Ship's speed measurement - construction and principle of operation of logs

References:

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Fransiszek Wróbel – Vademecum nawigatora
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Introduction

Speed measurement has always been of the utmost importance to the navigator. The accuracy of a dead reckoning position plotted after a long passage without star sights being taken, is dependent upon a sound knowledge of the vessel's heading and speed.

To be of value, the speed of any object must be measured relative to some other point. At sea, speed may be measured relative to either the seabed (ground reference speed) or to the water flowing past the hull (water reference speed). Both of these types of speed measurement are possible and both have their place in modern navigation systems.

Introduction

The mariner’s speedometer is **log**.

Mariners originally measured speed by observing a chip of wood passing down the side of the vessel.

Later developments included a wooden board attached to a reel of line. Mariners measured speed by noting how many knots in the line unreeled as the ship moved a measured amount of time; hence the term knot.

Mechanical logs using either a small paddle wheel or a rotating spinner arrived about the middle of the 17th century. The taffrail log still in limited use today was developed in 1878.

Introduction

Modern logs use electronic sensors that induce small electric fields proportional to a vessel's speed.

An engine revolution counter or shaft log often measures speed aboard large ships.

Doppler speed logs are used on some vessels for very accurate speed readings.

Inertial and satellite systems also provide highly accurate speed readings.

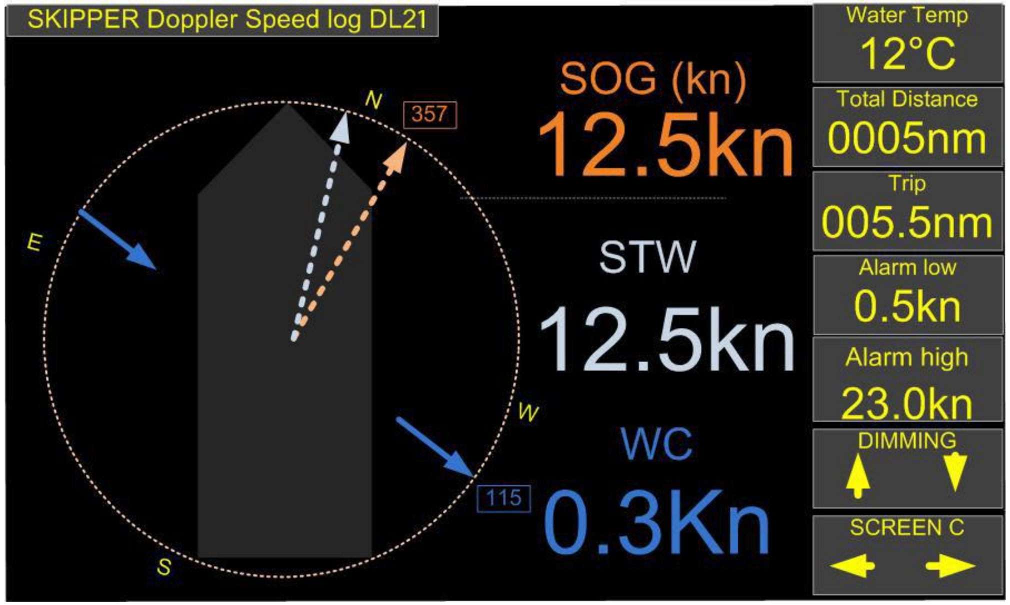
Introduction

Modern logs, in addition to the basic function of the speed of the ship measurement, provide a lot of information equally important for navigation. This information allows you to:

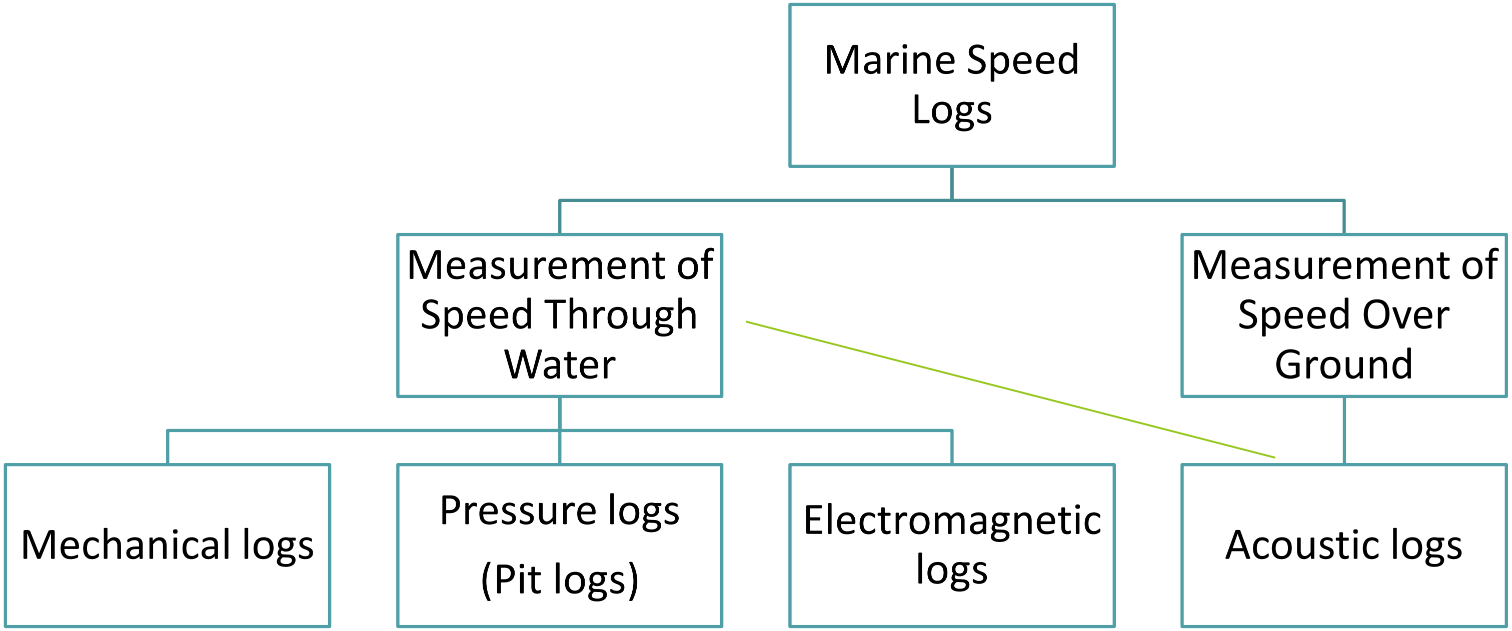
- Determination of water velocity (currents) on rivers, roadsteads and restricted waters
- Determination of the effect of the water current on the hull setting and on the anchorage chain tension
- Indication of forward and reverse speed during maneuvers, and in multiple-axis logs the velocity of the bow and stern
- Obtaining the information needed for the appropriate selection of lines due to the influence of the water currents while mooring

Introduction

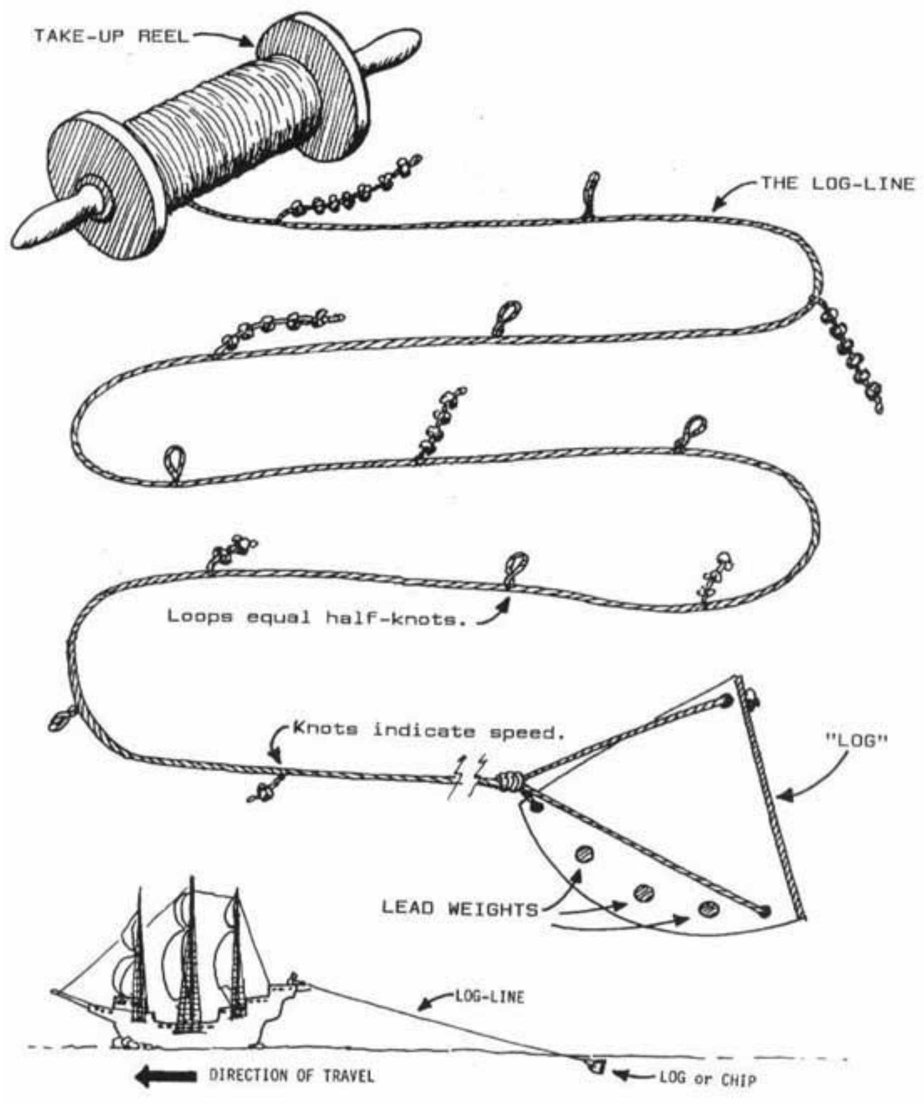
Because of the reference point, logs are divided into logs measuring relative velocity (Speed Through Water) and absolute velocity (Speed Over Ground, True speed). Relative velocity (STW) is the speed of movement of the ship's hull relative to the surrounding water. Absolute velocity (SOG) is the speed of hull movement relative to a fixed point on land.



Introduction



Mechanical logs - history



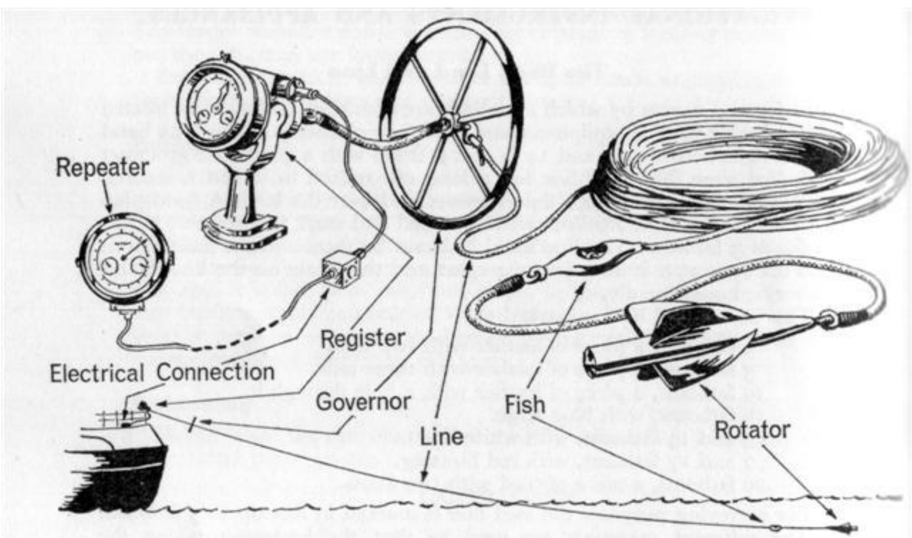
Mechanical logs – taffrail log

Mechanical logs – taffrail log

The taffrail is the aftermost railing around the stern of a ship, to which a log could be mounted with a clamping mechanism (thus resulting in the name taffrail log). These instruments were mechanical and torpedo-shaped, and were dragged from the stern of a ship in order to determine the vessel's speed through the water.

Mechanical logs – taffrail log

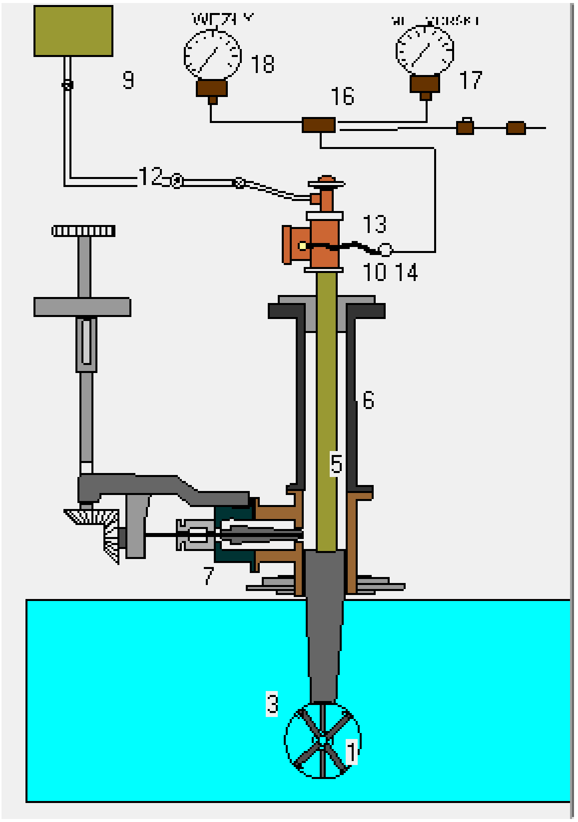
The taffrail log consists of a propeller, or rotator, with four vanes, a reading dial, and a stiff braided line that connects the two parts. As the propeller rotates, it exerts torque on the braided line, which the dial in turn registers.



Towed log (Trident type).

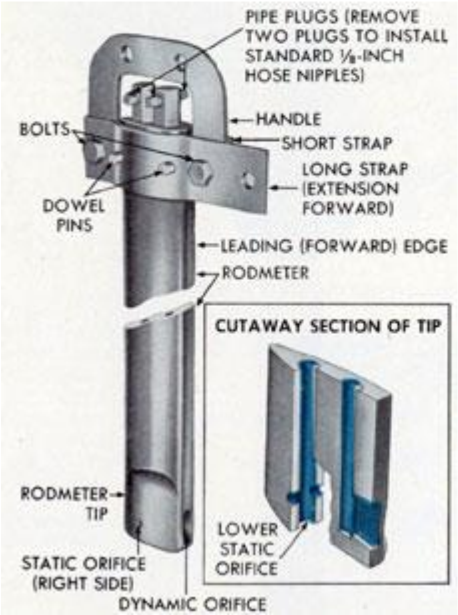
Mechanical logs – impeller log

- An impeller or small propeller that projects outside the vessel's hull below the bottom of the boat.
- The movement of the vessel's hull through the water causes the impeller to rotate.
- The rotation of impeller produces the electric impulse that is proportional to the counts or revolutions of impeller and the is translated into distance and speed.
- The problem with this log is that the projection below the boat is liable to be damaged by fishing gear and debris floating in water.



Speed measurement using water pressure

When a tube, with an opening at its base, is vertically submerged in water, a pressure, proportional to the depth to which the tube is submerged, will be developed in the tube. If the tube is held stationary the pressure remains constant and is termed ‘static’ pressure. If the tube is now moved through the water, whilst keeping the depth to which it is submerged constant, a second pressure called ‘dynamic’ pressure is developed.



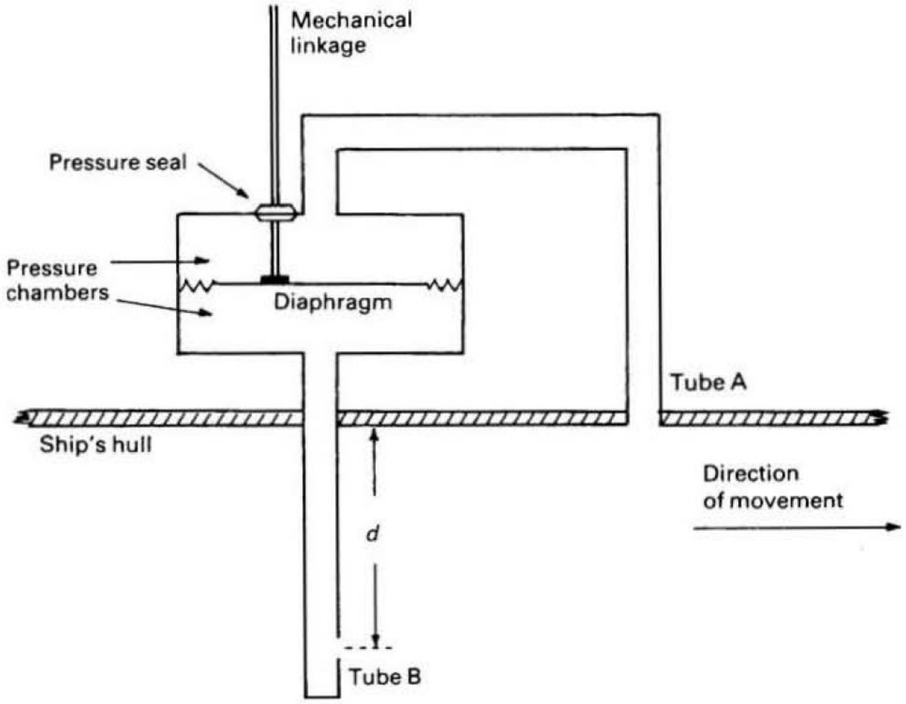
Speed measurement using water pressure

The total pressure in the tube, called a Pitot tube, is therefore the sum of both the static and dynamic pressures. To ensure that the dynamic pressure reading, and thus speed, is accurate, the effect of static pressure must be eliminated. This is achieved by installing a second tube close to the first in such a way that the static pressure produced in it is identical to that created in the Pitot tube but without the pressure increase due to movement through the water.

Speed measurement using water pressure

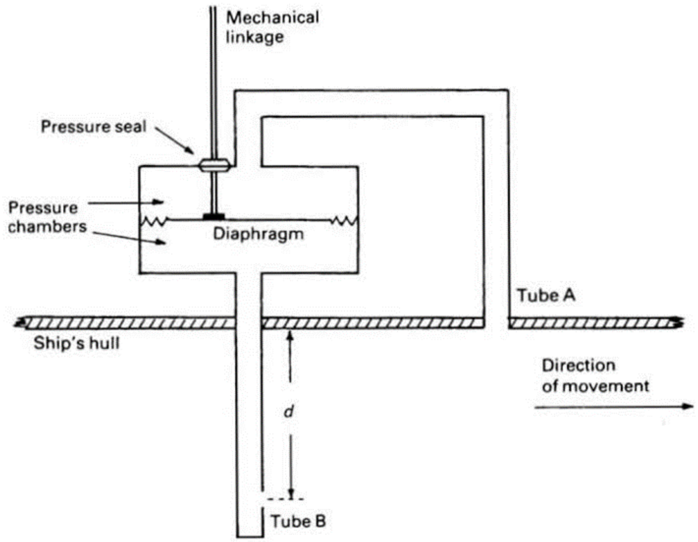
In a practical installation, tube B, the Pitot tube, extends below the vessel’s hull to a depth *d*, whereas tube A, the static pressure intake tube, is flush with the hull. With the vessel stationary, the static pressures from tube A to the top of the diaphragm and tube B to its underside almost cancel.

The unequal pressures, which cause a small indication of speed to be displayed when the vessel is stationary, are compensated for in the log electromechanical system and the erroneous indication is cancelled.



Speed measurement using water pressure

As the vessel moves through the water, in the direction shown, water is forced into tube B producing a combined pressure in the lower half of the chamber equal to both the static and dynamic pressures. The difference in pressure, between upper and lower chambers, now forces the diaphragm upwards thus operating the mechanical linkage. Obviously the greater the speed of the vessel through the water, the more the diaphragm will move and the greater will be the speed indicated.



Speed measurement using water pressure

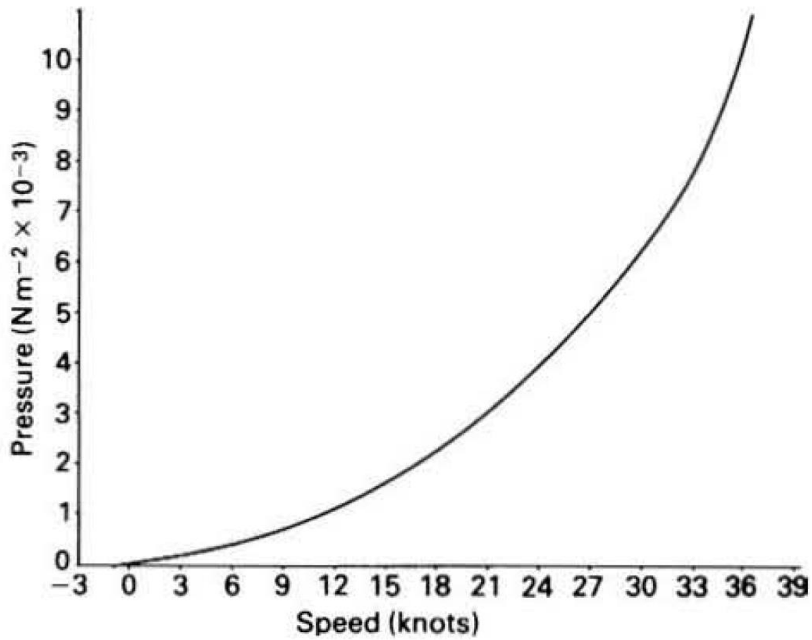
The dynamic pressure developed in tube B, by the relative movement through the water, is proportional to the square of the vessel’s speed. Pitot’s Law states that this pressure p is proportional to the square of the ship’s speed v multiplied by the coefficient K.

$$p = Kv^2$$

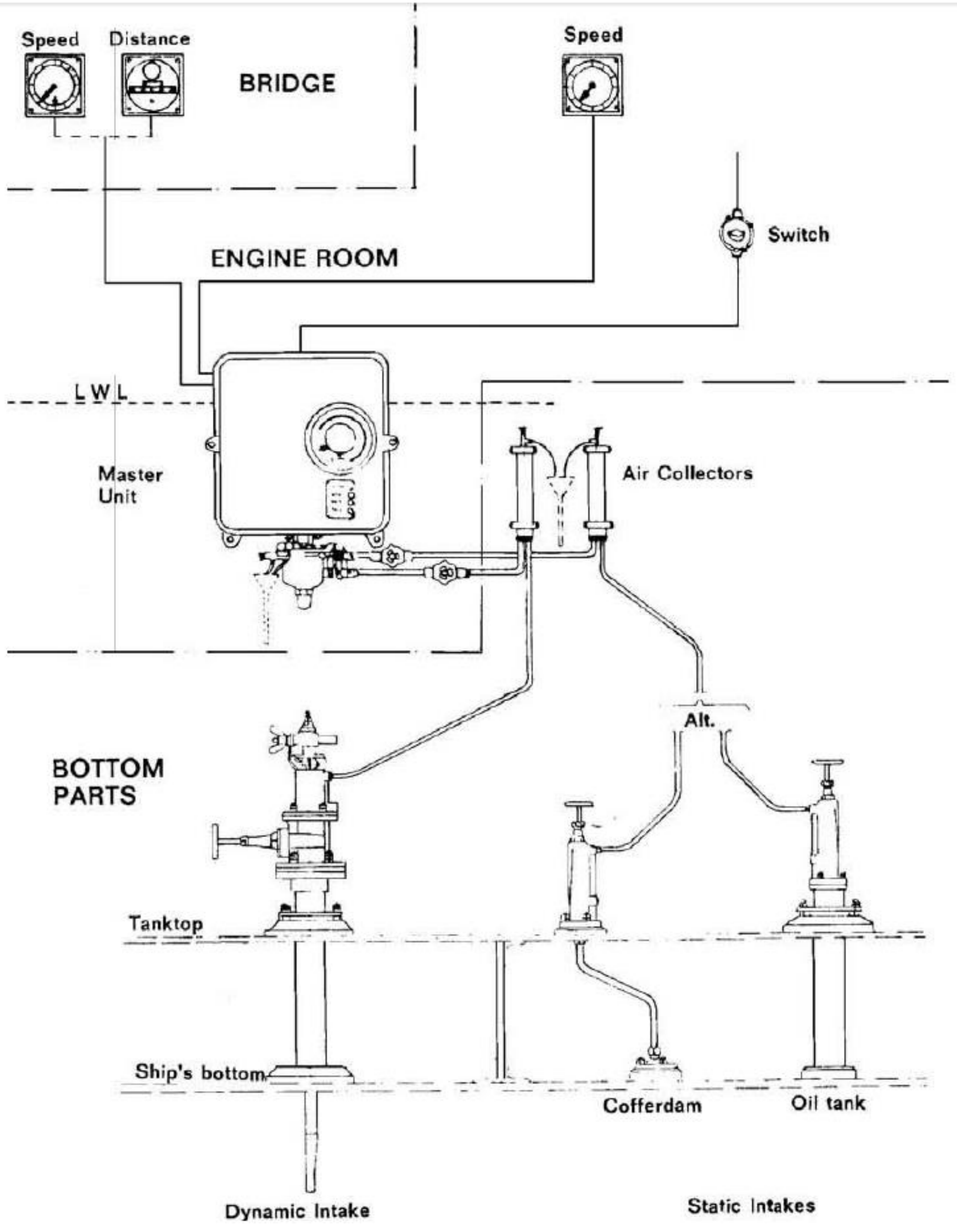
where the constant K is derived from the vessel’s tonnage, shape of hull, speed of the ship, and the length of the protruding part of the Pitot tube (distance d).

Speed measurement using water pressure

The speed indication produced is not linear. It is necessary therefore to eliminate the non-linear characteristics of the system and produce a linear speed indication. This is achieved mechanically, by the use of precisely engineered cones or electronically using CR (capacitive/resistive) time constant circuitry.

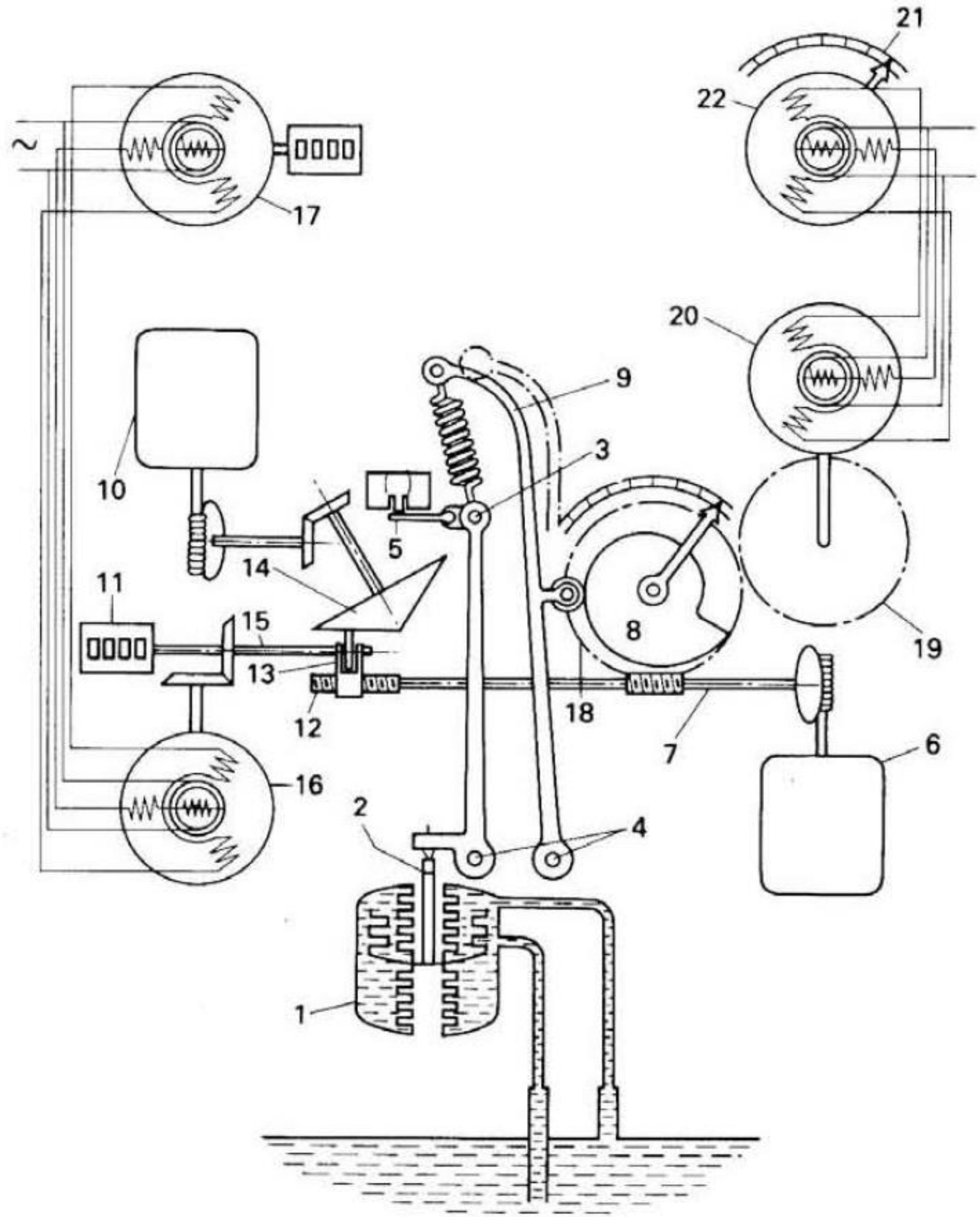


Description of operation



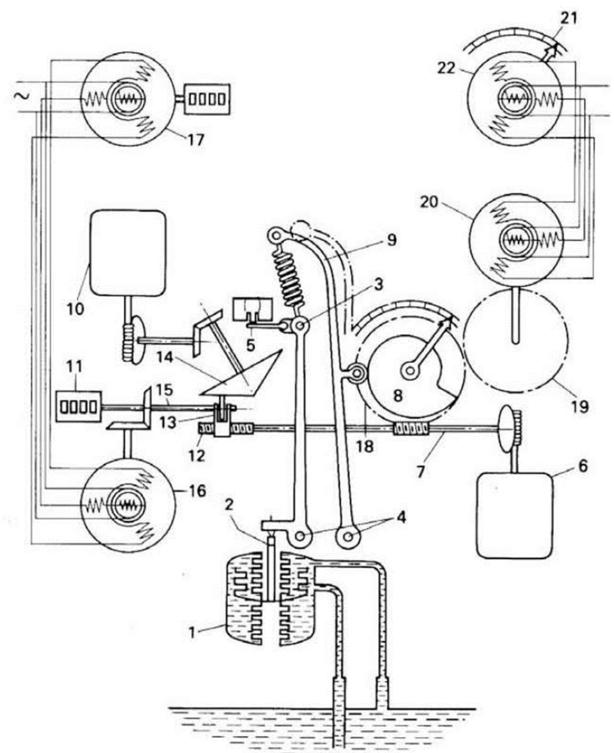
Description of operation

1. Pressure chamber
2. Pressure rod
3. Lever
4. Pivot
5. Electric start contact
6. Reversible motor
7. Main shaft
8. Spiral cam
9. Lever
10. Constant speed motor
11. Distance counter
12. Screw spindle
13. Friction wheel
14. Distance cone
15. Distance shaft
16. Servo transmission system
17. Servo transmission system
18. Gear wheels
19. Gear wheels
20. Speed servo transmitter
21. Remote speed indicator
22. Servo receiver



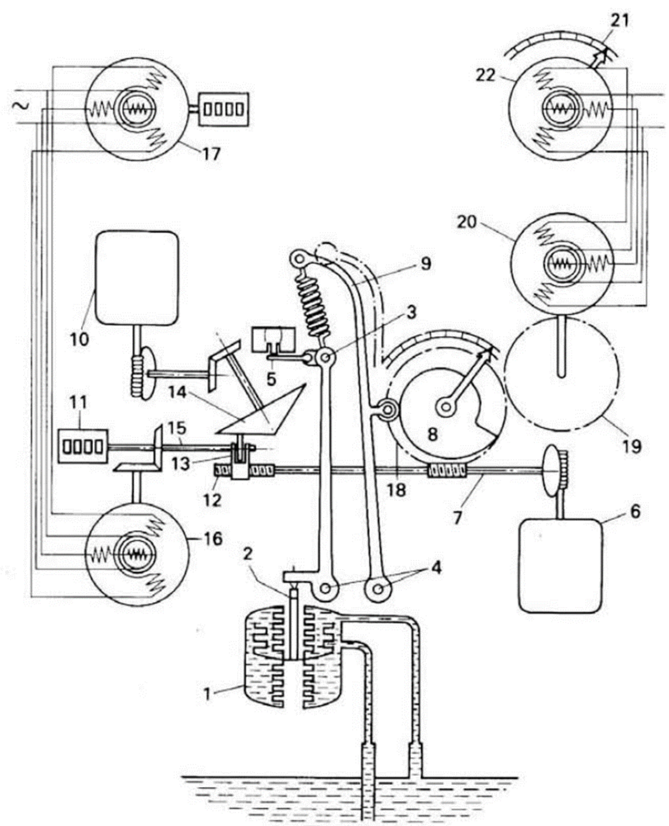
Description of operation

An increase in the vessel's speed will cause an increase in the dynamic pressure beneath the diaphragm in the pressure chamber (1). This causes the diaphragm to move upwards, pushing the pressure rod (2) and moving the lever (3) to the right on pivot (4). The upper end of the lever (3) moves the electric start contact (5) to the right to connect power to a reversible motor (6). The motor now turns causing the main shaft (7) to move a spiral cam (8) clockwise. This action tilts the lever (9), also pivoted on (4), to the left.



Description of operation

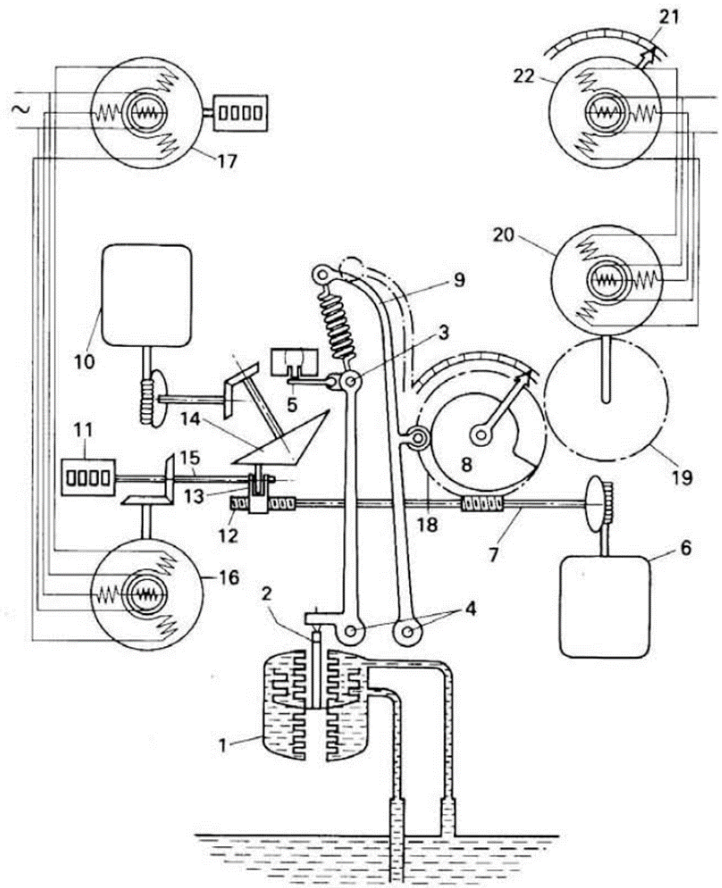
The deflection stretches the main spring, producing a downward pressure on the diaphragm, via lever (3), causing it to cease rising at an intermediate position. This is achieved when equilibrium has been established between the dynamic pressure, acting on the lower side of the diaphragm, and the counter pressure from the spring on the upper side. At this point the motor (6) stops and thus holds the spiral cam (8) in a fixed position indicating speed.



Description of operation

This method of pressure compensation provides accurate indications of speed independent of alterations of the diaphragm caused by ageing. The shape of the spiral cam (8) has been carefully calculated to produce a linear indication of speed from the non-linear characteristics of the system.

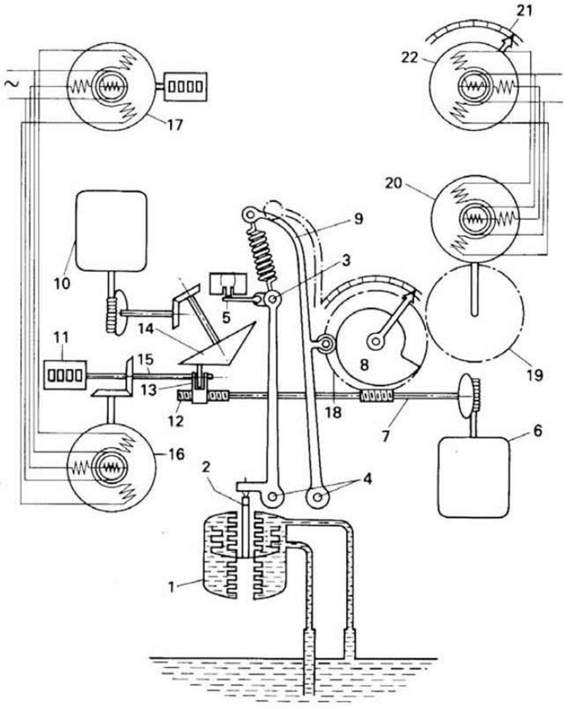
Also attached to the spiral cam is a second gearing mechanism (19) that transfers the movement of the speed indicator to the three-phase speed transmission system (20). An identical servo-receiver (22) is fitted in the remote speed repeater unit fitted on the ship’s bridge and thus remote speed indication has been achieved.



Description of operation

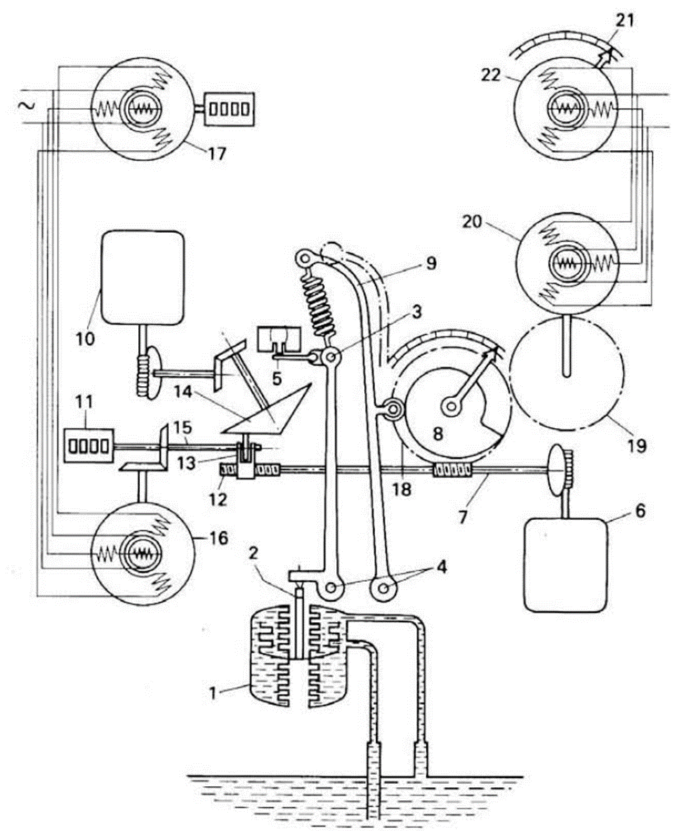
Distance recording is achieved by using a constant speed motor (10) which drives the distance counter (11), via friction gearing. The constant speed motor has been used in order that a distance indication may be produced that is independent of the non-linear characteristic of the system. The motor is started by contact (5) as previously described. The main shaft (7), whose angle of rotation is directly proportional to the speed of the ship, is fitted with a screw spindle (12).

The rotation of the shaft causes a lateral displacement of the friction wheel (13). At zero speed, the friction wheel rests against the apex of the distance cone (14), whilst at maximum speed the wheel has been displaced along the cone to the rim.



Description of operation

The distance indicator (11) is driven from the constant speed motor (10) via the cone. The nearer to the rim of the cone the friction wheel rides, the greater will be the distance indication. Revolutions of the distance shaft (15) are transmitted to the remote distance indicator via the servo transmission system (16 and 17).



Description of operation

Because the speed computed by the pitometer is a function of the difference between pressure readings, the pitometer does not produce an accurate result when the ship's velocity is low and the two pressure readings are nearly the same. The accuracy of the Pitot type speed log when correctly installed and calibrated is typically better than 0.75% of the range in use.

Electromagnetic speed logs

Electromagnetic speed logs continue to be popular for measuring the movement of a vessel through water. This type of log uses Michael Faraday's well-documented principle of measuring the flow of a fluid past a sensor by means of electromagnetic induction. The operation relies upon the principle that any conductor which is moved across a magnetic field will have induced into it a small electromotive force (e.m.f.).

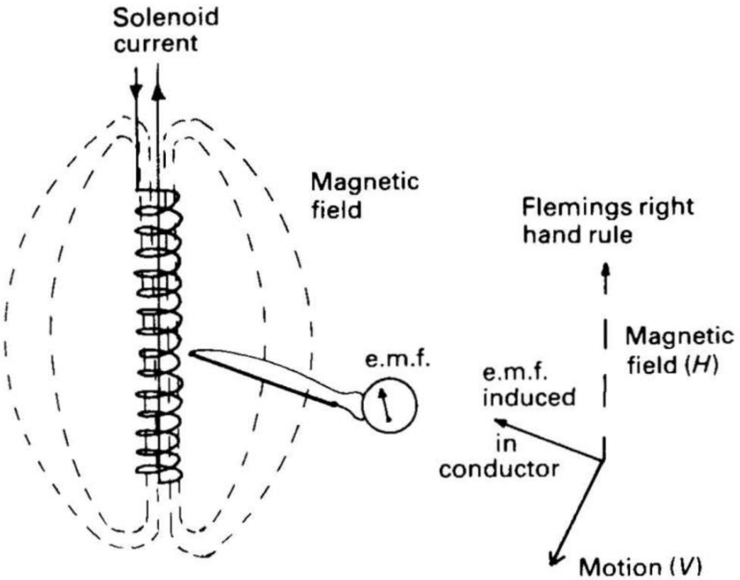
Alternatively, the e.m.f. will also be induced if the conductor remains stationary and the magnetic field is moved with respect to it. Assuming that the magnetic field remains constant, the amplitude of the induced e.m.f. will be directly proportional to the speed of movement.

Electromagnetic speed logs

In a practical installation, a constant e.m.f. is developed in a conductor (seawater flowing past the sensor) and a minute current, proportional to the relative velocity, is induced in a collector. The magnetic field created in the seawater is produced by a solenoid which may extend into the water or be fitted flush with the hull. As the vessel moves, the seawater (the conductor) flowing through the magnetic field has a small e.m.f. induced into it. This minute e.m.f., the amplitude of which is dependent upon the rate of cutting the magnetic lines of force, is detected by two small electrodes set into the outer casing of the sensor.

Electromagnetic speed logs

Figure shows a solenoid generating a magnetic field and a conductor connected in the form of a loop able to move at right angles to the field. If the conductor is moved in the direction shown, a tiny current will be induced in the wire and a small e.m.f. is produced across it. In the case of an electromagnetic speed log, the conductor is seawater passing through the magnetic field. Fleming's right-hand rule shows that the generated e.m.f. is at right angles to the magnetic field (H). Induced current flowing in the conductor produces an indication of the e.m.f. on the meter. If we assume that the energizing current for the solenoid is d.c. (direct current) the induced e.m.f. is βlv, where β = the induced magnetic field, l = the length of the conductor, and v = the velocity of the conductor.

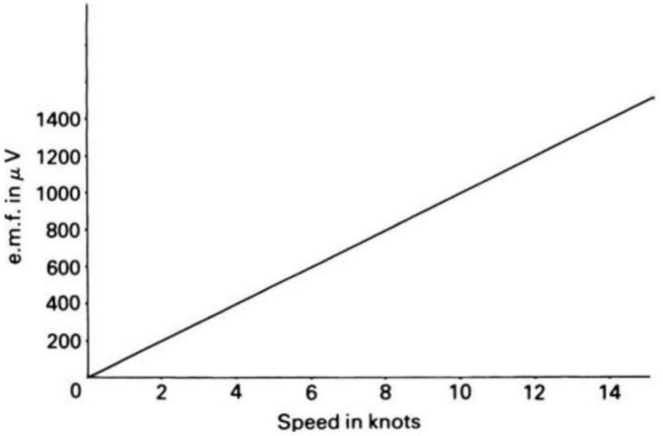


Electromagnetic speed logs

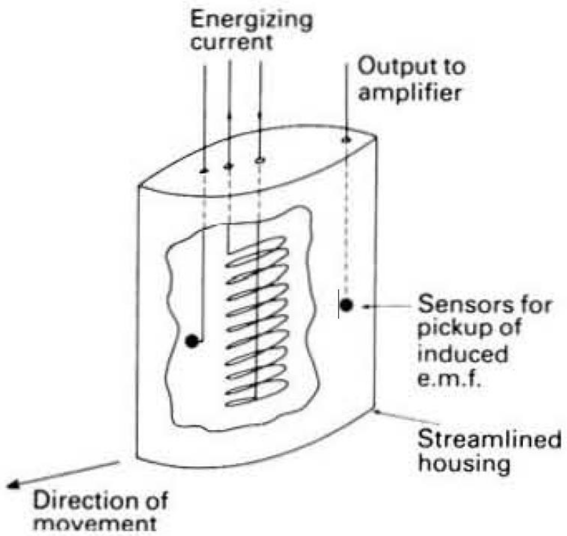
Because β is approximately equal to H (the magnetic field strength), e.m.f. = Hlv assuming no circuit losses.

To reduce the effects of electrolysis and make amplification of the induced e.m.f. simpler, a.c. (alternating current) is used to generate the magnetic field. The magnetic field strength H now becomes Hmsinωt and the induced e.m.f. is: Hmlvsinωt. If the strength of the magnetic field and the length of the conductor both remain constant then, e.m.f. $\propto$ velocity.

Figure illustrates that the changes of e.m.f., brought about by changes in velocity, produce a linear graph and thus a linear indication of the vessel's speed. The e.m.f. thus produced is very small but, if required, may be made larger by increasing the energizing current, or the number of turns of wire on the solenoid.



Electromagnetic speed logs



Electromagnetic speed logs - summary

- The a.c. supply to the solenoid produces inductive pick-up between the coil and the wires that carry the signal. This in turn produces a ‘zero’ error that must be compensated for by ‘backing off’ the zero setting of the indicator on calibration.
- The induced e.m.f. is very small (for reasonable amplitudes of energizing current), typically l00 µV per knot.
- The induced e.m.f. and hence the speed indication will vary with the conductivity of the water.
- The device measures the speed of the water flowing past the hull of the ship. This flow can vary due to the non-linearity of a hull design.
- Ocean currents may introduce errors.
- Pitching and rolling will affect the relationship between the water speed and the hull. Error due to this effect may be compensated for by reducing the sensitivity of the receiver. This is achieved using a CR timing circuit with a long time constant to damp out the oscillatory effect.
- Accuracy is typically 0.1% of the range in use, in a fore and aft direction, and approximately 2% thwartships.

Electromagnetic speed logs - advantages

The development of electromagnetic logs results from a number of advantages over logs of other types. The most important of these are:

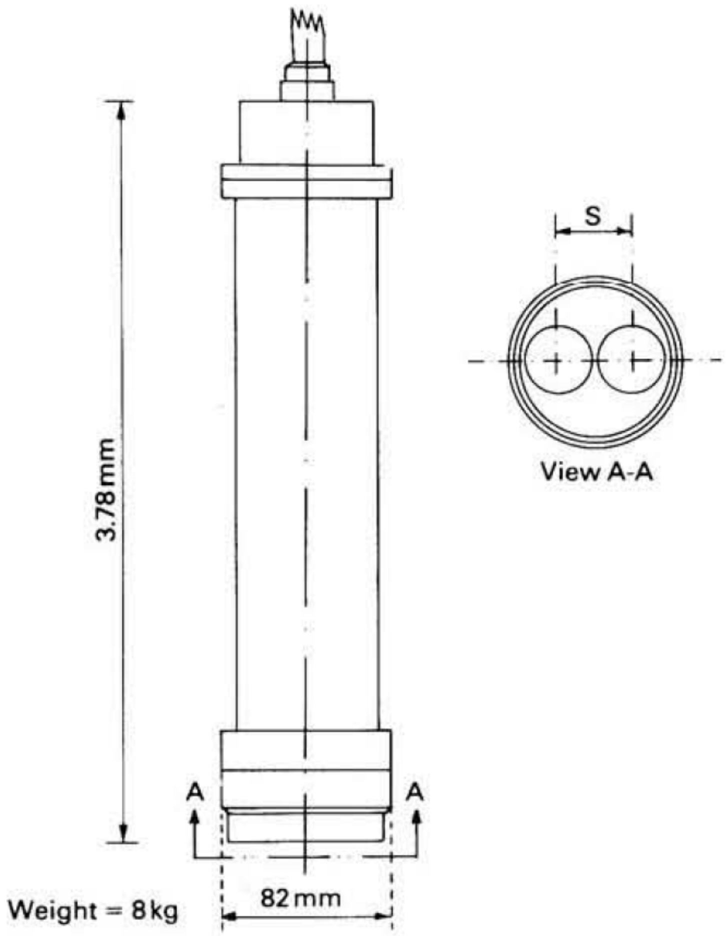
- No moving parts in the measuring system, eliminating the need for periodic inspections and troublesome maintenance;
- High sensitivity and accuracy of displayed values;
- Wide range of measured speeds and possibility of speed measurement when the ship moves backwards;
- Linearity of external characteristics;
- Independence of the accuracy of the log display from fluctuations in voltage and frequency and on the water's properties, ie. salinity, temperature and draft;
- Simple zeroing and calibration;
- Simple operation;

Speed measurement using acoustic correlation techniques

Speed logs using acoustic correlation techniques measures the speed with respect to the seabed or to a suspended water mass. The log derives the vessel’s speed by the use of signal acoustic correlation. Simply, this is a way of combining the properties of sonic waves in seawater with a correlation technique. Speed measurement is achieved by bottom-tracking to a maximum depth of 200 m. If the bottom echo becomes weak or the depth exceeds 200 m, the system automatically switches to water-mass tracking and will record the vessel’s speed with respect to a water mass approximately 12 m below the keel.

Speed measurement using acoustic correlation techniques

The transducer transmits pulses of energy at a frequency of 150 kHz from two active piezoceramic elements that are arranged in the fore and aft line of the vessel. Each element transmits in a wide lobe perpendicular to the seabed. As with an echo sounder, the transducer elements are switched to the receive mode after transmission has taken place.

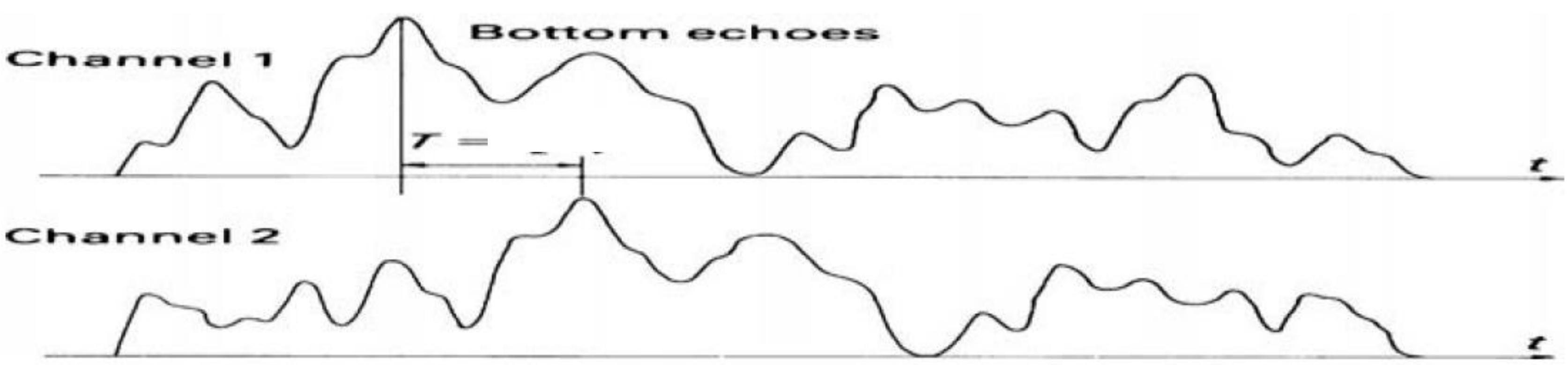


Speed measurement using acoustic correlation techniques

The seabed, or water mass, reflected signals possess a time delay (*T*) dependent upon the contour of the seabed. Thus the received echo is, uniquely, a function of the instantaneous position of each sensor element plus the ship's speed. The echo signal, therefore, in one channel will be identical to that in the other channel, but will possess a time delay as shown. The time delay (T), can be presented as:

$$T = s/v$$

where s = the distance between the receiving elements and v = the ship's velocity.



The Doppler Principle

In the early 19th century, Christian Doppler observed that the colour emitted by a star in relative movement across the sky appeared to change. Because light waves form part of the frequency spectrum, it was later concluded that the received wavelength must be changing and therefore the apparent received frequency must also change. This phenomenon is widely used in electronics for measuring velocity. The wavelength is compressed in time when received from a transmitter moving towards a receiver and expanded in time from a transmitter moving away.

Speed measurement using the Doppler effect

The phenomenon of Doppler frequency shift is often used to measure the speed of a moving object carrying a transmitter. Modern speed logs use this principle to measure the vessel's speed, with respect to the seabed, with an accuracy approaching 0.1%.

If a sonar beam is transmitted ahead of a vessel, the reflected energy wave will have suffered a frequency shift the amount of which depends upon:

- the transmitted frequency
- the velocity of the sonar energy wave
- the velocity of the transmitter (the ship)

Speed measurement using the Doppler effect

The frequency shift, in hertz, of the returned wave is:

$$f_d = f_t - f_r$$

where f_t = the transmitted wave frequency, and f_r = the received wave frequency.

The Doppler shift formula, for a reflected wave, is given as:

$$f_d = 2 v f_t / c$$

where v = the velocity of the ship, and c = the velocity of the sonar wave (1500 m/s in seawater).

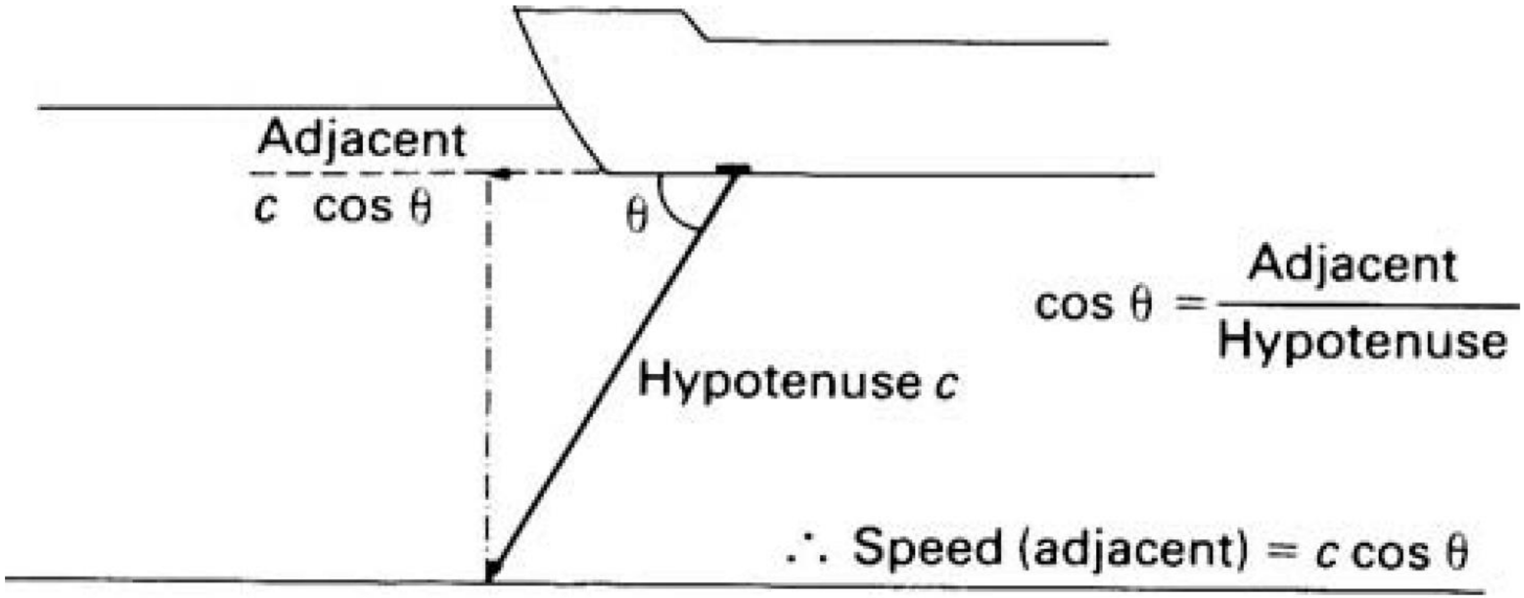
Speed measurement using the Doppler effect

Obviously there can be no objects directly ahead of a vessel from which the acoustic wave may be reflected. The wave is therefore transmitted towards the seabed, not vertically as with echo sounding, but ahead at an angle of 60° to the horizontal. This angle has been found to be the optimum angle of incidence with the seabed, which will reflect a signal of sufficient strength to be received by the transducer. The shape of the seabed has no effect on the frequency shift. Provided that the seabed is not perfectly smooth, some energy will be reflected.

The angle between the horizontal plane and the transmission must now be applied to the basic Doppler formula:

$$fd = 2vft\cos\theta/c$$

Speed measurement using the Doppler effect



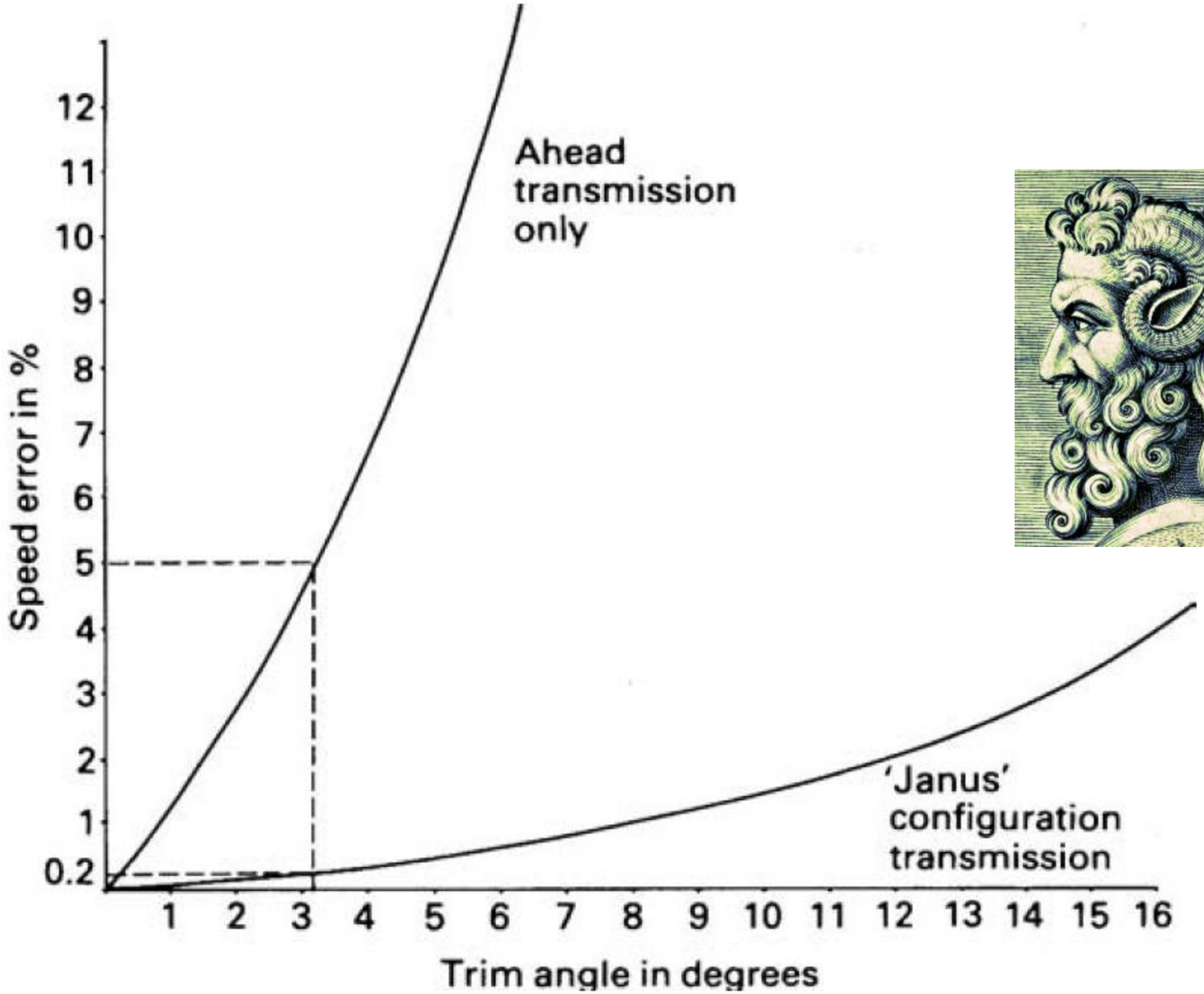
Speed measurement using the Doppler effect

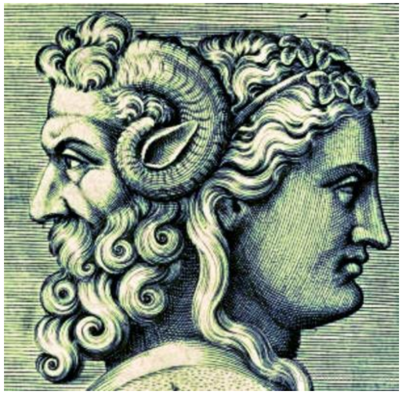
It follows that if the angle changes, the speed calculated will be in error because the angle of propagation has been applied to the speed calculation formula in this way. If the vessel is not in correct trim (or pitching in heavy weather) the longitudinal parameters will change and the speed indicated will be in error. To counteract this effect to some extent, two acoustic beams are transmitted, one ahead and one astern. The transducer assembly used for this type of transmission is called a 'Janus' configuration after the Roman god who reputedly possessed two faces and was able to see into both the future and the past.
The Doppler frequency shift formula now becomes:

$$fd = 2vft/c\ (+ \cos\theta + \cos\theta')$$

(+ cos 60° + cos 60°' = 1) therefore the transmission angle can effectively be ignored, in heavy weather one angle increases as the other decreases effectively cancelling the effects of pitching on the speed indication.

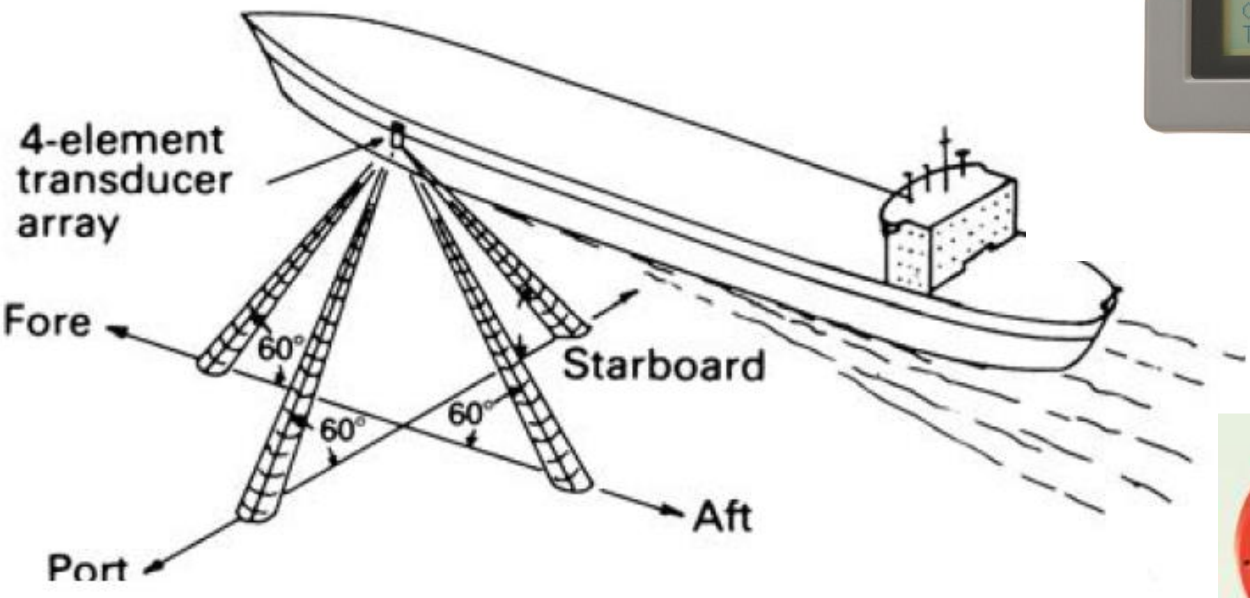
Speed measurement using the Doppler effect

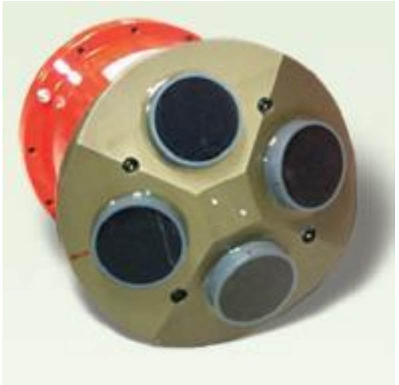




Speed measurement using the Doppler effect

The addition of a second transducer assembly set at right angles to the first one, enables dual axis speed to be indicated





Doppler logs - choice of frequency

As with depth sounding, the size of the transducer can be kept within reasonable limits by using a high frequency. This is particularly important in the situation where many elements are to be mounted in the same assembly. Unfortunately, attenuation losses increase exponentially with the transmission frequency. The choice of frequency is therefore a compromise between acceptable transducer size and the power requirements of the acoustic wave in order to overcome the signal losses due to the transmission media. Frequencies used in speed logging systems vary widely and are usually in the range 100kHz to 1MHz.

Doppler logs - choice of frequency

The factor with the greatest effect on speed accuracy is the velocity of the acoustic wave in seawater. Propagation velocity is affected by both the salinity and the temperature of the seawater through which the wave travels. However, velocity error due to these two factors can be virtually eliminated by mounting salinity and temperature sensors in the transducer array. Data from both sensors are processed to provide corrective information for the system. Alternatively, the Krupp Atlas Alpha transducer system effectively counteracts the effects of salinity and temperature by the use of a phased beam.

Doppler logs - choice of transmission mode

Continuous wave mode (CW) transmission

Two transducers are used in each of the Janus positions. A continuous wave of acoustic energy is transmitted by one element and received by the second element. Received energy will have been reflected either from the seabed, or, if the depth exceeds a predetermined figure (20 m is typical), from a water mass below the keel. Problems can arise with CW operation particularly in deep water when the transmitted beam is caused to scatter by an increasing number of particles in the water. Energy due to scattering will be returned to the transducer in addition to the energy returned from the water mass. The receiver is likely to become confused as the returned energy from the water mass becomes weaker due to the increasing effects of scattering. The speed indication is now very erratic and may fall to zero.

CW systems are rarely used for this reason.

Doppler logs - choice of transmission mode

Pulse mode operation

To overcome the problems of the CW system, a pulse mode operation is used. This is virtually identical to that for depth sounding where a high energy pulse is transmitted with the receiver off. The returned acoustic energy is received by the same transducer element that has been switched to the receive mode. In addition to overcoming the signal loss problem, caused by scattering in the CW system, the pulse mode system has the big advantage that only half the number of transducers is required.

Doppler logs - Comparison of the pulse and the CW systems

- Pulse systems are able to operate in the ground reference mode at depths up to 300 m (depending upon the carrier frequency used) and in the water track mode in any depth of water, whereas the CW systems are limited to depths of less than 60 m. However, CW systems are superior in very shallow water, where the pulse system is limited by the pulse repetition frequency (PRF) of the operating cycle.
- The pulse system requires only one transducer (two for the Janus configuration) whereas separate elements are needed for CW operation.
- CW systems are limited by noise due to air bubbles from the vessel’s own propeller, particularly when going astern.
- Pulse system accuracy, although slightly inferior to the CW system, is constant for all operating depths of water, whereas the accuracy of the CW system is better in shallow water but rapidly reduces as depth increases.

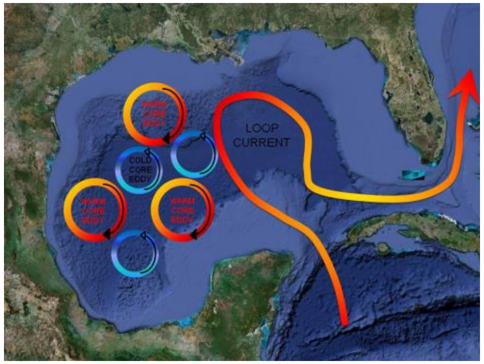
Doppler logs - Environmental factors affecting the accuracy

Unfortunately environmental factors can introduce errors and/or produce sporadic indications in any system that relies for its operation on the transmission and reception of acoustic waves in salt water.

- Water clarity. In exceptional cases the purity of the seawater may lead to insufficient scattering of the acoustic energy and prevent an adequate signal return. It is not likely to be a significant factor because most seawater holds the suspended particles and micro-organisms that adequately scatter an acoustic beam.
- Aeration. Aerated water bubbles beneath the transducer face may reflect acoustic energy of sufficient strength to be interpreted erroneously as sea bottom returns producing inaccurate depth indications and reduced speed accuracy. Proper siting of the transducer, away from bow thrusters, for instance, will reduce this error factor.

Doppler logs - Environmental factors affecting the accuracy

- Vessel trim and list. A change in the vessel's trim from the calibrated normal will affect fore/aft speed indication and an excessive list will affect athwartship speed. A Janus configuration transducer reduces this error.
- Ocean current profile. This effect is prevalent in areas with strong tides or ocean currents. In the water track mode, a speed log measures velocity relative to multiple thermocline layers several feet down in the water. If these layers are moving in opposite directions to the surface water, an error may be introduced.
- Ocean eddy currents. Whilst most ocean currents produce eddies their effect is minimal. This problem is more likely to be found in restricted waters with big tidal changes or in river mouths.



Doppler logs - Environmental factors affecting the accuracy

- Sea state. Following seas may result in a change in the speed indication in the fore/aft and/or port/starboard line depending upon the vector sum of the approaching sea relative to the ship's axis.
- Temperature profile. The temperature of the seawater affects the velocity of the propagated acoustic wave. Temperature sensors are included in the transducer to produce corrective data that is interfaced with the electronics unit.

Doppler logs – advantages

- measurement of absolute speed (true speed, SOG),
- no protruding elements underneath the bottom of the hull and moving parts
- obtaining more accurate measurements in shallow waters
- obtaining additional navigational information that is very useful for ship maneuvering, mooring, anchoring, etc.
- easy to connect logs to other navigation devices that require speed information in the strictly defined form

Doppler logs – disadvantages

- limited propagation distance of the acoustic wave in the seawater
- strong environmental disturbances,
- complicated electronic equipment, hence costly repairs,
- difficulties in choosing locations for installation of transducers with favorable hydroacoustic conditions

THE END