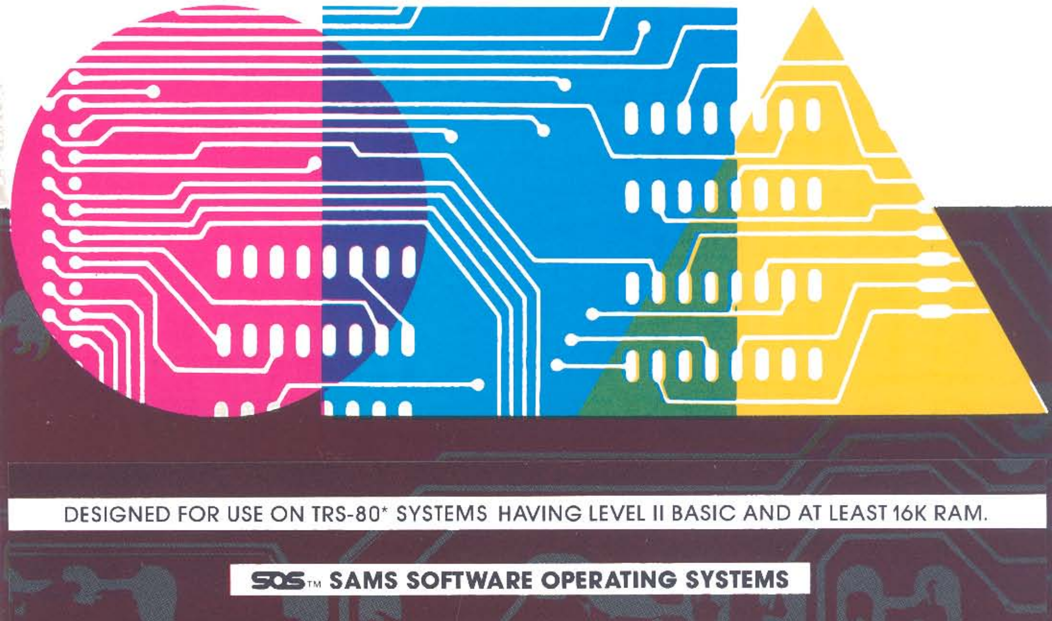
ACTIVE FILTER DESIGN

- Low and High-Pass
(Bessel, Butterworth, 1, 2, and 3-dB Chebyshev)
- State-Variable Filter
- Bandpass Filters with Q's less than 10 and 50
- Staggered-Tuned Butterworth Bandpass Filters
(2, 3, or 5 States)
- Notch Filter

BY HOWARD M. BERLIN



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Active Filter Design

This tape describes programs for the rapid design of various types of active filters. Those included are the state-variable filter (3 op-amps); second- through sixth-order low-pass and high-pass filters having either Bessel (best delay), Butterworth (maximally flat), or Chebyshev (equal ripple) responses; bandpass filters; and notch filters. Each design determines the performance based on user selected standard resistor and capacitor values. For a more detailed discussion about active filters, either the *Design or Active Filters, with Experiments,* or the *Active Filter Cookbook* (Howard W. Sams & Co., Inc., Indianapolis, IN 46206) are recommended references.

LOW-PASS AND HIGH-PASS FILTERS

The LPHP program enables us to design second- through sixth-order low-pass or high-pass filters having either Bessel, Butterworth, or Chebyshev (1-, 2-, or 3-dB) responses. Shown in Figs. 1 through 10 are the circuits of the low-pass and high-pass filters.

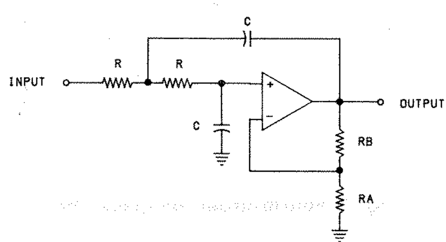

Fig. 1. Second-order low-pass filter.

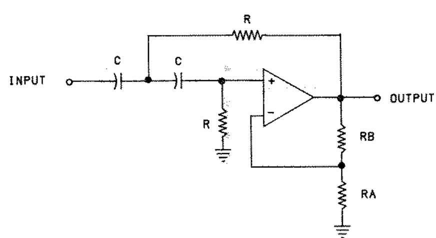

Fig. 2. Second-order high-pass filter.

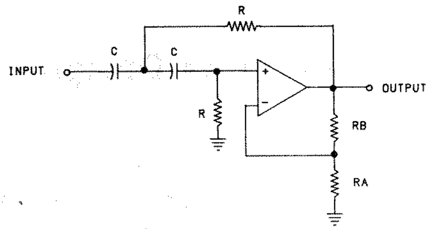

Fig. 3. Third-order low-pass filter.

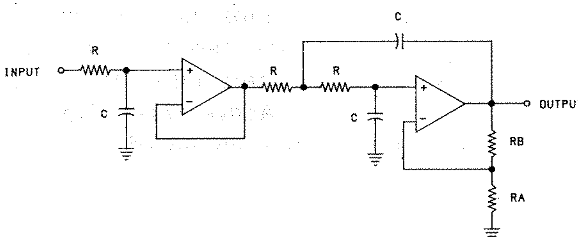

Fig. 4. Third-order high-pass filter.

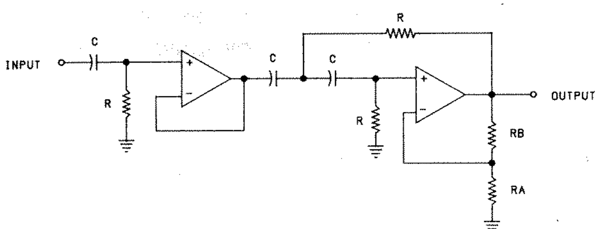

Fig. 5. Fourth-order low-pass filter.

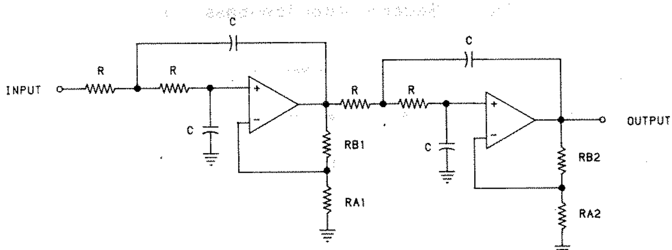

Fig. 6. Fourth-order high-pass filter.

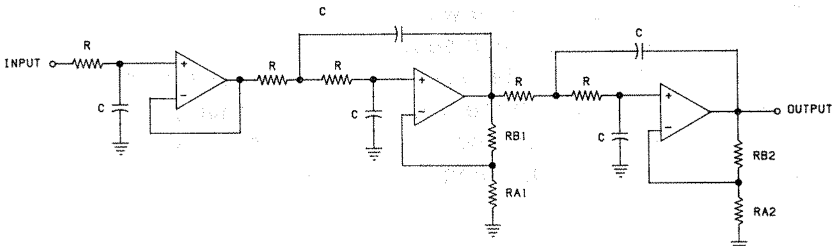

Fig. 7. Fifth-order low-pass filter.

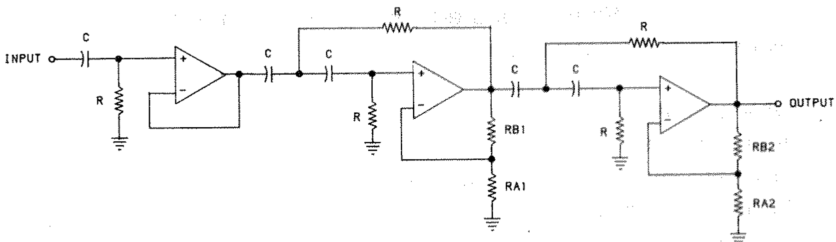

Fig. 8. Fifth-order high-pass filter.

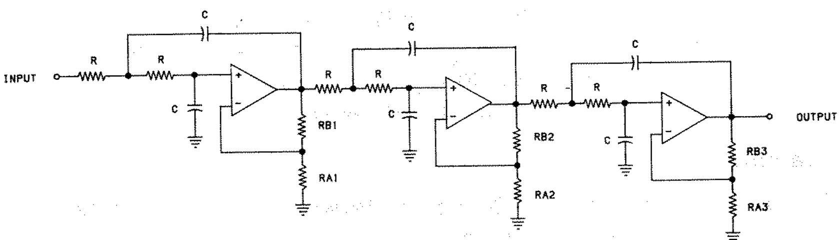

Fig. 9. Sixth-order low-pass filter.

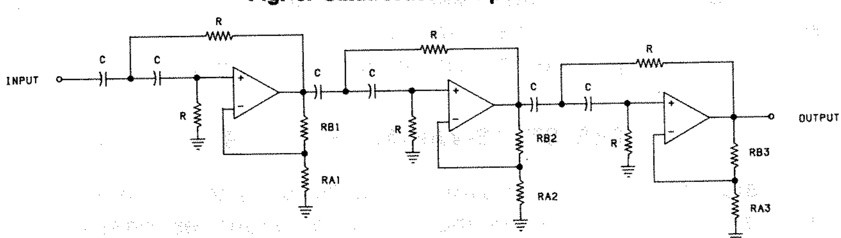

Fig. 10. Sixth-order high-pass filter.

Each second-order section is of the voltage-controlled voltage-source design (often referred to as a Sallen-Key filter) with both the frequency determining resistors R and capacitors C made equal. For the third- and fifth-order filters, the first section is a simple first-order passive network followed by a voltage follower. The damping values for each second-order section are controlled by resistors RA and RB. Because the program restricts the design of the filter to having both the frequency determining resistors and capacitors equal for each second-order section, the overall pass-band gain will be fixed, being set by the values chosen for RA and RB.

Example 1

Design a third-order, 350-Hz high-pass filter having a 1-dB Chebyshev response. When executed, the LPHP program requires the following initial information:

Type of filter
Order of filter
Low-pass or high-pass response
Cutoff frequency
Standard capacitor value

From this information, the remaining ideal component values are determined, after which we are asked to enter standard component values that are closest to the ideal values. The output results and final circuit for the design are shown in Figs. 11 and 12.

Example 2

Design a sixth-order, 3000-Hz Butterworth low-pass filter. As shown in the output results in Fig. 13, we only have to determine the frequency determining resistors and capacitors as for the first section, since they are the same for the remaining sections in a Butterworth design. The final circuit is shown in Fig. 14.

THE STATE-VARIABLE FILTER

The state-variable filter, shown in Fig. 15, uses three operational amplifiers, so that there are the following output responses: second-order low-pass, second-order high-pass, and a single pole bandpass. Resistors R and capacitors C determine the cutoff (or center) frequency, while resistors RA and RB control the damping (or Q). For the low-pass and high-pass outputs, the passband gain is unity. For the bandpass output, the center frequency gain will be equal to the value picked for the Q of the filter.

```
        LOW-PASS AND HIGH-PASS FILTER DESIGN
SELECT TYPE OF FILTER RESPONSE:
      1. BESSEL
      2. BUTTERWORTH
      3. 1-DB CHEBYSHEV
      4. 2-DB CHEBYSHEV
      5. 3-DB CHEBYSHEV

? 3
1-DB CHEBYSHEV FILTER DESIGN

SELECT:
LOW-PASS (1) OR HIGH-PASS (2) ? 2
ORDER OF FILTER ? 3
CUTOFF FREQUENCY IN HZ ? 350

1ST SECTION (1ST ORDER):

C IN UF ? .01
   THEN R = 20.56 K-OHMS
TRY ANOTHER VALUE FOR C (YES/NO) ? NO

2ND SECTION (2ND ORDER):

C IN UF ? .022
   THEN R = 18.84 K-OHMS
TRY ANOTHER VALUE FOR C (YES/NO) ? YES

C IN UF ? .033
   THEN R = 12.56 K-OHMS
TRY ANOTHER VALUE FOR C (YES/NO) ? NO
RA IN K-OHMS ? 10
   THEN RB = 15.04 K-OHMS
TRY ANOTHER VALUE FOR RA (YES/NO) ? NO

DESIGN SUMMARY: 3RD ORDER 1-DB CHEBYSHEV FILTER

                    1ST SECTION     2ND SECTION
C (UF)                 .01              .033
R (K-OHMS)             20.56            12.56
RA (K-OHMS)                             10
RB (K-OHMS)                             15.05

INPUT STANDARD VALUES FOR:
C (IN UF)? .01,.033
R (IN K-OHMS)? 20.5,12.7
RA (IN K-OHMS)? 10
RB (IN K-OHMS)? 15
PASSBAND GAIN FIXED AT  7.96 DB

READY
>_
```

Fig. 11. Output results for Example 1.

As this type of circuit gives a second-order response for both the low-pass and high-pass outputs, it will not be possible to obtain optimum performance with all three outputs simultaneously. For either a low-pass or a high-pass Butterworth response, Q must be equal to 0.707 (damping equals 1.414, or 1/Q). Consequently, the bandpass response suffers terribly! Even for a second-order 3-dB Chebyshev filter, Q must be 1.3, which is not much better. We should then design either for a second-order Butterworth low-

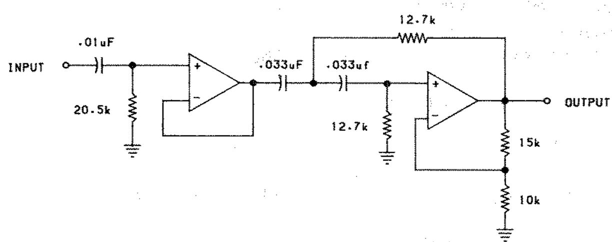

Fig. 12. Final circuit for Example 1.

pass/high-pass response (Q = 0.707), or for a high-Q bandpass response.

An additional feature of the basic state-variable filter is an additional operational amplifier stage, as shown in Fig. 16, to simultaneously add the low-pass and high-pass filter outputs to create a notch or band reject filter.

For designing state-variable filters, the program requires the following initial information:

1. Type of response (low, high, bandpass, or notch)
2. Cutoff, center, or notch frequency
3. Damping factor, or Q
4. Standard capacitor value

From this information, the remaining component values are determined, after which we are asked to enter standard component values that are closest to the ideal values. In addition, we are then able to determine the response of the filter at a given frequency, based on the standard component values selected.

```
            LOW-PASS AND HIGH-PASS FILTER DESIGN
SELECT TYPE OF FILTER RESPONSE:
        1. BESSEL
        2. BUTTERWORTH
        3. 1-DB CHEBYSHEV
        4. 2-DB CHEBYSHEV
        5. 3-DB CHEBYSHEV
? 2
BUTTERWORTH FILTER DESIGN
SELECT:
LOW-PASS (1) OR HIGH-PASS (2) ? 1
ORDER OF FILTER ? 6
CUTOFF FREQUENCY IN HZ ? 3000
1ST SECTION (2ND ORDER):
C IN UF ? .0022
    THEN R = 24.13 K-OHMS
TRY ANOTHER VALUE FOR C (YES/NO) ? NO
RA IN K-OHMS ? 100
    THEN RB = 6.8 K-OHMS
TRY ANOTHER VALUE FOR RA (YES/NO) ? NO
2ND SECTION (2ND ORDER):
RA IN K-OHMS ? 18
    THEN RB = 10.55 K-OHMS
TRY ANOTHER VALUE FOR RA (YES/NO) ? NO
3RD SECTION (@2ND ORDER):
RA IN K-OHMS ? 12
    THEN RB = 17.78 K-OHMS
TRY ANOTHER VALUE FOR RA (YES/NO) ? NO
DESIGN SUMMARY: 6TH ORDER BUTTERWORTH FILTER
                   1ST SECTION     2ND SECTION     3RD SECTION
C (UF)               2.2E-03         2.2E-03         2.2E-03
R (K-OHMS)           24.13           24.13           24.13
RA (K-OHMS           100             18              12
RB (K-OHMS)          6.8             10.55           17.78
SELECT STANDARD VALUES FOR:
C (IN UF) ? .0022,.0022,.0022
R (IN K-OHMS) ? 24,24,24
RA (IN K-OHMS) ? 100,18,12
RB (IN K-OHMS) ? 6.8,10.5,17.8
PASSBAND GAIN FIXED AT  12.46 DB
READY
>_
```

Fig. 13. Results for Example 2.

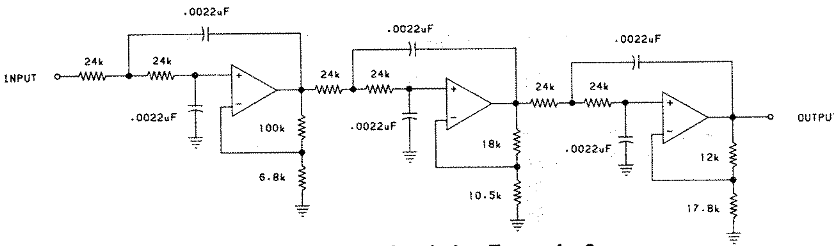

Fig. 14. Final circuit for Example 2.

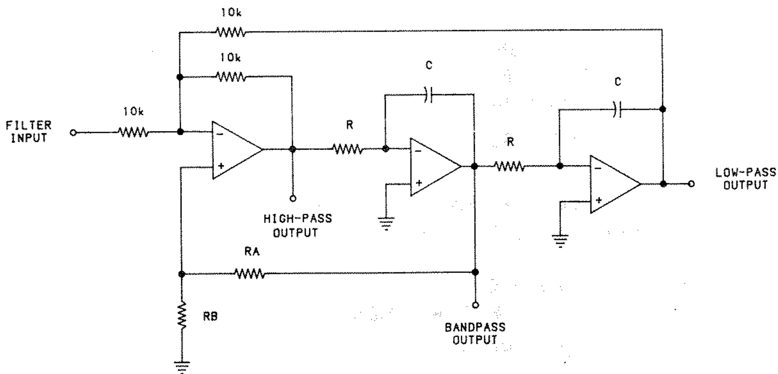

Fig. 15. Basic state-variable filter.

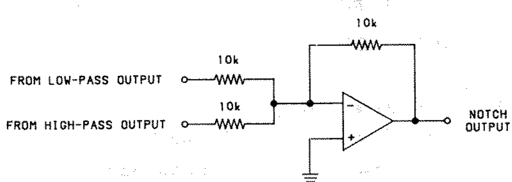

Fig. 16. Creating a notch filter with an additional op-amp summing amplifier.

A BANDPASS FILTER FOR Q LESS THAN 10

For values of Q less than 10, the multiple-feedback circuit of Fig. 17 is often used, since it uses a minimum of components. Furthermore, the design is simplified by making both frequency determining capacitors equal. Resistors R1 and R3 determine the center frequency passband gain, while the center frequency is set by all three resistors.

When executed the program requires the following initial information:

1. Design determined by knowing either Q, 3-dB bandwidth, or the 3-dB frequencies
2. Standard capacitor value
3. Center frequency
4. Center frequency voltage gain

after which the resistor values are determined. In addition, we are then able to determine the filter response at any frequency based on the standard values chosen.

A BANDPASS FILTER FOR Q LESS THAN 50

The simple multiple-feedback circuit of Fig. 17 is not stable for values of Q greater than 10. However, relatively simple bandpass filters having Q values between 10 and 50 are possible with the addition of a second op-amp and three resistors, as shown in Fig. 18. Using the BNDPASS2 program, the design of the filter is simplified by making both capacitors equal, as before. In addition, because of the nature of the filter design, the center frequency voltage gain must be greater than:

$$G > (Q)^{1/2}$$

so that high gain accompanies high Q.

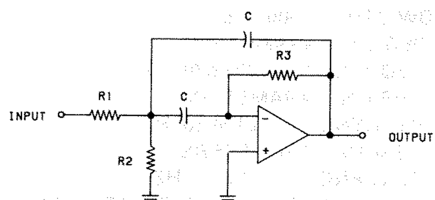

Fig. 17. Bandpass filter for Q less than 10.

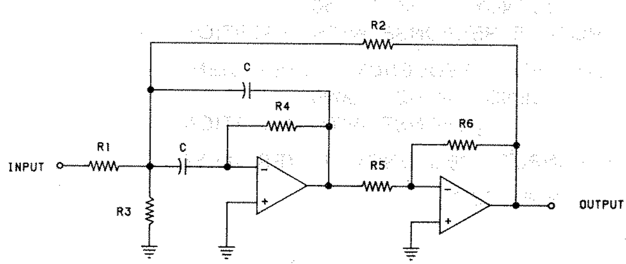

Fig. 18. Bandpass filter for Q less than 50.

STAGGERED-TUNED BUTTERWORTH BANDPASS FILTERS

Very often it is required to have a bandpass filter that passes a range of frequencies, instead of a single frequency. In most cases a single stage bandpass section like those previously described will not offer the necessary response. Consequently, it may be necessary to cascade two or more bandpass sections in order to do the job. The TUNEDBP program allows for the design of either a 2, 3, or 4 stage Butterworth (maximally flat passband) bandpass filter. The program calculates the required center frequency and Q for each stage. In addition, the insertion loss of the filter is also determined, which must be made up when designing the individual stages. The following example illustrates the use of the TUNEDBP program.

Example 3

Design a 3-stage bandpass filter having a lower 3-dB frequency of 2050 Hz and an upper 3-dB frequency of 2350 Hz. When the

```
 STAGGERED TUNED BUTTERWORTH BANDPASS FILTER DESIGN
NUMBER OF STAGES DESIRED ? 3
LOWER 3-DB FREQUENCY (IN HZ) ? 2050
UPPER 3-DB FREQUENCY (IN HZ) ? 2350
    CENTER FREQUENCY = 2194.9 HZ
    3-DB BANDWIDTH = 300 HZ
1ST SECTION DESIGN PARAMETERS:
    CENTER FREQUENCY = 2329.88 HZ        Q =  14.6
2ND SECTION DESIGN PARAMETERS:
    CENTER FREQUENCY = 2194.88 HZ       Q =  7.3
3RD SECTION DESIGN PARAMETERS:
    CENTER FREQUENCY = 2067.7 HZ       Q =  14.6
GAIN OF CASCADED STAGES MUST BE AT LEAST 12.2 DB

AMPLITUDE RESPONSE (1=YES, 0=NO) ? 1
INPUT FREQUENCY IN HZ ? 1750
    AMPLITUDE RESPONSE WITH INSERTION LOSS = -43.5 DB

ANOTHER INPUT FREQUENCY (1=YES, 0=NO) ? 1
INPUT FREQUENCY IN HZ ? 3000
    AMPLITUDE RESPONSE WITH INSERTION LOSS = -52.1 DB

ANOTHER INPUT FREQUENCY (1=YES, 0=NO) ? 0

DESIGN COMPLETED

READY
>_
```

Fig. 19. Output results for Example 3.

TUNEDBP program is run, the results, as shown in Fig. 19 are obtained.

For our example, we see that the first and third sections have values of Q that are greater than 10 (i.e., 14.6). Consequently, we should use the filter circuit shown in Fig. 18 and the BNDPASS2 program to calculate each section separately. For the second section, the Q is less than 10 (i.e., 7.3), so that we are able to use the circuit of Fig. 17 and the corresponding BNDPASS1 program. If the Q of any stage is found to be greater than 50, then the state-variable filter should be used. In addition, the overall gain of the three stages must be at least 12.16 dB, or a voltage gain of 4.05 in order to overcome the insertion loss presented by the filter.

Fig. 21 shows one of many circuits that are possible to satisfy our design. The voltage gain for the first and third sections is 4, while the gain for the second section is 2, giving an overall gain of 32 (+30.1 dB).

THE NOTCH FILTER

Fig. 20 shows a notch filter for values of Q less than 25. For values of Q greater than 25, the state-variable notch filter should be used. As with all the filter designs discussed, both capacitors are made equal to each other.

The NOTCH program requires the following initial information:

1. Design determined by knowing either Q, 3-dB bandwidth, or the 3-dB frequencies
2. Standard capacitor value
3. Notch, or null frequency
4. Passband voltage gain

after which the remaining resistor values are determined.

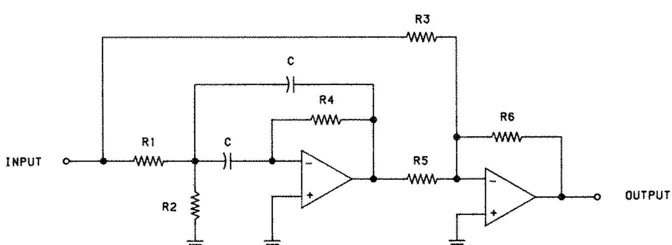

Fig. 20. Notch filter.

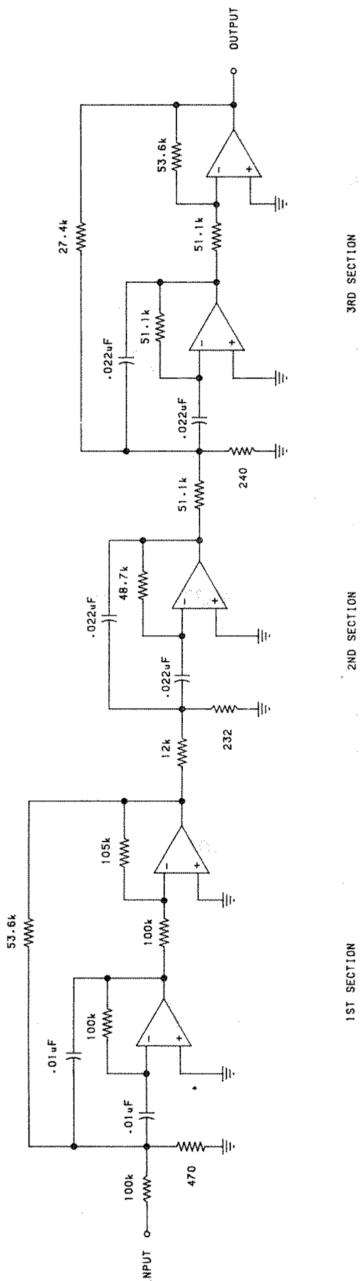

Fig. 21. Final circuit for Example 3.