A TRANSISTORIZED TELEMETER TRANSMITTER

BY

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PREFACE

"What is telemetry about?" Many classmates have asked me this question in recent months. Those who were somewhat vaguely familiar with the term had no idea as to how the over-all system functioned. Not much is written in the literature on this subject and from what can be found it is difficult to grasp an over-all picture. Most missile telemetry systems in present operation are classified SECRET by the Air Force. If not the entire system, then the frequencies are so classified. Telemetry is not being taught in engineering colleges at the present time. For these reasons the author through experience and research has assembled basic information to help the interested student become acquainted with telemetry.

The word, "telemeter," is of Greek origin and means "to measure from afar." It is the objective of this work to expand this basic idea through telemetry theory and design and construction of a unit which will perform one type of measurement, "from afar."

I wish to express my appreciation and gratitude

to Dr. Harold Fristoe for the suggestions and assistance which he has furnished. I, also, wish to thank Mr. Joseph Block and Mr. Gerhardt Arnie, Boeing Airplane Company Engineers, for their very enthusiastic encouragement to enter this field of Electrical Engineering.

Finally, I wish to express my thanks and appreciation to my sister, Barbara Ann, for her excellent work and suggestions in the preparation and typing of this thesis.

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CHAPTER I

INTRODUCTION

A telemeter is a system for measuring a quantity, transmitting the result to a distant station, and there indicating or recording the quantity measured. Some of the variables measured are pressure, light, radiation, flow, temperature, acceleration, yaw, pitch, roll, stress, velocity, and vibration.

Telemeters were originally used to relieve human operators of tedious duties in industrial processes. Today telemeters perform a very important role in aircraft and missile testing. Telemetered data is frequently all that remains from a test firing since most missiles are nonrecoverable. Information gathered from space probes and satellites enable man to prepare for his advent into space. These devices are in effect "pioneers" that proceed before man to inform him of the environmental conditions with which he must cope if he is to exist in that region.

Some parts of the telemeter must meet rigid specifications. It must operate accurately in an environment of extreme temperature and pressure changes, high acceleration, shock, and vibrations. Specifications may limit space and power requirements. The life of performance may vary from less than a minute to continuous duty.

Components of a Telemeter

A telemeter may be divided into three major divisions. Beginning with the variable to be measured, a transducer or pickup is necessary to convert the magnitude of the variable into a modulating function. The transducer output then goes to the second part of the telemeter, the radio link or transmitter. Here the information from the transducer modulates a subcarrier oscillator which in turn modulates the transmitter. The transmitter output goes to an antenna. Part of the transmitted energy is picked up by the third part of the telemeter, the data recovery apparatus. This part of the telemeter is normally referred to as a ground station. This relationship is shown in Figure 1.

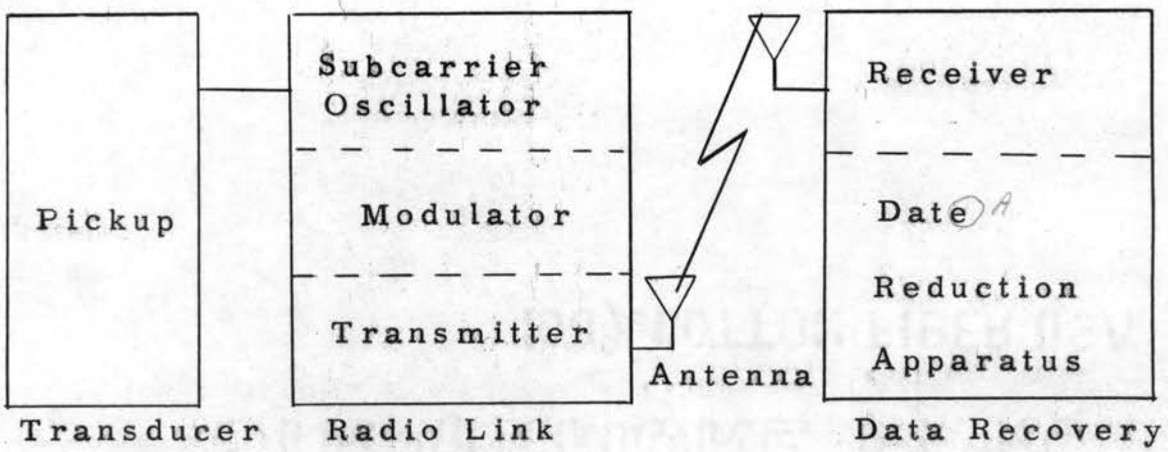

Figure 1. Major Divisions of a Telemeter

Transducers employ electro-mechanical principles. Typical transducers include thermocouples, strain gages, bourdon tubes, and various mechanical and electrical devices which change inductance, capacitance, voltage, or resistance in a circuit. These instruments are presented and discussed more thoroughly in Chapter II.

The transmitter is the heart of the telemeter. Its purpose is to generate the active radio link. One transmitter usually serves many transducers. This is done by multiplexing more than one channel of information over a single radio link. This may be done by either time division or frequency division of the transmitted wave. The choice of multiplexing determines the type of circuits composing the transmitter. For example AM/FM means a frequency division multiplex with subcarrier amplitude modulated in accordance with the information contained in each channel and with the subcarrier frequency modulating the RF carrier.

The transmitting and receiving antennas of a telemeter are of utmost importance in the performance of a system. The transmitter antenna must not interfere with the aerodynamic characteristics of the vehicle, yet must perform efficiently. The entire skin of the vehicle, a stub, a notched fin, or a flush-mounted slot antenna may be used for the radiator. The receiving antennas are high gain directional types usually of helical construction. They are automatically aimed at the vehicle by a servomechanism linked to the tracking radar.

The receiving equipment also depends upon the type of multiplexing used. High sensitivity is necessary since the transmitter is often limited by space and weight specifications and therefore has a low power output. Several receiving stations monitor the signal simultaneously to insure maximum recovery of telemetered intelligence.

The data reduction equipment will also depend upon the type of multiplexing used. For time division multiplexing, it will consist of commutating devices and sync controllers. For frequency division multiplexing, band pass filters are used to separate the channels. After the intelligence is recovered from the transmitted wave, it is recorded on a magnetic tape, oscillograph, or ink recorder.

Objective

The objectives of this thesis are (1) to acquaint the reader with telemetry theory and applications, and (2) to design, construct, and test a transistorized telemeter transmitter capable of monitoring fuel flow.

CHAPTER II

TRANSDUCERS

The desired intelligence originates at the transducer which is arranged to continuously respond to the variable to be measured. Its function is analogous to a voltmeter, ammeter, or similar instrument. It converts the measurement of a variable quantity into a more usable form of electrical output. As an example, the voltmeter converts voltage to an indicated value on a scale. A transducer converts a physical distortion to a voltage, current, inductance, resistance, or capacitance change.

A good transducer has high sensitivity, is approximately linear in the range of operation, and does not overload the normal process of the variable it is monitoring. All transducers extract some energy from the system being monitored. It is seen that if the transducer causes a realizable change in the system, then the data recovered from that channel could never be an accurate representation of the system activity. Transducers are built to rigid specifications and are calibrated for a particular system to insure highest accuracy. Frequently, automatic in-flight calibration is employed. Like most airborne equipment, transducers are subject to space and weight limitations. These factors often demand some compromise with the desirable characteristics listed above.

It has been mentioned that transducers are used to monitor such variables as temperature, velocity, pressure, and stress. The temperatures desired will usually be those of the outer skin of the airframe at several places, engine and nozzle temperatures, and perhaps temperatures in various compartments of the vehicle. Velocity measurements may be desired in the slipstream and in fuel lines. Pressure and stress measurements may be desired in several locations also. Some transducers will have other parts of the telemeter closely associated but ordinarily the transducer output is wired to a remote commutator or transmitter. Thus a transducer may be located anywhere on or within the vehicle depending upon the particular variable it is measuring.

Transducers are frequently custom designed for a particular application. Some are applicable or easily adaptable to several applications. An example of this would be thermocouples or strain gages. Transducers may employ a common electro-mechanical principle yet be completely different in physical appearance.

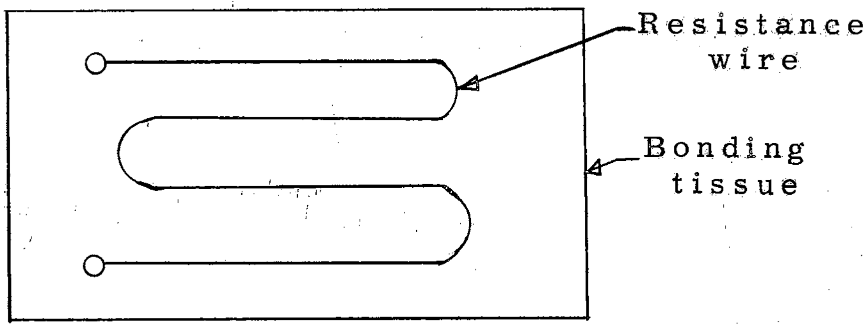

Figure 2. Strain Gage

The strain gage transducer in Figure 2 consists of a fine resistance wire cemented in a hairpin fashion on a piece of flexible tissue. The bonding tissue is fastened to the surface or structural member by a special cement in the desired direction of strain measurement. When the surface is put in tension, the wire stretches, the cross sectional area of the wire decreases, and there is a net increase in resistance across the terminals. The inverse occurs when the surface is put in compression. The resultant effect is evaluated by the gage factor defined by G. H. Lee[1] as

$$\frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R}{Re}$$

where R is the electrical resistance,

L is the length of the wire and

e is the unit strain.

In the commercial form of the gage, the gage factor is about 2.0 for cupronickel wire and ranges up to 3.5 for Elinvar wire. The allowable current through the gage is about 25 milliamperes. The gages are available in a wide variety of lenghts, resistance, wire materials, types of mountings, lead connections, and directional arrangements. A compilation of the American and British manufacturer's products is given by Dobie and Isaac.[2]

At the junction of two dissimilar metals, there exists an emf known as the Seebeck effect which is a function of temperature. This principle makes possible a very versatile temperature sensitive transducer called a thermocouple. The construction of this transducer is shown in Figure 3.

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[1] Lee, G.H., An Introduction to Experimental Stress Analysis, (New York, 1950) p. 117

[2] Dobie, W. B. and Isaac, P.C.G., Electric Resistance Strain Gages, (London, 1948)

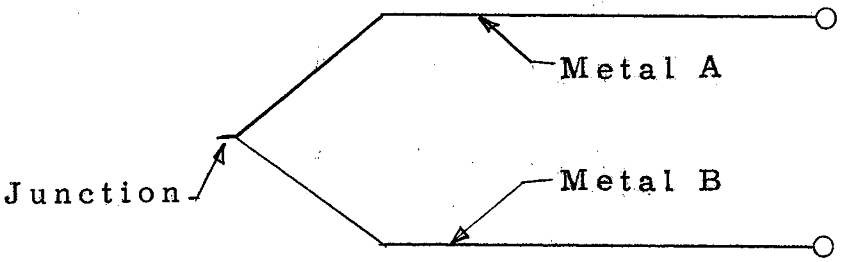

Figure 3. Thermocouple

The characteristics of metals used for thermocouples include (1) a high coefficient of thermal emf with temperature, (2) a continuously increasing relation of emf to temperature over a wide range, (3) freedom from phase changes or other internal phenomena giving rise to discontinuities in the temperature-emf relation, (4) resistance to oxidation, corrosion, or contamination, and (5) homogeneity and reproducibility to fit an established temperature-emf relation.[3] Typical materials used are platinum and alloyed platinum and rhodium, copper and constantan (55% Cu, 45% Ni), iron and constantan, and chromel P (90% Ni, 10% Cr.) and alumel (95% Ni, Al, Si, Mn).

There are several types of transducers which measure acceleration. The accelerometer shown

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[3] Sweeney, R. J., Measurement Techniques in Mechanical Engineering, (New York, 1953) p. 151

in Figure 4 will measure acceleration or deceleration in the horizontal plane only. When the velocity is zero or constant the mass remains centered. During acceleration or deceleration the mass will compress one of the springs thereby moving the arm of the potentiometer. The equation of motion is

$$M \frac{d^2X}{dt^2} + KX = 0$$

where M is the mass and K is the spring constant. The output across the potentiometer terminals and the arm is a varying resistance. A voltage output can be devised by adding a simple bias circuit. An accelerometer independent of direction may be constructed by suspending a mass with strain gage elements so that the mass is free to move in any coordinate system. Again the output may be either a resistance or voltage change.

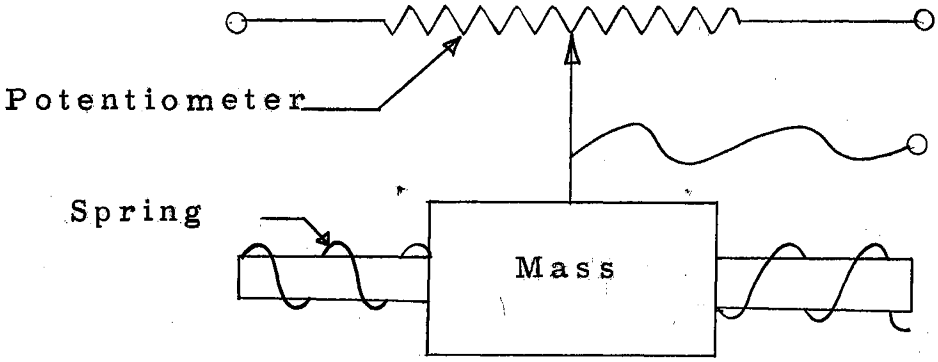

Figure 4. Accelerometer

Variable inductance pressure transducers work on the principle of a pressure differential mechanically changing the air gap of an iron core inductor. This varies the reluctance of the flux path and thereby changes the effective inductance of the coil. Two transducers of this type are shown in Figure 5.

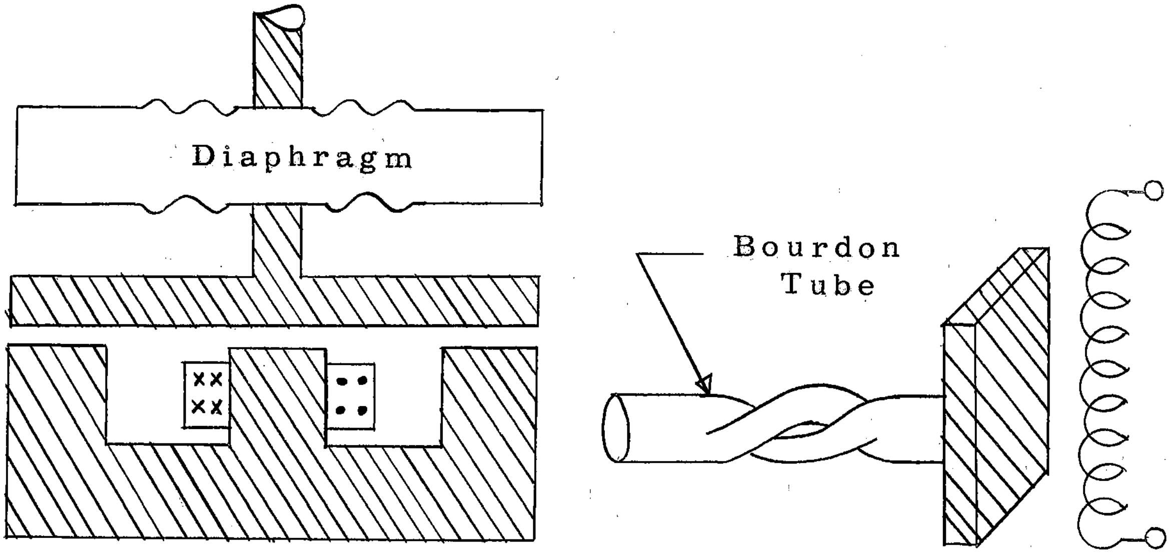

Figure 5. Variable Inductance Transducers

The inductance of the coil is governed by the relation $L = \mu A R$

where L is the inductance in henries,

μ is the permeability of the core material,

A is the cross sectional area of the flux path,

and R is the reluctance.

One type of variable capacitance transducer used in determining position in relation to the earth's gravitational field is shown in Figure 6. The mass attached to the moveable capacitor plate will align itself with the gravitational field as the fixed plate maintains a reference to the vehicle.

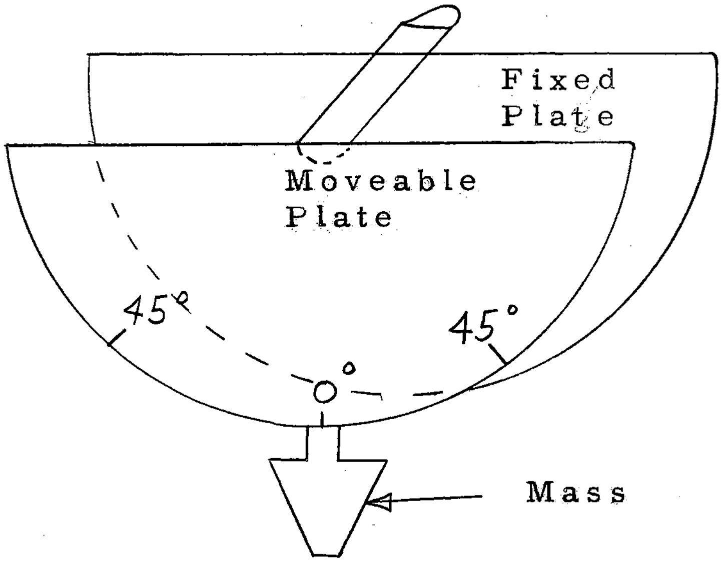

Figure 6. Variable Capacitance Transducer

The effective capacity is given by the relation

$$C = \frac{\epsilon A}{S}$$

where C is the capacity,

ϵ depends on the dielectric (permittivity),

S is the distance between the plates, and

A is the total plate area normal.

The transducers mentioned are typical of those presently in use. One other type which is finding much use in radiation measurements is the voltage output transducer. Examples of this type of transducer are ionization chambers and geiger counters.

The transducer is one of the most critical components of a telemeter. It is frequently located in areas subject to severe environmental conditions whereas the transmitter may be located in a temperature controlled and pressurized compartment. Keeping a transducer properly calibrated is sometimes difficult. There is the problem of noise pickup in the cable carrying the transducer output to the transmitter. Though some transducers are shock mounted, most must perform during shock, vibration, and acceleration. All these factors tend to decrease the efficiency and accuracy of the telemeter.

CHAPTER III

SUBCARRIER OSCILLATORS

The function of the subcarrier oscillator is to receive the transducer output and use it to modulate its normal waveform. The type of modulation may be amplitude, frequency, phase shift, or pulse width. The three general types of subcarrier oscillators are (1) inductance-capacitance, (2) resistance-capacitance phase shift, and (3) multivibrator.[4] The subcarrier oscillator circuit may employ vacuum tubes; however, the obvious advantage of transistors have revolutionized this circuitry in recent years. Also, due to the circuit size reduction, much smaller power requirements, and increased ruggedness, the transistorized subcarrier oscillator is often mounted with the transducer as one unit.

Most transistor oscillators are modeled after familiar oscillator circuits employing electron tubes.

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[4] Nichols, M.H. and Rauch, L.L., Radio Telemetry, (New York, 1954) p. 253

Methods for calculating frequency of oscillation and starting conditions are analogous also, in that the equivalent circuits may be drawn and solved using the appropriate mesh or nodal equations. The following circuits are typical of those adaptable to telemeter use.

Shown in Figure 7 are simplified Hartley and Colpitts transistorized oscillators which closely resemble their electron tube counterparts. These oscillators readily lend themselves to the variable inductance and variable capacitance type transducers. A time variation of L or C will result in a frequency modulated output waveform. For a rigid analysis of these circuits see Oakes.[5]

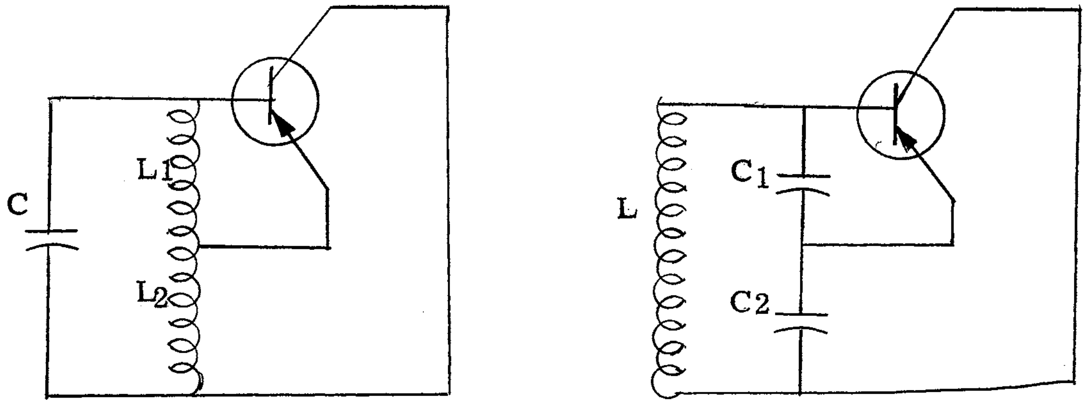

Figure 7. Transistorized Hartley and Colpitts Oscillators

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[5] Oakes, J.B., "Analysis of Junction Transistor Audio Oscillator Circuits," Proc. I.R.E. Vol. 42, August 1954

The circuit in Figure 8 presents a transistorized Colpitts oscillator which is frequency modulated by a thermocouple transducer input. The emf produced by the thermocouple causes a current to flow in the lower control winding. This changes the effective inductance of L.

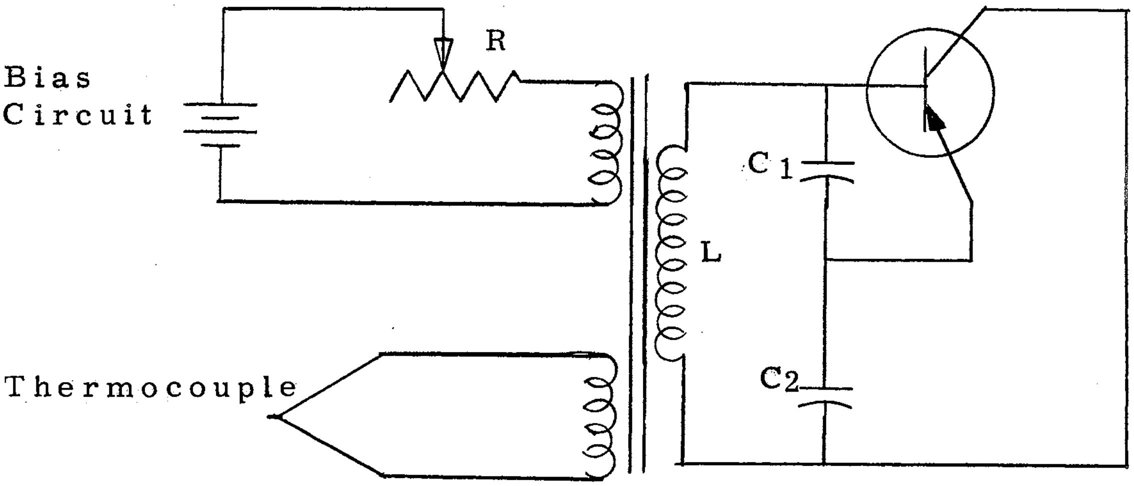

Figure 8. Thermocouple Controlled Oscillator

Strain gage transducers find frequent use in phase-shift type oscillators. A circuit of this type is shown in Figure 9. It can be considered to be composed of a current amplifier with a current feedback network. A complete analysis of this circuit is given by Shea.[6]

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[6] Shea, R. F., Transistor Circuit Engineering, (New York, 1957) pp. 222-226

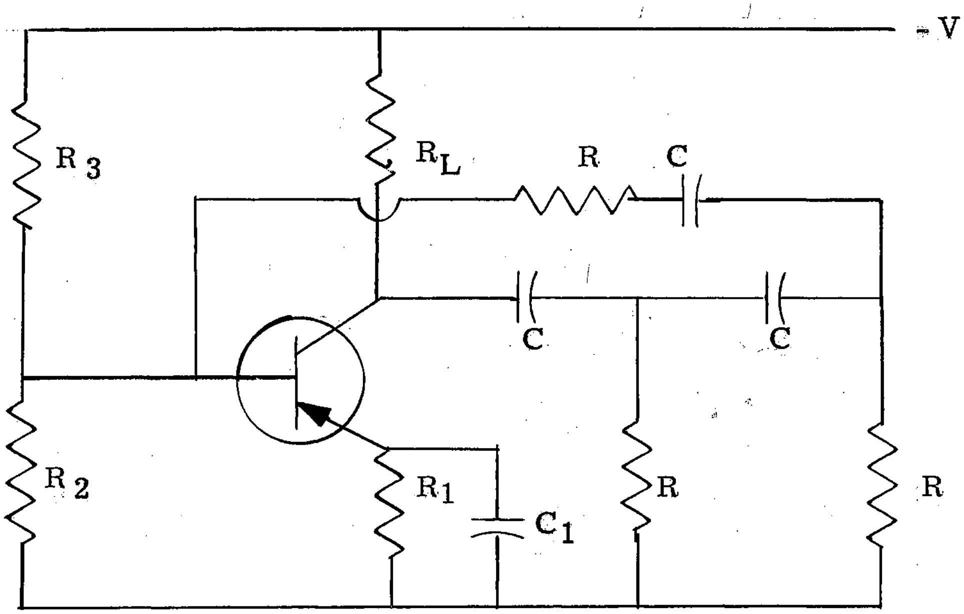

Figure 9. Transistorized Phase Shift Oscillator

The circuit presented in Figure 10. is a transistorized Eccles-Jordan multivibrator. A circuit of this type is used frequently as a binary counter. The associated transducer is usually an ionization chamber. The operation of this circuit is fully described by Bothwell.[7]

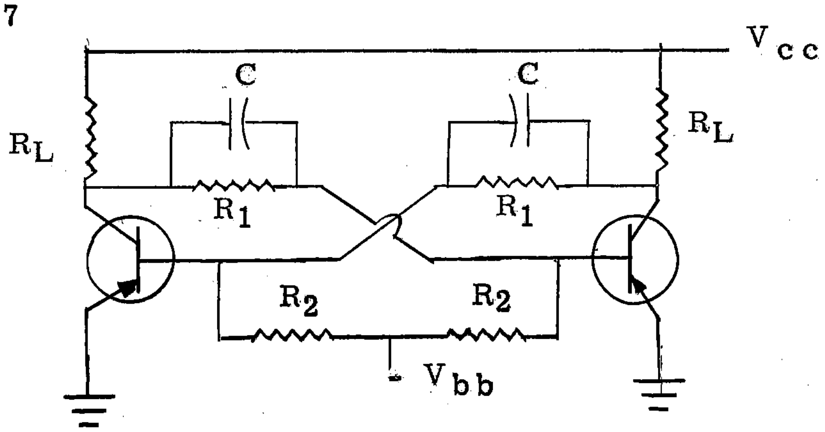

Figure 10. Transistorized Multivibrator

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[7] Bothwell, T.P., "Junction Transistor Flip-Flop Design Methods for Computing Applications." A.I.E.E. Winter General Meeting, (New York City, February 1955)

CHAPTER IV

MULTIPLEXING

A separate radio link for each channel of information would be inefficient and impractical. This would lead to many problems involving antenna complications, space, weight, and power. Multiplexing, the process of transmitting several channels of information over one radio link, solves these problems; however, it introduces other minor problems. When one transmitter carries several channels of information, there is developed an inherent noise called crosstalk. This tends to limit the number of channels which can be successfully multiplexed onto a carrier.

There are two basic methods of multiplexing. The first is frequency division multiplexing which uses a separate subcarrier frequency for each channel with enough spacing between channels to insure noninterference in adjacent side bands. Figure 11 is a block diagram of a telemeter employing frequency multiplexing.

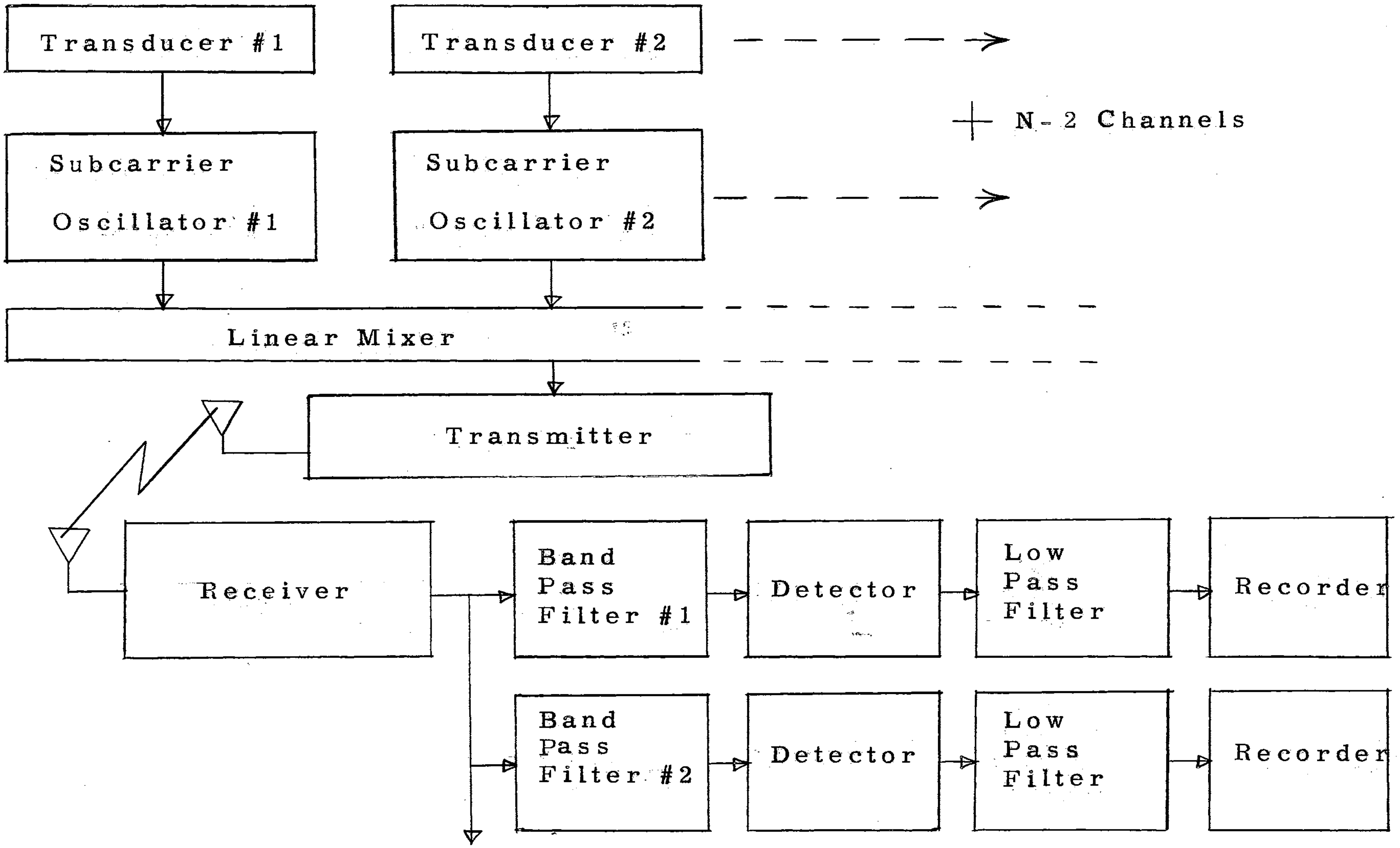

Figure 11. Block Diagram of A Frequency Division Radio Telemeter

At the transmitting end of Figure 11, the transducer picks up the information and modulates the subcarrier oscillator. The subcarrier oscillators feed into a linear mixer and the output of the linear mixer modulates the transmitter. Several types of modulation are used, however, frequency modulation (FM) is predominant. The system may employ two types of modulation at different levels such as AM/FM. To go further it is even possible to have a hybrid system employing both frequency and time division.

The second method of multiplexing is called time division multiplexing. This method samples the information in the channels in a cyclic serial sequence and puts out a pulse (or pulses) for each channel which is modulated in accordance with the information in that channel. These pulses are then used to modulate the carrier which may be of the constant amplitude type such as frequency modulated (FM) or it may be amplitude modulated by the pulses such as pulse position modulation (PPM). Figure 12 is a block diagram of a time division multiplexed telemeter.

Figure 12 shows how the channel inputs are fed into a mechanical commutator. The one shown has only six inputs and is merely illustrative. A typical

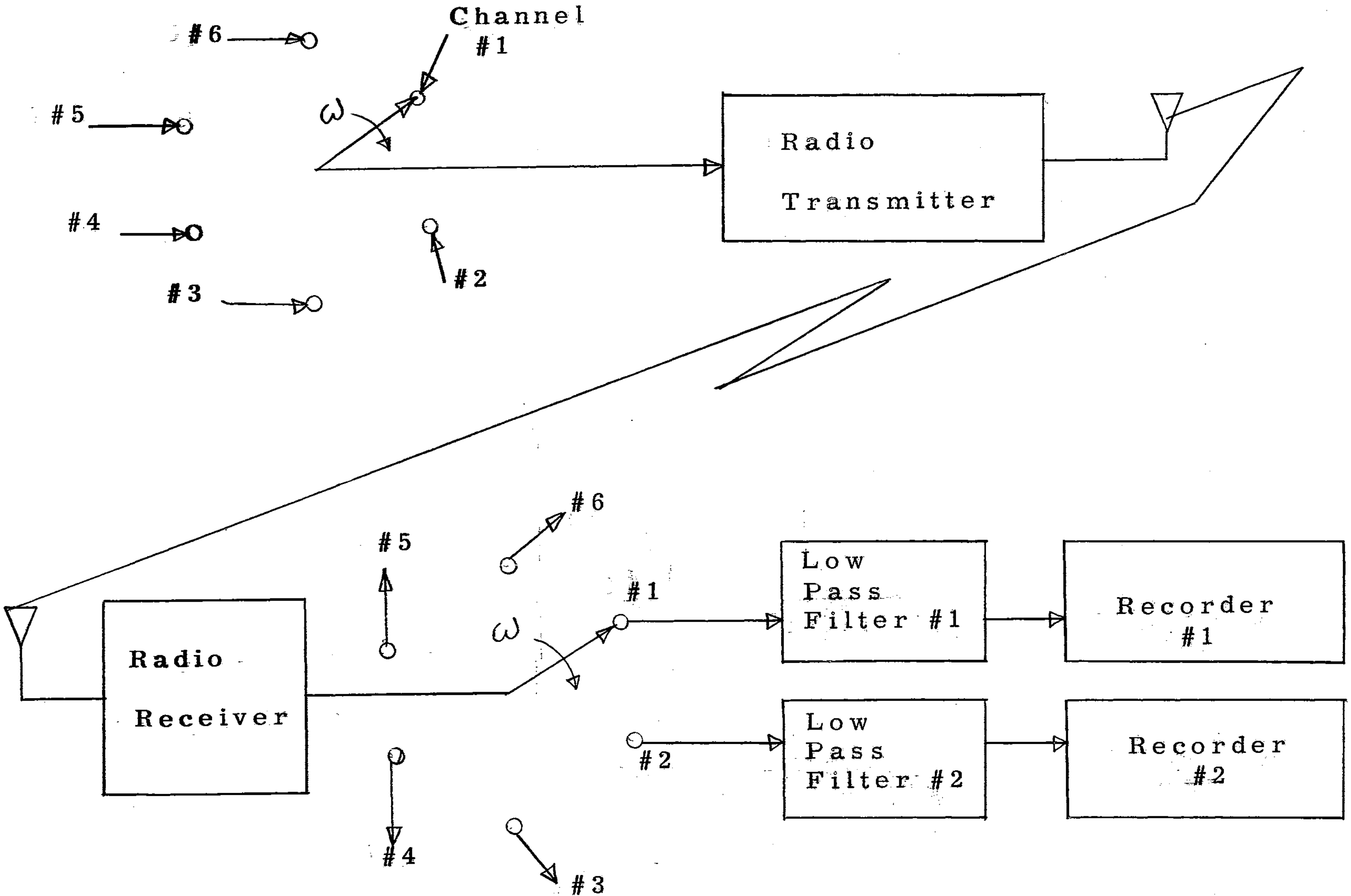

Figure 12. Block Diagram of A Time Division Radio Telemeter

commutator may have 50 taps and rotate at 2.5 to 60 rps. It should be noted also that the transmitter and receiver commutators must be perfectly synchronized. This is accomplished in a manner similar to television practice.

The channel inputs modulate the transmitter in one of several aforementioned ways. The receiver output feeds back through the synchronized receiver commutator to the filters which pass on the information to be recorded.

There are advantages and disadvantages in each type of multiplexing.[8] In frequency-division multiplexing the failure of an individual channel will not stop transmissions from the other channels. In time-division multiplexing, a failure in one series-connected unit could very well cause a complete failure of the system. Frequency division multiplexing can handle higher frequency information because of its continuous monitoring of the information channels. Time division multiplexing requires less bandwidth for the same number of information channels than would be required

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[8] Tepper, Marvin, Fundamentals of Radio Telemetry, (New York, 1959) p.34

in frequency division multiplexing. Occasionally, circumstances warrant a combination of time and frequency division multiplexing. An example of this would be several thermocouples with slow temperature variations time multiplexed onto a subcarrier oscillator within a frequency multiplexed system. A system of this type is commonly referred to as a hybrid system.

CHAPTER V

DATA RECOVERY AND REDUCTION

The data recovery and reduction phase of the telemeter system is by far the most complex part of the system. Its function is to receive the weak radio signals, amplify, demodulate, segregate, record, and analyze the information. In early systems much of this work was done manually. One method presented the demodulated signals on an oscilloscope while a continuous photographing process produced the recording. These photographs were manually scaled to obtain the desired information. This process, besides being extremely laborious, was subject to errors due to zero axis ambiguity, compromising on trace width, and human measurement factors.

The initial phase of data recovery involves obtaining the maximum possible signal from the radio link. The most efficient method results from using high gain directional helical antennas in conjunction with the tracking radar. This insures that the antenna is properly directed at all times. Also, several ground stations monitor the vehicle along its path to insure obtaining a complete set of data. It is easily possible for one station to be blanked out due to roll of the vehicle making the station fall in the shadow of the transmitting antenna.

The emf induced in the antenna is fed directly to the telemeter receiver. All radio receivers for telemetry use the superhetrodyne principle. This means that the receiver accepts the antenna signal in one frequency band, amplifies, and transforms it to a lower frequency band for use in the IF stages and demodulator. These parts of the receiver are the most critical. The demodulator and video amplifiers which follow are conventional. The main characteristics of a good telemeter receiver are high selectivity and low noise figure. High selectivity is mainly a function of the IF amplifiers. The noise figure expresses the amount of noise added to the signal by the receiver as the signal passes through the receiver to the IF amplifiers output.

The receiver output is recorded by one of several methods. Magnetic tape and oscillograph recorders, are the most common. Other methods employ disk recorders, ink recorders, and photographic film recorders.

Now that the transmitted data has been received, recovered, and recorded, the final problem is analysis. There is no single solution to this problem, for the basic requirements differ from project to project, and within a project, from time to time. In some cases the main requirements are those of accuracy; in others, speed; in still others, the flexibility of the system. In all cases the solutions must be evaluated in terms of the economics of the situation.

The three main processes of data analysis are (1) that of taking the data from the record, (2) that of manipulating it, and (3) that of putting it down again. Much can be said about each of these operations. The first process is handled by equipment which will read bar-graph film recordings, magnetic tapes, or oscillograph traces. Manipulation or computation is performed by electric calculators, digital computers, and analog computers. Any of the aforementioned recorders will perform the third function.

The present trend in data recovery and reduction is to analyze the data as it is received. This allows adjustments of equipment to insure getting readable data while it is being received. This also expedites making copies of the tape for the research teams and other personnel involved. There are several fully automatic data analyzers available.

CHAPTER VI

DESIGN OF TELEMETER TRANSMITTER

Fuel flow is one of the primary items monitored during a missile launching. This information is of vast importance to missile engineers in analyzing the success or failure of a firing. There are several ways by which this information could be telemetered to ground stations. A simplified block diagram of the method the author chose to use is presented in Figure 13.

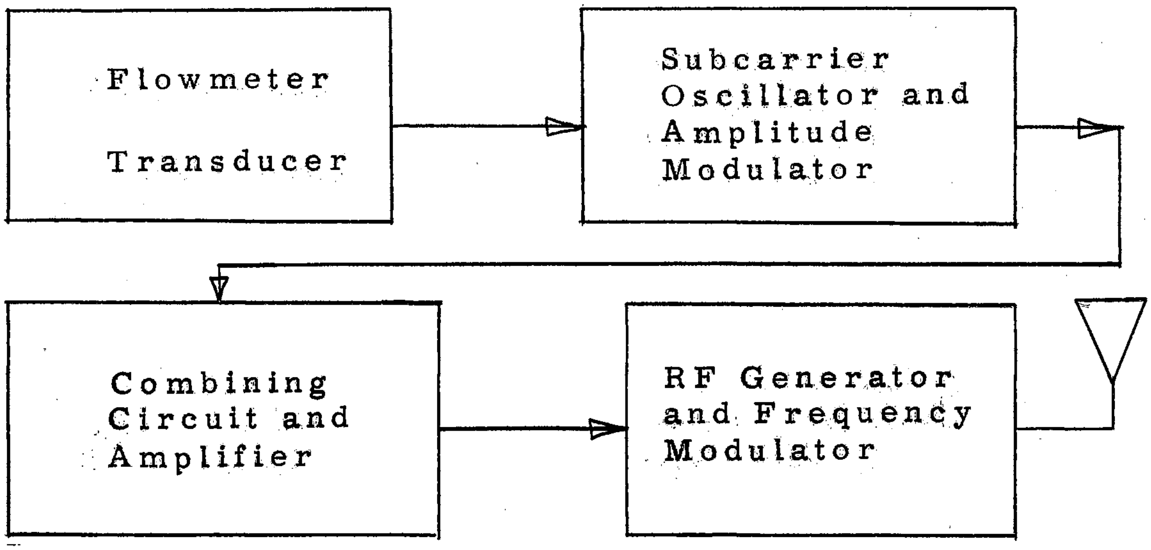


Figure 13. Block Diagram of AM/FM Transmitter

The flowmeter transducer in Figure 13 is a small device which operates from a propeller located in the fuel line. It is actually a miniature AC generator with an output voltage of 1 volt. The frequency of the voltage varies from 50 to 400 cps and is dependent upon the velocity of the fuel stream. This transducer can be simulated by an audio frequency generator.

The transmitting part of the telemeter consists of the subcarrier oscillator and amplitude modulation circuit, the linear combining circuit, and the RF generator and frequency modulation circuit. Design criteria for this unit could be set up as follows:

(1) small size
(2) light weight
(3) rugged
(4) operate independent of missile power
(5) dependable

Subcarrier Oscillator and Amplitude Modulator

The purpose of this circuit is to generate a carrier frequency and use the transducer output as a modulating voltage on the carrier. Double sideband amplitude modulation will be used. This allows a simple detector to be used in the receiving circuit without supplying a demodulating frequency that has to be kept in synchronism with the channel frequency.

A transistorized Colpitts oscillator circuit will be used. Subcarrier frequency is 10.5 kilocycles. This choice is due mainly to the availability of a small torroid coil of 3.67 millihenries. The transistor for this circuit should have a large β, $f_{\alpha co} >$ 15 KC, low C_c, and a high temperature operating range. A Sylvania type 2N34 meets these specifications. Parameters of this transistor are given in the appendix. A 30 volt miniature battery is to be used as the power source. Since low power modulation is necessary, the circuit will be base modulated. The circuit is shown in Figure 14.

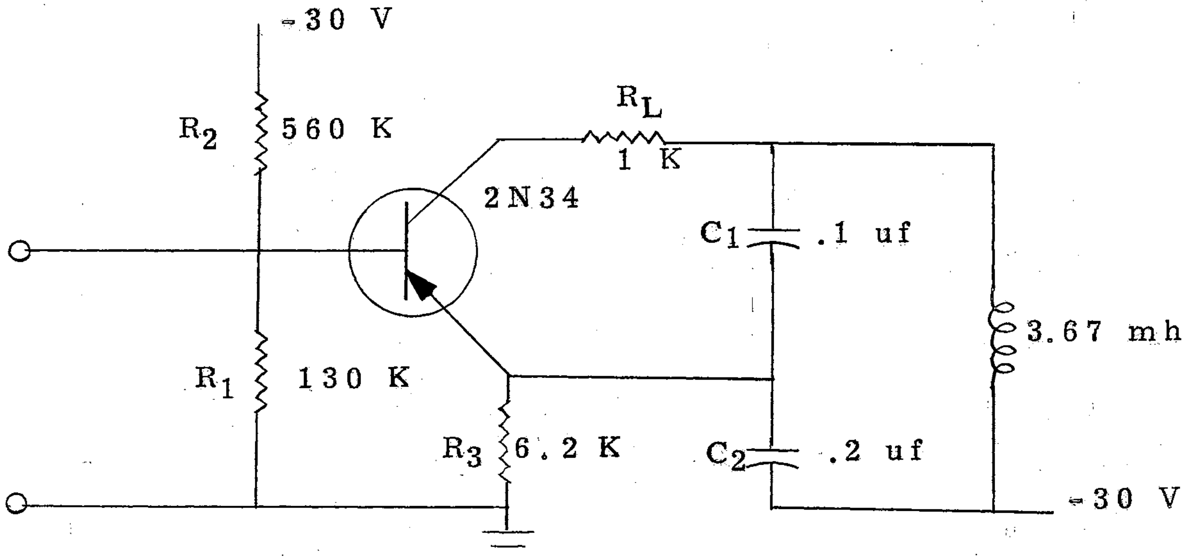


Figure 14. Schematic of Subcarrier Oscillator and Amplitude Modulator

At low frequencies the transistor parameters have negligible effect on frequency selective components of the circuit. Thus the values of C_1 and C_2 can be calculated to resonate with the coil at 10.5 kilocycles.

$$f_R = \frac{1}{2\pi\sqrt{LC_T}}$$

$$C_T = \frac{1}{(2\pi f_R)^2 L} = \frac{10^3}{4\pi^2 \times 10.5^2 \times 10^6 \times 3.67}$$

$$C_T = .0627\ \mu f$$

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

Let $C_1 = .1\ \mu f$ and solve for

$$C_2 = \frac{C_T C_1}{C_1 - C_T} = \frac{(.0627)(.1)}{.1 - .0627} = .202\ \mu f$$

Resistors R_1, R_2, and R_3 establish the dc operating point with no modulator input. For good circuit stability during temperature changes, R_1 should be a thermistor. This will tend to maintain the same operating point as the V_c vs I_c curves raise upward with increased temperature. R_3 is made large enough to swamp the emitter to base diode. A large R_3 thus improves stability.

Amplitude modulation is accomplished by amplifying the signal applied to the base circuit through the transistor and letting it superimpose upon the tank circuit oscillations. This is merely a means of varying the operating point at the audio rate of the modulation frequency.

The output of this circuit is a 10.5 Kilocycle carrier amplitude modulated by a 50 to 400 cps audio signal. This can be represented mathematically.

Let the carrier $= A \cos \omega_c t$

Let the modulation voltage $= m \cos \omega_m t$

The amplitude modulated carrier will then be equal to $A(1 + m \cos \omega_m t) \cos \omega_c t$

Letting $|m| < 1$ and expanding and regrouping the terms gives:

$$A\left[\cos \omega_c t + \frac{m}{2} \cos(\omega_c - \omega_m)t + \frac{m}{2} \cos(\omega_c + \omega_m)t\right]$$

Thus double sideband amplitude modulation results in the carrier frequency plus two side frequencies spaced ω_m from the carrier. This is shown in Figure 15. The time division of the two periodic waves is not scaled.

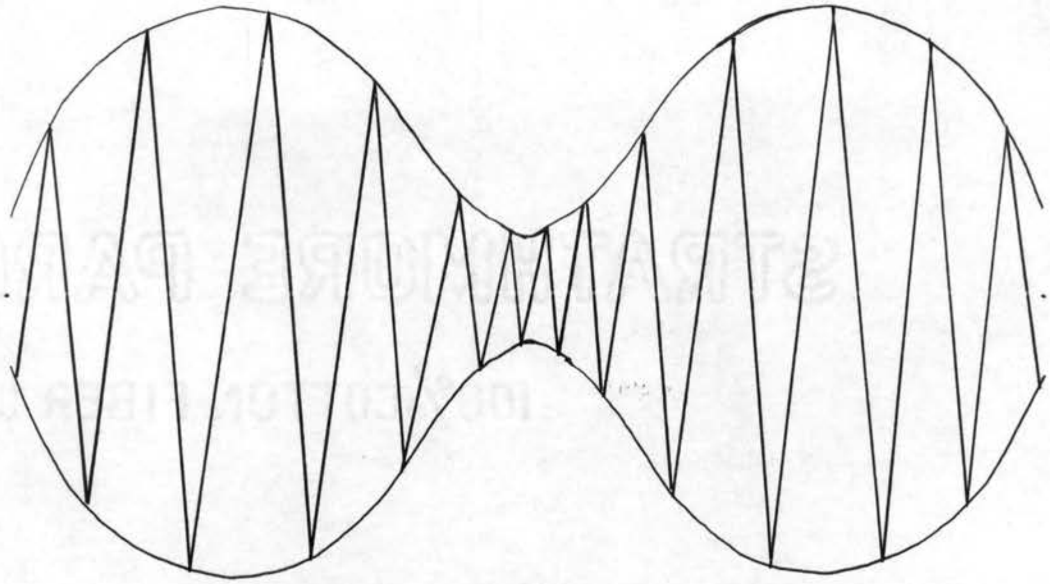


Figure 15. Subcarrier Oscillator Output with Double Sideband Modulation

Combining Circuit and AM Signal Amplifier

The function of this circuit is to linearly combine the modulated outputs of the subcarrier oscillators of all channels and to amplify this voltage for use as a modulating signal to the FM transmitter.

Two major requirements for this circuit are, (1) a high input impedance, and (2) a near constant gain over a wide band of frequencies. The high input impedance is necessary to prevent loading of the oscillators. These requirements can be met with a resistive voltage divider network input to a grounded collector amplifier. Voltage gain would be approximately that of the common emitter stage while current gain would be slightly less than unity.

A common collector stage has inherent negative feedback which is valuable in stabilizing the gain of the amplifier and reducing nonlinear distortion. This circuit is shown in Figure 16.

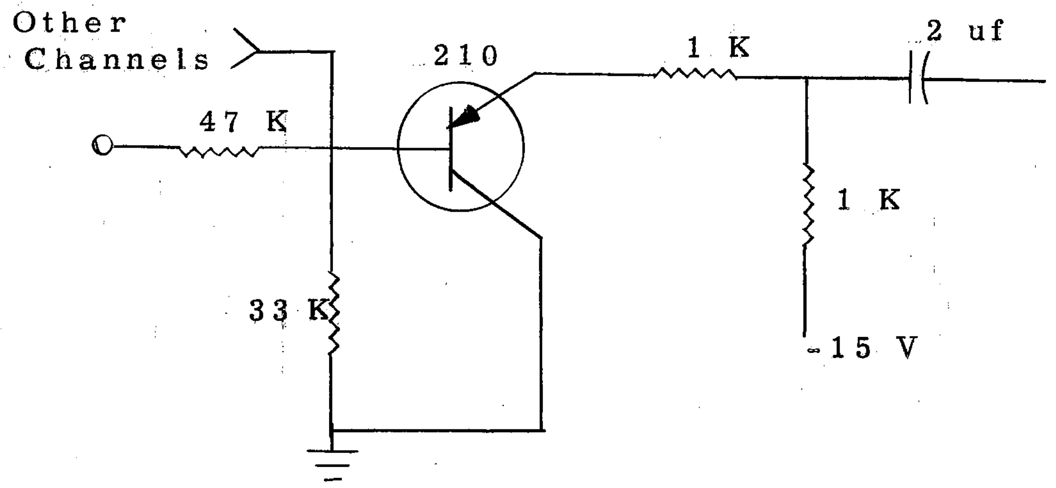


Figure 16. Schematic of Combining Circuit and AM Signal Amplifier

A NPN type transistor was selected for this circuit so that a common battery and ground could be used for the entire transmitter. The alpha cutoff requirement is determined by the highest subcarrier oscillator frequency to be passed. The input resistors were chosen to prevent loading of the oscillator tank circuits. The load resistors in the emitter circuit provide 100% negative feedback. The characteristics of this circuit are very similar to that of a cathode follower. The 2 micro-farad capacitor was selected to pass the lowest frequencies with little attenuation. The output of this circuit is a linear summation of the AM subcarrier oscillator outputs.

RF Generator and Frequency Modulator

This circuit generates the RF carrier and frequency modulates the carrier with the output of the linear combining circuit. In a practical telemeter a power amplifier would follow this stage to boost the signal delivered to the transmitting antenna.

At the present time the FCC allocates two general radio telemetry bands. They are from 216 to 220 megacycles and 2200 to 2300 megacycles. Due to the lack of a receiver for these frequency bands, the frequency of operation was set at 100 megacycles. This does not detract from the principles being shown and allows the use of a common FM receiver covering the band of 88 to 108 megacycles.

The more important parameters of the transistor for this circuit should be a high alpha cutoff frequency and a large collector dissipation. A Texas Instruments type 2N1143 meets these specifications. This is a very recent special transistor manufactured by a gaseous diffusion process providing a diffused base "mesa structure". Alpha cutoff frequency is 480 megacycles and collector dissipation is 750 milliwatts.

A Hartley type RF oscillator was constructed with a variable capacitor in the LC tank for tuning. The circuit is shown in Figure 17.

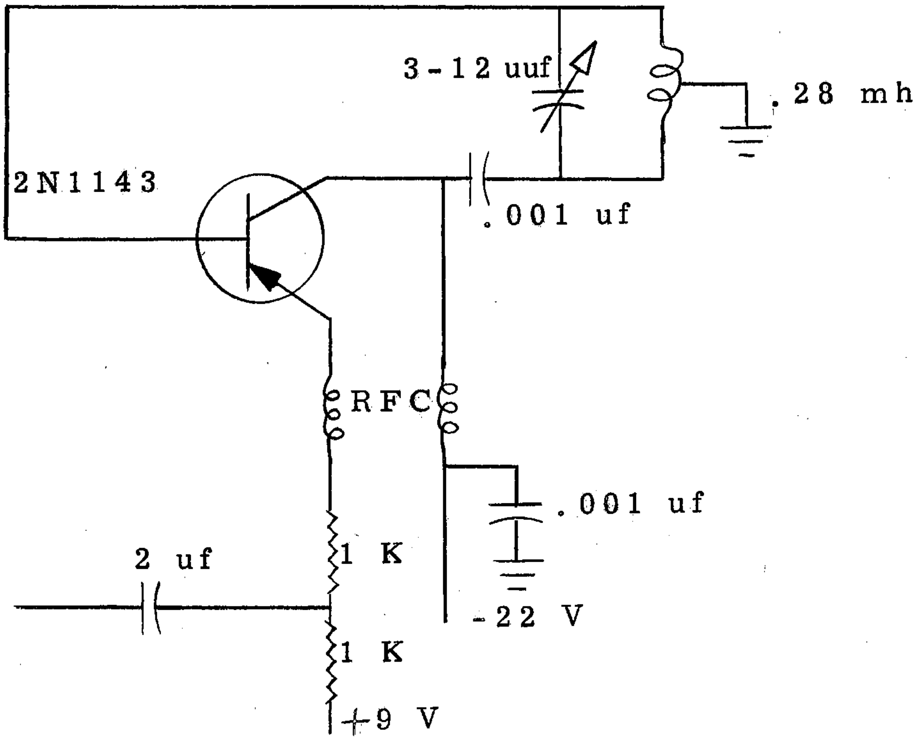


Figure 17. Schematic of RF Generator and Frequency Modulator

The variable capacitor, when set at 9 uuf, will resonate at 100 megacycles with a coil of approximately .28 microhenries. A coil of this value can be formed by 2 turns of #14 wire around a coil form of 1.25 inch diameter. The emitter resistors and bias fix the d-c operating point. Two radio frequency chokes are used as RF suppressors.

The modulating signal is applied to the emitter. This changes the d-c operating point and results in a phase shift of the fed-back energy. The oscillator changes frequency by the amount necessary to restore the proper phase relationship and continues to oscillate, but at a different frequency. Thus the oscillator is frequency modulated by the emitter fed signal. A schematic of the transmitter package is shown in Figure 19.

Data Recovery

The comparative success of any telemeter system ground station depends primarily upon its receiving equipment. For the frequency multiplexing method used in the transmitter the block diagram for data recovery would appear as shown in Figure 18.

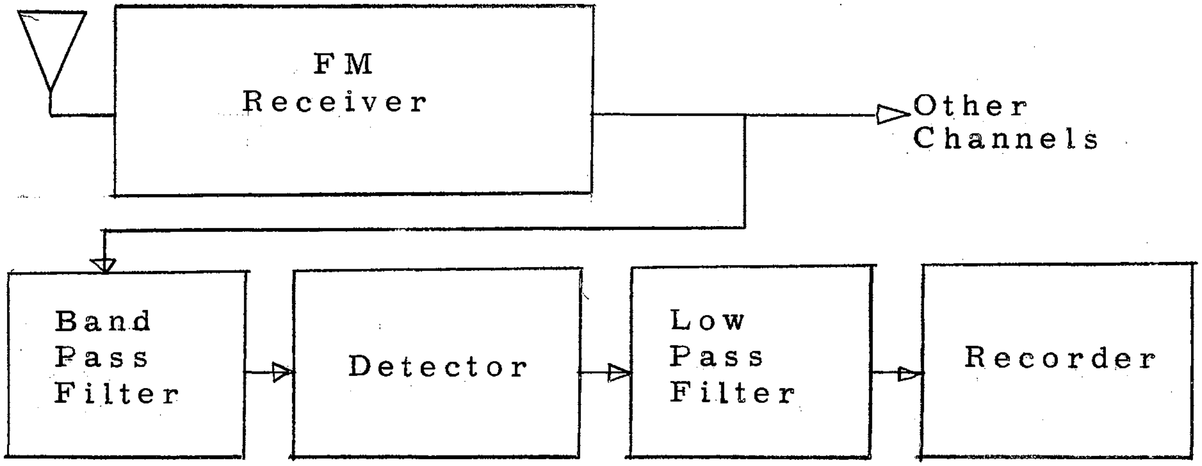


Figure 18. Block Diagram for Data Recovery

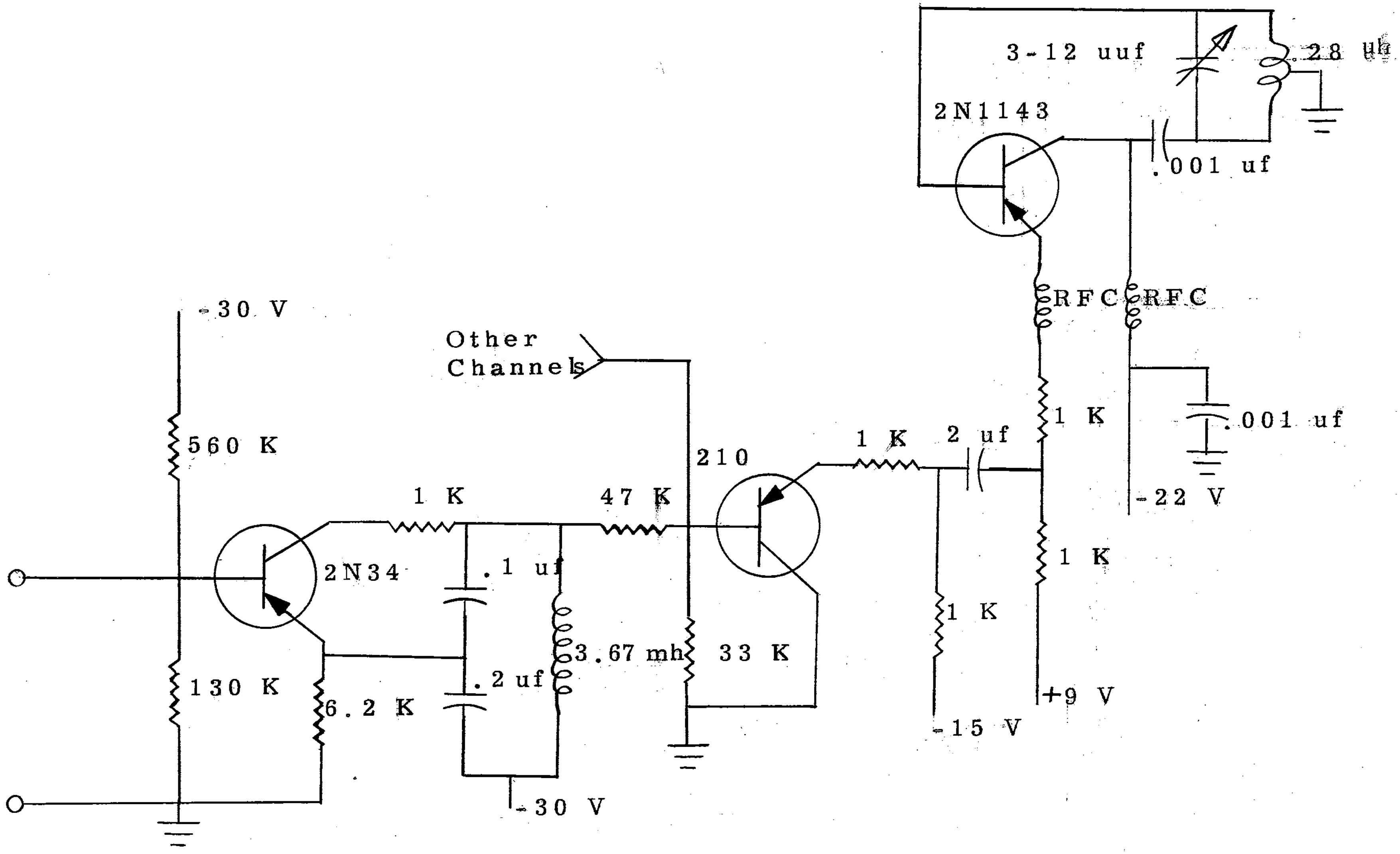
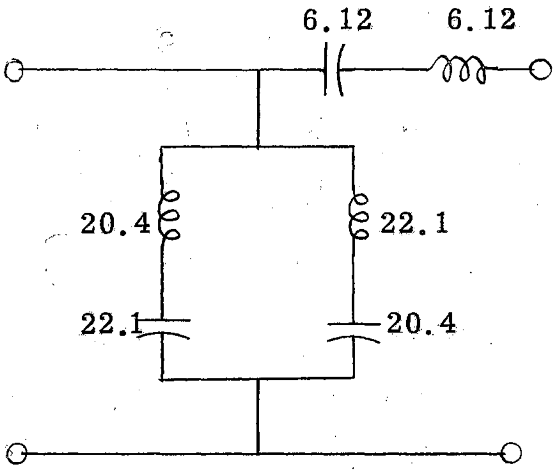


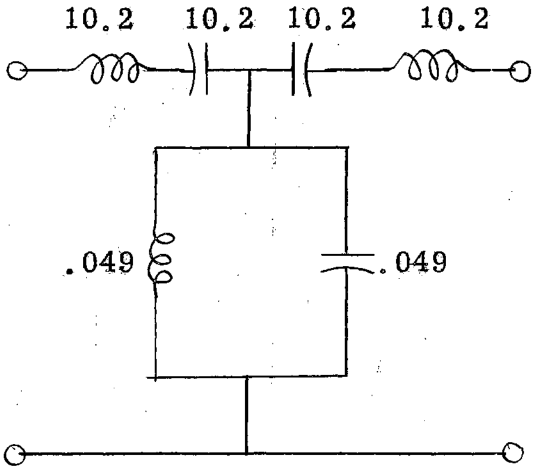
Figure 19. Transmitter Schematic

Although the purpose of this manuscript does not include the data recovery equipment, the author feels that some discussion of filter design would be in order. Filters, both active and passive, comprise a large percentage of the total ground station equipment. A composite filter design chart has been presented for both π and T sections by C. J. Merchant.[9] To demonstrate use of the charts a band pass filter for the 10.5 KC subcarrier oscillator is now presented.

The filter will consist of a full K section with half sections terminating with m equal to .6.



Half Section
m = .6



Full K-Section
m = 1

The values of X_L on the chart are equal to the inductive reactance when $f = \frac{f_m}{R}$ where

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[9] C. J. Merchant, "Band Pass Filter," Electronics Volume No. 18, March 1945, p. 146

$f_m = \sqrt{f_1 f_2}$. f_1 = lower sideband frequency and f_2 upper sideband frequency. The values of X_C are equal to the capacitive reactance when $f = f_m R$.

The most narrow bandpass filter given on the chart is a ratio of $\frac{f_2}{f_m} = 1.05$. In this case $f_2 = 1.05 \times 10.5$ KC $= 11$ KC. Therefore, the filter will pass frequencies between 10 and 11 KC.

Assuming the terminal impedance R equal to 600Ω, the frequency used in calculating the inductors is $\frac{10.5 \times 10^3}{600} = 17.5$ cps . The frequency used in calculating the capacitors is equal to $600 \times 10.5 \times 10^3 = 6.3$ megacycles. Using the formulas $L = \frac{X_L}{2\pi f}$ and $C = \frac{1}{2\pi X_C f}$ the component values for the filter were calculated. After combining series elements the final filter is shown in Figure 20.

A filter of this type cannot easily be constructed from standard parts. They are manufactured as one package units. Some provide for minor tuning adjustments.

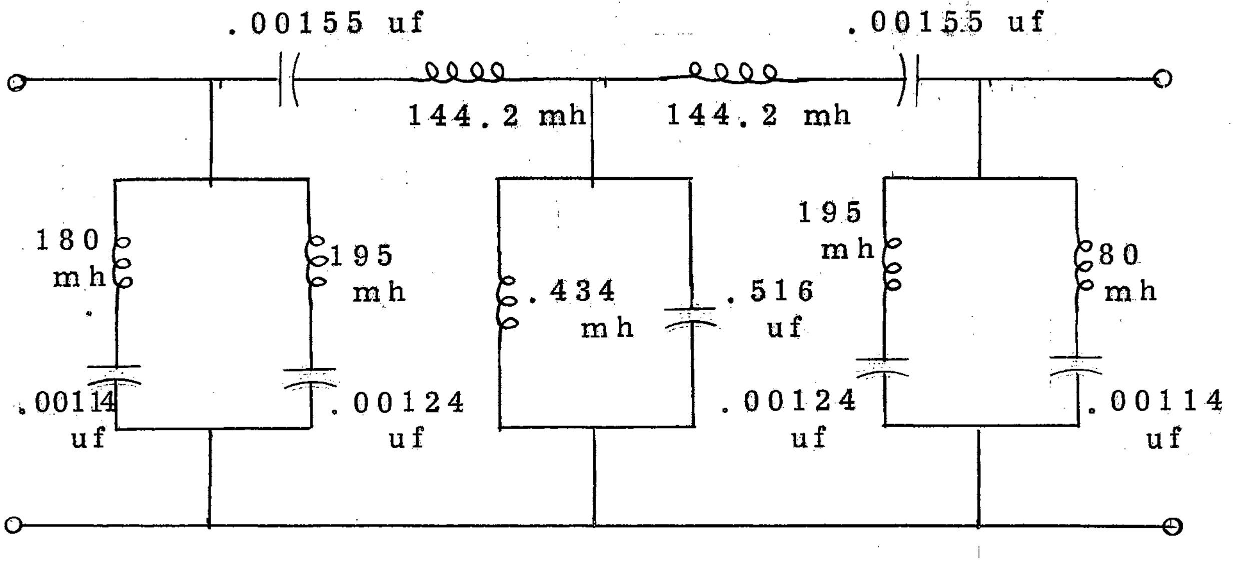


Figure 20. Band Pass Filter

CHAPTER VII

TRANSMITTER TESTS AND RESULTS

The initial tests of the transmitter were conducted with each stage operating independently. These tests were performed on the prototype "breadboarded" circuits before the final compact transmitter was assembled.

Subcarrier Oscillator and Amplitude Modulator

An audio signal generator was used to simulate the transducer output. An oscilloscope was used to observe the circuit output appearing across the LC tank. The initial test arrangement is shown in Figure 21.

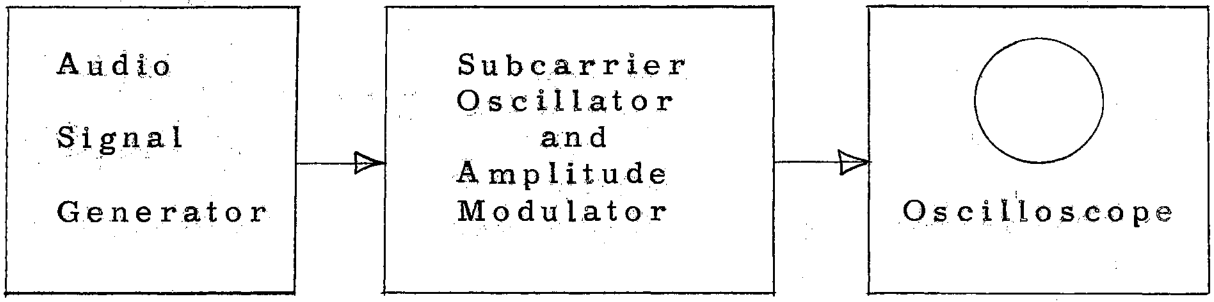
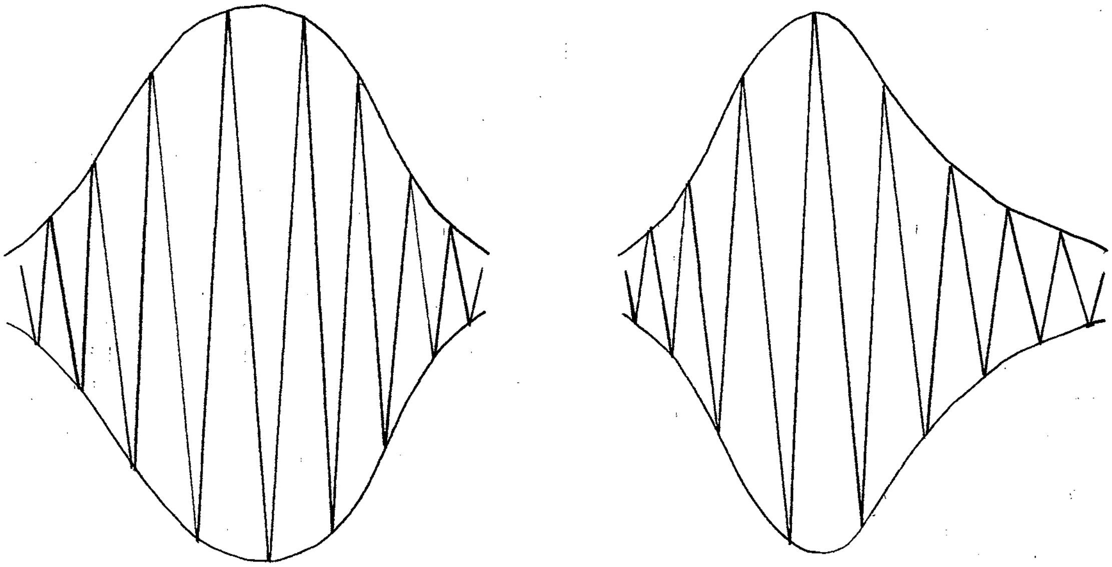


Figure 21. Subcarrier Oscillator and Amplitude Modulator Test Diagram

With no modulating voltage input the oscillator output was viewed on the oscilloscope. The frequency of operation was calculated by a time base measurement (f = 1/t) and found to be very near 10.5 kilocycles. The base to ground resistor was adjusted to give maximum oscillator voltage across the LC tank. This voltage measured 4.5 volts RMS.

A small modulating voltage was applied and the frequency of the generator was varied from 20 to 400 cps. The waveform showed that above 100 cps the modulation envelope assumed an RC charge and discharge shape as shown in Figure 22.



(a) below 100 cps (b) above 100 cps

Figure 22. Modulation Waveforms Before Correction

The emitter to ground resistor was reduced from 10 K to 6.2 K. This resulted in extending the undistorted 100% modulated waveform to above 200 cycles. At 300 cycles the modulation envelope was undistorted up to 80% modulation. At 400 cycles the envelope indicated distortion when modulated above 70%. This is shown graphically in Figure 23.

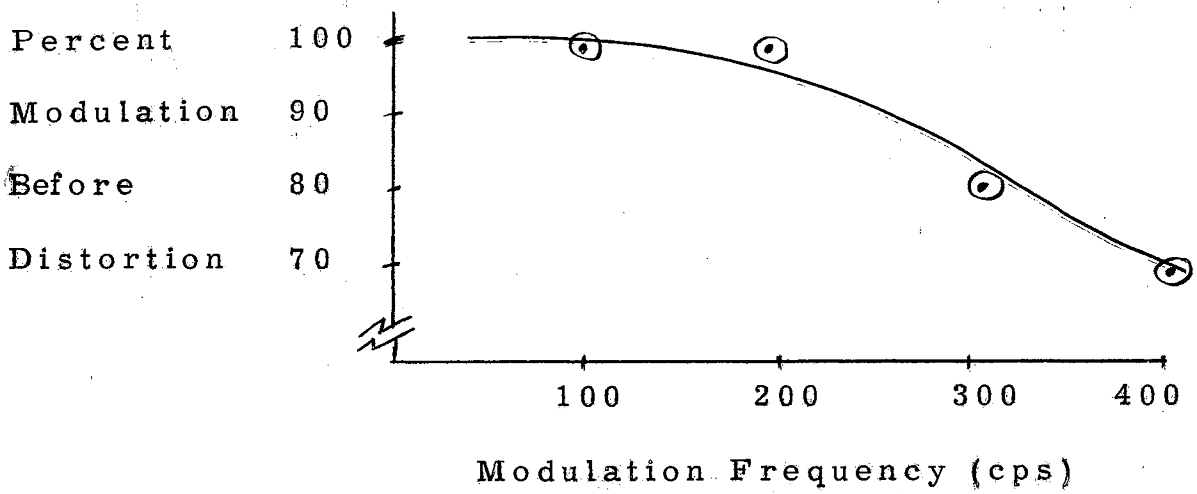


Figure 23. Modulation Distortion versus Frequency

The power required to modulate the carrier 100% was determined by two measurements. The voltage of the audio signal generator was measured at the point of 100% modulation. A series resistor was then inserted in the generator lead and the voltage measured across it to determine the current. Modulation power was calculated by multiplying these factors together. This data is presented graphically in Figure 24.

An examination of Figure 24 reveals that the power output requirements for the flowmeter are entirely feasible. At the mid frequency range of 200 cycles only .25 milliwatt is required to modulate the carrier 100%. The voltage across the oscillator tank circuit varied from 6 volts at 50 cycles to 7 volts at 400 cycles under conditions of 100% modulation. This indicates the stage performs more efficiently at higher frequencies. This is also shown by the decreasing modulation power requirement as frequency was increased.

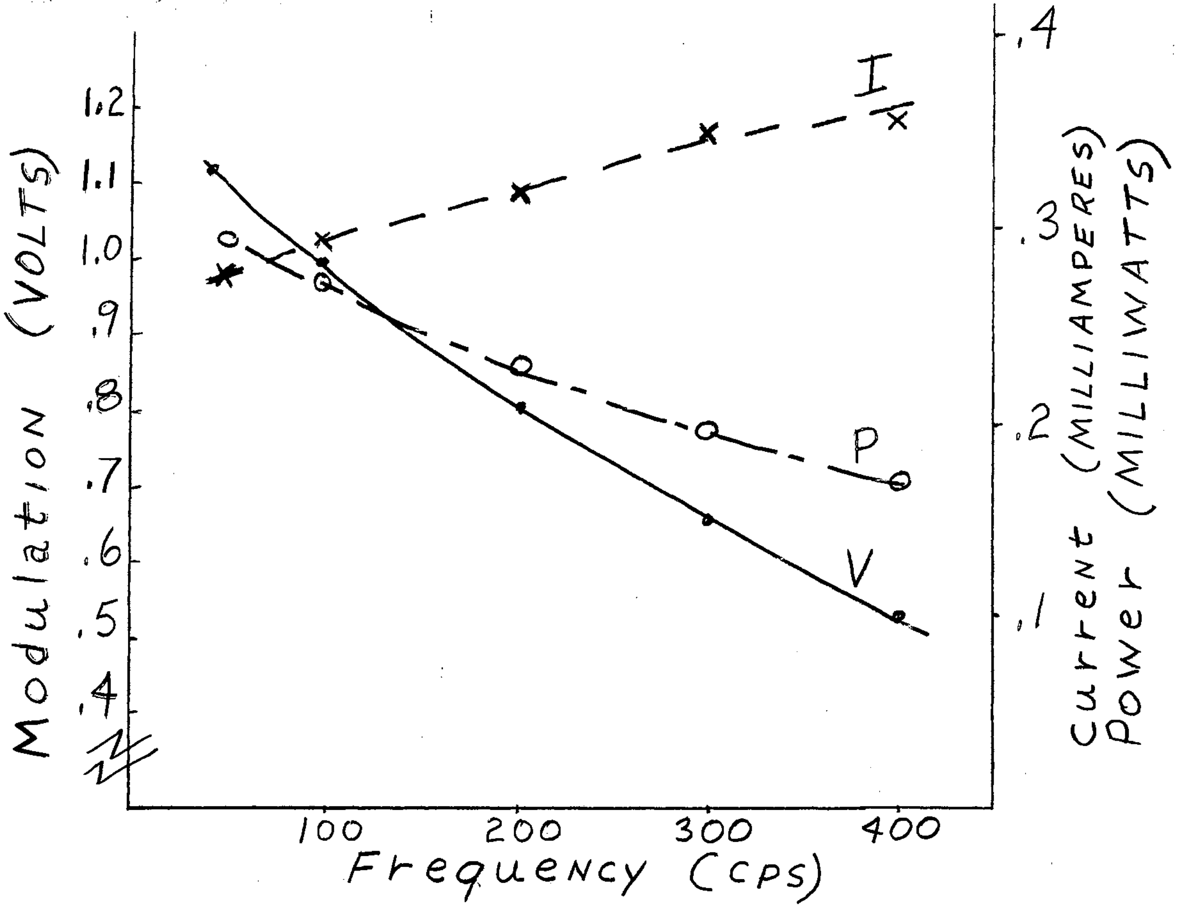


Figure 24. Subcarrier Oscillator Modulation Power

Combining Circuit and Amplifier

The combining circuit and amplifier was tested for gain and linearity over a broad band of frequencies. A 2 volt signal was applied across the 33 K base to ground resistor and the supply voltage was varied for maximum gain and stability. The frequency of the input signal was varied from 20 cycles to 20 kilocycles and the output did not vary a measureable amount. This indicated a wide constant gain bandpass. The voltage out was measured from the center of the split 2 K load to ground. With a 1 volt signal into the base circuit the output voltage was a .6 volt. The gain of this circuit is .6. Gain has been sacrificed in this circuit for wide bandpass, linearity, and a low output impedance.

RF Generator and Frequency Modulator

The RF generator was modulated with a 1 volt, 600 cps signal applied across the split 2 K emitter resistor. The transmitter was tuned to 100 megacycles by adjusting the collector tank capacitor. The signal was picked up on a standard FM receiver and also observed on an oscilloscope connected across the primary of the receiver output transformer. This is illustrated in Figure 25.

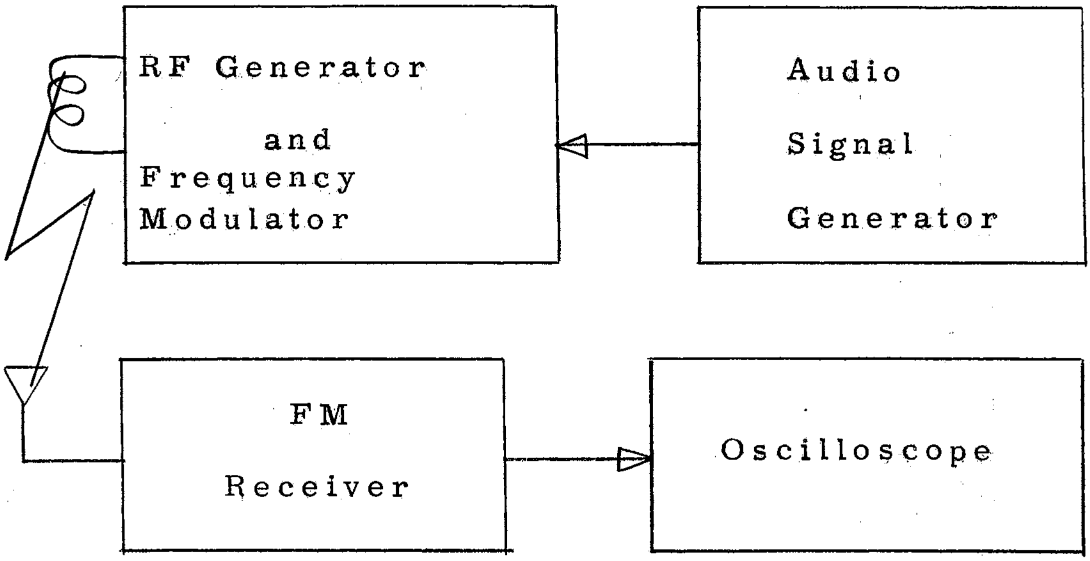


Figure 25. RF Generator and Frequency Modulation Test Diagram

Exact tests on this stage were not performed due to limitations of the receiver. For example the degree of frequency stability could not be ascertained because the receiver was known to drift. A picture of the signal prior to entering the ratio detector of the receiver also was unobtainable due to detuning effects of any connections at this point. The signal picked up and observed consisted of half cycle wave-forms of the modulating signal.

The transmitter operated properly with the modulating signal in the range of 1 to 4 volts. With a 2 volt signal input the collector dissipation was 94.5 milliwatts. The modulating frequency was varied within the limits of the audio band. The transmitter operation was satisfactory at these frequencies.

Final Tests

The circuits were reassembled in a plastic box 2" x 6" x 3/4". A package of this size could be made very rugged by sealing with a resilient compound. This package is exclusive of batteries.

All circuits were tested again individually and found to be operating normally. The RF generator circuit appeared more stable. This was attributed to the reduction of leads and battery connections.

A 200 cps, 1 volt signal was applied to the subcarrier oscillator and amplitude modulator circuit. This was sufficient to slightly over modulate the subcarrier. The output voltage was 6.4 volts appearing across the voltage divider. The voltage into the common collector circuit was 2.5 volts. The output voltage of the common collector circuit was 1.5 volts. This voltage was sufficient to modulate the RF generator. The transmitted signal was picked up on the FM receiver.

CHAPTER VIII

SUMMARY

The purpose of this thesis has been to (1) acquaint the reader with telemeter importance and techniques, and (2) use these techniques in designing and developing a telemeter transmitter capable of relaying fuel flow information. It is believed that both purposes have been fulfilled.

The transmitter meets the initial design specifications in that it is only 2" x 6" x 3/4" dimensionally, weighs approximately 6 ounces, is sturdy, dependable, and carries its own power source.

Certain limitations were found in the amplitude modulator circuit. However, the distortion above 200 cycles per second does not interfere with the information being conveyed. This distortion could be eliminated by decreasing the values of capacitance and increasing the inductance in the oscillator. The remainder of the transmitter circuits operated satisfactorily.

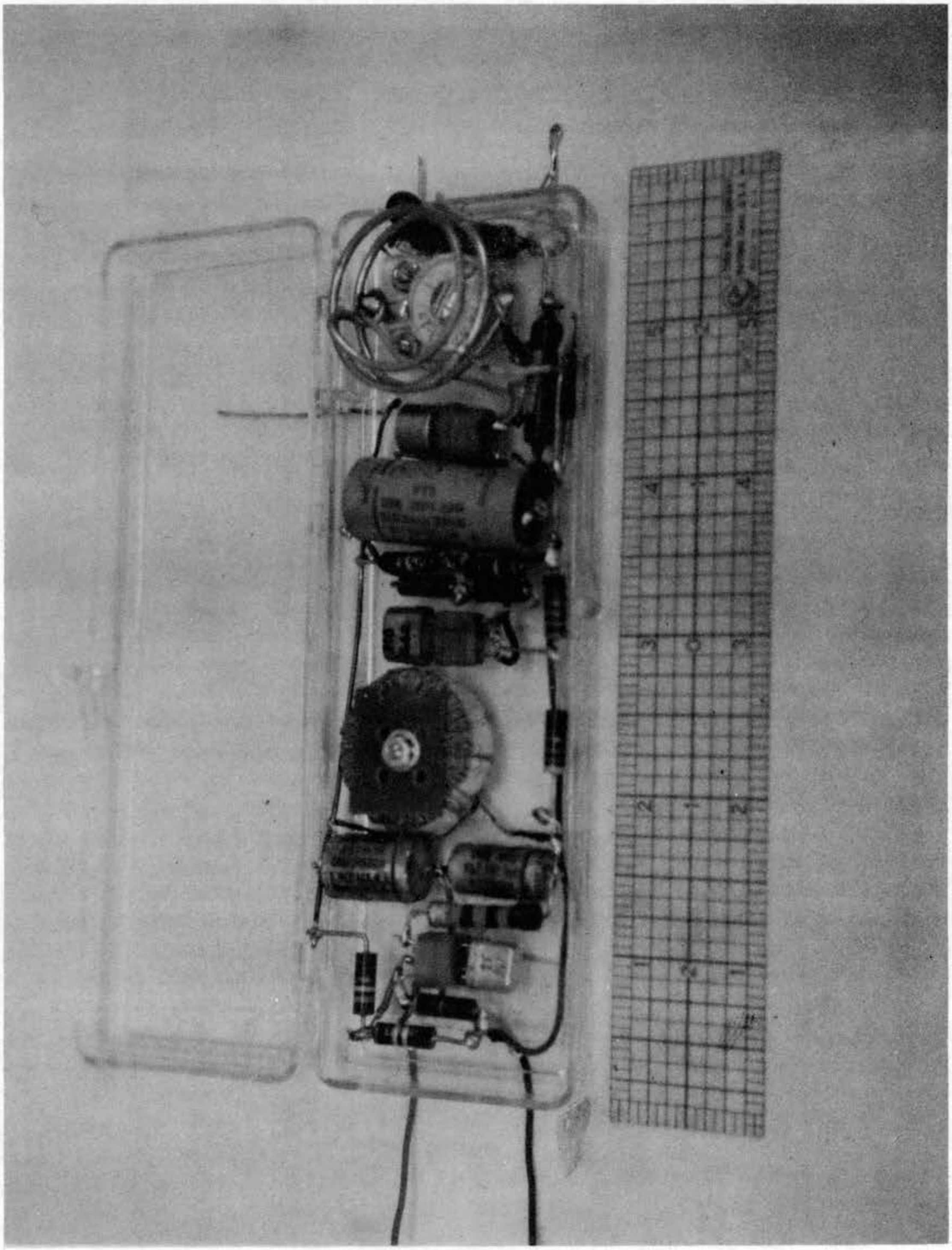


Figure 26. Photograph of Transmitter.

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APPENDIX A

TRANSISTOR PARAMETERS

Sylvania Type 2N34

150 mw at 25°C

V_c max = -40 V

Max T = 75°C

$B = 40$

r_e = 26 ohms

r_b = 800 ohms

r_c = 2 meg ohms

f_{aco} = 600 KC

C_e = 15 uuf

I_{co} = -5 ua

NF = 18

Texas Instruments Type 2N1143

750 mw

V_{cb} = -25 V

V_{eb} = -.5 V

I_c = -100 ma

I_e = 100 ma

f_{aco} = 480 mc

max T = 100°C

r_b = 75 ohms

Texas Instruments Type 210

Audio Type

V_c max = 20 V

VITA

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