

COURSE OBJECTIVES

CHAPTER 10

10. SUBMARINES AND SUBMERSIBLES

1. Be familiar with the basic layout and construction of submarines including:
 - a. Pressure Hull
 - b. Outer Hull
 - c. Main Ballast Tanks
 - d. Depth Control Tank
 - e. Trim Tanks
2. Calculate the effects of the following on submarine buoyancy and trim.
 - a. Water salinity
 - b. Water temperature
 - c. Depth
 - d. Transverse weight shifts
 - e. Longitudinal weight shifts
3. Quantify the stability of a submarine for a given BG
4. Qualitatively describe how the components of submarine resistance alter as the submarine submerges
5. Qualitatively describe the advantages and disadvantages of an odd bladed highly skewed submarine propeller
6. Be qualitatively aware of the following seakeeping characteristics of submarines:
 - a. Suction effect due to proximity to the surface
 - b. Suction effect due to surface waves
7. Be qualitatively aware of the following aspects of submarine maneuvering and control:
 - a. The use of fair-water planes and stern planes for depth control
 - b. The effect of hull lift

10.1 Introduction

Submarines and the desire to explore the ocean's depths date back as far as Alexander the Great and Ancient Greece. Besides the limited success of the *Hunley* in the Civil War, technology did not permit the submarine to become a viable weapon of war until the invention of the steam engine and the construction of the *Holland (SS-1)* in 1900.



USS Holland at USNA

The submarine played significant roles in both the major wars of this century. In World War I, the German U-boat attacks on Allied shipping demonstrated the vital role the submarine could and would play in future global maritime conflicts. During World War II, the United States submarine force capitalized on many technological advances in submarine construction and powering, as well as development of sonar and radar, to allow the boats to travel faster, deeper, and remain undetected by the enemy. The U.S. submarine force, which accounted for about two percent of the fleet, destroyed 1,314 enemy ships, totaling 5.3 million tons or 55% of all enemy ships lost. The U.S. submarine campaign in the Pacific Theater deprived Japan of vital raw materials and effectively shut down the Japanese war machine. With these great successes also came great losses. Fifty-three submarines (1 in WWI and 52 in WWII) and 4,022 submariners remain on "Eternal Patrol" – a casualty rate which matched or surpassed most infantry divisions.

The period following World War II brought great changes in submarine technology and tactics. The advent of nuclear power allowed submarines to stay submerged indefinitely and ushered in the era of "stealth weapons". The teardrop hull design tested on the *USS Albatross* allowed submarines to achieve submerged speeds previously only imagined. The teardrop hull was originally tested on the *Holland* but was scrapped due to *Holland's* limited power and ventilation systems, which required mostly surface transit. The development of the ballistic missile allowed strategic missile submarines to patrol as the ultimate nuclear deterrent. The successes of the United States submarine force against the Soviets in the Cold War was a deciding factor in the fall of the Soviet Union.

The use of submarines in commercial fleets is severely limited. This is mainly due to their significant operating and construction costs. However, with the increasing use of the seas, in particular the retrieval of mineral wealth, the submarine or submersible will have an ever growing role. This chapter will explore the hydrostatic and hydrodynamic properties of submarines and compare them with those possessed by surface ships. In many instances the differences will be considerable. It will also look at the structure, construction and layout of submarines and their dynamic behavior through the water.

10.2 Submarine Construction and Layout

You will recall from Chapter 6 that ships are constructed with a structure dependent upon the primary load that they have to withstand.

- **Longitudinal Bending:** Wave action causes the ship to Hog or Sag creating successive compressive and tensile stresses in the structure, particularly the keel and weather deck. Longitudinals are used to combat these stresses.
- **Hydrostatic Pressure:** Water pressure attempts to crush the ship from the sides. Transverse frames combat this loading.

Most modern ships use a combination of longitudinals and transverse frames as they are subjected to both types of loading.

By far the most significant load the submarine has to withstand is hydrostatic pressure. Consequently, it should be no surprise to learn that they are transversely framed. Figure 10.1 illustrates typical submarine construction.



Figure 10.1 A hull section of the SSN-21 class shown during assembly. The transverse frames are shown clearly at left (the hull is a ring stiffened cylinder)

10.2.1 Inner Hull

There are two hulls in a submarine. The inner hull or pressure hull (or “people tank”) holds all the pressure sensitive systems of the submarine including the submariners. The inner hull must withstand the hydrostatic pressure to the submarine’s maximum or “test” depth. You will recall that absolute pressure is given by the following:

$$P_{abs} = P_{atm} + \rho gh$$

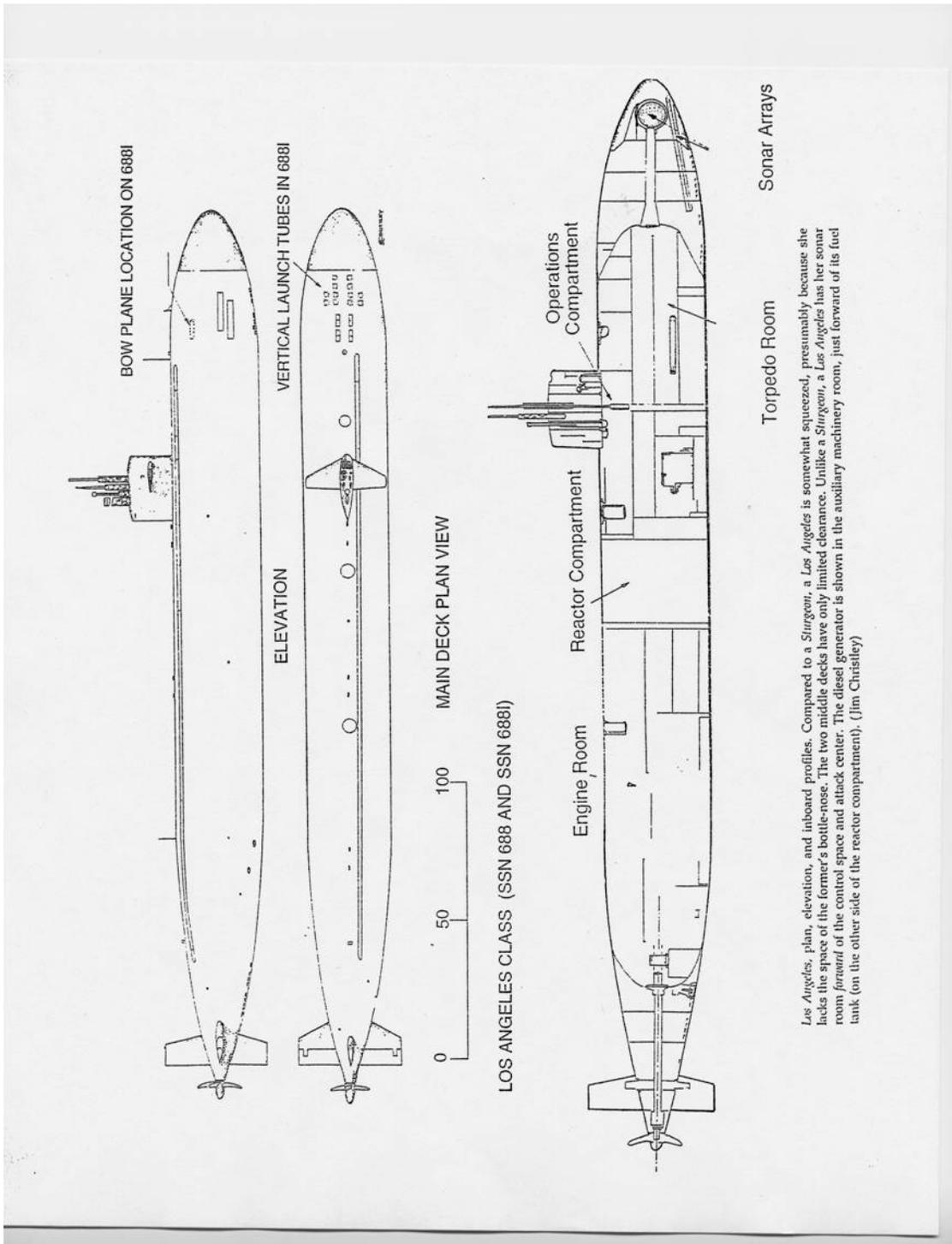
where :

$$\rho gh = \text{hydrostatic pressure} = P_{gage}$$

A useful thumb rule is that pressure increases by 44 psi per 100ft of depth.

Any ingress of water into the inner hull can have a considerable effect upon stability and may threaten the remaining structural integrity of the ship. Consequently, the inner hull has to be strong. As inferred above, the inner hull is transversely framed and due to the deep depths achievable by modern submarines it has thick plating. The number of transverse frames and thickness of plating used is a compromise between cost, weight, operating ability and space; more frames and thicker plating means higher cost, greater weight, less space for equipment and crew but a greater diving depth.

Inner hull sections are perfectly circular. Any “out of roundness” has a significant impact on its ability to support the hydrostatic load. For example, a 0.5% deviation from a perfect circle may reduce the hydrostatic load carrying capacity of a submarine structure by over 35%!



Los Angeles, plan, elevation, and inboard profiles. Compared to a *Sturgeon*, a *Los Angeles* is somewhat squeezed, presumably because she lacks the space of the former's bottle-nose. The two middle decks have only limited clearance. Unlike a *Sturgeon*, a *Los Angeles* has her sonar room *forward* of the control space and attack center. The diesel generator is shown in the auxiliary machinery room, just forward of its fuel tank (on the other side of the reactor compartment). (Jim Christley)

Figure 10.2 688 Class Submarine profiles
 (Reproduced from *U.S. Submarines Since 1945* by Norman Friedman with the permission of Naval Institute Press, Annapolis, MD.
 Profiles are the work of Mr. James L. Christley.)

It is also important that the inner hull remains within its elastic limit for material strength, even at high levels of stress. You will recall from Chapter 5 that this will occur provided the hull material remains below the yield stress σ_y . Consequently, very high strength steels are used with high yield stresses. Common steels used in U.S. submarines are HY-80 and HY-100 (the “HY” designates high yield and the following number is the steel’s yield stress in thousands of pounds per square inch). Some of the more advanced Russian Submarines use Titanium for their inner hulls.

10.2.2 Outer Hull

Figure 10.2 shows that in certain places down the length of a submarine, the inner hull reduces in cross section and is surrounded by an outer hull or submarine fairing. The outer hull is simply a smooth fairing that covers the non-pressure sensitive equipment of the submarine such as Main Ballast Tanks and anchors to improve the submarines hydrodynamic characteristics. The fairing does not need to withstand the diving depth hydrostatic pressure, so high strength materials are not required. Mild steel and Fiber Reinforced Plastics are commonly used.

Modern submarines also have anechoic tiles or a synthetic “skin” covering the outer hull to reduce the active sonar signature and dampen radiated noise from the submarine to the water.

10.2.3 Submarine Construction

Submarine construction is very expensive. High strength materials necessary to achieve deeper depths are expensive and difficult to use in manufacturing. High strength steels are notoriously difficult to bend, fabricate and weld. Quality control of the manufacturing process is also critical as any out of roundness can severely compromise submarine structural integrity.

Consequently, the number of shipyards with the expertise to manufacture submarines is limited. In the U.S., General Dynamics’ Electric Boat in Groton, Connecticut and Northrop Grumman Shipbuilding in Newport News, Virginia are the only submarine manufacturers.

10.2.4 Submarine General Arrangement

10.2.4.1 Main Ballast Tanks

Recall in Chapter 2 Archimedes’ Principle states that for an object wholly or partially immersed in a fluid, the buoyant force will be equal to the weight of the displaced volume of water. This applies to submarines just as it did for surface ships, the only difference being that the submerged volume is equal to the entire hull volume.

Positively Buoyant: $F_{B, \text{SURFACE SHIP}} = \rho g \nabla_{\text{SUBMERGED}}$
 (floats) $F_{B, \text{SURFACED SUB}} = \rho g \nabla_{\text{SUBMERGED}} < \rho g \nabla_{\text{TOTAL}} > \Delta$

Neutrally Buoyant: $F_{B, \text{ SUBMERGED SUBMARINE}} = \rho g \nabla_{\text{SUBMERGED}}$
 $= \rho g \nabla_{\text{TOTAL}}$

Negatively Buoyant: $F_{B, \text{ SUBMERGED SUBMARINE}} = \rho g \nabla_{\text{TOTAL}} < \Delta$
(sinks)

Figure 10.3 shows the location of the Main Ballast Tanks (MBTs) on a submarine. These are by far the largest tanks on board as they have to be able to alter the displacement of the submarine from being positively buoyant (surfaced) when empty to somewhere near neutrally buoyant (submerged) when full.

The Main Ballast Tanks are “soft tanks” because they do not need to withstand the hydrostatic pressure when the submarine is submerged. This is because they will be full at the submerged depth with the pressure equalized across them.

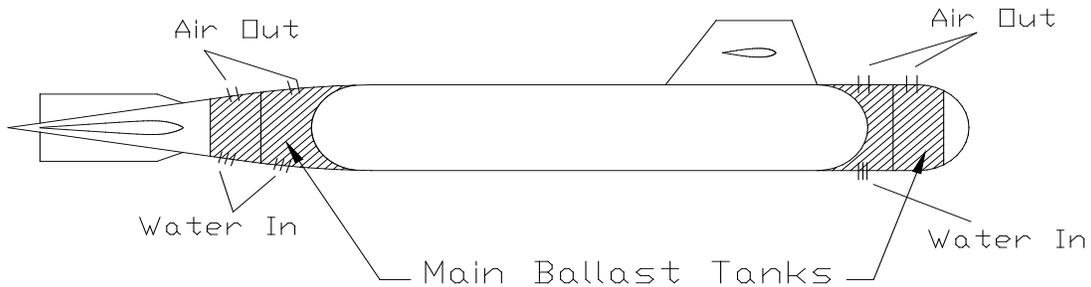


Figure 10.3 Location of Typical Submarine’s Main Ballast Tanks

10.2.4.2 Variable Ballast Tanks

In addition to the MBTs there are other tanks required to ‘fine tune’ the displacement and trim characteristics of the submarine once it is submerged. These are called variable ballast tanks. Figure 10.4 shows their usual location

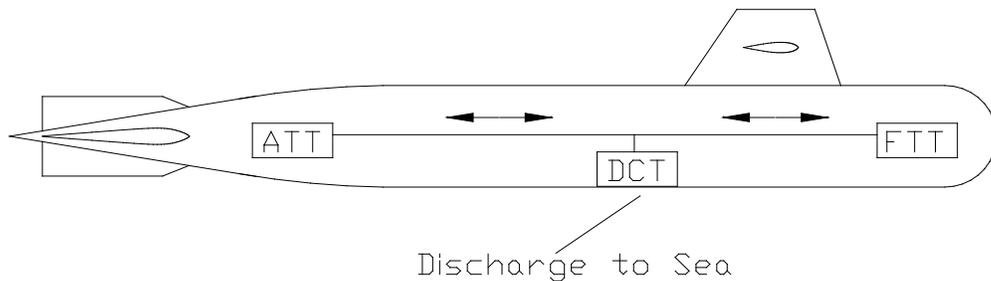


Figure 10.4 Location of Variable Ballast Tanks

- **Depth Control Tank (DCT):** The DCT is used to alter the buoyancy characteristics of the submarine once it is submerged. For reasons covered in the next section, environmental factors can often cause the submarine to move from a

neutrally buoyant condition to being negatively or positively buoyant. Moving water in or out of the DCT can compensate for this. The DCT is termed a 'hard tank' because it can be pressurized to submergence pressure allowing its contents to be "blown" overboard and also the submarine can ingest water into the tank from any depth.

- **Trim Tanks:** As the name suggests these are used to control the trim of the submarine. Submarines are very sensitive to longitudinal weight shifts, additions and removals. Moving water between the after and forward trim tanks can compensate for these changes. They are 'soft tanks' because they are not required to withstand the external hydrostatic pressure.

10.3 Submarine Hydrostatics

Just like a surface ship, submarines obey the principles of static equilibrium and Archimedes. The submarine experiences a buoyant force equal to the weight of liquid it displaces. When surfaced or neutrally buoyant, this buoyant force is equal to the weight of the submarine (its displacement).

10.3.1 Neutral Buoyancy

A surface ship automatically maintains static equilibrium by alterations in its draft and the reserve buoyancy above the waterline. That is, by changing the vessel's draft, its submerged volume is altered to reflect any changes to its displacement due weight removals or additions, changes in water density, or as a passing wave causing excess buoyancy.

Unfortunately, a submerged submarine is given no such luxury. The crew must actively maintain a state of static equilibrium by changing the weight of the submarine to match the (usually) constant buoyant force. The buoyancy is constant because the submerged volume of a submarine is constant (at a given depth) and there is no excess or reserve buoyancy as in a surface ship. Hence the submarine needs a DCT that will allow for compensation due to changes in the environment.

10.3.1.1 Salinity

Water density (ρ) will change whenever there is an alteration in its salinity level. This is a fairly frequent occurrence, for example:

- Changes in salinity are common when operating near river estuaries or the polar ice cap.
- Due to constant evaporation, the Mediterranean Sea has a higher salinity level than the oceans.



In the Straits of Gibraltar the colder, less saline water from the Atlantic mixes with the warmer, more saline water from the Mediterranean to produce strong currents ranging from two to four knots. This allows some submarines to pass through the Straits by covertly “riding” the subsurface currents. Unfortunately, these salinity differences can also cause very large changes in a submarine's buoyancy and internal waves. In the mid 1980's, a Soviet submarine covertly transiting the Straits learned this the hard way when it lost depth control and collided with the underside of a tanker!

Example 10.1 The 8000LT USS Hardluck is submerging in Long Island Sound to conduct a “Tiger Cruise”. The water temperature is 75⁰F and Long Island Sound is diluted by 10% fresh water. The Diving Officer calculated the trim for the open ocean. How should the trim be corrected?

$$\begin{aligned} @ 75^0\text{F} \quad \rho_{\text{fresh}} &= 1.9350 \text{ lb-s}^2/\text{ft}^4 \\ \rho_{\text{salt}} &= 1.9861 \text{ lb-s}^2/\text{ft}^4 \end{aligned}$$

Solution:

In the open ocean the submarine is neutrally buoyant.

$$\Rightarrow \Delta = \rho g \nabla$$

$$\nabla = \frac{\Delta}{\rho g} = \frac{8000\text{LT} \quad 2240\text{lb} / \text{LT}}{1.9861\text{lb} - \text{sec}^2 / \text{ft}^4 \quad 32.17 \text{ ft} / \text{sec}^2}$$

$$\nabla = 280,470 \text{ ft}^3$$

The water in Long Island Sound is 10% fresh, 90% salt

$$\rho_{\text{LIS}} = 10\% \rho_{\text{FW}} + 90\% \rho_{\text{SW}}$$

$$\rho_{\text{LIS}} = 0.10 (1.9350\text{lb} - \text{sec}^2 / \text{ft}^4) + 0.90(1.9861\text{lb} - \text{sec}^2 / \text{ft}^4)$$

$$\rho_{\text{LIS}} = 1.9810\text{lb} - \text{sec}^2 / \text{ft}^4$$

So the buoyant force (F_B) acting on the submarine in Long Island Sound can be found.

$$F_B = \rho g \nabla$$

$$F_B = (1.9810\text{lb} - \text{sec}^2 / \text{ft}^4)(32.17 \text{ ft} / \text{sec}^2)(280,470 \text{ ft}^3)$$

$$F_B = 1.787 \times 10^7 \text{ lb} = 7979\text{LT}$$

Hence submarine displacement (8000LT) is greater than the buoyant force (7979LT). The submarine is acting heavy. To compensate, 21LT of water must be pumped out of the DCT.

10.3.1.2 Water Temperature

Changes in water temperature are common throughout the ocean. Temperature affects water density, which in turn affects the magnitude of the buoyant force.

Example 10.2 An 8000LT submarine exits the Gulf Stream where water is 85°F and enters 65°F water. How much water will the Diving Officer need to flood on or pump off?

$$\begin{aligned}\rho @ 85^\circ\text{F} &= 1.9827 \text{ lb}\cdot\text{s}^2/\text{ft}^4 \\ \rho @ 65^\circ\text{F} &= 1.9890 \text{ lb}\cdot\text{s}^2/\text{ft}^4\end{aligned}$$

Solution:

The submarine is neutrally buoyant in the Gulf Stream.

$$\begin{aligned}\Rightarrow \Delta &= \rho g \nabla \\ \nabla &= \frac{\Delta}{\rho g} = \frac{8000 \text{ LT } 2240 \text{ lb} / \text{LT}}{1.9827 \text{ lb} - \text{sec}^2 / \text{ft}^4 \cdot 32.17 \text{ ft} / \text{sec}^2} \\ \nabla &= 280,950 \text{ ft}^3\end{aligned}$$

As it leaves the Gulf Stream the water density changes which alters the size of the buoyant force.

$$\begin{aligned}F_B &= \rho g \nabla \\ F_B &= (1.9890 \text{ lb} - \text{sec}^2 / \text{ft}^4)(32.17 \text{ ft} / \text{sec}^2)(280,950 \text{ ft}^3) \\ F_B &= 1.798 \times 10^7 \text{ lb} = 8025 \text{ LT}\end{aligned}$$

So the submarine displacement is 25 LT smaller than its buoyant force. The Diving Officer will have to flood 25 LT of water into the DCT.

10.3.1.3 Depth

As a submarine increases its depth the increasing hydrostatic pressure increases the stress on the hull. This stress then strains the hull. The hull shrinks. So the submerged volume of a submarine decreases with depth which in turn reduces its buoyant force. So to maintain neutral buoyancy, water must be pumped from the DCT reducing the submarine displacement to keep pace with the smaller F_B .

This effect has been accentuated with the introduction of anechoic tiles mentioned in section 10.2. These tiles are compressed when operating at modern maximum diving depths but usually show little change in volume past moderate depths as the rubber material is compressed to its maximum.

10.3.2 Neutral Trim

The second goal the submarine crew is actively seeking is neutral trim. Trim is particularly sensitive on a submarine once submerged due to the lack of a waterline.

You may recall from Chapter 3 that the distance of the metacenter above the keel can be found by adding BM (the metacentric radius) to KB. This can be used in either the transverse or longitudinal directions to find KM_T or KM_L respectively. Figure 10.5 graphically illustrates the relationships for a surface ship.

BM_L is very much larger than BM_T because ships tend to be longer than they are wider and so their second moment of area is much greater longitudinally than transversely.

$$\overline{BM}_L = \frac{I_L}{\nabla_S} \overline{BM}_T = \frac{I_T}{\nabla_S}$$

Ships are longer than they are wide

$$\Rightarrow I_L \gg I_T$$

$$\Rightarrow \overline{BM}_L \gg \overline{BM}_T$$

The situation for the surfaced submarine is quite similar to the surface ship. Figure 10.6 illustrates the geometric relationships for a surfaced submarine. You will notice that G is situated below B; the importance of this will become evident in the next section.

For clarity, M_T has been shown significantly above the location of B, in practice the distance between the two locations is very small while the submarine is surfaced.

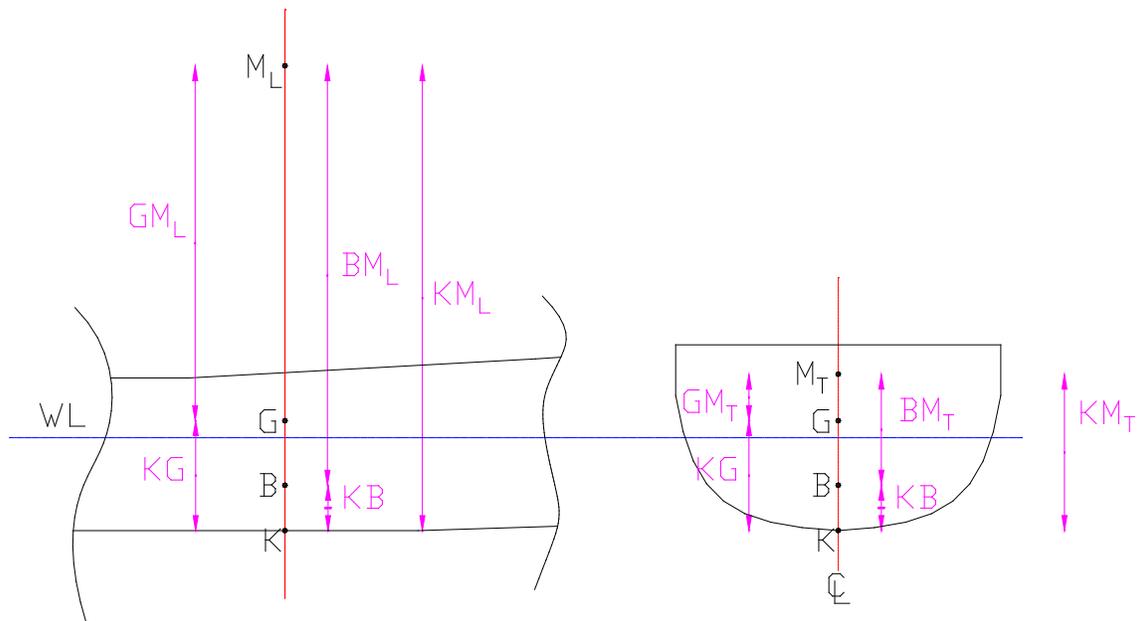


Figure 10.5 K, B, G, and M Geometry for a Surface Ship

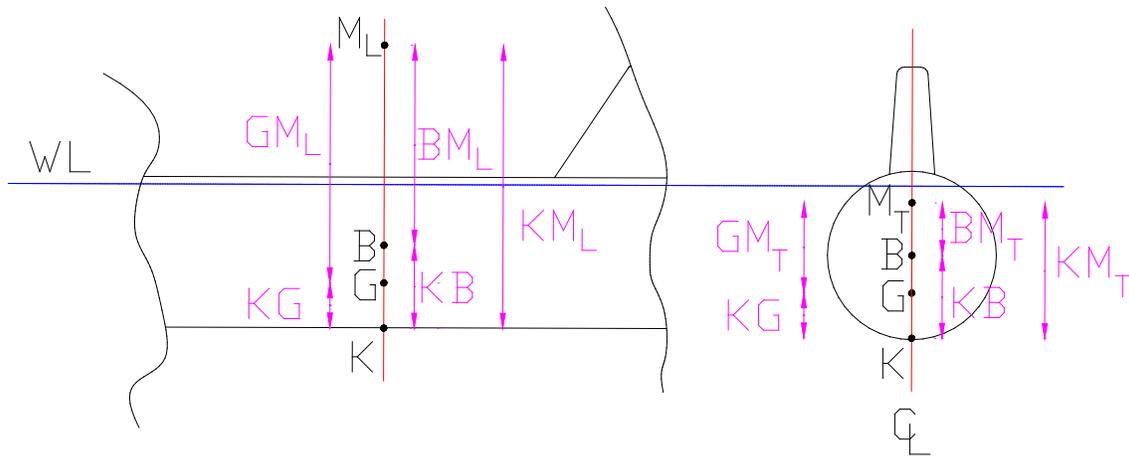


Figure 10.6 K, B, G, and M Geometry for a Surface Submarine

As the submarine submerges, its waterplane disappears. With no waterplane there is no second moment of area of the waterplane and so no metacentric radius. Hence the center of buoyancy and the metacenter are both located at the centroid of the underwater volume - the half diameter point.

$$\overline{GM}_L = \overline{KB} + \overline{BM}_L - \overline{KG}$$

$$\overline{GM}_T = \overline{KB} + \overline{BM}_T - \overline{KG}$$

but as the waterline disappears...

$$I_L = I_T = 0$$

$$\overline{BM}_L = \overline{BM}_T$$

So...

$$\overline{GM}_L = \overline{KB} - \overline{KG}$$

$$\overline{GM}_T = \overline{KB} - \overline{KG}$$

So...

$$\overline{GM}_L = \overline{GM}_T = \overline{BG}$$

What actually happens is that as the submarine submerges, B moves vertically up very slightly because of the additional hull volume and sail being submerged and M moves vertically down as the water-plane disappears. When finally submerged, the positions of B, M_T and M_L are coincident. Figure 10.7 shows the geometric relationships for a submerged submarine.

A consequence of this is the submerged submarine has the same initial stability characteristics longitudinally as it does transversely.

Because submarines are much longer than they are wide, the submerged submarine is very sensitive to trim. This accounts for the need for trim tanks.

WL

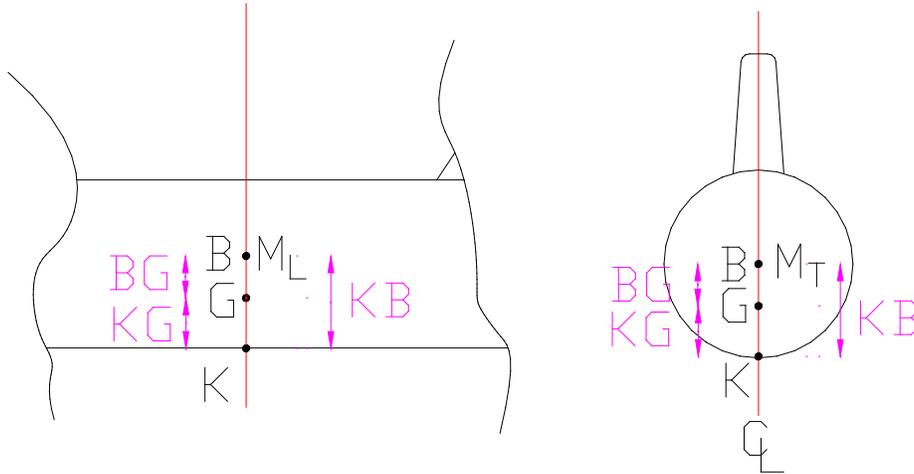


Figure 10.7 K, B, G, and M Geometry for a Submerged Submarine

10.3.2.1 Transverse Weight Shifts

You may recall from Chapter 3 that the analysis of a transverse weight shift in a surface ship involved the situation shown in Figure 10.8.

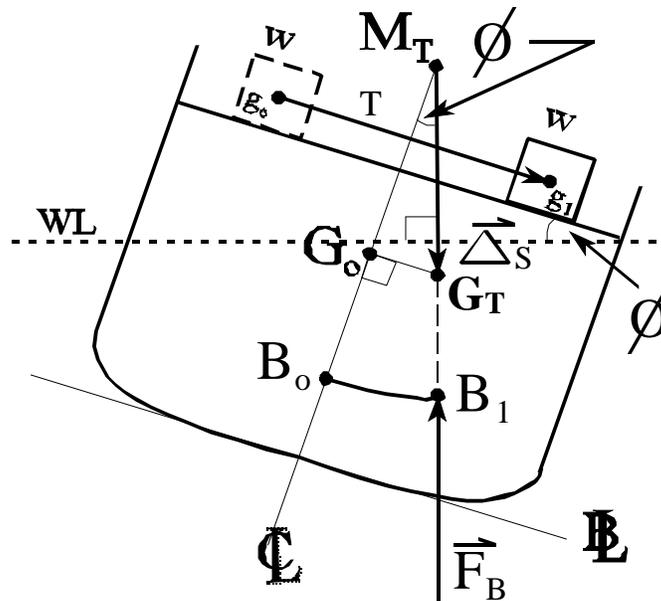


Figure 10.8 The Inclining Surface Ship

From the geometry of the triangle $G_0G_T M_T$ and from a knowledge of the size and distance the weight is being shifted, an equation can be formulated as follows.

$$\tan \phi = \frac{\overline{G_0 G_T}}{\overline{G_0 M_T}} \quad \overline{G_0 G_T} = \frac{wt}{\Delta_s}$$

$$\Rightarrow \Delta_s \overline{G_0 M_T} \tan \phi = wt$$

This same equation is used to estimate the value of GM_T of a ship in the Inclining Experiment. With GM_T known it is then possible to calculate the vertical center of gravity, KG.

Unfortunately, this equation relies upon the existence of the triangle $G_0G_T M_T$ which is only true at small angles. At larger angles the metacenter is not stationary and moves about causing any calculation using this system to be inaccurate. Angles of list at large angles are only available from an analysis of the curve of static intact stability, the list angle corresponding to the intercept of the Righting Arm Curve with the x axis.

For a submerged submarine, with both the Center of Buoyancy (B) and the Metacenter (M) are coincident, so the calculation of the heeling angle is greatly simplified. Figure 10.9 shows a submarine listing due to a transverse weight shift.

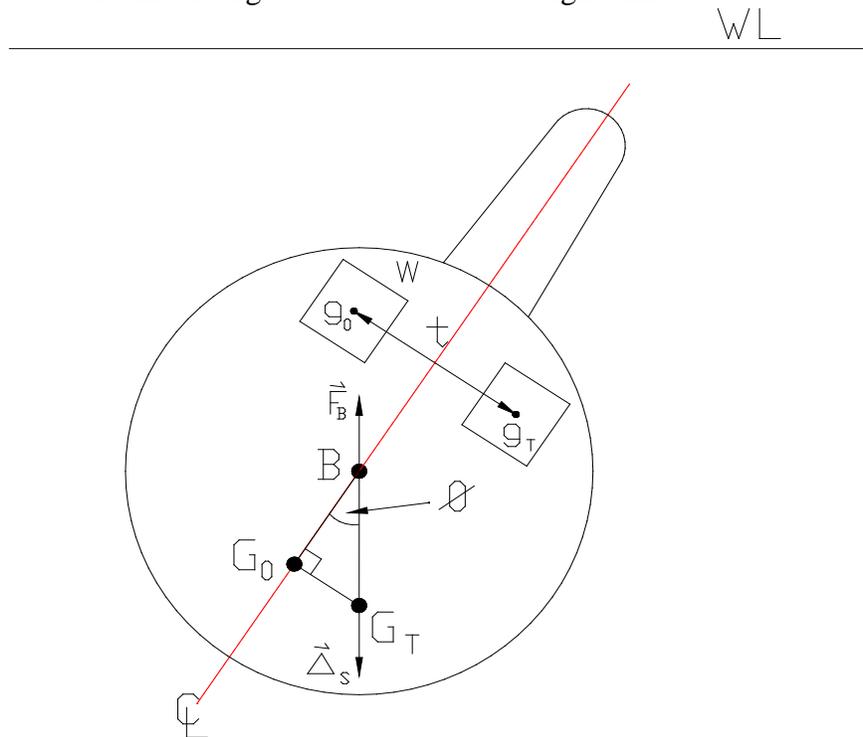


Figure 10.9 The Inclining Submerged Submarine

The analysis of this situation involves the triangle $G_0G_T B$ and a knowledge of the weight shift.

$$\tan \phi = \frac{\overline{G_0 G_t}}{\overline{B G_0}} \quad \overline{G_0 G_t} = \frac{wt}{\Delta_s}$$

$$\Rightarrow \Delta_s \overline{B G_0} \tan \phi = wt$$

This equation is valid for all list angles since the position of the center of buoyancy (B) will be constant for any list condition. If we know the distance from the center of buoyancy to the center of gravity (BG_0), the submarine displacement Δ_s , and the weight shift, the angle of list can always be determined quite easily.

One way to think of this is that your trim pivot point is no longer based on the centroid of the waterplane, F. Once submerged, the submarine will trim and list about the center of Buoyancy, which is the centroid of the total volume of the submarine. Equivalently, once the waterplane has disappeared in the diving evolution, the metacentric radius, \overline{BM} , collapses to zero, so the metacenter may be thought to still predict the movement of B. Thus as the sub trims or lists, B remains fixed with respect to the hull. This becomes the point about which trim and list angles develop.

Example 10.3 A submerged submarine weighs 7200 LT with $KB = 15$ ft, $KG = 13.5$ ft. A piece of machinery weighing 6 LT is moved from 10 ft stbd of the centerline to a position 13 ft port of the centerline. Its distance above the keel does not change. What is the angle of list created by this movement?

Solution:

Using the equation we have just proved.

$$\Rightarrow \Delta_s \overline{B G_0} \tan \phi = wt$$

$$\tan \phi = \frac{wt}{\Delta_s \overline{B G_0}}$$

$$\tan \phi = \frac{6LT \cdot 23ft}{7200LT \cdot 1.5ft} = 0.0128$$

$$\phi = 0.73^\circ \text{ to port}$$

10.3.2.2 Longitudinal Weight Shifts

For a surface ship, the analysis of a longitudinal weight shift is involved. The process is complicated by the ship trimming about the center of floatation (F) which is seldom at midships.

For a submerged submarine, the analysis of longitudinal weight shifts is exactly the same as in the transverse case. This is because the characteristics of a submerged submarine are

exactly the same longitudinally as they are transversely, both being controlled by the distance BG_0 . Hence the following equation holds for all angles of trim.

$$wl = \Delta_s \overline{BG_0} \tan \theta$$

Because submarines are much longer than they are wide, the value of the longitudinal moment arm (l) can be much larger than the transverse moment arm (t); this much larger moment arm (l) necessitates the addition of trim tanks that can compensate for longitudinal weight shifts.

Example 10.4 A submarine weighs 7200 LT and has zero trim. $KB = 15$ ft, $KG = 13.5$ ft. 40 submariners weighing 200 lb each move aft a distance of 300 ft.

- a. What will be the new trim angle?
- b. How much water must be transferred between the 2 trim tanks to return the trim to zero? The distance between trim tanks is 200ft.

Solution:

- a. Using the equation above.

$$wl = \Delta_s \overline{BG_0} \tan \theta$$

$$\tan \theta = \frac{wl}{\Delta_s \overline{BG_0}}$$

$$\tan \theta = \frac{40 (200lb)(300 ft)(1LT / 2240lb)}{(7200LT)(1.5 ft)} = 0.0992$$

$$\theta = 5.67^\circ \text{ by the stern}$$

- b. To return the trim to zero, the moment created by shifting the water must be equal and opposite to the moment created by the moving people.

$$40 (200 lb) (300 ft) = w (200 ft)$$

$$w = 12,000 \text{ lb pumped from ATT to FTT}$$



One may think that a submarine firing four torpedoes weighing nearly two tons apiece would develop a significant trimming moment by the stern. However, the neutrally buoyant torpedoes are impulsed out of the tubes by water which fills the space left by the torpedoes. As a result, the submarine remains neutrally buoyant overall and develops no trimming moment after firing a salvo of torpedoes.

10.4 Submarine Intact Stability

As with the case of weight shifts, the absence of a waterplane and the stationary nature of B greatly simplifies the analysis of submerged submarine hydrodynamics.

Earlier figures indicated that the Center of Gravity (G) has to be below the Center of Buoyancy (B) for the submarine to be stable. Figure 10.10 illustrates this point.

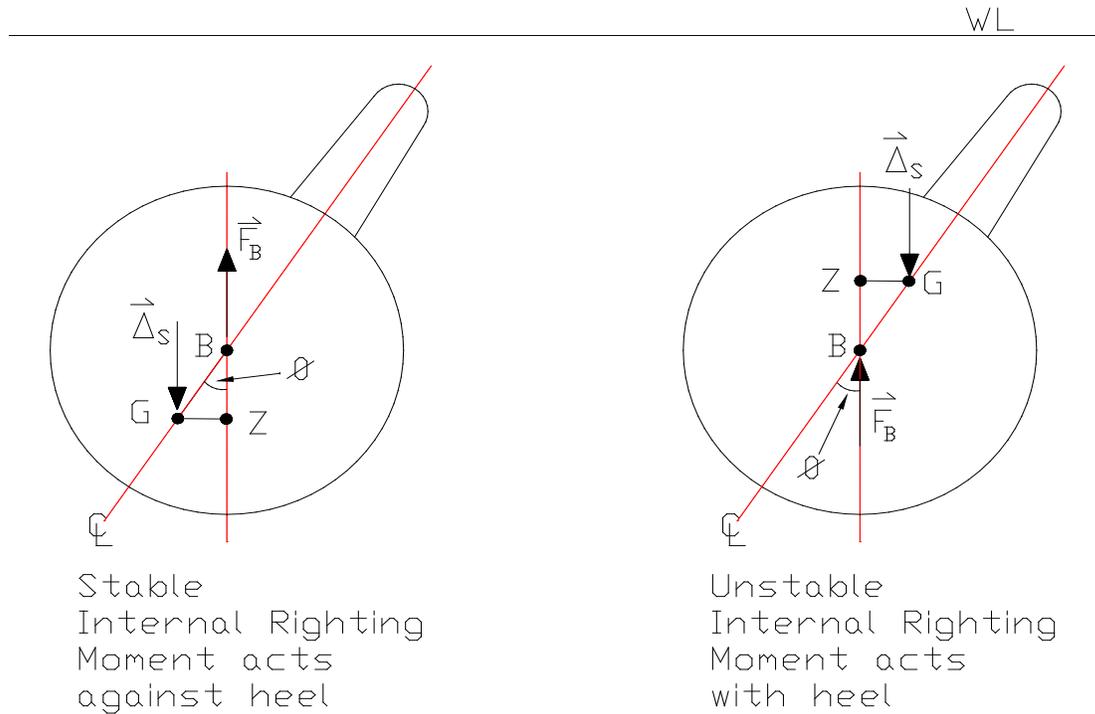


Figure 10.10 Submarine Initial Stability

The level of stability is wholly dependent upon the distance between B and G (BG). Because this distance is constant, an analysis of the triangle BGZ reveals that the Righting Arm (GZ) is purely a function of the angle of heel.

$$\text{Righting Arm} = \overline{GZ} = \overline{BG} \sin \phi$$

This equation holds for all submerged submarines, in all conditions. Hence the curve of static intact stability will always be a sine curve with a peak value equal to BG. Figure 10.11 shows the curve for all submarines.

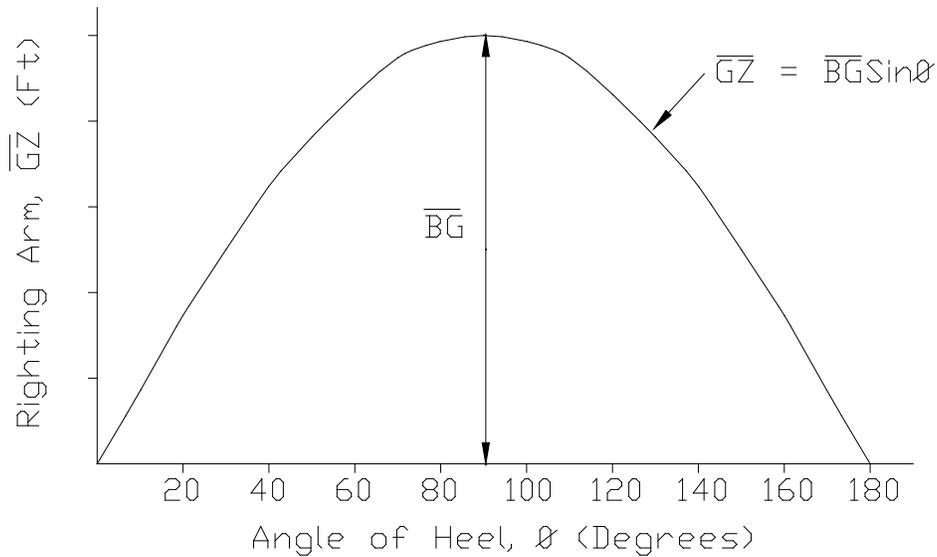


Figure 10.11 Curve of Intact Statical Stability for Submerged Submarine

Stability characteristics will always be as follows.

- **Range of Stability:** The range of heeling angles through which a Righting Arm is maintained against the heeling motion.

$$\text{Range of stability} = 0 - 180^\circ$$

- **Angle of Maximum Righting Arm:** The angle of heel creating the maximum righting moment.

$$\text{Angle of } GZ_{\max} = 90^\circ$$

- **Maximum Righting Arm:** The size of the maximum righting arm.

$$GZ_{\max} = BG \cdot \sin(\phi) = BG \cdot \sin(90^\circ) = BG$$

- **Dynamic Stability:** The energy required to move the submarine slowly through all angles of heel until capsize

$$\begin{aligned} \text{Dynamic Stability} &= \Delta_S BG \int_0^{180} \sin(\phi) d\phi \\ &= 2\Delta_S BG \end{aligned}$$

10.5 Submarine Powering

Submarine powering suffers the same constraints inflicted on surface ships. However, submarines must also move through the water as quietly as possible to remain undetected.

10.5.1 Submarine Resistance

You will recall from Chapter 7 that the resistance of a surface ship is made up from a combination of three resistance forms. Submarines share the exact same equations as surface ships and with similar applications. The components of total resistance are written again below in both dimensional and non-dimensional terms:

$$R_T = R_V + R_W + R_{AA} \qquad C_T = C_V + C_W$$

where C_V = the viscous resistance of the hull, itself made up from factors associated with its skin resistance and its form.

$$C_V = (1 + K)C_F$$

C_W = the wave making resistance of the hull. This element is caused from the energy the ship loses in making waves.

R_{AA} = the ship's resistance in air (not applicable to a submerged submarine!)

Recall that as the surface ship speed changes, the resistance component that contributes most to the total resistance changes. At low speed, viscous resistance is the major factor. As speed increases, wave making becomes the dominant resistance component.

In the case of a surfaced submarine, this is no different. In fact, the effect is more pronounced. The surfaced submarine generates a very large bow wave and wavemaking resistance is a significant contributor to resistance even at slower speeds.

When the submarine submerges, the skin friction resistance will increase due to the greater wetted surface area. However, the wave making element disappears provided the submarine is deep enough to not cause surface interactions. Consequently, the modern submarine experiences less resistance when submerged than on the surface



Modern submarines are capable of achieving submerged speeds more than two times greater than those achieved on the surface. A radical change in submarine design following World War II yielded the cigar-shaped, diesel-powered *USS Albacore*. Launched in 1953, this revolutionary submarine achieved submerged speeds in excess of 30 knots and laid the foundation for modern submarine hull design.

10.5.2 Submarine Propellers

Modern submarines use highly skewed propellers with an odd number of blades. The governing factors in submarine propeller design are cavitation and vibration, often at the expense of propeller efficiency.

10.5.2.1 Odd Blade Number

The number of blades is chosen to minimize vibration. An odd number of blades is used because there are an even number of appendages at the stern: a rudder at the top and bottom and stern planes both port and starboard. An odd number of blades guarantees that no two blades will be entering the disturbed flow behind the appendages at the same time. Therefore, the forces causing vibration will not reinforce each other. Figure 10.12 demonstrates this principle.

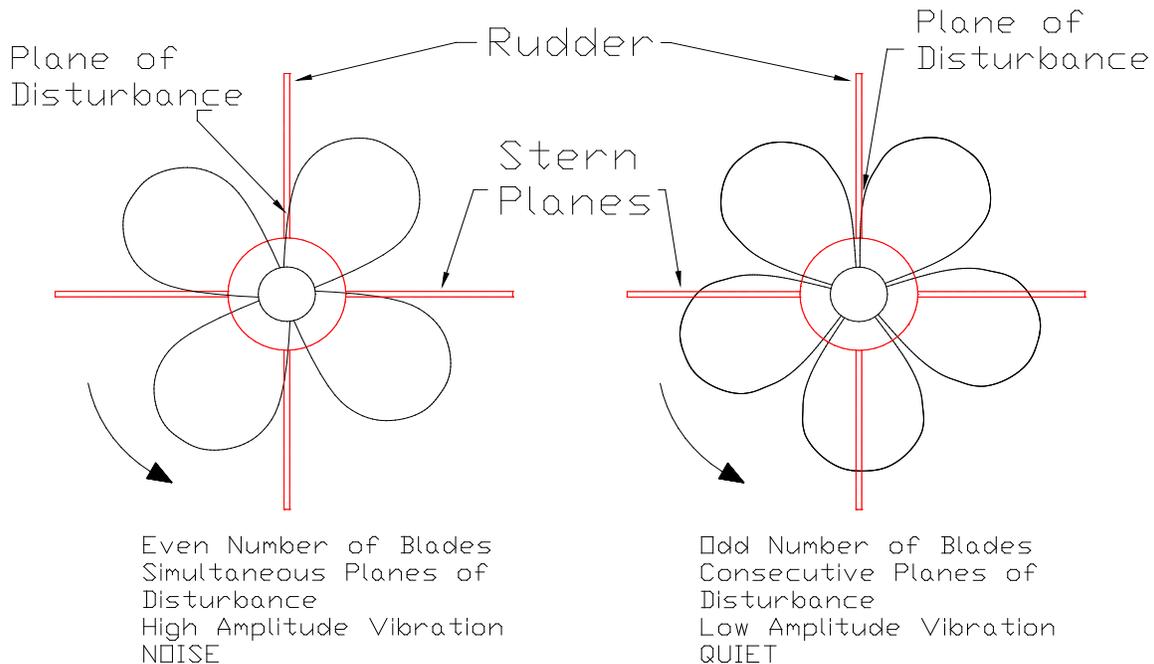


Figure 10.12 Advantage of an Odd Number of Propeller Blades

10.5.2.2 Skewed Propeller

Skewing the propeller has several advantages.

- **Reduced Vibration.** The entire blade does not enter disturbed flow at the same time. In fact, the blade tip may be leaving as another part of the same blade is entering. The amount of the propeller subjected to a disturbance at any one time is reduced and therefore vibration is reduced.

- **Reduced Cavitation.** The shape is thought to produce a radial flow near the blade tips which sweeps cavitation sheets into the tip flow (vortices - or rotating flow). Here the cavitation bubbles collapse gradually reducing the noise level.

Unfortunately, highly skewed propellers have some disadvantages.

- Very inefficient for backing.
- Very difficult and expensive to manufacture.
- The unusual shape reduces the strength of the blades.

For the special considerations of submarine operation and the absolute need for stealth, the advantages of the highly skewed propeller outweigh the disadvantages.

10.6 Submarine Seakeeping

You will recall from Chapter 8 that a surface ship will respond to any external forcing function. Of the six rigid body ship motions, heave, pitch and roll are simple harmonic motions because they experience a linear restoring force. If the encounter frequency matches the resonant frequency of heave, pitch, or roll, these motions will be maximized, particularly for roll which has a sharply tuned response characteristic for submarines (meaning it is lightly damped and is slow to cease its harmonic motion).

Because surface waves affect water velocities beneath the surface, a submerged submarine can experience the same motions as a surface ship. In fact, the motion of roll is often very pronounced due to the submarine's cylindrical shape.

10.6.1 Suction Force

In addition to the usual surface ship motions, a submerged submarine running close to the surface is affected by suction forces caused by the water surface, waves and the shape of the hull.

10.6.1.1 Water Surface Effect

When a submarine is traveling near the surface, at periscope depth for instance, a low pressure is created on the top surface of the hull causing a net upward lifting force or suction force. The magnitude of the suction force depends upon speed, depth, and hull shape. A higher speed creates a bigger force. The closer the hull is to the surface, the greater the suction force. Large flat surfaces, like missile decks on SSBN's, create greater suction forces than round SSN hulls.

The effect can be minimized by traveling at very slow speeds while at periscope depth and trimming the submarine by the stern (since trimming by the bow would put the periscope under the water). This latter action places more of the hull farther away from the surface and changes the flow around the hull shape, thereby decreasing the magnitude of the suction force.

10.6.1.2 Wave Action

Wave action on the surface is also responsible for surface suction forces. Water particle velocity decreases with depth. Consequently, the top surface of the submarine experiences faster water velocity and lower pressure than the bottom surface.

The suction effect of surface waves may be minimized in two ways. First, and most obviously, the submarine can minimize or negate the effect of waves by diving deeper where waves do not exist. The submarine may also choose a heading angle relative to the direction of waves to minimize the suction effect. For example, a submarine traveling beam to the seas experiences greater rolling motions but minimizes the suction force. Unfortunately, this course would also present a less comfortable ride for the crew.

10.7 Submarine Maneuvering and Control

Just like a surface ship, a submarine controls its course with a rudder and its speed with the engines and screw propeller. However, the submarine has the added complication of controlling its depth.

Submarine depth control can be accomplished in many ways. Making the buoyant force equal the submarine displacement is the obvious technique and was discussed earlier in the chapter. However, a finer and more positive degree of control is often required. This is achieved by equipping the submarine with control surfaces. Submarines use a combination of stern planes, fairwater planes (on the sail), bow planes (on the hull), and sometimes, dihedrals to control depth.

10.7.1 Fairwater Planes

The fairwater planes are used primarily to maintain an ordered depth. Positioning the planes to the "up" position causes an upward lift force to be generated. Since the planes are located forward of the center of gravity, a small moment (M) is also produced which causes the submarine to pitch up slightly. However, the dominant effect is the lift generated by the control surface. Figure 10.13 illustrates the effect.

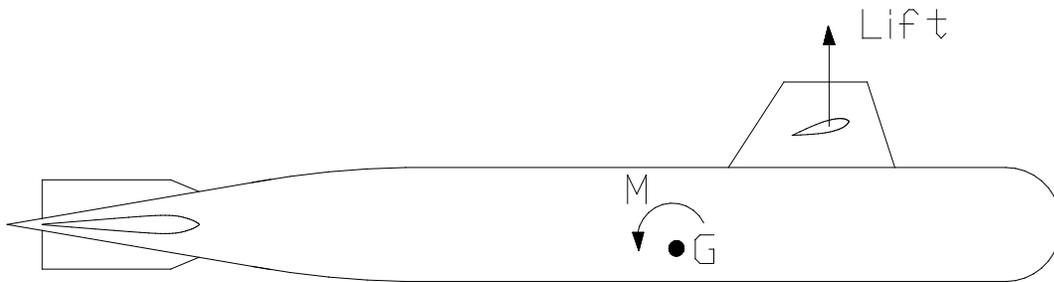


Figure 10.13 The Effect of the Fairwater Planes

10.7.2 Bow Planes

Bow planes perform the same function and work by the same principles as the fairwater planes. Some submarines use retractable bow planes to enable them to operate under and around ice.

10.7.3 Stern Planes

The stern planes have a much bigger effect on the pitch of the submarine because of their distance from the center of gravity. Positioning the planes as shown in Figure 10.14 creates a lift force in the downward direction. This creates a moment (M) which causes the submarine to pitch up, much like the action of the surface ship's rudder discussed in Chapter 9. Once the submarine has an up angle, the hull produces an upward lift force. The net effect is that the submarine rises at an upward angle. Stern planes are often used

to correct a forward and aft trim problem until water can be moved between trim tanks. Additionally, stern planes are also the preferred method of depth control at higher speeds as the submarine “flies” through the water creating an angle of attack with between the hull and the water much like a plane flying through the air.

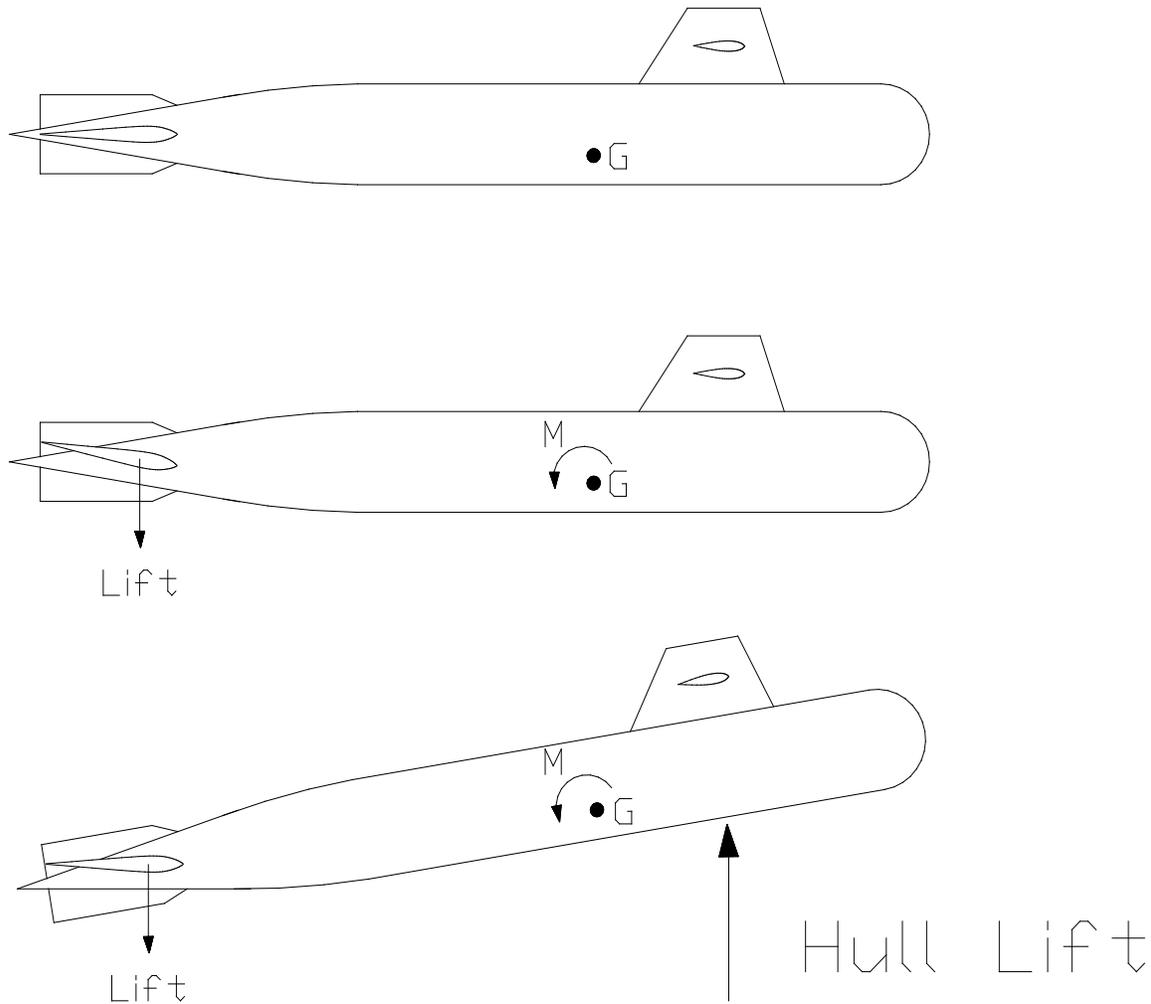


Figure 10.14 The Effect of the Stern Planes

10.7.4 X-Dihedrals

Some submarines employ an “X” configuration at the stern where the traditional “+” or cruciform shape of the rudder and stern planes are rotated 45 degrees. These four control surfaces at the stern are controlled by the operator through a control system which moves the planes to achieve the desired turning and/or trimming effect on the submarine. This unique stern configuration improves depth control and maneuvering and can eliminate the need for fairwater/bow planes. Because these control surfaces require a control

system, they are difficult to control manually in the event of a casualty. Figure 10.15 illustrates this concept.

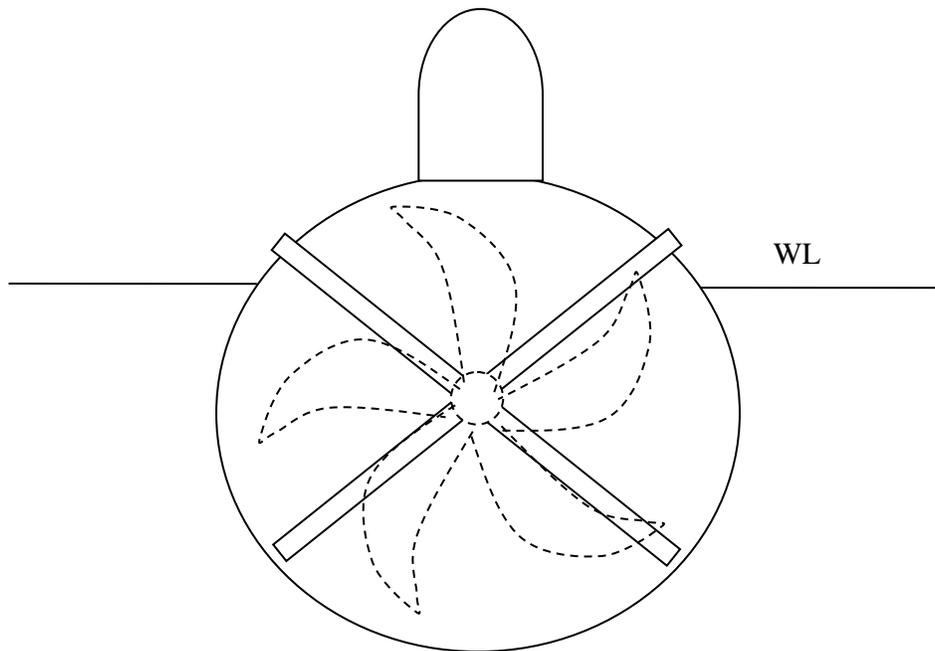


Figure 10.15 X-Dihedral Stern Configuration

10.7.5 Snap Roll

Submarines may experience a phenomenon during high speed turns which results in a large, undesired depth excursion – this is “snap roll”. Snap roll occurs when the submarine begins turning and develops a transverse velocity as it “slides” through the turn (think of advance and transfer). This transverse velocity component combines vectorially with the large forward velocity of the heeling submarine to create a lift force on the fairwater (and to a lesser extent, bow) planes which produces an even greater heeling moment on the ship. The large heeling angle, in turn, causes the rudder to act as a diving stern plane and may result in a significant depth excursion. This effect can be mitigated by limiting the rudder angle during high speed turns, thus limiting the diving plane effect of the rudder. In addition, the use of “X”-dihedrals may mitigate this effect.

PROBLEMS - CHAPTER 10

Section 10.2 Construction & Layout

1. Why are submarines constructed with a transverse framing system in preference to a longitudinal framing system?
2. What is “out of roundness?” What is the significance of this term in relation to submarine structures?
3. A deep-submergence research submarine is capable of operating at a depth of 2,375 feet. Calculate the hydrostatic pressure acting on the submarine’s hull at this depth. What factors would be involved in selecting a material for the submarine’s pressure hull?
4. Submarine pressure hulls are constructed out of high strength steel ($\sigma_Y = 80,000\text{--}100,000$ psi) or titanium alloys ($\sigma_Y = 130,000$ psi). Why would pressure hulls be made out of such materials? Discuss your answer in terms of strength, ductility, temperature, and endurance.
5. What is the difference between hard tanks and soft tanks?
6. Draw a diagram showing the inner hull, outer hull, and main ballast tanks. Which of these must be able to withstand hydrostatic pressure when submerged?

Section 10.3 Hydrostatics

7. Qualitatively describe the changes (if any) that occur to a surfaced submarine’s weight (displacement), displaced volume, and buoyant force as it transits from fresh water to salt water.
8. Qualitatively describe the changes (if any) that occur to a submerged submarine’s weight (displacement), displaced volume, and buoyant force as it moves from cold water to warm water.
9. How does increasing depth affect submarine buoyancy?
10. A SEAWOLF class submarine displaces 8,060 LT when surfaced, and also displaces 9,150 LT when submerged. What factors account for the weight change between the surfaced and submerged conditions?

11. A LOS ANGELES class submarine is neutrally buoyant at a displacement of 6,900 LT in salt water at a temperature of 45°F ($\rho = 1.9933 \text{ lb-s}^2/\text{ft}^4$). The submarine transits into water that is one degree warmer ($\rho = 1.9931 \text{ lb-s}^2/\text{ft}^4$). How many pounds of water must the Diving Officer add or remove from the depth control tank in order to maintain neutral buoyancy.
12. An OHIO class submarine has departed homeport enroute to its patrol area. The submarine is operating in the Gulf Stream ($T = 70^\circ\text{F}$, $\rho = 1.9876 \text{ lb-s}^2/\text{ft}^4$), and is neutrally buoyant at a displacement of 18,700 LT. The submarine exits the Gulf Stream and enters the colder water of the North Atlantic Ocean ($T = 50^\circ\text{F}$, $\rho = 1.9924 \text{ lb-s}^2/\text{ft}^4$). How many pounds of water must the Diving Officer add or remove from the depth control tank in order to maintain neutral buoyancy?
13. A submerged SSN-688 class submarine has been patrolling the arctic ice pack. While under the ice, the sub was neutrally buoyant at a displacement of 6,900 LT assuming water conditions of 70% salt water and 30% fresh water at a temperature of 30°F. The submarine is now transiting south into the North Atlantic where the ocean is 100% salt water at a temperature of 35°F. What action must the Diving Officer take to maintain neutral buoyancy?

$$\text{@ } 30^\circ\text{F} - \rho_{\text{fresh}} = 1.9399 \text{ lb-s}^2/\text{ft}^4$$

$$\text{@ } 35^\circ\text{F} - \rho_{\text{fresh}} = 1.9400 \text{ lb-s}^2/\text{ft}^4$$

$$\text{@ } 30^\circ\text{F} - \rho_{\text{salt}} = 1.9947 \text{ lb-s}^2/\text{ft}^4$$

$$\text{@ } 35^\circ\text{F} - \rho_{\text{salt}} = 1.9945 \text{ lb-s}^2/\text{ft}^4$$

14. A surfaced submarine's pressure hull is a right cylinder 30 feet in diameter and 300 feet in length. When at depth, the hydrostatic force compresses the hull's length by one inch. Neglecting any changes in diameter due to hydrostatic forces, calculate the change in buoyancy due to compression of the hull.
15. A submerged submarine is neutrally buoyant at a displacement of 6850 LT and is at zero trim; $KB = 16.5 \text{ ft}$ and $KG = 13.5 \text{ ft}$. To enter its assigned patrol area, the submarine must pass through a choke point that may be mined. In order to detect possible mines with its sonar, the submarine's CO directs the Diving Officer to trim the sub 4 degrees down by the bow. If the sub's trim tanks are located 320 feet apart, how many pounds of water must be transferred between trim tanks to achieve the desired trim angle? How do the locations of the centers of buoyancy and gravity change once the sub has been trimmed?

16. A SEAWOLF class submarine is operating at neutral buoyancy and zero trim at a displacement of 9,100 LT; $KB = 20$ ft and $KG = 16.5$ ft. In preparation for an exercise, the crew loads 8 Mk48 torpedoes (3,434 lb each) into the tubes. To load the tubes, each torpedo is moved forward a distance of 30 feet.
- What is the effect of loading torpedoes on the submarine's LCG?
 - Calculate the trim angle that results from loading torpedoes.
 - Using an appropriate diagram, show the relationship between LCB and LCG before and after loading torpedoes.
 - If the submarine's trim tanks are located 310 feet apart, how many pounds of water must be transferred to restore the sub to level trim?
 - If KG increases, how does this affect the submarine's tendency to trim?
17. A submerged submarine has a trim angle of 2 degrees up. It is desired to pump water between the forward and aft trim tanks to correct the trim to zero degrees. The sub is neutrally buoyant at 7,500 LT, $KG = 13.5$ ft and $KB = 15.7$ ft. The trim tanks are 300 feet apart.
- Should water be pumped from the aft trim tank to the forward trim tank, or from the forward trim tank to the aft trim tank?
 - What is the effect of pumping water in the direction you chose in part (a) on the submarine's LCG?
 - What is the relationship between LCB and LCG in the initial condition? Final condition? Use a diagram to show this relationship.
 - How many pounds of water must be pumped to achieve zero trim?

Section 10.4 Stability

18. A submerged submarine has a $KB = 14.5$ ft and $KG = 13$ ft. Its displacement is 6,500 LT.
 - a. Write the equation for the curve of intact statical stability.
 - b. Compute the submarine's maximum righting moment.
 - c. At what heeling angle does the maximum righting arm occur?
 - d. What is the range of stability?
 - e. Using integral calculus, compute the submarine's dynamic stability.
 - f. Repeat all of the above for $KG = 14$ ft. Compare your results.

Sections 10.5-10.7 Powering, Seakeeping & Control

19. A surfaced submarine traveling at full power can achieve a speed of 15 knots, yet when submerged at a depth of 400 ft can achieve 25 knots at full power. What accounts for the difference in speeds?
20. Why do submarines use an odd number of blades on their propellers?
21. Name two advantages and two disadvantages of skewed propellers for submarines.
22. Describe two sources of surface suction.
23. Draw a profile of a submarine showing the rudder, fairwater planes, and stern planes. What are each of these control surfaces used for?
24. What is snap roll?