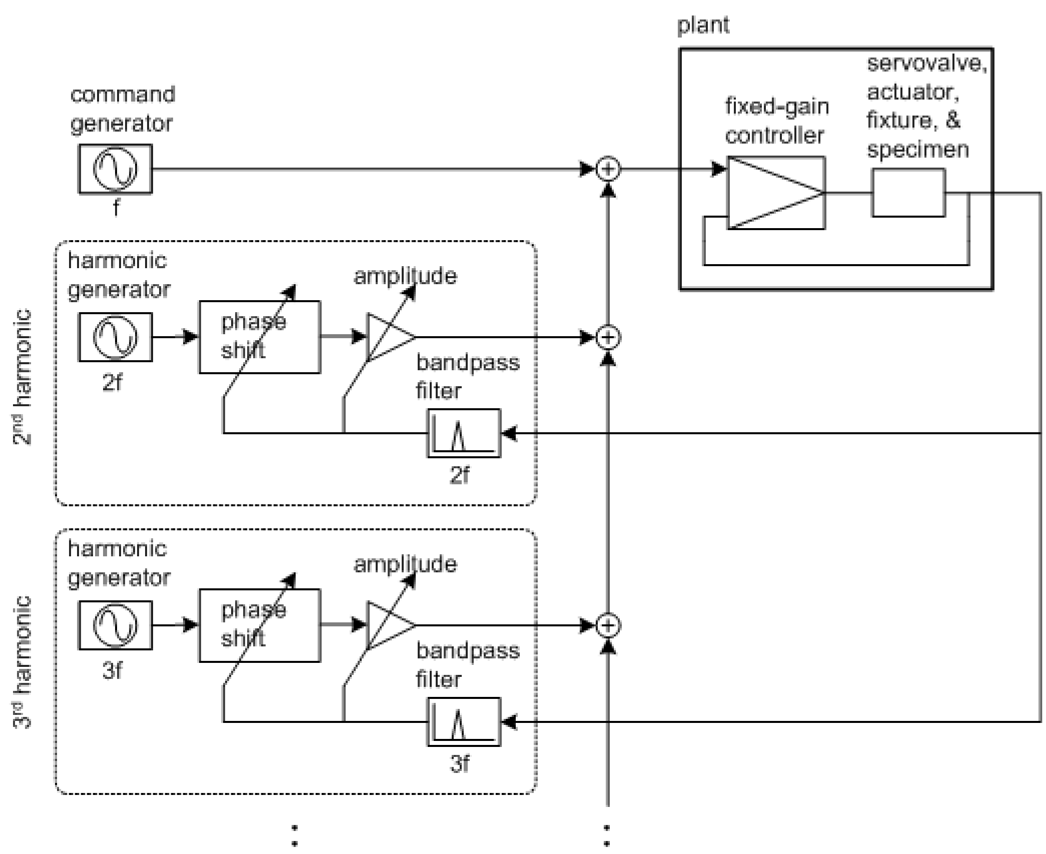
# How To Use Adaptive Harmonic Cancellation (AHC)

Adaptive Harmonic Cancellation (AHC) greatly reduces harmonic distortion of the response of a control system driven by a sinusoidal command. It measures the harmonic distortion directly and adapts in realtime the cancelling waveform that it applies to the control system input.

AHC is optimized to work with sinusoidal command waveforms (both fixed and swept frequency). To improve the fidelity of the system's response to a sine command, AHC can be augmented with Amplitude/Phase Control (APC). APC and AHC complement each other: APC enhances the fundamental frequency component of the system response while AHC cancels the harmonics.

## How AHC works

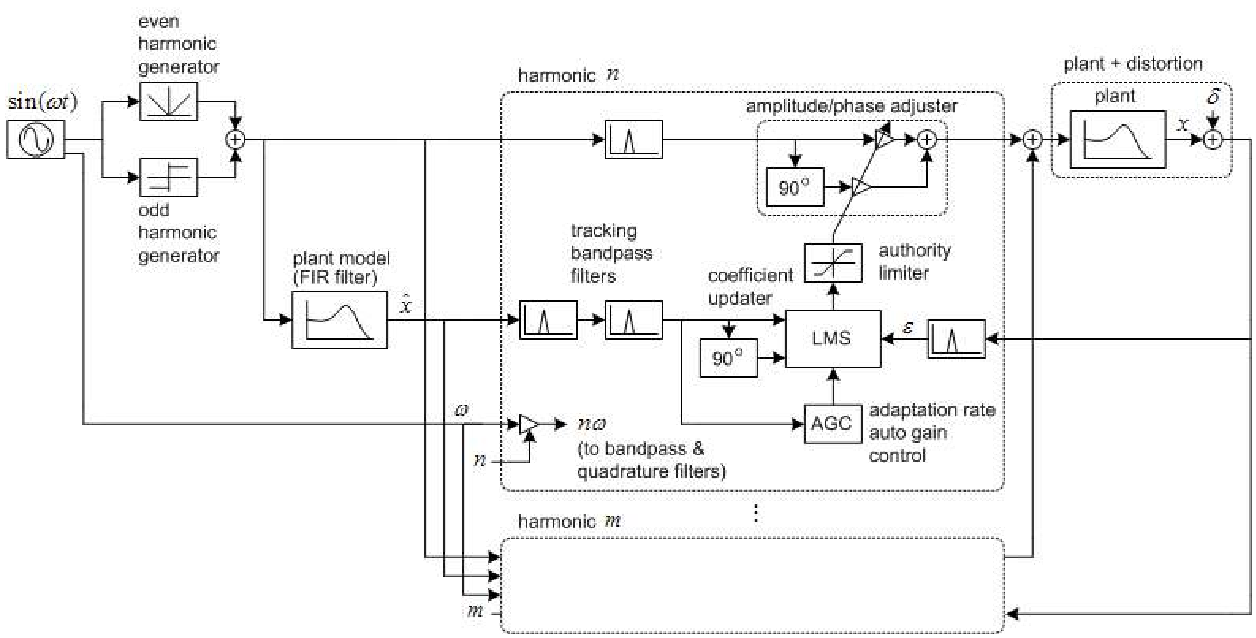
When a control system consisting of a fixed-gain controller, actuator, fixture, and test specimen (hereafter called the *plant)* is driven by a sinusoidal command, nonlinearity in the plant will cause frequency components at multiples of the command frequency to spontaneously appear at the plant output. These harmonics cause unwanted discrepancies between command and



feedback. Eliminating a harmonic is conceptually straightforward: simply add to the command a "cancelling signal" of the same frequency as the harmonic and with amplitude and phase such that what propagates through the plant and emerges at the output has the same amplitude but opposite polarity as the harmonic, thereby cancelling it. In order for this scheme to work properly, the cancelling signal must have the correct amplitude and phase to a high degree of precision that can only be obtained by adapting them according to online measurement of the harmonic.

As shown in the diagram above, AHC consists of a parallel network of cancellers, each dedicated to a single harmonic. A bandpass filter tuned to the harmonic frequency extracts the harmonic from the plant output. The extracted harmonic is used as an error signal to adapt the amplitude and phase of the cancelling signal which is then added to the command input of the plant. Once the harmonic is cancelled, the adaptation error is zero and the amplitude and phase are constant at appropriate values.

A more detailed view of the internal structure of AHC is shown below:




The amplitude/phase adjusting network in each harmonic canceller is based on the trigonometric identity

$$A\sin(\omega t) + B\cos(\omega t) = C\sin(\omega t + \phi),$$

which states that by suitable choice of coefficients $A$ and $B$, a sinusoid of any amplitude $C$ and and any phase $\phi$ can be obtained. In AHC, these coefficients are modified using the Least Mean Square (LMS) algorithm in such a way as to drive the response error $\varepsilon$ to zero. It is beyond the scope of this document to discuss specifics about the LMS algorithm; there are many good digital signal processing textbooks available on this topic.

Note in the diagram the presence of a model of the plant, which give the LMS algorithm critical phase information that it needs to adapt canceller coefficients. The transfer function of this plant model must be measured online during a training procedure prior to cancelling harmonics.

Also note in the diagram above that the harmonic generator output and the plant response are filtered by narrowband bandpass filters. These extract content from the signal only at the harmonic frequency. The center frequencies of these bandpass filters are varied according to a multiple of the current command generator frequency, allowing AHC to work with sine sweep command waveforms. This frequency is also used to update the quadrature (90°) phase shifters. Because AHC needs current frequency information, you must use the built-in sine and sine sweep function generators. You cannot use an external sine generator or a sine time history file with AHC because these command sources do not provide current frequency information.

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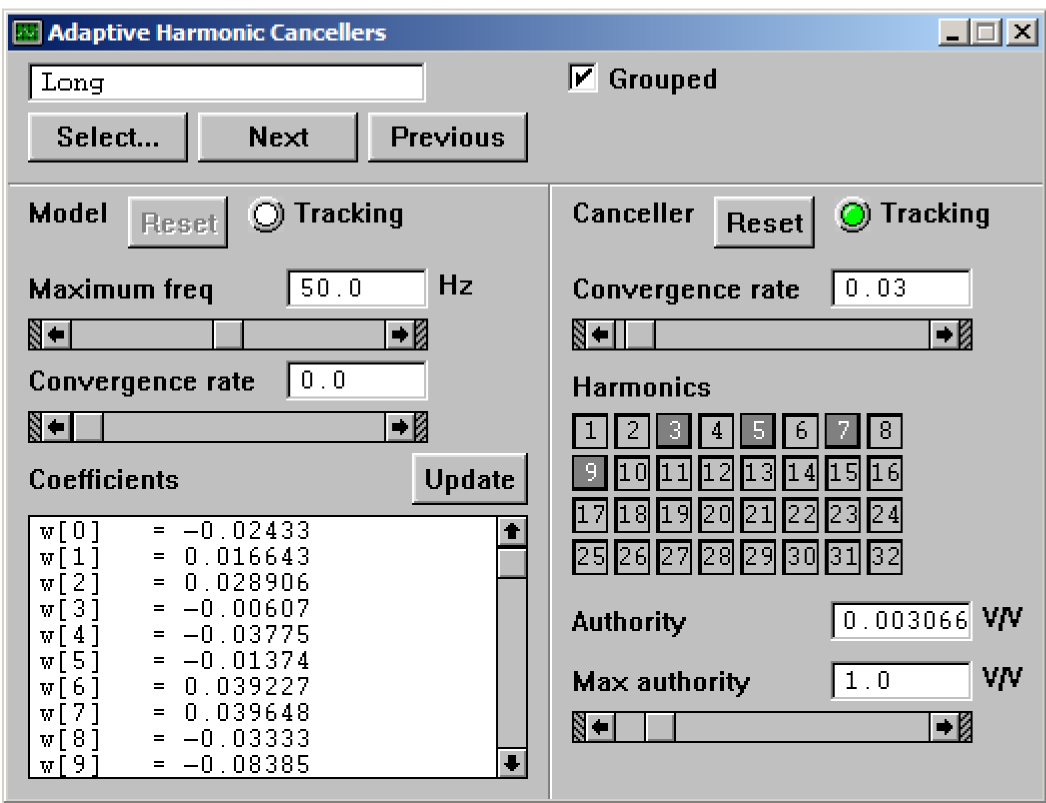
We now turn to specifics on using AHC. After a description of AHC's user interface, a step-by-step operating procedure will be presented.

# AHC Panel Adjustments



Channel list selector 


Select an individual AHC channel for manipulation or examination.

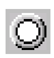
The Select button calls up a dialog with all channels presented in a list from which a single channel can be selected. Next and Previous buttons cycle through the list without having to call up the channel selection dialog.

Grouped checkbox 


Specify whether the selected channel is to be grouped with other channels for purposes of setting the Maximum Frequency, Model Convergence Rate, Canceller Convergence Rate, Harmonics, and Max Authority. When checked, changes to any of these parameters will be broadcast to other channels in the group. When unchecked, changes to any of these parameters will not affect other channels

Model Reset button

Reset the coefficients of the model to zero.

Model tracking indicator 

Displays the current state of the model coefficient adaptation process. The tracking indicator is green if coefficients are adapting, white if not. The conditions for tracking are:

- The AHC mode is set to Training.
- The model convergence rate is nonzero.
- The command waveform is not constant at zero or any other level.

Maximum Frequency slider bar

Set the maximum frequency up to which AHC will cancel harmonics. This value should be the set to the maximum frequency used to train the model. AHC cannot cancel harmonics outside the range of frequencies in which it has been trained.

If the command waveform is a sine sweep, when a harmonic exceeds the maximum frequency, cancellation of that harmonic is automatically disabled. Once the harmonic frequency is within range again, cancellation of that harmonic is automatically reenabled.

Model Convergence Rate slider bar

Set the convergence rate of the model coefficient adaptation process. A value of zero means no adaptation; higher values increase the speed of the adaptation process at a cost of decreased model accuracy. Too high of a value will cause the adaptation process to diverge, driving the coefficients to infinity. A convergence rate of less than one is usually (but not necessarily) safe.

Model Coefficients Update button

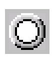
Update the Model Coefficients text display with current values of the model coefficients.

Model Coefficients text display

Displays textually the current values of the model coefficients. This information is also displayed graphically in the Impulse Response Function (IRF) Plotter.

Canceller Reset button

Reset the canceller coefficients of all active harmonics to zero.

Canceller tracking indicator 

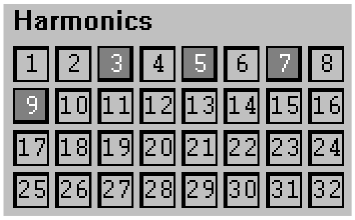
Displays the current state of the canceller coefficient adaptation process. The tracking indicator is green if coefficients are adapting, white if not. The conditions for tracking are:

- The AHC mode is set to Tracking.
- The canceller convergence rate is nonzero.
- The command waveform is not constant at zero or any other level.

Canceller Convergence Rate slider bar

Set the convergence rate of the canceller coefficient adaptation process. A value of zero means no adaptation; higher values increase the speed of the adaptation process at a cost of decreased cancellation quality. Too high of a value will cause the adaptation process to diverge, driving the coefficients to infinity. A convergence rate of less than one is usually (but not necessarily) safe.

Harmonics grid selector




Select the harmonics to be cancelled. Do not use the first harmonic unless you are cancelling cross-coupling disturbance on another channel (discussed in a later section).

Authority display

Displays the maximum amplitude of any cancelling signal that AHC has added to the command. Not all of the signals will have this amplitude, only the largest one.

Max Authority edit box

Set an upper limit on the amplitude of any cancelling signal that AHC adds to the command. This is a safety feature designed to limit the amplitude of motion should AHC's adaption process become unstable.

## AHC Operating Modes

AHC has four operating modes available from a popup menu on the Main Panel:


These modes are:

Disabled: AHC is off.

Frozen: AHC is on and cancelling, but canceller coefficients are unchanging. This mode is not recommended for normal operation. If you freeze the coefficients and then change the command frequency, the harmonic amplitude corresponding to the frozen coefficients may be inappropriately large at the new frequency, resulting in damage to or destruction of your specimen and test system.

Tracking: AHC is on and cancelling, and canceller coefficients are changing. This is the mode recommended for normal operation.

Training: AHC is on but not cancelling. Plant input and output are passively monitored while model coefficients are updated. This mode is used to determine model coefficient values prior to running Frozen or Tracking modes.

## Training the Model

Perform the following procedure for every active control channel:

Step 1: *Set up the random function generator*. The random function generator consists of a uniform distribution random number generator followed by a bandpass filter. This filter has four parameters that you must enter:

<u>Maximum frequency</u>: This is the cutoff frequency of the bandpass filter. Set this according to the highest frequency expected in your test waveform. Due to internal technical considerations, this maximum frequency must not exceed 64 Hz. Also enter this maximum frequency into the Maximum Frequency edit box in the AHC Panel. This tells AHC not to cancel harmonics that exceed the frequency up to which its model has been trained.

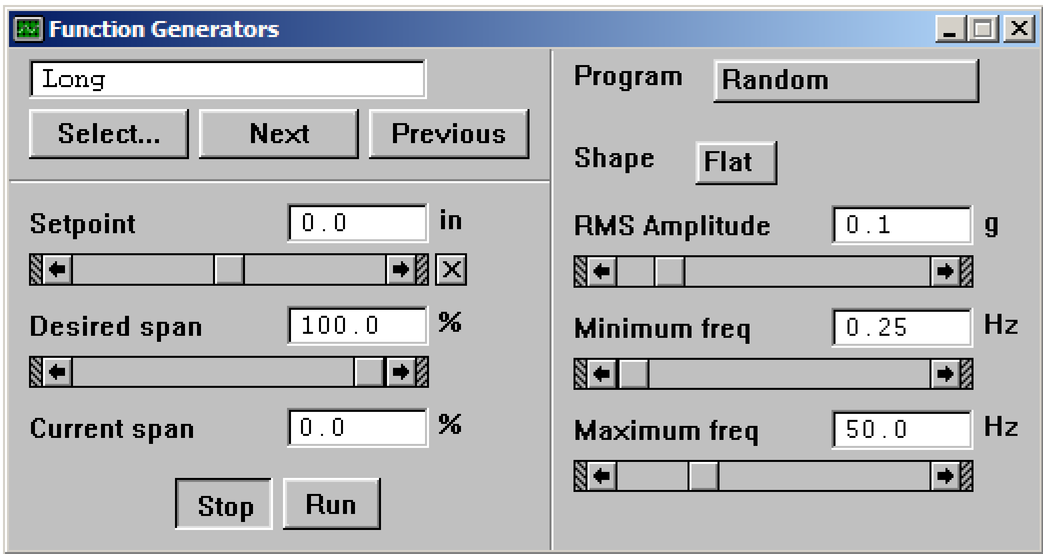
<u>Minimum frequency</u>: This is the cut-in frequency of the bandpass filter. Set this according to the lowest frequency expected in your command waveform. A minimum frequency of zero is allowed. In seismic controllers in acceleration control mode, this frequency should match the cut-in frequency of the Reference Generator.

<u>RMS amplitude</u>: 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 an inaccurate estimates of the plant model. 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.

<u>Shape</u>: 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 systems, "Flat" works well, but in displacement control systems, "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.

An example random function generator setup is as follows:

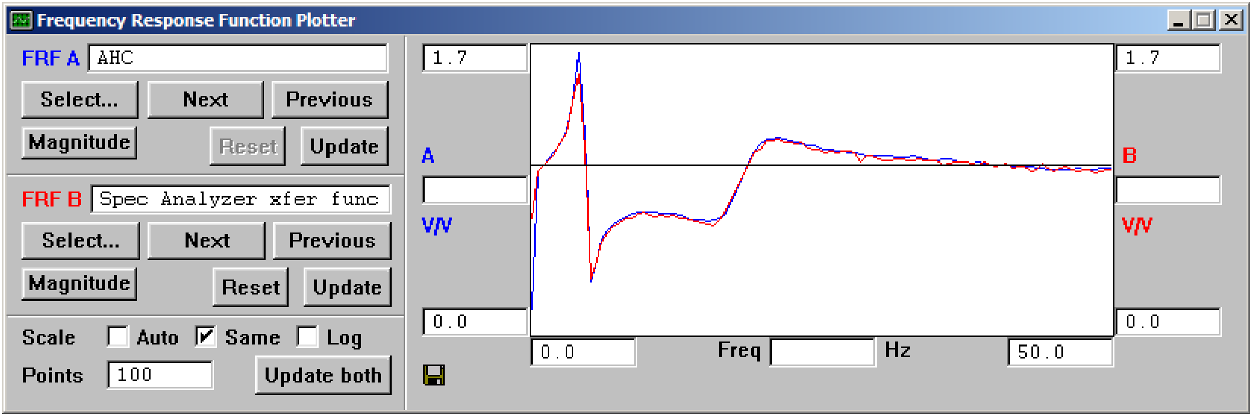



Step 2: *Turn on AHC in Training mode from the Main Panel.* In Training mode, AHC is on but is not cancelling. Instead, it passively monitors command and feedback to the plant and updates its model accordingly.

Step 3: *Run the random function generator*. First, make sure that the function generators of all other channels are in a stopped state. Then start the function generator by pressing the Run button.

Step 4: *Adapt the coefficients.* When motion has begun, move the Model Convergence Rate slider bar away from zero. The coefficients of elements in the training row will begin to change. This can be observed textually in the model coefficient display of the AHC Panel, and graphically in the FRF and IRF Plotters. Another indication of adaptation is the green color of the tracking indicator next to the Model Convergence Rate slider bar.

While training is in progress, it is a good idea to verify that it is proceeding correctly by comparing the transfer function estimated by AHC with that estimated independently by the Spectrum Analyzer. In the example, Channel A (blue) of the FRF Plotter shown below shows the model's transfer function identified by AHC; Channel B (red) shows the same transfer function identified by the Spectrum Analyzer. Note that they are similar, but not the same (especially the phase responses, not shown) because embedded in the AHC transfer function are effects of filters internal to AHC that the Spectrum Analyzer cannot see.




When the coefficients have stopped changing alot, it is time to begin a process known as "coefficient polishing". Slowly reduce the convergence rate in stages, waiting a while between stages to allow time for the coefficients to approach their optimum values. Finally, after the convergence rate has been reduced to zero, stop the function generator by pressing the Stop button.

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Training is now complete. At this point is a good idea to save AHC setup and transfer function coefficient values to a settings file using the Main Panel's File, Save Settings menu item.

## Cancelling the Harmonics

Perform the following procedure for every active control channel:

Step 1: *Set up the sine or sine sweep function generator.*

Step 2: *Turn on AHC in Tracking mode from the Main Panel.* At this point you may also want to turn on Amplitude/Phase Control (APC) to improve the fidelity of response to the sine command.

Step 3: *Run the sine or sine sweep function generator.* First, make sure that the function generators of all other channels are in a stopped state. Then start the function generator by pressing the Run button.

Step 4: *Cancel selected harmonics.* After motion has begun, observe the response using the Digital Oscilloscope. It is convenient to view the response in Frequency Display Mode so that individual harmonics are easily discernable. Noting which harmonics have significant amplitude, designate them for cancellation by pressing the corresponding buttons in the Harmonics grid selector in the AHC Panel. Then move the Canceller Convergence Rate slider bar away from zero. In the Digital Oscilloscope, selected harmonics will begin to shrink in amplitude. The authority displayed in the AHC Panel will increase as the amplitudes of the cancelling signals that AHC adds to the command are increased. Another indication of adaptation is the green color of the tracking indicator next to the Canceller Convergence Rate slider bar.

If the authority reaches the maximum authority limit, it is either because the maximum authority is too low, or AHC is unstable at that harmonic. To determine which is the case, increase the Max Authority in the AHC Panel by small increments while observing the response harmonics in Digital Oscilloscope (in Frequency Display Mode). If the amplitude of a harmonic keeps increasing with increasing authority, then AHC is unstable at that harmonic. Almost always the cause of this behavior is an inadequately trained plant model. You may need to go back and retrain or refine it.

Reducing the maximum authority to the minimum possible will reduce the danger of damage due to large amplitude motion should AHC's adaption process become unstable for whatever reason.

When running sine sweeps at a fast sweep rate, you may find that AHC is not able to adapt quickly enough to keep up. Try increasing the convergence rate. However, if you increase the convergence rate beyond unity, you risk AHC instability and the large, potentially damaging motion that will result. You may have to reduce the sweep rate instead.

## Cancelling Cross-Coupling Disturbance

AHC can be used to cancel the cross-coupling disturbance that sometimes occurs in a multichannel control system when motion on one channel couples into another. Using the term "primary" to refer to the primary motion channel and "secondary" to refer to the channel disturbed by the primary channel, apply the following procedure to the secondary channel:

Step 1: *Train AHC as usual.*

Step 2: *Set up the phased function generator.* The phased function generator synchronizes itself both frequency- and phase-wise with another channel's function generator (called the "master" function generator). In this case, designate the primary motion channel's sine generator as the master. Next, specify a very small amplitude, small enough for the resultant motion to not be noticeable. Even though no motion is desired on the secondary channel, you must drive it with sine command becauses AHC uses it to drive its internal harmonic generators. The command amplitude does not have to be large, but it does have to be nonzero.

Step 2: *Turn on AHC in Tracking mode from the Main Panel.*

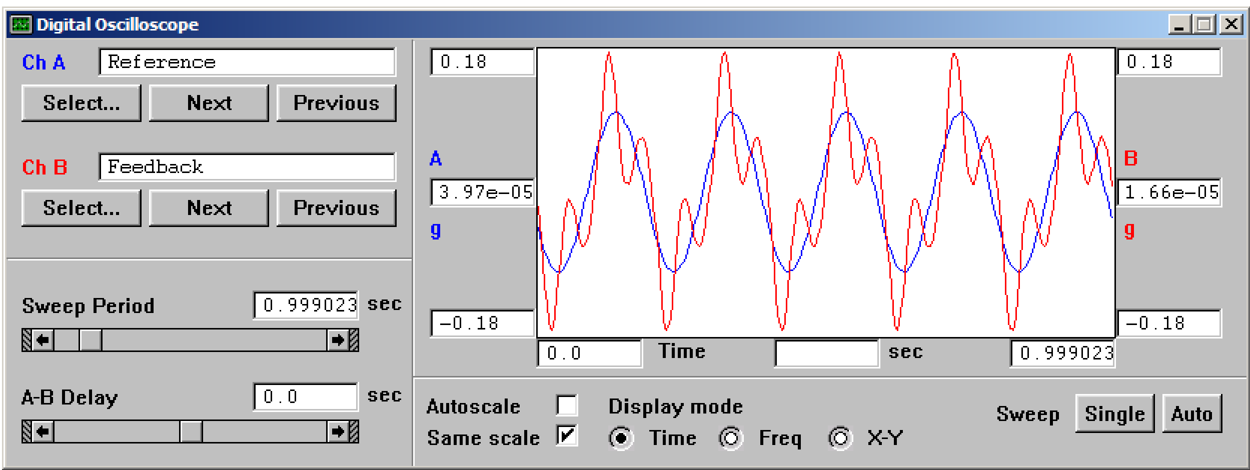
Step 3: *Run the sine or sine sweep function generator*. Start the primary function generator by pressing the Run button. The secondary function generator will start as well because it is linked to the primary function generator.

Step 4: *Cancel selected harmonics.* When you observe the secondary channel's response in the Digital Oscilloscope (in Frequency Display Mode), there will probably be a sizeable component of disturbance at the fundamental frequency, i.e., the primary function generator's sine frequency. Cancel this "first harmonic" by selecting the "1" button of the Harmonics grid selector in the AHC Panel. Note that the first harmonic button is used only to cancel cross-coupled disturbance at the fundamental frequency on secondary channels. It is not used for regular cancellation on primary channels.

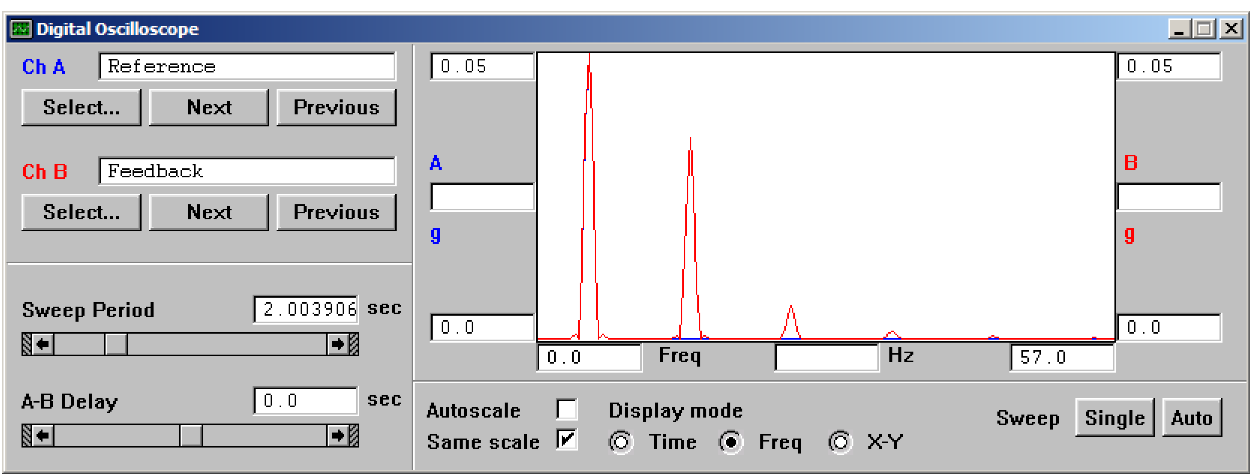
## Viewing the Results

You can use the Digital Oscilloscope to monitor command and response waveforms in either the time domain or the frequency domain. In all examples shown below, command is shown on Channel A (blue) and response on Channel B (red). APC is enabled in all of these examples.

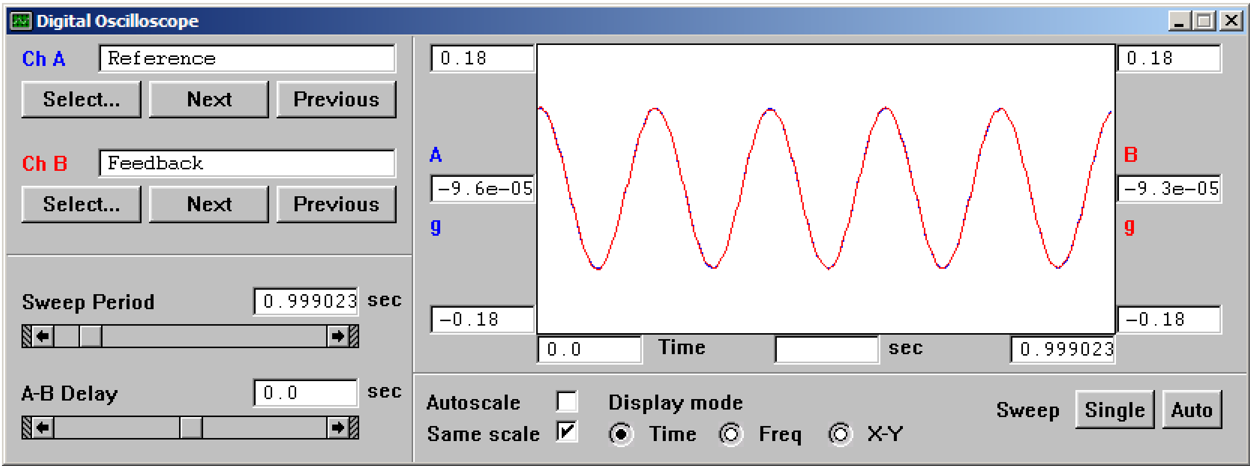
Below is an example showing command and response time domain signals without AHC:




In the frequency domain, harmonics are clearly visible in the response:



With AHC, the harmonics are gone and, because of APC, command and response time domain signals are almost perfectly overlaid:




In the frequency domain, the harmonics are gone and the response amplitude at the fundamental frequency matches the command amplitude: