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Turning Characteristics and Capabilities of High-Speed Monohulls

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ABSTRACT

The turning characteristics and capabilities of displacement vessels are well understood and documented. Standards for the maneuvering capability of displacement vessels exist. However, the same information regarding high speed craft is not so readily available. Most documents in the public domain contain information on what high speed craft shouldn't be able to do, not what they should be able to do.

This paper examines various aspects of the turning capabilities and characteristics of high speed monohull craft with regard to typical behavior and what type of maneuvering performance should be achievable. The dynamics, characteristics, and relationships of a hard chine monohull in a high speed turn are investigated and summarized.

The execution of high speed turns on hard chine monohulls can sometimes lead to unexpected responses. This paper identifies several of the typical symptoms. The severity of these events will be discussed, and typical causes are identified. Notional maneuvering criteria are also proposed.

INTRODUCTION

Maneuverability standards for displacement ships now exist after almost a 40 year developmental period. The standards have been proven and prediction methods for use in the design stage exist. However, maneuvering standards do not exist for high speed craft, and the number of prediction methods is limited. While the maneuvering capabilities required for displacement ships may be applicable to high speed monohulls, they do not evaluate the complete situation. In high speed monohulls, dynamic effects are significant and as a result there is a strong coupling between motions and accelerations on all three axes: pitch, yaw, and roll. The effects that can result due to the association of the motions need to be considered.

High speed craft often operate in restricted areas and in places where there is congestion due to ship traffic, and therefore require better maneuverability than ships do. The accelerations imparted on vessel passengers due to maneuvering at high speed must be considered. Guidance exists through Classification Society Rules and International Standards to limit maneuvering performance of the vessel to minimize the effects it causes on passengers, but no information is available indicating what level of maneuvering capability a high speed craft should possess. Criteria of this type are required for the industry.

In order to have a comprehensive understanding of the situation, the interrelationships between motions and accelerations of the craft about the different axes must be understood. These relationships are identified and the critical ones with respect to their impact on maneuvering characteristics are reviewed.

Not only must the vessel possess adequate maneuvering characteristics, but the vessel's response to maneuvering inputs must be predictable, controllable, and free from dangerous instabilities at high speed. When these qualities are not present, the vessel can exhibit unexpected responses to maneuvering inputs, often resulting in dangerous situations. There are a few unusual responses that occur most frequently. These examples of bad behavior are identified and potential causes are discussed to aid the designer in the development of a new design and troubleshooting an existing vessel.

With this knowledge, it is possible to identify the normal turning characteristics of high speed monohulls and develop a set of guidelines that establish a minimum level of maneuvering performance for this type of craft.

EXISTING MANEUVERING STANDARDS

The development of maneuvering standards for commercial displacement ships was a long process which started in the 1960's. Until then, although maneuverability had been a concern, an agreed maneuvering standard had been an elusive goal. Much work was done on the topic between 1971 and 1991 by IMO, MARAD, SNAME, and the USCG, and a set of maneuvering criteria was proposed in 1991 (Gray 2002). These proposed interim maneuvering standards were adopted in 1993 by the IMO, and were subsequently revised in 2002 with the introduction of IMO Resolution MSC.137(76).

The minimum basic maneuvering qualities traditionally examined are: turning ability, initial turning ability, course keeping ability, yaw checking ability, and stopping ability. Performance of the as-built vessel is measured on trials through turning circles, Z-maneuvers, pull out maneuvers, Duidonne spirals, and stopping tests.

The 1991 proposed standards introduced some recognition of the inherent maneuvering differences of high speed craft. Variations in allowable performance of overshoot angles in zig-zag maneuvers with the parameter L/V (ship length divided by service speed) reflect inherent differences in maneuverability of smaller, faster ships, but not specifically high speed craft (Daidola 2002). While this approach does attempt to account for the effects of speed, what is not accounted for is the strong couple between turning maneuvers and roll angles that is present on high speed craft. Since these maneuvering standards do not consider speed or roll effects, they appear inappropriate for planing craft (Lewandowski 1995).

No maneuverability standards (proposed or adopted) exist for high speed craft. However, there is one path that a designer can follow to identify maneuvering performance that a high speed craft should NOT be capable of. Class society rules require that a Failure Modes and Effect Analysis (FMEA) be performed on the craft's systems and equipment to determine whether any reasonably probable failure of improper operation can result in a hazardous or catastrophic effect (Ranzenbach 2011). The Rules lead the designer to Annex 4 of IMO High Speed Craft Code for guidance on how to perform the FMEA.

The basis of the FMEA process and outcome provided in the IMO HSC is passenger safety. IMO HSC categorizes the effects caused by system or equipment failures (or operator errors) with four different safety levels, based on severity: minor, major, hazardous, and catastrophic. Like the various class society rules, the Code requires no corrective action be taken unless the effect is classified as a hazardous or catastrophic effect.

Drawing further from the body of the IMO HSC Code, it is stated that the vessel should be controllable and capable of performing the maneuvers required for safe operation up to the critical design conditions (i.e. speed). The effects generated by these maneuvers, or failure of craft systems, are to be considered when determining operational limitations. Thus it can be deduced that normal maneuvering of the vessel should not generate an effect that can be classified as hazardous.

Applying the HSC Code requirements with respect to FMEA, the maximum horizontal accelerations experienced during normal turning maneuvers should be limited 0.35g's such that the maneuver is not classified as hazardous. For reference, 0.35g's is actually a substantial amount of acceleration. 0.25g's is the horizontal acceleration at which a person standing up, holding on, is no longer able to maintain balance. At a horizontal acceleration of 0.45g's, a person will fall out of their seat if not wearing a seat belt (IMO HSC 2008).

DYNAMICS OF A MONHULL IN A HIGH SPEED TURN

The static and dynamic equations of equilibrium of planing monohulls have been developed and are available in the public domain (Hsu 1967 and Lewandowski 2004). Because the motions of the craft are closely coupled around all six degrees of freedom (see Figure 1), the calculations are somewhat complicated and are not for the casual user. The accuracy of the calculations is affected by both static and dynamic forces, and the force coefficients are not well understood as they are typically non-linear with speed. It is not the intent to repeat, reproduce or build upon these equations, but to summarize, identify and explain the critical dependencies and interrelationships that affect the turning characteristics and capabilities of high speed monohulls.

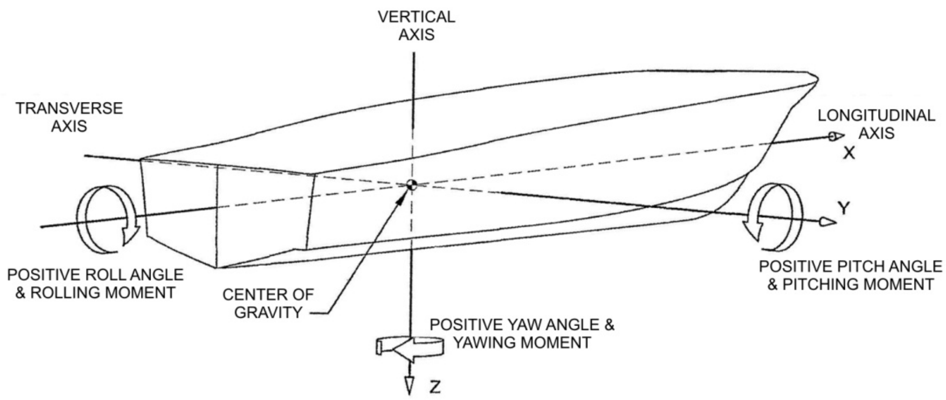

FIGURE 1. Six Degrees of Freedom with Positive Angles & Moments

The maneuverability of both displacement ships and high speed monohulls are influenced by hull form geometry, appendage design, and transverse stability. Two characteristics of a turn that are common between displacement ships and high speed monohulls are the loss of speed in a turn and the presence of a drift or yaw angle (difference between the vessel's heading and instantaneous trajectory). But that's about where it ends.

When a vessel is in a steady turn, a trace of its center of mass describes a circle. The diameter of this steady state turning circle is referred to as the tactical diameter. The sum of the transverse forces acting on the ship must provide the centripetal force required to make the center of mass follow the circle (See Figure 2). The rudder or water jet nozzle is deflected and the vessel yaws inward. As a result, the hydrodynamic flow across the hull bottom obtains a transverse component. The transverse component of the flow imparts a side force on the hull, and increases the drag on a hull (Kennard 1970). The longitudinal component of centrifugal force, the increased drag of the rudder (or reduced thrust from the water jet), and the induced drag on the hull results in a reduction in vessel speed until an equilibrium condition is reached.

A high speed monohull typically exhibits the same behavior as a displacement ship when operating in displacement mode. At these speeds the dynamic effects are minimal and the side force generated by the yaw angle is insufficient to develop a steady roll angle. The casual operator of small craft will note that these vessels do exhibit some inboard roll angle when in a hard turn at displacement speeds, but in the author's experience this is only present on small craft with vectored thrust for steering. The vectored thrust is applied very low relative to the vertical center of gravity of the vessel and it is strictly this rolling moment that generates a roll angle. The effect is especially noticeable at higher displacement speeds when trim angles are high but the dynamic forces present are not sufficient to provide a net lift force (no dynamic rise in CG).

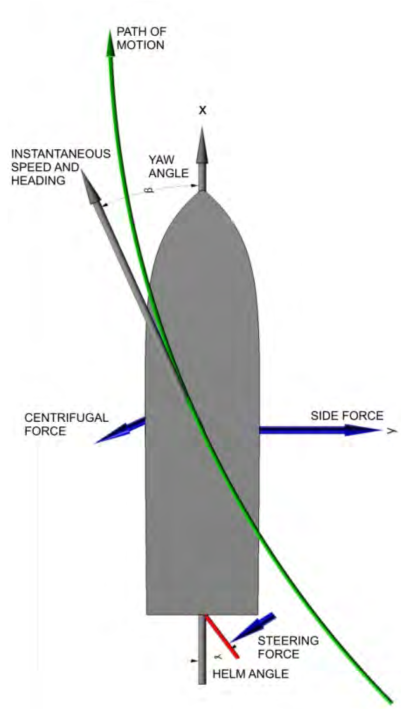

FIGURE 2. Partial Free Body Diagram of a Displacement Monohull in a Steady Turn

On larger displacement vessels, especially those with a high vertical center of gravity relative to the static waterline, an outboard roll angle is typically observed while making hard over turns at high speed. The only significant forces present in this scenario are the side force from the yaw angle and the centrifugal force due to acceleration of the center of gravity. Because of the significant distance between the two centers of effort, an outward roll angle is obtained.

When in calm water, the pitch and heave characteristics of a vessel do not affect its turning characteristics. Once vessel speed increases to the point where dynamic lift forces increase to levels approaching that of the buoyant forces, the behavior of the vessel changes and the equations of equilibrium become more complex. In this operating regime, pitch and heave are contributing factors to the drag, wetted area, submerged volume, and therefore the force and moment restoring coefficients of the hull. The ultimate challenge is that the hull's hydrodynamic coefficients exhibit a non-linear response to outside influences (wind, waves, passenger movements, etc).

When travelling in a straight path, a helm angle is commanded and the vessel enters a transient condition because the forces and moments are no longer in balance. Due to the added drag the craft experiences in a turn, if power is held constant, the vessel will slow down. This amount of speed loss can be significant for planing monohulls, and is typically much higher than for displacement ships at the same ratio of turning radius to waterline length (Martin 1976). Because of this speed loss, on a planning monohull, the magnitudes of the normal lift and drag forces reduce and new a condition of equilibrium is achieved.

During this transient condition, the high speed monohull yaws in response to the steering force. As the path of the vessel starts to turn, the centrifugal force of the vessels' center of gravity builds. Equilibrium in and around the "transverse" axis must now be established. The craft begins to roll inboard sharply as the turning force is applied very rapidly as opposed to a fairly long duration but constant exponential buildup of the dynamic restoring moment (due to lag in yaw angle and rate of turn) (Lewandowski 1994). The roll motion is significant and the shape of the underwater hull changes markedly when operating at high speed (Lewandowski 1994). Now that a roll angle is introduced, the steering force has both horizontal and vertical components that must be accounted for independently (Lewandowski 1998). The vertical force is always positive when rolled inboard, thereby lifting the stern, and again altering the equilibrium condition as the trim angle of the hull decreases, wetted surface area changes, etc.

As the forces and moments balance out, the inboard roll angle typically reduces from the magnitude experienced during the transient condition. A steady state condition is achieved where vessel drag, thrust, trim angle, roll angle, yaw angle, lift force, side force, steering force, dynamic restoring moment, and yaw rate are constant. The vessel proceeds through the turn at a constant rate of turn, unless acted upon by outside forces, until the steering command is removed.

At displacement speeds, the tactical diameter is virtually independent of approach speed, which is because both the required centripetal force and the hydrodynamic forces and moments on the ship are proportional to the square of the velocity (Lewandowski 1995). However, on planing monohulls, tactical diameter tends to increase with speed (Sugai 1963). It has been noted that as vessel speed and tactical diameter increase, the rate of turn decreases (Martin 1976).

For dynamically supported monohulls, a unique situation exists when the approach speed to the turn is only marginally above the minimum planing speed of the hull. In this case the speed loss experienced can cause the vessel “falls off plane”. When this occurs, the dynamic roll resorting moment is eliminated, the turn tightens, and the craft typically returns upright or takes on an outboard roll angle. This is valuable information to the operator because slowing down to pre-planing can significantly increase turning capability and can be used to avoid a collision. However, on jet powered craft, throttle reduction must be limited to ensure adequate thrust is maintained to provide the necessary steering forces to turn the vessel. Additionally, a maneuver of this type will generate a transverse acceleration as the vessel changes from an inboard to an outboard rolling condition which can affect the vessel occupants; so they should be informed.

It has long been established that wind and current effects can significantly alter the turning capabilities of a marine vessel. High-speed monohulls, typically have high freeboards and this, combined with their light weight, can allow wind forces to have substantive effects on the turning capabilities. This is of particular interest to operators because in the event of an evasive maneuver, when possible and when all other influencing factors are equal, the turn should always be made with the wind as opposed to into it (like birds when taking flight to avoid a threat). Figure 3 presents full scale trial data comparing the turning circle characteristics of a high speed monohull as affected by a 15 knot wind.

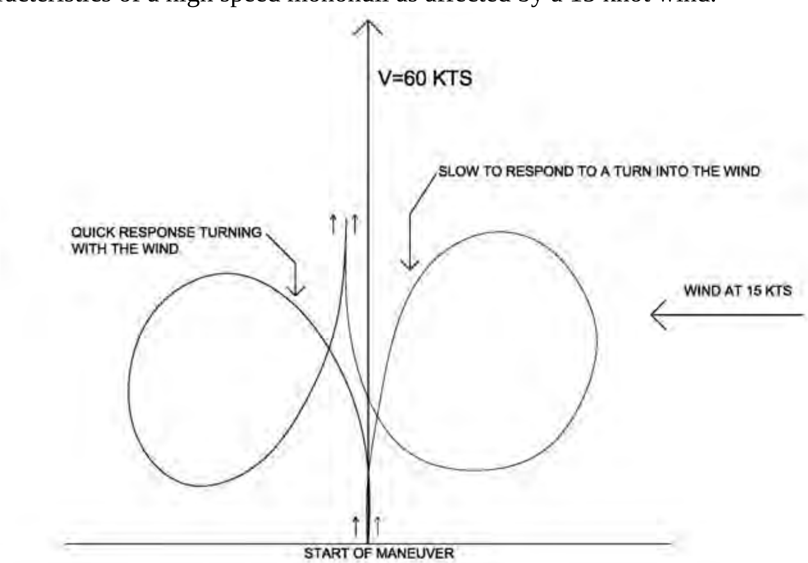

FIGURE 3. Effects of Wind on the Turning Capabilities of a High Speed Monohull

Effects of Appendages

As mentioned above, the selection and design of appendages has an influence on the turning capabilities of high speed monohulls. Typical appendages found on high speed monohulls are rudders, fixed course stability fins, spray rails, bilge keels, and centerline keels. Because these appendages can a substantive impact on the turning characteristics of high speed monohulls, they demand a brief discussion.

Keels

Bilge keels and centerline keels tend to improve the course keeping ability, or directional stability of monohulls. Intuitively it would be thought that the addition of these appendages would reduce the turning ability of the vessel, but this is not necessarily the case. In some instances, the addition of centerline keels has actually increased the turning ability of a vessel in that it reduced the turning circle diameter (Sugai 1963). It is also noted that the centroid of the skeg area also influences the turning circle diameter; turning performance increases when the skeg area centroid is shifted forward.

The addition of the centerline keels has been documented to cause, or to increase the magnitude of, steady outboard roll (Spangler 1983). This is believed to be a result of the transverse flow component across the hull that is generated when executing a turn. Therefore, although no confirmation could be identified in the references, the author suspects a similar response due to the addition of bilge keels.

Rudders

On many high speed craft, rudders provide the primary source of turning forces. Rudders also increase the directional stability of the monohull vessel by acting somewhat like the fletchings on an arrow. While different, the integral struts associated with pod drives, stern drives, and outboard motors behave like rudders when operating at an angle of attack and provide turning forces in addition to the vectored thrust. The turning force generated by the rudder induces an inboard rolling moment on the vessel because of geometric relationship between the rudder and the VCG (Lewandowski 2004). High aspect ratio rudders are typically preferred for turning performance because the high aspect ratio increasing efficiency (Sugai 1963). However, it is noted that increasing the aspect ratio of the rudder increases the inboard rolling moment generated by the rudder because the center of effort is located further away from the VCG of the vessel, which is especially true for pod drives.

Fixed Course Stability Fins

Fixed course stability fins are another type of appendage typically found on high speed craft. These appendages are used on water jet propelled vessels to provide good course keeping a characteristics, both in a straight line and in a turn. When operating on a straight course they stabilize the heading of the vessel. In fact, a properly sized course stability fin can provide sufficient directional stability to give a water jet powered monohull the ability to maintain a straight course when one of the outboard water jets is not functioning. In the case of a high speed turn, the fins also serve to increase the directional stability of the vessel. The purpose of the fins is to prevent excessive side slip (a sudden and uncontrollable increase in yaw rate) during the turn. The forces acting on the course stability fin are opposite in direction to the forces generated by a rudder, and therefore reduce the turning moment and serve to decrease roll angle.

Spray Rails

Spray rails are affixed to hulls for many reasons including but not limited to decreasing wetness, increasing dynamic lift and trim, and decreasing vertical accelerations. Depending on the desired result, spray rails are located on the hull to perform one of two basic functions: 1) to promote hydrodynamic flow separation from the hull, and 2) to generate a local area of high hydrodynamic pressure. Even though only one of the basic functions is typically required, the spray rail inherently always provides both. While spray rails typically do not directly affect the turning capability, they can have a significant impact on the roll angle characteristics of a high speed turn. If located to promote separation on the inboard side of the hull in a turn, the reduced bottom and side wetting can decrease the roll angle into the turn. On the other hand, if located to promote separation (or ventilation) on the outboard side of the hull, outboard roll angle in a high speed turn can be reduced.

Inboard Versus Outboard Banking Turns on a High Speed Monohull

A monohull tends to exhibit an inboard roll angle in a high speed turn. The magnitude of the inboard roll angle tends to increase with speed, except when the vessel is not dynamically supported (Spangler 1983). As mentioned above, the motions of a vessel about different axes are coupled. Of primary interest to this study of roll angle in a turn is the roll-yaw couple. At displacement speeds, the side force generated by the yaw angle generates a roll moment. A side force that generates a turn to starboard develops a roll angle to port, as shown in Figure 4.

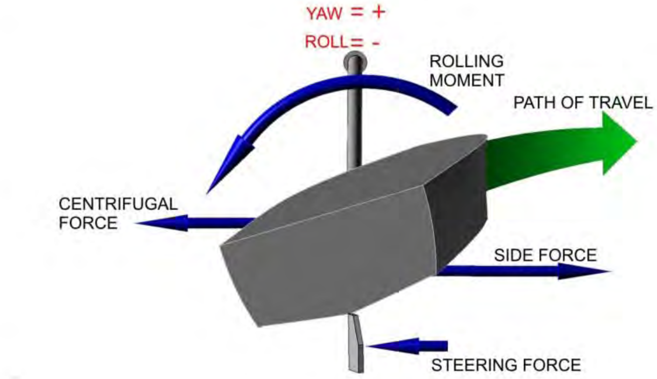

FIGURE 4. Depiction of Roll-Yaw Couple of a Monohull in a Turn at Displacement Speeds

This relationship of the roll-yaw couple is also experienced on high speed monohulls when proceeding on a straight course. For a hard chine monohull in a planing condition, the rolling moment coefficient is dependent on the distribution of load (pressure) between the two halves of the planing surface. In the planing condition, the hydrodynamic side force is also affect by this pressure distribution and therefore must be considered (Savitsky 1958). These effects are significant because even a small angle of roll dramatically changes the geometry of the wetted surface, which affects the pressure distribution.

The test program completed by Savitsky in support of the 1958 technical report examined four different unsymmetrical planing conditions. These conditions are illustrated in Figure 5 and are labeled with the specific inputs and the measured outputs in these conditions. It is important to note that positive forces are opposite to the positive direction of the coordinate axes indicated in Figure 1. For example, a force acting in the negative "Y" direction as shown in Figure 1 is referred to as positive.

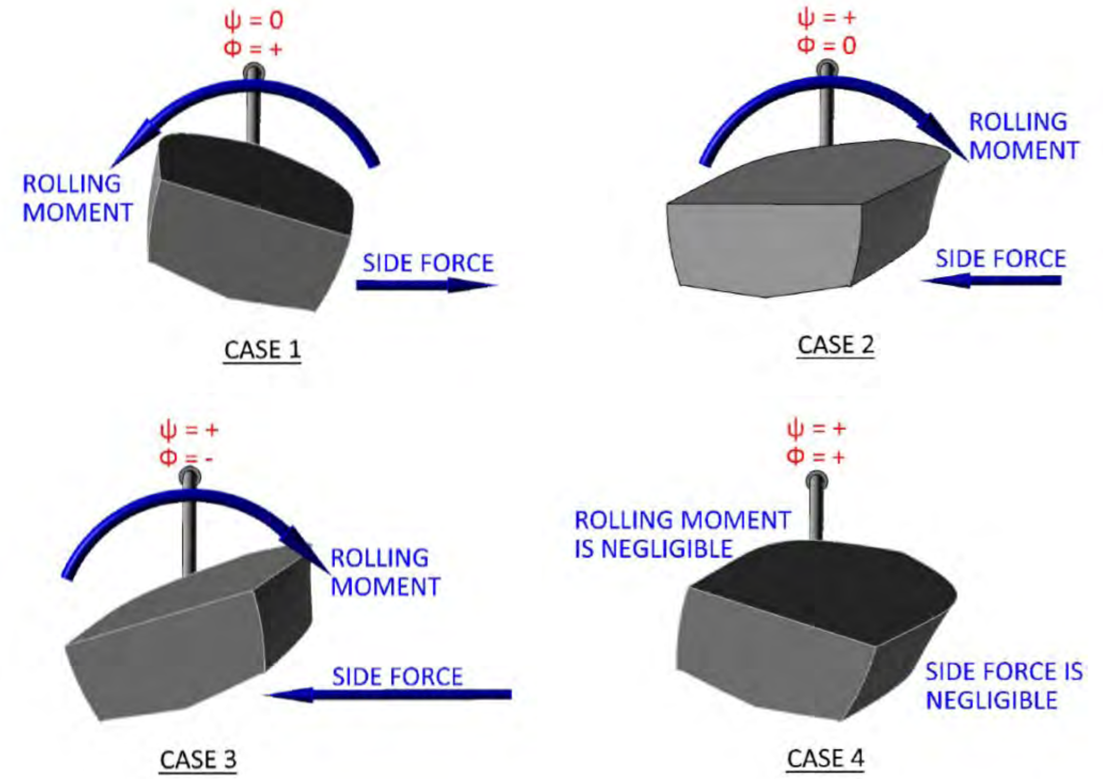

FIGURE 5. Side Forces and Rolling Moments Developed during Unsymmetrical Planing Conditions

In Case 1, the hull is subjected to a positive roll angle (ϕ) without a yaw angle (ψ). As a result, a negative side force and a negative rolling moment are generated. This situation describes the situation where trim control devices (or live loads on a small craft) cause a roll to starboard – the vessel turns to starboard.

In Case 2, the hull is subjected to a positive yaw angle without a roll angle. As a result, a large positive side force and a large positive rolling moment are generated. This is *opposite* to the behavior observed at displacement speeds in that the side force is opposite to the yaw angle and acts to turn the vessel away from the desired path of motion.

In Case 3 the hull is subjected to a positive yaw angle and a negative roll angle. The results are the same as Case 2; a large positive side force and a large positive rolling moment are generated, and the side force again acts to turn the vessel away from the desired path of motion.

Case 4 is the situation where the hull is subjected to a positive yaw angle and positive roll angle. The results of this orientation are unique in that the side force and rolling moments developed are minimal and negligible. One can surmise that this is the natural state of equilibrium for a dynamically supported monohull exposed to a yaw angle and roll angle because in this condition, large hydrodynamic forces do not exist.

Case 4 is the only case where the combination of roll and yaw angle do *not* produce a large side force which opposes the intended direction of travel through a turn. Therefore, this “equilibrium” condition is the one being experienced when a dynamically supported monohull is in a turn. Because the hydrodynamic side force is minimal in this condition, for planing monohulls, *it is the steering force which is actually turning the vessel by rotating the boat*. The steering force and associated moment initiate the yaw angle and contribute to the hydrodynamic rolling moment to achieve a steady state inboard roll angle.

Nonetheless, under certain conditions and with a particular combination of rudder arrangement, dynamic righting moment, vertical center of gravity, deadrise angle, and rate of turn, the inward rolling moment can be overcome and the craft will roll outwards (Hatch 1963). Unfortunately, the exact conditions that result in outboard roll angles on hard chine monohulls are not understood. However, at high speed, an outboard roll angle in a turn is relatively uncommon for hard chine monohulls. When this phenomenon occurs, it is typically unnerving to passengers because it is so unusual. Excessive outboard roll angles in a high speed turn can be dangerous and should therefore be avoided.

The explanation on why outboard rolling angles should be avoided consists of three reasons. The first is that the transverse acceleration experienced during the roll transient combines with the centrifugal force due to the turn to increase the total acceleration felt by the occupants. Since the safety of the passengers can be affected by the transverse acceleration, minimizing it should be considered good practice.

The second reason outboard roll angles should be avoided has to do with the relationship of the resultant acceleration vector with the orientation of the vessel occupants. When the vessel is rolled into the turn the resultant acceleration vector is close to the vertical (body) axis of the occupants. The specific roll angle where the resultant acceleration vector is parallel to the vertical (body) axis of the occupants is called the ideal bank angle (Hsu 1967). A turn where the roll angle is at the ideal bank angle is referred to as a coordinated turn, which is illustrated in the left hand side of Figure 6. A coordinated turn is the most comfortable to the passengers, which can be readily appreciated when you recall your last flight on a commercial airliner where the pilots rolled the aircraft into the turns throughout the flight.

Other than passenger comfort, there are physical considerations as well. In an inboard banking turn the resultant acceleration vector maximizes the normal force between the occupant and the deck and maximizes traction, like cars on the road. When the vessel is rolled outward in a turn, the resultant acceleration is off of the body axis and can be outside of the stance of a passenger, destabilizing them, as shown in the right hand side of Figure 6. Because the "banking" of the deck has a "negative" slope, traction is decreased. As a result, it is physically more challenging for a passenger, especially one who is standing, to hold their position.

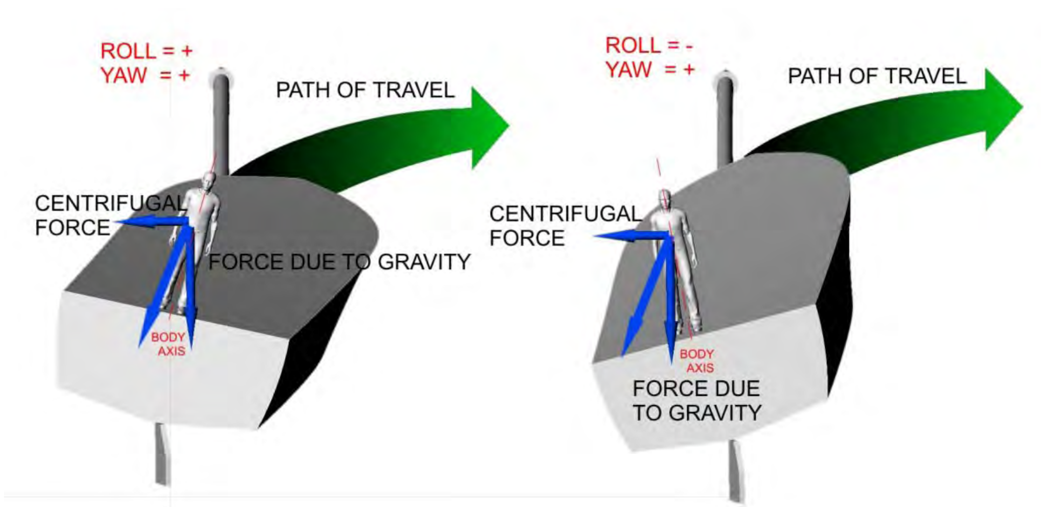

FIGURE 6. FBD of Forces Felt by Occupants in Inward and Outward Banking Turns

Finally, when a vessel rolls outboard in a turn, and roll angles are large, the potential to wet the outboard hull side is introduced. This occurrence could generate a hydrodynamic suction force to further increase outboard roll angle. On a related note, if hull side wetted occurs, the potential is likely for the vessel to remain in a rolled condition after the steering input is removed. To correct this issue, the power will have to be reduced and the vessel slowed until buoyant forces become dominant and the vessel returns upright, which could have impacts on mission capabilities.

In summary, an outboard roll angle should be avoided on a hard chine monohull because the transverse accelerations are higher, the traction an occupant has on the deck is less, and the potential for other handling issues to exist is increased. It is noted however that high speed catamarans typically roll outwards in a high speed turn. Catamarans typically have more transverse stiffness than monohulls. As a result, the magnitude of outboard roll angles and transverse acceleration developed by rolling motion is less, and therefore is less cause for concern.

Effect of Vertical Center of Gravity on Roll Angle

Some research has indicated that increasing the vertical center of gravity of a planing craft can cause an increase or decrease in roll angle, depending on the deadrise angle (Lewandowski 1994). However, a high vertical center of gravity most often causes or increases outward roll in a turn (Deakin 1991). The two primary rolling moments developed when a hard chine monohull is operating in a high speed turn are from the centrifugal force due to transverse acceleration of the center of gravity and the steering force. By definition, the application of the steering force must act on the hull somewhere below the water surface. And, by definition, the sum of the transverse forces must sum to zero or else pure transverse motion would develop. If the situation is simplified and only these two forces are considered, Figure 7 illustrates the impact of raising the vertical center of gravity on the primary rolling moments experience by a hard chine monohull.

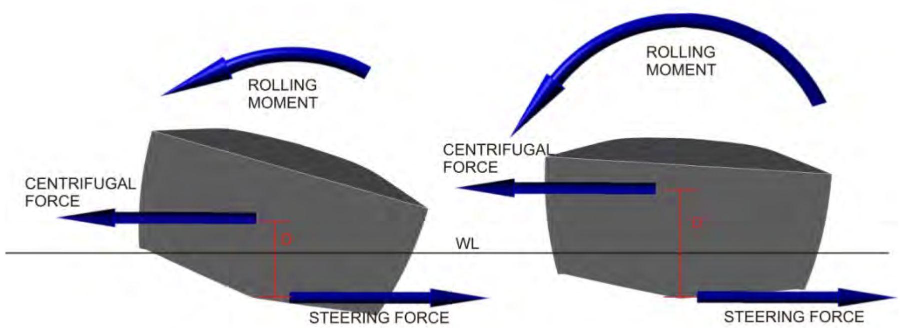

FIGURE 7. Effect of Raising Vertical Center of Gravity on Rolling Moment

Effect of Hull Section Shape on Roll Angle

Unless the VCG is very high, a properly designed hard chine monohull typically exhibits an inboard roll angle in a turn, and the amount of inboard roll angle increases with an increase in deadrise (Hatch 1963). On the contrary, a round bilge monohull, when executing a hard over turn at high speed, typically rolls outboard, even if VCG is appreciably low.

The cause of this phenomenon is believed to be due to the introduction of the transverse hydrodynamic flow across the hull bottom (Wakeling 1994). The transverse flow accelerates as it travels across the turn of the bilge and an area of negative pressure is developed, as shown in Figure 8.

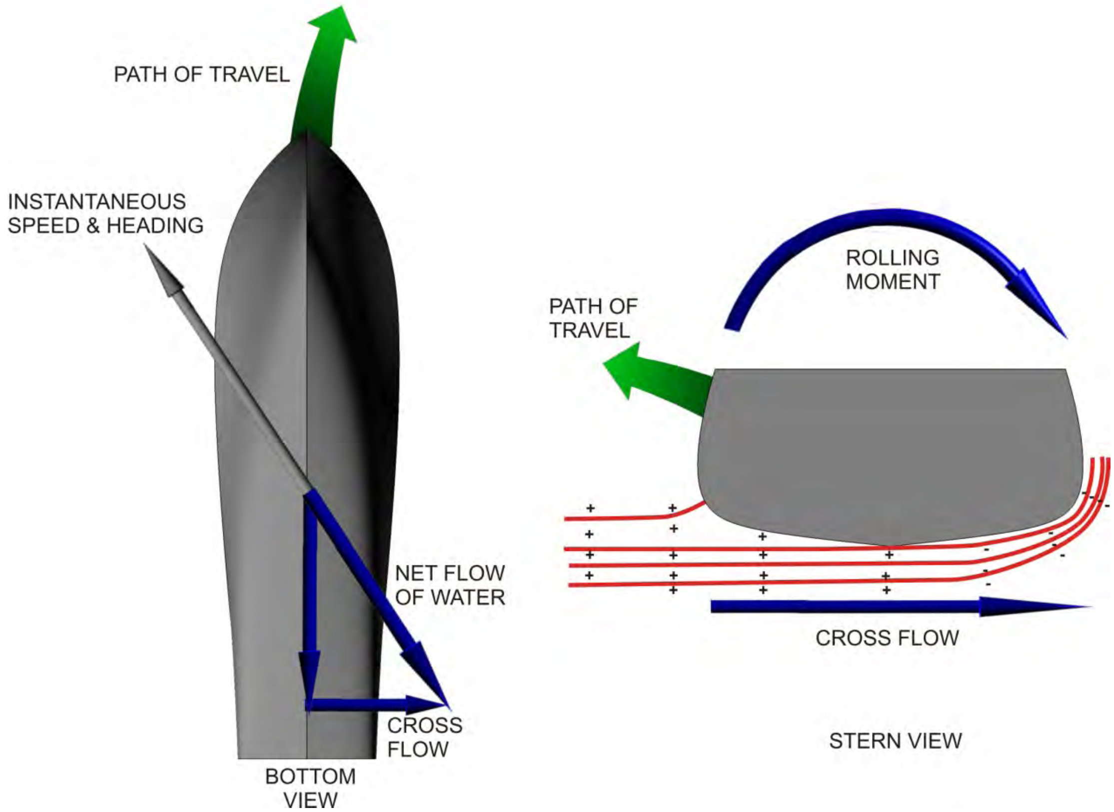

FIGURE 8. Transverse Flow Across a Round Bilge Hull Form in a Turn

This negative low pressure area generates a hydrodynamic suction force on the hull. Because of its location on the hull, the suction force generates an outward rolling moment rather than a righting moment as on a hard chine hull, which, when combined with the rolling moment created by the centrifugal acceleration of the center of gravity, rolls the vessel outboard in the turn.

DLBA was involved in a project where the goal was to reduce, or eliminate if possible, the outboard rolling characteristics of a hybrid, high speed monohull which has round bilge sections forward and hard chine sections aft. Based on the theory described above, spray rails were added to the hull at the turn of the bilges to introduce cross flow separation and a path for air from the free surface to ventilate the bilge. Hydrodynamic model testing was completed with the model fixed in yaw and roll and the dynamic roll moment was measured. Spray rails were introduced in different positions and combinations to ensure the stagnation lines continued to cross the spray rails with the vessel oriented in turning equilibrium. The addition of the selected spray rail configuration resulted in a reduction of the roll-yaw couple. A reduction in roll moment was observed for a given yaw moment, as shown in Figure 9.

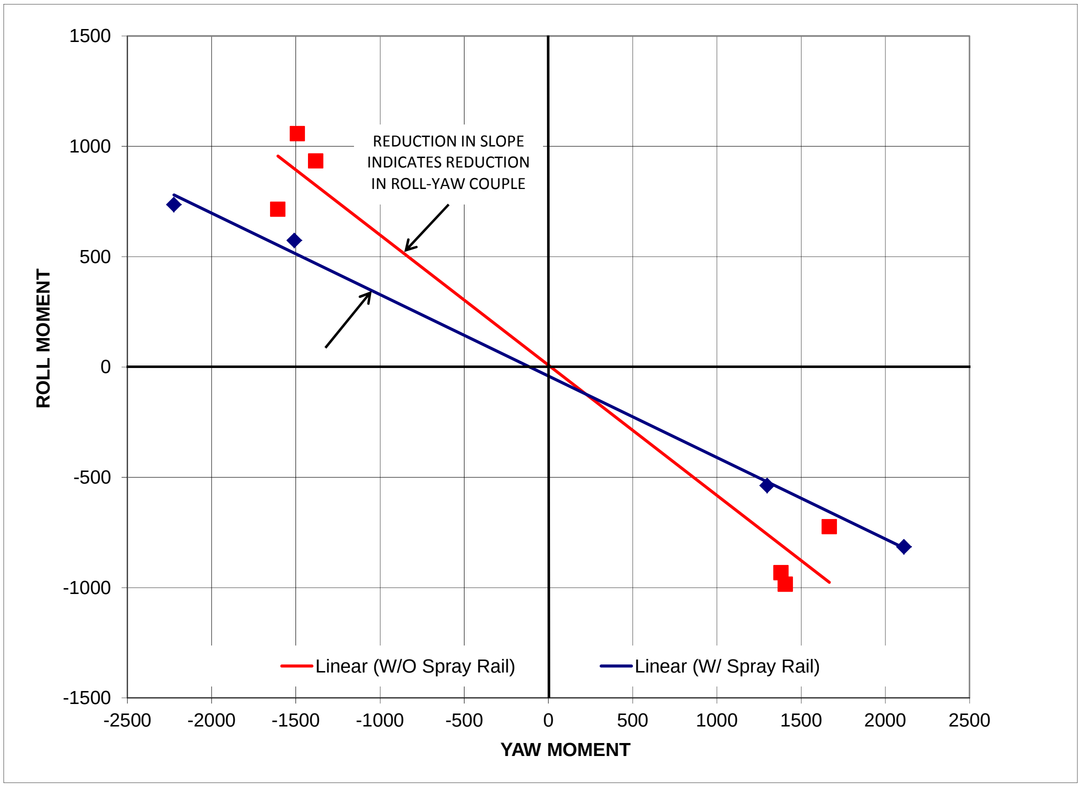

FIGURE 9. Roll Moment versus Yaw Moment on a Round Bilge Hull with and without Spray Rails

Effect of Roll Angle on Turning Capability

The natural tendency for a displacement vessel proceeding on a straight course is that when a starboard roll angle is introduced, the vessel will turn to port, and vice versa (Deakin 2009). Therefore, it can be deduced that when healing into the turn, the induced yaw moment tends to reduce the rate of turn (Deakin 2009). This tendency is confirmed by Martin in his observation that steady roll angle decreases with increasing rate of turn.

Based upon this relationship, it is possible to improve the turning capability of a high speed monohull by reducing its roll angle. Other than increasing the height of the vertical center of gravity (which is typically not recommended for various reasons), the only other physical change identified in reviewing the references to decrease roll angle is to decrease deadrise.

There are however dynamic control systems commercially available today to influence roll angles in a turn. One example is the Humphree Coordinated Turn Optimization System (CTOS). The Humphree CTOS system uses transom mounted interceptors to generate a dynamic rolling moment to either increase or reduce roll angle in a turn to achieve a coordinated turn. During sea trials of a high speed monohulls to which this CTOS system is fitted, it has been observed that reducing the roll angle increases the rate of turn of the vessel.

COMMON HANDLING ISSUES FOR MONOHULL VESSELS IN A HIGH SPEED TURN

The stability of a high speed monohull in a high speed turn is a delicate balance due to the magnitude of the dynamic forces being generated. The dynamics of the hull and/or appendages can be sensitive to minor changes in operating conditions, and in some cases these small changes can result in a dramatic change in performance characteristics. This sensitivity, when coupled with the magnitude of the dynamic forces associated with high operating speeds, can lead to sudden changes in the attitude or trajectory of a high speed monohull. These sudden changes can be hazardous to passengers due to the accelerations that they generate. Two common handling issues that occur on high speed monohulls that subject the passengers to large accelerations are roll angle reversals and sudden increases in yaw rate (excessive side slip). Failure of the vessel to right after a turn is another common handling issue, and while it does not necessarily generate large accelerations, it does create an uneasy feeling for passengers.

Roll Angle Reversal

When a high speed monohull experiences a sudden roll angle reversal (from rolling inboard to rolling outboard), large transverse accelerations are generated. This action is compounded by the influence of the roll-yaw couple which now, in this operating condition with the hull rolled outboard, increases yaw rate. As a result, the transverse accelerations experienced by the vessel can exceed 0.35g's and therefore can be hazardous to the vessel occupants. As such, they should be avoided. The most common cause of this type of behavior is ventilation of control surface appendages. In some cases it is the trailing edge of the surface that is ventilated, or in the case of a base ventilated control surface, flow separation at the leading edge (when at a high angle of attack) creates a cavity that extends to the free surface and ventilates the leading edge of the control surface.

When this hydrodynamic phenomenon occurs, a force reversal on the control surface is experienced. As a result, the control surface now increases the outward rolling moment and roll the hull outward. Behavior of this type is most frequently corrected by relocating the control surface forward on the hull bottom to eliminate the ventilation path. This type of behavior has also been observed on stern drive propelled craft. In this instance it was corrected by adjusting the vertical position of the intersection of the hydrodynamic flow relative to the cavitation plate on the outdrive. A transom flap was added to lower the free surface to the underside of the cavitation plate and the undesirable behavior was eliminated.

Sudden Increase in Yaw Rate

Water jet propelled monohulls most frequently exhibit this characteristic. While in a high speed turn, the stern of the vessel "breaks free" and "spins out" with yaw rate increasing suddenly. The vessel also tends to decelerate quickly because the yaw rate is so significant the vessel is soon oriented on a heading that was opposite to the original course and the propulsive thrust is now directed towards decelerating the vessel instead of maintaining forward speed. When this phenomenon occurs, the transverse accelerations can again exceed 0.35g's, and the total horizontal acceleration experienced by the vessel in this instance is even higher as it also has a longitudinal component.

This phenomenon occurs because the induced hydrodynamic forces and associated moments acting on the hull are exceeded by the yawing moment produced by the water jet. This is most likely to occur on water jet propelled vessels for two primary reason. First, in the absence of rudders, the hull has less directional stability in a turn than that of a propeller driven craft with rudders. And secondly, with the vectored thrust of a water jet, the steering moment generated by a water jet is typically greater than that generated by rudders.

Depending on the application, this turning characteristic may be desirable. For applications where it is undesirable, the addition of, or enlargement of, fixed course stability fins eliminates the behavior.

Failure to Right after a Turn

In some instances a high speed monohull will enter a hard turn at high speed and after successful execution of the turning maneuver the vessel will not return to an upright orientation. A residual roll angle exists even though the vessel has returned to a straight course. This phenomenon can occur on monohulls that roll inboard or outboard during the turn.

The exact causes of this behavior are less understood but can typically can be linked to negative hydrodynamic pressures (suction forces rather than lifting forces) that are manifested during the maneuver. The negative pressures are generated when a portion of the wetted hull geometry locally accelerates the hydrodynamic flow. Typically this is a result of some level of wetting of the hull sides (which usually have a large amount of curvature) during the maneuver. In this case, spray rails are added to the hull to promote flow separation at the chine and eliminate the hull side wetting.

Troubleshooting Maneuvering Issues

The above discussion only touches on a couple of the common handling issues experience by monohulls in a high speed turn and therefore is not a comprehensive review. However, the corrective actions identified above may be used to address other maneuvering issues. Table 1 below summarizes the corrective actions, or at least items for review, that should be considered when troubleshooting maneuvering issues of high speed monohulls:

	Roll Angle Reversal	Sudden Increase in Yaw Rate	Failure to Right after a Turn	Steady Outboard Roll Angle
Review Rudder Geomtery & Location	X	X		
Review Fixed Course Stability Fin Geometry & Location	X	X		
Addition or Removal of Spray Rails			X	X
Elimination of Undesirable Ventilation Paths	X	X		
Review Vertical and/or Longitudinal Center of Gravity			X	X
Reduce Hull Bottom Loading			X	X

Table 1. Common Maneuvering Issues and Potential Mitigating Actions

PROPOSED TURNING CRITERIA FOR HIGH SPEED MONOHULLS

Based upon review of the references and personal operating experience, it is proposed that the following capabilities/qualities be considered as the defining qualities of good maneuverability of a hard chine monohull at high speed:

- The vessel should be capable of a controllable hard over turn at maximum speed without a sudden increase in yaw rate (excessive “side slip“) or change in roll angle.
  - This feature may be desired on small combatants and “thrill ride” vessels where passengers are restrained.
- The vessel should exhibit moderate inboard roll in a turn.
- The vessel should be able to maneuver within a reasonable turning circle.
- Horizontal accelerations generated during maneuvers should not exceed 0.35g’s to avoid being hazardous to occupants.

With respect to these qualities, quantitative criteria are only required with respect to maximum and minimum turning circle diameters.

Maximum Recommended Turning Circle Diameter

The most recently developed regression equation identified to approximate the steady turning circle diameter of high speed monohull (equipped with propellers and rudders) was developed by Lewandowski in 2004 and is based upon the work completed by Denny and Hubble in 1991. This equation was used to predict the steady turning circle diameters of six high speed monohull vessels for which full scale sea trial data is available. The correlation of the predictions and sea trial data are provided in Figure 10.

The figure indicated good correlation between the predicted turning capability and the actual turning capability, especially within a 10% error band, for the vessels with the largest turning diameters. Many vessels have the ability to turn tighter than predicted by the regression equation. As a result, the Lewandowski equation can be considered a good reference for the maximum recommended turning circle diameter.

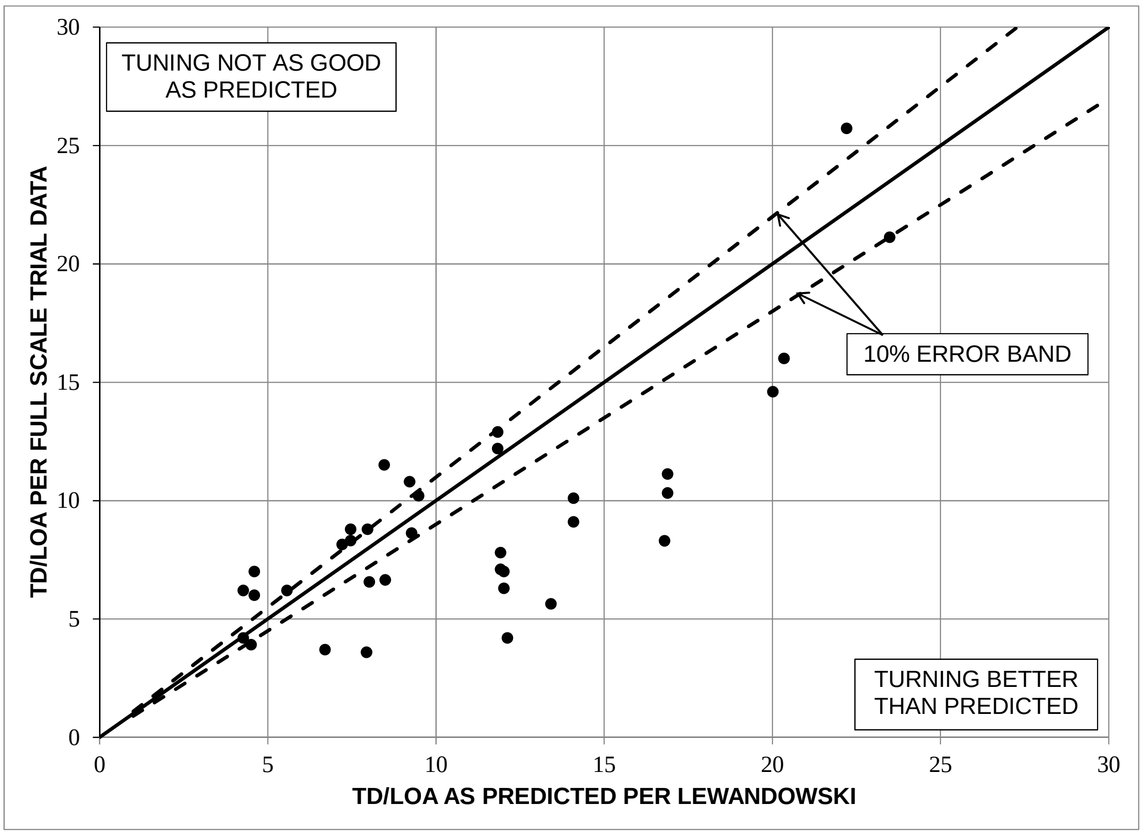

FIGURE 10. Correlation of Full Scale Trial Data of Various High Speed Monohulls with Predictions based on Lewandowski (Rudder Deflection = 30 degrees or max)

Minimum Turning Circle Diameter

The centrifugal acceleration experienced when a vessel is experiencing a yaw angle can be calculated from the following equation, as derived from Savitsky (1972):

$$AT = \frac{\left(UA * \frac{UC}{UA}\right)^2}{R} * \cos\beta$$

Where:

AT = Transverse Acceleration (m/s^2)
UA = Approach Velocity (m/s^2)
UC = Steady Turning Velocity (m/s)
R = Turning Radius (m)
β = Yaw Angle (degrees)

This equation can be rearranged to yield the minimum turning radius for a pleasure craft or passenger vessel as a function of speed where the acceleration does not exceed 0.35 g's (3.43m/s^2). And considering that yaw angles of high speed monohulls are typically less than 10 degrees, and that the cosine of angles less than 10 degrees has a value of essentially 1.0, the equation can ultimately be simplified as follows:

$$R_{MIN} = \frac{\left(UA * \frac{UC}{UA}\right)^2}{3.43}$$

The relationship between the steady turning velocity, UC, and the approach (initial) velocity, varies from vessel to vessel, and can be predicted or measured on sea trials. Using the equation above, Figure 11 presents the minimum turning diameter as a function of approach velocity (in knots) for typical UC/UA values of 0.75 to 0.95. The execution of turning maneuvers with smaller turning diameters than shown in this figure will result in transverse accelerations greater than 0.35 g's and therefore should not be conducted.

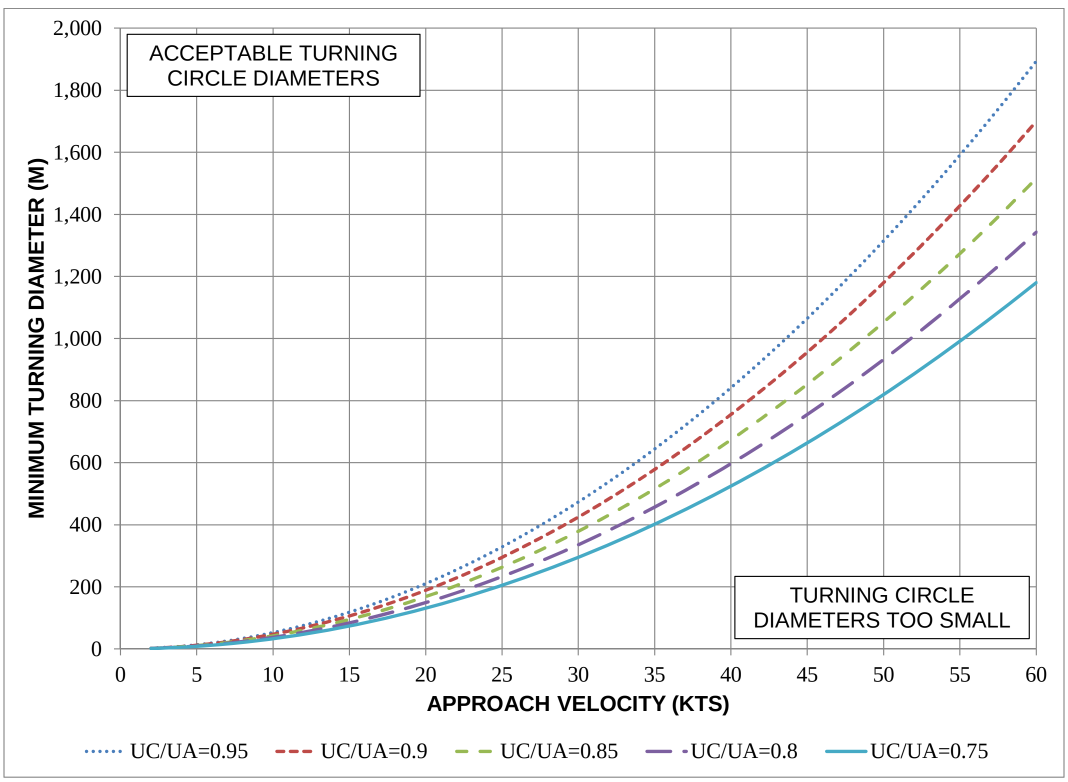

FIGURE 11. Minimum Turning Diameter to Not Exceed a Transverse Acceleration of 0.35g's

CONCLUSIONS

1. Generating accurate turning predictions for hard chine monohulls operating at high speed are challenging because the hydrodynamic force and moment coefficients are highly speed dependent, all motion modes are strongly coupled, and techniques exist to predict any of the nonlinear force or moment coefficients for horizontal-plane motions (Lewandowski 2004). However, analytical methods applying first principles, statics, and dynamics do exist to predict turning capabilities of high speed craft (Lewandowski 1994 and Hsu 1967). More simplistic approaches are available through regression equations to predict rates of turn (Martin 1976), speed loss in a turn (Denny 1991), and turning circle diameter (Denny 1991 & Lewandowski 2004).
2. Good turning characteristics of high speed monohulls are established. A high speed monohull should be capable of a predictable, controllable hard over turn at maximum speed while rolling inboard to the turn.
3. A high speed monohull should be able to maneuver within a turning circle diameter not great than 10% of the predicted diameter based on the regression equation developed by Lewandowski in 2004.
4. A high speed monohull (recreational craft passenger vessel) should not be able to execute turning maneuvers where the horizontal accelerations developed exceed 0.35g's to avoid being hazardous to occupants. A method for calculating the minimum recommended turning circle diameter is presented.

RECOMMENDATIONS FOR FUTURE WORK

1. A radio controlled, self-propelled model testing program of a large scale hard chine monohull turning at high speed should be conducted with systematic variations in deadrise angle, VCG, and speed to determine a prediction method for outboard roll angles in a turn.

2. Most of the references are based on or are relative to vessels with propellers and rudder. Information and discussion on vessels which vector thrust to create steering forces are not well covered. This information would be of specific interest to jet powered personal watercraft manufacturers if techniques to improve the turning capability of such craft could be improved without wholesale changes to the product design.
3. Further comparison between the results of the Lewandowksi prediction for turning capability and full scale trial data should be completed. The development of a larger database will result in higher confidence in the existing equation or identify potential modifications to achieve increased accuracy.

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