Turning the Battleship

How the NORTH CAROLINA Steering System Works

Steering the Battleship NORTH CAROLINA

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How do you turn a battleship with a displacement of 44,500 tons, steaming through the water at top speed of nearly 28 knots, with two rudders that weigh more than 50 tons each? And how does the strength of a single individual in the ship’s pilot house move the rudders against the tremendous torque created by the rushing seawater from the ship’s propellers?

The answer is an electrohydraulic steering gear system consisting of two units, one for each rudder, on the port (left) and starboard (right) sides of the ship in separate compartments. Each unit comprises two double-action (push/pull) hydraulic rams connected to a rudder yoke for its respective rudder, as well as two power units consisting of powerful hydraulic pumps driven by 75-H.P. electric motors. Under normal operation only one power unit will be running in the steering gear rooms on each side of the ship, with the other available for back-up. (For the sake of clarity, this article uses the present tense to explain how the various elements of the steering gear work.)

Electrical devices called “selsyns” or “synchros” (for self-synchronizing) transmit steering information from the ship’s bridge, and other locations, to a receiver in each steering gear room. Another device, a servo control unit, converts the electrical signals from the selsyns into mechanical power to operate the hydraulic pumps which pushed the rams and rudders in one direction or another. This basic steering technology still is used today in large Navy vessels and commercial ships.

The first step in the process is to transmit the turning information from the helmsman at the ship’s steering wheel high in the pilot house to a receiving unit in the far aft end of the ship. As the steering wheel turns in the pilot house, an electric current is generated in the transmitting unit and sent to the receiving unit. The receiver is actually an electric motor, but the way it’s wired to the transmitter makes it turn precisely in parallel with the steering wheel. You can see the selsyns, or synchros, in Figure 1. They are located directly below the ship’s steering wheel in the pilot house (as well as with steering wheels in other locations in the ship).
Figure 1: Selsyn Transmitting Units in Battleship’s Pilot House

Figure 2: Receiving Selsyn in Steering Gear Room

Figure 2 shows the receiving selsyn in the battleship’s steering gear room. (The selsyn units were manufactured by the Westinghouse Electric and Manufacturing Company and you can see the company’s nameplate at the bottom of the photo.) The receiving unit (electric motor) is connected through its shaft to a servo control unit that operates a variable-speed hydraulic pump, called a Waterbury-type pump, which will be described more fully later in this article. The Waterbury pump is connected via a series of high-pressure pipes to the pistons in the hydraulic ram, which in turn move the rudder to port or starboard. One piston pushes the yoke on one side of the rudder and the other simultaneously pulls in the opposite direction on the other side.
Figure 3 shows one of the two hydraulic rams in the port steering gear ram room. Each ram controls a piston that is connected to the yoke of the rudder, via a tie rod, shown at the back of the photo. The shaft for the rudder follow-up mechanism is connected to the servo control unit that will be described later. The rudder follow-up mechanism is a critical element in synchronizing the position of the ship’s steering wheel with the angle of the ship’s rudders.

The Battleship NORTH CAROLINA has two steering gear ram rooms and two steering power rooms for each of its two massive 20-foot-by-20 foot rudders (seen in the cover page for this article). The port and starboard rooms are not connected in any way, mechanically, hydraulically, or electrically. Instead their respective steering gear systems operate independently but in synchronization with the ship’s steering wheel(s). In addition, the port and starboard rams and the steering gear power units are in separate rooms. You can see how these rooms looked during the ship’s construction in Figures 4 and 5. These show the port rooms. Armor plating surrounds the four steering control rooms, each of which can be made watertight at battle stations with closed hatches.

All of the photos in this article, except for the steering wheel in the pilot house, were taken in the port rooms.
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Figure 4: Steering Gear Power Room in 1941
Descriptions of Steering Gear Equipment
The rams for each rudder are operated by two duplicate and completely independent power units. The connection to the rams can be switched from one power unit to the other by means of a six-way transfer valve. Under normal operation only one power unit would be operating for each rudder. However, under special circumstances, such as entering port or refueling a ship, both units could be operating – with one unit on standby.

The illustration in Figure 6, scanned from the U.S. Navy’s “Principles of Naval Engineering,” shows a simplified overview of a double-ram electrohydraulic steering system. All of the basic elements in Figure 6 can be found in the NORTH CAROLINA’s steering gear. The black-shaded piping demonstrates that hydraulic fluid is being pumped into opposite ends of the two rams to provide the push/pull motion to the rudder yoke. The illustration also shows an idle pump operating on standby.
The steering gear equipment was provided by the Hyde Windlass Company, of Bath Maine. A part of this company, Hyde Marine, still manufactures ship machinery. The pumps were provided by the Waterbury Tool Company, which is no longer in business. The selsyn units were provided under subcontract to Hyde Windlass by Westinghouse.

The steering gear consisted of these basic components:

- Selsyn transmitters and receivers
- 440-Volt, three-phase electric motor (constant speed)
- Variable-speed Waterbury pump
- Servo control unit for Waterbury pump
- Hydraulic rams
- Auxiliary rudder centering pump
- Redundant power sources
- Sound-powered telephones

**Selsyn Transmitters and Receivers**

In addition to steering the ship, self-synchronizing selsyns are used throughout the NORTH CAROLINA, for such functions as communicating the desired speed and direction via the telegraphs in the pilot house and engine rooms, training the gun turrets, and passing critical ship information to the fire control computers. Selsyn units are still in wide-spread use today, for steering modern navy vessels, training weaponry, and for controlling the direction of equipment such as satellite dishes, and even in multiple motors for lifting drawbridges.
Figure 7: Wiring for Selsyn Units

Figure 7 shows how the selsyn transmitter and receiving units are wired together. The selsyn units behave much as typical electric motors, the difference being that any rotation of the rotor/shaft in the transmitting unit is matched exactly in the rotor/shaft of the receiving unit. As the rotor turns in the transmitting unit, an electric current is induced in the receiving unit, and electromagnetism forces the rotor in the receiving unit to exactly parallel the rotor in the transmitting unit. At that point, no further current flows, until the next turning operation. In the wiring diagram in Figure 7, the external power to the selsyn units is 115-volt, single-phase power. The selsyns on the NORTH CAROLINA, however, use 440-volt, single-phase power.

The selsyn was patented by a German citizen, Carl Joseph August Michalke, in Germany in 1896, and in the United States in 1901. One of the wiring diagrams in Michalke’s U.S. patent submission is identical to the wiring of the NORTH CAROLINA’s steering selsyns, manufactured nearly forty years later.
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Figure 8: Mechanical Representation of Selsyn Operation

Figure 8 shows a mechanical representation of a selsyn system. In a ship as big as the NORTH CAROLINA, such a mechanical process would be impossible because of the importance of watertight integrity throughout the sections of the ship and the great distances from the various steering locations to the aft end of the ship. Electrical circuits, such as for the selsyns, can be made watertight as they pass through the various compartments of the ship.

The Battleship is designed to enable steering from five different locations: the pilot house (bridge), the conning tower, secondary conning (in level 7 of the foremast), central control (just in front of the plotting room on the 1st Platform deck), and the steering gear room itself. A switch in central control selects which steering wheel and selsyn transmitter are in use at any given time. This switch is still in place in central control, as pictured in Figure 9.
For redundancy, the circuits for the transmitter and receivers are duplicated on the port and starboard sides of the ship. In addition, each of the two steering gear rooms is equipped with two receivers and duplicate hydroelectric motors and tubing. Under normal circumstances only one receiver and hydroelectric motor in each steering gear room is operating. Figure 10 shows the switches for the selsyn cables and transmitters.
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Another set of selsyn transmitters and receivers communicates the angle of the rudder to the pilot house. Figure 11 shows the selsyn transmitter attached to the yoke of the rudder and Figure 12 shows the angle indicators for both rudders on the steering column in the pilot house.

Manually operated wheels, called trick wheels, can be used to control the hydroelectric motors and rams to turn the ship if the selsyn electrical circuits are completely disrupted. In fact, this happened several times during the ship’s 1942 sea trials, proving that the ship could be steered effectively using only the trick wheels. As a historical note, “trick wheel” comes from an old nautical term for the time spent at a ship’s wheel, such as, “I relieved the pilot after he had completed his trick at the wheel.”

Figure 11: Selsyn Transmitter for Rudder Angle.
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Figure 12: Rudder Angle Indicators on Steering Column in Pilot House

Figure 13: Trick Wheel (bottom right) for Port Side Steering Gear
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You can see the trick wheel for the steering control gear in Figure 13. The hydraulic fluid reservoir is installed at the top of the steering gear system to ensure that the entire system is always full of fluid. The rudder angle indicator is connected to the rudder follow-up mechanism.

The servo control unit directs the volume and direction of hydraulic fluid from the Waterbury pump that operates the hydraulic rams, as explained below. Using a selsyn in combination with the servo control unit enables a single helmsman in the pilot house to control the entire steering gear mechanism and both rudders. It takes eight complete turns of the steering wheel to move the rudder 70 degrees from its left-most to its right-most position. The rudders themselves take about 36 seconds to complete the 70-degree turn. Another set of selsyns communicates the angles of the two rudders to the helmsman.

**Electric Motor**

The hydraulic pump, with a variable-speed transmission, is driven by a 75-horsepower, 440-volt, three-phase electric motor, shown on the left-hand side of Figure 13. This motor ran at a constant speed; the actual volume and direction of hydraulic fluid were controlled by a hydraulic motor and variable-speed transmission called a “Waterbury pump.”

If power fails to the hydraulic pumps, a brake on the electric motor shaft will lock, preventing the rudder from moving out of control and damaging the steering gear equipment.

**Waterbury Pump**

In the early 1930s, the Waterbury Tool Company perfected a type of hydraulic pump, called an axial-piston variable displacement pump or transmission. As stated in the company’s 1930 patent submission, the pump had many advantages because of the fact “that gradual speed changes may be secured with such transmission without abrupt and sudden variations such as are inherent in the utilization of other types of transmissions.” This is a very good thing given the NORTH CAROLINA’s role in refueling other ships while still underway!

The Waterbury pump in ship’s steering gear consists of eleven stroke pistons that rotate in a cylinder called a “tilting box.” The cylinder, while rotating at the speed of the 75 H.P. motor, can be tilted in such a way that the length of the stroke of the pistons, and thus the force and direction of the hydraulic fluid, can be controlled by tilting the cylinder. As the cylinder rotates, each piston goes through a complete stroke cycle. As the degree of angle in the tilt increases, the stroke of the piston becomes longer and applies more power to the pumping stroke. Tilting the cylinder in one direction or the other changes the direction of the flow of the hydraulic fluid, and thus the direction of the hydraulic rams. The use of the Waterbury pump in the battleship provides rapid, powerful, and very precise movements of the hydraulic rams connected to the rudders.
Figure 14: Diagram of an Axial Piston Waterbury-Type Pump (Author: Evan Mason 2010)

Figure 14 illustrates how the rotating cylinder and pistons operate. The cylinder and pistons rotate around a shaft connected to the constant-speed electric motor. The pistons are connected to the tilting block, which can be rocked on an axle that runs perpendicular to the drive shaft. If the tilting block is exactly perpendicular to the turning shaft, the pistons do not reciprocate and no hydraulic fluid is pumped. The pump is considered to be in the neutral position. However, as the tilting block is rocked, the pistons will begin to reciprocate and pump fluid in one direction or the other. The rocking action is referred to as “stroking” the hydraulic pump. In the NORTH CAROLINA, stroking the hydraulic pump is controlled by a servo control unit, described next.

Waterbury-type pumps also are used to operate anchor windlasses, cranes, winches, and other gear on the NORTH CAROLINA.

**Servo Control Unit: Differential Control and Rudder Follow-Up Mechanism**

A selsyn receiver by itself does not generate enough torque (only 7 foot pounds) to directly control the Waterbury pumps operating at 385 pounds per square inch (psi). As seen in Figure 15, the selsyn receiver and the trick wheel are connected to the trick wheel shaft. Either the selsyn receiver or the trick wheel can operate the servo control unit. The selsyn receiver is connected via a gear box to the shaft of the trick wheel. The gear box uses 90-degree miter gears to transmit the horizontal turning motion of the selsyn receiver to the vertical or perpendicular turning motion of the trick wheel shaft and the shaft to the servo control unit. A clutch is provided to disconnect the trick wheel from the servo control unit when the ship is being steered remotely.
The servo control unit contains several key elements required for steering the ship:

- Differential control unit
- Servo control pump and piston
- Automatic stroke control piston

The differential control unit joins the shaft from the trick wheel/selsyn on its forward end to the rudder follow-up assembly on its aft end, as shown in Figure 16. When the steering shaft is rotating in either direction, the rudder follow-up shaft is disconnected from the differential gear by a clutch. When the steering shaft stops rotating, at the end of a steering turn, the rudder follow-up shaft takes control of the differential. A cylindrical cam, rotating within the differential control unit, has grooves recessed on its outside surface. A cam follower roller moves within the grooves. The grooves are designed to move the cam follower roller, connected to the hydraulic pump by a series of levers, to stroke the pump in whichever direction the steering turn calls for. Further, the grooves cam “store” the required position of the turns from 35 degrees port to 35 degrees starboard.
Imagine we could peel off the outside of the cylindrical cam and lay it flat. It would look like Figure 17. As the cam rotates in response to the turning of the steering shaft, the grooves force the cam roller and follower to move in one direction or the other (up or down in this illustration), corresponding to a turn to port or starboard. This motion is transmitted to the hydraulic pump through a series of levers. Because of the steep incline of the groove at its center, the cam follower moves rapidly to its maximum up or down position, thus stroking the hydraulic pump to its maximum speed in one direction or the other.
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Once the pump is running at top speed, the cam roller and cam follower are maintained in position through the longitudinal (no incline) groove, port or starboard. As the cam rotates, the cam roller and follower are not moving up or down while in either longitudinal groove. The length of the grooves in the rotating cam is proportional to the degree of angle of the rudder. In effect, the cam “remembers” what degree of rudder angle has been transmitted by the steering gear by how much the cam has been rotated and the position of the cam roller in the longitudinal grooves.

Once the steering shaft stops turning and the rudders begin to turn, the rudder follow-up assembly engages the differential control unit and begins to “unwind” the rotation of the cam. (The shaft from the rudder follow-up assembly turns in the opposite direction of the steering shaft.) When the unwinding of the cam is complete and the rudders are at the angle required by the turn, the cam roller moves to the center of the inclined section of the groove and the stroking of the pump is put into neutral.

Stops installed on a worm gear are another important element of the differential gear control. They prevent the cam from turning more than 35 degrees in either direction.

The cam follower is actually connected through the series of levers to a separate hydraulic pump and piston called a servo control. This separate pump is attached to the outside of the main Waterbury pump (not visible in Figure 16), but operates independently. The piston of the servo control is attached to the tilting wheel in the main hydraulic pump. It’s this piston that actually controls the stroking of the Waterbury pump. The cam follower, through the levers, actuates the servo pump and piston. This piston is visible at the top of the Waterbury pump in Figure 18. At the top of the piston is a brass pressure gauge.
The normal operating pressure of the Waterbury pump is 385 psi. An automatic stroke control piston, also shown in Figure 16, held in position by a powerful adjustable spring, is designed to force the cam follower into its neutral position if the pressure of the Waterbury pump exceeds its normal operating range. If the pressure rises too high, the piston overcome the resistance of the adjustable spring and move a V-shaped guide over a lug connected to the cam follower, forcing it into its neutral position. As a result, the Waterbury pump is also put into its neutral until the pressure drops and the piston resumes its normal position. The cam follower is attached to the cam roller by a spring, so no movement of the differential cam is required when the automatic piston stroke control engages. This also lets the cam resume its normal operation when the pressure in the Waterbury pump returns to safe levels.

If the helmsman is ordered to execute a “hard-over” turn to starboard, he immediately rotates the steering wheel to starboard and the rudders begin to turn. However, the helmsman can spin the steering wheel much faster than the hydraulic rams and the steering gear can turn the rudders. The cam mechanism in the servo control unit “remembers” where the helmsman last positioned the steering wheel and the control unit continues to operate the Waterbury pump at full power until the rudders come to the desired position. The rudder follow-up assembly, also connected to the cam, returns the Waterbury pump to idle once the rudders
are properly positioned. The pressure of the hydraulic fluid in the steering gear system locks the rudders in position until the next steering command is transmitted.

Figure 19 shows the gear rack attached to the rudder yoke, pinion, and shaft for the rudder follow-up assembly. The other end of the shaft is connected to the servo control unit that operates the Waterbury pump. The shaft communicates the angle of the rudder to the servo control unit.

**Hydraulic Rams**

Each rudder is turned by two double-action (push/pull) hydraulic ram pistons via a yoke tiller connected to the rudder. To turn the rudder, one piston pushes on the yoke on one side while the other piston pulls on the yoke on the other side. The push/pull and turning power of the hydraulic system is controlled by the Waterbury pump and transmission. The rudder is held at its desired position by a hydraulic lock until another turn movement is initiated.

The hydraulic rams, shown in Figure 19, are operated by pistons and pipes that are connected to a six-way transfer valve that permits the rams to be operated by either side of the steering gear equipment in one control room. The lever for the transfer valve is on the floor between the two trick wheels, shown in Figure 20.
According to the NORTH CAROLINA’s construction documents, each rudder is designed to withstand a transverse force, or torque, from the rushing seawater of 375,000 foot pounds when the rudder is at a 35-degree angle and the ship is moving forward at 28 knots. The normal operating pressure of the Waterbury pump is 385 psi when the ship is moving forward. In a hydraulic ram system, force is calculated by multiplying psi times the number of square inches of the piston head, called a plunger. The hydraulic ram plungers are 16.5 inches in diameter, which equates to 213.825 square inches. Multiplying 214.825 square inches by 385 psi equals 82,323 pounds of force. With two rams operating in opposite directions, the total force applied to the rudder yoke is approximately 164,646 pounds.

As you can see in Figure 21, the tie rods are connected to a yoke enveloping the rudder shaft. The distance from the center point of the rudder shaft and the center of the tie rod pin is 42 inches. The yoke acts as a 42-inch lever, multiplying the force from the rams on the rudder shaft. Rotational torque is calculated as force times the length of the lever, with maximum torque when the force is perpendicular to the lever. Maximum torque on the rudder shaft is equal to 3.5 feet times the 164,646 pounds of force from the rams, or 576,261 foot pounds. With the rudder angled at 35 degrees, the torque is reduced by 35 percent, down to 375,000 pounds, exactly the rudder design specification.

When operating astern, the psi of the hydraulic system can reach 1,600 psi, enough to withstand the more than 1.5 million pounds of force on the Rudders when the ship is going backwards at full-speed (about 15 knots).
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Figure 21: Hydraulic Steering Rams

**Auxiliary Centering Pumps**
The NORTH CAROLINA can be steered with only one rudder, providing that the other rudder is in its centered position. In the event of a steering gear failure (referred to as a “casualty” by the Navy), a backup hydraulic pump can be used to force the out-of-service rudder back to its center position. One of these pumps is located in each steering control room. The pumps are connected to the six-way transfer valves in their respective steering gear power rooms. Figure 22 shows the auxiliary centering pump in the starboard steering gear power room. Each pump can operate either rudder.
Redundant Electrical Supply
As with all critical battleship systems, such as the gun turrets, engine room, battle lighting, and fire control, the two steering gear rooms have completely separate main and alternate power circuits from the turbo and diesel generators. A control panel, shown in Figure 23, provides a way to manually switch from one power source to another. A switch on the control panel, shown at the bottom of Figure 23, can select the main or alternate power supply. The starboard steering room normally is powered from the aft turbo generator in Machinery Room #3, while the port side room is powered from the forward turbo generator in Machinery Room #1. The alternate power is from the ship’s diesel generators, which will be running during general quarters.
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Figure 23: Steering Gear Power Switchboard

**Sound-Powered Telephones**

The steering control rooms are in constant communication with the pilot house, or any of the alternate steering locations. The jacks for the sound-powered telephones are to the side of the steering gear switchboards in each steering control room. The jacks are shown in Figure 24. These jacks are connected to the battleship control circuit 1JV, as well as an auxiliary control circuit.

Each steering gear power room normally is manned by a quartermaster, a machinist’s mate and an electrician’s mate.
Historic Footnotes
The original selsyn units installed during the ship’s construction were quite unreliable and noisy. A memo from October 14, 1941, noted that the selsyns “have pulled out of synchronization on six different occasions.” Another memo from January 23, 1942, complained that the selsyn resistors (used to avoid short circuits in the system that could have destroyed the selsyns) “keep burning out.” Captain O.M. Hustvedt wrote in February of 1942 that the selsyns in the ship’s steering gear had a pronounced hiss that “interferes with the perception of sound incidental to safe navigation.”

After more than a year of complaints, Westinghouse installed modified selsyns in March of 1942. A Westinghouse engineer, however, had pointed out that the Navy itself had specified that the selsyn resistors be installed inside the selsyn units, which caused the resistors to overheat and fail. The engineer recommended moving the resistors outside the selsyn units and installing them in a drip-proof assembly adjacent to the selsyn receivers in the steering control rooms. This was done when the original selsyns were replaced. The external resistors are visible to this day, as seen in Figure 25, between the two electric motors in the steering gear power room.
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When the ship was built, there was a steering wheel in central control, next to the forward gyroscope. You can see the steering wheel in the photo of central control taken during the ship’s construction in Figure 26.

As you can see from a current photo of central station in Figure 27, the steering wheel is no longer in place.
A likely reason relates to the replacement of the original selsyns in early 1942. The steering (transmitter) selsyns were replaced in the pilot house, the conning tower, and in secondary conning. The selsyns in central control, however, were not replaced because they could be used as replacements for the receivers in the steering control rooms, if necessary, but the new steering selsyns could not. It’s conceivable that the selsyns from central control were used to replace broken receivers at some point during the ship’s service.

Another interesting footnote is about the angle indicators that are visible from the trick wheels in each of the steering control room. You can see one of the angle indicators in Figure 28 in the back corner of the steering gear power room. The angle indicators are connected to the steering equipment by a set of mechanical shafts and gears, and the indicators show the angle of the rudder in the opposite steering control room. These angle indicators were added late in the construction of the ship when the shipbuilders realized there was no way to know the angle of a rudder in the opposite steering gear power room if that rudder’s steering gear room was flooded. This mechanism was duplicated in later battleships such as the NORTH DAKOTA and the NEW JERSEY.
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You can see this add-on system on the bulkhead between the steering gear control room and the room with the hydraulic rams. Note: this angle indicator should not be confused with the angle indicator shown with the trick wheel assembly in Figure 13. The angle indicator in Figure 28 is for the opposite port rudder, while the angle indicator in Figure 13 is for the rudder associated with the starboard steering gear.

**Conclusion**

Although the NORTH CAROLINA was decommissioned in 1947, the basic components of the ship’s steering gear equipment are quite similar to the steering gear in large ocean-going vessels today. Steering transmitting and receiving selsyns are still used, as are large hydraulic rams for turning the rudders. Smaller Navy vessels such as destroyers use a single hydraulic ram, while large ships such as aircraft carriers use a two-ram system, the same as the one used on the NORTH CAROLINA.

The steering gear equipment employed a series of force-multipliers: From the human power of turning the ship’s steering wheel, to the 7 foot pounds of torque from the selsyn receivers, to the 164,646 pounds of hydraulic force from the hydraulic rams, and finally to the 375,000 foot pounds of force on the ship’s rudders during a full-speed, 35-degree turn.

The intricacy of the ship’s steering equipment, the mechanical physics employed, and the precision manufacturing and installation required to mesh all the pieces are all impressive. The Battleship NORTH CAROLINA’s steering system represented state-of-the-art technology when the ship was commissioned in 1941.

A seaman on a modern Navy ship would have no problem in identifying the similarities between the Battleship’s steering control gear and the steering equipment in his or her own ship.