

# V/F Converter ICs Handle Frequency-to-Voltage Needs

National Semiconductor  
Appendix C C  
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Simplify your F/V converter designs with versatile V/F ICs. Starting with a basic converter circuit, you can modify it to meet almost any application requirement. You can spare yourself some hard labor when designing frequency-to-voltage (F/V) converters by using a voltage-to-frequency IC in your designs. These ICs form the basis of a series of accurate, yet economical, F/V converters suiting a variety of applications.

Figure 1 shows an LM331 IC (or LM131 for the military temperature range) in a basic F/V converter configuration (sometimes termed a stand-alone converter because it requires no op amps or other active devices other than the IC). (Comparable V/F ICs, such as RM4151, can take advantage of this and other circuits described in this article, although they might not always be pin-for-pin compatible).

This circuit accepts a pulse-train or square wave input amplitude of 3V or greater. The 470 pF coupling capacitor suits negative-going input pulses between 80  $\mu$ s and 1.5  $\mu$ s, as well as accommodating square waves or positive-going pulses (so long as the interval between pulses is at least 10  $\mu$ s).

### IC Handles the Hard Part

The LM331 detects an input-signal change by sensing when pin 6 goes negative relative to the threshold voltage at pin 7, which is nominally biased 2V lower than the supply voltage. When a signal change occurs, the LM331's input comparator sets an internal latch and initiates a timing cycle. During this cycle, a current equal to  $V_{REF}/R_S$  flows out of pin 1 for

a time  $t = 1.1 R_T C$ . The 1  $\mu$ F capacitor filters this pulsating current from pin 1, and the current's average value flows through load resistor  $R_L$ . As a result, for a 10 kHz input, the circuit outputs 10  $V_{DC}$  across  $R_L$  with good (0.06% typical) nonlinearity.

Two problems remain, however: the output at V1 includes about 13 mVp-p ripple, and it also lags 0.1 second behind an input frequency step change, settling to 0.1% of full-scale in about 0.6 second. This ripple and slow response represent an inherent tradeoff that applies to almost every F/V converter.

### The Art of Compromise

Increasing the filter capacitor's value reduces ripple but also increases response time. Conversely, lowering the filter capacitor's value improves response time at the expense of larger ripple. In some cases, adding an active filter results in faster response and less ripple for high input frequencies.

Although the circuit specifies a 15V power supply, you can use any regulated supply between 4  $V_{DC}$  and 40  $V_{DC}$ . The output voltage can extend to within 3  $V_{DC}$  of the supply voltage, so choose  $R_L$  to maintain that output range.

Adding a 220 k $\Omega$ /0.1  $\mu$ F postfilter to the circuit slows the response slightly, but it also reduces ripple to less than 1 mVp-p for frequencies from 200 Hz to 10 kHz. The reduction in ripple achieved by adding this passive filter, while not as good as that obtainable using an active filter, could suffice in some applications.

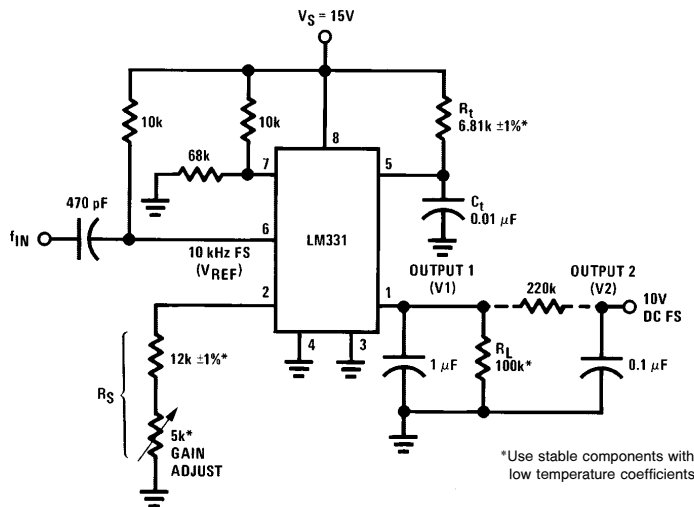


FIGURE 1. A Simple Stand-Alone F/V Converter Forms the Basis for Many Other Converter-Circuit Configurations

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### Improving the Basic Circuit

Further modifications and additions to the basic F/V converter shown in Figure 1 can adapt it to specific performance requirements. Figure 2 shows one such modification, which improves the converter's nonlinearity to 0.006% typical.

Reconsideration of the basic stand-alone converter shows why its nonlinearity falls short of this improved version's. At low input frequencies, the current source feeding pin 1 in the LM331 is turned off most of the time. As the input frequency increases, however, the current source stays on more of the time, and its own impedance attenuates the output signal for an increasing fraction of each cycle time. This disproportionate attenuation at higher frequencies causes a parabolic change in full-scale gain rather than the desired linear one.

In the improved circuit, on the other hand, the PNP transistor acts as a cascade, so the output impedance at pin 1 sees a constant voltage that won't modulate the gain. Also, with an alpha ranging between 0.998 and 0.990, the transistor exhibits a temperature coefficient of between 10 ppm/°C and 40 ppm/°C—a fairly minor effect. Thus, this circuit's

nonlinearity does not exceed 0.01% maximum for the 10V output range shown and is normally not worse than 0.01% for any supply voltage between 4V and 40V.

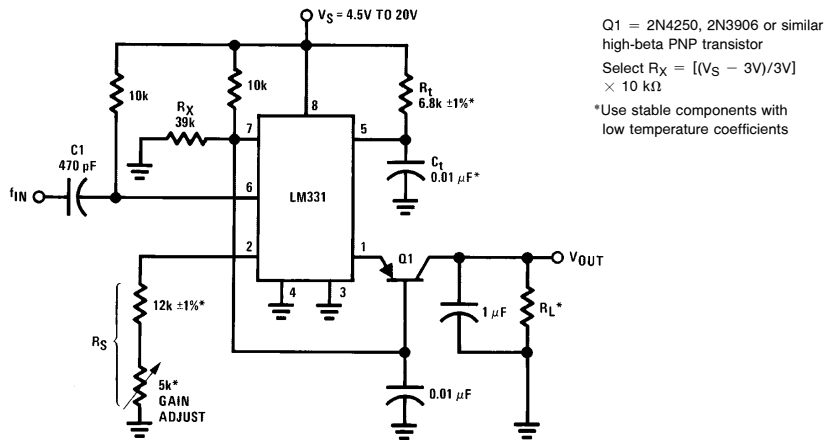
### Add an Output Buffer

The circuit in Figure 3 adds an output buffer (unity-gain follower) to the basic single-supply F/V converter. Either an LM324 or LM358 op amp functions well in a single-supply circuit because these devices' common-mode ranges extend down to ground. But if a negative supply is available, you can use any op amp; types such as the LF351B or LM308A, which have low input currents, provide the best accuracy.

The output buffer in Figure 3 also acts as an active filter, furnishing a 2-pole response from a single op amp. This filter provides the general response

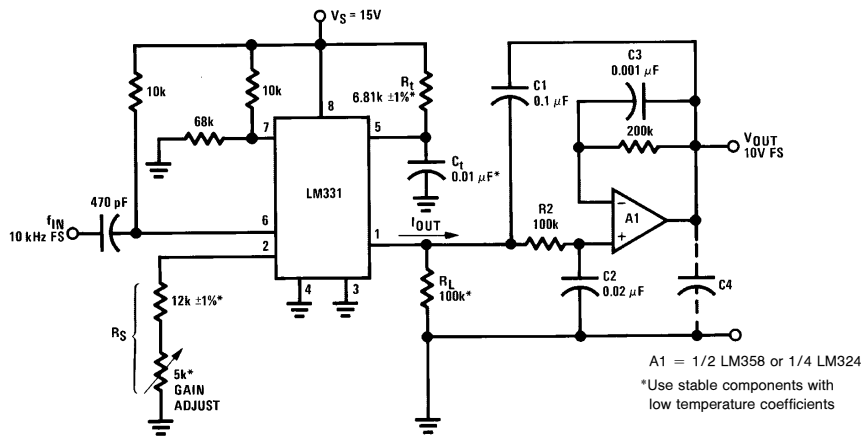
$$V_{OUT}/I_{OUT} = R_L / (1 + K1p + K2p^2).$$

(p is the differential operator d/dt.) As shown,  $R_L$  controls the filter's DC gain. The high frequency response rolls off at 12 dB/octave. Near the circuit's natural resonant frequency, you can choose the damping to give a little overshoot—or none, as desired.



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FIGURE 2. Adding a Cascade Transistor to the LM331's Output Improves Nonlinearity to 0.006%



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FIGURE 3. The Op Amp on This F/V Converter's Output Acts as a Buffer as Well as a 2-Pole Filter

### Dealing with F/V Converter Ripple

Voltage ripple on the output of F/V converters can present a problem, and the chart shown in *Figure A* indicates exactly how big a problem it is. A simple, slow, RC filter exhibits low ripple at all frequencies. Two-pole filters offer the lowest ripple at high frequencies and provide a 30-times-faster step response than RC devices.

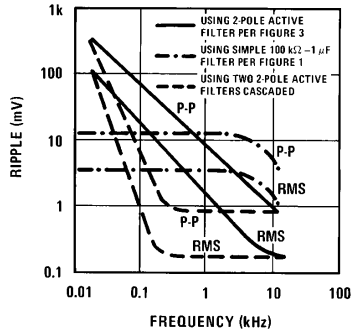
To reduce a circuit's ripple at moderate frequencies, however, you can cascade a second active-filter stage on the F/V converter's output. That circuit's response also appears in *Figure A* and shows a significant improvement in low-ripple bandwidth over the single-active-filter configuration, with only a 30% degradation of step response.

*Figures B* and *C* show filter circuits suitable for cascading. The inverting filter in *Figure B* requires closely matched resistors with a low TC over their temperature range for best accuracy. For lowest DC error, choose  $R_5 = R_2 + (R_{IN}|R_F)$ . This circuit's response is

$$-V_{OUT}/V_{IN} = n / (1 + (R_F + R_2 + nR_2)C_4p + R_F R_2 C_3 C_4 p^2)$$

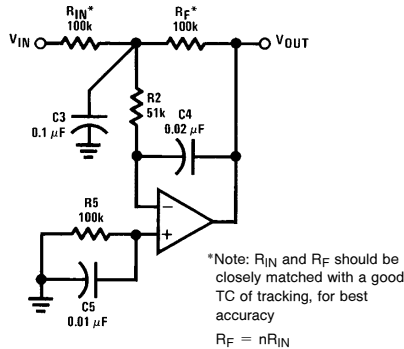
where  $n = \text{DC gain}$ . If  $R_{IN} = R_F$  and  $n = 1$ ,

$$-V_{OUT}/V_{IN} = 1 / (1 + (R_F + 2R_2)C_4p + R_F R_2 C_3 C_4 p^2)$$



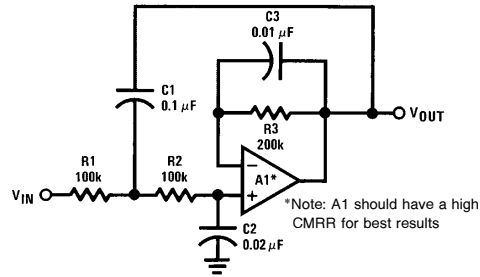
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**FIGURE A. Output-Ripple Performance of Several Different F/V Converter Configurations Illustrates the Effect of Voltage Ripple**



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**FIGURE B. You Can Cascade This 2-Pole Inverting Filter onto an F/V Converter's Output**



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**FIGURE C. This 2-Pole Noninverting Filter Suits Cascade Requirements on F/V Converter Outputs**

The circuit shown in *Figure C* does not require precision passive components, but for best accuracy, choosing an A1 with a high CMRR is critical. An LM308A op amp's 96 dB minimum CMRR suits this circuit well, but an LM358B's 85 dB typical figure also proves adequate for many applications. Circuit response is

$$V_{OUT}/V_{IN} = 1 / (1 + (R_1 + R_2) C_2 p + R_1 R_2 C_1 C_2 p^2)$$

For best results, choose  $R_3 = R_1 + R_2$ .

### Components Determine Response

The specific response of the circuit in *Figure 3* is

$$V_{OUT}/I_{OUT} = R_L / (1 + (R_L + R_2) C_2 p + R_L R_2 C_1 C_2 p^2)$$

Making  $C_2$  relatively large eliminates overshoot and sine peaking. Alternatively, making  $C_2$  a suitable fraction of  $C_1$  (as is done in *Figure 3*) produces both a sine response with 0 dB to 1 dB of peaking and a quick real-time response having only 10% to 30% overshoot for a step response. By maintaining *Figure 3's* ratio of  $C_1:C_2$  and  $R_2:R_L$ , you can adapt its 2-pole filter to a wide frequency range without tedious computations.

This filter settles to within 1% of a 5V step's final value in about 20 ms. By contrast, the circuit with the simple RC filter shown in *Figure 1* takes about 900 ms to achieve the same response, yet offers no less ripple than *Figure 3's* op amp approach.

As for the other component in the 2-pole filter, any capacitance between 100 pF and 0.05  $\mu\text{F}$  suits  $C_3$  because it serves only as a bypass for the 200 k $\Omega$  resistor.  $C_4$  helps reduce output ripple in single positive power-supply systems when  $V_{OUT}$  approaches so close to ground that the op amp's output impedance suffers. In this circuit, using a tantalum capacitor of between 0.1  $\mu\text{F}$  and 2.2  $\mu\text{F}$  for  $C_4$  usually helps keep the filter's output much quieter without degrading the op amp's stability.

### Avoid Low-Leakage Limitations

Note that in most ordinary applications, this 2-pole filter performs as well with 0.1  $\mu\text{F}$  and 0.02  $\mu\text{F}$  capacitors as the passive filter in *Figure 1* does with 1  $\mu\text{F}$ . Thus, if you require a 100 Hz F/V converter, the circuit in *Figure 3* furnishes good filtering with  $C_1 = 10 \mu\text{F}$  and  $C_2 = 2 \mu\text{F}$ , and eliminates the 100  $\mu\text{F}$  low-leakage capacitor needed in a passive filter.

Note also that because  $C_1$  always has zero DC voltage across it, you can use a tantalum or aluminum electrolytic capacitor for  $C_1$  with no leakage-related problems;  $C_2$ , however, must be a low-leakage type. At room temperature, typical 1  $\mu\text{F}$  tantalum components allow only a few nanoamperes of leakage, but leakage this low usually cannot be guaranteed.

### Compensating for Temperature Coefficients

F/V converters often encounter temperature-related problems usually resulting from the temperature coefficients of passive components. Following some simple design and manufacturing guidelines can help immunize your circuits against loss of accuracy when the temperature changes.

Capacitors fabricated from Teflon or polystyrene usually exhibit a TC of  $-110 \pm 30 \text{ ppm}/^\circ\text{C}$ . When you use such a component for the timing capacitor in an F/V converter (such as  $C_t$  in the *figure*) the circuit's output voltage—or the gain in terms of volts per kilohertz—also exhibits a  $-110 \text{ ppm}/^\circ\text{C}$  TC.

But the resistor-diode network ( $R_X$ ,  $D_1$ ,  $D_2$ ) connected from pin 2 to ground in the *figure* can cancel the effect of the timing capacitor's large TC. When  $R_X = 240 \text{ k}\Omega$ , the current flowing through pin 1 will then have an overall TC of 110  $\text{ppm}/^\circ\text{C}$ , effectively canceling a polystyrene timing capacitor's TC to a first approximation. Thus, you needn't find a zero-TC capacitor for  $C_t$ , so long as its temperature coefficient is stable and well established. As an additional advantage, the resistor-diode network nearly compensates to zero the TC of the rest of the circuit.

### Bake it for a While

After the circuit has been built and checked out at room temperature, a brief oven test will indicate the sign and the size of the TC for the complete F/V converter. Then you can add resistance in series with  $R_X$ , or add conductance in

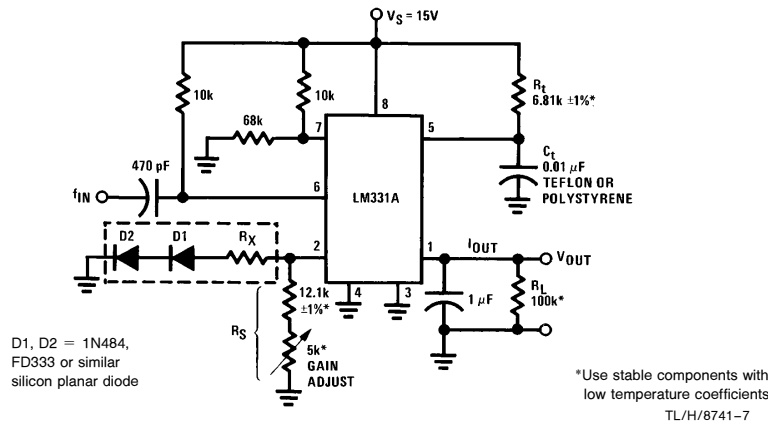
parallel with it, to greatly diminish the TC previously observed and yield a complete circuit with a lower TC than you could obtain simply by buying low TC parts.

For example, if the circuit increases its full-scale output by 0.1% per  $30^\circ\text{C}$  (33  $\text{ppm}/^\circ\text{C}$ ) during the oven test, adding 120  $\text{k}\Omega$  in series with  $R_X = 240 \text{ k}\Omega$  cancels the temperature-caused deviation. Or, if the full-scale output decreases by  $-0.04\%$  per  $20^\circ\text{C}$  ( $-20 \text{ ppm}/^\circ\text{C}$ ), just add 1.2  $\text{M}\Omega$  in parallel with  $R_X$ .

Note that to allow trimming in both directions, you must start with a finite *fixed* TC (such as the  $-110 \text{ ppm}/^\circ\text{C}$  of  $C_t$ ), which then nominally cancels out by the addition of a finite *adjustable* TC. Only by using this procedure can you compensate for whatever polarity of TC is found by the oven test.

You can utilize this technique to obtain TCs as low as 20  $\text{ppm}/^\circ\text{C}$ , or perhaps even 10  $\text{ppm}/^\circ\text{C}$ , if you take a few passes to zero-in on the best value for  $R_X$ . For optimum results, consider the following guidelines:

- Use a good capacitor for  $C_t$ ; the cheapest polystyrene capacitors can shift value by 0.05% or more per temperature cycle. In that case, you would not be able to distinguish the actual temperature sensitivity from the hysteresis, and you would also never achieve a stable circuit.
- After soldering, bake or temperature-cycle the circuit (at a temperature not exceeding  $75^\circ\text{C}$  in the case of polystyrene) for a few hours to stabilize all components and to relieve the strains of soldering.
- Do not rush the trimming. Recheck the room temperature value before *and* after you take the high temperature data to ensure a reasonably low hysteresis per cycle.
- Do not expect a perfect TC at  $-25^\circ\text{C}$  if you trim for  $\pm 5 \text{ ppm}/^\circ\text{C}$  at temperatures from  $+25^\circ\text{C}$  to  $60^\circ\text{C}$ . None of the components in the *figure's* circuit offer linearity much better than 5  $\text{ppm}/^\circ\text{C}$  or 10  $\text{ppm}/^\circ\text{C}$  cold, if trimmed for a zero TC at warm temperatures. Even so, using these techniques you can obtain a data converter with better than 0.02% accuracy and 0.003% linearity, for a  $\pm 20^\circ\text{C}$  range around room temperature.
- Start out the trimming with  $R_X$  installed and its value near the design-center value (e.g., 240  $\text{k}\Omega$  or 270  $\text{k}\Omega$ ), so you



Two Diodes and a Resistor Help Decrease an F/V Converter's Temperature Coefficient

will be reasonably close to zero TC; you will usually find the process slower if you start without any resistor, because the trimming converges more slowly.

- If you change  $R_X$  from 240 k $\Omega$  to 220 k $\Omega$ , do not pull out the 240 k $\Omega$  part and put in a new 220 k $\Omega$  resistor—you will get much more consistent results by adding a 2.4 M $\Omega$  resistor in parallel. The same admonition holds true for adding resistance in series with  $R_X$ .
- Use reasonably stable components. If you use an LM331A ( $\pm 50$  ppm/ $^{\circ}$ C maximum) and RN55D film resistors (each  $\pm 100$  ppm/ $^{\circ}$ C) for  $R_L$ ,  $R_t$  and  $R_S$ , you probably won't be able to trim out the resulting  $\pm 350$  ppm/ $^{\circ}$ C worst-case TC. Resistors with a TC specification of 25 ppm/ $^{\circ}$ C usually work well. Finally, use the same resistor value (e.g., 12.1 k $\Omega$   $\pm 1\%$ ) for both  $R_S$  and  $R_t$ ; when these resistors come from the same manufacturer's batch, their TC tracking will usually rate at better than 20 ppm/ $^{\circ}$ C.

Whenever an op amp is used as a buffer (as in *Figure 3*), its offset voltage and current ( $\pm 7.5$  mV maximum and  $\pm 100$  nA, respectively, for most inexpensive devices) can cause a  $\pm 17.5$  mV worst-case output offset. If both plus and minus supplies are available, however, you can easily provide a symmetrical offset adjustment. With only one supply, you can add a small positive current to each op amp input and also trim one of the inputs.

#### Need a Negative Output?

If your F/V converter application requires a negative output voltage, the circuit shown in *Figure 4* provides a solution with excellent linearity ( $\pm 0.003\%$  typical,  $\pm 0.01\%$  maximum). And because pin 1 of the LM331 always remains at 0  $V_{DC}$ , this circuit needs no cascade transistor. (Note, howev-

er, that while the circuit's nonlinearity error is negligible, its ripple is not.)

The circuit in *Figure 4* offers a significant advantage over some other designs because the offset adjust voltage derives from the stable 1.9  $V_{DC}$  reference voltage at pin 2 of the LM331; thus any supply voltage shifts cause no output shifts. The offset pot can have any value between 200 k $\Omega$  and 2 M $\Omega$ .

An optional bypass capacitor ( $C_2$ ) connected from the op amp's positive input to ground prevents output noise arising from stray noise pickup at that point; the capacitance value is not critical.

#### A Familiar Response

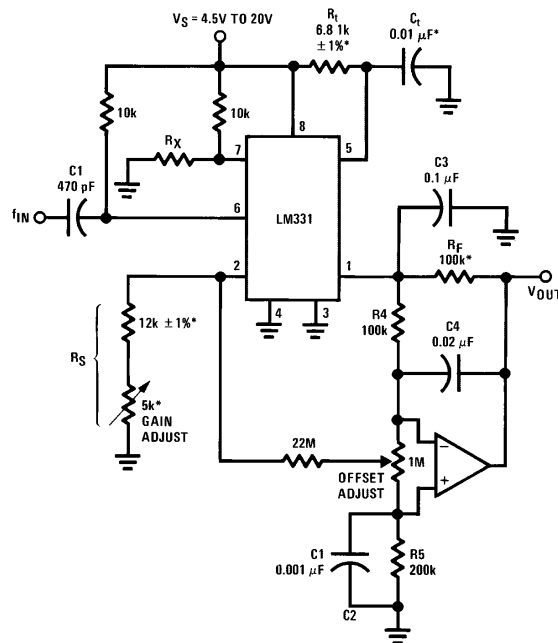
The circuit in *Figure 4* exhibits the same 2-pole response—with heavy output ripple attenuation—as the noninverting filter in *Figure 3*. Specifically,

$$V_{OUT}/I_{OUT} = R_F / (1 + (R_4 + R_F)C_4p + R_4R_F C_3C_4p^2).$$

Here also,  $R_5 = R_4 + R_F = 200$  k $\Omega$  provides the best bias current compensation.

The LM331 can handle frequencies up to 100 kHz by utilizing smaller-value capacitors as shown in *Figure 5*. This circuit increases the current at pin 2 to facilitate high-speed switching, but, despite these speed-ups, the LM331's 500 ppm/ $^{\circ}$ C TC at 100 kHz causes problems because of switching speed shifts resulting from temperature changes.

To compensate for the device's positive TC, the LM334 temperature sensor feeds pin 2 a current that decreases linearly with temperature and provides a low overall temperature coefficient. An  $R_Y$  value of 30 k $\Omega$  provides first-order compensation, but you can trim it higher or lower if you need more precise TC correction.



\*Use stable components with low temperature coefficients

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**FIGURE 4. In This F/V Circuit, the Output-Buffer Op Amp Derives its Offset Voltage from the Precision Voltage Source at Pin 2 of the LM331**

### Detect Frequencies Accurately

Using an F/V converter combined with a comparator as a frequency detector is an obvious application for these devices. But when the F/V converter is utilized in this way, its output ripple hampers accurate frequency detection, and the slow filter frequency response causes delays.

If a quick response is not important, though, you can effectively utilize an LM331-based F/V converter to feed one or more comparators, as shown in Figure 6. For an input frequency drop from 1.1 kHz to 0.5 kHz, the converter's output

responds within about 20 ms. When the input falls from 9 kHz to 0.9 kHz, however, the output responds only after a 600 ms lag, so utilize this circuit only in applications that can tolerate F/V circuits' inherent delays and ripples.

### Author's Biography

Bob Pease is a staff scientist in the Advanced Linear Integrated Circuit Group at National Semiconductor Corp., Santa Clara, CA. Holder of four patents, he earned a BSEE from MIT. Bob lists tracking abandoned railroad roadbeds and designing V/F converters as hobbies.

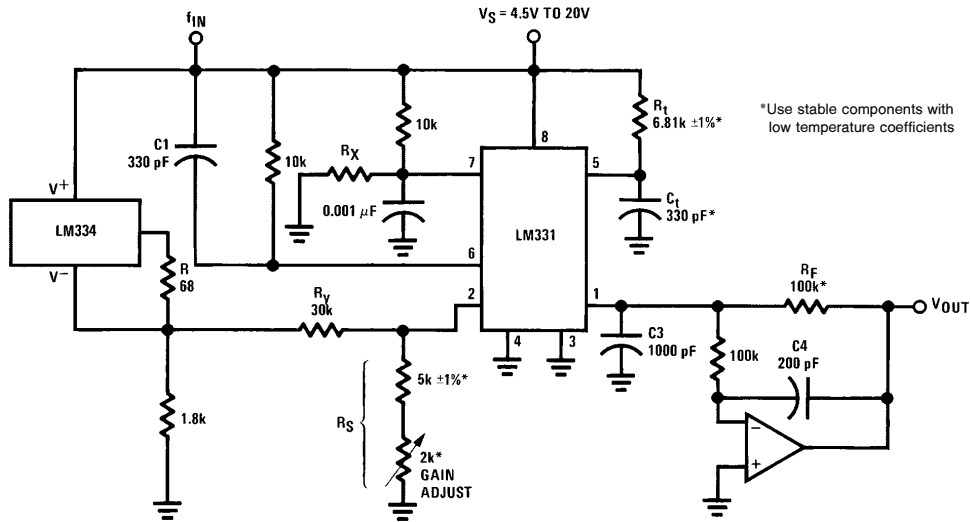


FIGURE 5. An LM334 Temperature Sensor Compensates for the F/V Circuit's Temperature Coefficient

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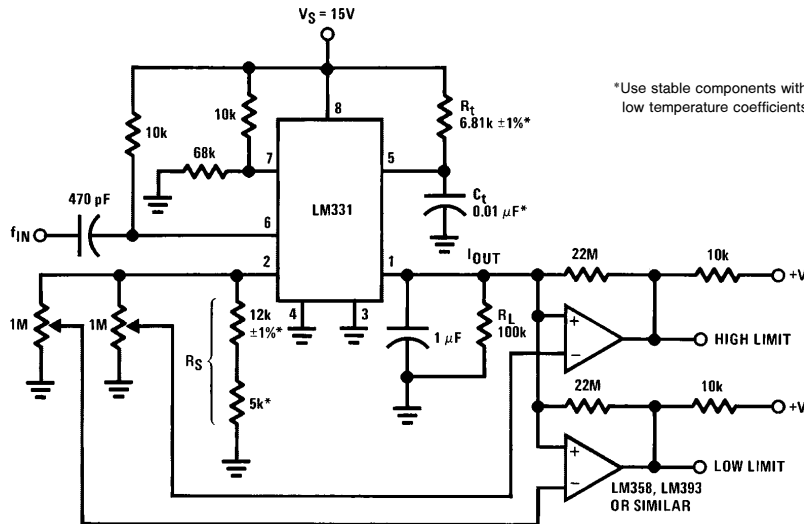


FIGURE 6. Combining a V/F IC with Two Comparators Produces a Slow-Response Frequency Detector

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