THE MANUAL STEERING CRITERION BASED UPON PHASE MARGIN

DAVID CLARKE
David Clarke Associates,
11 Lyndon Drive, East Boldon, Tyne & Wear, NE36 0NU, U.K.

CHRIS COX and PAT FOX
Sunderland Polytechnic, Control Systems Centre,
School of Electrical Eng'g & Applied Physics,
Edinburgh Building, Chester Road, Sunderland, SR1 3SD, U.K.

ABSTRACT

Aspects of ship manoeuvrability will become part of the ship design process in 1993 when a new Resolution is adopted by the International Maritime Organisation. Course keeping ability will be judged by the width of the spiral loop, and it is pointed out here that the current proposal is too general and does not account for several important parameters.

INTRODUCTION

A new Resolution may be adopted in 1993 by the International Maritime Organisation (IMO), which will mean that ship manoeuvrability will become a much more important aspect of the ship design process, with several manoeuvring criteria having to be addressed and calculations having to be performed to ensure that the ship will satisfy these criteria. Later, full-scale trials will have to be performed to verify that the ship does satisfy the criteria in practice. Those aspects of manoeuvrability which are to be examined have been covered in detail by IMO [1], [2]. These manoeuvrability criteria are concerned with the turning, yaw checking, initial turning and course keeping abilities of the ship. These criteria are fairly easily verified during full-scale trials, by means of turning circle and zig-zag tests, with the exception of course keeping ability.

Traditionally, course keeping ability has been considered in terms of spiral manoeuvre, that is a plot of the rate of turn of the ship versus applied rudder angle, where instability is evident by the plot having a tinct "S" shape, the width of the spiral loop being taken to be a sure of the instability. This must be regarded only as a measure of the tic stability of the system, which may also be dynamically stable or table.

The most important aspect is not whether the ship is statically stable unstable but whether it is controllable by the helmsman. In order to mine controllability, the full dynamical behaviour of the ship must be sidered. Nomoto [3] and Koyama et al [4] were the first to look at this blem and to realise that the important factor was the phase margin of system, and for a helmsman to be able to control the ship, that it must algebraically larger than -20 deg. In coming to this conclusion they mined the linear equations of motion, including the dynamical behaviour the steering gear.

The concept of phase margin was at first suggested by IMO [5] as a terion for course keeping, but with the value for an acceptable phase rgin having been set at -5 deg. However, IMO have now moved away from idea of phase margin as a criterion for course keeping, back to a lief that the spiral loop width is quite adequate as an alternative [2].

There are several reasons behind the change from the phase margin terion, back to the spiral loop width. In Ref. [2] IMO suggest that the ncept of phase margin is not widely understood, and in any event there is suitable manoeuvre or full scale trial procedure to evaluate it. On the her hand they argue that the spiral loop width is relatively well known, not so well understood, and is readily measured and verified within the isting repertoire of full scale trials.

The purpose of this paper is to re-examine the validity of the sumptions made and to provide an explanation and understanding of phase rgin as it effects manual steering.

MATHEMATICAL MODEL

The equations of motion used to describe the manoeuvring behaviour of a ship are now well established. Although the basic statement of Newton's Laws of Motion in three or more degrees of freedom gives no scope for variation, the expressions used for the hydrodynamic forces and moments take a wide variety of forms. Nevertheless, the differences occur mainly in the higher order or non linear terms and the first order or linear terms are accepted without argument.

In an earlier paper, Clarke et al [6] cover the development of the linear equations from first principles, and show that the dimensionless form of the linear equations of motion is

$$(Y'_{\dot{v}} - m')\dot{v}' + Y'_v v' + (Y'_{\dot{r}} - m'x'_G)\dot{r}' + (Y'_r - m')r' + Y'_\delta \delta = 0$$

$$(N'_{\dot{v}} - m'x'_G)\dot{v}' + N'_v v' + (N'_{\dot{r}} - I'_Z)\dot{r}' + (N'_r - m'x'_G)r' + N'_\delta \delta = 0 \quad \ldots (1)$$

expressed in terms of the non-dimensional acceleration and velocity derivatives, and where the variables are the dimensionless sway velocity v', dimensionless yaw rate r' and the rudder angle δ. It is quite straightforward to rearrange these two simultaneous equations as a pair of decoupled second order equations as follows.

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

$$T'_1 T'_2 \ddot{v}' + (T'_1 + T'_2)\dot{v}' + v' = K'_v\delta + K'_v T'_4\dot{\delta} \quad \ldots (2)$$

where the terms in equation (2) and their algebraic relationships with the acceleration and velocity derivatives of equation (1) can be found in the literature and particularly in Clarke et al [6]. It is now possible to use only the first equation above, in terms of the non-dimensional yaw rate, which has been found extremely useful in the analysis of full-scale trial results, since in practice yaw rate is much more simple to measure than sway velocity. The manner of expressing the coefficients in terms of gains and time constants is immediately consistent with normal control engineering practice. It is also worth noting that the number of variables required to describe the system has been reduced from 13 in equation (1) to 6 in equation (2).

When described by the linear equation in yaw rate, equation (2) above, response of the ship to any harmonic excitation must itself be monic, and the two are related to each other by the transfer function, ch is found by taking the Laplace transform of the first line of ation (2), and ignoring any initial conditions, this is

$$-\frac{r'}{\delta}(s) = \frac{K'(1 + T'_3 s)}{(1 + T'_1 s)(1 + T'_2 s)} \qquad \ldots (3)$$

This transfer function relates the yaw rate response to the rudder ut, but it is more convenient to use the heading response to the rudder ut, in which case the transfer function needs to be multiplied by a tor 1/s, which takes care of the necessary integration. The dynamic aviour of the steering gear must be also taken into account if we are to dy the manual steering behaviour of the ship. This may be simply resented by a first order transfer function whose non-dimensional time stant is T'_E, which when combined with equation (3) gives

$$G(s) = \frac{\psi'}{-\delta_*} = \frac{K'(1 + T_3' s)}{s(1 + T'_1 s)(1 + T'_2 s(1 + T'_E s)} \qquad \ldots (4)$$

Equation (4) now represents the transfer function of the ship plus ering gear. If we assume that while steering the ship, the helmsman aves in a particular manner which may be represented by another transfer ction H(s), then the block diagram of the ship steering control loop may represented as shown in Fig. 1.

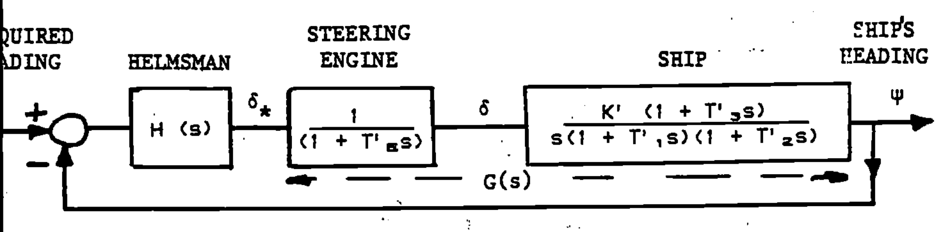

Figure 1. Block diagram of steering control loop

Since the ships in which we are primarily interested are dynamically table, then the problem of manual ship control can be reduced to finding se types of ship for which the transfer function of the helmsman H(s) is sufficient compensation to ensure a stable behaviour of the closed loop tem, as depicted in Fig. 1.

The problem of the controllability of a ship can therefore be reduced o an examination of the magnitude and phase of the transfer function for he ship plus the steering engine. In other words, when the magnitude in quation (4) is unity, what is its phase? If it is less than -180 deg., hen it is unstable, but if it is not less than say -195 deg., the 20 deg. hase advance which the helmsman can provide will still give rise to a table system by bringing the phase above -180 deg. to an acceptable figure f -175 deg.

The magnitude of the ship plus steering engine transfer function (4) ay be expressed in logarithmic form as,

$$
\begin{aligned}
20 \log G(\omega)[\mathrm{db}] = {} & 20 \log K' + 10 \log [1 + (T'_3\omega')^2] \\
& - 20 \log \omega' - 10 \log [1 + (T'_1\omega')^2] \\
& - 10 \log [1 + (T'_2\omega')^2] \\
& - 10 \log [1 + (T'_E\omega')^2]
\end{aligned}
\qquad \ldots (5)
$$

and for an unstable system the phase can be written as

$$
\begin{aligned}
\text{Phase } \phi \text{ [deg]} = {} & -270 + \tan^{-1}(-\omega' T'_1) - \tan^{-1}(\omega' T'_E) \\
& \tan^{-1}(\omega' T'_3) - \tan^{-1}(\omega' T'_2)
\end{aligned}
\qquad \ldots (6)
$$

The steps taken in obtaining equations (5) and (6) from equation (4) can be found in most textbooks on automatic control.

Using equation (4) , the characteristics of any ship or range of ships can be easily investigated. The family of ships studied by Nomoto [3] had the following characteristics:-

$K'/T'_1 = -0.50$; $T'_2 = 0.35$; $T'_3 = 0.60$.

The relationship between these constant non-dimensional values, and their corresponding real time equivalents, is through the length over speed ratio L/U, where for the general time constant we have,

$$T' = T/(L/U)$$

The hydrodynamically based time constants do not change, for any speed or ship length. The reverse is true, however, for the steering gear time constant which is taken by Nomoto to be

$T_E = 2.5$ sec. so that $T'_E = 2.5/(L/U)$.

Here it can be seen that as long as $L/U > 10$, then from the last equation, T'_E will be much smaller than T'_2, and will not have a great effect on the overall dynamics of the system. However, when the reverse is true and $L/U < 10$, then the steering engine causes an increasing time lag which can greatly detract from the manual handling ability of the ship. By increasing the speed of the steering gear, that is making $T_E < 2.5$ sec., this problem can be alleviated to a certain degree.

Using the data given above the behaviour of a whole family of ships may be examined by varying the parameters $1/T'_1$ and L/U. However before comparison can be made with the work of Nomoto [3] and Koyama et al [4], one further relationship must be established.

The steady state solution of the yaw rate equation (3) is simply found by ignoring the time derivatives of r', so that

$$r' = K'\delta$$

but this linear relationship does not represent the true situation for the

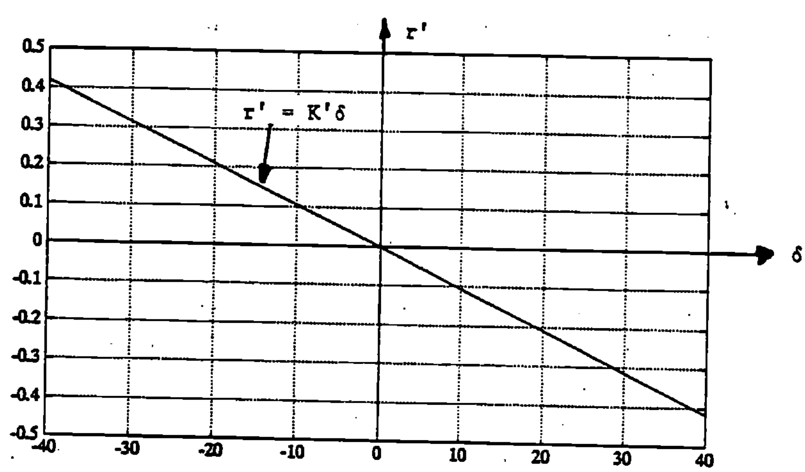

Figure 3a. Diagram of spiral curve for stable linear ship.

larger yaw rates and rudder angles, since in reality the steady state behaviour is non-linear. This may be represented here by the inclusion of a cubic term, so that

$$r' + \alpha' r'^3 = K'\delta \qquad \ldots (7)$$

This curve is shown diagrammatically in Fig. 3, and represents the well known spiral curve. In reality this phenomenon is much more complicated than modelled here, but all that is required of the simple model for this purpose, is that it has the same properties. The height of the loop can be easily found by setting $\delta = 0$, and then the loop height is $2/\sqrt{-\alpha'}$).

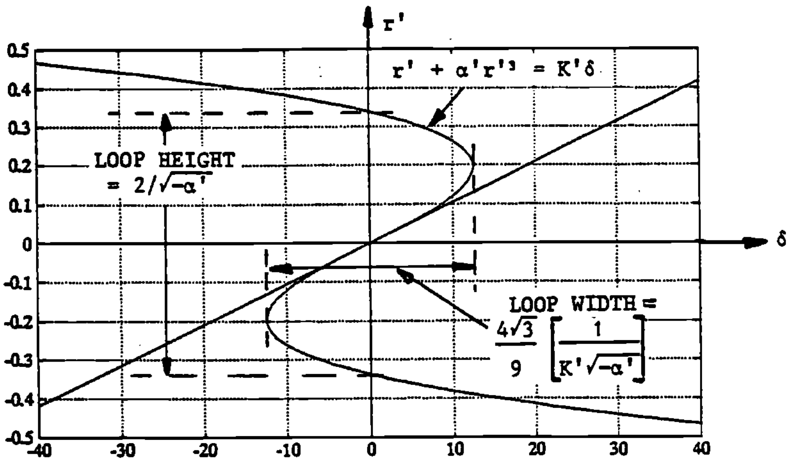

Figure 3b. Diagram of spiral curve for an unstable ship.

The loop width can be found by differentiating equation (7) with respect to r' and setting the right hand side to zero, then the loop width can be shown to be

$$\delta_{LOOP} = 2 \left[\frac{2\sqrt{3}}{9}\right] [1/(K'\sqrt{-\alpha'})] \qquad \text{... (8)}$$

Now for all the family of ships examined by Nomoto, $K'/T' = -0.5$, so that in this case we can eliminate K' from the last expression to yield

$$\delta_{LOOP} = - [1.540/(\sqrt{-\alpha'})](1/T') \qquad \text{... (9)}$$

This is an important relationship, since it allows the results of a linear transfer function analysis to be related to the non-linear concept of spiral loop width. It must not be forgotten that the result shown in equation (9) will vary for other ship types for which the ratio K'/T' is different.

MANUAL STEERING CRITERIA

In the simulation work carried out by Nomoto [3], he produced what seemed to be a universal diagram which he entitled the "Map Demonstrating Ease of Manual Steering", which is reproduced here as Fig. 4. The diagram shows what appear to be lines of constant phase margin, plotted for ships with various values of spiral loop width and length over speed ratio L/U. Also indicated were the regions on the diagram in which ships were either easy or more difficult to steer. Points referring to the specific combinations of spiral loop width and L/U of the test cases were also shown.

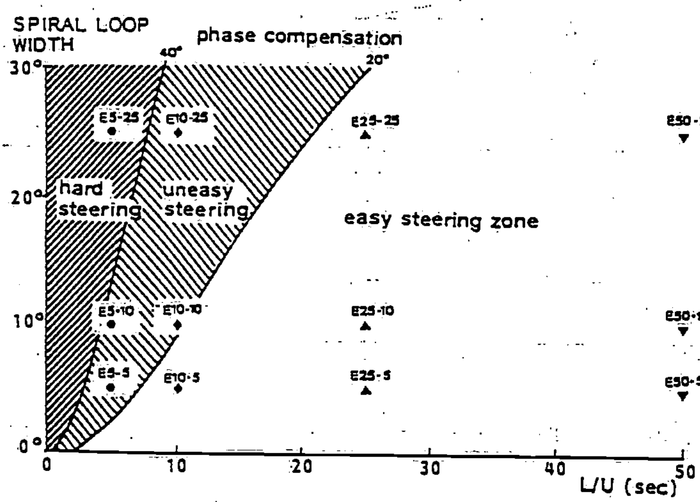

Figure 4. Map demonstrating ease of manual steering (Taken from Ref. [3]).

Later work by Nobukawa et al [2] centres upon the same universal diagram shown in Fig. 4, but concentrates on a different area of it. They argue that if a ship is being controlled by a pilot, who gives verbal commands to the helmsman, rather than by the helmsman using his own skill, then the level of acceptable instability must be reduced. This results in the acceptable phase margin being reduced from -20 deg., to -5 deg. However they fail to realise that the required gain must also be reduced in these circumstances. This is illustrated in Fig. 5, which is reproduced from Nobukawa et al [7]. This diagram has also been submitted to IMO by the Government of Japan [5] and it currently holds an important place in the formulation of the manual steering criterion. It is therefore important to examine Figs. 4 and 5 rather critically and establish exactly how they have been derived and what are their limitations.

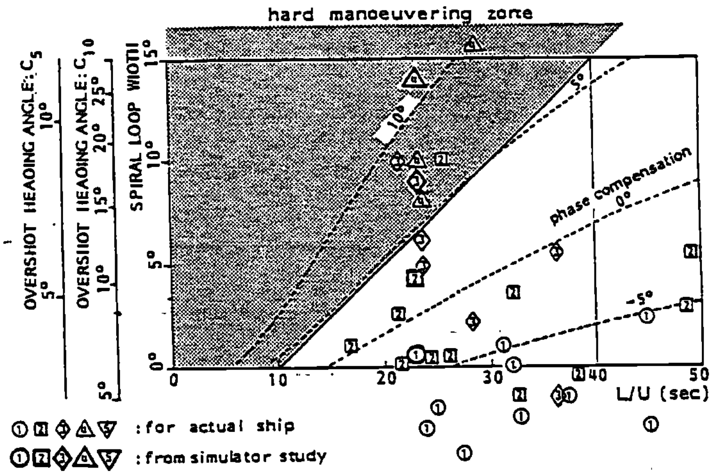

Figure 5. Map demonstrating ease of manoeuvring from the viewpoint of the pilot (taken from Ref. [7])

The simplest way to examine the magnitude and phase of any system is to plot them as rectangular co-ordinates on a diagram called a Nichols Chart, which shows the magnitude on a logarithmic scale (dB) as ordinate, and shows the phase in degrees as abscissa. Fig. 6 shows a sketch of a Nichols Chart, with a plot for a stable ship and one for an unstable ship. It can be seen that for the stable ship the trajectory moves from the top right to the bottom left of the diagram with increasing frequency. This denotes a reducing magnitude with frequency, together with a phase change from -90 deg. to -270 deg. The most important aspect is the manner in which the trajectory crosses the horizontal axis, where it has unit magnitude. In this case it crosses to the right of the vertical axis, which is at a phase of -180 deg. This gives a positive phase margin and indicates stability in the closed loop system. This situation is similar to that depicted in Fig. 2 for the Nyquist Stability Plot, where the trajectory crosses the unit circle in the third quadrant.

Turning now to the case of the unstable ship, its trajectory moves from the top left, towards the origin and then moves towards the bottom left, as the frequency increases. Again this indicates a reducing gain with frequency, but in this case the phase commences at -270 deg., increases to a maximum near the vertical axis and then reduces back towards -270 deg. In this case the trajectory crosses to the left of the vertical axis, which indicates closed loop instability and is similar tothe unstable case shown in Fig. 2.

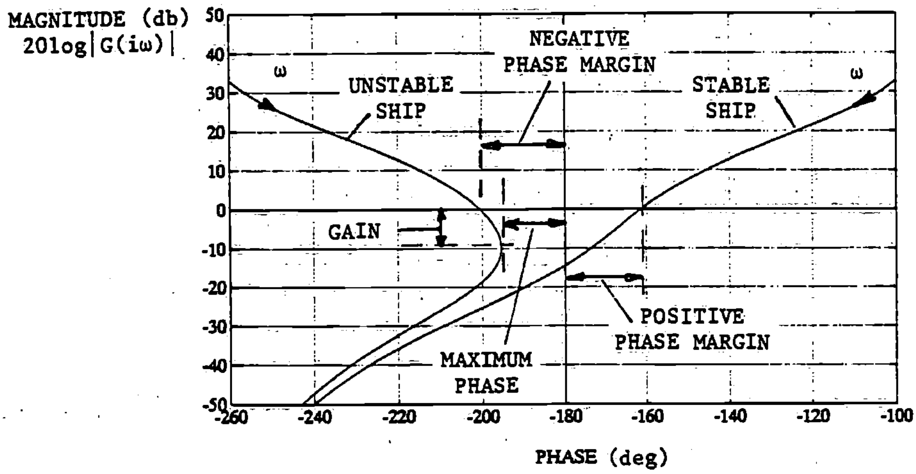

Figure 6. Nichols Chart showing stable and unstable ship.

For closed loop stability to result, the plot for an unstable ship has to be moved to the right on the Nichols Chart, so that it passes through the horizontal unit gain axis to the right of the origin. In Fig. 7a a shift of the trajectory can be achieved by the helmsman's compensating action introducing a phase advance. In Fig. 7b the helmsman's action is slightly different. Here he introduces an increase in gain, combined with a smaller amount of phase advance, in order to achieve stability. In the first case the required phase advance is given by the intersection of the trajectory with the horizontal axis, whereas in the second case the required phase advance is given by the smaller horizontal distance from the peak of the trajectory to the vertical axis. Further, in the first case, in Fig. 7a, there is no gain change required but in the second case, in Fig. 7b, the gain introduced into the system must be sufficient to move the peak of the trajectory vertically up the diagram to coincide with the horizontal axis.

It must be remembered that the helmsman's ability to introduce an increase in gain and advance the phase at the same time is limited, as indicated earlier.

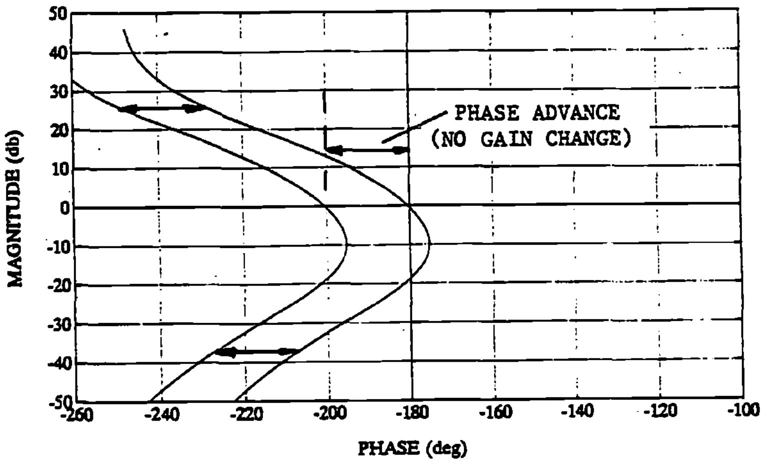

Figure 7a. Sketch showing phase advance being used to achieve stability.

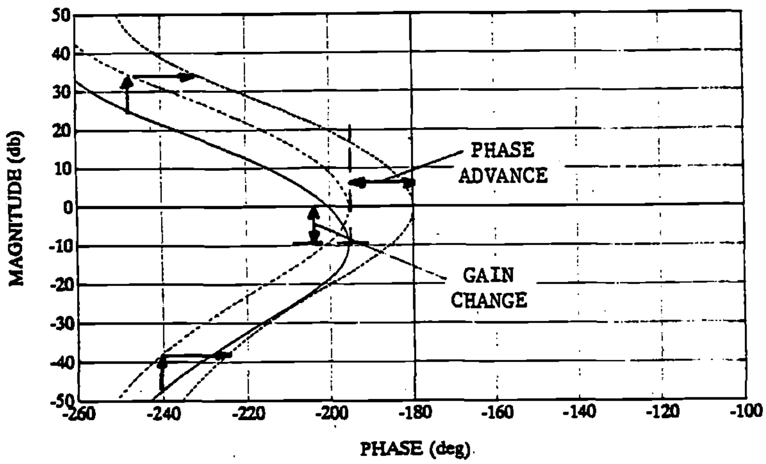

Figure 7b. Sketch showing gain change and phase advance being used to achieve stability

The magnitude and phase plots for the generalised family of ships given by Nomoto [3], have been plotted in Fig. 8, for a value of L/U equal to 10. The range of 1/T' is from +1 to -1 which covers a very wide range of ships from stable to unstable. It is interesting to note that the intersection of the trajectory with the horizontal axis moves progressively to the left as the value of 1/T' reduces.

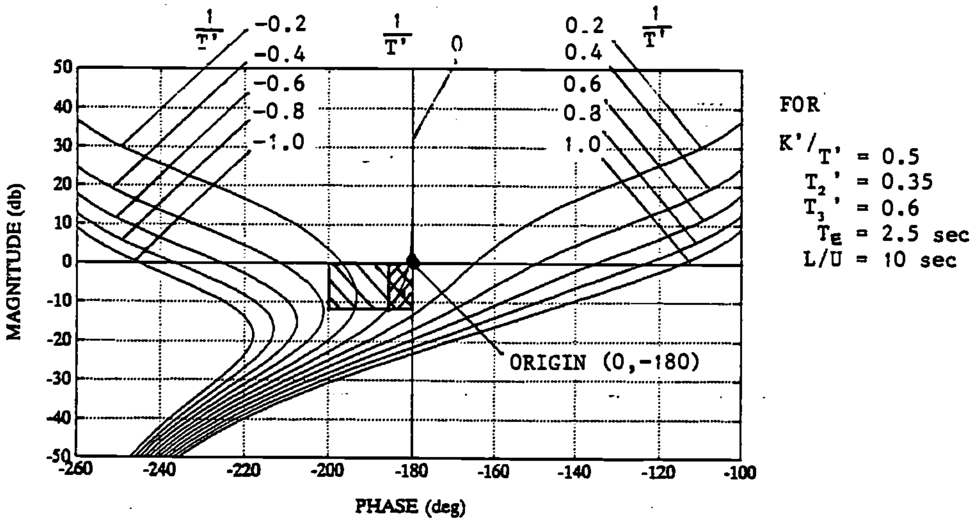

Figure 8. Nichols Chart for family of ships.

It has already been stated that the trajectory of a ship which will be closed loop stable must pass to the right of the origin on the Nichols Chart. The shaded area shown on Fig. 8 indicates a gain change of 4 (12 dB) and a phase margin of -20 deg., which have been given by Nomoto [3], Koyama et al [4] and Clarke et al [6], as the approximate characteristics of the helmsman. This implies that the helmsman may be able to control the ship satisfactorily if its gain and phase trajectory passes through or to the right of the shaded box, thereby achieving closed loop stability when the helmsman's compensating effect is included. The smaller shaded area indicates the -5 deg. phase margin suggested by Nobukawa et al[7].

Clearly in Fig. 8, all the ships whose trajectories begin at the top right of the diagram have positive values of 1/T' and are stable, since their trajectories pass well to the right of the origin and the shaded box. On the other hand for the ships whose trajectories begin at the top left of the diagram, all have negative values of 1/T' and are statically unstable. This means that they will possess spiral loops of varying sizes, dependent on the value of 1/T' and $-\alpha$, as shown in equation (9).

A second inner shaded area can also be seen inside the main box in Fig. 8. This box indicates a gain of 4 (12 dB) but a phase margin of -5 deg., as recommended by Nobukawa et al [7], for the case where a pilot is iving instructions to the helmsman. Clearly in this case there will be ore unstable ships, with trajectories on the left of the Nichols Chart hich now do not pass through the inner box and therefore would be xtremely difficult to steer in this manner. Ref. [3], [4] and [7] refer o "phase to be compensated", rather than phase margin as used here. These uantities are numerically the same, but with a sign reversal.

MANUAL STEERING MAP

e are now in a position to be able to construct a manual steering map, imilar to those shown in Figs 4 and 5, due to Nomoto[3] and Nobukawa [7].

Using equations (5), (6) and (9), lines of constant phase margin can e drawn on the map or diagram, which has spiral loop width as the ordinate nd the ratio L/U as abscissa. Fig. 9a shows the phase margins applicable o the case where the maximum phase is considered, as was the case in Fig. b. These curves are the same as those produced by Nomoto [3] and Nobukawa 7], indicating that they adopted the maximum phase condition.

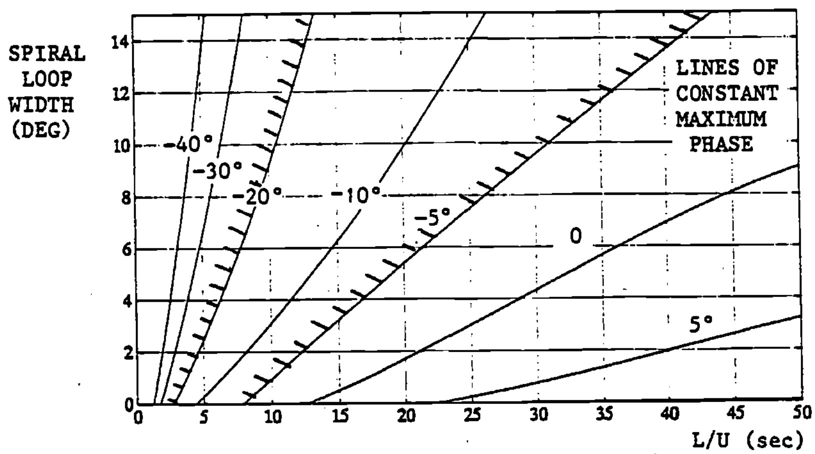

Figure 9a. Construction of manual steering map.
Lines of constant maximum phase

However, as an integral part of that process, an increase in gain s also required, as shown in Fig. 7b. Lines of constant gain are shown in 'ig. 9b. Finally, lines of constant phase are shown in Fig. 9c for the nity gain crossing case, also illustrated in Fig. 7a. It should be noted hat in Figs. 9a and 9c, the constant pahse lines are similar only when the spiral loop width is small.

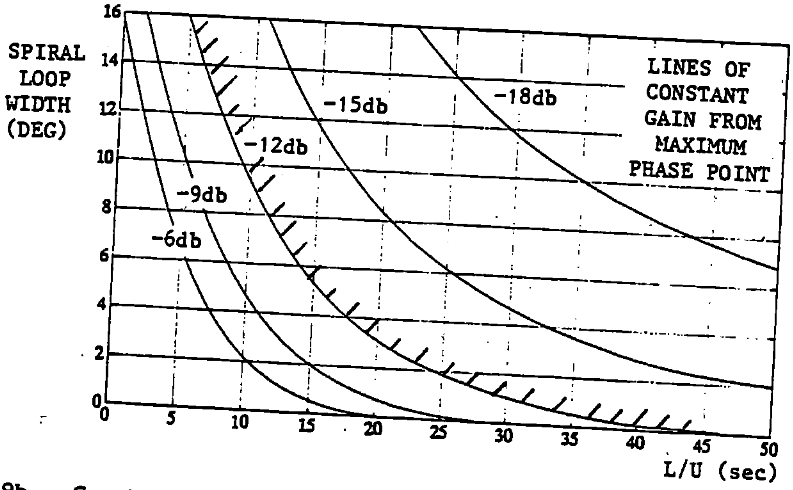

Figure 9b. Construction of manual steering map. Lines of constant gain from maximum phase point.

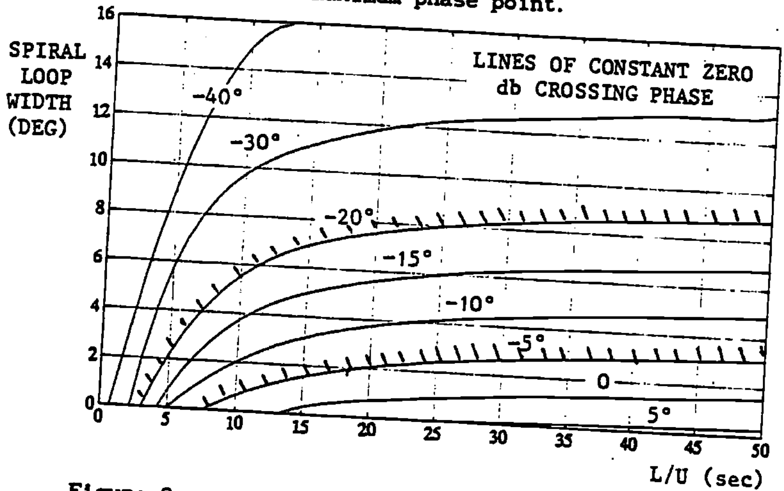

Figure 9c. Construction of manual steering map. Lines of constant zero crossing phase.

The consequences arising from the locations of these constant phase margin and gain lines are extremely important when the limitations of the helmsman's steering ability are recalled. This particularly applies to the constant gain lines, which have been previously ignored.

As quoted earlier, Nomoto [3] gives the helmsman's limits as 20 deg. phase margin and 12 dB gain. These values have been indicated on the data shown in Figs. 9a, 9b and 9c, and the corresponding lines have been plotted together in Fig. 10a. It is interesting to compare the shape of the permissible region under the hatched lines, with that suggested by Nomoto [3]. The same process carried out for the -5 deg. phase margin case set by Nobukawa et al [7], results in Fig. 10b. This time the permissible region under the hatched lines is much smaller than that being suggested by Nobukawa and, more importantly, than that forming the basis of the IMO criteria.

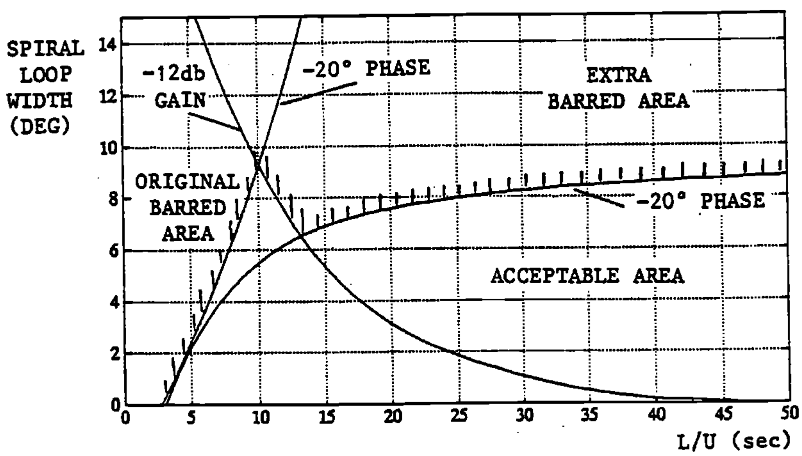

Figure 10a. Nomoto limits.

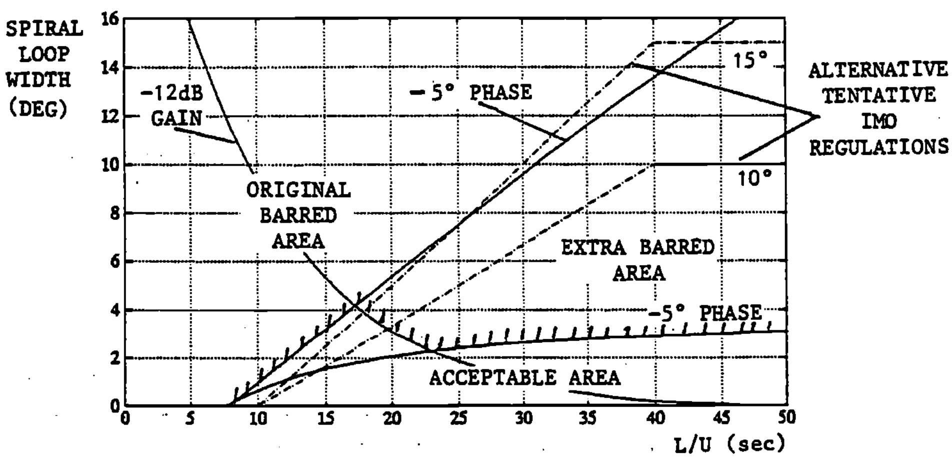

Figure 10b. Nobukawa and IMO limits.

Figure 10. Comparison of limiting factors on manual steering map.

gles. This problem is concerned with stability when the rudder angle is ose to zero.

This situation has serious consequences and must be borne in mind by designer, until such time that the tentative IMO regulations are proved and amended.

CONCLUSION

has been shown that the tentative IMO regulation concerning maximum iral loop width is inadequate. The current proposal is invalid over a rge range of loop width and L/U, previously considered acceptable. The lmsman has a limited capability to increase the gain of the system, and is constraint appears to have been neglected. This paper suggests lower miting values of spiral loop width, which are considered to be tisfactory. The designer should be aware of this situation, until IMO end their criterion values.

REFERENCES

Interim guidelines for estimating manoeuvring performance in ship design. International Maritime Organisation (IMO), MSC/Circ 389, 10 January 1985.

Report of the ad-hoc Working Group on manoeuvrability of ships and manoeuvring standards, International Maritime Organisation (IMO), DE 34/4, 4 June 1990, and DE 34 W.P.7, 7th March 1991.

Nomoto, K., Some aspects of simulator studies in ship handling, PRADS-International symposium on practical design in shipbuilding, Tokyo, October 1977.

Koyama, T., Kose, K., Hasegawa, K., A study on the instability criterion of the manual steering of ships, Journal of the Japan Society of Naval Architects, Volume 142, December 1977.

Manoeuvrability of ships and manoeuvring standards, International Maritime Organisation (IMO) , DE 34/INF. 2, submitted by Japan, 1990.

Clarke, D., Gedling, P., and Hine, G., Application of manoeuvring criteria in hull design using linear theory, Transactions of the Royal Institution of Naval Architects, Vol. 125, pp 45-68, 1983.

Nobukawa, T., Kato, T., Motomura, K., and Yoshimura, Y., Studies on manoeuvrability standards from the viewpoint of marine pilots, Joint International Conference on Marine Simulation and Ship Manoeuvrability, Tokyo, pp 59-66, June 1990.

Manoeuvrability of ships and manoeuvring standards, International Maritime Organisation (IMO), DE 35/4, submitted by Japan, 9th October 1991.