COMPUTERIZED OP-AMP CALCULATOR

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Find all the circuit values for three important op-amp configurations in an instant with this spreadsheet template.

■What electronics hobbyist wouldn't love to be able to calculate all the resistor and capacitor values for a differential op-amp circuit in less than a minute? Better yet, imagine being able to do it for inverting, non-inverting, and differential configurations simultaneously. You can eliminate arithmetic errors, change designs in mid-stream, or perform "what-if" analyses to your heart's content.

Well, the op-amp "calculator" we'll describe in this article helps you do it. It's an op-amp design template written for use with the popular and powerful *Supercalc*, an electronic spreadsheet from Sorcim Corporation. It was developed on a Xerox *820*, with an 80 column display, operating under CP/M, but it should work on any computer running *Supercalc*. Note that you'll need to use horizontal scrolling on a 40-column display.

To use the template, simply load in an installed *Supercalc* program, then load the template, which we've named OPAMPC. Figure 1 shows the screen after loading. At the upper left is the *user choice* selection. The number (no alphabetical prefixes or suffixes, please) of the desired op-amp is typed in, and the gain-bandwidth product (GBP) is automatically returned to the right. (That selection is customized by the user).

Next, the desired input resistance (INPUT R), voltage gain (A_V), low-frequency cutoff (LOW F_C), and high-frequency cutoff (HIGH F_C) are entered. The rest of the operation is automatic.

Resistor and capacitor values are simultaneously calculated for three basic configurations, and automatically rounded to the nearest EIA standard values. Circuit parameters are then recalculated using those values, and displayed in the ACTUAL column. Percent deviation from desired performance is returned in the next column to the right. In most cases, those errors are kept to less than 10%.

Why use *Supercalc*? There are a number of reasons. First, *Supercalc* is a versatile piece of software that can be adapted to many different purposes. For that reason, it is among the first programs a new computer owner buys. Secondly, because of its many logical and arithmetic commands, much of a programmer's work is already done, so designing and entering a template is quicker than writing a program in say, Pascal or BASIC. We could have used *Visicalc*, another electronic spreadsheet, but doing so would have forced us to sacrifice the automatic rounding-to-EIA-standards that makes OPAMPC so convenient. No doubt, some enterprising programmers will come up with ways to adapt this template to their particular spreadsheet program.

Three types of error messages are included, summarized at the upper right of the worksheet. Each amplifier configuration is represented separately, listed under INDEX. If the actual or desired *G*ain-*B*andwidth *P*roduct (GBP) is greater than the rated GBP of the selected op-amp, a 1 appears. If not, 0 is returned. A similar function is provided to test whether R2

```
==========================================================================
      USER CHOICES
--------------------------------------------------------------------------
     DEVICE:      1458  RATED GBP: 5e5      ------ERROR FLAGS------
    INPUT R:       1e5        INDEX         GBP R2
  GAIN (Av):         5    A12. Invert.       0   0    1 = TOO HIGH
     LOW Fc:        25    A24. Non           0   0    0 = OK
    HIGH Fc:       2e4    A36. Diff          0   0

     >> 0 Indicates Selected R or C Out of Range <<

DIFFERENTIAL AMP MODE
                                        ACTUAL                %ERROR
            R1      1e5                GAIN: 5e0                2.00
            R2    5.1e5             LOW Fc:  23                -6.38
            R3      1e5                 GBP: 1e5
            R4    5.1e5              Rin +: 6e5
            C1  6.8e-2mF             Rdiff: 7e5
            C2    1e-2mF
--------------------------------------------------------------------------
```

FIG. 1—VIDEO DISPLAY (80 column) as it looks during a sample differential amp calculation using OPAMPC.

(negative feedback resistor) is less than 1 megohm, a necessity for proper DC stability in common bipolar op-amps. If you're using BiFET's, you can change the flag point to account for their lower current requirements. Refer to the device manufacturer's data.

An R2 error will also occur if calculations result in a value out of the lookup table's range. That will be corroborated in the individual amplifier sections.

Structure of OPAMPC

OPAMPC is functionally divided into three sections. In USER CHOICES, device number and desired circuit parameters are entered. GBP and R2 error flags are included, along with an index of the calculation section.

The CALCULATION area of the spreadsheet contains the formulas necessary to determine component values from the user's choices. Inverting, non-inverting, and differential configurations are treated separately. Spacing between the subsections aids readability and quick access when using the window mode.

The LOOKUP TABLES are the key to the rounding function. That section is automatically searched by the CALCULATION area to find the standard resistor or capacitor value closest to the calculated one. Don't be intimidated by its 151-line length! It's quickly built, using *Supercalc*'s automatic functions.

Theory of operation

Figure 2 shows three common amplifier designs, and the formulas used to determine component values. The OPAMPC template is based on an AC model, and was specifically written for audio applications. Power supply connections are not shown, nor are compensation or offset circuits. Many devices use internal compensation, and offset is usually not a big problem. If in doubt, consult one of the many op-amp design books available.

Most of the formulas shown in Fig. 2 were simply converted into *Supercalc* format and entered onto the worksheet (more on that later).

Inverting amp

OPAMPC ignores the negative component of the inverter's output, a common convention. Remember, though, that the output signal will actually be 180° out of phase with the input.

The 1E6 factor in the calculation for C1 produces an answer in microfarads, instead of farads. That applies to the other configurations as well. 1E6 is *Supercalc* shorthand for 1×10^6. Using the optional resistor R3 will minimize input offset, although, commonly, the non-inverting input is simply tied to ground.

Non-inverting amp

In the non-inverting amp, for minimum offset, $R3 = R1 \| R2$ (the symbol $\|$ means "in parallel with"). The value of R3 is equal to the input resistance, so whatever value you select in the USER section appears opposite R3. We know that the gain of a non-inverting op-amp is $1 + (R2/R1)$, but how do we use that formula without selecting a fixed value for R2 and R1? Remember that whatever combination of resistors we pick must have a parallel value equal to R3.

The trick is trying to get R1 and R2 solved for two different equations simultaneously in a way *Supercalc* could handle. After trying many of the normal methods for that, unsuccessfully, we hit upon the idea of simply defining $R1 + R2 = 1$ megohm. That automatically kept the feedback resistor below our design limit of 1 megohm, eliminating an annoying and clumsy term in the calculations to boot.

You may have noticed that an undefined condition will exist if the user selects a gain less than or equal to 1, because $(A_V - 1)$ will then equal 0, by which you can't divide, or a negative number, whose square root is not a real number.

The low-frequency rolloff points of the inverting and non-inverting inputs respectively are $-f_C$ and $+f_C$. The value of $+f_C$ is user-selected and equal to LOW F_C. The value of $-f_C$ is arbitrarily set for five times $+f_C$ in order to minimize low-frequency noise gain.

Differential amp

The calculations for the differential configuration are virtually identical to those for the inverting mode, except that they apply to both inputs. Best CMRR (Common Mode Rejection Ratio) requires $+f_C = -f_C$, where $+f_C$ is the cutoff frequency of the non-inverting input, and $-f_C$ is the cutoff frequency of the inverting input. For simplicity, we let $R1 = R3$ and $R2 = R4$. That results in differing input resistances for the inverting and non-inverting inputs.

User-selected INPUT R becomes the resistance of the inverting input, with the non-inverting input R being calculated and returned opposite $r_{in}+$. It will always be higher than the user-selected figure, but that is not generally a problem in signal circuits. The differential input resistance, R_{DIFF}, appears in cell F42, and is the sum of $R_{IN}+$ and $R_{IN}-$.

Lookup table

Seldom do calculations yield precise, convenient, standard values for resistors and capacitors. If we intend to translate our design to the real world, however, that is necessary.

Consequently, OPAMPC contains lookup tables, which effectively round calculated values to EIA standards. We use *Supercalc*'s built-in LOOKUP function and some long lists to do this.

Building the worksheet

To ease entry, we've divided OPAMPC into two files, called OPCALC.CAL, which contains amplifier formulas and the user choice section, and LOOKVAL.CAL, the resistor, capacitor, and op-amp lookup tables. Once we've built and saved those two files, we'll combine them into a single template called OPAMPC.CAL. (.CAL signifies a file of *Supercalc* type. The file type is understood and need not be stated when working within the *Supercalc* program.)

Good practice calls for frequent saves and backing up all files on a separate disk.

To build the lookup tables, first enter the headings as shown in Fig. 3. The column widths were selected only so

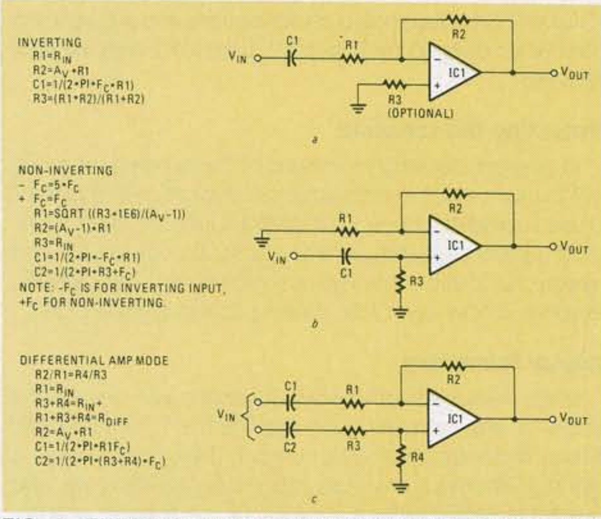

FIG. 2—THREE OP-AMP CONFIGURATIONS. An inverting amp is shown in *a*, a non-inverting amp in *b*, and a differential amp in *c*.

the headings would fit. Once the tables are integrated on the OPAMPC worksheet, column width will be irrelevant.

Next, starting at cell D3, enter the following series of numbers in column D:

1E−5	2.2E−5	4.7E−5
1.11−5	2.7E−5	5.6E−5
1.5E−5	3.3E−5	6.8E−5
1.8E−5	3.9E−5	8.2E−5

Put a 0 in C2 and D2 and enter the formula D3 + C*.9 in cell C3. Replicate it in the range C4:C100. Now, enter the formula D3 + C*10 at cell D15 and replicate it from D16:D100. Enter 0's at the bottom of the capacitor list in cells C101 and D101.

The resistor table is built similarly. Zeros go into cells F2 and G2. The following list is entered into column G, starting at G3:

1	1.8	3.3	5.6
1.1	2	3.6	6.2
1.2	2.2	3.9	6.8
1.3	2.4	4.3	7.5
1.5	2.7	4.7	8.2
1.6	3	5.1	9.1

The formula G3 + C*.95 goes into cell F3 and is replicated from F4 to F150. Similarly, cell G27 gets G3 + C*10, which is replicated in the range G25:G150. Zeros are then entered at F151 and G151.

The op-amp list should be customized for whatever devices you favor. We've shown a few popular ones as an example in Fig. 3. The list can be as short or long as you want, but remember to put a 0 at the beginning and end to avoid ERROR or N/A messages. You will also need to modify the expression in E5 to match the list's range.

You'll notice the resistor list is longer than that used for capacitors. For accuracy's sake, the complete USA Standard C83.2 (formerly EIA GEN 102), Series 10, sequence is used for resistors. That way, no matter what the result of a calculation (assuming it is not out of range) a standard value within ±5% of it can be found. We selected Series 20 values (±10%) for the capacitor list, because "in-between" capacitors are scarce.

```
WIDTH:  12          8      8        12       4    10        5
  !     A     !!    B  !!  C   !!    D    !! E!!   F     !! G !
 1! OP AMP LIST MAX GBP CAPACITOR LOOKUP         RESISTOR LOOKUP
 2!        0 0          0        0              0         0
 3!      324 .2E6       D3*.9    1E-5       mF  G3*.95    1
 4!      741 .2E6       D4*.9    1.2E-5     mF  G4*.95    1.1
 5!     1458 .5E6       D5*.9    1.5E-5     mF  G5*.95    1.2
 6!     1458 5E5        D6*.9    1.8E-5     mF  G6*.95    1.3
 7!        0 0          D7*.9    2.2E-5     mF  G7*.95    1.5
 8!                     D8*.9    2.7E-5     mF  G8*.95    1.6
 9! R and C values      D9*.9    3.3E-5     mF  G9*.95    1.8
10! are USA Standard    D10*.9   3.9E-5     mF  G10*.95   2
11! C83.2.              D11*.9   4.7E-5     mF  G11*.95   2.2
12!                     D12*.9   5.6E-5     mF  G12*.95   2.4
13! Res. use series 10  D13*.9   6.8E-5     mF  G13*.95   2.7
14! Caps. use series 20 D14*.9   8.2E-5     mF  G14*.95   3
15!                     D15*.9   D3*10      mF  G15*.95   3.3
16!                     D16*.9   D4*10      mF  G16*.95   3.6
17!                     D17*.9   D5*10      mF  G17*.95   3.9
18!                     D18*.9   D6*10      mF  G18*.95   4.3
19!                     D19*.9   D7*10      mF  G19*.95   4.7
20!                     D20*.9   D8*10      mF  G20*.95   5.1
21!                     D21*.9   D9*10      mF  G21*.95   5.6
22!                     D22*.9   D10*10     mF  G22*.95   6.2
23!                     D23*.9   D11*10     mF  G23*.95   6.8
24!                     D24*.9   D12*10     mF  G24*.95   7.5
25!                     D25*.9   D13*10     mF  G25*.95   8.2
26!                     D26*.9   D14*10     mF  G26*.95   9.1
27!                     D27*.9   D15*10     mF  G27*.95   G3*10
                          ...To row 101...      ...To row 151...
```

FIG. 3—LOOKUP TABLE HEADINGS and general layout, in formula display. The column widths shown were selected only so the column headings would fit. Once the tables are integrated with the OPAMPC worksheet, column width will be irrelevant.

After we've built the lookup table on the worksheet, we'll save it on disk as LOOKUP.CAL. Making another backup copy is an excellent idea. The tired hand or mind, not to mention a faltering powerline, could trash a screen or disk, obliterating many hours of work. If you don't have a backup copy of a file on another disk, you don't have the file.

In order to reduce calculation time when using the worksheet, it is advisable to use only the lookup-table values, not the formulas. Otherwise, every time we hit <!>, the "force calculation" command, the lookup table will recalculate, greatly reducing the speed of the worksheet. So, do another save of the lookup table, but this time with values only. Name the file LOOKVAL.CAL.

```
  !     A     !!   C   !!     D     !!   E   !! F!! G !!    H  !
 1!                          OPAMPC
 2!=============================================================
 3!      USER CHOICES
 4!-------------------------------------------------------------
 5!     DEVICE:               RATED GBP: 2e5     -----ERROR FLAGS-----
 6!    INPUT R:                    INDEX         GBP R2
 7!  GAIN (Av):                   A12. Invert.    0   0    1 = TOO HIGH
 8!     LOW Fc:                   A24. Non        0   0    0 = OK
 9!    HIGH Fc:                   A36. Diff       0   0
10!
11!    >>> 0 Indicates Selected R or C Out of Range <<<
12! INVERT MODE
13!              STANDARD                  ACTUAL            %ERROR
14!            R1                          GAIN:
15!            R2                        LOW Fc:
16!            C1          mF                GBP
17!            R3
18!-------------------------------------------------------------
19!
20!
21!
22!
23!
24!NON-INVERT MODE
25!                                        ACTUAL            %ERROR
26!          - Fc                          GAIN:
27!          + Fc                        LOW Fc:
28!            R1                            GBP
29!            R2
30!            R3
31!            C1          mF
32!            C2          mF
33!-------------------------------------------------------------
34!
35!
36!DIFFERENTIAL AMP MODE
37!                                        ACTUAL            %ERROR
38!            R1                          GAIN:
39!            R2                        LOW Fc:
40!            R3                           GBP:
41!            R4                         Rin +:
42!            C1          mF            Rdiff :
43!            C2          mF
44!-------------------------------------------------------------
```

FIG. 4—OPCALC.CAL HEADINGS. The headings should be typed in exactly as shown here.

Op-amp calculation area

Now we'll build a worksheet called OPCALC.CAL. It will contain all the amplifier calculations and error messages. Set the worksheet for manual calculation before starting.

Refer to Fig. 4 and format the columns to these widths:

Column A: 12	Column E: 8
Column B: 0	Column F: 6
Column C: 8	Column G: 5
Column D: 12	Column H: 8

Type in the headings exactly as they appear in Fig. 4, using *Supercalc*'s text formatting options as needed.

You'll notice that column B has a width of 0. That effectively hides the unrounded results of the amplifier calculations, so as to avoid confusion. You can still enter formulas, which will then show up on the status line. If ever the need should arise, Column B can be expanded to the standard 9 characters to show the precise results.

After checking your work for accuracy, refer to Fig. 5 for the formulas. You'll note the columns are expanded beyond their normal width for clarity. You don't have to do that on your worksheet, since any formula entered in a cell will show up in the status line, regardless of column width.

```
  :   A   ::          B          ::  C  ::    D   ::  E ::     F      ::        G         :: H :
 1:                                        OPAMPC
 2:==================================================================================
 3:          USER CHOICES
 4:----------------------------------------------------------------------------------
 5:   DEVICE:                            RATED GBP: LOOKUP(C5,A49:A53)
 6:   INPUT R:                                 INDEX           GBP           R2
 7:  GAIN (Av):                            A12, Invert.   IF(F16>E5,1,0) OR(C15>1E6,C15=0)  1 = TOO HIGH
 8:    LOW Fc:                             A24, Non       IF(F28>E5,1,0) OR(C29>1E7,C29=0)  0 = OK
 9:   HIGH Fc:                             A36, Diff      IF(F40>E5,1,0) OR(C39>1E8,C39=0)
10:
11:   >>> # Indicates Selected R or C Out of Range <<<
12: INVERT MODE
13:          CALCULATED            STANDARD            ACTUAL                           %ERROR
14:        R1 C6                  LOOKUP(B14,F49:F198)   GAIN: C15/C14                  ((F14-C7)/C7)*100
15:        R2 C7*B14              LOOKUP(B15,F49:F198) LOW Fc: 1/(2*PI*C14*(C16*1E-6))  ((F15-C8)/C8)*100
16:        C1 1E6/(2*PI*C8*B14)   LOOKUP(B16,C49:C158)     GBP F14*C9
17:        R3 (B14*B15)/(B14+B15) LOOKUP(B17,F49:F198)
18:----------------------------------------------------------------------------------
19:
20:
21:
22:
23:
24:NON-INVERT MODE
25:                                                    ACTUAL                           %ERROR
26:       - Fc 5*C8               2*C8                 GAIN: (C28+C29)/C28              ((F26-C7)/C7)*100
27:       + Fc C8                 C8                 LOW Fc: 1/(2*PI*(C31*1E-6)*C28)    ((F27-C8)/C8)*100
28:        R1 SQRT((B30*1E6)/(C7-1)) LOOKUP(B28,F49:F198)   GBP F26*C9
29:        R2 (C7-1)*B28          LOOKUP(B29,F49:F198)
30:        R3 C6                  LOOKUP(B30,F49:F198)
31:        C1 1E6/(2*PI*C8*B28)   LOOKUP(B31,C49:C158)
32:        C2 1E6/(2*PI*B30*B27)  LOOKUP(B32,C49:C158)
33:----------------------------------------------------------------------------------
34:
35:
36:DIFFERENTIAL AMP MODE
37:                                                    ACTUAL                           %ERROR
38:        R1 C6                  LOOKUP(B38,F49:F198)   GAIN: C39/C38                  ((F38-C7)/C7)*100
39:        R2 C7*B38              LOOKUP(B39,F49:F198) LOW Fc: 1E6/(2*PI*C38*C42)       ((F39-C8)/C8)*100
40:        R3 C6                  LOOKUP(B40,F49:F198)    GBP: F38*C9
41:        R4 B39                 LOOKUP(B41,F49:F198)  Rin +: C40+C41
42:        C1 1E6/(2*PI*B38*C8)   LOOKUP(B42,C49:C158)  Rdiff : F41+C38
43:        C2 1E6/(2*PI*(B40+B41)*C8 LOOKUP(B43,C49:C158)
44:----------------------------------------------------------------------------------
```

FIG. 5—OPAMPC FORMULAS. Columns have been expanded and formula display has been selected in this example. During normal use, the worksheet is formatted as in Fig. 1.

Use the replicate function to simplify entering the lookup statements in column C. Be sure to select the *ask for adjust* option to prevent REPLICATE from changing the address of the lookup table. Notice that capacitor and resistor lookup tables have different addresses. When done, save the completed worksheet as OPCALC.CAL.

The union

To complete the OPAMPC template, start with a blank worksheet and load OPCALC.CAL (All) onto the screen. Ignore any error indications. Move the cursor to A48 and load LOOKVAL.CAL. You should ask for options and answer P (for part) when queried by *Supercalc*. Then load range A1:G151 into A48.

Protecting the template

To prevent inadvertent erasure of the contents of a cell, which might result in erroneous calculations, it is important to use *Supercalc*'s PROTECT command. Once the entire worksheet is protected, the user choices section, cells C5:C9 are UNPROTECTED to allow entry at those points only. The OPAMPC template is now complete. Save to disk as OPAMPC.CAL.

Display formatting

Unless instructed otherwise, *Supercalc* will present the results of any calculations in the "general" format. It will display them as ordinary real numbers if the column is wide enough. Otherwise, it will use exponential notation. We have found that intelligibility is improved if the resistors and capacitors are expressed exponentially. The same is true of the GBP.

Integer notation is preferred for the device number, gain, low f_C, and error flags. Percent of error (%error) requires the <$> (two-point decimal or "dollar sign") format.

Using op-ampc

Invoke the GLOBAL command to set the worksheet for manual calculation by columns. Position row 2 at the top of the screen. Next, use WINDOW to put a horizontal split at row 12. Make sure that both sections scroll independently. Later, when you become more familiar with OPAMPC, you can eliminate clutter on the screen by using the GLOBAL command to suppress the border.

Let's say we wish to design a differential amplifier, using a 1458 IC. Place the cursor into the upper left cell of the bottom window. Looking at the index in the upper window, you can see that the differential configuration starts at cell A36. Use <=> to jump there, then put the cursor back into the upper window and start entering your performance choices in column C. Remember to use only the device number in cell C5. No alphabetical suffixes or prefixes are allowed.

To calculate, invoke the <!> command twice. A quick glance to the right will tell you if any errors have occurred. The error flags section gives information even on configurations not currently displayed. Column C, in the lower window, displays rounded values. To the right, in column F, actual performance, recalculated using the rounded values, is shown. The percentage of deviation from the entries in the user choice section appears in column H.

Input resistance for all except the non-inverting (+) input of the differential amp will be within ±5% of that selected. The high frequency cutoff selection is included only to calculate required GBP, so no error checking is done for it.

OPAMPC is a valuable tool for the electronics hobbyist. It allows a designer to quickly calculate the three most common op-amp configurations at once. Its speed makes rapid design changes and "what if" analyses routine. Of course, it can't eliminate the "fine-tuning" necessary to produce the optimum design, but it does get you well into the ball-park.

If you have any questions about this template, feel free to contact the author on CompuServe. Address your message to Kirk Vistain, user number 72356,1355. OPAMPC is easy to enter and easy to use. Have fun with it!