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A SWEEP METHOD FOR MEASURING ENVELOPE DELAY

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Approved

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Introduction

Equipment has been developed which in conjunction with generally available sweep generators and oscilloscopes, makes it possible to determine rapidly the envelope delay characteristic as well as the amplitude characteristic of any amplifier or system. Measurement made with it when compared with other methods of determining envelope delay agreed within 0.01 microsecond in absolute value and even better in relative values.

Theory of Operation

If a signal consisting of two frequencies is fed into an amplifier, the signal at the output will consist of these same two frequencies but each will have had its phase shifted by an amount determined by the phase shift of the amplifier at each of the two frequencies.

That is, if the input signal is

$$S_i = \cos(2\pi f_1 t+\varphi_1)+\cos(2\pi f_2 t+\varphi_2)$$

the output will be

$$S_o = A\cos(2\pi f_1 t+\varphi_1+\theta_1)+B\cos(2\pi f_2 t+\varphi_2+\theta_2)$$

If the two frequencies are close enough together so that the envelope delay is constant in the interval between f_1 and f_2 the envelope delay will be

$$T_E = \frac{d\theta}{d\omega} = \frac{\Delta\theta}{2\pi\Delta f} = \frac{\theta_2-\theta_1}{2\pi(f_2-f_1)}$$

Since f_1 and f_2 are known the measurement of T_E resolves itself into measuring $\theta_2-\theta_1$.

If the output signal is detected in a square law detector,

$$S_o^2 = A^2\cos^2(2\pi f_1 t+\varphi_1+\theta_1)+B^2\cos^2(2\pi f_2 t+\varphi_2+\theta_2)$$

$$+2AB\cos(2\pi f_1 t+\varphi_1+\theta_1)\times\cos(2\pi f_2 t+\varphi_2+\theta_2)$$

$$= \frac{A^2+B^2}{2} + \frac{A}{2}\cos(4\pi f_1 t+2\varphi_1+2\theta_1)+\frac{B}{2}\cos(4\pi f_2 t+2\varphi_2+2\theta_2)$$

$$+AB\cos[2\pi(f_1+f_2)t+\varphi_1+\varphi_2+\theta_1+\theta_2]$$

$$+AB\cos[2\pi(f_2-f_1)t+\varphi_2-\varphi_1+\theta_2-\theta_1]$$

This shows that there is a d-c term, three high-frequency terms (roughly 2f) and a term, the last term above, at a frequency of the difference of the two frequencies and shifted in phase by the difference in phase shift of the two frequencies.

It should be noted that $\Delta\theta = \theta_2-\theta_1$ is not dependent on A or B.

By selecting just the $\Delta f = f_2-f_1$ term by circuits tuned to it, a sine wave is obtained;

$$AB\cos(2\pi\Delta f t+\varphi+\Delta\theta)$$

By measuring this phase of this detected output signal relative to the same signal at the input to the amplifier where $\Delta\theta = 0$,

$$\varphi+\Delta\theta-\varphi = \Delta\theta.$$

This shows that the phase of this Δf signal is $\Delta\theta$ and since Δf is known,

$$T_E = \frac{\Delta\theta}{2\pi\Delta f}.$$

To get the delay at any other frequency, f_1 and f_2 are changed, keeping Δf constant. Then, the envelope delay will always be proportional to the $\Delta\theta$, since Δf is constant. This may be written

$$T_E = \frac{1}{2\pi f\Delta} \times \Delta\theta$$

An easy way to measure $\Delta\theta$ is to feed the sine wave at Δf of unknown phase into a modulator with a sine wave of the same frequency but constant phase. The output is then proportional to

$$K \sin \Delta\theta$$

This can be seen by considering what a modulator does. It multiplies the two waves. Therefore the output

$$S_T = \cos(2\pi\Delta ft+\varphi)\times\cos(2\pi\Delta ft+\varphi+\Delta\theta)$$

$$= \tfrac{1}{2}\cos(2\pi 2\Delta ft+2\varphi+\Delta\theta)+\tfrac{1}{2}\cos\Delta\theta$$

By filtering out $2\Delta f$ there is only

$$S_T = \tfrac{1}{2}\cos\Delta\theta.$$

If the phase of the reference signal is shifted by 90 degrees this would be $S_T = \frac{1}{2} \sin \Delta\theta$.

In most simple modulators (not balanced) there is a d-c term which can easily be balanced out.

Instead of using just two frequencies, a group of frequencies can be used. Two practical cases are those obtained by modulating a carrier either in amplitude or frequency. When this is done, the phase of the modulating frequency after detection can be used, provided the amplitude of the two side bands have been made equal before detection by an amplitude limiter before the discriminator in the case of frequency modulation, or by a frequency limiter before the amplitude detector in the case of amplitude modulation. Both these systems have the disadvantage that the probe used for looking at the point in the amplifier under test cannot be a simple detector but must be a wide-band cathode follower to take the signal into the measuring equipment. The beat between the two side bands can be used in either of these cases (twice the modulating frequency) as is done when just two frequencies are used. However, the second harmonic of the modulating frequency generated in the simple type of detector is of the same frequency and gives spurious results.

For these reasons it was decided to use just two frequencies and a simple diode detector. In order to generate two frequencies whose difference is constant while their absolute frequency is varied rapidly as is done in a sweep, it is necessary to modulate the signal from the sweep generator by a constant frequency in a double balanced modulator.

Equipment

A block diagram of the equipment for accomplishing the above is shown in Fig. 1.

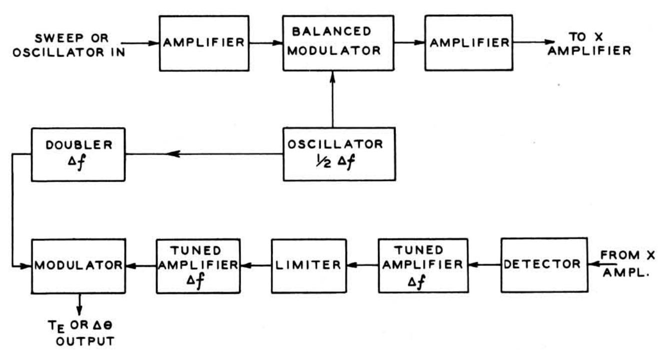

Fig. 1 - Block diagram of the equipment.

A signal at the frequency for which the envelope delay is to be measured is fed through an amplifier into a doubly balanced modulator where it is modulated by the output of an oscillator at $\frac{1}{2}\Delta f$. Neither of the input signals appear at the output of the modulator, but only the products, that is, $f + \frac{1}{2}\Delta f$ and $f - \frac{1}{2}\Delta f$. After further amplification this signal is fed to the amplifier under test. The signal from the output of the amplifier under test is fed to a detector the output of which is tuned to Δf. After amplification and limiting, this signal is fed to a modulator to be modulated by a signal of fixed phase at Δf derived by doubling the $\frac{1}{2}$ Δf signal from the oscillator. The low-frequency side-band output of the modulator is a d-c signal proportional to

$$K + \sin \Delta\theta = K + aT_E$$

The K can be balanced out and the a determined by calibration. T_E can be read on a calibrated d-c meter if a single frequency input is used or on an oscilloscope if a sweep input is used.

For the equipment which was built a Δf of 200 kc was chosen as a compromise between resolution (ability to measure speed of change of T_E with f) and size of d-c variation in the output meter or scope reading. Lower Δf would increase the resolution but the d-c changes due to a change in T_E would be reduced. The d-c changes could be increased at the expense of some additional circuits by multiplying both the reference and varying Δf by the same factor before feeding them into the phase detector modulator.

Circuit Diagram

The circuit diagram follows the block diagram closely. The signal from the sweep generator, after amplification, goes to the balanced modulator. This consists of two modulator tubes V3 and V4 fed in push pull by both the input signal and the 100-kc fixed frequency. The 100 kc is fed by a balanced transformer and the signal by a plate-cathode phase splitter V2. The balance controls on the modulator are (1) the G_1 bias which, in conjunction with the tuning of the two halves of the secondary of the 100-kc transformer, balances out the 100 kc in the output; (2) the G_3 bias which minimizes the second harmonic in the output; (3) the low-frequency signal balance by means of the potentiometer in the cathode of the phase splitter which makes both halves of the modulator modulate equally; (4) the high-frequency signal balance by means of the cathode condenser which does the same as (3) for the high frequencies, and (5) the neutralizing condenser between the grid and plate of one of the modulators to compensate for the capacity feed-through at high frequencies of the other modulator due to stray capacity of the wiring, etc.

The output of the modulator is amplified in tube V5 and fed to the amplifier to be tested by the cathode follower tube V6.

The oscillator V9 and the buffers V7 and V8 need no explanation.

The output of the amplifier is detected in the probe whose output is tuned to 200 kc. The tuned circuit has a condenser divider so that the proper signal level may be selected for the tuned amplifier and limiter which follows. Tube V14 is a tuned amplifier and V13 drives a double diode limiter which works satisfactorially without phase shift over about a 10 to 1 range. Care must be taken so that none of the stages before the limiter saturate or draw grid current; otherwise there would be phase shift with amplitude. This is the reason for using a 6AG7 with unbypassed cathode resistor to drive the limiter.The output of the limiter goes through another tuned amplifier V12 to the first grid of modulator V11. The potentiometer across the tuned circuit in the plate of tube V12 serves to put the proper amount of sine wave signal on the modulator to give a calibrated output. G_3 of the modulator V11 is fed a fixed-phase 200-kc signal through the tuned amplifier V10 from the doubler circuit in the plate of tube V8. The primary of the double transformer is tunable so that the phase of the 200-kc output may be changed over about 180 degrees. This changes the amplitude of the 200-kc signal some, but the modulator is insensitive to amplitude of this signal if it is large enough. The output current of the modulator is read on a 0-1.0 ma meter or can be observed by an oscilloscope after filtering out the 200 kc. A 0-1.0-ma meter in the limiter circuit serves to indicate when the signal is within the proper range and can be used to check the amplitude characteristic of the amplifier.

Care must be taken that no unmodulated 100 or 200-kc signal gets into the tuned amplifier. Therefore the first stage of the 200-kc amplifier should be shielded. One side of the filament should be grounded at tube V14.

Photographs of the experimental equipment are shown in Fig. 3.

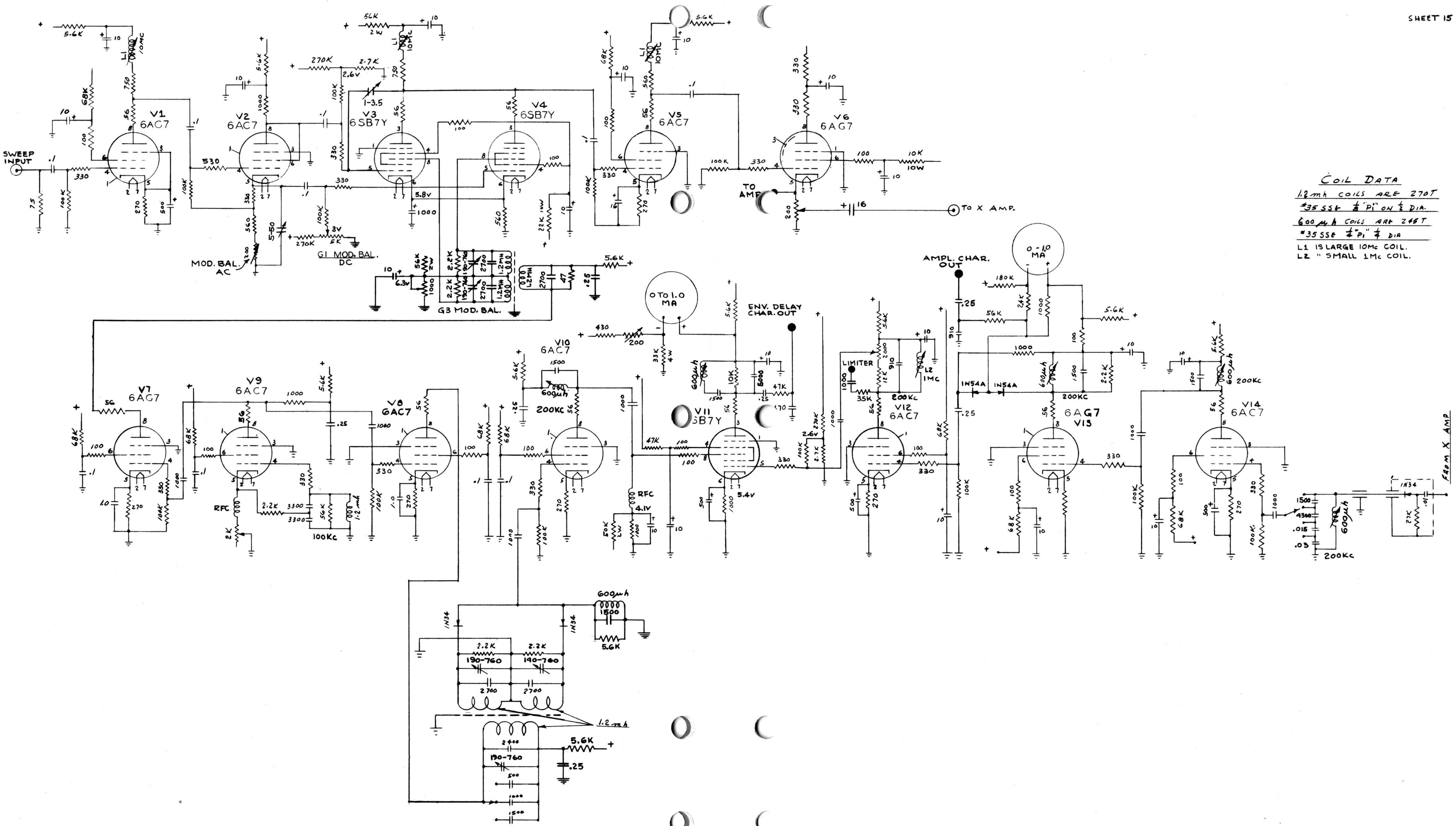

Fig. 2 – Circuit diagram of the equipment.

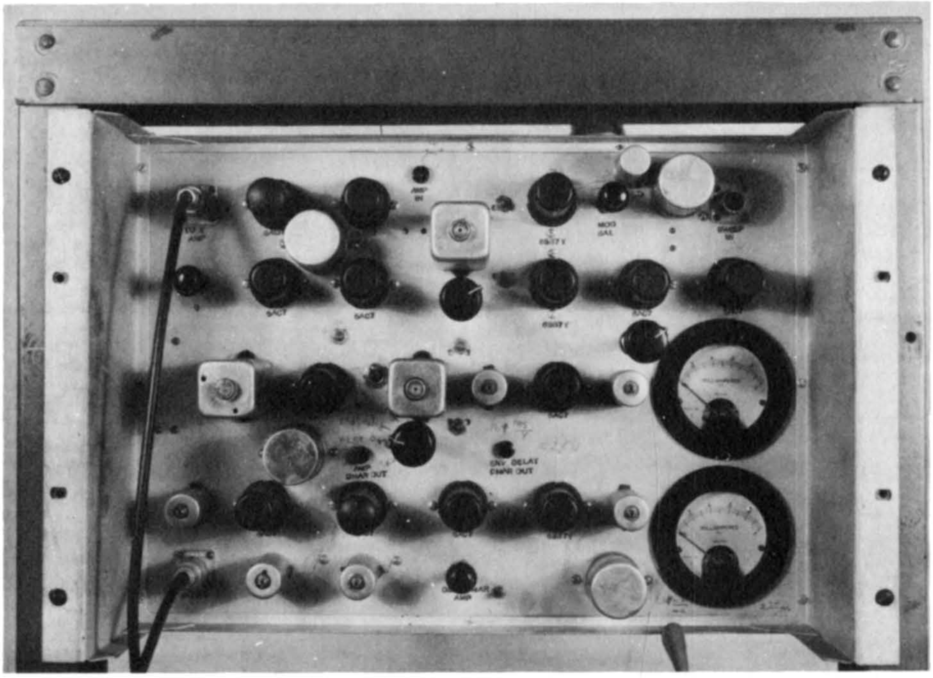

Fig. 3a – Front view of the equipment.

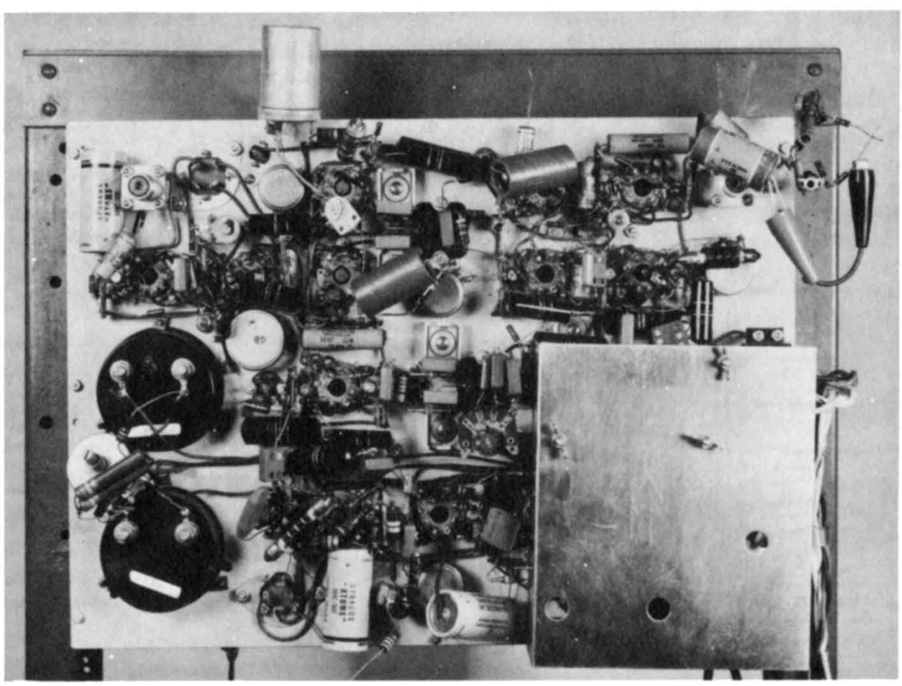

Fig. 3b. Back view with shield in position

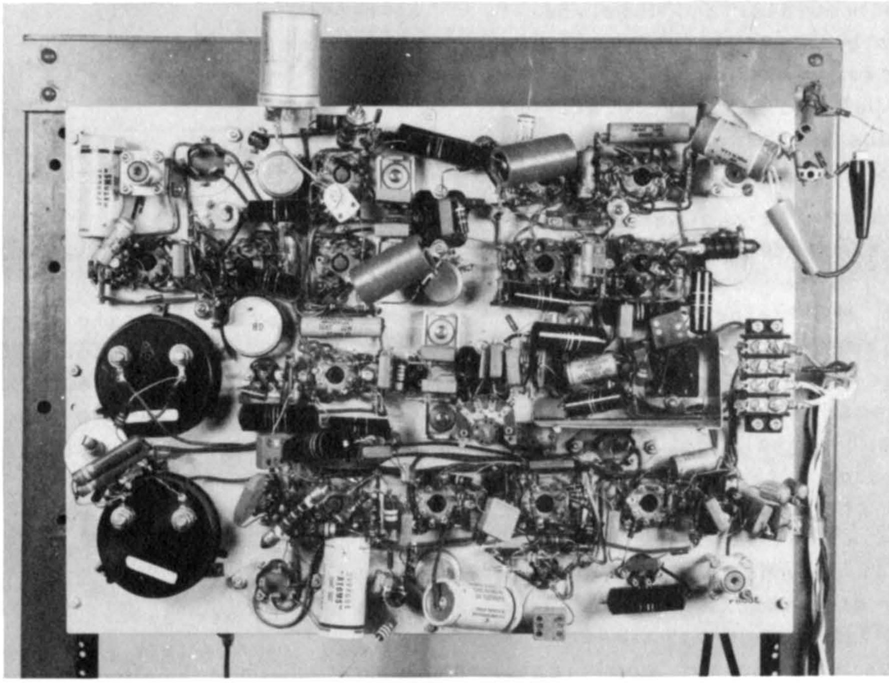

Fig. 3c. Back view with shield removed

Operation

The oscillator is first adjusted to the desired frequency (100 kc). Then the balanced modulator is balanced. This is done by looking at the output signal. With no input, the G_1 and G_3 biases are adjusted in conjunction with the relative tuning of the two halves of the transformer to make the output 0. This can later be checked more accurately by connecting the probe to the output and looking at the test point on the plate of tube V12.

After the output has been adjusted for 0 with no input, a sweep signal is introduced, being careful not to use more than about 0.3 volt peak to peak. The output should be single valued at both low and high frequencies and should have a single base line. The low-frequency balance potentiometer in the cathode of V2 should be adjusted for a single trace at low frequencies and the condenser in the cathode of tube V2 should be adjusted for the high-frequency end. If the base line spreads out at the high-frequency end it is because there is more capacity between one of the grids and the common plate than the other. A small variable capacitor is added to the low side to make them equal. This is adjusted until the base line becomes single valued at the high frequencies. After this adjustment, the condenser in the cathode of tube V2 may have to be readjusted slightly. The peaking in the plates of tube V1, V3 and V4, and V5 are adjusted to give flat response. These may belater readjusted slightly to give as flat an envelope delay response as possible.

The doubler circuits are tuned in the normal fashion.

The probe is connected to the output with a signal fed to the input, and the circuits in the plates of tubes V13 and V14 and the grid of V14 are tuned for maximum by observing the signal at the amplitude characteristic out or the amplitude meter reading. The circuit in V12 is tuned for maximum by observing the signal at the limiter test point.

With a sweep input and a scope at the envelope delay characteristic output, the tuning of the doubler (the phase control) is adjusted until the sweep is approximately at the same level during sweep as during the blanked off time. The sweep should be adjusted for maximum flatness from about 0.5 Mc and up by slight adjustment of the peaking controls in the plates of the modulator and tube V5. If this adversely affects the amplitude response it should be corrected by adjustment of the peaking in tube V1. Below 0.5 Mc there will be spurious responses due to harmonics generated in the detector adding to the desired signal.

The delay characteristic meter is calibrated by adjusting the "meter 0" potentiometer until the meter reads center scale for no signal input and then the "delay characteristic calibrate" potentiometer adjusted to give exactly full scale or exactly 0 reading at the maximum or minimum possible excursion with a single-frequency input signal (not sweep) and adjustment of the phase control. The device is now ready to use to check the envelope delay characteristic of an amplifier. If the amplification of the amplifier under test is greater than unity the probe gain should be reduced to keep the amplitude characteristic meter on scale. If it is less than unity, additional gain should be provided but the input to the balanced modulator should not be increased. The sweep input should not be raised higher than 0.5 volt peak-to-peak if accurate results are desired. Point-by-point measurements may be made by reading the meter or sweep measurements may be made by using an oscilloscope.

The probe input condenser size is a compromise. For accurate point-by-point measurements to low frequencies without the need for calibrated correction, it should be as large as possible. For following rapid changes in amplitude such as occur when sweeping a low-pass filter a small condenser is desirable. A 3000-μμf condenser is a fair compromise but should be changed for individual situations. An 0.01-μf condenser is used in the probe which is large enough for low-frequency point-by-point measurements. For sweeping, a small condenser should be used in series with this one.

The envelope delay is:

$$T_E = \frac{\Delta\theta}{2\pi\Delta f}$$

If the 1-ma meter reads 0 degrees to 90 degrees from center scale to full scale it reads 0.5 sin Δθ, or if I_m is in ma from center scale

$$2I_m = \sin\Delta\theta; \qquad \Delta\theta = \sin^{-1} 2I_m$$

therefore

$$T_E = \frac{\sin^{-1}2I_m}{2\pi\times 200\times 10^3} = 0.798\ (\sin^{-1}2I_m)\times 10^{-6}$$

Since for small angles sin θ = θ if θ is in radians

$$T_E \cong 0.80\times 2I_m\times 10^{-6}$$

this is quite accurate in the range between -0.3 to +0.3 microsecond, being in error by less than 0.01 microsecond. Since the scope measures this 0 to ±0.5-ma current as the voltage across a 10K resistor

$$T_E \cong 0.16V_s\times 10^{-6}$$

in the range ±2 volts.

For larger delays the full formula must be used for accurate results.

$$T_E = 0.798(\sin^{-1}2I_m)\times 10^{-6} = 0.1596(\sin^{-1}V_s)\times 10^{-6}$$

The meter or scope can of course be calibrated directly in microseconds.

Results

Several devices were measured by other methods and then with this equipment point by point. Some of the results are shown in Figs. 4

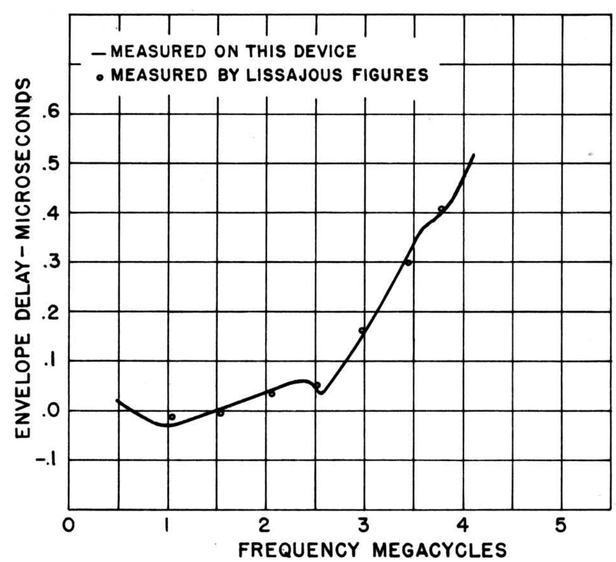

Fig. 4 - Envelope delay of a television receiver.

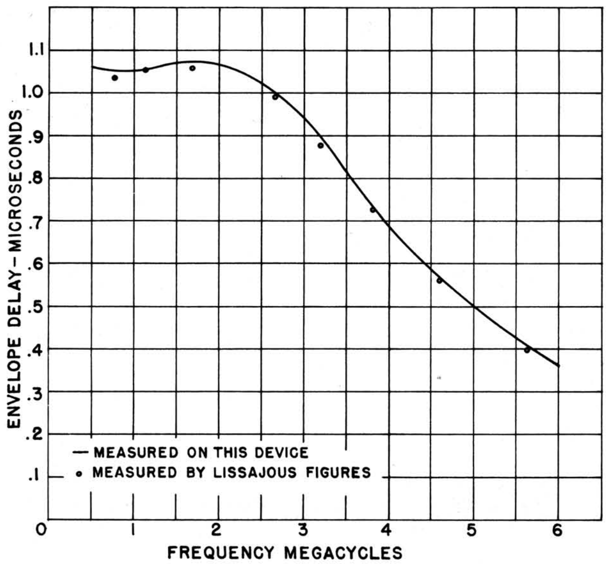

Fig. 5 - Envelope delay of phase correcting circuit.

and 5. It can be seen that they agree within about 0.01 μsec. Most other methods of measuring phase give readings at certain discreet frequencies only, whereas, with this device, any frequency can be used. This makes it possible to find variations between the discreet frequencies which would be missed by the other methods. Fig. 4 shows a variation of this type near 2.5 Mc. Fig. 6 shows two oscillograms of characteristics of circuits taken with a sweep input.

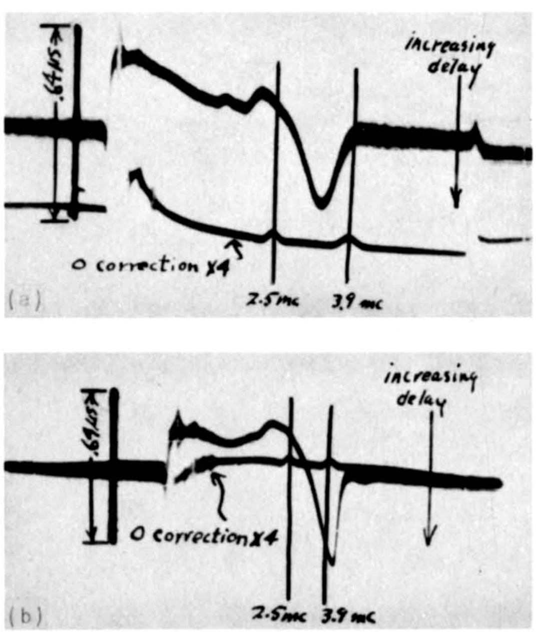

Fig. 6 - Oscillograms of the envelope delay characteristics of two television receivers.

Receivers are measured by modulating a Mega-Pix or other modulator at r.f. with the output of this device, and connecting the probe to some point after the second detector depending on how much of the video is to be measured.

When measuring a receiver, the harmonics of line frequency near 200 kc cause some trouble but usually only outside the band being measured where the limiter is not effective.

Since this experimental equipment is rack mounted, the probe lead was extended with additional coaxial cable to reach the receiver circuits and the input circuit retuned to 200 kc. This caused some small peaks in the characteristic due to the long ground.

Possibilities for Future Development

Since this equipment is experimental there are a number of things which could be done differently if another circuit were built. For instance, there is no need for the extra positive bias on the two modulators over that required for proper biasing. The 100-kc input to the balanced modulator could be reduced in ways other than loading the primary of the transformer with 47 ohms. Other types of oscillators might be used. Other limiters might be used.

In addition to this type of change, there are others which might improve the operation in one respect or another. For instance, the frequency difference might be lowered so that greater resolution would be obtained and also readings at lower frequencies could be used. This would reduce the accuracy unless the reference and unknown frequencies were both multiplied up before application to the detector modulator. These multipliers would also help to limit any amplitude changes.

The oscillator could be locked to horizontal so that the output signal could be blanked and fed through equipment using clamps.

For use of the equipment where the detector must be remote from the input, the reference phase must be reconstructed from the signal itself. This cannot be done point by point but must be done when using a sweep. One way of doing this is with an a-f-c circuit whose response is so slow that it ignores changes in phase during the sweep. Another way is to feed the signal into a narrow filter which ignores the sweep frequency sidebands.

Instead of using a reference signal one can measure the frequency changes of the 200-kc signal with time as the input is swept through the frequency range by putting this 200-kc signal through a discriminator. By converting this information to phase changes of the 200-kc signal by integration one gets a signal corresponding to envelope delay. A second integration would give phase response. (Integration of the signal out of the phase detector modulator would also give phase response.)

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