TEXAS
INSTRUMENTS

AN-D Versatile Monolithic V/Fs can Compute as Well as Convert With High Accuracy

ABSTRACT

The best of the monolithic voltage-to-frequency (V/F) converters have performance that is so good it equals or exceeds that of modular types. Some of these ICs can be designed into quite a variety of circuits because they are notably versatile. Along with versatility and high performance come the advantages that are characteristic of all V/F converters, including good linearity, excellent resolution, wide dynamic range, and an output signal that is easy to transmit as well as couple through an isolator.

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1   Introduction

One of the recently introduced monolithic types, the LM131, has both high performance and a design that is rather flexible. For instance, it can compute and convert at the same time; the computation is a part of the conversion. Among other functions, it can provide the product, ratio and square root of analog inputs.

This IC has an internal reference for its conversion circuitry that is also brought out to a pin, so it is available to external circuits associated with the converter. Not surprisingly, it turns out that any deviations of the reference, due to process variations and temperature changes have equal and opposite effects on the scale factors of the converter and the external circuitry. (This presumes, of course, that the scale factor of the external circuitry is a linear function of voltage.)
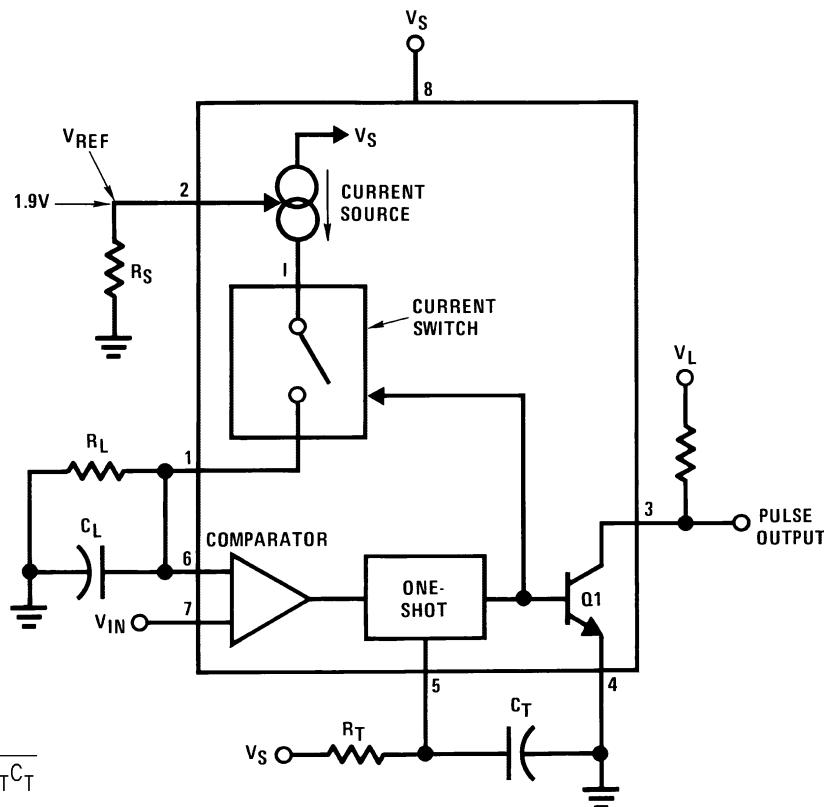
2   Precision Relaxation Oscillator

Before looking at some applications, quickly take a look at the basic circuit of an LM131 V/F converter (Figure 1). Basically, this IC, like any V/F converter, is a precision relaxation oscillator that generates a frequency linearly proportional to the input voltage. As might be expected, the circuit has a capacitor, C_L, with a sawtooth voltage on it. Generally speaking, the circuit is a feedback loop that keeps this capacitor charged to a voltage very slightly higher than the input voltage, V_{IN}. If V_{IN} is high, C_L discharges relatively quickly through R_L, and the circuit generates a high frequency. If V_{IN} is low, C_L discharges slowly, and the converter puts out a low frequency.

When C_L discharges to a voltage equal to the input, the comparator triggers the one-shot. The one-shot closes the current switch and also turns on the output transistor. With the switch closed, current from the current source recharges C_L to a voltage somewhat higher than the input. Charging continues for a period determined by R_T and C_T. At the end of this period, the one-shot returns to its quiescent state and C_L resumes discharging.

Resistor R_S sets the amount of current put out by the current source. In fact, the current in pin 1, with the switch on, is identical to the current in pin 2. The latter pin is at a constant voltage (nominally 1.90V), so a given resistor value can set the operating currents. When connected to a high impedance buffer, this pin provides a stable reference for external circuits.

The open-collector output at pin 3 permits the output swing to be different from the converter's supply voltage, if the load circuit requires. The supplies do not have to be separate, however, and both the converter and its load can use the same voltage.
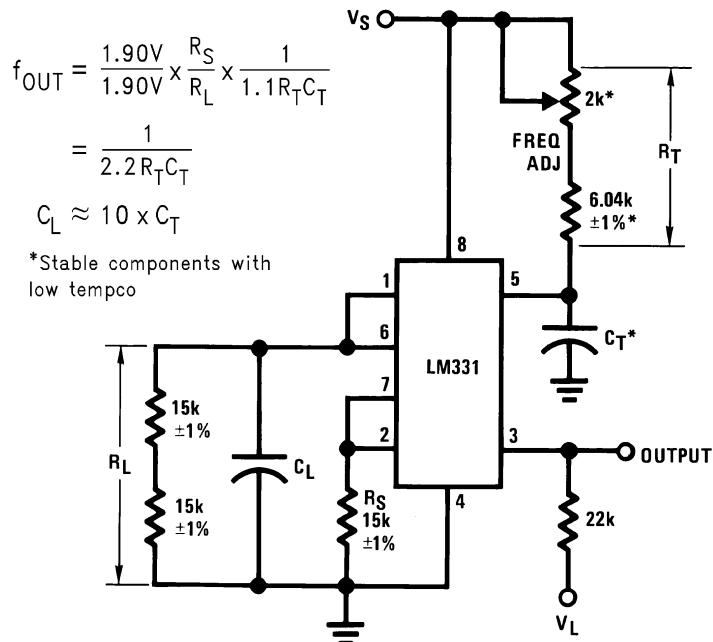
$$f_{OUT} = \frac{V_{IN}}{V_{REF}} \times \frac{R_S}{R_L} \times \frac{1}{1.1 R_T C_T}$$

A   A voltage-to-frequency converter such as this is a relaxation oscillator with a frequency proportional to the input voltage. Current pulses keep C_L's average voltage slightly greater than the input voltage.

Figure 1. Voltage-to-Frequency Converter

3   Steady as She Goes

By far the simplest of the circuits that make use of the reference output voltage from the LM131 is one that simply ties this output pin right back to the signal input. This connection is just a V/F converter with a constant input, which makes it a constant-frequency oscillator. Even with this simple circuit (Figure 2), variations in the reference voltage have two opposite effects that cancel each other out, so the circuit is particularly stable. In this type of circuit, the temperature-dependent internal delays tend to cancel as well, which is not true of relaxation oscillators based on op amps or comparators.

$$f_{OUT} = \frac{1.90V}{1.90V} \times \frac{R_S}{R_L} \times \frac{1}{1.1R_TC_T}$$

$$= \frac{1}{2.2R_TC_T}$$

$$C_L \approx 10 \times C_T$$

*Stable components with low tempco

A   A V/F converter is a stable-frequency oscillator if its input is connected to its reference output. If the reference voltage changes, the effects of the change cancel out, so the frequency does not change. With low tempco components for R_T and C_T, frequency stability vs temperature can be as good as ±25 ppm/°C.

Figure 2. Stable-Frequency Oscillator Using a V/F Converter

Resistors R_L and R_S are best taken from the same batch. (R_L must be larger than R_S, so it is made up of two resistors.) By doing this, the tempco tracking, which is the critical parameter, is five to ten times better than it would be if R_L were a single 30.1 kΩ resistor.

Although the reference output, pin 2, cannot be loaded without affecting the converter's sensitivity, the comparator input, pin 7, has a high impedance so this connection does no harm.
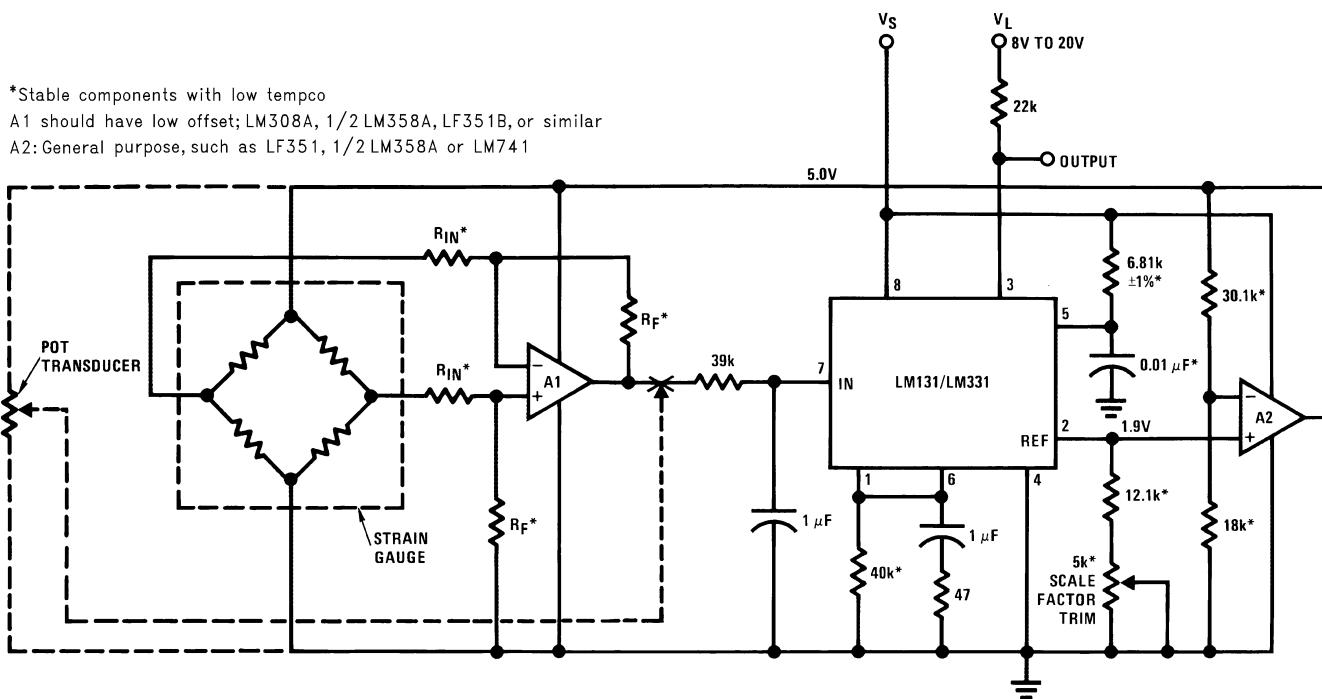
Frequency stability is typically ±25 ppm/°C, even with an LM331, which as a V/F converter is specified only to 150 ppm/°C maximum. From 20 Hz to 20 kHz, stability is excellent, and the circuit can generate frequencies up to 120 kHz.

Although the simplest way of using the reference output is to tie it back to the input, the reference can also be buffered and amplified to supply such external circuitry as a resistive transducer, which might be a strain gauge or a pot (Figure 3). As in the stable oscillator already described, deviations of the internal reference voltage from the ideal cause the transducer's and the converter's sensitivities to change equally in opposite directions, so the effects cancel.

In this circuit, op amp A2 buffers and amplifies the constant voltage at pin 2 of the converter to provide the 5V excitation for the strain gauge. Amplifier A1, connected as an instrumentation amplifier, raises the output of the strain gauge to a usable level while rejecting common-mode pickup.

A potentiometer-type transducer works just as well with this circuit. Its wiper output takes the place of A1's output as shown at the X.
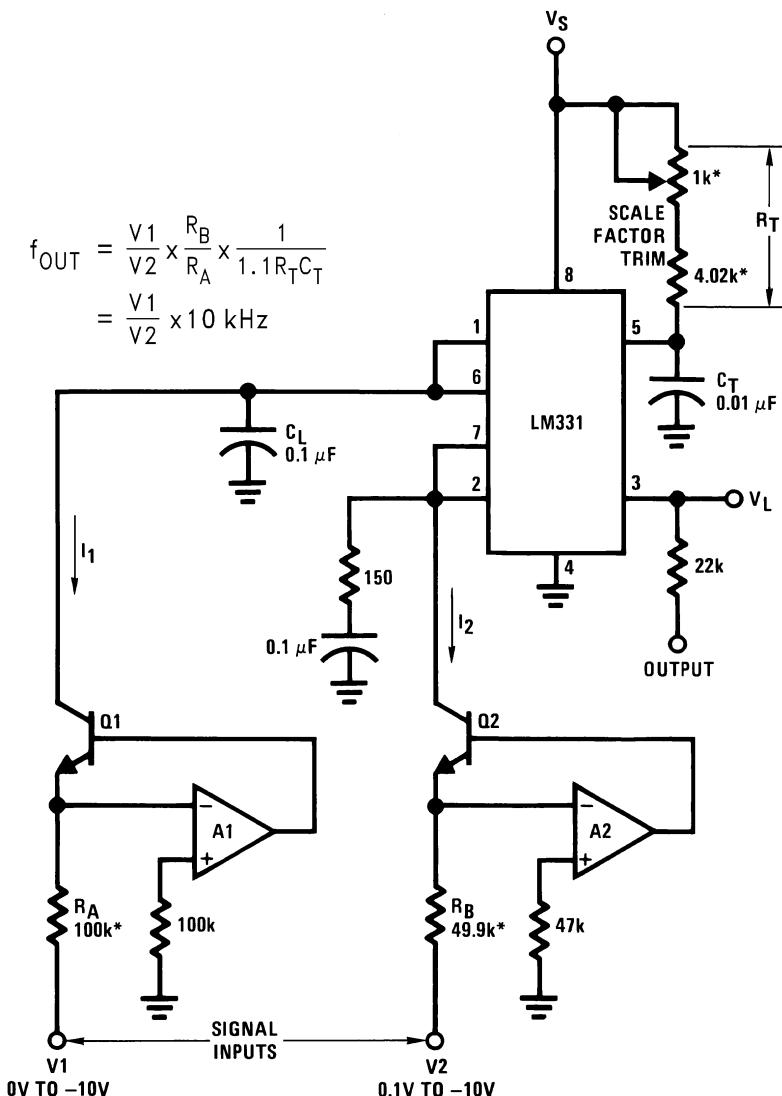
The reference terminal is both a constant voltage output and a current programming input. So far, its been shown simply with one or two resistors going to ground. It is, however, a full-fledged signal input that accepts a signal from a current source quite well.

A   In this strain-to-frequency converter, the converter's reference excites the strain gauge (or the optional pot) through buffer amp A2. This makes the circuit insensitive to changes in the reference voltage.

Figure 3. Strain-to-Frequency Converter

This extra input is what enables the LM131 to compute while converting. For instance, it will convert the ratio of two voltages to a frequency proportional to the ratio (Figure 4). The circuit is still a V/F converter, but has two signal inputs, both of them going to rather unorthodox places at that. The inputs, shown as voltages, are converted to currents by two current pumps (voltage-to-current converters). Of course, if currents of the proper ranges are available, the current pumps are not needed. The left current pump, which includes Q1 and A1, determines how fast capacitor C_L discharges between output pulses. The other pump sets the current in the reference circuit to control the amount of recharge current when the one-shot fires. Tying the comparator input, pin 7, to the reference pin sets the comparator's trip point at a constant voltage.
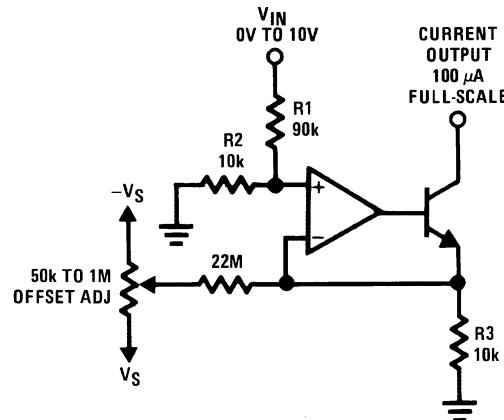
$$f_{OUT} = \frac{V1}{V2} \times \frac{R_B}{R_A} \times \frac{1}{1.1 R_T C_T}$$

$$= \frac{V1}{V2} \times 10 \text{ kHz}$$

A   *Stable components with low tempco
     A1, A2 should have low offset and low bias current: LM351B, LM358A, LF353B, or similar Q1, Q2: 2N3565, 2N2484,
     or similar high β

B   This circuit converts the ratio of two voltages to an equivalent frequency without a separate analog divider. Full-scale
     output is 15 kHz. The two op amp circuits convert the inputs to proportional currents.

Figure 4. Convert Ratio of Two Voltages to Equivalent Frequency

To get an idea of how the circuit works, consider first the effect of tripling the input voltage, V1. This make
C_L discharge to the comparator trip point three times as fast, so the frequency triples. Next, consider a
given change, such as doubling the voltage at the other input, V2. This doubles the recharge current to C_L
during the fixed-width output pulse, which means C_L's voltage increases twice as much during recharging.
Since the discharge into Q1 is linear (for V1 constant), it takes twice as long for C_L to discharge—the
frequency becomes half of what it was before.

Although the current pumps in Figure 4 must have negative inputs, rearranging the op amps according to
Figure 6 makes them accept positive inputs instead. Trimming out the offset in the op amp gives the ratio
converter better linearity and accuracy. The trim circuit in Figure 6a needs stable positive and negative
supplies for the offset trimmer, while the one in Figure 6b needs only a stable positive supply. Unmarked
components in Figure 6b are the same as in Figure 6a.

R1, R2, R3: Stable components with low tempco Q1: $\beta \geq 330$
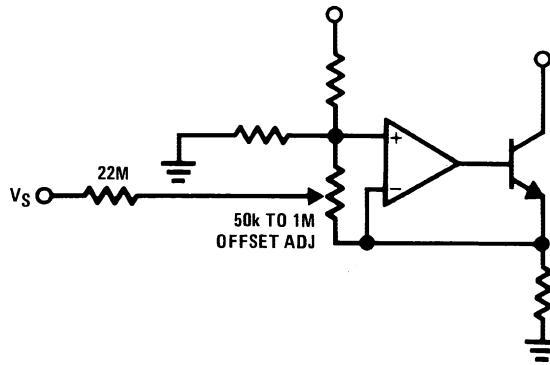
Figure 5. (a) Current Pump

Figure 6. (b) Current Pump

Figure 7. These current pumps adapt the converter circuits in Figure 4 and Figure 10 to positive input voltages. Optional offset trimming improves linearity and accuracy, especially with input signals that have a wide dynamic range

Note that the full-scale range of the current pumps can be changed by varying the value of the input resistor(s). If either of these pump circuits is used with a single positive supply, the op amp should be a type such as 1/2 LM358 or 1/4 LM324, which has a common-mode range that includes the negative-supply bus.

4 Computing Square Roots Implicitly

An analog divider computes the square root of a signal when the signal is fed to the divider's numerator input, and the output is fed back to the divider's denominator input.
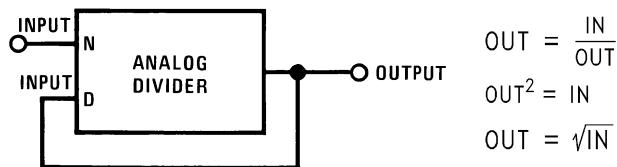

$$OUT = \frac{IN}{OUT}$$
$$OUT^2 = IN$$
$$OUT = \sqrt{IN}$$

Figure 8. Implicit Square Root Computation With Analog Divider

This type of computation is called implicit, because the end result of the computation is only implied, not explicitly stated by the equation that defines the computation.

In the implicit square root computing loop described in the text, a V/F converter serves as a divider. Since it is a converter, its inputs are voltages (or currents), but its output is a frequency. To connect its output back to one of its inputs so it will compute a square root means that its output frequency must be converted back to a voltage. This is taken care of by the frequency-to-voltage converter.
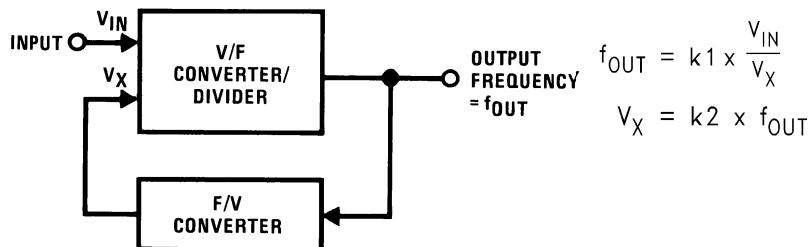

$$f_{OUT} = k1 \times \frac{V_{IN}}{V_X}$$

$$V_X = k2 \times f_{OUT}$$

Figure 9. Implicit Square Root Computation With V/F Converter

Doing some algebraic substitution shows that:

$$f_{OUT} = k3 \times \sqrt{V_{IN}}$$

where

$$k3 = \sqrt{k1/k2}$$

(1)

5   It'll Take Reciprocals

Taking the ratio of two inputs—in other words, doing division—is only one of the mathematical operations that can be combined with converting. Another one is a special case of division, which is taking reciprocals. In this instance, the numerator (V1 in Figure 4) is held constant, and the denominator, V2, changes over a wide range such as one or two decades. In this case, since the frequency is the reciprocal of the input, the period of the output is proportional to the input. When operated this way, the V2 current pump should have an offset trimmer. A constant current circuit is still needed to discharge capacitor C_L.

Nonlinearity (that is, deviation from the ideal law) with an LM331 is a little better than 1% for 10 kHz full-scale. Increasing C_T to 0.1 µF reduces the nonlinearity to below 0.2% while decreasing full-scale output to 1 kHz.

Two inputs can also be multiplied while converting to a frequency. The multiplying converter circuit (Figure 10) that does this has a more elaborate current pump than the ratio circuit of Figure 4. This pump is really two cascaded circuits; it includes op amps A2 and A3 as well as transistors Q2 and Q3. Current from this pump goes to pin 5 to control the one-shot's pulse width. (This current ranges from 13.3 µA to 1.33 µA.)

As in the ratio circuit, the left current pump controls the discharge rate of C_L. The other pump, however, controls the one-shot's pulse width to vary the amount that C_L charges during the pulse. If the V2 input is close to zero, the current from the pump into pin 5 is small, and the one-shot develops a wide pulse. This allows C_L to charge quite a bit. It takes a relatively long time for C_L to discharge to the comparator threshold, so the resulting frequency is low. As V2 goes negative (a greater absolute magnitude), the output frequency rises. Op amp A3 must have a common-mode range that extends to the positive supply voltage, which the specified types do.

Multiplying, dividing and converting can all be done at the same time by combining the V2 input current pump of Figure 4 with the circuit of Figure 10. If a scale-factor trimmer is needed, R4 in Figure 10 is a good choice, better than input resistors such as R1 or R2. Using the latter as trimmers would make the input impedance of the circuit change with trim setting.

Two V/F converter ICs along with some extra circuitry will take the square root of a voltage input. Square root functions are used mostly to simulate natural laws, but also to linearize functions that have a natural square-law relationship. One of the latter is converting differential pressure to flow, where flow is proportional to the square root of differential pressure.

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*Stable components with low tempco

$$f_{OUT} = \frac{V1}{10V} \times \frac{V2}{10V} \times 10\ kHz$$
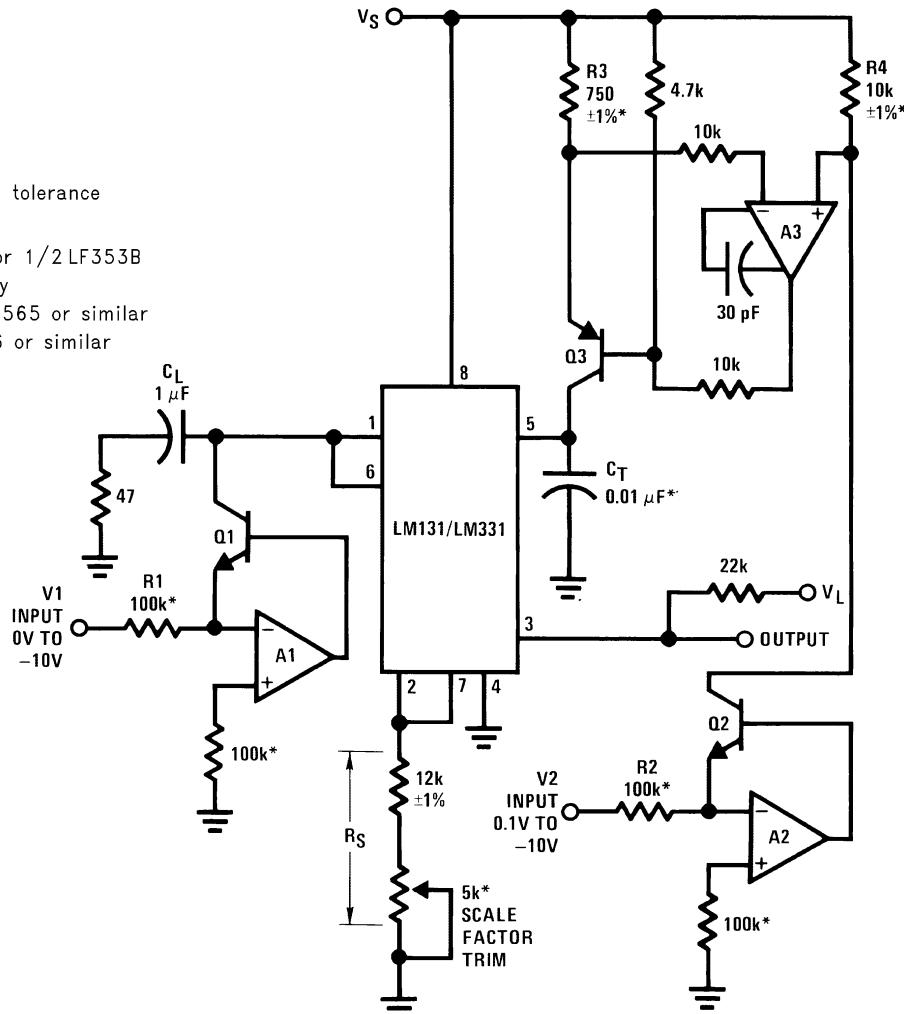
V_S = 15V, regulated and stable

$R3 = \left(\dfrac{15.00V}{+V_S} \times 750\,\Omega \text{ with} \pm 1\% \text{ tolerance}\right)$

A, A2: Each is 1/2 LM158/LM358A or 1/2 LF353B
A3: LM301A, LM307, or LF13741 only
Q1, Q2: High β such as 2N2484, 2N3565 or similar
Q3: High β such as 2N4250, 2N3906 or similar

A   A current pump that includes op amps A2 and A3 controls the pulse duration of the converter's internal one-shot.

Figure 10. The Product of Two Input Voltages Becomes an Equivalent Frequency in This Converter

6   Versatile Pin Functions Give Design Flexibility

Two features, the reference and the one-shot, of the LM131/LM331 V/F converter deserve a closer look because they are the key to its versatility. The simplified schematic of the chip, shown here along with a transducer and the components needed for a basic V/F converter (Figure 11), will help to illustrate how these features work.

The reference circuit, connected to pin 2, is both a constant voltage output and a current setting, scale-factor control input. The constant voltage can supply external circuitry, such as the transducer, that feeds the converter's input.

One great advantage of using the converter's internal reference to supply the external circuitry is that any variation in the reference voltage affects the sensitivities of the converter and the external circuitry by equal and opposite amounts, so the effects of the variation cancel.

While providing a constant voltage output, pin 2 also provides scale-factor, or sensitivity control for the converter. Current supplied to an external circuit by this terminal comes from the supply (V_S) through the current mirror and the transistor. The op amp drives this transistor to hold pin 2 at a constant voltage equal to the internal reference, which is nominally 1.9V.

The current mirror provides a current to the switch that is essentially identical to that in pin 2. This means that a resistor to ground or a signal from a current source will set the current that is switched to pin 1. In most circuits, a capacitor goes from pin 1 to ground, and the switched current from this pin recharges the capacitor during the pulse from the one-shot.

The one-shot circuit is somewhat like the well known 555 timer's circuit. In the quiescent state, the reset transistor is on and holds pin 5 near ground. When pin 7 becomes more positive than pin 6 (or pin 6 falls below pin 7), the input comparator sets the flip-flop in the one-shot.

The flip-flop turns on the current limited output transistor (pin 3) and switches the current coming from the current mirror to pin 1. The flip-flop also turns off the reset transistor, and the timing capacitor C_T starts to charge toward V_S. This charge is exponential, and C_T's voltage reaches 2/3 of V_S in about 1.1 $R_T C_T$ time constants. (The quantity 1.1 is −ln 0.333...) When pin 5 reaches this voltage, the one-shot's comparator resets the flip-flop that turns off the current to pin 1, discharges C_T, and turns off the output transistor.

If the voltages at pins 6 and 7 still call for setting the flip-flop after pin 5 has reached 2/3 V_S, internal logic not shown in this simplified diagram overrides the reset signal from the one-shot's own comparator, and the flip-flop stays set. In this instance, C_T continues charging past 2/3 V_S.
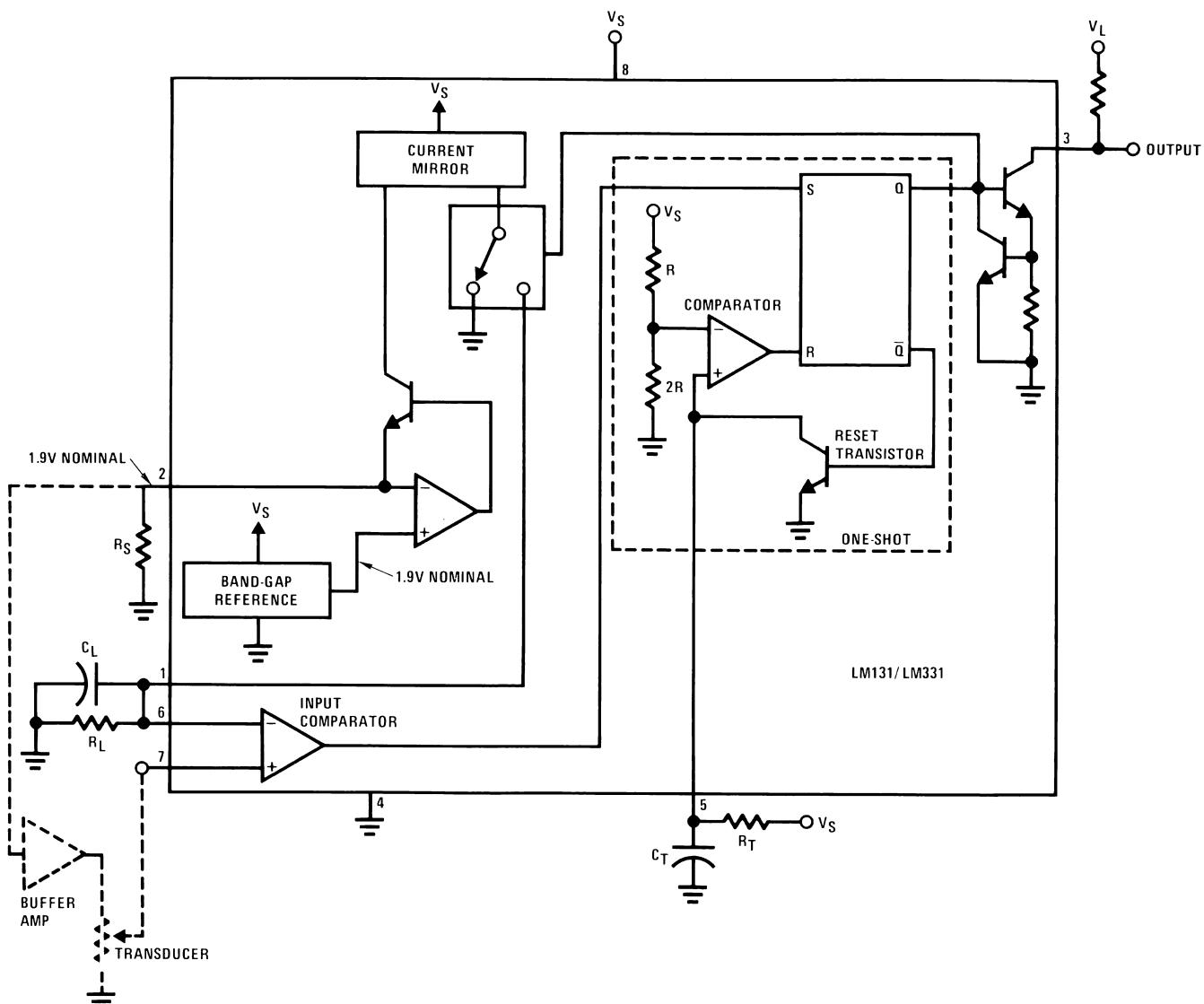
Figure 11. Simplified Schematic of LM131/LM331 V/F Converter, Plus a Transducer and Components Needed for a Basic V/F Converter

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7 Root Loop Computes

The circuit in Figure 12 is an implicit loop (see Section 4) that uses IC1 as a voltage-to-frequency converter and divider, and IC2 as a frequency-to-voltage converter. The F/V converter, IC2, and the current pump that includes A1 and the transistor return the output of IC1 to its denominator input. A relatively elaborate feedback circuit like this is needed to convert IC1's frequency output back to a current for its denominator input.
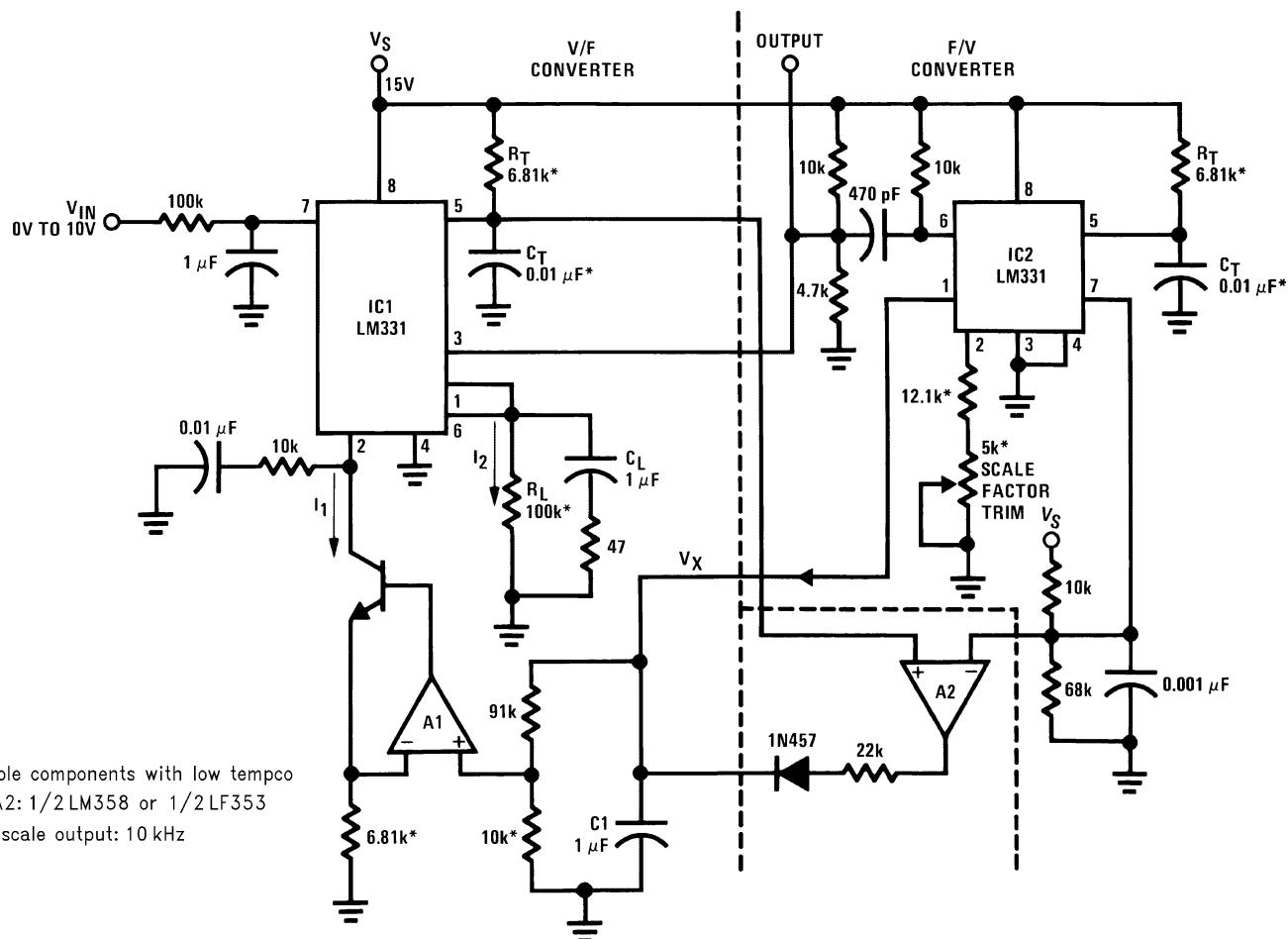
Looking at the circuit in more detail, IC1 puts out a frequency proportional to V_{IN} divided by the feedback voltage, V_X. The current I_1 is generated by a current pump that has V_X as its input (Figure 6*a*). To develop the feedback IC2 converts the pulse output from IC1 into standard width precision current pulses that charge capacitor C1. This capacitor integrates them into the voltage V_X, thus closing the loop.

Op amp A2, serving as a comparator, ensures that the circuit will always start and continue running. If V_{IN} suddenly jumps to a higher voltage, one pulse from the one-shot in IC1 may not be enough to recharge C_L to a voltage higher than the input. In such a case, the IC's internal logic keeps its internal current switch turned on, and the voltage on C_L ramps up until it exceeds the input. During this time, however, IC1's output has not changed state. (Such a temporary hang-up is not unique to this circuit, and equivalent things happen to other V/Fs besides the LM131/LM331.) What is worse here, though, is that the lack of pulses to IC2 means that V_X and I_1 decay. The recharging current, I_2, is the same as I_1, so it not only becomes progressively harder for the voltage on C_L to catch up with the input, it may even fail to catch up entirely if ($I_2 \times R_L$) is less than the input voltage.

As a sign of this condition, when the converter hangs up, the one-shot's timing node, pin 5, continues to charge well beyond its normal peak of 2/3 V_S. As soon as the comparator A2 detects this rise, it pulls up voltage V_X, current I_1 increases, and the loop catches its breath again.
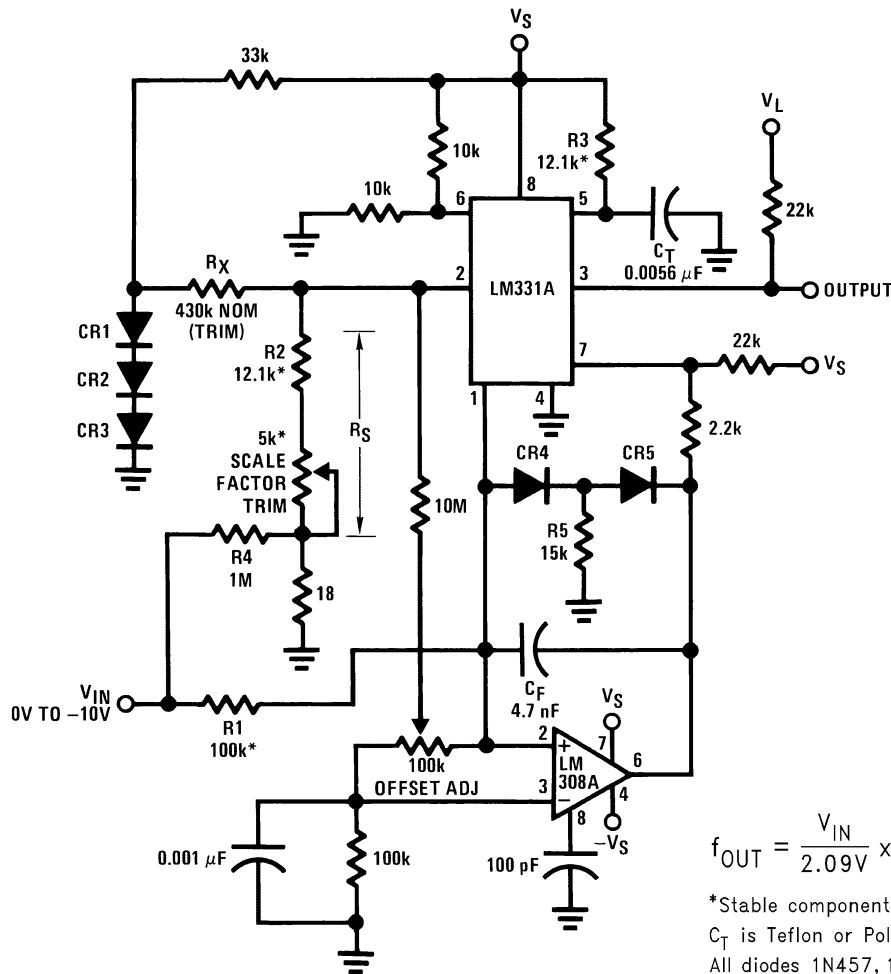
After all these nonlinear computations, this last circuit is about as linear as it can be. It is a precision, ultralinear V/F converter based on an LM331A (Figure 13) that has several detail refinements over previous V/F converter circuits. Choosing the proper components and trimming the tempco give less than 0.02% error and 0.003% nonlinearity for a ±20°C range around room temperature.

This circuit has an active integrator, which includes the op amp and the integrating feedback capacitor, C_F. The integrator converts the input voltage, which is negative, into a positive-going ramp. When the ramp reaches the converter IC's comparator threshold, the one-shot fires and switches a pulse of current to the integrator's summing junction. This current makes the integrator's output ramp down quickly. When the one-shot times out, the cycle repeats.

A   Two converter ICs generate an output frequency proportional to the square root of the input voltage. The circuit is an
implicit loop in which IC1 serves as a divider and V/F converter. This IC's output goes back to its denominator input
through F/V converter IC2 to make the circuit output equal the input's square root.

Figure 12. Circuit Output is Equal to the Square Root of the Circuit Input

A   This circuit features an ultraprecision V/F converter, capable of better than 0.02% error and 0.003% nonlinearity for a ±20°C Range about room temperature.

Figure 13. V/F Converter Augments the Basic Converter With an External Integrator

There are several reasons this converter circuit gives high performance:

- A feedback limiter prevents the op amp from driving pin 7 of the LM331A negative. The limiter circuit arrangement bypasses the leakage through CR5 to ground via R5, so it will not reach the summing junction. Bypassing leakage this way is especially important at high temperatures.

- The offset trimming pot is connected to the stable 1.9V reference at pin 2 instead of to a power supply bus that might be unstable and noisy.

- A small fraction (180 µV, full-scale) of the input voltage goes via R4 to the R_S network, which improves the non-linearity from 0.004% to 0.002%.

- Resistors R2 and R3 are the same value, so that resistors such as Allen-Bradley type CC metal-film types can provide excellent tempco tracking at low cost. (This tracking is very good when equal values come from the same batch.) Resistor R1 should be a low tempco metal-film or wirewound type, with a maximum tempco of ±10 ppm/°C or ±25 ppm/°C.

In addition, C_T should be a polystyrene or Teflon type. Polystyrene is rated to 80°C, while Teflon goes to 150°C. Both types can be obtained with a tempco of −110 ±30 ppm/°C. Choosing this tempco for C_T makes the tempco, due to C_T, of the full-scale output frequency 110 ppm/°C.

Using tight tolerance components results in a total tempco between 0 ppm/°C and 220 ppm/°C, so the tempco will never be negative. The voltage at CR1 and R_X has a tempco of −6 mV/°C, which can be used to compensate the tempco of the rest of the circuit. Trimming R_X compensates for the tempco of the V/F IC, the capacitor, and all the resistors.

A good starting value for selecting R_X is 430 kΩ, which gives the 135 µA flowing out of pin 2 a slope of 110 ppm/°C. If the output frequency increases with temperature, a little more conductance should be added in parallel with R_X.

When doing a second round of trimming, though, note that a resistor of, say, 4.3 MΩ, has about the same effect on tempco when shunted across a 220 kΩ resistor that it does when shunted across one of 430 kΩ, namely, −11 ppm/°C. This technique can give tempcos below ±20 ppm/°C or even ±10 ppm/°C.

Some precautions help this procedure converge:

*   Use a good capacitor for C_T. The cheapest polystyrene capacitors will shift in value by 0.05% or more per temperature cycle. The actual temperature sensitivity would be indistinguishable from the hysteresis, and the circuit would never be stable.
*   After soldering, bake and/or temperature-cycle the circuit (at a temperature not exceeding 75°C if C_T is polystyrene) for a few hours, to stabilize all components and to relieve the strains from soldering.
*   Do not rush the trimming. Recheck the room temperature value, before and after the high temperature data are taken, to ensure that hysteresis per cycle is reasonably low.
*   Do not expect a perfect tempco at −25°C if the circuit is trimmed for ±5 ppm/°C between 25°C and 60°C. If it has been trimmed for zero tempco while warm, none of its components will be linear to much better than 5 ppm/°C or 10 ppm/°C when it is cold.

The values shown in this circuit are generally optimum for ±12V to ±16V regulated supplies but any stable supplies between ±4V and ±22V would be usable, after changing a few component values.

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