The Vintage Marine Depth Sounder Project.

(Circuit Analysis Technique by Complimentary Flip and a Motor Current Source Drive Servo to use Motor Back *emf* as a Speed Regulator)

Dr. H Holden. 2026.

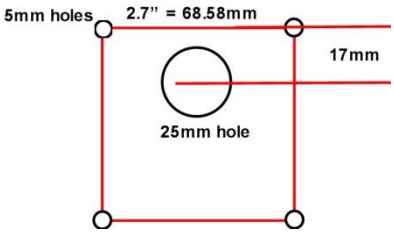
Background:

Many Marine Depth Sounders have been designed and built over the years and there have been a plethora of commercial products. I had a relatively modern one in my small boat. As is typical with many modern products with LCD displays, they are not very tolerant of high range temperature cycling. This can occur on hot days in boats with rain covers on them and poor ventilation.

The LCD screen failure in my "modern" unit is shown below. The unit was seldom exposed to direct sunlight and always had a cover while not in use. The unit's base mounted with 4 holes on the corners of a square that appeared to be in the order of 2.7 inches apart, and a 1 inch diameter hole was drilled in the top of the dashboard to accommodate the wires. I decided to keep this mounting hole array as it was already in the dashboard and simply transfer it to the mounting bracket of my new Depth Sounder.



Base mounting holes approximate geometry:



Close examination of the LCD screen showed that the surface of it had multiple fine parallel microscopic fractures. And the screen could not be repaired, only replaced. Then I had to decide what to do about it. I decided to go for an older unit. Exactly the opposite theme of the notion of: “Out with the old and in with the new”

Why go to a vintage unit? It is certainly not to acquire more features. This is simply because the components in vintage equipments are less specialised and easier to get. The schematics and other support data is often available, because they were “designed to be repaired” and not be dependent on unavailable proprietary firmware and unpublished schematics. These features are the norm in more modern equipment.

Initially I investigated the idea of replacing the LCD screen in the Lowrance unit. However the part was difficult to find and there is no manufacturer support for these units, as they have been replaced be newer models. Aside from the depth reading, there were a number of other functions in this unit that I did not use. Due to this I had the idea of going to a vintage unit, which would provide the basic function I wanted, Depth Sounding, but be easier to service and maintain and perhaps be a little more resistant to temperature extremes too.

Before Depth Sounders “went digital” there were a family of devices where the depth display consisted of a rotating disc with a Neon lamp on it. The disc rotated the Neon lamp typically around a printed scale, from 0 to 60 feet, or in another range 0 to 60 Fathoms (which is six times as deep). And there were variants on this theme with different range depth scales.

The signal burst from the transducer propagates through the water at the speed of sound in water and is reflected from the bottom. The time it takes the transmitted signal burst to return to the Transducer (also being used as a microphone) is the “round trip time” This time represents the time taken for the wave to travel twice the depth.

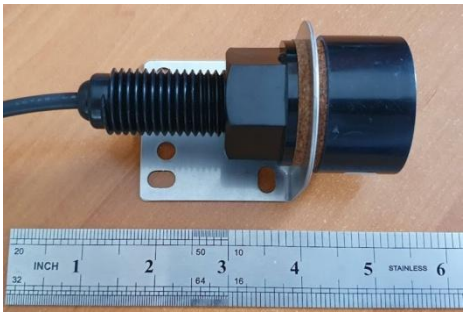
When the reflection arrives back at the Transducer, the detected wave is amplified and applied to the Neon lamp as a blip of brief illumination. At this point the lamp has now rotated at some constant angular velocity further from its origin at 12 o’clock when the pulse burst was transmitted. With each rotation of the disc and the burst of transmitted energy at each 12 o’clock location, the delayed return signal strobes the Neon lamp at the same point on the scale for the same indicated depth.

Most of these vintage units also contain a Delay Time Monostable circuit synchronized to the start of the transmitted wave. This in effect represents a dummy return signal. This is to create a minimum depth alarm. If that is set at say 12 feet and the depth recording falls equal to or below that, the alarm will sound. The signal created by the monostable circuit also strobes the Neon lamp briefly so that the user can see what minimum depth they have selected on the rotating Neon lamp display.

The vintage unit I bought, a Marine 480 Model is shown below. It was said on the box to be an Aqua-Marine MFG product made in Japan, still in its original box. It came with its original Transducer, but not the Transducer mounting bracket, because that is an “optional” part.

Unfortunately a lot of second hand units of this nature get separated from their Transducers. On opening this unit up, I discovered it was made by Copal in Japan printed on its PCB.

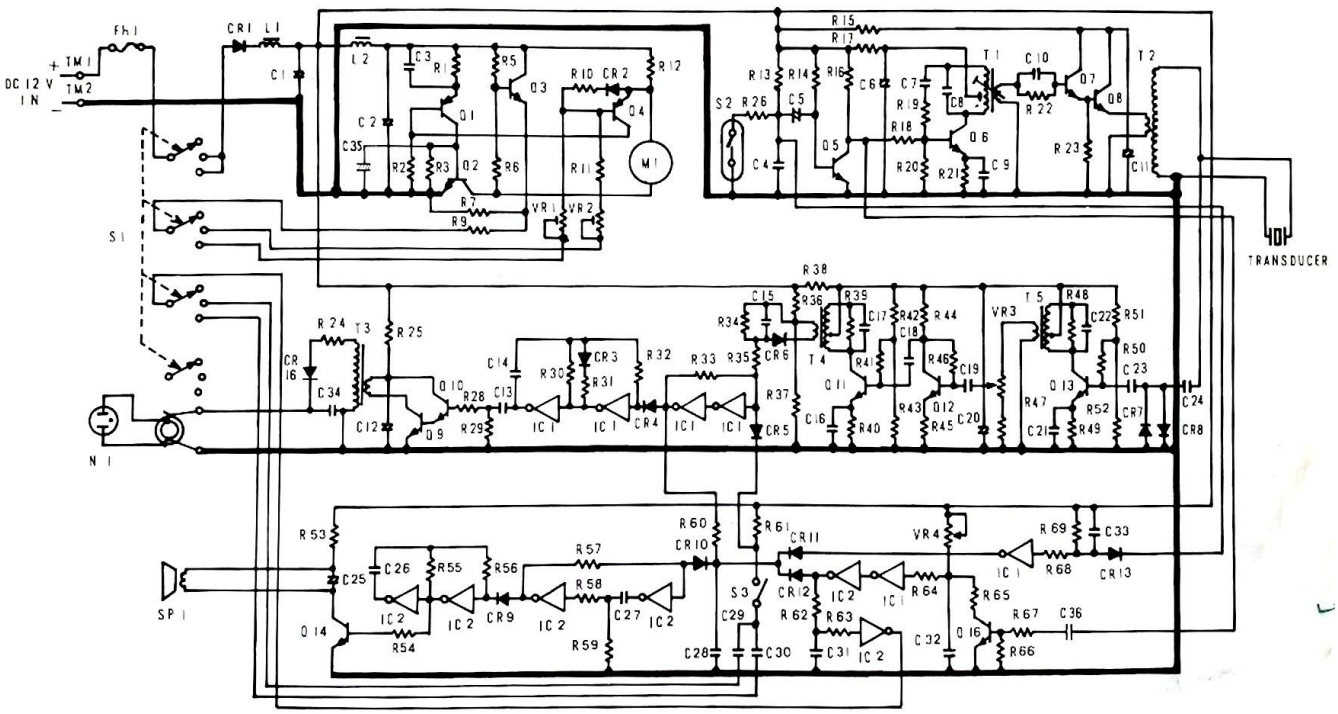




I quickly found that a right angle Stainless Steel bracket from Jaycar (used for the Bull Bar mounting of an Antenna) was suitable to mount The Transducer on the Transom of my small boat.

One thing which pleasantly surprised me is that unlike a lot of more modern equipment, the manufacturers provided a Schematic and a detailed parts list. Here is the schematic, some features of which will be discussed in this article. One feature, specifically the DC motor servo control design (which spins the rotating disc carrying the Neon Lamp) is very interesting.

SCHEMATIC MARINE 480



The switch S2 is a reed switch which is activated by a magnet on the rotating disc when the neon lamp is at 12 o'clock on the scale. This is also the moment that a burst of a high voltage 200kHz sine wave is applied to the Transducer for around 400uS.

The schematic was much more straightforward than I imagined it might be (aside from the deceptively simple but brilliant Motor servo) and the design makes frequent use of the common garden CD4069 Cmos Hex Inverter IC. These parts are still readily available from multiple sources. For example Jaycar still stocks this part for only $1.15 each.

Operating Principles and Calibration of the Marine 480 and other similar Vintage units:

The Calibration of a unit like this revolves around (no pun intended) two basic principles. One is the rotational speed (RPM) of the disc holding the Neon Lamp. The other is the assumed speed of sound in Seawater (if the unit is used in a boat in Seawater boat). That remark means the average speed of sound in typical seawater, at some average temperature and depth that the designer's have modelled. The actual speed of sound in water is affected by Salinity, Temperature and Depth.

It was very easy to work out the figures the manufacturer had assumed for the speed of sound in this unit, because they quoted the frequency of the pulses which occur with each disc rotation the in their manual.

In the 0-60 Feet range they specified 2462 pulses per minute (equal to the disc RPM) +/- 4% This is 41.03333Hz or a period of 0.0243704 seconds. Since that at full scale of 60 feet, represents a 120 foot round trip, the assumed speed of sound in the water is 120/0.0243704 = 4924 feet per second.

In the case of the 60 Fathom range (360 feet) the round trip time is 720 feet. However they specified 416.7 RPM +/- 4% or 6.945Hz or a period of 0.1439885 seconds. This implied an assumed speed of sound of 720/0.1439885 = 5000.4 feet per second. The speed of 5000.4 ft/s modelled in the 60 fathom range is close to a typical figure in seawater at 20 Deg C.

I had initially considered that one reason the speed of sound in the 60 fathom range was modelled higher than the 60 foot range is that the speed of sound in water increases a little with depth, due to the increasing pressure. However on investigating this as a cause for the two different speed assumptions, the calculations suggested that effect is too small and would not account for the difference in the two figures.

The 4% tolerance would overlap the two speed figures easily, unless they were both 4% off in the same direction. It may possibly be that in the 60 ft range, the calibration constant was derived by a practical experiment with a sinker and line and a fudge factor of 0.9848 applied to a theoretical 2500.4 f/s value. One other possibility, it may have been considered that the speed of sound should be modelled a little lower in the 60 foot range because the boat might often be in fresh water lakes or estuarine areas where the water's salinity is lower and therefore the typical speed of sound lower. Without asking the original designers, it may be difficult to know for sure and it remains conjecture.

Therefore, in a machine like this, the most important factor in the calibration of the instrument is the DC motor's RPM. To this effect there are two potentiometers seen on the schematic VR1 & VR2, to set the speed of the motor in the 60 feet and 60 fathom range modes. The preset PCB potentiometers which calibrate the speed are switched in separately for the two ranges.

However, examination of the schematic shows something more interesting. There is no feedback from the Disc position sensor reed switch to the motor servo control circuit to help control the motor's RPM. Nor is there a Tacho generator (frequency generator) on the motor's shaft to monitor its RPM. If those additional items were actually there, it would require a reference of one kind, or another, to compare those signals to, so as to create an error voltage to control the motor's speed via the motor drive amplifier. The reference could be provided as a stable DC voltage value, from a voltage regulator.

Therefore, it raised the question, in the absence of such feedback and comparator mechanism capable of measuring the motor's shaft RPM exactly to compare to a stable reference, how does the motor servo circuit work to create a long term stable motor RPM. It would have to be invariant of temperature and other factors that might affect it over time, including increasing friction or increased losses in the motor with age? This is where the examination of the motor servo becomes very interesting.

Operation of the Motor Drive Servo Amplifier:

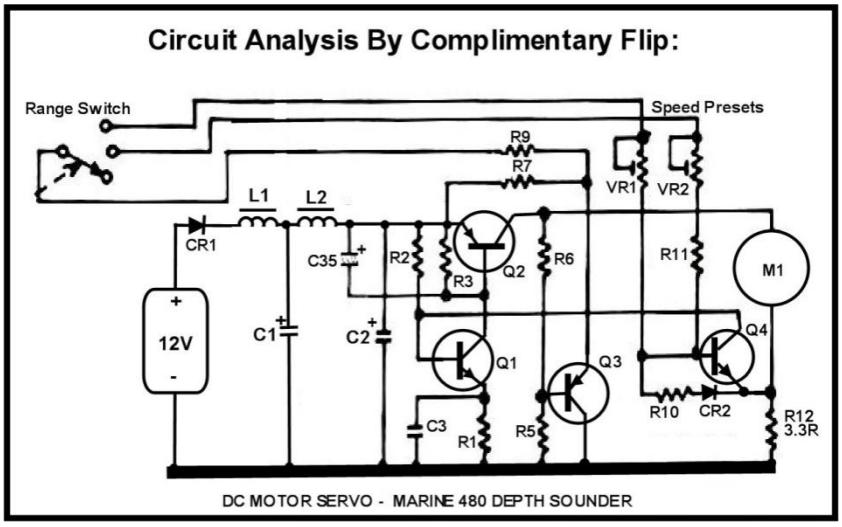
Circuits containing NPN and PNP BJT's, Diodes and other parts which are polarity dependent, are such the circuit operations remain the same if all the polarity dependent components are reversed (and the power supply too) For example NPN transistors become PNP's, PNP transistors become NPN, two terminal devices such as Diodes and polarity sensitive Capacitors are reversed.

This "flipping" process does not have to be done physically, only conceptually, and it is simply a concept which, in some cases, aids circuit analysis. It works particularly well for analysing many historical vintage positive ground circuits which had a preponderance of PNP transistors.

This technique has practical applications as well as theoretical ones.

For example in converting what was once a positive ground circuit into a negative ground one in an instrument. I have applied this method to convert items such as early car electronic rev-counters from positive ground to negative ground. This way the PCB, which often screws to the instrument's body and all other non polarity dependent parts remain the same and unchanged. The transistor polarity types are switched, diodes & electrolytic capacitors reversed in orientation. Also any polarity sensitive two terminal items, such as the meter movement connections, also require reversal. Unfortunately this "trick" is not as easy with circuits containing IC's because complementary versions of the parts seldom exist, though occasionally they do for a simple transistor arrays.

Sometimes it is easier for a circuit analysis to flip the circuit into its complementary form. One reason is that we are mostly analysing circuits with voltages and currents with respect to a common/ground system, typically negative for most modern circuitry. Therefore to avoid errors in the circuit analysis, the circuit of the motor servo is presented below in its flipped polarity form, with complimentary transistors and the diodes and polarity sensitive capacitors reversed. This does not change the circuit's theoretical operation and it could have well been built in this form if the designers had decided to do so. For convenience this flipped version of the motor servo below will be presented again later.



Examination of the motor drive amplifier shows that two motor parameters are being monitored to help control the motor's speed.

The back ***emf*** of a motor is proportional to is speed of its shaft rotation linearly and the relation is ***emf*** = Ke.ω, where Ke is the speed constant and ω is the angular frequency of rotation. The speed constant effectively contains fixed factors related to the field intensity B of the permanent field magnet (for the motor under consideration) and the number of turns and the geometry of the motor's windings such as their cross sectional area.

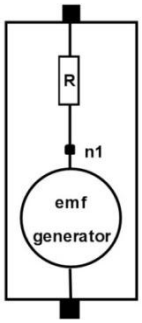
Assuming all of the factors which comprise the speed constant Ke, remain constant over time, including the magnetic field intensity B, then the value of the back ***emf*** (if you could measure that accurately) would be a parameter which could be used, in a feedback loop, to control the drive to the motor to ensure exact speed regulation. And this technique could avoid the other methods, including having a frequency generator (field generator) attached to the motor's shaft or pulse counting the motor's shaft RPM and using frequency to voltage converter techniques and a comparison with a stable reference.

Therefore, it raised the question, how can a drive Voltage be applied to a DC motor, while still being able to measure or monitor the motor's back ***emf*** ? This is explained below:

Speed Control loop:

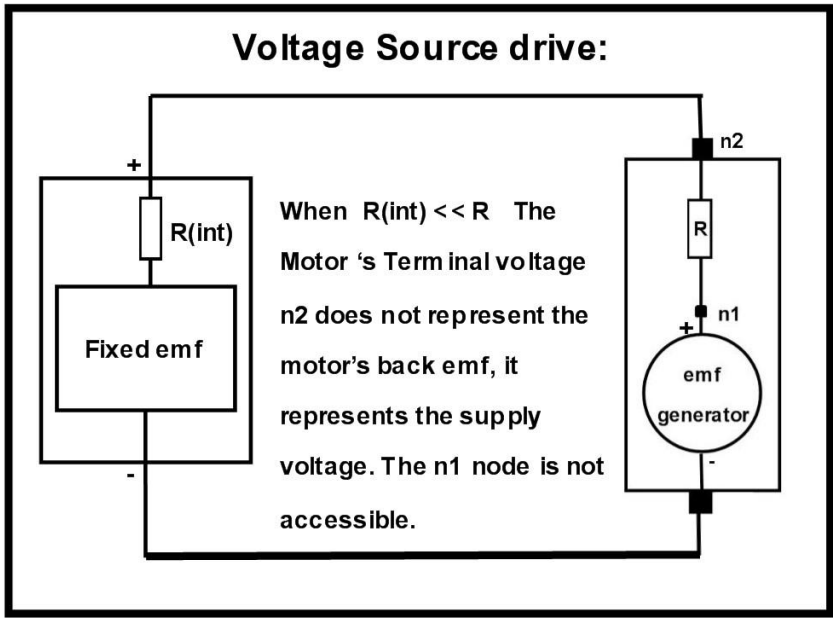
As noted the Terminal voltage of a DC motor is proportional to its RPM, but you would only see the true back ***emf*** value if you briefly disconnected the motor from its drive source and examined its terminal voltage.

The motor can be modelled as an ***emf*** generator in series with an inductance and in series with a resistance. We will ignore the inductance is this case. The series resistance R represents the resistance of the Brush system and the motor's Copper wire.



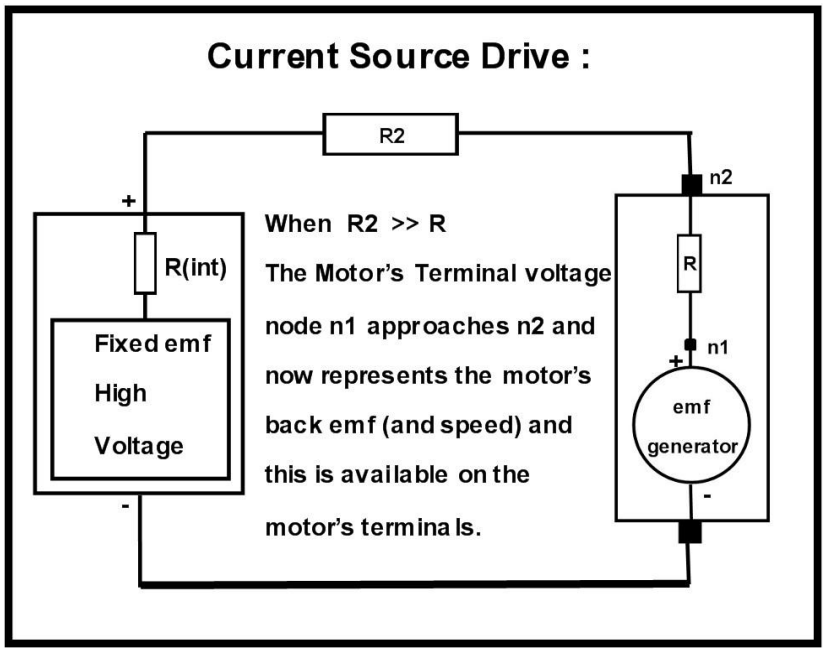
In a brief open circuit test, at some motor shaft speed, with a high input resistance meter or scope, you will essentially measure the voltage on node 1 (n1) because the resistance R has little effect on the measurement.

However, if a DC Motor is supplied from a voltage source with a low internal resistance, in say the milli-Ohm region, you will only see in practice that supply voltage on the motor's external terminals. This is because the internal resistance of the voltage source can be orders of magnitude lower than the motors internal resistance R. This is shown on the diagram below.



The basic problem in the case where a low internal resistance Voltage Source is applied to a motor's terminals, you cannot make a connection to that imaginary circuit node, n1, in the motor model where the ***emf*** generator connects to the series resistance R. How can that node, or a voltage close to it, be brought to the outside world, on the motor's terminals?

If a motor is supplied by a current source, the voltage at the node n1 starts to approach the value of n2, on the motor's terminal because the value of the resistance R2 is substantially greater than the motor's internal resistance R. A current source can be simulated by a very high voltage source with a large value resistance R2 in series:



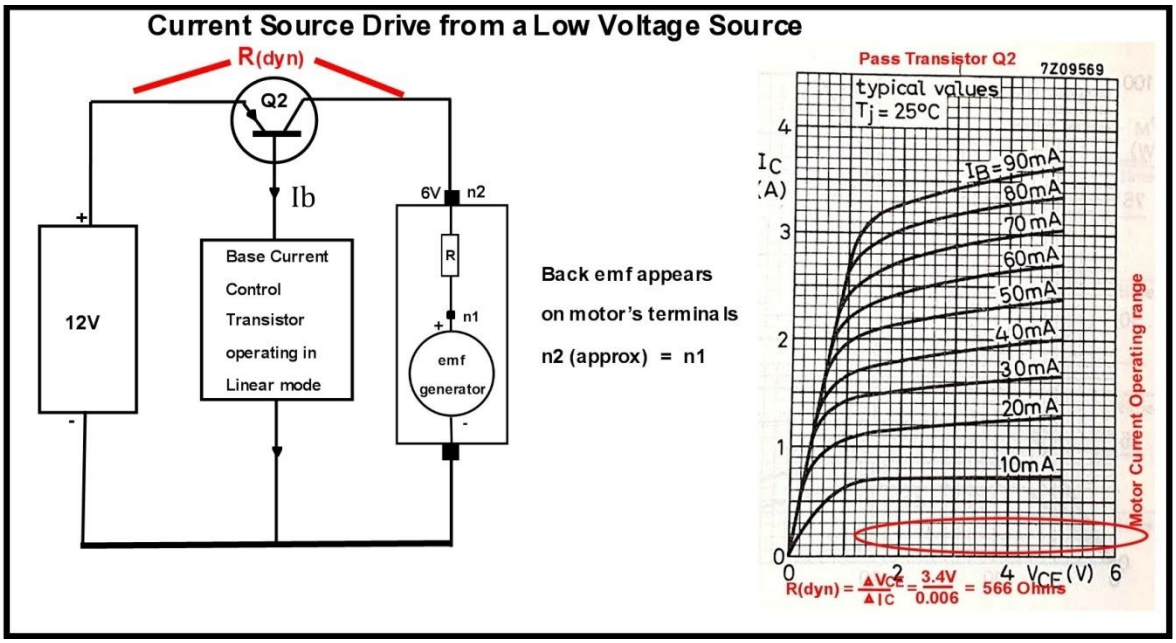
Under the above circumstance the voltage seen on the motor's terminal is no longer represents the power supply voltage, but becomes close to the value of the motors back ***emf***.

Between the two extremes of a very low internal resistance voltage source and what amounts to a very high internal resistance current source, a proportion of the motor's back ***emf*** appears across its two terminals and therefore becomes useful as a motor speed reference.

Generally a pure current source drive to a DC motor would never be a chosen method to power the motor because it will substantially reduce the motor's ability to respond to increasing or changing loads and reduce the motor's ability to supply Torque when required. However, in the application of the Depth Sounder, there is a very low constant motor load. It is just the small

frictional forces of the bearings and slip rings for the neon lamp and the windage losses of the spinning disc (also as will be explained later these losses are compensated for). And the current source driving the motor in this case, is not a perfect one, it is derived from the collector circuit of a pass transistor, which has a certain intrinsic dynamic source resistance.

This works because the transistor's collector circuit has a dynamic resistance. In other words a change in collector voltage only results in a relatively small change in collector current. The graph below is not of the exact pass transistor, only a similar one, but it is provided to illustrate that a transistor's collector circuit can have a relatively high dynamic resistance and behave as a partial current sink or current source:



The curves in the collector current area that the motor operates in, at around 200mA, are not on this graph. However it can be seen from the family of curves above that zone, the lower the collector current the lower the slope of the curve and the higher the dynamic resistance. As can be seen above about 1.5V collector voltage and above, the graph in the region of 700mA collector current, has almost become flat with a minimal slope. Looking at voltage shift of 3.4V, over a collector voltage shift between 1.6V and 5V, this is only associated with an approximate 25mA to 30mA change in current, or a value on the graph that appears to be under 50mA.

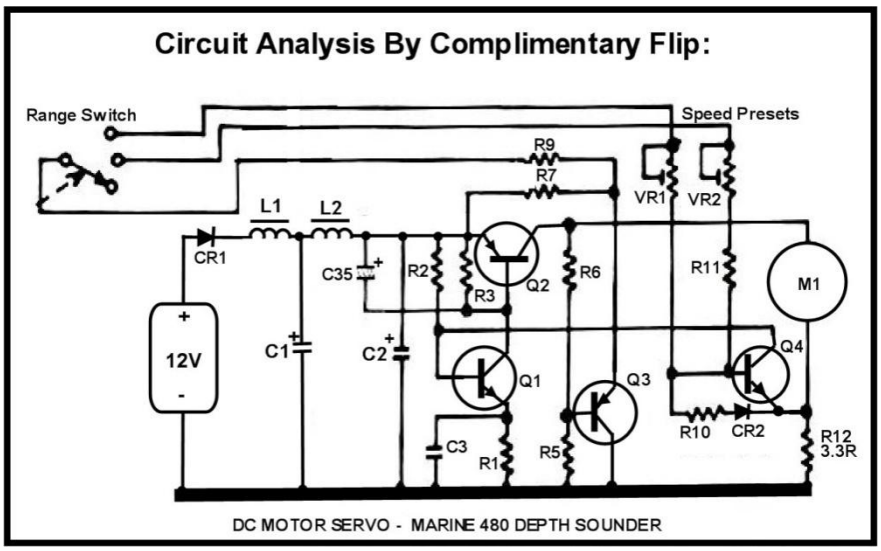
As a very rough approximation the dynamic resistance of the transistor in the 200mA collector current area is in the order of 566 Ohms and is two orders of magnitude higher at least than the motor's internal resistance R. This has a similar effect as a voltage source of about 120V

powering the motor to a 6V level seen on its terminals via a 566 Ohm resistor. In this arrangement a large proportion of the motor's back ***emf*** voltage appears on the motor's two terminals. In effect, the previously inaccessible back ***emf*** voltage of node n1, has been brought outside the motor, to the motor's two terminals.

It should be noted again that the transistor's collector is not a perfect current source. It simply elevates the effective source resistance high enough that the motor's terminal voltage becomes significantly controlled by the value of its back ***emf***. The motor current will still increase with increased loading on the motor's shaft shaft. Obviously with a perfect current source, the current would remain at a fixed value regardless of the activities of the motor and its load.

Now that the the motor's terminal voltage can be used as the measure of the motor's rpm and that value, or a sample of it, can be placed in the feedback loop to the pass transistor's base current control circuit. The arrangement can now be used to stabilise the back ***emf*** and thereby stabilise the motor's speed. And the circuit can be better analysed.

Referring to the schematic re-presented below:



A number of the circuit's features in the flipped circuit form, become more obvious with the knowledge that Q2 operating in a linear mode is acting as a partial current source (not a pure voltage source) and the motor's terminal voltage is substantially its back ***emf*** voltage representing its speed.

Q3's is an emitter-follower buffer. The back ***emf*** across the motor (including the current sense resistor R12) is divided down by R5 & R6 and applied to the base of Q3. Its emitter to collector current will be in the order of 70 to 100 times its emitter to base current for a good transistor.

Therefore Q3 is acting as buffer with good current sinking ability, to monitor a sample of the motor's back ***emf*** without that pulling the measured voltage at the junction of R5 & R6 to any significant extent.

Q3 sinks current via the calibration potentiometers VR1 or VR2 from the base circuit of Q4 reducing Q4's base-emitter current. If the Motor's speed and back ***emf*** drops Q3 sinks more current from Q4's base circuit, via the speed preset potentiometer, therefore Q4's base current and its collector current decreases. As a result, this allows R2 to divert additional base current to Q1 and this increases Q1's collector current, thereby increasing Q2's base current. This shifts the operating point of Q2 to supply more motor current and increase the motor RPM. This returns the RPM and the back ***emf*** to close the previous value before the drop in speed.

The system is a "speed control loop" based on negative feedback, in that increasing RPM and back ***emf*** results in a decrease of applied motor current while decreasing RPM and back ***emf*** results in an increase of applied motor current. The system settles on an equilibrium speed where the motor's own back ***emf*** is is the variable, with respect to circuit constants, which is controlling the speed.

R10 and CR2 appear to have been added to reduce the temperature sensitivity of Q3's base-emitter junction by shunting some base-emitter current away from Q3 as the temperature elevates. CR2 is an OA90 Germanium diode and Q3 a typical Silicon signal transistor.

In essence, the designers found a way to accurately long term speed control the motor, using its own back ***emf*** as the variable to be monitored and thereby controlled in a feedback loop.

The underlying assumption here, due to the dependence of back ***emf*** on the field intensity B of the motor's permanent magnets, the designers must have concluded that B was a stable value over the life of the motor and instrument. At least as stable as other types of references that might be used in a more elaborate servo system.

There is the shaft sensor present too, to coordinate the start of the 200kHz pulse transmission, which the designers chose not to use for motor speed control, even though it could have been used, with the addition of some relatively simple circuitry. This says something about the designer's confidence in the stability of the motor speed control servo, using just the motor's back ***emf***.

Current, Load & Torque Control:

A common technique in many DC motor servos is to monitor the motor current with a series current sensing resistor and feed that back into the control device or amplifier powering the motor. In this design the presence of such a system might likely be more important than usual because, as previously noted, a current source drive, even a partial one, reduces the motor's ability to respond to drag or frictional forces.

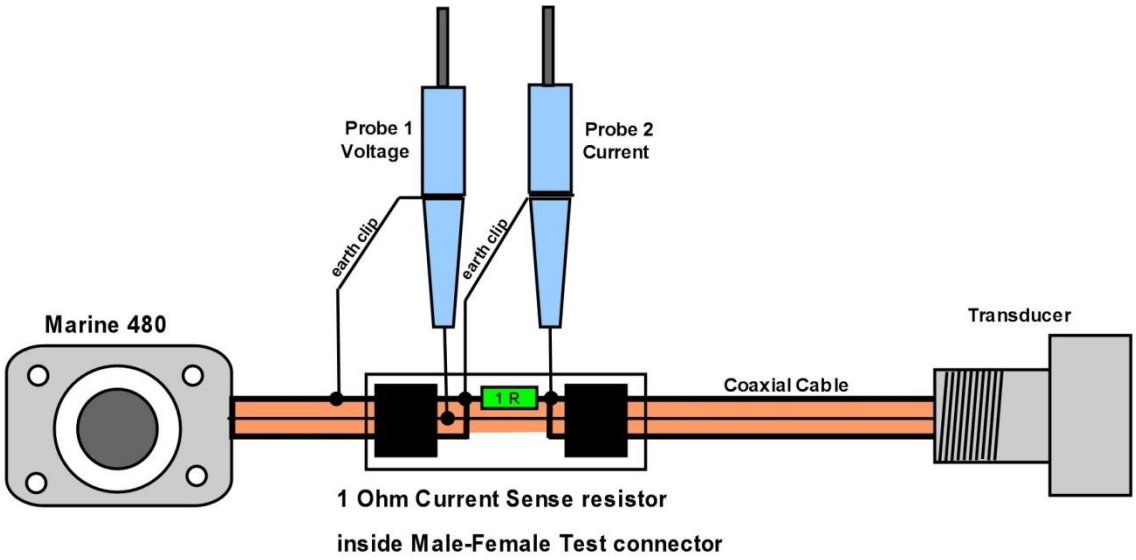
If the motor current increases due to increased loading on its shaft, or increased friction, the motor current still increases, because as noted Q2 is not a perfect current source, otherwise it would fix the current regardless of the motor's activity.

When the current increases so does the voltage drop across the 3.3 Ohm current sensing resistor R12. All else equal, this reduces the base-emitter current in Q4. As noted before in the case of speed control, this has the net effect of increasing the current supplied to the motor. This feedback loop could be thought of as "positive" to the extent that increased motor drag drives the motor with more energy to bring the speed back to its original value to supply the energy delivered to that mechanical load, while keeping the RPM stable. Obviously if this compensation loop had too much gain, drag or applied load could result in the motor speeding up, or having hunting behaviour. It is highly likely that this loop and the proportions of it are such that as mechanical load is applied to the motor (within reasonable limits that do not stall it) the compensation is just enough to stabilise the motor's speed, and not have it slow down or speed up.

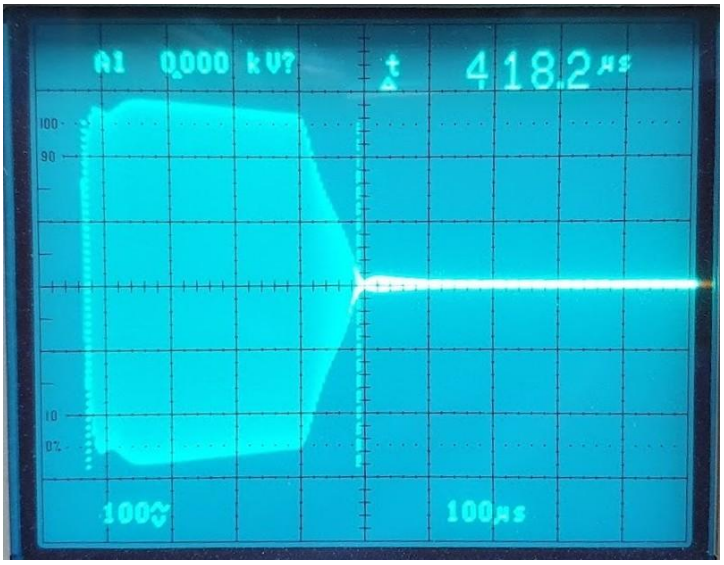
Transducer Drive Measurements:

I considered that it would be a good proposition to measure the drive to the transducer and measure the applied voltage and transducer current, in case one day the unit gave trouble, it would be a handy reference. This data was not provided in the manual.

I constructed a series fitting so as to be able to measure the transducer's current and the transducer voltage. A dual scope recording could then be made. I placed a non-reactive 1 Ohm current sensing resistor in series with the coaxial sheath, rather than the central conductor and this way the two scope probe's earth clips could be common. The unit itself during these recordings was powered from an isolated 12V battery source.



Initially I made a recording of the voltage applied to the Transducer at the time of the start of the burst. The Neon lamp illuminates at this time starting at 12 o'clock on the disc position. The recording blow shows that the burst of 200kHz drive to the transducer lasts approximately 400 uS and that the drive has decayed away to zero after about 418uS:



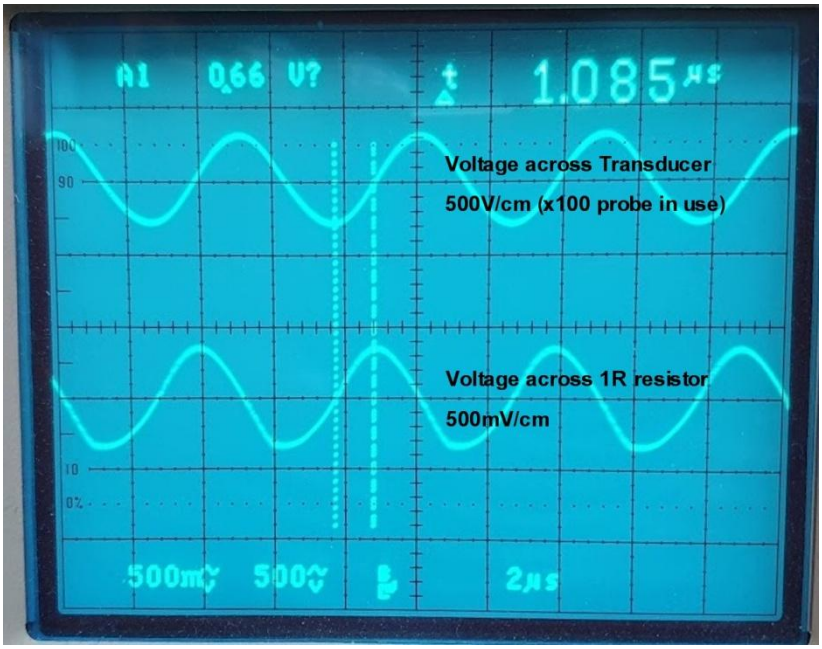
The peak voltage at its highest during the burst is 280Vp, dropping to around 260Vp by the end of the burst. Approximately 270Vp for an average peak voltage or about 191V rms for the

200kHz sine wave during the burst. With a fully charged 12v battery at other times I measured 300Vp on the transducer or about 212V rms.

Since the unit can only “look for echoes” after this time and taking the round trip into account and assuming that it would be reasonable to start to attempt to display an echo at a later time by illuminating the Neon lamp, and the speed of sound in water being 5000 ft/s, then the most shallow depth the unit could display would be in the order of (5000f/s x 420uS)/2 = 1 foot.

However it is more in the order of 1.5 feet since the Neon lamp’s initial activation time appears to approaches that on the scale and it could be difficult to resolve less than 1.5 feet in practice. However by then, at least in a boat with an outboard motor, the leg of that and the propeller would likely have already hit the bottom.

The recording below is of both the voltage and the current recorded simultaneously during the the 200kHz burst:



This recording shows that the with 300V peak applied to the transducer (212V rms) the peak current is close to 350mA or around 247mA rms, but note that the current waveform leads the voltage. This indicates that the transducer at resonance has a significantly capacitive reactive property. The period was very close to 5uS and the frequency close to 200kHz, this can be seen from the recording looking closely at the graticule markings. The cursor measured 1.085uS. The

phase advancement of the current, indicating a phase angle of 1.085/5 x 360 = 78 degrees, even though it looked more like 90 degrees on the trace at a glance.

The real power transferred is only from the parts of the voltage and current product that are in phase. This would be 247mA rms x 212V rms x cosϕ. The manufacturers specified the output power at 15 Watts. (Of course this is not continuous power, the 12V DC current consumption of the whole unit is only 400mA) The pulse is there, in the 60 feet mode example for about 400uS out of a period of about 24mS or a low duty cycle of 1.7%.

The phase angle, from the manufacturer's 15W power rating specification, could be expected to be in the order of 0.247A x 212V x cosϕ = 15W, making cosϕ about 0.286 and ϕ about 73.4 degrees. Analysis of the scope trace suggested the current was leading the voltage by about 78 degrees, making the expected power during transmission time about 11 Watts. So it is in the ball park.

As expected, the power transistor (about the size of a TO-220 part) which drives the output transformer which drives the transducer, is not on a heat sink, despite the 11W to 15W pulses because the duty cycle is so low, it is not required.

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