by researching the subject at a good library. Specific articles you may find particularly helpful have appeared in *EDN* ("Thermoelectric Coolers Tackle Jobs Heat Sinks Can't," Jim McDermott, May 20, 1980, pp. 111-117) and *Electronics* ("Thermoelectric Heat Pumps Cool Packages Electronically," Dale Zeskind, July 31, 1980, pp. 109-113). The *Encyclopedia Britannica* has a very thorough article on the subject.

Thermoelectric module manufacturers have published helpful literature about their field. By far the most complete reference quide is Cambion's "Thermoelectric Handbook." Specifi-

An Easy-to-Use Universal Active Filter

Imagine a single-chip active filter that can be tuned with a single resistor, uses no external capacitors, and simultaneously functions as a lowpass, bandpass and notch filter. Such a filter could save countless hours of design and breadboard evaluation time.

Happily a new generation of such filters is now available. They are collec-

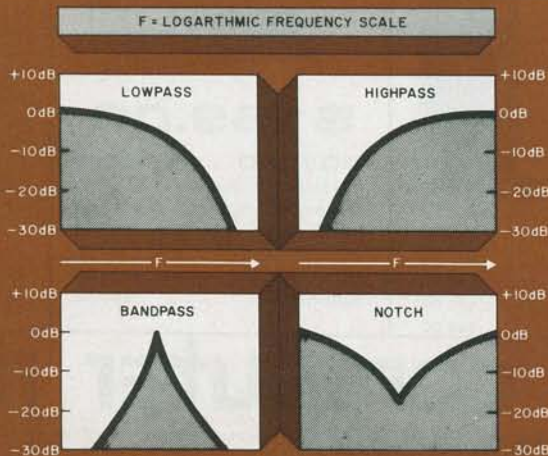


Fig. 8. Frequency responses for the four filter categories.

tively known as *switched capacitor filters,* and their operating paramaters are easily tuned by a few external resistors. *No* external capacitors, the nemesis of conventional active filters, are required.

After I wrote about this topic in the November 1982 installment of "Solid-State Developments," an engineer with National Semiconductor sent some samples of his company's MF-10 universal switched capacitor filter. The MF-10 contains two independent filters in a 20-pin DIP.

To say the MF-10 is easy to use is an understatement. In only a few short hours of bench time, I've used this new chip in as many roles as all the conventional active filter circuits I've built over the past ten years.

Of course conventional active filters have many important applications in both digital and analog circuits. For example, they are used to block undesirable signals and to detect touch-tone and modem signals. In these and many other roles, active filters are far superior to passive filters since they incorporate gain-restoring operational amplifiers.

But, while conventional active filters are exceptionally useful, they can be very tricky to design. If you've never designed one, you might wish to take a quick tour through the pages of any of the many excellent books on the subject. You'll find numerous circuit arrangements, some fairly complex, and enough design equations to wear out your calculator finger.

Even if you successfully wade through the circuits and equations and design you own filter, you will almost certainly find that the first breadboard version you build has a resonant frequency that differs, perhaps substantially, from your design frequency. That's because the resonant frequency of all such filters is only as accurate as the tolerances of the circuit's resistors and capacitors. Precision resistors are relatively cheap and easy to find. But precision capacitors are much more expensive.

All these design drawbacks are overcome by a switched capacitor filter like the MF-10. In this column we'll cover in some detail the operation and use of this device. Then we'll experiment with a tunable MF-10 combination lowpass/notch/bandpass filter. Before finding out how the MF-10 works, however, let's review some active filter basics.

Active Filter Basics. Depending upon their function, most active filters are designated *lowpass, highpass, bandpass* or *notch* filters. The role of the filter is defined by its name. For example, a lowpass filter passes with little or no attenuation all frequencies below a specified cutoff point while blocking all other frequencies. A notch filter attenuates only a very narrow band of frequencies while passing with little or no attenuation those frequencies outside the notch.

Figure 8 illustrates in graphical form the operation of the four basic filter types. Other active filters can also be implemented. For instance, the *allpass filter* shifts the phase of a signal without causing attenuation.

The operation of an active filter is described by a number of terms. Some of the more important ones are:

Passband—band of frequencies passed with little or no attenuation through the filter.

Stopband—band of frequencies attenuated by the filter.

Bandwidth (BW) of a bandpass filter is the difference between the upper and lower frequencies at points 0.707 times the filter's maximum response (−3-dB points).

Center frequency (f_o)—pass and attenuation regions for, respectively, bandpass and notch filters.

Cutoff frequency (f_c)—the point at which the gain in the passband of a filter falls to 0.707 times the attenuated gain (−3 dB point).

Q or *quality factor* of a bandpass or notch filter is f_o/BW. A high Q filter implies a very sharp or narrow frequency response at the center frequency.

Figures 9 and 10 show representative plots of the response of typical lowpass and bandpass active filters made in the conventional fashion with operational amplifiers. Note that the graphs are scaled logarithmically.

Both filters show a 0-dB (gain = 1) response in their passbands. This coincides with a voltage gain of 1. The "ideal" cutoff (Fig. 9) and response (Fig. 10) are included to illustrate that no active filter has a perpendicular cutoff.

The MF-10. The best conventional active filters typically require several op amps, at least two capacitors, and from three to seven resistors. The MF-10 contains *two* completely independent active

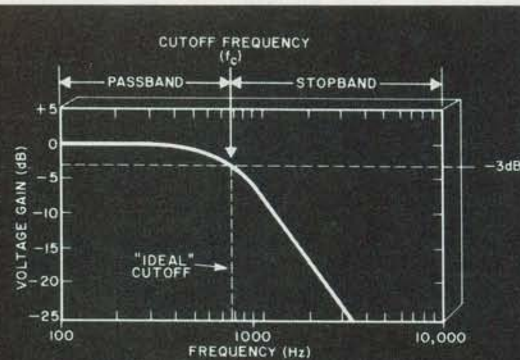


Fig. 9. Lowpass active filter characteristic.

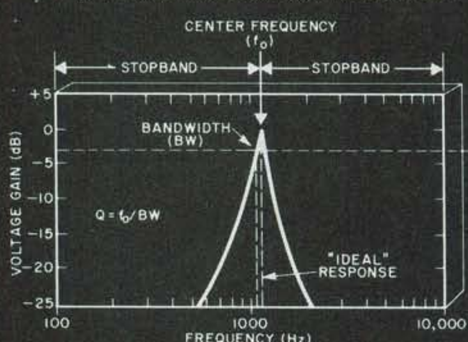


Fig. 10. Bandpass active filter characteristic.

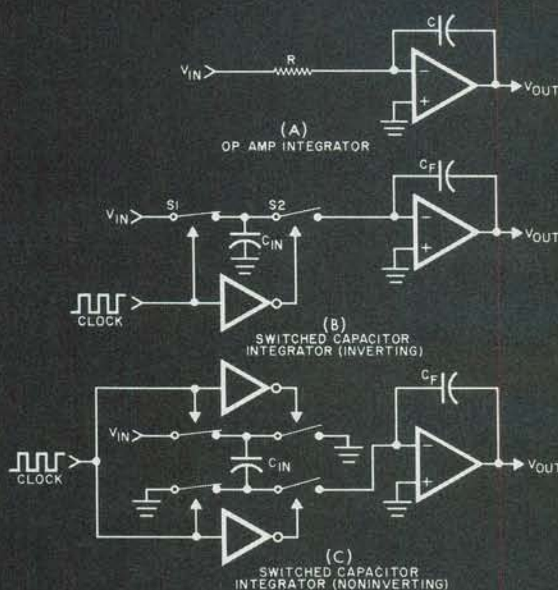
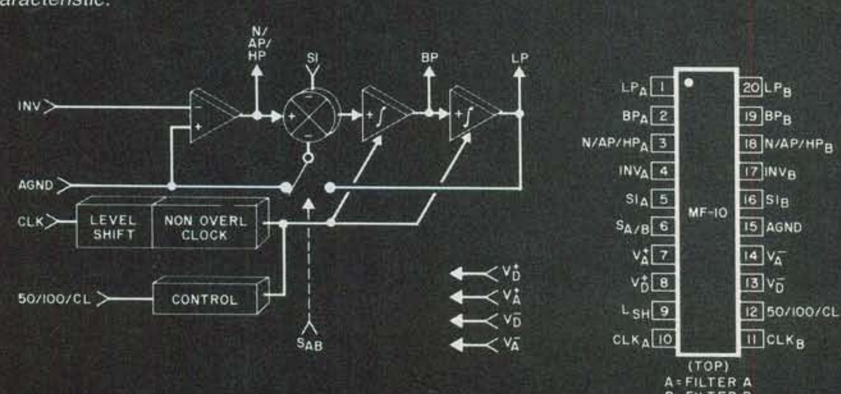


Fig. 11. Three diagrams showing operation of the switched capacitor integrator in the MF-10.

Fig. 12. Block diagram and pin arrangement of the MF-10 active filter.



filters, each of which performs five basic filter functions (lowpass, highpass, bandpass, notch and allpass) with only a few external resistors and no external capacitors—well, almost no capacitors. Unlike conventional active filters, the MF-10 requires an input clock, and clock circuits usually incorporate a capacitor or two. The clock capacitor poses no tolerance problem, however, since the clock's frequency can be easily tuned by changing the value of a single resistor.

The MF-10 is exceedingly easy to use since all five outputs are brought out of the chip. Furthermore, the two second-order filters in a single MF-10 can be cascaded to provide a fourth-order filter. Experienced active-filter designers will be happy to know such classical filter responses as the Butterworth, Chebyshev, Bessel and Cauer are easily implemented with the MF-10.

Another advantage of the MF-10 is its CMOS construction. This is why its typical power-supply current demand is only 8 mA. The supply voltage can range from ± 4 to ± 7 V when operated from a dual-polarity supply and 0 to $+10$ V when operated from a single-polarity supply.

Finally, as we'll observe firsthand in the test circuit that follows, the MF-10's response is easily tuned across a wide spectrum by simply varying the clock frequency. In applications requiring a precisely controlled notch or bandpass, the clock can be crystal controlled.

How the MF-10 Works. The key circuits in the MF-10 are a pair of noninverting integrators whose time constants are determined by their respective feedback capacitors and the clock frequency. A conventional integrator like the one in Fig. 11A has a time constant of RC. The precision of the circuit is therefore only as good as the tolerances of the RC components.

The integrators in the MF-10 replace the resistor of the integrator in Fig. 11A with a capacitor. This capacitor is alternately switched by the clock signal, first to the input voltage and then to the feedback capacitor, V_{in} and C_F respectively. As shown in Fig. 11B, the switched capacitor performs the role of the resistor in 11A by transferring the voltage at the input to C_F.

The amount of charge transferred by C_{in} to C_F is determined by the time C_{in} is allowed to charge to V_{in}, and the time C_F is allowed to charge to the voltage C_{in}. In his paper "Introducing the MF-10," Tim Regan, a National Semiconductor applications engineer, shows how the current transferred through C_F to the output of the integrator is V_{in} C_{in} divided by the clock period or V_{in} C_{in} times the clock frequency, F_{clk}. Therefore, the effective resistance of C_{in} is the reciprocal of C_{in} F_{clk}. In other words, the effective resistance of C_{in} can be varied simply by altering the clock frequency. The time constant of the circuit is C_F/C_{in} F_{clk}.

Since the switched capacitor integrator employs on-chip capacitors, you may be wondering why its performance is better than a standard integrator with external RC components. The reason is that the time constant of the switched capacitor integrator is entirely dependent upon the *ratio* of C_{in} and C_F, both of which are fabricated on the same die and thus have precisely controlled dimensions and values.

Incidentally, Tim Regan notes in his paper that the integrators in the MF-10 are noninverting. This requires a somewhat more complex switching arrangement than that shown in Fig. 11B wherein *both* sides of C_{in} are alternately switched. As shown in Fig. 11C, first the upper and lower sides of C_{in} are switched, respectively, to V_{in} and ground. Then the upper and lower sides of C_{in} are switched, respectively, to ground and C_F. This reverses the polarity of the charge on C_{in} that's applied to C_F, thereby preserving the polarity of V_{in} at the integrator's output.

For additional details about how the MF-10 works, see the application note for this chip and Tim Regan's paper. We'll now look at some practical aspects of using the MF-10 and experiment with an MF-10 in a typical circuit.

Using the MF-10. Figure 12 shows a simplified block diagram of one of the filters in an MF-10 and the pin outline for the actual chip. The MF-10 application note describes in detail the function of each pin. What follows is a brief summary.

LP, BP, N/AP/HP are, respectively, the lowpass, bandpass, notch/allpass/highpass outputs of each filter.

INV is the inverting input of each filter.

S1 is used as a signal input pin when the filter is in the allpass mode.

$S_{A/B}$ activates the internal switch that connects the input of the filter's second summer amplifier (see Fig 13) to analog ground AGND ($S_{A/B}$ = low) or the lowpass output ($S_{A/B}$ = high).

V_{+A} and V_{+D} are the analog and digital positive supply pins. They can be interconnected if desired. They should be bypassed with a capacitor (two if separate supplies are used).

V_{-A} and V_{-D} are the analog and digital negative supply pins.

L_{SH} is the level shift pin. It allows the user to use the MF-10 with a variety of power-supply and clock voltages. For example, when powered by a dual $\pm$5V supply and driven by a CMOS clock ($\pm$5V), the L_{SH} pin should be tied to ground or V_{-A}, V_{-D}.

CLK is the clock input to each filter. The clock should have a duty cycle of close to 50% for optimum results.

50/100/CL determines the ratio of clock frequency to filter center frequency (50:1 when high and 100:1 when at analog ground).

AGND is the analog ground pin.

Sample:

V^+_A and $V^+{}_D$ are the analog and digital positive supply pins. They can be interconnected if desired. They should be bypassed with a capacitor (two if separate supplies are used).

V^-_A and V^-_D are the analog and digital negative supply pins.

Again, be sure to refer to the MF-10 application note for additional information about these pin functions. The explanations given are but brief summaries.

A Tunable Lowpass/Bandpass/Notch Filter. Figure 14 is the circuit for a straightforward LP/BP/N filter made from one-half an MF-10 and an external clock. The clock is made from two inverters in a 4049. Its frequency, and thus the frequency response of the MF-10, can be altered by changing *R5*'s setting. Incidentally, while you may have often seen in this column simple oscillators such as this made from two NAND gates in a 4011, be sure to use the 4049 in this circuit. The 4011 may not oscillate at V_{DD} = +5 V. (If you must use the 4011, try buffering its output with a third gate.)

The MF-10 is connected in what the application note calls the Mode 1 configuration. At least eight other modes are available. Some of the circuit's key parameters are defined in Fig. 13. The circuit is extremely easy to use. The only significant constraints are to observe power supply limits and CMOS handling precautions. Otherwise, operating the circuit is a snap.

For example, with the other values given in Fig. 13, the LP gain is −0.1 (near f_o =0 Hz), the BP gain is −1 (at

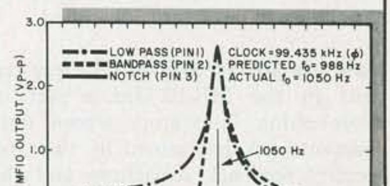


Fig. 14. Response of MF-10 (mode 1—at clock frequency of 99.435 kHz.

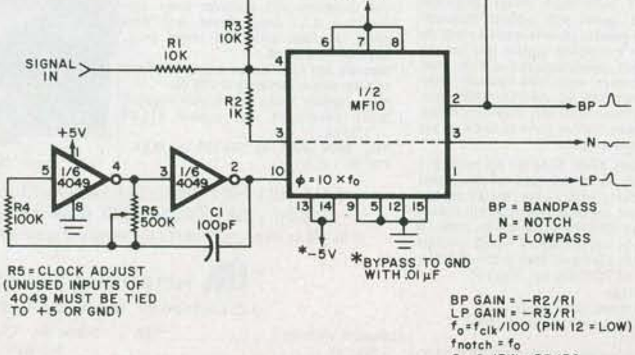


Fig. 13. An MF-10 active filter and clock circuit.

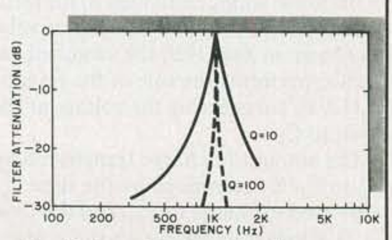


Fig. 15. Logarithmic plot of the same bandpass curve as shown in Fig. 14.

f_o), and the BP/notch Q is 10. The circuit can easily be tuned out to a maximum f_o of 30 kHz simply by altering the clock frequency (where the ratio of clock frequency-to-f_o is approximately 100:1). The gain and Q values can easily be altered by changing the resistors.

When the clock frequency of the test circuit was 99.435 kHz, I measured a f_o for the bandpass and notch outputs of 1050 Hz. This is outside the clock-to-f_o ratio specified for the MF-10. The *rounded* clock-to-f_o ratios (pin 12) are 50:1 and 100:1. The *actual* ratios given in the data sheet are 49.94:1 and 99.35:1. In both cases and depending upon the grade of the chip, the actual ratios have a typical and maximum tolerance range of, respectively, ± 0.2 and $\pm 1.5\%$.

My tests, made on successive days with careful attention to detail, gave a ratio of 94.7:1 (pin 12 low). I therefore tried two additional MF-10's and obtained almost exactly the same results. While I cannot account for the apparent discrepancy in clock-to-f_o ratio, the three MF-10's exhibited virtually identical tolerances.

Figure 14 is a plot superimposing on a linear scale the LP, BP and notch frequency response of the circuit in Fig. 13. The bandpass and notch curves appear quite normal, but the lowpass curve peaks sharply at f_o. This apparent anomaly results from the LP output being programmed by *R3/R1* for a gain of -0.1 at $f = 0$ Hz. This means the LP output should approximate the -0.26 V peak-to-peak at $f = 0$ Hz when V_{in} is 2.6 V peak-to-peak. Figure 14 confirms this is indeed the case.

Recall that frequency response curves for active filters are normally plotted on a logarithmic scale. Figure 15 is a log plot of the bandpass response in Fig. 14. The dashed plot represents the bandpass when the Q was increased from 10 to 100 by reducing *R2* to 100 ohms. Both of these plots as well as the linear scale plots in Fig. 14 are based upon actual measurements.

Going Further. While exceptionally versatile and easily tuned, the multipurpose filter in Fig. 13 is only one of several ways you can use the MF-10. Another way it can be operated is in a noninverting mode, or it can be configured for simultaneous highpass, bandpass and lowpass filtering. Indeed, the versatility and operating simplicity of this filter convince me that such filters will soon obsolete shelves of conventional active filter books, design notes, and computer programs. ◇