

THE RUDDER
A HIDDEN CAUSE OF A COMMON PROBLEM

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One article of faith that the designer of an autopilot assumes is that a vessel's turning response is a function of the rudder angle. If the response is non-linear or discontinuous on a given vessel, the autopilot will show poor performance and may not steer at all.

Because the real cause of the problem, the rudder, is under water and doesn't show, the man-in-the-field may never be able to locate and correct the problem. Although much time is lost attempting to adjust the autopilot, the autopilot is never able to perform as the designer intended.

The rudder has two functions:

- (a) Stabilizing Direction – (Keeping boat on a straight course when rudder is amidships or trail position.)
- (b) Turning – (Producing a side force at the stern for turning in a selected direction when rudder is not amidships.)

We will concern ourselves only with the stabilizing function in this paper. It has been known since the days of full rigged ships that the best steering with rudder amidships (or "trail") is obtained with a rudder that is wider aft than forward. This was attributed to "dead water" on either side of the rudder, which required a rudder angle of several degrees before the trailing edge contacted the "live water" moving at ship speed.

Many fishing and work boats having a flat plate rudder and a rudder stock across the full height of the rudder steered poorly manually and on autopilot. The addition of a wedge along the full height of the trailing edge however, usually cured the steering problem. This wedge was in many cases 50% wider than the rudder post.

Wind tunnel and large ship rudder studies indicated that the drag on a foil rudder was about 7% of the rudder post of the same diameter. Since drag slows ships and increases fuel consumption, designers were prompted to adopt the foil rudder for desirable drag reduction. However, the problem of poor steering with rudder amidships was even more pronounced with the foil rudders. Again the steering sensitivity was markedly improved by either adding a wedge, or an appreciable flat plate section extending aft from the trailing edge, much like the handle on a tennis racket. Both of these measures, though practical, are not popular because foil shapes copied from aircraft foils, do have these projections.

Recognizing the necessity for providing vessel response that is proportional to rudder angle, both for automated and human helmsman steering, we have undertaken a review of the literature concerning rudders. The following excerpt from this study, outlines two features of rudder design which are important for all vessels and critical when a vessel has an unstable hull.

These are:

- (a) The "Toggle Effect", caused by an unstable rudder together with steering gear slack.
- (b) "Dead Water", resulting from turbulent water flow close to the rudder.

HULL STABILITY

The main stabilizer of a hull is a deep keel, well aft, which prevents the hull from turning, much like the tail feathers on an arrow. The adaptation of hull designs for modern materials such as steel, aluminum and fiberglass reduced the structural need for deep keels. Therefore many hulls today do not possess this hull-stabilizing feature. With the hull unstable, the rudder must provide the necessary stability. If the rudder is also unstable, the task of stabilizing the system passes to the helmsman or autopilot. Either on attempting control of heading must be sufficiently sophisticated to continually correct the rudder position, since there is no stable point in the system at which a period of rest or "Null" can occur.

Vessels having these characteristics are called "cranky" by the literature. Helmsmen express their disapproval in saltier terms.

RUDDER STABILITY

The center of pressure (C.P.) of a rudder is the point at which the net forces, due to water motion, act on the rudder.

Stability of the rudder is defined in terms of the relationship of the C.P. to the rudder post:

Unstable	-	C.P. forward of rudder post
Neutrally stable	-	C.P. at rudder post
Stable	-	C.P. aft of rudder post

RUDDER STABILITY – continued

All authorities agree^{1,2,3,4} that for the “trail” or neutral rudder condition –

- (1) The stable rudder is required in most cases.
- (2) The slightly unstable rudder is permissible only for special purposes and under special conditions, not of our immediate concern.

The C.P. is not however a fixed point. Its position fore and aft is determined at a given instant by:

- (1) Rudder Angle - (forward at trail, aft at maximum angle)
- (2) Aspect Ratio (A/R) - (forward at low A/R, aft is higher)
- (3) Rudder Thickness Profile - (forward with foils, aft with wedge)
- (4) Rudder Post Projection - (forward with post, aft without)

The use on vessels of aircraft foil (streamlined) rudders of low Aspect Ratio (A/R) (aspect ratio of rudders is the ratio of height over width) to reduce drag, added a new but seldom recognized problem with regard to stability. Aircraft foils rarely have an Aspect Ratio less than 4. But a vessel must have its rudder behind the propeller, which limits the rudder height. The requirements for rudder area to steer the ship then dictate the width. The resulting Aspect Ratio is usually 1.0 to 1.5.

A foil with an A/R of 4 or better has its center of pressure³ about 22% from the leading edge at trail or neutral position. But with an A/R of 1, commonly used, this drops to 12% from the leading edge³. Because hydraulic steering system designers wish to keep rudder torque to a minimum, rudder counterbalances (C/B) of 20 to 30% are commonly used with these systems. The argument here is that the “locking” of the rudder by the hydraulic system allows much greater C/B than is possible with mechanical steering.

But with the center of pressure well ahead of the center of rotation at trail, the rudder is unstable. As stated previously, this condition is undesirable principally because of the “Toggle Effect”, but also because it can lead to annoying and sometimes destructive rudder vibration.

Note: A rule for C.P. location and recommended maximum counterbalance is given in Table 1.

Table 1

A rule for C.P. locations determined in tests by Lindsay Lord¹ is:

	<u>C.P. location as per- cent of chord from leading edge</u>	<u>Maximum C.B. for stability</u>
Flat plate rudders	17%	16%
4° wedge rudders	22%	17%
Foil rudder A/R 1.0 or less	10%	9%

Clement³ indicates that N A C A 0015 foil rudders shift their C.P. aft with increasing A/R. We may therefore modify the above foil rudder rules as follows:

	<u>C.P. location as per- cent of chord from leading edge</u>	<u>Maximum C.B. for stability</u>
Foil rudders A/R 1-2	12%	11%
(NACA 0012 2-3	18%	17%
to 0015) 3 and above	22%	21%

One method for readily modifying existing rudders for greater effective A/R is to add top and bottom horizontal plates or "boundary fences", as shown on Figure 6. The top plate gives an effective Aspect Ratio twice the actual ratio measured. Adding the bottom plate also gives an infinite A/R for practical purposes. In addition to the C.P. shift, due to increased effective A/R, this increases the side force on the rudder for a given rudder angle. It is then possible to obtain the desired lift with less torque and drag.

THE "TOGGLE EFFECT"

The lack of rudder stability at trail causes problems for steering, however, both manual and automatic that increase rapidly as slack or lost motion develops in the steering mechanism. Some slack is always present in mechanical steering systems.

With cable or chain steering gears, slack must be used to prevent excessive friction.

With hydraulic systems, properly designed, installed and maintained, the slack is small. This feature has prompted the adaptation of greater counterbalances of rudders to minimize torque at hard over with these systems, resulting in unstable rudders.

As generally installed, hydraulic systems have residual air entrapped, and use varying amounts of flexible hose. Maintenance work followed by improper or inadequate bleeding usually increases the air cushion. The resultant sponginess, plus any lost motion in rudder-to-steering cylinder linkage allows a free rudder movement through an angle, sometimes as great as 10° . When the rudder is unstable, each time it is moved past the zero or "trail" position, it "toggles" in the same direction until the lost motion is compensated. (See Figure 7). The result is the same as if the helmsman turned the wheel two or three times the required amount on each correction. This results in a degree of uncertainty as to rudder position with respect to helm and requires a continual rudder movement either by the helmsman or the automatic pilot in order to hold the vessel on course. If the hull is stable, the effect of the rudder instability will be less noticeable. If the hull is unstable, the combined effect can result in complete loss of steering control in some circumstances.

"DEAD WATER" OR TURBULENT BOUNDARY LAYER EFFECT

A second cause of lack of Rudder Sensitivity at "trail" is "Dead Water", the effect of which is shown on Figure 8. Because of propeller wash and hull wake, the rudder operates in turbulent flow. The water molecules touching the rudder have zero velocity with respect to the rudder and therefore can exert no turning effect regardless of vessel speed.

"DEAD WATER" OR TURBULENT BOUNDARY LAYER EFFECT – continued

At a certain distance, parallel to the rudder surface, the molecules are passing the rudder at ship speed. In between is the area known as the boundary layer in which velocities steadily increase from zero to ship speed. The thickness of this layer increases wedge fashion from the leading edge to the trailing edge.

The available formulas from turbulent flow on a flat plate indicate that each side of the rudder has a boundary layer thickness at a given point, approximating $T = (2.52\%) \times (\text{distance aft of leading edge})^{\frac{1}{2}}$. This represents 1.43° of angle per side from leading edge. Huckins determined experimentally and practically that a 4° wedge, widest at the trailing edge was essential for good steering control on planing hulls.² These values approximate the rule given on Figure 2, that the thickness of the wedge at trailing edge of a flat plate rudder is $(.04) (\text{Chord}) + (\text{thickness of rudder})$; which insures that the critical trailing edge of the rudder, which is responsible for most turning effect at small rudder angles, engages full velocity water flow or "live water" on both sides.

A rudder stock for full height of rudder is highly undesirable because it produces very high drag as well as increases the "Dead Water" effect, and moves the C.P. forward at "trail". On a vessel unfortunate enough to possess such a stock, improved sensitivity of rudder at trail can be obtained by making the wedge width equal to $(.04) (\text{Chord}) + (\text{rudder post diameter})$. A better solution is to replace the rudder post with an oval fairing as shown on Figure 1.B and fit trailing edge with a narrower wedge. Wedging also moves the trail C.P. aft. The wedge rudder has its C.P. at 22% of the chord from leading edge versus 17% for the flat plate. Increasing aspect ratio probably moves the C.P. aft as it does on foils, but at present we have not test data to substantiate this.

DIAGNOSING STEERING DEFECTS

To test an existing vessel for instability of hull-rudder system:

- (a) Set on course manually, at cruise speed.
- (b) Note wheel position (steady spoke).
- (c) Give wheel about 20% of full travel to start turn in desired direction.
- (d) When turn is well developed, bring wheel (steady spoke) to original position.
(Note: This method cannot be used on vessels with a single unbalanced ram on the hydraulic steering).
- (e) Vessel should slow to turn and come to a straight run. If it does so, a simple autopilot, correcting rudder proportionate to heading error can guide the vessel, given a steering engine of sufficient power.
- (f) Repeat (a) through (e) for both right and left turn.
- (g) If vessel continues turn, requiring opposite rudder to check, one or both of the foregoing stability problems is present. Only a sophisticated pilot capable of calculating and compensating for vessel and rudder instability can attempt to steer an acceptable course. However, the least maladjustment of such a pilot can result in a rapid downgrading of steering performance since the vessel and rudder are unforgiving of the least error. Rudder shape, counterbalance, post configuration and wedging should be examined. In addition, air in the system or (slack) lost motion of keyways or linkages should be eliminated.
- (h) If rudder is unstable as shown by values on Table 1.

STEPS TO CORRECT RUDDER INSTABILITY
(Existing Vessels)
In Order of Importance

- (1) Fillet rudder stock in area of rudder as shown on Figure 1B.
- (2) Wedge trailing edge – per Figure 2.
- (3) Decrease C.B. to values shown – per Figure 3. This moves C.P. aft.
- (4) Use top plate to double Aspect Ratio if original A/R is 1.5 or better. Plates (or boundary layer fences) as shown in Figure 5 also decreases rudder angle required to produce a given side force and therefore decrease torque required to steer. Drag to produce a given side force is also decreased.
- (5) Use top and bottom plate if original A/R is less than 1.5 – per Figure 5.

CAUTION

When increasing aspect ratio, maximum lift and rudder stall will occur at lower rudder angles. This will require less rudder angle, wheel turns, and rudder torque than previously. The practicality of this matter is that rudder stops may be set at lesser angles than formerly. Torque for maximum rudder angle should be recomputed when using the above corrections, to prevent existing steering engine from being overloaded due to decrease in C.B.

FOOTNOTES AND BIBLIOGRAPHY

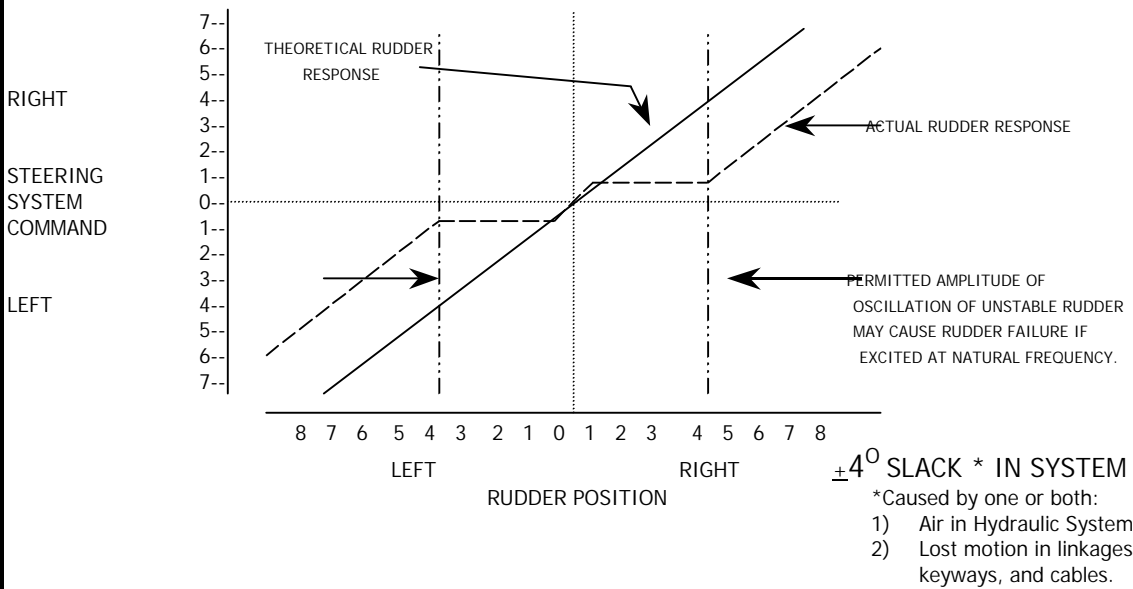
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Equation (11).

GLOSSARY OF TERMS

A	Angle, Rudder Aspect Ratio	Angle between rudder place and vessel centerline. $\frac{\text{Height}}{\text{Width}} = \text{A.R. Geometric}$ A.R. Effective = $\frac{\text{Height}}{\text{Width}}$ of imaginary rudder producing same effect.
B	Boundary Fence Boundary Layer	A flat plate vertical to a rudder or foil surface that prevents flow from spilling over top and bottom of rudder. The area adjacent to any surface immersed in a fluid in which fluid velocities vary from zero to surface velocity.
C	Center of Pressure	The point on a rudder at which all net forces, due to water motion, act.
D	Dead Water Drag	The area adjacent to a rudder surface in which fluid velocity approximates that of the surface. The frictional force due to motion in a fluid that retards motion.
F	Fence, Boundary Foil	Same as Boundary Fence. A 3-dimensional body having a shape to provide minimum drag in a fluid.
H	Hull	The body of a vessel.
L	Leading Edge Live Water	The front edge of the rudder. Water passing a rudder at or near ship velocity.
N	NACA 0015 Foil	A foil having a thickness at the quarter chord point of 15% of the chord.
R	Ratio, Aspect	Same as Aspect Ratio.
S	Stable	A body is stable if, when deflected from a position, it will return to that position unaided.
T	Torque Trail Trailing Edge Turbulent	Turning force. Rudder amidships, parallel to water flow. The aft edge of the rudder. Fluid flow with random internal flow directions.
U	Unstable	A body is unstable if, when deflected from a position, it tends to move away from the original position.
W	Wedge	A played or spread trailing edge, thicker than the thickness immediately preceding it.

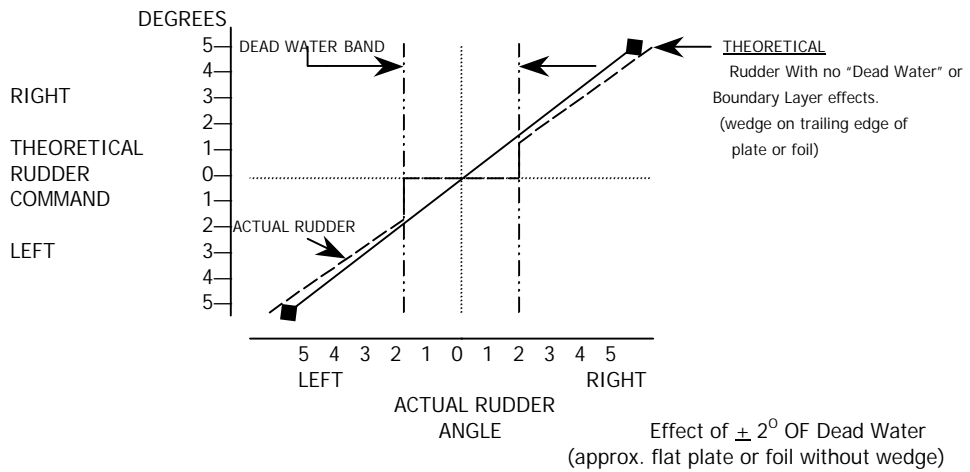
"TOGGLE EFFECT" OF UNSTABLE RUDDER

FIGURE 7



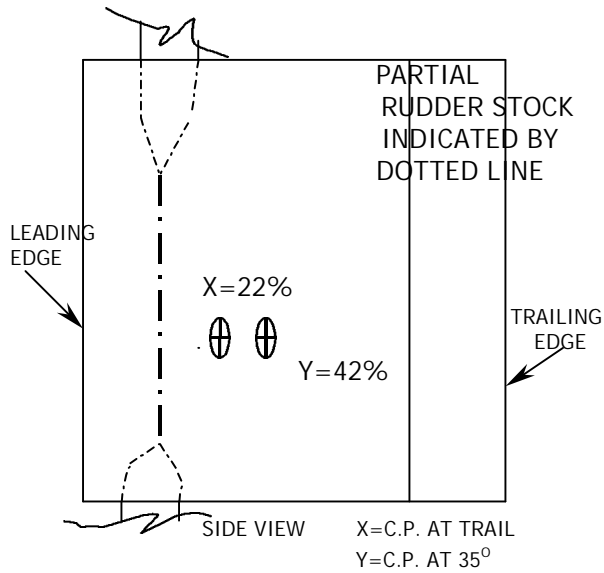
"DEAD WATER" ON RUDDER OR BOUNDARY LAYER EFFECT IN TURBULENT FLOW

FIGURE 8



R.M. FREEMAN, M. D. - NMEA Presentation, February 1978

RUDDER POST - FIGURE 1A



RUDDER STOCK PROJECTION ON RUDDER SURFACE SHOULD BE NO MORE THAN NEEDED FOR STRUCTURAL SAFETY, AND SHOULD BE FAIRED AS SHOWN IN FIGURE 1B

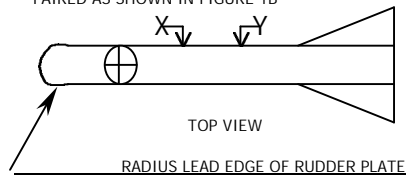
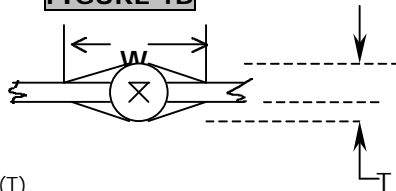
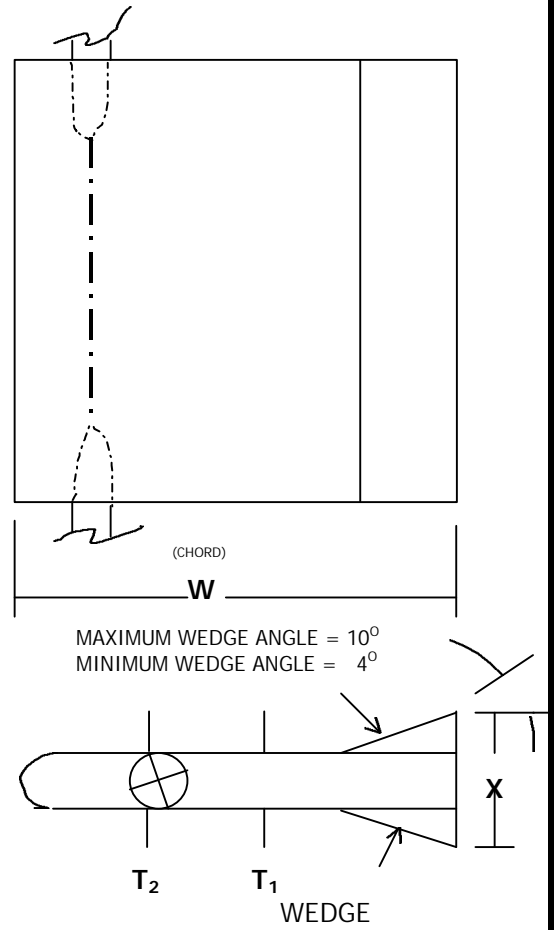


FIGURE 1B



$T = (.3) (W)$
 $W = (3.45) (T)$
FAIRED IN RUDDER STOCK
FOR RUDDERS WITH FULL RUDDER STOCK OR THICK REINFORCING

WEDGE DIMENSIONS - FIGURE 2



$$X = (W) (.04) + T^*$$

*T = THE LARGER OF T_1 OR T_2

WEDGE IS DESIREABLE ON ALL RUDDERS AND IS REQUIRED FOR FOR RUDDER STABILITY IN TEHTRAIL POSITION WHENEVER:

- CB EXCEEDS (.15) (W)
- RUDDER POST PROJECTS ON RUDDER SURFACE.

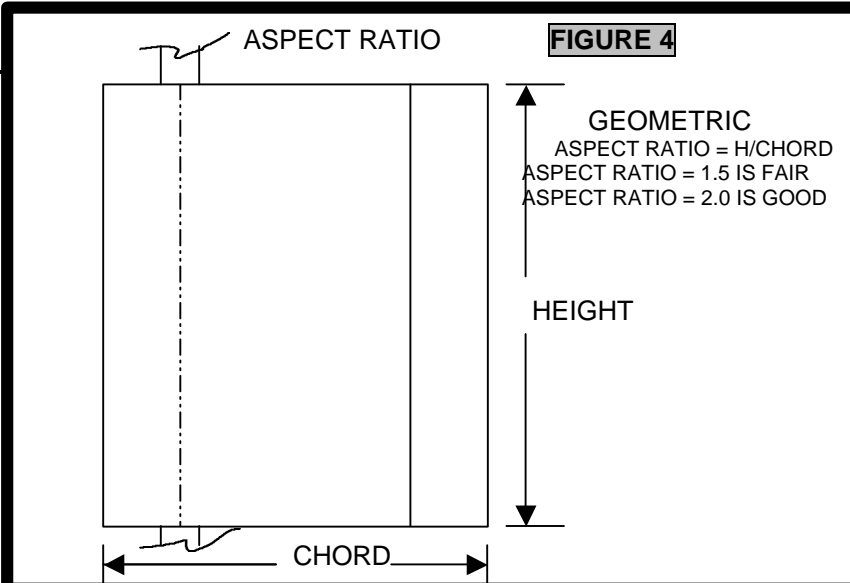


FIGURE 4

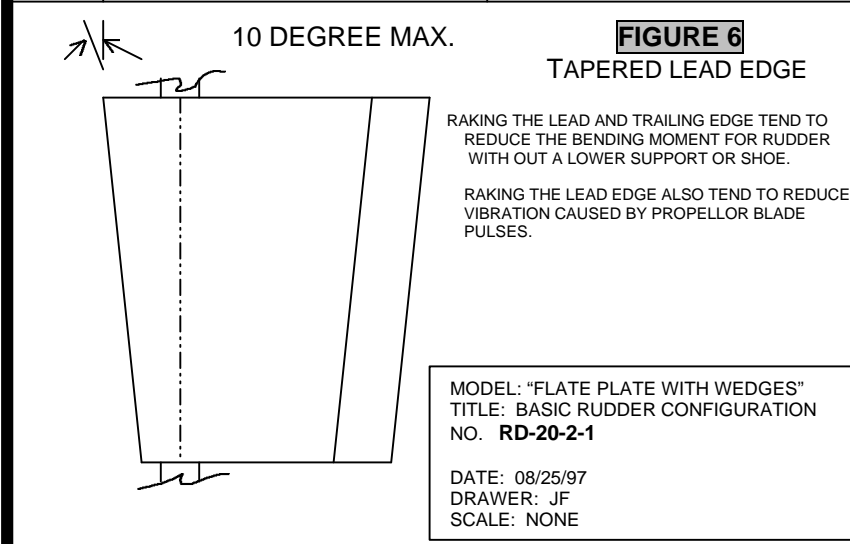


FIGURE 6

TAPERED LEAD EDGE

MODEL: "FLATE PLATE WITH WEDGES"
 TITLE: BASIC RUDDER CONFIGURATION
 NO. **RD-20-2-1**
 DATE: 08/25/97
 DRAWER: JF
 SCALE: NONE

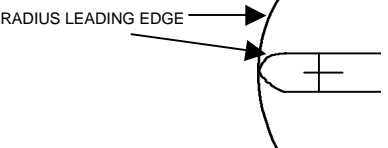
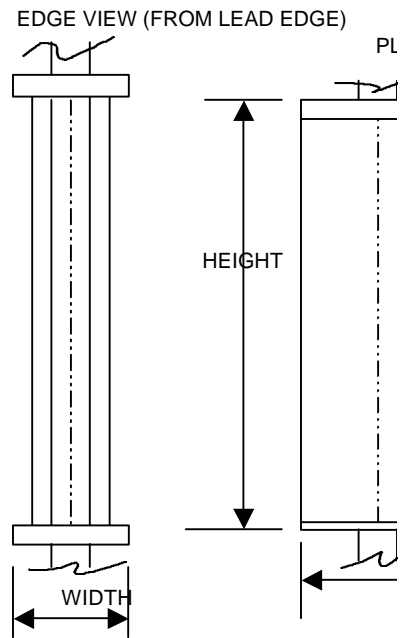


PLATE LENGTH = CHORD
 PLATE WIDTH = CHORD (.39)

BOTTO

WITHOUT PLATES, $A/R_{EFF} = A/R_{GEC}$
 TOP PLATE ONLY, $A/R_{EFF} = (2) (A/R)$
 TOP PLUS BOTTOM PLATES, $A/R_{EFF} = (4) (A/R)$