Edited by **David Newkirk, WJ1Z** • Electronic Publications Editor

Gyrating with *ARRL Radio Designer*

Op-amps—*operational amplifiers*—can do a lot more than just amplify. An op-amp's very high *open-loop* gain—its gain in the absence of any sort of feedback—lets it produce useful output even with a great deal of its output negatively fed back to its input. That negative feedback cancels some of the op-amp's input isn't as useless as it sounds, because, as Horowitz and Hill put it in the Feedback and Operational Amplifiers chapter of *The Art of Electronics*[1] (a book I think everyone seriously interested in electronics should own and use): "As more negative feedback is used, the resultant amplifier characteristics become less dependent on the characteristics of the open-loop (no-feedback) amplifier and finally depend only on the properties of the feedback network itself." Given an amplifier with enough open-loop gain at your frequencies of interest—some of the op-amps in the 1996 *ARRL Handbook*'s Op-Amp ICs table (page 24.26) have gains of 115 dB!—you can use well-engineered negative feedback to make that amplifier do some highly useful things. "Speaking in general terms," write Horowitz and Hill, "the property that is sampled to produce feedback is the property that is improved." To the engineer, *improved* can also mean *tailored*. And so, teamed with various types of feedback networks, op-amps can work as amplifiers with carefully tailored frequency and phase responses—that is, as filters. We can also use op-amps as comparators, oscillators, and current and voltage sources and converters. We can even configure them to behave as operational amplifiers—as differential-input, single-ended-output dc amplifiers that perform specific mathematical operations the analog way.

An op-amp can also do something that's exotic and practical at

[1]Notes appear on page 68.

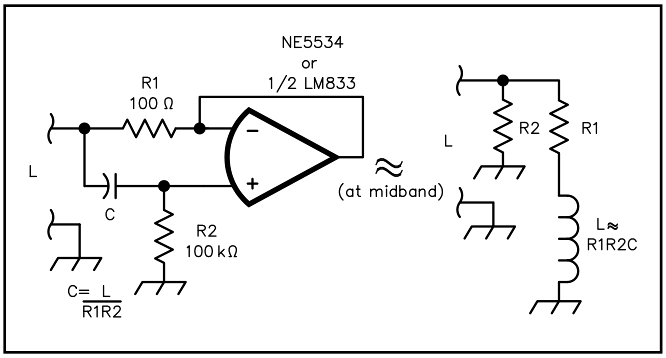

Figure 1—An op-amp *gyrator* based on a configuration shown in National Semiconductor Corp's application note AN-435. This circuit is idealized; it doesn't show the power-supply and bypassing components necessary in a real-life implementation.

Table 1

Comparing Real and Gyrated-Capacitor Inductors in *ARRL Radio Designer*

```
BLK
 CAP 1 2 C=0.024UF
 RES 1 3 R=100
 RES 2 0 R=100KOH
 OPA 3 3 2 0 A=1E5 R1=1E12 R2=30
 GYR240MH:1POR 1,0
END
BLK
 IND 1 2 L=0.12H Q1=100 F=50KHZ
 IND 2 0 L=0.12H Q1=100 F=50KHZ
 IND240MH:1POR 1,0
END
FREQ
 ESTP 100HZ 200KHZ 511
END
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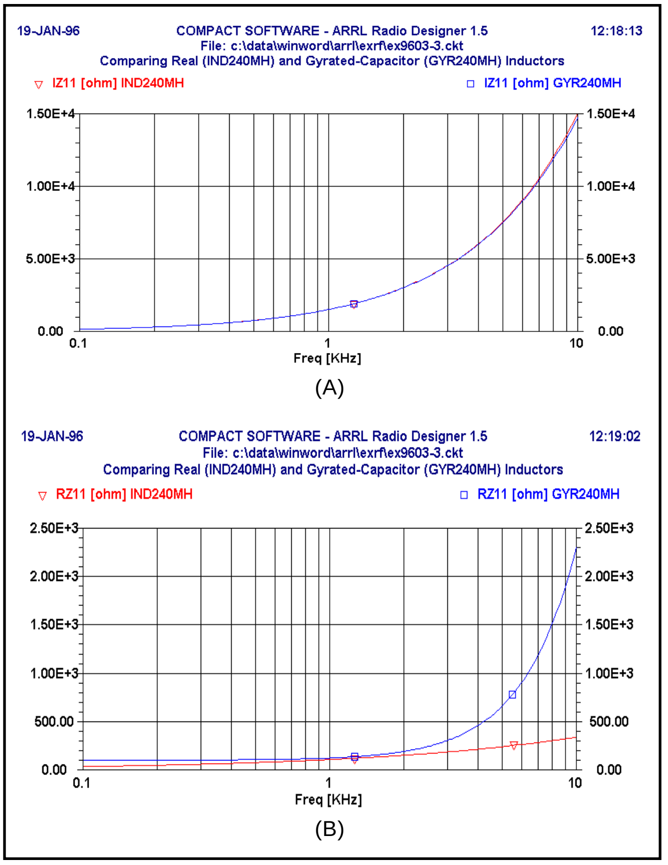

Figure 2—Between 100 Hz and 10 kHz, the reactances (A) of a real 240-mH inductor (IND240MH) and a 240-mH inductor simulated with the Figure 1 circuit (GYR240MH) track quite closely. The resistive portion (B) of their impedances match reasonably well from 100 Hz to 2 kHz, above which the simulated inductor's RZ_{11} starts to soar. The real inductor has a Q of 100 at 50 kHz and is based on a combination of Toko 181LY-series parts on page 182 of Digi-Key Corp's *Catalog 961*, available as a PDF file via the World Wide Web at **http://www.digi-key.com/961/181-183.pdf**. (*ARRL Radio Designer 1.5* simulation)

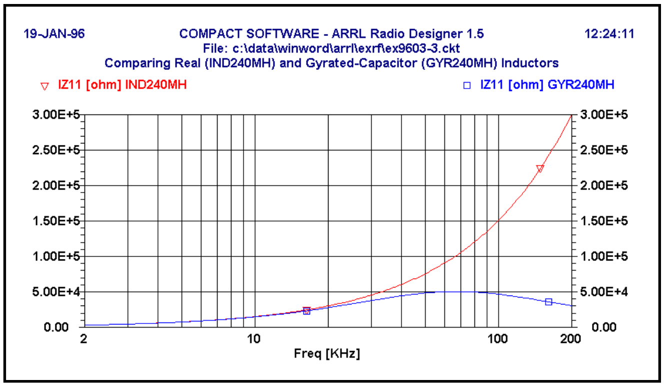

Figure 3—As frequency increases, the gyrated capacitor's inductive reactance falls short of the real thing, peaks, and begins to drop. In addition to this, practical op-amp considerations of bandwidth, stability and dynamic range become increasing important in gyrator performance at higher frequencies. NSC's AN-435 discusses some of these gyrator limitations and how to work with them. (*ARRL Radio Designer 1.5* simulation)

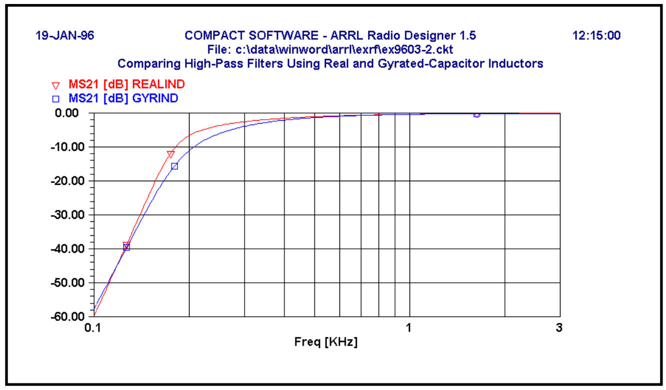

Figure 4—How *ARRL Radio Designer 1.5* simulates the performance of a high-pass audio filter using real (REALIND) and gyrated-capacitor (GYRIND) 240 and 330-mH inductors. The filter is a nine-element, **T**-configuration, 0.1-dB-ripple Chebyshev high-pass design; the real inductors are combinations of the Toko parts mentioned at Figure 2.

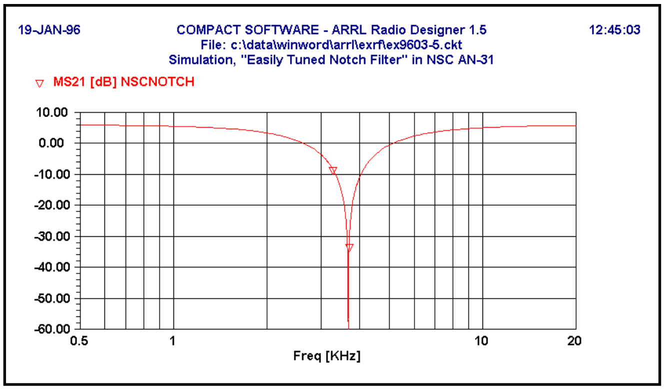

Figure 5—You can buy real components to get the real 240 and 330-mH inductances I've modeled so far, but what about a 4-H inductor with a Q of 23 at 3.671 kHz? That's what the gyrated 1-µF capacitor acts like in the "Easily Tuned Notch Filter" in NSC's AN-31 (see Note 2 for where to get it). Wilder still, the gyrated 1-µF capacitor used in a 60-Hz version of this circuit (Figure 5-28 on page 163 of Walter G. Jung, *Audio IC Op-Amp Applications* [Minneapolis: Howard W. Sams & Co Inc, 1978; ISBN 0-672-21558-6) acts as a 15.412-*kilohenry* inductance with the same Q. Don't expect a catalog search to turn up a real one!

the same time: It can make a capacitor behave like an inductor! In performing that function, *gyration*, the op-amp converts the capacitor's impedance to its inverse—that is, to an impedance that exhibits the properties of an inductance.[2] Figure 1 shows one possible gyrator hookup—one derived from an LM833-based circuit I found in the National Semiconductor Corporation (NSC) Application Note AN-435, "Designing with the LMC835 Digital-Controlled Graphic Equalizer."[3] Figure 2 compares the characteristics of a real 240-mH inductor with the gyrated-capacitor equivalent simulated by the Figure 1 circuit. (Table 1 shows the netlist I used in the analysis behind Figure 2.)

If R2's value is sufficiently high, R1 pretty much sets the simulated inductance's Q. The 680-Ω R1 used in the NSC application note's LM833-based gyrators results in Qs that are quite low—on the order of 3—for the simulated inductances used in controlling the graphic EQ's lower bands. Qs that low are less than what we might want for some audio filtering applications, and the 100-Ω R1 in Figure 1 improves the situation a little. But we can't just make R1 vanishingly small, because—among other reasons—decreasing R1 also raises the frequencies between which the gyrated capacitor acts acceptably enough like an inductor.[4] Ironically, at least in this gyrator topology, this relationship works against the simultaneous achievement of high Q and high inductance at low audio frequencies, where obtaining both at once would be a fine thing! So gyrated-capacitor inductors have their limits, as a look at Figure 3 further confirms for the higher-frequency side of things.

What about doing something *useful* with gyrators? Figure 4 compares audio high-pass filters that use real and gyrated-capacitor inductors, and Figure 5 shows the simulated response of a tunable notch circuit in NSC's AN-31. Yes, gyrators can do useful work—and *ARRL Radio Designer 1.5*[5] can simulate it.

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You can download circuit and report files for this month's gyrator explorations, packaged in the archive file exrf9603.zip, via *ARRL Radio Designer*'s home page (**http://www.arrl.org/ard/ardpage.html**), a subpage of *ARRLWeb* (**http://www.arrl.org/**), the League's World Wide Web service. The file is also available via the ARRL HQ telephone BBS (860-594-0306) and ARRL FTP site (**ftp://ftp.barc.org/pub/hamradio/arrl/**) and its mirrors. Past editions of Exploring RF are available via the Web, too; just check the *ARD* home page's "Articles About *ARRL Radio Designer*" subpage at **http://www.arrl.org/ard/ardarts.html**.

[1]Paul Horowitz and Winfield Hill, *The Art of Electronics*, 2nd ed (Cambridge: Cambridge University Press, 1989; ISBN 0-521-37095-7 hardback).

[2]An op-amp can also act as a *negative-impedance converter* (*NIC*)—an arrangement that converts an impedance to its negative equivalent. The gyrator is the better choice for simulating an inductor with a capacitor because it inverts the capacitor's reactance *and its reactance-versus-frequency characteristic*, whereas an "NICed"-capacitor exhibits an inductive reactance that decreases with frequency. See page 267 of Horowitz and Hill.

[3]Available on pages 1052-1059 of NSC's 1986 *Linear Applications Handbook*, and via the World Wide Web address **http://webdirect.natsemi.com/nscC/62742/h8664.pdf** in Adobe Systems Inc's *Portable Document File* (PDF) format. (You can find even more gyrator circuits—and a heap of other op-amp goodies—in the same book's application note AN-31, "Op Amp Circuit Collection," available via the Web address **http://webdirect.natsemi.com/nscC/62554/h7057.pdf** in PDF format.) The Web address **http://www.nsc.com/** takes you to National's home page.

[4]Per Arthur H. Seidman, *Integrated Circuits Applications Handbook* (New York: John Wiley & Sons, 1983, ISBN 0-471-07765-8), pp 344 and 345, the lower frequency limit, f1, can be determined by the equation

and the upper frequency limit, f2, can be determined by the equation

$$f2 = \frac{1}{2\pi R1C}$$

in both of which resistance is in ohms, capacitance is in farads and frequency is in hertz.

[5]Available from ARRL for $150 plus shipping as publication #4882. Contact HQ Publications Sales at (voice) 860-594-0250, (fax) 860-594-0303 or (e-mail) **pubsales@arrl.org**.