

# How to use the Excel Loop Design System

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Revised 15 November, 2008

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## Description:

**The Workbook 'loop7.xls' has 19 'tabs'**

### **2 are computational Worksheets**

'Control' is where **all** data are entered and all data associated with the loop, except 'Bessel', are computed.

'Bessel' computes the response of a 3<sup>rd</sup> order Bessel filter, which may be inserted in the forward path of the loop, if desired.

### **3 are Worksheets devoted to text information:**

'Notes' is a log of changes and short descriptions of their effects. Here you can find the date of the current revision.

'Macros' lists the available macros, their functions and their keyboard shortcuts.

'Parameters' lists all parameter symbols used and their definitions. At the bottom of the sheet is a block diagram to clarify where these parameters are located in a feedback instrument.

'Conversions' is a list of useful conversion factors

### **14 are graphical Charts:**

The four charts which are particularly useful for instrument design are indicated by '\*'

\*'Vel. Response' is the main chart. It shows the instrument Velocity Response, Forward Path Transfer Function, 1/Feedback Transfer Function, Loop Gain, and the transfer function of any added Inverse Filter, all as a function of frequency. This displays almost all significant information regarding loop performance.

\*'Loop Phase' displays the phase shift of the loop gain as a function of frequency and indicates the gain-crossover frequency and associated phase margin. This indicates how near the loop is to feedback oscillation.

'Vel. Resp. Phase' shows the phase shift of the instrument Velocity Response vs frequency. This is interesting to compare with other instruments.

‘Vel. Asymptotes’ is similar to ‘Vel. Response’ with the addition of significant asymptote lines and their formulas.

\*‘Compliance’ displays the closed-loop position sensitivity to an applied force. This suggests how the instrument will respond to applied error forces, as a function of their frequency of change.

‘Accel. Response’ displays the instrument response to a sinusoidal ground acceleration, as a function of frequency. It also indicates the response to steady-state acceleration changes, such as from instrument tilt.

\*‘Force Resp.’ displays the instrument response to a sinusoidal applied force, as a function of frequency. Note that Force Response = mass,  $M_0$  x Acceleration Response. This also suggests how the instrument will respond to applied error forces.

‘Disp. Resp.’ displays the instrument response to a sinusoidal ground displacement, as a function of frequency.

‘SpMa-X’ displays the Spring-mass response to a sinusoidal ground displacement, as a function of frequency,

‘SpMa-V’ displays the Spring-mass response to a sinusoidal ground velocity, as a function of frequency.

‘SpMa-A’ displays the Spring-mass response to a sinusoidal ground acceleration, as a function of frequency.

‘Bes.Mag’ displays the transfer function of the Bessel filter vs frequency.

‘Bes.Phase’ displays the phase shift of the Bessel filter vs frequency.

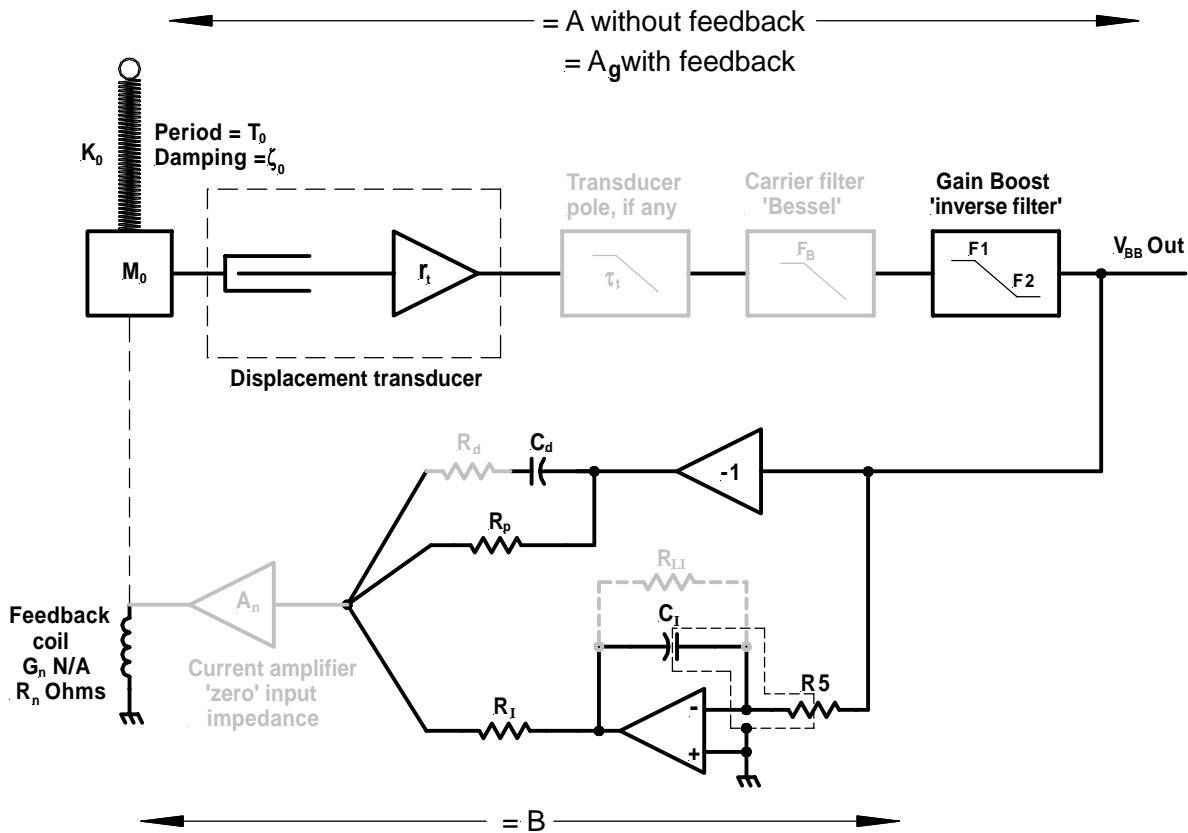
‘Bes.Grp.Dly.’ displays the group delay of the Bessel filter vs frequency.

## **Operation:**

When opening the spreadsheet, depending on your security settings, you will see a message stating that the workbook contains macros. Unless you are just browsing, select ‘Enable Macros’.

The workbook normally opens to the ‘Notes’ worksheet where you can see the date of the latest revision and descriptions of all changes.

You may ignore any “Negative or Zero values in Log Plots” error messages. This appears to be a bug in Excel.



Block diagram showing some of the instrument parameters.

### Example for Designing the Feedback Loop:

Our aim will be to design a feedback seismometer with a Generator Constant of 1500 Vs/m, a high frequency rolloff at 30 Hz and the low frequency corner at a period of 30 seconds. Normally we would start by entering the values of all the parameters which we know, such as the effective mass value, the spring-mass free period, the feedback coil parameters and anything else which we want to define. Here we will take a parameter set from an unfinished design, intended for adding feedback to a CM-3 vertical seismometer.

First open the 'Control' worksheet (Click on the 'Control' tab at the bottom of the page)

Load the 'CM-3 Mods' data set to use as sample data.

Scroll down to line 132 so that the data set 'Parameters for CM-3 Mods' is visible.

Select (Click on) cell L134, the upper left corner of the data range enclosed by a dashed red line.

Type <ctrl>'1' to Load the data set into the working area.

TRUE	Use Proportional	
TRUE	Use Integral	
TRUE	Use Derivative	
FALSE	Insert Inverse Filter	
FALSE	Insert Bessel Filter	
TRUE	Integrator is feedback type	
<b>Parameters Defaults for CM-3 Mods</b>		
$C_d = 1.240E-05$	Fd	1.240E-05
$R_d = 0.00E+00$	Ohms	67
$C_1 = 4.4E-05$	Fd	4.4E-05
$\tau_{L1} = 1.00E+03$	sec	1.00E+03
$R_5 = 4.700E+06$	Ohms	4.700E+06
$R_p = 1.000E+06$	Ohms	1.000E+06
$R_1 = 8,000$	Ohms	62,000
$G_n = 9.526$	N/A	9.526
$A_n = 1.000$	A/A	1.000
$M_0 = 1.60$	kg	0.80
$\zeta_0 = 0.01$		0.01
$T_0 = 1.5$	sec	1.5
$r_t = 158,000$	V/m	158,000
$\tau_t = 0.00E+00$	sec	2.00E-04
<b>'Displacement Amp. Gain Boost - "inverse filter"</b>		
$F_1 = 0.0198$	Hz	0.020
$F_2 = 7.9577$	Hz	7.958
<b>Bessel Filter</b>		
$F_B = 1600$	Hz	1600

This is what the working parameters should look like after the 'CM-3 Mods' data set has been loaded.

Note: Later versions of the spreadsheet may have some values which are different from these. In order for the example below to match the spreadsheet data, please correct any values in the spreadsheet yellow cells which do not match these. In particular, the yellow cells for  $R_d$ ,  $R_1$ ,  $M_0$  and  $\tau_t$  should be changed to match the values above.

Now take a look at the 'Vel. Response' chart (Click on the 'Vel Response' tab)

The green curve is the instrument response.

The blue curve is, A, the response with feedback absent.

The red curve is 1/B where B is the transfer function of the feedback path.

The pink curve is the loop gain  $\equiv AB = A/(1/B)$

The orange line will represent the inverse filter when it is used.

Since the green curve does not appear to be the velocity response we want, we will go back to the 'Control' worksheet to begin the design process.

1. We want the mid-band velocity response 'generator constant'  $A_g$  to change from 13,545 to 750 (displayed on 'Vel. Response' chart and in cell D50). The value, 750, is the result of having an output stage following the feedback loop having a gain of x2. If we design the feedback loop for  $A_g = 750$ , that will result in an over all instrument generator constant of 1500 Vs/m which is the desired value. If a higher generator constant is desired, it may be obtained by adding additional gain following the feedback loop.

To correct  $A_g$ , scroll down to row 62 so that the various 'Helpful Calculation Tools' are visible. In yellow cell D66 if not already=750, enter 750, the desired value for  $A_g$ .

In the green cells we see that if we make  $C_d$ , the derivative branch capacitor = 223.9  $\mu$ F, **or** we change the mass,  $M_o$  to 0.0886 Kg, **or** we make the force transducer  $G_n = 172.043$  N/A **or** we add a driver amp having current gain,  $A_n = 18.060$ , we should end up with  $A_g = 750$ , as we desired.

We will choose to change  $A_n$  to from 1 to 18.060.

Select yellow cell D30 and type in 18.06 for  $A_n$ , then <enter>. Under 'Mid Band Velocity Response' cell D65 now says 'Matches' which indicates that the desired value for  $A_g$  of 750 has been achieved. Note that, in practice, adding such an amplifier might introduce excessive noise. In this example we won't worry about that.

2. Reset the high frequency corner of the instrument response to 30Hz.

In yellow cell D73 if not already=30, enter 30.

Below we see the values for the displacement transducer gain,  $r_t$ , and also  $C_d$ ,  $G_n$  and  $A_n$ , **any one** of which will achieve the desired 30 Hz rolloff. However changing  $C_d$ ,  $G_n$  or  $A_n$  will also change  $A_g$  from the desired 750 Vs/m.

So we will leave them alone and change  $r_t$  to 141375.

Select yellow cell, D34 and type in 141375 then <enter>. Under 'High Frequency Corner', cell D72 now says 'Matches' which indicates that the upper corner frequency now = 30Hz.

3. Reset the low frequency corner to correspond to a 30 second period.

In yellow cell D81 if not already=30, enter 30 for the desired  $T_{BB}$ .

Below we see values we can use for  $C_1$  **or** R5 **or**  $R_1$  which will give us the desired low frequency corner.

We will choose to change R5 to 5.223 Meg.

Select yellow cell, D26, and type 5.223E6 then <enter> Under 'Low Frequency Corner, Cell D80 will now say 'Matches' to indicate that our corner now is at 30Sec.

4. Now examine what we have so far.

Go to the 'Vel. Response' chart and look at the green curve. It matches the requirements except for the bump near the low frequency corner. That can be fixed by adjusting the Proportional feedback branch resistor  $R_p$ . If you type <ctrl>'d' to execute the macro 'Adjust **B**Damping', you will see the bump disappear. In the 'Control' worksheet cell D27, we can see that  $R_p$  has been reduced from 1megohm to 272.3 k, which changes the damping factor of the low frequency corner (of B) to 0.707 of critical.

5. Correct the loop gain at 0.03Hz

At 0.03 Hz, the loop gain is less than 4. While the present configuration would appear to work fine, many benefits of having feedback are not being realized in the vicinity of 0.03Hz. A good rule is that wherever you can, the loop gain should remain above 100. In general, the higher the loop gain the better. However, in raising the loop gain one must also take into consideration its characteristics in the vicinity of the gain-crossover frequency, to assure that the loop doesn't begin to oscillate.

What would it take to get the loop gain up to 100? Since the loop gain equals the vertical distance between the red curve,  $1/B$ , and the blue curve,  $A$ , if we were to raise  $A$  by a factor of slightly over 30, we should achieve the loop gain of 100 we are looking for. That could be done by adding gain to the position sensor amplifier, which would increase  $r_t$ . Try increasing  $r_t$  to 4,400,000. Now for the lower frequencies, the loop gain stays above 100 as we wanted. **But**, the gain-crossover frequency and the associated high-end rolloff is now at 934Hz, not 30. That was because when we raised the blue curve by a factor of 30, its intersection with the red  $1/B$  curve also moved to the right by a factor of about 30. What we need is a way to raise  $A$  at lower frequencies, but not at higher ones.

We need to use the '**Inverse Filter**'.

It would be more accurate to call this an amplifier rather than a filter, in that it provides a substantial gain boost for  $A$  at low frequencies, but one which falls to 1 well before reaching the upper corner, gain-crossover, frequency.

Note here that the spreadsheet always assumes that the inverse filter gain = 1 at high frequencies. If the actual inverse filter circuit has a high-frequency gain greater than 1, that factor should be included in the value used for the transducer gain,  $r_t$ .

The design of the inverse filter involves a bit of trial and error.

First we will set  $r_t$  back to 141372, then select cell D17 and type <ctrl>'t' to set it to TRUE, enabling the inverse filter.

To start, we can set its lower corner frequency,  $F_1$ , to be approximately the  $V_{bb}$  low corner frequency. Enter 0.032 for  $F_1$  in cell D37. Initially  $F_2$  can be 20x higher giving a DC gain of 20. Enter 0.64 for  $F_2$  in cell D38. Now looking at the

loop gain in 'Vel. Response' we see that it does not dip as low at 0.04 Hz, but it is still well below 100. To make it higher, we can start increasing  $F_2$ , a little at a time.  $F_2=1.5$  is still too low, but with  $F_2=1.6$  Hz the loop gain should be high enough. We note that this gives the 'filter' a DC gain of 50.

The orange curve in the 'Vel. Response' chart now displays the response of the resulting Inverse Filter. It should be noted that this filter response is also included in the blue line plotting A.

#### 6. Cleanup:

It should be possible to reduce the size of the integrator capacitor,  $C_I$ . The Mass Centering Range Test at Row 88 indicates that  $R_I$  may be allowed to go as high as 365K. It is currently 8K. Let's change  $R_I$  to 100K. Type 100000 in yellow cell D28. Now looking at the Low Frequency Corner calculator at Row 79 we see that it is now suggesting  $3.52\mu\text{f}$  for  $C_I$ , down from  $22\mu\text{f}$ . Set  $C_I$  to  $3.52\mu\text{f}$  by typing  $3.52\text{e-}6$  in cell D24.

Check the phase margin on the Chart 'Loop Phase'. It is 87 degrees which is super conservative.

However, we forgot something. The forcing coil resistance adds a pole to A. We can approximate its effect by adding its resistance as  $R_d$ , in series with  $C_d$ . Assume 67 ohms and enter 67 in cell D23 of the 'Control' worksheet.

Also, the position transducer has a pole with a time constant of about 1ms. Set  $\tau_t$  to 1ms by entering  $1\text{e-}3$  in cell D35.

Going back to 'Loop Phase' we see that the phase margin has now gone from 87 to 68 degrees. Although that is still quite conservative, there may be numerous small effects not included in the spreadsheet which will tend to reduce the phase margin. Hopefully 68 degrees is good enough that losing a little more will not create a big problem.

We now have a feedback seismometer design which meets our original requirements, and which is likely to work properly when the parts are assembled.