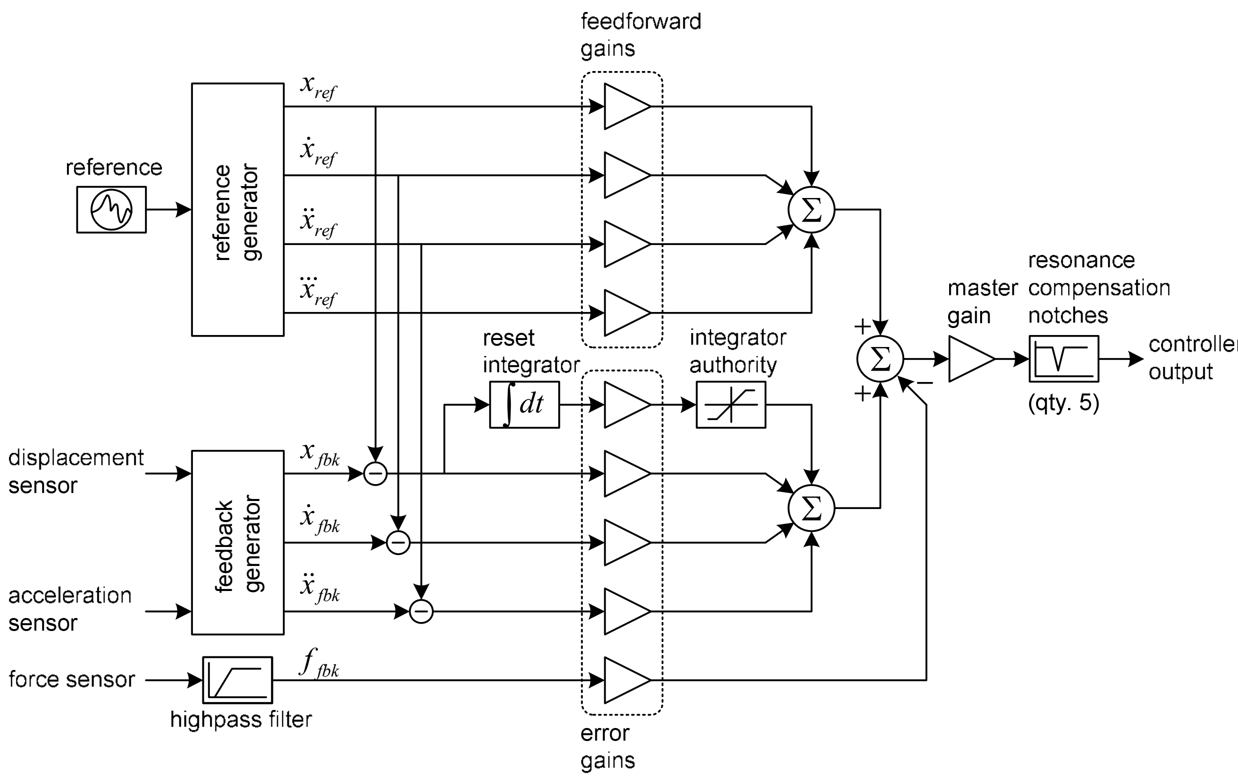
How To Tune Three-Variable Control (TVC)

BKT 13-Sep-10

Three-Variable Control (TVC) is what is known in control theory literature as *state variable control*, with additional special features. The three state variables that TVC can control are displacement, velocity, and acceleration. It is a common misconception that all three state variables are controlled simultaneously. The truth is that only one state variable is the primary control variable, with the others serving only as compensation signals to improve damping and stability.

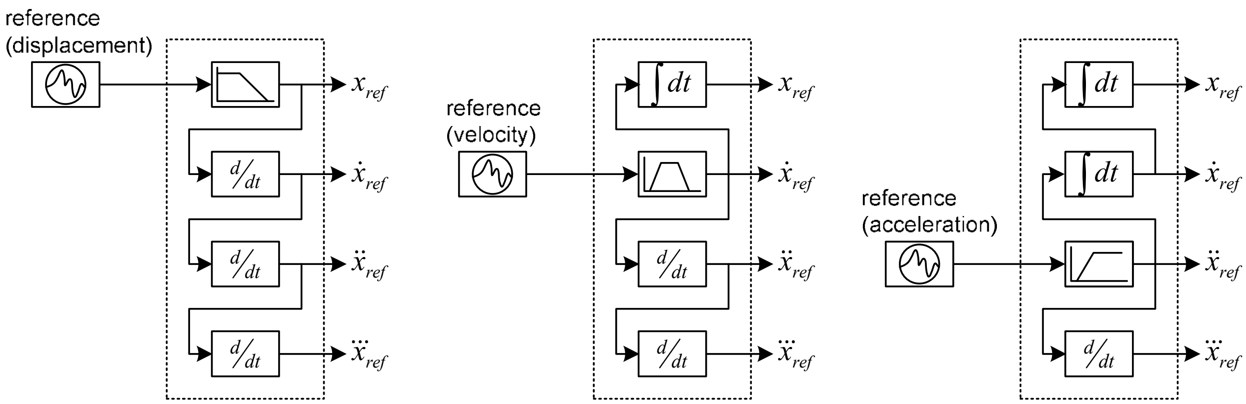
A detailed view of the internal structure of TVC is shown below:



On the reference side, the Reference Generator takes the reference signal, which represents desired displacement, velocity, or acceleration depending on control mode, and creates the reference states x_{ref}, $\dot{x}_{ref}$, $\ddot{x}_{ref}$, and $\dddot{x}_{ref}$. On the feedback side, displacement and acceleration sensors are combined by the Feedback Generator to create the feedback states x_{fbk}, $\dot{x}_{fbk}$, and $\ddot{x}_{fbk}$. In addition, the force sensor output is highpass filtered to remove its static force component and the result used as a stabilization signal to suppress the oil column resonance. Error states are formed by subtracting reference and feedback states. Note that even though there are more than three state variables, the name "*Three*-Variable Control" is retained for historical reasons.

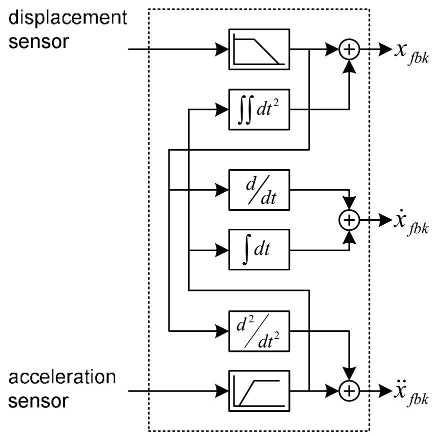
The reference and error states are weighted by feedforward and error gains, respectively, and summed together, along with integrated displacement error that provides rejection of static offsets in the system. This sum is scaled by the Master gain, which is used to quickly reduce all gain effects in order to recover control of the system should it become unstable. Finally, a series of five notch filters are applied to compensate for oil column and specimen resonances. The resulting controller output is then used to drive the servovalve of a hydraulic actuator.

A detailed view of the internal structure of the Reference Generator for each of the three control modes (displacement, velocity, and acceleration) is shown below:



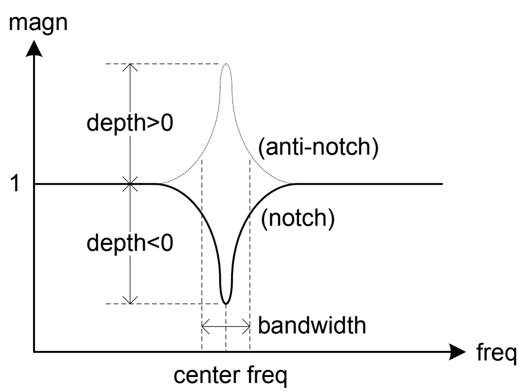
The reference signal is processed by the Reference Generator as a displacement, velocity, or acceleration signal depending on control mode. In displacement control, the reference is lowpass filtered to form the displacement reference, which is then differentiated to obtain the velocity, acceleration, and jerk references. In velocity control, the reference is bandpass filtered to form the velocity reference, which is then integrated to obtain the displacement reference, and differentiated to obtain the acceleration and jerk references. In acceleration control, the reference is highpass filtered to form the acceleration reference, which is then integrated to obtain the displacement and velocity references, and differentiated to obtain the jerk reference. The highpass filtering of the reference that occurs in velocity and acceleration control modes removes static offset and low frequencies from the reference signal to prevent the integrator outputs from becoming too large.

The purpose of the Feedback Generator is to compute wideband estimates of velocity and acceleration feedback from limited bandwidth displacement and acceleration sensors. A detailed view of the internal structure of the Feedback is shown below:



To obtain a wideband estimate of velocity, the differentiated displacement sensor signal is combined with the integrated acceleration sensor signal via a crossover filter, seen in the above diagram as a lowpass and a highpass filter. The crossover filter ensures that the velocity estimate consists primarily of differentiated displacement at low-to-medium frequencies where the displacement sensor is most accurate, and integrated acceleration at medium-to-high frequencies where the acceleration sensor is most accurate. The wideband acceleration estimate is obtained from the wideband velocity estimate by differentiation.

The notch filters are used to compensate for resonances and antiresonances. As shown below, the notch filter frequency response is defined by three parameters: center frequency, 3dB bandwidth, and notch depth:



Note that the notch response at the center frequency can be upward or downward, depending on whether the notch depth is positive or negative. Negative notches are used to suppress resonant peaks, whereas positive notches are used to boost antiresonant valleys. A total of five notches are provided. One notch can be used to suppress the oil column resonance if there is no force feedback in the system. The other four can be used to suppress up to two resonance/ antiresonance pairs.

We now turn to specifics on tuning TVC. During the tuning procedure, you will be making extensive use of the following user interface panels:

- Random Function Generator Panel
- Observer Panel
- Three-Variable Control Panel
- Resonance Compensator Panel

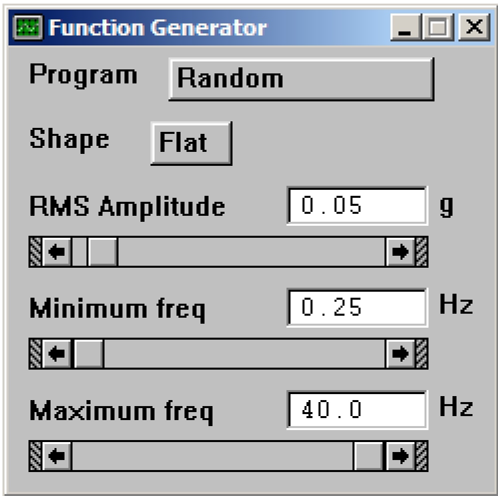
A description of these panels will be presented first, followed by basic step-by-step TVC tuning procedures for displacement, velocity, and acceleration control modes. Lastly, some advanced topics such as the tuning of notch filters to combat resonances and antiresonances will be discussed.

It should be emphasized that control tuning is an art. Each control system is different, having its own unique blend of dynamics and peculiarities. Your system may tune differently than the system used to generate the examples presented here. With enough practice you will learn how to modify the procedures presented here to fit your particular case.

One word of caution: When tuning, *do not move a gain slider bar until you first determine its minimum and maximum limits*. Otherwise you may inadvertently scroll the gain to a large value, causing instability that could destroy your specimen and damage your test machine. Do not assume that the limits are reasonable values; check them yourself. You can do this by clicking on the striped regions to the left and right of the scrolling arrows as show below:

The minimum or maximum limit is then displayed in the slider bar's value edit display box where you can change it if necessary.

Random Function Generator Adjustments



Because TVC tuning is done almost exclusively in the frequency domain, the Random Function Generator is used to excite the system so that good transfer function estimates can be obtained. The Random Function Generator consists of a uniform distribution random number generator followed by a bandpass filter. This filter has four parameters adjustable from the Random Function Generator Panel:

Shape popup menu

> This is the shape of the bandpass filter's magnitude response as a function of frequency between minimum and maximum frequencies. Five shapes are available: 1/F^2, 1/F, Flat, F, and F^2, where "F" denotes frequency. The primary consideration in selecting the shape is to get the most energy into the system across the frequency band of interest without damaging the system by excessive velocity or acceleration. In acceleration control, "Flat" works well, but in displacement control, "Flat" will result in excessive velocity and acceleration at high frequencies; "1/F" or "1/F^2" is much gentler on the system in that case. Shapes "F" and "F^2" accentuate acceleration at high frequencies and so should not be used. Note that theoretically a shape of "1/F" or "1/F^2" results in a filter magnitude response that tends toward infinity as the frequency tends toward zero. This is neither desirable nor practical, so the filter response is rolled off to zero as the frequency approaches the minimum frequency. In addition, for technical reasons the minimum frequency is not allowed to be less than 1% of the maximum frequency when "1/F" and "1/F^2" shapes are selected.

RMS Amplitude slider bar

> Adjust the RMS amplitude to the minimum value possible to prevent damage to the test specimen. Keep in mind, however, that using too low of an amplitude will result in inaccurate estimates of the transfer function. If your system is significantly nonlinear, try to use an RMS amplitude similar in amplitude to the test waveform if possible, because in such systems the transfer function is a strong function of signal amplitude. Also, keep in

mind that you are setting RMS amplitude, not peak amplitude; peak amplitude will be somewhat higher than RMS amplitude.

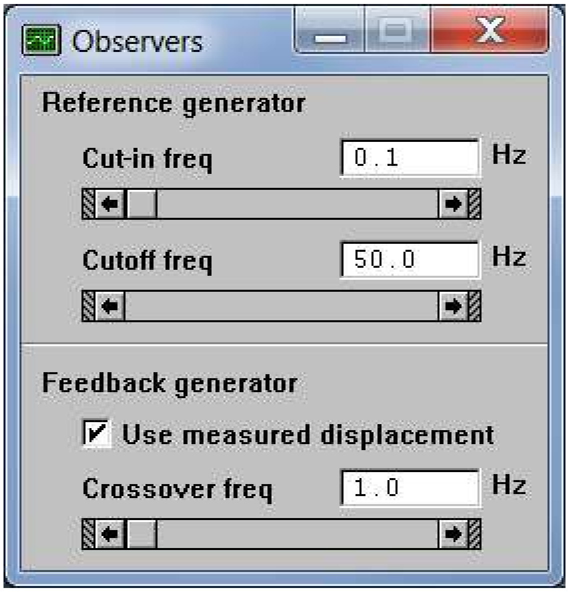
Minimum Frequency slider bar

This is the cut-in frequency of the bandpass filter. Set this according to the lowest frequency expected in your test waveform. A minimum frequency of zero is allowed. In velocity and acceleration control modes, this frequency should match the cut-in frequency of the Reference Generator.

Maximum Frequency slider bar

This is the cutoff frequency of the bandpass filter. Set this according to the highest frequency to which you expect to control.

Observer Panel Adjustments



The Observers Panel is where adjustments for the Reference Generator, Feedback Generator, and Force Observer are made (the term "observer" is control theory terminology for a special-purpose filter that computes a feedback signal):

Reference Generator Cut-in Frequency slider bar

> Valid only in velocity and acceleration control modes, this is the frequency below which energy content in the reference signal is removed to prevent large commanded displacement. Because reference signals (such as earthquake records) differ on low frequency content, you may have to adjust this frequency often on a per-test basis. A lower value is better because less frequency content is removed from your reference signal, which results in improved reference-feedback matching.
>
> Physical displacement limits place a lower bound on this frequency. For sine waves, the amount of displacement amplitude X that can be expected given acceleration amplitude A can be computed from the formula $X = A/(2\pi f)^2$. Discontinuities in the derivatives of the reference signal also place a lower bound on this frequency, because the highpass filter acts as a double differentiator at low frequencies, greatly amplifying derivative discontinuities that emerge as large transients in the Displacement Reference.
>
> You can determine whether the cut-in frequency is high enough for your reference signal to prevent these problems by using the Preview feature available on the Main Panel, which allows you to play out a reference waveform and observe the Reference Generator outputs without actually moving the system. Use the Digital Meter's Max/Min displays to view the range of excursion of the displacement reference signal; if it exceeds the physical displacement limits, the cut-in frequency must be increased.

Keep in mind that the filter is only second order and therefore makes a gradual transition between passband and stopband. Therefore a significant amount of signal energy below the cut-in frequency will leak through the filter.

Reference Generator Cutoff Frequency slider bar

Valid only in displacement and velocity control modes, this is the cutoff frequency of the lowpass filter and bandpass filter, respectively.

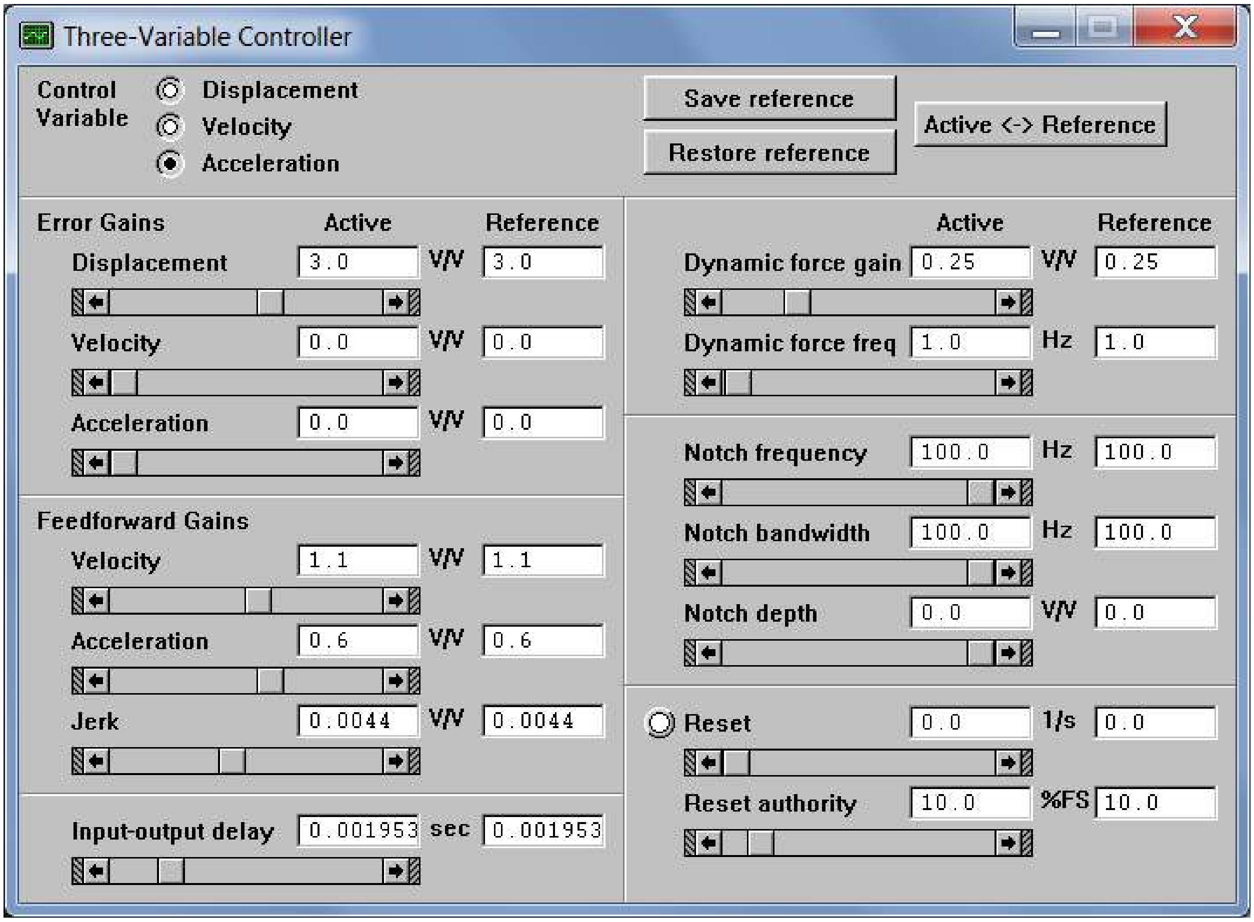
Feedback Generator Crossover Frequency slider bar

This is the frequency below which the displacement sensor has maximum influence on the computed feedbacks, and above which the acceleration sensor has maximum influence. You should leave this at the default value of 1.0 Hz.

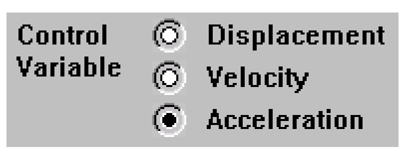
Feedback Generator "Use measured displacement" checkbox

When checked, the measured displacement feedback is used as the observer output without the inclusion of double integrated acceleration. This is the typical selection because it prevents low frequency displacement drift. Uncheck this box when foundation motion is significant to obtain an improved estimate of displacement in the inertial frame.

TVC Panel Adjustments

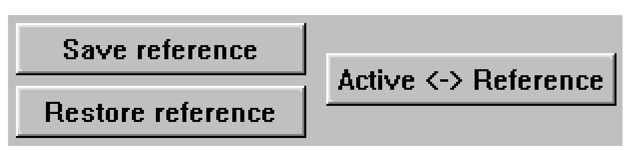


Control Mode radio button selector



Selects the control mode. In multichannel systems, the selected control mode is applied to all channels, not just the channel displayed in the panel.

Save/Restore/Switch Reference Gains buttons



"Save Reference Gains" copies the active gain values to the reference gain display boxes; "Restore Reference Gains" copies the reference gain values back into the active gain slider bars; "Active <-> Reference" swaps active and reference gains. Use the Save button to temporarily store a set of gains that you deem satisfactory but wish to improve. If subsequent tuning yields worse results, you can then use the Restore button to get back the original "good" gains. If you have two sets of satisfactory gains but wish to see which one is better, you can quickly switch between the two using the Switch button.

The Restore and Switch buttons are inactive when the program waveform is running because sudden gain changes while the system is in motion can result in large transients.

Error Gain slider bars

Adjusts the gain applied to the displacement, velocity, and acceleration errors. The displacement error gain is the most important of the three gains, because it provides positioning stability and influences low to medium frequency response.

Feedforward Gain slider bars

Adjusts the gain applied to the velocity, acceleration, and jerk references, affecting response below, at, and above the oil column natural frequency, respectively.

Dynamic Force Gain slider bar

Adjusts the gain applied to the dynamic force feedback, which is a highpassed version of the regular force feedback. It provides damping of the oil column resonance.

Dynamic Force Frequency slider bar

Adjusts the cut-in frequency of the highpass filter applied to the force feedback. A value of 0.5 to 1.0 Hz is recommended for most systems.

Notch Frequency slider bar

Adjusts the center frequency of the notch filter applied to the controller output. Use a value equal to the frequency of resonance that you are trying to compensate.

To aid tuning, the frequency response of the TVC notch filter can be viewed in the FRF Plotter.

Notch Bandwidth slider bar

Adjusts the 3dB bandwidth of the notch filter applied to the controller output. Use a value equal to the bandwidth of resonance that you are trying to compensate.

Notch Depth slider bar

Adjusts the depth of the notch filter applied to the controller output. Use a negative value to suppress a resonance, a positive value to boost an antiresonance, and a zero value to do nothing.

Reset Integrator Gain slider bar

Adjusts the time constant of the reset integrator to remove static offsets in the system.

Reset Integrator Tracking indicator 

Displays the current state of the reset integration process using this color code:

- White: The reset integrator is off.
- Green: The reset integrator is integrating ("tracking") and its contribution to the controller output is less than the Maximum Authority limit.
- Red: The reset integrator is on but its output is pegged at the Maximum Authority limit (plus or minus).

The conditions for tracking are:

- Hydraulics are on and in high pressure.
- The system is at rest.
- The reset gain is greater than zero.

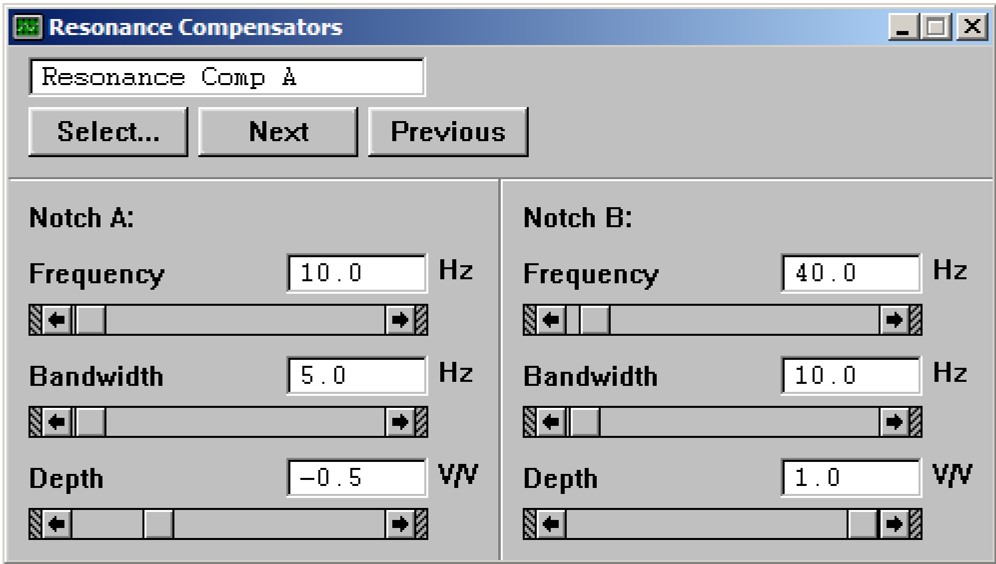
Reset Integrator Maximum Authority slider bar

Adjusts the maximum amount of correction that reset integrator is allowed to apply to the controller output.

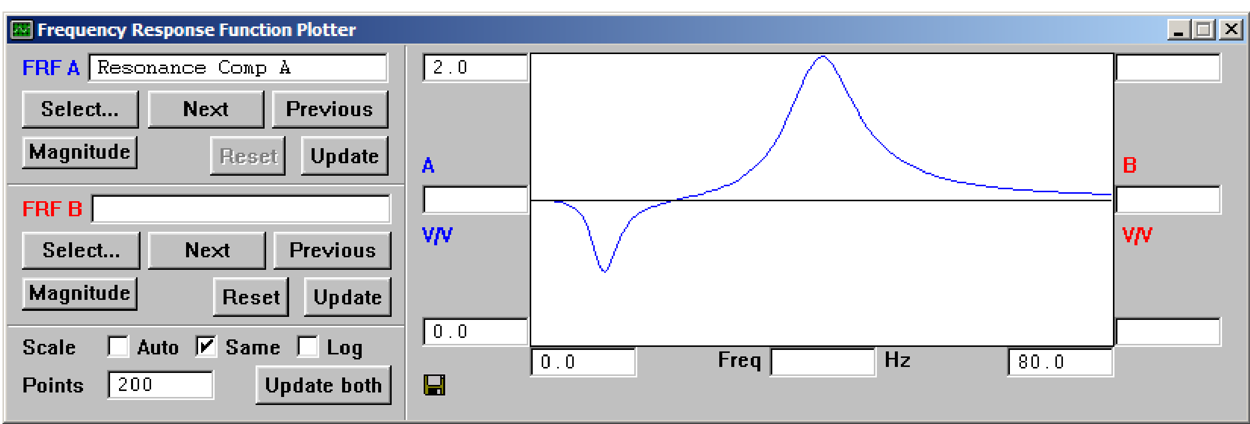
Input-Output Delay slider bar

Adjusts the amount of delay applied to the reference in order to align it with the feedback for display and error calculation purposes.

Resonance Compensator Panel Adjustments



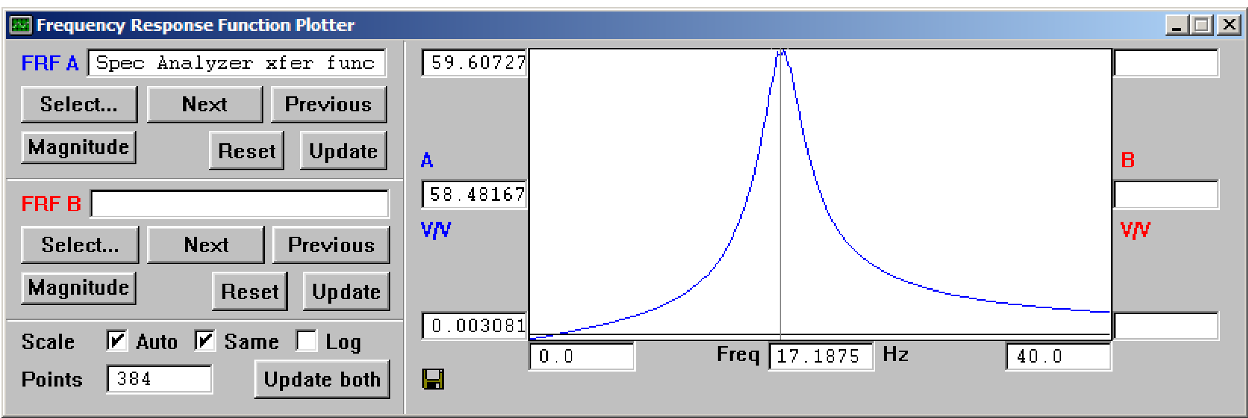
The Resonance Compensator consists of four identical notch filters, grouped into two pairs for user interface purposes because resonances usually come in resonance/antiresonance pairs. Like the TVC notch filter, the frequency response of the Resonance Compensator notch filters can be viewed in the FRF Plotter. For the tuning shown in the panel above, the frequency response looks like this:



Determining the Oil Column Natural Frequency

Before starting the tuning process, it is useful to know the value of the oil column natural frequency. Certain gains have affect below while others have affect above this frequency; knowing on which side a deficiently-tuned region of frequency response lies suggests which gain adjustment will yield the most improvement. Furthermore, if the oil column natural frequency lies significantly above the maximum frequency of operation, tuning is simplified because some of the tuning steps described in later sections can be omitted.

To measure this frequency, measure the transfer function between the controller output and the force feedback using the Spectrum Analyzer. The oil column natural frequency lies close to the peak of the magnitude response; in the example shown below, this frequency is approximately 17 Hz.



Displacement Control Tuning

While tuning, keep in mind these points, which apply not only to displacement control mode but to all control modes:

- As gains are increased, the valve command may become large to the point of saturation at ±10 volts. When this happens, the frequency response measured by the Spectrum Analyzer can be misleading. Always look at the controller output on the Digital Oscilloscope to verify that the valve command is not saturating. If it is, you may have to either reduce the gain or reduce the reference amplitude.
- While tuning you will mostly be looking at the frequency response in the FRF Plotter. As you approach a satisfactory tuning, i.e., one that yields a frequency response near unity, you should look at the reference and feedback on the Digital Oscilloscope to verify that they are reasonably similar. This is because it is possible to have a frequency response near unity yet have dissimilar reference and feedback, which can happen if there are nonlinearities at play or if the system has been tuned such that the phase response is nonlinear.

Step 1: *Set up the Reference Generator*. Set the cutoff frequency to the maximum allowable value. Note that the cut-in frequency cannot be adjusted because it has no effect in displacement control mode.

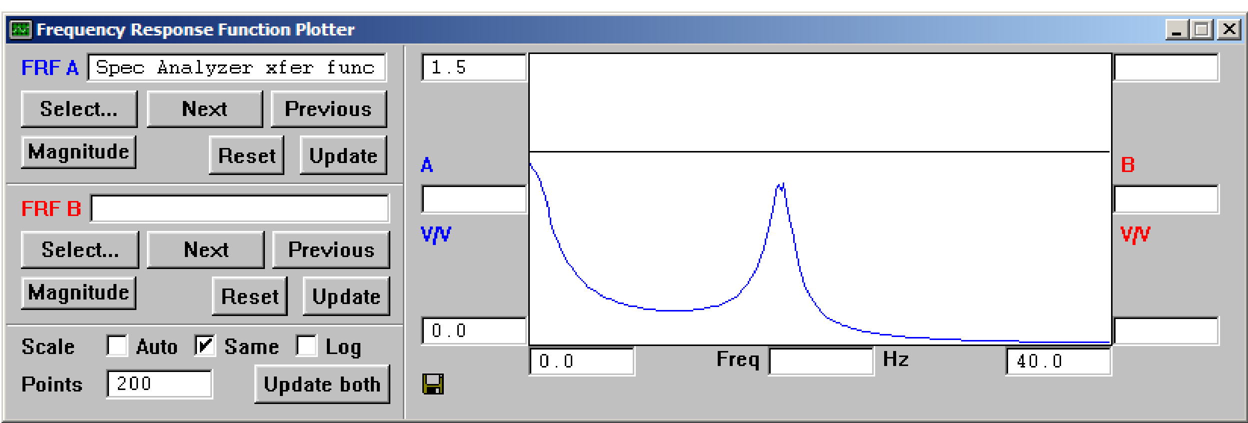
Step 2: *Set up the Random Function Generator*. Set the shape to "1/F^2" or "1/F", the minimum frequency to zero, and the maximum frequency according to the desired control bandwidth.

Step 3: *Enter initial TVC and Resonance Compensator parameters values*:

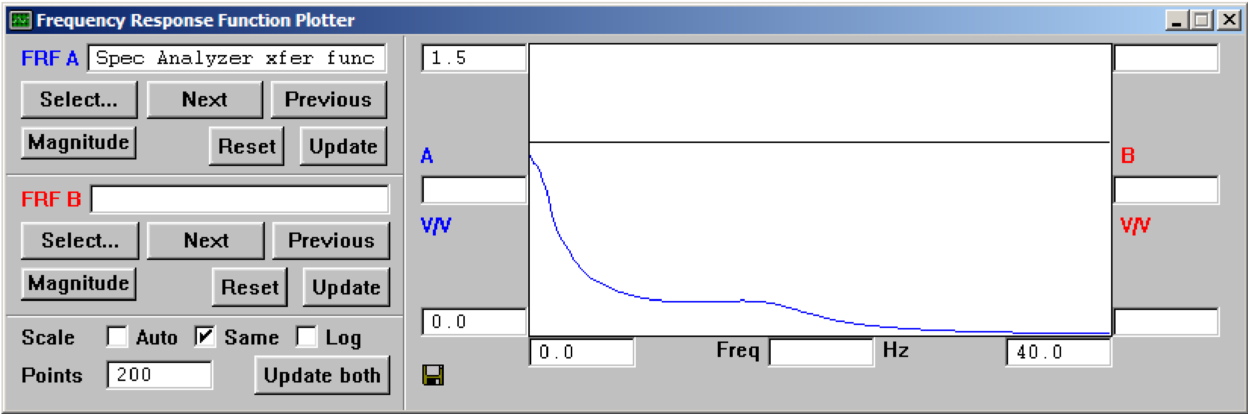
Displacement error gain	1.0	Dynamic force gain	0.0
Velocity error gain	0.0	Dynamic force freq	0.5 Hz
Acceleration error gain	0.0		
		Notch frequency	any value
Feedforward gains	all zero	Notch bandwidth	any value
		Notch depth	0.0
Input-output delay	0.0		
		Reset	0.0
		Reset authority	5 %
Resonance Compensators A & B:		Notch frequency	any value
		Notch bandwidth	any value
		Notch depth	0.0

Step 4: *Run the Random Function Generator*. Press the Run button.

Step 5: *Increase the displacement error gain*. Increase the displacement error gain until the frequency response is adequate at low frequencies, but without causing the oil column resonance to peak above unity magnitude, as shown below:



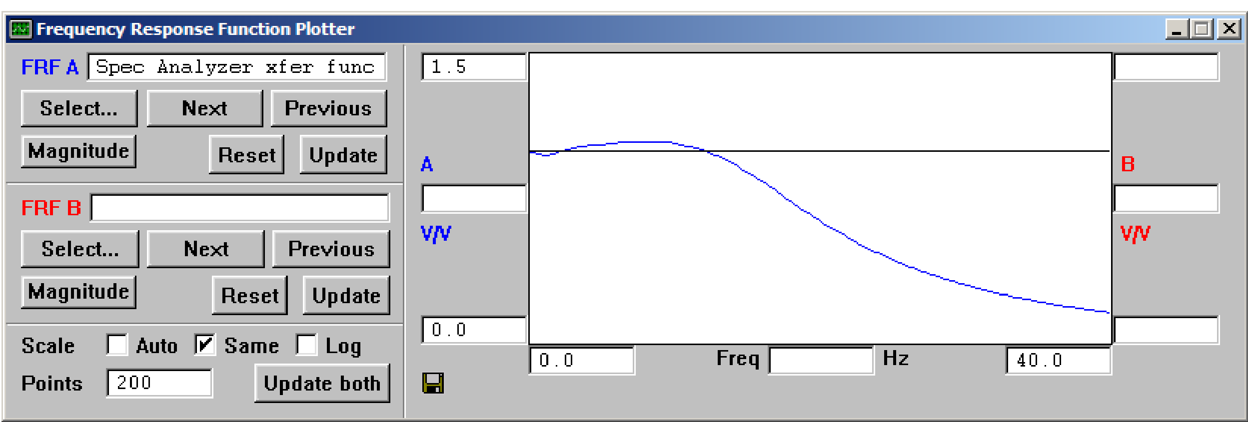
Step 6: *Increase the dynamic force gain*. Increase the dynamic force gain until the oil column resonant peak is barely visible, as shown below:



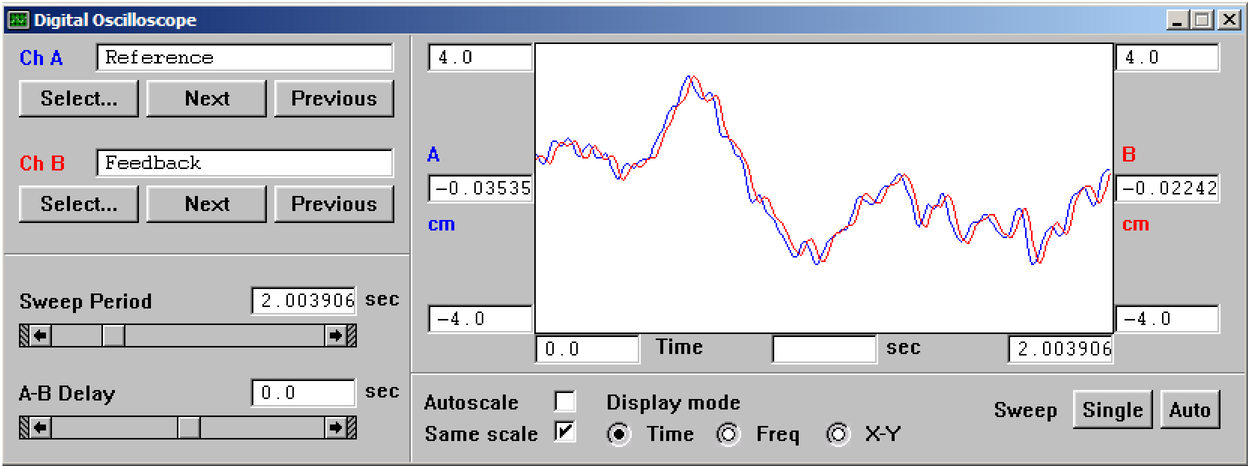
Note that if the force feedback is phased properly, the dynamic force gain will be <u>positive</u>, and increases in the positive direction result in more oil column resonance suppression (up to a point). It is easy to drive the system into instability by using too much of this gain, so be careful.

In systems without force feedback this gain parameter has no effect. Instead you can use the TVC notch filter to suppress the oil column resonance. This is discussed in a later section.

Step 7: *Increase the velocity feedforward gain*. Increase the velocity feedforward gain to boost the frequency response below the oil column natural frequency. This will also boost the response at the oil column natural frequency, causing it to peak above unity magnitude. Increase the dynamic force gain (or deepen the TVC notch) to bring the response back down. The frequency response then should look like this:

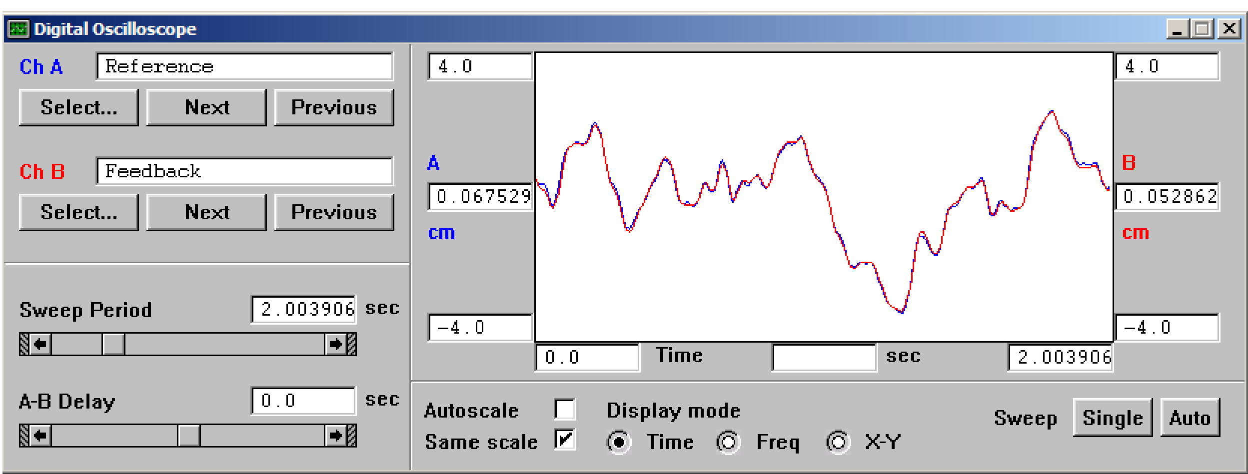


Step 8: *Adjust the input-output delay*. Although the controller is now optimally tuned, there is a delay between reference and feedback, as shown in the time response below



This delay is inherent in all closed-loop control systems. Although the feedback is almost a perfect copy of the reference, the difference between the two waveforms is large solely because of the delay. This difference can be minimized by delaying the reference by an amount of time determined by the input-output delay adjustment so that it is aligned with the feedback for display and error calculation purposes. It has no effect whatsoever on stability or the quality of control.

To adjust the input-output delay, observe the reference and feedback waveforms in the Digital Oscilloscope and increase the delay until they are aligned visually, as shown below:



Step 9: *Stop the Random Function Generator*. Press the Stop button to bring the system to rest.

Step 10: *Adjust the reset integrator*. Ideally the controller output signal is zero when the system is at rest. This may not be the case if there is a static offset somewhere in the system.

To remove a static offset, increase the reset integrator gain and observe the rate at which the controller output signal is driven to zero. More reset gain will result in faster offset removal. Values in the range of 0.1 to 1.0 are typical.

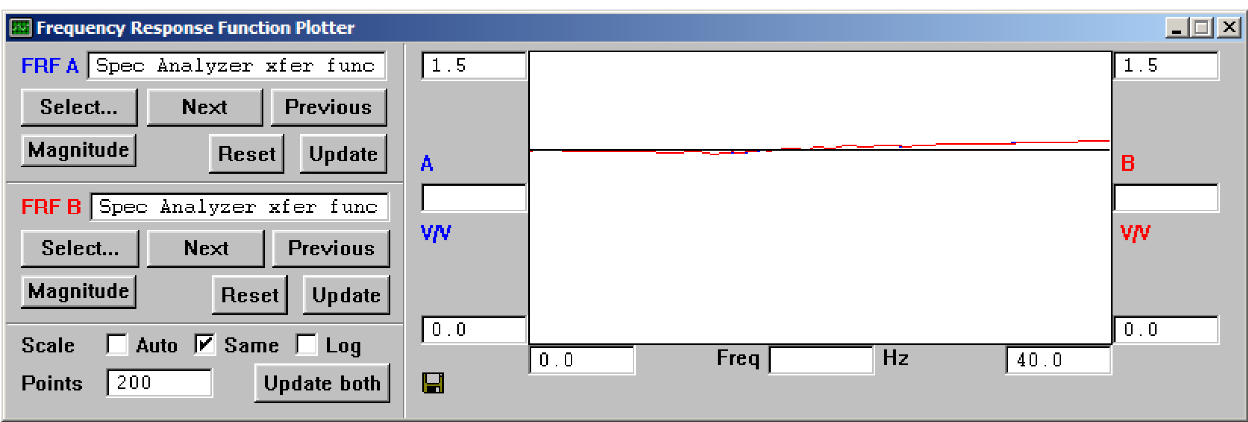
If you observe that Reset Integrator Tracking indicator is glowing red, that means that the correction that reset integrator needs to apply to remove the offset is beyond the its authority limit. Increase the Reset Integrator Maximum Authority slider bar in small increments until the indicator glows green. If the indicator is still red after having increased the authority a reasonable amount, it could be that there is a problem with the electrical or mechanical system that you should diagnose before continuing.

Velocity Control Tuning

Step 1: *Set up the Reference Generator*. Set the cut-in frequency to the lowest anticipated velocity reference frequency, keeping in mind the physical displacement limits. Set the cutoff frequency to the maximum allowable value.

Step 2: *Set up the Random Function Generator.* Set the shape to "1/F", the minimum frequency to match the cut-in frequency of the Reference Generator, and the maximum frequency according to the desired control bandwidth.

Step 3: *Complete the steps outlined in the following section on Acceleration Control Tuning, starting with Step 3.* Velocity control tuning is done much like acceleration control tuning except for the setup of the Reference Generator and the Random Function Generator. When completed, the frequency response looks like this:

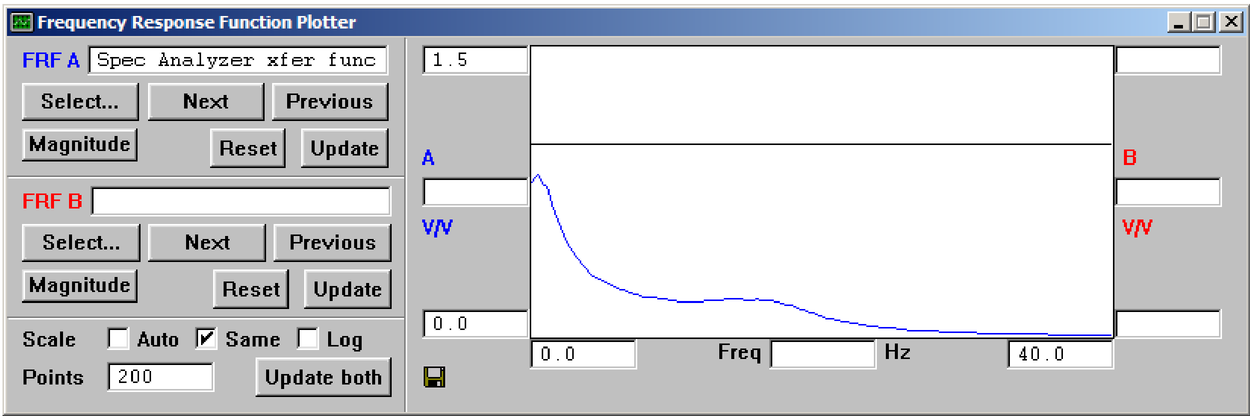


Acceleration Control Tuning

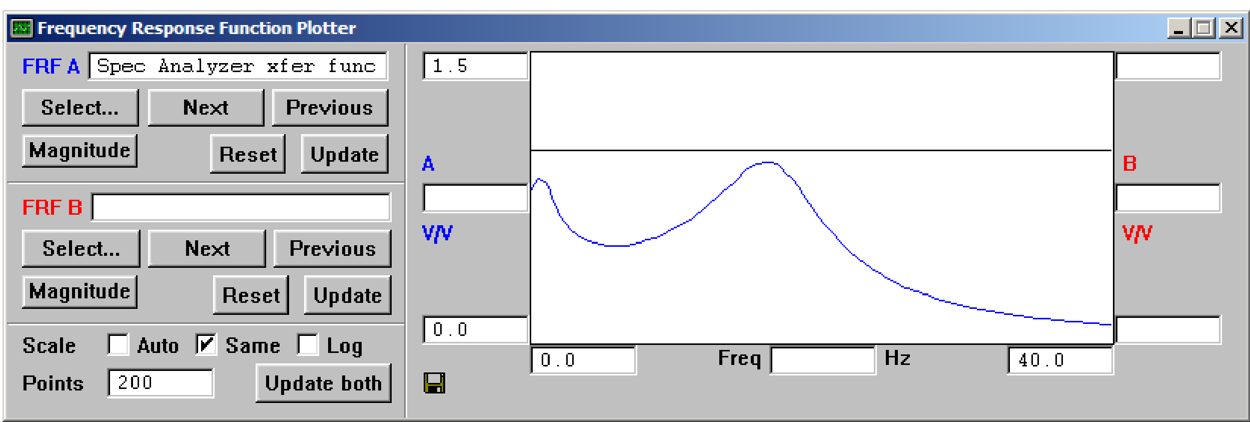
Step 1: *Set up the Reference Generator*. Set the cut-in frequency to the lowest anticipated acceleration reference frequency, keeping in mind the physical displacement limits. Note that the cut-off frequency cannot be adjusted because it has no effect in acceleration control mode.

Step 2: *Set up the Random Function Generator.* Set the shape to "Flat", the minimum frequency to match the cut-in frequency of the Reference Generator, and the maximum frequency according to the desired control bandwidth.

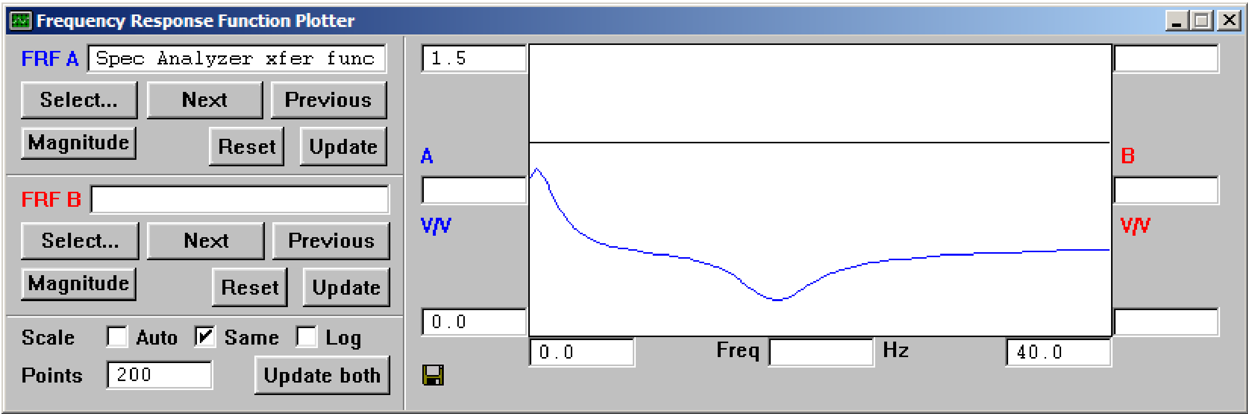
Step 3: *Perform basic displacement control tuning.* Do Steps 3 through 6 described in the Displacement Control Tuning section, after which the frequency response should look like this:



Step 4: *Increase the velocity feedforward gain.* Increase the velocity feedforward gain to boost the frequency response below the oil column natural frequency. This will also boost the response at the oil column natural frequency, but don't be concerned about it at this point. The frequency response then should look like this:

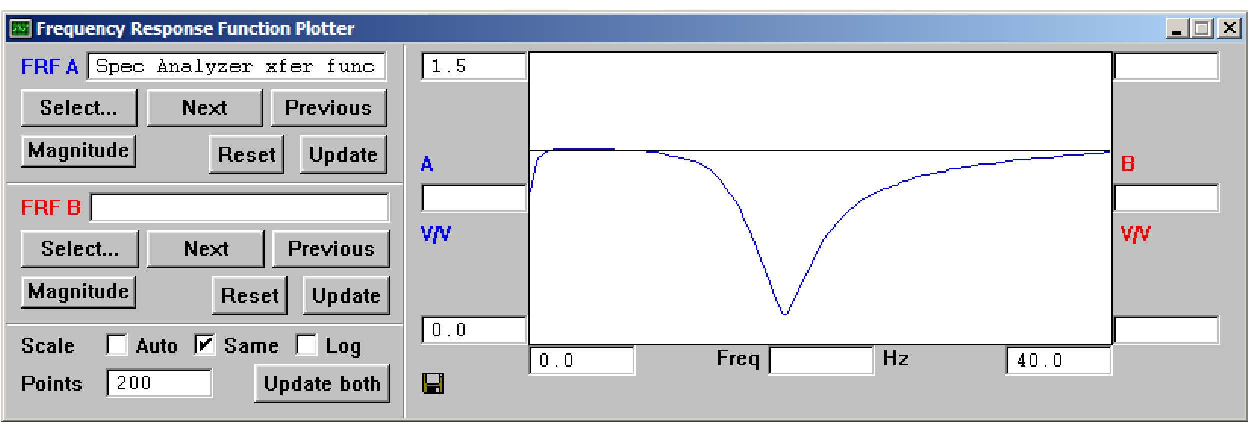


Step 5: *Increase the jerk feedforward gain*. Increase the jerk feedforward gain to boost the frequency response above the oil column natural frequency. This may cause the peaking response at the oil column natural frequency observed in the previous step to be reduced due phase cancellation. Add only enough jerk feedforward gain so that the frequency response is flat overall, as shown below:

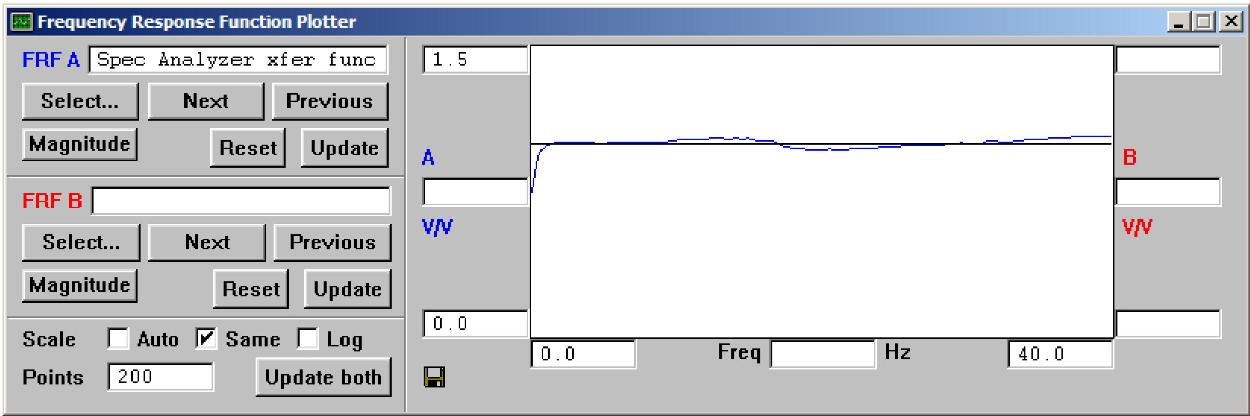


Step 6: *Continue boosting response below and above the oil column natural frequency*. Repeat the previous two steps, increasing velocity and jerk feedforward gains in small increments. Do not use large increments or else the effect of one gain will wash over into the other gain's frequency region, causing peaks or valleys in the frequency response that make it hard to determine which gain to adjust. In other words, make sure the overall response is reasonably flat at a given level (except near the oil column natural frequency) before boosting it to the next level.

When you have finished boosting the frequency response either side of the oil column natural frequency to unity, it should look like this:



Step 7: *Increase the acceleration feedforward gain*. Increase the acceleration feedforward gain to boost the response near the oil column natural frequency to unity. You may have to make slight adjustments to velocity and jerk feedforward gains to keep the response below and above the oil column natural frequency at unity. The frequency response should then look like this:

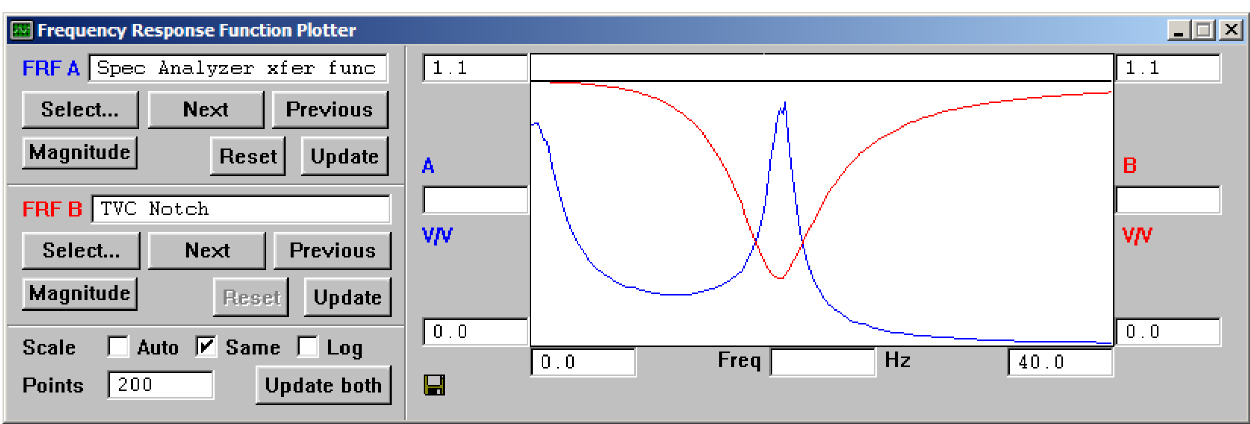


Step 8: *Adjust the input-output delay and the Reset Integrator.* Do Steps 8 through 10 described in the Displacement Control Tuning section.

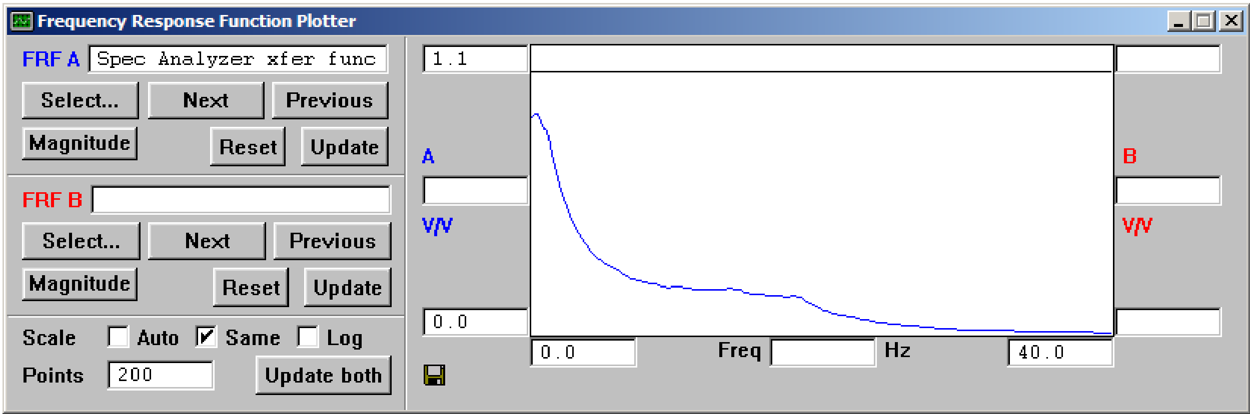
Suppressing Oil Column Resonance Using a Notch Filter

Force feedback is the preferred method of suppressing the oil column resonance because it tracks changes in oil column natural frequency with temperature and actuator displacement. However, if a force sensor is not available, a notch filter can be used instead with similar results.

In the figure below, the frequency response (Channel A (blue)) shows a large peak at the oil column natural frequency. Channel B (red) shows the frequency response of the notch filter that will be applied to eliminate the resonant peak.



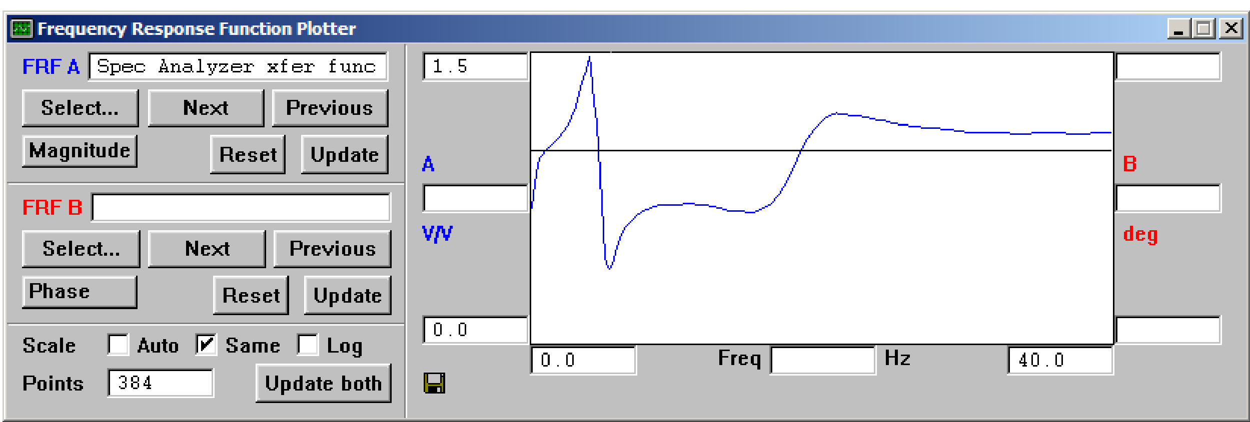
With the notch filter applied, the oil column resonance has been completely suppressed:



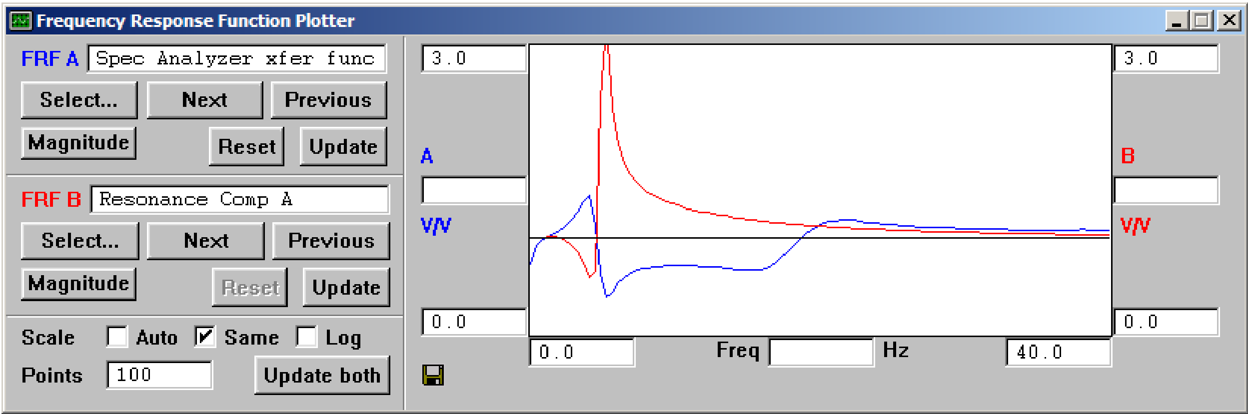
Compensating Payload Resonances Using Notch Filters

The tuning procedures presented so far assume that the payload is a rigid mass. If instead the payload has resonant modes, the task of tuning becomes more complex. Resonances and antiresonances cause sharp peaks in the frequency response. To deal with these, the notch filters of the Resonance Compensator are employed.

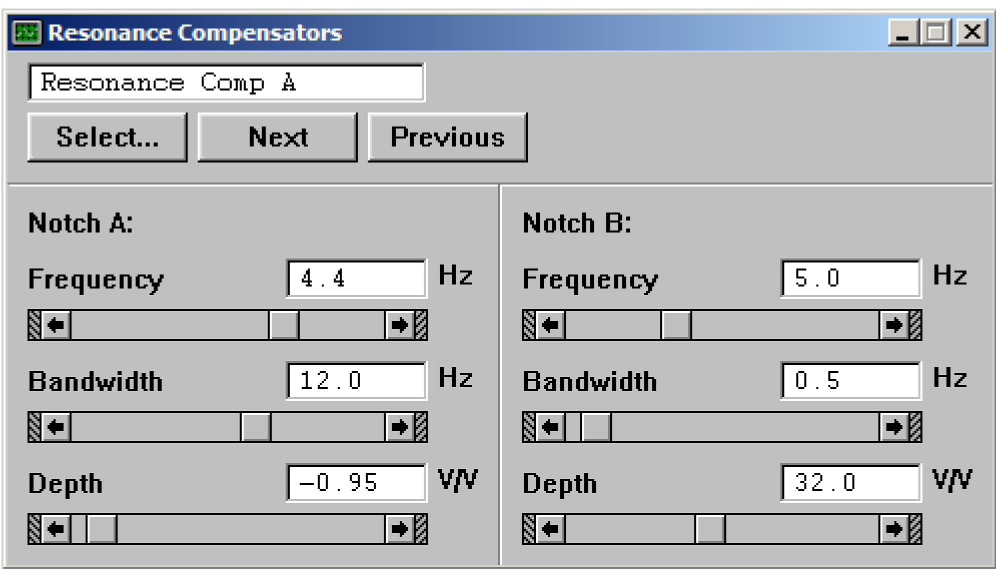
In the following example, a bare seismic table is tuned using the tuning procedures previously discussed. Then a heavy, lightly damped 5 Hz resonant specimen is placed on the table, but the tuning is left unchanged. The resulting frequency response then looks like this:



There is a resonance at 4 Hz followed by a sharp transition to an antiresonance at 5.4 Hz. Using the Resonance Compensator Panel, a notch is placed on top of the resonance and an antinotch on top of the antiresonance, as shown in Channel B (red) below:

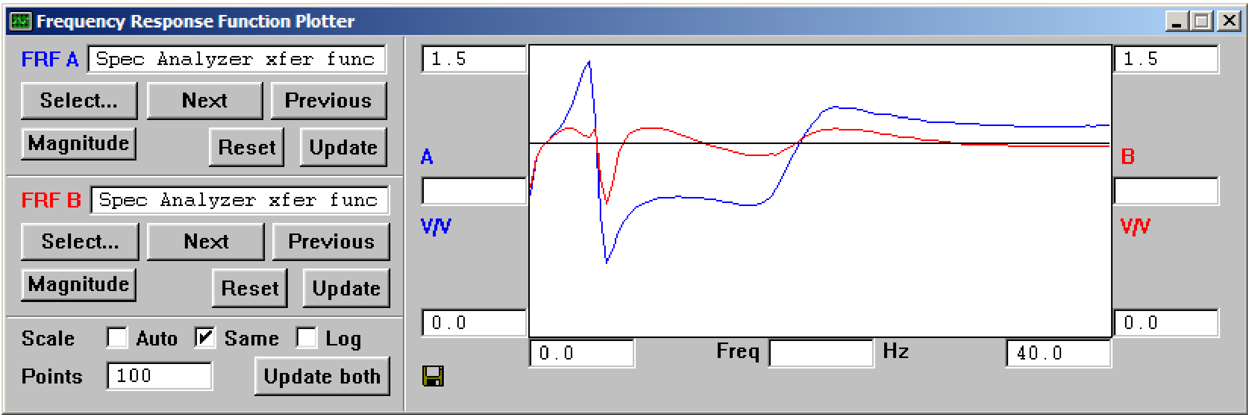


The Resonance Compensator notch filter parameters that achieve this composite notch frequency response are as follows:



Note that the center frequencies of the notch and antinotch are slightly offset from the measured resonance and antiresonance frequencies; this is almost always the case, so remember to always offset the notch frequencies a little bit for best results.

With the notch and antinotch filters as above, the system frequency response is that shown in Channel B (red) below superimposed on the original frequency response in Channel A (blue):



The frequency response is far from perfect, but it is still considerably improved.

While tuning the Resonance Compensator notches, you may have to adjust the TVC gains a little. In the above example, the jerk feedforward gain was reduced by 13% to reduce peaking caused by the large gain of the antinotch.

Switching Control Modes With Hydraulics On

Most operators like to warm up the system in displacement control, then switch to acceleration control to run the test. Contrary to expectation, switching the control mode is not simply a matter of pressing the Control Mode radio button in the TVC Panel. There are many controller parameters that depend on the control mode and so must be modified to values appropriate for the new mode. Because of the large number of modifications required and the ease of forgetting one, the recommended way of changing modes is to have different settings files for different modes. Before a settings file can be downloaded, the hydraulic power must be turned off because the downloading of new calibration, gains, etc. can cause large controller transients. However, cycling hydraulic power can be very inconvenient and time consuming in some systems, especially if accumulators have to be discharged and recharged. In such systems, it would be convenient start up the system with an acceleration settings file, then change only a minimum necessary number of parameters to allow warmup in displacement mode, then change back to acceleration mode, with hydraulics on throughout.

To change from acceleration (or velocity) to displacement control for system warmup purposes, first press the Save Reference Gains button to save currently active gain values, and then set all the feedforward gains to zero. You can now warm up the system with a low frequency sine wave. If you are using any notch filters, you must make sure that the sine wave frequency is well below all notch center frequencies or else large motions may result.

When you are finished with system warmup, switch back to acceleration (or velocity) control and then restore the feedforward gains by pressing the Restore Reference Gains.