

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

National Semiconductor
 Application Note C
 Robert A. Pease
 August 1980



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 μs and 1.5 μs, as well as accommodating square waves or positive-going pulses (so long as the interval between pulses is at least 10 μs).

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

$t = 1.1 R_t C_t$. The 1 μF 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.

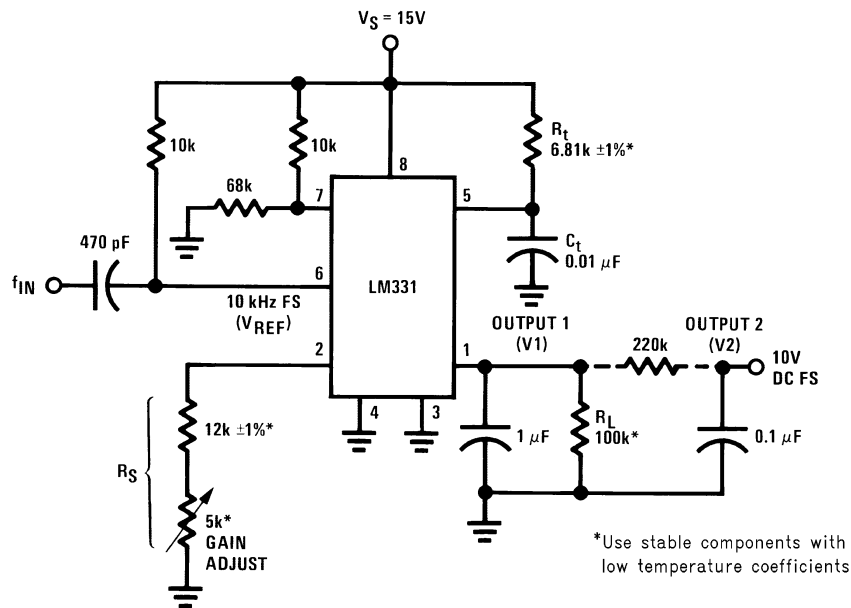
Two problems remain, however: the output at V1 includes about 13 mVp-p ripple, and it also lags 0.1 second behind an input frequency step change, settling to 0.1% of full-scale in about 0.6 second. This ripple and slow response represent an inherent tradeoff that applies to almost every F/V converter.

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 kΩ/0.1 μF 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.



00874101

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

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.

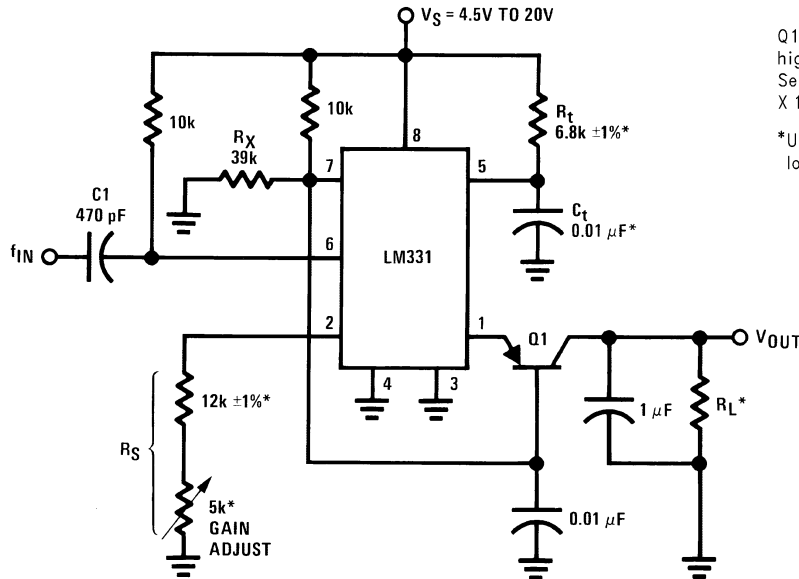
Add an Output Buffer

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.



Q1 = 2N4250, 2N3906 or similar high-beta PNP transistor
Select $R_X = [(V_S - 3V)/3V] \times 10 \text{ k}\Omega$

*Use stable components with low temperature coefficients

00874102

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

Add an Output Buffer (Continued)

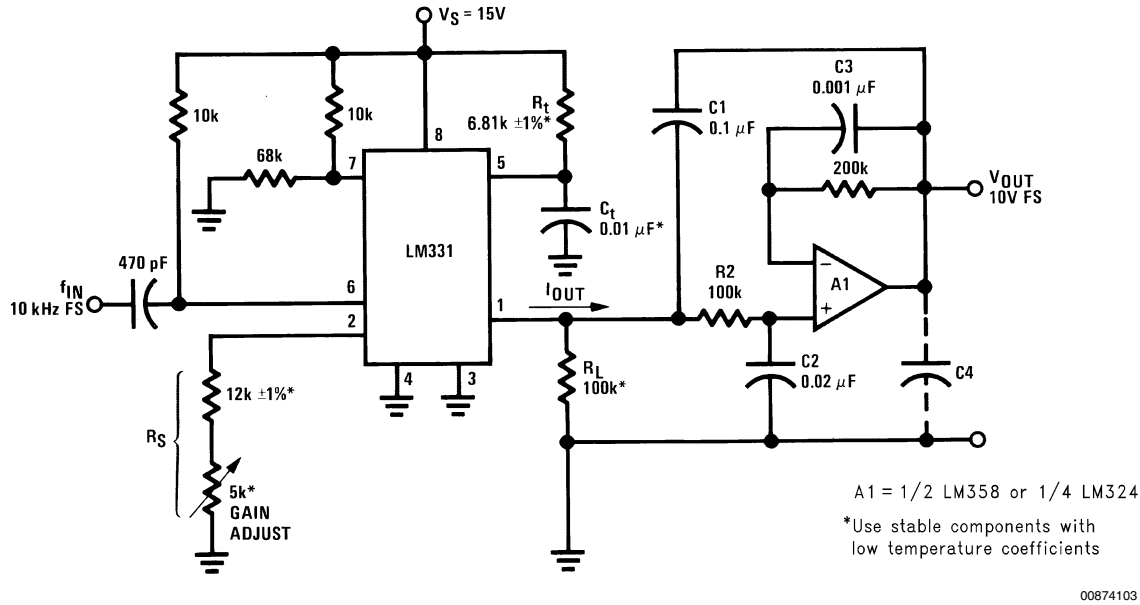


FIGURE 3. The Op Amp on This F/V Converter's Output Acts as a Buffer as Well as a 2-Pole Filter

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 4 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 4 and shows a significant improvement in low-ripple bandwidth over the single-active-filter configuration, with only a 30% degradation of step response.

Figure 5 and Figure 6 show filter circuits suitable for cascading. The inverting filter in Figure 5 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 $n = DC \text{ gain}$. If $R_{IN} = R_F$ and $n = 1$,

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

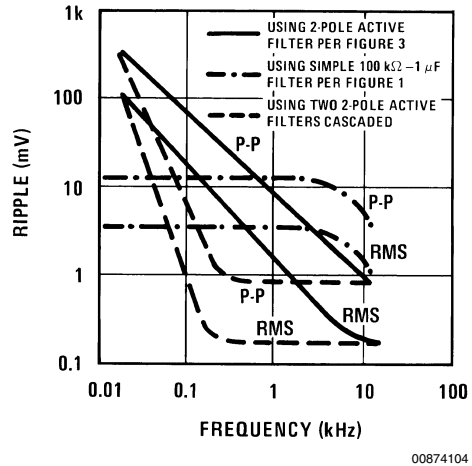
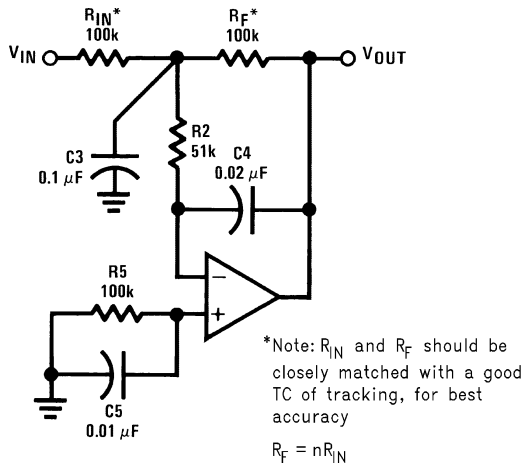


FIGURE 4. Output-Ripple Performance of Several Different F/V Converter Configurations Illustrates the Effect of Voltage Ripple

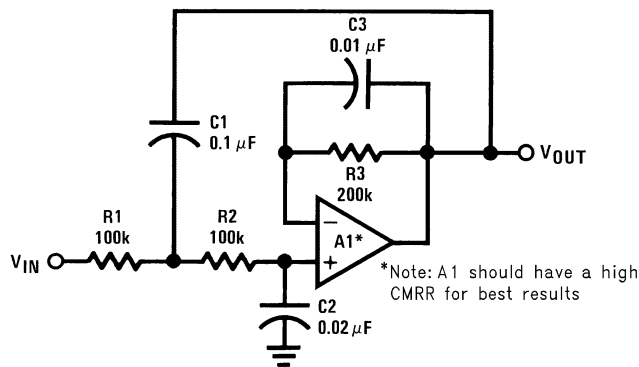
Dealing with F/V Converter Ripple

(Continued)



00874105

FIGURE 5. You Can Cascade This 2-Pole Inverting Filter onto an F/V Converter's Output



00874106

FIGURE 6. This 2-Pole Noninverting Filter Suits Cascade Requirements on F/V Converter Outputs

The circuit shown in *Figure 6* 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

$$V_{OUT}/V_{IN} = 1/(1 + (R_1 + R_2)C_2p + R_1R_2C_1C_2p^2).$$

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

Components Determine Response

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

$$V_{OUT}/I_{OUT} = R_L/(1 + (R_L + R_2)C_2p + R_LR_2C_1C_2p^2).$$

Making C2 relatively large eliminates overshoot and sine peaking. Alternatively, making C2 a suitable fraction of C1 (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 C1:C2 and R2: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 μF suits C3 because it serves only as a bypass for the 200 kΩ resistor. C4 helps reduce output ripple in single positive power-supply systems when VOUT approaches so close to ground that the op amp's output impedance suffers. In this circuit, using a tantalum capacitor of between 0.1 μF and 2.2 μF for C4 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 μF and 0.02 μF capacitors as the passive filter in *Figure 1* does with 1 μF. Thus, if you require a 100 Hz F/V converter, the circuit in *Figure 3* furnishes good filtering with C1 = 10 μF and C2 = 2 μF, and eliminates the 100 μF low-leakage capacitor needed in a passive filter.

Note also that because C1 always has zero DC voltage across it, you can use a tantalum or aluminum electrolytic capacitor for C1 with no leakage-related problems; C2, however, must be a low-leakage type. At room temperature, typical 1 μF 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 ± 30 ppm/°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 ppm/°C TC.

But the resistor-diode network (R_x, D1, D2) connected from pin 2 to ground in the *figure* can cancel the effect of the timing capacitor's large TC. When R_x = 240 kΩ, the current flowing through pin 1 will then have an overall TC of 110 ppm/°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°C (33 ppm/°C) during the oven test, adding 120 kΩ in series with $R_X = 240$ kΩ cancels the temperature-caused deviation. Or, if the full-scale output decreases by -0.04% per 20°C (-20 ppm/°C), just add 1.2 MΩ in parallel with R_X .

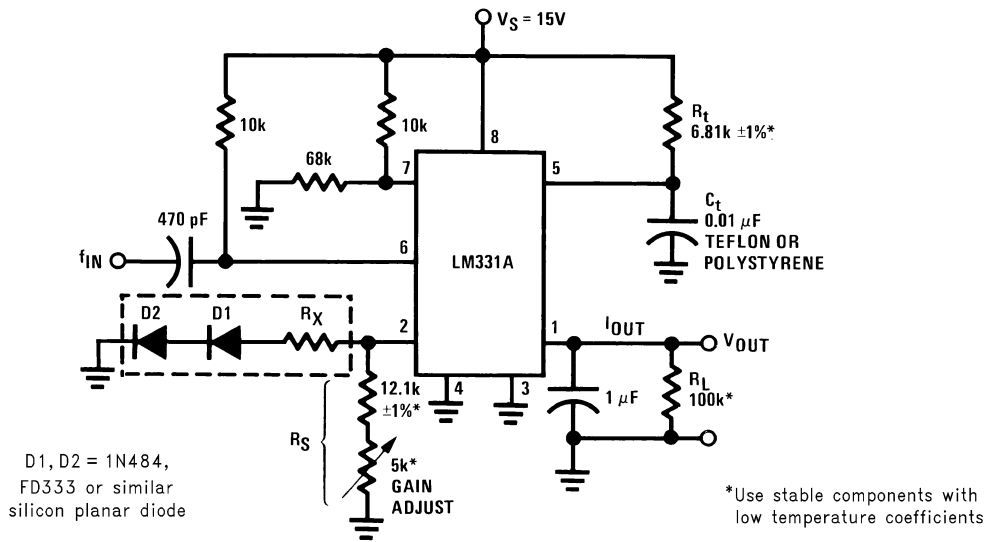
Note that to allow trimming in both directions, you must start with a finite *fixed* TC (such as the -110 ppm/°C of C_t), which then nominally cancels out by the addition of a finite *adjustable* TC. Only by using this procedure can you compensate for whatever polarity of TC is found by the oven test.

You can utilize this technique to obtain TCs as low as 20 ppm/°C, or perhaps even 10 ppm/°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°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°C if you trim for ± 5 ppm/°C at temperatures from +25°C to 60°C. None of the components in the *figure's* circuit offer linearity much better than 5 ppm/°C or 10 ppm/°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 kΩ or 270 kΩ), so you 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 kΩ to 220 kΩ, do not pull out the 240 kΩ part and put in a new 220 kΩ resistor—you will get much more consistent results by adding a 2.4 MΩ 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 (± 50 ppm/°C maximum) and RN55D film resistors (each ± 100 ppm/°C) for R_L , R_t and R_S , you probably won't be able to trim out the resulting ± 350 ppm/°C worst-case TC. Resistors with a TC specification of 25 ppm/°C usually work well. Finally, use the same resistor value (e.g., 12.1 kΩ $\pm 1\%$) 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/°C.

Whenever an op amp is used as a buffer (as in *Figure 3*), its offset voltage and current (± 7.5 mV maximum and ± 100 nA, respectively, for most inexpensive devices) can cause a ± 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.



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

00874107

Need a Negative Output?

If your F/V converter application requires a negative output voltage, the circuit shown in *Figure 7* 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

Need a Negative Output? (Continued)

circuit needs no cascade transistor. (Note, however, that while the circuit's nonlinearity error is negligible, its ripple is not.)

The circuit in *Figure 7* 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 kΩ and 2 MΩ.

An optional bypass capacitor (C2) 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.

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

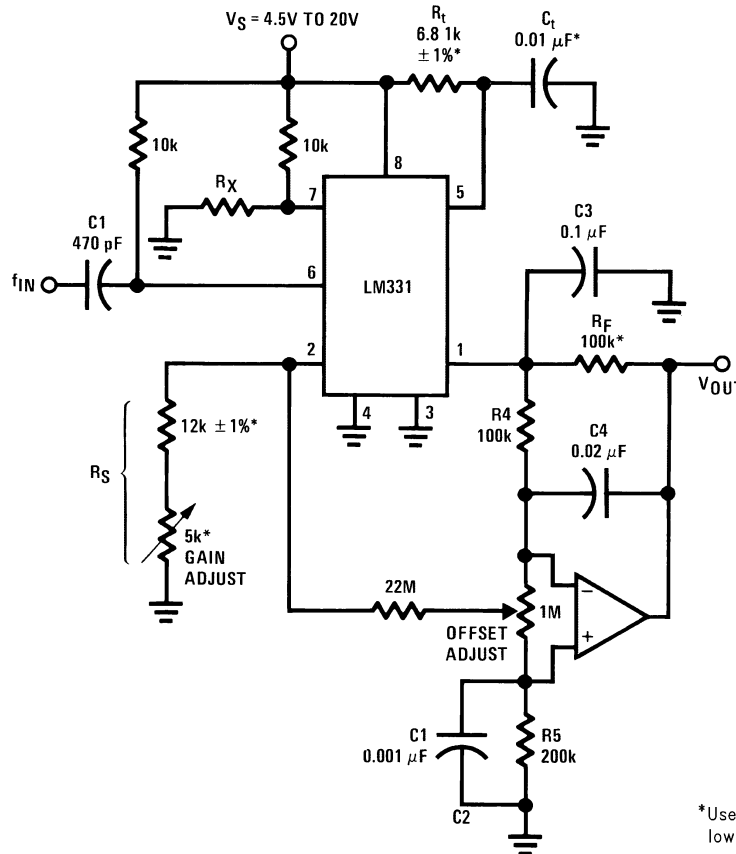
Here also, R₅ = R₄ + R_F = 200 kΩ provides the best bias current compensation.

The LM331 can handle frequencies up to 100 kHz by utilizing smaller-value capacitors as shown in *Figure 8*. This circuit increases the current at pin 2 to facilitate high-speed switching, but, despite these speed-ups, the LM331's 500 ppm/°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 kΩ provides first-order compensation, but you can trim it higher or lower if you need more precise TC correction.

A Familiar Response

The circuit in *Figure 7* exhibits the same 2-pole response—with heavy output ripple attenuation—as the noninverting filter in *Figure 3*. Specifically,



*Use stable components with low temperature coefficients

00874108

FIGURE 7. 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

A Familiar Response (Continued)

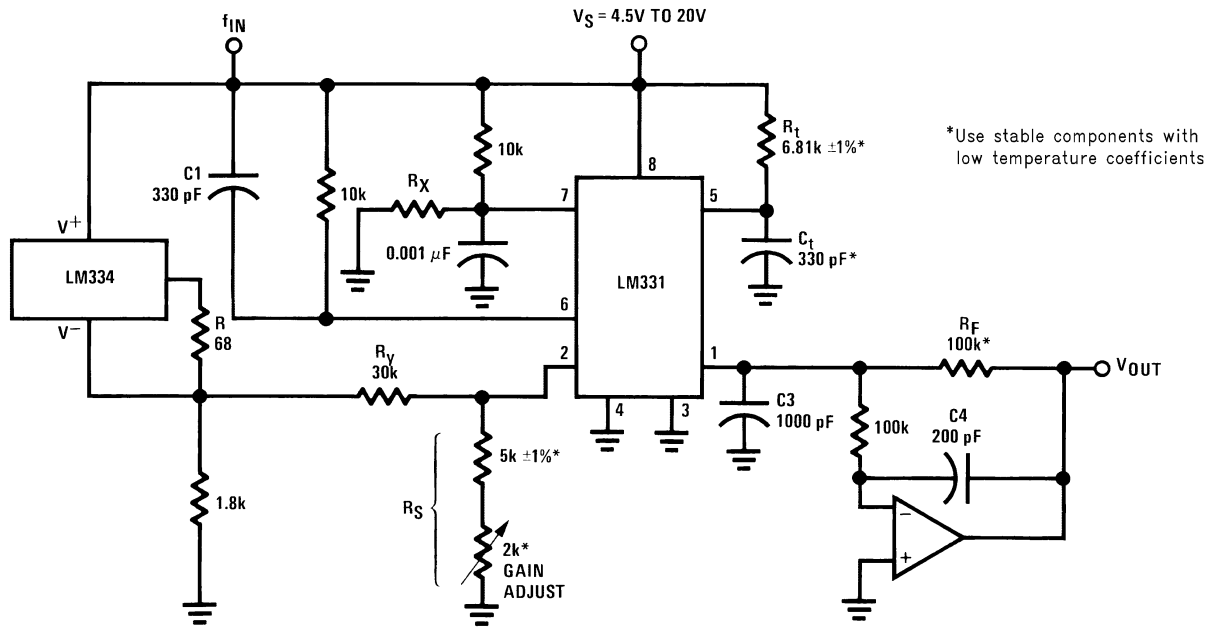


FIGURE 8. An LM334 Temperature Sensor Compensates for the F/V Circuit's Temperature Coefficient

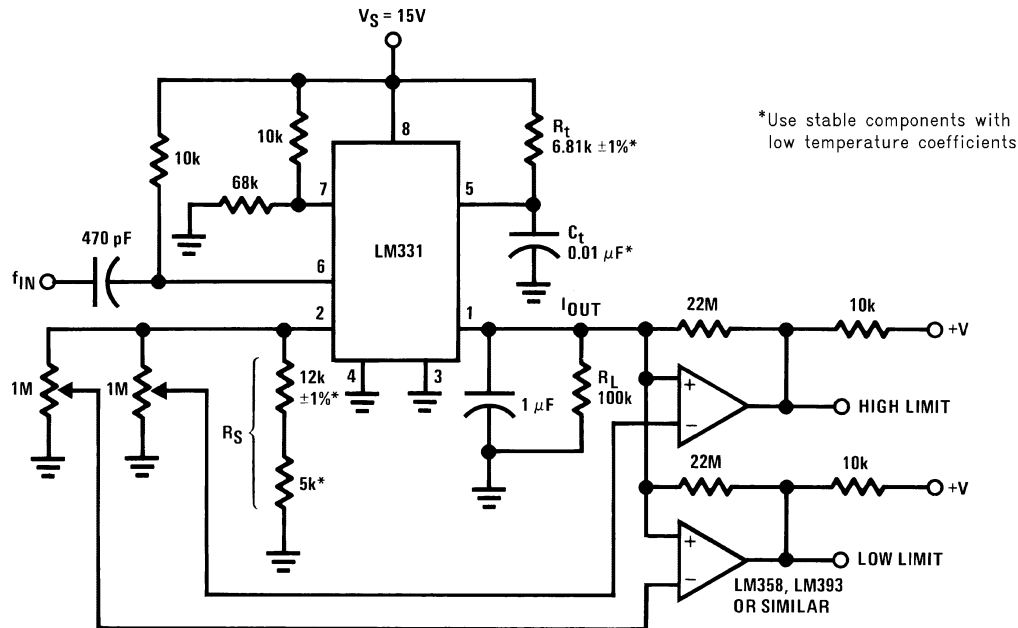
Detect Frequencies Accurately

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 9*. 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.

Detect Frequencies Accurately (Continued)



00874110

FIGURE 9. Combining a V/F IC with Two Comparators Produces a Slow-Response Frequency Detector

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.

LIFE SUPPORT POLICY

NATIONAL'S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS WRITTEN APPROVAL OF THE PRESIDENT AND GENERAL COUNSEL OF NATIONAL SEMICONDUCTOR CORPORATION. As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.
2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.



National Semiconductor Corporation
Americas
Email: support@nsc.com

National Semiconductor Europe
Fax: +49 (0) 180-530 85 86
Email: europe.support@nsc.com
Deutsch Tel: +49 (0) 69 9508 6208
English Tel: +44 (0) 870 24 0 2171
Français Tel: +33 (0) 1 41 91 8790

National Semiconductor Asia Pacific Customer Response Group
Tel: 65-2544466
Fax: 65-2504466
Email: ap.support@nsc.com

National Semiconductor Japan Ltd.
Tel: 81-3-5639-7560
Fax: 81-3-5639-7507

www.national.com