Bob Pease on bounding and clamping techniques

Paul Rako - September 28, 2011

Tim Hoeppner, a product development engineer at Norscan Instruments Ltd. asked if he could purchase and old 1983 *EDN* article that Bob Pease references in his excellent book on troubleshooting. Since I have paper copies of *EDN* back to 1974, his request landed in my inbox. I guess nominally we are supposed to charge 25 bucks for old articles, but I could tell Tim was a diligent engineer with an inquisitive mind, so I just scanned the 10-page article and mailed it to him. His response shows his good character, as he wrote back:

- Thank you very much for digging this up for me. Being a junior engineer I'm just learning about all of Bob's amazing work for the electronics industry. I read his bio on *EDN* after he passed away and was immediately inspired. I ended up purchasing several of his and Jim Williams' books and am so impressed. I was amazed at how fun they are to read. I really think you guys at *EDN* are doing an awesome job at promoting all their work, it must have been quite the honor to know them.

I was glad to dig out and scan the article for Tim since it was such a good one. I have not OCR'ed it since that takes well over a day, but here are the raw scans, click on any image to get the 1024 wide one that you should be able to read.

Bounding, clamping techniques improve circuit performance
EDN, November 10, 1983

Bounding, clamping techniques improve circuit performance

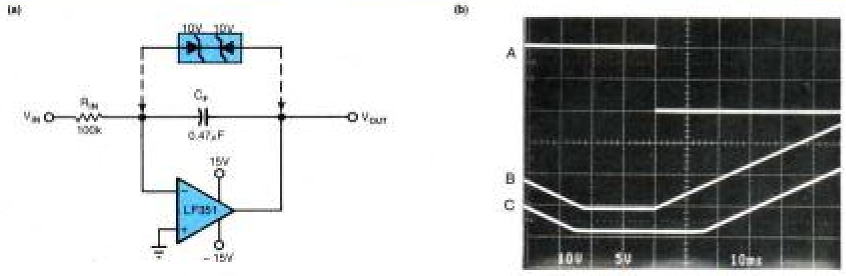
Circuit configurations that limit amplifiers' input or output excursions can yield improvements in symmetry and transient response and simultaneously protect circuits from overdrive damage.

Robert Pease, *National Semiconductor Corp*

By applying the bounding and clamping techniques described in this article, you can reduce saturation delays arising from overdrive and prevent damage to your amplifier circuit or its succeeding stages. The techniques also allow you to obtain functions that are otherwise difficult to realize—eg, absolute-value (precision-rectifier) circuits and high-symmetry clamps.

Sometimes it's necessary to use a feedback bound if you need prompt response from a circuit. Consider, for example, **Fig 1a**'s integrator circuit without the zener feedback bound (shown by dashed line). If the input voltage is near +10V, the output can hit its negative rail at −13V. When the input next goes negative, you might expect the circuit to start immediately integrating upward. However, as **Fig 1b** shows, the output response can be delayed because the amplifier has been "out of control" so long. The feedback capacitor charges to 23V (not just 13V); the higher voltage translates to an extra 16-msec delay before the output can begin to move.

In some servo or control-loop systems, this delay can degrade performance to an intolerable level. However, you can avoid the delay by using the feedback clamp. The zener-diode pair allows the op amp to retain control



TRACE	VERTICAL	HORIZONTAL
A	10V/DIV	10 mSEC/DIV
B	5V/DIV	10 mSEC/DIV
C	5V/DIV	10 mSEC/DIV

Fig 1—A simple, unbounded integrator circuit (a) *can suffer from long delays when recovering from amplifier saturation—trace* **C** *in* **(b).** *Adding the bounding-diode (dashed-line) circuit eliminates the delay (trace* **B**).

Simple bounding degrades speed

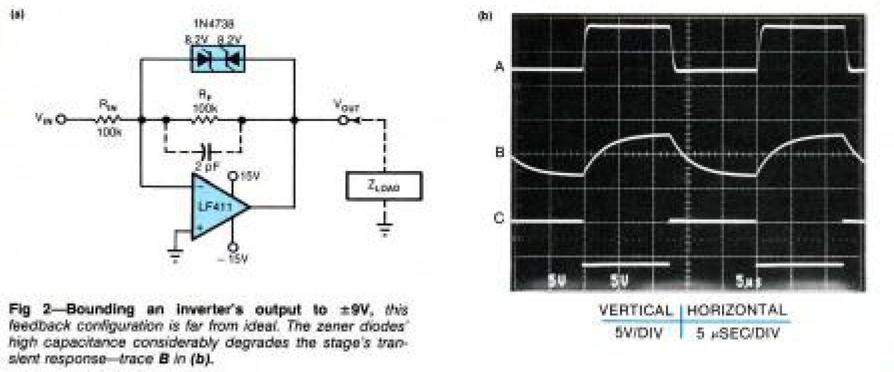


Fig 2—Bounding an inverter's output to ±9V, *this feedback configuration is far from ideal. The zener diodes' high capacitance considerably degrades the stage's transient response—trace* ***B*** *in* ***(b).***

at all times; therefore, as soon as the input goes negative, the output rises. Indeed, the op amp's output never reaches −13V, because as soon as it attains approximately −10.7V, a zener diode conducts and holds the summing junction at 0V. Any excess current fed to the input does no harm; it's merely shunted off by the feedback bound.

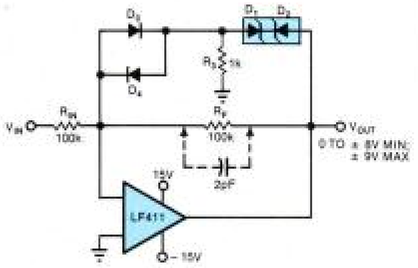
Feedback bounds can help in other areas also. Imagine a situation, for example, in which an inverter circuit must drive a load from 0V to at least ±8V, but damage or overload considerations dictate that the output not exceed ±9V. A pair of ideal zener diodes, implemented as the Model 1N4738 diodes are in **Fig 2a**'s circuit, would do the job. Real zener diodes, however, are far from ideal; even the best of them have high capacitance.

Because the 1N4738's 45-pF junction capacitance acts as a large damper, it degrades the unbounded circuit's fast response (**Fig 2b,** trace **A**), slowing it down considerably (trace **B**). You can avoid this undesirable slowdown by using the circuit in **Fig 3.** Here the feedback bound is not merely a pair of zener diodes, but a network of zeners and signal diodes. When the op amp's output tries to slew rapidly, a capacitive current flows through the zeners; however, it flows through R_3 to ground instead of through D_3 or D_4.

This network's speed performance is vastly improved over that of **Fig 2**'s circuit. In fact, you'd be well advised to add the 2-pF feedback capacitor to avoid overshoot and ringing. **Fig 3**'s circuit does not give perfect performance, however, because zener tolerances can cause the positive and negative limits to be mismatched by as much as 0.5V or even by 10%. Fortunately, the next circuit (**Fig 4**) yields inherently high symmetry, along with other benefits.

When driven to its positive limit, the output voltage is $V_{D3(ON)}+V_{D2(ON)}+V_{D5}$. At the negative limit, it's $V_{D1(ON)}+V_{D4(ON)}+V_{D5}$. Inasmuch as the dominating term (zener voltage V_{D5}) is the same for both expressions, and the signal diodes' forward voltages tend to match within 10 or 20 mV, you can see that this circuit's bound symmetry shows improvement by a factor of 10 to 20 compared with the basic 2-zener circuit.

Note that when V_{OUT} is +8.5V, D_1 is definitely ON, but D_2 is just preparing to conduct. Thus, the low



NOTES:
D_1, D_2 = 1N4737A (7.5V ± 5%)
D_3, D_4 = LOW-LEAKAGE OR FAST-RECOVERY TYPES, DEPENDING ON APPLICATION

Fig 3—This configuration eliminates the zener diode's capacitive effects *by shunting capacitive currents to ground.*

leakage of D_1 and D_2 is responsible for the circuit's excellent linearity and accuracy in its linear region. For this reason, a high-leakage diode such as a 1N914 is inappropriate, but a collector-base junction is a wise choice (see **box**, "So you say you need a diode?"). Resistors R_1 and R_2 ensure that D_3 is always biased ON for all conditions at the input or output.

Improve the integrator

Did the addition of zener diodes to **Fig 1a**'s circuit fully solve the integrator's problem? Not quite: The design of zener bounds is not so trivial. Consider, for example, **Fig 5a**'s configuration. Assume the output is driven near its limit. When the input signal goes to zero, the integrator's output should hold at +10V, but instead it droops down a full volt because of zener leakage (**b**). Close inspection of a typical 10V zener's spec sheet reveals, for example, that 1-μA leakage at 7.6V is acceptable.

Considering the 1-μA max at 7.6V, a leakage of 10 to 100 μA could exist at 8.5 or 9.5V (because of a soft knee)—and this high figure would *not* be a reason for rejection by the zener's manufacturer. Leakages of this order, however, can cause gross errors in a simple bound circuit.

Fortunately, you can also use the high-performance bound circuitry of **Fig 3** or **Fig 4** with the integrator. With these substitutions, the integrator performs with excellent accuracy to within 0.5V of its limit without leakage problems. This statement is valid even if the zener diode is leaky or has a soft knee, because the leakage flows through R_2 (**Fig 3**) or R_1, R_2 (**Fig 4**). Thus it can't flow into the summing point and cause errors. You can, therefore, use standard, low-cost components

So you say you need a diode?

When you need an appropriate diode for a critical application, you're often faced with a difficult choice. Diodes have combinations of characteristics, so it's necessary to consider the particular parameters that are crucial to your circuit. The nearby **table** gives salient characteristics for fast-recovery and low-leakage diodes, as well as home-brew diodes made from transistor junctions.

Note, for example, that the ubiquitous 1N914 (or 1N4148) features fast recovery, but it's relatively leaky. A 2N4250's collector-base junction, on the other hand, has extremely low leakage, but slow recovery time. The same device's emitter junction, meanwhile, offers very fast recovery, but will withstand only 6V and is moderately capacitive. So you can see, your choice inevitably involves a tradeoff. The nearby **figure (a)** and **(b)** show typical hookups for transistor-junction diodes.

What about monolithic diode arrays? Forget it—these diodes are likely to have excessive leakages and capacitances to the substrate; moreover, when one diode conducts, it injects carriers in such a way that every other diode in the IC array develops a high leakage.

It's a little-known fact that slow, low-leakage diodes often not only turn off slowly, but they also turn *on* slowly. The **photo** shows the output voltage of **Fig 11b**'s circuit in the special case in which $V_Z=0$ (both zeners shorted), $R_{IN}=1\ k\Omega$, $D_1=1N914$ and $D_2=1N457$.

The 1N914 turns on and off very quickly. The 1N457 stores charges and conducts for 500 nsec after the input voltage falls to zero. It also fails to start conducting until 40 nsec after its terminal voltage has risen above 0.7V. Fortunately, you can avoid these overshoots by using emitter-base junctions and 1N914s.

Be warned that the overshoot shown is excessive mainly at repetition rates below 20 kHz—it actually shrinks and looks acceptable at frequencies above 800 kHz, so it's a particularly insidious and sneaky kind of overshoot. Note also that not all manufacturers' 1N457s exhibit this phenomenon, so take care in qualifying your particular vendor.

For extremely low leakage (for example, in **Fig 13a**'s circuit), consider using collector-base junctions. If, for instance, you need leakage lower than 100 pA, then it's often much less costly to test transistors with a 98% yield to this spec than to shop for a diode with low leakage but a high price.

Some low-leakage transistors to consider are the 2N930, 2N3707 and 2N4250. However, most other inexpensive, small-signal transistors have an excellent yield to a leakage spec of 30 pA max at 5V, even though the spec sheet guarantees 10 nA.

What about zener diodes? Typically, 6.2V (and higher) zeners have crisp knees, low leakage and adequately low series resistance. On the other hand, devices below 4.7V usually have soft knees, unacceptable leakage, high series resistance, high noise and poor stability. For low-voltage bounding, therefore, you'd be well advised to consider "IC zeners", such as the LM385-1.2 and -2.5 or the LM336-2.5 and -5.0 for 1.2, 2.5 and 5V needs; the adjustable LM385 suits use in 1.2 to 5.3V applications.

in these two high-performance bound circuits in a variety of applications.

Adjustable bound is better

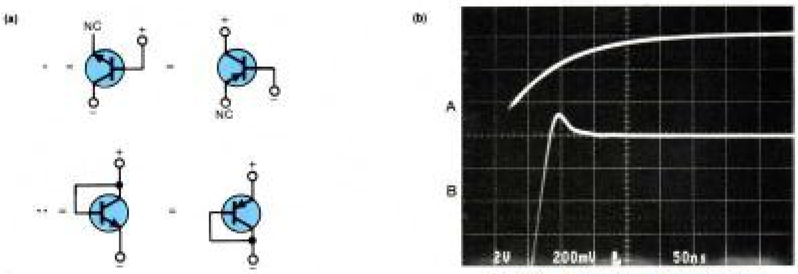
You might have noticed that some of the circuits presented could have substantial temperature coefficients (2 or 3 mV/°C), because of the zener-diode drift. Fortunately, you can use a micropower voltage reference—such as the LM385—to improve the TC (the reference's equivalent circuit is shown in **Fig 6a**). Applied in **Fig 6b**'s circuit, the device senses D_5's ON voltage, and uses this voltage to compensate for the forward voltage of D_1 and D_4 or D_2 and D_3, whichever is the case.

The resulting bound voltage has a low 0.2-mV/°C TC and a reasonably low (40Ω at 1 mA) impedance at any bound voltage from 3.75 to 6.3V. The LM385 itself is limited to 5.3V, but you could add an LM336-5 or similar 5V reference-diode IC to make, for example, a high-performance ±10V adjustable bound. Insert the device between points A and B in **Fig 6b** and adjust potentiometer R_3 for the desired output voltage.

Finally, if your application can't tolerate leakage-induced errors at high temperatures, consider the high-performance circuit in **Fig 7.** By adding a diode/resistor stage to a normal bound circuit, you can obtain excellent, low-leakage performance at temperatures as high as 125°C. The bound-current leakage is less than 1 nA at ±10.4V output at all temperatures. In addition, the output is limited to less than ±12V for bound currents as high as 1 mA. Note that an LM11A is a good choice for this circuit—its bias current is less than 0.15 nA; moveover, its offset measures less than 0.12 mV over −55 to +125°C.

TYPICAL DIODE CHARACTERISTICS

TYPE	RECOVERY TIME	CAPACITANCE (0V)	MAXIMUM VOLTAGE	LEAKAGE (5V)	SERIES RESISTANCE
1N914 OR 1N4148 (FAST; GOLD DOPED)	2 NSEC	1.5 PF	75V	7 NA	2.6 Ω
1N457 OR 1N484 (LOW LEAKAGE)	300 NSEC	3 PF	70 TO 125V	100 PA	2 Ω
ID-100-1 (LOW LEAKAGE)	200 NSEC	1 PF	30 V	6 PA (MAX)	5 Ω
COLLECTOR-BASE JUNCTION (EMITTER OPEN)*	200 NSEC	3 PF	30 TO 60 V	4 PA (TYP)	3 Ω
C/B-EMITTER JUNCTION**	1 NSEC	5 PF	6 TO 8V	10 PA	4 Ω



TRACE	VERTICAL	HORIZONTAL
A	2V/DIV	50 NSEC/DIV
B	0.2V/DIV	50 NSEC/DIV

Diode characteristics vary wildly, *as is evident in the* **table.** *Your choice almost invariably involves a tradeoff involving speed, capacitance, voltage breakdown and leakage. It's often wise to use transistor junctions as diodes—***(a)***'s two possible connections yield extremely low leakage and very fast recovery time, respectively. The* **photo** *shows a 1N457's long turn-on time in* **Fig 11b***'s circuit. Trace* **A** *is the circuit's input voltage;* **B** *is the diode voltage.*

Single-zener network enhances symmetry

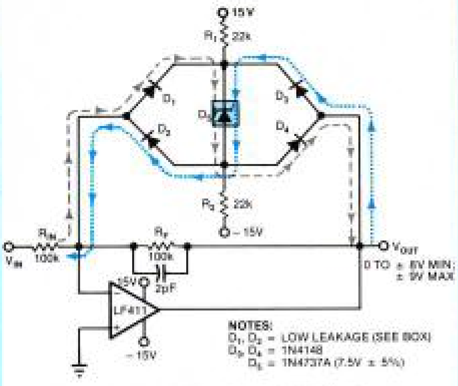


Fig 4—Improving on Fig 3's circuit, *this feedback connection enhances symmetry by a factor of 10 to 20 by using the same zener diode to set both positive and negative limits.*

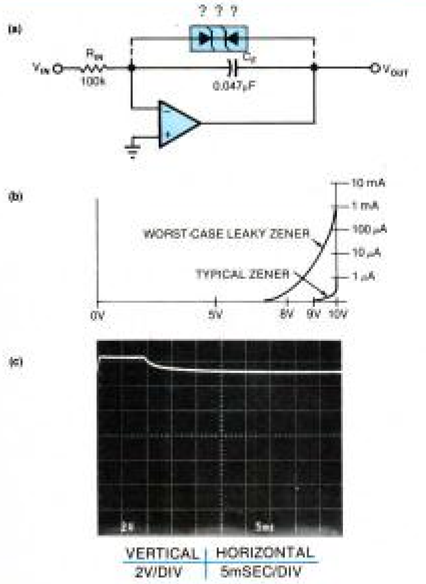
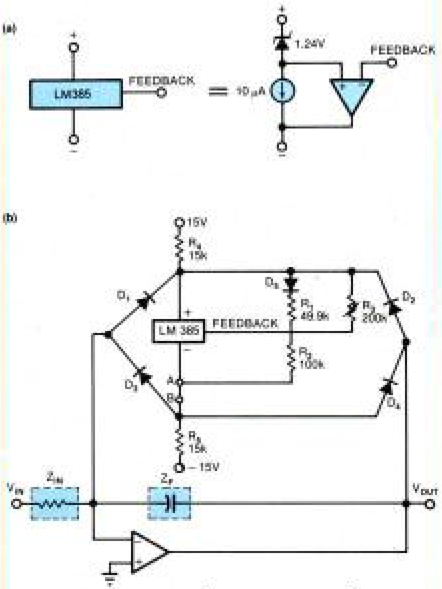


Fig 5—Zener-diode leakage *degrades performance in this circuit. It can cause the output to droop a full volt more negative, for example, than the theoretical bounded −10V. Overcome this problem by using* ***Fig 3****'s or* ***Fig 4****'s circuit.*



$$V_{BOUND} = V_{D1} + V_{D4} + 1.24V + \frac{R_2}{R_3}(1.24V - V_{D5}) + 1.24V\frac{R_2}{R_3}$$
$$= 1.24V\left(3 + \frac{R_2}{R_3}\right)$$

NOTES:
DIODES = LOW-LEAKAGE TYPES

Fig 6—Improve temperature coefficients *by using an "IC zener".* ***(a)*** *gives the IC's equivalent circuit;* ***(b)*** *shows a circuit whose output limits are set by a resistor ratio.*

The bound circuits presented to this point all have finite slope when overdriven. For example, when the input current increases from its normal 10 to 100 µA levels to 1 or 5 mA beyond the desired limiting input threshold, the output voltage can increase by as much as 80 to 100 mV. To obtain a very sharp knee in a precision analog circuit, you might want to hold this error down to 1 mV.

You can attain this low error, but at the cost of some speed and complexity. **Fig 8** shows a general-purpose limiter using two or more op amps. If sections **A** and **B** are connected, for example, V_{OUT} will be $-V_{INA}$ or $-V_{INB}$, whichever is more positive. Thus, if V_{INB} is +8V, the output will normally be $-V_{INA}$, but it will be limited to −8V as its most negative value.

If, instead, you disconnect section **B** and connect

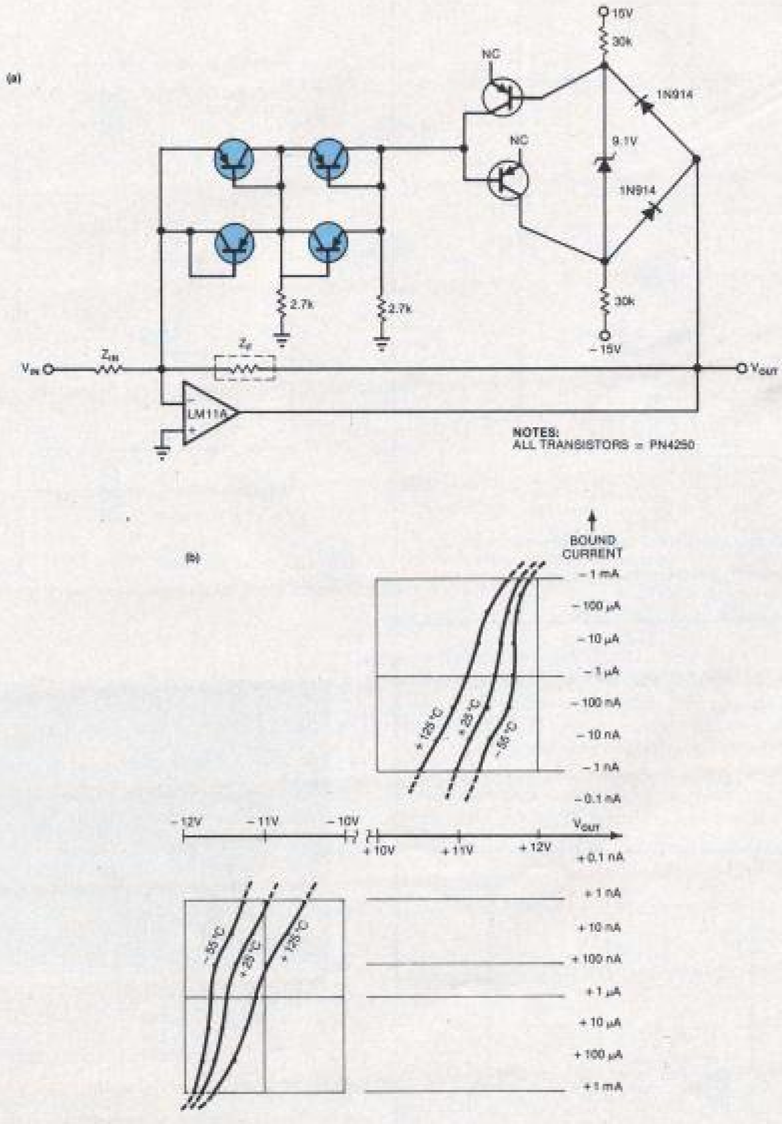
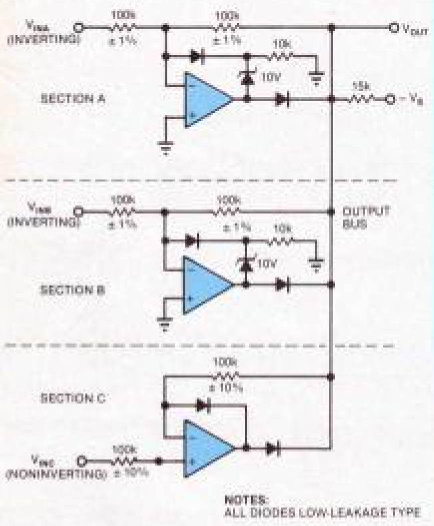


Fig 7—Eliminating leakage effects, *this circuit operates at temperatures as high as 125°C. Using a low-bias-current amplifier, it limits outputs to ±12V. Note the use of transistor junctions as low-leakage diodes.*

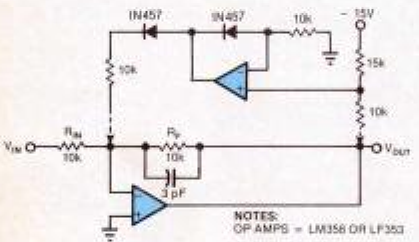


NOTES:
ALL DIODES LOW-LEAKAGE TYPE

Fig 8—Featuring a very sharp knee, *this circuit limits output change to less than 1 mV for inputs as large as several volts beyond the limiting threshold. The circuit also performs the absolute-value (rectification) function.*

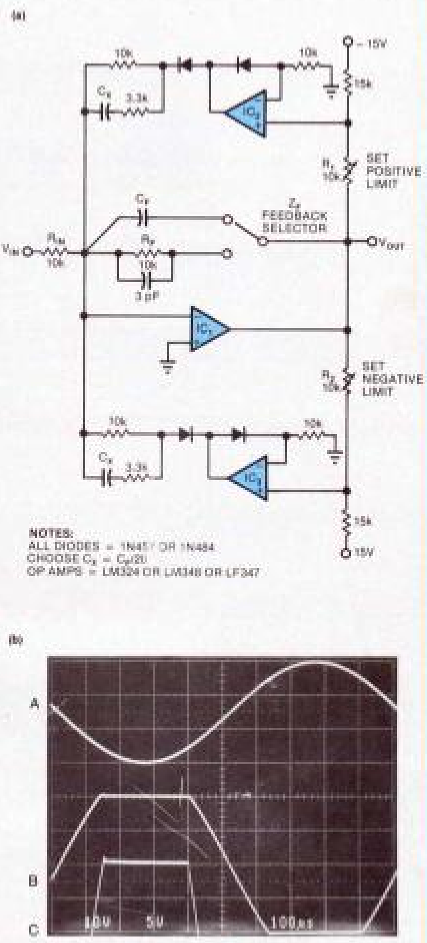
section C, then $V_{OUT} = -V_{INA}$ or $+V_{INC}$, whichever is more positive. In the case that both V_{INA} and V_{INC} are connected to the signal input, the circuit performs a positive absolute-value (precision-rectifier) function, with excellent accuracy at frequencies below 1 kHz.

What are the circuit's shortcomings? Frequency response, for one. Even with high-speed amplifiers and fast diodes, performance is poor above 10 kHz. In



NOTES:
OP AMPS = LM358 OR LF353

Fig 9—Active feedback provides clean, sharp limiting. *It's the basic building block for* ***Fig 10****'s complete circuit.*



NOTES:
ALL DIODES = 1N457 OR 1N484
CHOOSE $C_X = C_F(2)$
OP AMPS = LM324 OR LM348 OR LF347

TRACE	VERTICAL	HORIZONTAL
A	10V/DIV	100 μSEC/DIV
B	5V/DIV	100 μSEC/DIV
C	0.5V/DIV	100 μSEC/DIV

Fig 10—This variable-limit, active-feedback configuration *allows you to use either capacitive or resistive feedback to configure an integrator or an inverter, respectively. Choose op amps to suit your speed requirements.*

addition, the method has the disadvantage of only providing a negative limit (or a positive one by reversing all diodes). On the other hand, it performs a useful function by selecting the highest of a group of voltages. For example, if you use four op amps and eight diodes, then you can obtain an output that's the most positive of four inputs.

What about active feedback? Intuitively, it would seem that you could make a high-precision limiter by using an op amp that senses when the output signal approaches the limit voltage, then reaches back and provides a feedback current to stop the output's advance. The circuit in **Fig 9** is an example of such a scheme. It admittedly looks as if it'll oscillate and misbehave, but lab tests prove it doesn't.

The complete version of the circuit is shown in **Fig 10a.** You can obtain clean limiting **(b)** for capacitive or resistive feedback (Z_F), but the circuit won't handle both cases unless you use damping capacitors (C_X) equal to 1/20 the feedback capacitor. In order of increasing speed, you can use LM324, LM348 or LF347 op amps to develop a faster response.

Outside the feedback loop

If you want to limit your circuit's output by clipping the input excursions, you can use a simple clamping scheme such as that shown in **Fig 11a.** However, the zener diodes' leakage and capacitance create some problems in this circuit. **Fig 11b** suggests a way to

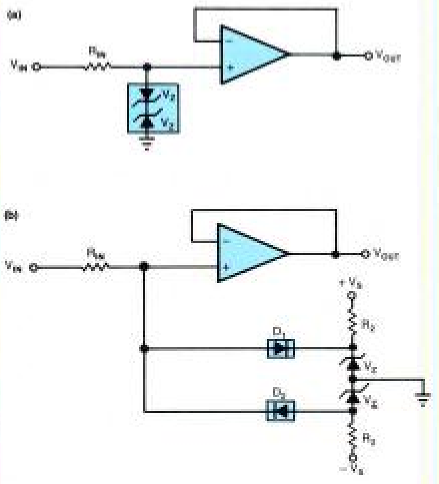


Fig 11—Clamp your op amp's inputs *with these simple circuits. The configuration in* **(b)** *eliminates the effects of the zener diodes' capacitance. In choosing D_1 and D_2, you must consider a speed/leakage tradeoff.*

Bounding and clamping: what and why?

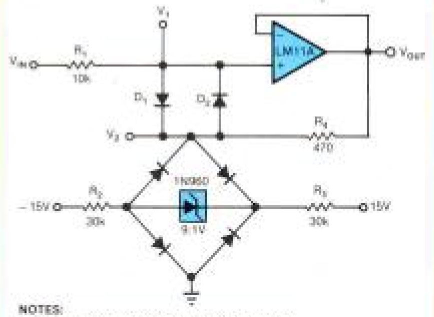
Bounding, clamping, limiting and clipping—what do these terms mean, and what distinguishes them? They all apply to voltage-level restrictions, at either a circuit's input or output. As for their differentiation, it's somewhat unclear—in fact, they're often used interchangeably for a given circuit configuration.

For the purposes of this article, however, "bounding" pertains to limiting circuits inserted in an amplifier's feedback loop; "clamping" to networks applied to the amplifier's input terminal. The former generally produces a sharp output-clipping action; the latter simply prevents overdrive.

Usually, an input signal is coupled resistively to a unity-gain follower's input. For small signals, there's no attenuation (and no current drain by the clamping network). When the signal exceeds the preset threshold, however, the clamping network conducts heavily, preventing the amplifier from being driven any further.

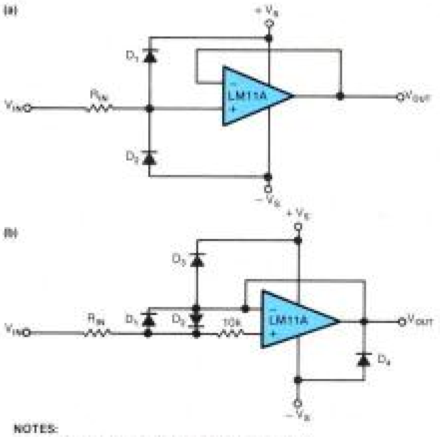
Given this behavior, what reasons are there for limiting? There are many:

- To eliminate undue delays when an integrator must recover from its supply-determined limit.
- To eliminate undue delays when any amplifier circuit must recover from its supply-determined limit. (Not all amplifiers recover in a like manner—some chopper-stabilized designs take several seconds.)
- To avoid thermal errors caused by an amplifier's output stage overheating in a limit condition.
- To avoid degradation or outright damage to an amplifier's inputs.
- To avoid overdriving or damaging circuits connected to an amplifier's output.
- To obtain specific symmetrical or asymmetrical shaping.
- To obtain a nonlinear curve for simulation of nonlinear circuits (for example, using analog-computer techniques).
- To control an oscillator's amplitude.
- To rectify an ac signal.



NOTES:
DIODES = LOW-LEAKAGE OR FAST-RECOVERY
TYPES, DEPENDING ON APPLICATION

Fig 12—Entirely eliminating zener-capacitance effects, *this input-clamping configuration ensures that the zener never turns off.*



NOTES:
R_{IN} = 22K ±10%, ½W CARBON COMPOSITION
DIODES = NPN BASE-COLLECTOR JUNCTION
(EMITTER OPEN)

Fig 13—These input-protection circuits *guard the op amp's inputs from damaging overvoltages. The circuit in* **(b)** *is more efficacious than* **(a)***'s brute-force approach; it offers full protection and negligible input leakage.*

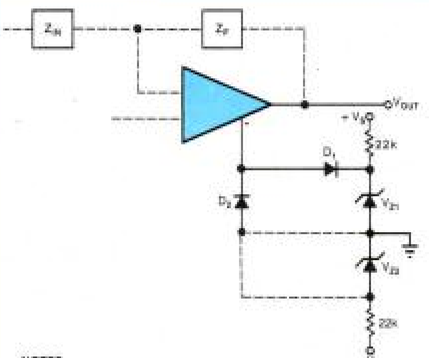
minimize these effects. Remember that if you want fast response, you must use fast diodes (such as the fast-recovery, high-leakage 1N914). Conversely, if R_{IN} must have a high value, you should choose a low-leakage type. Choose R_2 and R_3 to ensure that the zeners are biased above the knee.

If you'd like to try more elegant schemes, consider **Fig 12**'s high-performance, symmetrical clamping circuit. The two 30-kΩ resistors ensure that the zener never turns off; therefore, its capacitance never has to be charged up during a cycle. The value of R_4 is critical in this circuit, because the op amp's output must bootstrap point V_2 to a voltage very close to that at V_1.

With the values shown, $V_1 - V_2$ is only 0.15V when $V_{IN} = 10V$. Therefore, diode D_1 leakage is negligible at room temperature. When V_{IN} rises further and D_1 starts to conduct, the current through R_4 biases the zener to a low-impedance condition, well above its knee. Note that if R_4 is too low, then the op amp might not be able to drive it.

The input-clamping techniques shown here use an op amp connected as a unity-gain follower, but they're generally applicable to any unity-gain amplifiers, such as emitter followers, source followers or any high-impedance amplifier.

Suppose you don't really require clean signal limiting, but simply need to protect an amplifier's inputs from such damage as might result from electrostatic discharge or an inadvertent 115V line connection. The clamping circuits in **Fig 13** provide complete input protection, even when driven to extremes—moreover,



NOTES:
* = PIN 8 FOR LM301A, LM308 OR LM363H;
PIN 15 FOR LM363D; PIN 5 FOR LM11.
V_{OUT} IS CLAMPED TO V_{Z1} + 0.5V; −(V_{Z2} + 0.5V).

Fig 14—Use an op amp's compensation terminal *to obtain bounding. This method can make it easier to clamp differential-input amplifiers, for example. Connecting D_2 to ground yields a −0.5V negative limit; connecting it to the zener yields more negative limits.*

they cause no performance degradation throughout the full common-mode range of the op amp.

Fig 13b's circuit is similar to **13a**'s brute-force approach, but it reduces input leakage to subpicoampere levels. When the input is severely overdriven, D_3 or D_4 might conduct, but the op amp's inputs won't be subjected to overvoltage or overcurrent conditions. In addition, protection diodes D_1 and D_2 are bootstrapped in normal operation with barely 1 mV across them. Therefore, their leakage is less than 1 pA.

Finally, note that not every clamp or bound must be connected to an amplifier's inputs or in its feedback loop. For example, you can limit an LM308's or LM301A's output to +5, −0.5V levels by putting a suitable clamp on its frequency-compensation terminal (**Fig 14**). This method is especially useful with difficult-to-clamp (because of differential inputs) instrumentation amplifiers. For example, it works with the LM363, making it easy to use as a comparator. **EDN**

Author's biography

Robert Pease is a staff scientist at National Semiconductor Corp (Santa Clara, CA). Before joining National, he designed op amps and analog modules for Teledyne Philbrick. Bob earned a BSEE degree at MIT; he holds four patents. His spare-time activities include tracking abandoned railroad tracks and designing V/F converters.

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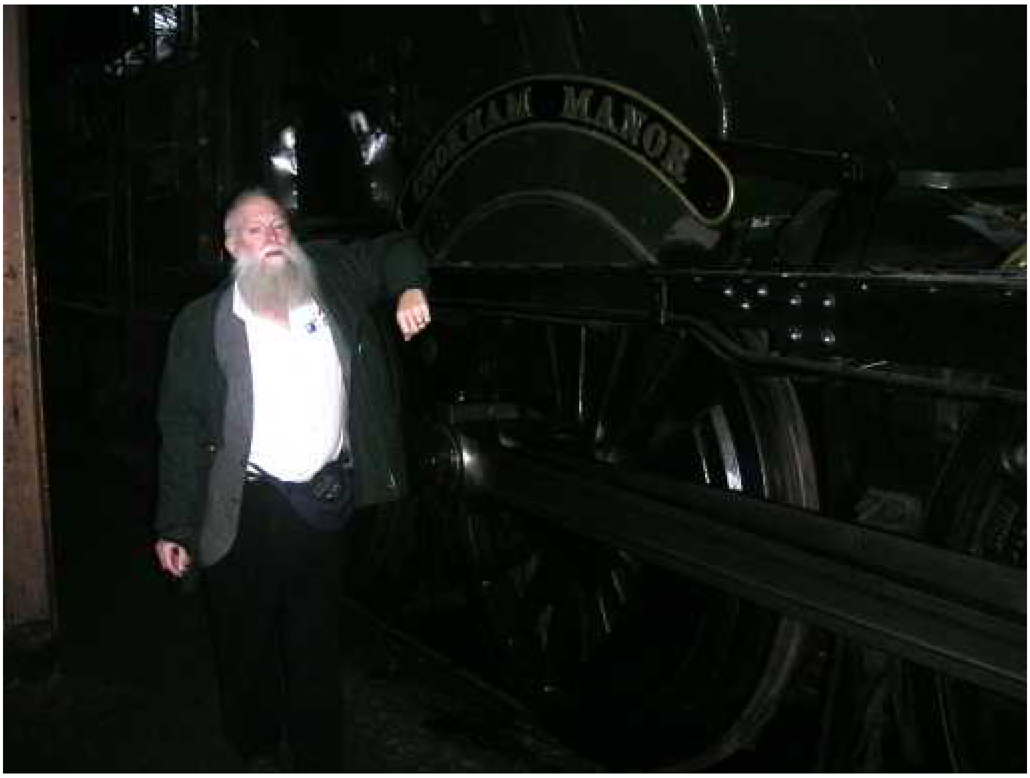
So there you have it, and Data I/O and Otto get a free ad to boot. Remember this those ads are from 1983, so don’t count on the address and phone numbers being right. I hope you enjoy the article, Pease was a real giant and a real friend. I keep opening my email program to write him and ask him something, most recently about my upcoming cover story on error budgets. Then I realise Bob is gone. It really has saddened me and ruined what started out a pretty good summer. I guess its time to remove his name from my address book.

[Update] I just read Bob’s bio on the last page. The comment about how he “tracked abandoned railroad tracks” reminded me of when we were are on the analog seminar together. We were driving from Manchester to London, and we stopped at one of the many rail museums. The next picture really sums up Bob’s rebellious nature. Click to enlarge.

I also found this pic of Pease standing next to a locomotive.



And finally, here is another anti-authoritarian shot of Pease, touching the naval mine in the War Museum in Manchester, despite the sign.


TNT
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PLEASE DO NOT TOUCH THE OBJECT
OR STEP ON THE PLINTH