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TURNING MANEUVER LIMITATIONS IMPOSED BY SUDDEN STRUT SIDE VENTILATION ON A 200-TON 80-KNOT HYDROFOIL CRAFT

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Naval Ship Research and Development Center
Bethesda, Maryland

May 1975

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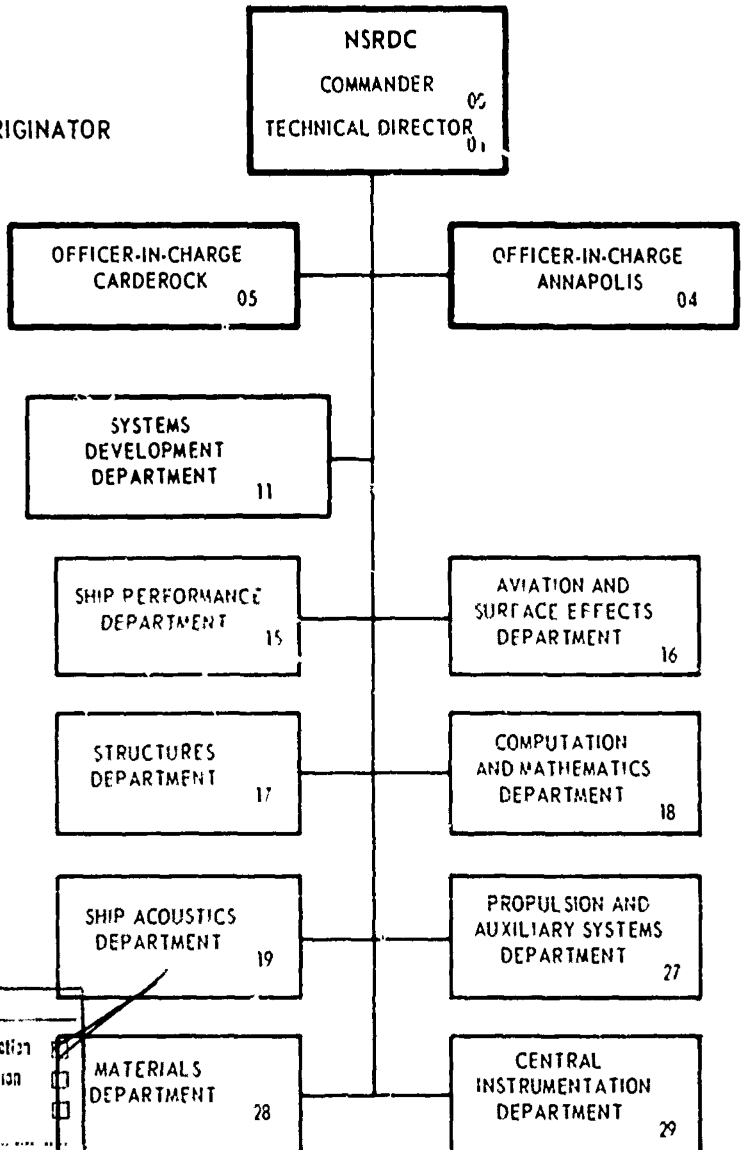

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Predictions of turning characteristics of an 80-knot hydrofoil craft performing ordinary coordinated turns indicate that, in principle, sudden strut side ventilation will limit craft maneuverability only if large turning rates are attempted in a seaway. A six-degree-of-freedom computerized simulation of a 200-ton craft performing coordinated turns in calm water indicated no danger of sudden strut side ventilation providing the control system is properly tuned to produce essentially zero strut yaw angles with respect to the flow at the maximum craft speed.

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Although it is concluded that the maneuverability of a 200-ton 80-knot hydrofoil will not be severely restricted by sudden side ventilation, initial misalignment of the struts to the flow during construction, the possibility of crash maneuvers, and such phenomena as breaking waves have not been considered in this report. It is almost certain that these problems will have major consequences with respect to the likelihood of sudden strut side ventilation because the predicted ventilation yaw angles are small.

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ABSTRACT

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ADMINISTRATIVE INFORMATION

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INTRODUCTION

An investigation into expected turning characteristics of high-speed hydrofoil craft was performed by the author. This work was undertaken to determine limitations to turning maneuvers imposed by the relatively low sudden strut side ventilation yaw angles that have been experimentally recorded for high-speed struts.[1] An earlier study of turning capabilities for flat turns for high-speed hydrofoils indicated that the necessity to prevent sudden strut side ventilation may preclude relatively large turning rates for an 80-knot hydrofoil craft performing coordinated turns.[2]

Sudden strut side ventilation can affect craft motions in either of two extreme ways, depending on which strut is ventilated, as well as on which side of the strut ventilation occurs. It could, on the one hand, prevent initiation of a turning maneuver or it could, on the other hand, cause a turn to "tighten." In the former case, the craft may have to severely reduce speed or become hullborne to relieve itself of the vent. In the latter case, large lateral loads could cause physical damage to the craft struts. The consequences of sudden strut side ventilation are predictable if the ventilation characteristics of the struts are known.

The present investigation produced estimates of the hydrodynamic yaw angles on struts attached to high-speed hydrofoil craft performing coordinated turns. These estimated angles were compared with predicted angles for sudden strut side ventilation to determine limitations to the craft maneuverability.

This information is essential to the U.S. Navy's high-speed hydrofoil program because sudden strut side ventilation must either be eliminated entirely as a characteristic of the struts or be avoided in practice by

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1 Holling, H.D., E.S. Baker, and E.P. Rood, "High Speed (80 Knots) Experiments for a Newly Designed Hydrofoil (TAP-1)," NSRDC Report to be published.

2 Rood, E.P., Jr., "Estimated Hydrodynamic Strut Side Forces on a 200-Ton 80-Knot Hydrofoil Craft," NSRDC Report SPD-584-01 (Oct 1974).

limiting the craft's maneuverability. Also, knowing the estimated yaw angles required for turning maneuvers, the hydrofoil craft developer can make a reasonably accurate decision whether to use present strut designs or to develop new designs relatively less likely to suffer sudden strut side ventilation. These new struts could be developed perhaps with boundary layer control of ventilation inception or perhaps with permanent side ventilation (using paired asymmetric struts with one side permanently ventilated at the design speed).

To avoid large lateral forces on the struts, it is necessary that the craft execute coordinated turns. This type of turn is a banked maneuver similar to that executed by fixed wing aircraft. All current U.S. Navy hydrofoil craft use coordinated turns. Therefore, the hydrodynamic yaw angles on the struts of the craft examined in this study were calculated for the craft in a coordinated turn. The calculations were made by solving the six-degree-of-freedom equations of motion.

THE COORDINATED TURN

Hydrofoil craft perform turning maneuvers with variations of two basic turning modes. The first mode is the flat turn, in which the craft does not roll throughout the turn, with the required lateral forces being produced by the struts. As shown in Figure 1, rolling motion is precluded by differential deflection of control surfaces to balance the roll torques produced by the forces on the struts. The second mode is the coordinated turn in which the craft is rolled, or banked, into the turn as shown in Figure 2 so that the required centripetal forces are produced by the foils, with the struts experiencing only small forces produced by the rotation of the craft about its center of gravity. The strut control surfaces are used to produce a net torque on the craft of approximately zero and a net strut side force of approximately zero.

The coordinated turn requires smaller strut yaw angles and thus less chance for sudden side ventilation than does the flat turn. It also produces a net craft acceleration that is normal to the deck and therefore comfortable for personnel.

With either mode of turning, the initial torque producing the angular momentum for the turn is imparted by the strut with the control surface. This torque is then reduced to zero by that control surface as the craft enters a steady turn with constant angular momentum, constant centripetal force, and constant roll angle.

Craft roll angles and turning rates are easily calculated for the ideal coordinated turn (see Figure 3). The struts have negligible side forces exerted on them, the craft speed and angular momentum are constant, and the net force on the craft foils consists of a vertical component equal to the craft displacement (less negligible buoyancy) and a horizontal component equal to the centripetal force. In this steady turn, the flow vector is constant relative to the craft, and the craft trajectory is a circle. Figure 3 shows that the craft turning rate is proportional to the tangent of the roll angle, and inversely proportional to the speed. For an 80-knot craft rolled 15 degrees, the turning rate would be 3.6 deg/sec, producing a turning diameter of 4300 ft.

As the craft turns, angles of yaw are induced on the struts due to the angular velocity of the craft. Assume for the moment that the craft has a pair of fixed aft struts and a single steerable forward strut, and that the drift angle is zero. Figure 4 shows approximate values for the yaw angles on the struts for a craft traveling 80 knots, and turning at a rate of 3.6 deg/sec. The dimensions of the craft are for a displacement of 200 tons and will be justified in a later section of this report. The yaw angles on the aft struts with respect to the flow are 0.34 deg. The angle of yaw on the steerable forward strut needs only be enough to cause the net torque on the craft to be zero. It would be roughly 0.18 deg with respect to the flow if all three struts produced equal loads for equal angles. It is apparent that the strut angles are very small for this ideal coordinated turn. However, it will be shown later that the angles are not always small in practice.

Coordinated turns are ordered by the craft automatic control system. Basically, a roll command is sent to the port and starboard foil control surfaces causing them to act differentially to roll the craft into the intended turn. As the craft rolls, a roll feedback or a centripetal acceleration feedback, or an equivalent, commands the lateral control surface (usually a steerable strut) to turn the craft into the turn. The craft is prevented from "winding up" on itself by a turning rate feedback which partially cancels the command to the lateral control surface. An equilibrium condition is reached with the craft rolled and the lateral control surface partially deflected with respect to the craft.

In the present investigation the craft was turned by a roll feedback to the steerable strut. This method of performing coordinated turns may not be as desirable from a view of minimizing strut yaw angles compared with feeding centripetal acceleration to the strut. In the latter case, the strut would be rotated only if the craft accelerated into the turn, although the time to initiate the turn would be relatively longer, while in the former case, the strut would rotate as the craft rolls regardless of craft translatory motion. There could be situations where the craft rolls unintentionally, producing large adverse angles on the steerable strut.

It is possible to construct the control system to produce fully coordinated turns for certain design conditions. However, because the control system gains are constant, operation of the craft at other than design conditions produces turns that are combinations of both flat and coordinated turns in which substantial yaw angles can be produced on the struts. These off-design conditions are such as near-surface operation or broaching of the outboard foil, or speeds other than the design speed for the control system. All will produce unbalanced loads with respect to the design condition on the struts and foils. In these cases, it is possible, for example, for the turning rate to be decreased by the unbalanced loads, resulting in the control system commanding the steering strut to assume a large yaw angle to the flow. It would be difficult to vary control system gains or other circuitry to anticipate such off-design craft behavior; it is more desirable to avoid adverse results from such behavior. Sudden strut side ventilation is a possible adverse result and the possibility of its occurrence during off-design maneuvers was examined in the present study.

SUDDEN STRUT SIDE VENTILATION

Sudden strut side ventilation is the almost instantaneous filling of a water vapor cavity with air at atmospheric pressure. Because atmospheric air pressure and cavity pressure differ by 2100 psf, the sudden decrease in strut loading can produce a significant effect on craft maneuverability and structural integrity. With blunt-based, base-ventilated struts anticipated for use on 80-knot hydrofoil craft, sudden side ventilation occurs when the low pressure cavity on the side of the strut physically joins the high pressure base-cavity. Model experiments have consistently shown that the low pressure cavity then fills with high pressure air almost instantly. The reduction in net loading is from 25 to 80 percent.

What are the consequences of sudden strut side ventilation for an 80-knot craft? If the craft is executing a turn, side ventilation of a strut would cause a sudden torque to act on the craft. Depending on which strut and on which side of the strut ventilation occurs, the craft turn rate would either increase or decrease. A decrease in the turn rate could be catastrophic if the craft were turning to avoid an obstacle. On the other hand, an increase in the turn rate could cause an overload of the structure, or even cause the craft to roll over.

Model experiments indicate that once the strut is side ventilated, the craft must either severely reduce speed or the yaw angle on the strut must be reversed to remove the ventilation. Because smoothly changing predictable hydrodynamics are essential for craft control, it is clear that sudden strut side ventilation must be avoided.

Recent data[1] from high-speed model experiments show that a base-ventilated parabolic strut moving at a speed of 80 knots will suffer side ventilation at a yaw angle of 3-1/4 deg for a depth-to-strut chord ratio of 1, and 1-1/2 deg for a depth-to-strut chord ratio of 2, where the depth is measured from the surface to the strut/foil intersection. Side ventilation inception angles from the experiment are summarized in Figure 5. It is also known from those experiments as shown in Figure 6 that a reduction in craft speed greatly increases the sudden side ventilation inception yaw angle. In those experiments a fully-ventilated foil of the type anticipated for high-speed hydrofoil craft was attached horizontally to the tip of the vertical strut. Those experiments also showed that a loss of the high pressure ventilation on the foil substantially decreased the pressure both on the foil and on the low pressure side of the yawed strut. The lowered pressure on the strut produced cavitation and thus sudden side ventilation at lower yaw angles for a given speed than for the higher-pressure ventilated foil condition. The reduction in yaw angle was as much as one degree.

However, a properly designed foil should not lose its ventilated cavity. A foil should be designed so that only an unusually large pitch down attitude of the craft would allow the ventilated cavity to "wash off." This design criterion is within the state of the art. Therefore this study assumed that the foil is always fully-ventilated.

Although hydrofoil craft generally operate with the foil depth equal to approximately one strut chord length, it is necessary that the depth of the inboard foil be increased to over two chord lengths during some turning maneuvers to prevent broaching of the outboard foils. As noted above, deeper depths produce lower strut side ventilation inception angles.

Although strut side ventilation angles are presumed independent of craft size, the yaw angle of a strut is very much dependent on craft size. A turning craft rotates and translates at its center of gravity. The rotation occurs because the craft is turning. The translation is produced by the drift angle, the angle between the craft longitudinal axis and the velocity vector. Yaw angles of the struts with respect to the apparent water flow are caused by both the translation and the rotation of the craft. Components produced by translation are independent of craft size. However, components produced by rotation are directly proportional to the distances from the center of gravity to the struts. Therefore larger craft in general have larger yaw angles and are thus more susceptible to sudden strut side ventilation than are small craft performing the identical turning maneuver.

THE CRAFT

This investigation studied the turning characteristics of a 200-ton hydrofoil craft with three identical strut/foil structures - one forward, and two aft. This arrangement, with the two aft structures equally distant from the centerplane, and the forward structure in the plane, is known as split canard. The longitudinal distance from the center of gravity to the forward strut was 48 ft, and the longitudinal distance from the center of gravity to the aft struts was 13 ft. The distance between the aft struts was 32.6 ft.

The struts were base-ventilated with parabolic profiles. The foils were fully-submerged and normally fully-ventilated on their upper surface. Lift modulation was accomplished with 30 percent chord flaps. The strut and foil hydrodynamics are discussed in detail in the next section of this report.

It was assumed that the fixed struts were manufactured with no error in their alignment to the flow. Error in the alignment could produce sudden strut side ventilation for smaller than predicted turning rates. Because the ventilation inception angles are so small, a one-degree alignment error could prevent safe craft operation at a speed of 80 knots.

The craft hull shape and deck geometry were not needed in this study because hullborne operation, wave impact on the hull, and air drag were ignored. The specific type of craft thruster was also undefined as it was used only to generate craft speed. That is, its performance characteristics were assumed adequate to hold the craft at constant speed. Any interactions between the thruster and the strut and foil hydrodynamics were ignored in the computer program used for this study.

Some of the craft geometric and mass distribution characteristics are presented in Table 1 for comparison with two other craft, PCH (HIGHPOINT) and PHM (PEGASUS), scaled to 200 tons of displacement. From the data in the table, it is apparent that the imaginary craft studied in this investigation had a shorter distance between its forward and aft strut/foil structures than would be expected for its displacement. Therefore, yaw angles of the struts due to craft angular velocity would be somewhat smaller than expected. Further, the mass was more concentrated at the longitudinal axis of the craft. It would be expected that roll response would be quicker, and pitch and yaw response slower, than present construction design would indicate. None of these apparent deviations is significant enough to discredit the conclusions from this study.

THE STRUT AND FOIL HYDRODYNAMICS

The craft was dynamically supported by three identical strut/foil structures, one of which is geometrically described in Figure 7. The strut for each structure had a base-ventilated parabolic profile, and the foil had a fully-ventilated Tulin-Burkhart 2-term camber profile.[3] These profiles were chosen because their hydrodynamic characteristics were representative of those which may be used on an 80-knot hydrofoil designed with current technology.

The base-ventilated strut exhibits two characteristics important for high-speed craft. First, the blunt base provides one path along which atmospheric air is fed to the foil. Second, the parabolic profile, with maximum thickness at its trailing edge, does not cavitate for low yaw angles as would a streamlined profile. The fully-ventilated foil also exhibits two characteristics favorable for high-speed foils. First, it has a low lift coefficient at moderate angles of attack, and second, its full vent produces smooth loading during broaching of the foil because its upper surface is always exposed to atmospheric pressure.

The hydrodynamics of the strut were estimated using recent data from model experiments performed at the high-speed outdoor facility at Langley Field,[1] and also using unpublished data from the same facility for experiments performed with scale models of high-speed strut/foil structures. Lift and drag curves for a speed of 80 knots are shown in Figure 8. These curves and those for other speeds were used to model the strut hydrodynamics for the present study.

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[3] Spangler, P.K., "Performance and Correlation Studies of the BuShips Parent Hydrofoil at Speeds from 40 to 75 Knots," NSRDC Report 2353 (Dec 1966).

Note, however, that the side force loadings for the present strut are lower than those for the strut examined in Reference 2. This difference is resolved by observing that the present strut was attached to fully-ventilated foils, producing lower strut loadings than for the strut in Reference 2, which was attached to fully-wetted foils.

The foil hydrodynamics were estimated using experimental model data from the BuShips parent hydrofoil.[3] These data were modified for flap effects using data obtained by Conolly,[4] and using data mentioned above. Examples of the foil lift, drag, and lift/drag ratio are shown in Figures 9, 10, and 11. The foil drag data were corrected by subtracting the calculated strut induced, parasite, and spray drags. It was assumed that the foil could be either superventilated or base-ventilated, but never supercavitating, for speeds up to 80 knots. In particular, choking of the air flow to the foil vent was not considered. If this phenomena does exist for prototype craft, the results from this study would nevertheless be valid. Although choking of the air flow decreases the sudden strut side ventilation yaw angle, it also increases the side force corresponding to a given strut yaw angle. The result is almost a net trade-off. In other words, if strut ventilation would occur in one case, it would probably also occur in the other.

Time dependent corrections to the hydrodynamics were ignored in this study. The author felt that the frequencies involved were low and that the corrections to the phases and amplitudes of the instantaneous lift and drag were insignificant. Therefore, time-varying hydrodynamics were calculated using instantaneous angles of attack, speeds, etc.

[4]Conolly, A.C., "Experimental Investigations of Supercavitating Hydrofoils with Flaps," General Dynamics/Convair Report GD/C-63-210 (Dec 1963).

THE SIX-DEGREE-OF-FREEDOM DYNAMIC SIMULATION

Calculation of the yaw angles on the struts of a hydrofoil executing a turn requires solution of the six-degree-of-freedom differential equations. The unknowns in the equations are the craft control surface deflections. Boundary conditions to the problem include craft depth of submergence, roll angle, and other commands to the control system.

Calculation of the proper control surface deflections for a given turning maneuver was performed for the present study using an existing six-degree-of-freedom computerized simulation. Essentially the simulation consisted of three parts: the equations of motion (with unspecified hydrodynamic coefficients and control surface orientations), the hydrodynamics, and the control system. The existing simulation was in the process of being developed at the time it was assigned for use in this study. Considerable debugging and modification of the simulation program produced a computer program valid for the present purposes.

However, the control system needs fine tuning to remove some minor pitch-heave coupled motion whose amplitude increased with craft speed. Since an increase in speed increased the hydrodynamic torque about the craft center of gravity, perhaps the control system as used was not adequately tuned to respond to large pitching torques. It is conjectured that an increase in the distance between the forward and aft foil strut structures would have damped the motions by producing larger restoring forces due to pitching velocity. In that case, the foil flaps would have been more effective in cancelling pitching torques. The largest amplitudes of coupled motion encountered were 0.5 deg of pitch and 0.3 ft of heave at the center of gravity for calm water calculations.

The calculations for the craft in a seaway became unstable for some conditions, possibly due to inadequacies in the control system or the computer numerical computation procedure. Fortunately it was not necessary to perform extensive seaway calculations, as will be shown in the next section.

THE EFFECTS OF A SEAWAY

The simulation included a seaway representation as well as the calm water case. Computer data were obtained for sea state 3 and for sea state 5 for comparison with previous two-degree-of-freedom hand calculations[2] which hopefully would not have had to be repeated in this study. The craft speed was maintained at 80 knots, and the seaway direction was from abeam. Figure 12 compares the simulation results with the previous calculations of the standard deviation of the effective strut yaw angle.

The computer calculated the yaw angle on the strut at a spanwise location 40 percent from the free surface and toward the strut/foil intersection, whereas hand calculated yaw angles from Reference 2 were obtained by averaging the orbital velocity induced yaw angles over the length of the strut. The orbital velocity in a seaway is an exponential function of the depth beneath the free surface. Since the average value of the orbital velocity along the strut span is approximately the value at 40 percent of the span, the computer calculated and hand calculated data can be directly compared.

The comparison was favorable, and there was no need to repeat the calculations from Reference 2 for all speeds and depths of submergence. The results from Reference 2 are presented in Figure 13, which shows the standard deviation of the effective strut yaw angle as a function of strut depth of submergence, sea state, and craft speed.

In Figure 12, note that the aft strut experienced larger yaw angles than did the forward strut. Because the craft was not yawed, this result is attributed to the rolling motion of the craft. The craft roll was an input to the strut yaw command. As the craft rolled, the strut turned into the roll (as required for a coordinated turn). It is conjectured that, in a beam sea, the rolling motion therefore indirectly reduced the forward strut effective yaw angle.

All of the turning characteristics examined in the present study were obtained for calm water conditions. A complete evaluation of turning characteristics in a seaway would have required a statistical approach taking into account the fact that as the craft turned through a seaway, the direction of the seaway constantly would change relative to the craft.

In this study the probability distribution could have been obtained with the computerized simulation by commanding the craft to perform many successive turns beginning at random points in time. Eventually one would have been able to construct probability distributions of strut yaw angles as functions of initial seaway heading, turn rate, and turning distance. This procedure would have consumed a lot of time and money, and therefore it was not followed.

An alternative procedure that was followed assumed two conditions. First, it assumed that the strut yaw angles for a craft in a coordinated turn in a seaway are the direct sums of those for a turning craft in calm water and those for a non-turning craft moving through a seaway of constant heading relative to the craft. Second, it assumed that the probability for sudden strut side ventilation was greater for a beam sea than for a sea from any other direction. Both of those assumptions are believed valid for the present study.

This maximum probability is not the probability that sudden side ventilation will occur at some instant during the entire turn. It is the probability that, when the craft passes through the beam sea heading, the strut will ventilate. It follows therefore that if there is negligible probability for ventilation with the beam sea heading, there is negligible probability throughout the turn.

Furthermore, knowledge of the probability for ventilation as a function of seaway heading will not permit calculation of the probability for side ventilation for the entire turn. This is because the real seaway is not in fact truly random with time. Changes in the orbital velocity are physically constrained (predetermined) for small increments in time. Therefore the orbital velocity induced yaw angles on the strut are not random from instant to instant. This renders calculations of the probability for ventilation during the entire turn an impossibility given only the probability as a function of seaway heading. Nevertheless, it is appropriate to calculate the probability for any one discrete heading at some random instant in time.

Knowledge of the maximum instantaneous probability for side ventilation during a given turn is useful information to the design engineer. This is because it is most likely that a craft will suffer sudden side ventilation for a beam sea heading than for any other heading.

RESULTS FOR CALM WATER COORDINATED TURNS

Figures 14(a) through 14 (k) show the forward and aft strut effective yaw angles and the craft roll angle as functions of time for calm water coordinated turns. Results are presented for two speeds (60 and 80 knots), and two depths of forward strut submergence (deep and shallow). In each case, the craft was executing a turn because the roll angle was a feedback to the strut yaw angle, causing the craft to turn as explained in the above section describing the coordinated turn. The craft roll angles shown in the figures were manually commanded to the control system. Three nominal helm commands (HLMCM) were used to cause the craft to roll approximately 5, 10, and 15 deg, respectively. These values are designated HLMCM = 5, 10, and 15 in the figures. The effective strut yaw angle shown in the figure was the angle relative to the water flow at the strut, i.e., the local angle of attack. The yaw angle was measured about an axis parallel to the craft yaw axis, i.e., it is a vector pointing "down." Similarly, the turn was executed with the bow swinging to starboard.

In each of the graphs, there are transient responses of the effective strut yaw angles to the turn command which eventually disappeared as the craft settled into a steady turn.

Summaries of the above figures are shown in Figures 15 through 18. Figure 15 shows the average forward and aft strut effective yaw angles for the steady turn as functions of the craft roll angle. Figure 16 shows the maximum strut yaw angles as functions of the craft roll angle. The maximum angle usually occurred during the transient motion associated with initiation of the turn. However, turns with the outboard foil near the free surface caused large unsteady strut yaw angles sometimes exceeding the transient angle in value. The larger of the two angles was plotted in Figure 16.

Figure 17 shows the steady turning rates as functions of the craft roll angles. The craft drift angle is shown in Figure 18 as a function of the craft roll angle. A positive drift angle meant that the craft bow was to starboard of the velocity vector at the center of gravity.

DISCUSSION

Calm Water - Forward Strut Deeply Submerged

The steady turning characteristics of the craft with the forward strut deeply submerged were as expected. The craft quickly settled into a steady turn with all three struts having small yaw angles to the flow. In fact, a comparison of the computer calculated turn rates shown in Figure 17 with simple hand calculations explained in Figure 3 shows the turn was essentially 100 percent coordinated although the craft usually had a non-zero drift angle, indicating that it was crabbing slightly.

However, Figure 16 shows that in one case the maximum strut yaw angles exceeded the value for sudden strut side ventilation during the transient period after the craft was rolled. This condition occurred for a craft speed of 80 knots and a roll angle of 13.5 deg. The forward strut was submerged 2.1 chord lengths and the aft inboard strut 3 chord lengths. The forward strut yaw angle was 1-1/2 deg, and the aft inboard strut yaw angle was 1 deg. It is concluded from Figure 5 that both the forward strut and the aft inboard strut had yaw angles approximately equal to those required for side ventilation.

Note, however, that side ventilation would not be expected for a craft speed of 60 knots because the strut yaw angles were too small (see Figures 6 and 15). In addition, Figure 15 shows that the strut yaw angles for a speed of 60 knots were negative while those for a speed of 80 knots were positive. The implication is that an automatic control system can be tuned to provide zero strut yaw angles at some specified speed (in this case somewhere between 60 and 80 knots) At off-design speeds, either positive or negative yaw angles would develop in a turn, depending on the sense of the speed difference. If the speed were exceeded, positive angles would be expected. If the speeds were not met, negative angles would be expected.

This statement is supported by data obtained from a computerized simulation of the 40-knot hydrofoil PCH. At 40 knots the strut yaw angles for coordinated turns were small. However, an increase of the speed to 80 knots caused very large positive yaw angles.

The conclusion is that an 80-knot hydrofoil with deeply submerged foils can be designed to perform coordinated turning maneuvers with roll angles up to perhaps 15 deg without suffering sudden strut side ventilation. From Figure 17 it is seen that a 15-deg roll angle for a speed of 80 knots corresponds to a turning rate of 4.8 deg/sec, which produces a turning diameter of 3700 ft.

Calm Water - Forward Strut at Shallow Submergence

The maneuverability of the craft with the foils at shallow submergence was limited. For the larger roll angles, the craft was rolled enough to cause the outboard foil to broach the free surface. When this happened, the hydrodynamic forces on the craft were suddenly unbalanced, leading to large fluctuations in the craft orientation as the foil loaded and unloaded. As shown in Figures 14(d), 14(e), and 14(k), the effective strut yaw angles for both the forward and the aft struts fluctuated wildly, taking on values in excess of two degrees. There are, therefore, strong implications that sudden strut side ventilation is likely when the outboard foil approaches the free surface in a turn. Further, it is most likely that the inboard aft strut would ventilate. As indicated in a previous section, ventilation of that strut would cause the craft turn to tighten. Perhaps the resulting large angles of the struts to the flow would produce structural damage caused by large hydrodynamic forces. From Figure 5 it is seen that the yaw angle required for sudden side ventilation is a function of the depth to which the strut is submerged. The deeper the submergence, the lower the yaw angle.

In the above case of outboard foil broaching, the aft outboard strut would not be expected to ventilate because its submerged length is very small. Likewise, the forward strut would not be expected to ventilate because it has a relatively small submerged length. However, the aft inboard strut is submerged as much as one chord more than the forward strut. For example, if the forward strut is submerged one chord length, the aft inboard strut will be submerged an additional chord length for a roll angle of 15 deg. At this submergence of two chord lengths, the strut would suffer sudden side ventilation at a yaw angle of 1-1/2 deg for a speed of 80 knots. Looking at Figures 15 and 16, one sees that this value for the yaw angle was essentially exceeded for roll angles greater than 5 deg for a speed of 80 knots.

However, the figures also show that a reduction of the craft speed to 60 knots would reverse the signs for the strut yaw angles. It is concluded that proper tuning of the control system would produce zero mean yaw angle, with fluctuations equal to the difference between the maximum yaw angle in Figure 16 and the mean angle in Figure 15.

This difference is approximately 0.75 deg, maximum, for the cases studied in this investigation. It is concluded from Figure 5 that sudden side ventilation would not be expected for calm water coordinated turns if the control system is properly tuned to provide essentially zero strut yaw angles at the maximum craft speed, and if there are no manufacturing misalignments of the strut to the flow.

Seaway - Forward Strut Deeply Submerged

The seaway induced yaw angles are oscillatory and have a zero average. Therefore, turning rates are in general independent of the seaway. However, the chance of sudden strut side ventilation is increased in a seaway because the effective strut yaw angles are larger. The probability for sudden strut side ventilation is determined by the probability that the seaway will increase or decrease the effective strut yaw angle enough to cause sudden ventilation. (A strut will ventilate with either a negative yaw angle or a positive yaw angle.) Therefore, given the strut submergence and yaw angle for a calm water turn, the strut ventilation yaw angle, and the standard deviation of the seaway induced yaw angle, the probability for sudden strut side ventilation can be calculated for a given seaway heading at a random instant in time.

As shown in Figure 2, the respective submergences of the craft struts are functions of the forward strut depth of submergence and the craft roll angle.

As the craft rolls, the outboard strut decreases submergence, and the inboard strut increases submergence. A change in strut submergence has a two-fold effect on the probability for sudden strut side ventilation.

First, an increase in depth decreases the yaw angle required for sudden strut side ventilation (Figure 5). Second, an increase in depth also decreases the standard deviation of seaway induced induced yaw angles (Figure 13). The first effect increases the probability for side ventilation; the second decreases the probability.

Calculations made for the present study indicate almost no chance for sudden ventilation on any strut, if the forward strut is submerged at least two chord lengths, once the turn becomes steady. The calculations assumed that the calm water yaw angles on the struts were essentially zero - a valid assumption explained above. However. the transient at the initiation of the turn for a speed of 80 knots posed a potential problem. For a roll angle of 15 deg (turning rate = 4.8 deg/sec) the chances were 2/1000 for sea state 3 and increased to 120/1000 for sea state 6 that the forward strut would suffer sudden side ventilation. For a roll angle of 10 deg (turning rate = 3.5 deg/sec), the chances were 2/1000 that the forward strut would ventilate for sea state 6. Neither of the aft struts ventilated in any sea state.

Assuming almost no chance of ventilation is the design condition for a speed of 80 knots, it is concluded that craft operation is limited to sea state 5 for a turning rate of 3.5 deg/sec, and to sea state 2 for a rate of 4.8 deg/sec. These limitations do not in principle appear overly restrictive.

A reduction of the craft speed to 60 knots would eliminate the probability for sudden strut side ventilation due to the seaway because the required yaw angle for ventilation inception increases dramatically with lowered speed.

Seaway - Forward Strut at Shallow Submergence

Calculations similar to the above indicated that the rapid increase in side ventilation inception angle predominates over the increase in yaw angle for decreasing depth of submergence in a seaway. Therefore, the seaway did not affect craft maneuverability with respect to the occurrence of sudden side ventilation.

CONCLUSION

It is concluded that sudden strut side ventilation will not in principle severely limit maneuverability for ordinary coordinated turns for an 80-knot 200-ton hydrofoil craft, providing the struts have no error in their alignment to the flow at manufacture and providing such phenomena as breaking waves are ignored.

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1. Holling, H.D., E.S. Baker, and E. P. Rood, "High-Speed (80 Knots) Experiments for a Newly Design Hydrofoil (TAP-1), NSRDC Report to be published.

2. Rood, E.P., Jr., "Estimated Hydrodynamic Strut Side Forces on a 200-Ton 80-Knot Hydrofoil Craft," NSRDC Report SPD-584-01 (Oct 1974).

3. Spangler, P.K., "Performance and Correlation Studies of the BuShips Parent Hydrofoil at Speeds from 40 to 75 Knots," NSRDC Report 2353 (Dec 1966).

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TABLE 1

Comparison of Geometric and Mass Distribution Characteristics of Three Hydrofoil Craft Scaled to 200 Tons by the Cube Root of the Displacement Ratio

Characteristic	PCH (HIGHPOINT)	PHM (PEGASUS)	80-KNOT CRAFT
Δ	117	221	200
$\left[\frac{200\ \text{tons}}{\Delta}\right]^{1/3}$	1.19	0.960	1
Scaled to 200 tons:			
L	70	84	61
I_x	1,700,000	1,500,000	422,000
I_y	12,200,000	13,000,000	11,200,000
I_z	11,800,000	12,800,000	13,200,000

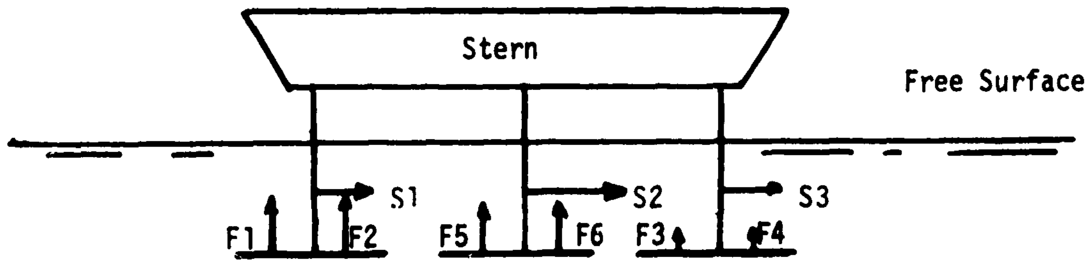
Δ = displacement (tons)

L = length between forward and aft strut/foil structures (ft)

I_x = moment of inertia about longitudinal axis through center of gravity ($ft\text{-}lb\text{-}sec^2$)

I_y = moment of inertia about transverse axis through center of gravity ($ft\text{-}lb\text{-}sec^2$)

I_z = moment of inertia about vertical axis through center of gravity ($ft\text{-}lb\text{-}sec^2$)



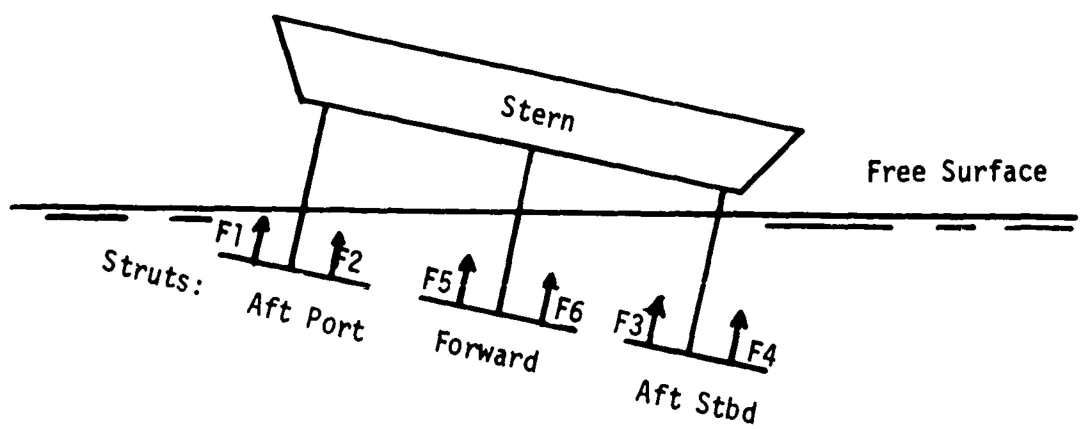
Struts: Aft Port Forward Aft Stbd

Forces S1, S2, and S3 provide lateral acceleration

Forces F1, F2, F3, and F4 cancel rolling moments produced by S1, S2, and S3

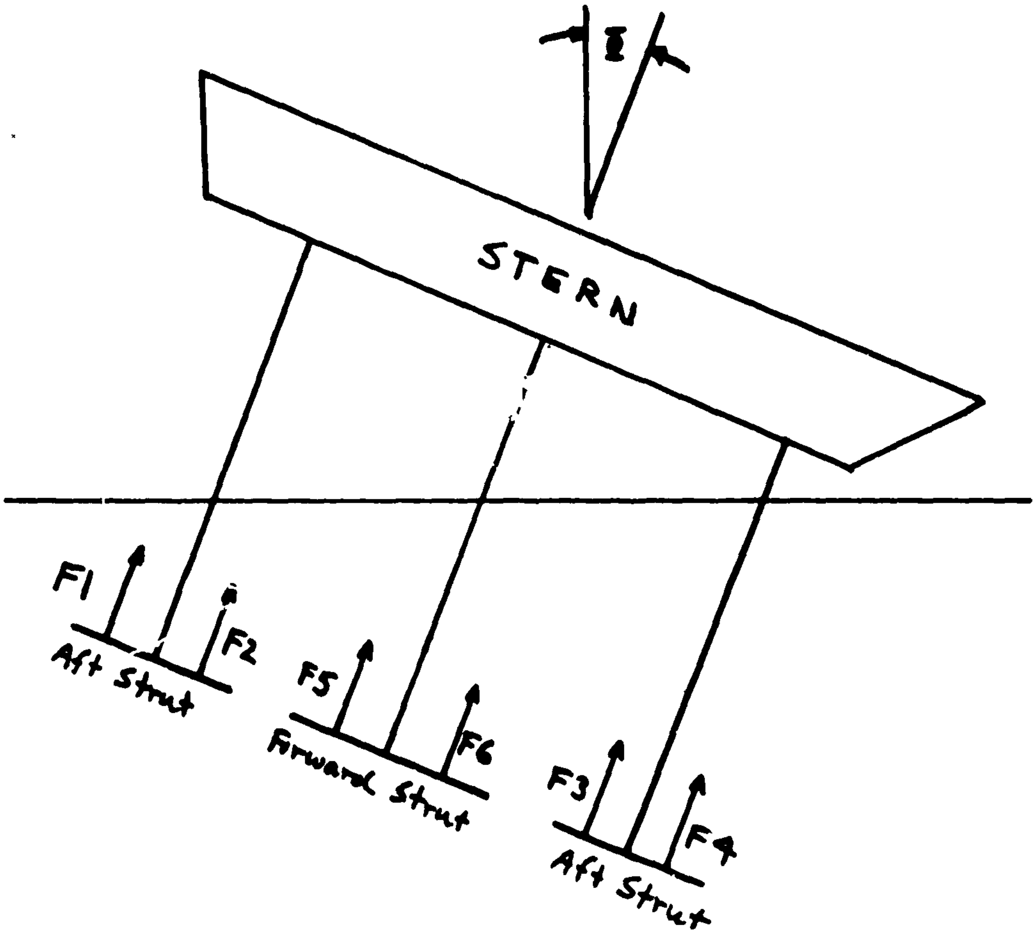
Forces F1 through F6 balance the craft weight

Figure 1 - Foil and Strut Forces for a Flat Turn to Starboard



The horizontal components of the forces FI through F6 provide the lateral acceleration, while the vertical components balance the craft weight.

Figure 2 - Foil and Strut Forces for a Coordinated Turn to Starboard



$$F = F1 + F2 + F3 + F4 + F5 + F6$$

Craft speed $= V$

Craft mass $= m$

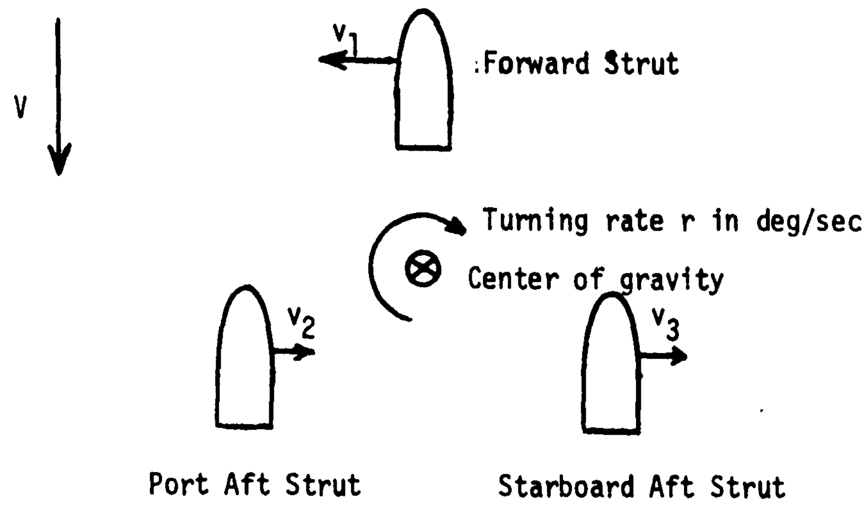
Turning radius $= R$

Turning rate $= r$

$$\left.\begin{array}{l} F \sin \Phi = m V^2/R \\ \dfrac{360\,(\mathrm{deg})}{r} V = 2\pi R \end{array}\right\} \quad r = \frac{360F}{2\pi m}\,\frac{\sin\Phi}{V}$$

$$\text{Since } F = mg/\cos\Phi : \quad r = \frac{(360)(32.2)}{6.28}\,\frac{\tan\Phi}{V} = \frac{1846}{V}\tan\Phi$$

Figure 3 - Calculation of Craft Turning Rate as a Function of Roll Angle and Speed for the Ideal Coordinated Turn



V is the oncoming flow

v_1, v_2, and v_3 are apparent flows caused by r

Longitudinal distance from c.g. to forward strut = 48 ft

Longitudinal distance from c.g. to aft struts = 13 ft

$v_1 = 48\ r\ /\ 57.3$ in ft/sec

$v_2 = v_3 = 13\ r\ /\ 57.3$ in ft/sec

Forward strut yaw angle v_1/V are induced by r

Aft strut yaw angles v_2/V and v_3/V are induced by r

If V = 80 knots and r = 3.6 deg/sec, then the forward strut induced yaw angle is 1.3 deg and the aft strut yaw angles are 0.34 deg

Figure 4 - Calculation of Strut Yaw Angles Induced by Craft Turning Rate for a Craft Speed Equal to 80 Knots

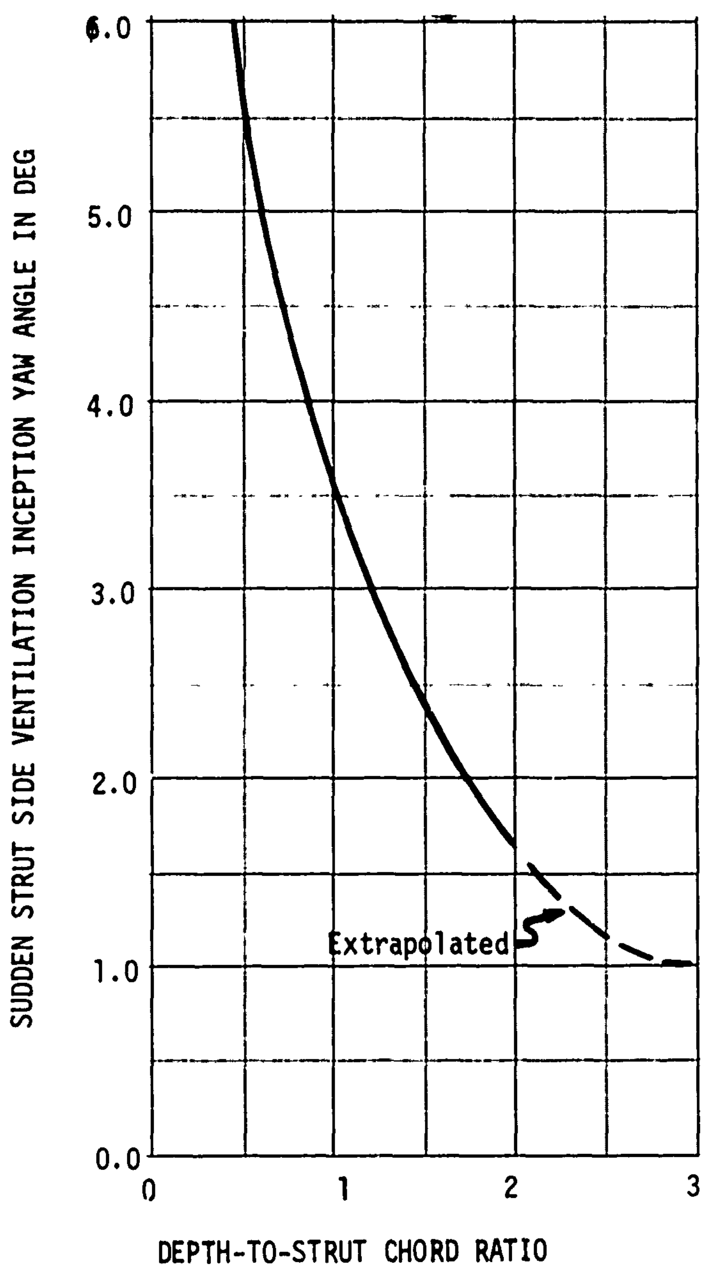


Figure 5 - Sudden Strut Side Ventilation Inception Yaw Angle as a Function of Strut Depth-to-Chord Ratio for a Base-Ventilated Strut Attached to a Fully Ventilated Foil for a Speed of 80 Knots

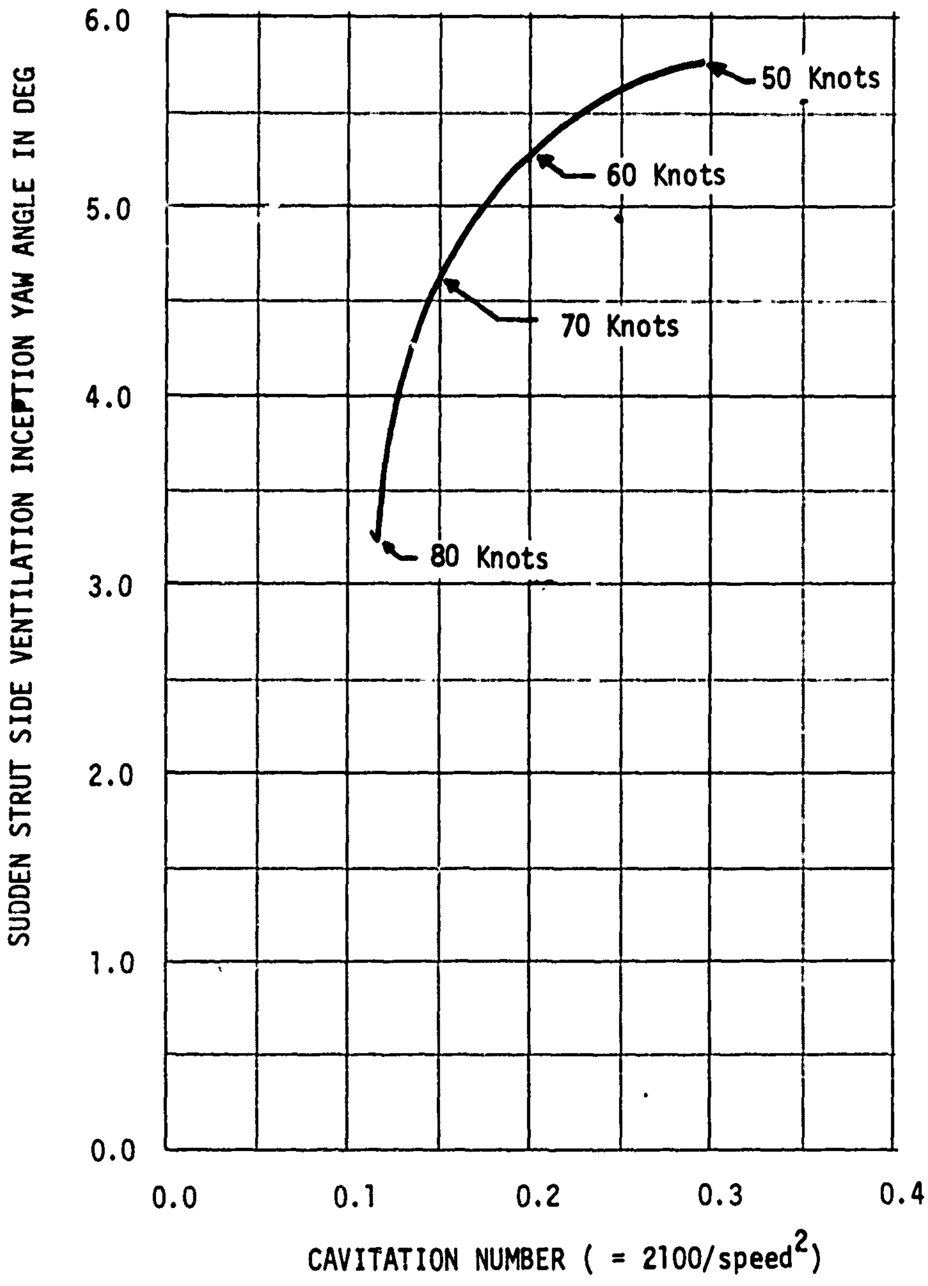


Figure 6 - Sudden Strut Side Ventilation Inception Yaw Angle as a Function of Cavitation Number for a Strut Depth-to-Chord Ratio Equal to One

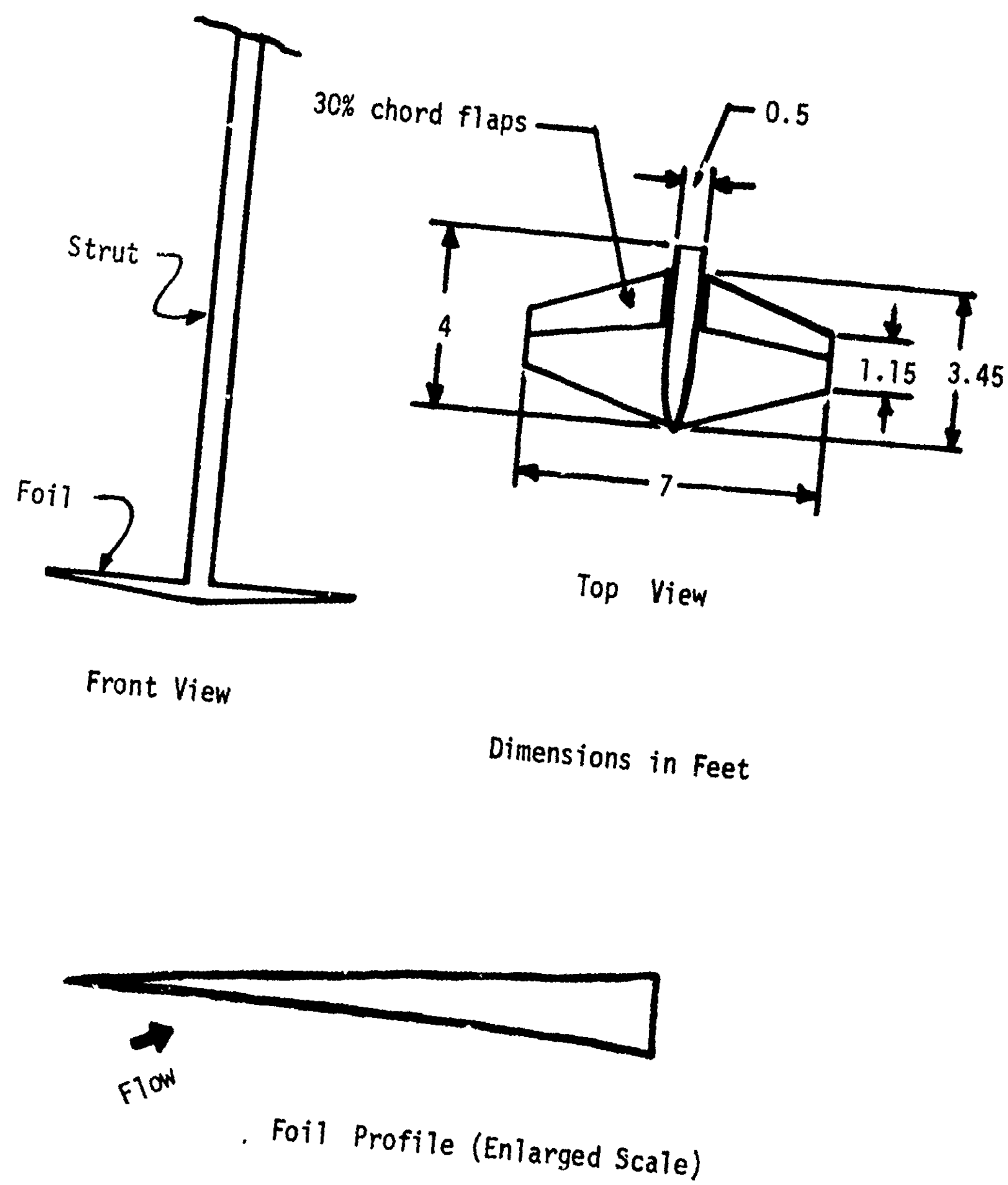


Figure 7 - The Strut/Foil Structure

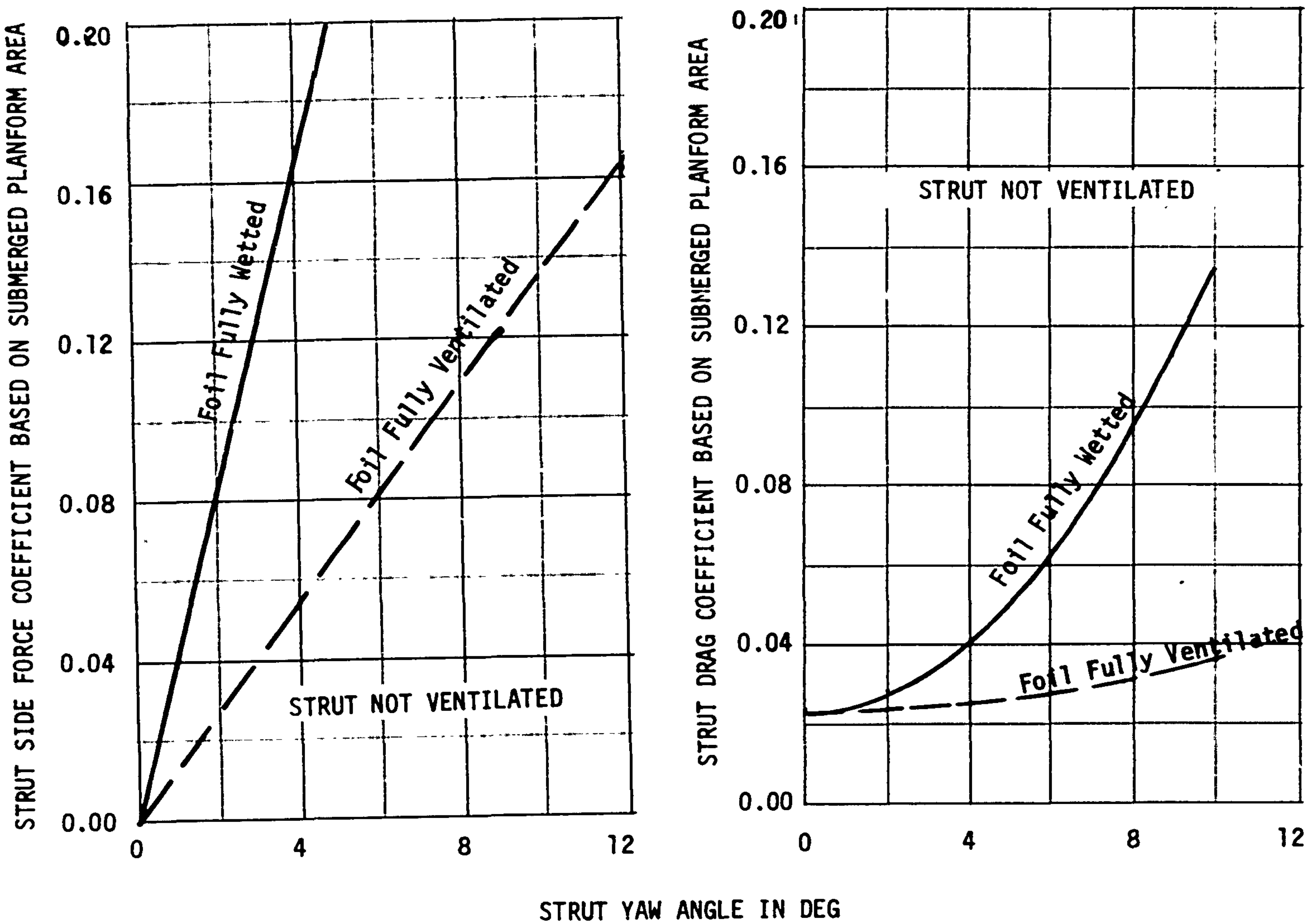


Figure 8 - Fully-Wetted Strut Side Force and Drag Coefficients as Functions of the Strut Yaw Angle for a Speed of 80 Knots and a Strut Submergence of One Strut Chord Length

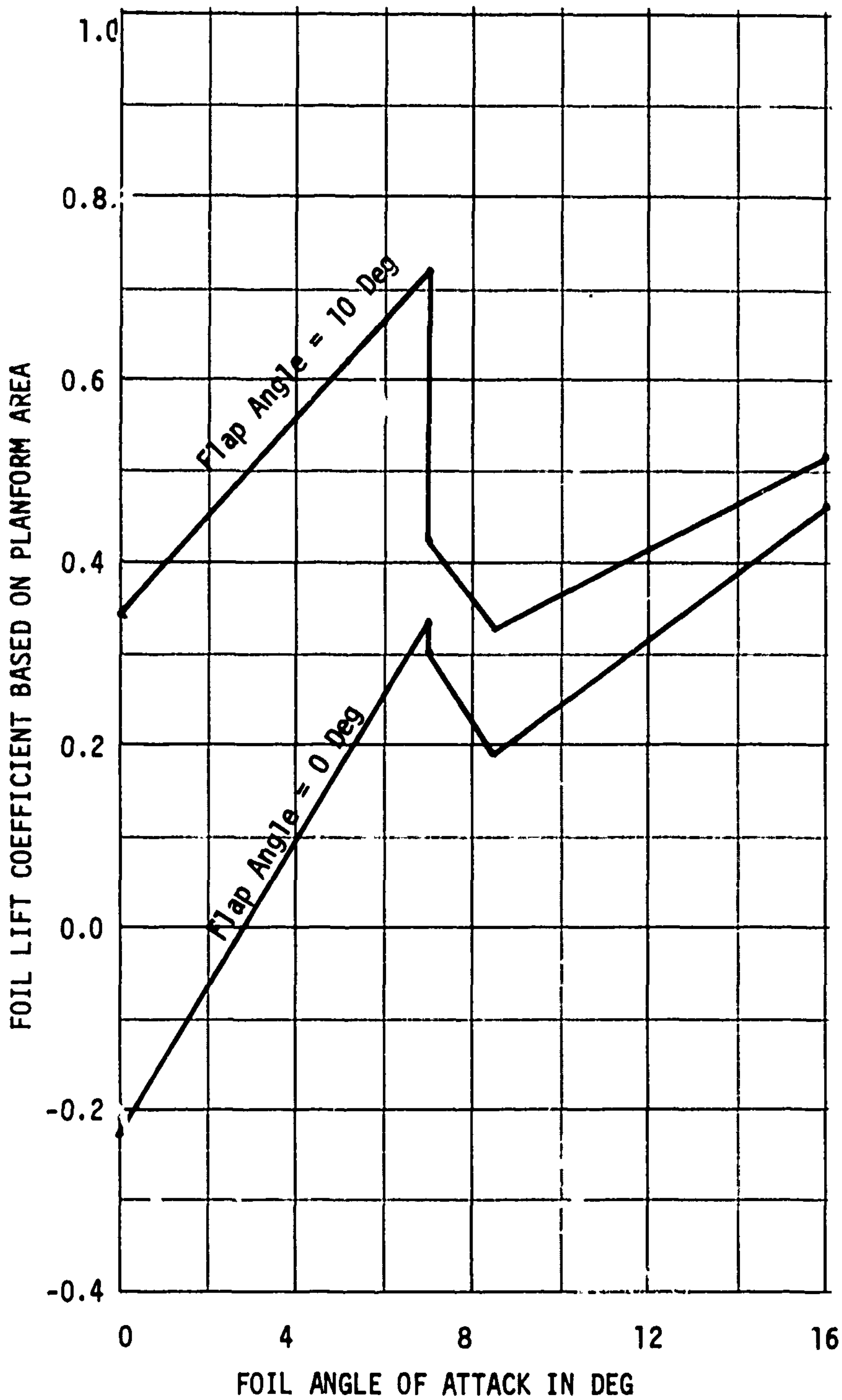


Figure 9 - Foil Lift Coefficient as a Function of Foil Angle of Attack for a Speed of 80 Knots

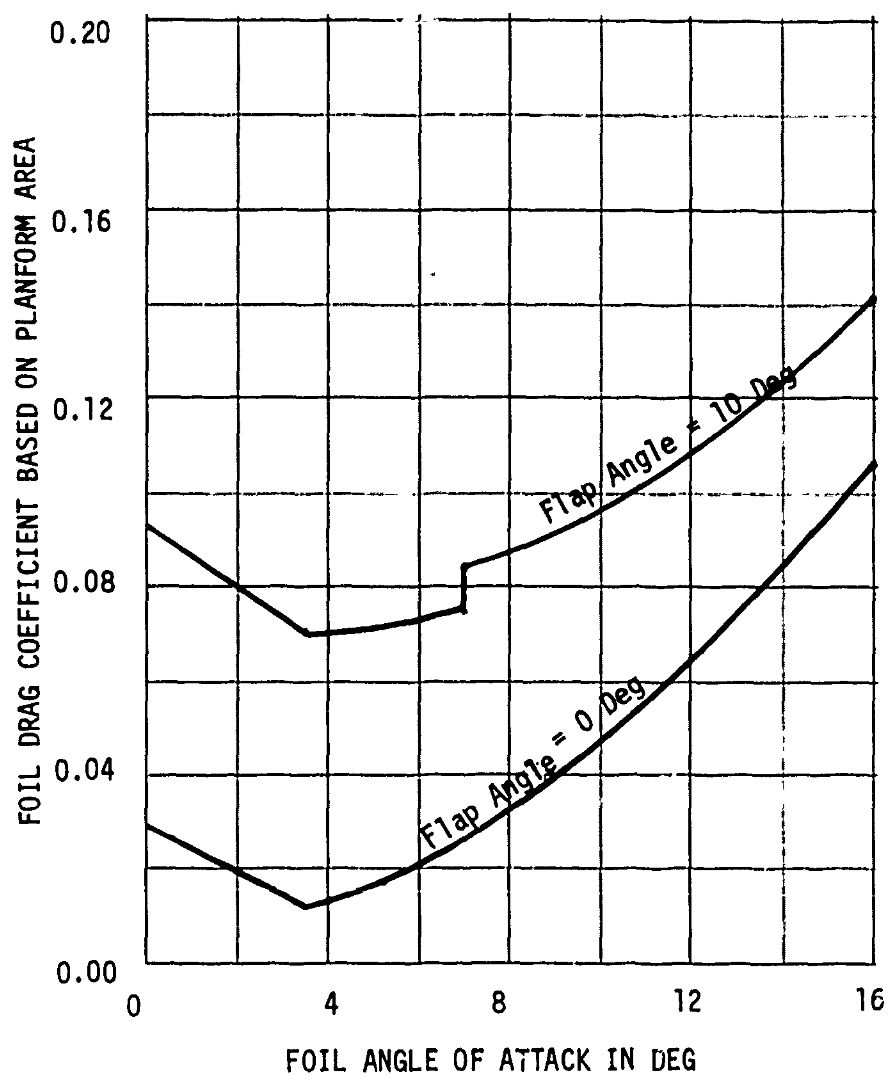


Figure 10 - Foil Drag Coefficient as a Function of Foil Angle of Attack for a Speed of 80 Knots

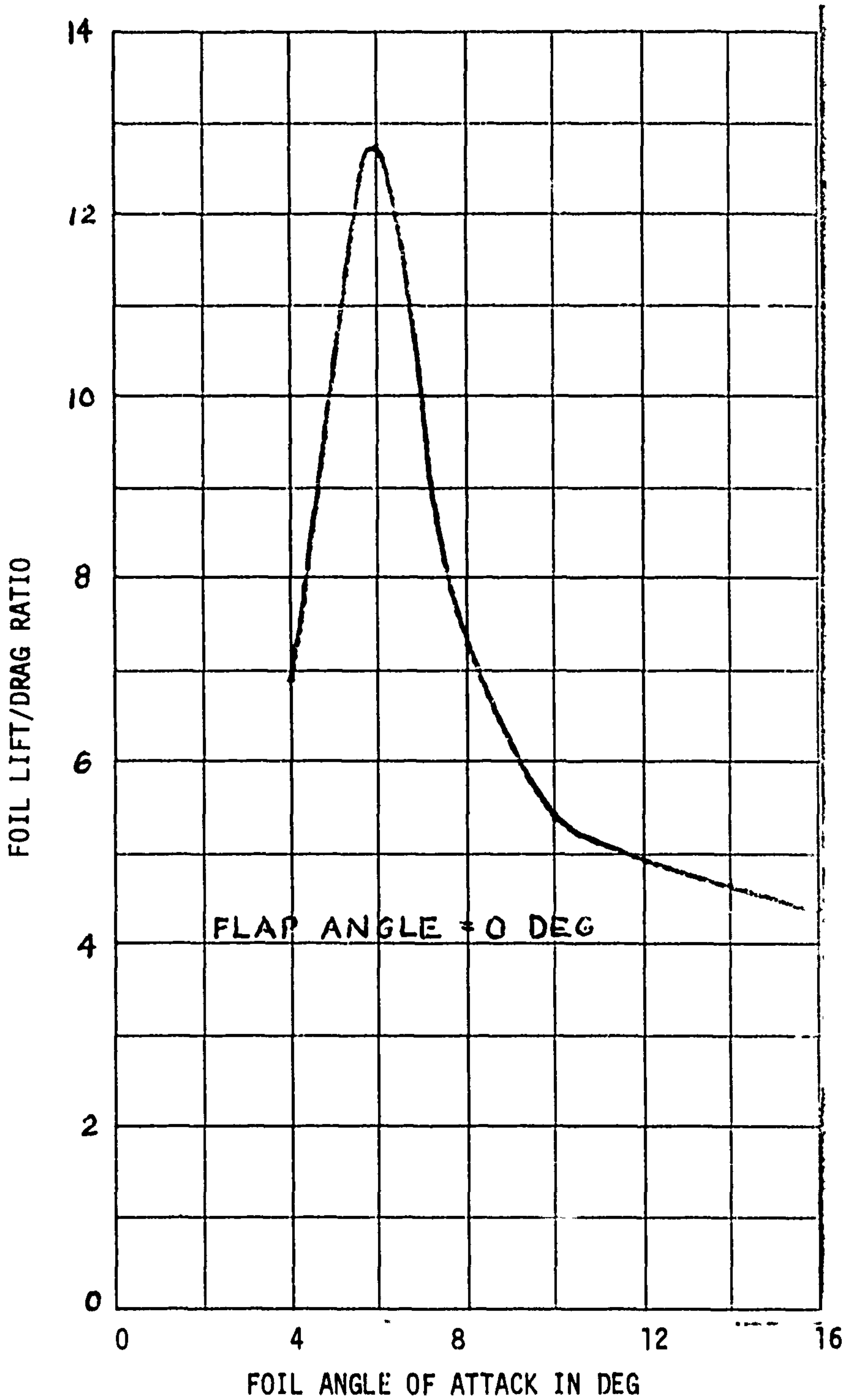


Figure 11 - Foil Lift/Drag Ratio as a Function of Foil Angle of Attack for a Speed of 80 Knots

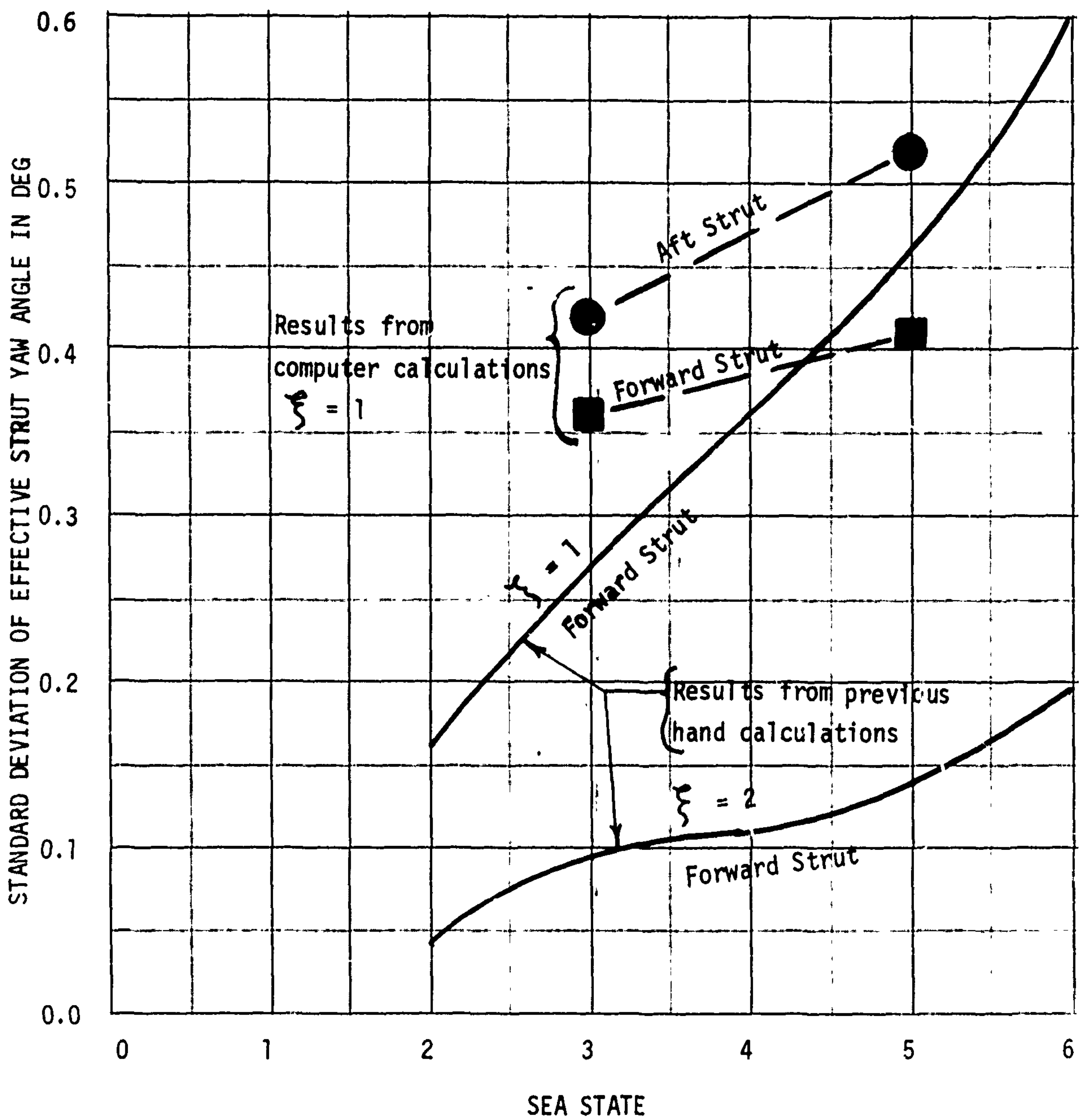


Figure 12 - Comparison of Computer Calculated and Previous Hand Calculated Standard Deviation of Effective Strut Yaw Angle in a Beam Sea for a Speed of 80 Knots for Various Sea States

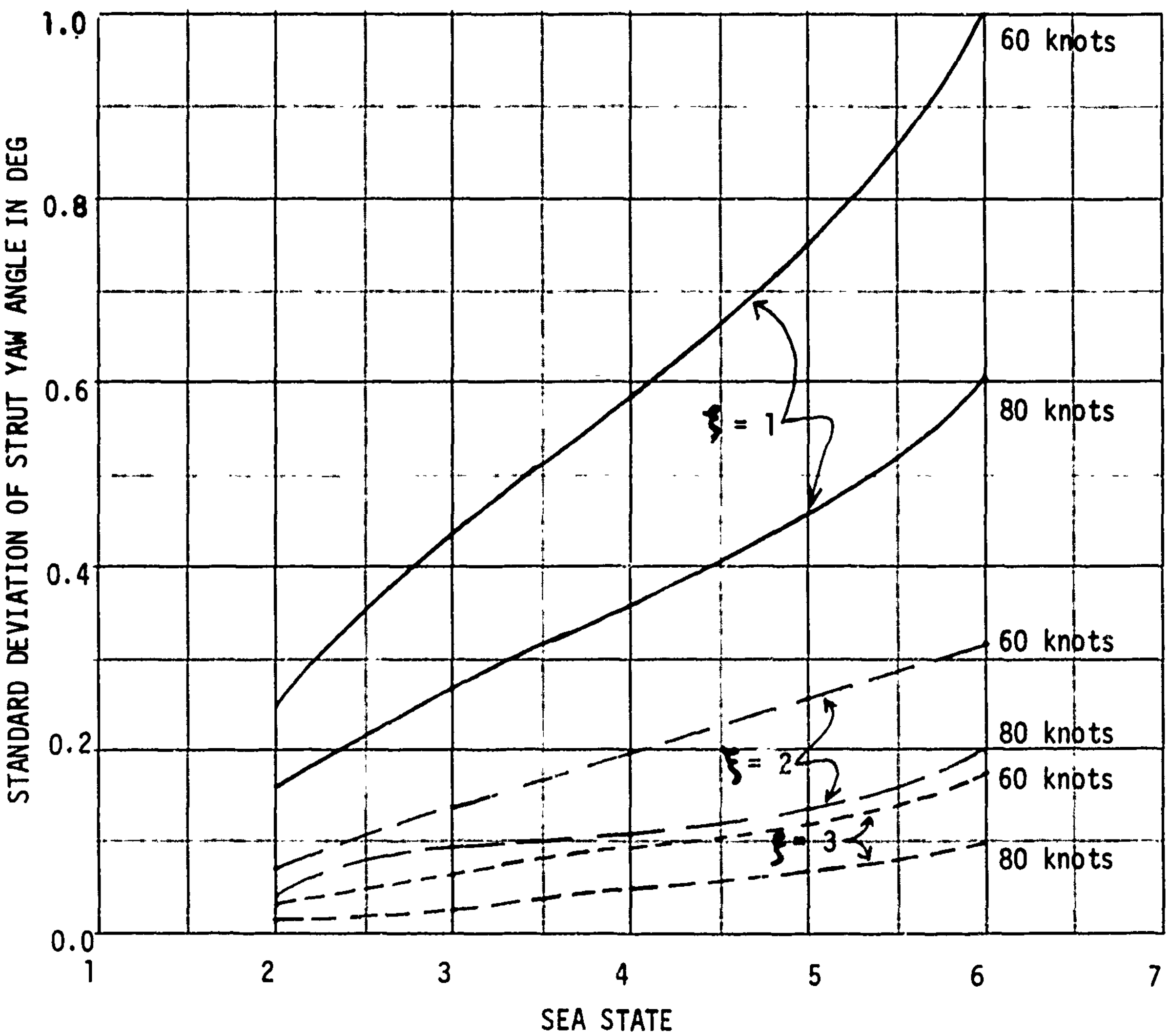


Figure 13 - Standard Deviation of Strut Yaw Angle as a Function of Sea State for Several Values for Strut Depth-to-Chord Ratio ξ

Figure 14 - Strut Yaw Angle and Craft Roll Angle as Functions of Time for Calm Water Coordinated Turns for Various Turning Commands (HLMCM)

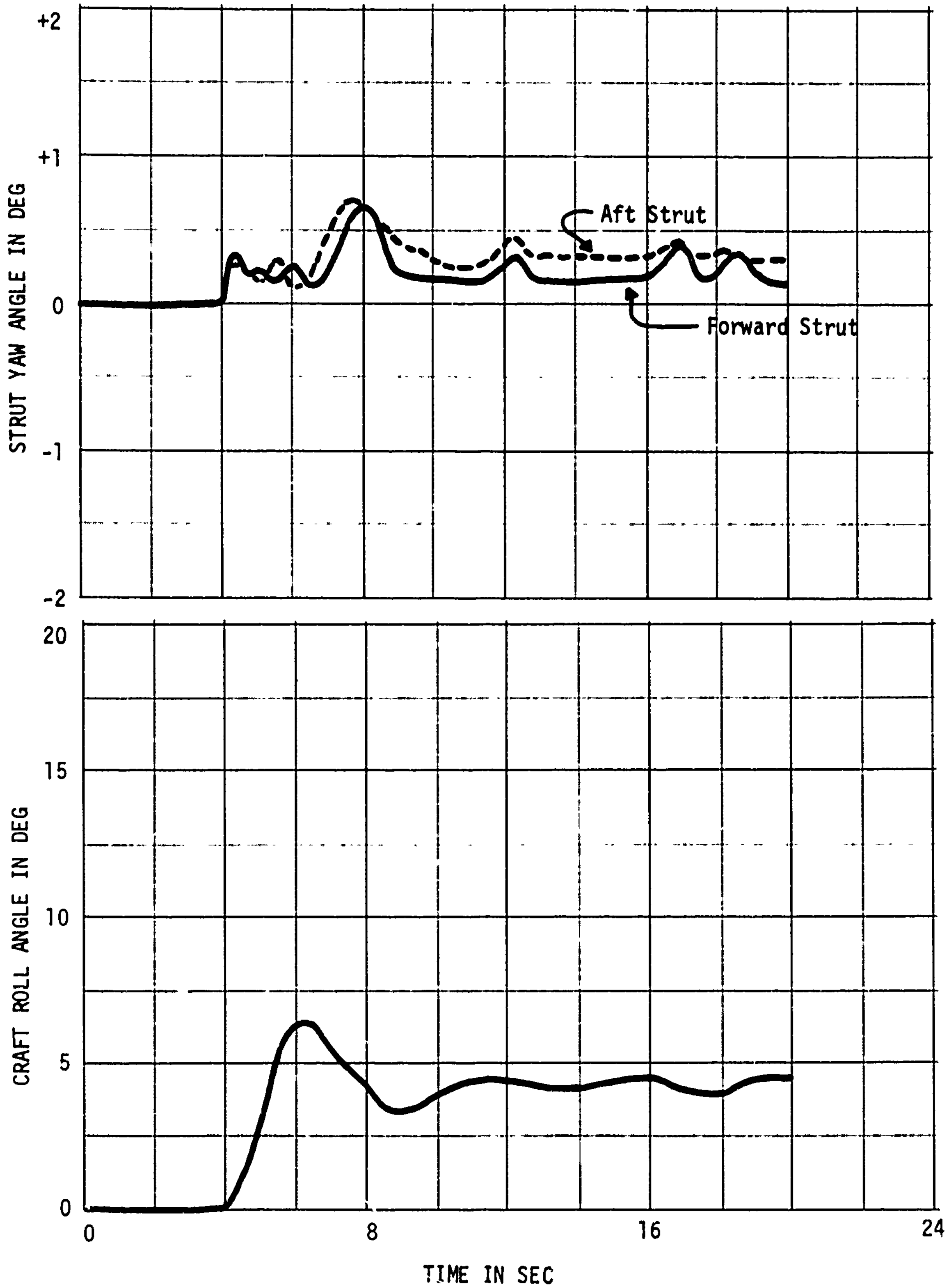


Figure 14(a) - Speed = 80 Knots; Forward Strut Depth-to-Chord Ratio = 2.1; HLMCM = 5

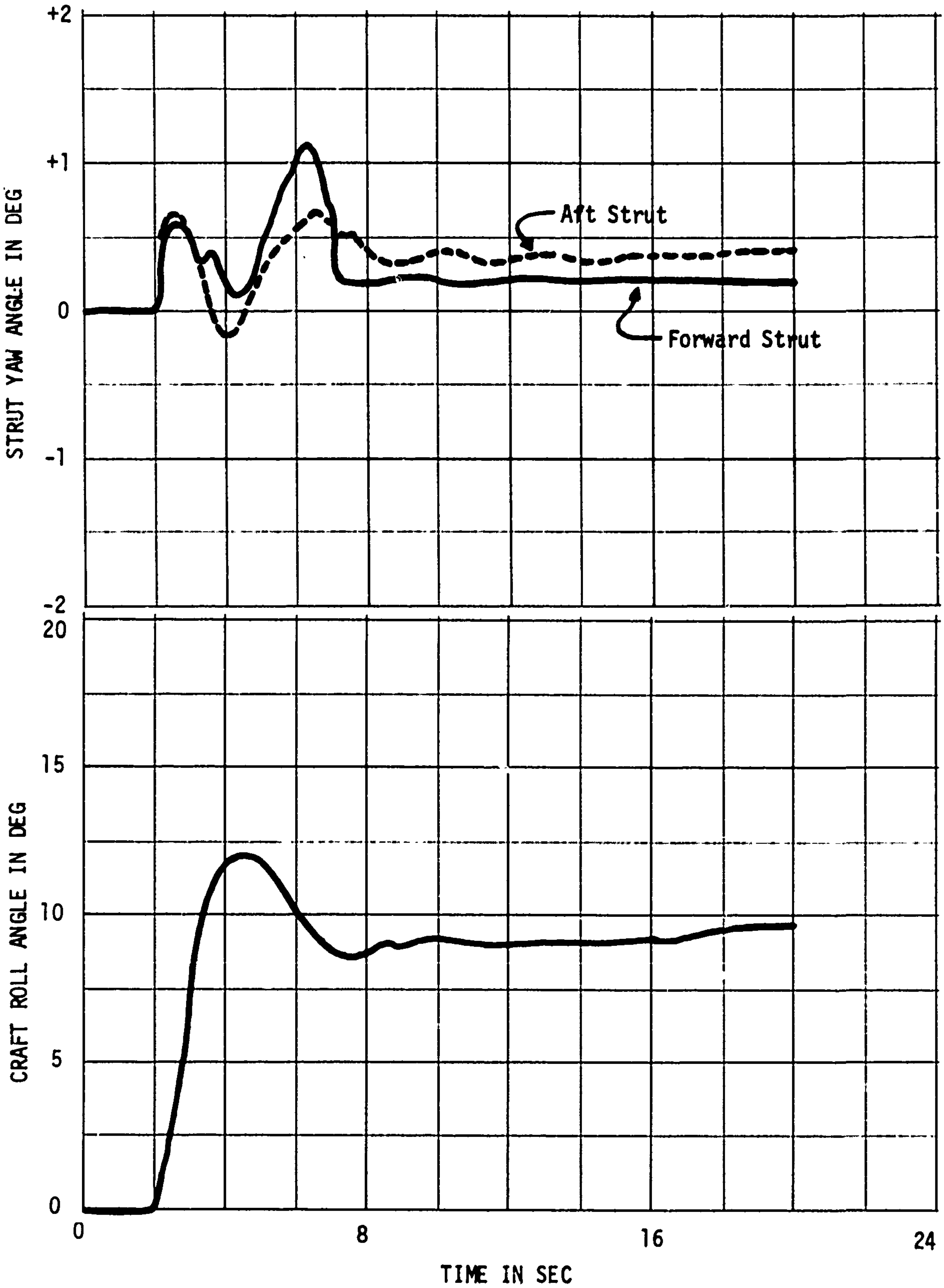


Figure 14(b) - Speed = 80 Knots; Forward Strut Depth-to-Chord Ratio = 2.1; HLMCM = 10

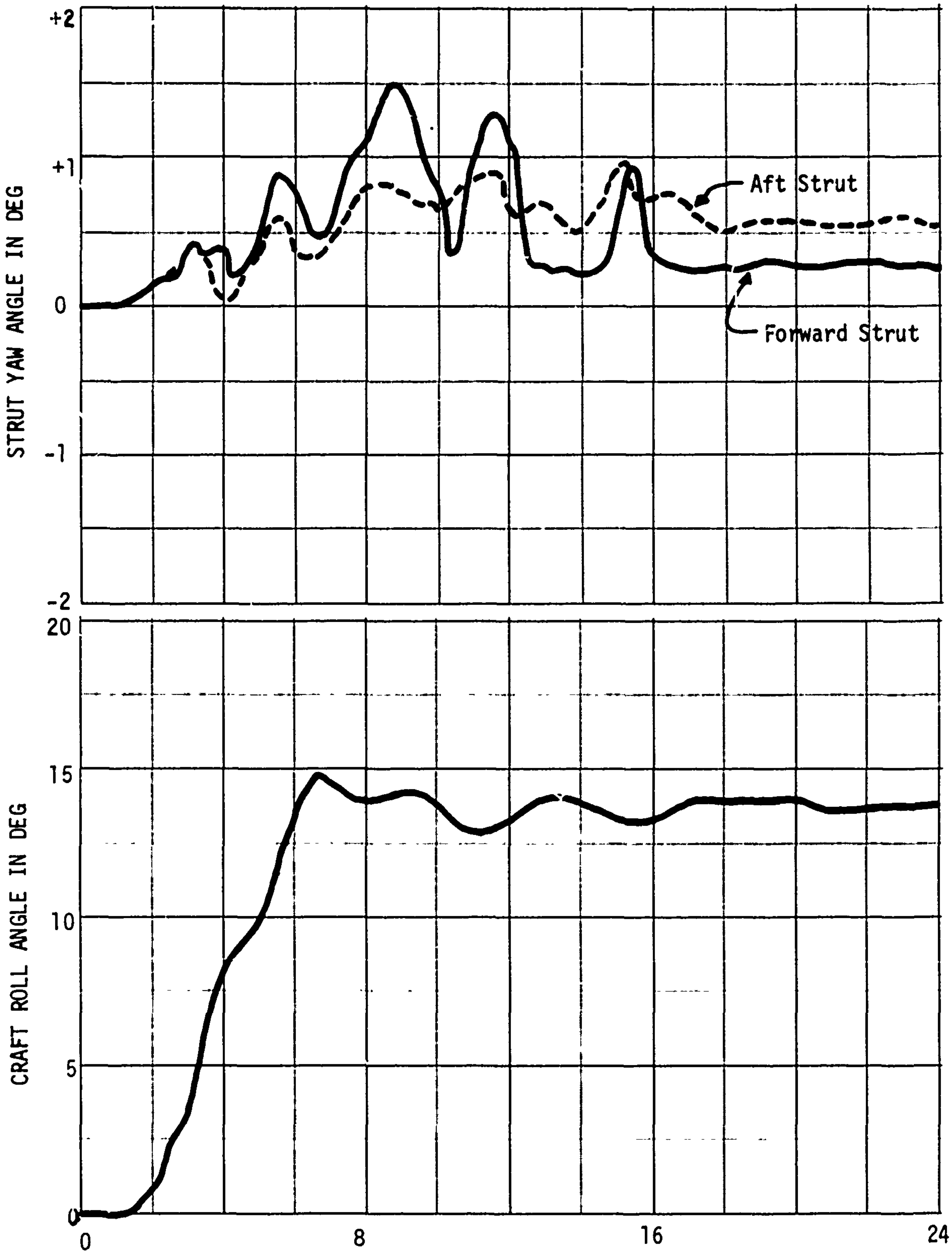


Figure 14(c) - Speed = 80 Knots; Forward Strut Depth-to-Chord Ratio = 2.1; HLMCM = 15

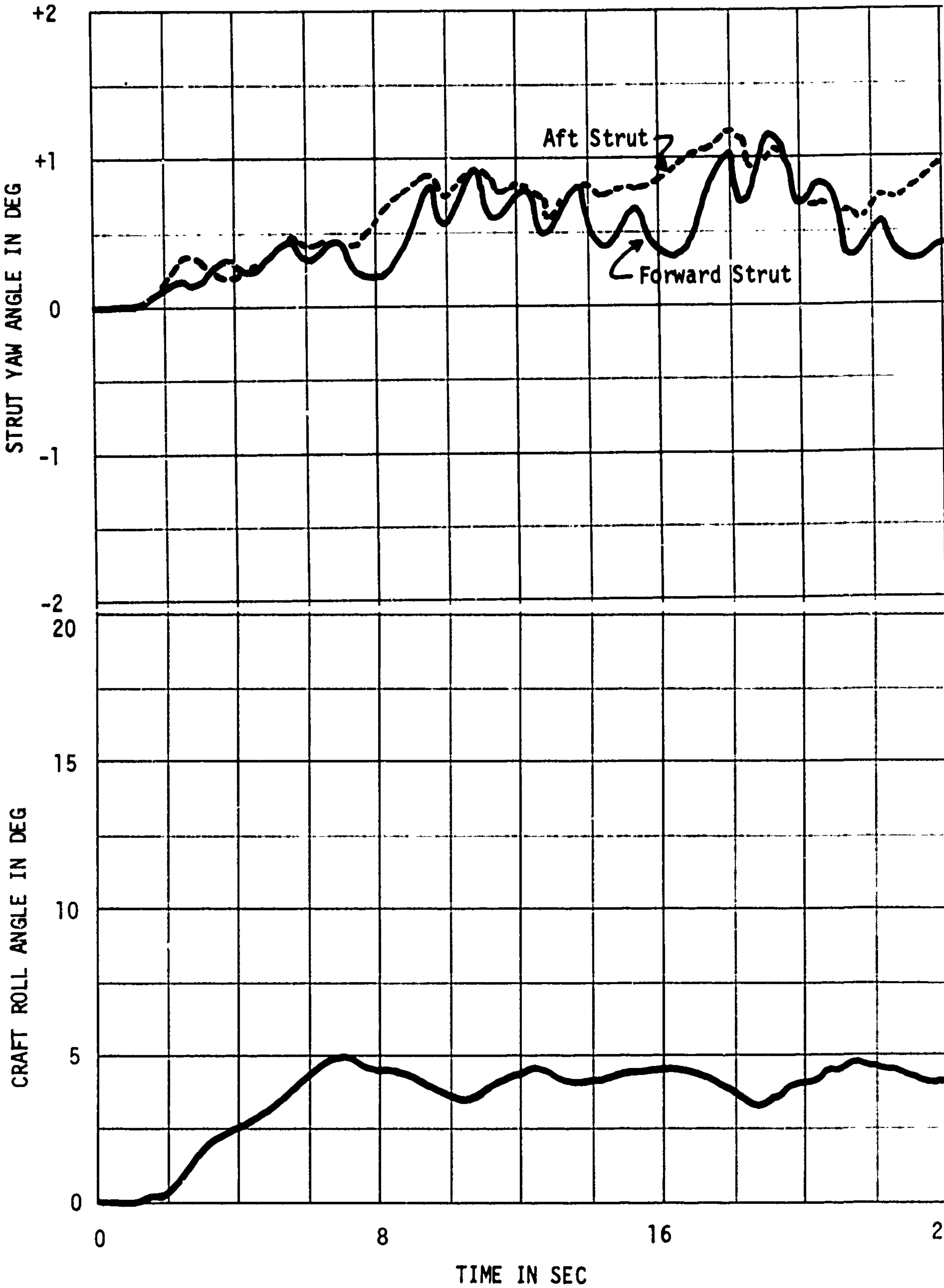


Figure 14(d) - Speed = 80 Knots; Forward Strut Depth-to-Chord Ratio = 1.1; HLMCM = 5

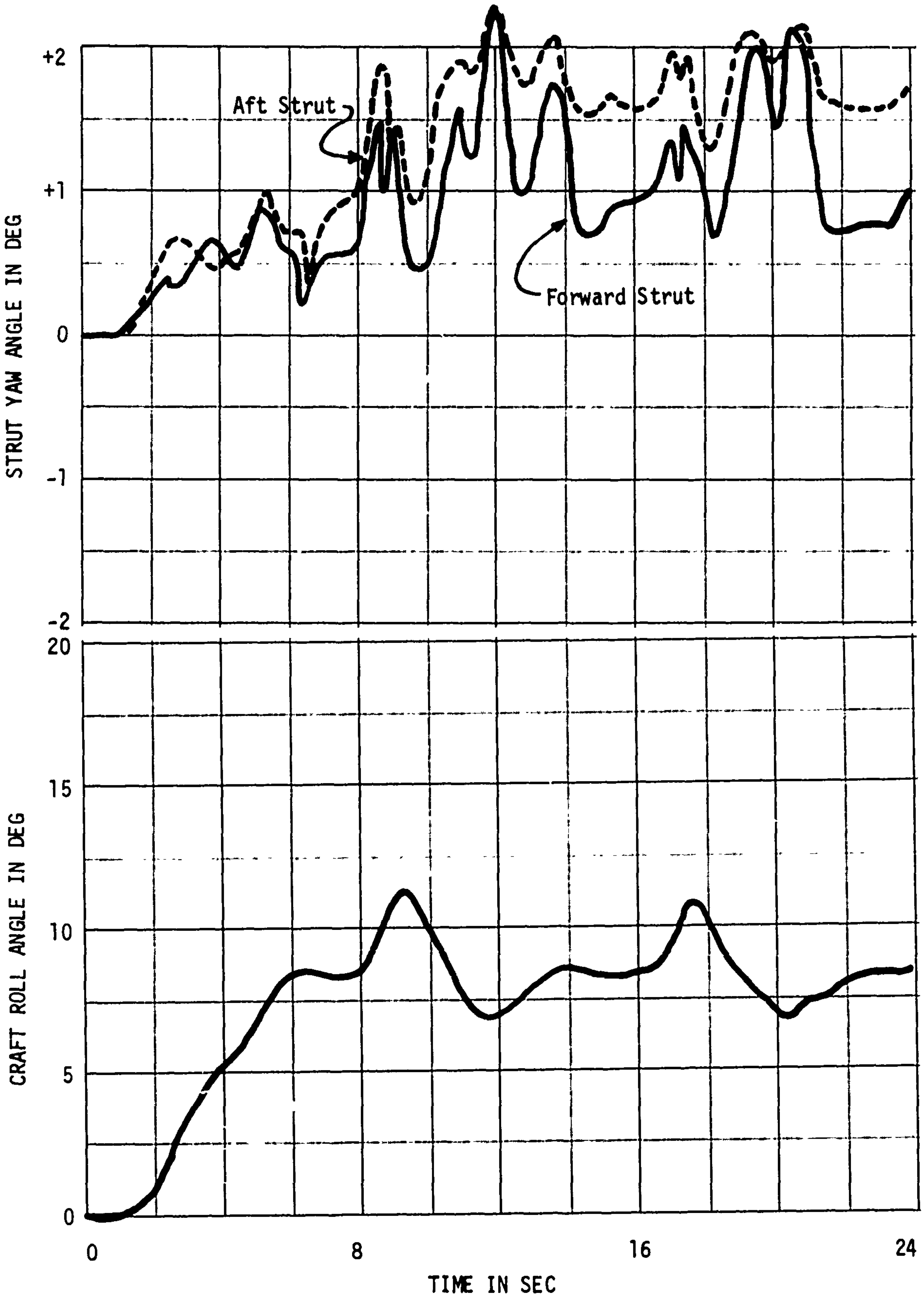


Figure 14(e) - Speed = 80 Knots; Forward Strut Depth-to-Chord Ratio = 1.1; HLMCM = 10

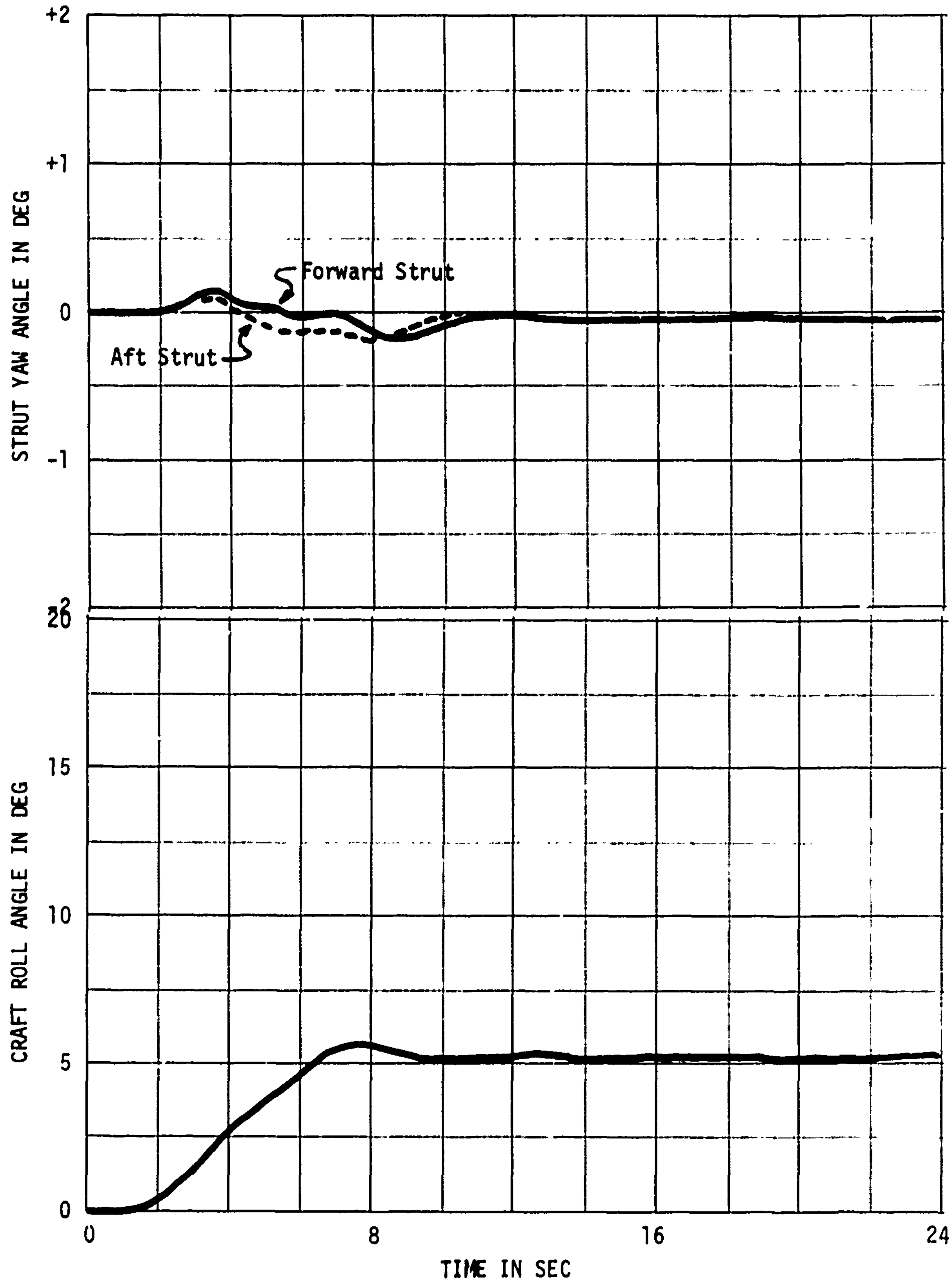


Figure 14(f) - Speed = 60 Knots; Forward Strut Depth-to-Chord Ratio = 2.1; HLMCM = 5

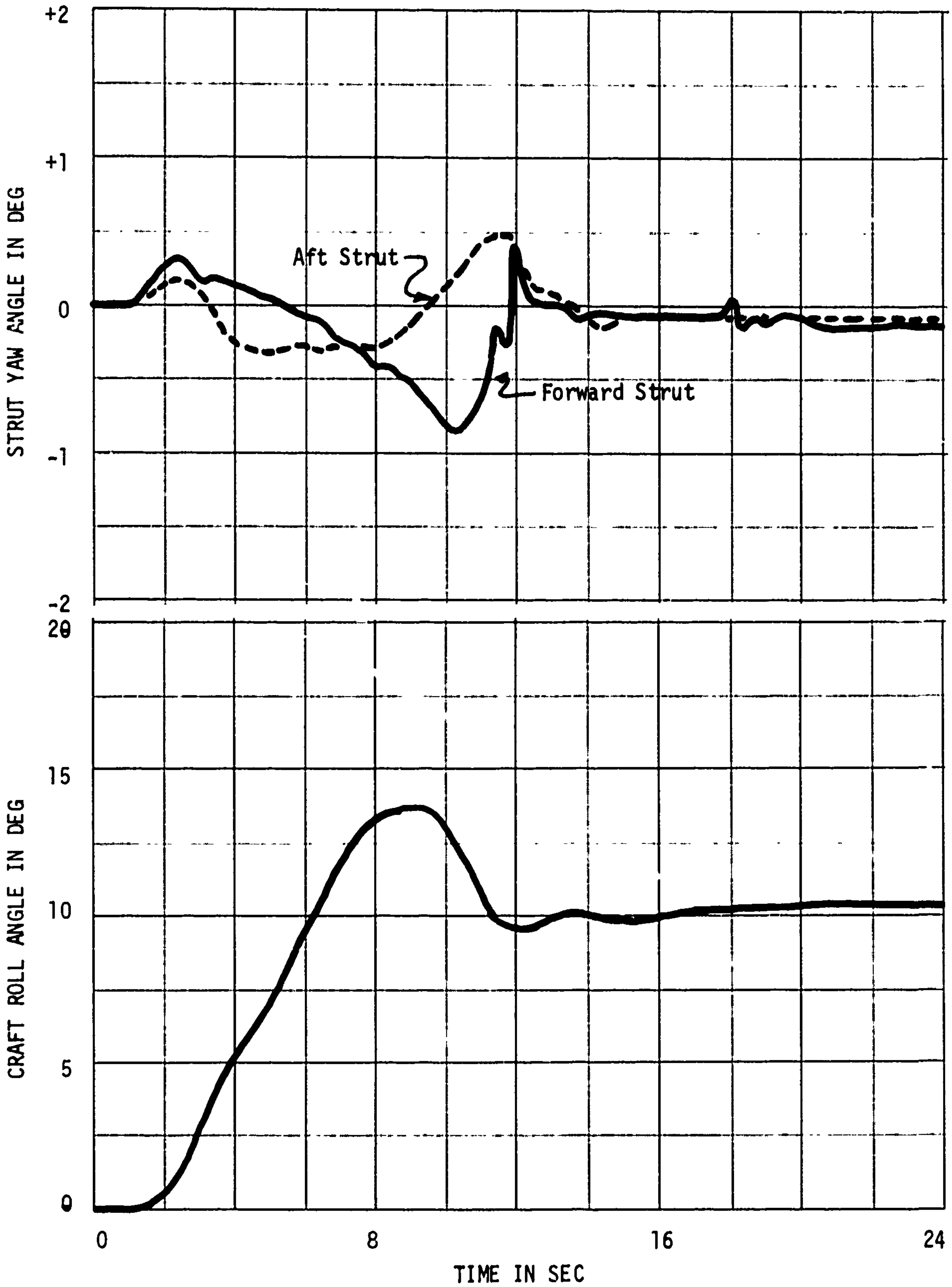


Figure 14(g) - Speed = 60 Knots; Forward Strut Depth-to-Chord Ratio = 2.1; HLMCM = 10

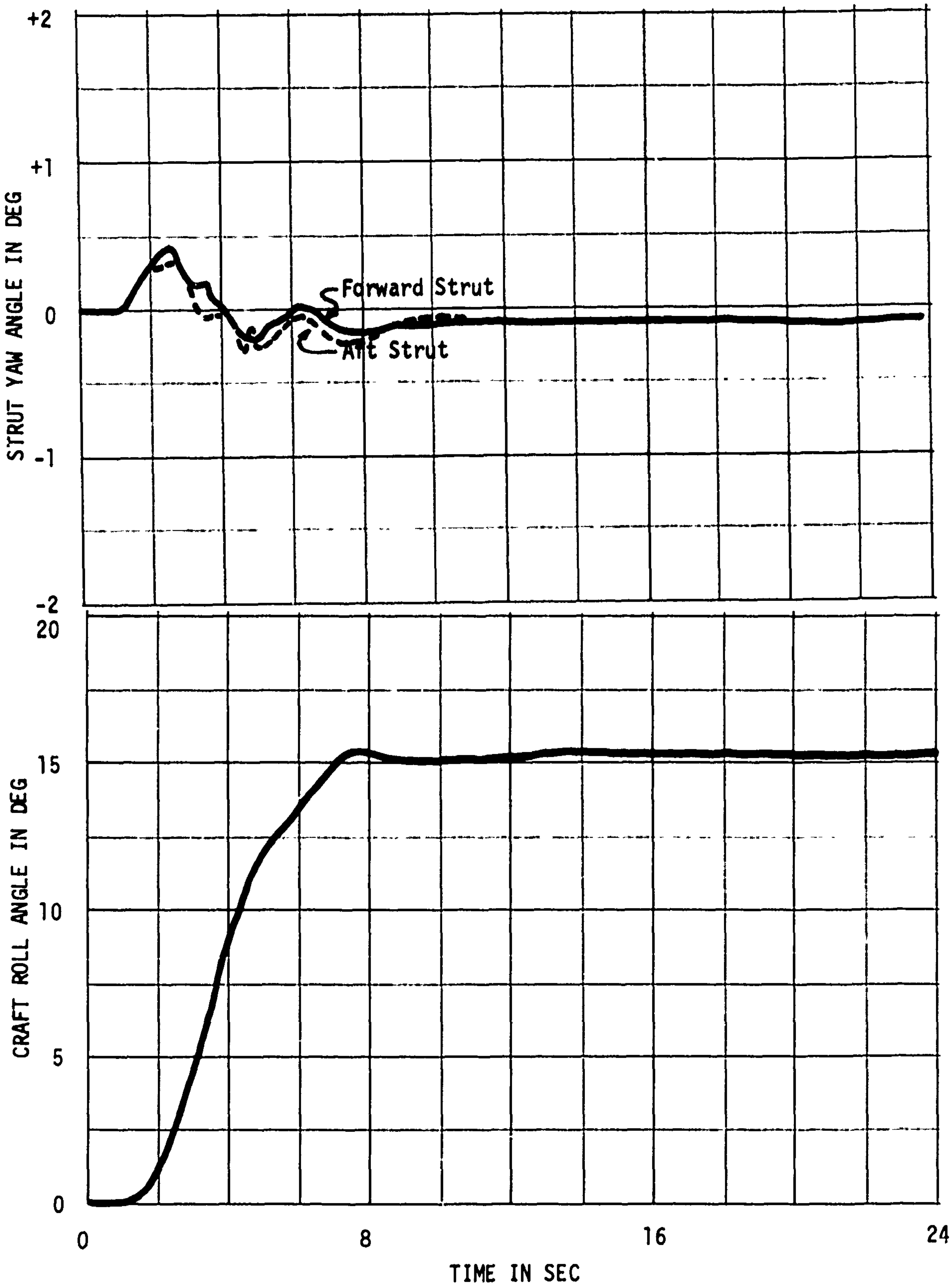


Figure 14(h) - Speed = 60 Knots; Forward Strut Depth-to-Chord Ratio = 2.1; HLMCM = 15

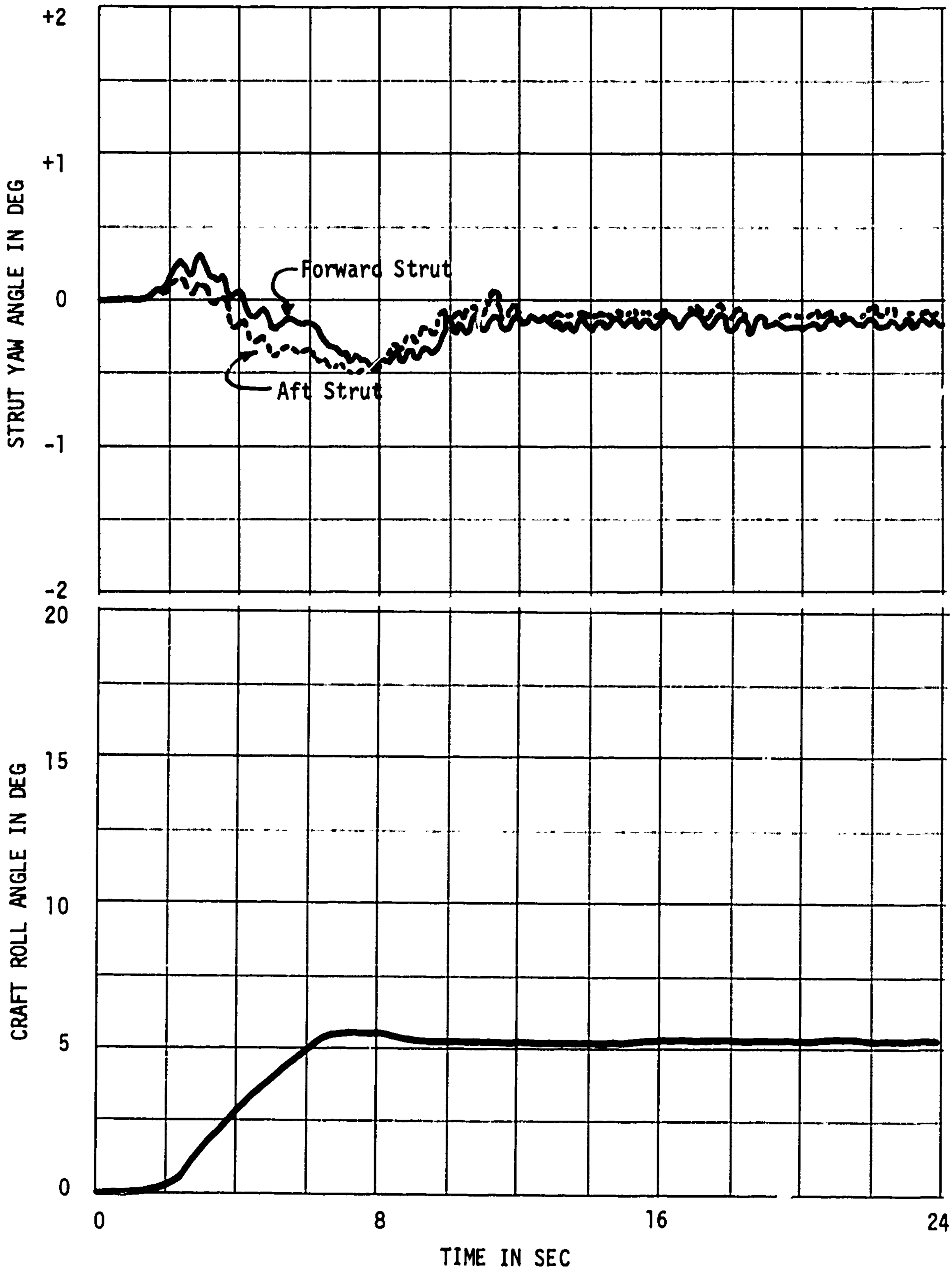


Figure 14(i) - Speed = 60 Knots; Forward Strut Depth-to-Chord Ratio = 1.3; HLMCM = 5

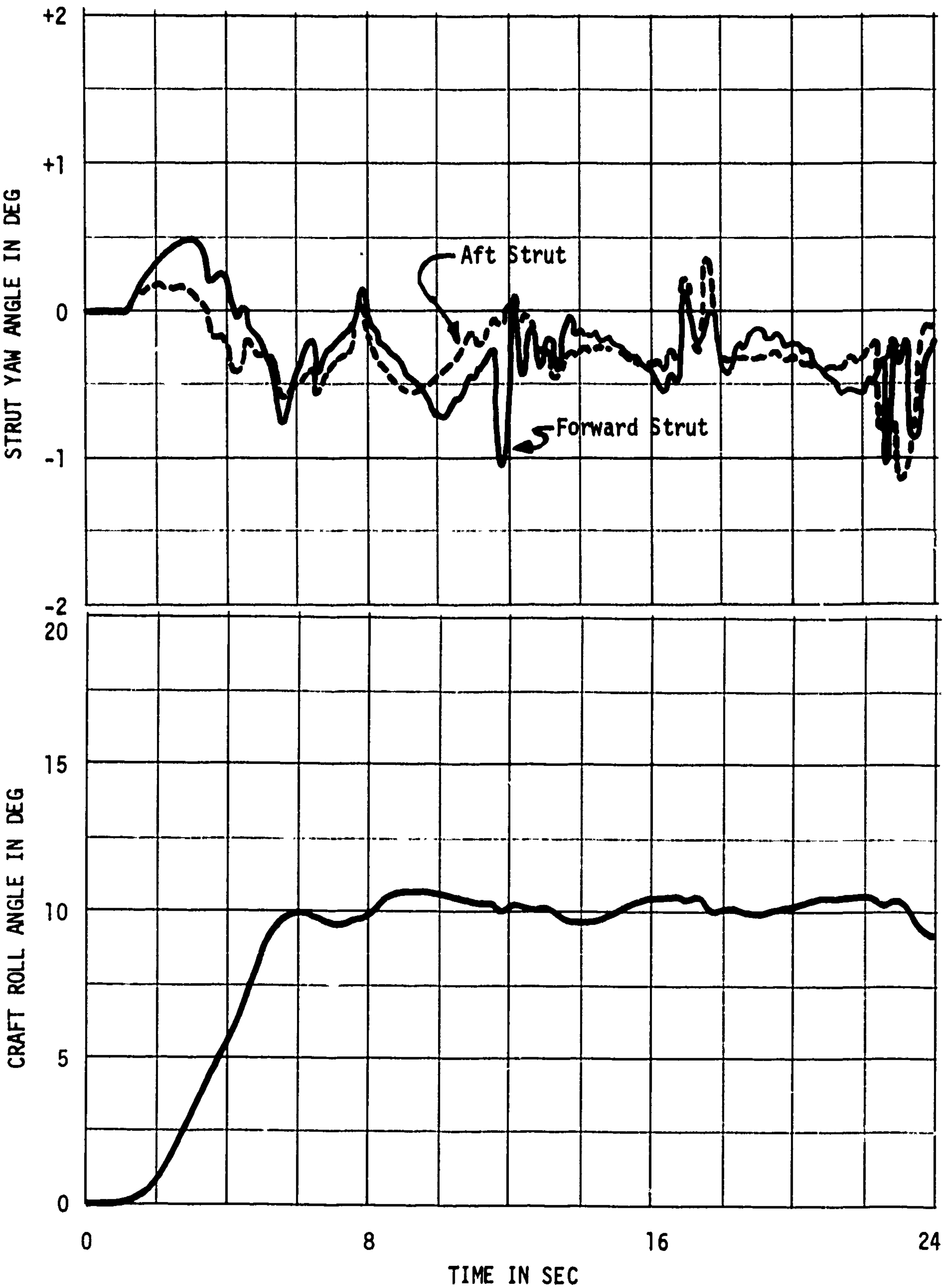


Figure 14(j) - Speed = 60 Knots; Forward Strut Depth-to-Chord Ratio = 1.3; HLMCM = 10

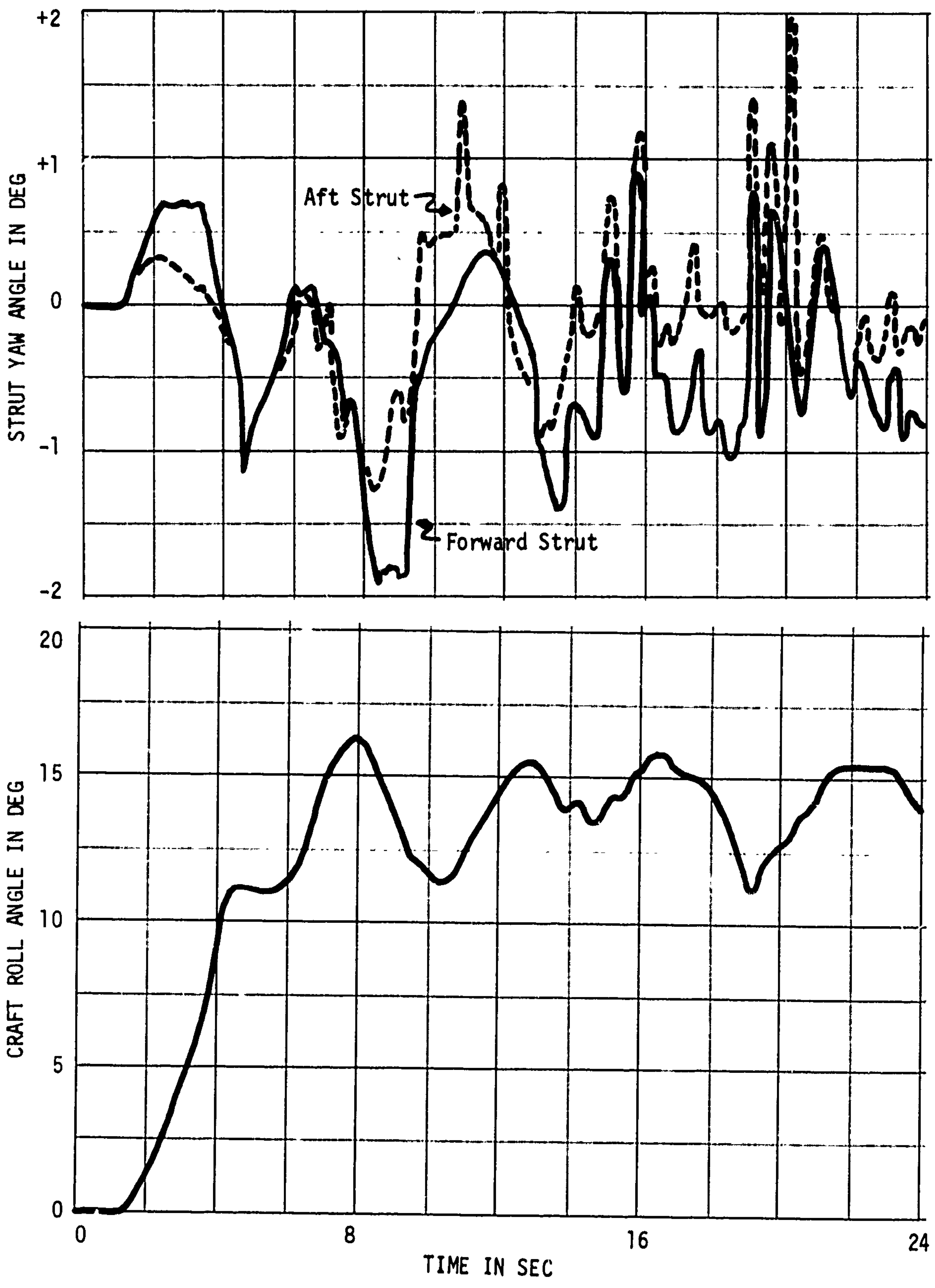


Figure 14(k) - Speed = 60 Knots; Forward Strut Depth-to-Chord Ratio = 1.3; HLMCM = 15

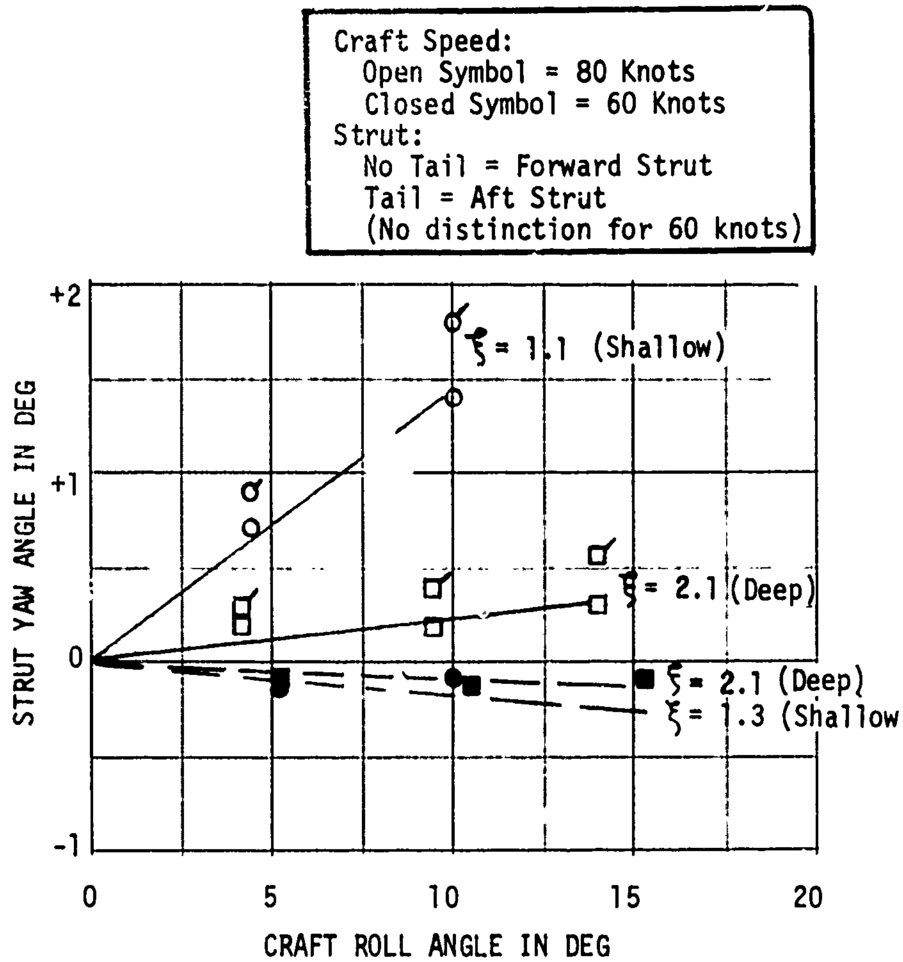


Figure 15 - Average Strut Yaw Angle for the Steady Coordinated Turn in Calm Water as a Function of the Craft Roll Angle

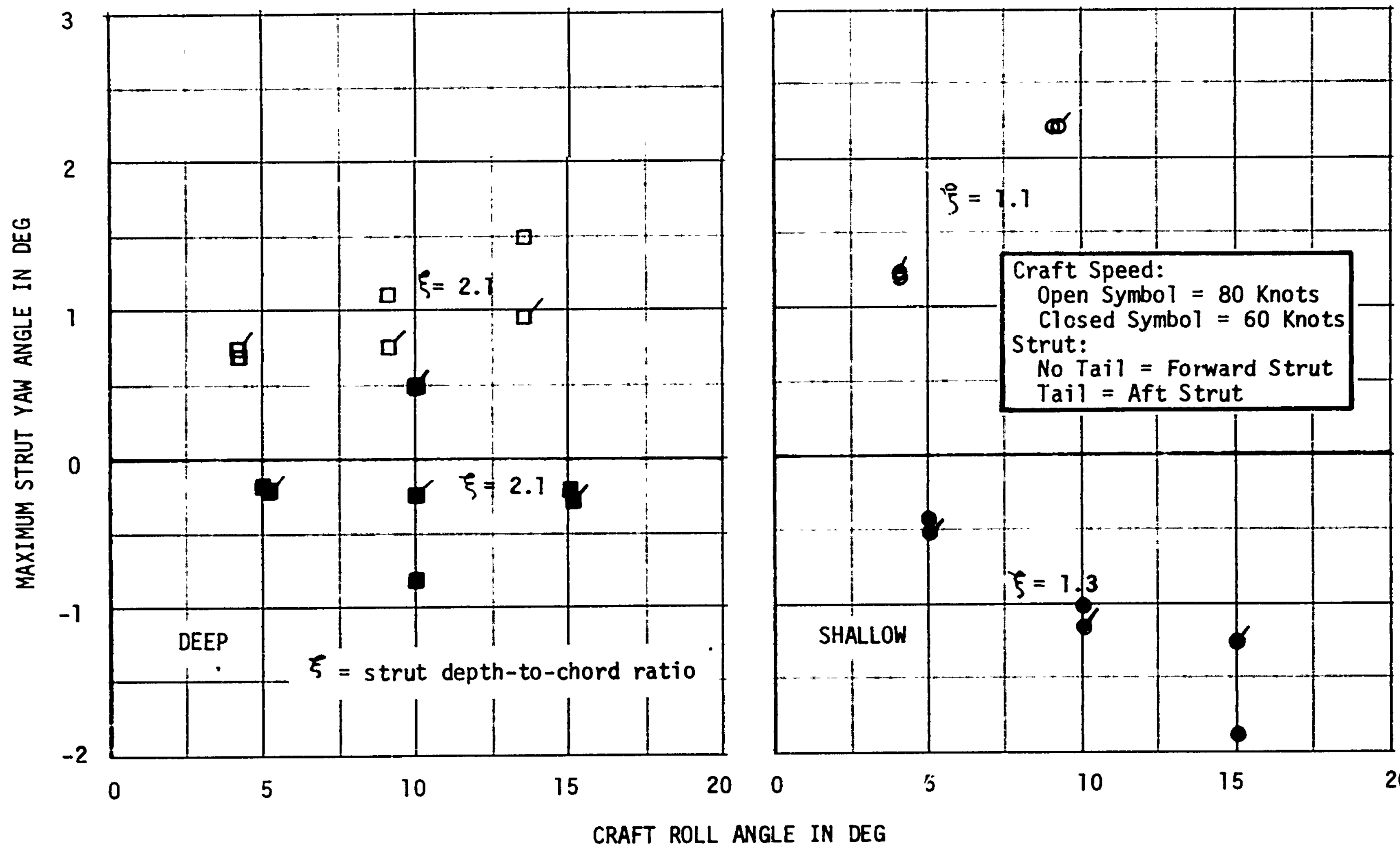


Figure 16 - Maximum Strut Yaw Angle for the Steady Coordinated Turn in Calm Water as a Function of the Craft Roll Angle

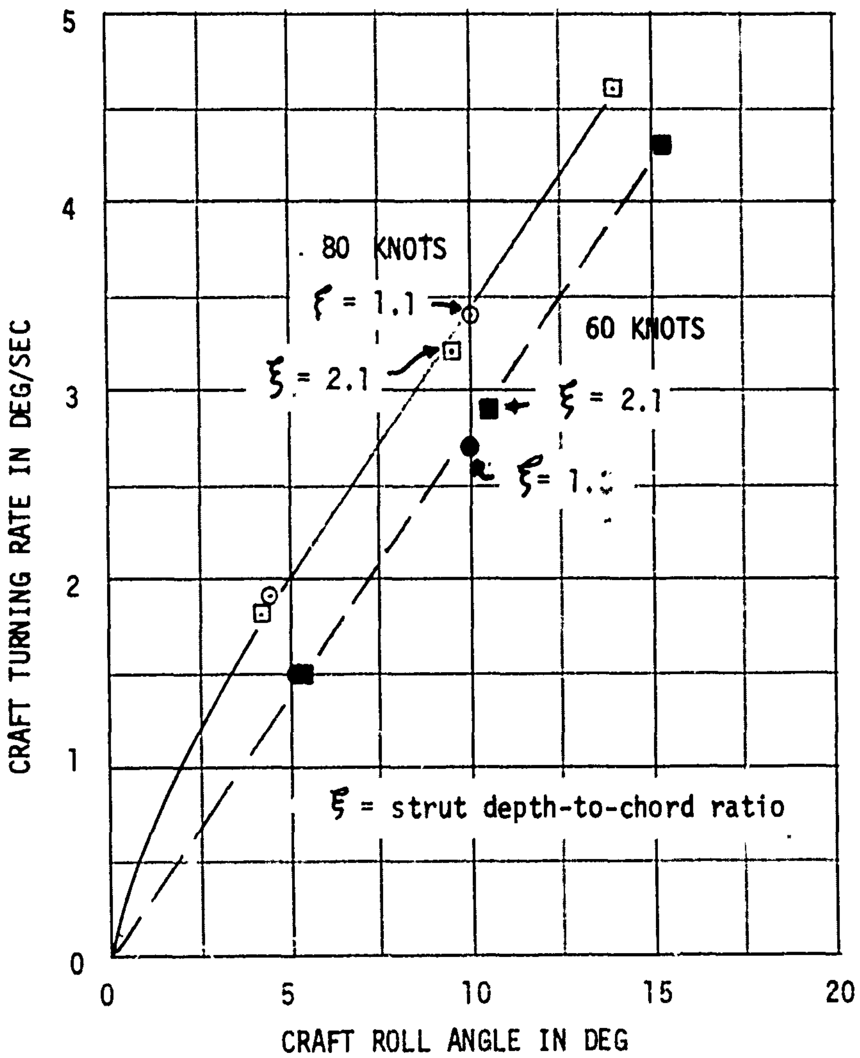


Figure 17 - Craft Turning Rate for the Steady Coordinated Turn in Calm Water as a Function of the Craft Roll Angle

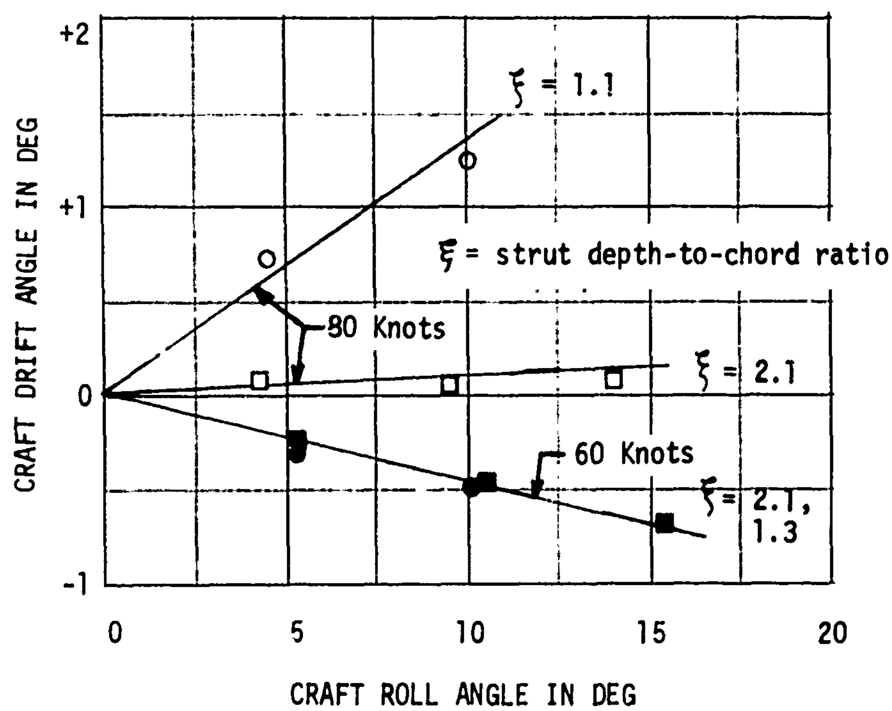


Figure 18 - Craft Drift Angle for the Steady Coordinated Turn in Calm Water as a Function of the Craft Roll Angle