# AS Electronics Project

# Audio Millivolt Meter

By
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# 1. Aim:

There are many occasions where I need to be able to measure small audio signals from various pieces of equipment and circuits. A millivolt meter would be very handy on these occasions and therefore my project is an Audio Millivolt Meter.

# 2. Specification:

- The input impedance for the meter will be 100KΩ so that it will not affect the circuit to which the meter is being applied.
- The meter will have a four selectable ranges of 10mV, 100mV, 1V and 10V
- The frequency response will be that of the Hi-Fi range, which is 20Hz → 20KHz.
- The power supply will be two PP3s giving arranged to give a split rail supply of ±9V. Using a split rail supply saves having to bias the op-amps.
- The meter will use a moving coil meter for the display
- The meter will be housed in a suitable black plastic box with an aluminium top.
- The meter should be portable so it should be of a suitable size.

# 3. Solution:

I have looked at two articles in electronics magazines (*2, 3*) for distortion meters which feature mV meters, and I have also looked at a millivolt meter circuit in an Op-Amp book (*2*). The designs are all basically the same. They consist of the following stages:

**Figure 1** - Stages of the meter

The four step attenuator at the input of the circuit gives the meter its four ranges of 10mV, 100mV, 1V and 10V. The gain stage amplifies the output signal from the attenuator. This is then amplified again by the meter drive stage. The output drives a full wave rectifier which drives the moving coil meter. Two gain stages are required due to the gain-bandwidth product of the op-amp.

## 3.1 Attenuator Stage:

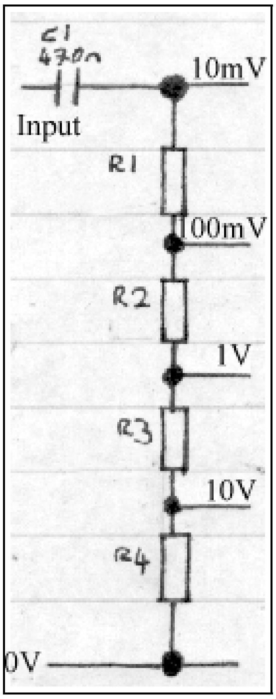


**Figure 2** - Attenuator Stage

The attenuator stage of the meter gives it its ranges of 10mV, 100mV, 1V and 10V. A capacitor is connected in series with the input to stop any D.C. The basic sensitivity of the meter is 10mV, so the attenuator attenuates the input voltage for full scale for each of the range to 10mV. The input impedance of the meter is 100KΩ so:
R1 + R2 + R3 + R4 = 100KΩ
The following calculations show how the value of each resistor is obtained:

**100mV Range:**

$$R1 = \frac{0.090V}{0.100V} = \frac{R1}{R1 + R2 + R3 + R4} = \frac{R1}{100K\Omega} = 0.9$$

$$R1 = 0.9 * 100K = 90K$$

**1V Range:**

$$R2 = \frac{0.990V}{1.000V} = \frac{R1 + R2}{R1 + R2 + R3 + R4} = \frac{R1 + R2}{100K\Omega} = 0.99$$

$$R1 + R2 = 0.99 * 100K\Omega = 99K$$

$$R2 = (R1 + R2) - R1 = 9K$$

**10V Range:**

$$R3 = \frac{9.990V}{10.000V} = \frac{R1 + R2 + R3}{R1 + R2 + R3 + R4} = \frac{R1 + R2 + R3}{100K\Omega} = 0.999$$

$$R1 + R2 + R3 + R4 = 0.999 * 100K\Omega = 999.9K$$

$$R3 = (R1 + R2 + R3) - (R1 + R2) = 900\Omega$$

$$R4 = R1 - R2 - R3 = 100\Omega$$

$$R1 + R2 + R3 + R4 = 100K\Omega$$

Using the results from the above, the following value resistors will be used:

R1 = 90K
R2 = 9K
R3 = 900Ω
R4 = 100Ω

## 3.2 Gain Stage:

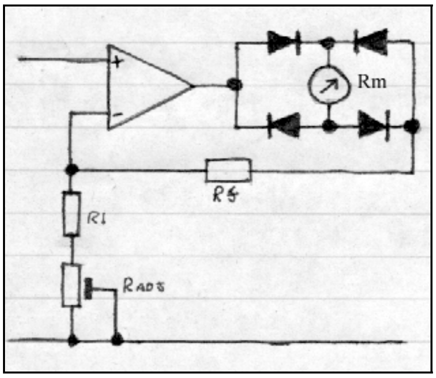


**Figure 3 -** Meter drive circuit

### 3.2.1 Circuit Operation

Figure 3 shows the meter drive circuit. The diodes rectify the A.C output from the op-amp. With no signal at the input to the op-amp, there is no output signal and so the diodes are 'turned off' (i.e. not forward biased). This effectively means that the feedback loop of the op-amp is open circuit and so the op-amp will deliver its full gain of the 10 x $10^{12}$. This is the typical gain for the op-amp that I am using. When an input signal is applied, the output increases very rapidly until it reaches about 0.7V when the diodes are forward biased. The feedback loop is now effectively complete, reducing the gain of the op-amp.

### 3.2.2 Meter Drive Circuit

The output voltage from the attenuator needed for the meter to read full scale is 10mV. The meter has a resistance of 3.75KΩ and needs 100µA to make it read full scale. Therefore, the voltage required to make the meter read full scale is:

$$Vfsd = 3750\Omega * 0.0001A = 0.375V$$

This shows that 375mV is required to make the meter read full scale for 10mV at the output of the attenuator.

The circuit is powered from two 9V PP3 batteries. Allowing for discharge after some use, the supply voltage could be ±8V. I have assumed that the maximum op-amp output swing must be at least 1V less than the supply rails as an op-amp cannot drive the output to the supply rail due to voltage drops across its internal drive circuit. This gives a maximum output swing of ±7V which is 14V pk-pk. 14V ÷ 2 = 7V peak. 7V X 0.7071 = 4.95V rms. On any half cycle only two diodes in the feedback loop will be forward biased and will appear in series with the meter. These two diodes produce a 1.2V offset, so the maximum swing available across the meter is 4.95V - 1.2V = 3.75V rms.

Rf is included to in order to allow for the op-amp to be operated with a reasonably large output swing and to allow for sensibly sized resistors in the gain setting. Since 0.375V is dropped across the meter:

VRf + VRm = 3.375V

3.375V - 0.375V = 3V

This shows that 3V is dropped across Rf.

$$\frac{Rf}{Rm} = \frac{3V}{0.375V}$$

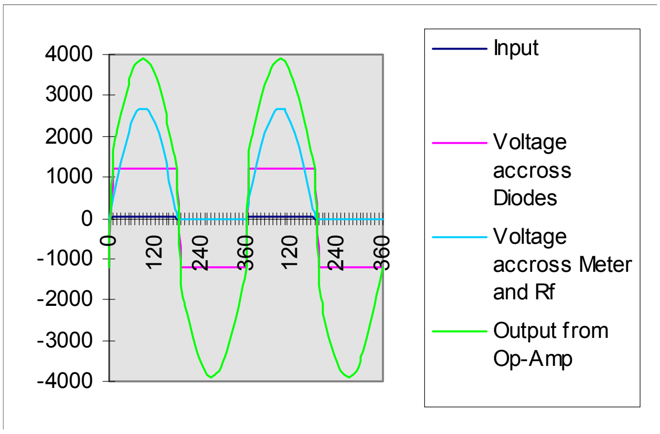


**Figure 4 -** Meter circuit waveforms

$$Rf = \frac{3V}{0.375V} * 3750\Omega = 30K\Omega$$

Rf could be a maximum of 30KΩ but this will make the op-amp's output swing be 1V less than the supply rail and only just cause the meter to read full scale. To make sure that the op-amp is not delivering its full output to just make the meter read full scale a value half way will be used, so making Rf 15KΩ will allow a wide margin.

$$0.375V + \frac{15000\Omega}{3750\Omega} * 0.375V$$

$$= 0.375V + 1.5Vrms$$

$$= 1.875V$$

The calculation on the left shows the output from the op-amp taking into account the 3.75K meter and the 15K feedback resistor. The total AC output voltage is 1.875V.

The basic sensitivity of the meter is 10mV, so the overall gain required to get from 10mV to 1.875V is: $\frac{1.875V}{0.01V} = 187.5$. Two gain stages are required as one gain stage would not give the required bandwidth at that high gain. At least two gain stages are required. I have chosen the gain for the first stage to be 9. So the second stage has a gain of $\frac{187.5}{9} = 20.8 = 21$

A non-inverting configuration is used for both gain stages, also a FET op-amp is used. This presents a large input impedance to the attenuator stage. If an inverting configuration was used, the input resistor would need to be extremely large so as not to shunt the attenuator. Having a large input resistor would mean an unacceptably large feedback resistor would be needed.

In R1' a variable resistor is included to allow for gain adjustment so that the FSD of the meter can be adjusted for calibration.

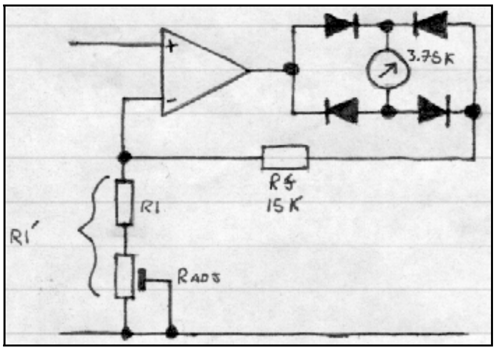


**Figure 5** - Meter Drive Stage

$$Av = 1 + \frac{(Rf + Rm)}{R1'}$$

$$21 = 1 + \frac{18750}{R1'}$$

$$R1' = \frac{18.75}{21} = 937\Omega$$

The values of R1 and RADJ are not critical so long as the total resistance adjustment range spans 937Ω - 680Ω. I have chosen to use a 560Ω variable resistor and a 680Ω resistor.

This gives a gain range of:

$$1 + \frac{18750}{680} = 27.6$$ - Maximum Gain

$$1 + \frac{18750}{1240} = 15.1$$ - Minimum Gain

### 3.2.3 Primary Gain Stage

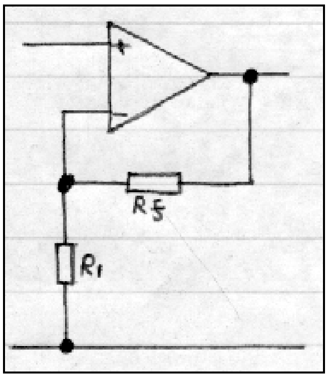


**Figure 6** - Primary Gain Stage

The required gain for this stage is 9. I have chosen Rf to be 47K so:

$$R1 = \frac{Rf}{Av - 1}$$

$$R1 = \frac{47000\Omega}{9 - 1} = 5.8K\Omega \text{ Nearest prefered value is } 5.6K\Omega$$

$$\text{Final Av} = 1 + \frac{47000\Omega}{5600\Omega} = 9.39$$

Rf = 47K
R1 = 5.6K

### 3.2.4 Op-Amps

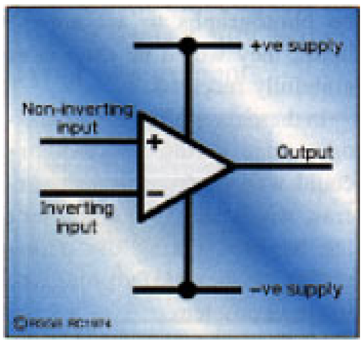


**Figure 7** - Circuit symbol for an Op Amp

An Op Amp is a very close approximation to a perfect amplifier. Ideally, this should have an infinite gain. In reality, those commonly used have gains of 100,00 or more, which is sufficiently close to infinity for most applications. Another characteristic is that, ideally, they should have infinite input impedance. Op Amps in use today come very close to this. Output impedance is also important, and this should be low. In an ideal Op Amp it would be zero.

The bandwidth of an Op Amp can vary quite widely. An ideal Op Amp would have infinite bandwidth, but this would be impossible to create. In reality, Op Amps have a limited bandwidth. Many of the chips used for audio applications may only exhibit their full gain over a relatively small bandwidth, after which the gain drops away.

The amplifier also has two inputs. One is called the *inverting* input and is marked with a '-' sign. The other is the *non-inverting* input and is marked with a '+' sign. This is illustrated in Figure 7. The output of an op amp is proportional to the difference between the inverting and non-inverting inputs, as shown in Figure 8. This is why Op Amps are often called *differential* amplifiers.

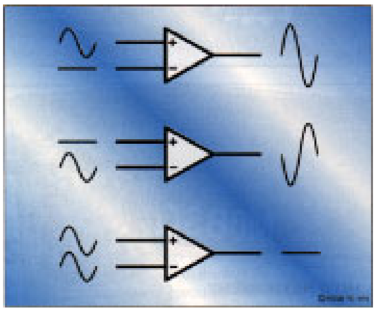


**Figure 8** - Output signal from Op Amp with different configurations of input signal

# 4. The Complete Circuit

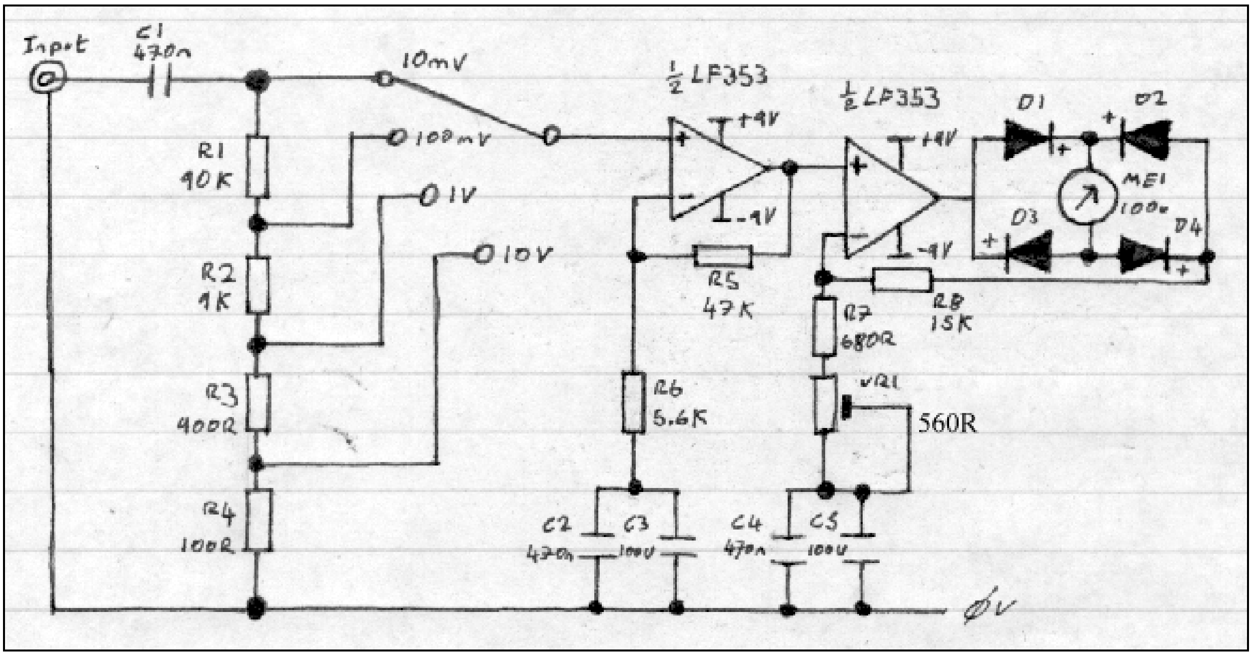


**Figure 9 -** Complete Circuit Diagram

| | | | | | |
|---|---|---|---|---|---|
| **R1** | - | *90K KΩ* | **C1** | - | *470nF* |
| **R2** | - | *9K KΩ* | **C2** | - | *470uF* |
| **R3** | - | *900R* | **C3** | - | *100uF* |
| **R4** | - | *100R* | **C4** | - | *470nF* |
| **R5** | - | *47K KΩ* | **C5** | - | *100uF* |
| **R6** | - | *5.6K KΩ* | **D1-D4** | - | *1N4148* |
| **R7** | - | *680R* | **IC** | - | *LF353* |
| **R8** | - | *15K KΩ* | **ME1** | - | *100uF* |
| **VR1** | - | *560R* | | | |

Figure 9 shows the complete circuit diagram for the mV meter. The left hand side of the diagram is the attenuator, the middle is the primary gain stage and the right hand side is the meter drive stage. The input signal is attenuated to 10mV by the attenuator. This signal is then amplified by the primary gain stage to about 90mV. The meter is driven via a full-wave bridge rectifier, and by including the rectifier in the feedback circuit of the amplifier is made to compensate for the non-linearity of the diodes. The FSD of the meter can be adjusted by adjusting VR1, this enables the unit to be calibrated against a known input voltage. Adjusting VR1 changes the gain of the last stage which resulting in either a larger or smaller voltage being displayed by the meter. Two gain stages are used to keep the required bandwidth whilst achieving the required gain. C2 - C5 have been included to give unity gain at D.C. to prevent any D.C. offset affecting the operation of the circuit.

## 5. Construction

The meter circuit is housed in a black plastic box with an aluminium top. The resistors that make the attenuator can be soldered straight onto the ‘range selection’ switch. I have used one phono socket and two terminal posts (one for the signal the other for ground) for the inputs. These are connected together, so there will be effectively one input. The gain stage is not a big circuit and fits on quite a small piece of veroboard. This is mounted onto two of the fixing screws of the meter by a ‘L’ bracket. The case layout and veroboard layout for the gain stage are shown below :

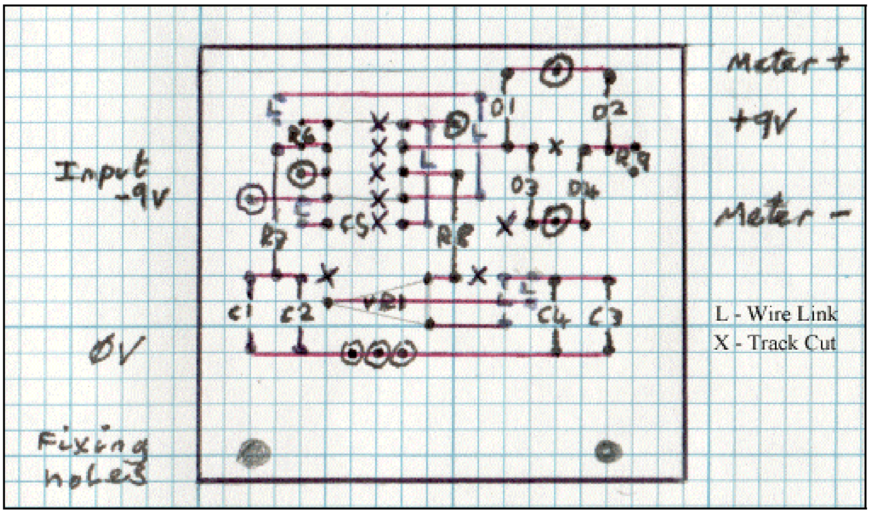


**Figure 11 -** VeroBoard layout for primary gain stage and meter drive stage

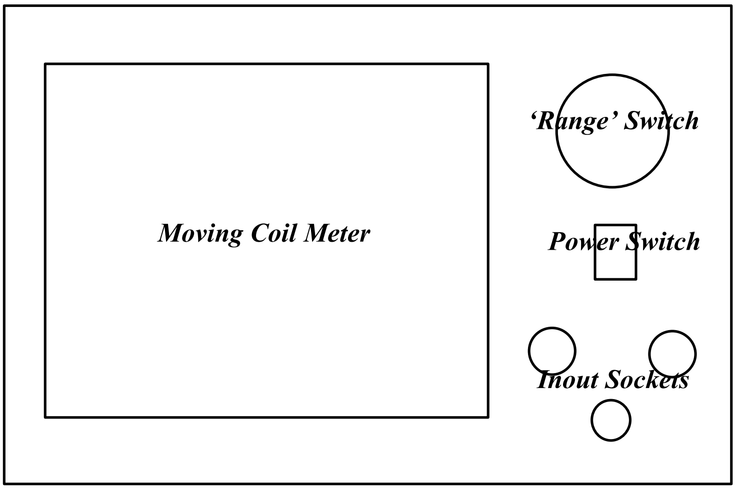


**Figure 10 -** Case Layout (To Scale)

# 6. Testing

## 6.1 Attenuator:

A static D.C. test was carried out on the attenuator in isolation. A voltage was applied to the input and the voltage was measured with a digital multi-meter at the output on each of the five ranges. The results show that the voltage was decreased by a factor of ten on each range, which was as expected.

| Range | Input Voltage: 10V<br>Voltage Measured | Input Voltage: 5V<br>Voltage Measured |
|---|---|---|
| 10mV | *10V* | *5V* |
| 100mV | *1.024V* | *0.5V* |
| 1V | *0.103V* | *0.051V* |
| 10V | *.0.01V* | *0.0051V* |

## 6.2 First Gain Stage:

The second gain stage was disconnected from the circuit, leaving only the attenuator and the first gain stage connected. A signal generator was connected to the input of the attenuator. The output from the signal generator (at 1KHz) was set to the rated FSD for each of the ranges in turn. The output of the gain stage and the signal generator were again measured with a digital multi-meter.

| Input Voltage | Range | Measured Output Voltage |
|---|---|---|
| *0V* | *10mV* | *0V* |
| *0V* | *100mV* | *0V* |
| *0V* | *1V* | *0V* |
| *0V* | *10V* | *0V* |
| *0.01V* | *10mV* | *0.0953V* |
| *0.1V* | *100mV* | *0.0944V* |
| *1V* | *1V* | *0.095V* |
| - | *10V* | - |

The voltage range from the signal generator was 0.005V - 2V. Therefore I was unable to measure the upper limit of the 10V range. The average of the measured results is 0.0949V, which is within 10mV of the calculated output of 0.0939V.

## 6.3 Second Gain Stage:

The second gain stage was re-connected to the circuit. A signal generator was connected to the input of the attenuator. The output from the signal generator (at 1KHz) was set to the rated FSD for each of the ranges in turn and the variable resistor in the meter drive stage was adjusted to read full scale. The output of the gain stage and the signal generator were again measured with a digital multi-meter. The voltage across the meter was also measured

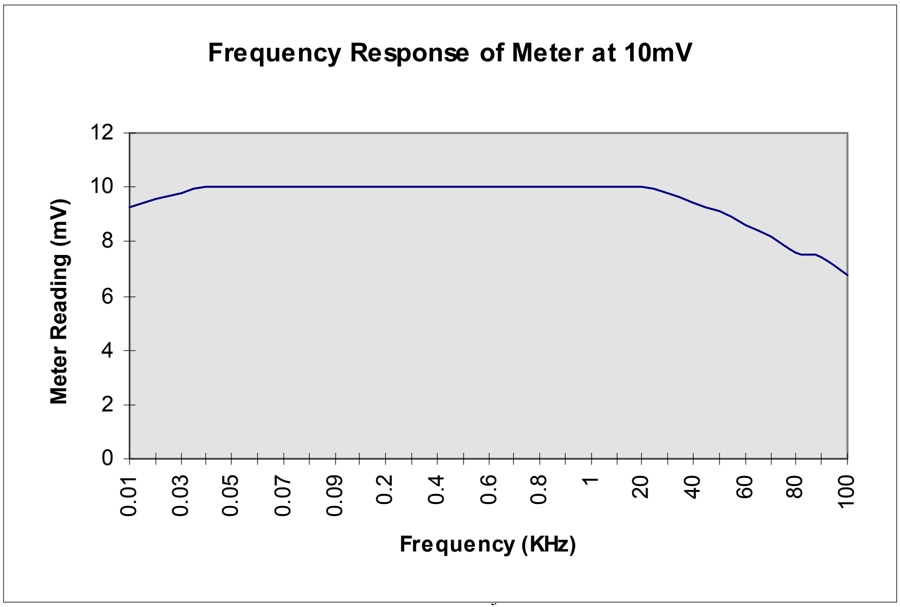
| Input Voltage | Range | Measured Output Voltage | Voltage Across Meter |
|---|---|---|---|
| *0V* | *10mV* | *0.1V* | *-0.017V* |
| *0V* | *100mV* | *0.003V* | *-0.005V* |
| *0V* | *1V* | *0.07V* | *-0.01V* |
| *0V* | *10V* | *0.08V* | *-0.01V* |
| *0.01V* | *10mV* | *0.0952V* | *0.262V* |
| *0.1V* | *100mV* | *0.094V* | *0.263V* |
| *1V* | *1V* | *0.095V* | *0.275V* |
| - | *10V* | - | - |

As before, I was unable to measure the 10V range. The average gain for the meter drive stage was 30 even though the maximum calculated gain was 27.6! The voltage across the meter was also less than the calculated value. I then measured the actual resistance of the meter and found it to be 3.79KΩ. This might explain the lower voltage across the meter and the large gain.

## 6.4 Bandwidth Of Meter:

The frequency of the signal was then increased from 10Hz to 100kHz. The upper and lower bandwidth limits (-3dB points) of the meter will be indicated when the meter reads 0.7071 of the mid-band reading. The meter was initially set to read full scale at 1kHz with a 10mV input on the 10mV range. The signal generator frequency was varied from 10Hz to 100kHz and the meter reading noted. At 10 Hz, the meter response was still above 0.7071. The upper cut-off was reached at 90kHz. This is close to the limits of the signal generator and I had no means to measure whether this cut-off was due to the meter or falling output from the generator, or a combination of both.

| Range | I/P (mV) | Freq (kHz) | Meter Reading (mV) |
|---|---|---|---|
| *10* | *10* | *0.01* | *9.3* |
| *10* | *10* | *0.02* | *9.6* |
| *10* | *10* | *0.03* | *9.8* |
| *10* | *10* | *0.04* | *10* |
| *10* | *10* | *0.05* | *10* |
| *10* | *10* | *0.06* | *10* |
| *10* | *10* | *0.07* | *10* |
| *10* | *10* | *0.08* | *10* |
| *10* | *10* | *0.09* | *10* |
| *10* | *10* | *0.1* | *10* |
| *10* | *10* | *0.2* | *10* |
| *10* | *10* | *0.3* | *10* |
| *10* | *10* | *0.4* | *10* |
| *10* | *10* | *0.5* | *10* |
| *10* | *10* | *0.6* | *10* |
| *10* | *10* | *0.7* | *10* |
| *10* | *10* | *0.8* | *10* |
| *10* | *10* | *0.9* | *10* |
| *10* | *10* | *1* | *10* |
| *10* | *10* | *10* | *10* |
| *10* | *10* | *20* | *10* |
| *10* | *10* | *30* | *9.8* |
| *10* | *10* | *40* | *9.4* |
| *10* | *10* | *50* | *9.1* |
| *10* | *10* | *60* | *8.6* |
| *10* | *10* | *70* | *8.2* |
| *10* | *10* | *80* | *7.6* |
| *10* | *10* | *90* | *7.4* |
| *10* | *10* | *100* | *6.8* |



# 7. Component & Price List

*(Using Maplin Catalogue)*

In the table below I have put together a price list for the components used to make the meter. Included are the sockets and black plastic case.

| **Item** | **Page** | **Code** | **Price** | **Quantity** | **Total Cost** |
|---|---|---|---|---|---|
| *91K 0.6w Metal Film Resistor* | *819* | *M91K* | *£0.08* | *1* | *£0.08* |
| *9K1 0.6w Metal Film Resistor* | *819* | *M9K1* | *£0.08* | *1* | *£0.08* |
| *910R 0.6w Metal Film Resistor* | *819* | *M910R* | *£0.08* | *1* | *£0.08* |
| *100R 0.6w Metal Film Resistor* | *819* | *M100R* | *£0.08* | *1* | *£0.08* |
| *220R Sub-Miniature Carbon Preset* | *853* | *UF98G* | *£0.20* | *1* | *£0.20* |
| *Poly Layer 0.47* | *235* | *WW47D* | *£0.49* | *3* | *£1.47* |
| *General Electrolitic 100uF 25V* | *239* | *AT48C* | *£0.24* | *2* | *£0.48* |
| *1N4148 Signal Diode* | *879* | *QL80B* | *£0.08* | *4* | *£0.32* |
| *LF353 FET Dual Op-Amp* | *950* | *AV47B* | *£0.70* | *1* | *£0.70* |
| *DIL Socket 8-Pin* | *1051* | *BL17T* | *£0.12* | *1* | *£0.12* |
| *2 pole 6 way Break before make switch* | *1135* | *FF74R* | *£1.00* | *1* | *£1.00* |
| *DPDT Switch* | *1132* | *FH04E* | *£1.25* | *1* | *£1.25* |
| *PP3 Battery Clip* | *118* | *HF28F* | *£0.19* | *2* | *£0.38* |
| *Large Green Terminal Post* | *410* | *HF05F* | *£0.79* | *1* | *£0.79* |
| *Large Red Terminal Post* | *410* | *HF07H* | *£0.79* | *1* | *£0.79* |
| *Chassis Mounting Phono Socket* | *353* | *YW06G* | *£0.49* | *1* | *£0.49* |
| *100x100 (Strip 3939)* | *624* | *JP49D* | *£2.02* | *1* | *£2.02* |
| *Plastic Box with Alu Top - SB-4BA* | *422* | *BZ30H* | *£4.09* | *1* | *£4.09* |

***Total Cost:*** ***£14.66***

0.6w Resistors are used as they are the standard size that Maplin supply and also there is no need for resistors with greater power handling. 25V Electrolytic capacitors are used as the next lowest value is 10V which does not give much of a margin for 9V maximum output from the Op-Amps.

# 8. Evaluation

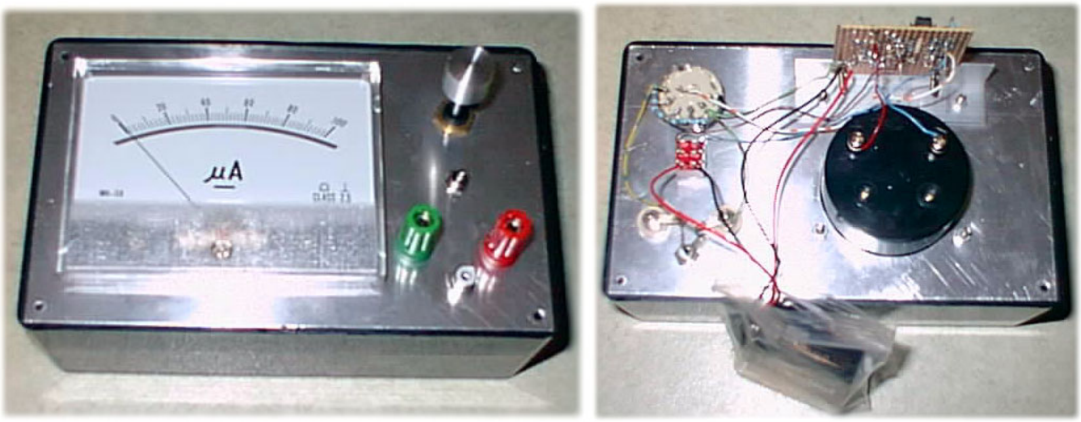


**Figure 12 -** The finished meter. The first image shows the font of the aluminium panel. The second image shows the back of the aluminium panel.

The meter works correctly and the tests show that it meets or exceeds the specification:

- The meter has a measured input impedance of 92.48 KΩ.
- The meter does have four selectable ranges of 10mV, 100mV, 1V and 10V which function correctly.
- The frequency response is less than 10Hz → 90KHz or greater. This is better than the audio range which is 10Hz → 20KHz.
- The meter is powered from two 9V PP3s arranged to give a split rail supply of ±9V.
- The meter uses a moving coil meter with a mirrored scale so that the reading the meter is more accurate than using an unmirrored scale.
- The meter is in a suitably sized black plastic box with an aluminium top.

An improvement that could be made to the meter is voltage protection so that the meter can not be damaged by a large input voltage.

# 9. References

**[1]** *Operational Amplifier User's Handbook - R.A. Penfold*
**[2]** *A Total Harmonic Distortion Meter by Robert Penfold - Electronics Today International*
**[3]** *Measure thd to 0.001% by John Linsley-Hood - Electronics World February 1998*
**[4]** *Maplin Catalogue - September '97 to February '98*
**[5]** *RSGB RadCom October 1998 - An Introduction to Op Amps*
**[6]** *Own AS Electronics course notes*
**[7]** *Own GCSE Electronics course notes and project*