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Phase Shift Method of Checking Distortion

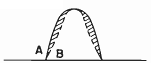
By the Engineering Department, Aerovox Corporation

INTEREST in high-fidelity audio has experienced a phenomenal growth during the past ten years. For many years, the transmitting radio amateurs comprised the largest known group having an avocational interest in electronic equipment. Today, however, authorities estimate that high-fidelity enthusiasts outnumber the "hams". The reasons are fairly obvious. In the first place, the audio-hobbyist does not need to meet any license requirements. The inevitable weeding-out process of a technical examination therefore is absent and a larger number of people automatically become free to pursue their interests. Secondly, audio is closely associated with the enjoyment of good music, something in which an entire family can participate.

The critical audio technician applies exacting tests to his equipment. One such test is *distortion measurement.* This test is of prime importance, since it rates directly the fidelity of the examined equipment. The *Research Worker* has made it a point, at appropriate intervals, to acquaint its readers with current practices in distortion measurement (See the following issues: November 1950, October 1950, March-April 1945, and May 1942).

Prior Measuring Techniques

Standard methods of measuring harmonic distortion have, up to this time, used some variation of the following technique: (1) A sine-wave signal of exceptional purity, having a desired frequency, is applied to the input terminals of the amplifier or other device under test. (2) The amplifier output then is applied to a test circuit in which the fundamental test-signal frequency is suppressed by an appropriate band-elimination filter. (3) Assuming that no harmonics were present in the test signal, the filter would have zero output voltage. Any harmonics actually present at the output of the tested device would pass through the filter, since the latter is tuned to remove only the fundamental, and would show up as a measurable filter-output voltage. This voltage then may be construed to indicate that the tested device has distorted the originally pure test signal. (4) This distortion voltage is measured, and the harmonic distortion percentage determined from the ratio of harmonic voltage to the total fundamental and harmonic voltage. For this purpose, the two voltages might be measured before and after the filter. The measurement is made with an oscilloscope or a.c. vacuum-tube voltmeter. Several test frequencies through the audio spectrum are employed. This system is the basis of all commercial harmonic distortion meters which indicate *total distortion.*



SINE-WAVE INPUT (A) COMPARED WITH DISTORTED OUTPUT(B) OF SAME PEAK AMPLITUDE

FIGURE 1.

Several difficulties confront the technician in the actual practical application of this method. First, and very important, a pure sine-wave test-signal source is an absolute requirement. An oscillator or audio signal generator meeting this specification seldom is found outside of the advanced laboratory and is an exceedingly expensive instrument. Indeed, many high-priced audio oscillators are not completely satisfactory for the purpose. Attempts to correct for the inherent distortion of the average oscillator often give rise to a number of inaccuracies, because of involved mathematical relationships. Furthermore, the distortion tests are complicated and delayed when corrections must be made. The second important difficulty concerns the filters. Ideally, a distortion filter must attenuate the fundamental frequency completely, while transmitting all of the harmonics with no attenuation. *The farther you fall from this goal,* the greater will be the error due to residual fundamental or attenuated harmonic voltages. A filter having sufficiently sharp cutoff and low enough attenuation of the harmonic frequencies to permit distortion measurements lower than a few per-cent must be designed critically and must be constructed with expensive high-Q components. The third difficulty has to do with the indicating instrument. For best results, this should be a *full-wave* square law a.c. vacuum-tube voltmeter, not a common type.

Aside from harmonic distortion checking, the measurement of *intermodulation distortion* has received

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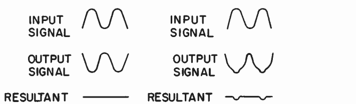


(A) UNDISTORTED OUTPUT (B) DISTORTED OUTPUT

EFFECT OF MIXING INPUT AND OUTPUT WAVES WITH 180-DEGREE PHASE DIFFERENCE

FIGURE 2.

considerable attention during recent years. This is a measurement of the interaction between signals of two different frequencies passed simultaneously through an amplifier or other device under test. Intermodulation tests are favored in many quarters, since they seem to correlate more closely with actual listening tests. In one system of intermodulation testing (the one credited to the Society of Motion Picture and Television Engineers, SMPTE), a low- and high-frequency signal are applied simultaneously to the tested device. If the latter has none of the nonlinearities which give rise to discords and dissonances in the output, the two signals will be delivered with no interaction between the two. If this is not true, the output will consist of the high-frequency signal amplitude-modulated by the low frequency. The technique of determining the degree of modulation then consists of the following steps: (1) The modulated high-frequency component is separated by means of a high-pass filter. (2) It then is demodulated and the average value of this signal set to a predetermined reference level by means of a gain control. (3) The low-frequency envelope of the demodulated signal finally is separated by means of a low-pass filter and its amplitude measured with an a.c. vacuum-tube voltmeter calibrated in intermodulation percentage.

Difficulties also confront the technician in applying the intermodulation method and in interpreting the results obtained. The required high- and low-pass filters must have sharp cutoff to prevent interference from the eliminated band of frequencies, and flat transmission throughout the pass band. This requirement dictates costly, high-Q filters. Also, there is at present, lack of standardization with regard to the test-signal amplitude ratio, the signal frequencies to be used, and uniform rating of amplifiers in terms of intermodulation percentage. Furthermore, separate tests must be made at a number of combinations of low and high test frequencies, in order to compensate for the amplifier frequency response. It accordingly is insufficient to state that an amplifier has a certain percentage of intermodulation — one must say at what frequency combination the test was made and also with what signal amplitude ratios. There is no simple arithmetic relationship between the intermodulation percentage and a "corresponding" amount of harmonic distortion.

View of the Problem

An amplifier should be a linear device. Otherwise, it cannot be a faithful reproducer. By linear, we mean that the output signal should follow the input signal *directly*. If the input is doubled, for example, the output also should increase by twice its original value. As the input signal waveform goes through its many positive and negative values, the output waveform should go through *similar* variations, although at higher amplitude (being amplified). All distortion, whether viewed as harmonic, phase, or intermodulation, is a matter of output waveform departing from that of the input signal.

It follows from these remarks that a check of amplifier linearity (output versus input) should establish a great deal with respect to fidelity. Such a test can be performed with any input signal — no expensive, high-purity generator is needed, since a high-fidelity system should reproduce faithfully even a distorted wave applied to its input terminals. Also, elaborate output filters would not be required.

One method would be to apply, at each selected test frequency, a series of input voltage steps, and to check the corresponding output voltage steps. If the output voltage than is plotted against input voltage, a straight line will be obtained for a true high-fidelity amplifier, having no distortion. If the line is not straight in any particular, the percentage whereby it deviates from true linearity is an indication of the distortion present. And such non-linearity can give rise to harmonic, phase, and intermodulation distortion.

The foregoing point-by-point method of linearity checking is laborious. It is especially tedious if measurements are to be made at a number of test frequencies and at various settings of volume and tone controls in the amplifier.

Rapid, automatic methods of making this test therefore are desirable. The following paragraphs describe circuits and methods for accomplishing this purpose.

The Phase-Shift Method

Assume that a sine-wave test signal is applied to the input terminals of an amplifier under examination. One half-cycle of the input signal is shown as A in Figure 1. Now, if the output signal of the amplifier is adjusted to the same peak amplitude and viewed on the same axis as A, provided it is of the same phase, might appear as B in Figure 1. The area under curve B minus the area under curve A would indicate the amount of deviation of the output signal waveform from the input signal waveform. And if this difference is divided by the area under curve A, the distortion percentage would be indicated. The shaded area in Figure 1 shows the difference between the two areas.

Distortion may be checked in this manner by examining the amplifier input and output signals successively on the screen of an oscilloscope, being careful to adjust the two signals to the same peak amplitude. For each comparison, the patterns may be pencil-traced on thin paper or may be photographed by double exposure. This scheme requires that both input and output signals be of the same phase, sometimes necessitating the use of a suitable phase-shifting resistance-capacitance network in case the amplifier under test shifts the phase in the undesired direction.

In the phase-shift method of distortion measurement, the input signal is reversed 180 degrees with respect to the output signal, and the two signals mixed after they are adjusted to equal amplitudes. If there is no distortion, the two signals being equal in amplitude and opposite in phase (See Figure 2A) will cancel, giving a zero resultant. If, on the other hand, the output signal is distorted, only those portions of the output signal which are equal and opposite to the input signal will cancel. The other portions, representing distortion (variations from true linearity) will remain, as shown in Figure 2(B) and can be measured with an a.c. vacuum-tube voltmeter or oscilloscope.

The peak amplitude of the distortion components remaining at "null" may be compared with the peak amplitude of the output signal (with the input signal removed temporarily from the mixing device) to determine the distortion percentage.

If the test oscillator signal is distorted, the two signals still will cancel each other, giving zero resultant, if no *additional* distortion has been introduced by the amplifier. The reason for this is that (initial distortion included) the input and output signals will be equal in amplitude and opposite in phase in all parts.

Figure 3 shows a typical complete setup for checking amplifier distortion by means of the phase-shift method.

In this arrangement, the 12AU7 mixer tube, V_1, receives signals from the oscillator and from the amplifier output. The amplifier is terminated with a non-inductive load resistor, R_1, which has an ohmic value equal to the rated output impedance of the amplifier and rated to withstand at least twice the normal power output of the amplifier.

The input signal level into the mixer is adjusted with the gain control, R_2, and the level of the output signal by means of the second gain control, R_3. These controls are adjusted to make the two signals, as presented to the 12AU7 grids, exactly equal in amplitude.

180-degree phase reversal of the input signal applied to the mixer is obtained through transformer T. This must be a high-quality transformer of the high-fidelity type. An interstage component designed for operation between a single plate and pushpull grids is satisfactory. Switch S allows selection of the proper phase for bucking action in the mixer stage.

The cathode output of the mixer is applied to the grid of a 6C4 distortion-products amplifier, V_2. When there is no distortion in the amplifier under test, the 12AU7 output will be zero. Output of the 6C4 is applied to an a.c. vacuum-tube voltmeter or oscilloscope for measurement of the distortion voltage and examination of its waveform.

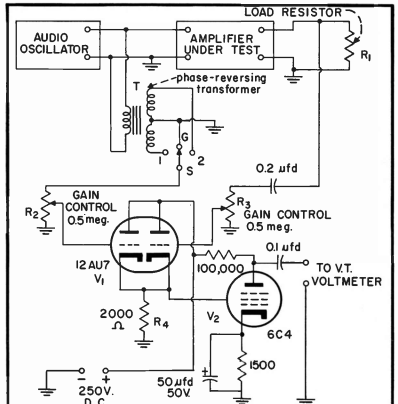
The setup, as shown, will give satisfactory results in the majority of applications. However, when phase shifts within the amplifier (or network) under test are not of the order of magnitude other than those encountered in conventional amplifiers, it may become necessary to insert a simple R-C phase-shifting network, designed for use at the test frequency, in series with one of the signal leads to the 12AU7 stage.

The instrumentation is operated in the following manner: (1) Set the oscillator output voltage to drive the test amplifier to its full power output (output watts = E^2/R_1; where E is the voltage measured across load resistor R_1 with a high-impedance-input a.c. vacuum-tube voltmeter). (2) Connect an oscilloscope or a.c. vacuum-tube voltmeter to the 6C4 output terminals. (3) Adjust gain controls R_2 and R_3 for null — minimum deflection of the meter or 'scope. (4) If complete null cannot be obtained with switch S in its position 1, throw to position 2 and readjust the gain controls. Select the setting of switch S which gives the lowest reading (5) Read any voltage remaining at the best obtainable null and record this as E_1. (6) Remove the oscillator voltage from the 12AU7 by setting switch S half-way between its two contacts and thus grounding the grid. (7) Read the voltage then indicated by the meter. This is the full amplifier output including distortion components, and must be recorded as E_2. (8) Determine the distortion percentage (D) by means of the formula: $D(\%) = 100\ E_1/E_2$.

There is an advantage in employing an oscilloscope as the 6C4 output indicator. The 'scope permits an examination of the signal waveform, as well as its peak voltage value. This often is invaluable in determining the nature of the distortion and helps to determine what remedies should be applied for its correction. It is good practice to use the 'scope even when a v. t. voltmeter also is in the circuit.

The setup shown in Figure 3 illustrates the basic essentials of any circuit for checking distortion by the phase-shift method. Many variations are possible, and the reader may introduce obvious refinements which might appeal to him. An entire distortion meter might be constructed, for example, with a self-contained power supply and built-in v. t. voltmeter or miniature oscilloscope. It is possible also to build the distortion meter into the same case with an audio oscillator, so that patch connections need to be made only from the oscillator output to the amplifier and from the amplifier output back to the instrument.

We believe that the phase-shift method of distortion checking does a creditable job in a reasonably foolproof manner and recommend this method, or some variation of it, to the serious audio experimenter unable to afford expensive fidelity testing equipment. Components, such as transformers, couplers, etc., may be checked, as well as amplifiers.



COMPLETE SETUP FOR PHASE-SHIFT METHOD OF DISTORTION MEASUREMENT.

FIGURE 3.