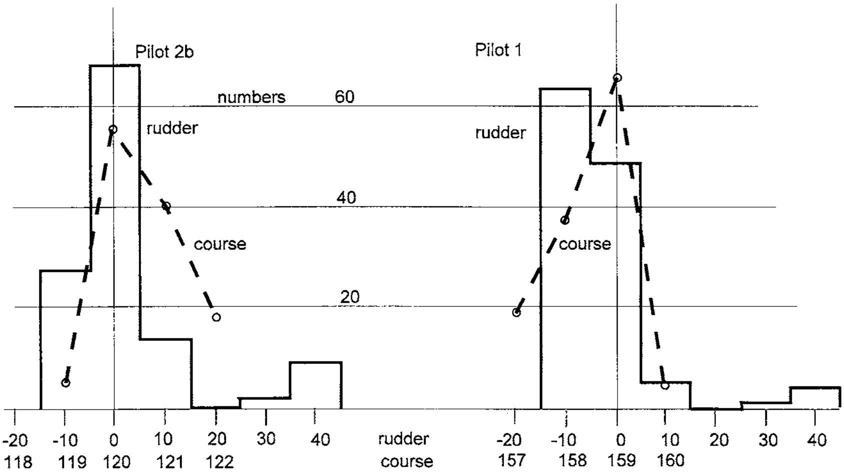

Fig.6. Distribution of rudder angles and deviations from the course

In addition to the exercises with model BLUE LADY described above there were also performed exercises with the model of another tanker, 148 000tdw, WARTA. Model WARTA which has width of histeresis loop about 3.6^0 did not pose any difficulties in manoeuvring and the results of exercises performed with this model are not, therefore, referred to in this place.

6 Limiting value of directional instability for safe manoeuvring

Width and height of the histeresis loop are good measures of directional instability therefore limiting value of directional instability could best be established in terms of histeresis width or height or both. From practical point of view it is more advisable to use histeresis loop width. Width of the histeresis loop increases with increasing of the negative value of the coefficient K (equation 1) with negative D. Similarly overshoot angles in zig-zag test increase with large time constants T_1 and T_2 which occur at negative D.

From the conducted exercises it is clear that with large directional instability measured by histeresis loop width the ship is difficult to handle and, in particular, in restricted waterways and in heavy traffic might be dangerous. In order to steer such a ship large rudder angles have to be used and deviations from the adopted course are large. Large overshoot angles and large deviations occur when using counter rudder in order to reverse the turn which is dangerous to other traffic.

The maximum allowed amount of directional instability should be established taking into account possibility to handle the ship by the pilot of average abilities. During the exercises arranged in SHRTC it appeared that when steering on straight course all pilots performed well when steering models WARTA and BLUE LADY in full load and ballast condition. For these models width of histeresis loop was less than 6^0 and such width could be accepted. All pilots performed quite well also when steering the model BLUE LADY trimmed to the bow when steering on straight course in spite of that the width of histeresis loop in this condition was 23.6^0. However handling this model was very difficult because of difficulty to control yawing and to counter turning. In some areas the model could not properly negotiate narrow passages or avoid collision. Such directional instability could not be accepted. It might be concluded that the allowable limit of directional instability measured by histeresis loop width lies between 6 and 23^0 which is rather large interval. Unfortunately there was no model available which has histeresis loop width between these values. Clearly, however, a ship having histeresis loop width larger than 10^0 can not perform 5/5 and 10/10 zig-zag test which means difficulties in controlling yaw because overshoot angle with the counter rudder 10^0 could be as large as 30^0 and that means large deviation when controlling yawing. Therefore it is proposed that the limiting value of histeresis loop width should be 10^0. This conclusion coincides with the latest proposal by Japanese [4] although they proposed to establish directional instability criterion in terms of overshoot angle at 10/10 zig-zag test.

7 Relation between histeresis loop width and overshoot angles

Establishing standard for directional instability in terms of histeresis loop width has one drawback because conducting spiral test necessary to measure this quantity is difficult and time consuming for full scale ships. It is not possible to conduct spiral test in towing tank and wide water areas are required for remote controlled or manned models.

Bearing this in mind the proposal was advanced by Japanese [1,2,4] to use overshoot angles established from zig-zag tests instead in view that there exists a relation between overshoot angles and histeresis loop width.

On the basis of tests of several ships performed in Japan Nobukawa et al [1] prepared a diagram showing relation between spiral loop width and overshoot angles estimated from zig-zag tests. This diagram is reproduced in fig.5. In the same figure points are plotted evaluated from results of spiral and zig-zag test of the model BLUE LADY in two loading conditions and of the model WARTA (both tanker models dynamically unstable).

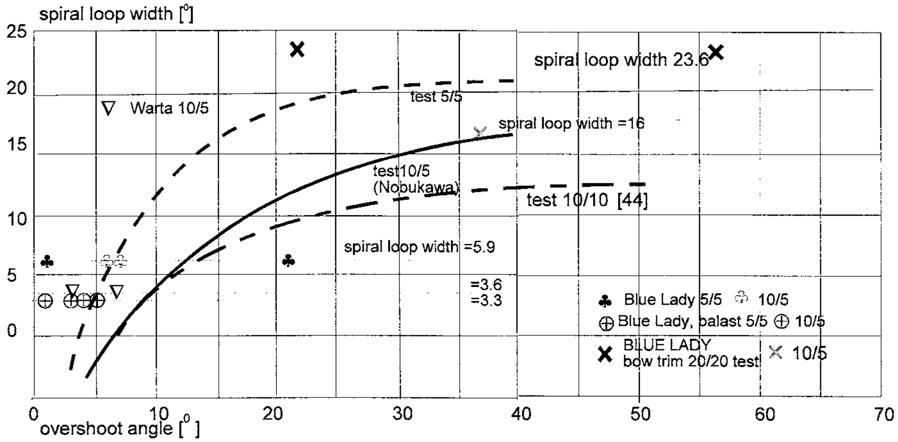

Fig7. Relation between spiral loop width and overshoot angles

The aim of this exercise was to check the possibility to establish relation between these two quantities. If this relation would be accurate enough, then checking the standard of directional stability in the form of spiral loop width could be accomplished by zig-zag test and performing spiral test which is time consuming and difficult to perform could be avoided.

The results of the tests with two models lead to the following conclusions:

- there is rather wide discrepancy of the results, especially results of 5/5 zig-zag tests
- the points evaluated from 10/5 zig-zag test lie very close to the line marked 5/5 obtained from Japanese tests
- the 5/5 zig-zag test for directionally unstable vessel are unreliable and sometimes (model WARTA) impossible to perform because model after applying counter rudder does not turn back but is entering a turning circle of the very large diameter.

- the general conclusion is that much more tests with directionally unstable models must be available before definite relation between spiral loop width and overshoot angles taken from 10/5 zig-zag test is established.

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