Lab 1: The Bipolar Junction Transistor (BJT): AC Characterization

Electronics II

Contents

Day 2: BJT AC Characteristics

Purpose

Previously, we measured some of the DC characteristics of a BJT transistor. In this part of the lab, we will look at the AC operation of the transistor. In this course and in other courses, you may have encountered names such as R_{pi} or g_m when performing calculations. These parameters are specific to the device (and the device model) that you are using. In order to compare devices of different types, we use a different set of network parameters. In this lab, you will become familiar with the h-parameters and the hybrid-pi model of the bipolar junction transistor.

Part 4 The Transistor's h-Parameter and Bandwidth

The four h-parameters describe all of a transistor's small-signal AC characteristics for a given set of DC bias conditions, at one frequency. At low to medium frequencies, they are independent of frequency. The four hybrid parameters are:

h_{ie}: the AC input impedance with the output short-circuited
h_{oe}: the output admittance with the input open-circuited
h_{fe}: the AC forward current gain with the output short-circuited, and
h_{re}: the reverse, or feedback, voltage ratio with the input open-circuited

You may want to reference the Sedra and Smith companion website's Appendix C.1.3 for a better understanding of the h-parameters. Keep in mind the h-parameters are sub scripted differently, although it is simmilar in concept.

The second subscript, **e**, indicates that these parameters are measured with respect to the emitter, the emitter being the terminal common to both the input circuit and the output circuit. All but the last h-parameter will be measured in this exercise, the last one being so close to zero as to be practically unobservable using the equipment of the ELEC 3509 laboratory.

The one other transistor parameter of major interest is its unity-gain bandwidth, f_T, the frequency at which its AC current gain is reduced to one. In most cases, equipment bandwidth limitations prevent the direct measurement of f_T for any active device, so it is usually determined by extrapolating results at lower frequencies. In this case, this can be done by observing the low-frequency current gain h_{fe}, and by measurements of the beta cut-off frequency, f_β, the frequency at which h_{fe} drops by 3 dB; f_T is the product of f_β and h_{fe} (see Figure 1).

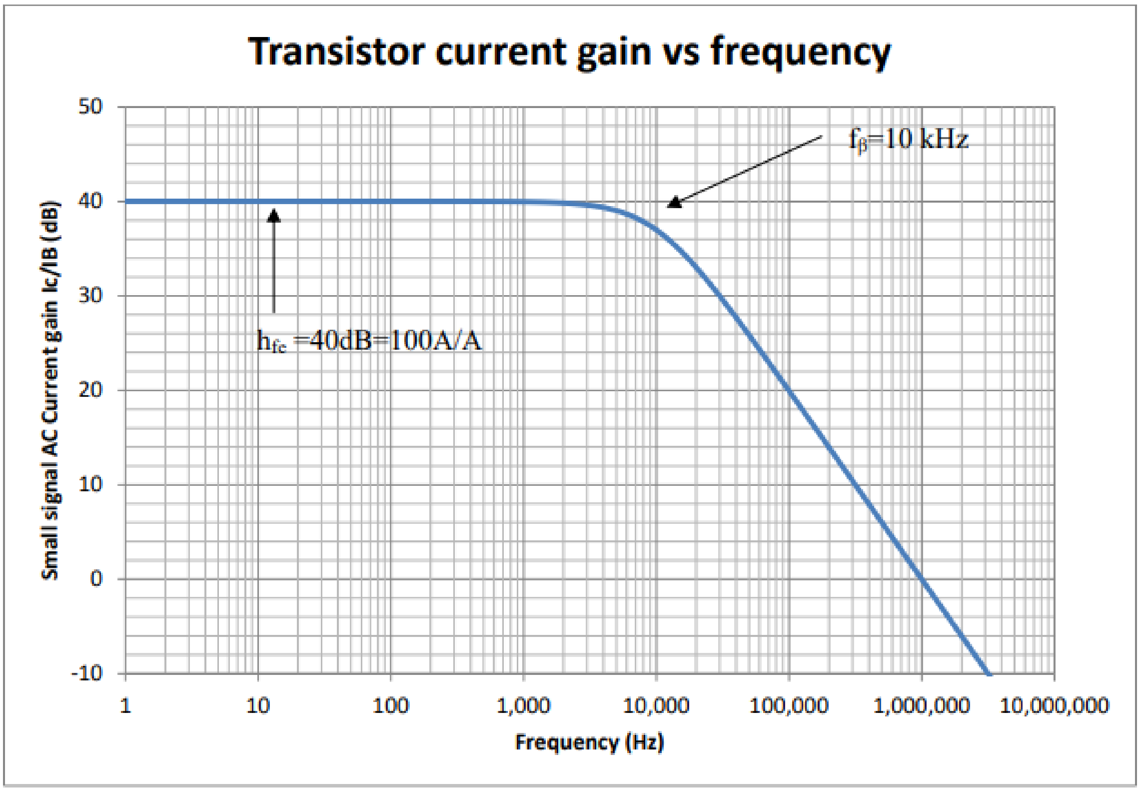

Figure 1: An example plot showing current gain vs frequency. Here, the f_T can be seen directly to be 1 MHz, but can be calculated by multiplying $h_{fe} = 100$ by $f_\beta = 10$ kHz (note: your transistor's values will not be the same as in this sample).

(a): DC-Biasing Circuit

Set up the circuit shown in Figure 2 in Multisim. This is the same circuit as Part 2, with VDC1 being 15 V. Use a value of R_C to maintain a V_{CE} around 6 V.

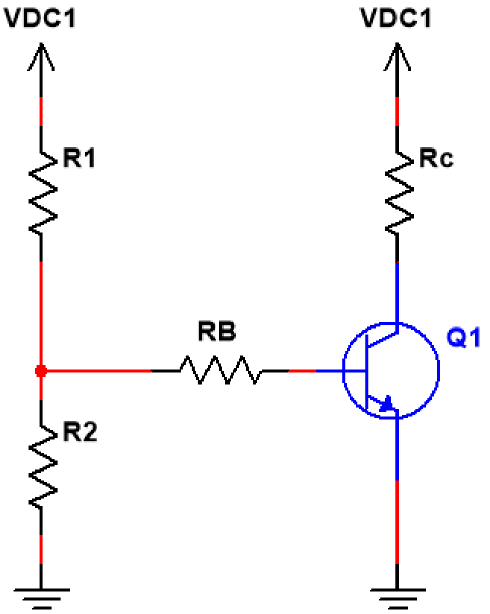

Figure 2: Test Circuit for Part 4(a) - Device Under Test

(b): AC-Coupling of Input and Output Signals

Add the additional circuitry shown in Figure 3. This additional circuitry couples AC test signals into and out of the DC-biased transistor circuit, which is the device under test (D.U.T). Figure 4 represents a "black-box" view of the D.U.T. in the test circuit.

In your report, explain the purpose of the capacitors C_1 and C_2, making sure to identify what would happen if they were absent.

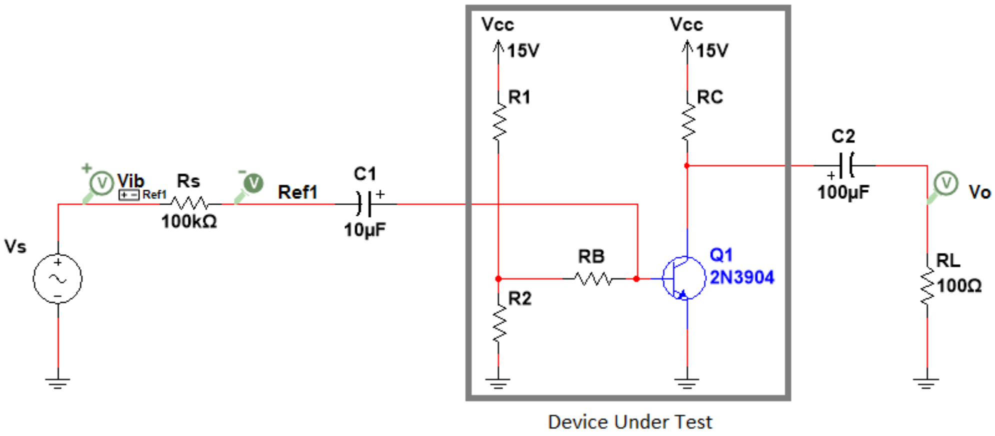

Figure 3: AC Test Circuit for the Biased BJT

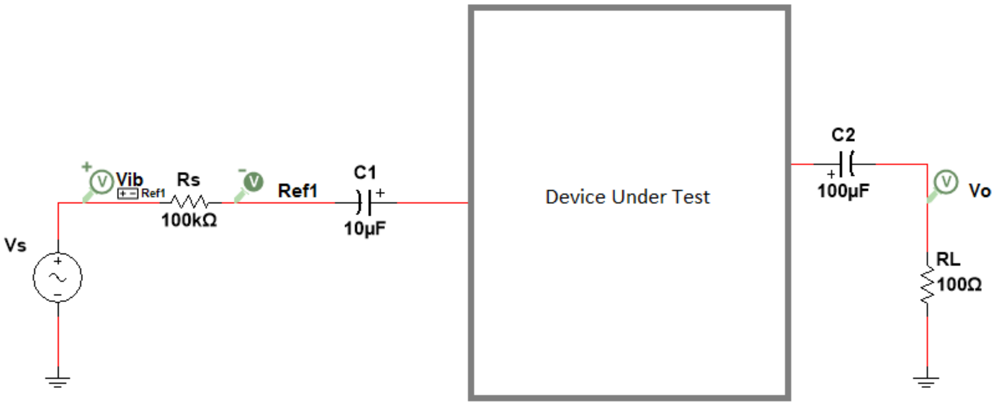

Figure 4: "Black-Box" View of the DUT in the AC Test Circuit

(c): The AC Input Impedance, h_{ie}, and the AC Forward Current Gain, h_{fe}

Experiment

Setup Multisim to run an interactive simulation. With the AC voltage source's frequency set to 1 kHz, adjust its amplitude to give i_b (AC base current) of 1 μA RMS. To approximate how this would be done with hardware, measure the amplitude of the voltage across Rs and use this to calculate i_b.

Using either the grapher view of a transient simulation or an oscilloscope in an interactive simulation, observe the output signal and qualitatively ensure that it is not distorted. If it is, double check i_b and the DC bias.

Using the simulation outputs and some clever reasoning, calculate the following:

AC input impedance:

$$h_{ie} = \frac{v_{be}}{i_b} = \frac{v_{be}}{v_{ib}} R_s \tag{0.0.1}$$

AC forwarding current gain:

$$h_{fe} = \frac{i_c}{i_b} \tag{0.0.2}$$

Where:

$$i_c = \frac{v_o}{R_L} \tag{0.0.3}$$

The expected range of results for h_{ie} and h_{fe} can be found in the attached specifications for the 2N3904 transistor.

Note the output short-circuit condition properly required for measuring h_{ie} and h_{fe} is only approximately met by the 100 Ω load resistance that was used in the test circuit. However, the error that it produces here is small. In later calculations of the hybrid-pi parameters, the fact that there exists an AC output voltage will have to be taken into account

Report

In your report, show your results and calculations. Describe why the value of the load resistor cannot be made to be zero.

(d): The AC Output Admittance, h_{oe}, and the AC Reverse, or Feedback, Voltage Ratio, h_{re}

Since we are dealing with very low frequencies, the AC output admittance, h_{oe}, can be found from the DC characterization you performed in Day 1. In this case, it is the slope of the I_C vs. V_{CE} characteristic curve at the point of DC operation. Use the I_C vs. V_{CE} graph from Part 2 of Lab 1 to find h_{oe}, ignoring the fact that I_C may not be exactly the same in the graph as it is in this part of the experiment, but it will be close. The units of h_{oe} are amps/volt, or $m\Omega^{-1}$. Express the admittance in Siemens, or Ω^{-1}, as this is usual since its value will be quite small. The expected range of h_{oe} can be found in the attached specifications.

Note that in general, AC parameters cannot be found from looking at the DC I-V curves, although this is usually ok if we are not working at very high frequencies.

The AC feedback voltage ratio, as previously mentioned, is too small to measure in the ELEC 3509 laboratory. Therefore, take $h_{re} = 0$.

(e): The Unity-Gain Bandwidth, f_T, and the Beta Cut-Off Frequency, f_β

Note

See Appendix A at the end of this lab for more information about making AC measurements with an oscilloscope. The differential voltage probes in Multisim take this into account already.

Experiment

Make sure AC i_b is still set to approximately 1.0 μA RMS at 1 kHz. Measure the voltage across R_S and R_L. From these, calculate the current gain, h_{fe}.

In Multisim, perform an AC Sweep from 1 Hz to 10 MHz with 10 points per decade. This should provide enough data points to make a plot like Figure 1. Typically, you won't be able to directly measure unity-gain frequency (0 dB) however. Instead you must be able to reach and exceed the point where the current gain drops to 71% of its low frequency value (a 3 dB drop). This frequency is f_β. Note that you cannot assume that the signal generator voltage will remain constant over frequency. You must re-measure the voltage across R_S each time.

From these values, calculate f_T:

$$f_T = h_{fe}(lowfrequencies) * f_\beta$$

Change the DC bias conditions so that the DC I_C is 0.5 mA and find f_T again. Change R_C to keep V_{CE} around 7.5 V. Repeat with $I_C = 1$ mA. Make a plot of current gain/frequency for these two new currents and find h_{fe}, f_β and as a result, f_T.

Report

For all three bias conditions, plot current gain (in dB) as a function of frequency (in a log scale). On the plot, show your values of h_{fe} and f_β.

Part 5: The BJT High-Frequency Hybrid-Pi Model

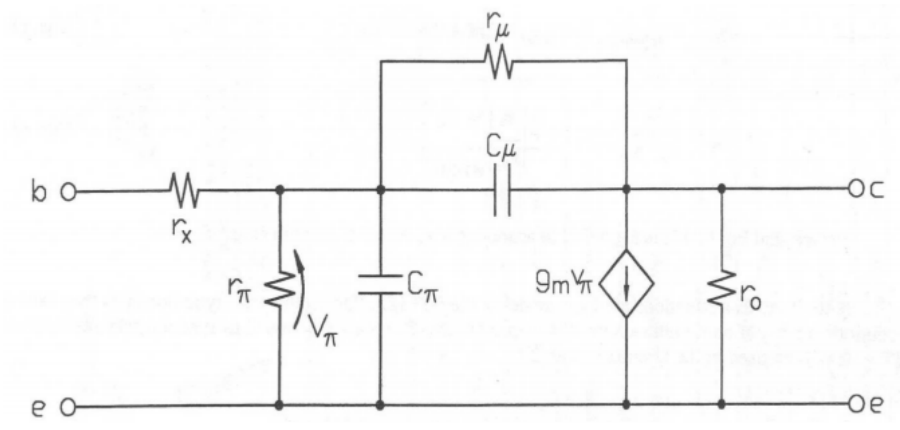

Figure 5: The High-Frequency Hybrid-Pi Model of a BJT

Report

Figure 5 shows the high-frequency hybrid-pi model of a BJT. The equations given below define its elemental values in terms of the previously measured circuit parameters. For your report, calculate all of these values, and make a copy of them as they will be needed for designing the amplifiers of the first project.

$$g_m = \frac{I_C}{V_T} \tag{0.0.4}$$

$$V_T = \frac{KT}{q} = \frac{1.381 * 10^{-23} J^o/K}{1.602 * 10^{-19} C} * T \approx 25mV at 20^\circ C \tag{0.0.5}$$

$$r_\pi = \frac{h_{fe}}{g_m} \tag{0.0.6}$$

(If through experimental error $\mathrm{r_x}$ becomes negative, then set $\mathrm{r_x} = 0$)

$$r_\mu = \frac{r_\pi}{h_{re}} \approx \infty \tag{0.0.7}$$

$$r_o = (h_{oe} - \frac{h_{fe}}{r_\mu})^{-1} \approx {h_{oe}}^{-1} \tag{0.0.8}$$

$$w_\beta = 2\pi f_\beta \tag{0.0.9}$$

$$C_\pi = \frac{1}{r_\pi * \omega_\beta} - C_\mu (1 + |\frac{v_o}{v_{be}}|_{@1KHz}) \tag{0.0.10}$$

Notice that Equation 0.0.10 is modified to account for $\mathrm{v_o} \neq 0$. If C_π negative set $\mathrm{C}_\pi = 0$.

The 2N3904 transistor specifications are provided in the following page.

2N3903 (SILICON)
2N3904

$V_{CB} = 60$ V
$I_C = 200$ mA
$C_{ob} = 4.0$ pf (max)

CASE 29
(TO-92)

NPN silicon annular transistors, designed for general purpose switching and amplifier applications, features one-piece, injection-molded plastic package for high reliability. The 2N3903 and 2N3904 are complementary with types 2N3905 and 2N3906, respectively.

MAXIMUM RATINGS ($T_A = 25°C$ unless otherwise noted)

Characteristic	Symbol	Rating	Unit
Collector-Base Voltage	V_{CB}	60	Vdc
Collector-Emitter Voltage	V_{CEO}	40	Vdc
Emitter-Base Voltage	V_{EB}	6	Vdc
Collector Current	I_C	200	mAdc
Total Device Dissipation @ $T_A = 60^oC$	P_D	210	mW
Total Device Dissipation @ $T_A = 25^oC$ Derate above 25^oC	P_D	310 2.81	mW mW/^oC
Thermal Resistance, Junction to Ambient	θ_{JA}	0.357	^oC/mW
Junction Operating Temperature	T_J	135	^oC
Storage Temperature Range	T_{stg}	-55 to +135	^oC

ELECTRICAL CHARACTERISTICS ($T_A = 25°C$ unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Collector-Base Breakdown Voltage ($I_C = 10\ \mu$Adc, $I_E = 0$)	BV_{CBO}	60	—	Vdc
Collector-Emitter Breakdown Voltage* ($I_C = 1$ mAdc)	BV_{CEO}*	40	—	Vdc
Emitter-Base Breakdown Voltage ($I_E = 10\ \mu$Adc, $I_C = 0$)	BV_{EBO}	6	—	Vdc
Collector Cutoff Current ($V_{CE} = 40$ Vdc, $V_{OB} = 3$ Vdc)	I_{CEX}	—	50	nAdc
Base Cutoff Current ($V_{CE} = 40$ Vdc, $V_{OB} = 3$ Vdc)	I_{BL}	—	50	nAdc

*Pulse Test: Pulse Width = 300 μsec, Duty Cycle = 2%

V_{OB} = Base Emitter Reverse Bias

2N3903, 2N3904 (continued)

ELECTRICAL CHARACTERISTICS (continued)

Characteristic		Symbol	Min	Max	Unit
ON CHARACTERISTICS					
DC Current Gain* ($I_C = 0.1$ mAdc, $V_{CE} = 1$ Vdc)	2N3903 2N3904	h_{FE}*	20 40	— —	—
($I_C = 1.0$ mAdc, $V_{CE} = 1$ Vdc)	2N3903 2N3904		35 70	— —	
($I_C = 10$ mAdc, $V_{CE} = 1$ Vdc)	2N3903 2N3904		50 100	150 300	
($I_C = 50$ mAdc, $V_{CE} = 1$ Vdc)	2N3903 2N3904		30 60	— —	
($I_C = 100$ mAdc, $V_{CE} = 1$ Vdc)	2N3903 2N3904		15 30	— —	
Collector-Emitter Saturation Voltage* ($I_C = 10$ mAdc, $I_B = 1$ mAdc) ($I_C = 50$ mAdc, $I_B = 5$ mAdc)		$V_{CE(sat)}$*	 — —	 0.2 0.3	Vdc
Base-Emitter Saturation Voltage* ($I_C = 10$ mAdc, $I_B = 1$ mAdc) ($I_C = 50$ mAdc, $I_B = 5$ mAdc)		$V_{BE(sat)}$*	 0.65 —	 0.85 0.95	Vdc
SMALL SIGNAL CHARACTERISTICS					
High Frequency Current Gain ($I_C = 10$ mA, $V_{CE} = 20$ V, f = 100 mc)	2N3903 2N3904	$\|h_{fe}\|$	2.5 3.0	— —	—
Current-Gain—Bandwidth Product ($I_C = 10$ mA, $V_{CE} = 20$ V, f = 100 mc)	2N3903 2N3904	f_T	250 300	— —	MHz
Output Capacitance ($V_{CB} = 5$ Vdc, $I_E = 0$, f = 100 kc)		C_{ob}	—	4	pf
Input Capacitance ($V_{OB} = 0.5$ Vdc, $I_C = 0$, f = 100 kc)		C_{ib}	—	8	pf
Small Signal Current Gain ($I_C = 1.0$ mA, $V_{CE} = 10$ V, f = 1 kc)	2N3903 2N3904	h_{fe}	50 100	200 400	—
Voltage Feedback Ratio ($I_C = 1.0$ mA, $V_{CE} = 10$ V, f = 1 kc)	2N3903 2N3904	h_{re}	0.1 0.5	5.0 8.0	$X10^{-4}$
Input Impedance ($I_C = 1.0$ mA, $V_{CE} = 10$ V, f = 1 kc)	2N3903 2N3904	h_{ie}	0.5 1.0	8 10	Kohms
Output Admittance ($I_C = 1.0$ mA, $V_{CE} = 10$ V, f = 1 kc)	Both Types	h_{oe}	1.0	40	μmhos
Noise Figure ($I_C = 100\ \mu$A, $V_{CE} = 5$ V, $R_g = 1$ Kohms, Noise Bandwidth = 10 cps to 15.7 kc)	2N3903 2N3904	NF	— —	6 5	db
SWITCHING CHARACTERISTICS					
Delay Time	$V_{CC} = 3$ Vdc, $V_{OB} = 0.5$ Vdc, $I_C = 10$ mAdc, $I_{B1} = 1$ mA	t_d	—	35	nsec
Rise Time		t_r	—	35	nsec
Storage Time	$V_{CC} = 3$ Vdc, $I_C = 10$ mAdc, $I_{B1} = I_{B2} = 1$ mAdc 2N3903 2N3904	t_s	— —	175 200	nsec
Fall Time		t_f	—	50	nsec

*Pulse Test: Pulse Width = 300 μsec, Duty Cycle = 2%

V_{OB} = Base Emitter Reverse Bias

Lab 1 Appendix A: Making AC voltage measurements

This is more relevant to previous year's labs which had older AC function generators, although it is still important to know in your electrical careers.

There are two ways of measuring AC voltage (which can be used to find AC currents). One method is to use the multimeter in AC voltage mode and measure across the device in mind. This reports the RMS voltage, and is accurate for low frequencies (up to 10 kHz).

Using the oscilloscope is a time intensive but more accurate method that is needed for higher frequency measurements. If we are measuring a voltage with respect to ground, we can simply place a scope probe on the net in question and observe the waveform in the scope. However, if we are measuring the voltage across a device where neither terminal is AC grounded, then it is more difficult. Some of the more obvious methods will not work:

- Using the multi-meter may not be accurate, as the multi-meter is not designed for high frequency measurements and the highly capacitive input impedance of the meter will short out the terminals you are measuring at high frequencies.
- Connecting a scope and its corresponding ground terminal across the device also will not work since the ground terminal of the probe is connected to the ground of the other probe and every other ground. This will short out the circuit.
- You also cannot measure one terminal to ground and then measure the other terminal to ground and subtract the results (as you would for DC). This is because there may be a phase shift between the nodes, even if the device you are measuring across is a resistor.

The **correct way to make the measurements** is to create a new waveform which shows the voltage difference between both terminals. To do this, perform the following steps:

1. Connect both probes, one at each end of the terminal. Make sure coupling mode is set to AC (Vertical → Menu → Coupling). Ensure that the waveforms are triggered properly (Trigger → Menu). If they are, then the waveforms will remain stationary on the display. Make sure both waveforms are displayed with a decent magnitude: not too small and not clipping. At least 1 period of each (preferably 2) should be visible.
2. Then we must tell the oscilloscope to display another waveform which shows the difference between both probes. Do this by pushing the MATH button and set the scope to do 2 channel operations and not FFT (this is located on the bottom left of the screen). Then use the buttons to select channel 1 and channel 2 as the sources (the operands), and set the operation to subtract. A red waveform appears which is either Ch1-Ch2 or Ch2-Ch1.
3. Use the measurement operations or the cursors as you normally would.
4. You can disable the red math channel by selecting the MATH button and turning the channel off.

For measurements of small magnitude (less than 50 mV peak-peak), we can improve accuracy significantly by averaging in the time domain. This reduces thermal the noise that the scope itself adds in due to its high resistance and large bandwidth.

Normally, the scope records a single sample, and immediately displays that value. Any noise that is sampled is also displayed. When in averaging mode, the scope records the last N samples for a given part of the display, and averages those and displays that. The signal magnitudes add up together in phase, while the noise on all of the measurements tends to cancel each other out. Note that if the signal is changing (some part of your circuit is modified, or improper triggering for instance) the averaged signal will take some time to change as the previous values and new values are averaged together.

To set the scope in averaging mode:

1. First make sure that the waveform you want to average is visible on the screen, is not too small or clipping, is triggered properly, and has several periods visible.
2. Press the "Menu" key in the acquire section of the scope (the rightmost column).

3. Select the “average” option on the bottom. To restore the scope into normal operation, use the “sample” option on the top.
4. When “Average” is selected, you can turn the dial on the top of the scope (the one next to the “select” and “coarse” buttons) to change the number of samples. Increasing the number of samples improves accuracy but takes longer- this is the tradeoff with all measurements. Realistically, only a few averages are necessary - accuracy goes up with the square root of the number of samples.

Note that when you make a change to the circuit, you will need to reset the scope’s built-in memory, so you don’t average the changed values with the previous values. You can do this by turning averaging off and then back on again. If your average is small enough, you don’t need to worry about this (the previous samples will be forgotten before you change the scope settings).