WANT TO "PROBE" A VEHICLE'S EHT?

You'll need this

1000:1 AC EHT Probe for Ignition Systems

by Dr Hugo Holden

It's surprisingly tough to measure the actual output voltage of an automotive (or aircraft/boat) ignition system. You can't use a standard high-voltage probe because the voltages involved are way too high; they can exceed 50kV! Nor can you use a standard EHT probe because these are designed for DC use and will severely distort a fast-rising (or falling) AC waveform. This simple design is the answer.

Peak voltages from the ignition coil secondary windings are typically in the range of 10-30kV but can be higher – and can exceed 50kV in some circumstances.

These high voltages occur for a very brief time across a spark plug's terminals before spark ionisation, or under any test condition when the spark plug is not connected.

This 'open-circuit' coil secondary voltage value is an important ignition system parameter.

The rate that the voltage increases with time is another important parameter. A fast rise time to the spark ionisation voltage is thought to be beneficial in overcoming the ohmic resistance of fouled spark plugs, because less energy is dissipated due to a shorter time interval before spark ionisation.

Also, a certain voltage threshold is always required to initiate spark ionisation (the spark's early phase, known as phase one).

This voltage depends on the spark plug's gap and the composition of the gases and the gas pressure and temperature between the gap.

However, during the spark's burn time (phase two), the spark plasma has a low impedance, and the spark gap voltage is relatively low – just 30V with some aviation spark plugs and around 1000V for a typical automotive spark plug.

By comparison, in free air (ie, outside the cylinder and not under pressure, a typical automotive spark plug has a gap voltage of around 600V.

To measure the high initial pre-spark ionisation peak voltage or the open-circuit output voltage of the spark generating system, you need a special probe with a flat frequency response also having the ability to avoid corona discharge, which is a big problem with potentials over 30kV.

Making the measurement

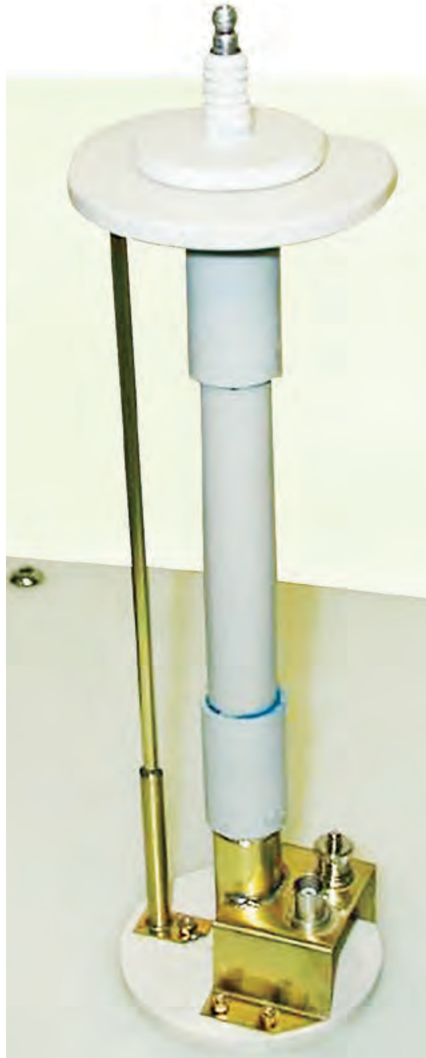
Ideally, we want to use an oscilloscope to capture these spark events. So we need to scale down the typical 30kV open-circuit voltage down to say 30V (ie, dividing it by a factor of 1000) and feed it into the typical 1MΩ//15pF input impedance of a scope. This needs to be done while maintaining a broad frequency response, so that the recorded waveform maintains its original shape.

We also need to make sure that the oscilloscope (and user!) is not at risk of damage from these high voltages.

While inexpensive high-voltage or "EHT Probes" are generally available (eg, to measure CRT anode voltages), they are meant for measuring static DC voltages. We published a design to build a low-cost EHT probe in the April 2010 issue (siliconchip.com.au/Article/121). That design is capable of measuring up to about 25kV.

But this type of EHT probe gives very low false readings on fast rise-time waveforms; the rise times of ignition system secondaries are in the microsecond range, and the high-order Fourier components can be in the 100kHz to 1MHz range.

High-voltage compensated probes which can handle 40kV are available, but they are hard to find and expensive. Also, on some common ignition system tests, they could be pushed



passed their maximum ratings. Worse, the probe tips do not easily interface with insulated spark plug connectors, which are the best way to link up circuits running at these high voltages.

Also, the probe needs to have a total load resistance of at least 50MΩ, so there is little loading of the system being tested. This equates to 1kΩ/V for a 50kV test. A 200MΩ load is feasible, yielding 4000Ω/V, however, the higher the resistance, the more low-pass filtering effects occur due to distributed capacitance. High-frequency compensation, therefore, becomes a little more difficult.

A high series resistance value leads to a low-pass filter effect, because even just 1pF of stray capacitance results in a significant low-pass filter being formed. For example, with 100MΩ and 1pF, the filter created roll-off (-3dB) point is only 1.6KHz.

My probe design

Fig.1 and the photo at left show my probe design. I'm using a spark plug as a feed-in element, by trimming the metal part away. Bramite (similar to Garolite) was used as insulating material along with PVC tubing, and parts of the assembly are glued with Torr Seal from Varian Vacuum Technologies (a white epoxy resin which is also

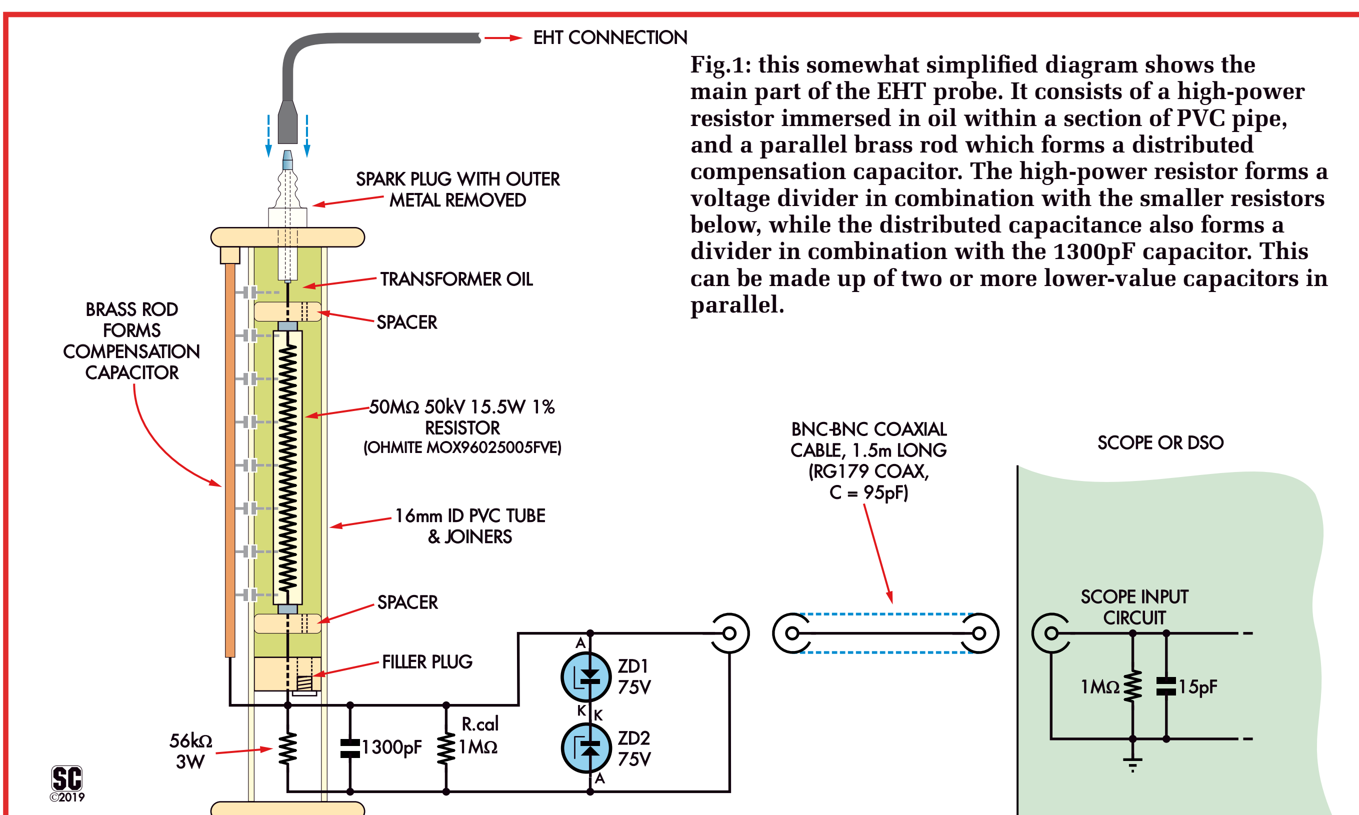


Fig.1: this somewhat simplified diagram shows the main part of the EHT probe. It consists of a high-power resistor immersed in oil within a section of PVC pipe, and a parallel brass rod which forms a distributed compensation capacitor. The high-power resistor forms a voltage divider in combination with the smaller resistors below, while the distributed capacitance also forms a divider in combination with the 1300pF capacitor. This can be made up of two or more lower-value capacitors in parallel.

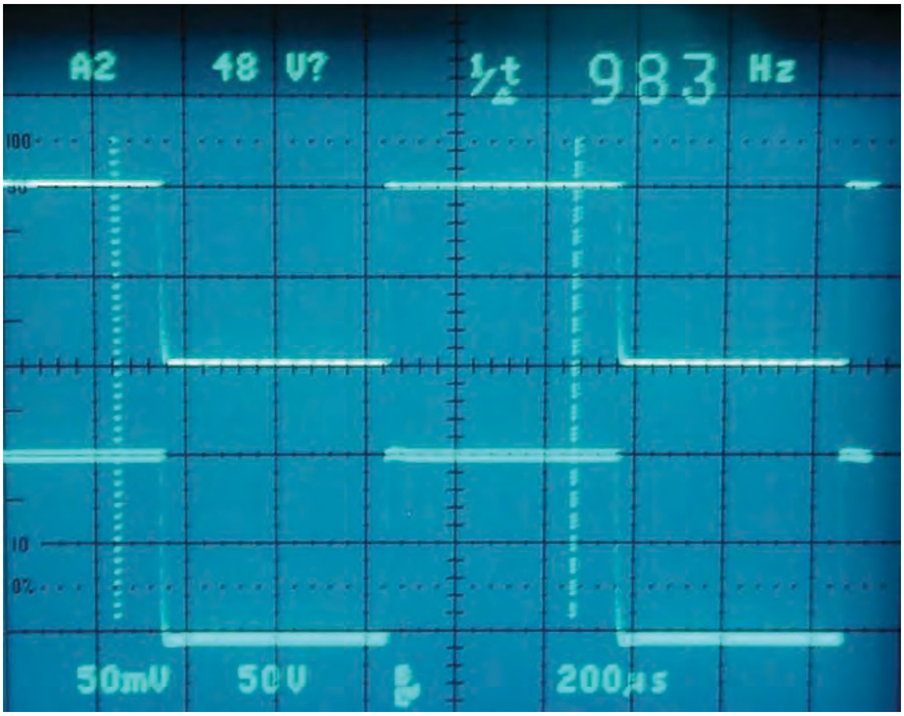


Fig.2: the upper trace shows the 100V peak-to-peak square wave I'm applying to my prototype while the lower trace shows the resulting 100mV peak-to-peak waveform at the output. You can see from its shape, with no apparent undershoot or overshoot, that the probe is correctly compensated.

an excellent insulator).

The input capacitance of the probe is a little lower, at about 2pF, compared to a spark plug which is typically around 8-10pF. The typical output capacitance of an automotive ignition coil is around 50pF, and the HT wiring contributes another 10pF or thereabouts.

As shown in the diagram and the photo, the main body of the probe is made from PVC pipe. This is filled with oil and houses the 50kV resistor. Without the dielectric oil, the corona discharge becomes very difficult at peak voltages over 30kV. The oil solves this problem.

The main compensation capacitor is a brass rod which runs alongside this oil-filled tube, acting as a high-frequency coupling capacitor distributed along the length of the resistor by proximity.

It's connected directly to the low-voltage end of the 50kV resistor and supported by the upper insulating plate.

It must be mounted parallel with the 50kV resistor and centred 30mm from the middle of the PVC pipe for correct operation. That means there will be around 18mm from the edge of the rod to the edge of the pipe, depending on the exact outer diameter of the pipe.

This dimension is critical for correct operation.

There are effectively three resistors in parallel at the bottom of the divider: 56kΩ, 1MΩ and the 1MΩ input impedance of the scope. These combine with the 50MΩ resistor to provide the 1000:1 division ratio at DC and low frequencies.

At higher frequencies, the compensation capacitor and 1300pF of capacitance form a capacitive voltage divider with a similar ratio, in parallel with the resistive divider.

The 75V zener diodes were added just in case any corona discharge occurs accidentally, which could harm the oscilloscope input amplifiers.

Construction

Start by using a 16mm hole saw to cut two round pieces of Bramite. Place the Bramite sheet on a sheet of scrap timber which is firmly supported at either end, so that you drill won't go into anything critical while doing this. The resistor leads can pass through the central guide holes.

Cut three larger discs from the Bramite using much larger hole saws; one around 22mm in diameter, one around 44mm and one around 64mm. (Tip: you can buy a hole saw set which will have most of the required sizes).

Enlarge the central holes in the 22mm and 44mm discs so that the body of the spark plug will fit through both.

Now make a hole in the middle of one of the PVC end caps for the spark plug body to pass through, plus a small hole in the other end cap for the resistor lead, as well as a larger one, to suit the filler plug.

Use the end cap with two holes as a template to trace them out in the middle of the brass sheet, which will later be bent into a bracket and attached to this end cap.

Glue the 22mm and 44mm discs together, and glue the PVC endcap to the bottom of the 44mm disc. Now place one of the spacer discs over one of the resistor leads and feed this lead up through the PVC endcap and two round plates. Cut this lead short, then solder it to the tip of the spark plug.

Next, pull the resistor back down so that the spark plug is reaching down inside the PVC endcap and seal around the spark plug using the Torr Seal epoxy, so that it is oil-tight.

Spread some epoxy all around the edge of the spacer and then slide the PVC pipe over the resistor. Spread a generous amount of epoxy around the end of the pipe, then push it into the end cap firmly. Allow the epoxy to set, with the pipe' right-way-up' so that the upper spacer is resting on top of the resistor body.

Place the second spacer over the remaining resistor lead, spread some epoxy all around its edge and push it up into the pipe as far as it will go. Make sure that the resistor is fully wedged between the two spacers so

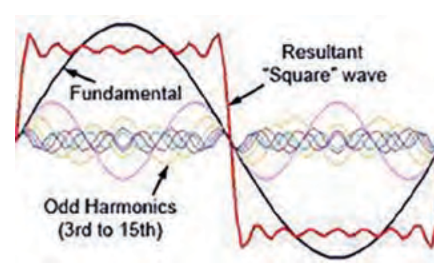


Fig.3: Fourier theory says that a square wave can be formed from an infinite number of sinewaves with different amplitudes and phases. The higher-frequency sinewave components have lower and lower amplitudes as the frequency increases. This means that you can tell whether the frequency response of a device is flat by feeding a square wave into its input and looking at the resulting shape at the output.

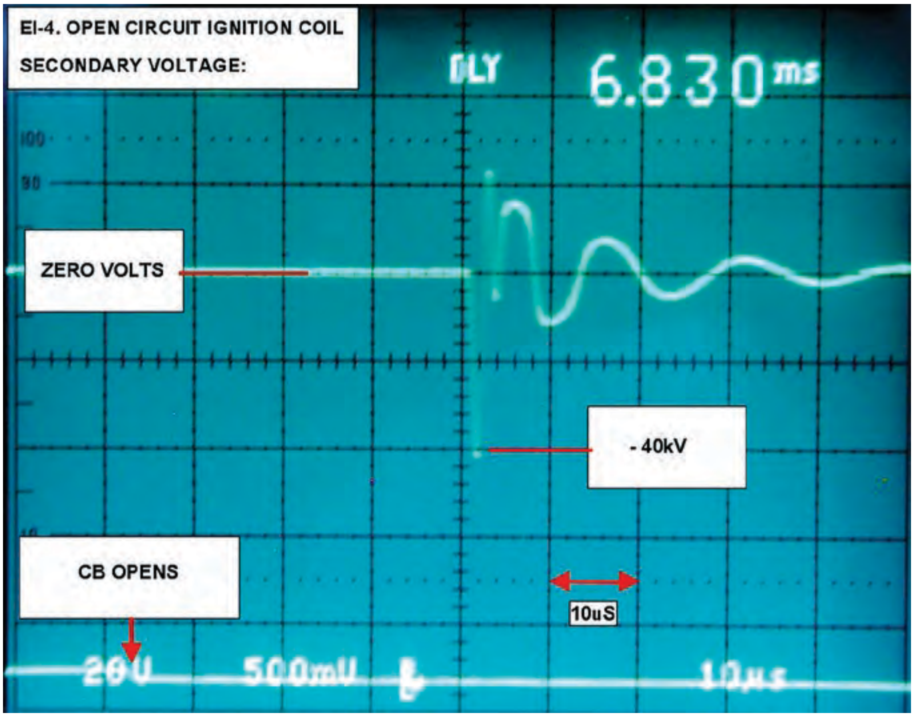


Fig.5: the output voltage of an unloaded ignition coil being driven by a Tung-Sol EI-4 capacitor-discharge ignition (CDI) system, captured using the probe described here. No sparks or corona discharges are occurring, resulting in an extremely high peak voltage of -40kV, which matches well to the expected peak of 39.6kV as determined by the coil turns ratio and primary voltage. After the initial discharge, the residual coil magnetic field energy and energy stored in the coil's distributed capacity decays away in an oscillatory manner, due to the self-resonance of the ignition coil.

it won't move later.

It's also a good idea to push some epoxy into the hole surrounding the resistor lead, if you can get in there.

Up-end the whole assembly, resting it on two equally tall objects on either side, so that it sits vertically, until the epoxy on the second spacer has set.

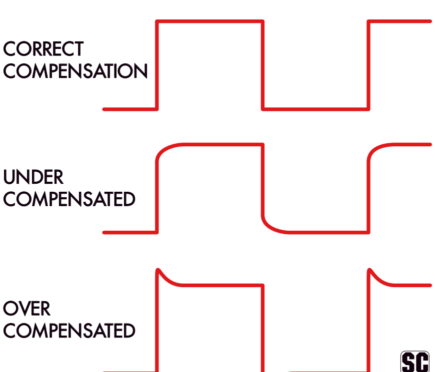


Fig.4: compare your calibration waveform to the three shapes shown here. If it looks nice and square, like the one at the top, you're finished. If it's rounded (under-compensated), reduce the value of the 1300pF capacitor. If it has overshoot (over-compensated), increase the value of that capacitor (eg, by adding a low-value ceramic capacitor in parallel).

Bend the remaining resistor lead so that it will pass through the small hole in the end cap that you drilled earlier, once the end cap is fitted onto the end of the pipe. It should be long enough to reach through the cap; if not, extend it by soldering on some stiff wire. Glue on the end cap using more epoxy, and also seal around the wire exit.

Now is also a good time to coat the inside of the hole you made for the bung with epoxy and press it in. Make sure it will be oil-tight when the epoxy sets.

Now up-end the assembly, again resting it on a couple of blocks and let the epoxy set. The next step is to pour a little transformer oil into the oil filler hole. Wait a few minutes and check that you don't have any oil leaking out anywhere. If you do, you will need to drain it, clean it up and apply some more epoxy to seal the leak areas. Then try filling it with oil again.

If it looks good, add a bit more oil, then a bit more, then start pouring it in slowly until the pipe is almost full of oil. Wait a while for any air bubbles to surface, then add a little oil until it's just about full. Leave a small air bubble inside to allow for thermal expansion.

Screw the plug into the bung to seal it up and clean up any oil that squirts out around the edges. Do it up tight so it won't accidentally come loose; that could be messy! It's a good idea to silicone around and over the bung as insurance against oil leaking out.

By the way, if you can't get a proper oil filler bung, you could consider drilling and tapping the end cap to accept a regular screw thread, but if you're going to take that approach, it may be necessary to thicken the end cap material by gluing one or more PVC discs inside it, to give enough 'meat' for the screw to form a good seal.

Final assembly

Drill the holes you marked earlier in the brass sheet and bend it to form a bracket to support the PVC pipe (see photo). Also, drill a hole to fit the BNC socket next to the pipe. Make sure the resistor wire end exiting the pipe won't touch this, as the bracket will be Earthed.

I glued a 50mm wide sheet of brass foil around the bottom of the tube so that I could solder it to the bracket; however, you could also use a section of large diameter brass tube or come up with some other arrangement to attach the bottom of the tube to the supporting bracket.

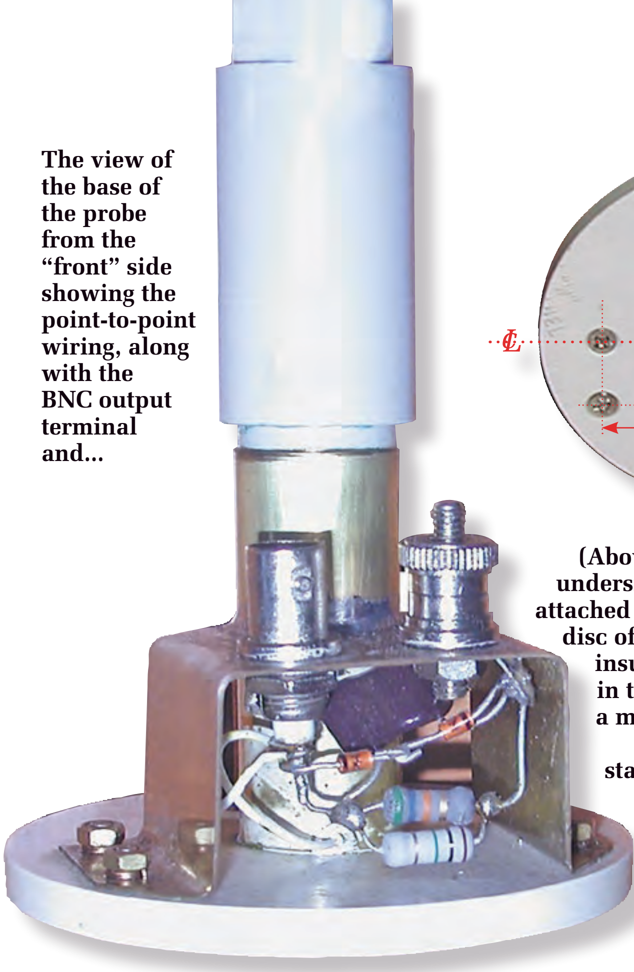
Once it has been secured, bend the projecting resistor lead over (making sure it isn't contacting any of the metalwork), trim it and solder it to the central pin of the BNC socket. If you've used brass foil or a brass tube at the base of the PVC pipe, as I did, you will need to solder an insulated wire to the resistor lead instead and feed it through a hole in the supporting tube, then seal it up.

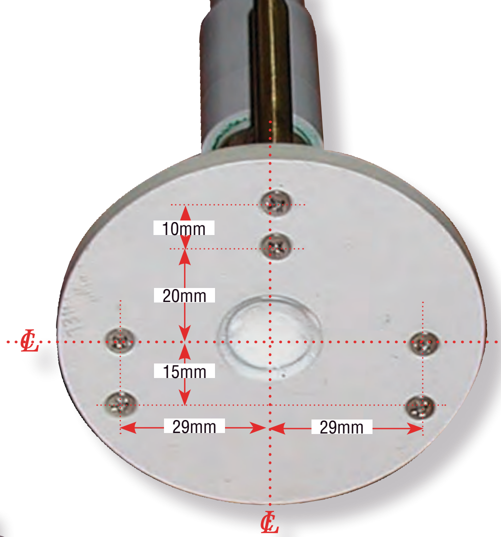
Now solder the few other electronic components between the BNC ground tab and the end of the power resistor lead, with the zener diodes wired back-to-back across them. See the accompanying photo, which shows how I arranged the components.

Try to leave the 1MΩ resistor and 100pF capacitor accessible, as you may need to replace these with different components during calibration.

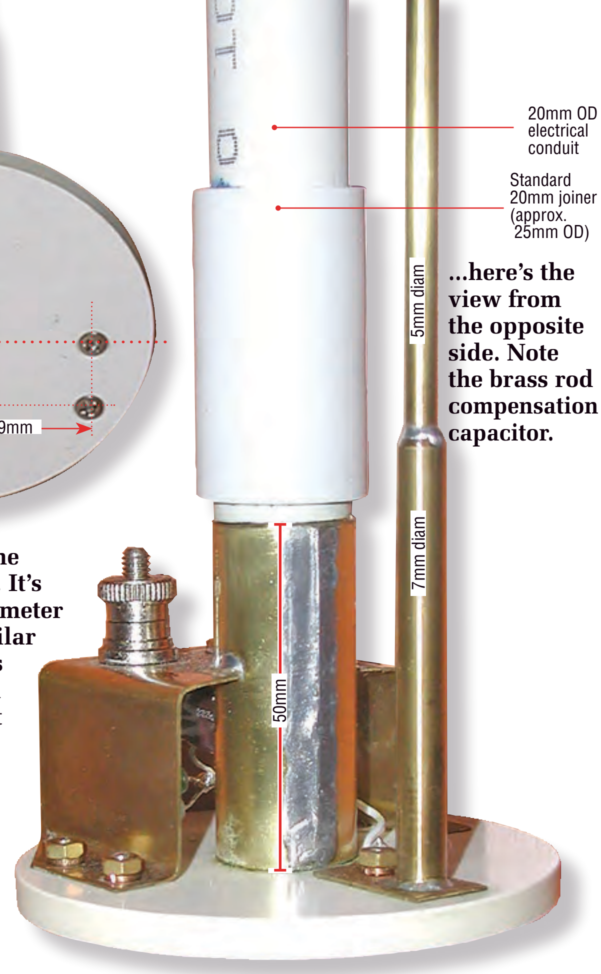
Now cut the brass rod so that it's just a bit too long to fit between the top and bottom plates. As you can see from the photo, I made a bracket from a small brass plate and some brass tubing. This had the advantage of both holding the rod in place and

The view of the base of the probe from the "front" side showing the point-to-point wiring, along with the BNC output terminal and...





(Above): looking at the underside of the probe. It's attached to an 80mm diameter disc of Bramite or similar insulation, which is in turn mounted on a much larger sheet for working stability. All holes should be countersunk.



...here's the view from the opposite side. Note the brass rod compensation capacitor.

also providing a convenient place to make the electrical connection.

However you do it, make sure the rod is fixed in place and parallel with the PVC pipe, with the dimensions described above - the critical one being the 30mm from the centre of the PVC pipe/resistor to the centre of the brass rod.

I held the top of the brass rod in place by inserting it into a blind (shallow) hole drilled in the inside face of the top plate. I soldered the 5mm rod to a length of 7mm diameter rod, to make it easier to tap the bottom of the rod for an M3 screw to make the electrical connection. I then soldered this 7mm rod to the bracket, as shown in the photos. But there are other ways of doing this.

Regardless, you will need to run a wire from the bottom of the rod to the bottom lead of the resistor in the PVC pipe and solder or clamp it at both ends.

Calibration

You should find that your probe provides very close to a 1000:1 division ratio when connected to a device with a 1MΩ input impedance. Note that many DMMs have a higher input impedance than this, at least when measuring volts. If you want to use a DMM for calibration and it has a 10MΩ input impedance, clip a 1.1MΩ resistor across the DMM's leads for the tests.

For the first test, use a relatively high voltage DC source such as a 48V supply or a bench supply wound up to maximum.

Measure the voltage across the supply outputs using your DMM and write it down, then connect the probe tip to the + supply and the output ground to the – supply. Measure the voltage at the BNC cable tip, keeping in mind the above comments about input impedance.

You should get very close to 1/1000th of the voltage. For example, if your test supply measures 48.4V, you should get 48.4mV at the probe output.

If you get a higher value, you can slightly reduce the value of the 1MΩ resistor in the probe to compensate. Similarly, if its output is low, slightly increase the value of the 1MΩ resistor.

AC calibration is just as, if not more critical than DC calibration. For this, you need a function or pulse generator capable of producing a 1kHz square wave of similar.

Ideally, it should be able to deliver a square wave of around 100V peak-to-peak. I used a Tektronix PG506 calibration generator.

If you only have a low-voltage pulse generator, you should build our Precision Signal Amplifier from the October 2019 issue (siliconchip.com.au/Article/12025). It's a simple and relatively cheap device which can boost the output of a function generator up to about 30V peak-to-peak, just sufficient for this calibration procedure.

The AC calibration is set by the 1300pF (1200pF | | 100pF) capacitor. This forms a divider with the brass rod, which acts as an HF coupling capacitor distributed along the length of the resistor. Fig.2 shows my probe's square wave response with the probe plugged into the input of a Tektronix 2465B scope.

The upper trace is the input voltage which is a near 1kHz, 100V peak-to-peak square wave from the PG506 generator. The lower trace is the output voltage which is close to 100mV peak-to-peak. Without the compensation capacitor network consisting of the brass rod and 1300pF capacitor, the output waveform bears little resemblance to the input waveform and looks more like a sinewave.

I used sinewave testing to determine that the probe has a flat response from DC to over 1.5MHz. The highest frequency of interest in an automotive ignition system is about 300kHz.

But you don't need a sinewave sweep to check the frequency response; a single square wave test will do the job much more easily and quickly.

According to the Fourier theorem, a square wave or rectangular wave is composed of a fundamental frequency and a plethora of harmonic frequencies, the higher-order ones being responsible for the rapid rise on the leading edge of the waveform.

This is shown in the simplified diagram of Fig.3.

Therefore, if a square wave is passed through the system, it is immediately apparent from its shape at the output whether the frequency response across a broad range of frequencies is flat or not.

If the HF response is limited, the fast rising and falling edges are rolled off. If the rising and falling edges are peaked, then the HF response is excessive. If the flat top of the wave has distortions or bends or tilts, then the medium frequency (MF) or LF responses are abnormal.

Most oscilloscopes have a calibration output voltage which is a square wave, so that the compensation capacitor on the 10:1 probe being used can be set for a flat response. The procedure for calibrating this probe is much the same, except that you may need to replace the 100pF capacitor with a higher or lower value to achieve calibration.

Fig.4 shows what square waves look like at the output of a probe which is correctly compensated, under-compensated or over-compensated.

If your square wave looks like the one in the middle, you need to reduce the value of the 100pF capacitor (try removing it entirely first).

If it looks like the one at the bottom, then you need to increase the value of the 100pF capacitor or connect another low-value 100V capacitor in parallel.

As noted in the parts list, it's best to use NP0/C0G ceramic capacitors here as they do not change in value with temperature.

Otherwise, your probe's calibration could be different on cold and hot days. They're also extremely linear for the best possible performance. *SC*

Parts list – 1000:1 AC EHT Ignition Probe

1 spark plug
1 200mm length of 20mm outside diameter PVC conduit
2 PVC end caps to suit conduit
1 450mm x 225mm x 6mm (or similar) sheet of Bramite (#)
1 100 x 50mm sheet of 1mm thick brass plate
1 250mm-long, 5mm diameter brass rod
(***or*** 1 200mm long, 5mm diameter rod and 1 50mm long, 7mm diameter rod)
1 1/8" NPT female bung and matching plug
1 50MΩ 50kV 15.5W 1% resistor (Ohmite MOX96025005FVE) [Digi-key, Mouser]
1 1200pF 100V NP0/C0G ceramic capacitor [eg, Kemet C322C122J1G5TA]
1 100pF 100V NP0/C0G ceramic capacitor [eg, AVX SR151A101JAR]
1 56kΩ 1% 3W resistor [eg, Stackpole RSMF3JT56K0]
1 1MΩ 1% 0.25W resistor
2 75V 1W zener diodes
1 chassis-mount BNC socket
1 1.5m-long RG179 coaxial cable fitted with BNC plugs at each end
Various brass machine screws, washers and nuts
1 tube of Torr Seal epoxy resin
1 one-litre bottle or can of transformer oil

(#) *Bramite is a material used as the backboard in meter boxes. It should be available from electrical wholesalers.*