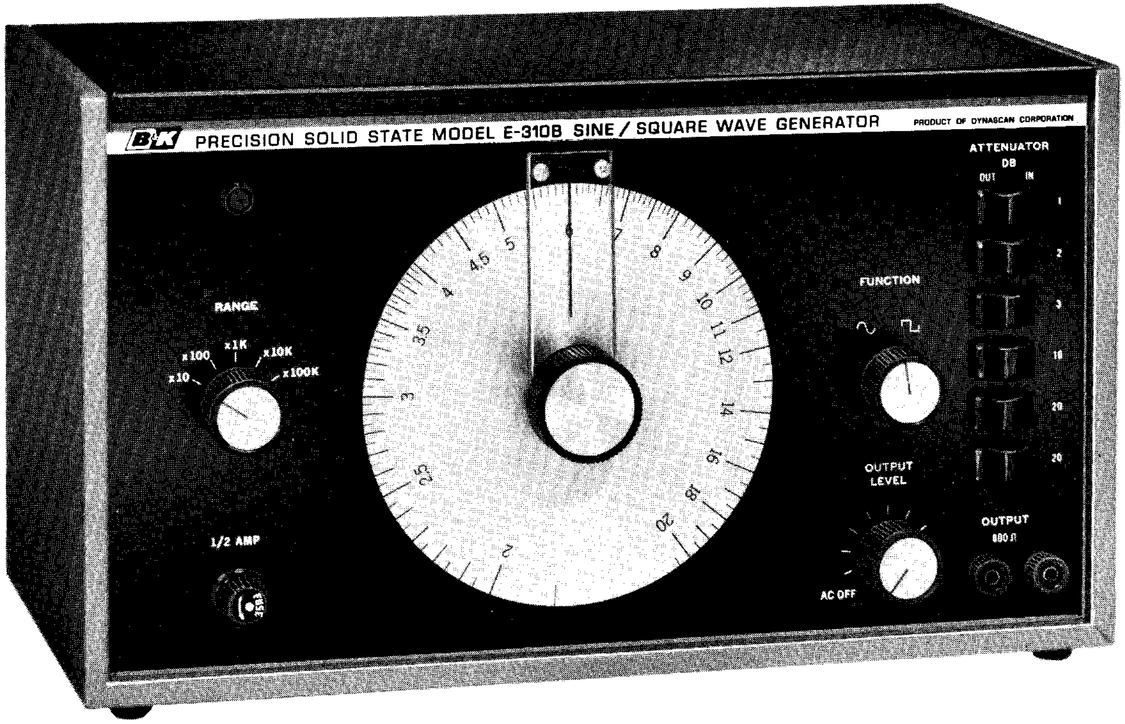
INSTRUCTION MANUAL

B+K PRECISION E-310B

Sine/Square Wave Generator



B+K PRECISION

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PRICE $5.00

B&K/PRECISION SOLID STATE MODEL E-301B
SINE/SQUARE WAVE GENERATOR

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INTRODUCTION

The B&K/Precision Model E-310B is a wide range audio generator which provides both sine and square wave outputs. Its dual function features have been designed to provide the most effective all-inclusive generator facilities for the laboratory and for the service technician. Its accuracy and wide-range output level make it suitable for most laboratory applications. Used in conjunction with the attenuators which provide up to 56 db attenuation, very accurate low-level calibrated outputs may be obtained. This feature is useful in making stage gain checks of all types of amplifiers which operate in the frequency range of 20 Hz to 2 MHz. The low distortion sine wave output may be used as a standard in testing frequency response of audio amplifiers, modulating r-f generators and many other applications. The extremely fast square wave rise time is ideal for rapid evaluation of audio amplifier characteristics, including frequency response, phase and frequency distortion, high and low frequency boost and attenuation. The overall performance of an amplifier can be analyzed with this instrument. The fine vernier tuning permits accurate resetting of the frequency dial. The all solid-state zener-regulated circuitry makes the instrument immune to frequency or output level variations due to line voltage fluctuations and provides excellent short term frequency stability.

The accurate step attenuators are an excellent means of calibrating oscilloscope vertical attenuators, while the overall frequency response of an oscilloscope can be evaluated by using the square wave output.

SPECIFICATIONS

SINE WAVE:

Frequency Range: 20 Hz to 2.0 MHz in 5 decade ranges: 20-200 Hz; 200 Hz to 2 KHz; 2-20 KHz; 20 KHz to 200 KHz and 200 KHz to 2 MHz.

Output: 0-7 volts RMS into high impedance loads; 0-6 volts RMS into 600 ohm.

Amplitude Variation: ± 2 db nominal, 25 Hz to 200 KHz.

Distortion: 0.25% typical; 0.5% maximum, 100 Hz to 200 KHz; 1% maximum, 25 Hz to 100 Hz.

SQUARE WAVE:

Frequency Range: 20 Hz to 200 KHz in 4 ranges: 20-200 Hz; 200 Hz to 2 KHz; 2-20 KHz; 20-200 KHz.

Output: 0-10 volts peak (nominal).

Rise Time: Less than 100 nanoseconds at 20 KHz.

Symmetry: Balanced within 5% or less; 20 Hz to 100 KHz.

FREQUENCY CALIBRATION ACCURACY: ±2%, 20 Hz to 2 MHz; or one cycle, whichever is greater.

ATTENUATORS: (Sine and square wave outputs). Total of 56 db in six steps (20 db, 20 db, 10 db, 3 db, 2 db and 1 db). Accuracy: ±5% when terminated in 600 ohm load.

Output Control: Adjust output for maximum to less than 0.25 millivolt when used with step attenuators.

POWER REQUIREMENTS: 110-130 volts, 50-60 Hz AC; 15 watts (Available for 120/240 volts, 50-60 Hz operation).

DIMENSIONS: 12¾ x 7¼ x 8" deep. Weight 10 lbs.

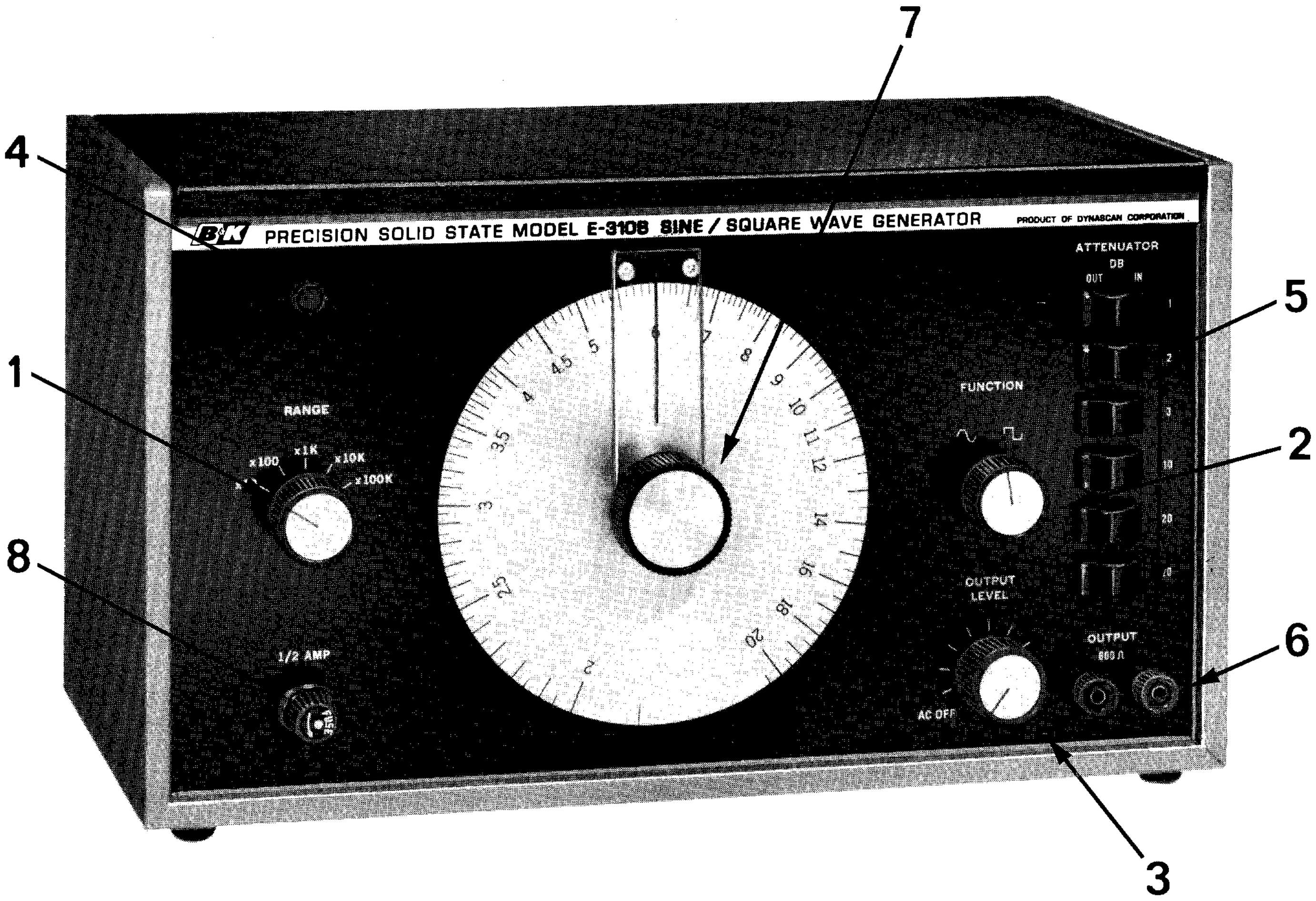


Figure 1. Front Panel Controls of E-310B

DESCRIPTION AND FUNCTION OF CONTROLS

1. RANGE SWITCH—Selects one of five frequency ranges for sine wave output and one of four frequency ranges for square wave output.

SWITCH POSITION	FREQUENCY RANGE
X10	20 Hz to 200 Hz
X100	200 Hz to 2 KHz
X1K	2 KHz to 20 KHz
X10K	20 KHz to 200 KHz
X100K	200KHz to 2 MHz (Sine wave only)

2. Sine (∿)/Square (⎍) Wave switch — Selects either sine wave or square wave output.
3. AC OFF/OUTPUT LEVEL—Turns unit on and off and provides a continuously variable output level adjustment.
4. Pilot Light—Indicates whether unit is on or off.
5. Step ATTENUATOR—Provides up to 56 db of attenuation in 6 steps when output is terminated into 600 ohms impedance. No fixed attenuation is provided when the ATTENUATOR switches are in the OUT position. When the switches are placed in the IN position, the indicated amount of attenuation is placed in series with the output signal. The total attenuation is the sum of attenuation levels indicated at the individual attenuator switches.

   Steps are: 20 db, 20 db, 10 db, 3 db, 2 db, 1 db. Each attenuator is not in the circuit when the switch is in the OUT position. Each attenuator is inserted into the circuit in the IN position of the switch. The total attenuation of the signal is the sum of all the attenuator switches in the IN position.
6. OUTPUT JACKS—The sine and square wave outputs are made available at these jacks.
7. Tuning Knob—Provides frequency selection from the frequency dial with a 12 to 1 reduction ratio.
8. Circuit Protection—Fuse accessible at front panel.

OPERATING INSTRUCTIONS

GENERAL

This section describes the basic operation of the front panel controls and the use of the attenuator network. Before the generator is connected to a circuit, the signal level normally present in the circuit to be tested should be determined in order to prevent possible damage to the circuit by excessively high level input signals. As a precaution, the OUTPUT LEVEL control should be set towards minimum and some of the ATTENUATOR switches placed in the IN position before connecting the generator. It is good practice to operate with some minimum amount of fixed attenuation.

If the point where the signal is to be injected has a d-c potential, a capacitor should be placed in series with the output of the generator to avoid loading d-c circuits with the low output resistance of the attenuator and to protect the attenuator network. The capacitor value should be determined by the input impedance of the circuit under test and by the frequency range to be investigated. If a low-frequency signal is injected into a low impedance circuit, a large coupling capacity should be used. To minimize amplitude-versus-frequency variations due to input coupling networks, the product of the capacitor value in microfarads times the amplifier input impedance in megohms should be about ten times the period of the lowest frequency used. For example, if 100 Hz (period is 1/100, or .01 second) is the lowest frequency to be used, and the amplifier input impedance is 100,000 ohms (0.1 megohm), then the coupling capacitor value should be selected to give a time constant of about 0.1 second (ten times the period of .01 seconds) as follows:

$$0.1 \text{ (Megohms)} \times C \text{ (Mfd)} = 0.1, \ \& \ C \text{ (Mfd)} = \frac{0.1}{0.1} = 1.$$

A coupling capacitor of about one microfarad should therefore be used.

Use shielded cable to connect the generator output to the circuit under test. This is especially important when making distortion measurements and stage gain checks, particularly at low frequencies and low output levels. Unshielded leads can be used when the generator is being used as a signal source for point-to-point signal tracing and other non-critical applications. A VTVM should be used to monitor the generator output level when performing response checks on low impedance, frequency-sensitive circuits to verify the signal level being injected into the circuit under test.

OPERATING PROCEDURE

To place the generator into operation proceed as follows:

1. Connect the generator to a 110-130 volts 50/60 Hz a-c source.
2. Set the RANGE switch to the desired frequency band. (Frequency dial numbers are multiplied by range switch setting; for example, 10 KHz = 10 on dial and X 1K range switch setting.)
3. Adjust frequency dial to desired setting.
4. Set SINE-SQUARE wave switch to desired waveform.
5. To turn unit on, rotate OUTPUT LEVEL control clockwise. This knob also controls the output level of the generator.
6. The instrument is now ready for use. With all the attenuator switches in the OUT position and the output level control fully clockwise, the signal level available at the output jacks is approximately 8.0 volts RMS (22.6 volts peak-to-peak) for sine wave signal, and 10 volts peak-to-peak for square wave signal. The output level control varies the signal level from near zero up to the maximum levels given. If some of the attenuator switches are placed in the IN position the signal level at the output jacks will be reduced or attenuated from maximum. For proper operation of the attenuator switches, the output of the generator should be terminated externally into 600 ohms. A 620 ohm resistor or two 1200 ohm resistors in parallel are suitable for this purpose. The attenuators are useful for reducing the total signal level available at the output jacks, and also for obtaining accurate low level signals which cannot be measured accurately on the a-c ranges of VTVM's and multimeters. This is useful when testing high gain amplifiers which require very low level input signals for proper output.

LOW LEVEL CALIBRATED OUTPUT LEVELS

It must be remembered that to obtain accurate outputs, the attenuator must be properly terminated as outlined above. To obtain low level calibrated outputs, the OUTPUT LEVEL control is set to a reference point with all the attenuators in the OUT position. Table 1 is a conversion of db to volts using 1 volt as a reference. With the attenuators in the OUT position a meter is connected across the output terminals and the output level control is adjusted for a meter reading of 1.0 volt. Placing attenuators in the IN position will reduce the signal at the output jacks to the values shown in Table 1. For example, with 20 db attenuation the output would be .1 volts; with 30 db attenuation the output would be 32 millivolts (.032 volts); with 54 db attenuation the output would be 2.0 millivolts. If a reference other than 1 volt is used, the output would be proportionally related to the values shown on Table 1. For example, if .5 volts reference is used, the output with 54 db attenuation would be 1.0 millivolt (half of 2.0 millivolts).

The ATTENUATOR switches can also be used to obtain approximate output level signals without measuring the output level each time the generator is used. With all the ATTENUATOR switches in the OUT position and the output terminated, a meter is connected across the OUTPUT terminals. The OUTPUT LEVEL control is rotated to maximum and the meter reading noted. This is the maximum signal level available at the generator OUTPUT terminals. Figure 2, Conversion of Voltage Ratios to DB, is then used to determine the amount of attenuation required to obtain lower signal levels. For example, if the maximum output of the generator is 7.0 volts RMS and a signal level of .5 volts RMS is desired, it is only necessary to divide 7.0 by .5 which gives a 14 to 1 ratio. From Figure 2, the number of decibels corresponding to a voltage ratio of 14 is 23 db, therefore, introducing 23 db attenuation will reduce the 7.0 volt signal to .5 volts. The graduated marking around the OUTPUT LEVEL control can also be used as reference for other than maximum output level settings; however, it must be remembered that the output level is not proportional to rotation of the output control when terminated into 600 ohms. The signal level at each graduation must be determined.

REFERENCE: 1 VOLT

DB	VOLTS	DB	VOLTS	DB	VOLTS	DB	VOLTS	DB	MILLI-VOLTS	DB	MILLI-VOLTS
—1	.89	—11	.28	—21	.089	—31	.028	—41	8.9	—51	2.8
—2	.79	—12	,25	—22	.079	—32	.025	—42	7.9	—52	2.5
—3	.71	—13	.22	—23	.071	—33	.022	—43	7.1	—53	2.2
—4	.63	—14	.20	—24	.063	—34	.020	—44	6.3	—54	2.0
—5	.56	—15	18	—25	.056	—35	.018	—45	5.6	—55	1.8
—6	.50	—16	.16	—26	.050	—35	.016	—46	5.0	—56	1.6
—10	.32	—20	.10	—30	.032	—40	.010	—50	3.2		

Table 1. Conversion of DB to Volts

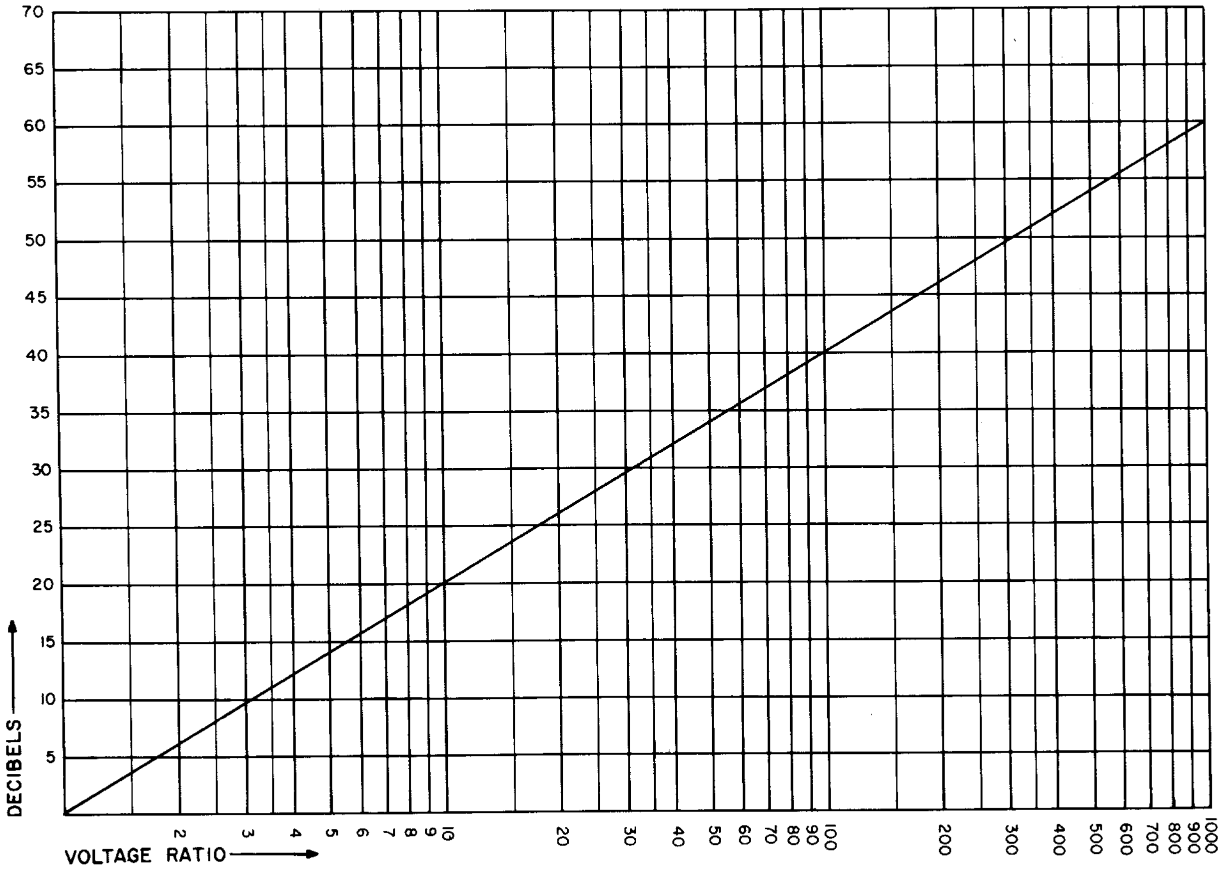


Figure 2. Conversion of Voltage Ratios to DB

CALIBRATION OF PEAK-TO-PEAK SQUARE WAVE AMPLITUDES

The attenuator network operation applies to sine wave and square wave signals. Sine wave signal levels can be determined using an a-c voltmeter of suitable accuracy and frequency range. The response of an a-c voltmeter to square wave input signals is dependent on the voltmeter design; therefore, a general statement regarding interpretation of a-c voltmeter readings with square wave input signals cannot be made. Peak-to-peak square wave levels can be determined as follows:

1. Use calibrated vertical attenuator of an oscilloscope, if provided.
2. If the oscilloscope does not have a calibrated vertical attenuator, the vertical amplifier of the oscilloscope should first be calibrated by using the sine wave signal output of the generator. The scope and a voltmeter are connected to the output of the generator and the OUTPUT LEVEL control on the generator is adjusted for a convenient reading on the voltmeter; for example, 10.0 volts peak-to-peak. If no peak-to-peak voltmeter scale is provided multiply the voltmeter RMS reading by 2.828.
3. The vertical gain control of the oscilloscope is then adjusted so that the sine wave pattern occupies a given number of divisions on the scope graticule. The peak-to-peak volts per division can then be determined. The generator is then placed in the square wave mode and the square wave peak-to-peak output level can be determined by using the calibration obtained with the sine wave signal.

   NOTE: If the low frequency response of the scope is not known the square wave output level calibration should be performed at a frequency of approximately 1 KHz.
4. After the square wave has been calibrated and the setting of the OUTPUT LEVEL control noted, the ATTENUATOR switches can be used to reduce the level of the square wave signal in the same manner as the sine wave is reduced.

TYPICAL APPLICATIONS

The overall performance of an audio amplifier can be evaluated by using the sine wave output signal from the generator. In order to arrive at valid conclusions when the amplifier is tested, it is necessary to know the manufacturer's specifications regarding bandwidth, maximum power output, maximum undistorted power output, input sensitivity, etc. The amplifier frequency response characteristic is usually presented as shown in Figure 3.

Care should be taken in interpreting the amplifier performance observations made with the scope and VTVM as these instruments may not have flat response characteristics over the frequency range to be investigated. This condition would give misleading indications of the true amplifier bandwidth. If the actual frequency response of the scope and VTVM is not known, the following test should be performed: with the generator terminated with 600 ohms, connect the VTVM and oscilloscope directly to the generator output terminals. Adjust the generator output to a convenient level as observed on the VTVM. If the VTVM has a db scale, adjust the generator output level for a convenient reference point, such as 0 db, —2 db, +1 db, etc. Place the generator RANGE switch in the ×10 position and rotate the tuning knob from the lowest frequency to the highest frequency of the dial and observe the variation in output level on the scope and VTVM. Repeat the procedure with the RANGE SWITCH in the X100 and X 1K positions. A log similar to that of Figure 4 can be constructed to record the response of the generator-VTVM combination. Although the generator has a response of ±1 db, output variations along with the meter response should be taken into consideration when making accurate bandwidth checks of amplifiers.

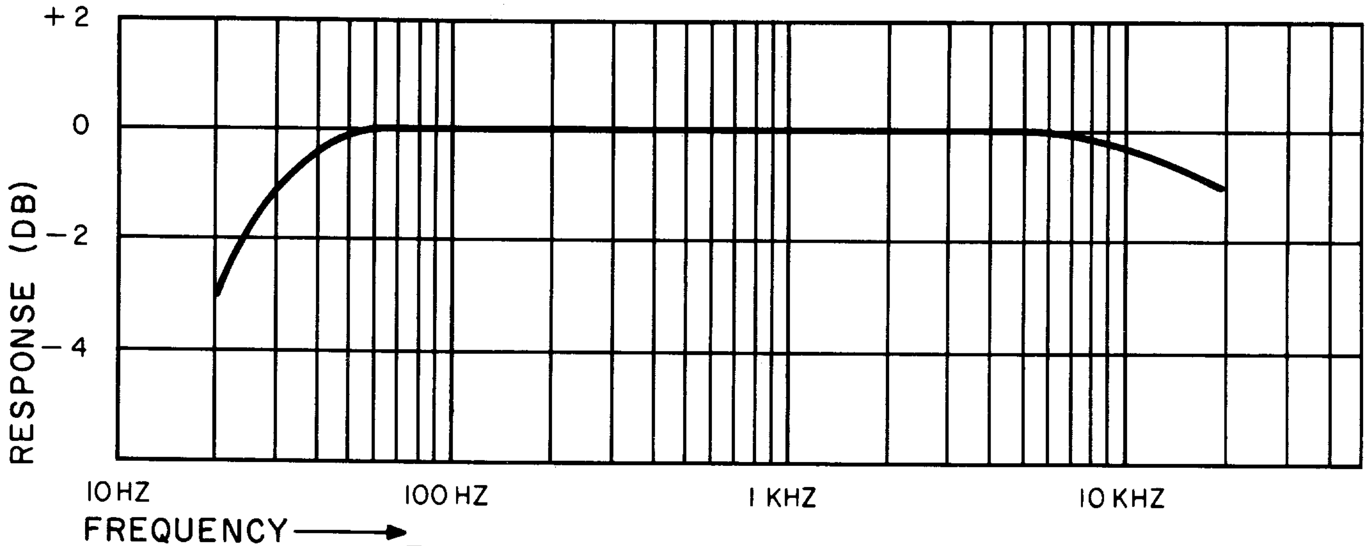


Figure 3. Typical Amplifier Response Curve

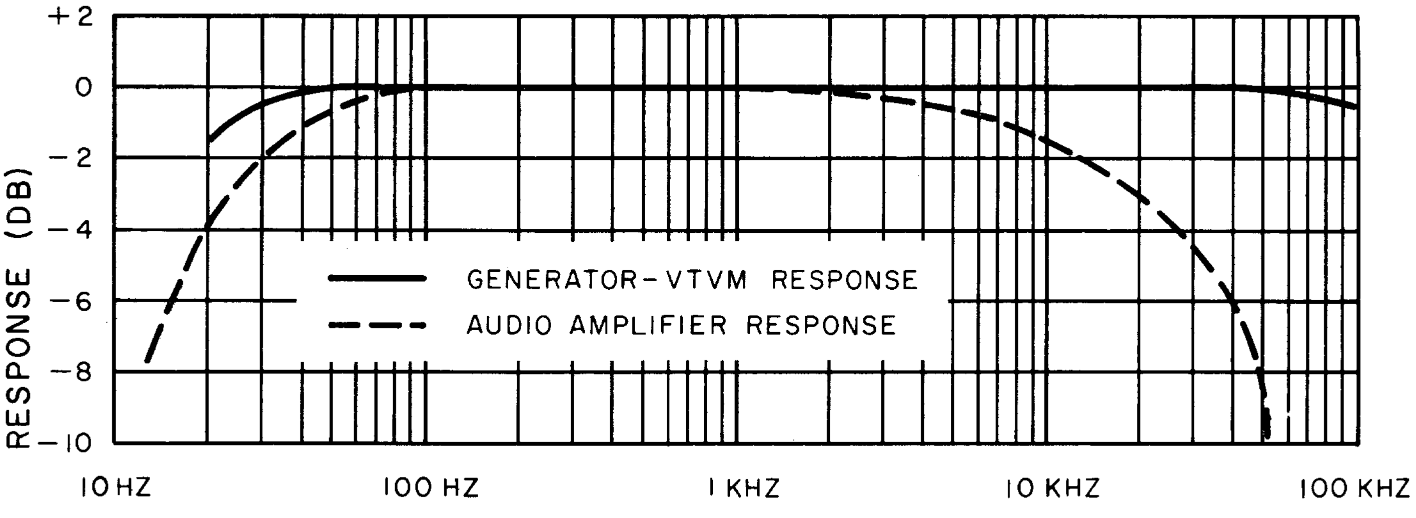


Figure 4. Comparison of Generator-VTVM and Audio Amplifier Response Curves

The roll-off of the generator-VTVM characteristic at low frequencies should be added to the amplifier response curve to give a better indication of the actual bandpass quality of the amplifier.

It should be noted that the setting of the bass and treble controls of the amplifier affect the frequency response of the amplifier. Figure 5 illustrates the response curves that may be obtained with settings of the bass and treble controls at minimum, mid-range and maximum.

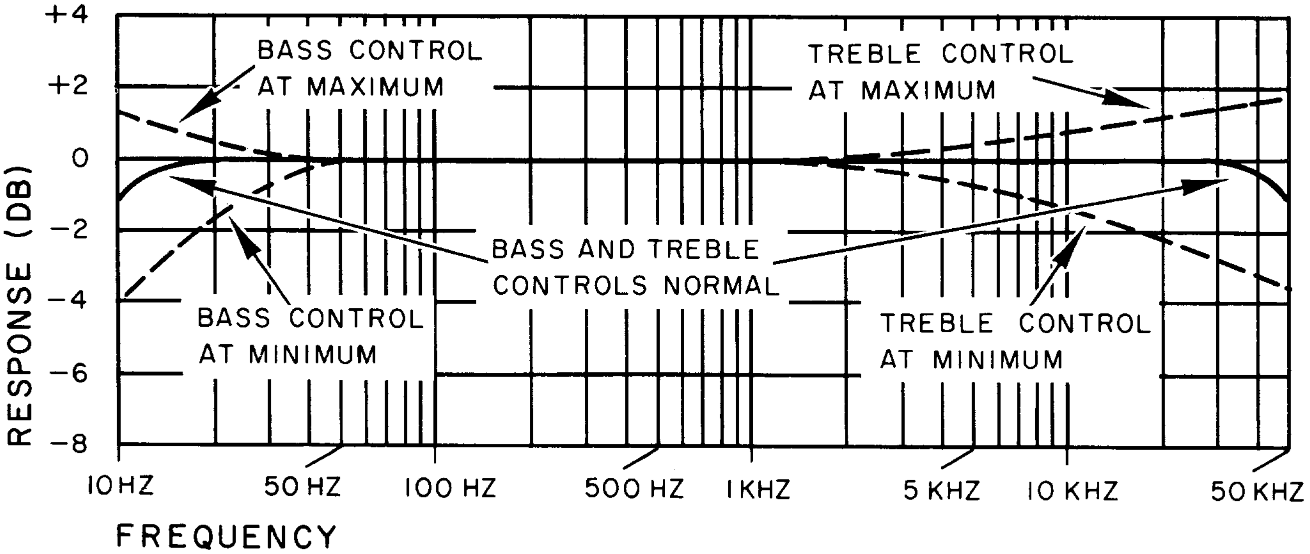


Figure 5. Effect of Base and Treble Controls on Amplifier Response

MEASUREMENT OF AMPLIFIER FREQUENCY RESPONSE AND HARMONIC DISTORTION

(See Figure 6.)

To check harmonic (non-linear) distortion in an amplifier, a distortion analyzer is connected to the amplifier output. The distortion introduced by the amplifier can be evaluated at various frequencies through the audio range. A scope may be also connected to the amplifier output (in parallel with the distortion analyzer) to determine if the distortion is due to the amplifier being overloaded which will result in clipping of the output waveform.

Proceed as follows:

1. Connect the generator to a 117 V AC 50/60 Hz power source and rotate the AC OFF/OUTPUT LEVEL control clockwise to turn unit on. Generally, the signal level input to an amplifier is very low; therefore, the ATTENUATOR network should be used as described earlier to preset signal levels to prevent possible damage to amplifier input circuits, particularly if solid state. The manufacturer's specifications on input signal level should be used as a guide in determining the amount of fixed attenuation to be introduced in the signal path.
2. The RANGE switch and frequency dial should be adjusted to obtain a frequency in the mid-range of the amplifier bandwidth. In wideband audio amplifiers 1000 Hz is usually used as a reference frequency.
3. Place the waveform switch to the Sine (∿) position.
4. Before connecting the generator to the amplifier, disconnect the speakers, if any, and connect a load resistor of suitable value to the amplifier output terminals. The resistor value in ohms should match the amplifier output terminal impedance to which connected; e.g.: 4 ohms, 8 ohms, 16 ohms. The wattage of the load resistor should be equivalent to the power output of the amplifier.
5. Adjust the OUTPUT LEVEL control to minimum and connect the generator output to the amplifier input. Always connect the ground lead of the generator to the amplifier ground point before connecting the signal lead. Connect an oscilloscope and a VTVM across the amplifier output load resistor. Set the amplifier volume control and the bass and treble controls, if provided, to midrange.
6. Adjust the OUTPUT LEVEL control on the generator and the volume control of the amplifier until a meter reading is obtained and a pattern is seen on the scope. Then adjust the input level to obtain the desired output test signal level. It may be desired to test at maximum rated power output or at a reduced listening level.

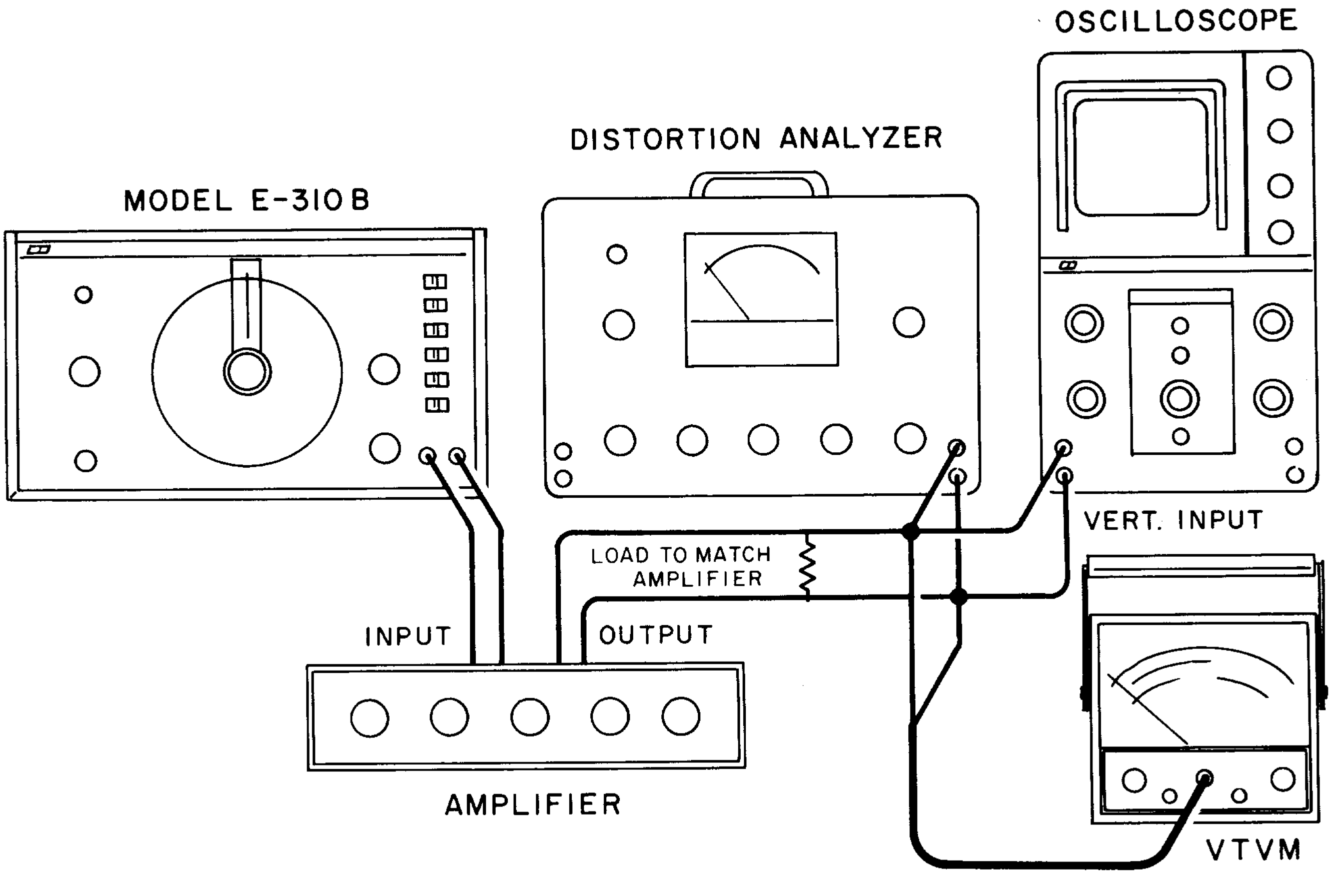


Figure 6. Typical Setup for Audio Amplifier Frequency Response and Distortion Measurements.

7. Adjust the setting of the amplifier volume control to obtain the desired output level as indicated by the voltmeter across the load resistor. To determine the power output being delivered by the amplifier use the formula

$$P = \frac{E^2}{R}$$

where E is the VTVM reading in rms volts and R is the value of the load resistor in ohms. The voltage level required for a desired power output can be determined by using the expression

$$E = \sqrt{PR.}$$

8. Adjust the generator RANGE switch and frequency dial over the frequency bandwidth of the amplifier and observe the variations in VTVM reading. The VTVM db scale is very convenient for observing amplifier output variations.
9. Use the distortion analyzer to determine distortion at various frequencies in the amplifier band.
10. The oscilloscope is useful in analyzing distortion, particularly overload clipping when the amplifier is operating at, or in excess of, rated power.

It should be noted at this point that although the point-by-point sine response curve as portrayed in Fig. 3 provides an accurate panoramic view of amplifier response, such a characteristic does not tell the complete story which will include the element of phase distortion. The technique of Square Wave testing, covered later in this manual, provides the required sensitive indication of phase relationships.

The generator becomes a useful trouble-shooting tool when it is used to locate defective frequency selective circuits in medium and wide-band amplifiers. A low frequency check (applying generator to input and oscilloscope to output) may indicate the output to be significantly greater than the same identical check at for example 500 Hz or a higher frequency.

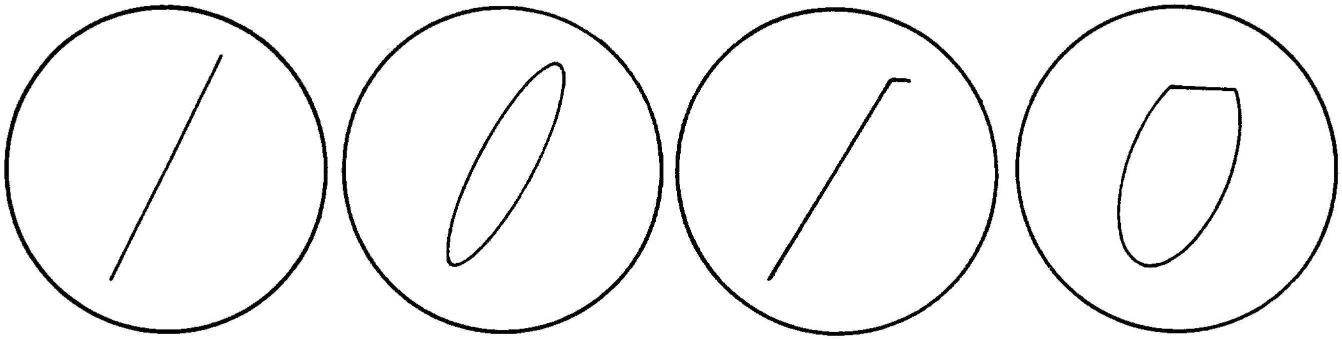
In this case the generator is being used to indicate the nature of the trouble. From then on the experience and background of the technician will assist in locating the exact trouble spot itself.

PHASE SHIFT ANALYSIS

The sine wave output can be used in some cases to determine the degree of phase shift in an amplifier at a particular frequency as follows (See Figure 7):

1. Set the sine output of the generator to the desired frequency.
2. Set the OUTPUT LEVEL control to maximum position and apply the generator output directly to the vertical plates of an oscilloscope.
3. Construct a simple resistive voltage divider by connecting a 2000-ohm potentiometer across the output of the generator. Feed the voltage developed across the arm of the potentiometer and ground to the input of the amplifier under test. Set the potentiometer for minimum voltage consistent with a sizeable oscilloscope pattern.
4. The output of the amplifier is fed directly to the horizontal plates of the oscilloscope. The resulting oscilloscope waveform will display an elliptical form should phase distortion in the amplifier exist at the test frequency. The degree of phase shift is, of course, indicated by the shape of the elliptical pattern. Top or bottom flattening of the elliptical shape indicates overloading produced by excessive input to the amplifier. Reduce input level as required by adjustment of the potentiometer divider to eliminate overload.

NOTE: The Vertical and Horizontal amplifiers of the oscilloscope are avoided in this example in order to eliminate whatever small degree of phase shift is inherent in their design. If the oscilloscope is known to have identical vertical and horizontal amplifier characteristics, the amplifiers may be used rather than connecting directly to the plates.



In-phase (or 180° out of phase) - no overload distortion

Phase shift - no overload distortion

In phase and overload distortion

Phase shift and overload distortion

Figure 7. Phase Shift and Overload Distortion Analysis.

EVALUATION OF SPEAKER SYSTEMS

The generator becomes especially useful when it is applied to the correction of the usual mismatch between the loudspeaker in audio systems and the loudspeaker enclosure itself.

In most instances the commonly encountered "boomy" bass response of commercial speaker-enclosure combinations can be transformed into smooth natural response which is characteristic of the well designed and adjusted audio system.

A brief method of checking a bass reflex speaker system is detailed as follows:

1. Select the sine wave output of the E-310B and connect in series with a 100 ohm resistor to the speaker voice coil.
2. Connect an a-c voltmeter or oscilloscope across the speaker voice coil.
3. Determine the two low frequency resonant peaks in the system by noting peak voltmeter readings. The frequency of these peaks will vary with the size of the speaker and cabinet but should occur in the region between 40 and 150 cycles. In a properly tuned system the two peaks should be rather broad and of approximately the same amplitude. If one of the peaks is greater than the other, try damping the port with additional layers of grille cloth.

Other applications of the instrument will suggest themselves to the technician and engineer in the course of test and design of electronic equipment. A few examples are: use of the generator to externally modulate r-f generators over a wide range of frequencies; to externally power impedance bridges at frequencies other than those provided internally; direct check of loudspeaker operation, using matching transformers where required; check of record equalization positions on preamplifiers; source of potential for capacitance checks using a capacitative divider and an a-c VTVM.

SQUARE WAVE APPLICATION NOTES

GENERAL

The square wave output of the generator can be used to display various types of distortion present in electronic circuits. A square wave of a given frequency contains a large number of odd harmonics of that frequency. If a 500 Hz square wave is injected into a circuit, frequency components of 1.5 KHz, 2.5 KHz, 3.5 KHz, are also provided. Since vacuum tubes and transistors are non-linear, it is difficult to amplify and reproduce a square wave which is identical to the input signal. Interelectrode capacitances, junction capacitances, stray capacitances as well as limited device and transformer response are a few of the factors which prevent faithful reproduction of a square wave signal. A well designed amplifier can minimize the distortion caused by these limitations. Poorly designed or defective amplifiers can introduce considerable distortion to the point where their performance is unsatisfactory.

As stated before, a square wave contains a large number of odd harmonics By injecting a 500 Hz sine wave into an amplifier we can evaluate amplifier response at 500 Hz only, but by injecting a square wave of the same frequency we can determine how the amplifier would respond to input signals from 500 Hz up to the 15th or 21st harmonic.

The need for square wave evaluation becomes apparent if we realize that some audio amplifiers will be required during normal use to pass simultaneously a large number of different frequencies. With a square wave we have a controlled signal with which we can evaluate the input and output quality of a signal of many frequencies (the harmonics of the square wave) which is what the amplifier sees when amplifying complex waveforms of musical instrument or voices.

The square wave output of the generator is extremely flat and it will not contribute to any distortion that may be observed when evaluating amplifier response; however, the scope used in conjunction with the generator must first be checked to determine its response and the amount of distortion it will introduce into the observations made. A d-c coupled oscilloscope should be used if available as it will introduce the least distortion, especially at low frequencies. When checking amplifier response, the frequency of the square wave input should be varied from the low end of the amplifier bandpass up toward the upper end of the bandpass; however, because of the harmonic content of the square wave, distortion will occur before the upper end of the amplifier bandpass is reached.

It should be noted that the actual response check of an amplifier should be made using a sine wave signal. This is especially important in limited bandwidth amplifiers (voice amplifiers). The square wave signal provides a quick check of amplifier performance and will give an estimate of overall amplifier quality. The square wave will also reveal some deficiencies not readily apparent when using a sine wave signal. Whether a sine wave or square wave is used for testing the amplifier, it is important that the manufacturer's specifications on the amplifier be known in order to make a better judgment of its performance.

A detailed discussion of the theory and use of square wave signals in amplifier testing is given in the following section.

SQUARE WAVE THEORY AND APPLICATION NOTES

ANALYSIS OF A SQUARE WAVE

The square wave output of the E-310B can be utilized to graphically display and reveal various types of distortion in electronic circuits. However, before attempting to correlate circuit analysis with square wave shapes, it might be well to establish the make-up and significance of the square wave itself. A theoretically perfect square wave can be considered to be comprised of an infinite series of sine waves. This statement is an expression of Fourier's Theorem which says that ANY SINGLE-VALUED CONTINUOUS PERIODIC QUANTITY CAN BE EXPRESSED AS AN INFINITE SERIES OF SINE WAVES. More specifically, in the case of the square wave, the wave is made up of a large number of odd harmonics (1st, 3rd, 5th . . . etc.).

Figure 8 illustrates the basic make-up of a square wave. All odd numbered harmonics are shown in in-phase relationship, i.e., each sine wave in the series begins its cycle at the beginning of the square wave cycle. To develop the square wave in Figure 8, it is merely necessary to draw a number of vertical lines thru the square wave and to add, algebraically (observing polarity), the magnitudes of the sine waves along this vertical line. For simplicity, we only consider the harmonic content up to the 9th harmonic in order that the sketches be made sufficiently illustrative.

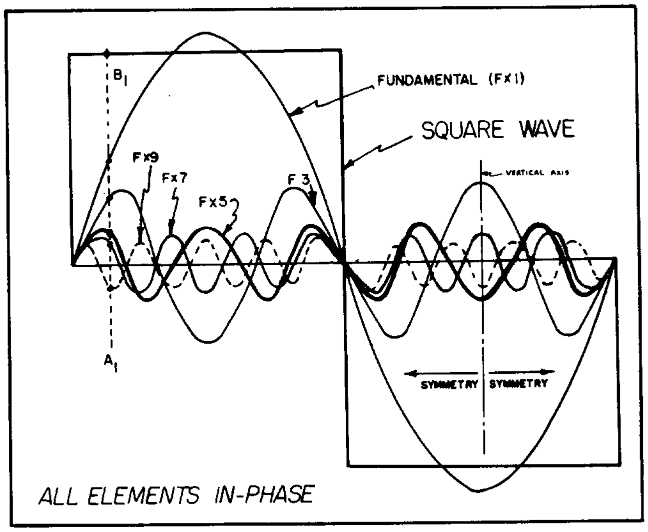


Figure 8. Make-up of a Square Wave.

At A_1 for example, we have algebraically added the fundamental, 3rd, 5th, 7th and 9th harmonic with the resultant summation at point B_1. If we repeat this same algebraic summation of wave magnitudes along a large number of vertical check lines such as A_1, we will obtain a resultant wave shape which will turn out to be the square wave which we had started out to analyze.

This graphical analysis over ½ cycle immediately reveals a striking symmetry to the left and right of the vertical axis for all harmonics. All harmonic wave trains are seen to begin the ½ cycle at zero amplitude and to end the ½ cycle at zero amplitude with the proper symmetry to left and right of the vertical axis to "build up" equally both corners of one-half cycle of the resultant square wave. If even-numbered harmonic waveshapes (2nd, 4th, 6th, etc.) were introduced into the content of a square wave, distortions of the square wave would be produced because of its non-symmetrical contributions of a ½ cycle of the square wave.

If all sine components of the square wave are beginning the ½ cycle at zero amplitude, they are in phase. In a well proportioned and shaped square wave we then have a whole series of sine waves varying in frequency from low to very high, all in phase and all in a related ampiltude. The amplitude of any particular harmonic is in inverse relationship to the order of the harmonic. In other words, the 3rd harmonic content has an amplitude one-third that of the fundamental component, etc.

Fourier's Theorem indicates the amplitude relation by the fraction preceding each mathematical expresssion for the harmonic element as noted in Figure 9.

$$Y = \frac{4}{\pi} E \; \overbrace{\text{SIN } X}^{\text{FUNDAMENTAL}} + \overbrace{1/3 \text{ SIN } 3X}^{\text{3RD HARM}} + \overbrace{1/5 \text{ SIN } 5X}^{\text{5TH HARM.}} + \overbrace{1/7 \text{ SIN } 7X}^{\text{7TH HARM}} + \ldots$$

$$\ldots.(\text{COS } X - 1/3 \text{ COS } 3X + 1/5 \text{ COS } 5X \ldots.)$$

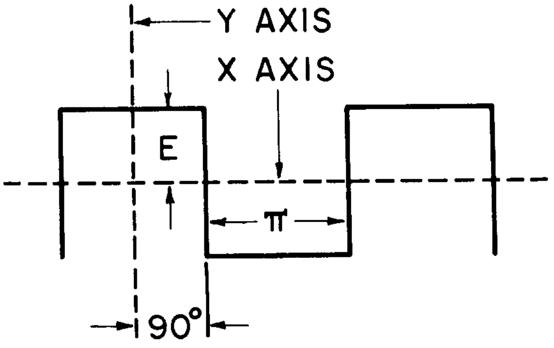


Figure 9. Fourier's Mathematical Description of a Square Wave.

When we apply a well-shaped square wave to the input of, for example, a wide band amplifier, we are in effect applying a large number of sine waves which must pass through the amplifier in the same phase relationship and with the same relative amplitude in order that the output of the amplifier be a faithful reproduction of the square wave applied to the input of the amplifier.

Continuing with the analysis of the Square Wave itself, we see that Figure 8 cannot begin to illustrate the practically infinite number of harmonics which constitute a sharp square wave. But if one takes Line A_1 of Figure 8 and imagines the presence of in-phase harmonics as high as the 100th or 500th and if we understand that we are to add all components to locate the resultant point on the square wave which is produced, we begin to see that a good square wave may start at ½ cycle at zero amplitude but it builds up to maximum amplitude in a very small fraction of the ½ cycle (practically instantaneously). This build-up from 10% above zero amplitude to 90% of maximum amplitude is appropriately termed rise-time of the square wave and is an important factor in the composition of the square wave.

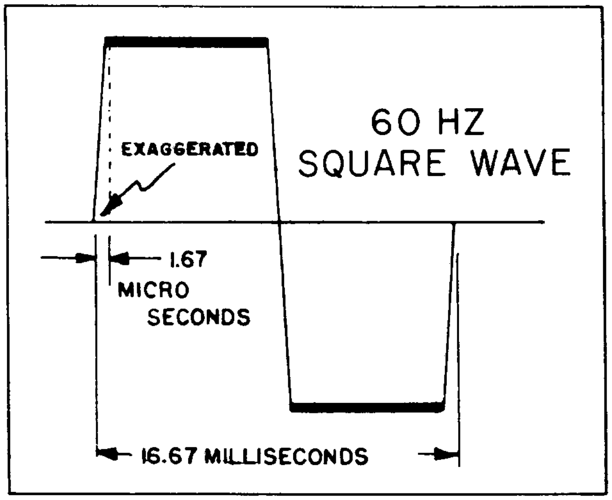


Figure 10. Square Wave Rise Time

If we consider the time axis of Figure 10 which illustrates a 60 Hz square wave, we see that the basic alternation of the waveshape is 60 Hz, but if we look closely we see that the fast rise of amplitude from zero to maximum occurs in far less time than one-sixtieth of a second and actually constitutes a relatively high frequency alternation. This leading edge of a square wave which includes the duration of the rise time is a sensitive indication of the high frequency characteristic of the circuit to be tested.

In Figure 8 we see that the shape of the flat top portion of the ½ cycle is influenced most strongly by the low order harmonics, i.e., 3rd, 5th, etc. Should the amplitude of the fundamental, for example, be reduced below the value required for good square wave shape, a curvature appears along the square wave top as illustrated in Figure 11. This may occur in a frequency selective circuit. On the other hand, in a theoretical case, a reduction in amplitude alone of the high frequency components would have no noticeable effect on the flat top because of the "balancing-out" effect created by the multiplicity of alternations along the flat top as indicated in Figure 12.

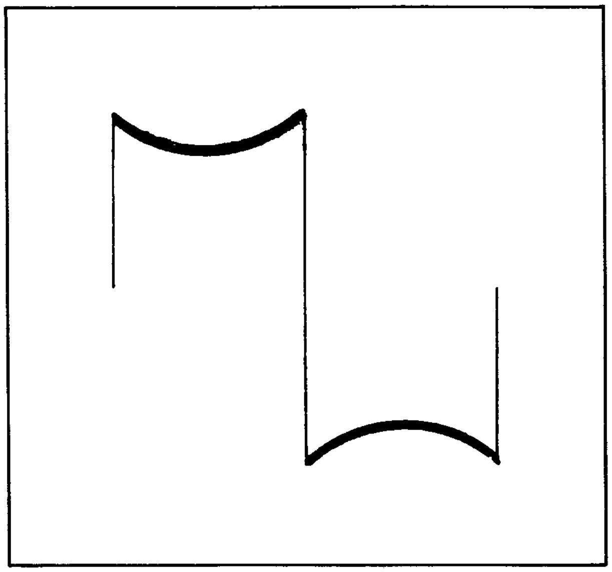


Figure 11. Reduction of Square Wave Fundamental Frequency Component in a Tuned Circuit.

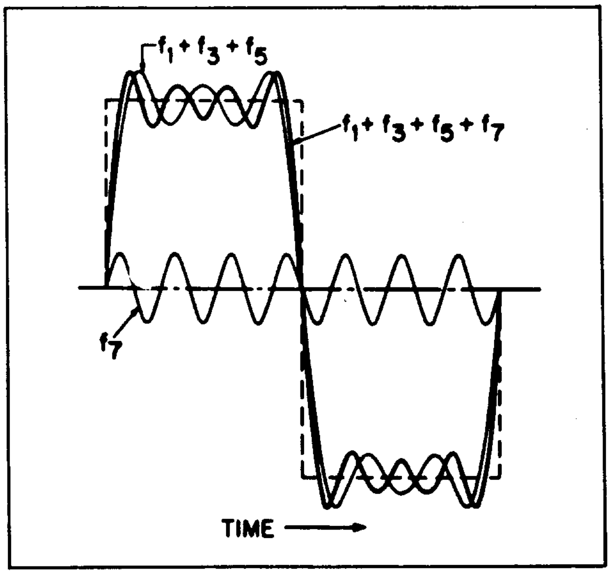


Figure 12. Loss of High Frequency Components of a Square Wave

We have already noted that the short rise time which occurs at the beginning of the ½ cycle is created by the in-phase sum of all the medium and high frequency sine wave components. The same holds true for the rapid drop at the end of the ½ cycle from maximum amplitude to zero amplitude at the 180° or ½ cycle point. Therefore, a theoretical reduction in amplitude alone of the high frequency components should produce a rounding of the square corners at all four points of one square wave cycle (See Figure 13).

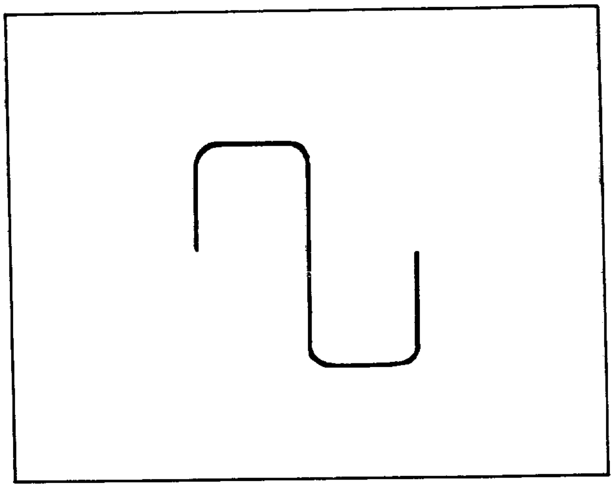


Figure 13. Square Wave Response With High Frequency Losses.

Thus far we have indicated that a useful square wave has fast rise time and well-squared proportions. Inasmuch as the square wave is to be observed on an oscilloscope, it might be wise to interpret the appearance of a square wave at various fundamental frequencies. If we first observe a 50 KHz square wave directly on a wide-band oscilloscope, we will probably notice a fairly sharp rise time. (See Figure 14.) A 50 KHz square wave has a 20-micro-second duration for one cycle. The rise time in this case might be .05 microsecond or one four-hundredth of one cycle. On this basis, if we should decide to establish a ratio between square wave cycle and rise time of 400 to one, we would find that a similarly shaped 80 Hz square wave with the same relatively sharp rise time would have a rise time of 31 microseconds, but would be perfectly usable at an 80 Hz fundamental square wave frequency.

It becomes evident that the value of rise-time cannot be quickly determined by the appearance alone of the waveshape on the oscilloscope. A 60 Hz square wave with a 15-microsecond rise time will appear to have shorter rise time than a 50 KHz square wave with a .05 microsecond rise time. (See Figures 14 and 15.).

The basic operation of the oscilloscope itself contributes to misleading appearance of rise time. To observe a single cycle of square wave at 30 KHz the oscilloscope beam is travelling at a relatively fast rate and the rise time portion of the trace is being traced by the oscilloscope beam many more times per second as compared to a 60 Hz square wave; for example, the rise time portion of the 60 Hz square wave may then appear extremely sharp, being practically invisible, wherein the rise time of the 30 KHz square wave may show relatively bright and thereby appear to be much slower than it really is.

At this point, it would be helpful to establish the relationship between rise time and the amplifier bandwidth required to transmit the leading edge of the square wave: Any cyclic time duration per cycle can be converted to frequency in Hertz as follows:

$$\text{A. Frequency in Hz} = \frac{1 \times 10^6}{\text{Time in Microseconds for one cycle}}$$

OR

$$\text{B. Time in Microseconds for one cycle} = \frac{1 \times 10^6}{\text{Frequency in Hz}}$$

If we substitute .05 Microseconds in the denominator of "A", frequency becomes 20 Megahertz.

However, it is generally recognized that if we are dealing with the special case of rise time of a square wave, the expression becomes:

$$F = \frac{1 \times 10^6}{2T} = \frac{1 \times 10^6}{2 \times .05\mu s.} = 10 \text{ MHz.}$$

or a minimum bandwidth of 10 MHz is required to satisfactorily transmit the leading edge of a square wave with .05 microsecond rise time.

It is significant to note that the rise time portion of the square wave determines the bandwidth required to faithfully reproduce the square wave. Should one square wave be twice the fundamental frequency of another, but both have the same rise time, then the same bandwidth (determined by the rise time) will be required by both for accurate reproduction.

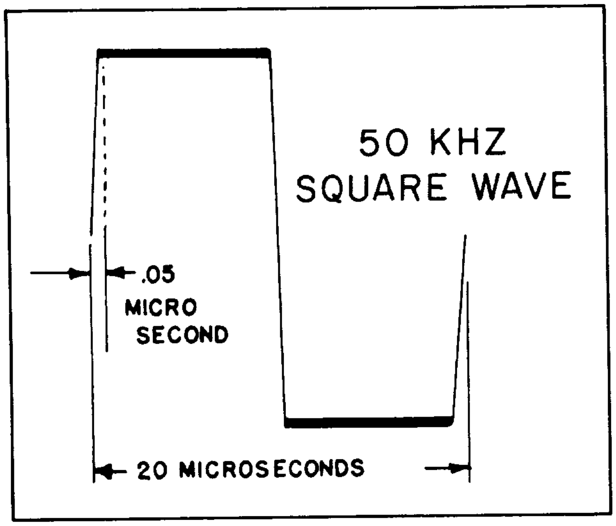


Figure 14. Rise Time of a 50 KHz Square Wave

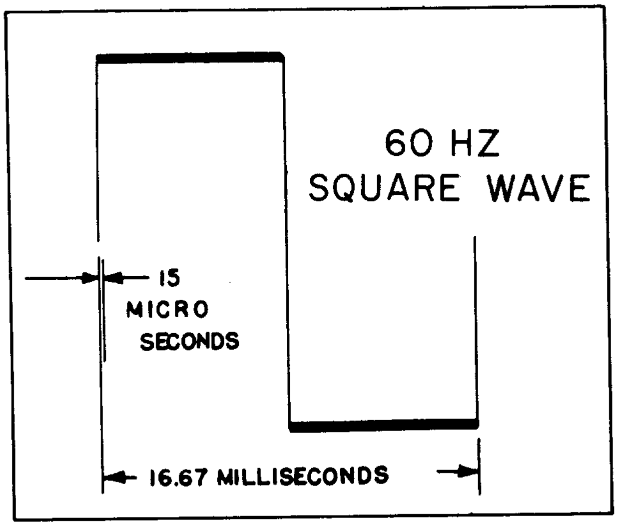


Figure 15. Rise Time of a 60 Hz Square Wave

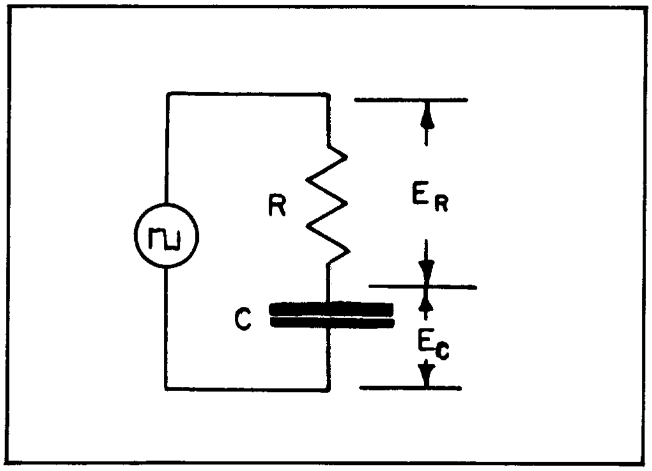


Figure 16. Applying a Square Wave to an R-C Circuit

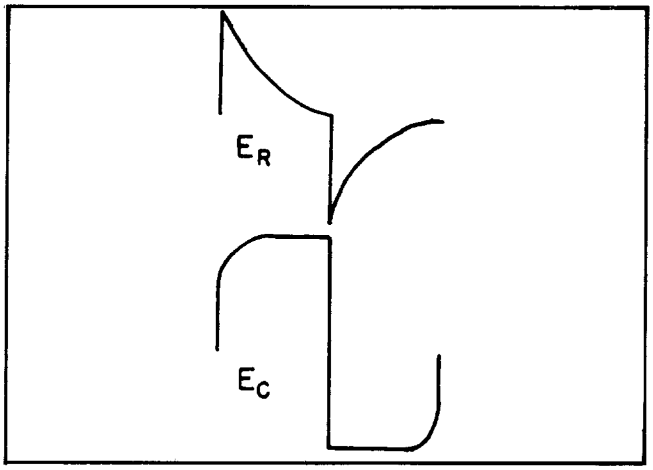


Figure 17. Comparison of Wave Forms Across R and C.

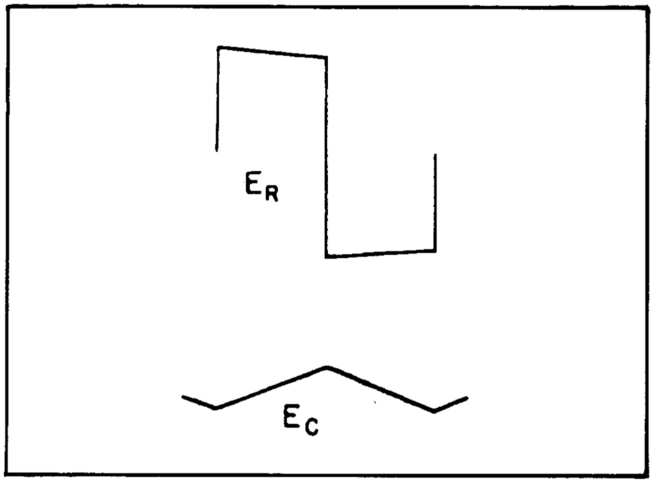


Figure 18. Waveforms Across R and C Using a High Frequency Square Wave

The preceding discussion leads us to the conclusions that a good square wave can be faithfully transmitted through an amplifier or network only if the network does not selectively suppress the amplitude of a harmonic or harmonics; does not shift the relative phase of a harmonic or harmonics; and does have sufficiently wide bandwidth (in the case of an amplifier) to permit accurate reproduction of the rise time portion of the cycle.

Inasmuch as minor deviations from the above requirements result in distortion of the square wave, we are logically led into a discussion of the interpretation of square wave distortions and their significance. As an example, let us take a simple RC circuit energized by a square wave potential. If time duration of a cycle of the square wave is quite long as compared to the time constant (R in megohms x C in microfarads) of the RC network shown in Figure 16, then we can say we are applying a relatively low frequency square wave to the network. In such a case, the waveform across C would appear as E_C in Figure 17 and the wave form across R would appear as E_R in Figure 17.

If we consider the RC network as a simple filter, then we can analyze the rounded corners of E_C in Figure 17 as an indication of high frequency component attenuation. In other words, the reactance of the capacitor at the higher component frequencies becomes lower, dividing down the higher components. Conversely most of these higher components now appear across R, producing the excellent leading edge for E_R, Figure 17.

Now, if we change the frequency of the square wave such that the time duration of a cycle is relatively small as compared to the RC time constant, then we can say that we are applying a higher frequency square wave to the network. In such a case, the waveform across C might appear as E_C in Figure 18.

Continuing the filter analysis, E_C of Figure 18 results from the fact that the relative reactance of C is low for all frequencies of the square wave inasmuch as we are applying a relatively high-frequency square wave to begin with. Therefore, the voltage across C shows poor high and low frequency response. E_R of figure 18 indicates the divider action of the filter which produces relatively low reactance for the highs and lows and results in the appearance of these components across R.

GENERAL SQUARE WAVE TESTING

Distortion can be classified into three distinct categories:

1. The first is frequency distortion and refers to the change from normal amplitude of a component of a complex waveform. In other words, the introduction in an amplifier circuit of resonant networks or selective filters created by combination of reactive components will create peaks or dips in an otherwise flat frequency response curve.
2. The second is non-linear distortion and refers to a change in waveshape produced by application of the waveshape to non-linear components or elements such as vacuum tubes, an iron core transformer, and in an extreme case a deliberate non-linear circuit such as a clipper network.
3. The third is delay or phase distortion, which is distortion produced by a shift in phase between one or more components of a complex waveform.

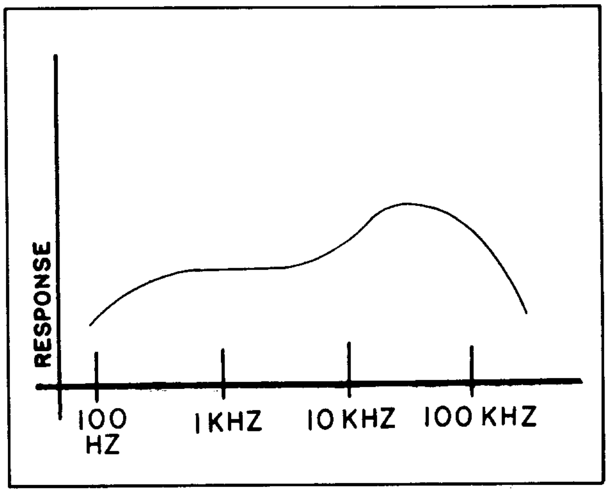


Figure 19. Response of Amplifier Having Poor Low Frequency Response and High Frequency Boost

In the examples used up to this point, we discussed amplitude reduction of a particular component in a square wave as though it occurred independently of phase distortion or was produced by a non-linear element. In actual practice, however, a reduction in amplitude of a square wave component (sinusoidal harmonic) is usually caused by a frequency selective network which includes capacity, inductance or both. The presence of the C or L introduces a difference in phase angle between components creating phase distortion or delay distortion. Therefore, in square wave testing of practical circuitry, we will usually find that the distorted square wave includes a combination of amplitude and phase distortion clues.

If we now proceed to the application of square waves to a typical wide band amplifier, we find that a square wave check accurately reveals many distortion characteristics of the circuit. The response of an amplifier is indicated in Figure 19, revealing poor low frequency response along wth overcompensated high frequency boost. A 100 Hz square wave applied to the input of this amplifier will appear as in Figure 20A. This figure indicates satisfactory medium frequency response (approximately 1 KHz to 2 KHz) but shows poor low frequency response. Next, a 1000 Hz square wave applied to the input of this same amplifier will appear as in Figure 20B. This figure displays good frequency response in the region of 1000 to 4000 Hz but clearly reveals the overcompensation at the higher 10 KHz region by the sharp rise at the top of the leading edge of the square wave.

As a rule of thumb, it can be safely said that a square wave can be used to reveal response and phase relationships up to the 15th or 20th odd harmonic or up to approximately 40 times the fundamental of the square wave. Using this rule of thumb, it is seen that wide band circuitry will require at least a two-frequency check to properly analyze the complete spectrum. In the case illustrated by Figure 19, a 100 Hz square wave will encompass components up to about 4000 Hz. To analyze above 4000 Hz and beyond 10,000 Hz, a 1000 Hz square wave should be satisfactory.

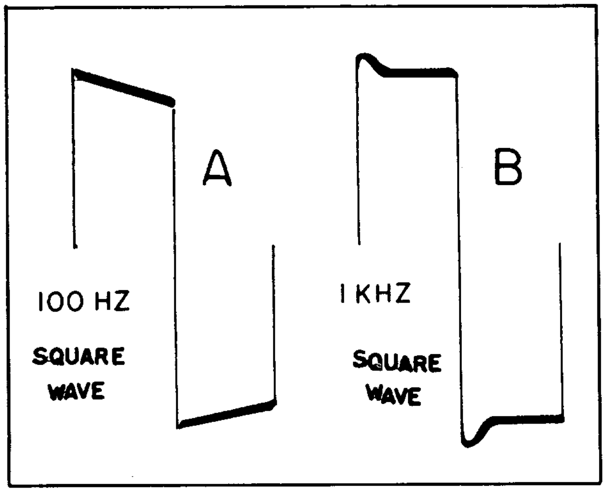


Figure 20. Resultant 100 Hz and 1 KHz Square Waves From Amplifier in Figure 18.

Now, the region between 100 Hz and 4000 Hz in Figure 19 shows a rise from poor low frequency response to a flattening out from between 1000 and 4000 Hz. Therefore, we can expect that the higher frequency components in the 100 Hz square wave will be relatively normal in amplitude and phase but that the lower frequency components in this same square wave will be strongly modified by the poor low-frequency response of this amplifier. See Figure 20A.

If the combination of elements in this amplifier were such as to only depress the low frequency components in the square wave, a curve similar to Figure 11 would be obtained. However, reduction in amplitude to a component, as already noted, is usually caused by a reactive element, causing, in turn, a phase shift of the component, producing the strong tilt of Figure 20A. Figure 21 reveals a graphical development of a similarly tilted square wave. The tilt is seen to be caused by the strong influence of the phase-shifted 3rd harmonic. It also becomes evident that very slight shifts in phase are quickly shown up by tilt in the square wave.

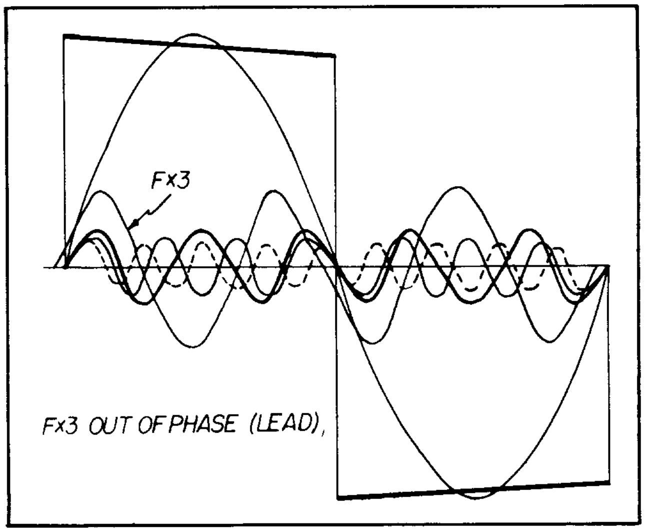


Figure 21. Square Wave Tilt Resulting From 3rd Harmonic Phase Shift.

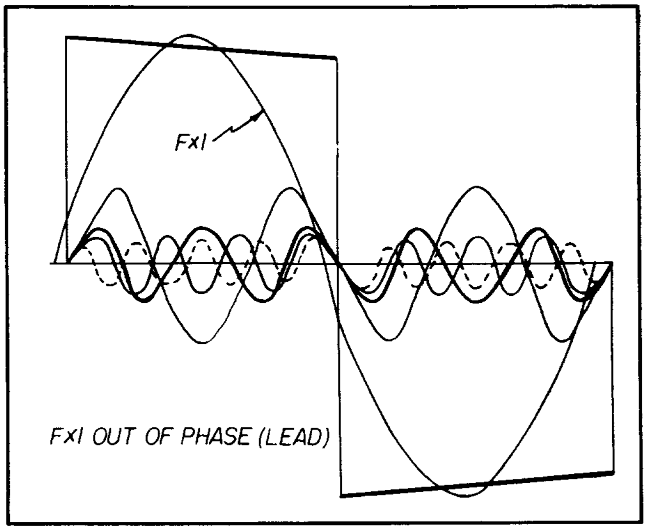


Figure 22. Tilt Resulting From Phase Shift of Fundamental Frequency in a Leading Direction

Figure 22 indicates the tilt in square wave shape produced by a 10° phase shift of a low frequency element in a leading direction. The tilting shape of the resultant wave results from the simple algebraic addition of all components along a vertical line as has been previously noted in this discussion. Figure 23 indicates a 10° phase shift in a low frequency component in a lagging direction. The tilts are opposite in the two cases because of the difference in polarity of the phase angle in the two cases as can be checked through algebraic addition of components.

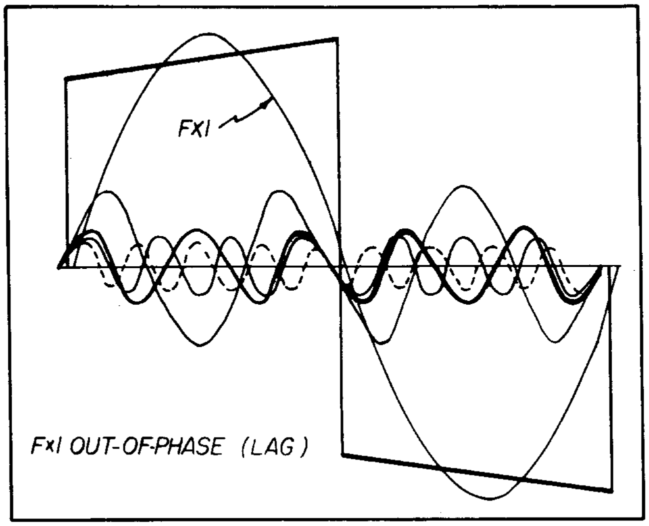


Figure 23. Tilt Resulting From Phase Shift of Fundamental Frequency in a Lagging Direction

Figure 24 indicates low frequency components which have been reduced in amplitude and shifted in phase. It will be noted that these examples of low frequency distortion are characterized by change in shape of the flat top portion of the square wave.

Figure 20B, previously discussed, revealed high-frequency overshoot produced by rising amplifier response at the higher frequencies. It should again be noted that this overshoot makes itself evident at the top of the leading edge of the square wave.

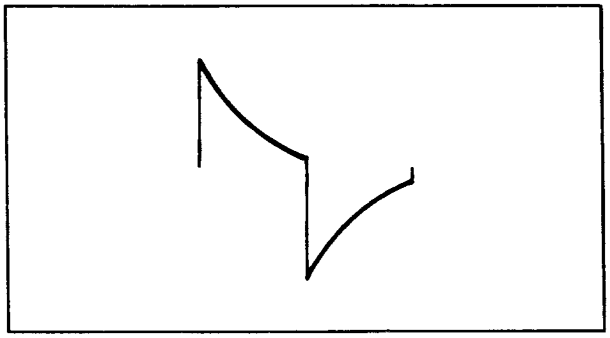


Figure 24. Low Frequency Component Loss and Phase Shift

This characteristic relationship is explained by remembering that in a normal well-shaped square wave, the sharp rise of the leading edge is created by the summation of a practically infinite number of harmonic components. If an abnormal rise in amplifier response occurs at high frequencies, the high frequency components in the square wave will be amplified disproportionately greater than other components creating a higher algebraic sum along the leading edge.

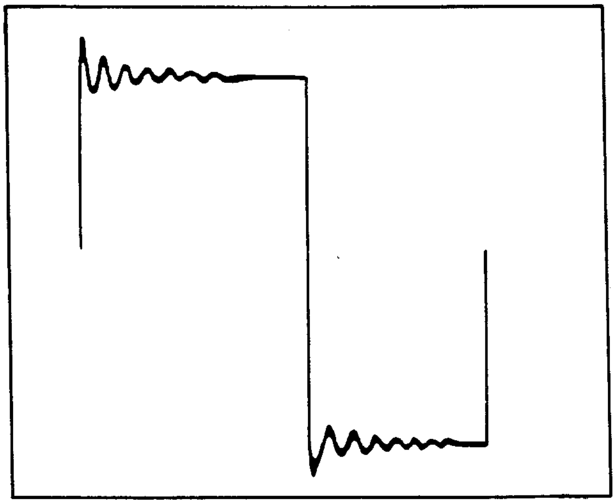


Figure 25. Effect of High Frequency Boost and Poor Damping

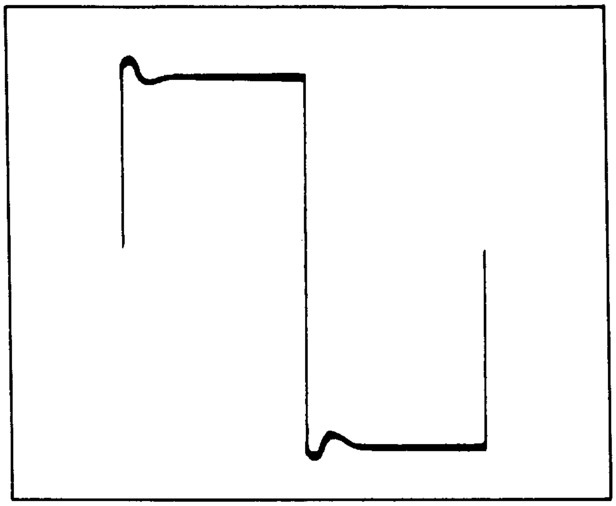


Figure 26. High Frequency Boost and Good Damping

Figure 25 indicates high frequency boost in an amplifier accompanied by a lightly damped "shock" transient. The sinusoidal type of diminishing oscillation along the top of the square wave indicates a transient oscillation in a relatively high "Q" network in the amplifier circuit. In this case, the sudden transition in the square wave potential from a sharply rising relatively high frequency voltage to a level value of low frequency voltage supplies the energy for oscillation in the resonant network. If this network in the amplifier is reasonably heavily damped, then a single cycle transient oscillation may be produced as indicated in Figure 26.

VIDEO AMPLIFIER TESTING

A common application of the square wave output of the E-310B is its use in the testing of TV video amplifiers. In actual operation, when amplifying picture information, the video amplifier must be capable of reproducing and amplifying rapid transitions from white to black and vice versa. These transitions are the equivalent of steep wave fronts and can be effectively simulated by substitution of a square wave voltage.

We have already noted that the square wave is quite sensitive to time delay or phase shift between components of a complex wave. In the video amplifier, maintenance of a linear phase characteristic is quite important inasmuch as phase distortion in the amplifier can cause certain picture elements to arrive out of step time-wise, creating detail interference or smear.

The instrument setup for checking a video amplifier is as follows:

1. Set up the E-310B for 200 KHz square wave output. Connect the black (ground) post to chassis and the red post to the grid of the 1st video amplifier through a .01 mfd capacitor.
2. Detune the front end or disable the local oscillator of the television receiver to prevent station information from interfering with the test waveform.
3. Connect the output of the video amplifier (input of the picture tube) directly to the vertical plates of the oscilloscope. If a wide-band oscilloscope such as B&K Model 1450 is being used, then the output of the video amplifier may be connected to the oscilloscope vertical input.
4. Sync the oscilloscope to obtain a stationary pattern on 200 KHz square wave.
5. A square wave pattern similar to Figure 27 indicates:
   A. "Ringing" or shock oscillation of one or more of the peaking coil circuits used to compensate the video amplifier at the higher frequencies.
   B. Phase shift at the higher frequencies indicated by rounding off of the leading corners of the square wave.

NOTE

It must be borne in mind that a square wave test at 200 KHz examines the characteristic of the amplifier from 200 KHz and up and therefore indicates conditions at the higher frequency limit of the amplifier. A 200 KHz square wave test, however, indicates nothing concerning the low frequency end; therefore, it becomes apparent that a two-frequency square wave test of video amplifiers becomes a minimum necessity: A 200 KHz test effectively reveals conditions from its fundamental frequency up to the high limit of the video amplifier. A test at approximately 60 Hz to 70 Hz discloses the low-frequency characteristic. A third frequency in the region between 60 Hz and 200 KHz may be used if desired; however, the two-frequency check is usually sufficient.

6. Next, to perform the low-frequency square wave check, set the E-310B for square wave output at approximately 70 Hz.
7. Set the OUTPUT LEVEL control as required to produce a sizeable pattern on the oscilloscope.
   NOTE: 70 Hz is recommended instead of 60 Hz so that any 60 Hz hum modulation which occurs will appear as a ripple voltage and not as a tilt distortion which might occur if the generator were accurately set to 60 Hz.
8. The relatively flat top of the resultant 70 Hz square wave of Figure 28 indicates good low-frequency response and insignificant low frequency phase shift. No rounding of the leading edge indicates no distortion of the highest frequency components in the 70 Hz square wave. The high components in this low frequency square wave do not approach the megahertz portion of the video amplifier response curve as far as ability to influence the shape of the square wave is concerned.

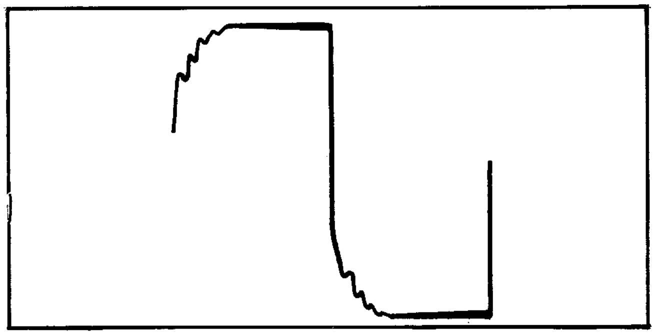


Figure 27. Ringing and Phase Shift in a Video Amplifier

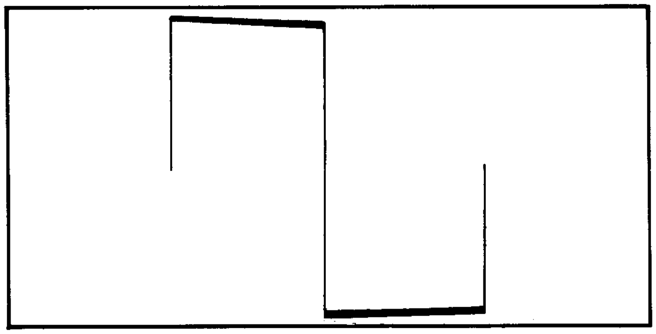


Figure 28. Good Video Amplifier Low Frequency Response.

If the output frequency of the generator is gradually increased up to 20 KHz, a progressive rounding of the leading corner will be noted. The small-radius corner at 20 KHz (see Figure 29) is just as significant to the observer as the large-radius corner at 200 KHz (see Figure 27) if it is kept in mind that compression or reduction of the radius is a logical result of reducing the fundamental frequency of the square wave such that progressively higher frequency components are indicating the high frequency distortion. As the fundamental frequency of the square wave is reduced back down to 70 Hz, the high frequency components which might conceivably affect the leading edge of the square wave are so high in order and therefore so insignificant in amplitude as to have negligible effect on the resultant square wave. We can therefore expect high frequency distortion to appear as a progressively larger rounding of the leading edge of a square wave as the frequency of the square wave is increased from a low value up towards a value approximately one-twentieth of the upper portion of the amplifier response spectrum (ten odd harmonics).

To go back to the 200 KHz square wave illustrated in Figure 27, the degree of lead-edge rounding appears to be quite large; however, a reference for comparison must be established before the observer can decide when rounding is excessive. Figure 30 therefore, indicates the degree of rounding of a 200 KHz square wave which correlates with a condition of fuzzy picture detail indicating significant high frequency loss. It is important that the observer correlate the degree of rounding with the fundamental of the square wave being used, i.e., had a 50 KHz square wave been used in the previous example, the rounding would have been less exaggerated; however, the analysis should be the same, meaning that the observer should be able to picture the degree of rounding of a 50 KHz square wave wherein a condition of fuzzy picture detail exists.

The sharp rise time of the square wave generated by the generator may induce ringing in a video amplifier (as observed on the oscilloscope) where peaking coils are used to boost the high frequency response. The degree of ringing can be controlled by changing the value of the damping resistors across the peaking coils. It is mainly a matter of experience with particular TV sets as to what degree of ringing will cause deterioration of picture quality. The technician should attempt to arrive at a compromise betwen ringing and rounding of the leading edge of a square wave.

To sum up the basic principles of video amplifier square wave testing, it should be said that experience in correlating square wave shape at particular fundamental frequencies with actual picture quality will fortify the technician with a series of reference square wave shapes against which new trouble jobs can be compared. No generalized textbook discussions can substitute for this kind of experience in square wave testing.

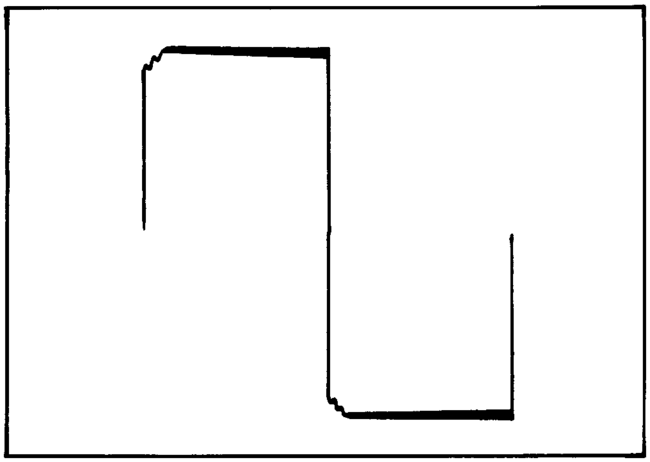


Figure 29. 20 KHz Square Wave Through a Video Amplifier

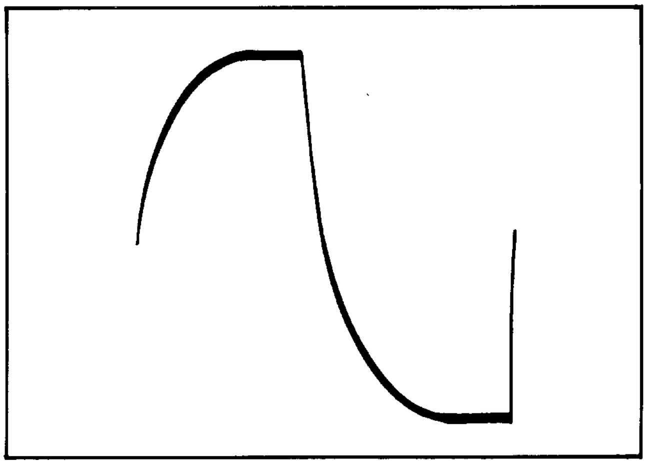


Figure 30. High Frequency Loss at 200 KHz

USE OF THE E-310B AS A PATTERN LINEARITY CHECKER

We have noted previously that the abrupt rise of a square wave from zero amplitude to a maximum in a fraction of a cycle is analagous to the transition of a TV raster line from dark to light. It becomes obvious that the application of a square wave of the proper frequency to the video amplifier will produce alternating black and white lines with sharp definition.

The horizontal synchronizing pulses of a TV set are 15,750 KHz. A square wave of 126 KHz will therefore produce 8 vertical pairs of black and white lines.

By the same token, a satisfactory number of horizontal black and white alternations or lines can be produced by feeding a square wave at any desired multiple of 60 Hz into the video amplifier. The generator therefore supplies the two rasters required for simplified linearity adjustments.

NOTE

Similar results will be obtained using sine wave output: the definition between black and white lines will be sharper with square wave as compared to the sine, however.

ADDITIONAL TROUBLE-SHOOTING AND ANALYZING AIDS

The following square-wave response nomographs of Figure 31 and the summary of square-wave analyzing waveforms of Figure 32 and Figure 33 are presented to provide a condensed reference of evaluation of amplifier performance using square-wave input signals.

SQUARE-WAVE RESPONSE NOMOGRAPH

This nomograph correlates tilt of square wave after passing through uncompensated RC-coupled video or audio ampilfier with low-frequency response of amplifier and time constant of coupling circuit.

When using rectangular or square waves for testing audio and video amplifiers, the output of the amplifier is compared with the input of an oscilloscope. The degree or percent of tilt of the top of the square wave represents the amplifier's deterioration of the lower frequencies.

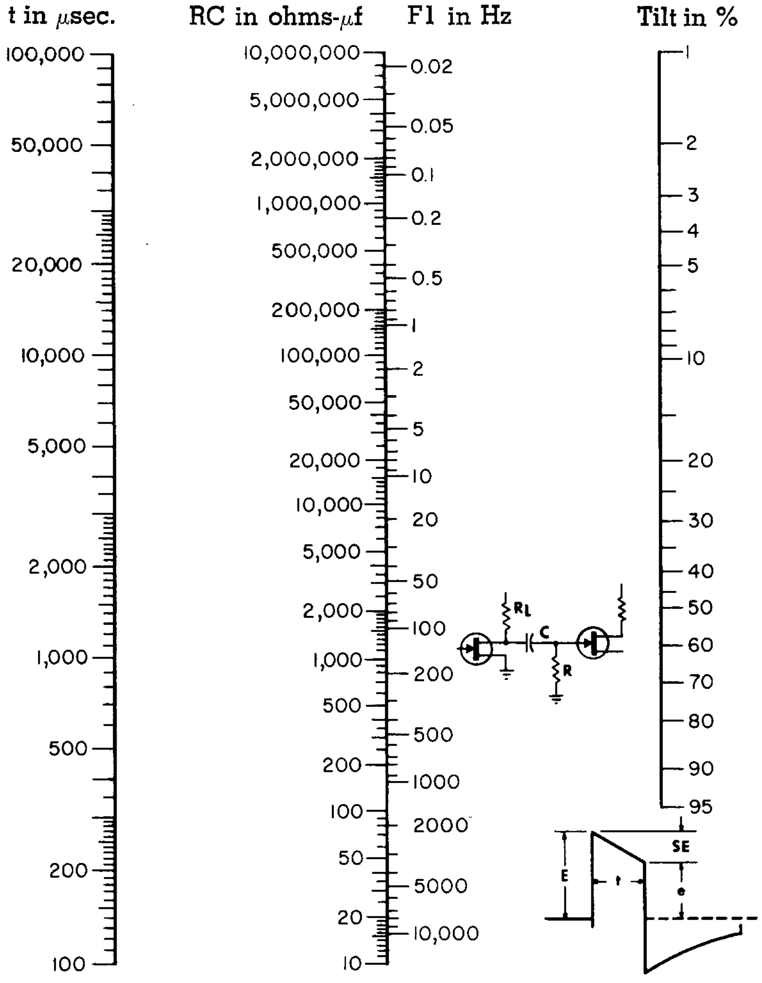
In the uncompensated RC-coupled FET amplifier stage shown, the effect of the amplifier on low frequencies is almost completely a function of the value of the RC time constant in the gate input coupling circuit. The smaller the time constant, the poorer the low-frequency response and consequently the greater the percent tilt "S" of a rectangular wave (referred to the peak voltage value "E" as indicated on the waveform diagram).

The accompanying nomograph is useful in computing the RC value required to give a maximum specified tilt "S" (expressed as a decimal part of "E" for a rectangular wave having a duration "t" or, conversely, it may be used to determine the tilt that will be obtained from a given time constant. The chart also gives the relationship between tilt and low-frequency cutoff of an amplifier coupling circuit (the frequency F1 at which the amplitude-frequency response characteristics is down 3 DB).

EXAMPLE OF USE

The percent tilt of an uncompensated video amplifier stage is specified as 2 percent maximum on a 60 Hz square wave. What will be the required time constant of the coupling circuit and the corresponding low cutoff frequency?

By means of a straight edge, connect the 2 percent point on the tilt scale with the 8,300 microsecond point (corresponding to the half-cycle duration of a 60 Hz square wave) on the "t" scale. The straightedge will cross the RC scale at approximately 410,000 ohms-μf. The corresponding low cutoff frequency F1 is found to be 0.4 cycle.



$$e = Ee^{-t/RC}$$

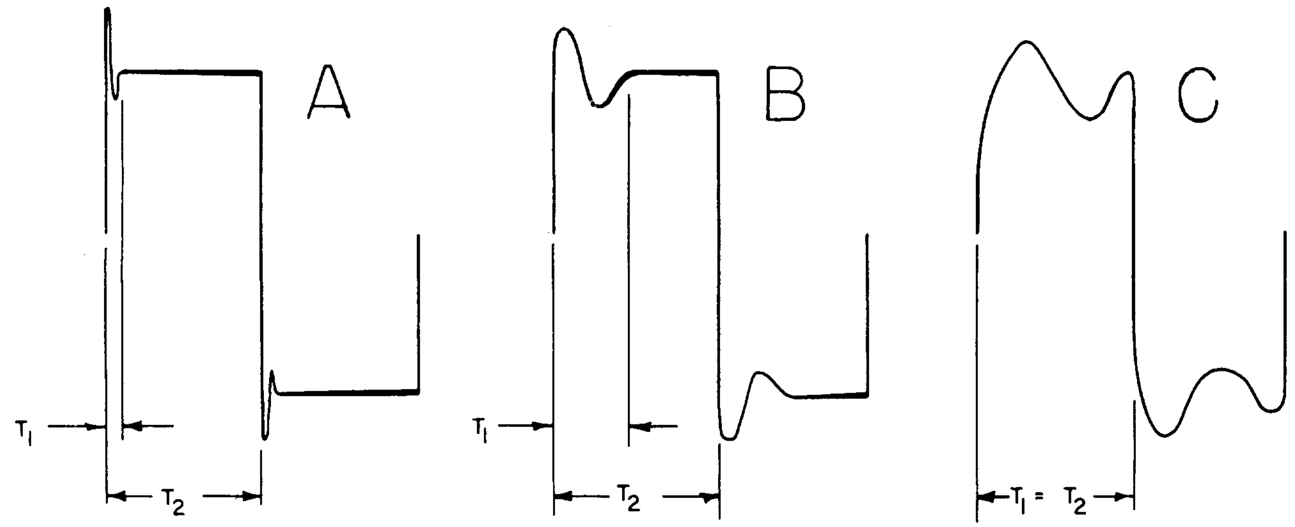
$$\frac{t}{RC} = \log_e \frac{E}{e} = \log_e \frac{1}{1-S}$$

$$RC = \frac{t}{\log_e \frac{1}{1-S}}$$

$$F1 = \frac{1}{2\pi RC}$$

$$= \frac{\log_e \frac{1}{1-S}}{2\pi t}$$

Figure 31.



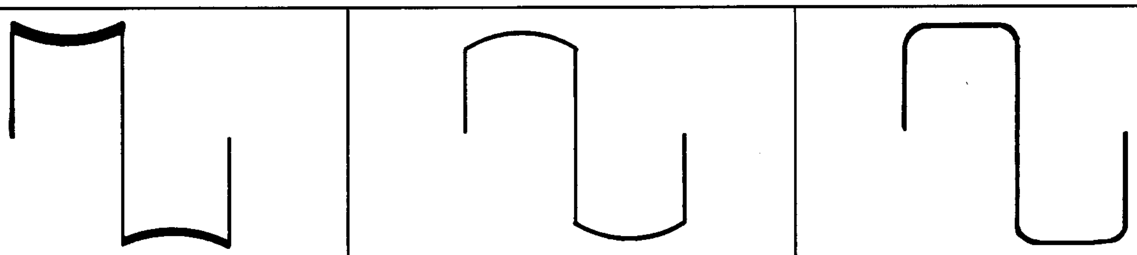
The three Square Wave patterns in A, B, C above indicate a damped resonant element in the circuit or amplifier under test.

A. The short time duration of the damped oscillation indicates that the fundamental frequency of the Square Wave is approximately 1/10 that of the damped oscillation. (T_1 approx. = $.1xT_2$).

B. A Square Wave shape is obtained by applying a higher frequency Square Wave to the same circuit or amplifier represented by A. The longer time duration of the damped oscillation indicates that in this case the fundamental of the Square Wave is closer to that of the damped oscillation as compared to A.
In this case the fundamental frequency of the Square Wave is approximately ½ that of the damped oscillation. (T_1 approx. = $.5xT_2$).

C. The wave-form pattern indicates that the fundamental frequency of the square wave approximately equals that of the damped oscillation.

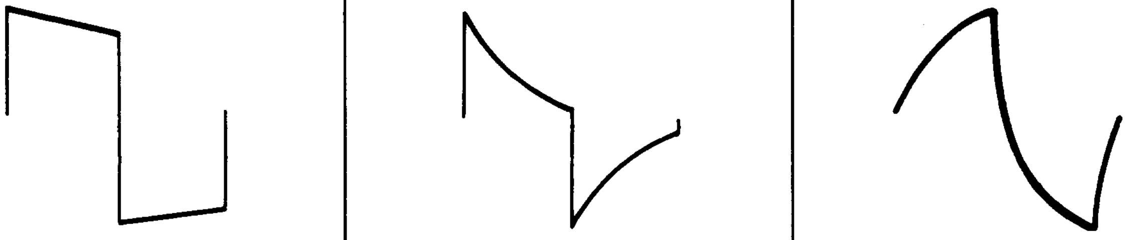
Figure 32.



A. Frequency distortion. (amplitude reduction of low frequency component). No phase shift.

B. Low frequency boost (accentuated fundamental).

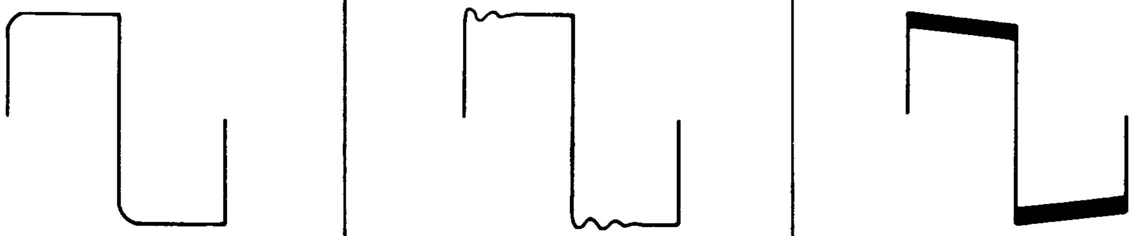
C. High frequency loss—No phase shift.



D. Low frequency phase shift.

E. Low frequency loss and phase shift.

F. High frequency loss and low frequency phase shift.



G. High frequency loss and phase shift.

H. Damped oscillation.

I. Low frequency phase shift (trace thickend by hum-voltage).

Figure 33.