# How To Use Amplitude/Phase Control (APC)

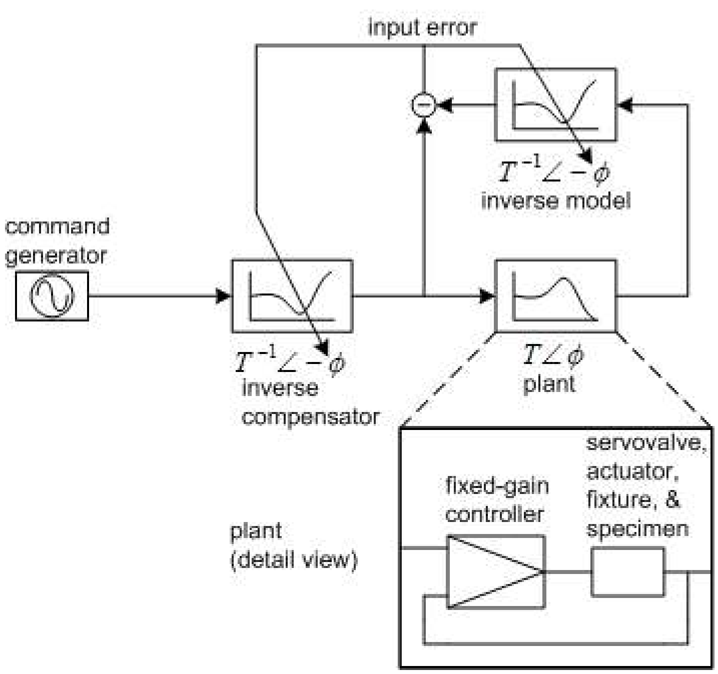
**BKT 14-Apr-01**

Amplitude/Phase Control (APC) is a control compensation technique that augments a fixed-gain controller to correct for closed-loop amplitude and phase irregularities in order to improve control fidelity. It measures control system dynamics directly and modifies the control compensation accordingly in realtime, making it possible to adapt to changing system dynamics.

APC is optimized to work with sinusoidal command waveforms (both fixed and swept frequency) and predominantly linear systems. If the command waveform is non-sinusoidal, use Adaptive Inverse Control (AIC) instead. If the system has significant nonlinearities, augment APC with Adaptive Harmonic Cancellation (AHC) to reduce harmonic distortion. APC and AHC complement each other: APC enhances the fundamental frequency component of the system response while AHC cancels the harmonics.

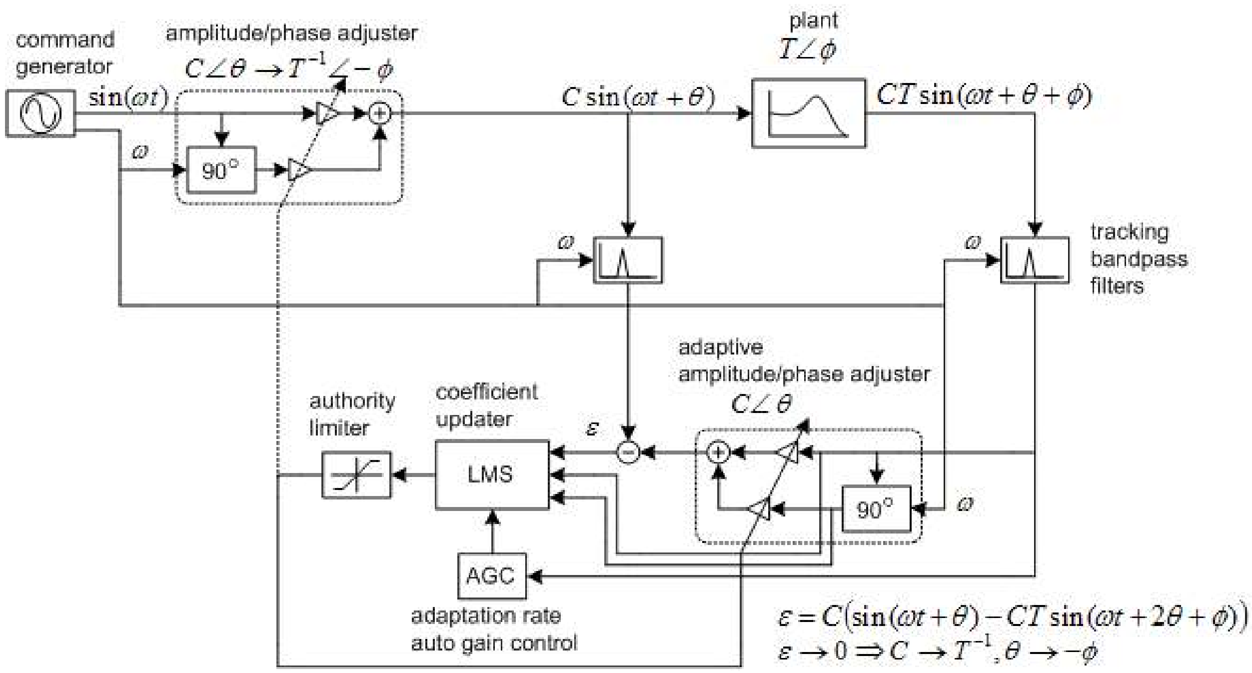
## How APC works

Amplitude/Phase Control (APC) is a control technique that eliminates amplitude and phase discrepancy between command and response when the command waveform is sinusoidal. This discrepancy arises from dynamics of the fixed-gain controller, actuator, fixture, and test specimen combination hereafter called the *plant*. Plant dynamics cause a sine command input to emerge at the plant output scaled in amplitude by a gain $T$ and shifted in phase by angle $\phi$ (notationally, $T\angle\phi$). APC corrects this amplitude and phase discrepancy by preceding the plant input with a compensator network that scales the command amplitude by gain $T^{-1}$ and shifts the phase by angle $-\phi$, resulting in an overall gain of $T^{-1} * T = 1$ and an overall phase shift of $-\phi + \phi = 0$. This is shown schematically below:



The inverse plant gain $T^{-1}$ and phase shift $-\phi$ is not known in advance, so it is computed online by estimating the plant input with an inverse model driven by the plant output, comparing the estimated input with the actual input to develop an input error signal, and updating the inverse model in such a way as to drive the input error to zero. Once the input error is driven to zero, the inverse model gain and phase becomes $T^{-1}\angle-\phi$, which is copied to the inverse compensator placed between the command generator output and the plant input.

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




Both inverse model and inverse compensators are amplitude/phase adjusting networks that implement 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 APC, these coefficients are modified using the Least Mean Square (LMS) algorithm in such a way as to drive the input 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 above that both the plant input and output signals are filtered by narrowband bandpass filters. These allow APC to filter out harmonic frequency components that arise due to plant nonlinearities and focus instead on the fundamental frequency. The center frequencies of these bandpass filters are varied according to the current command generator frequency, allowing APC to work with sine sweep commands. This frequency is also used to update the quadrature (90°) phase shifters. Because APC 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 APC because these command sources do not provide current frequency information.

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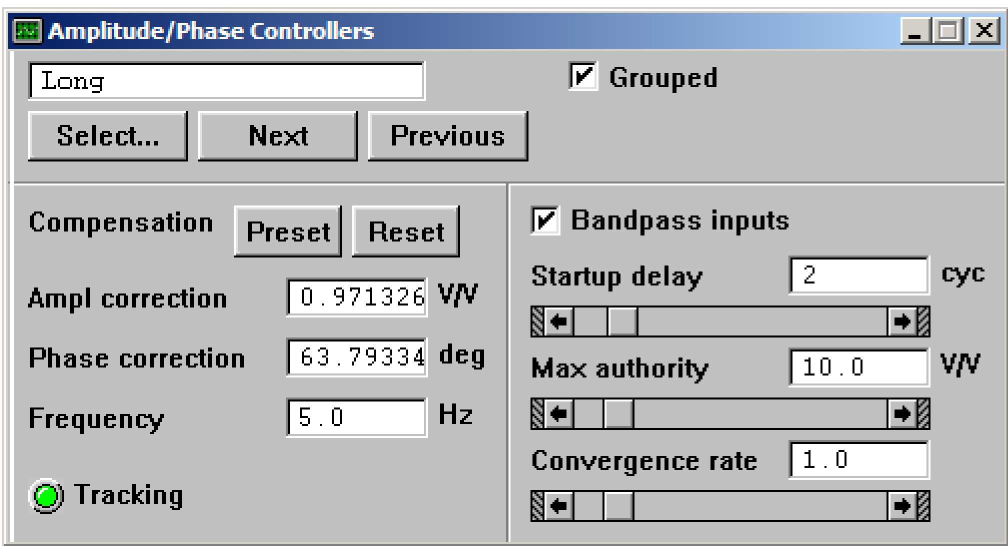
We now turn to specifics on using APC. After a description of APC's user interface, a step-by-step operating procedure will be presented.

# APC Panel Adjustments




Channel list selector 


Select an individual APC 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 Bandpass Inputs, Startup Delay, Max Authority, and Convergence Rate. 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

Compensation Preset button

Set the amplitude correction to unity and the phase correction to zero.

Compensation Reset button

Set both the amplitude correction and the phase correction to zero.

Amplitude and Phase Correction edit/display boxes

Displays the current amplitude and phase corrections being applied to the command. Also allows values to be entered so that APC can be set to correction values other than that provided by the Compensation Preset and Reset buttons.

Frequency display

Displays the current frequency of the command.

Tracking indicator 

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

- The APC mode is set to Tracking.
- The convergence rate is nonzero.
- The command waveform is not constant at zero or any other level.
- The number of sine cycles since the start of the command waveform is greater that the number of cycles of startup delay.

Bandpass Inputs checkbox 


Specify that APC's input signals are to be bandpass filtered to remove harmonic noise. This is a desirable thing except in certain rarely encountered situations that require the maximum possible adaptation speed, making the slight slowdown due to the delay of the filters unacceptable.  It is recommended that you leave this checked.

Startup Delay edit box

Set the number of sine cycles after the start of the command that must elapse before adaptation can begin.  This prevents adaptation during the transition from a stopped to a running state until transients have died out somewhat.

Max Authority edit box

Set the maximum amplitude correction that APC is allowed to apply to the command. This is a safety feature designed to limit the amplitude of motion should APC's adaption process become unstable.

Convergence Rate edit box

Set the convergence rate of the coefficient adaptation process. A value of zero means no adaptation; higher values increase the speed of the adaptation process at a cost of increased susceptibility to noise. The convergence rate should be no more than unity otherwise the potential for instability exists.

## APC Operating Modes

APC has three operating modes available from a popup menu on the Main Panel:


These modes are:

Disabled: APC is off.

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

Tracking: APC is on and controlling, and coefficients are changing. This is the mode recommended for normal operation.

## Operation

APC is very easy to use: just turn it on from the Main Panel, define a sine wave in the Cyclic Function Generator Panel or a sine sweep in the Sine Sweep Function Generator Panel, and press the Run button on the Main Panel.

In most cases you will not need to adjust anything on APC Panel. However there are a few situations that may arise where you may want to make modifications:

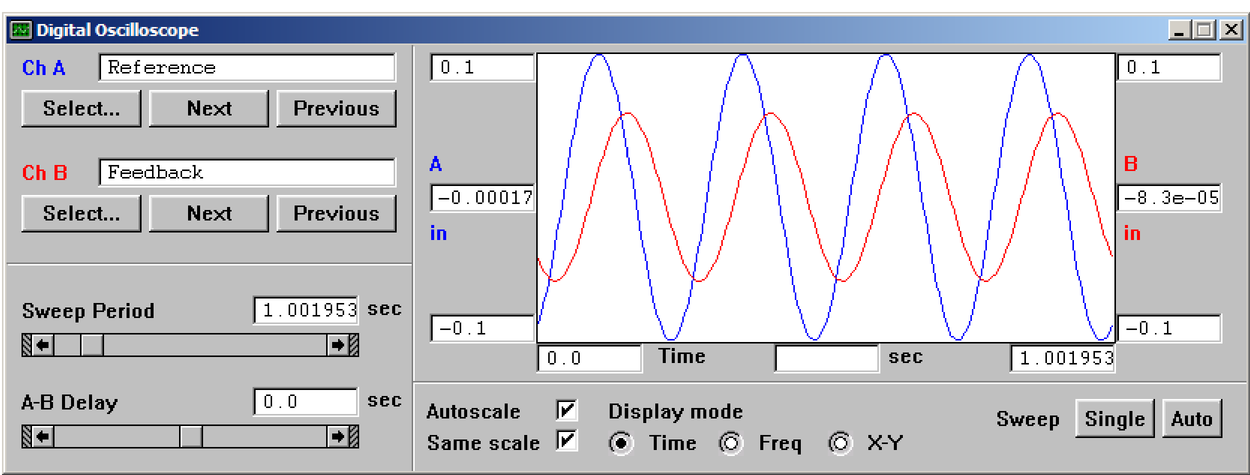
- When operating at a frequency that is close a resonance such as the oil column resonance or a specimen resonance, APC may cause the response amplitude to oscillate . Usually this can be cured by reducing the convergence rate.
- When running sine sweeps at a fast sweep rate, you may find that APC is 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 APC instability and the large, potentially damaging motion that will result. You may have to reduce the sweep rate instead.
- For safety purposes you may want to reduce the Max Authority value to reduce the danger of damage due to large amplitude motion should APC's adaption process become.
- If you observe that the response amplitude falls short of the command amplitude, it may be because the amplitude correction that APC needs to apply is beyond the maximum authority limit. You can verify that this is the case because the Amplitude Correction display value will be nearly equal to the Max Authority value. Increase the Max Authority in small increments, until the response amplitude matches the command and the Amplitude Correction falls below the Max Authority. If the response amplitude does not increase when Max Authority is increased, you may be at a physical limit of the system, in which case there is nothing you can do except reduce the command amplitude or frequency.

You may also want to access the APC Panel to verify that adaption is occurring by observing the changing correction values in the Amplitude and Phase Correction displays, or by noting the green color of the tracking indicator next to the Convergence Rate slider bar.

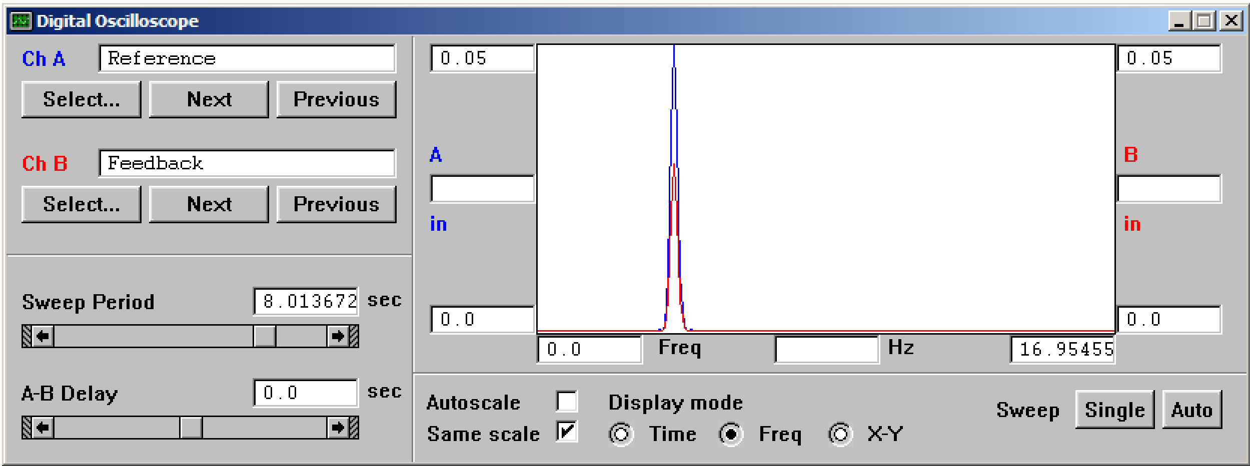
## Viewing the Results

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).

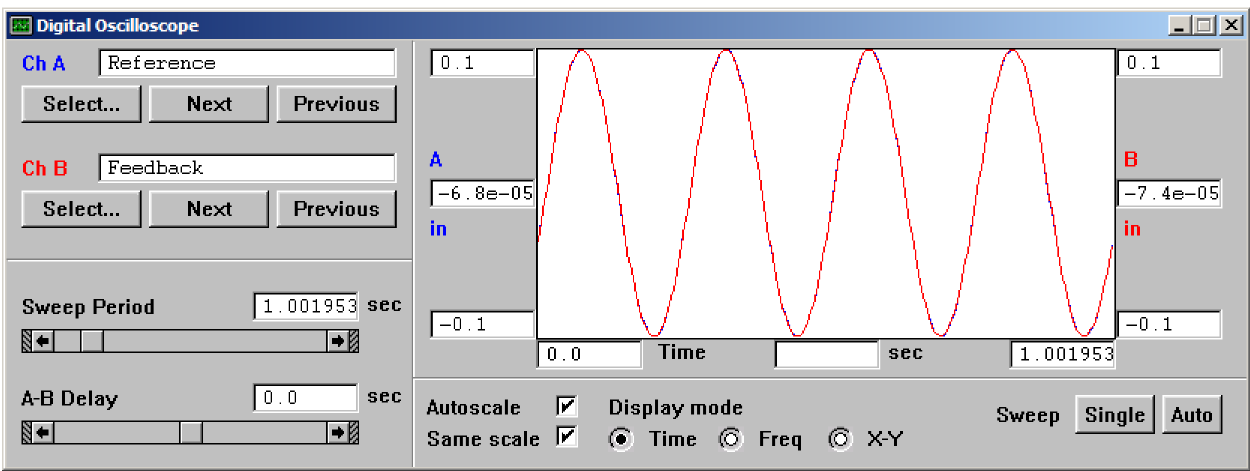
Below is an example showing command and response time domain signals without APC:



In the frequency domain, the response amplitude obviously falls short of the command amplitude:




With APC, command and response time domain signals are almost perfectly overlaid:




In the frequency domain, the response amplitude matches the command amplitude: