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High Power Ultrasonic Cleaner

This large and powerful Ultrasonic Cleaner is ideal for cleaning bulky items such as mechanical parts and delicate fabrics. It's also quite easy to build and is packed with features.

K 6022

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You've probably seen the small, low-cost ultrasonic cleaners available online. They are great for cleaning items like jewellery, glasses etc. But what if you want something a bit bigger and more powerful, to suit a wider variety of cleaning jobs? Cleaning fuel injectors or an old carburettor or any other intricate parts is a messy and time-consuming task, requiring soaking in harsh solvents such as petrol, kerosene or degreaser and scrubbing with various brushes to clean up the parts. It is a difficult and tedious task, and often does not reach the small apertures that are usually the essential areas to cleaned.

Our Ultrasonic Cleaner makes this task so much easier. Just place the components in a solvent bath, press a button and then come back later to remove the parts in sparkling clean condition. It will even clean internal areas! It uses a high-power piezoelectric transducer and an ultrasonic driver to release the dirt and grime with ultrasonic energy. For more delicate parts, the power can be reduced to prevent damage to the items being clean.

How does it work?

A metal container is filled with a solvent, deionised water, or normal hot water and a detergent or wetting agent. The ultrasonic transducer agitates the contents of the bath; at higher power levels, the ultrasonic wavefront causes cavitation, creating bubbles which then collapse. This is shown in Fig.1.

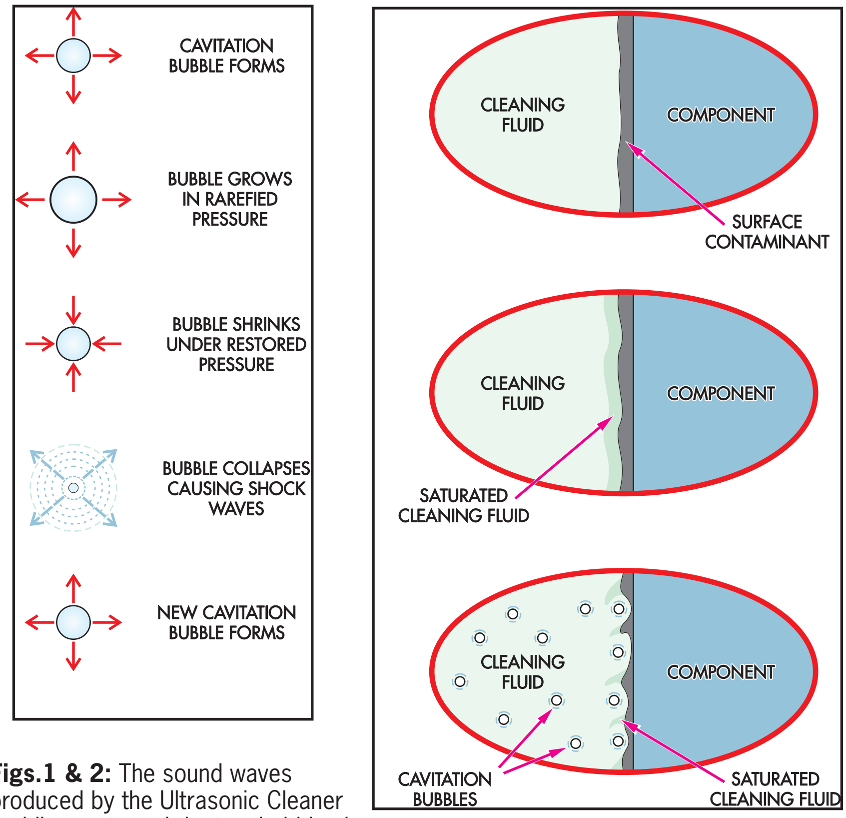
As the wavefront passes, normal pressure is restored, and the bubble collapses to produce a shockwave. This shockwave helps to loosen particles from the item being cleaned (Fig.2).
The size of the bubbles is dependent upon the ultrasonic frequency; they are smaller with higher frequencies.
We are using the commonly available bolt-clamped Langevin ultrasonic transducer, depicted in Fig.3. It comprises piezoelectric discs sandwiched between metal electrodes. The centre bolt not only holds the assembly together, but is critical in ensuring the piezo elements are not damaged when being driven. The bolt is torqued to a pre-determined tension and locked (glued) in place to prevent it loosening.

The bolt tension ensures the piezo discs always remain in compression even while it is operating, preventing the discs from breaking apart. When a voltage is applied to the piezoelectric discs, forces are generated by the piezo elements that move the two metal ends closer together and then further apart at the ultrasonic drive rate.

Our Ultrasonic Cleaner drives the piezo transducer at close to its nominal 40kHz resonant frequency.
Fig.4 shows the power applied versus frequency for the particular ultrasonic transducer we are using. It claims to have a resonant frequency of 40kHz with a 1kHz tolerance either side of this frequency. We found that the transducer resonates at 38.8kHz under load.
The transducer drive frequency needs to be controlled to within a fine tolerance to maintain a consistent power level. A small change in frequency from the resonant point will reduce the power quite markedly. Additionally, their impedance varies

Features

- Drives a nominal 40kHz, 50W or 60W-rated transducer
- Adjustable power level
- Power level display
- Stop and Start buttons with run operation indication
- Auto-off timer from 20 seconds to 90 minutes
- Soft start
- Over-current and startup error shutdown and indication
- Power level diagnostics
- Automatic or manual transducer calibration
- Standing wave minimisation
- Supports a resonance frequency of 34.88Hz to 45.45kHz



Figs.1 & 2: The sound waves produced by the Ultrasonic Cleaner rapidly create and destroy bubbles in the liquid. When the bubbles collapse, they generate localised shockwaves. This 'cavitation' stirs up the solvent layer that's in contact with the dirt, grease and grime, helping to break it up and more rapidly dissolve it away. You can do this by hand – it's called scrubbing – but it's a tedious job, and it's hard to get into nooks, crannies and internal spaces in the parts being cleaned!

depending on load. So when operating in free air, the impedance is much lower compared to when the transducer is driving a bath full of cleaning fluid.

Circuit details

The circuit of the Ultrasonic Cleaner is shown in Fig.5. It is based around a PIC16F1459 microcontroller (IC1). This controls the two Mosfets (Q1 and Q2) that drive the primary windings of transformer T1 in an alternating fashion. T1 produces a stepped-up voltage of 100V AC (RMS) to drive the ultrasonic transducer.

IC1 also drives the power LED (LED1) and level LEDs (LED2-LED6); plus it monitors the timer potentiometer (VR1) and switches S2 and S3, used for starting and manually stopping the cleaner operation. IC1 also monitors the current flowing through Mosfets Q1 and Q2 at its AN11 analog input, at pin 12. And it controls the soft-start charging of the main bypass capacitor using transistor Q5 and Mosfet Q6.

Transformer drive

A complementary waveform generator within IC1 is used to drive Mosfets Q1 & Q2 in push-pull mode. The transformer is centre-tapped to allow this type of drive. IC1's PWM generator includes an adjustable dead time, so that there is time for one Mosfet to switch off before the other Mosfet is switched on (Scope1). This prevents 'shoot-through' which would otherwise cause the Mosfets to overheat.

IC1's RC5 and RC4 digital outputs provide the complementary gate drive signals for Mosfets Q1 & Q2. Since these outputs only swing from 0V to 5V, we are using logic-level Mosfets. Standard Mosfets require gate signals of at least 10V for full conduction, but logic-level Mosfets will typically conduct fully at 4.5V, or sometimes even lower voltages.

With the STP60NF06L Mosfets we are using, the on-resistance (between drain and source) is 14mΩ at 30A with a 5V gate voltage. They are rated at 60A continuous and include over-voltage transient protection that clamps the drain-to-source voltage at 60V.

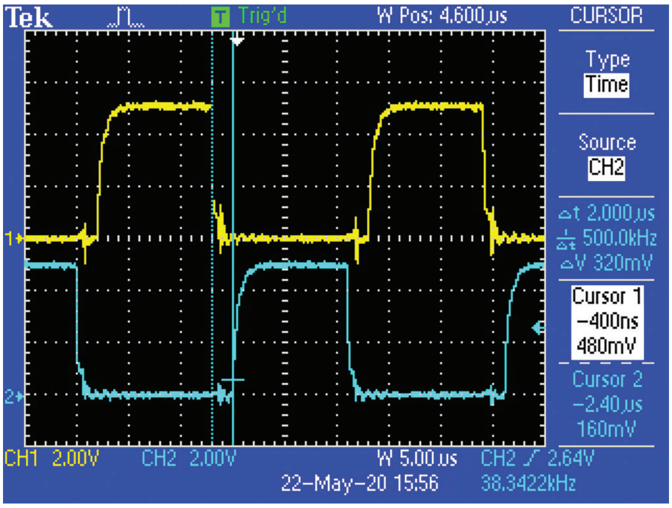
Q1 & Q2 are driven alternately and these, in turn, drive the separate halves of the transformer primary of T1, which has its centre tap connected to the +12V supply. When Mosfet Q1 is switched on, current flows in its section of the transformer primary winding. Q1 remains on for less than 25μs (assuming a 40kHz operating frequency) and is then switched off. Both Mosfets are off for two microseconds before Q2 is switched on. Q2 then draws current through its section of the T1 primary winding and remains on for the same duration as for Q1. Both Mosfets remain off again for two microseconds before Q1 is switched on again. The gap when both Mosfets are off is the "dead time" and accounts for the fact that the Mosfet switch-off takes some time.

Without dead time, the two Mosfets would both be switched on together for a short duration. This would cause massive short-circuit current spikes, not only resulting in overheating of the Mosfets but also drawing large current spikes from the supply filter capacitor and DC power supply.

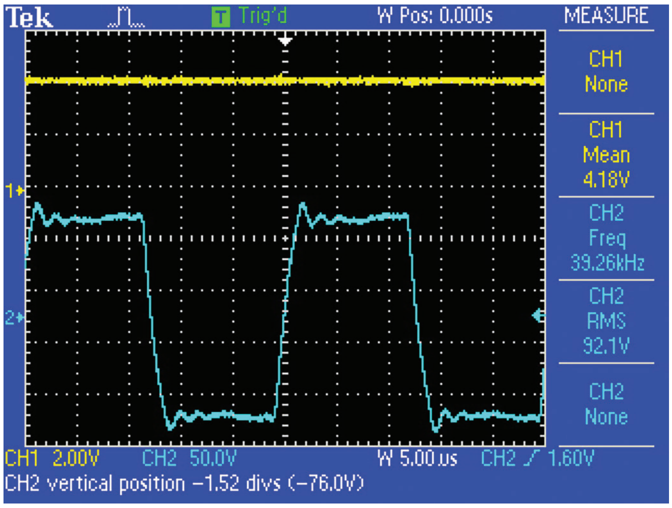
The alternate switching action of the Mosfets generates an AC square wave in the secondary winding of transformer T1. With a turns ratio of 8.14:1 (57-turn secondary and 7-turn primary), and 12V AC at the primary, the secondary winding delivers about 98V AC to the piezoelectric transducer.

Standing waves

Running the Ultrasonic Cleaner at a constant frequency near resonance is efficient, since the impedance of the transducer is almost purely resistive under those conditions. However, this is not ideal for minimising standing waves within the cleaning bath. Standing waves can build up in strength while the frequency remains constant.These waves are caused by reflections from the parts being cleaned and the tank walls being in-phase. This can damage delicate parts.



Scope 1: The gate drive to Q1 (top trace, yellow) and Q2 (bottom trace, cyan) measured at pins 5 and 6 of IC1. The vertical cursors show the dead time when both Mosfets are not driven as 2µs. That is for when Q1 switches off and Q2 switches on; the dead time is the same between Q2 switching off and Q1 switching on.



Scope 2: The lower trace (cyan) shows the transformer output voltage when driving the ultrasonic transducer at 39.26kHz. The top trace shows the current measurement voltage at the AN11 input of IC1 (TP1). 4.18V represents a 2.98A current driving the transformer primary with a 12V supply. This equates to approximately 35.8W delivered to the transducer.

Our Ultrasonic Cleaner has the option of reducing the power for use with delicate parts, but even larger parts can have delicate sections within them, especially in thin-walled cavities.

To avoid standing waves, the frequency can change over time to prevent the constant phase of the waveform, which would cause constructive interference at various locations in the bath. As the power versus frequency graph shows, changing the frequency even by a small amount will drastically alter the power. So it is not ideal if the frequency is varied continuously, as it reduces the cleaning power.

Instead, we operate the transducer at a fixed frequency for 10 seconds at a time, then run it over a range of different frequencies for a short time before returning to the maximum power frequency for another 10-second burst. In the intervening time, the frequency varies in small 37.5Hz steps over a 2.4kHz range for around 400ms. That means that power is reduced only about 4% of the time. The cycling in frequency alters the phase of the ultrasonic vibrations in the bath, giving time for standing waves that occur during the fixed frequency period to die down, thus preventing them from building up to a damaging level.

Over-current protection

Over-current protection for the Mosfets is provided in two ways. Both rely on current detection via the voltage across the 0.1Ω between the sources of Q1 and Q2 and ground.The first method uses NPN transistors Q3 and Q4. These have their base-emitter junctions connected across those 0.1Ω current-sense resistors. Over-current starts when the voltage across the 0.1Ω resistor exceeds about 0.5V, ie, with more than 5A through either Q1 or Q2. The associated transistor Q3 or Q4 then begins to conduct.

The current flowing from its collector to its emitter reduces the gate voltage to the associated Mosfet. This has the effect of increasing the Mosfet on-resistance, which then reduces the current. This protection is a fast-acting, cycle-by-cycle protection measure. At the same time, the voltages across

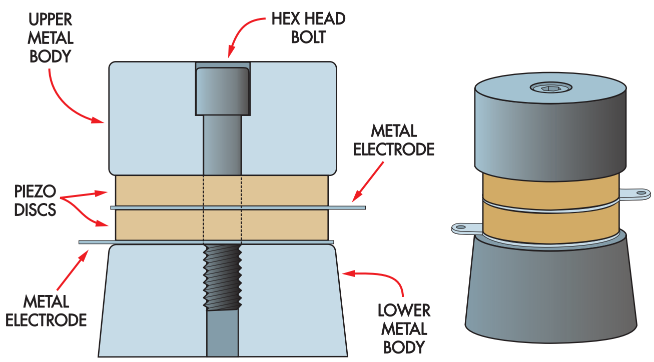


Fig.3: This shows the construction of the ultrasonic transducer that we're using. Two piezoelectric (ceramic) discs are sandwiched between the two halves of the body, with electrodes to allow a voltage to be applied across the piezo elements. The compression of the piezoceramics due to the tension from the bolt holding the whole thing together is critical to preventing early failure from the ultrasonic vibrations.

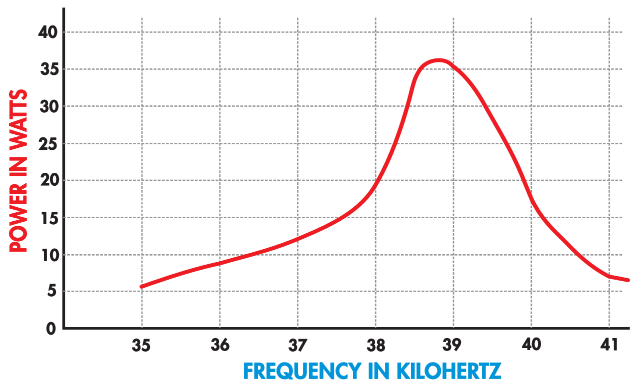


Fig.4: The frequency vs power curve for the transducer in our prototype. Most transducers with a nominal 40kHz resonance should be similar, but the exact frequency of the peak will vary, as will the steepness of the slopes. Hence, our Cleaner has an automatic calibration procedure to find this peak; the 100% power setting runs it at a frequency close to the peak, while lower power settings are at higher frequencies.

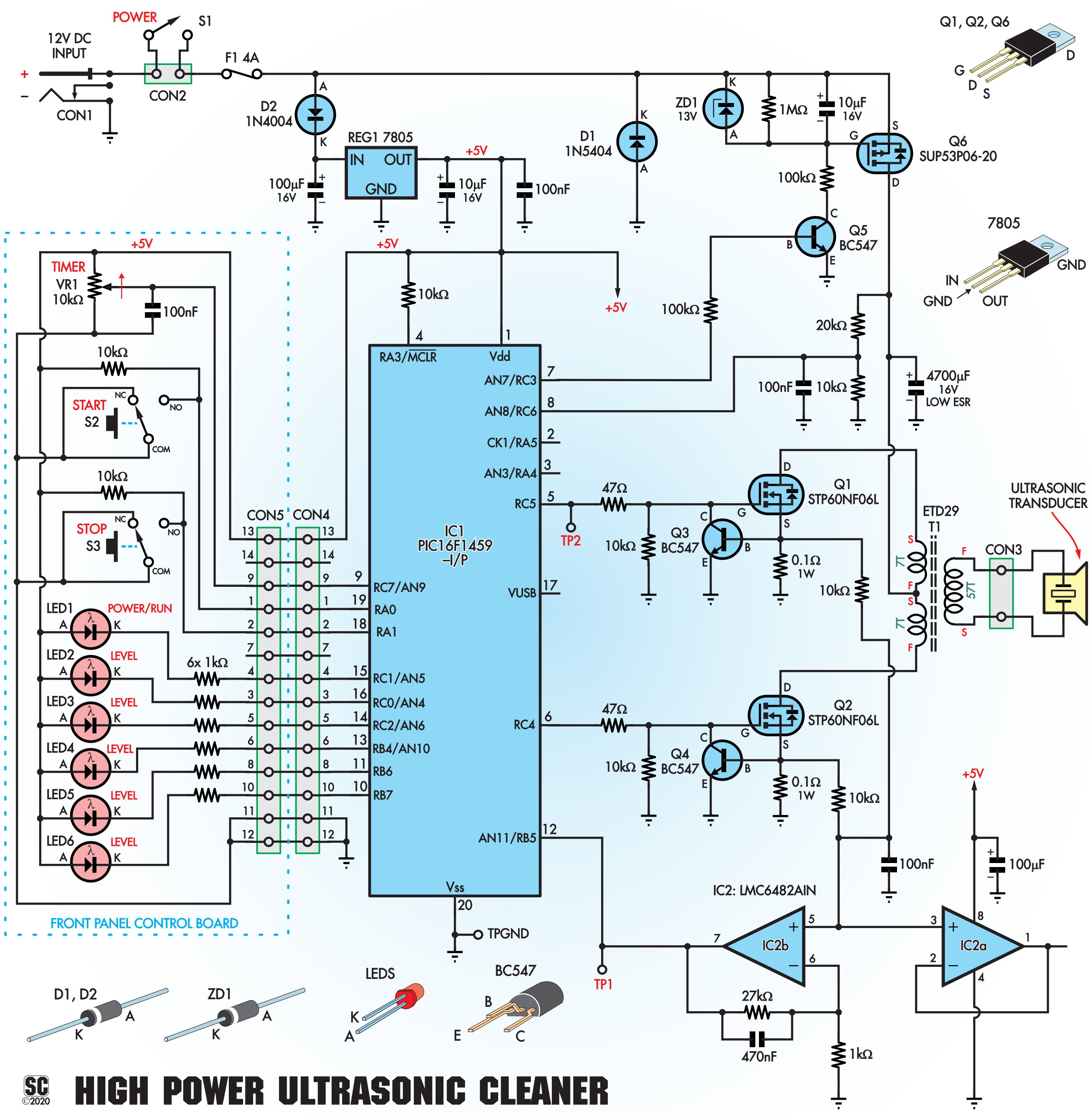


Fig.5: The complete Ultrasonic Cleaner circuit. IC1 produces complementary drive signals to the gates of Mosfets Q1 & Q2, which in turn drive the primary of transformer T1 in a push-pull manner. This results in around 100V AC at CON3. Current is monitored via two 0.1Ω shunt resistors at the sources of Q1 and Q2, via amplifier IC2b into analog input AN11 of IC1; the power is computed from this and a voltage measurement at analog input AN8.

the two 0.1Ω current-sense resistors are averaged by a pair of 10kΩ resistors and filtered by a 100nF capacitor. This averaged voltage is then applied to non-inverting input pin 5 of op amp IC2, which amplifies the signal 28 times (27kΩ ÷ 1kΩ + 1). The averaging effectively halves the sensed voltage, since only one of Q1 or Q2 is on at any given time.

So this results in an overall amplification of 14 times. The output from pin 7 of IC2b is measured by the AN11 analog input of IC1 (pin 12) – see Scope2. This voltage is converted to a digital value and processed by IC1. Should this voltage stay at 4.9V or more over a 160ms period, the drive to the transducer is switched off.

This voltage represents an average of 350mV measured across each 0.1Ω resistor, or a 3.5A average current flow. That's calculated as (4.9V÷14) ÷ 0.1Ω. An over-current error is indicated by flashing LED2, LED4 and LED6 on the front-panel level display. When this happens, the power will need to be switched off and restarted to resume cleaning. If the problem persists, the cause will need to be found.

Power control

The current measured at the AN11 input is also used for controlling the power applied to the ultrasonic transducer. The maximum power rating of the transducer is 50W, but this is not

The 40kHz transducer is available both here in Australia and online. Note, though, that if you do buy online you need to make sure you get a 40kHz type – there are other frequencies available and they look pretty much identical.

a continuous rating. The recommended continuous power is 43W. We limit power to a more conservative 36W. For a 12V supply, the current required for this power is 3A.

During operating, the current is monitored via AN11 and the drive voltage is also sampled, via a resistive divider, at analog input AN8 (pin 8). This allows the micro to calculate the power flowing into the transformer as the frequency is adjusted, so that it can maintain the power at the required level. IC1's instruction clock is derived from its internal oscillator, and thus the PWM output frequencies are derived from this as well. The internal oscillator can be adjusted in small steps using the OSCTUNE register. This can vary the internal oscillator frequency over a 12% range in 128 steps. For the 40kHz drive to the ultrasonic transducer, this allows a 4.8kHz control range in steps of 37.5Hz.

The 37.5Hz step resolution is sufficiently small to drive the ultrasonic transducer at the desired power level. However, the OSCTUNE register does not have sufficient frequency range to ensure we can drive an ultrasonic transducer that is resonant outside the range of 37.6kHz to 42.4kHz.
To widen the operating range, the unit calibrates itself automatically (it can also be initiated manually). This finds the approximate resonant frequency of the transducer using a coarser adjustment. Fine-tuning is then done via OSCTUNE; this allows a variety of different transducers to be used.
This coarser calibration is performed using the PR2 register, which sets the period and thus the frequency of the PWM drive waveform. For our circuit, this provides steps of approximately 540Hz. We restrict the coarse adjustment range to be from 34.88kHz to 45.45kHz. This range caters for all transducers that have a nominal 40kHz resonance.

So the transducer's resonance is found to within 540Hz by adjusting PR2, and this value is stored in non-volatile flash memory. OSCTUNE can then vary the frequency at least 1.8kHz above and 1.8kHz below the value initially set by the PR2 register (1.8kHz ≈ 2.4kHz - 540Hz). Different power levels are available by adjusting the drive frequency. The highest power is at the frequency closest to resonance, while lower power levels use a frequency above resonance that has the transducer producing a lower power.
Nine power levels are available, ranging from 100% (36W) down to 10% (about 3.6W). Depending on the transducer characteristics, the lowest power level may not be available.

LED indicators

LEDs2-6 indicate which of the nine power levels is selected, with LED2 lit to indicate the lowest power level. The next step up is with LED2 and LED3 lit, then LED3 and so on until LED6 only is on, showing the highest power level. The power level is adjusted by holding down the Start switch. It will then cycle up through the nine possible levels to the maximum, then down again. The switch can then be released at the desired level setting. The transducer is not driven during power level adjustments.
The On/Run LED (LED1) shows when power is applied to the circuit. This LED also acts as an operation indicator. The LED goes out during transducer calibration and then lights when the required value for PR2 is found. This takes a few seconds, unless there is something wrong, such as when there is no transducer connected. Once running, LED1 only lights when the transducer is being driven at the required power setting; it acts an 'in lock' indicator.

When the Stop switch is pressed, the drive to the transducer ceases, the level LEDs go off and the power LED turns on. LED1 then goes out when the main power source is switched off via S1, or if the supply itself is disconnected or switched off.

Cleaning timer

VR1 is the timer control. The voltage from its wiper is applied to the AN9 analog input of IC1 (pin 9), and it varies between 0V and 5V. This corresponds to a timer range from 20 seconds through to 90 minutes. The timer starts when the Start switch is pressed. After the selected period, the transducer drive stops. Switches S2 and S3 connect to the RA0 and RA1 inputs of IC1 respectively. The inputs are held high (at 5V) by 10kΩ pull-up resistors. A closed switch is detected when it is pressed as the input is pulled to 0V.

Note that we are using pushbutton changeover switches that have common (C), normally closed (NC) and normally open (NO) contacts. The pins on the switch are in a line, with the common pin at one end, NO in the middle and NC at the other end. Usually, that means that you would need to orientate the switch correctly on the PCB for correct operation.

However, we have designed the PCB pattern so that either orientation will work by wiring the C and NC connections together on the PCB.

Power supply

12V DC power for the circuit is fed in via CON1. It needs 4A minimum. If using a 12V battery, it should be rated at 10Ah or more. Power is switched by S1, which is wired back to the PCB using a plug-in screw connector and socket (CON2). Power then passes to the 5V regulator (REG1) via reverse polarity protection diode D2. Linear regulator REG1

Parts list

1 double-sided PCB coded 04105201, 103.5 x 79mm
1 double-sided PCB coded 04105202, 65 x 47mm
1 panel label, 115 x 90mm (see text)
1 diecast aluminium box, 115 x 90 x 55mm [Altronics H0452]
1 50/60W 40kHz ultrasonic horn transducer (resonance impedance 10-20Ω) [Altronics Z1690]
1 12V DC 60W switchmode supply or similar [Altronics MB8939B] (not included)
OR
1 12V battery (10Ah or greater) with 5A+ rated twin lead (not included)
1 EPCOS ETD29 13-pin transformer coil former, B66359W1013T001 (T1)
2 EPCOS ETD29 N97 ferrite cores, B66358G0000X197 (T1)
2 EPCOS ETD29 clips, B66359S2000X000 or equivalent (T1)
1 6A SPST mini rocker switch (S1) [Altronics S3188]
2 SPDT momentary push button switches (S2,S3) [Altronics S1393]
2 switch caps for S2 & S3 [Altronics S1403]
1 5A PCB-mount barrel socket, 2.5mm ID (CON1) [Altronics P0621A]
1 5A barrel plug, 5.5mm OD x 2.5mm ID [Altronics P0165] (not included)
1 vertical 2-pin pluggable header socket with screw terminals (CON2) [Altronics P2512]
1 2-way PCB mount screw terminal with 5.08 spacing (CON3) [Altronics P2040A]
1 14 pin box header (CON4) [Altronics P5014]
1 14 pin IDC plug (for CON4) [Altronics P5314]
1 14-pin IDC transition plug (CON5) [Altronics P5162A]
2 3AG PCB-mounting fuse clips (F1)
1 4A 3AG fuse (F1)
1 10k 16mm linear potentiometer (VR1)
1 knob to suit potentiometer
1 20-pin DIL IC socket (for IC1)
1 8-pin DIL IC socket (for IC2)
3 TO-220 silicone washers and bushes
4 stick-on rubber feet

Transducer housing parts
1 50mm length PVC DWV (Drain, Waste and Vent) fittings; end cap (Holman DWVF0192) and adaptor (Holman DWVF0022) ***or*** 1 40mm length of 50mm ID pipe
1 cable gland for 3-6.5mm cable
Neutral cure silicone sealant (eg, roof and gutter) (not included)
Epoxy resin (eg, JB Weld) (not included)

Parts for testing
1 100mm length of 0.7mm tinned copper wire
4 9mm-long M3 tapped spacers
4 M3 x 6mm machine screws
extra length of 0.63mm diameter enamelled copper wire

Cables, wiring & hardware
1 M3 x 6mm machine screw (for REG1)
3 M3 x 9mm machine screws (for Q1, Q2 & Q6)
4 M3 hex nuts
1 cable gland for 3-6.5mm diameter cable
1 800mm length of 1mm diameter enamelled copper wire (T1 primary)
1 3.6m length of 0.63mm diameter enamelled copper wire (T1 secondary)
1 1m length of 0.75mm square area dual sheathed cable or figure-eight wire (for transducer connection)
1 160mm length of 5A (1mm^2) hookup wire
1 200mm length of 14-way ribbon cable
8 PC stakes
1 30mm length of 5mm heatshrink tubing (for S1 connections)
1 roll of electrical insulating tape

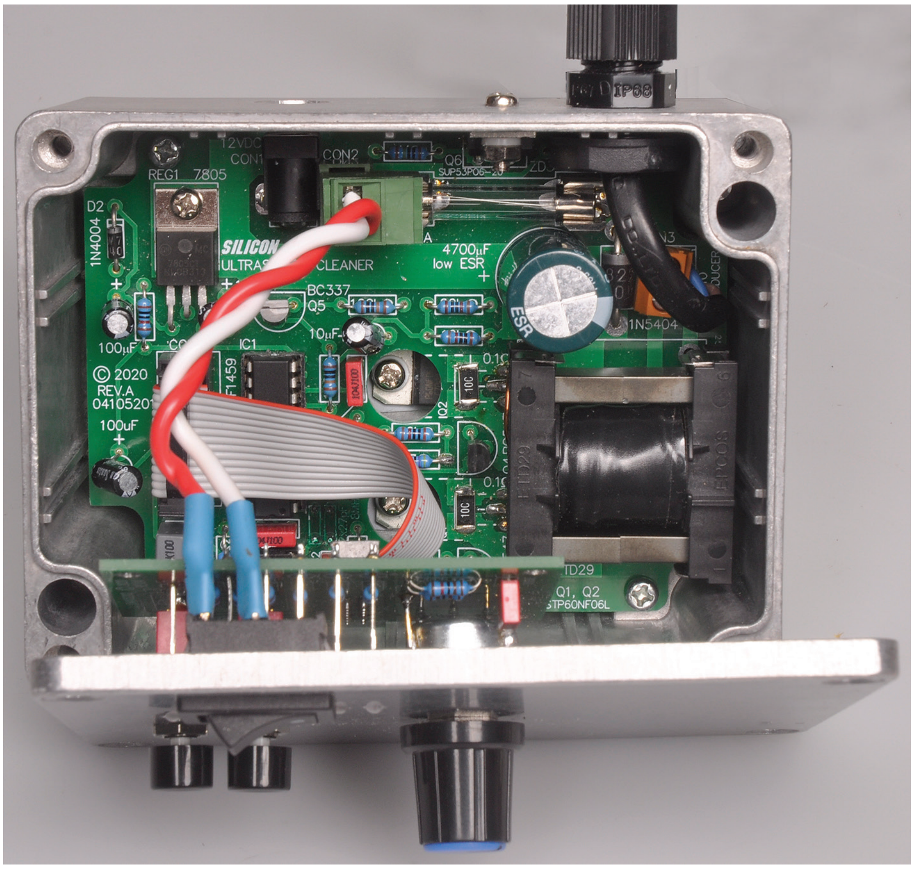
Semiconductors
1 PIC16F1459-I/P microcontroller programmed with 0410520A.hex (IC1)
1 LMC6482AIN CMOS dual op amp (IC2)
1 7805 5V 1A linear regulator (REG1)
2 STP60NF06L logic level N-Channel Mosfets (Q1,Q2)
3 BC547 NPN transistors (Q3-Q5)
1 SUP53P06-20 P-channel Mosfet (Q6)
1 13V 1W zener diode (ZD1)
1 1N5404 3A diode (D1)
1 1N4004 1A diode (D2)
6 3mm LEDs (red or green) (LED1-LED6)

Capacitors
1 4700µF 16V low-ESR PC electrolytic
2 100µF 16V PC electrolytic
2 10µF 16V PC electrolytic
1 470nF MKT polyester
4 100nF MKT polyester

Resistors (0.25W, 1% unless specified)

	4-band code	5-band code
1x 1MΩ	brown black green brown	brown black black yellow brown
2x 100kΩ	brown black yellow brown	brown black black orange brown
1x 27kΩ	red violet orange brown	red violet black red brown
1x 20kΩ	red black orange brown	red black black red brown
8x 10kΩ	brown black orange brown	brown black black red brown
7x 1kΩ	brown black red brown	brown black black brown brown
2x 47Ω	yellow violet black brown	yellow violet black gold brown

2x 0.1Ω 1W SMD 6432/2512-size



Another view of the PCBs sitting inside the diecast box – one mounted on the lid. Here you can clearly see one of the two MOSFETS with its mounting screw accessible through the hole in the PCB. Don't forget the insulating washer and bush underneath!

provides the 5V required by IC1 and IC2. 12V DC also goes to Mosfet Q6 via fuse F1. This Mosfet is used as a soft-start switch to charge the large 4700µF low-ESR bypass capacitor slowly. Without soft starting, charging the 4700µF capacitor would cause a substantial surge current. This can blow the fuse or cause a 12V switchmode supply to shut down.

When power is first applied, Q6 is off and the 4700µF capacitor is not charged. When the Start switch is pressed, the RC3 output of IC1 goes to 5V and this switches on transistor Q5. The gate voltage of P-channel Mosfet Q6 then begins to drop towards 0V as the 10µF capacitor charges via the 100kΩ resistor to the collector of Q5). As the Mosfet begins to conduct, it slowly charges the 4700µF capacitor. After half a second, the gate charging is stopped by switching off Q5 and after a 250ms delay. The voltage across the 4700µF capacitor is then measured using the AN8 analog input of IC1.

If the voltage across the capacitor is under 9V (3V at AN8), all the level LEDs flash twice per second. This indicates that either the 4700µF capacitor is leaky, or there is a short circuit causing the capacitor to discharge. Power can then be switched off, and the fault investigated.

If there is no error, Q5 is switched back on, to continue charging the gate of Q6. It takes one second for the gate to drop 7.5V below the source, at which time Q6 is almost fully on. After a few more seconds, the gate voltage will be very close to 0V, leaving the full 12V between the gate and source. Zener diode ZD1 protects the gate from over-voltage by limiting the gate-source voltage to -13V. Reverse polarity protection for the power section of the circuit is via a 4A fuse F1, diode, D1 and the integral reverse diodes within Mosfets Q1 and Q2. These diodes conduct current, effectively clamping the supply voltage at -0.7V and protecting the 4700µF electrolytic capacitor from excessive reverse voltage.

This current will quickly blow the fuse and cut power.

The bath

The ultrasonic transducer needs to be attached to the outside of a suitable container. This can be made from stainless steel, aluminium or plastic so that the ultrasonic vibration is efficiently coupled to the fluid. Stiffer materials couple the ultrasonic waves with fewer losses.

Ideally, the bath should have a flat side or base where the transducer can be attached. The material also needs to be compatible with the epoxy resin used to glue the transducer to the bath. Metals are the most compatible material. We found a series of "gastronorms" at a kitchen supply shop that are ideal.

These are the types of food containers you often see at buffets. They slot into steam tables that keep the food warm, and they are available in various shapes and sizes, with several good options at or near the ideal 4L volume. You can get them made from stainless steel, polycarbonate or polypropylene with the first two options being the best.
We got ours (pictured) from www.nisbets.com.au (they have shops in NSW, VIC, QLD & ACT).

We recommend either the 150mm-deep ¼ gastronorm tray (capacity 4L), the 100mm-deep 1/3 gastronorm tray (capacity 3.7L) or the 100mm-deep ¼ gastronorm tray (capacity 2.5L).
The 150mm-deep ¼ tray is tall and rectangular while the 100-mm deep 1/3 tray is more square and shallow. The other tray is in-between the other two.
You can also get stainless steel or clear or black polycarbonate lids to suit all these, which would be a good idea if you're cleaning with a strong-smelling solvent (especially if you plan to leave the solvent in the bath when you aren't using it).

Larger sized baths with more liquid will have a lesser cleaning effect than smaller containers with less fluid.
The fluid used in the bath can be tap water with a few drops of detergent as a wetting agent. Other fluids that can be

If I knew you were comin' I'd've baked a cake . . . these are some of the stainless steel containers we found at a kitchen supply shop which would be ideal for this project. Choose the size and depth which best suits your application.

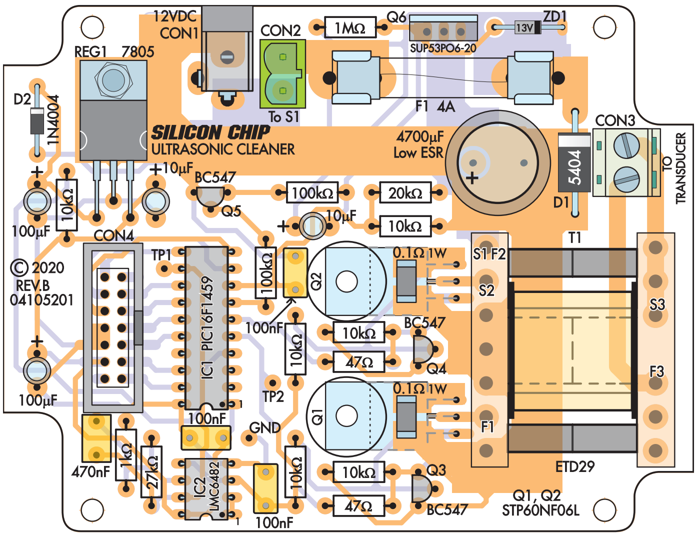
used include deionised water, alcohol (methylated spirits, isopropyl alcohol etc), acetone or similar solvents. Cleaning effectiveness is greatly enhanced when the fluid is warmed. Filling with around four litres is ideal for the power available from the ultrasonic transducer. With deeper containers, it might be possible to fill them with less liquid for cleaning smaller items. However, you would need to re-calibrate the unit after each fluid level change, and you might find that it would shut down with less liquid in the tank due to the transducer impedance dropping, and the power delivery going above 40W.

This approach would require some experimentation for successful use. The recalibration procedure will be described later. Note also that you would need to mount the transducer quite low on the container (or on the base) to allow different fluid levels to be used.

As mentioned in throughout the previous pages, the microcontroller in the Ultrasonic Cleaner uses three Mosfets and a step-up transformer to produce around 100V AC to drive an ultrasonic transducer at just under 40W.

This transducer is attached to the side of a vessel contain- ing cleaning liquid and objects to be cleaned. You select a power level and a time, and it does the rest. The electronic components are mounted on two PCBs which are housed in a diecast aluminium box. The lid of the box has all the controls and the indicator LEDs.

The only external wiring is for 12V DC power to the unit (it draws around 4A at full power) and one twin lead which emerges from the box via a cable gland and goes to the transducer that's glued to the liquid vessel. Building the Ultrasonic Cleaner isn't too difficult. The main steps are winding the transformer, soldering the components to the PCBs, drilling the case, mounting the parts in the case and wiring it up.
We shall now describe all the necessary steps in detail.



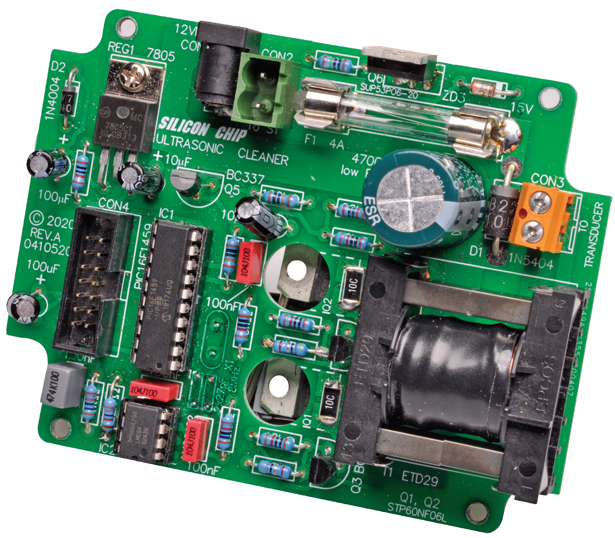
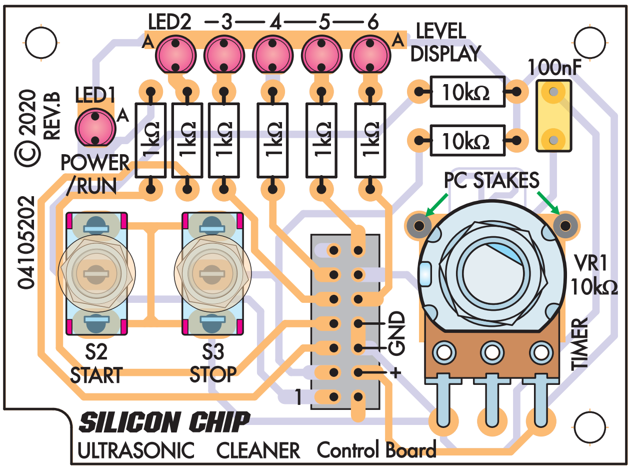


Fig.6: Fit the components to the main Cleaner PCB as shown here. Watch the orientation of the diodes, ICs, electrolytic capacitors and box header CON4. Mosfets Q1 and Q2 are mounted on the underside, with their leads coming up through six pads next to transformer T1. Two holes in the PCB give access to their tabs, so that they can be mounted to the bottom of the case for heatsinking. This final version PCB is slightly different to the photo of the early prototype at right (the empty pads just to the right of IC1 in the prototype are gone in the final version).



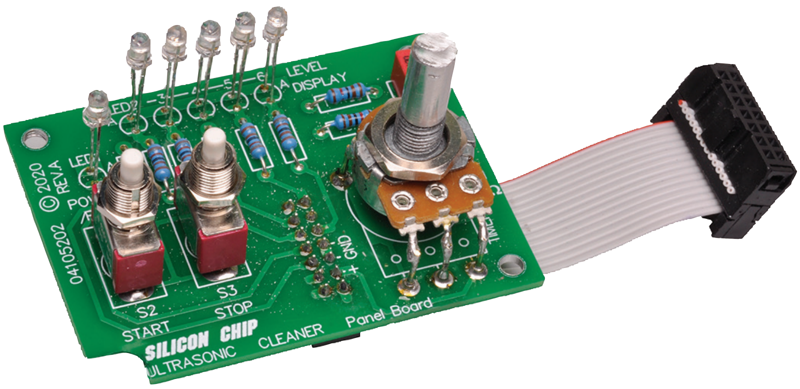


Fig.7: IDC header CON5 mounts on the back of this front panel board, while the LEDs, switches and potentiometer VR1 protrude through holes in the front panel. Make sure that VR1's body is grounded via the pads provided and also check that the LEDs are all orientated as shown.

PCB construction

The Ultrasonic Cleaner is built using two PCBs. The main PCB is coded 04105201 and measures 103.5 x 79mm while the smaller front-panel PCB is coded 04105202 and measures 65 x 47mm.

The assembled PCBs are housed in a diecast box measuring 115 x 90 x 55mm. The overlay diagrams for both boards are shown in Figs.6 & 7.
Start by fitting the resistors on both PCBs where shown. The resistor colour codes were given in the parts list, but it's always best to check the values with a DMM set to measure resistance to make sure they're going in the right places.

The 0.1Ω SMD resistors mount on the top of the PCB, solder one end first and check alignment before soldering the other end. Continuing with just the main PCB, fit diodes D1 and D2 and make sure that their cathode stripes face toward the top edge of the PCB as shown. ZD1 can also be mounted, orientated as shown. We recommend that IC1 and IC2 are mounted in sockets. Make sure that the notched faces toward the lower edge of the PCB. The three PC stakes can also be fitted now; they are marked as GND, TP1 and TP2 (you can leave these off and probe the PCB pads later, if desired).

Now mount REG1 flat onto the PCB with its leads bent down 90° to fit into the holes in the PCB. Secure it to the PCB using an M3 x 6mm screw and nut, then solder and trim its leads. Also mount the 3AG fuse clips now, making sure that the fuse clips have the correct orientation, with the end stops toward the outside of the fuse.

It is a good idea to insert the fuse before soldering the clips in place to ensure the fuse is aligned in the clips and that the clips are orientated correctly. Ideally, the fuse clips should also be soldered on the top of the PCB on one side of each clip, to minimise the connection resistance.

WARNING!

The transducer is driven at 100V AC which is more than enough to give you a shock. Touching both of the transducer terminals during operation will give you an electric shock, and it will be worse if your hands are wet. You must enclose the transducer in the PVC housing described in this article and only run it when so enclosed and attached to a bath filled to the correct level with cleaning fluid.

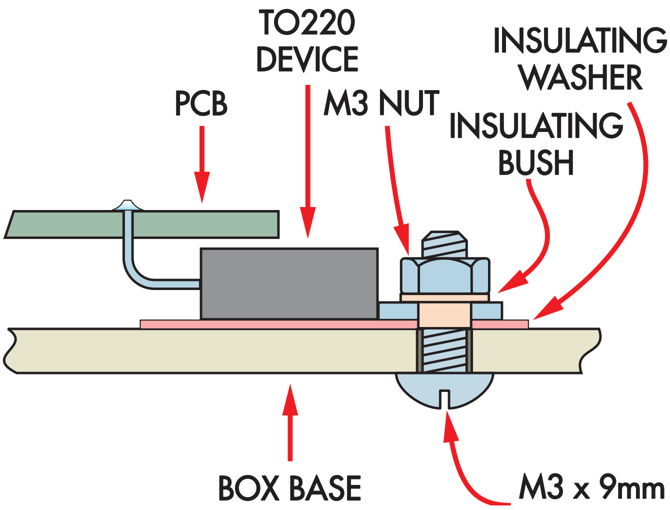
The DC socket (CON1) and the 2-way pluggable terminal block socket (CON2) can then be installed. Take care with CON2's orientation; insert the plug into the socket before soldering the socket. This will ensure the orientation is correct, as the screws need to face towards the fuse so that the assembly will fit on the PCB. Also fit the 2-way screw terminal (CON3), with the wire entry toward the edge of the PCB.

Mount the 14-way IDC box header (CON4) now. Make sure the notch is orientated as shown and it is pushed all the way down before soldering its pins. Fit the capacitors next, noting that the electrolytic ca- pacitors must be orientated with the longer positive leads through the holes marked "+". Then solder the three small transistors (Q3-Q5), which are all BC547s.

Mosfet Q6 (the SUP53P06-20) is mounted vertically with the mounting hole 22mm above the top of the PCB. Mosfets Q1 and Q2 mount on the underside of the PCB. Bend the three leads for each Mosfet upward by 90°, 5mm from the bottom edge of the Mosfet body. Then insert the leads into the PCB from the underside but do not solder them yet.

Now place the PCB into the enclosure, sitting on the internal mounting corners. Mark where the Mosfets sit, including their mounting hole locations, then remove the PCB and place the silicone

Fig.8: This is how the Mosfets are mounted to the board and the case (for heatsinking). Ensure that the tabs are fully isolated from the case before powering the Cleaner up. Initially, the Mosfets can be attached to the outside of the box for testing, then later moved to the inside (the mounting method is the same either way).



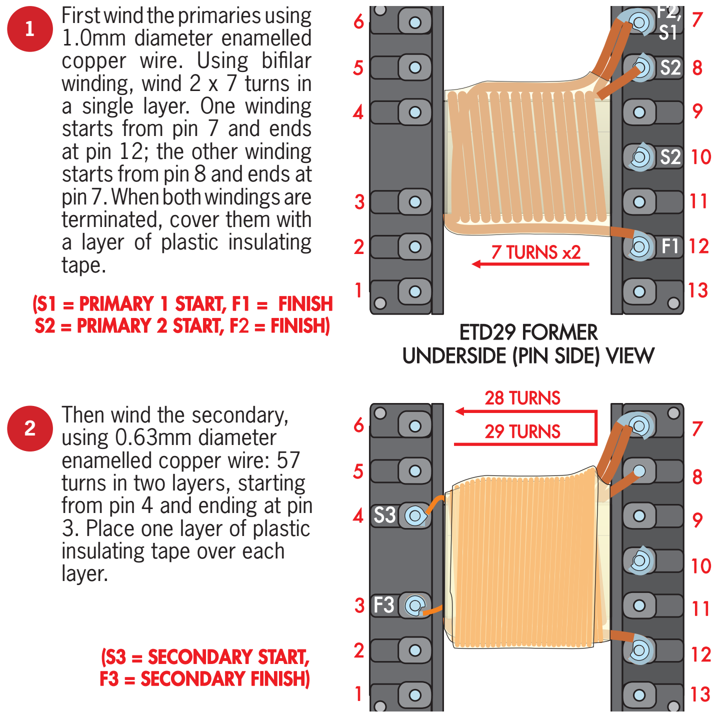
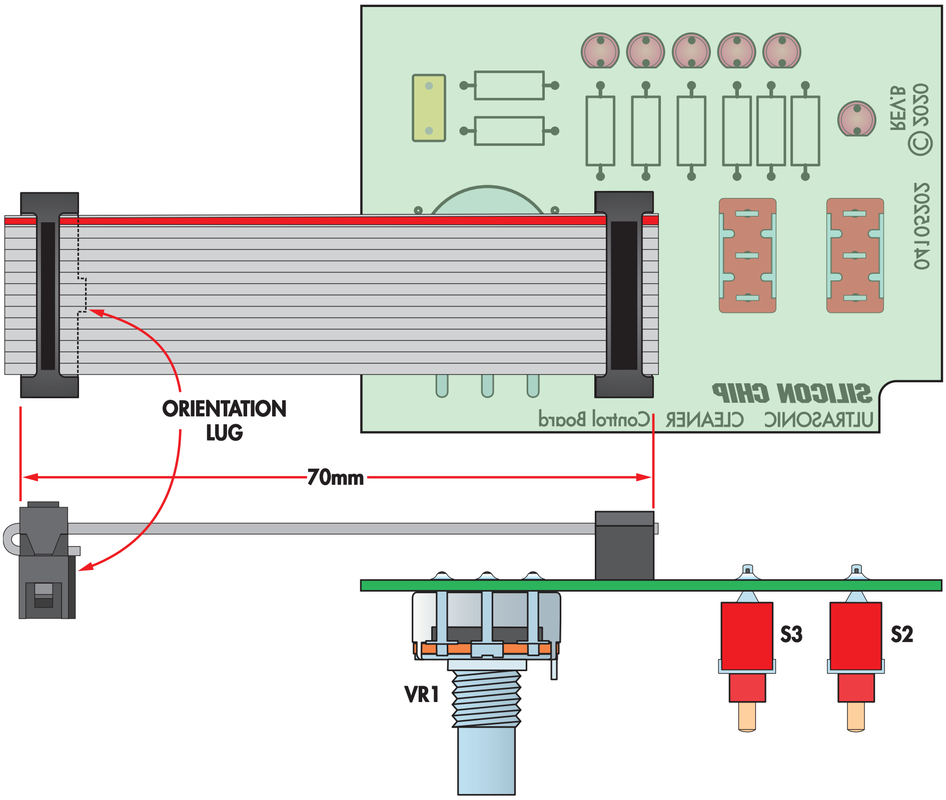


Fig.9: Follow these transformer winding instructions carefully, to make sure that your finished transformer has the correct phasing and turns ratio.

Fig.10: This is how the ribbon cable connects to the front panel board. If CON4 has been fitted correctly to the main board, then it should plug straight in. Note that the 'IDC transition header' used for CON5 on the front panel board is captive, ie, there is no socket. Its pins are soldered directly to the PCB.



insulating washers at these locations. Fig.8 shows how these Mosfets will be mounted, although we aren't attaching them to the case just yet.
Reinsert the PCB and adjust the Mosfets so that they sit flat on the bottom of the case, on the silicone washers. Now solder the leads on the top of the PCB.

Then remove the PCB and solder the leads on the bottom of the PCB as well. Similarly, for Q6, solder the leads on both sides of the PCB.

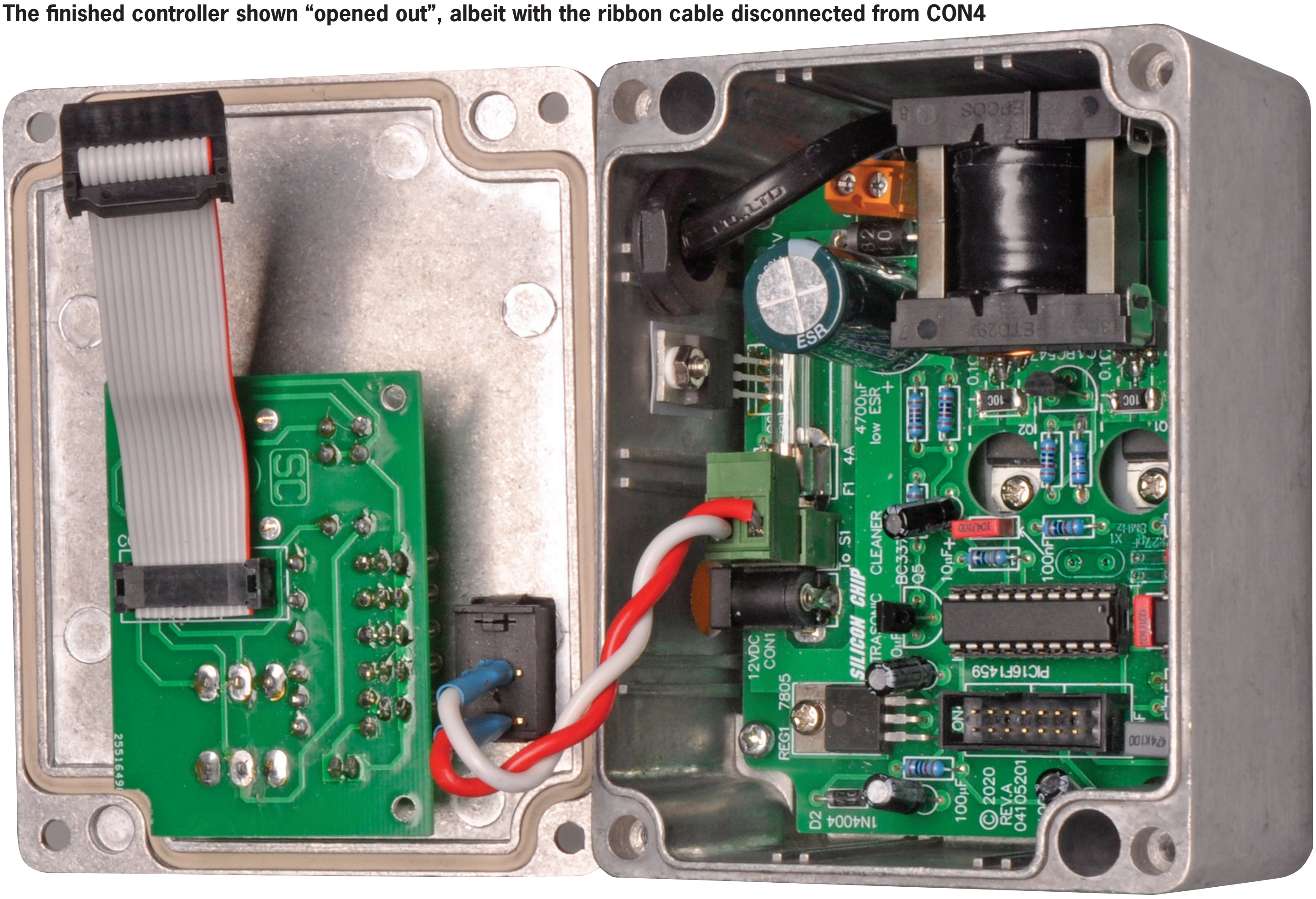
Winding the transformer

Fig.9 shows the transformer winding details. The primary windings are made from 1mm diameter enamelled copper wire (ECW) while the secondary winding uses 0.63mm diameter enamelled copper wire. Start with the primary windings. First, cut two 400mm lengths of the 1mm ECW and remove the enamel from one end of each wire using fine emery paper or a hobby knife.
Tin the wire ends and wrap one wire around pin 7 on the underside of the transformer bobbin, and the other onto pin 8. Solder both close to the bobbin.

Now close-wind seven turns of both wires (side- by-side) until the windings reach the opposite end of the former. The winding direction does not matter as long as both wires are wound together. Cover the windings in a layer of insulation tape. Pass the wires back along the spine of the former. Using a multimeter on the ohms setting, find the wire that's terminated to pin 7 and terminate its other end to pin 12 in the same way as before. The other wire end terminates at pin 7. Cover the windings in a layer of insulation tape.

The secondary winding uses the 0.63mm ECW. Terminate one end to pin 3 and wind on 29 turns (the direction does not matter). Then wrap a layer of

The finished controller shown "opened out", albeit with the ribbon cable disconnected from CON4



insulation tape over this winding and continue winding back over the first layer, in the same direction as before (clockwise or anticlockwise) to complete 57 turns. Terminate this to pin 4.

Once wound, slide the cores into the former and secure with the clips. These clips push on to the core ends and clip into lugs on the side of the bobbin.
It is best not to install the transformer directly onto the PCB just yet. It can be temporarily wired up using some short lengths of 0.7mm diameter tinned copper wire or similar, between pins 3. 4, 7, 8 & 12 of the transformer and the PCB pads for those pins. This is so that it will be easier to change the secondary windings, between pins 2, 4, 7, 8 &12 of the sockets, taking care to orientate them as shown on the overlay diagram.

Front panel control board assembly
There only a few parts left on this PCB, but be careful to mount them on the correct side. Most parts go on the top side, but the 14-way IDC transition header (CON5) goes on the underside. Fit CON5 first, taking care to orientate it with the pin 1 triangle as shown in Fig.7. Solder from the top side of the PCB. Now the IDC cable needs to be attached to this header. Fig.10 shows how the IDC cable is arranged in CON5. The wire can be secured by adding a small piece of soft timber (eg, pine) over the soldered pins on the PCB and another piece of timber on the other side of the PCB, and compress- ing the lot with a G-clamp or bench vice.

The other end of the IDC cable goes to the socket, again taking care to orientate the socket correctly with the locating tab as shown. Compress as before, with protective timber and a G-clamp or bench vice (or use a specialised tool like Altronics T1540). The resistors can also now be installed, if you haven't already. Also insert the five PC stakes from the top side of the PCB for the potentiometer mounting and connections, and fit the 100nF capacitor. The remaining assembly work for this board is done after the enclosure lid has been prepared. Cut the potentiometer shaft so that it is 12mm long from the threaded boss, or to suit the knob used. The front panel label (Fig.11) shows the position of the LEDs, power, start and stop switches and the potentiome- ter on the lid.

Attach the label to the lid, ensuring it is centred correctly. Break off the locating spigot on the potentiometer and mount the potentiometer onto the lid. Place the washer between the pot and lid, with the nut on the outside of the lid. Also attach the switches, with one nut on either side of the lid. Insert the LEDs into their pads from the top side of the PCB, taking care to orientate them all with the longer lead (anode) going into the pads marked "A". Do not solder the LEDs in yet.

Place the PCB onto the switch terminals and solder them in place. Scrape off the coating on the pot body where the two mounting PC stakes are to solder to the pot body (don't inhale the dust).

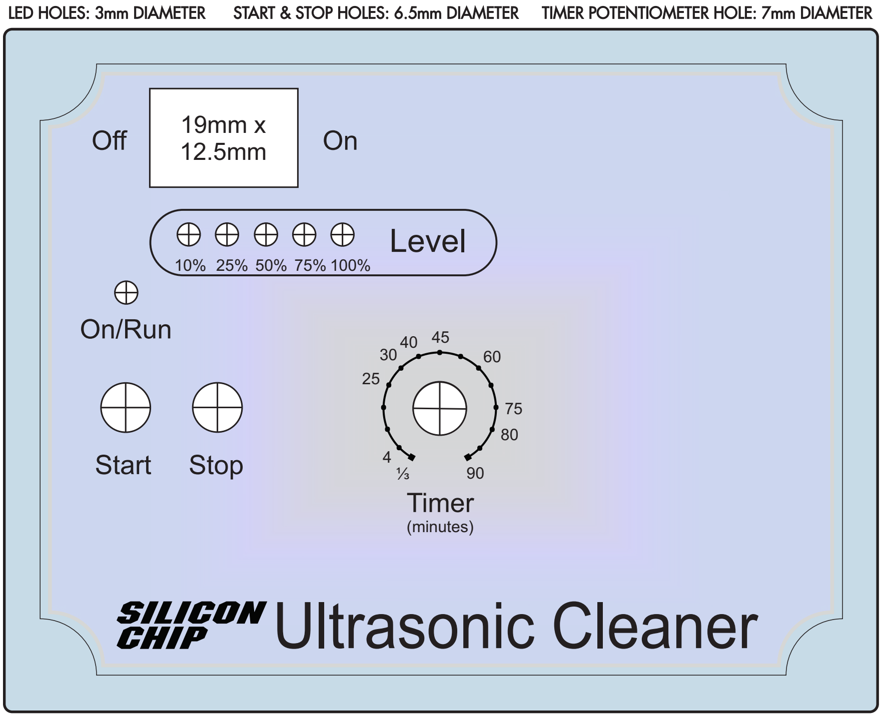


Fig.11: The lid/front panel artwork for the Ultrasonic Cleaner, which also serves as the lid drilling/cutting template.

This allows the solder to wet the pot body for a good solder joint. Solder the PC stakes to the pot terminals after bending the pot terminals over to meet the PC stakes.The LEDs can now be pushed up into the holes on the lid and soldered in place, then trimmed. The PCB is held in position by the switches and potenti- ometer. There is no need for extra support. If you absolutely must, you could attach 15mm-long standoffs to the corner holes.

Holes are also required in the base of the enclosure for mounting Mosfets Q1 and Q2. You should have marked the positions earlier; drill these to 3mm. Lightly countersink these holes inside the enclosure, plus the one for Q6 on the side, to prevent the insulating washer from being damaged by a rough hole edge.

Also lightly countersink the holes for Q1 and Q2 on the outside of the enclosure. This is so these Mosfets can be mounted temporarily on the outside of the enclosure for testing purposes. This way, you will have better access to the PCB for testing and fixing any problems without having to remove it from the box. Fit the four M3 x 9mm standoffs to the underside of the PCB using 6mm screws, then attach Mosfets Q1 and Q2 us- ing silicone washers, insulating bushes and M3 screws and nuts as shown in Fig.8.

Check that the metal tabs are isolated from the case using a multimeter on a high ohms setting. A reading in the megohm region means that isolation is good. Lower readings indicate a shorted connection to the case. Wire switch S1 to the board using 5A- rated hookup wire, with heatshrink tubing over the soldered terminations. Once the other ends of the wires are secure in the screw terminals for CON2, plug it into the CON2 socket.

Preparing the ultrasonic transducer

The wiring can be soldered to the transducer terminals; 0.75mm2 figure-8 wire or sheathed dual cable is suitable. The terminals on the transducer are exposed and need to be protected within a housing to prevent accidental contact as they are a shock hazard.

The 100V AC can cause a nasty shock, but only if both contacts are touched. Touching one contact or the front face of the transducer will not cause a shock since the transformer output is floating from the main circuit. Don't rely on this to protect you, though!

A suitable housing can be made using 50mm PVC DWV (Drain, Waste and Vent) fittings. We used an end cap and a screw thread adaptor (with the screw thread section cut off) to extend the length of the end cap to an overall outside length of 50mm. You could use the end cap and a short length of 50mm pipe instead of the adaptor.

Wire entry is via a cable gland that is secured in the side of the end cap. Place the cable gland hole in the side of the end cap, allowing sufficient room for the nut inside. The adaptor or pipe will require an area removed with a file

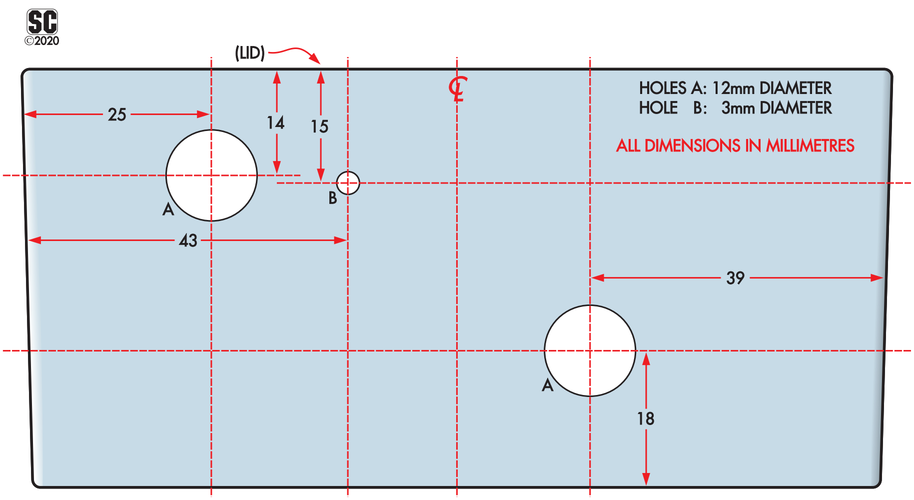


Fig.12: Only three holes need to be drilled in the side of the case, two 12mm and one 3mm in diameter. The 3mm hole is for mounting the tab of Mosfet Q6, while the others are for the DC socket and transducer cable gland.

Here's the transducer (left) and mounted inside our "plumber's special" DWV PVC "case". This photo was taken before we secured the transducer to the "case" with neutral-cure silicone sealant.

Here's the transducer glued to the cleaning bath (in this case a stainless steel cooking tray). We used J-B Weld, a two-part epoxy which we find works better than any other.

so that it clears the gland nut when inserted into the end cap. The terminals on the transducer will need to be bent over at their ends to fit into the housing. The transducer should be mounted within the enclosure using neutral-cure silicone sealant (such as roof and gutter sealant). Use just sufficient silicone to secure the transducer to the inside of the housing, around the outside of the lower bell-shaped section. Fully potting it in silicone will dampen the ultrasonic movements a little.

The face of the transducer should be kept clear of the sealant. This is so that the transducer can be secured to the outside of the bath with an epoxy resin. Connect the ultrasonic driver cable to the PCB at CON3. Make sure there are no strands of copper wire emerging from the terminals which could short out. The other ends of this cable connect to the ultrasonic transducer.

Testing

Before testing, insert the 3AG fuse into the clips if you haven't already done so. If you're powering the unit from a battery, or your power supply doesn't already have a DC barrel plug to match the socket on the Cleaner, attach the plug to the end of the power supply wires. When ready, apply power to the circuit and check the main 5V supply between pins 20 and 1 of IC1 and between pins 4 and 8 for IC2. You should get a reading of 4.75-5.25V across these pins. When first powered up and after the Start switch is pressed, the Ultrasonic Cleaner will run the calibration for the transducer. While you can do that now, as long as the transducer is attached, the calibration will be incorrect.

This is because the impedance of the transducer differs between when unloaded and loaded. When loaded (by attaching to the bath with fluid), the impedance is higher, so if you run it now, it will need to be re-calibrated later. The procedure to do that is described in the Calibration section below.
Once calibrated, the power level will be shown, and the power LED will light once the transducer is being powered at the set level. If no transducer is connected, the power LED will go out momentarily and one or two level LED(s) will light. Then the level LED or LEDs will extinguish, and the power LED will relight. No calibration will occur.

To properly test the board, you need to have the transducer at least temporarily attached to a suitable vessel, filled with a liquid such as water. That's because you need to check that the transformer is supplying the right voltage to achieve full power. Your transducer could differ from the one we have used, either by being a different type or just coming from a different batch.

Diagnostics

We have included a diagnostic display for the power level so that you can check whether your transducer is delivering full power. With the unit powered up and the transducer connected and attached to a bath, set the power level to 100%. The display will indicate if the transducer can or cannot deliver full power. If it can, the 100% LED will stay lit.

If the transducer cannot deliver that power level, the power will begin to reduce automatically until it shows what can actually be produced by the transducer. If this happens to you, you may be able to achieve full power by removing water from the bath. However, this may leave you with insufficient water for practical cleaning. If you decide to lower the water level, make sure to re-run the calibration procedure (see below) before testing for full power again.

The alternative to reducing the water level is to add more turns on the secondary of transformer T1. This will increase the transducer drive voltage to allow the extra power to be delivered. The number of turns needing to be added can be determined on a trial-and-error basis.

Once full power is possible, the transducer may not be able to be driven at the very low power levels. This can be determined by setting the level to the lowest setting. If this low power is not possible, the level display will increase by itself to a higher level, indicating the lowest power level available. Note that the over-current indication (the left, middle and right level LEDs flashing simultaneously) may show instead. If so, that suggests you have too many turns on the transformer secondary (see the troubleshooting section). The lowest power level available will depend on the steepness of the transducer's power/frequency curve.

This is a measure of how sharply the power drops away when off-resonance. Steep sides on the power/frequency curve for the transducer will mean that it can be driven at the lowest power. In contrast, other transducers with shallower curves might only be able to be operated one level above the minimum (ie, 20% rather than 10%).

Finalising construction
Once you are happy with the available power range, detach the PCB from the case. Transformer T1 can now be permanently installed on the PCB, rather than via short lengths of connecting wire. Before fitting the PCB in the box, disconnect the ultra- sonic driver cable (making sure that the power is off!), then feed its cable through the cable gland, the hole in the enclosure and the gland securing nut, then re-connect it to CON3. Make sure there are no strands of copper wire emerging from the terminals which could short out.

The three Mosfets are attached to the inside of the en- closure using the silicone washers and insulating bushes, M3 screws and nuts. Refer to Fig.8 (the same as before, but this time on the inside). Once again, check that the metal tabs are isolated from the case using a multimeter set for reading ohms, using the same procedure as before.

The PCB is secured to the enclosure using the two supplied screws. Insert the supplied Neoprene seal in the lid channel and cut it to length before attaching the lid using the screws provided. Finally, stick the four rubber feet to the base.

Calibration
As mentioned earlier, calibration happens automatically the first time you press the Start switch. To re-calibrate the unit, hold down the Stop switch, press the Start switch and then release both. This should be done while the transducer is loaded, ie, attached it to the fluid-filled bat. Running the transducer unloaded will cause a large current flow to the transducer due to its lower impedance. While the circuit prevents excessive current by switching off, it is still a good practice to avoid driving the transducer except when under load. During calibration, the resonance of the transducer will be found and stored in non-volatile flash memory. This means that the unit doesn't have to find the resonance frequency each time the Cleaner is used.

At the beginning of the calibration procedure, all five level LEDs will light, and then they will switch off. See the troubleshooting section if you are experiencing problems with the calibration.

Using the timer
When cleaning parts, set the timer for the maximum duration you want. The time can be changed while the Cleaner is running, and it will use the new time, providing that it is longer than what has already transpired. Setting to a time setting to less than what has already transpired will cause it to stop immediately, as will pressing the Stop button.

Troubleshooting
If you are having difficulty achieving calibration, you can run a more comprehensive diagnostics routine that will provide more information.
This is initiated by switching the power off, waiting 10 seconds, then pressing and holding the Start and Stop switches together while switching on the power. The diagnostics routine will start, as indicated by all five level LEDs lighting up. In this mode, the frequency to the ultrasonic transducer can be manually adjusted using the timer potentiometer (VR1). The frequency is 40kHz when the timer pot is set midway and can be varied from 37.6kHz to 42.4kHz by rotating VR1.

Further frequency changes can be made by setting the pot either fully anticlockwise or fully clockwise and pressing the Start switch. When holding the pot fully anticlockwise and pressing the Start switch, the frequency will drop by about 540Hz so that overall adjustment range is 540Hz lower, ie, 37.06-41.86kHz rather than 37.6-42.4kHz.

You can reduce this further in 540Hz steps to a minimum of 34.88kHz with the pot fully anticlockwise, by pressing the Start switch repeatedly with VR1 at its fully anticlockwise position. Similarly, the frequency range can be increased in 540Hz steps by holding the pot fully clockwise and pressing the Start switch. The maximum frequency can be increased up to 45.45kHz by doing this repeatedly.

You can monitor the drive frequency by connecting a frequency counter or meter at TP2. You can monitor the current draw with a voltmeter at TP1. You don't really need to know the frequency, so if you don't have the means to measure this, it is not critical. The most critical measurement is the current readings at TP1. Adjust VR1 to find the resonance point, where the current is at a maximum.

For the transducer to be able to deliver full power, the current measurement at TP1 needs to be 4.2V just below or above resonance. 4.2V equates to 300mV across the 0.1Ω resistors, so a 3A current. With a 12V supply, this represents a 36W power delivery.
If there is a current overload and the voltage at TP1 goes above 4.8V, the transducer drive will be cut off. This is to limit power applied to the transducer to a safe level. Overload is indicated by the outside and centre LEDs on the level display lighting. The drive is restored momentarily every

two seconds to check the current. Adjust the potentiometer to restore continuous drive. You can also press the Stop switch to switch off the transducer. To resume, you need to switch off the power and re-enter the diagnostics routine as described above.
As mentioned previously, if when at the resonance there is an insufficient voltage at TP1, then you will need more secondary turns on the transformer (or take water out). The correct number of turns or amount of water is when the TP1 voltage is close to 4.5V at resonance. This allows some leeway in frequency control to achieve 4.2V is at TP1, for 36W into the transducer when slightly off-resonance.
If the TP1 voltage when approaching resonance is too high (ie, above 4.5V), reduce the number of secondary turns or use more water in the bath.

Conclusion

To summarise, through these instructions not only have we shown how the ultrasonic cleaner works, we have also presented how to construct the kit, the PCB assembly steps, wiring it up, encapsulating the transducer, case preparation and final assembly. We have also described the testing and calibration procedures. We hope you enjoy building and effectively using the Ultrasonic Cleaner.

Important Note:
Please note that we can offer a warranty only on the components supplied with this kit. Because we are unable to guarantee your labour, there is no warranty on either partially or fully built kits. We are able to offer a repair service, but once construction has commenced, this service is chargeable.

Dear Kit Constructor,
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