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Characteristics of and suggested improvements in communication laboratory equipment at University of Missouri-Rolla

William Edgar Abernathie

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CHARACTERISTICS OF AND SUGGESTED IMPROVEMENTS IN COMMUNICATION LABORATORY EQUIPMENT AT UNIVERSITY OF MISSOURI - ROLLA

BY

WILLIAM EDGAR ABERNATHIE, 1947-

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1971

Approved by

William H. Frank (Advisor)
Abstract

This paper documents characteristics of and suggests improvements in Communication Laboratory Equipment built at the University of Missouri at Rolla. Included are Voltage Controlled Oscillators, Discriminators, Operational Amplifiers, and Multipliers. The graduate and undergraduate laboratory student thus has available equipment characteristics and, when building higher performance equipment, improvement suggestions.
Acknowledgement

The author wishes to express appreciation to Dr. William H. Tranter for suggestion of this thesis and encouragement in its preparation.

Appreciation is also extended to Richard Schroeder for his technical assistance and to Barbara Byrd for her typing.
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I. Introduction

The Communication Laboratory at the University of Missouri at Rolla has been building its own equipment, thereby eliminating the cost of buying it commercially and still providing the laboratory student with a sufficient quantity and quality to demonstrate communication principles. The equipment is normally simple in design and construction. Utilized are discrete components, integrated circuits, or a combination of both. This keeps parts and labor cost to a minimum yet makes repair and maintenance simple.

The finished circuits are normally mounted in a 5" X 7" aluminum chassis box with controls and adjustment potentiometers being mounted on or below the chassis surface. Circuit connections are terminated in banana jacks as is the DC power available at the laboratory bench. All interconnections are accomplished by use of banana plug jumpers color coded by length. Adaptors converting oscilloscope, waveform generators, spectrum analyzers, etc., to banana plugs are also provided.

When the prototype of this communication laboratory equipment was built, the circuit diagram and some operating data were recorded by the EE Department's technician. This is the only information available and it is not readily accessible to the laboratory student for guidance in using the equipment. Experimental communication research also uses this equipment and requires an idea of its limitations. Therefore, a need exists to provide the laboratory student with equipment specifications plus an understanding of circuit operation, and to provide the researcher with equipment specifications plus ideas on how to redesign for better performance. This paper hopes to fulfill this need.
for Voltage Controlled Oscillators, Discriminators, Operational Amplifiers, and Multipliers.
II. Review of Literature

The University of Missouri at Rolla seems to be in general agreement with other universities in its philosophy of the Communication Laboratory. The Georgia Institute of Technology\textsuperscript{1}, the Polytechnic Institute of Brooklyn\textsuperscript{2}, \textsuperscript{3}, and the University of Rochester\textsuperscript{4} all generally agree that:

1) the undergraduate laboratory should illustrate the principles of communications without overwhelming the student with practical applications, hence frequencies below five megahertz are used. The practical applications and circuit design are left to the graduate laboratory.

2) the laboratory is project oriented so that less equipment need be bought or built; only one group is conducting a particular experiment instead of the entire laboratory.

and 3) that the laboratory equipment is used for undergraduate projects and graduate research, besides being used by the laboratory student.

In the building of their equipment however, they differ. The Georgia Institute of Technology has built small pieces of equipment, but instead of mounting each in a box, has placed them all in what they call a Communications Simulator. It contains: three input summers, multipliers, a 100 KHz discriminator, attenuators, a diode detector, a 1 KHz and a 100 KHz 90° all pass shifting network, an analog comparator, and an assortment of logic circuits. BNC connectors are used to jumper circuits and all outputs are clamped to five volts and short circuit protected.

\textsuperscript{1}Superscripts refer to numbered references.
The University of Rochester has built complex equipment: a Fourier Synthesizer, a Relay Correlator, and a Parametric Display Unit.

The Polytechnic Institute of Brooklyn builds both simple and complex equipment. The complex equipment is prebuilt while some of the simpler equipment is built as part of an experiment in a graduate communication laboratory. The equipment includes: a 455 KHz Filter, a FM Generator with frequency deviation meter and a limited range sine wave output, a Probability Density Machine, a Logic Circuitry Box, a Clarke and Hess Discriminator, a Comparator, a Pulse Width Modulator, a Pulse Width to Amplitude Converter, and a Fading Channel Simulator.
III. Discussion and Results

A. Measurements

The following four sections of Discussion and Results will give descriptions and specifications of the Voltage Controlled Oscillator, the Discriminator, the Operational Amplifier, and the Multiplier. No comments are made on the measuring procedures in these sections since all measurements are straight-forward. The only instruments required are: an oscilloscope, a DC meter, a frequency counter, a ten-turn potentiometer, and a multifunction generator with a variable DC offset.

When more than one of a particular device is available, curves are given for only one device, but all other devices are checked against these curves to verify that they are similar. Values in the specification table are averages.

Several observations were made while taking measurements, and they are given below:

1. Voltage Controlled Oscillator

   Be sure to apply input attenuation when using the frequency counter, since overdriving its input will give erroneous readings.

2. Discriminator

   If the oscilloscope probes are connected to both the discriminator input and output, the oscilloscope can cause an overshoot in the input square wave resulting in large amplitude spikes in the discriminator output. These spikes produce output noise voltages in the discriminator output an order of magnitude higher than noise levels normally expected.
3. Operational Amplifier

The DC offset control does not function when the amplifier is operated open loop. The variable DC offset of the multifunction generator must be used to zero the output. When the generator offset is insufficient to zero the op amp output, measurements of the open loop gain are impossible since adding DC via a ten-turn potentiometer induces too much sixty-cycle hum.

An additional ten to twenty dB attenuation is needed, besides the -60 dB provided by the multifunction generator, to prevent saturation of the op amp when the open loop gain is measured.

When using the op amp as an integrator, the zero control is not sensitive enough to hold the output about zero. Instead, the output nearly zeros about one of the power supply voltages.

4. Multiplier

If the differential outputs of a multiplier are to be combined by an oscilloscope using the algebraic adding of A and B inputs, with one input inverted, the inputs must be set to AC if the DC output levels of the discriminator output far exceed the AC components. Failure to do this will drive the oscilloscope amplifiers into saturation and make voltage readings inaccurate.

B. The Voltage Controlled Oscillator

The Voltage Controlled Oscillator (VCO) is an oscillator whose frequency can be varied by a control voltage. For a sinusoidal oscillator, the output can be represented by \( V_o = \sin(2\pi f_t V_c) \), where \( f_t \) is a frequency deviation constant in Hertz per volt. Its uses include voltage-to-frequency conversion, frequency modulation (FM), phase modulation (PM), and demodulation as part of a phased-locked loop.
The VC0s in the laboratory are of two types, each with terminals for input, output, and timing capacitors. Both models are astable multivibrators whose output frequency can be linearly varied by a control voltage. When the input is zeroed however, they have an output frequency other than zero--their center frequency. The models are easily distinguished since Model 1 has a black chassis where Model 2 has a silver chassis. They further differ in their placement of terminals and adjustment potentiometers.

1. Model 1 (See Figure 1)

Model 1 is an astable multivibrator, composed of transistors Q1 and Q2. Its center frequency is controlled by the timing capacitors C1 and C2. Transistors Q3 and Q4 have replaced the base driving resistors of the multivibrator and act as voltage controlled current sources. These in turn are driven from the input buffer amplifier composed of transistors Q5 and Q6. As the input voltage varies so does the current and hence the charging times of the timing capacitor. This causes the frequency of the multivibrator to vary with the input control voltage. The output of the astable is coupled to a flip-flop, formed from transistors Q7 and Q8, for improvement of waveshape and output amplification.

If one or both of the timing capacitors are removed while the power is on, the astable will block--that is both transistors Q1 and Q2 will turn on and oscillation will cease. To restart the oscillator, momentarily disconnect one of the power leads. Blocking can also occur if the input is driven below a negative ten volts. Lowering the input voltage and momentarily disconnecting a power supply lead will restart the oscillator.
Due to the high input impedance of the input buffer amplifier, the leakage current of transistors Q5 and Q6 causes a voltage to appear on the input terminals. As the transistors warm up, the leakage increases, generates a larger input offset voltage, and causes a drift in the center frequency. The amount of drift will be the offset voltage times the frequency deviation constant, $K_f$. For this reason, the center frequency should be measured with the input terminals shorted. This drift and input offset voltage can be lowered by reducing the input impedance, or by driving the input from a low impedance source.

The symmetry control is incorporated into the network coupling the astable and the flip-flop. It should be adjusted each time a different set of timing capacitors is used to eliminate error due to capacitor tolerance.

The output of the VCO is a square wave with levels from ground to a positive voltage. This gives the output a DC component of one half of the positive swing. If the VCO is to drive a load which cannot tolerate this DC level, a capacitor should be placed in series with the positive VCO output terminal and the load.

2. Model 2 (See Figure 2)

Model 2 is similar to Model 1 in that transistors Q1 and Q2 form an astable multivibrator whose center frequency is determined by the timing capacitors C1 and C2. The base driving resistors have again been replaced by voltage controlled current sources, transistors Q3 and Q4. These are driven by the input buffer amplifier formed by the transistors Q5 and Q6. Here, as in Model 1, the input voltage varies the charging current to the timing capacitors causing the
multivibrator frequency to vary as the input control voltage. In addition, Model 2 has: diodes D5 and D6 to increase the reverse base to emitter breakdown voltage of transistors Q1 and Q2; diodes D1 and D2 for leading edge improvement; and transistors Q7, Q8, and Q9 along with the diodes D3 and D4 for anti-block circuitry. The output of the astable is coupled through transistors Q10 and Q11 for buffering and then to the low impedance output amplifier formed by transistors Q12, Q13, and Q14 plus diode D7. Capacitive coupling the output amplifier to the load removes the DC component.

The input buffer amplifier has an input voltage offset control so that no bias voltage appears at the input terminals. When properly adjusted, no change in center frequency will be noticed from open circuited to short circuited input. This control has limited effectiveness at high input impedances (greater than 100K ohms), since the leakage current from transistors Q5 and Q6 eventually overrides any setting. By lowering the 360K ohm and 300K ohm resistors to 50K ohms, the input impedance is reduced to approximately 25K ohms and the potentiometer can maintain a zero offset.

The symmetry control in Model 2 unbalances one of the voltage controlled current sources. This allows a wide range of variation, but also changes the output frequency upon adjustment. A dual potentiometer, controlling the quiescent current of the voltage controlled current sources, allows the center frequency to be varied.

The anti-block circuit will restart the oscillator if any of the timing capacitors are removed while the VCO is connected to the power supply; up to an output frequency of about 600 KHz. Above this frequency, a power supply lead must be momentarily disconnected as described for Model 1.
Model 2 also contains power supply filtering capacitors and reversed power supply protection diodes.

3. Operational Check

To determine if the VCO is operational, connect a low frequency sinusoidal signal to the input. When viewed on an oscilloscope, the period at output square wave should be seen to expand and contract at the frequency of the input.

If the center frequency of the VCO is above 100 KHz, a quicker method can be used to determine if the VCO is operational. Display about ten periods of the VCO output on an oscilloscope and then place a pair of fingers across each of the timing capacitors. The last few periods of the VCO output should appear "fuzzy" if the VCO is operating correctly.

If the VCO is not oscillating, try adjusting the symmetry control. Too large or small of a duty cycle can prevent the multivibrator from oscillating.
4. Specifications

Table 1. Specifications of the Voltage Controlled Oscillator

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<tr>
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<tr>
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<td>Fig. 3</td>
<td>Fig. 3</td>
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<td>Output Frequency vs Input Voltage</td>
<td>Fig. 4</td>
<td>Fig. 5</td>
</tr>
<tr>
<td>Input Voltage for Linear Output</td>
<td>5 V</td>
<td>5 V &lt;500 KHz</td>
</tr>
<tr>
<td>Frequency Deviation</td>
<td>15%</td>
<td>12% ccw, 14% cw &lt;500 KHz</td>
</tr>
<tr>
<td>Drift per 5 min. after warm up</td>
<td>.3%</td>
<td>.6%, .06% when Rin=25K</td>
</tr>
<tr>
<td>Duty cycle Error from a 150 KHz square wave</td>
<td>-4% @ +5 v</td>
<td>-1% ccw, -1% cw @ +5 v</td>
</tr>
<tr>
<td>Limit of Oscillation for fair output waveform</td>
<td>400 KHz</td>
<td>1.5 MHz</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>100K ohms</td>
<td>150K ohms</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>1K ohms</td>
<td>25 ohms</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>7.6 V</td>
<td>13.5 V</td>
</tr>
<tr>
<td>Frequency change with load</td>
<td>.07%</td>
<td>.0%</td>
</tr>
<tr>
<td>@ 1K ohms</td>
<td>.07%</td>
<td>.0%</td>
</tr>
<tr>
<td>@ 100 ohms</td>
<td>.17%</td>
<td>.007%</td>
</tr>
<tr>
<td>@ 50 ohms</td>
<td>.24%</td>
<td>.007%</td>
</tr>
<tr>
<td>@ 10 ohms</td>
<td>---</td>
<td>.07%</td>
</tr>
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*cw--full clockwise rotation
ccw--full counter-clockwise rotation
Figure 1. Circuit Diagram for the Voltage Controlled Oscillator, Model 1
Figure 2. Circuit Diagram for the Voltage Controlled Oscillator, Model 2
Figure 3. Center Frequency vs. Timing Capacitors for Models 1 and 2 VCOs (both clockwise cw and counter-clockwise ccw positions of Model 2's Frequency Adjust shown)
Figure 4. VCO Model 1, Output Frequency vs. Input Voltage
Figure 5. VCO Model 2, Output Frequency vs. Input Voltage (both clockwise cw and counter-clockwise ccw positions of Frequency Adjust shown)
C. The Discriminator

The Discriminator is a frequency-to-voltage converter. It can detect the modulation on a frequency modulated carrier, such as a VCO output. If \( \sin(2\pi f K_f V_c) \) is applied to the input of the discriminator, it will output \( K_d K_f V_c \) where \( K_d \) is a discriminator constant in volts per Hertz.

Since the VCOs in the laboratory are square wave generators, and a limiter will be recommended, all measurements on the discriminator will be made with square waves.

1. Model 1--labeled RS Discriminator* (See Figure 6)

Consider a frequency modulated carrier applied to the input of the RS Discriminator. First the input is buffered by the input amplifier, transistor Q1, and then converted to an amplitude modulated (AM) signal by capacitor C1. This capacitor is chosen to drop several volts at the center frequency of the input carrier. As the carrier frequency changes due to the modulating signal, the voltage drop across capacitor C1 also varies because the reactance of the capacitor is frequency dependent. This AM signal is then detected by the voltage doubling rectifier circuit composed of diodes D1 and D2 plus capacitors C1 and C2. The filtering capacitor C2 references the DC level of the voltage doubler output to ground. To allow the output of the discriminator to be zeroed at the center frequency, the DC level is shifted and the carrier further removed by the network composed of transistors Q2, Q3, and Q4. From here, the signal is then passed through the output filter and finally buffered by transistor Q5.

A major carrier frequency filter is capacitor C2. Therefore,

*Named for designer, EE Dept. technician--Richard Schroeder.
C2 should be large to remove as much of the carrier as possible, but small enough to avoid filtering the signal appreciably. Figure 7 shows the effect of C2 on the output noise voltage which is primarily due to attenuated carrier components. A reasonable value for C2 would appear to be about two to five times C1. As also noted from the figure, the noise is proportional to the input carrier frequency—being a minimum around 350KHz. Although this minimum may appear to be a function of the capacitor C1, the zero output control shifts the center frequency for a chosen C1, but will not appreciably affect the noise voltage level. To determine an approximate noise level, locate on Figure 7a the value of C1 for the center frequency used; regardless of the actual value of C1. Intersect this value of C1 with the set of noise curves, then read the value for the chosen C2 curve.

The DC level shifting network contains the zero control which allows the output to be zeroed for a particular center frequency. This level shifting however, causes a DC level to appear on the output terminal when no input is applied.

Figure 8 shows the range of center frequencies possible for given input amplitude using C1 = 150pf and C2 = 300 pf. The figure also shows that input thresholds of the RS discriminators can range from one to three volts.

2. Model 2—labeled CH Discriminator* (See Figure 9)

The CH Discriminator uses a pulse averaging technique instead of the AM conversion used in the RS Discriminator. A frequency modulated input is first buffered by the input amplifier composed of transistors Q1 and Q2 plus diodes D1 and D2, and then fed into two

*Named for designers, Clarke and Hess.
networks. The first network contains a capacitor whose reactance
drops several volts at the center frequency, and the second network
contains a potentiometer plus a capacitor which drops very little
voltage at the center frequency. Each network drives a diode-transistor
switch whose duty cycle depends on the network output voltage. The
first network's switch pulls the output voltage to the positive
supply, while the second network's switch pulls the output voltage
to the negative supply. Hence, the switch that is on the longest
will determine the polarity of the output voltage. As the modulating
signal varies the center frequency, the voltage drop in the first
network changes thereby varying the duty cycle of its switch. The
voltage drop in the second network doesn't change, however, its
potentiometer can be used to balance the first and second networks'
output voltages thereby zeroing the DC output level. Notice that
since the two switches must be biased on, no DC voltage appears
at the output when no signal is applied to the input. Since the
switches are switching at the carrier frequency, the output is fed
through an output filter to remove the carrier and then connected
to the output terminals.

Figure 10 shows the range of center frequencies possible for
a given input amplitude and, the threshold of the CH Discriminator
to be about one volt.

3. Operational Check

To determine if the discriminator is operational, apply an
input greater than the threshold voltage and of such frequency as to
allow the discriminator to be zeroed. Now with an oscilloscope or
DC meter on the output, vary the input frequency. The discriminator
is working if the output DC level varies with the input frequency.
4. Limiter

To reduce the sensitivity of the discriminators to input amplitude variations, a hard limiter was tried. By using the circuit in Figure 11, the results in Figure 12 were obtained. The limiter lowered the threshold of the discriminators and reduced their sensitivity to input amplitudes, but did not eliminate it.
5. Specifications

Table II. Specifications for the Discriminator

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<th>CH</th>
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<td>Fig. 13</td>
<td>Fig. 14</td>
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<td>Linear Output Swing @ 9 v input</td>
<td>2 v (fair to 6 v)</td>
<td>2 v</td>
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<td>@ 4 v input</td>
<td>1 v</td>
<td>2 v</td>
</tr>
<tr>
<td>Discriminator Constant Kd - volts/KHz @ 150 KHz</td>
<td>.43</td>
<td>.03</td>
</tr>
<tr>
<td>@ 9 v input</td>
<td></td>
<td>.03</td>
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<tr>
<td>@ 4 v input</td>
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<td>Threshold Voltage</td>
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<td>@ 9 v and 160 KHz Input Duty Cycle</td>
<td>1-3 v</td>
<td>1 v</td>
</tr>
<tr>
<td>@ 9 v input</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Impedance</td>
<td>40K ohms</td>
<td>12K ohms</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>700 ohms</td>
<td>10K ohms</td>
</tr>
<tr>
<td>Noise in Output @ 9 v input</td>
<td>Fig. 7</td>
<td></td>
</tr>
<tr>
<td>@ 100 KHz</td>
<td>.3 v pp</td>
<td>1.1 v pp</td>
</tr>
<tr>
<td>@ 160 KHz</td>
<td>.08 v pp</td>
<td>.8 v pp</td>
</tr>
<tr>
<td>@ 200 KHz</td>
<td>.04 v pp</td>
<td>.7 v pp</td>
</tr>
</tbody>
</table>
Figure 6. Circuit Diagram for the RS Discriminator
Figure 7a. RS Discriminator, Capacitors C1 and C2 vs. Input Center Frequency (@ 9 v input)

Figure 7b. RS Discriminator, Capacitors C1 and C2 vs. Output Noise Voltage (@ 9 v input)
Figure 8. RS Discriminator, Zero Control Range for Center Frequency and Input Amplitude ($C_1=150$ pf, $C_2=300$ pf) (cw—full clockwise rotation, ccw—full counterclockwise rotation of zero control) (Equipment variation range shown by solid and dotted curves)
Figure 9. Circuit Diagram for the CH Discriminator
Figure 10. CH Discriminator, Zero Control Range for Center Frequency and Input Amplitude (cw—full clockwise rotation, ccw—full counterclockwise rotation of zero control)
Figure 11. Limiter Circuit Diagram
Figure 12. Output Voltage vs. Input Amplitude for RS and CH Discriminators using Limiter
Figure 13. RS Discriminator, Output Voltage vs. Input Frequency and Input Amplitude (C1=150 pf, C2=300 pf)
Figure 14. CH Discriminator, Output Voltage vs. Input Frequency and Input Amplitude
Figure 15. Output Voltage vs. Duty Cycle for RS and CH Discriminators (@ 9 v, 160 KHz)
D. The Operational Amplifier

The Operational Amplifier (op amp) is an amplifier that can be idealized by infinite input impedance, zero output impedance, infinite gain, and infinite bandwidth. These characteristics cause the op amp to be highly linear when feedback is applied. Some of the uses of the operational amplifier are: fixed gain amplifiers, summing amplifiers, integrators, differentiators, limiters, comparators, function generators, and active filters.

In the laboratory, there are two types of operational amplifiers; one using an Intrinsics Model A101 integrated circuit, and one using a Model 709 integrated circuit. Each has terminals for: an output, a feedback element, two inputs, two series elements, and power supply (See Figures 16 and 17). Both amplifiers also have an adjustment potentiometer for eliminating the DC in the output with no input present. The Model A101 and Model 709 can be distinguished by looking under the chassis; the 709 is a fourteen pin dual in-line package, the A101 a 1 1/2 inch square package.

Typically the series resistors should range from 100 to 100K ohms, feedback resistors from 1K to 1M ohms, and the gain should be below 100.

1. Theory

In the laboratory, the major uses of the operational amplifier are fixed gain amplifiers, summing amplifiers, and integrators. Their theory follows.

In doing any work with the operational amplifier, the characteristics of infinite input impedance and infinite gain must be kept in mind. If voltage $E_i$ is applied to the inverting terminal of an op
amp through a series resistor $R_i$, (See Figure 18), the input current $I_i$ will be $I_i = (E_i - E_s)/R_i$ where $E_s$ is the voltage at the input of the op amp. The output voltage, $E_o$, will be the gain of the amplifier, $A$, times the voltage $E_s$; $E_o = AE_s$. If the current into the op amp is assumed to be zero due to the infinite input impedance, then the feedback current must cancel the input current; $I_i = -I_o = (E_i - E_s)/R_i = (E_o - E_s)/R_f$. By replacing $E_s$ by $-E_o/A$, solving for $E_o/E_i$, and letting $A$ go to infinity so that the $E_s$ term goes to zero, $E_o/E_i = -R_f/R_i$. Therefore, to use the op amp as a fixed gain amplifier, simply make the ratio $R_f/R_i$ be the desired gain.

To sum several inputs, each with its own gain, pick $R_f$ and then $R_{i1}, R_{i2}, \ldots, R_{in}$ so that the ratio $R_f/R_i$ is the desired gain. The feedback current must cancel the input currents, so the output voltage must be the sum of $R_f/R_i$ times the input voltages. Since the $E_s$ term is approximately zero, no inner action occurs between the inputs. Note that the gain of the op amp does not always have to be greater than one, it can also be used as an attenuator.

Also, the series and feedback elements are not limited to resistors. If $Z_f$ is made to be a capacitor and $Z_i$ to be a resistor, an integrator is formed. The voltage across the capacitor equals $E_o - E_s = \int (I_c/C) dt$, but since the feedback current must cancel the input current, $I_c = -(E_i - E_s)/R_i$. Again replacing $E_s$ by $-E_o/A$, and letting $A$ go to infinity so that the $E_s$ term goes to zero, the op amp output voltage equals the integral of the input voltage; $E_o = -(1/CR_i) \int E_i dt$.

2. Circuit Description

A simple operational amplifier would be composed of approximately four stages. The first stage is a differential amplifier for direct
coupling, high gain, and high input impedance. The second stage is another differential amplifier for more gain and high impedance so as not to load the first stage. The third stage is a level shifter to match the output voltage levels to the fourth stage; the low output impedance amplifier.

Also important to the op amp is its slewing rate; the maximum rate of change of output voltage with time. This effect is similar to the rise or fall times, but since the voltage response is the desired quantity, not the time response, the term slewing rate is used. Most op amps are limited in their frequency range not by frequency response, but by slewing rate. To use the operational amplifier at higher frequencies, the output voltage swing must be lowered. Use the slewing rate conservatively or the output will start to resemble a triangular waveform.

3. Operational Check

If the zero control cannot bring the op amp output voltage to within a couple of volts of ground when series and feedback elements are inserted, the operational amplifier is bad.

If zero output can be obtained, an input signal should be amplified by the ratio of \( R_f/R_i \) or squared by amplifier saturation if the op amp is working.
4. Specifications

Table III. Specifications of the Operational Amplifier

<table>
<thead>
<tr>
<th>Specification</th>
<th>A101</th>
<th>709</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Impedance</td>
<td>200K ohms</td>
<td>170K ohms</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>330 ohms</td>
<td>900 ohms</td>
</tr>
<tr>
<td>Output Voltage Swing</td>
<td>10 v</td>
<td>14 v</td>
</tr>
<tr>
<td>10 Volt Output Frequency</td>
<td>18 KHz</td>
<td>50 KHz</td>
</tr>
<tr>
<td>Slewling Rate</td>
<td>.9 v/us</td>
<td>2.8 v/us</td>
</tr>
<tr>
<td>Maximum Frequency For Gain of 1 @ 1v</td>
<td>200 KHz</td>
<td>800 KHz</td>
</tr>
<tr>
<td>Maximum Integrator Frequency</td>
<td>10 KHz</td>
<td>20 KHz</td>
</tr>
</tbody>
</table>
Figure 16. Wiring Diagram for the 709 Operational Amplifier
Figure 17. Wiring Diagram for the A101 Operational Amplifier
Figure 18. Diagram for Operational Amplifier Theory
E. The Multiplier

The multiplier is a circuit that performs the mathematical operation of multiplication upon two signals; \( E_0 = K(E_1)(E_2) \) where \( K \) is again constant. Multipliers are used for: Amplitude Modulators (AM), Double Sideband Modulators (DSB), Phase Detectors, Synchronous Detectors, Choppers Frequency Doubler, and Electronic Gain Controllers.

The laboratory contains three different multipliers: an Intronics Model M410 integrated multiplier, a Motorola MC1596 integrated balanced modulator-demodulator, and a 136C integrated modulator-demodulator. The modulator-demodulator is a multiplier, but only works with low level signals.

The 136C is distinguishable from the other two multipliers since its chassis is smaller--4" X 6". The M410 and MC1596 can be distinguished by looking under chassis; the M410 is a 1½" square package, the MC1596 a ten pin TO-5 package.

1. Theory

Multiplier operation can be accomplished in a number of ways:
by taking the log of the inputs, summing, and then taking the antilog;
by using the inputs to generate pulses proportional to the output product and then averaging; and by using a differential amplifier to ratio currents. The multipliers in the laboratory are not of the log-summer-antilog type due to their high operational frequency. Nor are they the time averaging type of multiplier since the integrated circuit is too small to contain filtering capacitors. The circuit diagram of the MC1596 verifies that it is of the current ratioing type, while the M410 and the 136C can reasonably be assumed of this type also although no circuit diagrams are available.
In the current ratioing method, one input controls the current source of a differential amplifier while the other input is amplified by the differential amplifier (See Figure 19). The gain of the differential amplifier is proportional to the emitter current, hence multiplication.

The transistor current \( I = (I_s)(e)\exp(qV_{be}/kt) \)

Giving \( dI = (I_s)(qV_{be}/kt)(dV_{be})(e)\exp(qV_{be}/kt) \)

If the quiescent \( V_{be} \) voltages are assumed to be equal, then \( I_0 = I_1 + I_2 = (2I_s)(e)\exp(qV_{be}/kt) \)

and then \( dI_1 - dI_2 = (q/2kt)(dV_{be1} - dV_{be2}) = (q/2kt)(e1) \)

\( dE = R(dI_1 - dI_2) = \omega = (Rc)(q/2kt)(I_0)(e1) \)

\( \omega = (Rc)(q/2kt)(a)(e2)(e1) = (e1)(e2)/K \)

where \( K \) is a constant

2. Circuit Description

As seen in Figure 20, the multiplier circuit diagram, the MC1596 multiplier is of the current ratioing type. Two cross-coupled differential amplifiers are used to reduce temperature variations.

The M410 (See Figure 21) is adjusted for multiplier operation by:

1) grounding the X input, inputting a 20 v pp sine wave on the Y input, and adjusting the \( X0 \) potentiometer for minimum output.

2) grounding the X and Y inputs, then adjusting the \( 00 \) potentiometer for zero DC output.

3) placing 10 volts on both the X and Y inputs, then adjusting the G potentiometer for 10 volts output.

The integrated circuit multiplier 136C (See Figure 22) is adjusted for multiplier operation by:
1) grounding the signal input and then adjusting the signal input potentiometer, the one closest to the signal input terminal, for minimum AC output.

2) grounding the carrier input and then adjusting the carrier input potentiometer, the one closest to the carrier input terminal, for minimum AC output.

3) repeating 1) and 2) till minimum AC output is obtained.

The multiplier using integrated circuit MC1596 (See Figure 23) is adjusted by grounding the signal input and using its offset control to zero the AC output. If this is not sufficient, DC may be fed in with the carrier to act as another adjustment potentiometer as in the 136C integrated circuit.

The AC output is used since no offset potentiometer zeros the output DC level, and the signal output should be zero when an input is grounded.

The multiplier adjustment procedure is the same procedure for setting the MC1596 and 136C modulator-demodulators for DSB modulation. By turning the signal offset control, a DC level will be added to the signal input and will change the multiplier from DSB to AM modulation. The DC input can also be added to the 136C multiplier via its bias terminal.

3. Operational Check

A simple test to determine if the multiplier is working is to apply the same input to both the X (signal) and Y (carrier) inputs. The output should look like a full wave rectified signal when observed on an oscilloscope. Using the multiplier as a DSB or AM modulator can also serve as an operational check.
If large signal levels are to be applied to the MC1596 and the 136C multipliers, use series resistors to keep the inputs below the specifications ratings.
4. Specifications

Table IV. Specifications for the Multiplier

<table>
<thead>
<tr>
<th>Specification</th>
<th>M410</th>
<th>136C</th>
<th>MC1596</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X or Signal</td>
<td>AC,DC</td>
<td>AC,DC</td>
<td>AC</td>
</tr>
<tr>
<td>Y or Carrier</td>
<td>AC,DC</td>
<td>AC,DC</td>
<td>AC,DC</td>
</tr>
<tr>
<td><strong>Input Resistance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X or Signal</td>
<td>30K ohms</td>
<td>200 ohms</td>
<td>600 ohms</td>
</tr>
<tr>
<td>Y or Carrier</td>
<td>20K ohms</td>
<td>100 ohms</td>
<td>60 ohms</td>
</tr>
<tr>
<td><strong>Maximum Input Voltages</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X or Signal</td>
<td>10 v</td>
<td>.6 v</td>
<td>3 v</td>
</tr>
<tr>
<td>Y or Carrier</td>
<td>10 v</td>
<td>.2 v</td>
<td>.2 v</td>
</tr>
<tr>
<td><strong>Output Resistance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300 ohms</td>
<td>2K ohms</td>
<td>8K ohms</td>
</tr>
<tr>
<td><strong>Maximum Useful Frequency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 MHz</td>
<td>1 MHz</td>
<td>1 MHz</td>
</tr>
<tr>
<td><strong>Linear Range</strong></td>
<td>Fig. 24</td>
<td>Fig. 25</td>
<td>Fig. 26</td>
</tr>
<tr>
<td>as Multiplier</td>
<td>10 v</td>
<td>.1 v</td>
<td>.15 v</td>
</tr>
<tr>
<td>Multiplier Constant</td>
<td>.1</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>
Figure 19. Diagram for Multiplier Theory\textsuperscript{8}
Figure 20. Circuit Diagram for the Multiplier MC1596
Figure 21. Wiring Diagram for the Multiplier M410
Figure 22. Wiring Diagram for the Multiplier 136C
Figure 23. Wiring Diagram for the Multiplier MC1596
Figure 24. Multiplier M410 used to square input (same signal on both inputs), Output Voltage vs. Input Voltage
Figure 25. Multiplier 136C used to square input (same signal on both inputs), Output Voltage vs. Input Voltage
Figure 26. Multiplier MC1596 used to square input (same signal on both inputs), Output Voltage vs. Input Voltage
IV. Conclusions

It is felt that the figures, curves, and specifications, of the preceding section, provide a complete description of the voltage controlled oscillators, discriminators, operational amplifiers, and multipliers used in the laboratory. This information should be of value to both the graduate and undergraduate who uses this equipment. It is still possible however, to add additional bits of information for the student who requires higher performance equipment and is trying to build it himself. This information plus comments on the laboratory bench will be listed in the next five sections.

A. Voltage Controlled Oscillator

Model 1 can be improved by using the output amplifier of Model 2. This would make their performance approximately equal.

Model 2 can be operated up to 8 MHz if the timing capacitors are soldered directly to the printed circuit board.

A better grade of PNP transistor for the voltage control current sources in Model 2 should improve its linearity.

The drift can be reduced by using a differential input amplifier, and the frequency stability can be improved by using a current mode astable multivibrator.

B. Discriminator

The CH Discriminator would probably prove to be the better discriminator if it had the filtering and the output amplifier of the RS discriminator.

The RS Discriminator noise could be further reduced by using a full wave rectifier to detect the AM instead of the voltage doubling rectifier.
The limiter should be added to each discriminator to reduce its sensitivity to input amplitude and lower its threshold voltage. The limiter in Figure 11 was limited in performance since the discriminator input capacitor would extend the trailing edge of the limiter output. This has the same effect on the discriminator as changing the input duty cycle. As the input voltage to the limiter increased, more power was available at its output and this duty cycle effect was less noticeable. It was still possible, however, to obtain 9 volts output for .04 volts input from the limiter.

If diodes to limit the input to the limiter were added, along with more gain and a capacitor driving output stage, limiter performance should be substantially improved.

C. The Operational Amplifier

The zero control for the 709 op amps only provides a negative adjustment voltage. Because of this, some of the op amps cannot be zeroed. Adding a positive diode voltage drop to the range of the zero control should correct this.

The input wires of the op amps were not made as short as possible and hence they pick up hum. They should be shortened.

The A101 op amps should have their non-inverting terminals made available to allow them to be used as high impedance buffers and as differential inputs to convert multipliers to single ended outputs. Diodes could be placed across the A101 inputs for protection.

D. Multipliers

The 136C and MC1596 multipliers outputs should be connected to differential inputs of an op amp to provide them with single ended operation.
Voltage dividers could also be added to their inputs to increase the input resistance and to raise the maximum input voltage levels. This would also provide the 136C and MC1596 with input protection.

E. The Laboratory

The communications laboratory experiments are conducted on a lab bench where all stations are supplied with both AC and DC power. The DC power is furnished by a current limited, well regulated, plus or minus fifteen volt power supply. The DC power at the bench is color coded as are the power supply terminals of the equipment:

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Bench</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>+15</td>
<td>Green</td>
<td>Red</td>
</tr>
<tr>
<td>Ground</td>
<td>Yellow</td>
<td>Black</td>
</tr>
<tr>
<td>-15</td>
<td>Pink</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

As seen above, this color coding gets confusing, especially since all jumper wires the same length are the same color. Reversed power supply leads probably burn out at least one piece of equipment per semester.

To begin to solve this problem, the bench terminals should be charged to: +15 = pink, ground = green, -15 = yellow. A special set of power supply jumpers could be constructed to match this color coding or some form of reversed power supply protection should be incorporated into the equipment.

Diodes across the power supply terminals would work since the DC supply is current limited, but would shut down all other experiments being performed on the bench. Series diodes followed by energy storing capacitors appear to work satisfactorily. This capacitor also filters noise picked up by the power supply wires running from the bench and lowers noise feedback into the DC supply for the piece of equipment.
The noise in the bench is another problem since signals from all the experiments can appear at any bench station. A major cause of this is that the DC supply is not connected to AC ground. Only when a grounded instrument, such as an oscilloscope, is connected to the equipment does the DC supply become grounded. This produces a high resistance ground path and significantly contributes to the bench noise. If at each bench station the DC ground is connected to the AC ground and the positive and negative DC supply terminals are also connected to the AC ground, via 100 mfd capacitors, the noise can be reduced by an order of magnitude. Power supply filtering will not accomplish this.

Further noise elimination can be accomplished by shielding DC power wires, inside the bench, from capacitive and inductive coupling with the AC lines. Lowering the input impedance of the equipment while increasing its output voltage will eliminate noise and hum picked up by the jumper wires.

All new equipment should strive for some form of power supply reversal protection, a lower input impedance, and a higher output voltage. Also, more attention should be paid to terminal layouts and less to artistic symmetry. Power supply terminals should be located at the upper horizontal edge of the chassis, away from input and output terminals. This keeps power wires from intertwining with signal wires and reduces noise pickup.
References


Vita

William Edgar Abernathie was born on December 16, 1947, in St. Louis, Missouri, and received his primary and secondary education there. He received his Bachelor of Science Degree in Electrical Engineering in January, 1970, from the University of Missouri - Rolla. He has been enrolled in the Graduate School of the University of Missouri - Rolla and employed by the University as a Graduate Teaching Assistant since that time.