Chapter 7W2

7W2: Op Amp Millivoltmeter

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7W2.1 The Problem: Millivoltmeter

Here’s a statement of the design task:

Given…

- a meter movement: 1mA full-scale, 100Ω
- op amp(s) of your choice
- other parts as needed

…design a voltmeter to the following specs:

- use a single 15V supply, if possible; if you can’t manage that, then use split supplies, ±15V
- full-scale (input-) voltage: 10mV
- accuracy 1% of full scale
- input resistance: ≥ 1M Ω
- reading for input grounded or open: 0 (to the usual 1% of f.s.)

…and if you’re not exhausted after that—or perhaps along the way—add some desirable features:

- protection for the meter movement (from consequences of overdriving the input)
- really fancy: valid reading for either input polarity, along with a polarity-indicating LED

7W2.2 Solution: Millivoltmeter

7W2.2.1 A Start: Amplify…

Comparing input range to the output voltage range that we need to drive the meter movement will let us determine what gain we need. We’ll also need to consider what form of amplifier is suitable.

7W2.2.2 Gain Needed

Let’s review the problem specifications that bear on gain:

- input voltage range: 0 to 10mV
- output voltage needed: 0 to 100mV, since meter movement drops 100mV full-scale. It is described as 100Ω and 1mA full-scale

So, a gain of 10 will do it.

7W2.2.2.1 What Amplifier Configuration

Should we use inverting or non-inverting? Either could satisfy the input-resistance requirement (1M).

Let’s try what the circuits would look like
7W2.2.2.2 Non-inverting Amp

This is the obvious choice, since this is a single-supply instrument and we want input impedance that is quite high. Here’s a sketch of the circuit:

![Non-inverting amplifier, to drive meter movement](image1)

The amplifier will need to be a “single-supply” type: its input must understand voltage levels down to zero, and its output must be able to go close to zero. A device like the LM358 that we use in Lab 7’s microphone amplifier satisfies these requirements.

7W2.2.2.3 Current-source version of Non-inverting Design

It is also possible to apply a current rather than voltage to the meter movement.

![Current, rather than voltage, applied to meter movement](image2)

The circuit of fig. 2 includes a current-limiting resistor (the 10k), in case the input is overdriven. This protection anticipates that described in § 7W2.2.4.1 on page 6.

7W2.2.2.4 Inverting Amp

Could the job be done with an inverting amplifier? Yes, but this design is awkward, if done with a single supply. It’s straightforward if done with split supply.

Split Supply

![Inverting design: straightforward if we use a split supply](image3)
**Single Supply**

Use of a single-supply makes the task harder, because the circuit must operate close to its “positive” supply (well, the more positive supply—in this case, ground).

![Inverting amplifier, to drive meter movement](image)

The inversion means that the op amp output will always be negative, so the op amp will have to be powered in the curious way shown. Input of the op amp now lives at the positive supply rail; the output runs from that rail to 100mV below it. This circumstance rules out an ordinary single-supply op amp like the ’358. We would need a “rail-to-rail” op amp, able to understand inputs all the way to the positive supply. This we can find: e.g., ADI’s OP282 or AD8531 (the latter’s power supply is limited to 6V, a restriction common in CMOS parts; we could use a supply voltage lower than 15V: say, 5V).

The op amp would also need to be able to take its output right up to the positive supply. Here, the configuration we have set up for ourselves is so odd that the characteristic does not seem to be specified; but probably the devices can sink current close to the positive supply (what is specified is the offset from positive supply while sourcing current).

So, it is possible to find an op amp that fits the configuration—though we’ll soon learn that this configuration is ruled out by the specifications of the amps that can handle what we require for this configuration: high-side, rail-to-rail input and output.

### 7W2.2.3 What op amp specs the designs would require

So far, we have shown only how to get a gain of ten. We now need to look at the harder part of the task: getting accurate results.

We are asked to keep errors at ±1%. In addition, the meter should read zero (to within 1% of full-scale) when the input is open. We don’t want to annoy the meter’s users with a wandering output at times when nothing is connected to the millivoltmeter.

#### 7W2.2.3.1 No Wandering, with input open

The non-inverting design of fig. 1 on the preceding page, with its astronomical $R_{in}$, would wander, if we did not add a resistor as shown in fig. 5. After a time, the input, and therefore output, would drift all the way to an extreme, pinning the meter movement at full-scale. To prevent this result, we must include a resistor to ground, as shown.

![A resistor to ground prevents drift, in the non-inverting design](image)

We chose the resistor value to satisfy the original problem specification, $R_{in} \geq 1M\Omega$. 
The inverting design already includes this taming resistor; no change is needed, in order to prevent that configuration from wandering.

**7W2.2.3.2 What magnitude of input error is tolerable?**

We are to keep errors under 1%. Then we can tolerate \( V_{\text{error, input}} = 0.01 \times V_{\text{full-scale}} = 0.1 \text{mV} = 100 \mu\text{V}. \) This value we might call our “error budget.”

**7W2.2.3.3 What \( V_{\text{offset}} \) is tolerable?**

This total DC error will result from the sum of two effects: \( V_{\text{offset}} \) and \( I_{\text{bias}} \). Since these two effects may have the same sign, we will allow each to use up only half the total error budget: we will allow 50 \( \mu\text{V} \) apiece.

**7W2.2.3.4 \( V_{\text{offset}} \)**

We need to shop for an op amp with \( V_{\text{offset}} \) around 50 \( \mu\text{V} \). That value is low—about 15 times smaller than what the ’411 shows us. It is attainable. But we should not expect to find it in an op amp that has been designed to optimize some other feature.

Hunting for a satisfactory op amp, we find that this \( V_{\text{offset}} \) goal knocks out of contention the single-supply rail-to-rail op amps required by the inverting design of § 7W2.2.2.4 on page 3. The two parts that could handle inputs up to the positive rail showed \( V_{\text{offset}} \)'s of 3mV and 25mV, respectively. So, let’s abandon the inverting design—which always seemed a bit perverse, anyway.

\( V_{\text{offset}} \leq 50 \mu\text{V}? \) Only a very few parts satisfy this specification, in the collection of “candidate op amps” (§ 8 on page 7):

- the LT1012A (at 25 \( \mu\text{V} \) max);
- the MAX420E (5\( \mu\text{V}, \) max)—a “chopper”—the sort that continually re-adjusts its offset so as to zero it, many times each second.
- LMP2015 (5\( \mu\text{V} \)) (another chopper)

Two other parts comes close: OPA627b at 100\( \mu\text{V} \) max, and OPA336, at 125\( \mu\text{V} \) max—slightly exceeding our error budget. The OPA336 typical value of 60\( \mu\text{V} \) would be acceptable. We will not, here, go into the hard question of when it might be all right to use something other than worst-case specifications.\(^1\) We might keep these two, then, in mind.

If we are to do the task single-supply, then only the LMP2015 will do.

**7W2.2.3.5 \( I_{\text{bias}} \)**

\( I_{\text{bias}} \) flows in the 1M input resistor, generating an error voltage. Again, we’ll assume that we can use up just half the error budget with this error: 50\( \mu\text{V}. \)

The \( I_{\text{bias}} \) that we can tolerate, then, is

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\(^1\)A knowledgeable friend of ours who designed digital circuits for a large computer maker told us that his company would have been unable to compete if they had not assumed that parts in their designs would work somewhat better than their worst-case, full-temperature-range specifications.
\[ I_{\text{bias}} \leq 50 \mu V / 1 M \Omega = 50 pA \]

This is a small value, but certainly available (even the humble LF411 comes close, showing 50pA as its typical \( I_{\text{bias}} \)). The challenge will be to find a part that delivers this good specification while also giving low \( V_{\text{offset}} \). If we mean to do the task single-supply, then we need also the peculiar virtues of an amp that can handle inputs and outputs close to ground.

Only the choppers keep the total error under 100\( \mu V \). The OPA627b at 100\( \mu V \) is close enough, with its 5pA \( I_{\text{bias}} \) (max), if we mean to use a split supply. And the LMP2015 is the only part that does it all: keeps the input error under 100\( \mu V \) and allows use of a single supply.

### 7W2.2.4 Refinements

#### 7W2.2.4.1 Protect Meter Movement Against Overdrive

The designs of figs. 1 on page 3 and fig. 3 on page 3 could drive the meter movement to the power supply. The op amp’s output current, typically limited to a few tens of milliamps, might not damage the movement. But it is easy to modify the circuit just slightly, so as to protect the meter movement. Simply putting a series resistor ahead of the movement and then boosting the amplifier’s gain makes sure that the movement could not be driven to more than 150% of full-scale.

![Figure 6: Slight change to limit overdrive of meter movement](image)

#### 7W2.2.4.2 Allow Both Positive and Negative Inputs

This change requires use of a split supply. If the meter movement is of one polarity only,\(^2\) then a four-diode bridge (familiar to you from power supplies) will put current through the movement in the forward direction regardless of the sign that reaches the bridge.

![Figure 7: A design permitting both positive and negative inputs](image)

\(^2\)Some movements are bipolar, starting with the needle at the center of its range of movement.
The design of fig. 7 uses a *current-source* scheme (like that of fig. 2 on page 3). Letting the circuit set a current rather than a voltage makes the design indifferent to voltage drops across the bridge diodes. The indicator LED’s are necessary to indicate input polarity.

### 7W2.2.5 The Point of this exercise…

This exercise was fussy. What we wanted to show was that a very simple task becomes challenging if the design can tolerate only very small errors. We hope this example will help to give you a feel for why such an amazing variety of op amps is available—with new ones being born each month.

### 7W2.2.6 Candidate Op Amps

All but one of these are unsuitable for single-supply work. If you designed the meter with a split supply, all are eligible (though the single-supply part is limited to +5V total voltage).

<table>
<thead>
<tr>
<th>Candidate Op Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{os} (\mu V) )</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>LM741C 2000 6000 -</td>
</tr>
<tr>
<td>LF411 800 2000 7 20</td>
</tr>
<tr>
<td>OPA111B 50 250 0.5 1</td>
</tr>
<tr>
<td>OPA627B 40 100 0.4 0.8</td>
</tr>
<tr>
<td>LT1012A 8 25 0.2 0.6</td>
</tr>
<tr>
<td>OPA354 60 12.5 1.5</td>
</tr>
<tr>
<td>MAX420E 1 5</td>
</tr>
</tbody>
</table>

**Single Supply**

| LMP2015 0.8 5 0.015 0.05 3 -- | chooser, CMOS. 5V |

\(*\) for "premium" grade only, otherwise not specified

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*Figure 8: Candidate op amps: most are eligible for split-supply, only*