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A General Model of Ship Manoeuvrability Assessment Based on Decisions' Analysis, and Its Practical Application

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Summary

A general methodology for the assessment of the inherent manoeuvring characteristics of ships, is presented. The methodology, which takes into account the non-linear nature of manoeuvring motion, is built on a specific set of manoeuvring requirements, translated into suitable criteria and measures of performance. These are later integrated in a hierarchical procedure which allows for combining effectively conflicting characteristics and producing a picture of overall manoeuvring capability. The problem is established as a typical decision problem in the presence of multiple objectives and conflict, with the first part of the paper devoted to the theoretical foundation of the general assessment model. Application is undertaken for the case of ferries, with consideration of a wide range of design parameters. As a result of this, areas of good or poor manoeuvring performance are identified. A clear distinction is made between the need to turn in limited space and the need to respond quickly to rudder commands. The methodology can be used in early ship design as well as in developing/optimising vessel type-specific manoeuvrability standards.

Nomenclature

a	: Control vector, i. e. the vector containing the variables which are under the control of the ship operator
A	: Control space, i. e. the space in which the control vector is allowed to vary
B	: Ship beam
c	: Rudder chord
C_b	: Block coefficient
Fn	: Froude mumber
GM	: Metacentric height
$\boldsymbol{h}$	: Initial conditions vector, i. e. the vector giving position and velocity of the ship just before the execution of a manoeuvre
$\boldsymbol{H}$	: Initial conditions space, i. e. the multi-dimensional domain in which the vector $\boldsymbol{h}$ obtains its values
L	: Ship length
L_{BP}	: Length between perpendiculars
lw	: Instability loop width
m_1^ψ	: First moment up to ψ degrees change of heading
r	: Rate-of-turn
r_{max}	: Maximum rate-of-turn during the execution of a turn
r_{mc}	: Rate-of-turn at the point of maximum curvature
r_{NS}	: Non-dimensionalised steady rate-of-turn over the corresponding speed
$r_{NS}^{(0)}$	: As above, for the remotest point of the vessel
r_{NSR}	: Non-dimensionalised steady rate-of-turn over the initial forward speed
R	: Turning radius
$R(w,h,t)$	: Performance monitoring function
ST_0^ψ	: Space measure applied up to ψ degrees change of heading
ST_R^ψ	: As above, for the remotest point of the vessel
ST_{YC}	: Space measure for yaw checking
t	: Time
t_S	: Time to check yaw
$t_{r\,max}$	: Time to reach maximum rate-of-turn
t^ψ	: Time to achieve ψ degrees change of heading
t_{rmc}	: Time to reach the point of maximum curvature of the rate-of-turn versus time, curve
T	: Ship draught
U	: Forward speed during turn
U_0	: Forward speed before turn
w_i	: Weighting factors
β	: Angle of drift
δ	: Rudder angle
Δ	: Ship displacement
λ	: Rudder aspect ratio
ϕ	: Angle-of-heel
ψ	: Ship heading
ψ_t	: Change of heading after t seconds
∇	: Ship volume

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1. Introduction

Ship manoeuvrability is receiving relatively limited consideration during the ship design process, disproportionate to its conspicuous effect on the safety and operational efficiency of a vessel. Although this may start changing, following the recent adoption of manoeuvrability standards by IMO, gaps of understanding at the cenceptual level and particularly as regards a satisfactory definition of "what constitutes a good manoeuvring vessel", Landsburg et al[11], should be noted as the underlying cause of this unacceptable state of affairs, see Appendix I.

Reference should be made to a number of serious efforts towards the development of reliable *quantification* and *assessment* procedures, from the earlier attempts of Nomoto[12], with his K, T indices, Norrbin[13], with his turning-index p, or the pioneering work of Gertler and Gover in DTMB relating to naval vessels[7], to more recent contributions, such as the statistical study of Barr et al[1], or other submissions to IMO by its member states, like this of Germany[8], or China[9]. These efforts, coupled with the increased concern of the public-at-large for safety, provided the impetus towards the recent adoption of IMO Resolution A. 751(18), containing a set of interim manoeuvrability standards.

In spite of the above, the heart of the problem, the quantitative specification of the benefits or the risks associated with manoeuvring capability, continues to be regarded as a very intricate subject. So far, ship owners have not been provided with clear cost incentives for improving the manoeuvring performance of their vessels. Furthermore, the beyond dispute ability of human beings to adapt to the individual properties of the systems with which they need to interact, has often been assumed to imply that skilful shiphandling can act as a compensatory factor to poor "inborn" manoeuvring characteristics. Using this argument in reverse, possible casualties can be easier attributed to human misjudgement than to poor performance of the vessels.

From different parties the necessity has been expressd for approaching the problem afresh in a systematic and rational manner, with the view of establishing a wide basis, which would be used for carrying out "in depth studies of the inherent manoeuvrability of different ship types", Clarke[4]. An attempt to put substance to this idea is presented here for the case of ferries. The basic principles of this approach, are summarised below:

a. Performance is assessed on the basis of the two fundamental considerations: the need to turn in limited space (*space requirement*), and, the need to respond quickly to rudder commands (*time requirement*). These are not compatible to each other considerations and they cannot be equally achieved for all ships. For this reason a specific set of operational requirements should be the platform on which the assessment would be developed.

b. A detailed study of ship manoeuvring behaviour is undertaken, through numerical predictions of manoeuvring motion in response to certain control actions. This is used for specifying which characteristics can represent manoeuvrability and which factors are critical for achieving satisfactory performance. Those performance-related qualities which are found as adequately defining manoeuvring ability will be called hereafter "*manoeuvring criteria*". Following this, attention is focused on developing reliable "*measures of performance*", i. e. on specifying quantities and related procedures which can be used for an effective assessment of performance with respect ro each earlier specified criterion and eventually produce quantitative information regarding any particular vessel.

c. While in (b) the focus was on generating the elements of the assessment in bulk, in (c) the main objective is to specify their exact role. In essence, the aim is nothing less than the development of a generalised model of behaviour, in the shape of an efficient assessment structure (*hierarchy*), whereby aspects of manoeuvring behaviour related to laws of nature, market terms and human perception are orderly assimilated. To this end, use is made of techniques borrowed from *decision analysis*, with the aid of which manoeuvrability assessment is established as a typical decision problem in the presence of *multiple conflicting objectives*.

The paper consists of two parts; the first part is devoted to the theoretical foundation of the assessment model which is eventually used for carrying out the assessment. The second part, presents a practical application of the proposed method, for the particular case of ferries. The application begins with the specification of requirements for this type of vessel, and through the derivation of suitable criteria and measures of performance it culminates with the proposal of areas of good or poor performance in respect to paricular manoeuvring qualities, as well as overall.

2. Foundation of the assessment model

2.1 *A general model for performance assessment*

A typical way of optimising the performance of a system is by seeking to maximise (or minimise) an objective function, whereby all the important for the assessment factors appear as function variables. In a number of cases this function can involve weighted sums of the distances of the critical quantities from their counterparts lying on a certain desirable state. In other cases the maximisation of the function is the only alternative because the specification of a "desirable" state is not clear beforehand. A general assessment model for ship manoeuvrability would rather suit the latter description, and its exact form could evolve as a result of seeking to maximise an objective function F, defined as:

$$F = \iint_{H \times A} \int_0^{t_{steady}} w(\boldsymbol{h}, \boldsymbol{a}, t) R(\boldsymbol{h}, \boldsymbol{a}, t) dt\, d\boldsymbol{a}\, d\boldsymbol{h} \quad (1)$$

where:

- t is time,
- $\boldsymbol{h}$ is the *initial conditions vector*, i. e. the vector giving position and velocity of the ship just before the execution of a manoeuvre,
- $\boldsymbol{H}$ is the *initial conditions space*, i. e. the multidimensional domain in which the vector $\boldsymbol{h}$ obtains its values,
- $\boldsymbol{a}$ is the *control vector*, i. e. the variables which are under the control of the ship operator,
- $\boldsymbol{A}$ is the *control space*, i. e. the space in which the *control vector* is allowed to vary,
- t_{steady} is the time needed to reach a steady condition during the execution of a certain manoeuvre,
- $R(\boldsymbol{h}, \boldsymbol{a}, t)$ is a function through which the performance of the system can be satisfactorily monitored,
- $w(\boldsymbol{h}, \boldsymbol{a}, t)$ is the weighting function, the form of which would reflect to what extent good performance in respect to the $R(h, a, t)$ quantity is critical for the system.

The state vector $\boldsymbol{h}$ represents thus the initial condition of the system at the time instant $t=0$ when the control vector obtains the value $\boldsymbol{a}$. Therefore, the function F is characterised by the inclusion of *any* practical manoeuvring procedure under *any* operational conditions.

Expression (1) means in effect that every manoeuvring procedure, described by the initial condition of the state variables, the control action taken, the time elapsed, and the relation of the system to its environment, can be associated with a relative importance factor, deriving basically from the "purpose of existence" of the object in view. The elegance of expression (1), nevertheless, is not enough to hide the complexity which it implies. How, for example, the perfomane monitoring function $R(\boldsymbol{h}, \boldsymbol{a}, t)$ can be specified and what basis could be used for the derivation of the weighting function?

A feasible route for modelling an essentially unknown system, is to emphasise the role of human perception. How people who own, design and operate ships perceive the implications of the underlying complex laws? The scope of utilising information of experts to systematise desirable or undesirable manoeuvring characteristics has been well appreciated in the past, as shown with SNAME's Panel H-10 study, *Landsburg et al*[11] or with a more recent Japanese submission to ITTC by *Yoshimura and Kose*[23]. Nevertheless, even in the context of the above assumption, it is apparent that to achieve an interface with any form of practical reasoning, a significant simplification of the above presented general model would be required. The first step to this end is, the "discretisation" of (1) or, in other words, its reduction to a form composed by a finite (preferably small) set of manoeuvring scenarios, making sense in the light of human experience whilst preserving the character of a "satisfactory" approximation. The second step would be to investigate the content of the function $R(h, \boldsymbol{a}, t)$. Perceptively, it is easier to imagine such a function analysed into a bunch of measurable elements each one of which would be in direct relation with an individual manoeuvring quality. If the above actions were taken, a consequence would be that the weighting function $w(\boldsymbol{h}, \boldsymbol{a}, t)$ would have also to be converted into a set of simple weighting factors. The described simplification enables one to expose the selected manoeuvring scenarios to expert judgement, assess their relative importance on the basis of the expressed preferences and hence derive the appropriate weighting factors. By this means the missing link is therefore established.

A point remaining unclarified relates to the decomposition of the performance monitoring function $R(\boldsymbol{h}, \boldsymbol{a}, t)$ into a number of perceptively distinct elements, denoted as $R_i(\boldsymbol{h}, \boldsymbol{a}, t)$. How is this going to be achieved? At first, the meaningfulness of the comparisons procedure must be ensured. Given then that an objective evaluation would probably require several functions $R_i(\boldsymbol{h}, a, t)$ linked to various objectives, the undesirable situation could arise where one would be asked to compare the relative importance of basically unrelated quantities. This can be avoided only if appropriate management action towards the R_is takes place, materialised with the adoption of a *structure* and a *hierarchy* for the evaluation.

Thus, to allow the evaluation structure to function, a certain model for it must be specified. Perhaps the most practical solution is to adopt an *additive model* in which the paricipating quantities appear as first order terms. An *additive multi-attribute evaluation model* can work successfully insofar as a certain degree of *preferential independence* between the elements of the evaluation exists, *Keeney and Raiffa*[10]. If for example preferences for turning ability, directional stability and stopping were compared, the result of trade-off analysis of turning against directional stability should not depend on the level of the stopping quality met in the system under investigation and round forth. The extent to which such a condition is satisfied for all the possible combinations of the above as well as at the other positions of the structure should rather be the subject of a separate study.

2.2 *The systems' methodology and the hierarchical structure*

The formulation which was finally reached reflects in effect what is called, *a systems approach*. It represents a particularly viable option when, because of gaps of understanding, the classical *reductionist method* is unable to produce satisfactory results, as is the case with the present problem where natural laws, economic prinhiples and human factors are forming a complex which is difficult to "penetrate" with conventional analysis. The underlying strength of the systems methodology on the other hand, lies in its hierarchical nature coupled with its potential of integrating effectively information with a qualitatively different character.

2.3 *Historical note*

The use of formal evaluation models has known increasing popularity in the practice of decision-making and management science. The models range from multi-attribute extensions of expected utility theory, e.g. *Keeney and Raiffa*[10], to approximate techniques like, SMART of *Edwards*[5], and AHP of *Saaty*[17]. Application of multiattribute evaluation techniques occurred in many operational areas, from marketing, social program evaluations and public policy problems, to technology choice and standards setting and regulations. A comprehensive list of references is provided by *Borcherding and Winterfeldt*[3].

2.4 *Construction of a Hierarchy*

a) General steps

The application of any formal evaluation model culminates in the elicitation of a tree of values and objectives such as the *analytical hierarchies of Saaty*[17], or the *objective hierarchies of Edwards*[5]. The following steps characterise generally their building process:

1. Identify the criteria on which the evaluation will be based. Express them in a form assisting decision-making.
2. Select a group of representatives consisted of individuals with a reason to care about the evaluation and with enough impact on the system, to be involved in the assessment.
3. Investigate the position and possible lower level decomposition of the entities specified in step 1, and define how they will be measured (measures or attributes). Subsequently, organise these on alternative hierarchical structures. Build the structures by starting with the most general objectives, followed by subobjectives etc. Try to achieve a consensus on a final form.
4. Elicit the relative importance of each element linked with the fulfilment of the governing objective in the adjacent upper level. Repeat this for any position of the hierarchy. Transform the expressed preferences to weighting factors.
5. Use the structure to obtain and compare the overall value of the alternatives of the assessment. Further, perform sensitivity analyses and derive conclusions regarding the "stability" of the solution.

b) Criteria and Measures

The term *criteria* is used in an analogous way to the use of the term *objectives* met in multiple-objectives decisions analysis literature, see e.g. *Keeney and Raiffa*[10]. For the term objectives however there is no formal universally applied definition. Here, criteria will be meant to signify a set of general characteristics corresponding to essential qualities of the system's behaviour, equally meaningful to a scientist and a ship operator, which can be taken as a basis of performance assessment

The *measures* will constitute the means on the basis of which the satisfaction received from the performance of a ship regarding each one of the specified criteria will be quantified. They are attached therefore to the responsibility of generating all the essential information which will allow the criteria to function.

c) The Model

The evaluation model which was adopted is usually met in the literature as *muli-attribute value model* and it can be expressed in abstract language as:

$$V(x)=\sum_{j=1}^{m} w_j u_j(x_{ij}),$$

where:

V is the attained overall value ($0<V<1$),

w_j are weighting factors as described in the foregoing,

u_j represent normalised forms of the performance records obtained by applying the x_i assessment procedures

Assuming that a large number of alternatives will be examined and the discretisation of the variables space will be dense enough, a linear *normalisation model* can be selected:

For higher value preference:

$$u_j(x_{ij})=\frac{x_{ij}-\min\{x_{ij}\}}{\max\{x_{ij}\}-\min\{x_{ij}\}}$$

For lower value preference:

$$u_j(x_{ij})=\frac{\max\{x_{ij}\}-x_{ij}}{\max\{x_{ij}\}-\min\{x_{ij}\}}$$

d) Derivation of the weighting factors

An important activity during the structuring of an hierarchy, is the derivation of weighting factors. There are various techniques devoted to this and examples of application of a number of them can be found in *Saaty*[17], *Edwards*[5], *Smith, Kamal and Mistree*[20]. The pairwise comparisons technique of Saaty has a clear mathematical foundation and it was preferred in the present research. A short description of the technique is given in the following:

Suppose that it is required to compare the importance of a set of n entities referring to the same upper level objective. The entities, denoted by $A_1, A_2, \cdots, A_n$, are written horizontally and vertically and a comparison in pairs of their importance with respect to the criterion of the next higher level, is initiated, see Fig. 1. The values given for dominance are in the scale 1 (equal importance) to 9 (abosolute preference), with the use of the intermediate values given according to the pattern 3 for "*weak*", 5 for "*essential*", and 7 for "*demonstrated*" preference. The values 2, 4, 6 or 8 are used whenever compromise between two adjacent values is required. This procedure leads in effect to a matrix having positive entries everywhere and satisfying the reciprocal

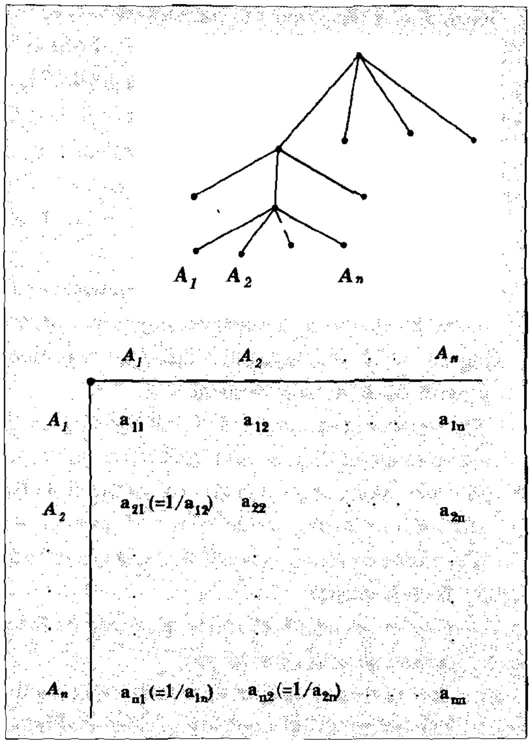


Fig. 1 The assessment tree and the matrix of preferences

property: If activity i has a number a assigned to it when compared with j this would imply that j will receive the reciprocal value $1/a$ when compared with i.

The matrix A built in this way is checked for consistency or, in other words, the compatibility of the preferences is examined. This is characterised by the consistency index, which equals:

$$\text{C. I.} = \frac{\lambda_{\max} - n}{n-1}$$

with $\lambda_{\max}$ being the maximum eigenvalue of A.

The calculation of the components of the eigenvector corresponding to the maximum eigenvalue provides the weighting factors, which can be used in the assessment process if the consistency condition, C. I. < 0.1, is satisfied. More mathematical details about the technique can be found in 17). The procedure has to be repeated for all the positions of the hierarchy, while at the end an overall consistency check will be required.

2.5 *Delineation of the manoeuvrability assessment process*

As was shown earlier, the representation of the system according to its purposes, its functions and its environmental constraints, takes on a hierarchical form. To combine all the essential performance features of the system, an assessment tree will be built, at the highest level of which will lie the overall manoeuvrability function, linked to the highest level objective of the assessment — the maximisation of manoeuvring performance — and representing in effect the *weighted* and *normalised* sum of all the individual performance indicators earlier selected. The lowest positions of the structure will contain control specifications and initial conditions. The following steps apply specifically to this assessment:

1. For each vessel group, set the range of variation of C_b, L/B, B/T, and select a step-increment for these variables.
2. For a meaningful comparison of alternatives, associate the principal dimensions with a standard deadweight and thereby define L, B, T, C_b, and rudder area.
3. Decide on a small set of candidate assessment structures.
4. For the above specified values of the variables set, carry out the (numerical) manoeuvring scenarios, associated with the selected criteria and suitable measures.
5. Whenever possible, validate the predictions, by comparing the observed performances with available performance records drawn from ship trials, tests or simulations.
6. Once performances for all possible combinations of the design variables are collected, initiate rationalisation studies for the measures and decide on the final form of the assessment structure.
7. Derive weighting coefficients for any position of the hierarchy, on the basis of preference for specific manoeuvring characteristics, as expained earlier.
8. Identify the maximum and minimum values obtained for each selected measure and normalise the values in [0, 1] scale.
9. Combine hierarchically the various aspects of manoeuvring performance, in order to obtain the value of the manoeuvrability index corresponding to any combination of the assessment variables.
10. Specify possible constraints which should be incorporated in the process and examine how they affect the results reached with the previous step.
11. Perform sensitivity studies in terms of the structure itself and the assigned weighting factors, to assess their impact on the assessment picture obtained.

3. Application: Manoeuvrability Assessment for Ferries

3.1 *The components of the assessment*

The invesigation endeavoured to begin with the declaration of a set of vessel-specific manoeuvring requirements and to end up with the specification of ranges of ship parameters in which "good" or "poor" manoeuvring performance arises. An extra feature of this assessment has been the consideration of the effect of lateral thrust devices, which is a rather common feature for this type of ships.

3.2 *Design parameters*

An investigation regarding the range of main design parameters of ferries currently in operation, gave a considerable scatter of data, e.g:

$0.25 < Fn < 0.35$, $0.53 < C_b < 0.65$

$4.70 < L/B < 7.04$, $2.93 < B/T < 5.07$

Data were collected from publications of the International Association of Ports and Harbours (IAPH), private communication with the Ministry of Mercantile Marine of Greece, and from published data on ferries operating in UK waters.

In most cases ships had two propellers and two rudders and usually bow thrusters were also installed (in a number of cases stern thrusters existed as well). *Norrby and Ridley*[14], claimed that most ferries carry "L-type thrusters of generous power", and this fact was confirmed from the sample of ships examined, with an average power to longitudinal underwater area ratio of 1.28 kW/m^2. It was found also that the examined ships carried rudders of at least 0.026(LT) area.

For the specific study presented here, the main dimensions were varied inside the following range:

$5.0 < L/B < 7.0$ $3.0 < B/T < 5.0$ $0.50 < C_b < 0.60$

For a reliable parametric investigation, a relatively small step will be required within each of the above ranges. Here however, it was feasible to examine only the extreme cases for L/B and B/T and use a 0.05 step for C_b. Even this resulted in having to test 12 ferries. The dimensions of these ferries, named F1, F2, F3, F7, F8, F9, F19, F20, F21, F25, F26 and F27, are presented below:

	L/B	B/T	C_b
*F*1	5.0	3.0	0.50
*F*2	5.0	3.0	0.55
*F*3	5.0	3.0	0.60
*F*7	5.0	5.0	0.50
*F*8	5.0	5.0	0.55
*F*9	5.0	5.0	0.60

	L/B	B/T	C_b
*F*19	7.0	3.0	0.50
*F*20	7.0	3.0	0.55
*F*21	7.0	3.0	0.60
*F*25	7.0	5.0	0.50
*F*26	7.0	5.0	0.55
*F*27	7.0	5.0	0.60

Moreover, a number of ship characteristics had to be standardised to facilitate the analysis, as:

- The ship displacement was fixed at the approximately average value of $\Delta = 900t$.
- All ships were assumed as carrying bow thruster located at $0.15L$ from the forward perpendicular, with installed power (in kW) taken on the basis of the next multiple of fifty in excess of $1.28(LT)$.
- The rudders were located at $x_r = [(-L_{BP}/2) + (L_{BP}/230) + (c/2)]$ (leading edge position), where c is the rudder chord. The rudder area was taken equal to $0.026(LT)$ and the aspect ratio λ was standardised at $\lambda = 1.5$.
- The propellers were selected from Wageningen B-series, by following a standard procedure, according to which, the propeller diameter was taken proportionally to ship draught.
- The service speed was fixed at 20 KN giving for the above range of dimensions: $0.258 < Fn < 0.314$
- The longitudinal centre of gravity was fixed at $0.02L$ aft and the height of the centre of gravity was taken for simplicity as equal to the ship's draught.

3.3 *Requirements*

A number of particular characteristics can be linked to the ferries operation, including:

i) The need to enter ports without losing control,

ii) The ability to turn quickly unaided and take a specific position in a limited space near the pier,

iii) The need for efficiency in manoeuvring astern and moving sideways,

iv) The possession of reasonable dynamic stability and lack of significant roll-yaw coupling,

3.4 *Derivation of suitable criteria and measures*

The above requirements can be translated into a number of specific assessment procedures. Before presenting these, a number of suitable criteria and measures are discussed:

a) *The Initial Turning and Yaw Checking Criterion (IT/YC)*

"The ship enters in a turn from steady forward motion of speed U_0, by setting the rudder at an angle δ_i. As soon as the rate-of-turn reaches its maximum, r_{max}, in time $t_{r\,max}$, the rudder is deflected to $-\delta_i$ until the rate-of-turn falls to zero, in time $t = t_s$", see Fig. 2.

This manoeuvre-criterion, was introduced by *Spyrou and Vassalos*[21),22)], and it can be interpreted relatively to the requirements for minimum space and minimum time. The following measures could be associated with this criterion:

Minimum time measures

- The maximum rate-of-turn, r_{max}, and the time needed to reach it, $t_{r\,max}$,

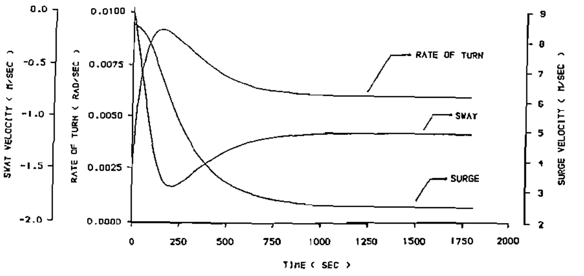
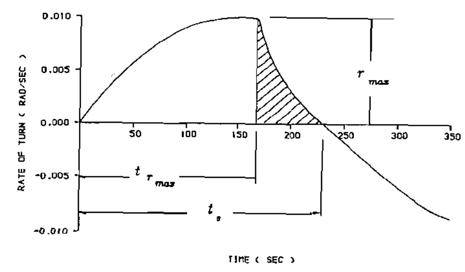


Fig. 2a Time-histories during a turning manoeuvre



(Fig. 3a)

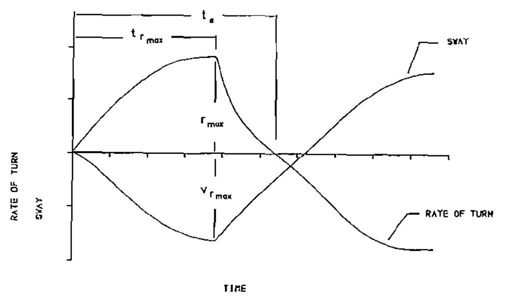
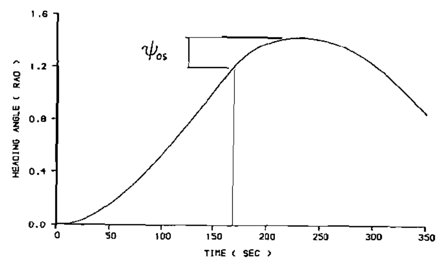


Fig. 2b The initial turning/yaw checking manoeuvre



(Fig. 3b)

Fig. 3 Approximate calclulation of the overshoot angle

- The time needed for checking the yaw, $t_s - t_{r\,max}$,
- The overshoot angle ψ_{os}, which is usually taken as a measure of the yaw checking capability, see Fig. 3 and it can be written as:

$$\psi_{os} = \int_{t_{r\,max}}^{t_s} r\, dt$$

It is easily noticed that ψ_{os} includes all the earlier defined measures. Also, from Fig. 3 it can be realised that, the above exact expression for ψ_{os} can be approximated, due to the shape of the yaw checking curve, by:

$$\psi_{os} = 0.5 r_{max}(t_s - t_{r\,max})$$

A critical matter which needs to be further addressed, is, the initial turning capability of the vessel. This indeed might lead to a selection between alternatives which can prove very uncertain. In Fig. 4, for example, the rate-of-turn time-histories of two ships, A and B, are given, for a specific setting of their controls. Ship B appears to have higher maximum rate-of-turn, but at the crucial initial stage it performs worse than A. It is realised that if it was to select which curve represents better initial turning characteristics, the decision would be by no means easy. It is thus necessary the decision to be based on a combination of factors, taking into consideration as much as possible of the history of motion leading to the maximum.

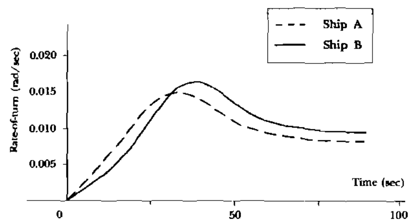


Fig. 4 Comparison of rates-of-turn

The simple integral of rate-of-turn over time (producing the area below the curve which equals the change of heading of the ship in that time) is a direct measure of ship responsiveness. The moments of this area around the vertical to the time axis corresponding to a suitable ψ change of heading, will shift attention (increasing with the order of the moment) to the very initial phase of the turn, while taking into consideration the whole history up to ψ heading change, producing therefore highly meticulous measures, nearer to the what the name of the criterion implies. The first order moment is given by the expression

$$m_0^{\psi} = \frac{1}{t^{\psi}} \int_0^{t^{\psi}} r\, dt = \frac{\psi}{t^{\psi}}$$

and in general

$$m_n^{\psi}=\frac{1}{[t^{\psi}]^{n+1}}\int_0^{t^{\psi}}(t^{\psi}-t)^n r\,dt=\frac{n\,!}{[t^{60}]^{n+1}}\int_0^{t^{60}}\psi^{[n-1]}\,dt$$

with $\psi^{[n-1]}$ the $(n-1)$-th order integral of ψ.

Minimum space measures

This should be an average of the time-varying turning-radius during the initial phase of a turn: This turning-radius is given by, see Fig. 5,

$$R=U(t)/[r-(d\beta/dt)]$$

with

β drifting angle

$U(t)$ momentary velocity

This led to the adoption of the following expression:

$$ST_0^{\psi}=S_0/(\psi-\beta)$$

where

ψ is, as for the m_n^{ψ} measures earlier described, the angle up to which the initial phase of a turn is considered to take place.

S_0 is the length travelled by the origin of the ship's axes during the turn.

In the above expression it is possible to substitute S_0 with S_1 where S_1 is the length travelled by the remotest point of the ship, see Fig. 6. The coordinates of this point, (x_S, y_S), are derived from the coordinates of the centre of the ship, (x_0, y_0) as below:

$$x_S=x_0-(L/2)\sin\psi-(B/2)\cos\psi,$$

$$y_S=y_0-(L/2)\cos\psi+(B/2)\sin\psi$$

For the yaw checking space measure ST_{YC}, the same thinking was applied, taken from the time moment when $r=r_{max}$ to the moment when $r=0$.

Constraints

Since the IT/YC manoeuvre establishes an, operationally, extreme situation for the case of roll coupling, a realistic constraint on allowed inclination during turn can be set, by monitoring the angle of heel during the execution of the manoeuvre, see Fig. 7.

b) *Steady-state behaviour*

Dynamic instability is measured with the width of the instability loop, *lw*, see Fig. 8.

The steady rate of turn, if divided by the corresponding steady velocity U, taking the ocurring speed drop due to the turn into consideration provides the steady turning radius of the ship's origin, R, according to the simple kinematic relationship:

$$r/U=1/R$$

This suggests a straightforward *space* quantity, in the form of the non-dimensionalised rate of turn r:

$$r_{NS}=r\nabla^{1/3}/U$$

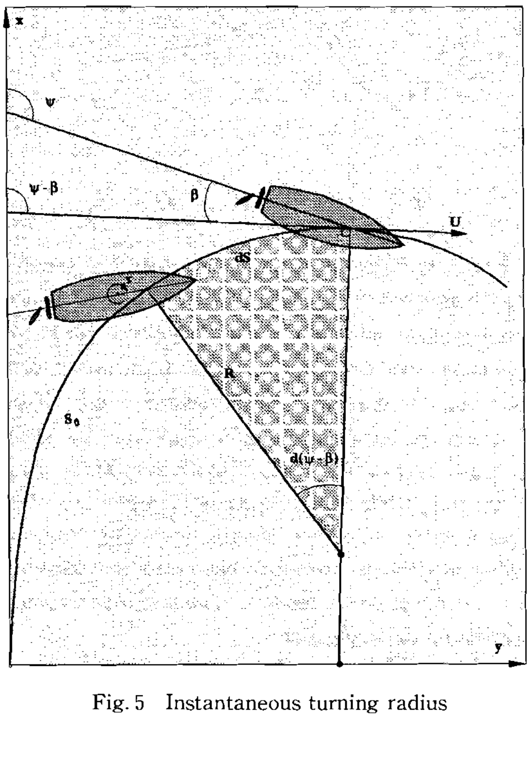


Fig. 5 Instantaneous turning radius

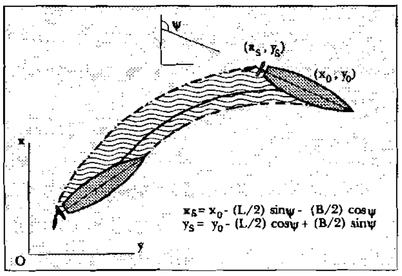


Fig. 6 Remote points trajectories

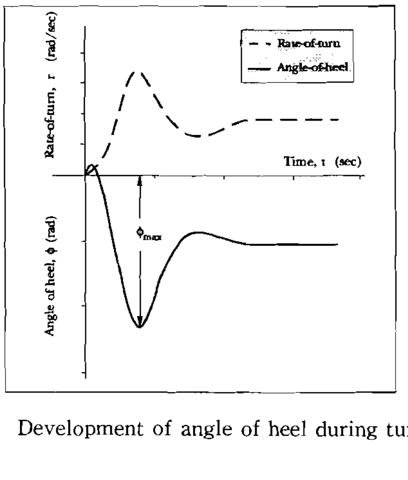


Fig. 7 Development of angle of heel during turn

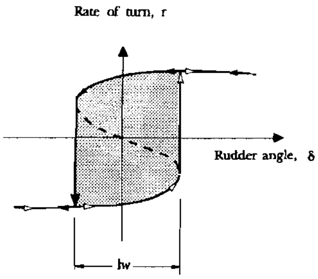


Fig. 8 Instability loop

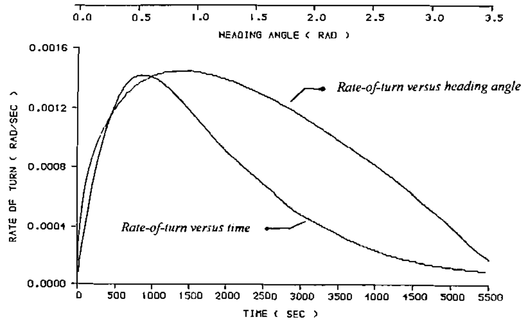


Fig. 9 Coasting turn

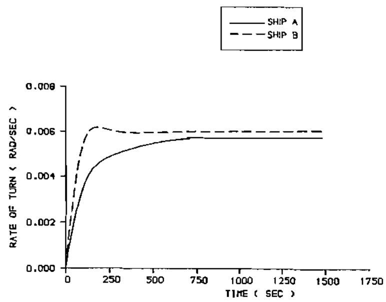


Fig. 10 Accelerating turn

where ∇ is the ship volume.

The length quantity $\nabla^{1/3}$ was preferred to the ship length L because the latter is a varying parameter during the assessment while this is not the case for ship volume.

It is possible also to write the above expression for the trajectory of the remotest point of the ship, taking the following alternative measure:

$$r_{NSR}=r\nabla^{1/3}/[(L/2)^2+R^2+RL\cos\beta]^{1/2}$$

On the other hand, the dimensional rate of turn, or, preferably, its non-dimensionalised counterpart r_0' with respect to the initial forward speed U_0,

$$r_{NS}^{(0)}=r\nabla^{1/3}/U_0$$

represent direct *time-relevant* quantities.

c) *Coasting-turn*

According to this manoeuvre, in a vessel travelling with steady forward speed U_0, the engines are stopped and simultaneously the rudder is deflected to maximum angle, say to port. In this manoeuvre, the responsiveness of the vessel, given that the rudder is no longer taking the benefit of the propeller wake, is the main quality of interest. Measures appropriate for this are, see Fig. 9:

- The peak of rate-of-turn after the initiation of the manoeuvre, r_{max},
- The time needed to reach this peak, $t_{r\,max}$,
- The change of heading $\psi=\psi_T$, achieved after a sufficiently large period of time t (for the case examined a period of 200 sec was found adequate).

d) *Accelerating turn*

This manoeuvre involves the execution of a turn with maximum rudder angle and full power from zero forward speed. In such a turn a peak of time history may not exist, see Fig. 10. For this reason, the point of maximum curvature should rather be taken as the characteristic point of the curve. This is the point at which the function

$$k(t)=\dot{r}(t)/[1+\dot{r}(t)^2]^{3/2}$$

reaches a maximum, where $k(t)$ is the function providing the curvature at each time instant.

Observing that good accelerating turning performance is important at the very initial stage of the manoeuvre (realised in practice as a "quick kick") the following measures are adopted:

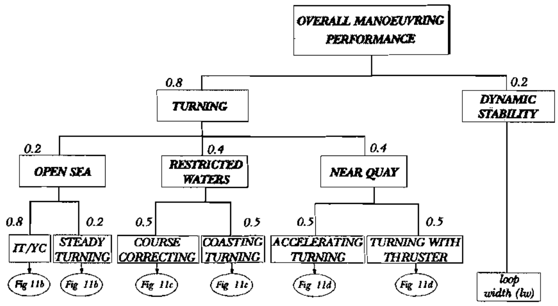
- The rate of turn at the point of maximum curvature of the (r, t) curve, r_{mc},
- The time needed for a 10° change of heading, t^{10},
- The distance travelled for a 10° change of heading, S^{10}

4. The detailed structure of the assessment

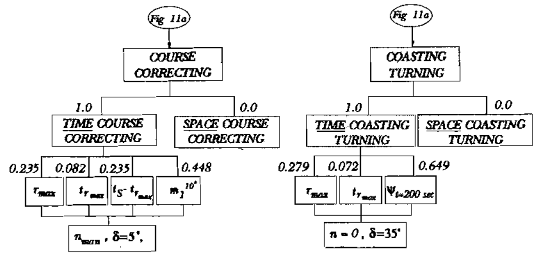
4.1 *Specification of measures in relation to the requirements*

a) High speed operation

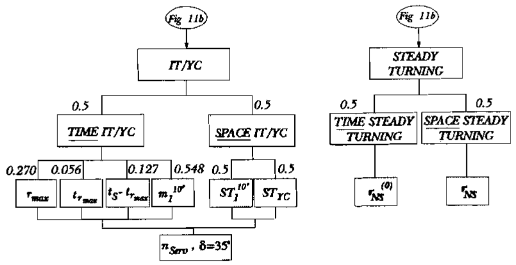
- Measurement of directional instability (loop width) at 1.0° bow trim, considered as the maximum bow trim allowed,
- Identification of maximum heeling during a tight turning manoeuvre (constraint of the assessment)
- Prediction of turning performance according to the IT/YC criterion with $\delta=35°$,



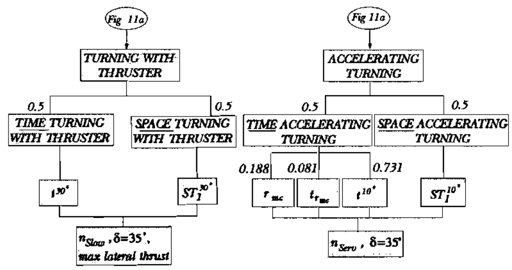
(Fig. 11a)



(Fig. 11c)



(Fig. 11b)



(Fig. 11d)

Fig. 11 The assessment structure

b) Moderate speed

- Course correcting capability related to the response-to-the-rudder quality and measured by means of the IT/YC manoeuvre with $\delta=5°$ rudder,
- Coasting turning accounting for an extreme of rudder effectiveness during deceleration.

c) Slow speed operation

- Accelerating turn performance,
- Turning with full thruster action and rudder set at max angle, initiated at a forward speed of 2 KN (assumed that it is possible to be retained by the engines).

The ability to manoeuvre astern and the effect of the environment were not taken into account is this application.

The final assessment structure selected for the investigation is presented in Figs. 11a to 11d.

4.2 *Analysis and investigation results*

All calculations were based on the mathematical model earlier presented by *Vassalos and Spyrou*[22]. Fig. 12 presents one example from the several numerical procedures carried out within the specified range of design parameters.

For all ships examined, it was noticed that directional

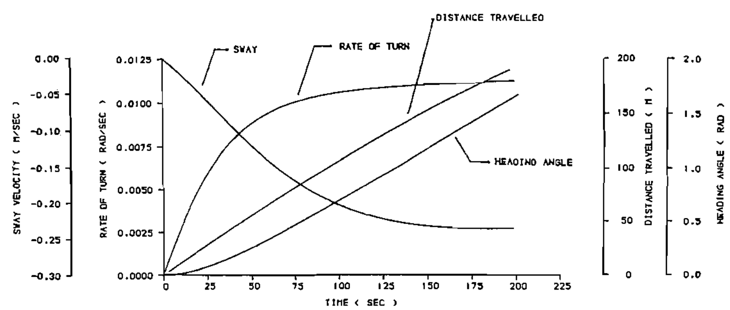


Fig. 12 Ferry F2: Turning with full rudder and thruster

instability was not very significant (at max $2\times3.132°$ loop width) and also the heeling angles obtained during turn were rather low. It must be stressed however, that the latter was largely due to the fact that the metacentric height GM was kept deliberately high.

Tables 1 to 7 present the performance of each examined vessel against the various measures linked with each criterion. The normalised performances,in dicated by ( )', are presented next to the absolute ones. It can be noticed that additional measures to those required in the structure of Fig. 11 appear in the Tables. In particular:

- With regard to the IT/YC criterion, the moment measure m_I^{φ}, discussed in the previous application, was applied up to $10°(m_I^{10})$ and up to $30°(m_I^{30})$ and the performances obtained were compared to each other. It can be concluded that the difference in performance is not very serious. It is interesting to mention, however, that in one case the maximum of the rate of turn curve occurred at a change of heading below 30° and in this case, therefore, no comparison was possible (Ship F26, Table 1) A similar investigation was applied in the case of the space measure ST, with analogous results.
- With regard to the steady-turning criterion, the performance obtained on the basis of the trajectory of ship's origin (steady turning-circle radius) was compared to the performance obtained on the basis of the ship's remotest point trajectory (Table 2). It can be observed that the difference between the two assessments is almost negligible.

The weighting factors appearing in the assessment structure were derived from the preferences matrices technique, with an example presented in Table 8. The assessment results are summarised in Figs. 13. The curved plane inside the parallelepiped formed by the main ship parameters represents "average" performance and therefore it divides the space into two, a sub-space of "good" and a sub-space of "poor" performance. It is interesting to notice that the directional stability and initial turning planes are almost vertical to each other and that the intersection of the two planes provides a space of good performance with regard to both qualities, see Fig. 14.

To understand how sensitive the result is to perturbations of the weights vectors, a sensitivity analysis was performed regarding the weights of the IT/YC time measures. In detail, one ferry was selected (F9) and the weights were systematically varied in the following way: The weights w_1, w_2, w_3, corresponding to r_{max}, t_{max}, $t_S-t_{r\,max}$ were perturbed in the ranges $w_1\pm0.1$, $w_2\pm0.02$, $w_3\pm0.04$ with the remaining weighting factor w_4 (corresponding to m_I^{10}) recovered in each case from the relationship $w_4=1-w_1-w_2-w_3$. It was found that, for the cases examined, the IT/YC function varied in the range 0.605 to 0.66 while at the higher location of the turning function the result was almost insensitive (The overall maneuvrability index, F^T, ranged from 0.711 to 0.720). In spite of this result, however, this matter should be studied more systematically in the future.

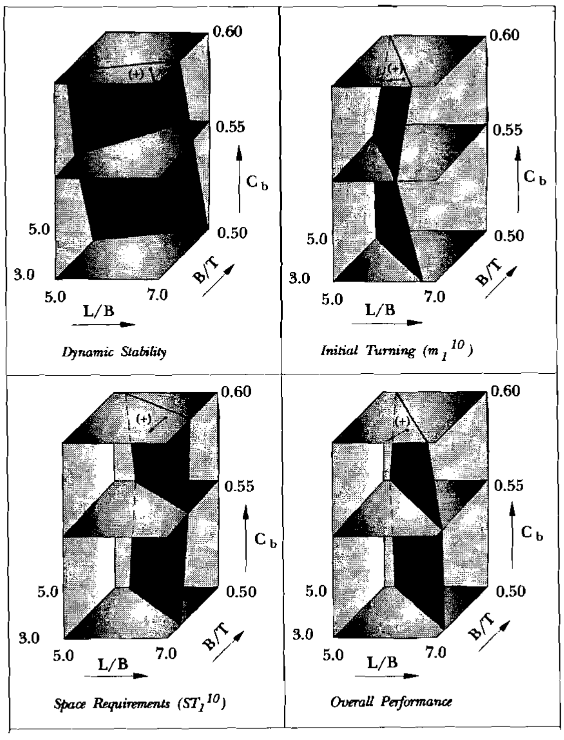


Fig. 13 Spaces of satisfactory or poor manoeuvring performance

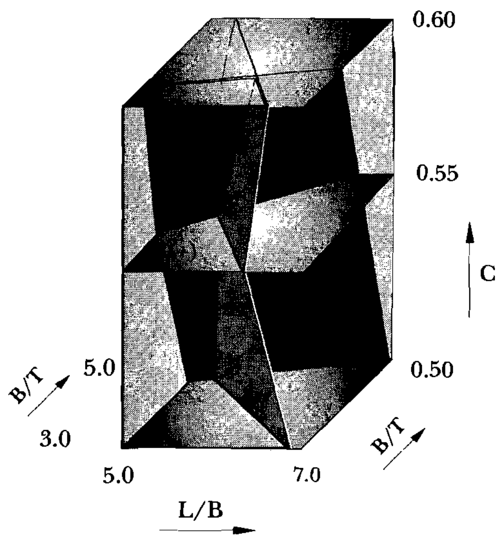


Fig. 14 Combination of initial turning with dynamic stability

Table 1 IT/YC performance of the ferries examined

SHIPS	r_{max}	$(r_{max})'$	t_{rmax}	$(t_{rmax})'$	$t_s - t_{rmax}$	$(t_s - t_{rmax})'$	m_1^{10}	$(m_1^{10})'$	m_1^{30}	$(m_1^{30})'$	ST_1^{10}	$(ST_1^{10})'$	ST_1^{30}	$(ST_1^{30})'$	ST_{YC}	$(ST_{YC})'$
F1	0.05329	0.730	21.5	0.240	6.7	0.622	0.00887	0.956	0.01393	0.903	1690.20	1.000	502.13	0.972	282.335	0.939
F2	0.05811	0.859	20.5	0.320	7.0	0.555	0.00884	0.946	0.01405	0.926	1708.73	0.993	497.58	0.983	329.398	0.808
F3	0.06342	1.000	19.9	0.368	8.2	0.289	0.00899	1.000	0.01443	1.000	1719.67	0.989	490.24	1.000	260.170	1.000
F7	0.04459	0.498	22.0	0.200	8.0	0.333	0.00748	0.453	0.01189	0.506	2889.09	0.571	669.72	0.574	406.380	0.595
F8	0.04832	0.598	24.5	0.000	9.5	0.000	0.00736	0.409	0.01164	0.457	2809.70	0.599	665.56	0.584	391.930	0.635
F9	0.05382	0.744	23.5	0.080	9.0	0.111	0.00775	0.551	0.01257	0.638	2980.80	0.538	653.60	0.612	284.101	0.934
F19	0.03222	0.169	12.0	1.000	5.0	1.000	0.00754	0.475	0.01126	0.383	2619.98	0.667	677.03	0.557	526.370	0.263
F20	0.03525	0.250	19.0	0.440	7.0	0.555	0.00707	0.304	0.01123	0.377	2433.46	0.734	656.38	0.606	323.300	0.825
F21	0.03833	0.332	19.0	0.440	7.5	0.444	0.00725	0.370	0.01134	0.399	2374.10	0.755	644.97	0.633	410.164	0.585
F25	0.02588	0.000	14.5	0.800	6.5	0.667	0.00623	0.000	0.00929	0.000	4482.58	0.000	911.65	0.000	621.550	0.000
F26	0.02954	0.097	17.5	0.560	7.5	0.444	0.00629	0.022			4224.77	0.092			362.445	0.717
F27	0.03298	0.189	22.0	0.200	8.2	0.289	0.00630	0.025	0.00992	0.123	4073.25	0.147	842.72	0.164	481.240	0.388

Table 2 Steady turning performance

SHIPS	$r\nabla^{1/3}/U_0$	$(r\nabla^{1/3}/U_0)'$	$r\nabla^{1/3}/U$	$(r\nabla^{1/3}/U)'$	r_{NSR}	$(r_{NSR})'$
F1	0.0815	0.735	0.1257	0.767	0.0948	0.783
F2	0.0885	0.855	0.1362	0.887	0.1015	0.895
F3	0.0970	1.000	0.1461	1.000	0.1078	1.000
F7	0.0686	0.514	0.1138	0.630	0.0845	0.611
F8	0.0748	0.620	0.1200	0.701	0.0887	0.681
F9	0.0820	0.743	0.1353	0.876	0.0969	0.818
F19	0.0479	0.161	0.0795	0.238	0.0632	0.255
F20	0.0558	0.296	0.0897	0.355	0.0700	0.369
F21	0.0581	0.335	0.0982	0.452	0.0756	0.463
F25	0.0385	0.000	0.0587	0.000	0.0479	0.000
F26	0.0465	0.137	0.0695	0.124	0.0553	0.123
F27	0.0519	0.229	0.0804	0.248	0.0624	0.242

Table 5 Turning with rudder and thruster

SHIPS	t^{30}	$(t^{30})'$	ST_1^{30}	$(ST_1^{30})'$
F1	78.25	0.901	4.196	0.941
F2	76.46	0.964	4.083	0.999
F3	75.30	1.000	4.082	1.000
F7	85.37	0.691	4.835	0.609
F8	83.89	0.736	4.866	0.593
F9	82.15	0.790	4.853	0.599
F19	97.40	0.322	5.206	0.416
F20	94.85	0.400	5.038	0.503
F21	91.93	0.490	4.877	0.587
F25	107.90	0.000	6.007	0.000
F26	102.62	0.162	5.778	0.119
F27	99.40	0.261	5.622	0.200

Table 3 Directional stability

SHIPS	lw	(lw)'
F1	0.406	0.968
F2	0.870	0.803
F3	1.373	0.625
F7	2.146	0.350
F8	2.891	0.086
F9	3.132	0.000
F19	0.316	1.000
F20	0.615	0.894
F21	0.953	0.774
F25	1.702	0.508
F26	2.154	0.347
F27	2.666	0.165

Table 6 Course correcting

SHIPS	r_{max}	$(r_{max})'$	t_{rmax}	$(t_{rmax})'$	$t_s - t_{rmax}$	$(t_s - t_{rmax})'$	m_1^{10}	$(m_1^{10})'$
F1	0.00874	0.531	162	0.367	29.7	0.850	1.614	1.000
F2	0.00978	0.733	173	0.000	35.0	0.729	1.580	0.909
F3	0.01087	0.944	165	0.267	48.2	0.431	1.545	0.815
F7	0.00923	0.625	157	0.542	49.1	0.410	1.438	0.473
F8	0.01022	0.818	165	0.267	57.0	0.232	1.408	0.446
F9	0.01116	1.000	150	0.767	67.3	0.000	1.398	0.419
F19	0.00671	0.138	143	1.000	23.0	1.000	1.480	0.640
F20	0.00702	0.198	157	0.533	28.0	0.887	1.393	0.406
F21	0.00750	0.291	169	0.133	34.0	0.752	1.356	0.306
F25	0.00600	0.000	150	0.767	36.0	0.706	1.255	0.035
F26	0.00671	0.138	159	0.467	39.0	0.639	1.257	0.040
F27	0.00733	0.258	164	0.300	45.0	0.503	1.242	0.000

Table 4 Accelerating turn

SHIPS	r_{mc}	$(r_{mc})'$	t_{rmc}	$(t_{rmc})'$	t^{10}	$(t^{10})'$	ST_1^{10}	$(ST_1^{10})'$
F1	0.0317	0.643	19.0	0.589	11.74	0.820	0.697	0.911
F2	0.0332	0.702	17.7	0.648	11.56	0.849	1.200	0.626
F3	0.0407	0.996	20.5	0.521	10.63	1.000	1.052	0.710
F7	0.0308	0.608	25.0	0.315	13.60	0.519	1.171	0.642
F8	0.0339	0.729	29.7	0.100	13.77	0.491	1.227	0.611
F9	0.0408	1.000	31.9	0.000	12.68	0.668	1.520	0.444
F19	0.0153	0.000	10.0	1.000	15.06	0.282	0.541	1.000
F20	0.0207	0.212	18.2	0.626	14.71	0.339	1.071	0.699
F21	0.0231	0.306	22.0	0.452	14.64	0.350	1.096	0.685
F25	0.0158	0.020	18.1	0.630	16.80	0.000	1.058	0.707
F26	0.0193	0.157	23.2	0.397	16.79	0.001	2.303	0.000
F27	0.0216	0.247	25.7	0.283	16.59	0.034	1.733	0.323

Table 7 Coasting turn

SHIPS	r_{max}	$(r_{max})'$	t_{rmax}	$(t_{rmax})'$	ψ_{200}	ψ'_{200}
F1	0.0142	0.548	44.0	0.811	120.95	0.515
F2	0.0166	0.806	50.0	0.649	145.85	0.807
F3	0.0172	0.872	74.0	0.000	152.12	0.886
F7	0.0151	0.645	56.0	0.486	133.20	0.661
F8	0.0173	0.881	58.0	0.432	152.63	0.892
F9	0.0184	1.000	67.0	0.189	161.71	1.000
F19	0.0097	0.064	37.0	1.000	81.21	0.043
F20	0.0113	0.237	46.0	0.757	99.67	0.262
F21	0.1116	0.269	43.0	0.838	100.96	0.278
F25	0.0091	0.000	44.0	0.811	77.61	0.000
F26	0.0101	0.107	49.0	0.676	87.57	0.118
F27	0.0106	0.161	54.0	0.541	92.96	0.182

Table 8 Examples of the weights derivation procedure

IT / YC	r_{max}	$t_{r_{max}}$	$t_S - t_{r_{max}}$	$m_I^{10'}$
r_{max}	1	5	3	1/3
$t_{r_{max}}$	1/5	1	1/3	1/7
$t_S - t_{r_{max}}$	1/3	3	1	1/4
$m_I^{10'}$	3	7	4	1

$\lambda_{max} = 4.1184$

ACCELERATING TURN	r_{max}	$t_{r_{max}}$	$ST_I^{10'}$
r_{max}	1	3	1/5
$t_{r_{max}}$	1/3	1	1/7
$ST_I^{10'}$	5	7	1

$\lambda_{max} = 3.0649$

COURSE CORRECTING	r_{max}	$t_{r_{max}}$	$t_S - t_{r_{max}}$	$m_I^{10'}$
r_{max}	1	3	1	1/2
$t_{r_{max}}$	1/3	1	1/3	1/5
$t_S - t_{r_{max}}$	1	3	1	1/2
$m_I^{10'}$	2	5	2	1

$\lambda_{max} = 4.004$

5. Concluding Remarks

The assessment of ship manoeuvrability presents a typical case of trying to identify a satisfactory solution in the presence of several competing objectives, directional stability cannot be easily reconsiled with turning ability, the same applies for turning in limited space as against being responsive to the rudder. A rationally developed hierarchical structuring of these objectives is an essential step towards the achievement of a solution which reflects the desires of those who benefit from the operation of these vessels.

The translation of the manoeuvring requirements as perceived by the ship operator into a specific set of assessment criteria and measures is a task requiring a detailed study of ship behaviour, taking into account the essentially non-linear nature of manoeuvring motion. In the presence of several satisfactory mathematical models for conventional ship forms, there is no justification for confining the assessment to the earlier established linear indices.

Within the above frame of mind, a general approach for the specification and assessment of ship manoeuvrability has been put forward. The proposed approach contains three stages: the specification of manoeuvrability *requirements* pertaining to a particular vessel type, the identification of suitable assessment procedures through detailed *theoretical studies* of the steady and transient manoeuvring behaviour, and the *integration* of the various performance related-entities in a properly organised assessment structure.

The practical feasibility of the new approach was demonstrated through application to a particular vessel type, namely ferries. With the main dimensions varying in the range $5.0 < L/B < 7.0$, $3.0 < B/T < 5.0$ and $0.50 < Cb < 0.60$ and with the displacement kept constant in all cases, areas characterised by "good" or "poor" performance were identified.

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Appendix I : *Definitions of Manoevvrability : A Corparison*

It is typical for different people or Bodies to attach to the terms "manoeuvrability" or "controllability" different meanings, this resulting often to vagueness and confusion. For example, in a number of cases the two terms are freely interchanged while in others the latter term is understood as describing a wider notion than the first. To help resolve this, the following short comments are offered on a collection of popular definitions:

a) Saunders, RINA and Panel H-10 of SNAME

Saunders understood manoeuvrability as synonymous to the old term "ship handiness" and distinguished it from controllability[18]:

"Manoeuvrability is an expression of the degree or rate at which a vessel can change her speed, course or attitude".

"Controllability is that quality of a ship and its parts and appendages which demonstrates the effectiveness of movement of the controls in producing any desired uniformity or any change, at a specified rate, in the attitude, position or motion of a moving ship".

The controllability definition emphasizes the role of the control mechanisms. The above definition have been the basis for the RINA's and the SNAME's Panel H-10 definitions, as it can be realised from the following:

According to RINA[16]:

"Controllability is that quality of a ship which determines the effectiveness of the controls in producing any desired change at a specific rate, in the attitude or position of the moving ship".

This is similar to the Panel's H-10 definition[15]:

"Controllability is defined as the relative ability of a piloted vessel to change position and orientation at desired rates of speed"

b) Dieudonne's definition[19] :

"Manoeuvrability is the readiness or the ability of a ship when traveling in good weather in calm sea, to take the path which the steersman desires it to follow"

This definition is practical and it could be satisfactory if it was not too restrictive for the role of the environment.

c) Fedyayevskiy, Sobolev[6] :

In the Russian literature the term "steerability" is basically preferred and it is given a meaning similar to the Dieudonne's definition of manoeuvrability:

"By steerability of a ship we mean its capability of moving along the trajectory needed by the shiphandler. The trajectory may be in a straight line or curvilinear. Because of this, we distinguish such qalities as stability on course and turning"

d) Barr[2] :

"Manoeuvrability defines a vessel's ability to change course, turn, stop or accelerate from rest".

"Controllability defines a vessel's ability to manoeuvre and also to maintain or correct course, speed and/or position".