Chapter 3

Speed measurement

3.1 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.

This chapter deals with the methods of speed logging that are in general use on board modern vessels. One of these, the pressure tube log, is old but it still gives a satisfactory performance. Another, the electromagnetic log, is often used on smaller vessels and the popular Doppler speed log is to be found everywhere.

3.2 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. 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 (see Figure 3.1).

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. 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.

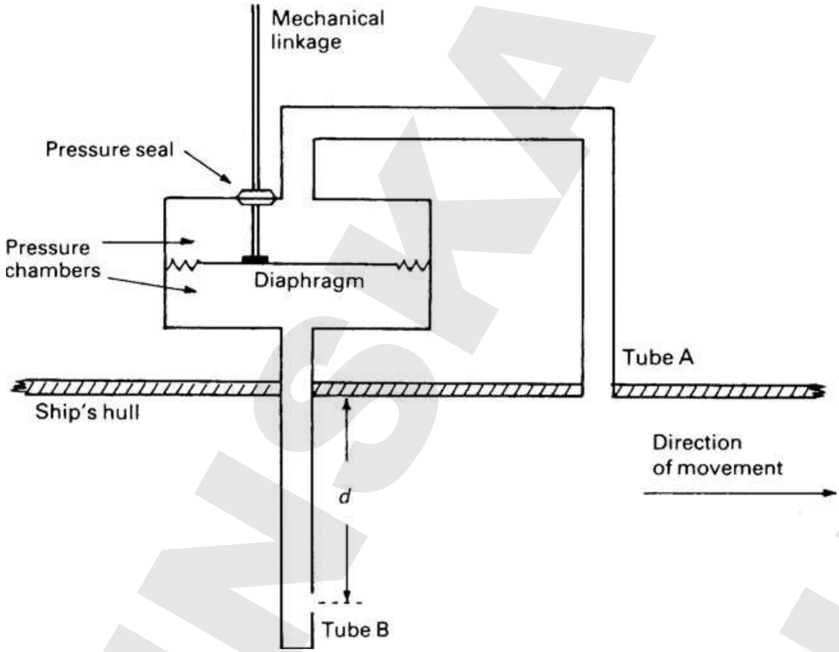


Figure 3.1 The pressure tank and tube intakes of a pressure tube speed logging system.

Unfortunately, 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.

$$p = K \times v^2$$

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).

As shown in Figure 3.2, 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.

3.2.1 A pressure tube speed logging system

Figure 3.3 shows a typical installation of the Pitot system on board a vessel with a double bottom. The Pitot tube is encased in a sea-cock arrangement with valve control, to enable the tube to be withdrawn, without shipping water, when the vessel goes alongside. The static pressure opening is controlled by the use of a valve. Both dynamic and static pressures are transferred via air collectors and strainer valves to the pressure chamber. The strainer valves are designed to prevent water oscillations in the interconnecting pipes during operation. Such oscillations would cause the diaphragm to oscillate producing an erratic speed indication.

Figure 3.4 shows the basic speed and distance translating system of a Pitot tube log. The diagram includes two repeating systems for speed and distance data transmission to remote indicators on the

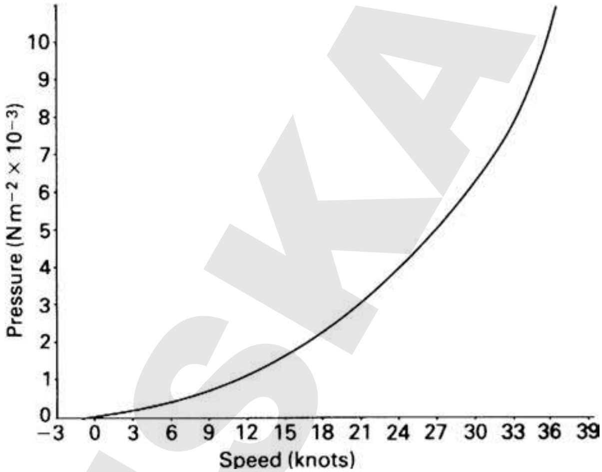


Figure 3.2 Graph indicating the non-linear increase in pressure due to speed.

ship's bridge. This system was superseded by the SAL24E which replaced some of the mechanical apparatus with electronics. The original log has been included here because it is still in use on many vessels and is a fine example of a pressure type speed logging system.

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. 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.

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.

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

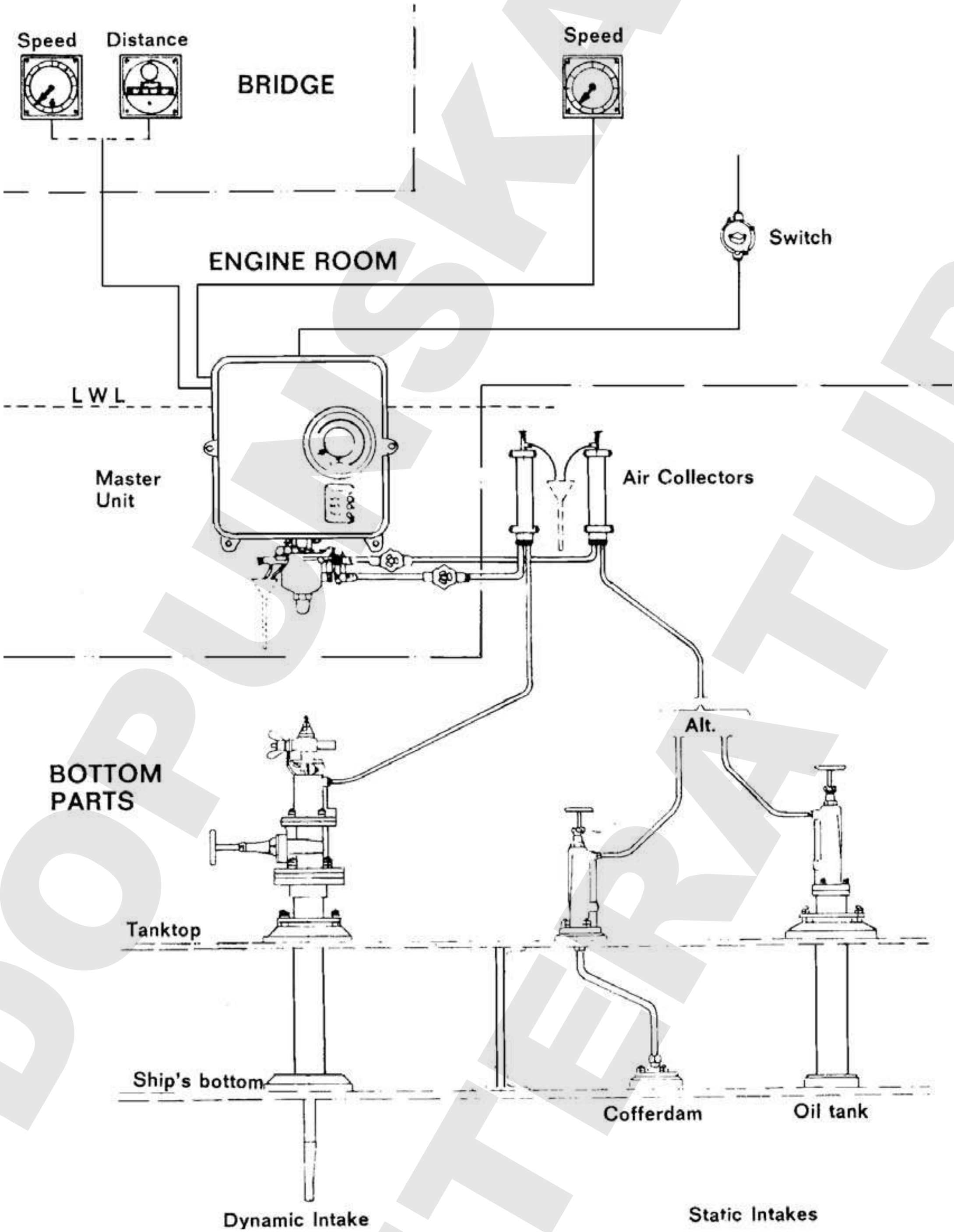
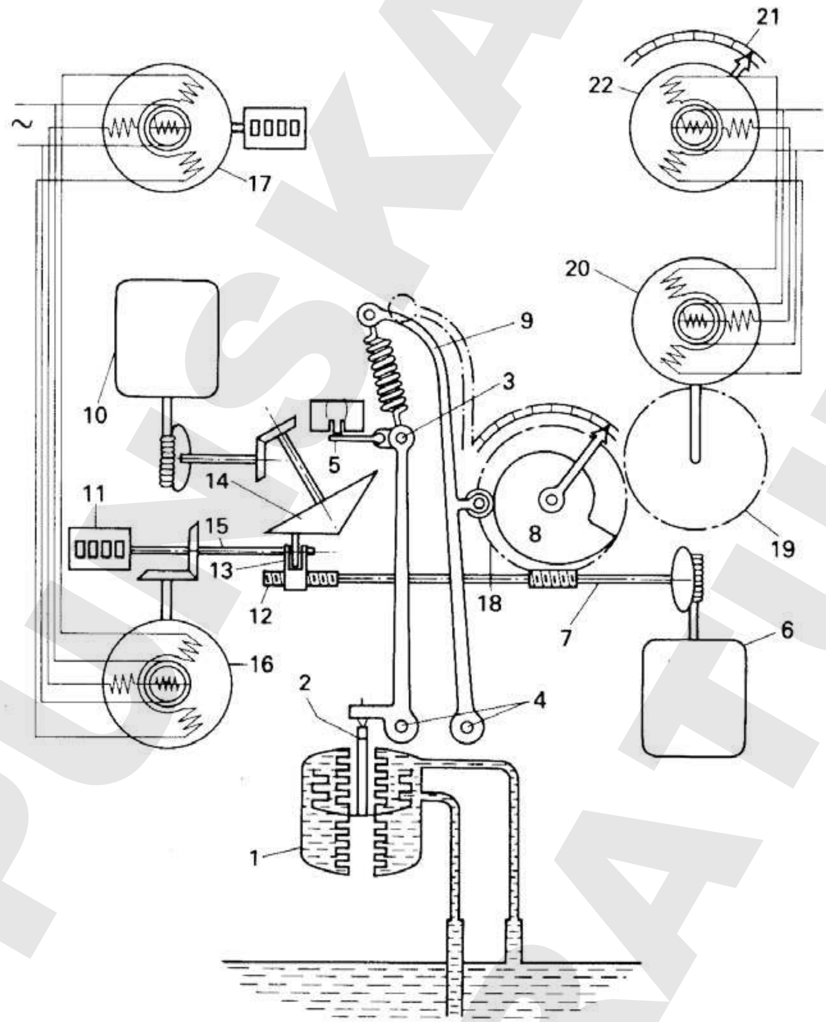


Figure 3.3 A shipboard installation. (Reproduced courtesy of SAL Jungner Marine.)



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

Figure 3.4 The mechanical speed translating system of the SAL 24 pressure tube log. (Reproduced courtesy of SAL Jungner Marine.)

along the cone to the rim. 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).

Operation of the SAL 24E

The SAL 24E utilizes the same system of tubes, pressure tank and diaphragm to convert pressure variations due to speed, to electrical pulses suitable to drive the electronic circuits that replace much of the mechanical arrangement of the SAL 24 log. The distance integration mechanism with servo, cone and counter has been fully replaced with electronic circuitry.

As previously described, when the vessel moves forwards, the dynamic pressure acting on the underside of the diaphragm causes it to move upwards forcing the pushrod upwards. As shown in Figure 3.5, this causes the pushrod arm assembly to move to the right on the pivot, increasing the

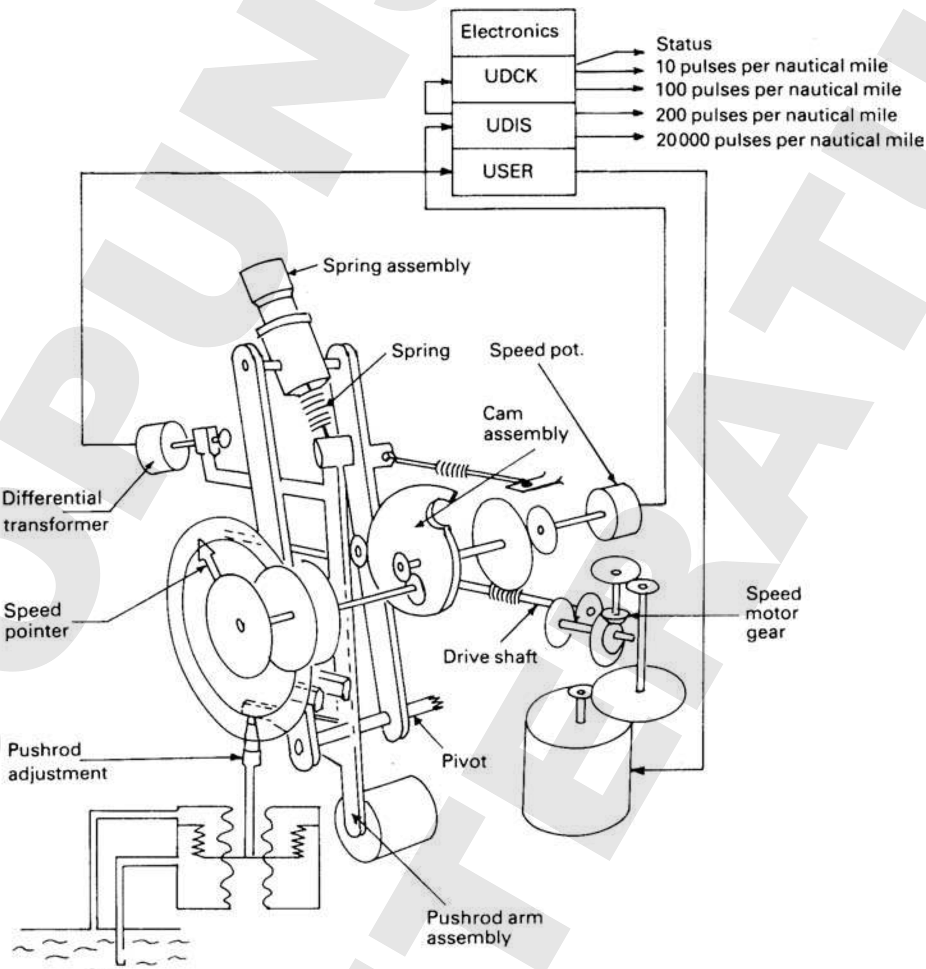


Figure 3.5 Pressure/mechanical assembly of the SAL 24E electronic pressure speed log. (Reproduced courtesy of SAL Jungner Marine.)

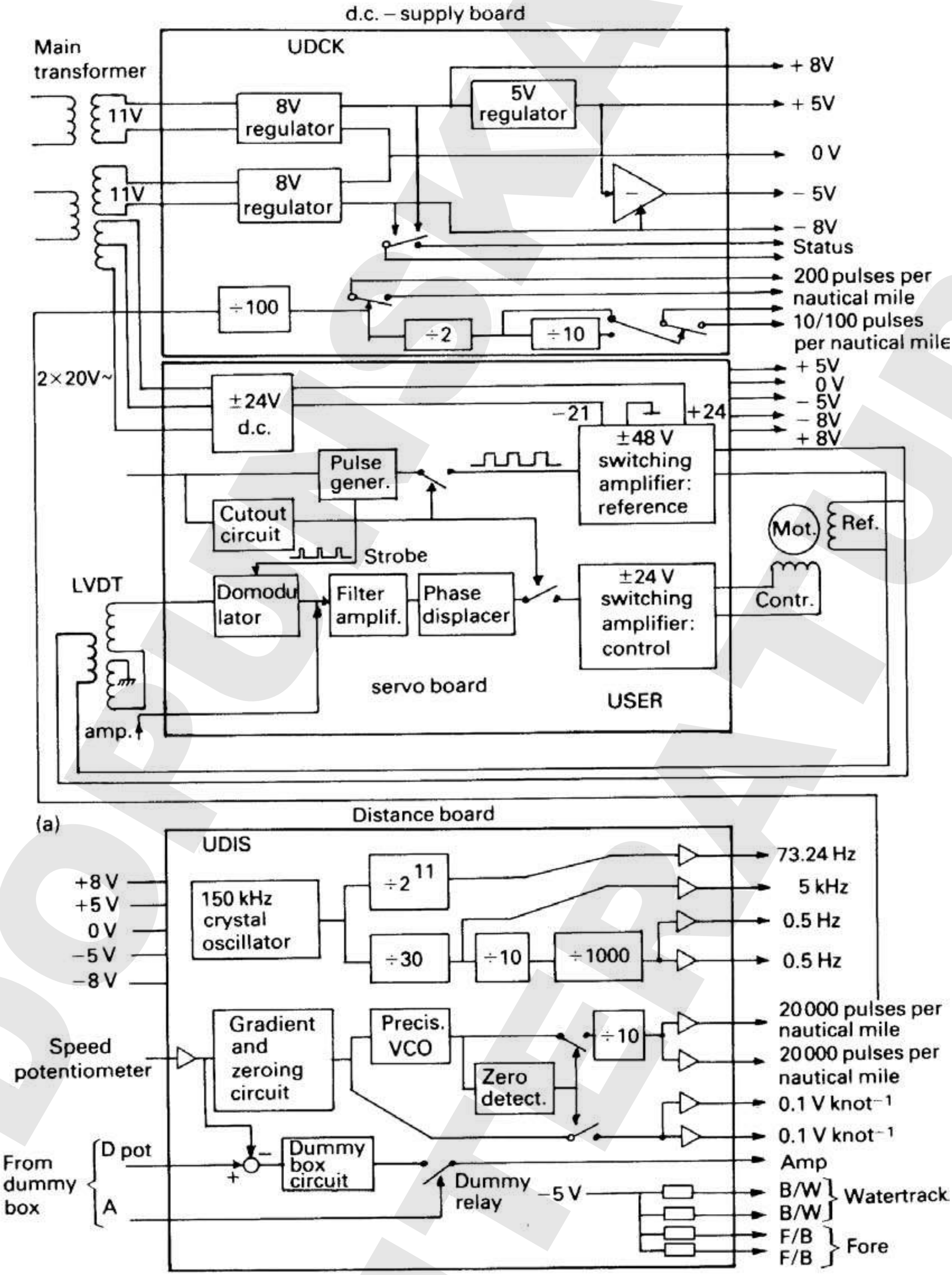


Figure 3.6 The electronics unit. (Reproduced courtesy of SAL Jungner Marine.)

tension on the spring assembly and producing an output from the differential transformer. This output is applied to the USER board, shown in Figure 3.6, where it is processed to provide the drive for the speed servo-control winding via a ± 24 V switching amplifier. The servo now turns and rotates the cam assembly via gearing and the drive shaft. An increase in speed is now shown on the speed pointer. As the cam rotates it forces the balance arm to the left and tightens the spring until the pushrod arm and the diaphragm bellows are balanced. The cam is carefully designed so that the spring force is proportional to the square of the rotation angle and thus the non-linearity of the pressure system is counteracted. The speed potentiometer turns together with the speed pointer to provide an input to the UDIS board. This input produces a variety of outputs enabling the system to be interfaced with other electronic equipment.

The accuracy of the Pitot type speed log when correctly installed and calibrated is typically better than 0.75% of the range in use.

3.3 Speed measurement using electromagnetic induction

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.

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.

Figure 3.7 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. 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.

β is approximately equal to H, the magnetic field strength. Therefore, 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. is used to generate the magnetic field. The magnetic field strength H now becomes $H\mathrm{m}\sin\omega\mathrm{t}$ and the induced e.m.f. is: $H\mathrm{m}lv\sin\omega\mathrm{t}$. If the strength of the magnetic field and the length of the conductor both remain constant then, e.m.f. $\simeq$ velocity.

Figure 3.8 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

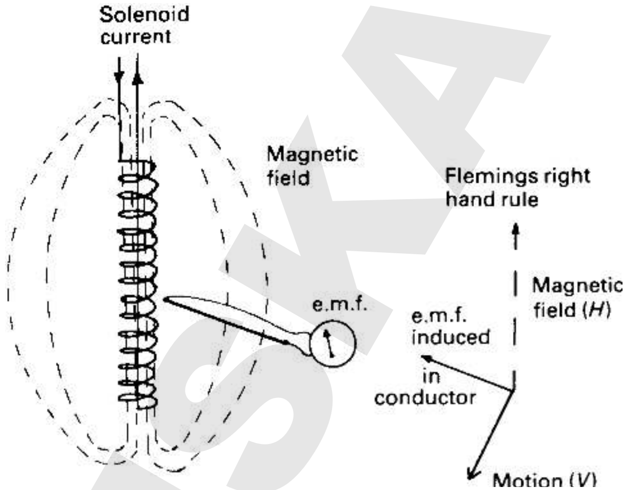


Figure 3.7 Effect of moving a conductor through a magnetic field.

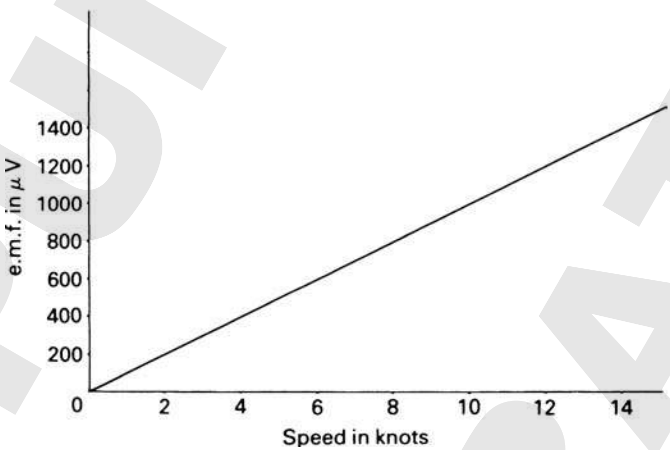


Figure 3.8 Relationship between the vessel's speed and the output from the sensors.

but, if required, may be made larger by increasing the energizing current, or the number of turns of wire on the solenoid.

The following points should be noted.

- 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 100 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.

Figure 3.9 shows a typical sensor cutaway revealing the solenoid and the pick-up electrodes. A speed translating system is illustrated in Figure 3.10.

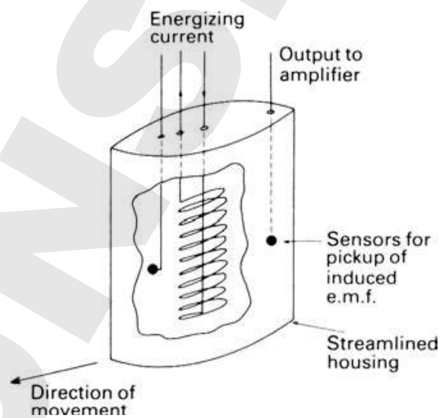


Figure 3.9 Constructional details of an electromagnetic log sensor.

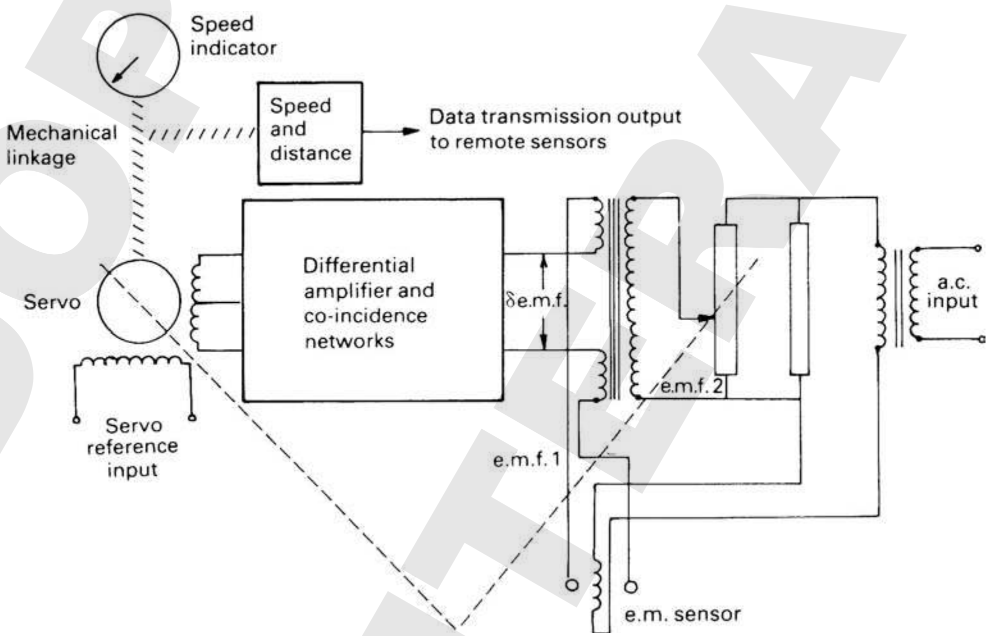


Figure 3.10 An e.m. speed log translating system.

Description of the speed translating system

The small signal speed voltage from the sensor, e.m.f.1, is applied to a differential transformer where it is compared to a reference voltage, e.m.f.2, produced from a potentiometer across the input a.c. supply. The potential difference produced across the reference resistor provides the energizing current for the solenoid in the sensor.

If the signal voltage e.m.f.1. differs from the reference voltage e.m.f.2. an error signal voltage δ e.m.f. is produced. This error voltage is applied to the speed signal amplifier where it is amplified to produce sufficient power to drive the servo motor. The servo will in turn produce a speed reading, via a mechanical linkage, on the indicator. Also coupled to the servo shaft is the slider of the speed potentiometer that turns in the direction to reduce the error voltage δ e.m.f. When this error voltage drops to zero the servo ceases to turn. The speed indicator is stationary until the next error voltage δ e.m.f. is produced. Each time an error voltage is created the servo turns to cancel the error and thus balances the system.

3.3.1 A practical electromagnetic speed logging system

The potential developed across the transducer electrodes is proportional to magnetic field strength (and consequently the energizing current) and the flow velocity in the volume of water influenced by the field. The magnetic field strength is in no way stabilized against any changes in the ship's main voltage, temperature, etc, but by effectively comparing the energizing current with the voltage at the electrodes, their ratio provides a measure of the ship's speed.

The input transformer T1 (shown in Figure 3.11) possesses a very high inductance and a step-down ratio of 5:1. This results in an input impedance, as seen by the pick-up electrodes, approaching 20 MΩ which when compared with the impedance presented by salt water can be considered an open circuit. Hence changes in salinity have no effect on the measured voltage and the resulting speed indication. A switched resistor chain (R1/R5) sets the gain of the overall amplifier in conjunction with resistor chain (R6/R10) which controls the amplitude of the feedback signal.

The output of IC1 is coupled, via IC2, which because of capacitive feedback (not shown), ensures that the circuit has a zero phase shift from T1 through T2, to the demodulator. Demodulation is carried out by TR1/TR2 that are switched in turn from an a.c. reference voltage derived from a toroidal transformer monitoring the energizing current of the transducer. By driving TR1/TR2 synchronously, the phase relationship of the voltage detected by the electrodes determines the polarity of the demodulated signal. 0° and 180° phasing produce a positive or negative component; 90° and 270° produce no output and hence a complete rejection of such phase-quadrature signals. The demodulated signal is applied to the Miller Integrator IC3 which in turn drives the current generator. Speed repeaters are current-driven from this source.

Operation of the loop

With no vessel movement, there will be a zero signal at the input to IC1 and consequently there will be no signal at the multiplier chip input. No feedback signal is developed at the input to IC1. As the vessel moves ahead, the small signal applied to IC1 is processed in the electronic unit to produce a current flow through the speed repeaters and the multiplier. There now exists an output from the multiplier, proportional to the speed repeater current and the reference voltage produced by the toroidal transformer monitoring the transducer energizing current. The a.c. from the multiplier is fed back to IC1 in series with, and 180° out of phase with, the small signal secondary of T1. This a.c. signal rises slowly and eventually, with the time constant of the demodulator, is equal to the signal p.d.

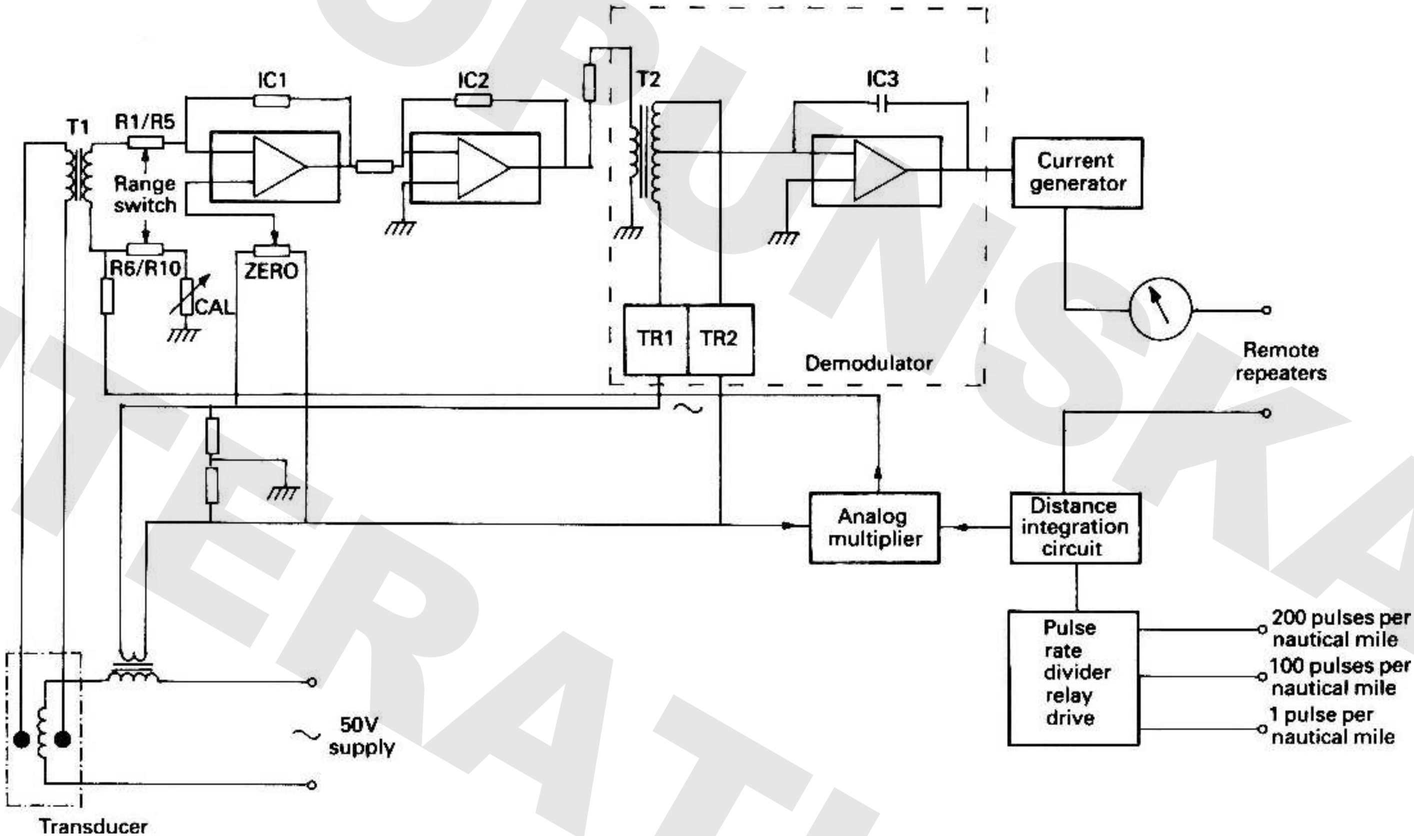


Figure 3.11 Simplified diagram of an e.m. log. (Reproduced courtesy of Thomas Walker and Son Ltd.)

developed across T1. At this time the resultant signal applied to IC1 falls to zero and therefore the demodulator output remains at a constant figure. Any further change in speed results in an imbalance in the secondary of T1 producing a resultant a.c. signal to IC1. As a result, the demodulator output increases or decreases (faster or slower ship's speed) until the balance condition is restored. The speed repeaters will indicate the appropriate change of speed.

Distance integration

The speed current is passed through a resistive network on the distance integration board, in order that a proportional voltage may be produced for integration. The output of this board is a pulse train, the rate of which is proportional to the indicated speed. The 10 ms pulses are coupled to the relay drive board which holds the necessary logic to give the following outputs: 200 pulses per nautical mile, 100 pulses per nautical mile, and 1 pulse per nautical mile.

3.4 Speed measurement using acoustic correlation techniques

Unlike the previously described speed log, which measure the vessel's speed with respect to water only, the SAL-ICCOR log 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

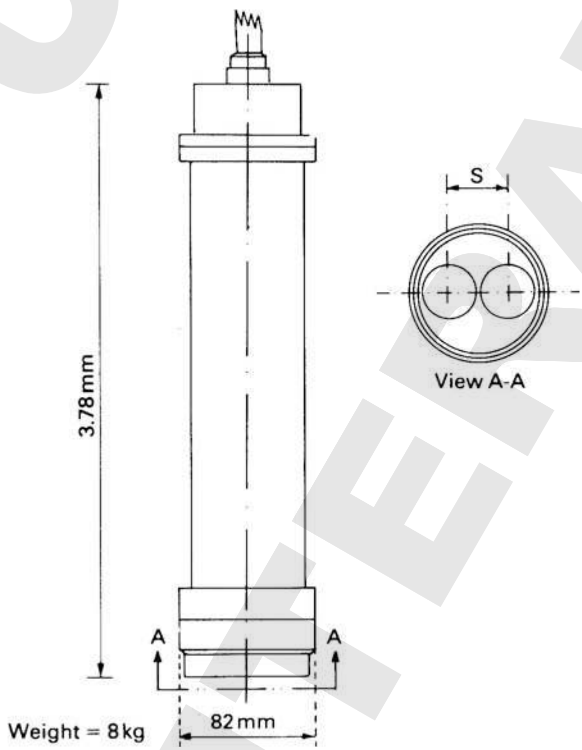


Figure 3.12 Piezoelectric ceramic transducer for the SAL acoustic correlation speed log.

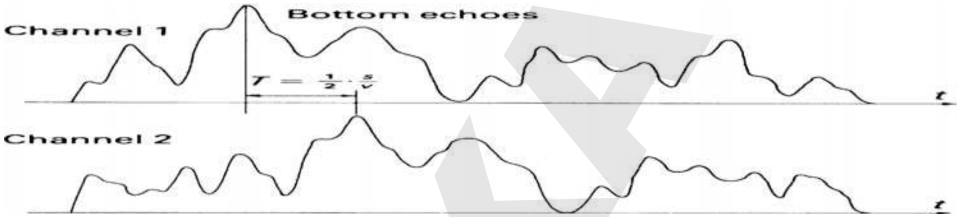


Figure 3.13 Illustration of the time delay (T) between each channel echo signal.

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.

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 (see Figure 3.12). 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.

The seabed, or water mass, reflected signals possess a time delay (T) dependent upon the contour of the seabed, as shown in Figure 3.13. 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), in seconds, can be presented as:

$$T = 0.5 \times s\ v$$

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

In the SAL-ACCOR log (see Figure 3.14), the speed is accurately estimated by a correlation technique. The distance between the transducer elements (s) is precisely fixed, therefore when the time (T) has been determined, the speed of the vessel (v) can be accurately calculated.

It should be noted that the calculated time delay (T) is that between the two transducer echoes and not that between transmission and reception. Temperature and salinity, the variables of sound velocity in seawater, will not affect the calculation. Each variable has the same influence on each received echo channel. Consequently the variables will cancel.

It is also possible to use the time delay (T) between transmission and reception to calculate depth. In this case the depth (d),in metres, is:

$$d = \frac{T}{2} \times C$$

where C = the velocity of sonic energy in seawater (1500 ms^{-1}).

Dimensions of the transducer active elements are kept to a minimum by the use of a high frequency and a wide lobe angle. A wide lobe angle (beamwidth) is used because echo target discrimination is not important in the speed log operation and has the advantage that the vessel is unlikely to 'run away' from the returned echo.

3.4.1 System description

Initiating the sequence, the power amplifier produces the transmitted power, at the carrier frequency of 150 kHz, under the command of a pulse chain from the clock unit. Returned echoes are received by two

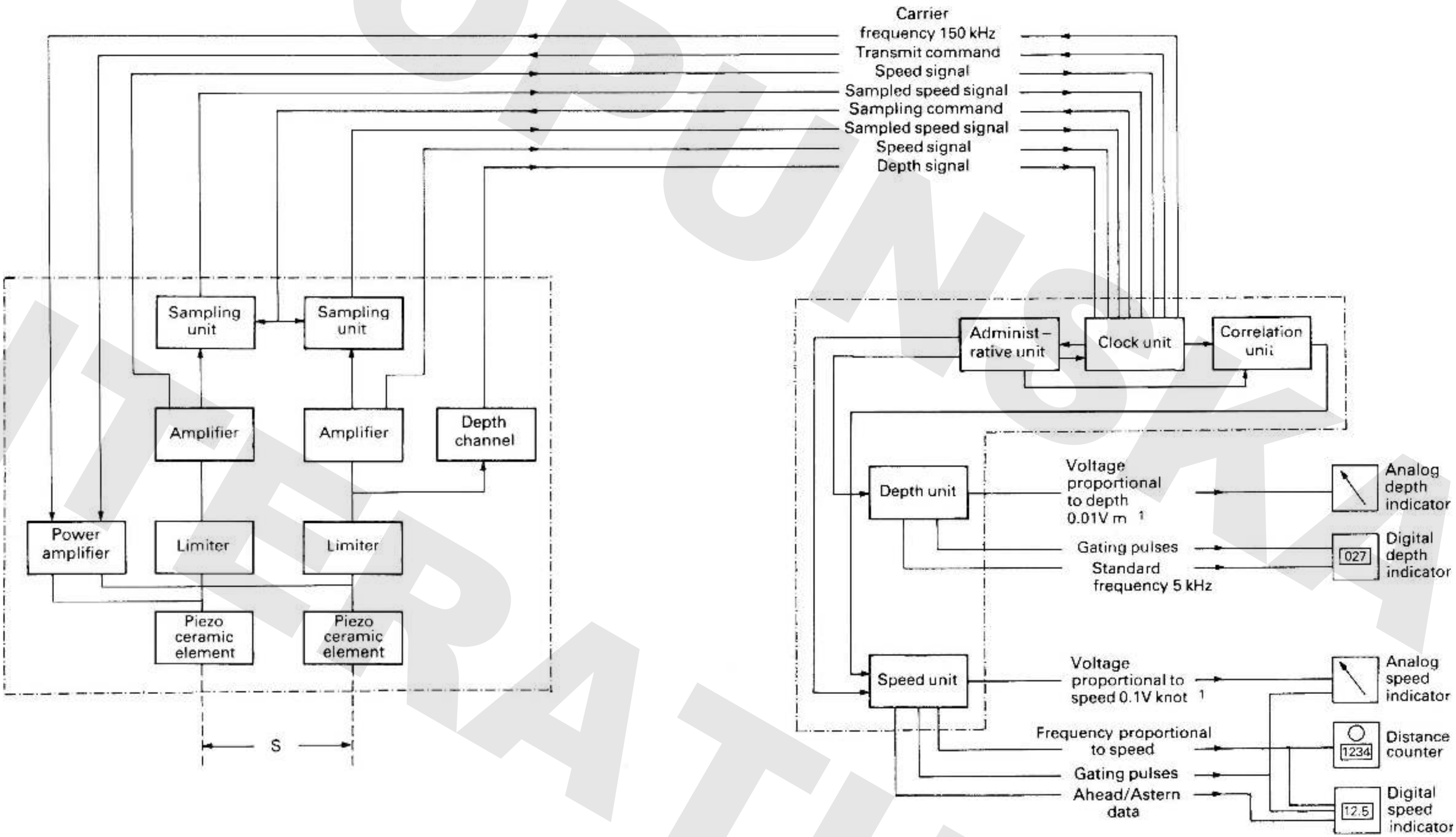


Figure 3.14 System diagram of the SAL-ACCOR acoustic correlation speed log. (Reproduced courtesy of SAL Junger Marine.)

independent identical channels and are pre-amplified before being applied to sampling units. Each sampling unit effectively simplifies the echo signal to enable interconnection to be made between transducer and main unit without the risk of signal deterioration. As with other functions, sampling is commanded by a clock unit, which also provides a highly stable 150 kHz for the carrier frequency. This frequency is also used as a standard frequency for the other functions on the electronics board, where it is divided to produce the 5 kHz needed to operate some of the speed indicators.

As the name suggests, the administration block controls most of the electronic functions. This block initiates the transmit/receive cycle, determines whether the system selects B-track or W-track operation and supervises the speed and depth calculations. The unit is effectively a microprocessor operating to a pre-determined program. Actual speed calculation takes place in the correlation block. The process extracts the time delay by correlating the sampled output of each channel.

The speed unit provides the following outputs to drive both speed and distance counters.

- An analogue voltage, the gradient of which is 0.1 V/knot, to drive the potentiometer servo-type speed indicators.
- A pulse frequency proportional to speed. The frequency is 200/36 pulses/s/knot. Pulses are gated into the digital counter by a 1.8-s gate pulse.
- A positive/negative voltage level to set the ahead/astern indication or the B track/W track indication.
- 2000 pulses per nautical mile to drive the stepping motor in the digital distance indicator.

The depth unit provides the following outputs to drive the depth indicators when the echo sounding facility is used.

- An analogue voltage with a gradient of $0.01\,\mathrm{Vm}^{-1}$, to drive the analogue depth indicator.
- Pulses of $2\,\mathrm{ms\,m}^{-1}$, which are used to gate a 5 kHz standard frequency into the digital depth indicator.
- A positive/negative voltage level to cause the indicator to display ‘normal operation’ or ‘over-range’.

When correctly installed and calibrated, a speed accuracy of ±0.1 knot is to be expected. Distance accuracy is quoted as 0.2%. The SAL-ICCOR speed log can be made to measure the vessel’s transverse speed with the addition of a second transducer set at 90° to the first.