She Turned Two Points In 37 Seconds

By Samuel Halpern

INTRODUCTION

During the British Inquiry into the loss of the SS *Titanic*, Edward Wilding, naval architect from the shipbuilding firm of Harland & Wolff, presented data on the turning characteristics of the sister ships *Olympic* and *Titanic*. As he put it before the commission,[1]

> "There is a little more information that I think the Court wishes to have. Since the accident, we have tried the *Olympic* to see how long it took her to turn two points, which was referred to in some of the early evidence. She was running at about 74 revolutions, that corresponds to about 21-½ knots, and from the time the order was given to put the helm hard over till the vessel had turned two points was 37 seconds…The distance run by log was given to me as two-tenths of a knot, but I think it would be slightly more than that - about 1,200 or 1,300 feet."

In addition, Wilding presented results of some of the turning tests conducted off Belfast Lough during *Titanic's* sea trials. It included results of turning circles made with the ship steaming at 11 knots, 19.5 knots, and 21.75 knots with the engines kept at the same speed ahead and the helm put hard-astarboard (left full rudder) while the ship turned to port.[2] He also presented results with the helm put hard-aport (right full rudder) and the ship turning to starboard with the starboard engine reversed to full speed astern. This was done at a speed between 18 and 20 knots.[3]

It is unfortunate that we don't have these results available to us today, but surprisingly, we can derive the turning characteristics of *Titanic* at full ahead speed under hard-astarboard helm from other data that we do have available to us.

Under examination by Mr. Hill on day 3 of the Ryan vs. Oceanic Steam Navigation Company trial in June 1913, it was reported that Wilding testified that trials of the *Olympic* found that the ship traveled about 440 yards forward and 100 yards laterally in turning two points.[4] It should be pointed out that a 100 yard lateral movement does not seem to be accurate for a heading change

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[1] British Inquiry, 25292-25293.

[2] Helm orders in those days were given in terms of helm or tiller movement, not rudder deflection. When the helm, which is connected to the rudder post, is put over to starboard, the rudder will move over to port causing the ship's head to turn to port. To put the helm over to starboard, the wheel is turned counter clockwise, or to the left. Today the order would be given as "left full rudder."

[3] British Inquiry, 25291.

[4] Prècis Law Report, "Ryan Vs. Oceanic Steam Navigation Company (Limited)," Friday June 20, 1913, transcribed and submitted by Senan Molony, *Encyclopedia Titanica Research Paper*, March 15, 2004.

of only 22.5°. He may have meant to say about 100 feet which, as we shall see later, is more in keeping with a heading change of just two points.

Wilding presented testimony at the Limitation of Liability Hearings in New York on May 1915. In his deposition he stated that subsequent tests conducted on *Olympic* to determine "the advance and lateral movements would be whilst the ship was turning two points under orders assumed to have been given, or reported to have been given at the time of the accident." With the ship going ahead at about 22 knots when the order for hard-astarboard and full speed astern was given, it was observed that the ship advanced 440 yards when two points (22.5°) was reached in the turn. This part agrees with the information he gave at the Ryan trial in 1913 as far as the forward movement is concerned. He was also asked at the Limitation of Liability Hearings about tests conducted on the *Titanic* during her trials in Belfast Lough when running at full speed. In his deposition he said:[5]

> "Running straight with the helm put hard over she turned in a complete circle; and the distance across the circle from the original course was between 4 and 4-½ lengths of the vessel [3,400 to 3,825 ft], in diameter; that is, the tactical diameter...She traveled forward about 2-½ lengths…about 2100 feet, or thereabouts; 700 yards."

He was also asked to explain further the diameter of the turning circle to which he said that her lateral movement was "under 4,000 feet; just under; between 3800 and 3900."

It should be pointed out that his responses at the Limitation of Liability Hearings and at the Ryan trial was mostly from memory, and some of these numbers may not be very precise. But what can be learn from this information is the following:

When running ahead at 21.5 knots, it took about 37 seconds for the ship to turn two points (22.5°) to port from the time the order for hard-astarboard helm was given. Also, the observed forward movement of the ship would be about 440 yards (1320 feet). Now 21.5 knots is the same as 36.3 feet per second. In 37 seconds the distance covered would be 1343 feet. If the ship really traveled about 1300 feet in 37 seconds then there would obviously be no time for the reversal of engines to take affect, if indeed such an order was given. Wilding said that the log registered a distance of 0.2 nautical miles, but that he thought it would be slightly more than that, "about 1,200 or 1,300 feet." The 440 yards he gave corresponds to the higher value. The measured log reading, 0.2 nautical miles, is 1216 feet, and corresponds to the lower value he gave. A vessel entering into a turn will start to slow down because of increased hydrodynamic drag on the hull, and the registered distance on the log was probably the correct value for the observed forward movement in 37 seconds as we shall see later.

Since Wilding gave the tactical diameter as "between 3800 and 3900" feet, we will take it to be about 3850 feet in developing a turning model for the ship. The value of 700 yards of forward movement that he gave appears not to be the ship's "Advance," which is defined as the distance between the furthest forward movement of the ship and the location of the ship when the order

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[5] Deposition Of Edward Wilding, "In The Matter Of The Petition Of The Oceanic Stem Navigation Company, For Limitation Of Its Liability, As Owner Of The Steamship *Titanic*," May 13 and 14, 1915.

was first given to put the helm over. Rather, it appears that his 700 yards is the distance between the ship's furthest forward movement and the location of the ship after completing a full 360° turn.

HOW A SHIP TURNS

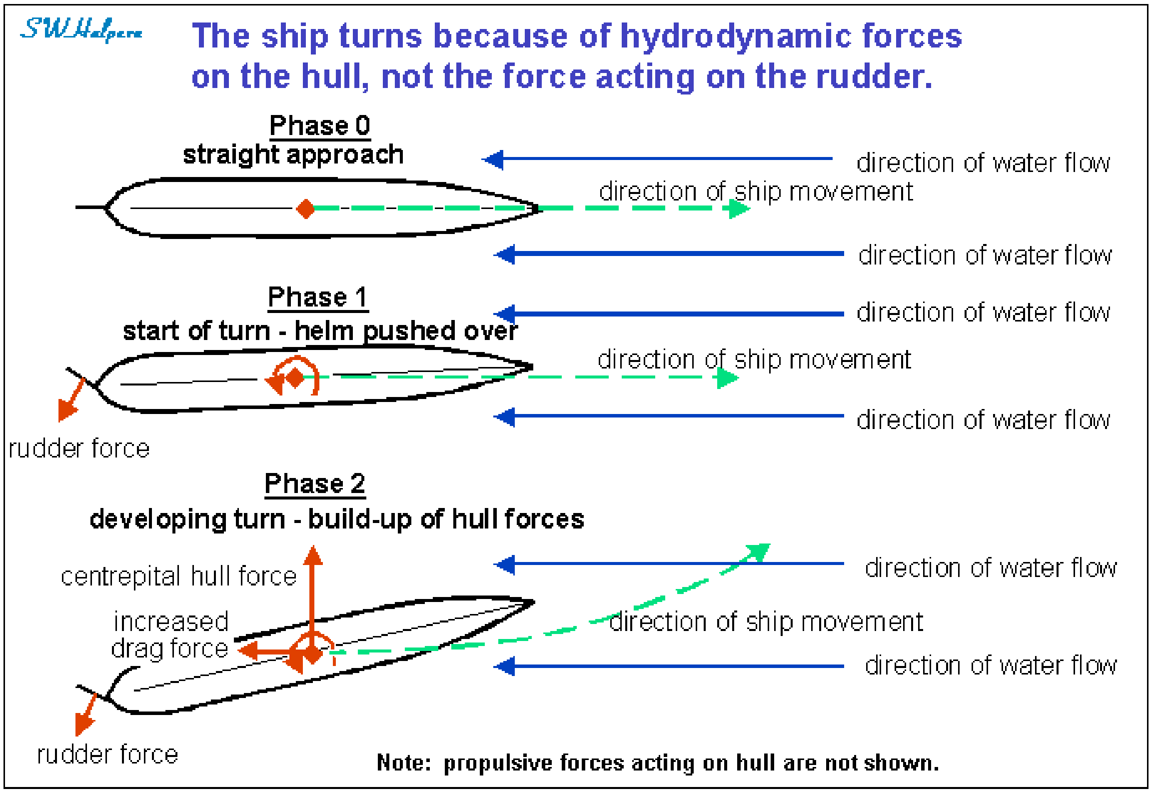
There are several recognized phases to a turn:

Phase 0 – is the approach phase, before the order is given to put the rudder over.

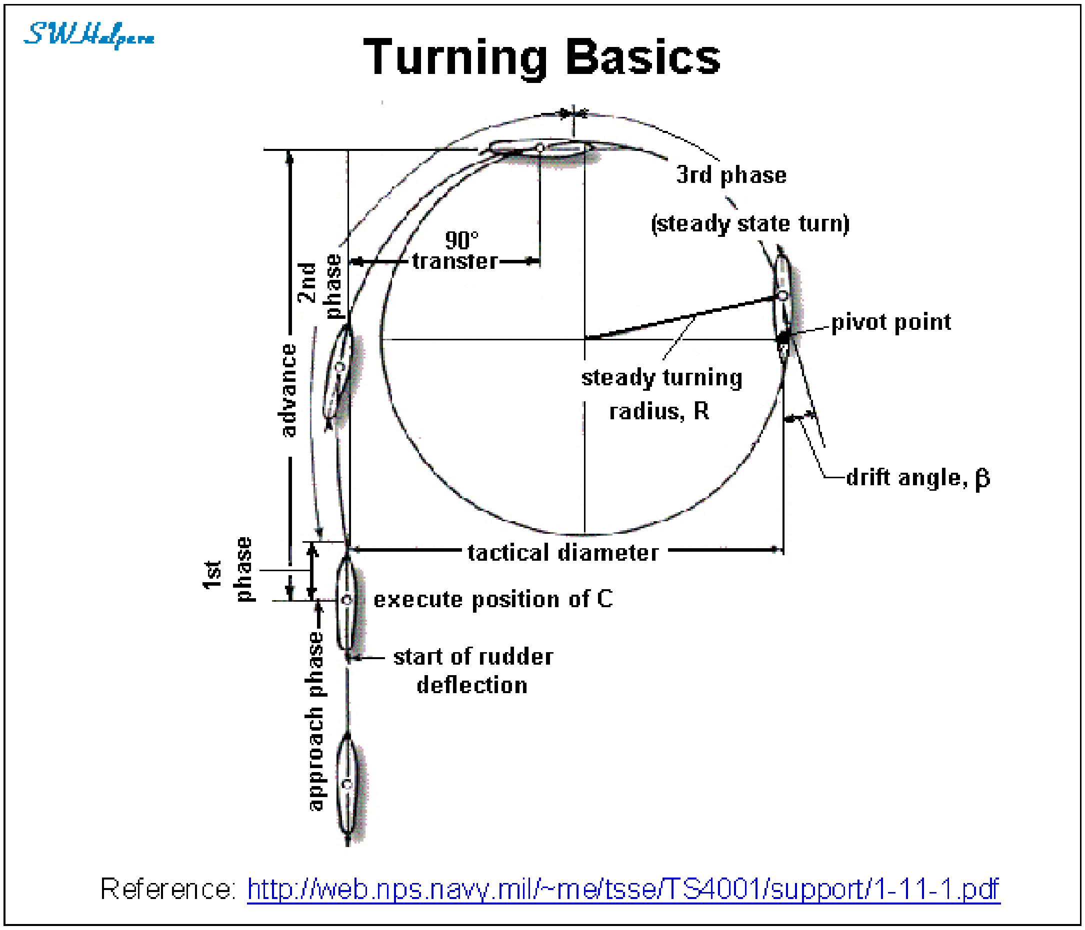
Phase 1 – is when the rudder is first put over from its centered position. At this time forces are built up on the rudder causing the ship's keel to swing away from the direction of the ship's forward movement. The ship will appear to start to skid initially toward the outside of the turn while its heading angle veers toward the inside of the turn. The force in tons acting on *Titanic's* rudder when put hard over at full speed is derived in Appendix A.

Phase 2 – is the build-up of hydrodynamic forces on the hull of the ship created by the angle formed between the ship's centerline and the direction the ship is actually moving. It is the hydrodynamic force created by the moving water acting on the hull of the ship which causes the ship to turn in a circular path.

Phase 3 – is when the ship is in a steady-state turn and all forces acting on the ship are fully developed and balanced.



The path taken by a ship during a turn is shown in the diagram below.



Reference: http://web.nps.navy.mil/~me/tsse/TS4001/support/1-11-1.pdf

Some definitions are:

Turning Circle – A ship's turning circle is the path followed by the ship when making a 360 degree turn.

Advance – Advance is the amount of distance run on the original course measured from the point where the rudder is first put over.

Transfer – Transfer is the amount of distance gained to the left or right of the original course after a heading change of 90° is completed.

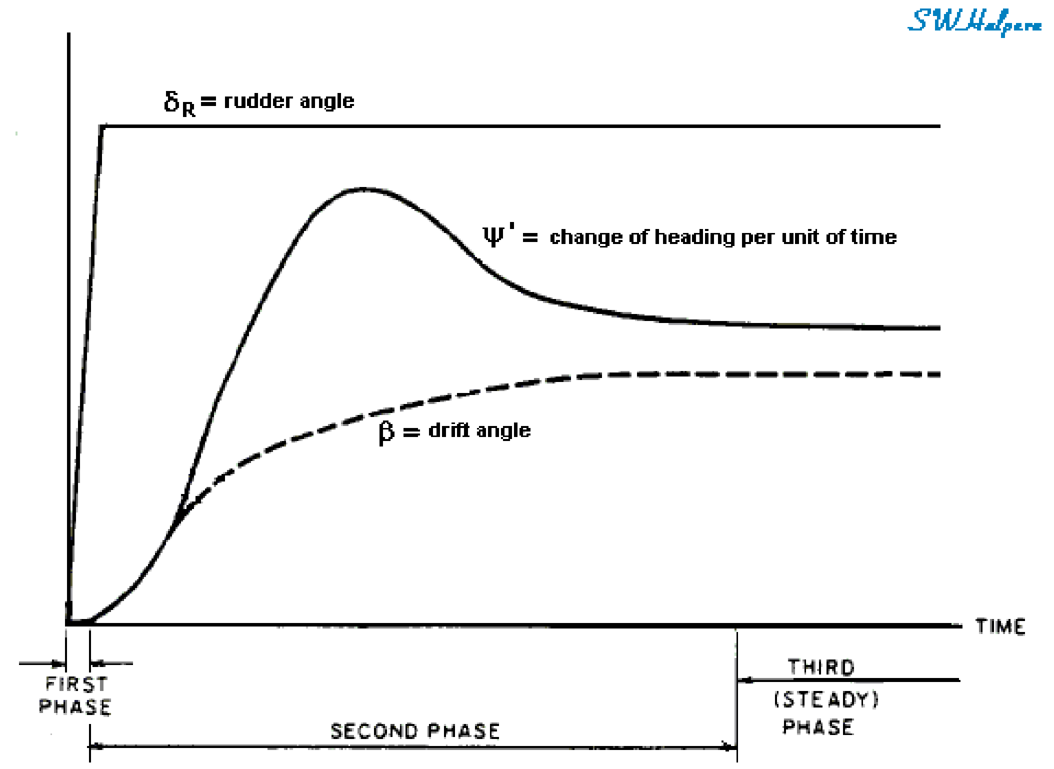
Tactical Diameter – Tactical diameter is the distance gained to the left or right of the original course after a heading change of 180° is completed.

Final Diameter – Final diameter is the distance perpendicular to the original course measured from the 180° point through 360° (shown here for steady turning radius, R).

Pivot Point – A point on the ship's centerline where the intersection of a line from the center of the ship's turning circle to the ship's centerline forms a right angle.

Drift Angle – Drift angle is an angle at any point on the turning circle between the intersection of the tangent to the turning circle at that point and the ship's keel line.

A typical plot of the rate of change in ship's heading over time, ψ', is shown in the diagram below. Also shown are the rudder angle (δ_R), and the change in drift angle (β), all as a function of time.



Reference: http://web.nps.navy.mil/~me/tsse/TS4001/support/1-11-1.pdf

Notice that when the turn reaches the third phase, the turning rate (i.e., the number of degrees the ship's head is turning per second) settles to a constant value, as does the drift angle which reaches a maximum value. In addition, the speed of the vessel will slow down from its approach speed to a steady-state turning speed that is determined by its block coefficient,[6] and the ratio of the diameter of its turning circle to the length of the vessel on the waterline. The cause of this decrease in speed is the increase in hydrodynamic drag on the hull of the vessel as the turn develops. Various curves of the ratio of speed-in-a-turn to approach-speed vs. turn-diameter to

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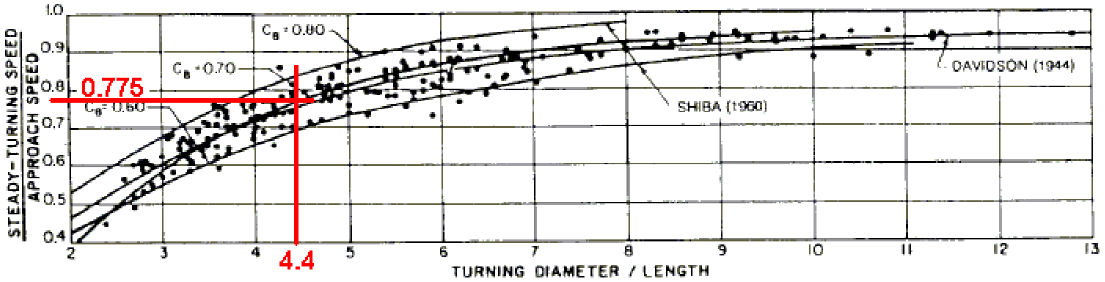
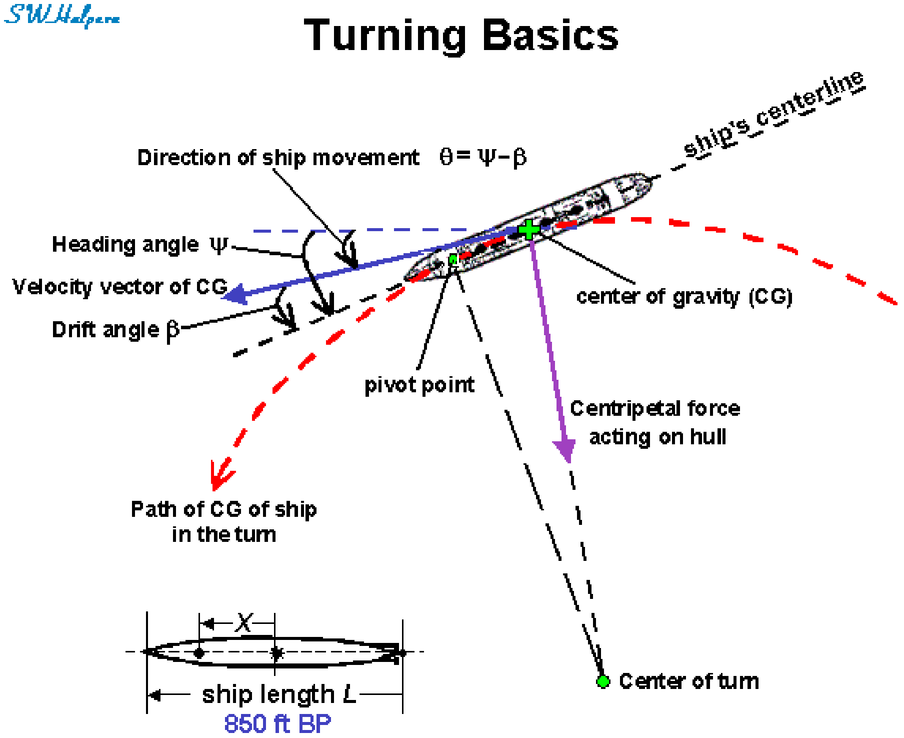
[6] The block coefficient is the nothing more than the ratio of the ship's actual underwater volume to the volume of a rectangular block of length, width and height equal to the ship's waterline length, breadth and draft, respectfully, under load conditions.

ship-length ratio for different ship block coefficients are shown in the diagram below. For *Titanic*, the block coefficient (taken from Harland & Wolff archives) is C_B = 0.684, the length between perpendiculars is 850 feet. We will take the final turning diameter for an approach speed of about 22 knots with hard over rudder to be 3,750 feet. This yields a diameter to length ratio of 4.41 which corresponds to a reduction of speed in a fully developed turn of 0.775 of the approach speed, or down to about 17 knots from 22 knots.



Reference: http://web.nps.navy.mil/~me/tsse/TS4001/support/1-11-1.pdf

With the ship turning at about 17 knots in a 3,750 foot diameter circle, the steady-state turning rate calculates out to 9/10 of a degree per second, or just under 7 minutes per 360° turn once the ship reaches the steady-state phase.



Key Reference: http://web.nps.navy.mil/~me/tsse/TS4001/support/1-11-1.pdf

Other parameters that we can derive for *Titanic* are its drift angle in the steady-state turn, and the location of the ship's pivot point. These are shown in the diagram above along with a few other related items of interest such as the velocity vector, $\mathbf{V}$, of the ship's center of gravity (CG), the instantaneous direction of ship's velocity vector, θ, relative to some reference line, and the ship's instantaneous heading angle, Ψ, relative to that reference line.

The velocity vector of the ship's CG, which is close to amidships for *Titanic,* is tangent to the ship's turning circle. Notice however, that the ship's head is pointing slightly to the inside of the turn, not in the direction that the center of the ship is actually moving. The angle between the ship's direction of movement and the ship's centerline is called the drift angle, $\beta = \Psi - \theta$. The drift angle reaches its maximum in the steady-state turn and is given approximately by:

$$\beta \approx 18\ \mathrm{L/R}$$

where β is in degrees, L is the ship's length between perpendiculars, and R is the radius of turn. For *Titanic*, L = 850 ft, and R = 1,875 ft. This gives a drift angle of 8.16 degrees with the helm over hard.

Along the ship's centerline ahead of the CG there is a location called the pivot point. To an observer on the ship standing at the pivot point, the center of the ship's turning radius will appear to be directly abeam; that is exactly 90° from the centerline to the inside of the turn. The location of the pivot point is given by:

$$\mathrm{X = R \sin} \beta$$

where X is the distance *ahead* of the ship's CG, R is the ship's turning radius, and β is the drift angle. For *Titanic* with R = 1,875 ft and $\beta = 8°$, X calculates out to 266 feet ahead of the ship's CG. That location is about 160 feet (a little more than 1/6th of a ship length) aft of the bow, putting it under the forward well deck just ahead of the navigation bridge. A distance of 1/6th aft of the bow for the pivot point is very typical of ships of this size and hull form.[7]

The forces acting on a ship during a steady turn are shown below. These forces comprise of the propeller thrust, F_T, the hydrodynamic force on the rudder, F_R, and the resultant hydrodynamic force acting on the ship's hull, F_H. The latter, acting at the center of the ship's lateral resistance, can be separated into two components: a hydrodynamic lift component, F_L; and a hydrodynamic drag component, F_D. It is the lift component acting toward the center of the turn that creates the centripetal force that is responsible for keeping the ship turning in a circle. The rudder force primarily holds the ship to a certain drift angle, β, thereby creating an angle of attack to the water flowing past the hull. The turning moment (force times distance) that is set up by the force on the rudder is balanced by a moment set up by the hydrodynamic hull force which is located slightly aft of the ship's center of gravity once the ship is in the steady-state turn. Initially, the hydrodynamic hull force begins well ahead of the center of gravity, providing somewhat

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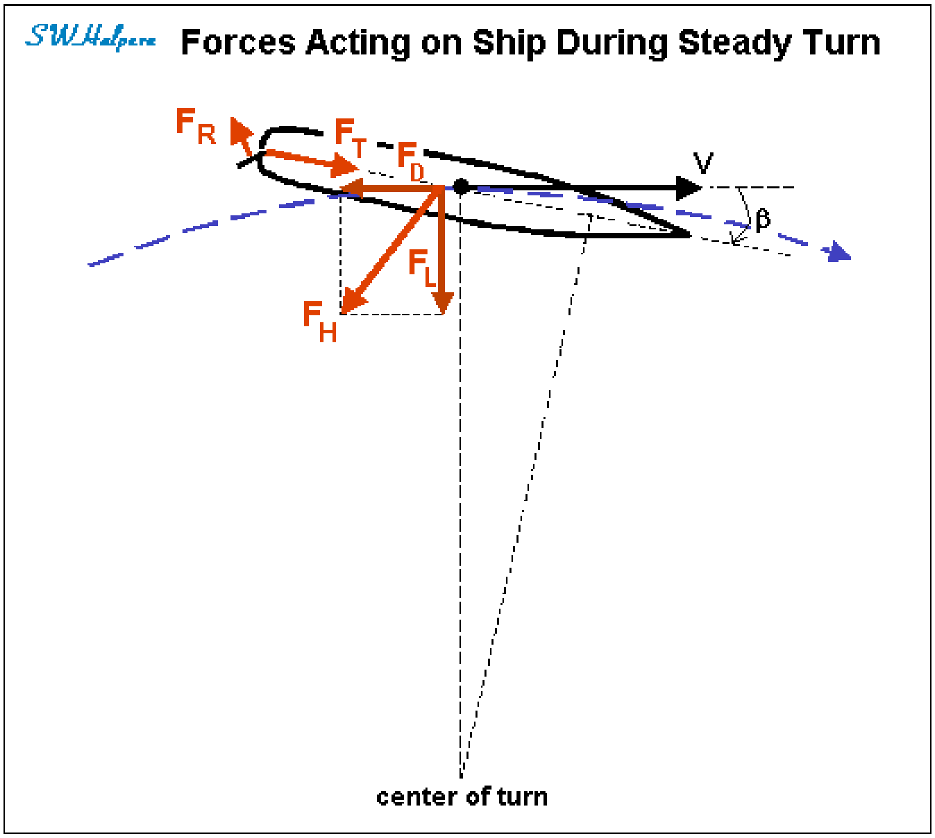
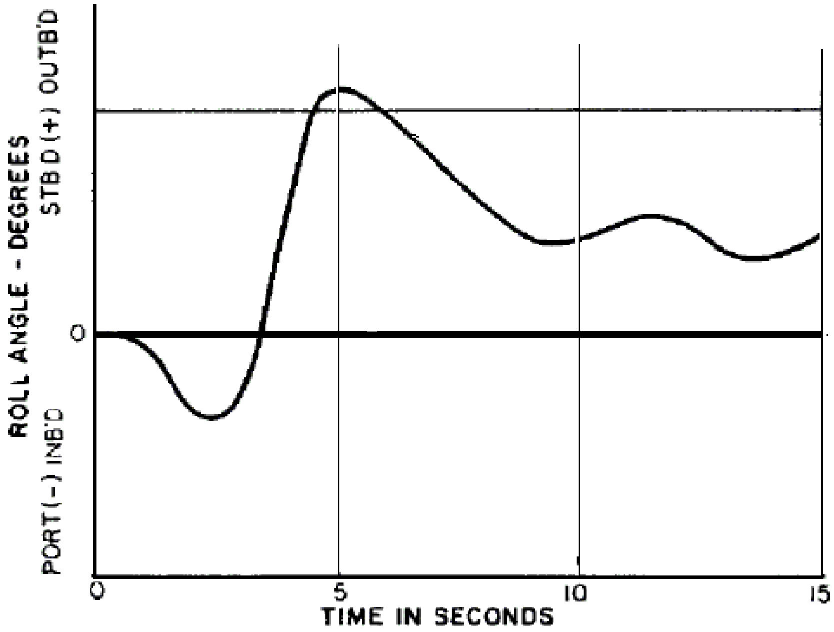
[7] Prof. Fotis A. Papoulias, Dept. of Mechanical Engineering, Naval Postgraduate School Monterey, CA 93943, http://web.nps.navy.mil/~me/tsse/TS4001/docs_lectures.htm.

increased initial turning efficiency leading to the overshoot in the turning rate curve seen above, and then moves aft as the turn enters the steady-state phase.



Another thing that happens to a ship in a turn is that it heels to the outside of the turn. The faster the turn, the greater the amount of heel. The reason for this is that the resultant hydrodynamic lifting force keeping the ship in the turn, F_L, can be considered to act at the center of the ship's longitudinal underwater profile, which is about ½ the ship's draft below the waterline and near amidships. The diagram below shows the development of the heel angle as a function of time. Notice that the initial heel is toward the inside of the turn, not the outside. This is caused by the force on the ship's rudder acting away from the turn center and well below the ship's longitudinal axis through the center of gravity. As the hydrodynamic hull force develops as the drift angle is built up, the centripetal force toward the turn center becomes much greater than the smaller rudder force. Since the center of this centripetal force also acts well below the ship's longitudinal axis, the ship will start to heel to the outside of the turn and settle onto a steady-state angle of heel within a very short period of time.

Angle of Heel in a Turn to Port



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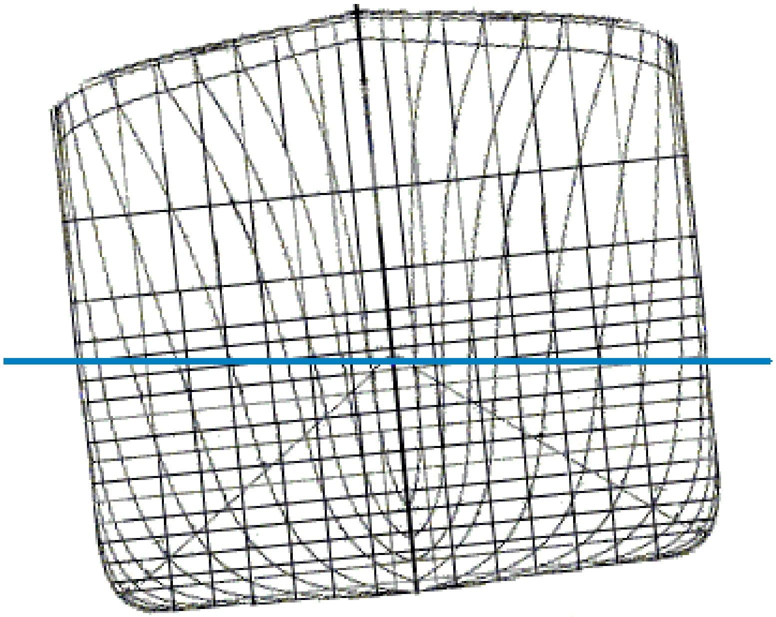
For *Titanic* in a steady-state, full-speed turn with hard over helm, the heel angle is estimated to be about 6°. This condition is shown below for *Titanic*, and is derived in Appendix B.

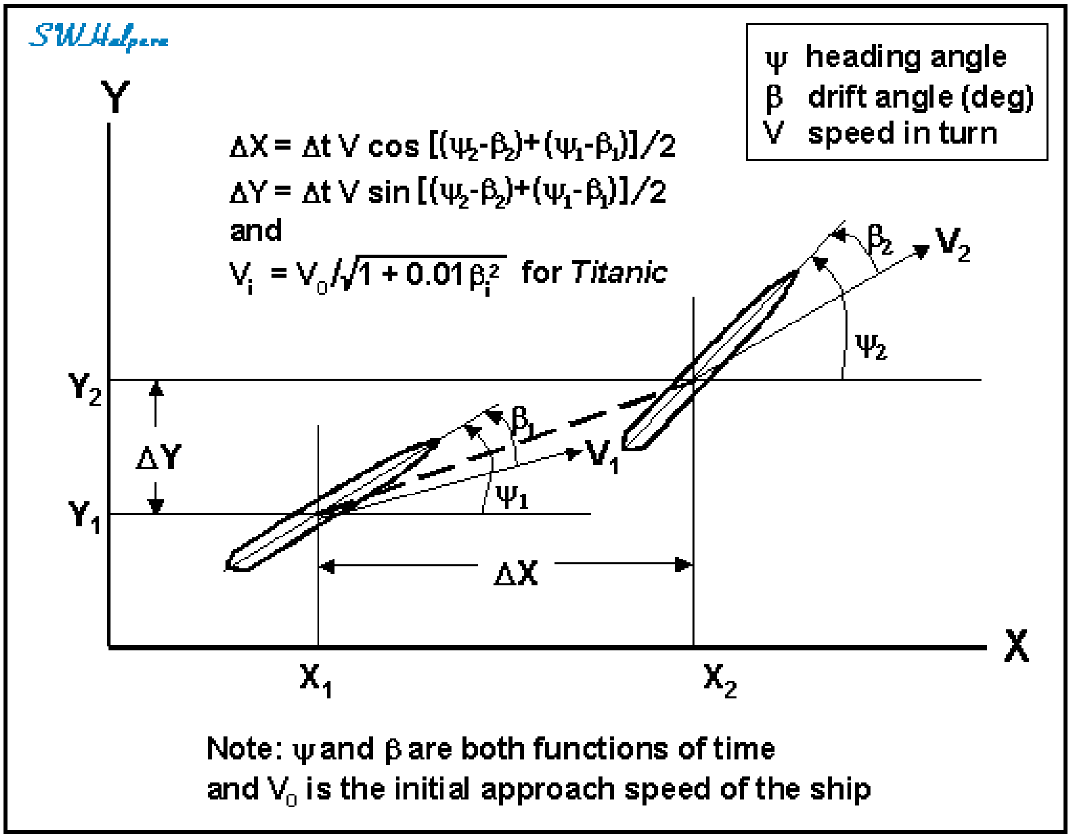
Six Degree Angle of Heel



MODELING A SIMPLE TURN MANEUVER

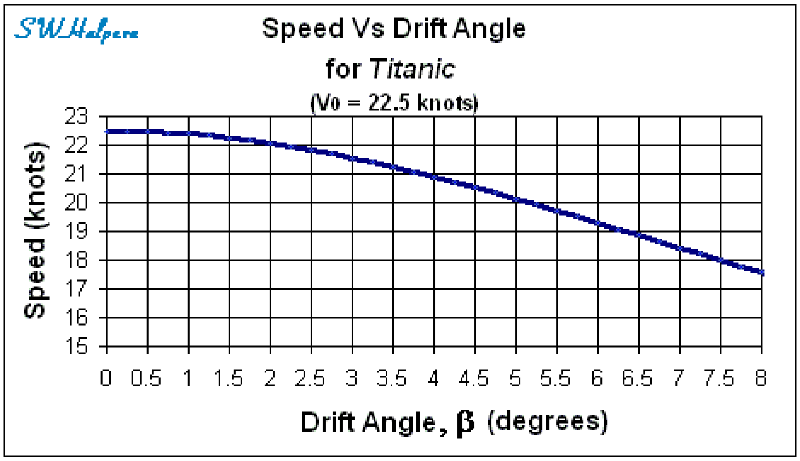
In the development of a turning model we need a way of showing the instantaneous coordinates of the ship, taken at the ship's center of gravity point near amidships, and a way of showing her instantaneous heading angle at any of these points. To do this we will choose a simple X, Y coordinate system, the origin of which is taken to be ship's location when the order is received to put the rudder over. Up to this point, the ship is traveling at an approach speed of V_0 knots. In the case of *Titanic*, we will take $V_0 = 22.5$ knots, or 38 ft/sec, as reported on the night of April 14, 1912. We will also take the positive X axis to be along the ship's initial heading.

To get the ships location and heading after the order to turn is given, we need to be able to specify the ship's speed, her heading angle, and her drift angle for any value of time. Knowing how these three parameters change from one time interval to another, we can find the next incremental location and heading of the ship from the previous values. This is diagramed below, where $\boldsymbol{\Psi}$ is the ship's heading angle, $\boldsymbol{\beta}$ is the ship's drift angle, and $\mathbf{V}$ is the ship's speed at a given instant of time, $\mathbf{t}$.



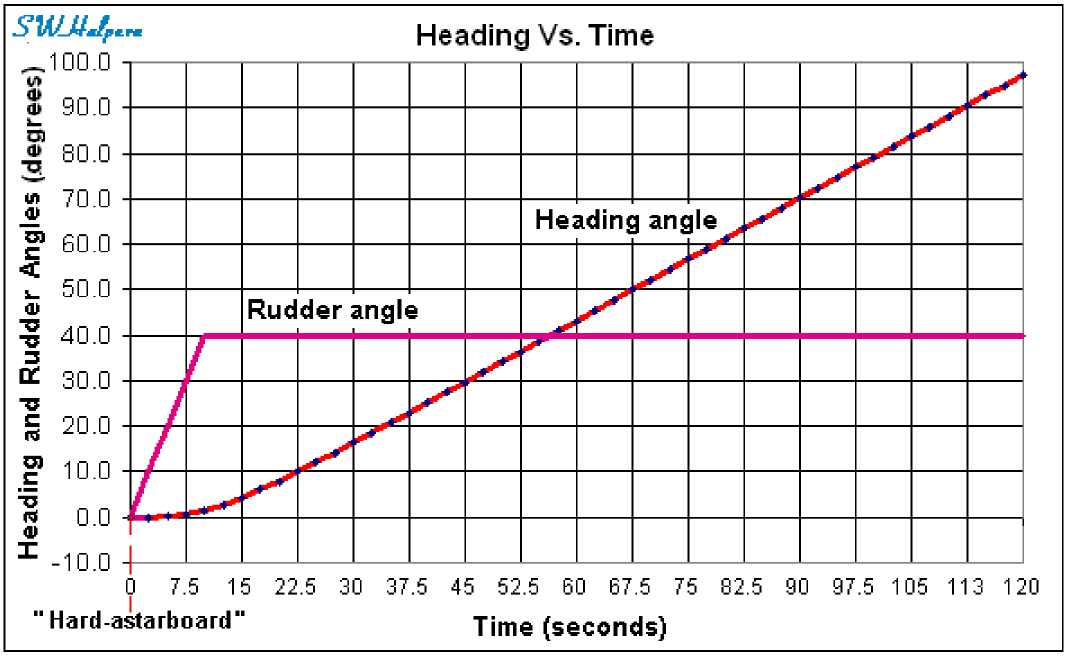
Note: ψ and β are both functions of time and V_0 is the initial approach speed of the ship

As we have discussed before, the ship's speed will decrease as the turn develops because of the increased drag on the hull that starts to build up as the ship enters a turn. For *Titanic* we found that the steady-state speed will be about $0.775\ V_0$. Therefore we should see the speed drop from $V_0 = 22.5$ knots to $V = 17.44$ knots (or 29.45 ft/sec) after the turn is fully developed. As discussed in detail in Appendix C, the drop in speed will depend on drift angle, β. The dependence of speed in knots on drift angle in degrees for *Titanic* is shown below.

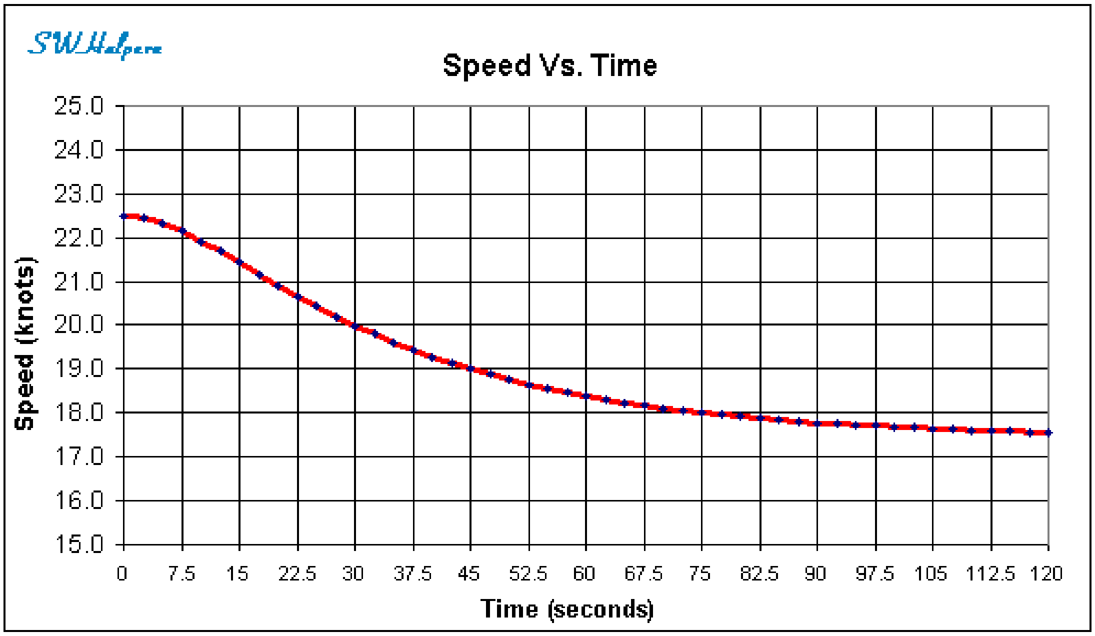


The next thing we need is to find how the heading and drift angles both change over time. For the heading angle Ψ we make use of what is called Nomoto's K and T indices equation, the solution of which is given in Appendix D. The model used for the drift angle is given in Appendix E.

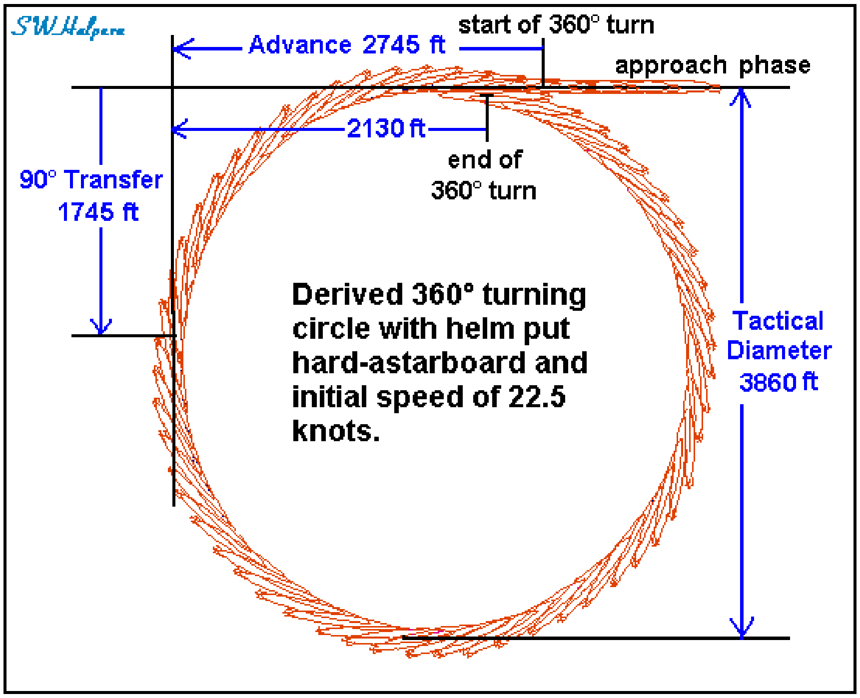
A plot of heading vs. time in 2.5 second increments for *Titanic* is shown below. Again, the initial approach speed was taken at 22.5 knots when a hard-astarboard helm order (left full rudder) is given. Heading angles to port of the approach line are represented by positive angles. Notice that in this model the ship's head turned 23° in 37.5 seconds. This should be no surprise since tests conducted on *Olympic* at full speed showed that she would turn 2 points (22.5°) in 37 seconds once the helm order was received.



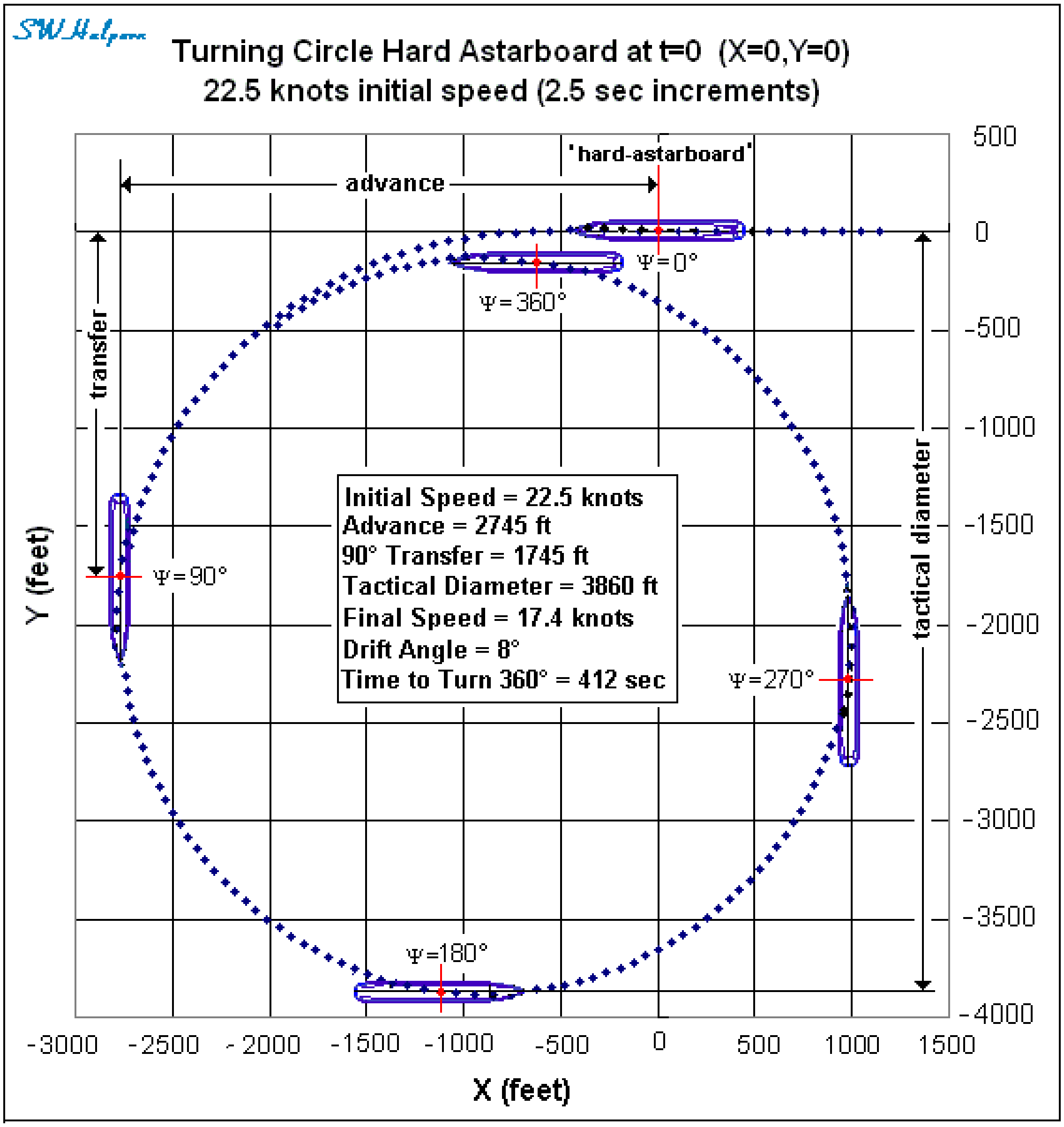
Below is a plot of ship speed vs. time in 2.5 second increments. Notice how the speed drops from an initial 22.5 knots and approaches 17.4 knots for the steady-state turn.



The following diagram shows the complete turning circle for *Titanic* taken in 7.5 second increments. Included on the diagram are the key characteristics of the turning circle such as the ship's Advance, Transfer, and Tactical Diameter. Notice that the distance from the completion of the 360° turn to the furthest advance point was about 2130 ft, or about 710 yards.



The following diagram is a more detailed plot of the ship's CG point taken in 2.5 second increments. The scale shown is 500 feet per division.



MODELING A PORT-AROUND ZIG-ZAG MANEUVER

During the maneuver to avoid the iceberg, *Titanic's* First Officer William Murdoch had not only called for the helm to be put hard-astarboard (left full rudder), but also ordered the helm put hard-aport (right full rudder) soon after the berg had passed aft of the bridge.[8] We also have evidence from several eyewitnesses that the berg was seen disappearing off *Titanic's* starboard quarter as the ship was coming to a stop following the collision. We also know that *Titanic's*

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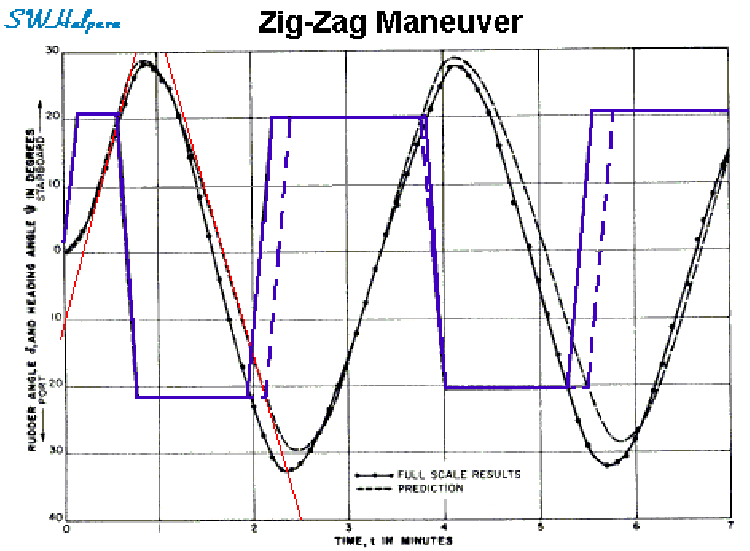
[8] American Inquiry, p. 527-528.

Fourth Officer Joseph Boxhall said that he overheard Murdoch tell Capt. Smith that he intended to “port around” the berg, but that she was too close to carry out the maneuver when the ship struck.[9]

From what we can piece together from all the primary source evidence is that at some point following the lookout warning that something was seen ahead, First Officer Murdoch ordered the helm be put hard-astarboard with the intent of going hard-aport so as to take the ship around the berg. However, the ship struck the iceberg before clearing it. He then ordered the helm hard aport *after* the berg had passed aft of the bridge in an apparent attempt to minimize contact with the berg along the ship’s starboard side. It was not a collision avoidance maneuver, but a maneuver to minimize contact damage. We know from other eyewitnesses that the iceberg continued to pass close to the side of the ship as it passed aft causing some ice to fall through some open portholes and also onto the windows of the Café Parisien causing them to get wet. The berg was so close to the ship’s side as it passed the stern that Quartermaster George Rowe thought it was going to strike the docking bridge located out on the poop.[10] We also know that the only serious damage to the ship from the iceberg was along her forward starboard side over a distance of about 200 to 250 feet.

To look into the affect of shifting the rudder after a turn in one direction had started, we will consider what is called a zig-zag maneuver, where the rudder is first put to one side, and then later shifted to the other side. This type of maneuver is part of what is typically done to characterize the overall turning capability of a ship. An example of a zig-zag maneuver showing a comparison of full-scale results (solid lines) to predicted results (dashed lines) for a given ship is shown below.



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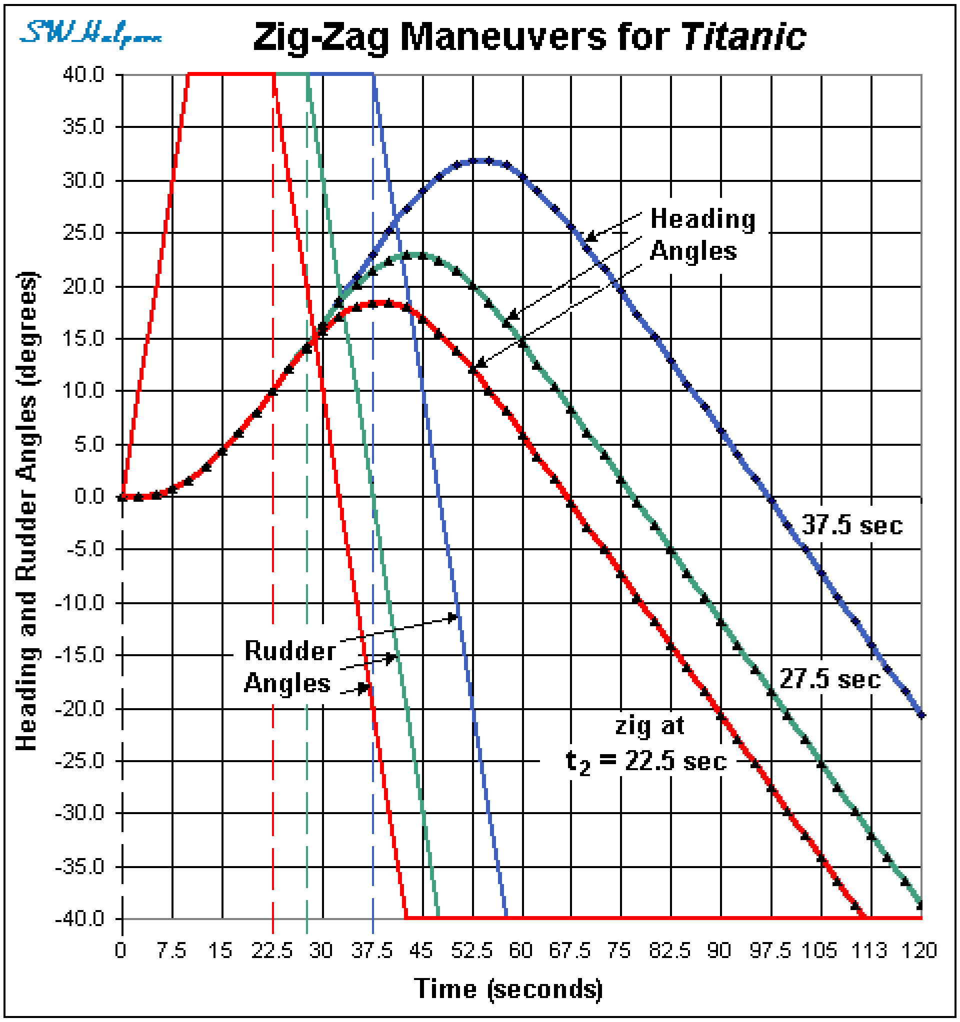
[9] American Inquiry, p. 230; British Inquiry 15355.

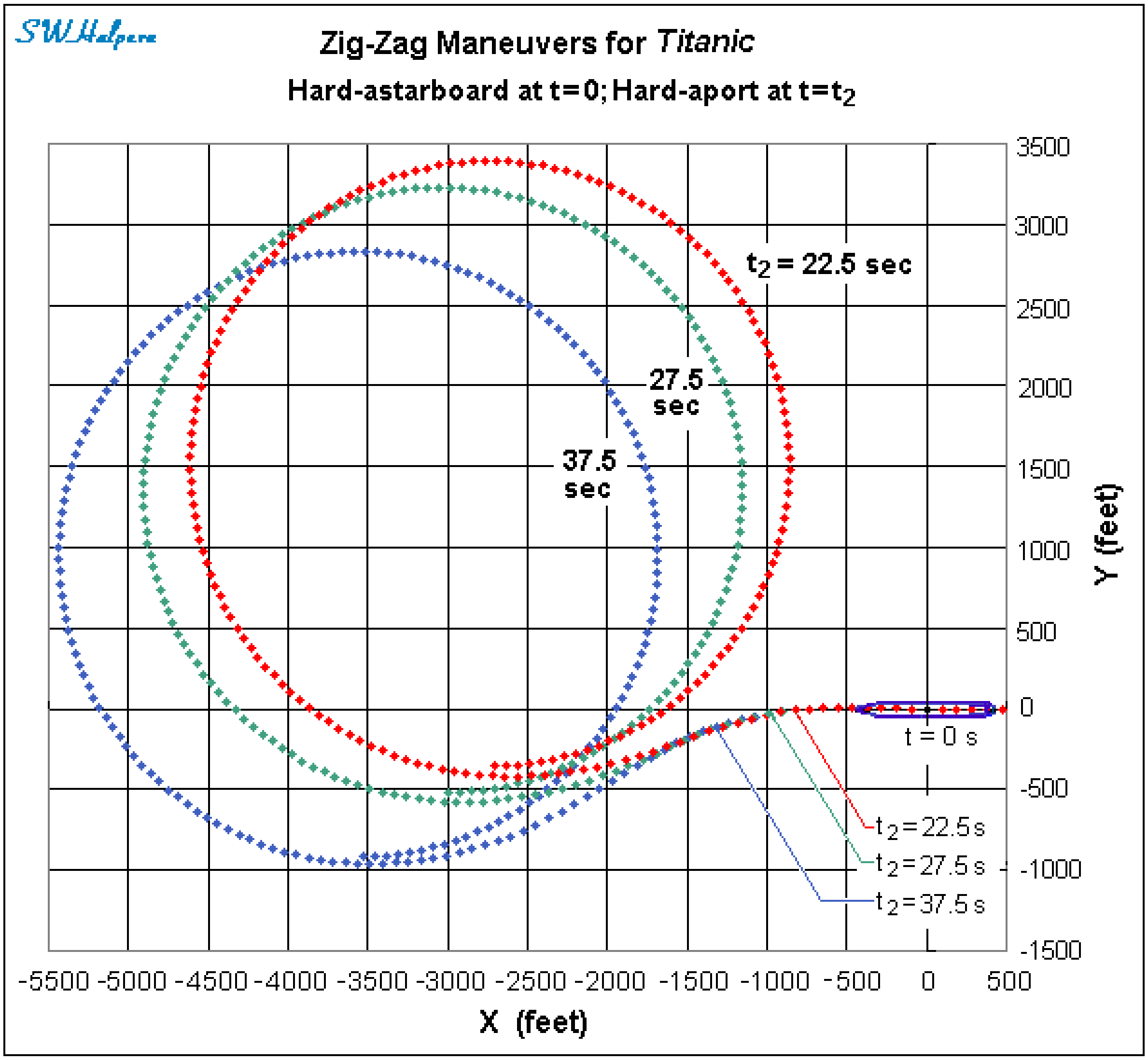
[10] American Inquiry, p. 522.

To obtain the predicted zig-zag performance for *Titanic*, we once again need to find how the ship's heading and drift angles change over time. In this case the helm is shifted from hard-astarboard (left full rudder) to hard-aport (right full rudder) at some specified time, t_2, following the initial t=0 hard-astarboard (left full rudder) order. The derivation details for drift and heading angles for *Titanic* in a simple zig-zag maneuver are given in Appendix E and Appendix F, respectively.

Several zig-zag maneuver plots of heading vs. time for *Titanic* in 2.5 second increments are shown below. Again, the initial approach speed was taken at 22.5 knots when the initial hard-astarboard helm order (left full rudder) is given at t = 0. The hard-aport order (right full rudder) is taken as a parameter t_2. Shown in the diagram are the results for three of these values: $t_2 = 22.5$ sec, $t_2 = 27.5$ sec, and $t_2 = 37.5$ sec. These times, when the rudder was ordered to be put to the opposite side, are highlighted by the three dashed vertical lines. Heading angles to port of the approach line are positive, while heading angles to starboard of the approach line are negative. Also shown are the corresponding rudder angle values for all three cases.



The following diagram is a detailed plot of the ship's CG point taken for these zig-zag maneuvers in 2.5 second increments. The scale shown, as before, is 500 feet per division.



Notice the overshoot in heading angles following the order to shift the rudder to the opposite side. For each case, it took about 17 to 18 seconds to check the swing of the ship to port once the order was received. Thereafter, the ship started its turn to starboard as shown. Notice that in the turn for t_2 = 27.5 sec, the ship reached a maximum heading angle of 23° (about 2 points) to port before it started to swing in the opposite direction. In the turning circle curves you can see how the final diameter circles are shifted as the hard-aport order times, t_2, get moved further out from the initial (t =0) hard-astarboard order.

ENCOUNTER WITH AN ICEBERG

The classical story of how *Titanic* encountered the iceberg was summarized in the final report of the British Wreck Commission:

> "At a little before 11.40, one of the look-outs in the crow's nest struck three blows on the gong, (Hichens, 969) which was the accepted warning for something ahead, following this immediately afterwards by a telephone message to the bridge 'Iceberg right ahead.' Almost simultaneously with the three gong signal Mr. Murdoch, the officer of the watch, gave the order 'Hard-a-starboard,' and immediately telegraphed down to the engine room 'Stop. Full speed astern.' (Boxhall, 15346) The helm was already 'hard over,' and the ship's head had fallen off about two points to port, when she collided with an iceberg well forward on her starboard side.
>
> Mr. Murdoch at the same time pulled the lever over which closed the watertight doors in the engine and boiler rooms. (15352) The Master 'rushed out' on to the bridge and asked Mr. Murdoch what the ship had struck. (Hichens, 1027) (Boxhall,15353) Mr. Murdoch replied: '"An iceberg, Sir. I hard-a-starboarded and reversed the engines, and I was going to hard-a-port round it but she was too close. I could not do any more. I have closed the watertight doors.' (15355)"

The report then went on to state the following conclusion:

> "From the evidence given it appears that the 'Titanic' had turned about two points [22.5°] to port before the collision occurred. From various experiments subsequently made with the SS 'Olympic,' a sister ship to the 'Titanic,' it was found that traveling at the same rate as the 'Titanic,' about 37 seconds would be required for the ship to change her course to this extent after the helm had been put hard-a-starboard.[11] In this time the ship would travel about 466 yards [1,398 ft], and allowing for the few seconds that would be necessary for the order to be given, it may be assumed that 500 yards [1,500 ft] was about the distance at which the iceberg was sighted either from the bridge or crow's nest."

From the above description, and the derived turning curve for *Titanic*, we can examine this conclusion and look further into the assumptions and claims that were made. The diagram below shows the positions of *Titanic* in 2.5 second increments beginning with the order "hard-astarboard" and ending at 37.5 seconds later when the ship's head had turned 23° (just about 2 points) as described. Also added to the diagram is an outline depicting an iceberg placed such that its initial contact with the ship was well forward on the starboard side. Notice, that we had to place the center of the berg well over to the port side of the original course line for it to make contact with the ship's forward starboard side at 37 seconds. We also chose a berg of about 250

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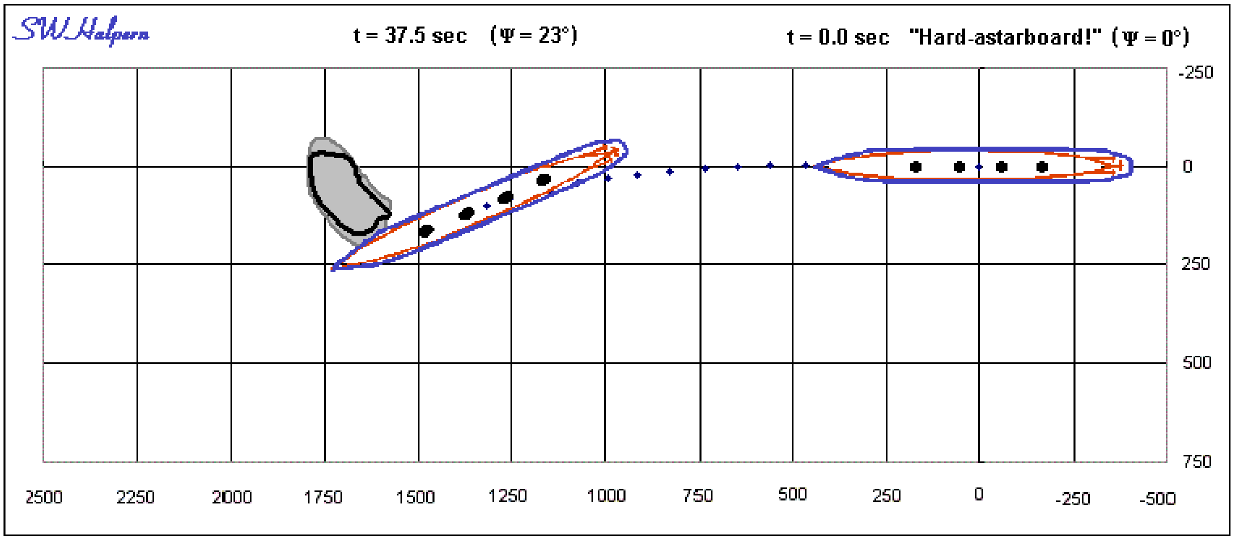
[11] The evidence presented by Edward Wilding was that Olympic turned two points from the time the order was first given, not after the wheel was put hard over.

feet across on the waterline, which is quite typical of a medium sized iceberg such as the one that *Titanic* struck.[12]



According to the Wreck Commission conclusion, the iceberg was first sighted about 1,500 feet ahead, which is only about 40 seconds of travel time for ship moving at 22.5 knots. Yet they also stated that the lookouts gave the warning to the bridge of an object ahead by striking the bell three times when first sighted, then called down by telephone to inform the bridge that an iceberg was seen "right ahead." In looking at the testimony of QM Robert Hichens, who was at the wheel at the time, the helm order was given *after* the phone call was received from the lookouts by Sixth Officer James Moody, who was standing right behind him. Moody then repeated what was said to First Officer William Murdoch (Hichens, 993). Hichens also said that the order came about half a minute following the three-bell warning (Hichens, 973). Despite this evidence, the Commission concluded that Murdoch's order came "almost simultaneously with the three gong signal," not allowing any time for the phone call and the relaying of information that took place immediately after.

The other conclusion was that the ship turned two points in 37 seconds. This of course came from the evidence presented by H&W's naval architect Edward Wilding to the Commission as we have noted before. But did *Titanic* turn as much as two points before striking the iceberg?

Robert Hichens gave the following in evidence:

> 948. Had you had any instructions before she struck? Had you been told to do anything with your helm before she struck? – [Hichens] Just as she struck I had the order "Hard-a-starboard" when she struck.
> 949. Just as she struck, is that what you said? - Not immediately as she struck; the ship was swinging. We had the order, "Hard-a-starboard," and she just swung about two points when she struck.

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[12] Samuel Halpern, "Iceberg Right Ahead," *Encyclopedia Titanica Research Paper*, http://www.encyclopedia-titanica.org/iceberg_right_ahead.html.

> 950. You got the order, "Hard-a-starboard"? - Yes.
> 951. Had you time to get the helm hard a starboard before she struck? - No, she was crashing then.
> 952. Did you begin to get the helm over? - Yes, the helm was barely over when she struck. The ship had swung about two points.
> 953. She had swung two points? - Yes.
> 954. (*The Commissioner.*) Do let me understand; had she swung two points before the crash came? - Yes, my Lord.
> 955. (*The Attorney-General.*) I am not quite sure that I understand what you had done to the helm before this. You had got an order, "Hard-a-starboard"? -"Hard-a-starboard," yes.
> 956. You proceeded at once to put the wheel hard-a-starboard? - Immediately, yes.
> 957. Before the vessel struck had you had time to get the wheel right over? - The wheel was over then, hard over.
> 958. (*The Commissioner.*) Before she struck? - Oh yes, hard over before she struck.

This evidence is somewhat confusing because when Hichens was first asked if he had time to get the helm over hard before the ship struck the ice, Hichens' original reply was, "No, she was crashing then (BI 951)." Then when he was asked again if he had time to get the wheel hard over before the vessel struck, Hichens replied, "The wheel was over then, hard over…Oh yes, hard over before she struck (BI 957-958)." The Attorney-General was still not completely satisfied, and later came back to ask Hichens more about it.

> 1011. Let us get the fact of what happened. Was Mr. Moody there when you put the helm hard-a-starboard? – [Hichens] That was his place, to see the duty carried out.
> 1012. Was it his duty to report it? - Yes; he reported the helm hard-a-starboard.
> 1013. To whom? - To Mr. Murdoch, the First Officer.
> 1014. Then you had put the helm hard-a-starboard and Mr. Moody had reported it hard-a-starboard to Mr. Murdoch? - Yes.
> 1015. So that he had reported, and then it was after that that she strikes, is that right? - She struck almost at the same time.
> 1016. Almost as he reported it? - Yes.

So according to Hichens' final story, Murdoch first gave the order "hard-astarboard." Hichens then immediately put the wheel hard over. As soon as the wheel was hard over, Moody reported to Murdoch that the wheel was over hard just about the time that the ship struck the ice. Yet, to put the helm over hard requires about 4 complete turns of the wheel, something that does not take more than about 10 seconds to do. But Hichens also said that the ship had turned 2 points *before* she struck (BI 954), which we know takes about 37 seconds from time the order to put the helm over is first received. So there seems to be about 27 seconds, or thereabouts, that is missing between him getting the wheel over hard and the ship turning two points.

It should be pointed out that Hichens, being inside an enclosed wheelhouse, was not able to see the ship strike the ice. But he was looking at the steering compass ahead of him and was able to see how far the ship was turning off her original course line. He said, "The vessel veered off two points; she went to the southward of west." Her course line before the helm order was given was "north 71 west" by the steering compass in the wheelhouse.[13]

In America, weeks before the British Inquiry took place, Hichens also testified about the orders he received while at the wheel. When senator Smith asked him who gave the order "Hard astarboard," Hichens replied (AI p.450):

> "Mr. Murdoch, the first officer, sir; the officer in charge. The sixth officer repeated the order, 'The helm is hard astarboard, sir.' But, during the time, she was crushing the ice, or we could hear the grinding noise along the ship's bottom."

So we see once again the claim that *Titanic* struck the iceberg just as he got the helm over hard, if not before. According to the turning characteristics for *Olympic* and *Titanic*, it should only have turned about 2° in the 10 seconds it would take to get the helm over hard, not 2 points (22.5°) that was claimed.

Is there any other evidence as to how far *Titanic* swung before striking the iceberg? The answer is yes. It comes from lookout Frederick Fleet who was the one who struck the warning bell in the crow's nest when the iceberg was first seen by him and Reginald Lee. This is his testimony taken at American Inquiry:

> Senator FLETCHER. When you gave the three bells did you immediately turn to the telephone?
> Mr. FLEET. Yes, sir.
> Senator FLETCHER. How long were you at the telephone?
> Mr. FLEET. I suppose half a minute.
> Senator FLETCHER. When you turned from the telephone and observed the course of the ship, you saw she had turned to port?
> Mr. FLEET. Yes, sir.
> Senator FLETCHER. Did she turn immediately and suddenly, or gradually, to port?
> Mr. FLEET. Just started to go as I looked up.
> Senator FLETCHER. Just started to go to port?
> Mr. FLEET. Yes, sir.
> Senator FLETCHER. To what extent did she change her course from the direct line?
> Mr. FLEET. You mean how far did she go?
> Senator FLETCHER. Yes.
> Mr. FLEET. A little over a point, or two points.
> Senator FLETCHER. Did she seem to respond readily to the wheel?
> Mr. FLEET. Well, we do not know that. We only know she went.
> Senator FLETCHER. You could see she was going?
> Mr. FLEET. Yes, sir.

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[13] The course on the steering compass (N 71° W, or 289°) was not the same as the ship's true course heading because of magnetic variation and compass deviation. At the time of the collision, *Titanic* was heading 266° true. A turn of about two points to port from her original course line would take it 3 to 4 degrees south of west as seen on the steering compass.

> Senator FLETCHER. And did she continue to bear to port?
> Mr. FLEET. Until the iceberg was alongside of her.

If we try to piece together what Fleet said together with what Hichens said, we get the following scenario. Fleet up in the nest spots an object ahead of the ship and rings the lookout bell three times to warn the bridge that something was seen ahead. He then goes to the telephone and rings down to the phone in the wheelhouse which was answered by Sixth Officer James Moody. Fleet tells Moody that an iceberg was seen ahead, which Moody repeats to First Officer William Murdoch. Murdoch immediately orders the helm be put "hard-astarboard," and Hichens immediately carries out the order. After coming off the phone, Fleet looks up and sees *Titanic's* head just starting to veer to port. After Hichens gets the wheel hard over, Moody reports to Murdoch that the helm is hard astarboard. The ship is then seen by Fleet to strike the iceberg after turning between one and two points. A turn of about one point should take about 22.5 seconds from the time the order is received, while a turn of two points should take about 37 seconds. Assuming that it only takes about 10 seconds to turn the wheel over four complete turns, we see that *Titanic* would have struck the iceberg anywhere from about 12 to 27 seconds *after* Hichens got the wheel over hard.

So why would Hichens believe the ship began crushing the ice just as Moody reported the helm hard over? And did the ship actually turn two points *before* striking, or was it a maximum swing of about two points that was reached before she started to swing the other way? This is where our analysis of the zig-zag maneuvering characteristics of the ship may help.

MURDOCH'S HARD-APORT HELM ORDER

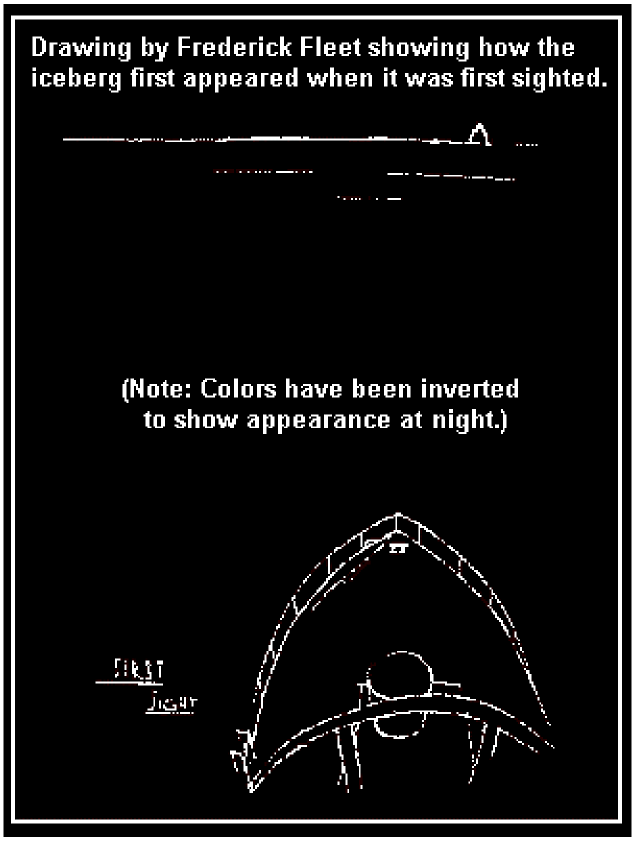
The most direct evidence of Murdoch ordering the helm shifted hard-aport comes from Quartermaster Alfred Olliver. At the time the three-bell warning was given by lookout Frederick Fleet, Olliver was attending to the lights in the standard compass located on a special platform amidships. Upon hearing the bells, Olliver left the compass and went forward toward the bridge. Just as he was entering the bridge the ship struck the iceberg. He also saw Murdoch at the switch that closes the watertight doors as he entered, and happened to notice the peak of an iceberg pass aft of the bridge on the open starboard side.

> Mr. OLLIVER. What I know about the wheel - I was stand-by to run messages, but what I knew about the helm is, hard aport.
> Senator BURTON. Do you mean hard aport or hard astarboard?
> Mr. OLLIVER. I know the orders I heard when I was on the bridge was after we had struck the iceberg. I heard hard aport, and there was the man at the wheel and the officer. The officer was seeing it was carried out right.
> Senator BURTON. What officer was it?
> Mr. OLLIVER. Mr. Moody, the sixth officer, was stationed in the wheelhouse.
> Senator BURTON. Who was the man at the wheel?
> Mr. OLLIVER. Hichens, quartermaster.
> Senator BURTON. You do not know whether the helm was put hard astarboard first, or not?
> Mr. OLLIVER. No, sir; I do not know that.
> Senator BURTON. But you know it was put hard aport after you got there?

> Mr. OLLIVER. After I got there; yes, sir.
> Senator BURTON. Where was the iceberg, do you think, when the helm was shifted?
> Mr. OLLIVER. The iceberg was away up stern.

Olliver sees only the very top of the iceberg as it passes aft of the bridge, and hears Murdoch order the helm be put hard-aport (right full rudder). Why would Murdoch do that? Before the hard-aport order was given, *Titanic* was under hard-astarboard helm with her head turning to port. Unable to clear the iceberg, it struck on the starboard side and scrapped along the side to the wrenching sound of twisting metal. Murdoch had to do something to minimize damage to the ship. Instinctively, that something was to order the helm shifted hard over to the opposite side in an attempt to pull the stern away from the iceberg that was fast moving aft. He gave the order for the helm to be put hard-aport after the peak of the berg had passed aft of the ship's pivot point. But as we see in the zig-zag curves, it takes about 17 to 18 seconds from when that second helm order is given for the initial turn to be checked, just about the time that it would take to get the wheel over all the way from one side to the opposite side as confirmed by Sixth Officer Moody. In that time interval, the ship would advance about another 650 ft thereby leaving the iceberg away up stern before her head would start to swing in the opposite direction.

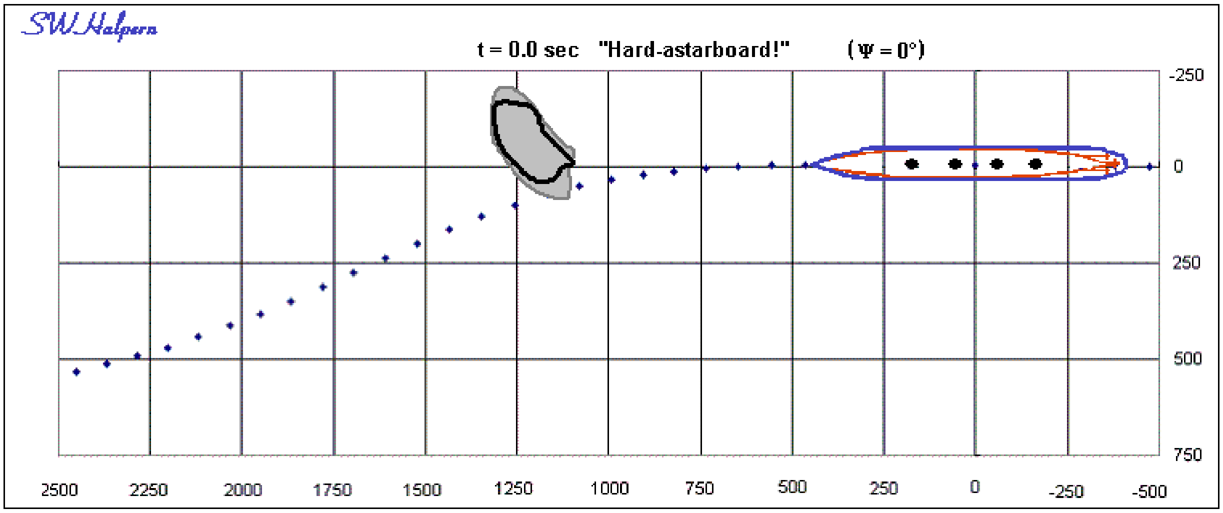
It is interesting to note that when Frederick Fleet was asked to sketch what he saw when the iceberg was first seen by him before he rang the lookout bell, he placed the berg fine off the ship's starboard bow. Soon after that he went to the bell and struck it three times, and then went to the telephone and rang down to the bridge and told Moody, who answered the loud-speaking phone in the wheelhouse, that an iceberg was seen "right ahead."

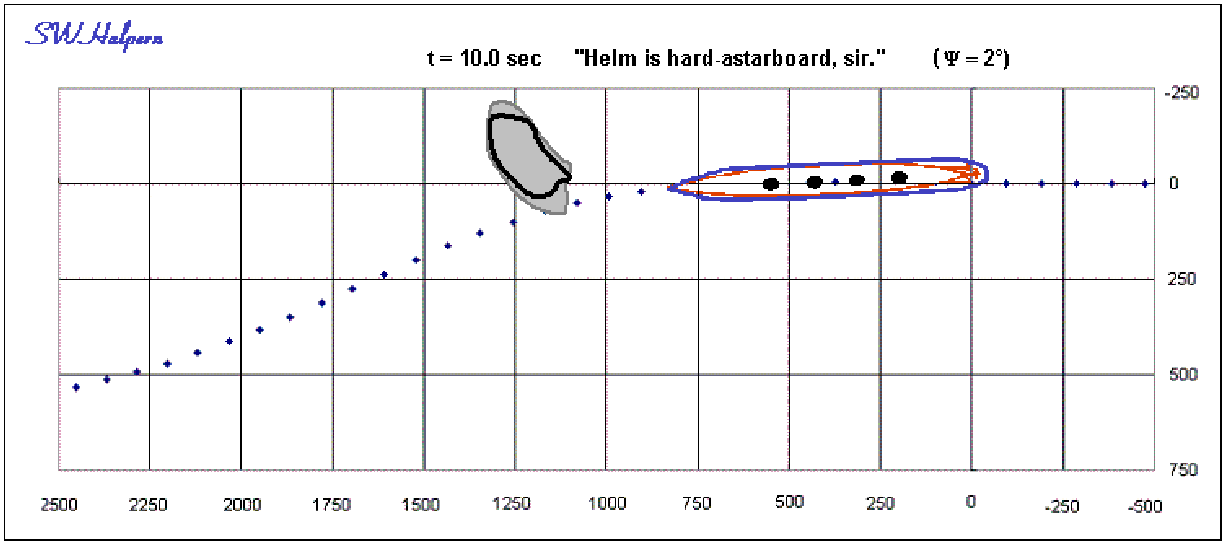

Drawing by Frederick Fleet showing how the iceberg first appeared when it was first sighted.

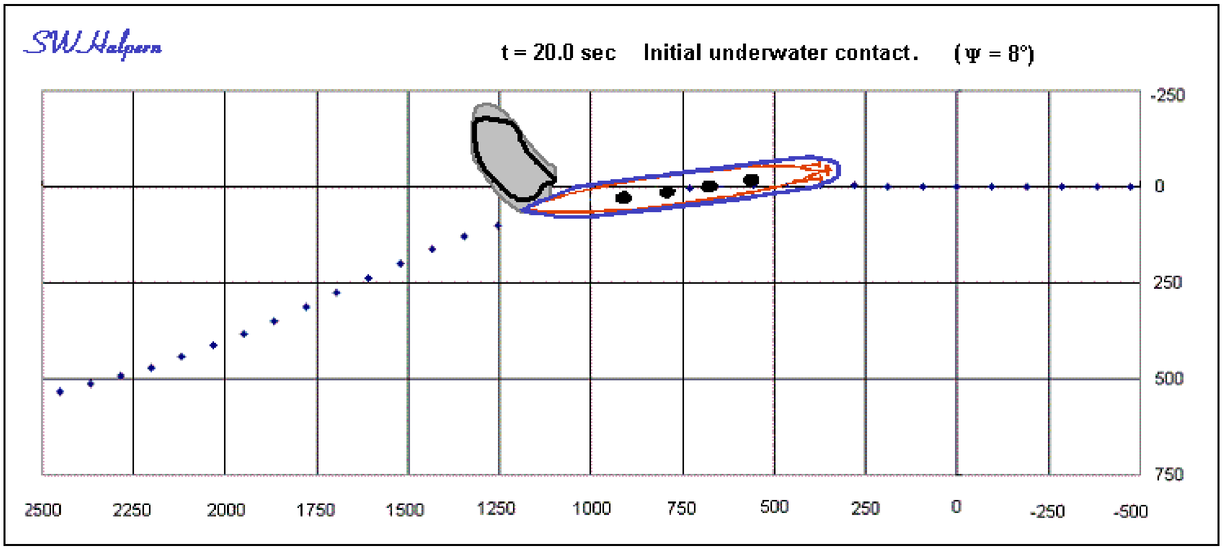
(Note: Colors have been inverted to show appearance at night.)

Both Fleet and Hichens estimated about a half a minute had gone by from the three-bell warning to when the initial hard-astarboard order was received. Standby QM Olliver left the standard compass platform when he heard the three-bell warning and was entering the bridge just when the ship struck. Knowing the distance that it takes to get down from the platform and walk to the bridge, and using a typical walking speed for pedestrians crossing a crosswalk at a busy intersection, and allowing some reaction time as well, it would take Olliver about 50 to 55 seconds to come onto the bridge after hearing the warning bells. Allowing about 30 seconds from the warning bell to when Murdoch issued his first helm order, we get about 20 to 25 seconds of time between the hard-astarboard order and the ship striking the iceberg. Within 5 seconds after initial contact, the iceberg would be passing aft of the bridge, and Murdoch would call out “Hard-aport” in an attempt to swing the stern away from the ship.

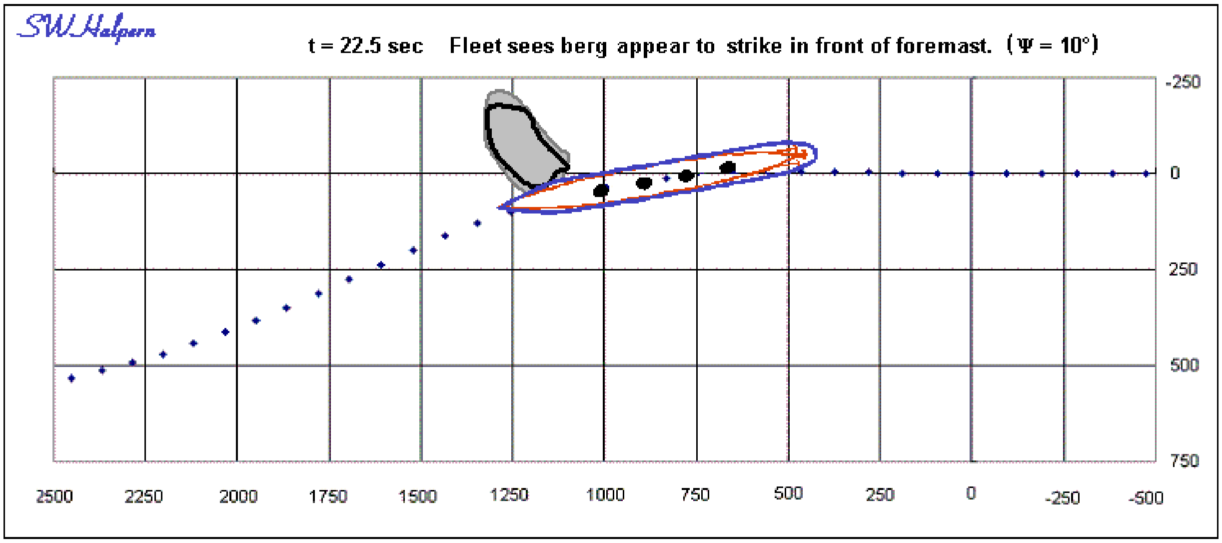
The following set of diagrams was created assuming the hard-starboard order came about 20 seconds before initial contact with the ice.



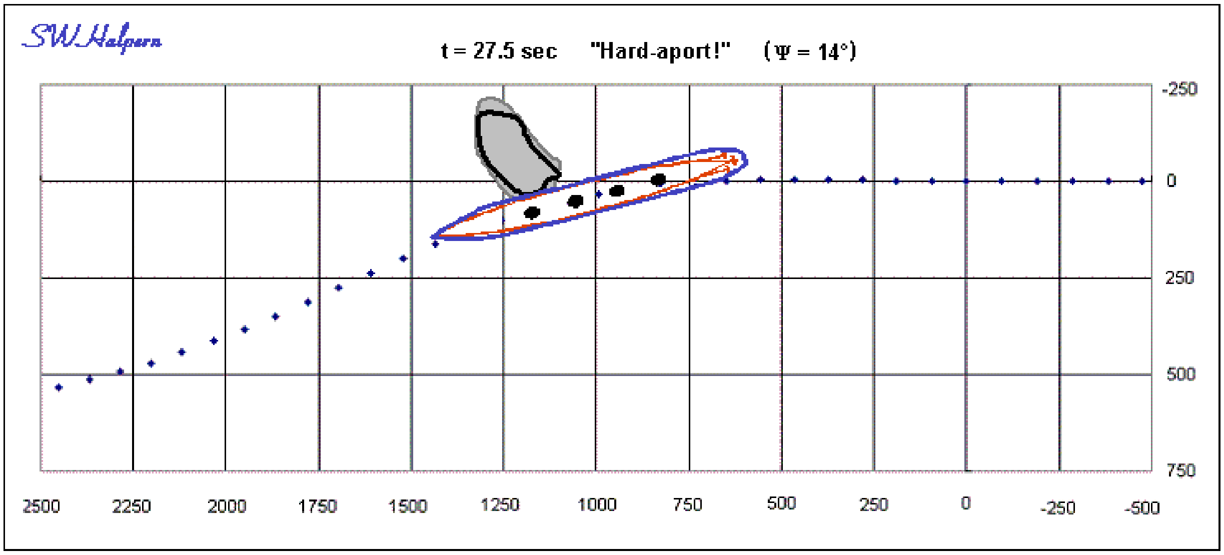




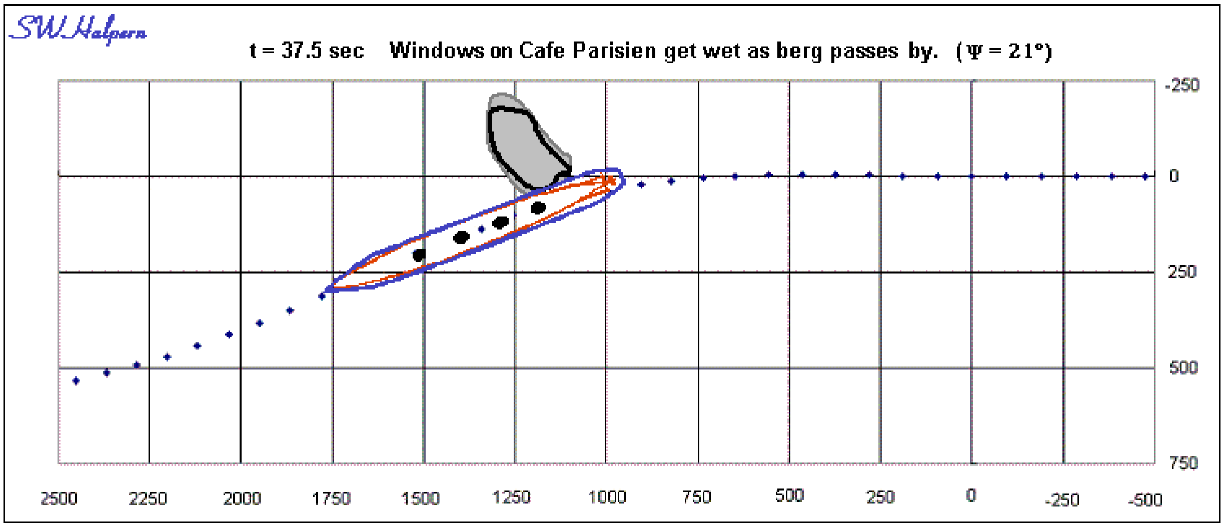
t = 20.0 sec Initial underwater contact. (ψ = 8°)

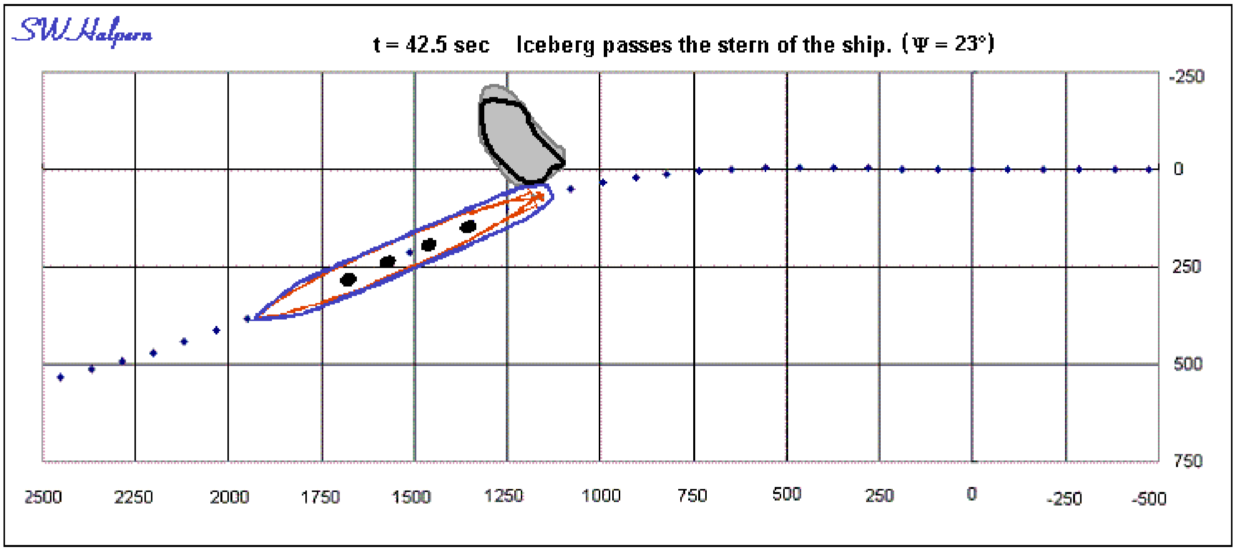


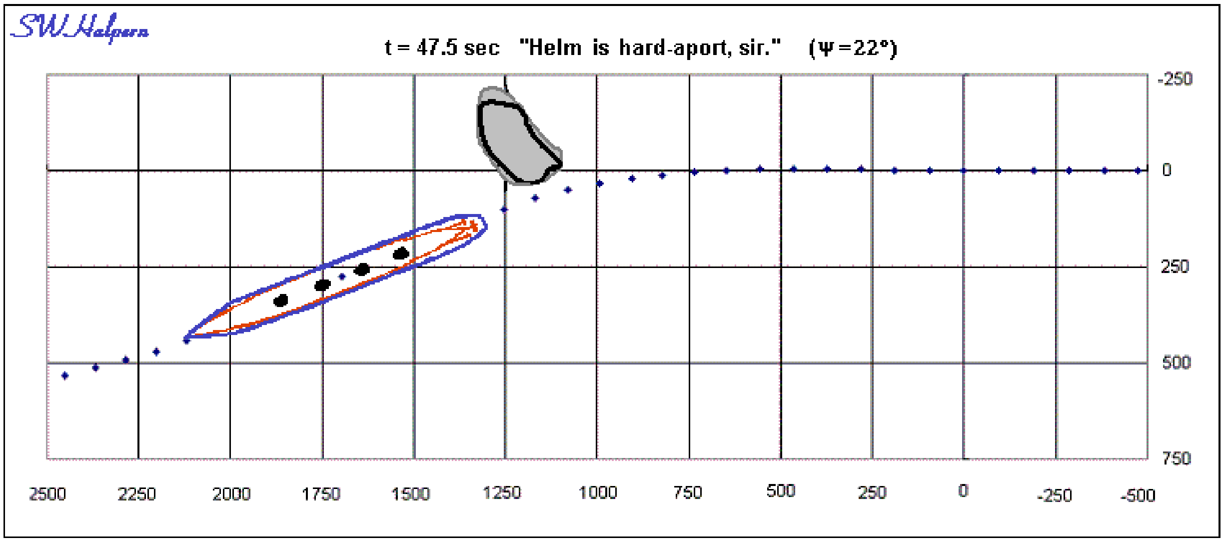
t = 22.5 sec Fleet sees berg appear to strike in front of foremast. (Ψ = 10°)

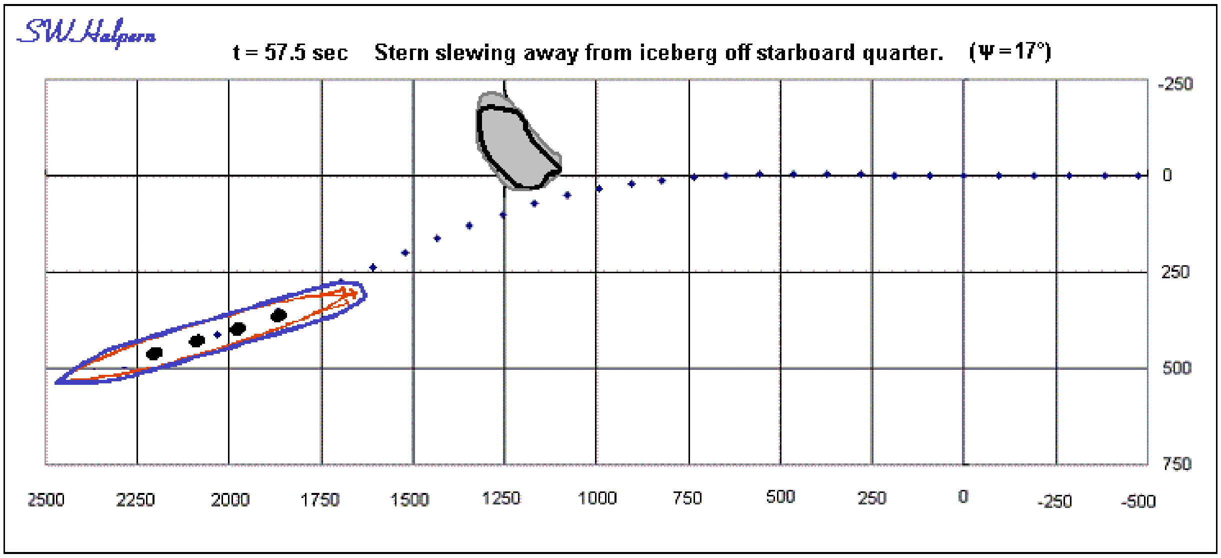


t = 27.5 sec "Hard-aport!" (ψ = 14°)


SW Halpern
t = 37.5 sec Windows on Cafe Parisien get wet as berg passes by. (Ψ = 21°)
-250
0
250
500
750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
-250
-500


SW Halpern
t = 42.5 sec Iceberg passes the stern of the ship. (Ψ = 23°)
-250
0
250
500
750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
-250
-500


SW Halpern
t = 47.5 sec "Helm is hard-aport, sir." (Ψ =22°)
-250
0
250
500
750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
-250
-500



Notice that in the sequence shown above, the visible part of the iceberg is slightly to starboard of the ship's initial course line.[14] It would appear fine on the starboard bow similar to what Fleet drew in his rough sketch of the first sighting as seen from afar. It is also likely that First Officer Murdoch saw the berg as soon as the lookout bell was struck and was watching the bearing to the berg when the call came down on the phone to the bridge. As all ship handlers know well, if the bearing to an object begins to open up you are *not* on a collision course. If it remains the same, you are on a collision course. In addition, it is also important to try and judge the distance away from the object before ordering any action taken. If you are too close, changing the heading of the ship might very well cause a collision since the initial movement of a ship entering a turn is for the stern to swing out while the ship continues to go straight ahead. If the object appears to be close at hand, the best action may not be to turn at all if it appears that the object is about to pass clear along the side.

All of this must have raced through Murdoch's mind before he ordered the helm over hard to starboard. In 1903, when he was second officer on board the *Arabic,* Murdoch allegedly was able to avoid a collision at night with a sailing vessel by countermanding an order to port the helm that was given by Chief Officer Fox, the man Murdoch was about to relieve as Officer of the Watch. According to the story, Murdoch brushed aside the quartermaster and held the wheel steady thereby preventing a collision that otherwise would have taken place.[15] What we find from this lesson is that William Murdoch did not merely react out of instinct, but took the time to access a situation before acting.

By the time sixth officer Moody repeated to Murdoch what Fleet had just told him, Murdoch decided that action must be taken, and so ordered the helm be put hard-astarboard to swing his ship's head away from the iceberg that was looming ever so larger in his direct field of view. The

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[14] The iceberg depicted in the sequence is shown with underwater and above waterline profiles.

[15] See the account, "The Life of William McMaster Murdoch," http://www.dalbeattie.com/titanic/wmmlifea.htm.

bearing line to the object had not opened as he was hoping it would. However, as it turned out, the ship was just too close to completely avoid contact and struck an underwater spur of ice on the starboard side in the vicinity of the peak tank. Within seconds, the visible part of the berg above the waterline appeared to strike the ship's side just ahead of the foremast where the crow's nest was located. Large chunks of ice then fell off the berg and into the forward well deck immediately aft of the foremast. For about 200 hundred feet, damage was rendered just above the level of the ship's tank top, opening up five major watertight compartments to the sea. Soon after the peak of the iceberg passed aft of the bridge, Murdoch ordered the helm put hard-aport to swing the stern clear in the hope of preventing further damage to the ship. But as the berg passed aft, ice fell through a few open portholes on E deck, and onto the windows of the Café Parisien high up on B deck.[16] To quartermaster George Rowe stationed out on the poop, it looked like the berg was going to hit the docking bridge there, passing within 10 feet of the ship's rail. Finally, with her swing over to port completely checked, the ship started to swing the other way, and the iceberg was seen fading away into the night off the ship's starboard quarter by several crew members who came topside to see what had happened.

Notice that in the sequence shown above, the maximum the ship's head veered off to port was 23 degrees, or about 2 points. It is likely that this peak swing to port is what QM Hichens remembered as he watched the compass card rotate in front of him as the ship was colliding with the iceberg. When the ship appeared to strike just ahead of the foremast from lookout Fleet's vantage point up in the crow's nest, her head would have already veered off to port about 10 degrees, or 1 point into the initial turn. This is when a slight jar or swaying motion was likely felt by a number of people on board the ship. The time from this jarring event to when the helm would have been reported hard over to port is about 25 seconds. It would be just about the time that Capt. Smith would be seen rushing from his quarters through the wheel house to ask William Murdoch what it was that they had struck.

WHAT ABOUT THOSE ENGINE ORDERS?

In the collision sequence we concentrated mostly on the helm orders that were given and how the ship would react to those orders. But we also know that Murdoch rang down engine orders on the engine telegraphs as well. Here we have some conflicting accounts. Fourth Officer Joseph Boxhall told the inquiries that Murdoch had ordered the engines be put "full speed astern" about the same time that he ordered the helm be put hard-astarboard.[17] According to Boxhall's story, he was just coming out of the officer's quarters on the starboard side when he hears three bells from the lookouts. He then hears the first officer give the order "hard-astarboard" and also hears the engine telegraph bells ring. Then, just before he enters the bridge, the ship strikes an iceberg. As soon as he gets onto the bridge, he sees Murdoch closing the watertight doors, turns around and finds Captain Smith standing alongside of him, who then asks Murdoch what it was they had struck. Of the three surviving eyewitnesses, Boxhall, Hichens and Olliver, only Boxhall talks about Murdoch telling Smith that he rang full speed astern on the engines and ordered the helm

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[16] In a written statement submitted by Alfred Fernand Omont to the British Wreck Commission.

[17] British Inquiry 15343-15357.

hard-astarboard. Hichens and Olliver only talk about Murdoch telling Smith that they struck an iceberg, and that he had already closed the watertight doors.[18]

Boxhall presents all these events as taking place in a very short time frame. We know the distance from the door leading out of the officer's quarters to the bridge is only about 60 feet. Again, if you use typical walking speeds for pedestrians crossing a crosswalk at a busy intersection, we find that it should take no more than about 15 seconds, including what is called startup time, for Boxhall to walk the 60 feet to the bridge.[19] During that time, all of the following had to have happened: 3 bells struck by the lookout, a phone call that came down from the crow's nest that was answered and the message given to the first officer, an order given to put the helm over and engine orders rang down on the engine telegraphs, and then enough time for the ship to turn off her course so as to strike the berg at the bluff of the bow moments before Boxhall reaches the bridge.

In contrast to this, we saw before that standby QM Olliver was at the compass platform amidships when those three-bells were struck up in the nest. Olliver had to go down the platform ladder and then down from the roof over the first class lounge to get to the boat deck in order to get to the bridge. He had to cover a walking distance of about 250 feet in all. That we estimated would take about 50 to 55 seconds. We also found that the ship would take about 22 seconds to turn about one point (about 11°), or 37 seconds to turn two points (about 23°) from the time the helm order was given. So did Boxhall really witness all that he said he did, or was he just trying to give the impression before the inquiries that there simply was no time for Murdoch to take any possible action that could have avoided the ship from striking the berg?

We cannot find any confirmation that Murdoch had given an order to reverse the engines full speed astern, as Boxhall claimed, by any surviving eyewitness who was working either below or was on the bridge when the accident happened. Even Second Officer Charles Lightoller said that he did not believe the engines were ever put full speed astern. And he should know because he took part in *Titanic's* sea trials off Belfast Lough where they actually did that.[20] If Murdoch was trying to swing the ship clear of the iceberg, the last thing he would want to do is reduce the ability of the ship to turn rapidly. On *Titanic*, the turbine engine that ran the central propeller must be stopped when going astern. This would reduce the rudder's response time because of the loss of added slip stream that comes from the ship's central propeller. But even if Murdoch gave an order to reverse, there just was not enough time to get the reciprocating engine propellers reversing before the collision took place. It was about two minutes after the collision that the valves that fed exhaust steam from the reciprocating engines to the turbine engine were seen to have lifted thereby bypassing the turbine engine.[21] And it was about then that people first noticed that the engines had come to a stop.[22] What we do know about the engines going in reverse

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[18] British Inquiry, 1026-1036; American Inquiry p. 533.

[19] TranSafety, Inc., *Road Engineering Journal*, October 1, 1997.

[20] British Inquiry, 13759; American Inquiry, p. 50.

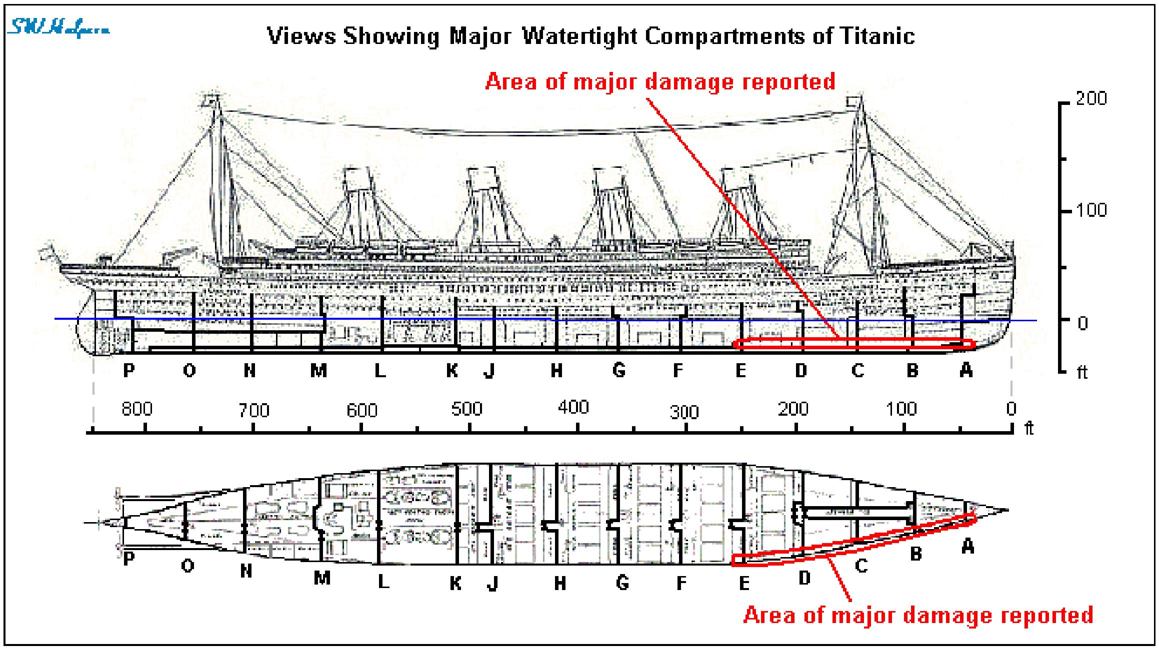
[21] British Inquiry, 3995-4003.

[22] British Inquiry, 3719-3729, 13743; American Inquiry, p. 975.

comes from witnesses who said that the engines were seen to reverse slowly for a very short time soon after they had first come to a stop. This was a minute or two after the collision, and apparently done to take the way off the ship and bring her to a complete stop. The bottom line in all of this, is that the engines played little or no part in the collision avoidance maneuver.

ICEBERG DAMAGE ALONG THE FORWARD STARBOARD SIDE

Most of the damage done to *Titanic* resulting from the allision with an iceberg happened underwater over a distance of about 200 to 250 feet, from some point forward of watertight bulkhead A to a few feet aft of watertight bulkhead E.



Notice that the area that major damage that was reported was along the part of the bow where the hull was widening toward the full breadth of the ship.[23] The reason for this has to do with how the ship and the iceberg made contact. When the ship hit the iceberg it was already in a turn to port thereby exposing her starboard side to the berg. The pivot point of the ship was located approximately under the forward well deck in the general vicinity of bulkhead C as we have seen. To an observer at the pivot point, the ship would appear to be turning around a point that was at right angles to the ship's centerline and to the inside of the turn. At the location of the pivot point, the path of the water flowing aft past the hull would appear to run parallel to the ship's centerline, while amidships it would appear to be run an angle to the ship's centerline equal to the drift angle that we talked about previously. The side of the ship near the tank top ahead of bulkhead D makes an angle of about 12° with respect to the centerline. That would be the strike angle with the berg. As a result, two impulsive force components would have been

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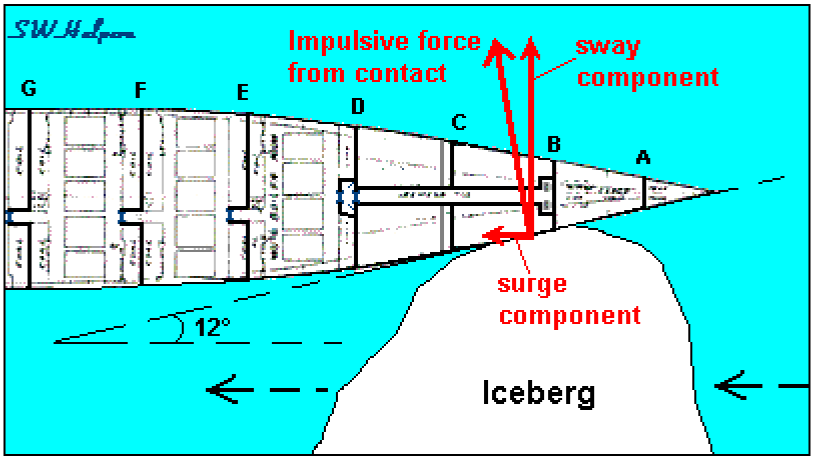
[23] There may have been some additional minor damage under stokehold plates in boiler room No. 4. See my article, "Where Did That Water Come From?" at http://www.titanicology.com/FloodingInBR4.html.

created; one a sway component trying to push the bow away from the berg, and the second a smaller surge component tending to slow the ship down. The sway component would be about 5 times greater than the surge component as seen in the vector diagram below.



It is the relatively rapid change in momentum caused by the impulsive force of the collision that produced the damage to the hull of the vessel, not some slight pressure acting along the side of the ship. The initial impulsive force can be estimated knowing the speed and mass of the ship, the strike angle, and the approximate point of initial contact. The details of this analysis are summarized in Appendix G.

The total loss of energy by the ship during the initial contact with the iceberg was very small, only 31,540,000 ft-lbs compared to 2,070,000,000 ft-lbs of total kinetic energy before collision. That is a loss of about 1.5% due to the crushing of ship structure. The ship's speed immediately after the impact was not significantly reduced, and only a very small sway component and an extra rotational component was imparted. All this matches well with the many eyewitness accounts that the collision was barely perceptible. To many it was just a grinding sound that lasted for a few seconds. To others it felt like some form of vibration. Some people actually slept through the collision and were awakened afterward by the stopping of the ship's engines or noises heard in the hallways. And some said it felt like a large wave struck the ship producing a very slight swaying motion not enough to spill water from a glass.

A few people reported feeling more than one continuous encounter. For example, second class passenger Lawrence Beesley was reading in his cabin just aft of the second class dinning room on D deck:[24]

> “There came what seemed to me nothing more than an extra heave of the engines and a more than usually obvious dancing motion of the mattress on which I sat. Nothing more than that--no sound of a crash or of anything else; no sense of shock, no jar that felt like one heavy body meeting another. And presently the same thing repeated with about the same intensity.”

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[24] Lawrence Beesley, *The Loss of the SS Titanic*, 1912, Ch. III.

The witnessing of what appeared to be more than one contact event with the iceberg was probably due to multiple strikes along the forward starboard side as the berg swept aft. We know that the damage was not just one continuous long gash, but several small non-continuous openings where rivets popped off causing seams in the hull plates to separate. The total composite area of damage amounted to about 12 square feet.[25] We also know that most of the damage ended by the time the ship's hull had completely widened out at the tank top level, although there is also much evidence that part of the iceberg continued to make some contact along the ship's side at least as far back as the Café Parisien as previously noted. However, there was not sufficient side pressure to cause any significant observed damage to the ship beyond the first five major watertight compartments. We also know that the aft part of the bilge keel visible on the wreck itself shows no sign of iceberg related damage.[26] This tends to suggest that the iceberg itself had sustained damage from the ship as the bilge area cut through the ice running along the side and under it as it widened out.

It can also be shown that even if the rudder was not shifted, once the momentum of the ship had changed as a result of the initial set of contacts along the forward starboard side, any remaining force caused by side contact with the berg along the ship's side would not be much greater than the hydrodynamic force of water acting on the ship's fully deflected rudder when running at full speed ahead. The maximum contact pressure (in force per unit area) would likely be no greater than the pressure on the rudder itself if the contact area with the iceberg were about 500 square feet. All of this is explained in Appendix H.

SUMMARY

In 1912, Edward Wilding, a Harland & Wolff naval architect, presented data on the turning characteristics of *Olympic* and her sister ship *Titanic*. Based on the data presented, and on an analytical turning model that was developed, we were able to recreate the turning circle of these ships when the helm was put hard over and the ship going at full speed ahead. What we found are the following:

Initial approach speed	22.5 knots
Maximum rudder angle	40°
Advance	2746 ft
90° Transfer	1745 ft
Tactical diameter	3860 ft
Speed in steady-state turn	17.4 knots
Time to turn 23°	37.5 sec
Forward movement in 37.5 sec	1316 ft
Lateral movement in 37.5 sec	109 ft

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[25] Samuel W. Halpern, "Somewhere About 12 square Feet," TRMA website at http://titanic-model.com/articles/Somewhere_About_12_Square_Feet2/Somewhere_About_12_Square_Feet2.pdf.

[26] The bilge keel extended outward and downward along the turn of the bilge. It did not extent beyond the maximum width of the ship, and so would not be damaged by a wall of ice in contact with the ship's side.

Time to turn 360°	412 sec
Advance relative to 360° point	2130 ft
Drift angle in steady-state turn	8°
Angle of heel in steady-state turn	6°

We also considered the performance of the ship during zig-zag maneuvers where the helm was ordered shifted over to the opposite side at some time, t_2, after the initial helm order was given. We then found the peak swing of the ship's head toward the original direction of turn before being checked, and the time it took for that peak to be reached. These results are summarized in the table below:

Time order to shift rudder given	**Ship's heading at time of order**	**Time when peak swing reached**	**Peak swing of ship in original direction**
22.5 sec	10.0°	37.5 sec	18.5°
27.5 sec	14.2°	45.0 sec	22.9°
37.5 sec	23.0°	55.0 sec	31.9°

We also looked at the classic story of *Titanic's* encounter with the iceberg. We found that the conclusion in the British Wreck Commission report did not include the half minute of time given by both lookout Fleet and QM Hichens for the phone call and exchange of information that took place from the lookouts in the nest to the officer in the wheelhouse before the hard-astarboard order was given. The report concluded that about 40 seconds had passed from when the iceberg was first sighted to when the collision occurred, and that the ship had turned about 2 points (22.5°) when the iceberg was struck on the starboard side. We have shown that if the ship had turned that amount when she first struck the berg, the berg would have had to be centered on the port side of the ship's approach course when the order to turn to port was first given. This does not fit with what was described.

We also have shown it would take about 50 to 55 seconds for QM Olliver out on the compass platform amidships to get to the bridge just as the ship struck. Olliver left the platform when he heard the 3-bell warning from the lookouts, and was entering the bridge just as the ship struck. During that time the call came down from the nest. Since QM Hichens received the hard-astarboard helm order after Sixth Officer Moody repeated what the lookout message was to First Officer Murdoch, a time of about 20 to 25 seconds seems to be a more realistic value from when the helm order was first given to when the ship struck the iceberg. In that time the ship would have turned about one point, which is consistent with what lookout Fleet said, and consistent with the berg being seen fine off the starboard bow when Murdoch ordered the helm be put hard-astarboard.

We also showed that QM Hichens' claim that the ship had turned two points just as she struck is inconsistent with his claim that he just managed to get the wheel hard over when she struck. Turning the wheel the full 4 turns needed would take about 10 seconds, while the ship needs about 37 seconds to turn two points. The two points mentioned by Hichens is more likely the maximum swing of the ships head to port when her swing was finally checked by the subsequent action of Murdoch calling for the helm to be put hard-aport and the berg passing along the starboard side. That action was most likely taken to minimize further damage in an attempt to swing the ship's stern away from the berg as it passed aft. As it were, the iceberg remained close to the ship's side as far back as the poop deck where it was seen to pass within 10 feet of the rail.

We also considered the dynamics of the initial impact with the iceberg and showed that the loss of energy was very small, about 1.5% of the ship's total kinetic energy before collision. That damage was caused by impulsive strikes along the starboard side forward that were sharp enough to open up several non-continuous seams in the ship's shell plating covering a distance of about 200 to 250 feet. This allowed water to enter the first 5 major watertight compartments. Furthermore, we showed that once the ship's underwater hull form widened out to the full breadth of the ship, any remaining side contact with the iceberg would not be enough to cause any deformity in the shell plate, but would allow ice to be deposited through open port holes and onto windows as was observed in different parts of the ship.

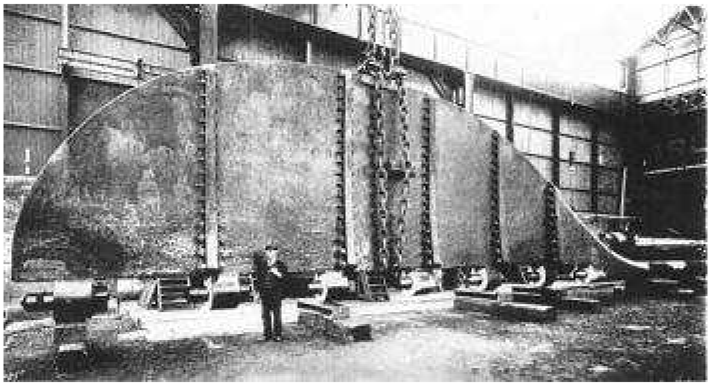
ACKNOWLEDGEMENT

I would like to thank Professor Fotis A. Papoulias of the Deptartment of Mechanical Engineering at the Naval Postgraduate School in Monterey, CA, for his kind permission to use several of the diagrams from his works on Ship Dynamics and Ship Maneuvering that appeared in several supplementary lecture notes for his lecture series TS4001. Much thanks must also be given to Capt. Charles Weeks for his critical review of this paper and the constructive suggestions he offered me. I also would like to acknowledge and thank George Behe and Bill Wormstedt for taking the time to review this work and for their helpful editorial comments. Finally, I would like to thank Ed Kamuda of the Titanic Historical Society for allowing me to use the sketch by *Titanic's* lookout Frederick Fleet of the first sighting of the iceberg.

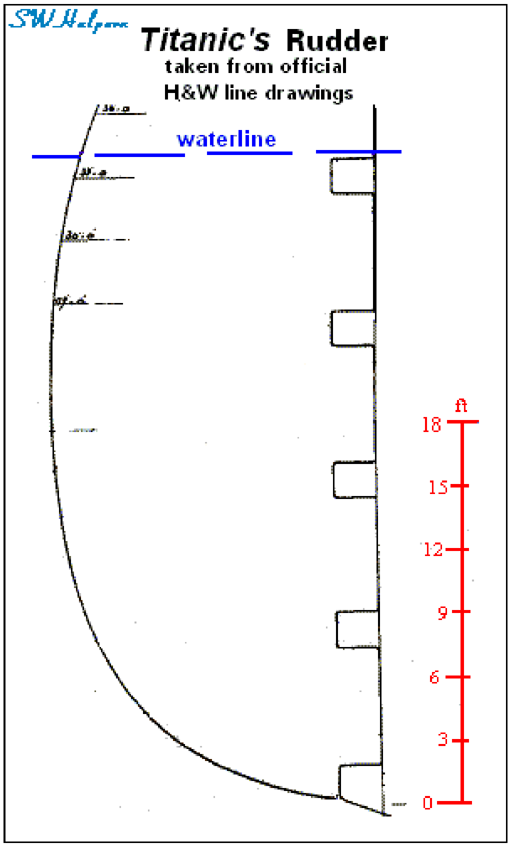
APPENDIX A – RUDDER FORCES

One of the things that we can get a good estimate of is the force acting on *Titanic's* rudder when the ship was traveling at full speed ahead and the rudder put hard over.

A photograph from *Engineering* of *Olympic's* rudder, which was identical to *Titanic's*, is shown below.



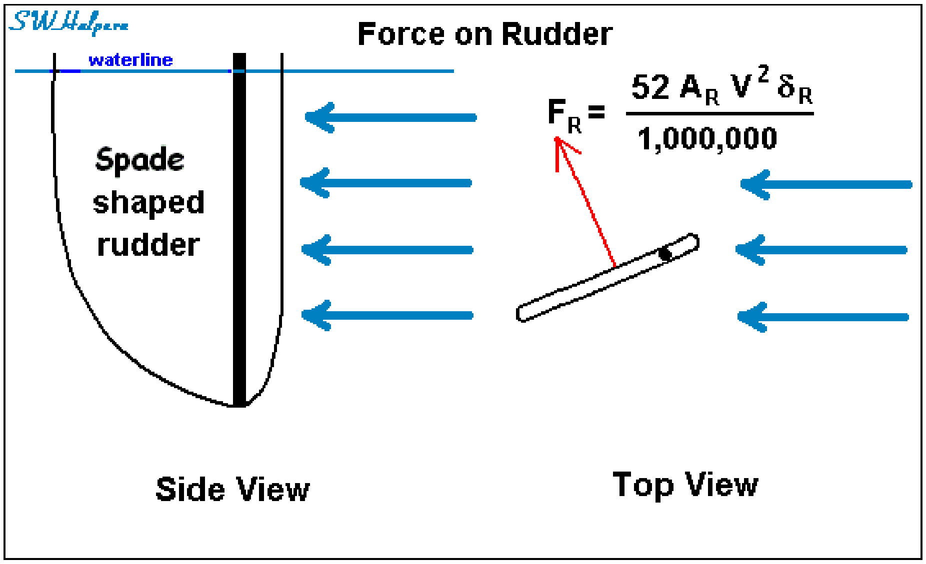
Details of *Titanic's* rudder below the waterline are shown in the diagram below. This was taken directly from H&W line drawings.



As seen in the photograph and in the drawing, *Titanic's* rudder was essentially a flat plate having somewhat of a spade shape in underwater profile. For a spade-shaped rudder working behind a ship's propeller, the force, F_R, acting on the rudder when it is deflected at an angle δ_R to the slip stream of the water is given approximately by:[27]

$$\mathbf{F_R = (52\ A_R\ V^2\ \delta_R)/1{,}000{,}000}$$

Where F_R is the force in long tons acting perpendicular to the plane of the rudder, A_R is the rudder area in square feet, V is the speed of the of the ship in knots, and δ_R is the rudder angle in degrees.



For *Titanic* running at 22.5 knots, and a full rudder deflection angle of 40 degrees, the force calculates out to 423 tons. Since the underwater area of the rudder works out to be about 402 sq. ft., this force would create a pressure of about 1.05 tons per square foot on the rudder plate.

A similar analysis assuming a simple rectangular plate rudder as shown below gave almost identical results.[28] Dividing the calculated rudder torque by the location of the center of pressure aft of the leading edge produced a rudder force of 421 tons, essentially the same as calculated for a spade-shaped rudder.

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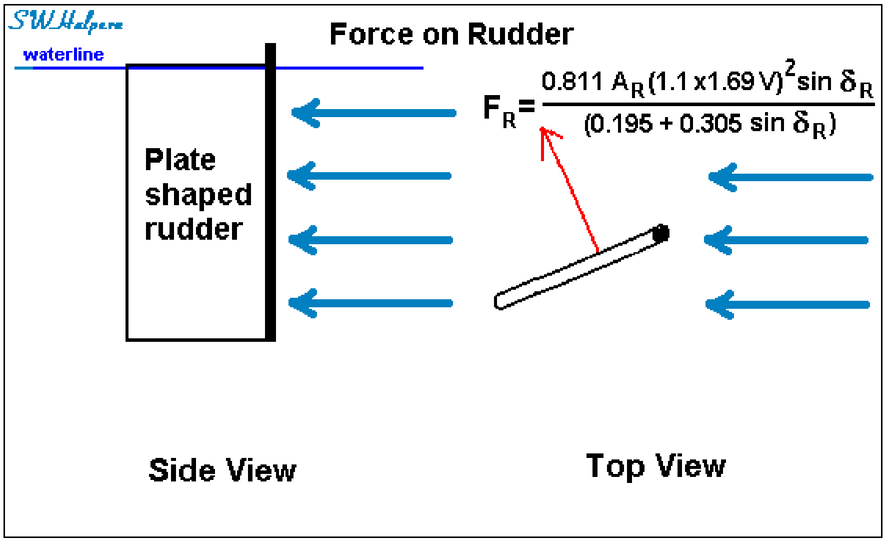
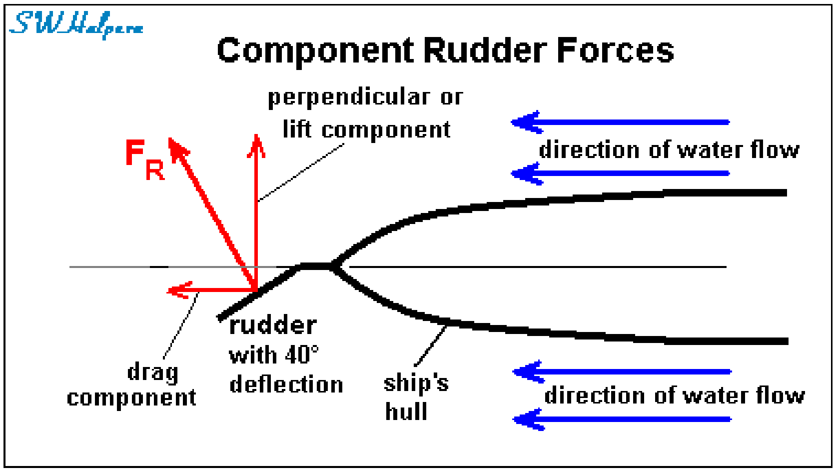
[27] See: http://www.sname.org/NAME/problem7.pdf. The original equation in the reference was for metric units. The rudder area was computed using Simpson's first rule.

[28] See: http://www.sname.org/NAME/problem8.pdf. In this case we used the velocity of the slip stream caused by *Titanic's* central propeller turning at 170 rpm and producing a slip of about 9.5%.This was derived from an analysis of speed vs. revolutions which was documented in an article which can be accessed at: http://www.encyclopedia-titanica.org/item/5661. This results in a slip stream velocity that is 1.1 times greater than the ship's speed through the water, or 24.9 knots across the rudder with the ship moving at V=22.5 knots.



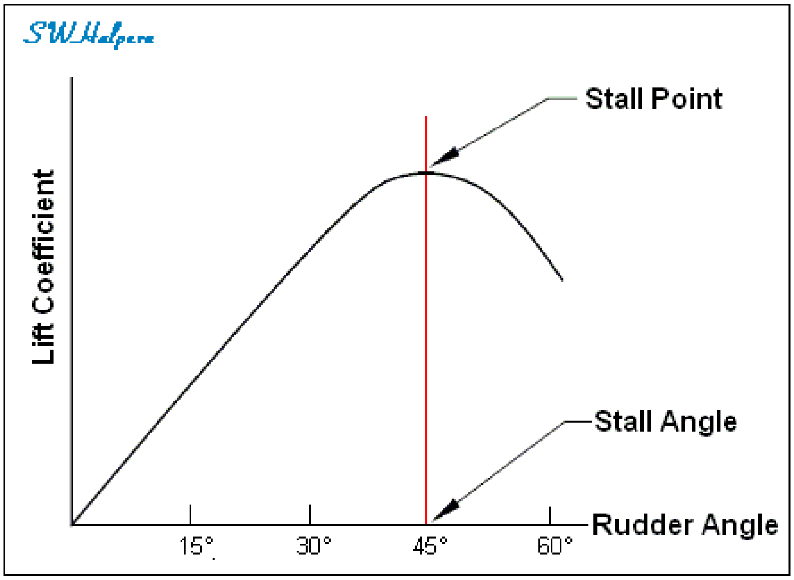
Since the maximum rudder deflection was 40° relative to the ship’s centerline under full helm, the force on the rudder would result in two forces acting on the ship. One force component, the lifting force, would be perpendicular to the ship’s forward movement, the other force component would be parallel but opposite in direction to the ship’s forward movement. The perpendicular or lifting force would set up a turning moment on the hull, while the parallel force would act as an added drag component on the hull trying to slow the vessel down. These two components are shown in the diagram below. With F_R = 423 tons of total force acting on *Titanic’s* rudder at the beginning of the turn, the perpendicular force component works out to be about 324 tons, and the drag component works out to be about 272 tons. These are both seen in the vector diagram below.



For a majority of hull forms, the greater the ship speed the faster the response time (a good thing); and the greater the amount of overshoot (a bad thing). This is because a greater speed increases the generated rudder force for a given rudder angle thereby causing the ship’s heading angle to veer off the original course heading more quickly. But the greater the ship speed also causes the ship to initially advance further forward in a given amount of time. It is also not surprising that a ship fitted with a large rudder will be more maneuverable than a ship fitted with a smaller rudder running at the same speed since rudder force is also directly proportional to rudder area. For a given ship speed, increasing the rudder dimensions will shorten the response time and slightly reduce the overshoot experienced by the hull.

The size of a ship's rudder in square feet is usually expressed as a percentage of the product of the ship's length between perpendiculars and the ship's draft.[29] For *Titanic*, this works out to be about 1/73 = 0.014. In comparison, *Lusitania* had a value of about 1/60 = 0.017.[30] A relatively narrow, deep rudder like *Titanic's* will tend to produce a greater pressure than a rudder of broad, shallow shape with the same area. Plus, having the rudder placed directly behind of one of ship's propellers increases it's efficiency due to the greater speed of the slip stream of water that would run past it, an advantage that *Titanic's* rudder had being positioned directly aft of the central screw.

At relatively small rudder angles, rudder force is created due to the difference in water flow rates across the port and starboard sides of the rudder. For a given speed, the force increases approximately in proportion to rudder angle. However, as the rudder angle increases, the amount of flow separation in the slip stream of the water over the rudder increases until a full stall occurs at about an angle of 45 degrees.



The maximum angle to which most rudders are put is about 35° to either side of the ship's centerline. *Titanic's* rudder, however, could be put over to 40° which is getting very close to the rudder stall point, the point beyond which the rudder produces less lift but significantly increasing drag.

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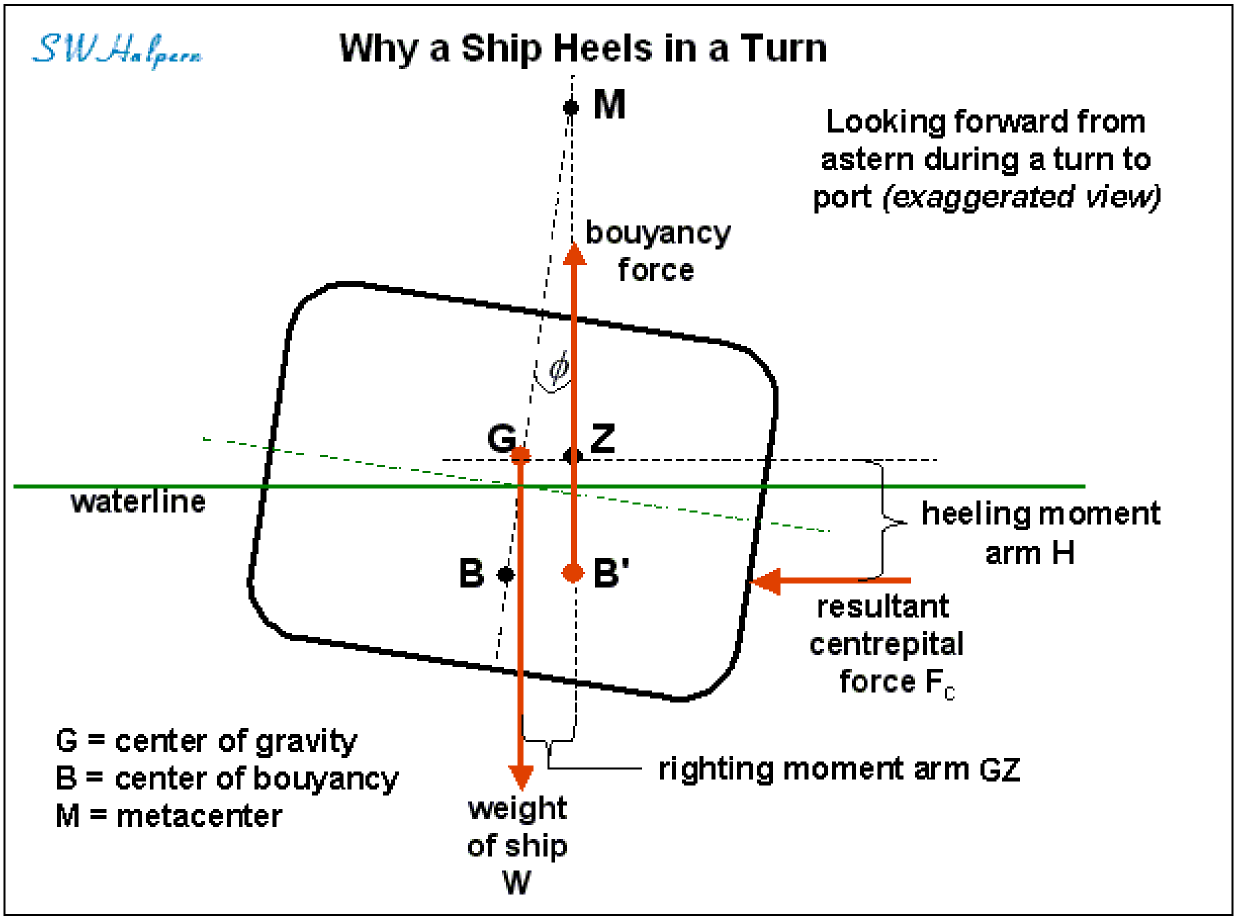
[29] See the related article on the rudder size issue by Capt. Charles Weeks, "Was The *Titanic's* Rudder Large Enough?" *Encyclopedia Titanica Research Paper*, at http://www.encyclopedia-titanica.org/titanic-rudder.html.

[30] Edward L. Attwood, *Theoretical Naval Architecture*, Longmans, Green and Co., 1922.

APPENDIX B – ANGLE OF HEEL IN A STEADY-STATE TURN

This centripetal force acting on the hull during a turn will be located approximately about ½ the ship's draft below the waterline near amidships. This will be a distance, H, below the ship's center of gravity thereby creating a heeling moment of H x F_C. To counter this heeling moment, the ship in the heeled condition will have a displaced center of buoyancy, B', as shown in the diagram below.



The displaced center of buoyancy in turn creates a righting moment of GZ x W, where GZ is the righting arm equal to GM sin ϕ, and W is the force of buoyancy which must equal the ships displacement weight in tons. For relatively small angles of heel, the righting moment is therefore given by:

$$\mathbf{W \times GM \sin \phi}$$

where in the above, GM is the distance between the ship's metacenter (M) and center of gravity (G), W is the ship's displacement weight, and ϕ is the angle of heel.

This righting moment must equal the heeling moment produced by H x F_C.

But the total centripetal force acting on the hull, F_C, is given by:

$$\mathbf{F_C = W/g \times V^2/R}$$

Where W again is the ship's displacement weight, V is the ship's speed in the turn, R is the radius of turn, and g the acceleration of gravity.

Setting these two equations equal to each other, we can easily solve for ϕ,

$$\mathbf{W \times GM \sin \phi = H \times F_C = H\ W/g \times V^2/R}$$

$$\mathbf{\sin \phi = H/GM \times V^2/R/g}$$

which for small angles of heel simplifies to:

$$\mathbf{\phi = H/GM \times V^2/R/g \times 57.3 \text{ (in degrees)}}$$

For *Titanic* we can take $H \approx 19.6$ ft, and GM = 2.6 ft.[31] Using V = 29 ft/sec (about 17 knots in steady-state turn), R = 1,875 ft, and g = 32 ft/sec^2, an estimated angle of heel of about 6° is obtained for a full speed turn with hard over rudder.

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[31] From Samuel Halpern, "A Matter of Stability and Trim," available on line at the TRMA website (http://titanic-model.com/db/research.shtml), we see the height of G above the keel was KG = 35.7 ft, the draft was T = 32.25 ft, and the ship's GM was 2.63 ft on April 14, 1912. H is taken as equal to (KG - T) + T/2 = KG - T/2. Using the above values for KG and T, we get H = 19.6 ft.

APPENDIX C – DRAG FORCE AS A FUNCTION OF DRIFT ANGLE

The force of drag acting on the hull is proportional to the square of the ship's speed through the water, and can be expressed as:

$$F_D = C(\beta)\ V^2$$

where $C(\beta)$ is a drag coefficient that depends on the drift angle β, and V is the speed of the ship.

The coefficient of drag can be written as:[32]

$$C(\beta) = K_1 + K_2\beta^2$$

Notice that before the turn begins, $V = V_0$, and $\beta = 0$. Therefore, $C(0) = K_1$, and $F_D = K_1\ V_0^2$. This drag component force must equal the thrust component, F_T, that is acting on the hull of the ship from its propellers which are turning at a given number of revolutions per minute.

Therefore,

$$F_T = F_D = K_1\ V_0^2$$

During the turn, the drift angle is not zero, and the force of drag is $F_D = (K_1 + K_2\beta^2)\ V^2$. As β first increases, the drag force will start to increase from what it was before because of the non-zero term $K_2\beta^2$. As a result, the ship will start to slow down as this force starts to build up. However, as the ship starts to slow down, the drag force will tend to become less because this force is also proportional to V^2 which is starting to decrease. For a fixed speed, the drag component must equal the thrust component otherwise the ship will want to either accelerate or decelerate, depending on which of the two forces, thrust or drag, is the greater. Therefore, we have:

$$F_T = F_D = (K_1 + K_2\beta^2)\ V^2$$

when the speed is down to V during a turn.

With the propellers producing the same amount of thrust at a given steam supply rate, we get:

$$F_T = K_1\ V_0^2 = (K_1 + K_2\beta^2)\ V^2$$

Therefore,

$$(V/V_0)^2 = K_1/(K_1 + K_2\beta^2) = 1/(1 + \beta^2\ K_2/K_1)$$

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[32] Capt. Max J. van Hilten (Maritime Pilots' Institute Netherlands), Dick Engelbracht (Royal Netherlands Naval College), Captain Jim Vink (Royal Netherlands Naval College), and Freek Verkerk (MARIN's Maritime Simulation Centre Netherlands), "Unpredictable Behaviour," *Port Technology International*, Edition 9, 1999.

For *Titanic* we found that in the steady-state turn with full rudder, $V/V_0 = 0.775$, and $\beta = 8.16°$. Using these values in the above equation, we find that $K_2/K_1 = 0.010$.

In our turning model we will consider an initial approach speed of $V_0 = 22.5$ knots. Therefore, the speed of the ship in a turn as a function of drift angle β is:

$$V = V_0 \, / \, \mathrm{sqrt}\,(1 + 0.01\ \beta^2) = 22.5 \, / \, \mathrm{sqrt}\,(1 + 0.01\ \beta^2) \qquad \text{for } 0° \le \beta \le 8.16°$$

APPENDIX D – SOLUTION TO NOMOTO'S K AND T INDICES EQUATION

Nomoto's K and T indices equation for a ship's heading angle is given by:

$$T\Psi'' + \Psi' = K\,\delta_R$$

where Ψ is the heading angle, Ψ' is the rate of change of the heading angle Ψ with respect to time, Ψ'' is the rate of change of Ψ' with respect to time, δ_R is the position of the rudder angle over time, and T and K are indices to be determined.

The change in rudder angle over time is taken as linear between $t = 0$ and $t = t_1$ and is given by:

$$\delta_R = \delta_a\, t/t_1$$

where δ_a is the maximum rudder deflection. (For *Titanic* this is 40°.)

The solution to Nomoto's indices equation is taken for two periods: phase 1, when $0 \leq t \leq t_1$; and for phase 2, when $t \geq t_1$.

For phase 1, the solution is:

$$\Psi = K\delta_a T/t_1\ [T\,(1 - e^{-t/T}) - t + t^2/2T] \qquad \text{for } 0 \leq t \leq t_1 \quad (1)$$

For phase 2, the solution is:

$$\Psi = C_1 T(1 - e^{-(t-t_1)/T}) + K\delta_a(t - t_1) + \Psi_1 \qquad \text{for } t \geq t_1 \quad (2)$$

where $C_1 = K\delta_a T/t_1(e^{-t_1/T} - 1)$ and $\Psi_1 = \Psi$ at $t = t_1$ using equation (1) above.

Notice that in equation (2) as $t \Rightarrow \infty$, entering the steady-state phase, $\Psi \Rightarrow \Psi_1 + C_1\, T + K\,\delta_a\, t$. The slope of this curve is $K\,\delta_a$, which is the rate of change of the ship's heading vs. time in a steady-state turn (phase 3). For *Titanic*, $K\,\delta_a = 0.9$ degrees/sec using 17.44 knots in the steady state. Since $\delta_a = 40°$, we find that the value of **$K = 0.023$** per sec.

The other index, T, can also be obtained by finding $t = \tau$ when the curve for the asymptote crosses 0. This gives us, $0 = \Psi_1 + C_1\, T + K\,\delta_a\,\tau$ which can be easily solved for τ in terms of the other parameters. The result is $\tau = T + t_1/2$.

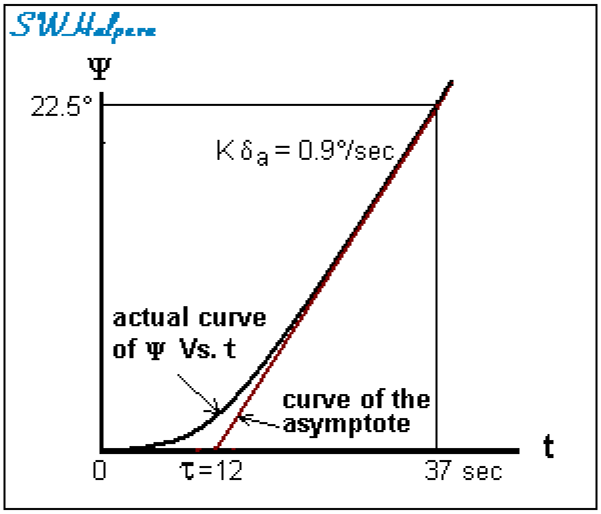
We also know that *Olympic* turned 22.5° in 37 seconds when the rudder was put over hard at full speed ahead. We also found that the slope of the asymptote curve is $K\,\delta_a = 0.9°$ per sec. Therefore,

$$37° - \tau = 22.5°/0.9°/\text{sec} = 25 \text{ sec}$$

or solving for τ gives $\tau = 37 - 25 = 12$ sec, the point in time where the asymptote curve crosses zero. Since $\tau = T + t_1/2 = 12$, we can solve for T if we know the value of t_1, the time it takes for the rudder to be put over.

In ships of *Titanic's* day, it took about 8 turns of the wheel to put the helm full over from one side all the way to the other side, or 4 turns of the wheel from centered to hard over on one of the sides.[33] Therefore, it is reasonable to assume that it takes about $t_1 = 10$ seconds for *Titanic's* helm, which is under the control of the ship's steering engine, to go from 0° all the way over to 40° on one side. With that we have $\tau = T + t_1/2 = T + 5 = 12$, which gives us a value for the T index of **T = 7** seconds.

A plot of Ψ vs. t is shown below along with the curve of the asymptote which is given by setting $\Psi = \Psi_1 + C_1 T + K \delta_a t$.



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[33] Nicholls's Seamanship and Nautical Knowledge.

APPENDIX E – CHANGE OF DRIFT ANGLE OVER TIME

As a ship enters a turn a drift angle, β, is built up between the ship's course angle and heading angle. This drift angle creates an angle of attack between the direction of the movement of water and the centerline of the hull thereby creating a hydrodynamic lifting force acting on the hull that causes the ship to turn. But there is also an increased hydrodynamic drag force acting on the hull causing the ship to slow down from its initial approach speed while in a turn. As we have seen, the speed of the ship in the turn will depend on the drift angle that is created. To get the complete turning circle for a ship, we need to know not only how its heading changes over time, but how its drift angle and speed change over time.

The heading change over time was derived from Nomoto's indices equation. We also derived a relationship of speed in the turn as function of drift angle. What we need is a relation for how the drift angle changes over time so we can derive the complete turning circle, which is specified by the ship's Advance, Transfer, and Tactical diameter.

The change in drift angle appears to be some form of exponential function which starts at zero and approaches a maximum value in the steady-state turn. We will therefore model the drift angle by the simple exponential function:

$$\beta = \beta_m \left(1 - e^{-t/T_B}\right)$$

where β_m is the magnitude of steady-state drift value, which for *Titanic*, is equal to 8.16° for hard over helm.

The time constant value T_B in the above equation is a parameter which can be chosen to produce the correct result for the ship's tactical diameter. We know from Wilding that the tactical diameter for *Titanic* in a full speed turn with hard over helm was seen to be between 3,800 and 3,900 feet. It appears that a value of $T_B \approx 30$ sec will produce the correct tactical diameter for *Titanic* in our turning model.

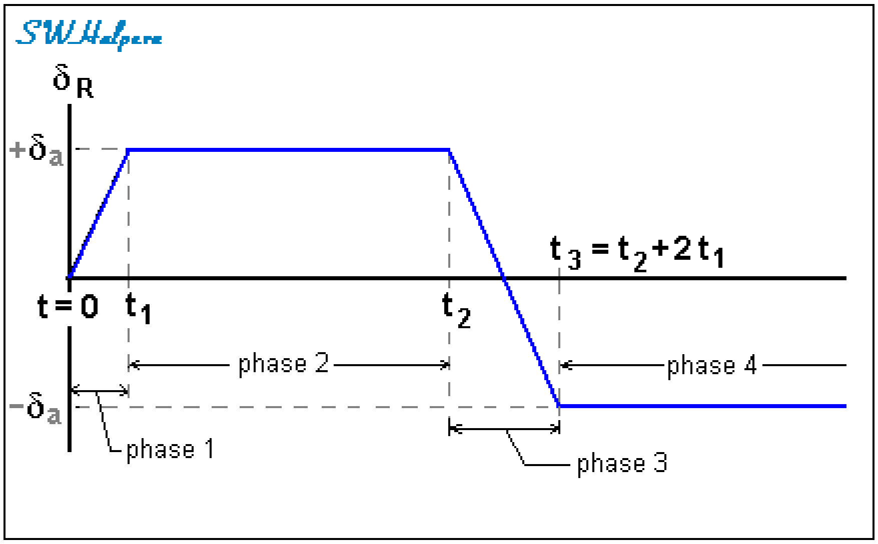
In a zig-zag maneuver, the helm is shifted over to the opposite side at time t_2. Therefore, for the zig-zag maneuver we will model the drift angle function by the following:

$$\begin{aligned} \beta &= \beta_m \left(1 - e^{-t/T_B}\right) && \text{for } 0 \leq t \leq t_2 \\ &= (\beta_2 + \beta_m)\, e^{-(t - t_2)/T_B} - \beta_m && \text{for } t \geq t_2 \end{aligned}$$

where β_2 is equal to β at $t = t_2$, or $\beta_2 = \beta_m \left(1 - e^{-t_2/T_B}\right)$, and β_m is the magnitude of the steady-state drift value for the ship noted as before.

APPENDIX F – HEADING ANGLE IN ZIG-ZAG MANEUVER

For a simple zig-zag maneuver the ship's helm is shifted twice, the first at t = 0 and the second time at $t = t_2$. A plot of the rudder angle is shown below.



The change in rudder angle over time is taken as:

$$\begin{aligned} \delta_R &= \delta_a\, t/t_1 && \text{for } 0 \le t \le t_1 \\ &= \delta_a && \text{for } t_1 \le t \le t_2 \\ &= \delta_a\,[1-(t-t_2)/t_1] && \text{for } t_2 \le t \le t_3 \\ &= -\,\delta_a && \text{for } t \ge t_3 \end{aligned}$$

where $t_3 - t_2 = 2\,t_1$, and again δ_a is the maximum rudder deflection off center, which for *Titanic* was 40°.

The solution to Nomoto's equation is now taken for four periods: phase 1, when $0 \le t \le t_1$; phase 2, when $t_1 \le t \le t_2$; phase 3, when $t_2 \le t \le t_3$; and for phase 4, when $t \ge t_3$.

As before, for phase 1, the solution is:

$$\Psi = K\delta_a T/t_1\,[T\,(1 - e^{-t/T}) - t + t^2/2T] \qquad \text{for } 0 \le t \le t_1 \quad (1)$$

And as before, for phase 2, the solution is:

$$\Psi = C_1\,T\,(1 - e^{-(t-t_1)/T}) + K\delta_a(t - t_1) + \Psi_1 \qquad \text{for } t \ge t_1 \quad (2)$$

where, as before, $C_1 = K\delta_a T/t_1\,(e^{-t_1/T} - 1)$ and $\Psi_1 = \Psi$ at $t = t_1$ using equation (1) above.

For phase 3, which is for $t_2 \leq t \leq (t_2 + 2t_1)$, Nomoto's equation is:

$$T\Psi'' + \Psi' = K\delta_a (1 - \tau/t_1)$$

where Ψ is again the heading angle, Ψ' is the rate of change of the heading angle Ψ with respect to time, Ψ'' is the rate of change of Ψ' with respect to time, and $\tau = t - t_2$ which is for $0 \leq \tau \leq 2t_1$.

The solution for Ψ in this equation is:

$$\Psi = C_2T(1-e^{-\tau/T}) + K\delta_a\tau - K\delta_aT/t_1[(1-e^{-\tau/T})T - \tau + t^2/(2T)] + \Psi_2 \text{ for } 0 \leq \tau \leq 2t_1 \quad (3)$$

where Ψ_2 is Ψ at $t = t_2$ using equation (2) above, $C_2 = C_1\, e^{-(t_2 - t_1)/T}$, and $C_1 = K\delta_aT/t_1\, (e^{-t_1/T} - 1)$ as before.

For phase 4, which is for $t \geq (t_2 + 2\, t_1)$, Nomoto's equation is simply:

$$T\Psi'' + \Psi' = -K\delta_a$$

The solution to this using $\tau = t - (t_2 + 2\, t_1)$ is:

$$\Psi = C_3T(1-e^{-\tau/T}) - K\delta_a\tau + \Psi_3 \text{ for } \tau \geq 0 \qquad (4)$$

where Ψ_3 is Ψ at $t = t_3 = t_2 + 2t_1$ using equation (3) above with $\tau = 2\, t_1$,

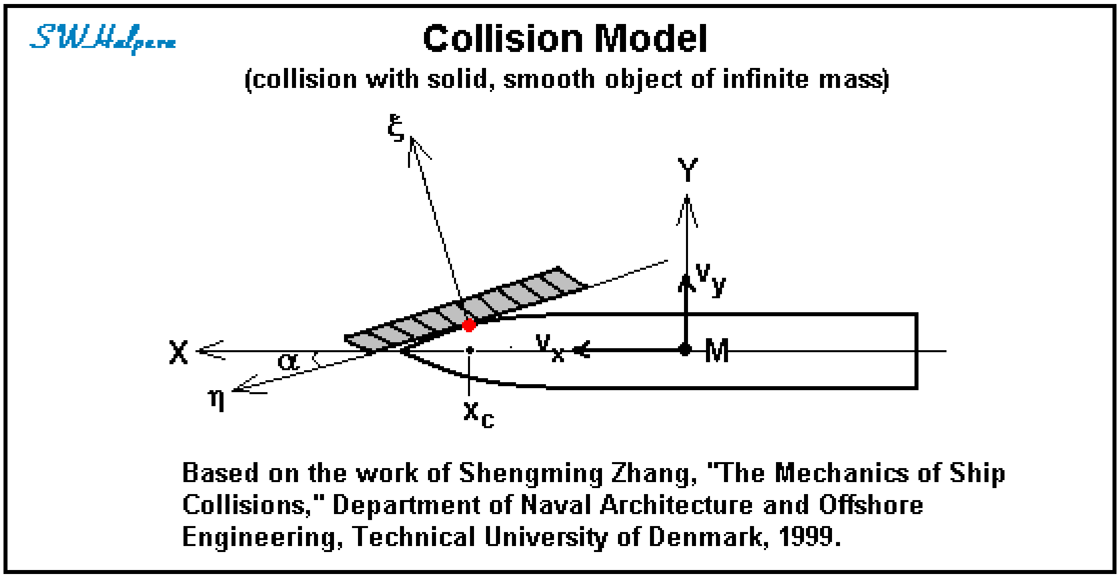
$C_3 = C_2\, e^{-t_2/T} + 2K\delta_a - K\delta_aT/t_1\, (e^{-2t_1/T} - 1 + 2t_1/T)$,

and as before,

$C_2 = C_1\, e^{-(t_2 - t_1)/T}$ and $C_1 = K\delta_aT/t_1\, (e^{-t_1/T} - 1)$.

APPENDIX G – DYNAMICS OF AN ALLISION WITH AN ICEBERG

The setup used in deriving the external dynamics of the collision is shown below.


Collision Model

(collision with solid, smooth object of infinite mass)

Based on the work of Shengming Zhang, "The Mechanics of Ship Collisions," Department of Naval Architecture and Offshore Engineering, Technical University of Denmark, 1999.

The notations and equations used for all the calculations come from the 1999 thesis of Shengming Zhang, “The Mechanics of Ship Collisions.”[34] In this case we use the scenario of a ship striking a rigid object that is smooth so that we are presented with a sliding case; i.e., small coefficient of friction.

The parameters used in the calculations were:

- Speed at impact 35 ft/sec (reduced from 38 ft/sec due to hydrodynamic drag during turn)
- Angle of impact relative to centerline, $\alpha = 12°$
- *Titanic's* displacement April 14, 1912 = 48,300 long-tons [Wilding]
- Radius of gyration = 0.24 L = 204 ft
- Kinetic energy of ship before impact ≈ 2,070,000,000 ft-lbs
- Point of major initial impact taken 75 ft aft of the bow, just ahead of bulkhead B
- Center of gravity of ship taken at amidships near bulkhead H
- Coefficient of friction of steel-on-ice = 0.03 (set to 0 for calculation simplicity)
- Coefficient of restitution = 0 (hull deformation only)
- Mass of iceberg taken to be much greater than mass of the ship (set to infinity for calculation simplicity)

Since the general contact area was located not too far from the ship’s pivot point, the velocity component of the ship at that point is approximately parallel to its centerline. Contact with an object of low frictional coefficient means that only two components in the horizontal plane need

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[34] Shengming Zhang, "The Mechanics of Ship Collisions," Department of Naval Architecture and Offshore Engineering, Technical University of Denmark, 1999, Chapter 2, Section 3.

be calculated at the contact point, sway and surge. Sway is perpendicular to the ship's centerline while surge is parallel to the ship's centerline. The contact angle is the angle of the ship's hull relative to the centerline as shown in the collision model above.

The results of the analysis using the equations derived by Shengming Zhang are as follows:

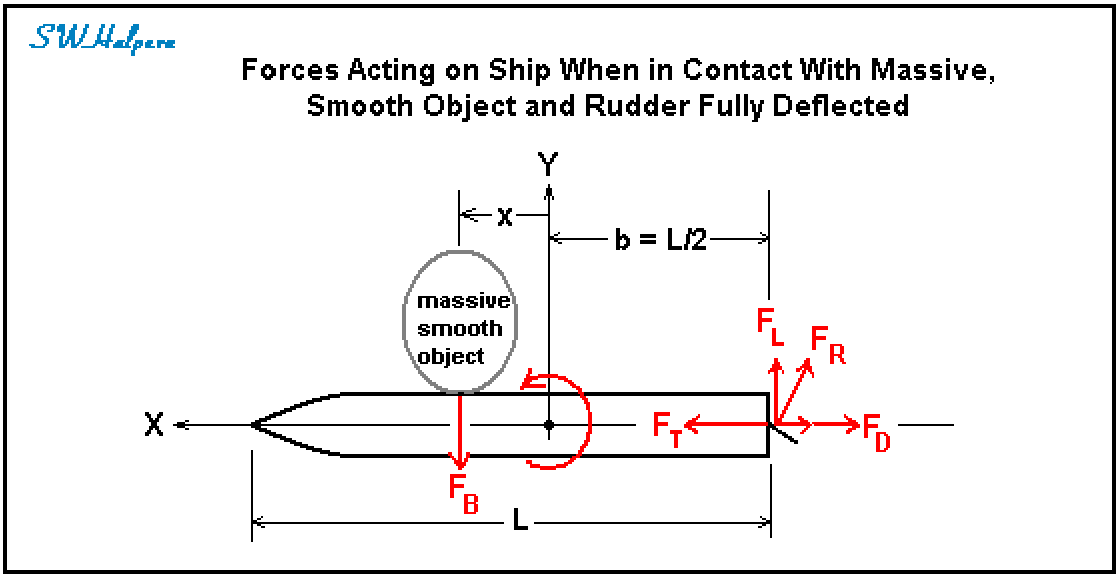
- Energy loss during initial collision = 31,540,000 ft-lbs
- Contact impulse I_ξ = 8,660,000 lbs-sec ≈ 3,870 ton-sec
- Forward velocity after collision = 34.5 ft/sec
- Initial sway velocity after collision = 1.4 ft/sec
- Added rotational velocity imparted to the ship = 0.99 degrees per sec to port

The instantaneous center, or pivot point with respect to the center of percussion (which was taken just ahead of bulkhead B) was also calculated. This is the point where zero collision forces would be felt by someone located in the vicinity of that point. The instantaneous center on *Titanic* during the impact with the iceberg was found to be located about 545 feet aft of the bow, or between the third and fourth funnels.

APPENDIX H – ICEBERG PRESSURE WITH FULLY DEFLECTED RUDDER

If the *Titanic* was turning to port under hard-astarboard helm (left full rudder) while the iceberg was passing along her starboard side, and if the helm had not been shift over to hard-aport (right full rudder) during the allision event, what would the expected force of the iceberg be on the ship's hull as it slid by aft?

To answer this question we make use the following picture.



In the above we show several forces acting on the hull of the vessel,

1. the thrust force from the ship's propellers, F_T
2. the hydrodynamic force on the ship's rudder, F_R
3. the lift component of the rudder force, F_L
4. the total drag force on the hull (including rudder drag component), F_D
5. the force from a massive, smooth object acting perpendicular to the vessel's hull, F_B

The total drag forces acting on the hull, F_D, must equal the total thrust forces, F_T, acting on the hull when the vessel is going at some given speed and not being accelerated in the fore/aft direction.[35]

As for the perpendicular forces, the lift component force of the rudder is given by:

$$F_L = F_R \cos \delta_R \qquad \text{where } \delta_R \text{ is the rudder angle}$$

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[35] Since the coefficient of friction of ice on steel is so small, there will no significant drag force acting on the hull caused by contact with the iceberg along the side. The only significant force from the berg is that acting in the perpendicular direction to the vessel's centerline as shown.

For *Titanic* we found that the force on her rudder when going at full speed (22.5 knots) was about F_R = 423 long tons with full rudder deflection of $\delta_R = 40°$, and the lift component, perpendicular to the ship's centerline, works out to F_L = 324 long tons (see Appendix A). So the problem here is to find the perpendicular force on the hull at the point of contact with the iceberg, F_B, which is acting along the starboard side.

Using the ship as the frame of reference, and considering the ship's center of gravity (taken at amidships) as the origin for the coordinate system, we can write the equations of forces and moments acting on the hull at a given point in time.

The sum of the longitudinal forces in the X direction is: $F_T - F_D = 0$, as we said before, and need not concern us.

The sum of the transverse forces in the Y direction is: $F_L - F_B = M y''$, where M is the mass of the vessel, and y" is the acceleration of the vessel in the transverse Y direction.

The sum of the moments acting on the vessel is: $F_L b - F_B x = I \omega'$, where I is the moment of inertia of the vessel about the vertical axis through its center of gravity, ω' is the angular acceleration about the vessel's center of gravity, $b = L/2$ half the vessel's length between perpendiculars, and x is the distance of the berg fore (+) or aft (-) of the vessel's center of gravity.

Considering the berg as fixed, we find $\omega' = y''/x$. Also, the moment of inertia of the vessel is given by $I = M k^2$, where k is the radius of gyration of the vessel about the vertical axis through its center of gravity. The radius of gyration can be considered as the radial distance from the given axis at which the mass of a body could be concentrated without altering the rotational inertia of the body about that axis. For a vessel like *Titanic*, the radius of gyration about the vertical axis through the center of gravity is given by $k = (0.19\ C_b + 0.11)L$, where C_b is the ship's block coefficient, and L is the length between perpendiculars.[36] For *Titanic*, $C_b = 0.684$ (from H&W archives), and L = 850 ft. Thus the radius of gyration is $k = 0.24\ L = 0.48\ b$ which happens to equal 204 ft for *Titanic*. This value is very close to $k = L/4 = b/2$, thus $I \approx M b^2/4$.

When we substitute all of this into the transverse force and moment equations above, we can solve for F_B in terms of F_L. What we find is the simple relationship,

$$\mathbf{F_B = F_L (1 - 4x/b)/(1 + 4x^2/b^2)}$$

A plot of F_B as function of iceberg distance from the bow is shown below. This is valid only when the point of contact with the berg is moving parallel to the ships centerline, not at some angle causing the ship to crash into the berg as during the initial collision event.

When the iceberg is more than about 325 ft from the bow it would exert a force on the hull as the rudder attempts to swing the ship's stern toward the berg. This force builds up to a maximum of

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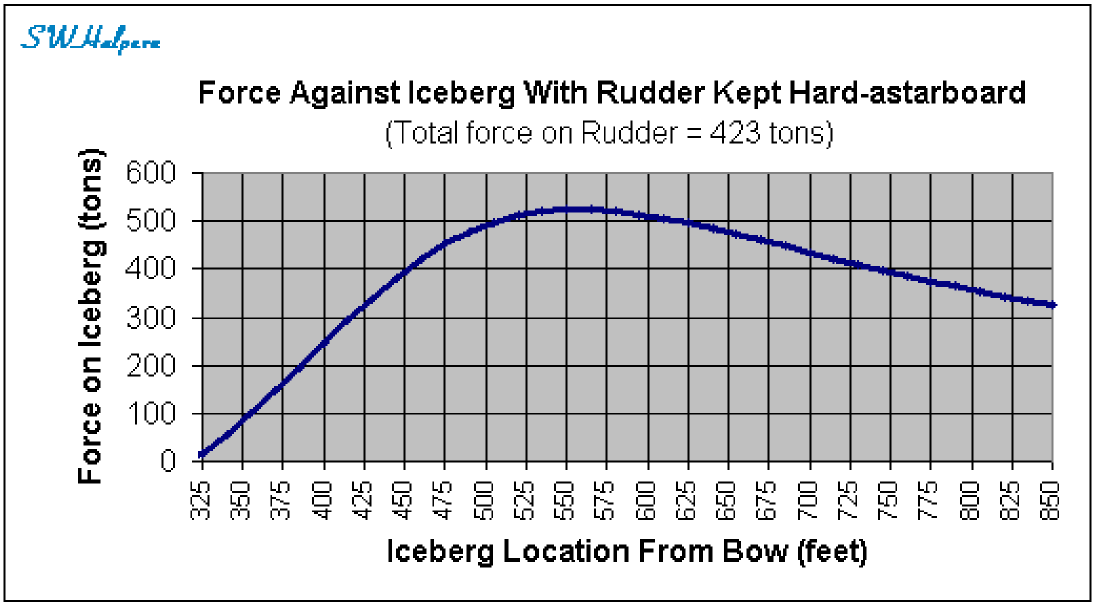
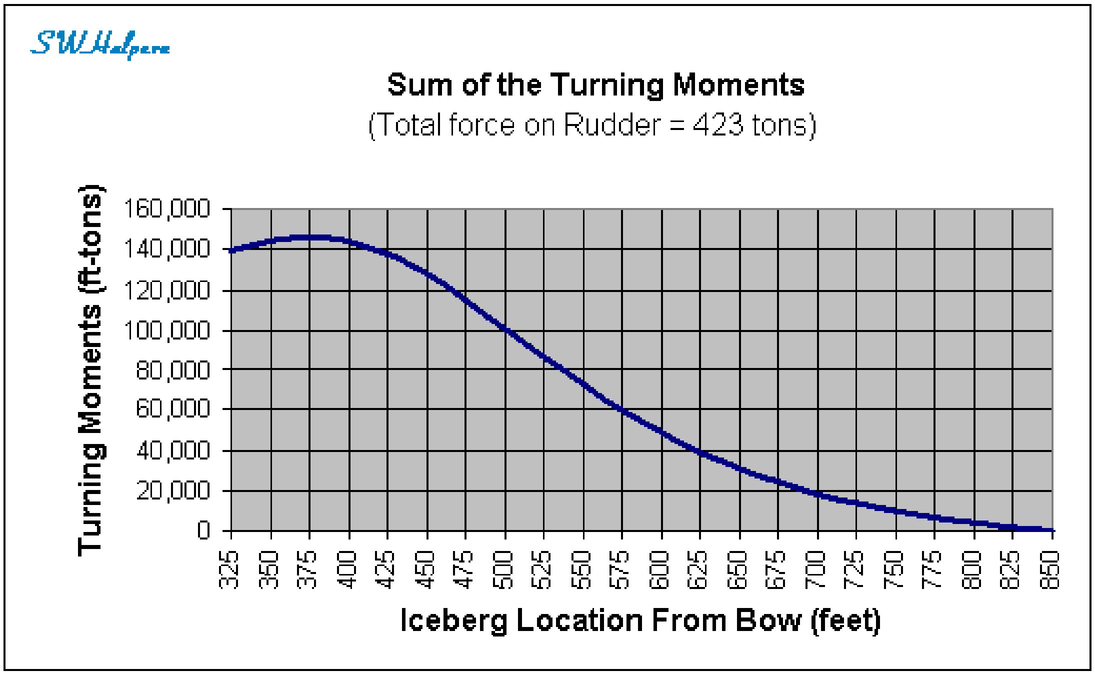
[36] [36] Shengming Zhang, "The Mechanics of Ship Collisions," Department of Naval Architecture and Offshore Engineering, Technical University of Denmark, 1999, Chapter 2, Section 2.2.

about 524 tons (compared to 423 tons of total force acting on the rudder) when the berg is 560 feet aft of the bow, and then starts to decrease until it exactly equals the lifting force of the rudder itself (324 tons) when the berg is alongside the stern of the ship. This then drops to zero as soon as contact with the ship is broken off.



The combined forces of rudder and iceberg sets up a turning moment to port which peaks when the berg is about 375 feet aft of the bow, and then decrease to zero when the berg is alongside the stern where the lifting force of the rudder is exactly cancelled by the force of the iceberg on the hull at that point.



The total *pressure* on *Titanic's* rudder when hard over at full speed is equal to the total rudder force, F_R, divided by the rudder area below the waterline. As show in Appendix A, this pressure is about 1.05 tons per square foot. As shown above, the iceberg would produce a maximum force of 524 tons on the ships hull due to the rudder trying to force the stern to swing into the berg. But the pressure along the hull depends entirely on the contact area between the iceberg and the ship. If the contact area covers something like the typical length of one of the cargo holds in the bow, about 50 feet, for a height of say 10 feet, about twice the height of the ship's double bottom, then we would have a contact area of 500 square feet. The maximum pressure on the hull would therefore be no greater than 1.05 tons per square foot, or the same as the pressure exerted on the ship's rudder during a full speed turn with full rudder deflection.[37]

It should be noted that the design specification for *Titanic's* hull plate was 40 ksi yield strength, or 2571 long-tons per square foot, and 30% elongation. The yield strength is the stress at which material strain changes from elastic deformation to plastic deformation thereby causing a permanent deformity. The ultimate tensile strength (UTS), the maximum stress a material can withstand when subjected to tension, compression or shearing, was a about 62 ksi, or 3985 long-tons per square foot.[38] So even if the contact area was as small as one of *Titanic's* shell plates (6'x 30' = 180 sq-ft), the maximum pressure exerted would be less than 3 tons per square foot, or only 0.1% of the yield strength of the plate.

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[37] To put this in another perspective, sea pressure at the depth of *Titanic's* keel was about 1 ton per square foot.

[38] Jennifer McCarty and Tim Foecke, *What Really Sank The Titanic*, Citadel Press, 2008, Ch. 10.